

THE GEOLOGY AND MINERALIZATION OF
THE AD-DAWADMI DISTRICT OF SAUDI ARABIA

by

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ABSTRACT

This district in the high pediment of central Saudi Arabia contains a complex of Precambrian granitic rocks together with two oval layered basic complexes and two belts of folded metasediments. Economic interest centres on sulphide mineralization in the metasediments, and on numerous vein deposits which formed an ancient silver-mining industry and which are emplaced in parts of an extensive fracture belt trending N-S across the district.

The oldest rocks are the conformable arenaceous and calcareous Ar-Ridaniyah, and the semi-pelitic Abt Formations, which were deposited during Precambrian in a transgressive subsiding probably marine environment. An ultrabasic and basic suite of rocks were intruded prior to deformation and metamorphism to greenschist facies. Two layered masses were later intruded, the detailed studies on Al-Jealani intrusion indicated an inverted cone-shaped mass formed from a basaltic melt in possibly one surge of magma in an elliptical structure forming layered gabbroic rocks with persistent dominant plagioclase. The pyroxene rich units were strongly amphibolitized. Layering originated through undercooling combined with convection currents in the magma. Investigations up to date show that these complexes are barren of mineralization. A multicycle history of granite intrusions took place after the emplacement of the layered masses. Three separate types are recognised, differentiated in time from more calcic to less calcic from an average calc-alkaline magma.

The fracture-controlled hydrothermal zinc-lead-silver mineralization is one of two main genetic types in the district. In the vein-type, the metals initially present in a N-S trending belt of pre-existing sedimentary rocks are thought to have been mobilized, concentrated and deposited by the medium of hydrothermal fluids related to post-kinematic granitic activity during the last orogenic episode. The ore minerals within the fractures are sphalerite, galena, native silver, silver sulphosalts and sulphides. The other genetic type is iron-zinc sulphide deposit in the form of metamorphosed and structurally

disrupted stratabound lenses within the calcareous horizon of the Ar-Ridaniyah Formation. The principal minerals are pyrrhotite and sphalerite, and the mineralization is interpreted as metamorphosed syngenetic-diagenetic in a sedimentary calcareous environment.

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GLOSSARY, ABBREVIATIONS AND SYMBOLS

The underlined terms are those used in this thesis.

Geographic names:

<u>Jabal</u>	Hill or mountain
<u>Wadi</u>	Valley, stream

Towns:

<u>Jeddah, Jiddah</u>	Jidda, Djedda
<u>Ad-Dawadmi</u>	Ad Dawadami, Dawadmi
<u>Arjah, Arja</u>	
<u>Um Ergaba</u>	Um Ergabah, Umm Ergaba
<u>Saffaga</u>	<u>Saffagah</u>
<u>Al-Jealani</u>	Harrat Jaelani
<u>Al-Hufairah</u>	<u>Hufayra</u> , Hufairah
<u>Ar-Ridaniyah</u>	Ardaniyah

Organisations:

<u>D.G.M.R.</u>	Directorate General of Mineral Resources
<u>U.S.G.S.</u>	United States Geological Survey
<u>B.R.G.M.</u>	Bureau de Recherches Geologiques et Minieres
<u>Argas</u>	Arabian geophysical and surveying company -

Miscellaneous:

<u>E.P.M.A.</u>	Electron probe microanalyser
<u>DH</u>	Drill hole
<u>P.L.</u>	Initials of French assistant geologist P. Laloux (used in numbering the ancient prospects)
<u>G.V.</u>	Initials of the French geologist G. Vincent (used in numbering the ancient prospects)
<u>S.P.</u>	Self-potential geophysical survey method
<u>E.M.</u>	Electromagnetic geophysical survey method

<u>μm</u>	micron
<u>cm</u>	centimetre
<u>m.</u> , <u>mr.</u>	metre
<u>$\text{\AA}$</u>	angstrom units (10^{-8} cm.)
<u>wt.%</u>	= weight %
<u>at.%</u>	= atomic %
<u>2V</u>	The optic axial angle
<u>T</u>	temperature
<u>P</u>	pressure

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CHAPTER 1

INTRODUCTION

1.1 LOCATION AND ACCESSIBILITY

Ad-Dawadmi district which is the subject of this geological research lies some 760 kilometres east north-east of Jeddah town, and some 320 kilometres west south-west of the capital, Ar-Riyad (fig. 1-1), on the asphalt road that connects these towns. The district is situated at the extreme east-central border of the Arabian Shield with the unconformably overlying Palaeozoic sediments. The area concerned covers about 2426 square kilometres and lies partly on aerial mosaic 98 and partly on 101. Ad-Dawadmi town is situated approximately in the middle of the district. A few other villages are also present in the district, namely: Arja, Musiddah, Ismairah, Hamrur, Saffagah and Al-Hufairah. The district lies between latitudes $24^{\circ}19'$ and $24^{\circ}45'$ north, and longitudes $44^{\circ}13'18''$ and $44^{\circ}43'8''$ east (fig. 1-2).

The district is accessible for field cars.

1.2 GEOLOGICAL SETTING

Bramkamp et al. (1963) considered the Ad-Dawadmi district, which is studied in detail in this thesis, to contain four main geologic units (fig. 1-3).

However, the geological setting is summarized on the basis of this study to be as follows :

A granitic batholith makes up over 80% of the district and constitute three granitic varieties, the earlier variety is heterogeneous and is greatly enriched with xenoliths. Two layered basic intrusions occur in the district, a southern one Al Jéalani covering an area of about 50 Km^2 and a northern, Arja covering 9 Km^2 , (fig. 1-4), both are oval in shape and contain inwardly dipping igneous layers. In the north and in the south east, metamorphic sedimentary

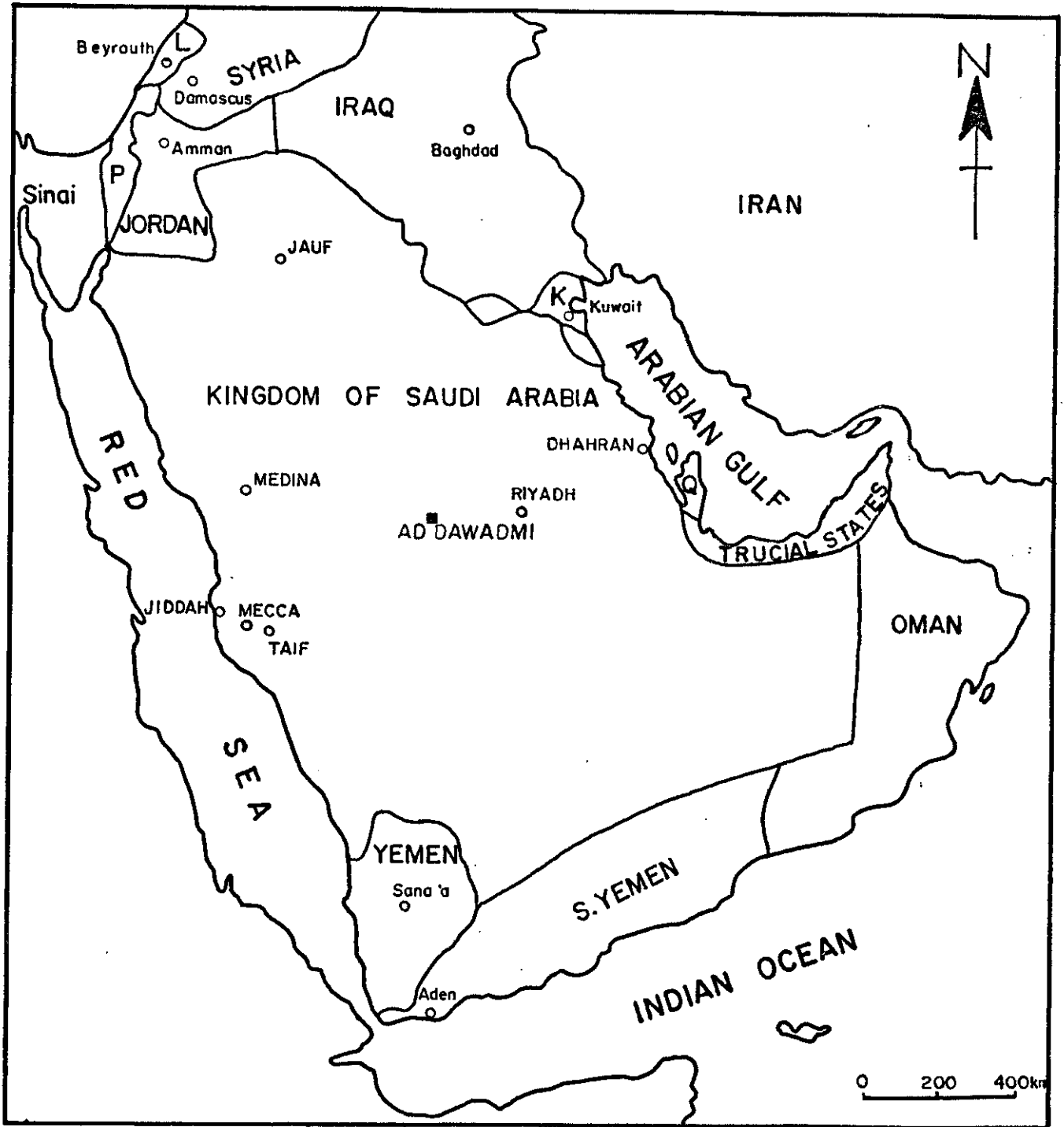


Fig : 1-1

ARABIAN PENINSULA

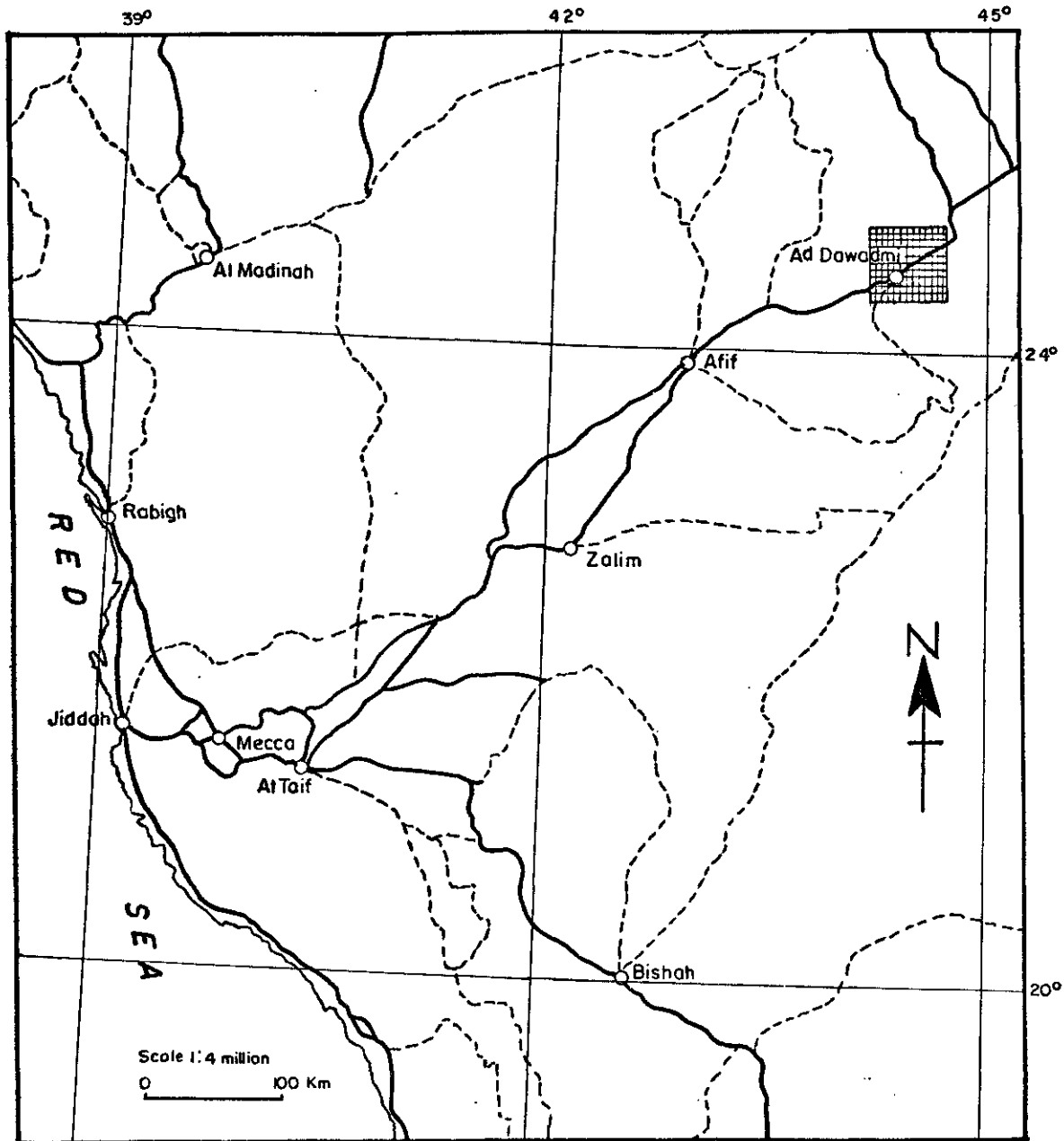
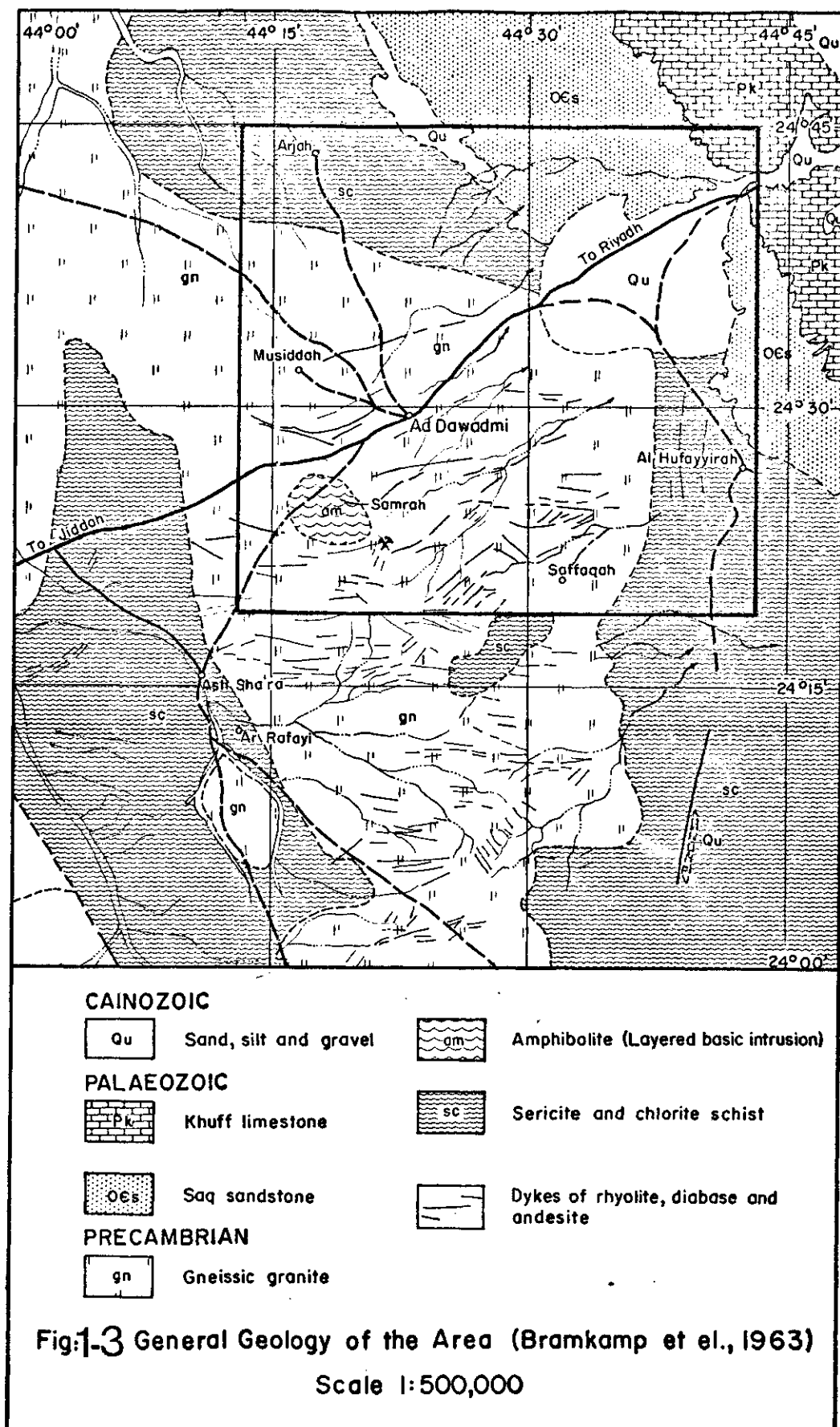
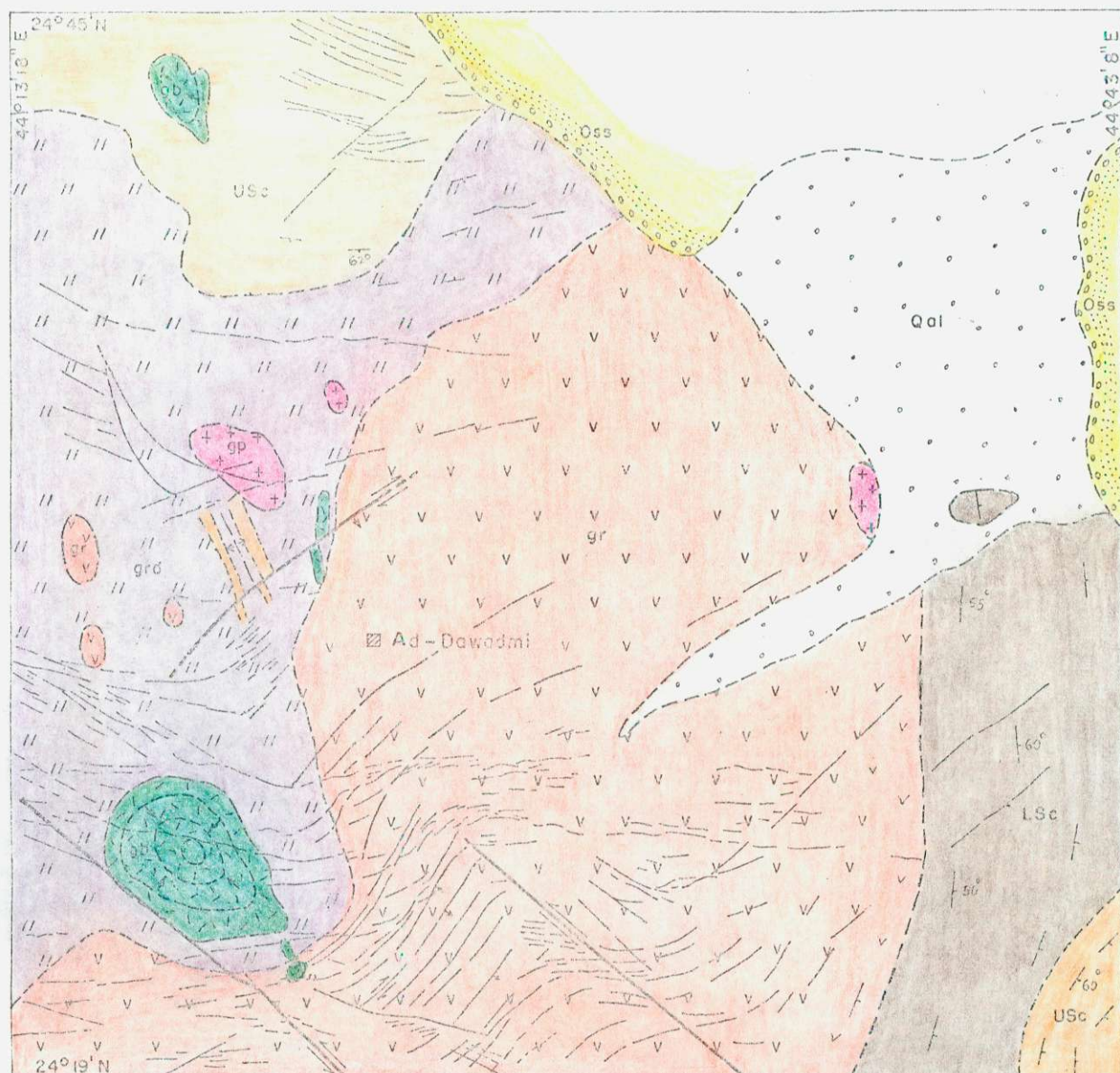


Fig :1-2

LOCATION OF THE DISTRICT





GEOLOGICAL MAP OF THE AD DAWADMI DISTRICT

Approximate Scale 1:250,000

LEGEND

Cainozoic

Qal Alluvium

Palaeozoic

Oss Sediments

Precambrian

gp Post-kinematic granite

gr Late-kinematic granite

grd Syn-kinematic granite

Layered basic intrusion

USc Abt Formation

LSc Ar-Ridaniya Formation

Fault indicated and inferred

Shear zones

Strike and dip of strata

Dip of layering

Geological contact, indicated and inferred

Town

fig: I-4

successions occur, these are unconformably overlain in the east by Ordovician sandstone.

A well developed fracture pattern characterises the district where swarms of dykes and zinc-lead-silver veins have been intruded.

The sequence of geological events started by the deposition of sediments in a transgressing probably marine basin, intruded during a long time span by ultrabasic, basic and extensive granitic intrusions. The district was affected by two principal orogenies, the multicyclic Hejaz orogeny (1000 - 660 m.y.B.P.) and Najd Orogeny (660 - 570 m.y.B.P.) Brown et al. (1972).

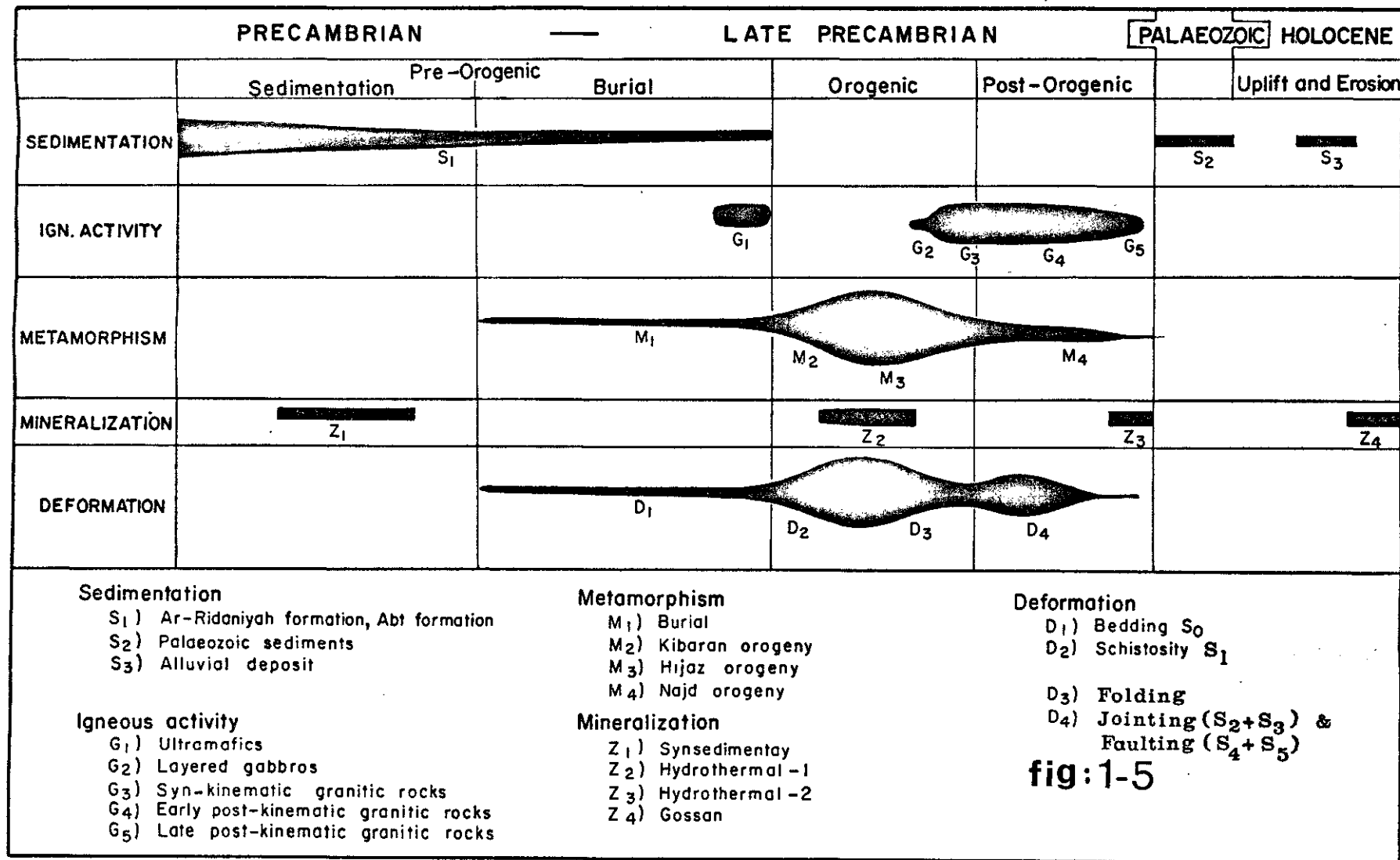
The metasediments and the early basic and ultrabasic intrusions suffered during the Hejaz orogeny deformation, folding and metamorphism to the greenschist grade.

The metasediments belong to two conformable Formations, the lower Ar-Ridaniyah, which constitute a quartzo-feldspathic unit at the base and an overlying Abt, which is essentially pelitic and semi-pelitic. The several phases of granitic intrusions which formed the present batholith, were preceded by successive intrusions of ultrabasic and basic rocks now represented by lenses, xenoliths, hybrid rocks and by the later elliptical layered basic masses.

The regional stratigraphy and the suggested tectonic history for the district are represented on page 25 and in fig. 1-5.

The emplacement of the early synkinematic granitic rocks, which are foliated heterogeneous and porphyritic, was followed by the emplacement of the homogeneous late-kinematic type at the waning stages of the multicyclic Hejaz orogeny.

The Najd orogeny, on the other hand, which is less widespread followed the Hejaz orogeny to produce the important Najd wrench fault system (fig. 6-1), Brown (1974). According to Brown, this orogeny is probably the continuation of the same east-west compressive forces of the Hejaz orogeny. The Najd orogeny is represented in the district



Regional stratigraphy and suggested tectonic history for

Ad-Dawadmi District

System	Depositional rock units in Ad-Dawadmi	App. thickness in meters	Tectonic episode and duration (Arabian)	Plutonic Rocks in Ad-Dawadmi district	Tectonic episode (African)	Depositional units in other areas of Arabian Shield
Cainozoic	Unconsolidated sediments	0-20	Unconformity			
Palaeozoic	Ordovician Saq Sandstone	200	Angular unconformity			
			NAJD OROGENY 660-570 m.y. Shearing, fracturing	Post-kinematic granite	Pan African tectonothermal event	
			Nonconformity			
Pre-Cambrian	Abt Formation	Over 3Km	HFJAZ OROGENY 1000-660 m.y. B.P. Metamorphism and folding	Late-kinematic adamellite, Syn-kinematic granitic rocks.	Katanga Orogeny	Halaban Group
	Ar-Ridaniyah Formation	3-5 Km	"KIBARAN" Orogeny (culminated at 1000 m.y.)	Layered gabbro, Ultrabasic rocks	Kibaran Orogeny north-east	Bahah Group
	Old basement, not represented.					

by the emplacement of post-kinematic granitic intrusions (570 m.y.B.P.), northwesterly sinistral wrench faults and secondary extensive fracturing and subsequent dyke intrusion.

The secondary fractures in the district were partly emplaced by zinc-lead-silver veins.

This vein-mineralization is related to the post-Kinematic granitic intrusions where the residual magmatic hydrothermal solutions leached out metals from the pre-existing rocks within the granitic batholith and deposited them along the developed fractures. Subsequent to this deposition, reactivation of movements along these fractures caused shearing, brecciation, mobilization and recrystallization of these ore deposits.

1.3 PURPOSE OF STUDY

The object of this research has been to study the geology of the area in order to formulate an understanding of its mineral potential. The field work was carried out during two winter seasons for a total period of seven months.

The granitic rocks and their relationships with the pre-existing country rocks was established. The geology and petrology of the Al-Jealani layered basic intrusion has been studied. The two metamorphic belts, Ar-Ridaniyah and Abt were mapped and duly investigated. The structure, the metamorphism, the nature of mineralization and its controls were studied.

1.4 CLIMATE, VEGETATION AND POPULATION

The district has a typical arid dry climate. Humidity is usually low. There are considerable diurnal and seasonal temperature variations from 0° - 25°C in winter and from 25° - 45°C in the summer. The annual rainfall of about 6 cm falls in a few stormy showers which cause flash floods in winter. The vegetation is scarce, represented only by scattered palm gardens around the villages behind artificial dykes at edges of wadis.

Water for irrigation and drinking is pumped from drilled or hand dug wells in wadis.

The population in the whole district makes up about 6000 people dwelling in the villages. Moving Bedu families live away from the villages rearing live-stock.

1.5 PHYSIOGRAPHY

Ad-Dawadmi district is part of Najd. The name applies to the vast plateau which slopes gently eastwards from the Hejaz escarpment at 1500 m above sea level. The district is part of a wide penéplain superimposed on a granitic batholith. The relief is predominantly low and the drainage system is poorly developed. A thin cover of sand, silt and gravel partly covers this plain.

The north-eastern area is drained by wadi Tasrhir, into which the wadis of Sidriyah and Dhaf flow. Wadi Tasrhir flows eastwards crossing the Khuff limestone escarpment. The north-west and northern areas of the district are drained by both wadis Arja and Mussiddah, which join and flow west-north-west to join a northerly flowing wadi which joins Wadi Ar-Risha.

Isolated individual hills of exfoliated granitic rocks, and ridges, 20 - 100 m high serve as landmarks. In the south-west, an elliptical layered basic intrusion occurs with characteristic circular or curved ridges rising locally to about 70 m. In the southeast, a series of northerly trending elongated ridges 20⁺ m high occur underlain by metamorphic rocks and intrusive concordant and discordant plutonic rocks. Long east-west trending dark grey and pink ridges mark the district, where it has been intruded by swarms of dacite and rhyolite dykes.

1.6 MINERALIZATION

Ancient mines and prospects are widespread in the district, essentially localized along and at intersections of shear and tension fractures. The mineralization in the district is of two styles.

The first style comprises structurally controlled sulphide vein deposits, and these are localized in fracture zones where wall rocks are strongly sheared and brecciated. The principal minerals in the veins are sphalerite, galena, pyrite, chalcopyrite and silver minerals represented by polybasite, argentite, pyrargirite, tetrahedrite (freibergite), native silver and occasional stromeyerite. Minor amounts of magnetite and hematite, arsenopyrite, pyrrhotite and occasional grains of millerite also occur. The gangue minerals are usually, quartz, calcite and chlorite and less abundant sericite and epidote. The mineralized fractures are mainly situated within the granitic batholith (Plate 1), which includes numerous inclusions of pre-existing basic and metasedimentary rocks. Other, less abundant vein mineralization occurs in the metamorphic belt of the Ar-Ridaniyah in the south-east and in Arja area.

The second style is sulphide deposits within the calcareous horizon of Ar-Ridaniyah Formation. Lenses of essentially, pyrrhotite-sphaerite assemblage with surface gossan exposures are stratabound, but are cut and displaced by mineralized faults which may derive sulphides both by mobilization from the stratabound zone and by hydrothermal solutions with associated cassiterite and stannite.

Jabal Humayyan, which constitutes the northernmost outcrops of the Ar-Ridaniyah belt contains ferruginous-siliceous lenses which are locally converted to gossan. These lenses are included within a series of schistose serpentinites and chloritites metamorphosed from olivine and/or pyroxene rich rocks. Geochemical investigations by BRGM showed local anomalous nickel and copper.

The silver mineralization discovered in the district to date has proved uneconomic. Investigation studies are still being carried out in Jabal Humayyan for nickel.

1.7 GEOLOGICAL MAPPING

Fig.1-3, represents a reconnaissance geological map by Bramkamp et al. (1963) within which the limits of the studied district lie.

Fig. 1-4 shows the geology, the physiography and the outline of the studied area.

A granitic batholith makes up over 80 percent of the district. Numerous biotite schist and basic xenoliths, besides older layered basic intrusions, occur within this batholith. The southeastern and the northern parts are occupied by metamorphic schist belts while the northeast part is underlain by unfolded Palaeozoic sediments which rest unconformably on the older rocks.

The geology of the district is plotted on 1 : 50,000 scale overlay for aerial mosaics 98 and 101. Aerial stereo-pair photographs at 1 : 60,000 scale were used for field mapping (Plate 1).

The layered basic intrusion of Al-Jéalani was mapped on 1 : 10,000 scale photographic enlargements from 1 : 50,000 mosaics (Plate 3).

Detailed plane-table geologic-topographic maps at 1 : 1,000 scale for both Samrah ancient mine (Plate 4) and Ar-Ridaniyah gossan zones (Plate 2) were done during the course of study of the district by the author.

Faults and fractures in the south were plotted on a separate map (fig. 6-2) to aid in the analysis of the fracture system which is so prominent in the district.

1.8 PREVIOUS WORK

Previous work relevant to the geology of the area is summarised in the following:

1. In 1932 K.S. Twitchell examined the ancient workings of Samrah mine and sampled the dumps.
2. Bogue, R.D. (1954), carried out some geological investigations at Samrah mine and sampled the old workings and the dumps.
3. Bramkamp et al. (1963) mapped the regional geology of the Wadi Ar-Rima quadrangle and compiled the 1 : 500,000 scale geological map, 206A.

4. Quin, H. (1964, a, b, c) carried out a program of sampling the dumps in Samrah ancient mine, mapped the old workings of Um-Ergaba, of Samrah and of Ar-Ridaniyah. He also studied the basic intrusion.
5. Theobald, P. (1966), studied the geology and the geochemistry of Samrah ancient mine and the vicinity.
6. Mytton (1965) spent few days on geological reconnaissance of the Ad-Dawadmi area.
7. Eijkelboom, G. (1966), mapped the regional geology of sheets 98 and 101, scale 1 : 100,000 as part of BRGM exploration of zone II.
8. Kiilsgaard (1968), evaluated the diamond drilling programme of Samrah prospect and estimated the reserves.
9. Lambolez, B. (1968), interpreted the airborne magnetic sheet 101, which covers the Ar-Ridaniyah area and the basic layered intrusion.
10. Several other geologists from BRGM spent varying amounts of time in the area, where they described the mineral localities and their exploration, these are: Lacombe and others (1969), Letalenet and others (1969), Bois and Shanti, M. (1971), Corpel et al. (1971).
11. Meaton (1971) carried out an exploration trenching programme of the ancient prospects and supervised a drilling of 12 holes in favourable sites in the district.

CHAPTER 2

THE METASEDIMENTARY FORMATIONS

2.1 INTRODUCTION

The metasedimentary successions in the district are divided on the basis of lithology and distribution, into two Formations, the basal one Ar-Ridaniyah Formation and the overlying Abt Formation (fig. 2-1). These two Formations have undergone regional metamorphism and recrystallization under conditions of repeated Precambrian orogenies. The most intense and widespread of these is the Hejaz orogeny, Brown, et al. (1972). Rocks of the two Formations flank the granitic batholith. The Abt Formation being spatially predominant. Their occurrence is not restricted to this area but both extend to the south, Abt extends to the north and west as well (plate 1). Numerous xenoliths are incorporated in the granitic batholith and have retained their structural trends.

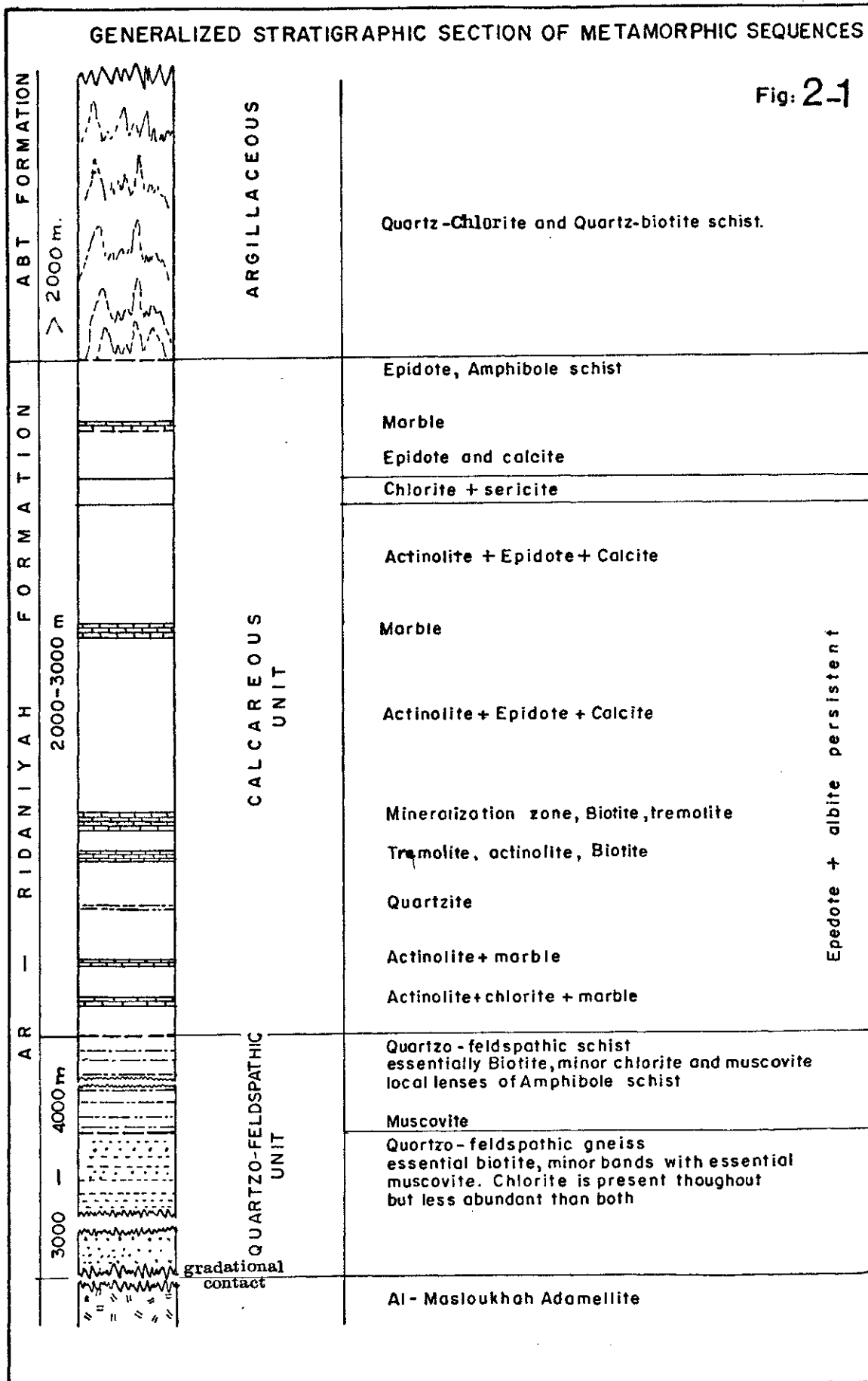
The two Formations exhibit continuous concordant contact. Both have been injected by pre-, syn-, late-, and post-kinematic rocks of ultrabasic, basic, intermediate and acidic nature, in the form of sheets, dykes, sills, and larger intrusive bodies. Contact metamorphic aureoles are locally developed superimposed on regionally metamorphosed rocks.

A belt of quartzo-feldspathic gneiss borders the granitic batholith in the east and separates it from the overlying Ar-Ridaniyah Formation. The gneiss grades easterly into quartzo-feldspathic schist. Both comprise the base of this Formation with no evidence of a sharp contact.

The emplacement of the granitic batholith with its longer north-westerly axis roughly parallel to the fold axes in both Formations, took place at the waning stages of metamorphism which affected the geosynclinal sediments during the Hejaz orogeny (see section 2.7).

GENERALIZED STRATIGRAPHIC SECTION OF METAMORPHIC SEQUENCES

Fig: 2-1



2.2 AR-RIDANIYAH FORMATION

Ar-Ridaniyah Formation, which is the lower in the geosynclinal sequence in the district is represented by its exposures in the southeastern corner of the map (plate 1). It covers an area of some 300 km^2 and attains an approximate average thickness of 5000m. The relief is flat for the major north part of the Formation, except for individual hills 5-10 meters high. In the south, ridges approximately N-S parallel to bedding are common. In the west, sand conceals a great part of the quartzo-feldspathic gneiss and schist horizons at the base of the formation, and contacts are mostly inferred. Local cross-cutting streams have provided some exposures.

In terms of lithologic features, sedimentary structures and composition, six rock units could be recognised. Four of these have been represented on the map (plate 1) as one lithologic unit i.e. calcareous schist, the rocks of which are dominantly calcareous thinly banded. A diagrammatic stratigraphical column is shown (fig. 2-1).

2.2.1 Quartzo-feldspathic gneiss: (As-734)

A 2-4 Km. wide belt of quartzo-feldspathic gneiss borders the even-grained Al-Masloukhah adamellite on the east. The contact is nowhere properly exposed, but an inferred gradational zone could be outlined. This inferred zone runs more or less parallel to the schistosity direction in the overlying Ar-Ridaniyah Formation. The schistosity in the quartzo-feldspathic gneiss is well developed 010° - 015° and dips 50° - 70° easterly in the south, and swings to 012° - $N00$ and dips 50° in the north. Aplite-pegmatite dykes occupy planes parallel to schistosity. They are especially abundant in the transitional border zone which ranges between 50-100 metres in width, situated between the Al-Masloukhah adamellite and this gneiss belt. Dark bands of thermally metamorphosed hornblende-plagioclase-hornfels are occasionally intercalated in the gneiss. The gneiss is cut by faults 030° - 140° and dip 60 - 70° NE infilled commonly with white quartz veins.

The quartzo-feldspathic gneiss is predominantly leucocratic, but occasional darker bands occur. It is of medium grain size generally, but finer grained bands are more common away from the border zone. Porphyritic bands are abundant in the vicinity of the border zone (As-742). In thin section the essential minerals of the gneiss are as follows: Plagioclase, occurs in two forms, phenocrysts with inclusions of muscovite, quartz and biotite, and fine grained in the groundmass; locally plagioclase inclusions occur in quartz. It is oligoclase in composition (An_{24-18}), and albite rims are common. K-feldspars, both microcline and perthitic orthoclase, occurs in small grains in the groundmass as well as in phenocrysts. The latter are more abundant than plagioclase phenocrysts. Inclusions of plagioclase, quartz and orientated biotite are common. The phenocrysts exhibit irregular outlines and evidence of replacement of pre-existing minerals.

Quartz occurs as deformed irregular grains, in elongated aggregates (fig. 2-2a), as worm-like grains in the myrmekitic intergrowths with feldspars, and as drop-like inclusions in feldspar phenocrysts.

The mafic constituents are represented by biotite, and chlorite. Biotite, brown with greenish tint is the main mafic mineral in the major part of the gneiss. It occurs in small orientated flakes commonly segregated into bands parallel to schistosity planes.

Muscovite dominates the biotite in the marginal layers bordering the adamellite, and occurs also in subordinate amounts in the overlying gneiss.

Chlorite is present in small amounts throughout the gneiss belt, but locally (As-742) it is dominant over both biotite and muscovite. Chlorite is probably a later alteration product of biotite throughout this horizon.

Allanite, apatite, sphene and opaque monoxides are common accessories.

2.2.2 Quartzo-feldspathic schist (As-792, As-747, As-748, As-791, As-789)

This is a poorly exposed unit at the base of the Formation. It grades westerly into quartzo-feldspathic gneiss. The boundaries are inferred and the contacts, where seen, are gradational. In thin section the quartzo-feldspathic schist is fine-grained, granulated, leucocratic, composed of subangular granoblastic, elongate quartz grains in orientated aggregates, and other small rounded grains randomly distributed. Quartz makes up over 50% of the rock (fig. 2-2 b and c).

Feldspars, both plagioclase and K-feldspars occur in the ground-mass, plagioclase is less dominant and tends to form poikiloblasts with inclusions (As-791), and is sericitized. Biotite, less common; amphibole, and muscovite constitute the ferromagnesian minerals where biotite is dominant. Amphibole in long laths is dominant in some bands (As-747). Sphene, opaques and apatite are common accessories, zircon is a local accessory.

The schistosity is well developed, 015° and dips $50-70^{\circ}$ E. Thin bands of amphibole schist are intercalated. Locally these were thermally metamorphosed by dyke intrusions to form plagioclase-hornblende hornfels (fig. 2-2i).

The quartzo-feldspathic gneiss and schist may have originated as an arkose.

2.2.3 Calcareous schist

Calcareous schist is a term used here to designate a unit composed of metamorphosed impure magnesian limestone interbedded with other calcareous sediments. Thin non-calcareous pelitic sediments are also interlayered. The unit is made up largely of the minerals tremolite, carbonate, calcite, epidote/clinozoisite, chlorite, albite, biotite and quartz. Sphene and opaques are present in accessory amounts.

This unit dominates other units of the Formation. It is cut by pre-kinematic intrusions, represented by the lensoid strongly deformed

quartz metadiorite and the leucocratic trachy-andesite and rhyolite dykes and sills. Syn-kinematic microadamellite and post-kinematic red porphyritic microgranites form sills and dykes concordant with the bedding.

2.2.3a Impure marble (fig. 2.2d)

Several impure marble beds (lime-silicate rocks) are intercalated within the calcareous schist horizon. One of these is host to the zinc mineralization. In addition to dolomite and calcite, the minerals present are albite, tremolite, biotite, epidote/clinozoisite, muscovite, chlorite and quartz. Albite and epidote are usual associations of marble bands. Biotite rich layers are intercalated with tremolite rich layers and/or clinozoisite rich calcareous bands with strongly defined compositional banding. Chlorite, opaque iron oxides and sphene are present in subordinate amounts.

Tremolite schist and biotite-sericite-schist layers are intercalated with the marble. Both are strongly schistose e.g. As-752(b), As-754(a), As-753, As-762, As-765.

2.2.3b Tremolite schist (As-798)

This rock is fibrous, strongly foliated colourless or light green. Tremolite forms over 80% of the rock. Quartz in minute rounded and angular grains is locally disseminated but commonly is segregated in lensoid aggregates with fine opaque dusty material in preferred orientation.

Amphibole poikiloblasts, probably post-kinematic, are abundant. Calcite is accessory. The abundance of tremolite points out that the original rock was a siliceous dolomite.

2.2.3c Actinolite schist (As-746)

The rock is fine grained and pale green. Actinolite grains show preferred orientation and form over 60% of the rock. Quartz forms 20%, and albite 15%, sphene and opaques making up the rest. Occasional stumpy, post-kinematic poikiloblastic grains of actinolite with rounded inclusions of quartz are present.

The original rock was probably a siliceous dolomite.

2.2.3d Tremolite-epidote-quartz schist (As-760(a))

This is a fibrous, strongly foliated, light green rock. It tends to be segregated into small lenses. Tremolite forms 80% of the rock. Quartz is in minute angular grains as well as in large poikiloblastic grains. Epidote, fine grained is restricted to calcite grain boundaries. Calcite is present in polygonal granoblastic post-kinematic grains.

The original rock as indicated by the occurrence of tremolite, epidote, quartz and calcite was a magnesian limestone with sand and clay impurities.

2.2.3e Epidote-tremolite-albite schist (As-825, As-754(b), As-811, As-784(a))

Dominant epidote in interlocking granoblastic polygonal grains forms over 50% of the rock. Tremolite occurs as oriented needles, but radiating slender crystals are also present. Albite, is largely poikiloblastic with inclusions of tremolite needles and epidote grains. Calcite is present in subordinate amounts.

The original rock as indicated by abundance of epidote and presence of tremolite and calcite could have been a magnesian limestone with clay impurities.

Plagioclase separated from seven samples of this sub-unit, gave an average strontium content of 500 ppm indicating a probable sedimentary origin (see Chapter 4 Sec. 3.10.2).

2.2.3f Actinolite-epidote-albite-quartz schist (As752 (a))

This is in form of intercalated segregated layers of amphibole-epidote and quartz-albite rich layers. Actinolite is in stout pale green grains showing weak preferred orientation, and many grains show cross-cutting orientation to foliation planes. Quartz is granular, segregated into lenses, and disseminated amongst other mineral grains.

Albite is poikiloblastic and in small grains interstitial to amphiboles. The original rock as indicated by occurrence of actinolite and albite was an impure magnesian limestone, containing some sand and clay.

2.2.3g Quartz-actinolite schist (As-773)

This is in form of intercalated segregated layers of actinolite and granular quartz. Actinolite is extensively poikiloblastic with inclusions of rounded quartz showing preferred orientation and clear segregation.

The original rock was a calcareous sandstone.

2.2.3h Calc-quartz-albite-clinozoisite-actinolite schist (As-764)

Segregated layers of the dark minerals clinozoisite- actinolite occur between granular quartz bands. Polygonal grains of calcite are erratically distributed. The original rock was a very impure limestone.

2.2.3i Quartz-chlorite-sericite schist (As-775, As-772)

This is a strongly foliated, very fine grained (As-775), originally argillaceous rock, made up of quartz evenly disseminated, showing dimensional preferred orientation. Chlorite in fine stout flakes is well orientated. The albite is sericitized.

The quartz-chlorite-sericite schist layers occur in thin intercalations in the upper part of the Ar-Ridaniyah formation.

2.2.3j Epidote-albite-calcite schist (As-776, As-778)

This is an impersistent layer (50 m. thick) intercalated in the upper part of the Ar-Ridaniyah formation. Opaques in fine dust occur in preferred orientation parallel to schistosity.

Epidote, albite and calcite are approximately equally abundant. Quartz, chlorite and opaques occur in subordinate amounts.

Albite is poikiloblastic with inclusions of epidote. Epidote occurs in small polygonal grains, or aggregates of grains oriented in preferred orientation. This rock is affected by thermal metamorphism when adjacent to microadamellite sill intrusions (fig. 2-2f).

2.2.4 Summary

The Ar-Ridaniyah Formation is most probably sedimentary in origin. It was essentially made up of dolomitic limestone, impure calcareous sedimentary rocks, argillaceous and arenaceous sediments. The quartz grains in the quartzo-feldspathic schist horizon are rounded and sub-rounded, probably detrital.. Textures characteristic of volcanics are

lacking. Locally, thin argillaceous bands were intercalated, which could also be interpreted as volcanic tuffs. Sedimentary structures like cross-bedding, current-bedding or graded bedding are not seen, and if present, could have been obscured by regional metamorphism and surface oxidation of the outcrops. Cyclic sedimentation is only represented by repeated occurrence of impure marble beds within a dominantly calcareous horizon.

The members of this Formation dip constantly at about 50°E , no large scale folding is present and there is no evidence to suggest that the succession has not been repeated by isoclinal folding or overturning. Only small scale folds which are restricted to thin pelitic bands were seen. Therefore the whole Ar-Ridaniyah Formation is probably one conformable succession of sediments.

Contact thermal metamorphism is locally displayed at the intrusive granite contacts where plagioclase-hornblende and epidote-calcite hornfels rocks were developed (As-742, As-778). Biotite in the quartzo-feldspathic schist has been later partially altered to chlorite.

Later dynamic metamorphism is locally exhibited along faults where brecciation and hydrothermal alteration to chlorite and sericite is well developed.

The mineralogy of the Ar-Ridaniyah Formation shows that it has suffered greenschist Bl.1 to Bl.2 facies metamorphism, and it is these minerals which define the schistosity.

From field observation and thin section study it is clear that the contact metamorphism is superimposed upon schistose rocks and thus post-dates the regional metamorphism.

2.3 ABT FORMATION

The Abt Formation is a purely clastic sequence metamorphosed to schists, it occurs:

- 1) In the southeast corner of the map (plate 1) where it constitutes the western limb of a broad open syncline, overlying the Ar-Ridaniyah formation conformably.
- 2) In the north, in the vicinity of Arja village.
- 3) As xenoliths incorporated in the granitic batholith.

The Formation is essentially made up of clastic material of sedimentary origin, which were regionally metamorphosed to greenschist facies (Bl.1 - Bl.2).

The Formation is composed of quartz-sericite-chlorite schist, which grades into biotite schist and to gneissic biotite schist towards its contact with the granite. Occasional quartzite bands and lenses are interbedded. Almandine garnet is locally developed at the contacts with the granite.

2.3.1 Quartz-sericite-chlorite schist (As-830)

A thick succession of this schist occurs to the north and west of Arja village. Only a small part is included in the map (plate 1). It occurs on small hills, which are usually elongated parallel to the strike of schistosity, N.50°W. Quartz-float is seen covering the low ground between these hills, derived from the abundant quartz and pegmatite veins.

In hand specimen, the rock is pelitic schist, highly fissile, lead grey in colour, banded, where white quartz bands alternate with darker bands of sericite and chlorite.

In thin section, the rock is fine grained, banded, quartz occurs in lensoid aggregates making about 35 percent of the rock, intercalated with sericite chlorite bands, which occur almost in equal abundances making about 45 percent of the rock. Albite, which makes up 15 percent of the rock occurs as lensoid poikiloblastic grains with irregular margins and numerous inclusions of orientated sericite. Calcite forms the remainder and is present in thin bands parallel or subparallel to schistosity (S_1) (fig. 2-2g). Sphene and apatite are present in accessory amounts.

2.3.2 Quartz-sericite schist (As-781)

Occurs in thin bands (2-5m. wide) within the lower part of the quartz-biotite-albite horizon in the south east corner of the map.

In hand specimen the rock is extremely fine grained, grey in colour, banded and schistose.

In thin section, it is very fine grained, schistose, with quartz-rich lenticular bands which are intercalated with sericite-rich bands (fig. 2-2e). Chlorite is less abundant, it occurs in small light green irregular flakes. The rock is probably a metamorphosed arenaceous argillite.

2.3.3 Quartz-biotite-albite schist (As-782)

It is most predominant as inclusions throughout the granitic batholith and in the vicinity of Arja village and Arja ancient mine at the edge of the granitic batholith.

In the south east corner it forms the west limb of the broad syncline, overlying Ar-Ridaniyah Formation (As-782), and only partly included in the mapped area.

In hand specimen the rock is light grey or grey, highly schistose and banded, fine grained, intensely folded and crenulated (fig. 2.2h).

In thin section (fig. 2-2a, b and c) the rock is composed of quartz (30%) and albite (20%) in bands or lenses intercalated with biotite (30%) in segregated bands, chlorite (10%) is less abundant, it occurs in smaller flakes relative to biotite, disseminated in both the leuco- and melanocratic bands. Calcite is seen infilling, joints parallel to schistosity planes and occasionally cutting them. Muscovite is present in subordinate amounts.

A gneissic-biotite schist (Ar-27) occurs at the contact with the granite, in the north, the rock has developed a coarser grained texture. Quartz is in granoblastic texture as well as in small grains.

Alkali feldspar and albite together form about 60% of the rock. The albite is poikiloblastic containing inclusions of biotite, sericite and drop-like quartz grains (fig. 2-2b). Muscovite is present in accessory amounts.

2.3.4 Arkosic quartzite (As-783)

In the Abt Formation, intercalations of arkosic quartzite bands are noticed in the south east corner of the map area. These attain thicknesses of few centimeters to over 20 meters. In hand specimen, the rock is light grey to pale brown, schistose but not banded.

In thin section the rock is fine grained, composed of angular and subangular quartz grains which make up about 35 percent of the rock. Albite occurs in small and poikiloblastic grains, it makes up 20 percent. Biotite and chlorite which make up 30 percent of the rock occur in equal amounts. Epidote and actinolite make up the remainder.

2.3.5 Summary

The Abt Formation is most probably sedimentary in origin. It was essentially made up of finely banded pelitic, and psammopelitic rocks. These are spatially more abundant than those of Ar-Ridaniyah Formation. In all localities in the district, these rocks show similar mineralogic and textural relationships. The quartz grains in the thinly inter-banded zones are rounded and subrounded, probably detrital. Textures characteristic of volcanics are lacking. Sedimentary structures like cross-bedding, current-bedding or graded bedding are not seen and if present could have been obscured by regional metamorphism, deformation and surface oxidation of the outcrops. The members of this Formation included in the mapped area are strongly folded. Small scale folding of 50 cm. amplitude and wave length prevail.

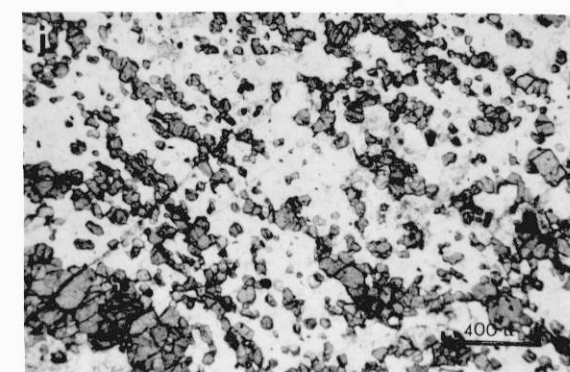
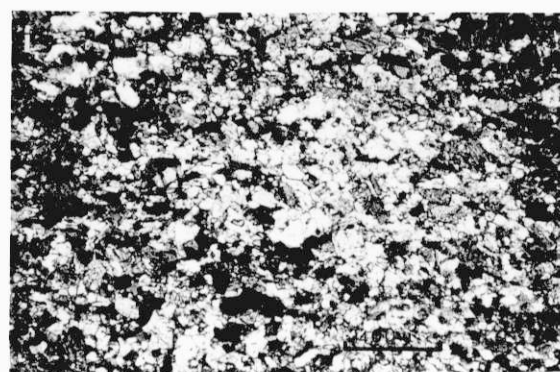
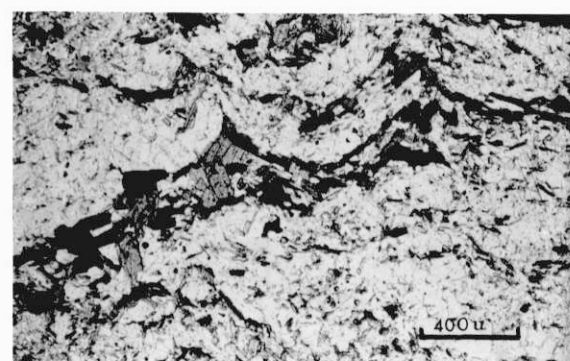
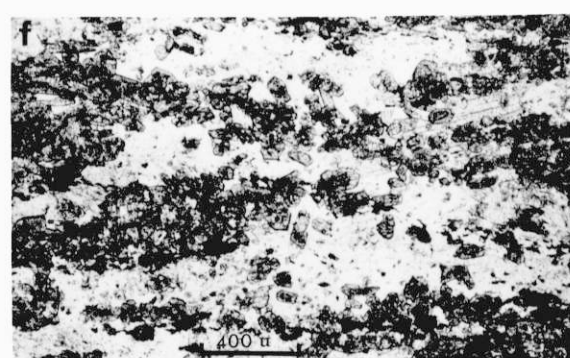
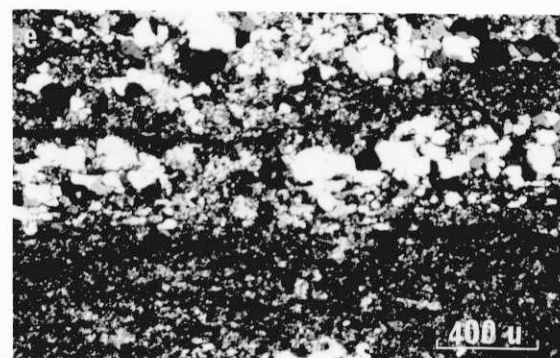
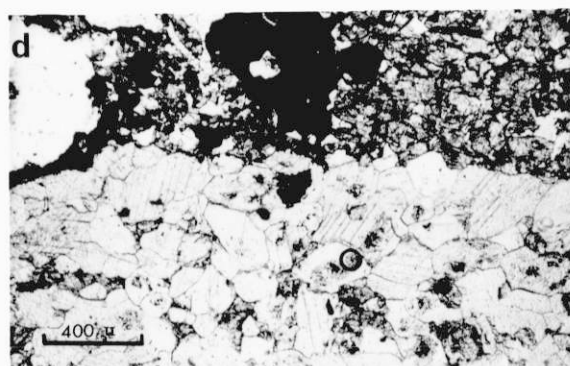
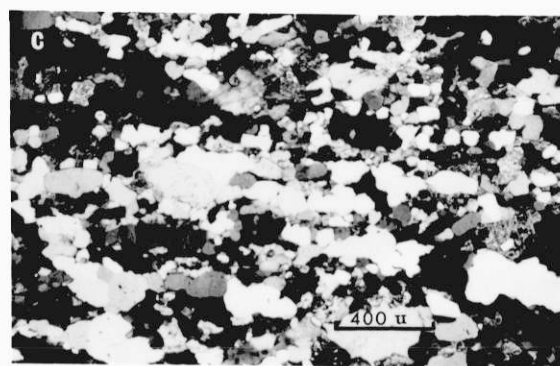
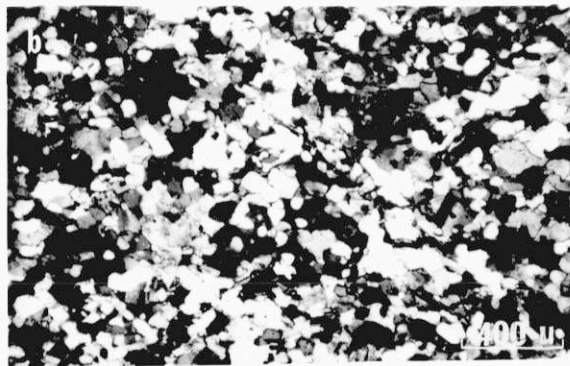
It is likely that large scale folding and overturning caused repetition in the succession. This is difficult to ascertain because of (1) the lithological similarities throughout and (2) the extensive dyke intrusions within the Formation.

Metasedimentary Formations

Figure 2-2

(a-j taken in transmitted light)

- a - Quartzo-feldspathic gneiss. Lenticular ragged deformed grains in planar fabric shown mainly by quartz. Few flakes of chlorite and biotite are in parallel orientation defining schistosity. Bottom of Ar-Ridaniyah Formation, CN, As-735.
- b - Quartzo-feldspathic schist. Section perpendicular to schistosity. Quartz is dominant forming 65% of the rock. Ar-Ridaniyah Formation, CN, As-736.
- c - Quartzo-feldspathic schist. Section parallel to schistosity. Strongly deformed, lenticular and elongate ragged quartz aggregate with shadowy extinction. Feldspathic grains are weakly deformed. Ar-Ridaniyah Formation, CN, As-747.
- d - Dolomitic limestone, clinozoisite, minor calcite and opaques at top and calcite and minor clinozoisite at bottom, with well defined bedding plane. Calcareous horizon. Ar-Ridaniyah Formation, CN, As-753.
- e - Quartz-sericite-chlorite schist. Lenticular quartz aggregates in parallel fabric intercalated with major fine-grained sericite and minor chlorite orientated matrix. Bottom of Abt Formation CN, As-781.
- f - Calcite-epidote rock, affected by thermal metamorphism, Schistosity is lacking. Top of the calcareous horizon, Ar-Ridaniyah Formation, CN, As-778.
- g - Quartz-chlorite-albite-sericite schist. Lenticular quartz aggregates, albite contains inclusions of chlorite. Calcite is less common in fractures parallel to schistosity. Abt Formation, Arja vicinity, PPL, As-830.
- h - Quartz-biotite-chlorite schist. Showing crenulation and mimetic crystallization of biotite flakes. Lower horizon of Abt Formation, CN, As-782.
- i - Plagioclase hornblende Hornfels, Lenses in the quartzo-feldspathic schist horizon, CN, As-746.
- j - Plagioclase-pyroxene-biotite hornfels, xenoliths in Arja layered basic intrusion, CN, Ar-87.

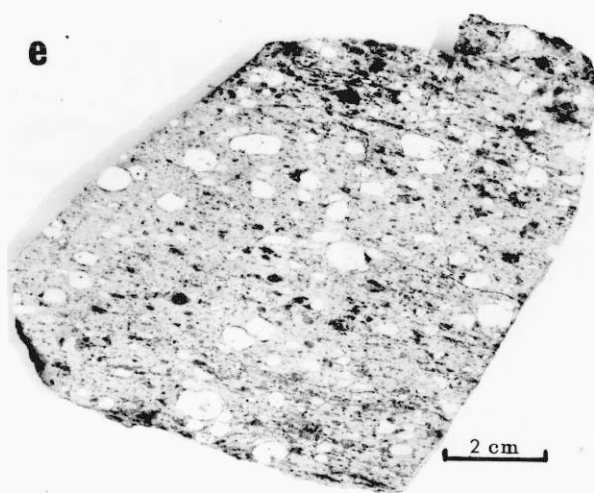
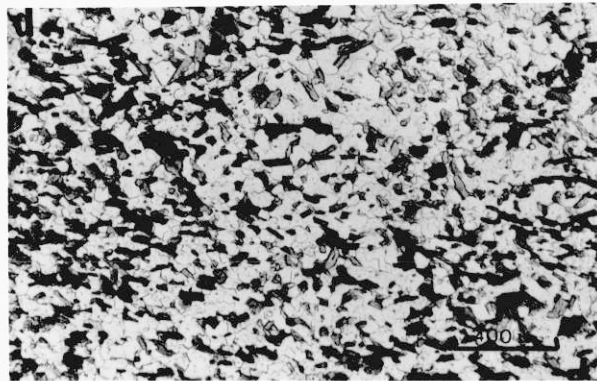
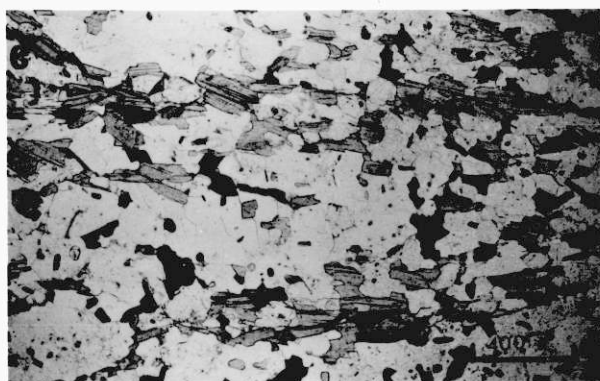
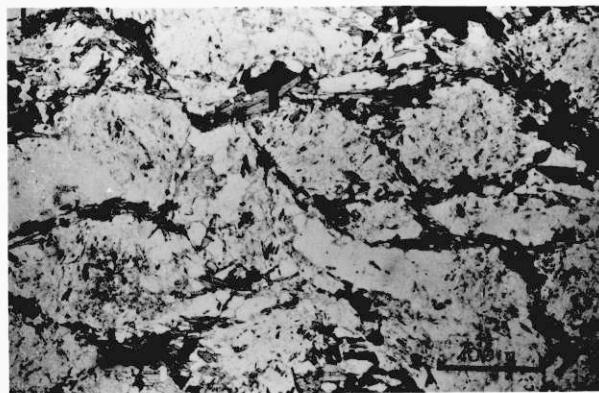
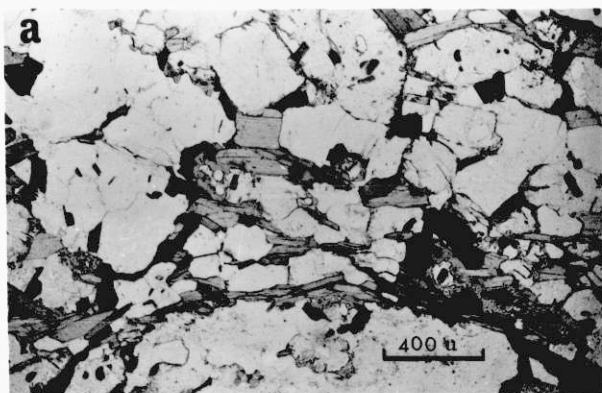


Metasedimentary Formations

Figure 2-3

(a-d taken in transmitted light)

- a - Granitized biotite schist. Gradational contact with granite, occasional grains of cordierite. Xenolith in Syn-kinematic granite, PPL, G-110.
- b - Gneissic biotite schist with poikiloblastic texture, rock is affected by thermal metamorphism. This demonstrates progressive metamorphism towards the contact with the granite. Nearby granite contact. PPL, Vicinity of Arja, Ar-27.
- c - Biotite schist, Abt Formation. This represents a zone in between quartz-chlorite-albite-sericite schist, (As-830 fig. 2-2g) and gneissic biotite schist affected by thermal metamorphism (Fig. 2-3b), PPL, Ar-24.
- d - Thermally metamorphosed rock composed of plagioclase, biotite quartz and occasional cordierite. Xenolith in Syn-kinematic granite. PPL, G-137.
- e - Pre-kinematic porphyritic dacite dyke rock. Plagioclase phenocrysts drawn parallel to planar fabric more defined by the mafic constituents. Dykes in Ar-Ridaniyah Formation PPL, As-826.



The mineralogy of the Abt Formation shows that it has suffered greenschist facies Bl.1-Bl.2 metamorphism (Winkler 1967), and it is these minerals which define the schistosity.

Zones of progressive metamorphism are well exhibited in the vicinity of Arja in the north where the quartz-albite-muscovite-chlorite subfacies (fig. 2-2g), (As-830) which belongs to Bl.1 grades southwards into quartz-albite-biotite subfacies (Bl.2) (fig. 2-3g) (As 829) then to gneissic albite-biotite schist nearby the contacts with granitic rocks, (fig. 2-3b), (Ar-27).

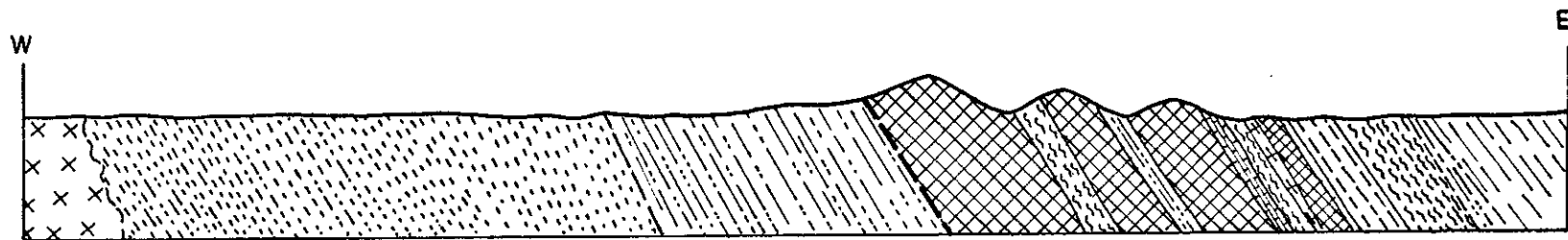
Garnet which is a higher pressure temperature mineral is present locally (As-784, As-1033) at contact zones with the granite and in the xenoliths along with biotite, cordierite, feldspars and quartz (fig. 2-3d). This contact metamorphism is superimposed upon schistose rocks (As-1033) and thus postdates regional metamorphism.

2.4 PRE-KINEMATIC INTRUSIVES

2.4.1 Ultramafic rocks

The quartzo-feldspathic gneiss and schist horizons at the bottom of the Ar-Ridaniyah Formation have been injected near their uppermost contact with the amphibole or calcareous schist by concordant sheets of originally, olivine rich rock. Delfour (1971) stated that this sequence of metamorphosed ultrabasic and serpentized plutonic rocks appears at the base of the syncline and underlies gabbro, metagabbro, diorite, and quartz diorite.

Lenses of quartzo-feldspathic, calcareous and amphibole schist are locally incorporated within this intrusive body (fig. 2-4). The sequence of metasediments and the metamorphic ultrabasic sheets lie within an easterly, steeply dipping monocline (plate 1). The ultramafic rocks have been metamorphosed to serpentine rocks, chlorite rocks, amphibolite and sporadically to talc-carbonate rocks with talc veinlets and pockets. Siliceous and ferruginous silica lenses, resistant to erosion, form several small hills rising to 10-20 meters above the



DIAGRAMMATIC CROSS SECTION, SHOWING STRATIGRAPHY OF THE METAMORPHIC ULTRAMAFIC ROCKS. AR-RIDANIYAH FORMATION. (Central exposures)

EXPLANATION

	Quartzofeldspathic gneiss
	Quartzofeldspathic schist
	Calc. schist
	Marble + carbonate
	Serpentine (massive), becomes schist in north outcrops
	Amphibolite
	Adamellite even-grained
	Micro-Adamellite sills

Fig. 2-4

surrounding flat ground.

The siliceous lenses contain in places considerable amounts of hematite and some limonite. In other places these form "pseudo-gossans". Traces of malachite and chrysocolla were noticed associated with chlorite and serpentine rocks.

2.4.1a Serpentinite

Serpentinite is the predominant rock in the metamorphic ultrabasic suite of the Ar-Ridaniyah Formation. It occurs in the northern outcrops of Jabal Humayyan, where it is schistose and sheared, and commonly intermingled with zones of chlorite schist and talc. Carbonate material is common and is intimately intergrown with serpentine mineral.

In hand specimen, this serpentinite is green to light green, fibrous, thinly banded, foliated and commonly with brown hematite staining after primary magnetite.

In the southern outcrops of this sequence, serpentine rock is commonly compact and massive. They are pale green to dark grey rocks irregularly veined by carbonate and talc material. In thin sections As-794, As-707, the rock is entirely antigorite in scaly form dusted with magnetite, which by oxidation to hematite gave the rock a brownish tint, and in thin brown stained zones around the magnetite. Chrysotile stringers occur locally.

2.4.1b Chlorite schist and chloritite

Chlorite schist and chloritite are less abundant and are commonly closely associated with the serpentine rocks as in the lenses in the northern outcrops. Chlorite rock is grey green in colour. Schistosity is locally well developed. Intercalations of both talc and carbonate material are common.

2.4.1c Talc

Talc is thinly banded with chlorite and serpentine schist. It occurs in the northern outcrops associated with strongly schistose

serpentine rocks. Talc occurs also in pockets, in fault zones and as streaky aggregates within the serpentine and chlorite schist. Hematite staining is commonly strong.

2.4.1d Carbonates

Pale, light brown to creamy coloured $\frac{1}{2}$ -3 cm. wide veinlets of carbonates are common in serpentine rocks. Carbonates are more abundant in talc pockets and bands. As-804a and As-804b show fibrous grains of both colourless antigorite and tremolite within carbonate rock.

This carbonate rock is probably metamorphosed ultrabasic plutonic rock. It occurs as small lenses within the metamorphic ultra-basic sequence.

2.4.1e Tremolite-rock

As-795, As-805, massive grey to dark grey rocks, essentially composed of tremolite, forming over 80 percent of the rock with subordinate amounts of chlorite or chlorite and clinozoisite. Calcite is present along cracks. Magnetite is in accessory amounts with sphene formed around the grains. This tremolite rock is probably metamorphosed pyroxene rich igneous rock. It is found intercalated in the form of lenses within serpentine rocks or overlying them.

2.4.1f Meta-Quartz-Diorite

Meta-quartz-diorite occurs in sporadic prekinematic intrusive bodies. Thin long axes are drawn parallel to (S_1) as a result of the regional dynamothermal metamorphism which they suffered. The intensity of metamorphism is approximately that of the Bl.2 subfacies of the greenschist grade.

In thin section, the rock is composed of about 40% albite poikiloblasts with characteristic ragged outlines and abundant inclusions. The ferromagnesian is tremolite/actinolite which occurs in long laths in (S_1) planes. It forms about 40% of the rock. Tremolite/actinolite is light brown to light green rimmed locally by colourless to light green chlorite. Chlorite also occurs in aggregates pseudomorphous after amphiboles (As-768).

2.4.1g Rhyolite-Rhyodacite dykes

These are porphyritic, and parallel or subparallel to schistosity (S_1). Locally, they cut bedding at an acute angle (plate 2). Compositionally, they are acidic to intermediate. In thin section, the acidic dykes are essentially composed of feldspars and quartz with subordinate amounts of calcite, epidote, biotite and muscovite. Sphene and apatite are occasional accessories.

Plagioclase phenocrysts are ovoid with their long axes parallel to (S_1). Plagioclase is of andesine composition and tends to break down to sericite. Plates of muscovite and calcite are common inclusions within the plagioclase phenocrysts (As-755 and As-759).

The mafic constituents are in lensoid aggregates parallel to (S_1), streaky and interleaved with the acidic matrix.

K-feldspar, quartz and plagioclase form the bulk of the matrix.

2.4.1h Dacite dykes

These are porphyritic, the plagioclase phenocrysts being drawn out parallel to (S_1) planes. They belong to the same generation as the former ones except that quartz is less abundant. The plagioclase phenocrysts are sericitized and set in a deformed and foliated groundmass of plagioclase, calcite, biotite and accessory apatite (fig. 2-3e), (As-826).

2.5 SYNKINEMATIC MINOR INTRUSIVES

2.5.1 Porphyritic microadamellite sills and dykes

Porphyritic microadamellite varies in width from 50 cms to 50 meters and intrudes the metasedimentary rocks in the calcareous schist zone of the Ar-Ridaniyah Formation. It has a fine grained groundmass of plagioclase, quartz and K-feldspar with minor biotite, muscovite and traces of epidote and opaques. Plagioclase phenocrysts are zoned and have albitized margins and clouded cores. They make up 30% of the rock. The colour index is less than 10%.

2.6 POST-KINEMATIC MINOR INTRUSIVES

2.6.1 Porphyritic red granite dykes

A porphyritic red granite dyke 50 meters wide and some 5 kilometers long intrudes the metasedimentary rocks parallel to the bedding 200 meters west of the Ar-Ridaniyah gossan exposure. The dyke comprises a fine grained matrix, rich in plagioclase, quartz and K-feldspars. The rounded K-feldspar phenocrysts are completely replaced by sericite which is being replaced by calcite.

2.7 METAMORPHISM

2.7.1 Regional metamorphism

The geosynclinal successions of the Ar-Ridaniyah and Abt Formations were regionally metamorphosed during the Hejaz orogeny. The metamorphism reached Bl.1 to Bl.2 subfacies of greenschist grade (table 2-1 and fig. 2-5). The deformation and metamorphism destroyed the original textures of the rocks and caused the preferred orientation of the minerals, thus producing metamorphic rocks of different mineralogical compositions and textures. Probable detrital sand grains retain their relict roundness within thinly interbedded chlorite and quartz bands of the Abt Formation. Relict textures are retained in the pre-kinematic minor intrusions. The outlines and relicts of phenocrysts remained intact, the albite was clouded with secondary sericite and sometimes replaced by calcite or clinozoisite. The mafic minerals were destroyed and pseudomorphed by biotite, epidote, chlorite, amphiboles and calcite.

In Ar-Ridaniyah the grade of metamorphism fluctuates in the zone Bl.2 and possibly Bl.1. The Abt Formation, however, exhibits an increase in the grade of metamorphism towards the granite contact. The mineral assemblage of Bl.1 subfacies, (quartz-albite-muscovite-chlorite) away from the granite becomes quartz-albite-biotite of Bl.2 subfacies.

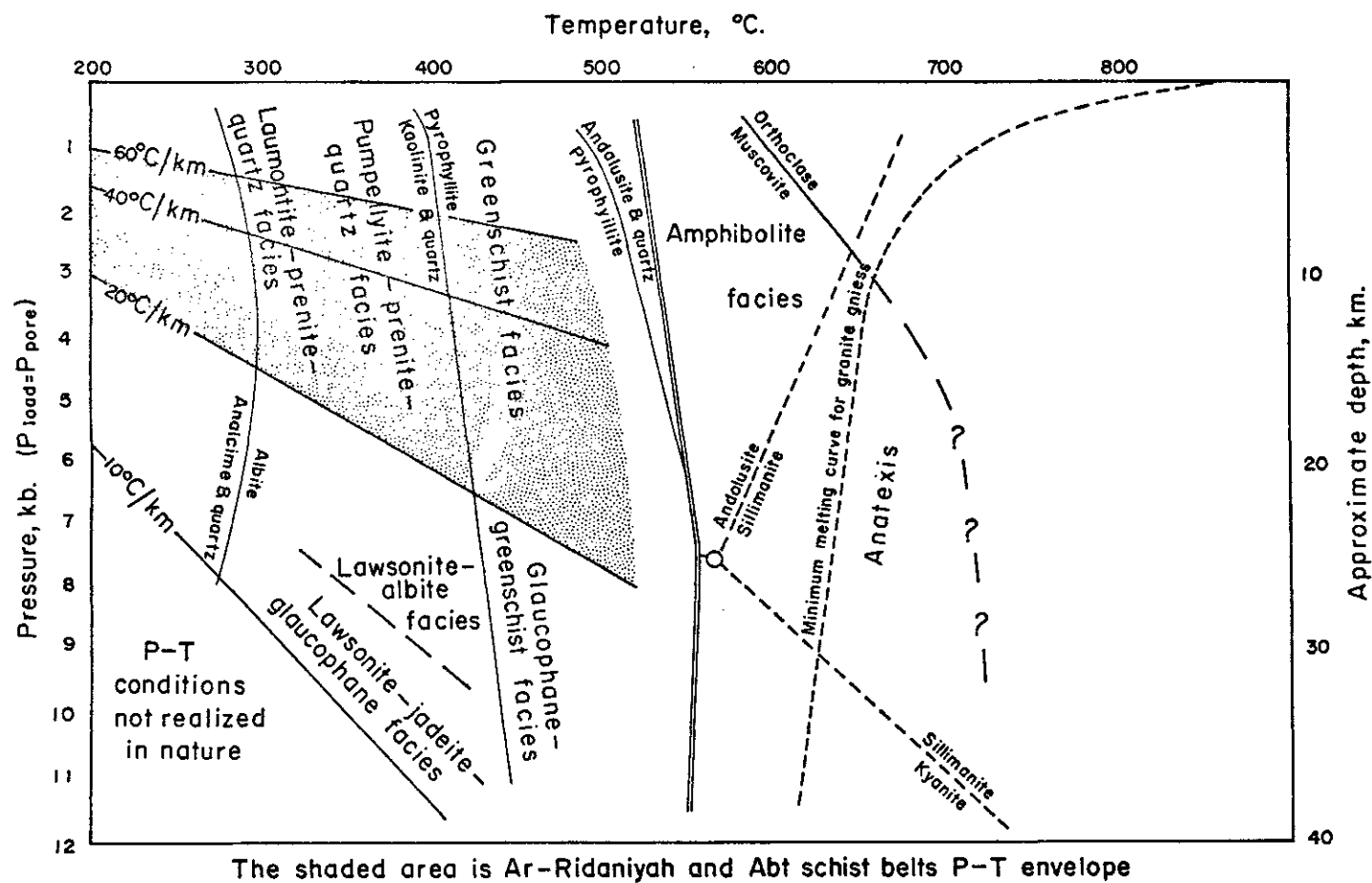


Figure 2-5 Pressure & temperature fields of metamorphic facies (after Winkler, 1965 & 1967)

Table 2-1

The Terminology of the Barrovian Facies Series

Greenschist Facies

<u>Reference</u>	B1.1	B1.2	B1.3
Turner and Verhoogen (1960)	Quartz-albite- muscovite-chlorite	Quartz-albite- epidote-biotite	Quartz-albite- epidote-almandine
Grampian Highland (Barrow, 1912)	Chlorite zone	Biotite zone	Garnet zone
Eskola (1939)	Greenschist facies		epidote amphibolite facies

Mineral assemblages characteristic of Bl.3 subfacies of the greenschist grade were not observed.

2.7.2 Contact metamorphism

Contact metamorphism by later basic and granitic intrusives is superimposed upon the regionally metamorphosed country rocks in aureoles around these intrusions as well as in the incorporated xenoliths.

In the vicinity of Arja village the Bl.2 biotite schist subfacies becomes gneissose towards the granite contact. At the contact these rocks are darkened, massive and granoblastic in texture and contain cordierite and garnet. The occurrence of garnet and cordierite together indicates contact metamorphism at medium pressure at moderate depths (Winkler, 1967). In Al-Hufayrah area small outcrops from the Abt Formation, in the main valley crossing the village, were thermally metamorphosed to biotite-garnet-cordierite-plagioclase hornfels. The pre-existing schistosity shows as parallel lineation on the outer surface of the exposures.

A contact metamorphic aureole is present at the exposed eastern boundary of Arja layered basic intrusion as well as the incorporated xenoliths. Plagioclase-pyroxene-biotite hornfels was formed (fig. 2-2j). The contact metamorphic aureole is between 20-50m.

The intermediate and acidic minor intrusions in Ar-Ridaniyah Formation formed localised zones of thermal metamorphism. Skarn rocks where schistosity is almost destroyed were formed in the calcareous horizon. The skarn mineral assemblage is essentially epidote, calcite and albite with minor quartz and secondary chlorite.

2.8 STRUCTURE

2.8.1 Introduction and regional structural setting

The metasedimentary-metavolcanic successions and the plutonic rock associations have suffered several Precambrian orogenic events since their deposition and emplacement. The most effective and long lasting

was the Hejaz orogeny (1000-660 m.y). It metamorphosed and deformed the rocks, which were later fractured during the Najd orogeny towards the end of Precambrian. An outline of the structural deformation in relation to the geology of the district is given in (fig. 1-5), and it is concluded that the deformational forces which affected the rocks in the district were largely directed east-west.

The structural study was mainly carried out in the southeast sector of the map, where a complete succession of the metamorphic rocks is well exposed. The (S) surface terminology is used in which (S_0) defines the original bedding, and (S_1), (S_2) etc. define successive generations of superimposed planar fabrics such as schistosity, cleavage, joints and faults.

The regional structural setting of the district comprises northerly trending open concentric folds represented by the major open synform in the southeast where only the west limb is included in (plate 1), and the "ghost" anticline retained within the quartz-monzonodiorite in Sidriyah area. The granitic emplacement has dominated the pre-existing rocks except for local inclusions which retain the pre-granite structures.

In the north, in the Arja area, the fold axes of structures preserved in xenoliths within the granite trend approximately east-west.

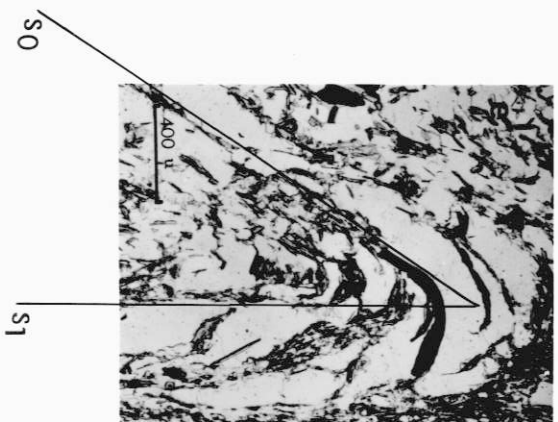
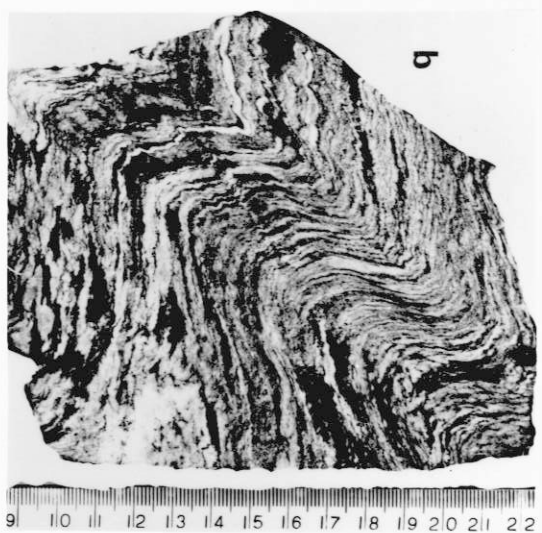
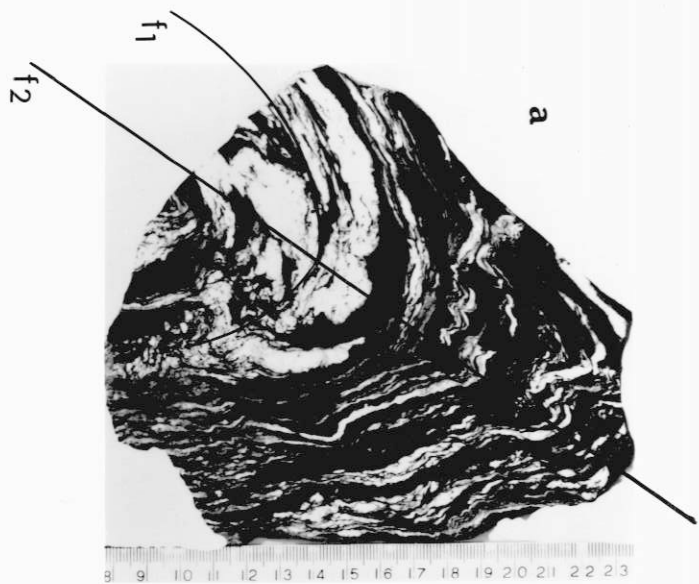
2.8.2 Folding

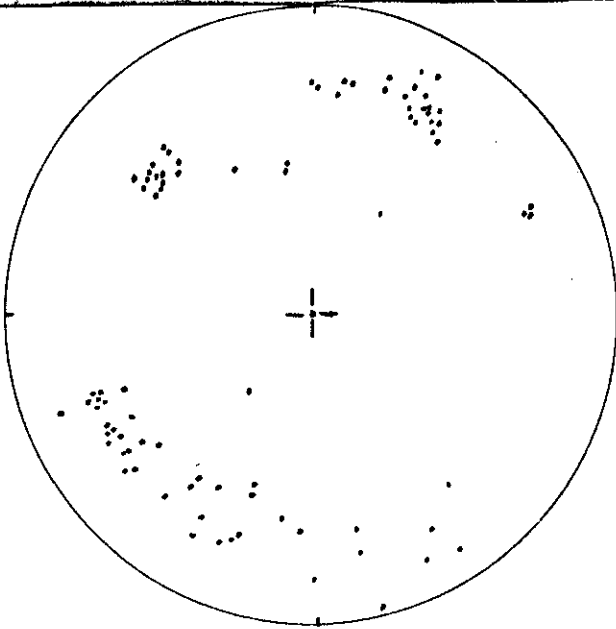
In Ar-Ridaniyah, the bedding (S_0) is generally sub-parallel to a schistosity (S_1) (fig. 2-7b and c), which is defined by the parallel orientation of chlorite and biotite. Folds are rare and have only been observed in drill cores where they deform argillaceous bands intercalated within unfolded calcareous horizons. In the hinge areas of microfolds, microscopic examination indicates that (S_1) is an axial planar fabric which sharply cross-cuts (S_0); platy minerals have also mimetically crystallized parallel to bedding in those areas to form polygonal arcs (fig. 2-6d and e).

Metasedimentary Formations

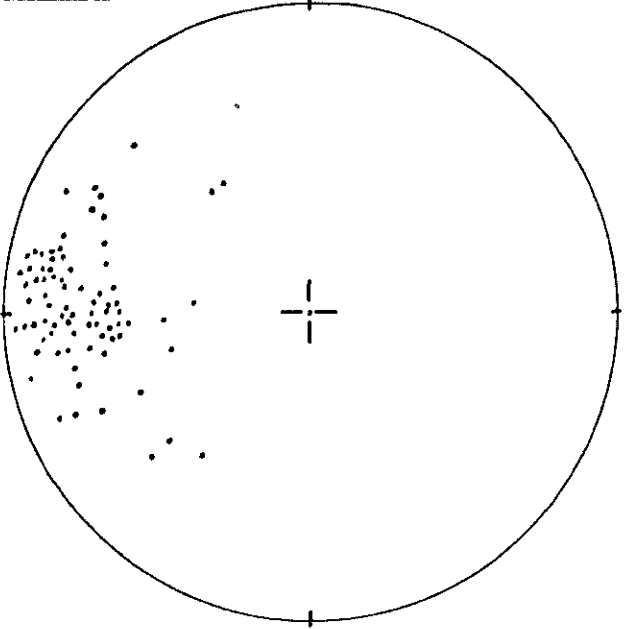
Figure 2-6

- a - Coaxial superimposed folds. Symmetrical refolding (f_2) of earlier tight folds (f_1). Quartz bands (white) in quartz-chlorite schist (dark).
- b - Tightly folded thinly intercalated quartz (white) and quartz-chlorite schist bands (dark). The folds have angular hinges and smaller parasitic crenulations on the limbs.
- c - Symmetrical open fold with rounded hinge and parasitic microfolds.
- d - Folding in quartz-chlorite schist. Closer examination reveals strong axial plane schistosity.
- e - Mimetic crystallization of biotite and chlorite-flakes parallel to (S_0) in hinge of a microfold. The intersection of axial plane schistosity and bedding can be seen. Depth of 66.90 mrs. DH.1 Ar-Ridaniyah.

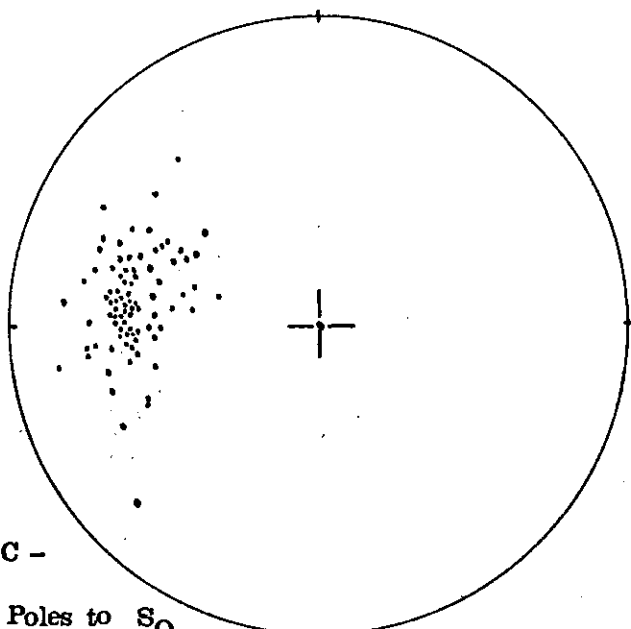




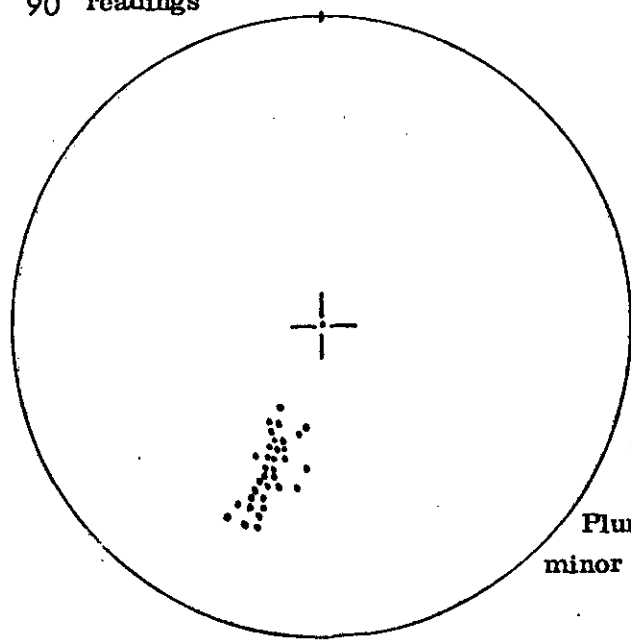
a - Poles to Joints $S_2 + S_3$
83 readings



b - Poles to S_1
79 readings

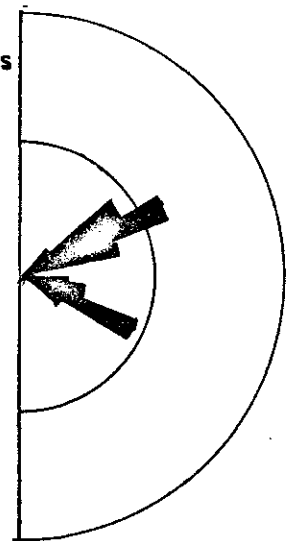


c - Poles to S_0
90 readings



e - Plunge of
minor fold axes

Faults
Summary frequency diagram
83 readings



d -

F - Joints
Summary frequency diagram
80 readings

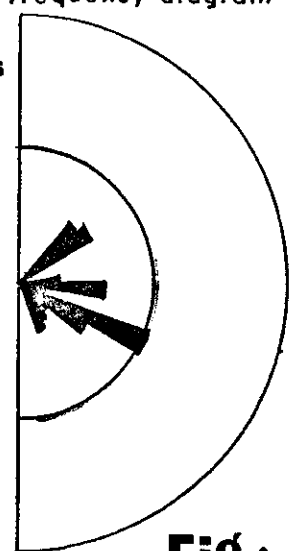


Fig: 2-7

In the Abt Formation, the folds are well exposed on the surface. In general they are of small amplitude and wave length (fig. 2-6b, c and d) (both less than about 50 cm.), asymmetric and close to open. The hinges are rounded and show well developed lineations due to intersection of axial planar schistosity with bedding and also of microfold axes.

Detailed studies of polished surfaces cut perpendicular to the fold hinges, show that there are two generations of coaxial folds (f_1 and f_2), both of similar style, (fig. 2-6a). The early folds recognized on polished surfaces, were not distinguished in the field and are probably of rare occurrence. They are thought to have formed in response to the same stress system that caused the later folds.

Measurements of fold axis plunges taken from the west limb of the major synform have been plotted on a stereogram (fig. 2-7e). They show a well defined grouping plunging between 20° and 60° to the south-southwest.

2.8.3 Fractures

Northeasterly trending faults (S_4):

These are the dominant transcurrent faults and zones of brecciation and mineralization with quartz, calcite and brown goossan which show malachite staining. Several of these fault zones were mined by ancients. This set of faults form a conjugate pair with the (S_4) faults. The sense of movement is commonly dextral.

Northwesterly trending faults (S_5):

These form a conjugate pair with (S_4) faults (fig. 2-7d). They are less abundant and less dominant than S_4 faults. They have developed also, zones of brecciation and limited mineralization. These mineralized zones were also worked by ancients. The length on these faults range from 100 meters to 2.0 kms. (S_5) schistosity is developed within the fault zones. The sense of movement is commonly sinistral.

Joints ($S_{2a,b}$, S_3)

The majority of the joints measured are prominent joints. These were plotted on an equal area net and on a rose diagram (fig. 2-7a and f).

There is one conjugate pattern of joints which consists of rather steep shear joints (S_{2a+b}) intersecting at about 50° and bisected by one set of tension joints, (S_3). The shear joints are parallel to sub-parallel with the dominant dextral and sinistral conjugate set of faults.

These joints are thought to have formed by east-west stresses responsible for the conjugate set of shear fractures.

2.9 SUMMARY AND CONCLUSIONS

1) The rocks of Ar-Ridaniyah and Abt Formations represent the oldest rocks in the district and are predominantly meta-sediments. However, it is possible that some of the fine-grained pelitic rocks are entirely or partly tuffaceous. Metavolcanic rocks were not seen in the district.

2) Sedimentary structures, like current bedding, cross bedding or graded bedding etc. were looked for but not detected. These may have been obscured by metamorphism, deformation and surface tarnish of the exposures.

3) The Ar-Ridaniyah Formation is the basal Formation, and has been intruded within its lower horizons by concordant ultrabasic sheets. The intrusions are of pre-kinematic and pre-metamorphism age.

4) The Ar-Ridaniyah Formation is now composed of quartzo-feldspathic gneiss and schist (actinolite-tremolite) and marble. The meta-igneous rocks are represented by serpentinite and chloritite and their local schist derivatives and plagioclase amphibole schist - the Abt Formation is essentially a chlorite-sericite schist with zones of quartzo-feldspathic schist and gneiss.

5) During the Hejaz orogeny (1000 - 660 m.y. BP., Brown, et al., 1972) both Formations including the pre-kinematic ultrabasic and basic intrusions have been deformed and metamorphosed in the green-schist facies of Bl.1 - Bl.2 and schistosity was also developed. Progressive metamorphism from Bl.1 to Bl.2 from north southwards is exhibited in the Abt Formation in the northern part of the area mapped.

6) Both Formations have been intruded by Precambrian granitic intrusions. Contact metamorphism is well developed in xenoliths and in the aureoles forming biotite, cordierite, garnet-bearing hornfels. Towards the granite contacts, the country rocks become coarser grained and gneissose.

7) Post kinematic granite intrusions in the form of dykes, sills and small bodies intruded the district during the later stages and after the culmination of the Hejaz orogeny.

8) The strike slip faulting of the district is related to the Najd orogeny (Brown et al., 1972) which succeeded the multicyclic Hejaz orogeny. Reactivation of movements along the same structural lineaments produced brecciation, silicification and recrystallization of wall rocks and mineral deposits along these lineaments.

CHAPTER 3

AR-RIDANIYAH MINERALIZATION

3.1 INTRODUCTION

The mineralization at Ar-Ridaniyah was discovered by aeromagnetic, and airborne electromagnetic (Barringer INPUT method) surveys. Ground magnetic, SP and IP geophysical surveys were carried out later. Two holes were drilled to determine the source of the main anomaly which is localized on a faulted lens of brown gossan. Plate 2 gives the log and the assays on the two holes. Within the drill section a number of mineralized horizons were intersected. They contain sulphides in amounts between 20 and 100 percent. The principal minerals are pyrrhotite and sphalerite, together with pyrite, marcasite, chalcopyrite and galena as minor constituents, native silver and acanthite are in accessory amounts. Stannite, cassiterite and arsenopyrite are found in small amounts in discordant veinlets.

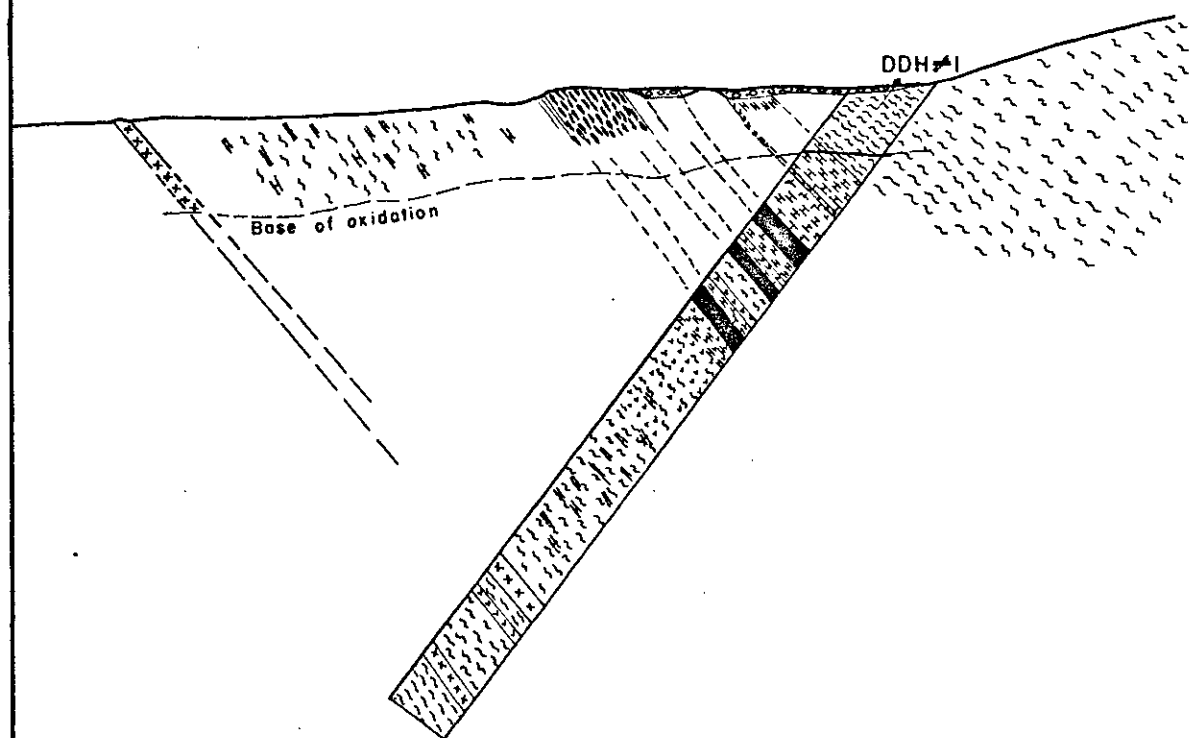
Zinc is the only ore metal present in economically interesting amounts (see figs. 3-1 and 3-2). Two styles of mineralization were recognised from the drill cores, namely a conformable strata-bound type (fig. 3-3b) and a younger discordant veinlet type (fig. 3-3c).

3.2 THE GOSSAN

The gossan which is the surface expression of the sulphides is localized along an impure dolomitic marble horizon, (Plate 2). Its main occurrence is a faulted lens, 180 m long and 26 m wide. A few other smaller lenses occur along the same horizon to the south. Similar gossan is also localized along northeasterly trending left-lateral faults cross-cutting the mineralized horizon. Ancient workings are abundant on the latter occurrences.

The gossan is reddish brown, containing vuggy cavities which are lined with calcite and gypsum (fig. 3-3a). X-ray diffraction studies

CROSS SECTION OF AR-RIDANIYAH DRILL HOLE - I



EXPLANATION

- Gossan
- Alluvium

- Calcareous biotite and calcareous amphibole schist, marble and dolomitic beds
- Dacite, Rhyodacite, interbedded with Biotite, amphibole and chlorite schist thin calcareous horizons also present
- Rhyolite - porphyritic
- Sulphide zone

ASSAY VALUES

Depth in meters	Ag g/t	Cu %	Pb %	Zn %
56.50-61.50	15.0	0.10	0.05	6.70
61.50-71.50	< 5	0.05	< 0.05	0.10
71.50-75.50	5	0.05	< 0.05	3.90
75.50-87.0	< 5	0.05	< 0.05	0.05
87.50-94.00	< 5	0.05	< 0.05	0.05-0.25

Fig:3-1

CROSS SECTION OF AR-RIDANIYAH DRILL HOLE - 2

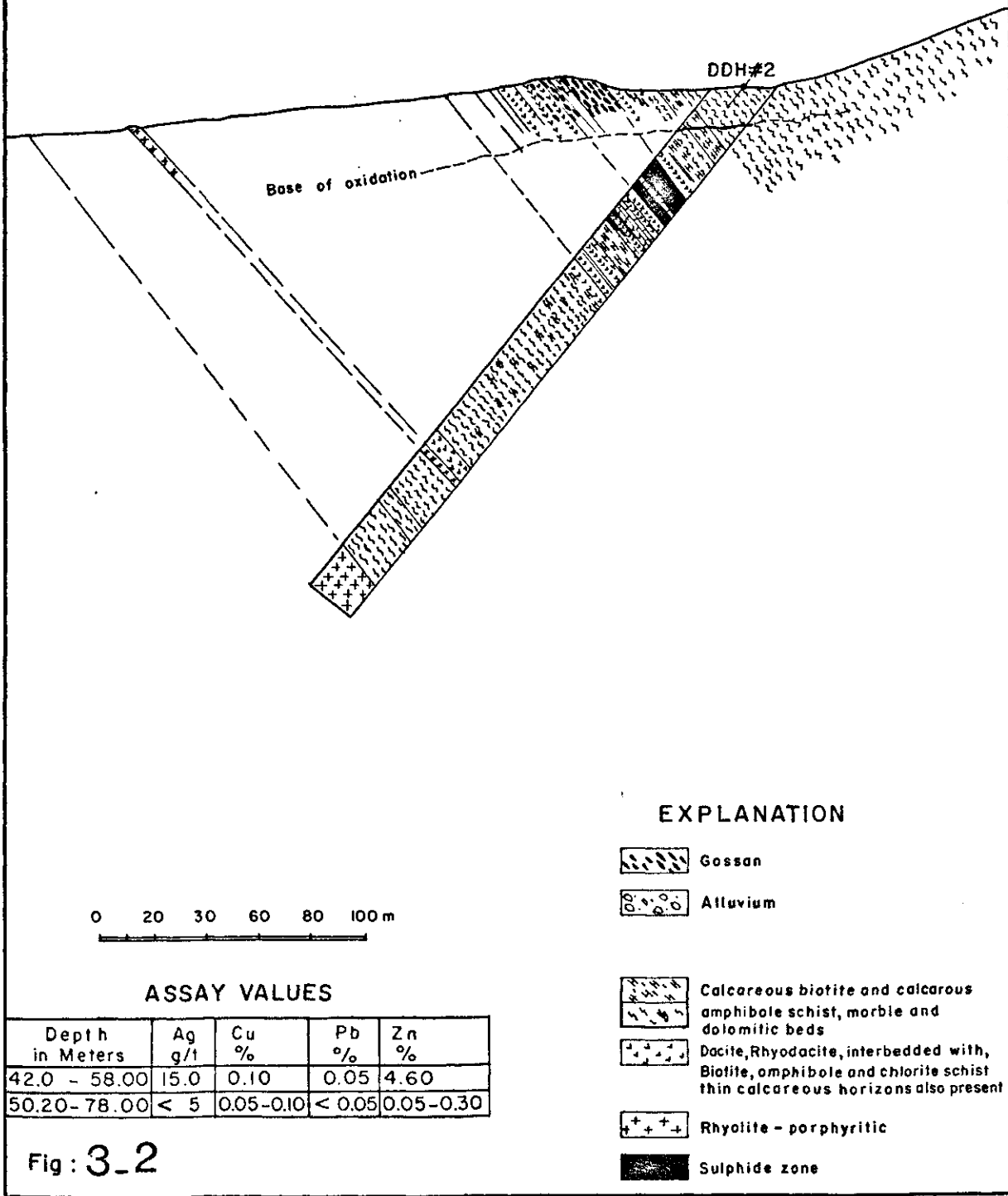
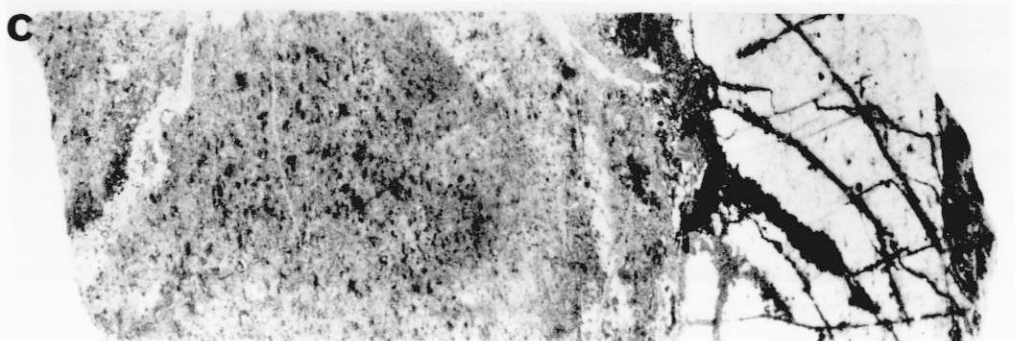
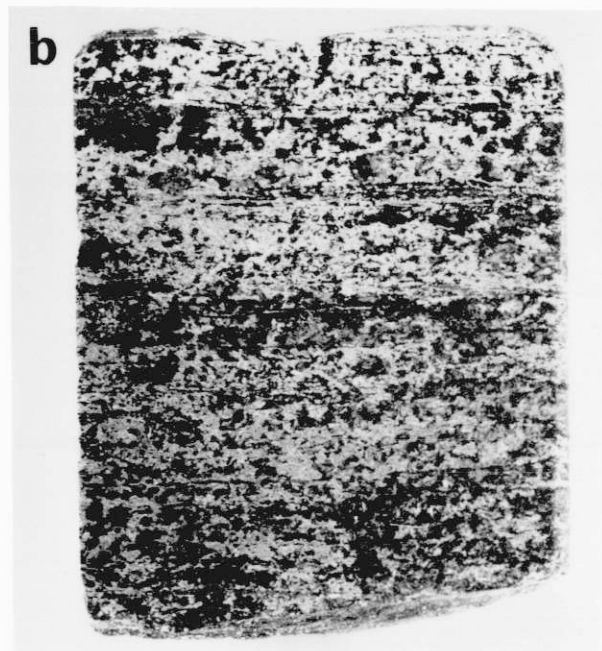
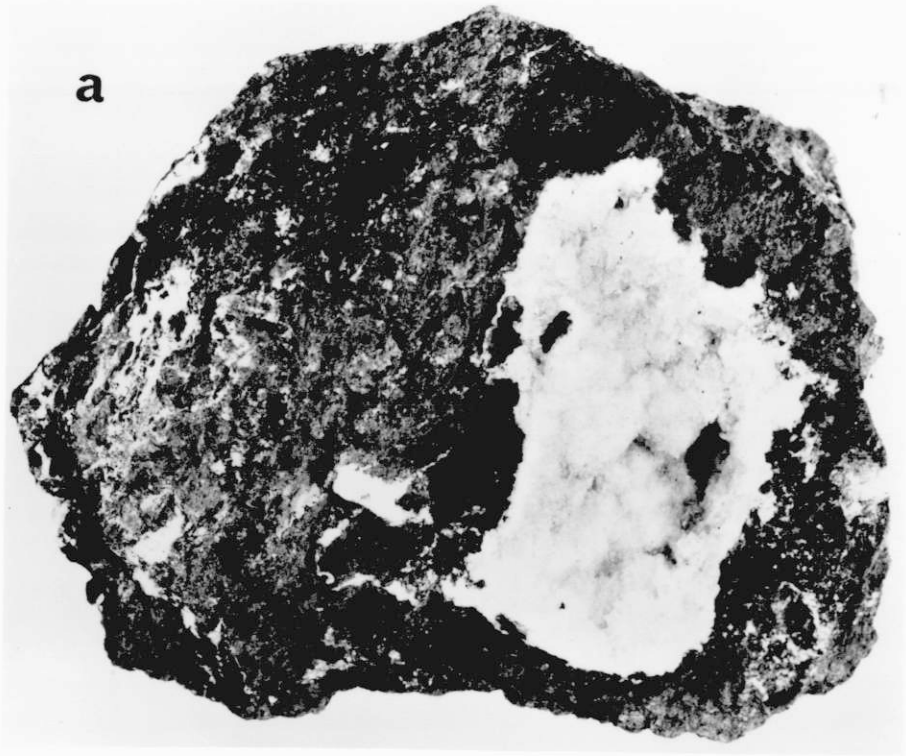


Fig : 3_2

Ar-Ridaniyah Mineralization

Figure 3-3

- a - A specimen of surface gossan of Ar-Ridaniyah composed mainly of hematite, goethite, limonite (black) and calcite (white) lining the cavities and filling cracks in the gossan. x 1.
- b - A core specimen of massive sulphide at depth of 57.5 mrs. DH.1 composed of pyrrhotite and less common pyrite (grey white) and sphalerite (grey and dark grey). The black patches and laminae are calc-silicate host rock minerals. Notice the planar fabric in sulphides parallel to (S_1) planes. x 1
- c - A core specimen at depth of 229.5 mrs, DH.1, showing discordant vein-type mineralization in pre-kinematic (grey) and post-kinematic (grey white) intermediate dyke rocks. White and light grey veinlets are predominantly pyrrhotite. Black and dark grey veinlets and specks are predominantly sphalerite. x 1



proved the presence of hematite, goethite, montmorillonite, calcite gypsum and quartz. No zinc or lead oxidation minerals were confirmed. The oxidised zone extends downward to a depth of about 20 m, below the surface.

3.3 PRIMARY SULPHIDE MINERALS

3.3.1 Pyrrhotite Fe_{1-x}S

Volumetrically, pyrrhotite is the most important sulphide phase in the mineralized body. It occurs in both massive and disseminated fabrics with variable grain size.

3.3.1.a Fabric

The pyrrhotite aggregates described here may contain up to a maximum of 15 percent of other sulphides and/or gangue in the massive aggregates, and up to 80 percent or more of other sulphides and/or gangue in the disseminated fabrics. In figs. 3-4, 3-5, 3-7 and 3-9 the fabric and relations of pyrrhotite with other sulphides are shown. The fabrics of the pyrrhotite in both the stratabound and vein-type mineralizations are similar, therefore in the following description the differences will be explicitly referred to when necessary.

Both massive and disseminated fabrics are developed. The former type is dominant and consists of coarse tabular or lensoid anhedral granular mosaics in which the grains have dimensions from 500 - 1000 μm . The grains are flattened parallel to the planar fabric of the silicate-carbonate host (fig. 3-4a) so that their lengths are approximately double their thicknesses. Grain boundaries are usually polygonal (fig. 3-7 f and i) linear but occasionally serrate.

Where the pyrrhotite is disseminated the mineral forms isolated clusters of 2-4 large grains, or single grains 50 - 100 μm as in the brecciated microveinlets. Grain shapes tend to be tabular polygonal with a preferred orientation parallel to schistosity (fig. 3-4a). In other cases they are irregular (fig. 3-4 b and c).

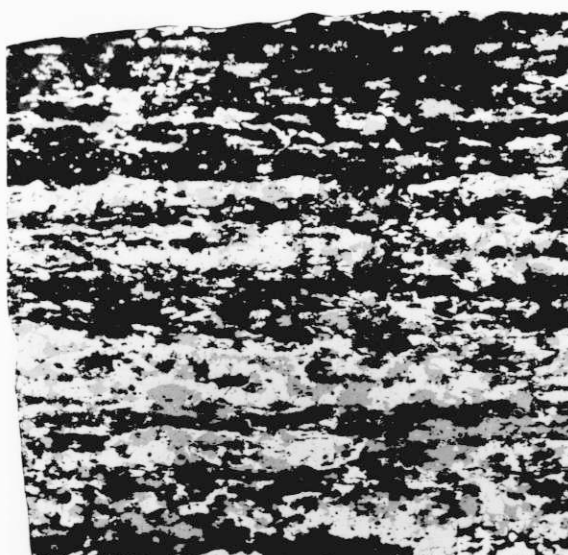
Ar-Ridaniyah Mineralization

Figure 3-4

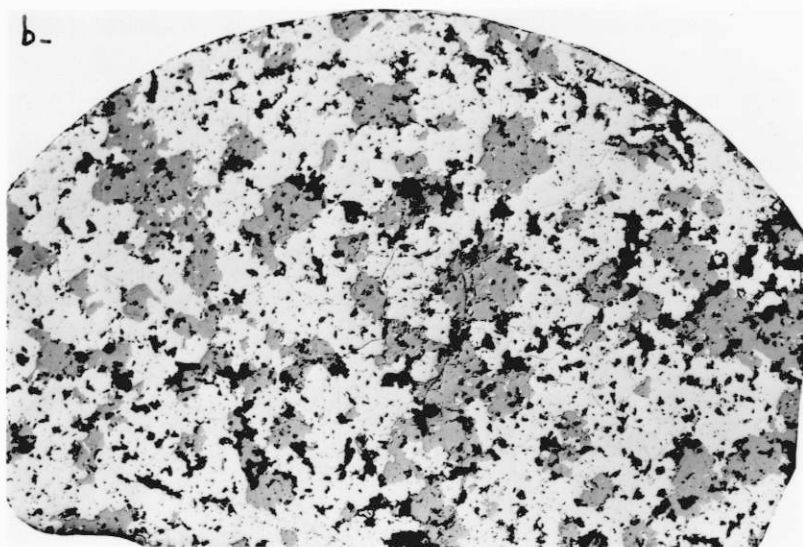
(a, b and c taken in reflected PPL)

- a - A polished specimen in stratiform mineralization showing Planar orientation of sulphides parallel to S_1 . Sulphides are dominantly pyrrhotite with less common pyrite (white) and sphalerite (grey). The gangue is composed predominantly of calcite and clinozoisite. X5, As-656, depth of 74.90 mrs. DH.1.
- b - A polished specimen in stratabound massive sulphides. Section is at right angles to (S_1). Sphalerite (grey) in subrounded aggregates in a matrix of pyrrhotites, and is of later crystallization than pyrrhotite (white). Notice the ratio of both minerals, and the irregular distribution of calc-silicate gangue and irregular shape of pyrrhotite aggregate. X5, As-658, depth of 92.0 mrs. DH.1.
- c - A polished specimen of vein-type discordant mineralization showing embayment of sphalerite (grey) to pyrrhotite (white) and extensive replacement of the pyrrhotite by chlorite (black). X5, As-662, depth of 229.5 mrs. DH.1.

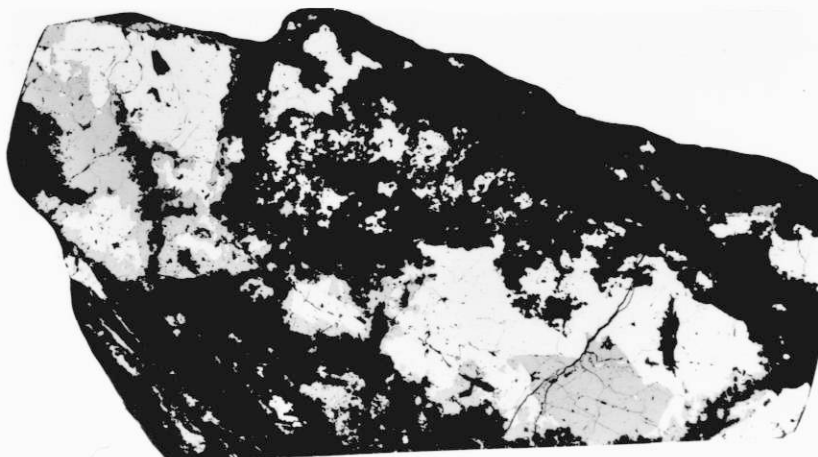
a-



b-



c-

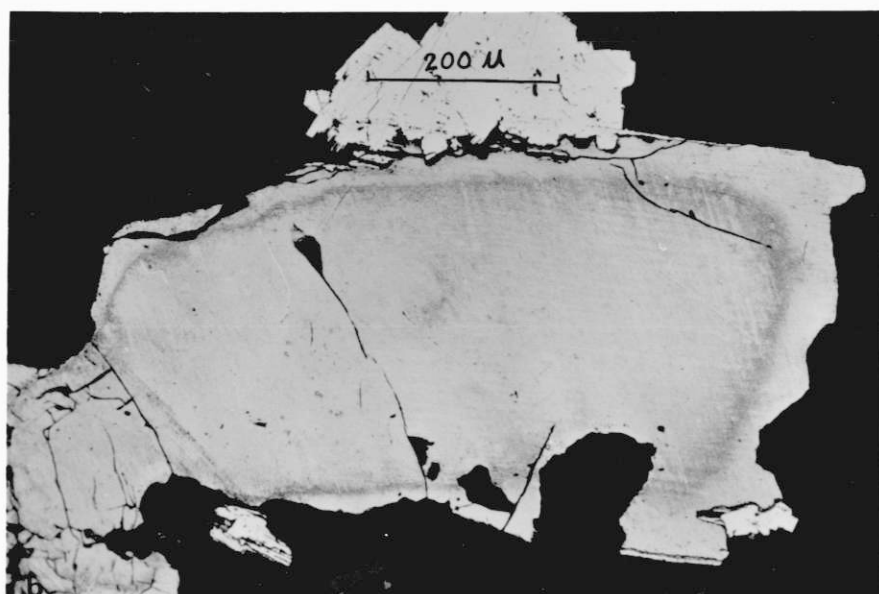


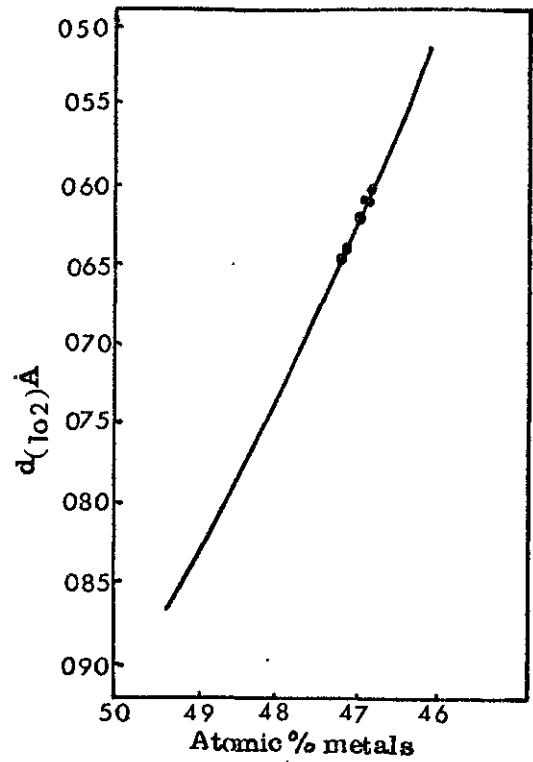
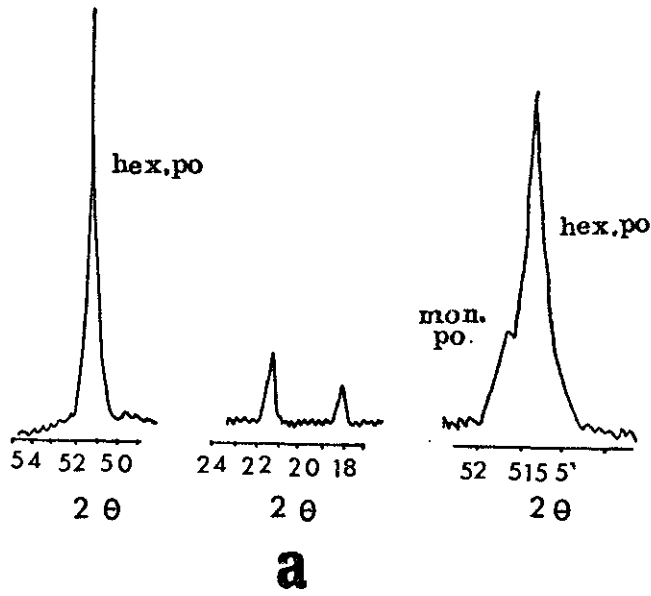
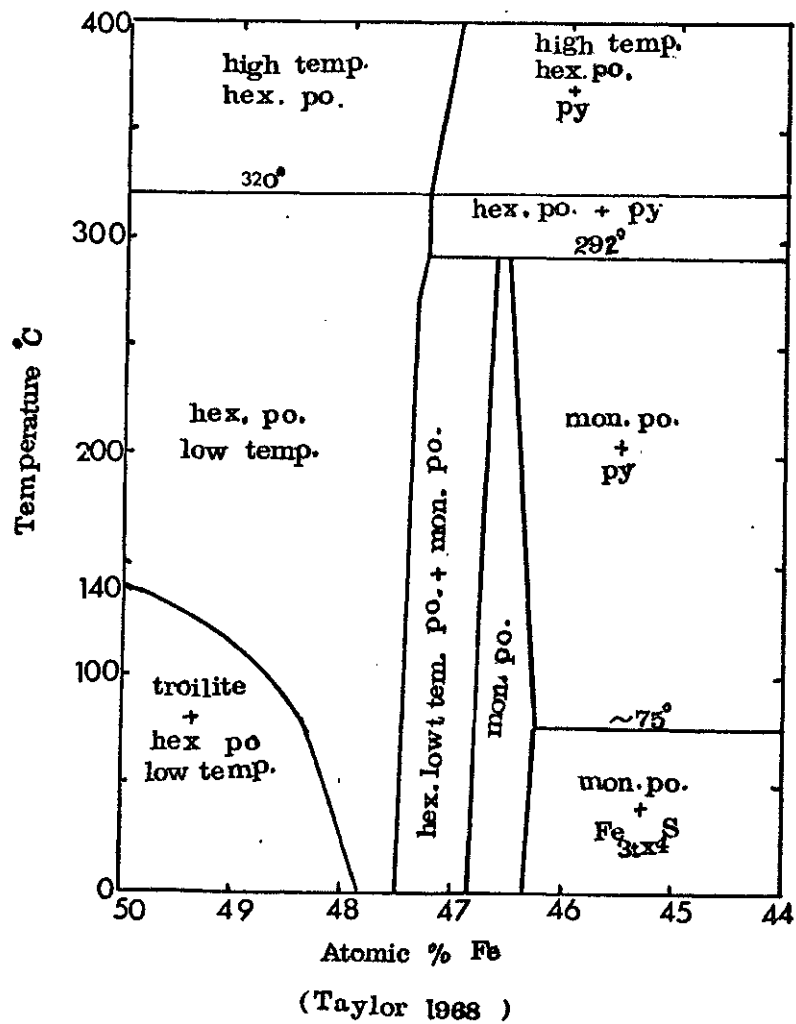
Ar-Ridaniyah Mineralization

Figure 3-5 (Etched pyrrhotite)

(a, b and c are taken in reflected PPL)

- a - Angular zigzag lamellae of monoclinic pyrrhotite (grey) in a host of hexagonal pyrrhotite (light grey). As-660, Stratiform mineralization at depth of 151.0 mrs, DH.1
- b - Monoclinic pyrrhotite (grey) rimmed by hexagonal pyrrhotite (light grey) which is marginally replaced by marcasite and gangue. As-659, stratiform mineralization at depth of 149.60 mrs, DH.1
- c - Hexagonal pyrrhotite (light grey). One grain contains lamellae of monoclinic pyrrhotite (grey). Notice the po-po grain boundary relationships and replacement of chlorite to pyrrhotite. As-660, stratiform mineralization at depth of 151.0 mrs., DH.1.



**c****Fig:3-6**

3.3.1.b Intergranular Textures and Structures revealed by etching

The internal textures are determined by the arrangement of gangue and sulphide inclusions within the pyrrhotite grains, structural modifications within the pyrrhotite phases were revealed by chemical etching.

The frequency of non-sulphide inclusions in the pyrrhotite may have been influential in delimiting the grain fabric developed during metamorphic recrystallization. The grains of the silicate and carbonate gangue show well developed orientation resulting in the planar schistosity fabric of the rock. It is possible that there has been local chemical mobility resulting in replacement of the gangue by sulphides and vice versa.

The minor inclusions within the pyrrhotite show a random distribution but commonly are oriented with their longer axes parallel to the schistosity. The inclusions are chiefly calcite, albite, tremolite, quartz, biotite and epidote or clinozoisite.

Etching of pyrrhotite by concentrated chromic acid indicates that hexagonal and monoclinic pyrrhotites are present in both concordant and discordant mineralizations. The common intergrowth takes the form of spindle shaped monoclinic lamellae in a hexagonal host, but the reverse may also occur (fig. 3-5 a and c). Another less common relationship is that in which hexagonal pyrrhotite forms a peripheral fringe around the monoclinic host which also contains amounts of the hexagonal phases. (Fig. 3-5b)

According to the experimental studies in the Fe-S system conducted by Arnold (1969) and more recently by Taylor (1970), mutual exsolution of low temperature hexagonal pyrrhotite in monoclinic pyrrhotite takes place from hexagonal low temperature pyrrhotite of composition approximately Fe 47.5 - 46.75 atomic % Fe at 292°C. Taylor notes that monoclinic pyrrhotite of $\text{Fe}_{7.5}\text{S}_8$ composition inverts rapidly and reversibly at $292^\circ\text{C} \pm 4^\circ\text{C}$ to a low temperature hexagonal pyrrhotite of the same composition (fig. 3-6c).

The textures observed in the Ar-Ridaniyah pyrrhotites indicate an original temperature of formation of 292°C according to this data.

3.3.1.c X-Ray Diffraction

The X-ray powder diffraction traverses across d (102) reflection of pyrrhotite showed that five of the six samples studied exhibit two peaks at this substructure reflection position. This split according to Desborough et al. (1965) indicates that the pyrrhotite is a mixture of hexagonal and monoclinic phases (fig. 3-6a). Sample (As-657) showed that the two peaks 2.060 and $2.050\text{\AA}$ are of low intensities which indicates that monoclinic pyrrhotite is the major phase. Sample (As-662) showed only one sharp peak $2.060\text{\AA}$ indicating a hexagonal pyrrhotite dominance over the monoclinic, Desborough et al. (1965). In the other four samples both phases are present in approximately equal amounts.

A convenient method for determining the composition of hexagonal pyrrhotite was given by Arnold et al. (1962). They found a close relationship between the d(102) $\text{\AA}$ spacing and the metal content provided the total concentration of Cu, Ni, Zn etc., was less than about 0.5 percent. Their graph is reproduced in (fig. 3-6b) and X-ray data for the pyrrhotites are given in Table 3-1.

The pyrrhotite in the six samples showed a composition ranging from 46.75 to 47.20 atomic percent iron, and an average of 46.94 percent iron. This is in accordance with Arnolds' (1967) observation that hexagonal pyrrhotite in association with monoclinic pyrrhotite is restricted in composition in the natural assemblages.

Samples As-662 and As-663 are from the discordant veinlets, while the rest are from the concordant mineralization.

Desborough et al. (1965) found that the mixture of both hexagonal and monoclinic pyrrhotite can form below the beta transformation i.e. 320°C .

The pyrrhotite compositions are plotted in (fig. 3-6b).

Table 3-1

X-ray data and compositions of pyrrhotite based on the (102) lattice spacing and continuous scanning using CoK α radiation and external silicon and fluorite standards

<u>Samples</u>	<u>degrees 2θ</u>	<u>d(102)Å^o</u>	<u>Atomic %Fe</u>	<u>Wt%Fe * (EPMA)</u>
As-652	51.375	2.065	47.20	
As-654	51.435	2.061	46.90	60.4
As-655	51.525	2.059	46.75	60.6
As-657	51.500	2.060	46.80	60.0
As-662	51.415	2.064	47.10	60.7
As-663	51.435	2.061	46.90	
Average			46.94	

Samples are taken from diamond drill hole No.1, Ar-Ridaniyah at depth of 58.90, 60.30, 71.60, 82.50, 229.60 and 238.0 meters inclined from the surface, arranged from top to bottom.

The mineral assemblage in all these specimens is mainly pyrrhotite but minor sphalerite or galena are present.

* J. Steed and N. Wilkinson kindly conducted the electron probe analyses used in this chapter.

Table 3-2

Electron probe analysis of pyrrhotite of Ar-Ridaniyah mineral assemblage in wt. percentages.

	<u>As-654</u>	<u>As-655</u>	<u>As-657</u>		<u>As-662</u>
			grain 1	grain 2	
<u>Element</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
Fe	60.4	60.6	60.0	60.0	60.7
S	39.0	37.1	38.5	38.0	37.6
Total	99.4	97.7	98.5	98.0	98.3

Co and Ni checked but not detected.

Analyses 1, 2 and 4 are for pyrrhotite in the pyrrhotite-sphalerite assemblage of the concordant mineralization.

Analysis 3 - is an exsolved bleb of pyrrhotite in sphalerite. Sample 5 is pyrrhotite grain in discordant mineralization shown in (fig. 3-7a).

3.3.1.d Mode of formation of Pyrrhotite

The original iron sulphides are believed to have been deposited within an impure calcareous sediment to form bodies of diagenetic pyrite in a dolomitic limestone horizon. Regional metamorphism has caused the desulphurisation of the pyrite to form pyrrhotite, this process being accompanied by redistribution of the sulphide phases by diffusion during recrystallization and deformation. Remnant pyrite as individual crystals or aggregates of crystals or corroded grains, forms islands within pyrrhotite (fig. 3-7 b,c,d and e). Antun (1967) studied the sedimentary pyrite of the lower part of the Cambro-Silurian sequence of Oslo, Norway. Within the thermal aureole of the Permian Drammen granite, pyrite has been transformed to homogeneous monoclinic pyrrhotite. The temperature of this transformation was less than 320°C with a very low sulphur fugacity. Jackaman (1971) studied the massive sulphide deposits of Wadi Wassat and Qatan of Saudi Arabia and concluded that the pyrrhotite formed by contact metamorphism of pyritic lenses by intruding diorite. McDonald (1967) compared the mineral assemblages of the McArthur River, Mt. Isa and Broken Hill N.S.W. deposits which occur in increasingly metamorphosed terrains, and showed that the pyrrhotite-pyrite ratio increases with increasing metamorphism.

Metamorphism caused the release of sulphur from the pyrite. This liberated sulphur reacted with iron-rich minerals within the pyritic lenses, but a certain amount of it was able to pass out of the system.

3.3.2 Sphalerite (Zn, Fe)S

Sphalerite is the principal economic sulphide of the Ar-Ridaniyah deposit and follows pyrrhotite in abundance. Locally, it may form

30 percent of the total volume of the sulphides. Sphalerite is probably of the same generation or slightly later in the paragenetic sequence than pyrrhotite (fig. 3-7a).

Under the microscope it is grey to dark grey with characteristic red internal reflections in oil. Lamellar twinning is sporadically developed when the sphalerite is etched (fig. 3-8 a,b and g).

3.3.2.a Fabric

Sphalerite occurs in the interstices of the massive pyrrhotite aggregates (fig. 3-4b) and is found more commonly at po-po grain boundaries than as inclusions within individual grains, this suggests metamorphic mobility of the sulphides in the sense of Stanton (1972).

Sphalerite of the stratiform type mineralization is in segregated individual aggregates (fig. 3-4b) or in compound bands in dimensionally preferred orientation parallel to the gangue and the pyrrhotite rich bands (fig. 3-4a). However, intergrown mixed bands of both sulphides are predominant, where sphalerite is always interstitial or marginal to pyrrhotite. Sphalerite aggregates with numerous gangue inclusions are abundant, and show protuberant extrusions into the enclosing pyrrhotite (fig. 3-4 b and 3-9 i and j). Primary orientation of gangue inclusions within sphalerite aggregates seems not to be affected by the later crystallization of sphalerite.

Sphalerite of the vein type mineralization on the other hand, commonly forms aggregates which form embayments in pyrrhotite and partly replaces it (fig. 3-7a). Individual small grains, 50-300 microns, are abundant within pyrrhotite aggregates. Small, corroded grains of brecciated sphalerite are present within younger post-mineralization fractures along with other sulphides.

Sphalerite in both stratiform and vein types shows replacement by both chalcopyrite and galena.

3.3.2.b Exsolution in sphalerite

Sphalerite of stratiform type shows exsolved inclusions of chalcopryrite and pyrrhotite. These occur in various forms (fig. 3-8g and fig. 3-9 a-g), predominantly as rounded droplets of variable diameters from sub-microscopic to 30 microns randomly in migrated emulsion texture. Tabular or lens-like bodies are embedded parallel to crystallographic directions. Irregular ragged forms are restricted to sphalerite grain boundaries (fig. 3-9 d and f).

The pyrrhotite inclusions are usually larger in size and often though not invariably associated with gangue inclusions. They are less abundant than chalcopryrite, subspherical or ovoid in shape. Chalcopryrite and pyrrhotite compound bodies occur as a form of exsolution (fig. 3-10c).

The sphalerite of the vein type, in addition to both chalcopryrite and pyrrhotite, shows exsolved stannite (fig. 3-8 e, 3-10e and f). As in the case of the stratiform type, chalcopryrite is predominant but appears to be more crystallographically controlled (fig. 3-9e). Stannite inclusions are at random and show variable grain size and irregularities (fig. 3-10f). Grain boundary segregation of stannite in sphalerite is common (fig. 3-10e). Pyrrhotite inclusions are identical to those in sphalerite of the stratiform type.

Electron probe analysis of sphalerite of Ar-Ridaniyah mineralization in wt. percentage.

	<u>As-654</u>		<u>As-655</u>	<u>As-657</u>	<u>As-662</u>
<u>Element</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
Zn	54.2	55.4	52.4	51.4	52.5
Fe	12.1	12.4	11.9	13.2	10.9
S	34.2	34.3	31.7	33.4	32.3
Total	100.5	102.1	96.0	98.0	95.7
FeS	18.35	18.67	17.77	20.0	16.4

Mn not detected. Cd - in traces.

Samples 1, 2, 3 and 4 are for sphalerite from the pyrrhotite - sphalerite assemblage of the concordant mineralization.

Sample 5 is sphalerite in the discordant mineralization.

3.3.2.c Relationships of pyrrhotite - sphalerite

The textural and compositional characteristics of these two minerals indicate one episode of mineralization in which sphalerite is slightly later (fig. 3-9h, i and j).

Sphalerite tends to show mutual boundaries with pyrrhotite at which sphalerite apparently replaces pyrrhotite. The relationship between these two minerals is identical in both the stratabound and the vein type mineralizations. Sphalerite is interstitial to pyrrhotite grains, it infills the open spaces and follows grain boundaries. Moreover, in the vein type mineralization sphalerite tends to be deposited around the earlier formed pyrrhotite grains and in this way it both encloses and replaces them.

Pyrrhotite occurs also as exsolved blebs or inclusions within sphalerite grains. These vary in size from submicroscopic to about 20 microns, however larger inclusions are also present. Together with chalcopyrite, pyrrhotite segregate at sphalerite grain boundaries and along twin planes.

In the stratabound type mineralization, sphalerite and pyrrhotite tend to form segregations intercalated in the layered gangue. In the 80 - 100 percent massive mineralization (fig. 3-4b) pyrrhotite is dominant, sphalerite forms subrounded polycrystalline inclusions with irregular digitations protruding the enclosing pyrrhotite.

3.3.2.d Possible conclusions to be drawn from the $\text{FeS} - \text{ZnS} - \text{FeS}_2$ phase relations and the chemical composition of the sphalerites:

The mineral assemblages of the $\text{FeS} - \text{ZnS} - \text{FeS}_2$ type are ubiquitous in the Ar-Ridaniyah deposit. On the microscopic scale, examination shows that pyrite, pyrrhotite and sphalerite occur intimately associated on the scale of millimetres in polished section. Thus there is a

reasonable basis for suggesting that the composition of sphalerites should fall within the narrow range about 20.8 mol.% FeS which is that predicted by the work done by Boorman (1967). His synthesis demonstrated the temperature independence of the equilibrium sphalerite compositions falling on the $\text{FeS} - \text{FeS}_2 - \text{ZnS}$ solvus below 550°C at atmospheric pressure. More recently, additional synthetic studies made by Scott and Barnes (1971) showed that, while the slope of the solvus is vertical and thus sphalerite compositions are temperature independent at low atmospheric pressures, the position of the solvus is significantly shifted as pressures are increased.

The Ar-Ridaniyah sphalerites show iron contents of significantly less than 20.8 mol.% FeS (16.4 - 20.0 mol. %, average 18.2 mol.%). These compositions are believed to indicate the metamorphic equilibrium of the Fe-Zn-S phases in rocks under conditions of greenschist metamorphism $P = 1-4 \text{ Kb}$ at $T = 500^\circ\text{C}$. This conclusion is wholly in agreement with the solvus predicted by Scott and Barnes (1971). (fig.3-11).

The presence of exsolved pyrrhotite and chalcopyrite in the Ar-Ridaniyah sphalerites does introduce some uncertainty into the interpretation of the sphalerite analysis using Scott and Barnes (1971) geobarometer. Notwithstanding the uncertainty introduced by these iron rich exsolution products, the results seem to be reasonable, if the evidence for metamorphic equilibration in the greenschist field provided by the non-sulphide minerals is accepted.

3.3.3 Pyrite FeS_2

Pyrite is a minor sulphide present in both stratiform type and vein mineralizations. Two varieties occur :

- (I) First generation pyrite in scattered isolated grains or mosaic aggregates which occur within a pyrrhotite matrix and show corroded boundaries. Islands of this type-I pyrite are very common in the massive pyrrhotite of the stratiform ores. Zoned idiomorphic pyrite grains are extensively intergrown with gangue and/or hematite. Hematite and gangue replace pyrite along the zone boundaries.

(II) Late stage pyrites found in two ways :- (a) as pyrite-marcasite intergrowths replacing primary pyrrhotite (fig. 3-7h), and (b) as extremely fine grained discordant and concordant veinlets which formed in minor fractures (fig. 3-7j), showing by their brecciation and displacement that they were affected by later stages of fracture activation.

Atoll and caries replacement textures are extensively developed in pyrite II where gangue and hematite replace pyrite during supergene oxidation.

Pyrite II also shows minor inclusions of hematite, sphalerite, galena and chalcopyrite.

3.3.4 Chalcopyrite CuFeS_2

Chalcopyrite is also a minor sulphide in Ar-Ridaniyah mineralization. It occurs mainly as an exsolved phase in sphalerite or as occasional small allotriomorphic grains in both vein type and stratiform type mineralization (fig. 3-10d). In relation to pyrrhotite and sphalerite, which are the major sulphides of the deposit, chalcopyrite shows a tendency to fill interstices. Chalcopyrite tends to replace both pyrrhotite and sphalerite. It shows local oxidation to covellite.

The grain boundaries with both pyrrhotite and sphalerite show the migratory tendency of the chalcopyrite during deformation and metamorphism.

The chalcopyrite which occurs as exsolution bodies in sphalerite is discussed under the sphalerite heading.

Electron probe microanalysis of chalcopyrite of Ar-Ridaniyah mineralization.

<u>Element</u>	<u>As-654</u>	<u>As-657</u>	<u>As-663</u>
	<u>1</u>	<u>2</u>	<u>3</u>
Cu	34.6	33.2	33.5
Fe	31.1	29.7	28.5
S	34.2	33.6	33.8
Total	99.9	96.5	95.8

Samples 1 and 2 are chalcopyrite blebs exsolved at grain boundaries of sphalerite in the concordant mineralization.

Sample 3 is for chalcopyrite replacing pyrrhotite in the discordant mineralization.

3.3.5 Marcasite (FeS_2)

Marcasite is a minor constituent in the sulphide assemblage. It is principally a secondary alteration mineral formed at the expense of pyrrhotite. It is closely associated with it and rarely occurs in individual grains or aggregates. Marcasite is always associated with fine granular pyrite as a product of pyrrhotite breakdown. It occurs in both stratabound and vein mineralization, but more commonly in the latter (fig. 3-8d). It is usually peripheral to pyrrhotite in the form of lamellar aggregates growing within alteration zones parallel to (0001) of pyrrhotite. Spindle shaped or tabular inclusions are also present within pyrrhotite aggregates at grain boundaries (fig. 3-7h).

Marcasite in polished section is whitish yellow, with metallic lustre, pleochroic in air and in oil showing yellow and light green interference colours.

Ramdohr (1969) suggested that marcasite forms from the decomposition of pyrrhotite in acid solution at low or moderate temperatures from either ascending or descending waters. All the evidence points to a supergene origin for the Ar-Ridaniyah marcasite.

3.3.6 Galena PbS

Galena is also present in very small amounts in both vein and stratabound mineralization, but more commonly in the former, where cassiterite and stannite also occur.

Galena is of the latest crystallization, it embays and probably replaces other sulphides (fig. 3-7g). Galena commonly forms irregular grains within pyrite, pyrrhotite and sphalerite. It also fills fractures

and frequently follows the grain boundaries in pyrrhotite aggregates.

In polished section galena is bluish grey white with a strong metallic luster. No silver mineral inclusions were detected. Occasionally remnants of pyrrhotite, sphalerite or pyrite occur in small inclusions.

Investigation of a few galena grains by E.P.M.A. detected no other elements in the galena. Microanalysis gave 87.7% Pb and 13.1% S.

Galena in vein mineralization is more abundant compared to stratiform type and is believed to be mobilized to its present sites from the stratabound mineralization in addition to that deposited from hydrothermal solutions.

3.3.7 Stannite ($\text{Cu}_2\text{FeSnS}_4$)

Stannite is present only in the vein type mineralization and is restricted to association with sphalerite occurrences. It occurs in very small amounts either as exsolved blebs, usually irregular (fig. 3-10f), as thin veinlets within sphalerite grains, or as segregations at sphalerite grain boundaries (fig. 3-10e). Idiomorphic grains of cassiterite are commonly present in the vicinity (fig. 3-10f). Unfortunately, EPMA analysis of several spots on stannite grains gave low totals, only two grains gave totals of 93.9 and 93.1 out of 100%.

For comparison, stannite from San Jose, Oruro, Bolivia and from Wheal Ager, Cornwall, (Springer, 1968) are as follows:

<u>Element</u>	<u>Bolivia</u>	<u>Cornwall</u>	<u>Ar-Ridaniyah</u>	
			<u>As-663</u>	<u>As-662</u>
Cu	29.5	29.2	28.9	29.3
Sn	27.6	27.7	22.8	21.6
Fe	11.1	10.5	12.7	12.9
Zn	1.8	3.1	0.9	1.1
S	30.0	30.0	28.6	29.3
Total	100.0	100.5	93.9	93.1

The stannite in polished section is olive green. Weakly pleochroic and anisotropic. Since no other optically distinct stannite-type phases are recognised the mineral is regarded as a typical tetragonal anisotropic stannite (see table of analyses).

3.3.8 Arsenopyrite FeAsS

Occurs as isolated grains in the vein type mineralization where it is associated with cassiterite and stannite. It is not an abundant mineral. The grain boundary relationships suggest that it is formed later than the associated sphalerite (fig. 3-8c). It is regarded as a product of late hydrothermal activity.

3.4 OXIDE MINERALS

3.4.1 Hematite Fe_2O_3 and Goethite $\text{Fe}_2\text{O}_3\cdot\text{OH}$

Both are secondary replacing pyrrhotite and pyrite (fig. 3-8c and f) in both vein and stratiform mineralization.

The surface exposures of the mineralized lenses are completely oxidized and leached. The iron sulphide phases are oxidized to hematite, goethite and less commonly to siderite. This oxidation extends downwards to about 20 meters below the surface and oxidation below this level is sporadic.

3.4.2 Cassiterite SnO_2

Cassiterite is restricted in its occurrences. It is seen only in the veinlets crosscutting the post-kinematic microadamellite sills. It occurs in small subrounded grains (fig. 3-10f), either isolated or in aggregates with closely associated sphalerite and stannite. It is present in small amounts (As-662). Cassiterite possibly alters to stannite, although no replacement textural relationships are observed.

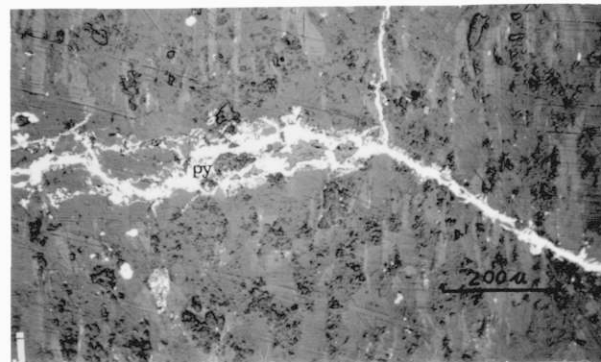
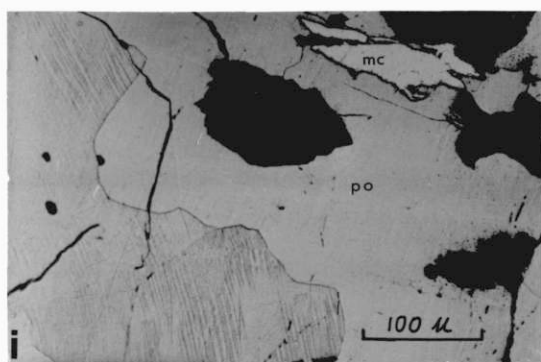
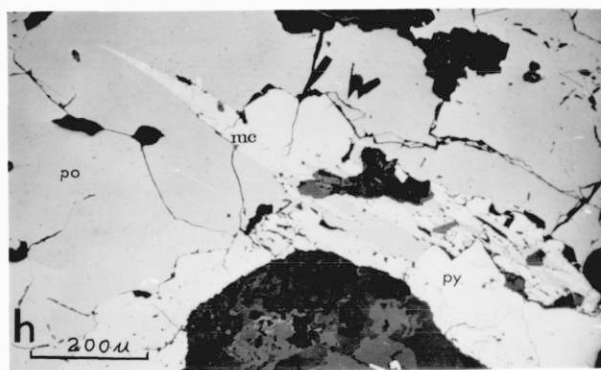
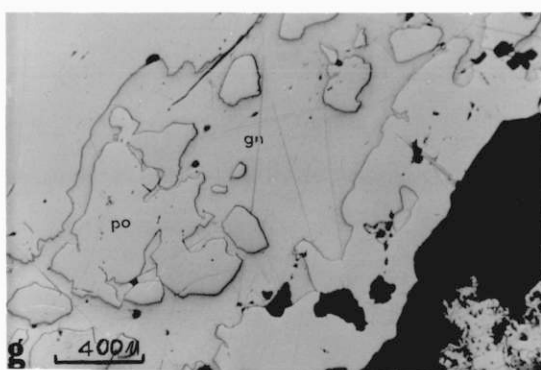
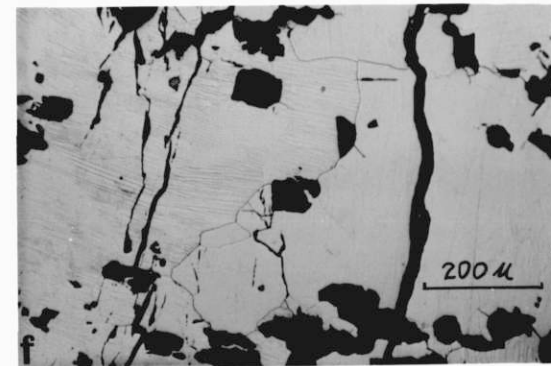
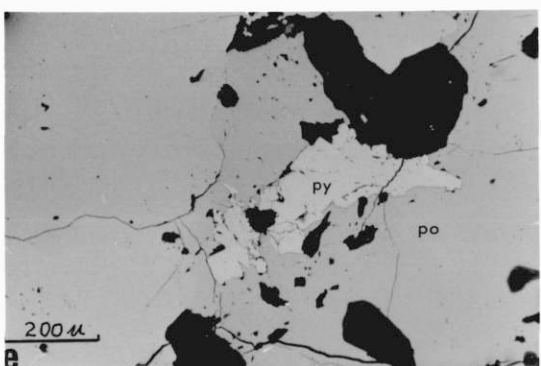
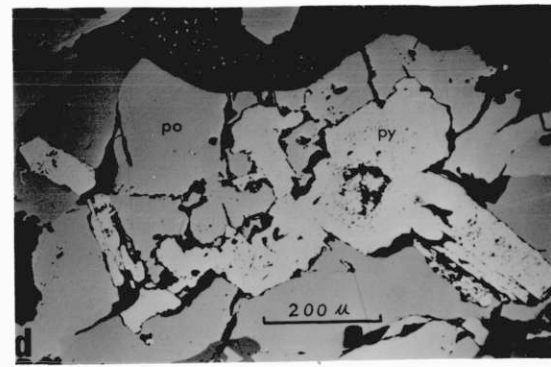
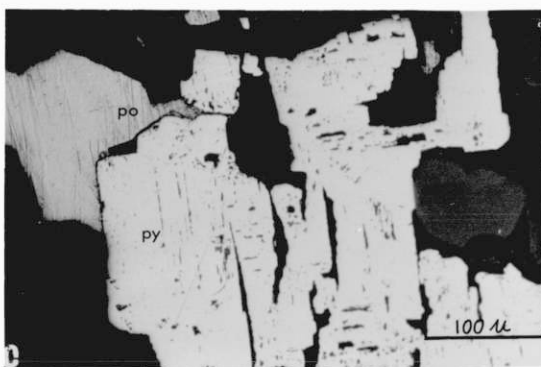
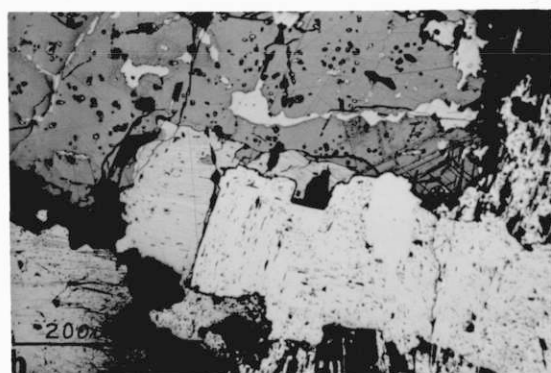
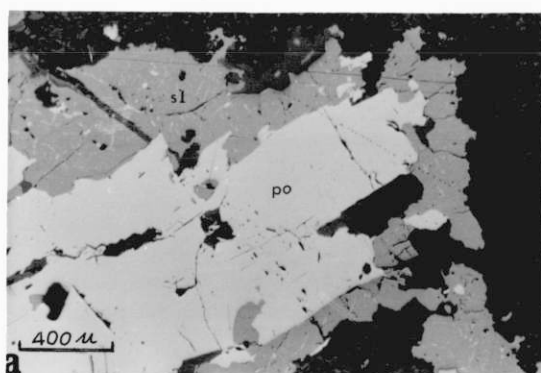
The occurrence of cassiterite and stannite in the vein mineralization suggests that the composition of the veins comprises material from two distinct sources. (a) A base metal sulphide component remobilized from the earlier stratabound bodies, and (b) a tin

Ar-Ridaniyah Mineralization

Figure 3-7

(a-j taken in reflected PPL, Oil immersion)

- a - Sphalerite (Sl) embaying and marginally replacing pyrrhotite (Po). As-662, vein-type mineralization, depth of 229.5. DH.1.
- b - Pyrite-1 (white), zoned and partly embayed by pyrrhotite (light grey). Gangue minerals replace pyrite along zoned planes. As-660. Stratiform mineralization, depth of 151.0, DH.1.
- c - Pyrite-1, zoned (Py) partly embayed and replaced by pyrrhotite and gangue along zoned planes. As-660. Stratiform mineralization depth of 151.0 mrs. DH.1.
- d & e Pyrite-1 (Py) corroded and enclosed in a matrix of pyrrhotite (Po) where pyrrhotite is replacing it. d-As-651, e-As-658, Stratiform mineralization at depths of 57.20 and 92.0 mrs. respectively, DH.1
- f - Po-Po grain boundary relationships, dominantly polygonal linear. Pyrrhotite aggregate is deformed and cemented by quartz. Monoclinic pyrrhotite lamellae occur in some grains As-663, vein-type mineralization, depth of 238.30 mrs, DH.1 (Etched section).
- g - Galena (gn) interstitial to pyrrhotite (Py) extensively replacing it. As-663, vein-type mineralization, depth of 238.30 mrs. DH.1.
- h - Pyrite⁻² (Py) and marcasite (mc) marginally replacing pyrrhotite (po). As-650, stratiform mineralization, depth of 54.0 mrs, DH.1.
- i - Po-Po grain-boundary relationships, polygonal linear. Dominantly hexagonal pyrrhotite, some grains host monoclinic lamellae (grey). As-650, stratiform mineralization at depth of 54.0 mrs, DH.1 (Etched section).
- j - Micro-veinlets of pyrite-2. As-661, depth of 217.0 mrs, DH.1.

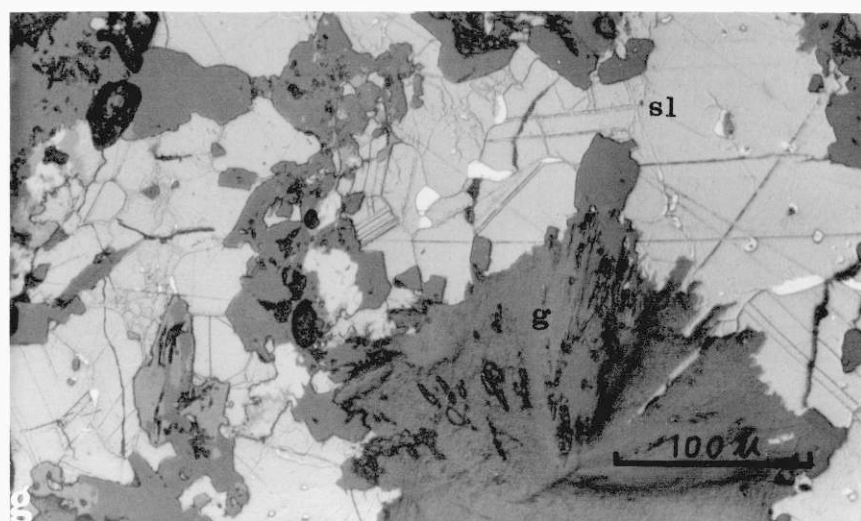
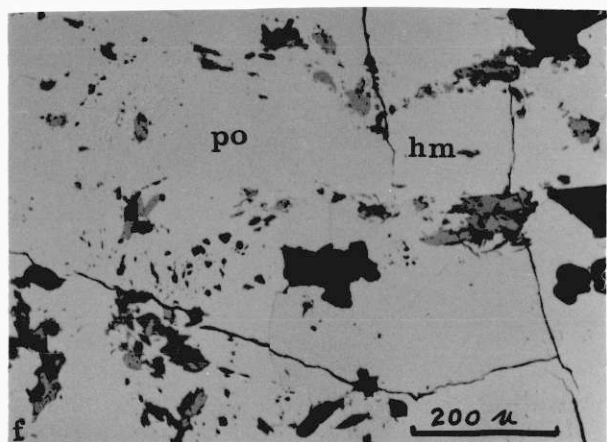
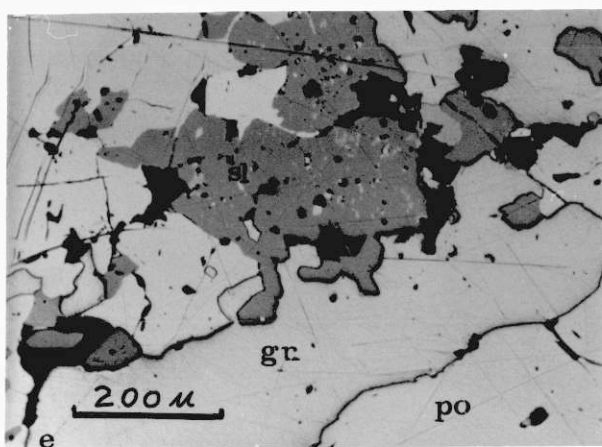
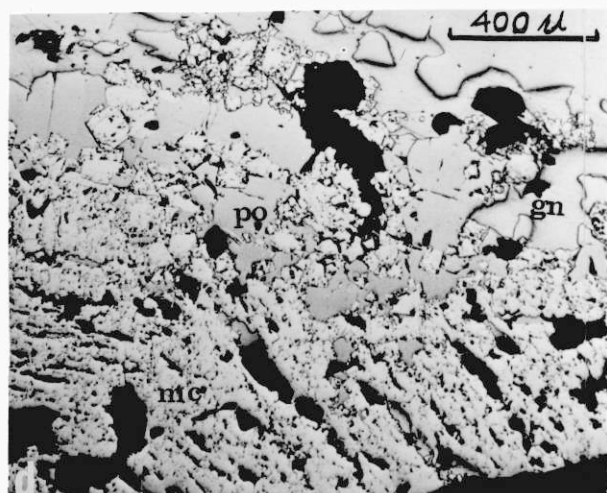
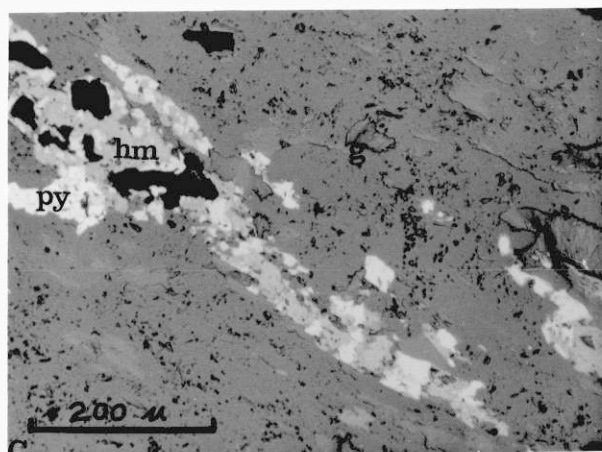
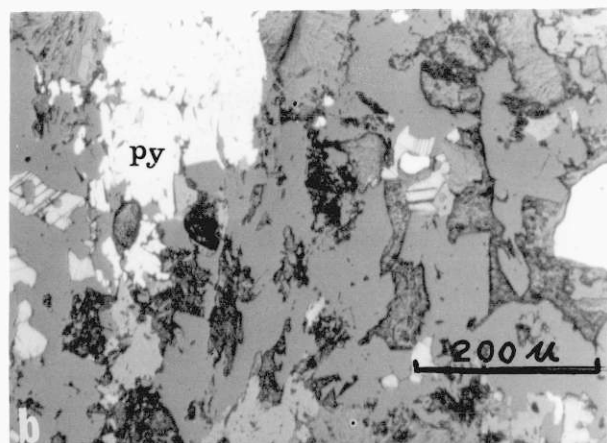
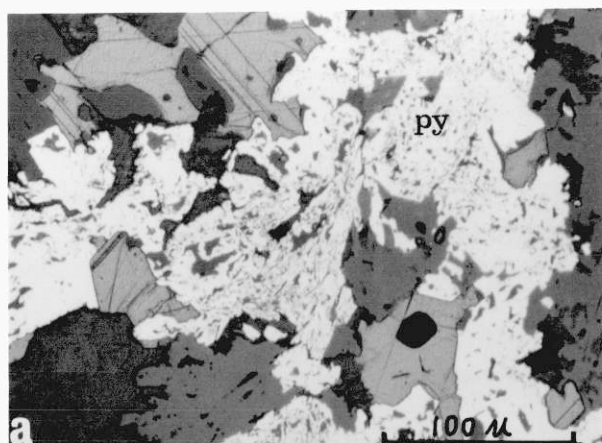


Ar-Ridaniyah Mineralization

Figure 3-8

(a-g taken in reflected PPl in oil immersion DH.1)

- a & b Twinned sphalerite and secondary pyrite. As-659, stratiform mineralization, depth of 149.60 mrs. Etched section.
- c - Hematite (hm) and goethite replacing pyrite. As-660, stratiform mineralization, depth of 151.0 mrs.
- d - Marcasite (mc) replacing pyrrhotite (Po). Galena (gn) interstitial to pyrrhotite. As-663, vein-type mineralization, depth of 238.30 mrs.
- e - Sphalerite (sl) interstitial to pyrrhotite (Po). Arsenopyrite (ars) interstitial to sphalerite. Galena replacing pyrrhotite and sphalerite. The sphalerite contains exsolved stannite (sn) and chalcopyrite grains. As-663, vein-type mineralization, depth of 238.30 mrs.
- f - Irregular inclusions of hematite (hm) and gangue in pyrrhotite. As-660, stratiform mineralization, depth of 151.0 mrs.
- g - Coarse pyrrhotite grains exsolved at grain boundaries of twinned sphalerite. As-659, stratiform mineralization, depth of 149.60 mrs. (Etched section).



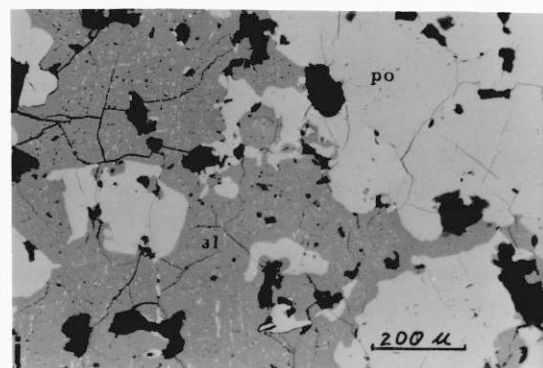
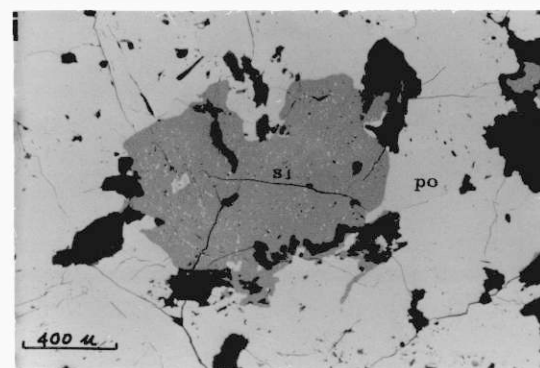
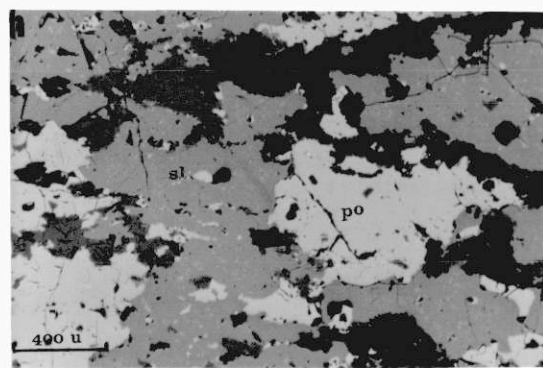
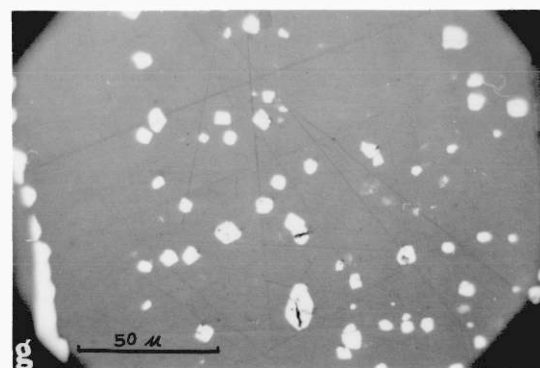
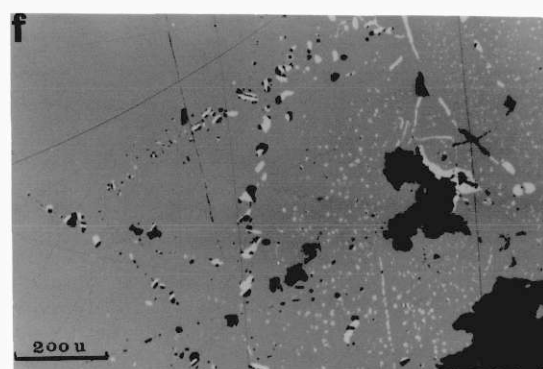
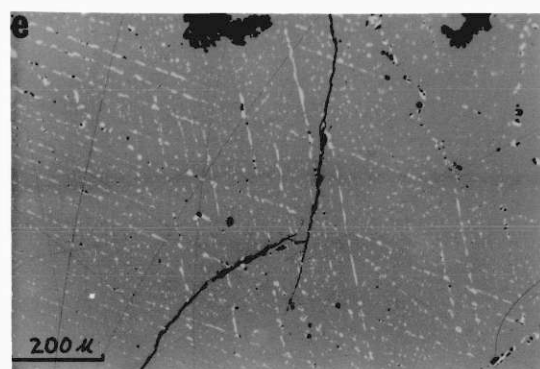
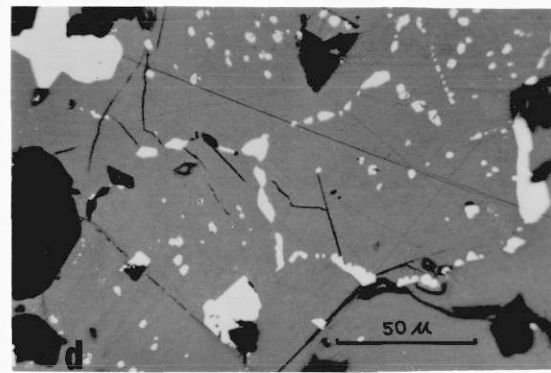
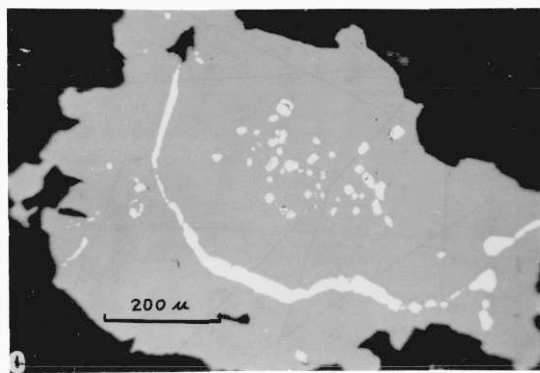
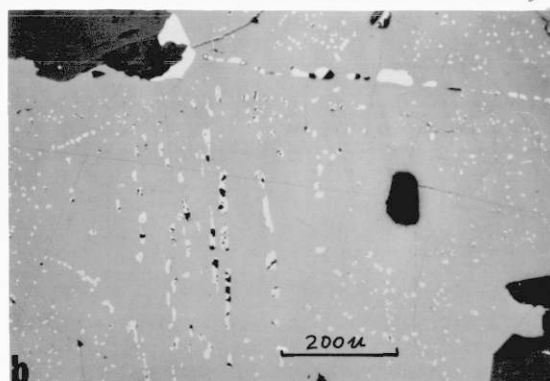
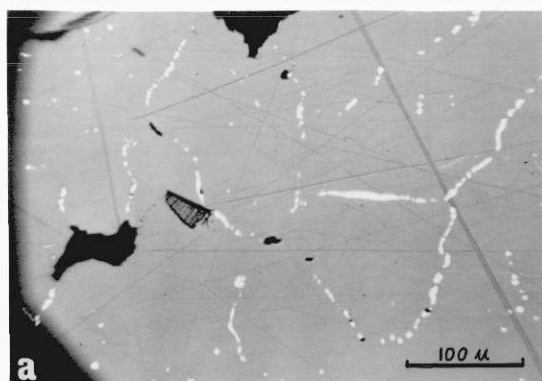
Ar-Ridaniyah Mineralization

Figure 3-9

(a-j taken in reflected PPL in oil immersion.

Specimens from DH.1)

- a - Unmixing of chalcopryrite and pyrrhotite (white) from sphalerite (grey) and subsequent segregation to sphalerite grain boundaries. As-657, Stratiform mineralization, at depth of 87.50 mrs.
- b - Exsolution of chalcopryrite and pyrrhotite along parallel planes and grain boundaries of sphalerite. Emulsion exsolution is also developed. Coarse exsolved grains are commonly pyrrhotite or compound grains of pyrrhotite and chalcopryrite. As-650, Stratiform mineralization, depth of 54.0 mrs.
- c & d Coarse unmixing of chalcopryrite and pyrrhotite in sphalerite away from the margins and along grain boundaries. c - As-654, d - As-657 stratiform mineralization, depths of 60.55 and 87.50 mrs. respectively.
- e - Chalcopryrite exsolved along crystallographic planes and in emulsion in sphalerite, As-662, vein-type mineralization, depth of 229.5 mrs.
- f - Unmixing and segregation of pyrrhotite (coarse) at sphalerite grain-boundaries. Chalcopryrite in emulsion exsolution. As-662, vein-type mineralization, depth of 229.5 mrs.
- g - Coarse compound grains of chalcopryrite and pyrrhotite exsolved from sphalerite. As-657, stratiform mineralization depth of 87.50 mrs.
- h - Massive sulphide fabric of sphalerite (Sl) and pyrrhotite (Po) in stratiform mineralization. As-652, depth of 59.65 mrs.
- i - Subrounded sphalerite (sl) aggregate with protuberances in a matrix of pyrrhotite (Po). As-658, stratiform mineralization at depth of 92.0 mrs.
- j - Sphalerite, interstitial to pyrrhotite matrix in stratiform mineralization. As-652, depth of 59.65 mrs.

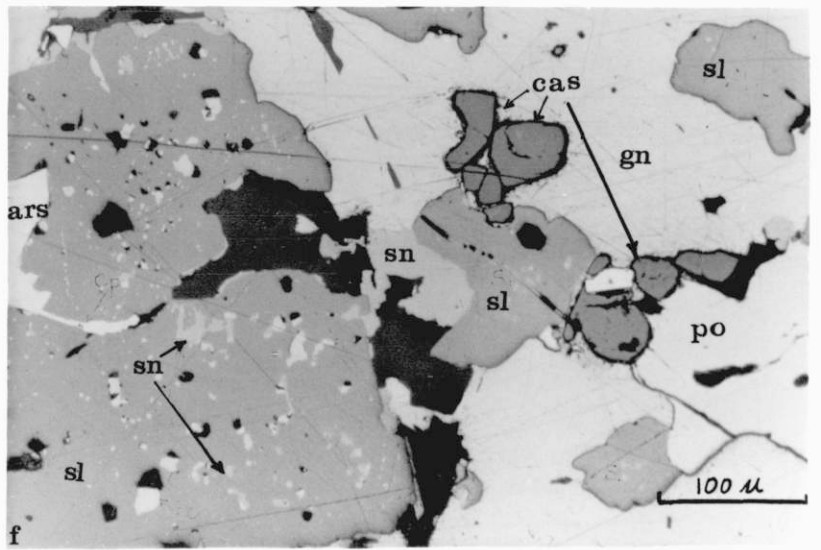
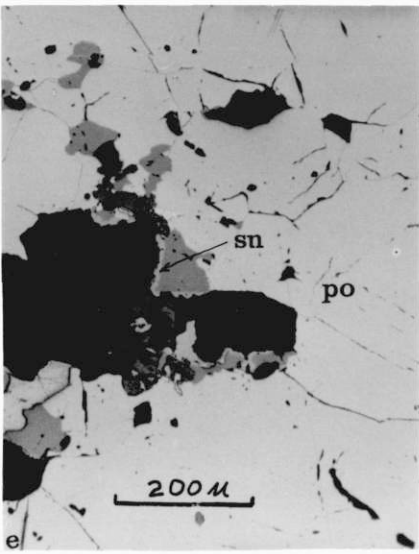
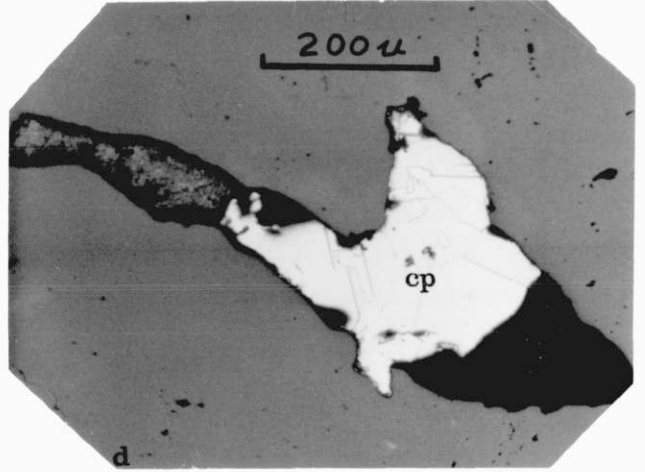
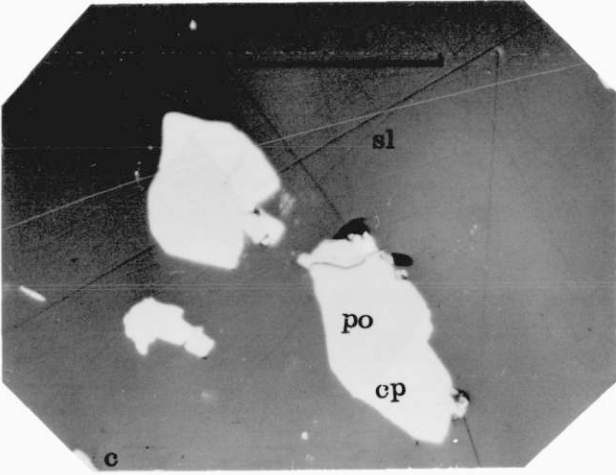
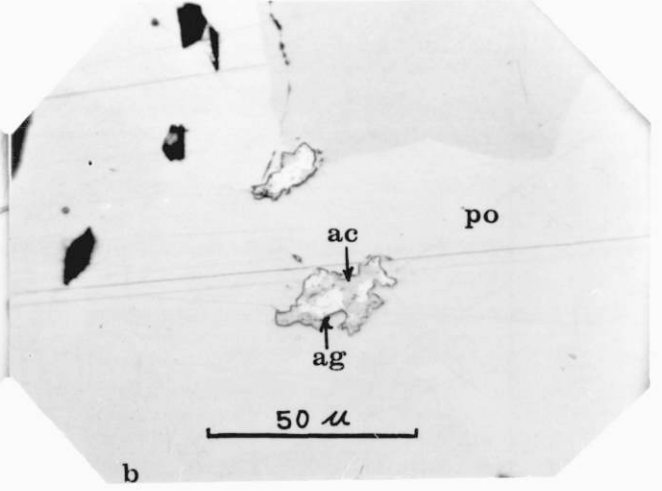
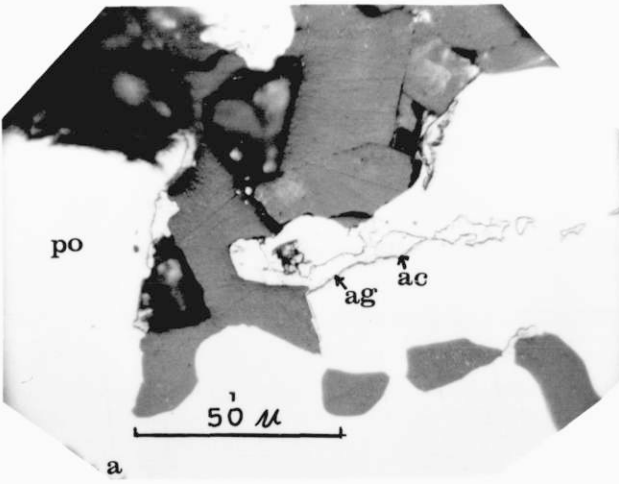


Ar-Ridaniyah Mineralization

Figure 3-10

(a-f taken in reflected PPL in oil
immersion from DH.1)

- a & b Fine inclusions of native silver (ag) rimmed by acanthite (ac) in pyrrhotite (Po). As-657, stratiform mineralization, depth of 87.50 mrs.
- c - Coarse compound grains of chalcopyrite (cp) and (Po) exsolved from Sphalerite (sl). As-659, stratiform mineralization, depth of 149.60 mrs.
- d - Etched chalcopyrite grain showing twinning. As-660, stratiform mineralization, depth of 151.0 mrs.
- e - Stannite (sn) rimming sphalerite in a matrix of pyrrhotite (Po). As-663, vein-type mineralization, depth of 238.30 mrs.
- f - Subrounded grains of cassiterite(cas). Stannite (Sn) marginal and in irregular exsolved bodies in sphalerite. Arsenopyrite (ars) interstitial to sphalerite. Galena (gn) interstitial to pyrrhotite and sphalerite. As-663 vein-type mineralization, depth of 238.30 mrs.



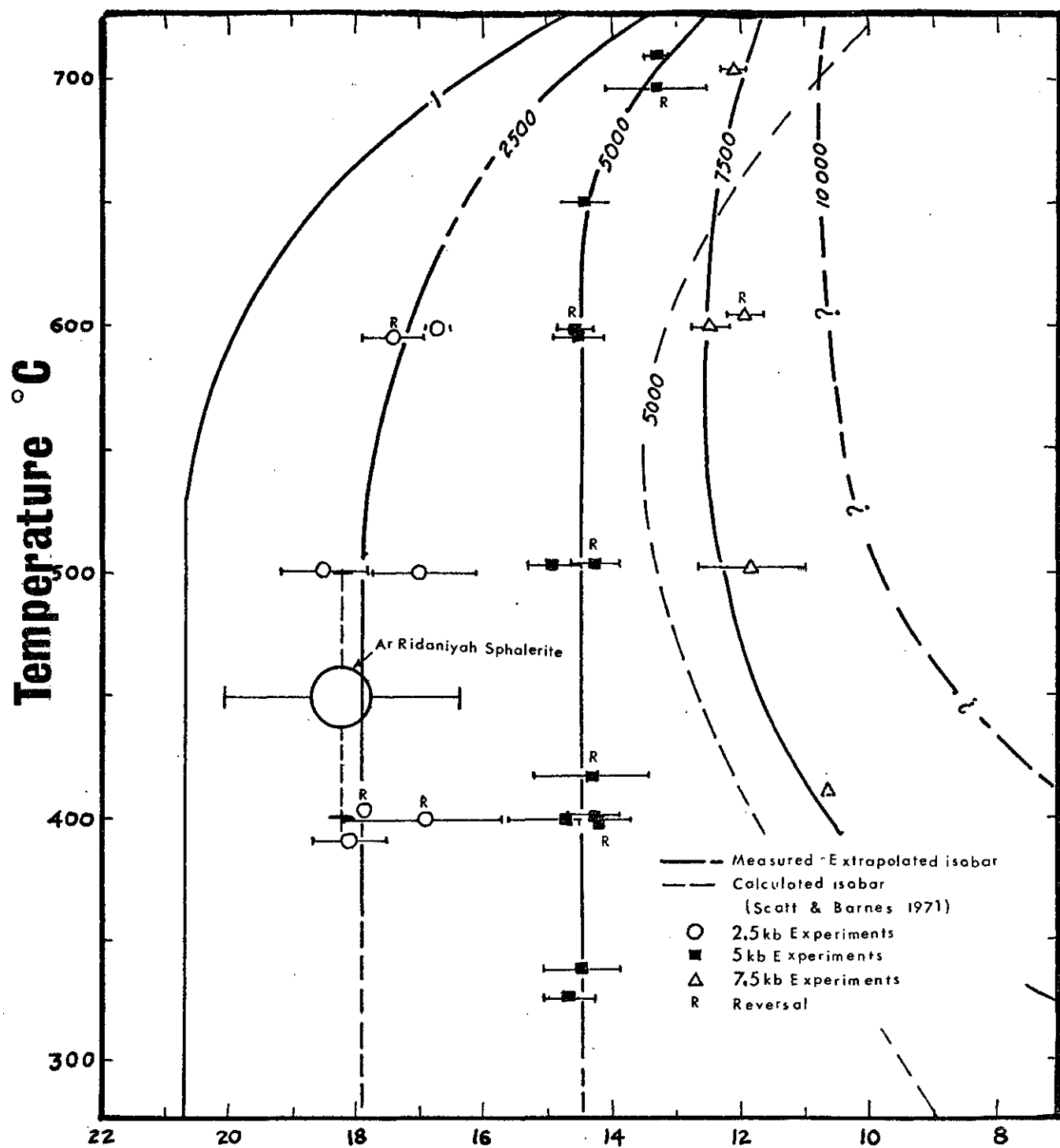


Fig:3-11

Mole % FeS in Sphalerite

(After Scott pers. comm.)

ISOBARS OF SPHALERITE + PYRITE + METASTABLE MON. + HEX.
PYRRHOTITE

bearing pulse originating in the microadamellite intrusions which form sill-like bodies in the calcareous formation of Ar-Ridaniyah.

3.5 SILVER MINERALS

Silver minerals are rare in Ar-Ridaniyah mineralization. Minute native silver grains rimmed by acanthite occur as veinlets (fig. 3-10a) or as inclusions (fig. 3-10b) in pyrrhotite grains. It seems that the native silver is replacing acanthite and that both minerals were formed by supergene alteration.

3.6 JABAL HUMAYYAN

Jabal Humayyan is situated 25 Km east of Ad-Dawadmi town. It includes several dark low hills at the extreme north of the Ar-Ridaniyah Formation.

Blanchot (1970) noticed a close similarity between the geological setting of this area and that of the Kambalda area in Western Australia. At Kambalda large nickel deposits have been discovered in the past few years (Woodall and Travis, 1969). He recommended an exploration program for nickel and copper.

3.6.1 Geological setting

Jabal Humayyan area (fig. 3-12) is an essentially metamorphic ultramafic suite of rocks deformed and metamorphosed to greenschist facies. The predominant rock types in decreasing order are serpentinite, chloritite and siliceous lenses. Talc and carbonates are less common.

The siliceous lenses have variable amounts of iron oxide content, accordingly these were classified into three categories, siliceous, ferruginous and "pseudogossan". Fig. 3-13 shows detailed geological sections along trenches dug by B.R.G.M. in separate locations.

The siliceous lenses, being resistant to erosion, form prominent low hills, 10-20 m. above the surrounding flat ground. Intercalations of the host rocks from Ar-Ridaniyah Formation are common, particularly calcareous and quartzo-feldspathic schist. Concordant pre-kinematic

basic and acidic minor intrusions occur throughout the area.

Serpentinites and chloritites are strongly deformed. The schistosity is predominantly north-south with prevailing steep easterly dips. Where the stratigraphic contacts are observable, the schistosity is concordant with the bedding.

3.6.2 Composition and texture of the siliceous lenses

Siliceous lenses are composed essentially of quartz, hematite, goethite and limonite. The common rock is cryptocrystalline in texture and has a porcelanous lustre. The content of iron oxide is variable from one outcrop to the other. The highly siliceous rocks often show a microbrecciated texture where small red siliceous fragments with a cryptocrystalline texture are cemented by finely crystalline quartz. Calcite and chlorite form accessory minerals.

3.6.3 Geophysical investigations

The geophysical investigations carried out by B.R.G.M. consisted of airborne magnetic, ground magnetic and self potential surveys.

All failed to find any strong anomalies at shallow depths (Corpel et al. 1971).

3.6.4 Geochemical investigations

The surface geochemical investigations carried out by B.R.G.M. on the area revealed that the ferruginous siliceous rocks often contain as much nickel and chromium as the serpentinite and chloritite rocks (Corpel et al. 1971). They thought that the silica and the iron removed from the ultramafic rocks during metamorphism leached out the nickel, chromium and the carbonates.

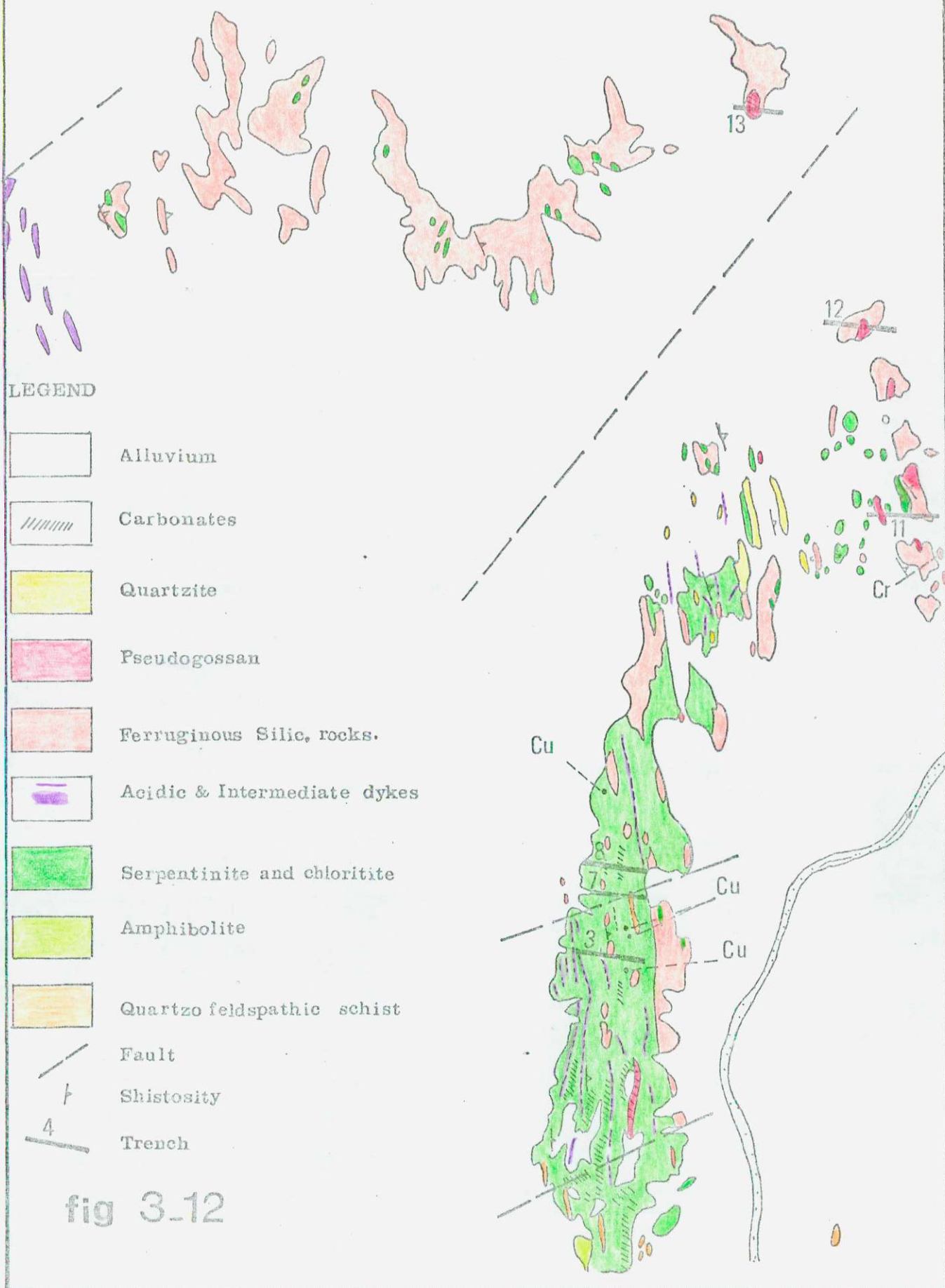
This silica and the associated Fe, Ni and Cr accumulated and deposited in lenses. However, samples from this siliceous rock contained up to 300 ppm copper and 325 ppm zinc. These high values suggest that the hematite and limonite are derived from sulphides

JABAL HUMAYYAN AREA

GEOLOGICAL MAP

(after Leca & Plat 1971)

Scale 1 : 20 000



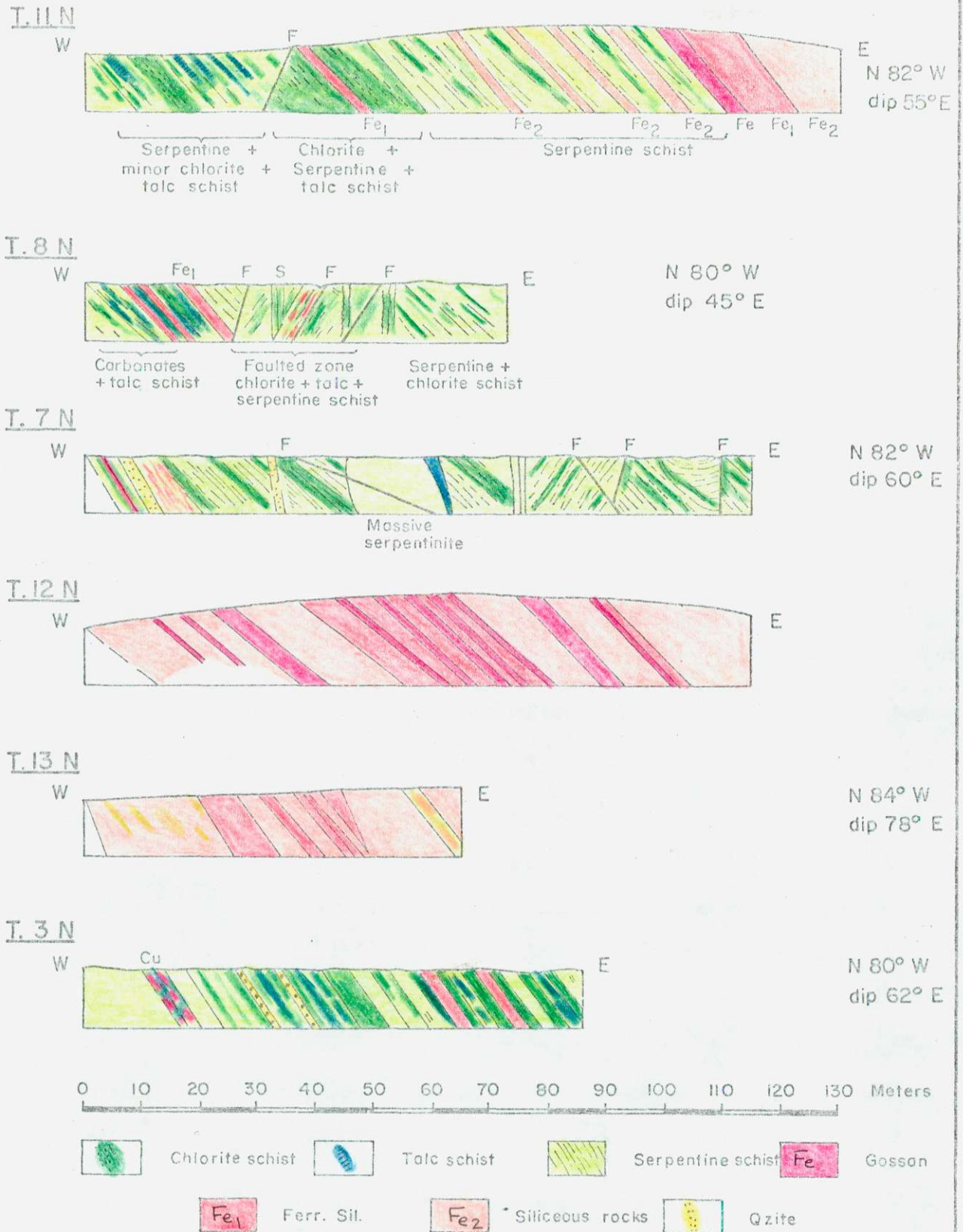


Fig. 3-13 Detailed Sections along trenches in Jabal Humayyan Metamorphic ultramafics.

rather than silicates (Corpel et al. 1971).

The nickel values from the soil ranged from 660-2350 ppm., higher than the enclosing metamorphosed ultramafics. This again suggests that this nickel originated from sulphides.

3.7 SUMMARY

3.7.1 Ar-Ridaniyah Mineralization

1 There are two styles of mineralizations, a stratabound and a discordant vein-type. Both styles occur in an impure dolomitic marble horizon which is intercalated with biotite, amphibole and chlorite schist bands. Extensive pre- and syn- and post-kinematic sill and dyke intrusions cut the calcareous horizon, predominantly concordant with the bedding.

2 The stratabound style mineralization which is in small lenses, the largest of which is a faulted lens 180 m long and 26 m wide appears on the basis of textural evidence to have a pre-metamorphic origin. Selective hydrothermal replacement does not seem likely and thus a syngenetic origin in a marine environment is proposed. The dominance of iron and zinc sulphides suggests a distant relationship to a hydrothermal system.

3 The sulphides form bodies in broadly conformable relationships to the enclosing strata, but in common with many low-grade metamorphic rocks containing conformable sulphides, there are local small-scale discordant fractures, veinlets and protruberances, which pierce the wall rock envelope.

4 The gossan lenses are the superficial expression of sulphide mineralization containing a pyrrhotite - sphalerite assemblage with other minor sulphides. These lenses occur entirely within a stratigraphic horizon of impure dolomitic marble of the Ar-Ridaniyah Formation; this forms the west limb of a broad syncline. As a result the mineralized lenses retain their forms with an easterly dip of about 55° . The host rocks have not suffered intensive folding and metamorphic grade is in the greenschist facies.

5 A conspicuous feature of these lenses is the occurrence of northeasterly trending left-lateral wrench faults cut and displace them. The faults show a dark brown partly gossanized surface trace easy to recognise, and have been reactivated by later movements.

6 The mineral assemblage of the stratabound-type is composed essentially of pyrrhotite and sphalerite, pyrite is less abundant. Chalcopyrite, galena and marcasite are in minor amounts. Native silver and acanthite occur in minute rare grains.

The mineral assemblage of the vein-type mineralization is again composed essentially of pyrrhotite and sphalerite, pyrite, galena and chalcopyrite are less abundant. Marcasite, cassiterite, stannite and arsenopyrite are in minor amounts. The cassiterite, stannite and arsenopyrite are restricted to this vein-type mineralization and are probably related to hydrothermal solutions which originated in the post-kinematic dyke and sill intrusions.

7 The internal fabric of the sulphide-rich bands maintains a sedimentary aspect when 40% or more of the gangue silicates and carbonates are present. The basal planes of recrystallized clay material and the long axes of the amphiboles mimetically reproduce the original sedimentary lamination of the host. The granoblastic fabric produced during the main phases of deformation and metamorphic recrystallization does not show any evidence of later modification. The principal gangue inclusions in the pyrrhotite - sphalerite ore are quartz, albite, epidote/clinozoisite, biotite, chlorite and calcite. Calcite rimmed by chlorite occurs very commonly within the sulphide bodies as a major component of the included gangue.

3.7.2 Jabal Humayyan mineralization

1 Jabal Humayyan mineralization occurs in form of siliceous lenses within metamorphic ultrabasic rocks located in the northern exposures of Ar-Ridaniyah Formation (Plate 1 and fig. 3-12).

2 The siliceous lenses contain variable amounts of hematite, goethite and limonite, locally they are rich with iron oxides and

termed "pseudogossan". Traces of malachite and chrysocolla were observed in the serpentinite and chloritite.

33 The magnetism and SP geophysical surveys on these lenses by BRGM to delineate the extent of the ultrabasic rocks and to explore any anomaly induced from sulphides, respectively, gave no significant results.

4 The silica lenses have been produced through metamorphism of the ultramafic rocks, the Fe, Ni and Cr associated have also been mobilized together with the silica.

5 One sample from the "pseudogossan" contained 300 ppm. Cu and 325 ppm. Zn. Three other samples contained 230, 270 and 580 ppm Zn. The nickel values from the soil covering the ferruginous silica lenses and the "pseudogossan" range from 660 to 2350 ppm. These values, according to Corpeil et al. (1971) suggest derivation from sulphides.

3.8 CONCLUSIONS

Two stages of mineralization can be recognised at Ar-Ridaniyah. They are distinct in both geometry and mineral content.

1. A conformable stratiform type which is composed of pyrrhotite-sphalerite rich bands intercalated with carbonate and silicate gangue. Pyrite, arsenopyrite and galena occur in this association as minor constituents. The pyrrhotite is believed to be a product of the metamorphic conversion of diagenetic pyrite. Regional metamorphism related to the Hejaz orogeny is believed to have played the chief role in this process but locally, contact metamorphism by post-kinematic sill intrusions may have played a part.
2. A later cross-cutting vein type mineralization in which pyrrhotite and sphalerite are accompanied by tin minerals, cassiterite and stannite, and arsenopyrite. The hydrothermal solutions responsible for this mineralization are believed to have originated from post-kinematic acidic and intermediate intrusions. Much

of the sphalerite and iron sulphides may have been redistributed after remobilization of the stratiform bodies, but the presence of tin minerals suggest that special geochemical characteristics must have been associated with this later, structurally distinct, phase of mineralization.

3. The ore reserves in Ar-Ridaniyah are estimated by the writer to a depth of 200 m, to be about 400,000 tons of average 4% Zn/ton. This estimated reserve, the grade and the remoteness of the deposit exclude the possibility of this deposit to be economic.
4. The geological setting and the surface geochemical sampling of Jabal Humayyan deposit point to the possibility of Ni mineralization. Therefore it is strongly recommended that a minimum of three drill holes should be sunk under the "pseudogossan" exposures which showed anomalous Ni values. BRGM recently, drilled one hole in the deposit to check an SP anomaly away from these "pseudogossan" lenses; apparently, poor or no mineralization was detected and no further drilling was done. Up to the end of this year 1972 no report has been published about this hole.

CHAPTER 4

LAYERED BASIC INTRUSIONS

4.1 INTRODUCTION

Two layered basic intrusions occur in Ad-Dawadmi district (plate 1). The northern one, Arja, was discovered during this course of field mapping; the southern one Al-Jéalani is larger in size ($\sim 50 \text{ km}^2$) and is more prominent. They are separated by a distance of thirty km. In plan view both are elliptical in shape with their longer axes trending northwesterly. Arja intrusion will be discussed briefly later in this chapter. The field and laboratory methods used in this study are discussed in appendix 2.

4.2 SCOPE AND PURPOSE OF INVESTIGATION

1. The two basic intrusions occur within an ancient silver mining district. Their investigation thus included the possibility of a genetic relationship to this mineralization. The major mineralized occurrence in the area (Samrah) is localized at the contact of xenoliths disrupted from Al-Jéalani basic intrusive mass within a suite of younger granites.
2. The varied recorded opinions about the structure and the nature of the southern intrusion (Al-Jéalani) encouraged its mapping and ascertaining its origin, i.e. whether it is a layered intrusion, or merely dykes intruded into pre-existing rocks.
3. The possibility of any economic ore deposits usually associated with such layered basic intrusions such as Ni, Pt, Cr, Fe, V, Ti etc. was a prime purpose, though none have yet been recorded.

4.3 AL-JE'ALANI INTRUSION

4.3.1 Structure and topography

This layered intrusion is oval in outline about 9 x 6 km., with its longer axis trending N 42°W (plate 4 and fig. 4-1). It is enveloped by light coloured granitic rocks, displaying spectacular contrast in colour and shape. The intrusion is made up of rather uniform concentric horizons dipping radially inward. Dips are generally steep, in the marginal layers ranging between 50-70°, and decreasing gradually towards the center to dips of about 20°. Local distortions in dips and layering are due to later dyke and granitic intrusions as displayed in the central area.

The drainage pattern over the intrusion is approximately radial, although minor streams follow concentric surfaces of horizons parallel to layering, before joining the main ones.

The layered basic rocks occupy remarkably flat country with a mild degree of relief in comparison to the surrounding rocks.

Concentric ridges were formed by differential erosion of the massive unaltered layers (fig. 4-2a). The altered rock units rarely form hills or ridges, except where intruded by younger granitic rocks.

4.3.2 Previous work

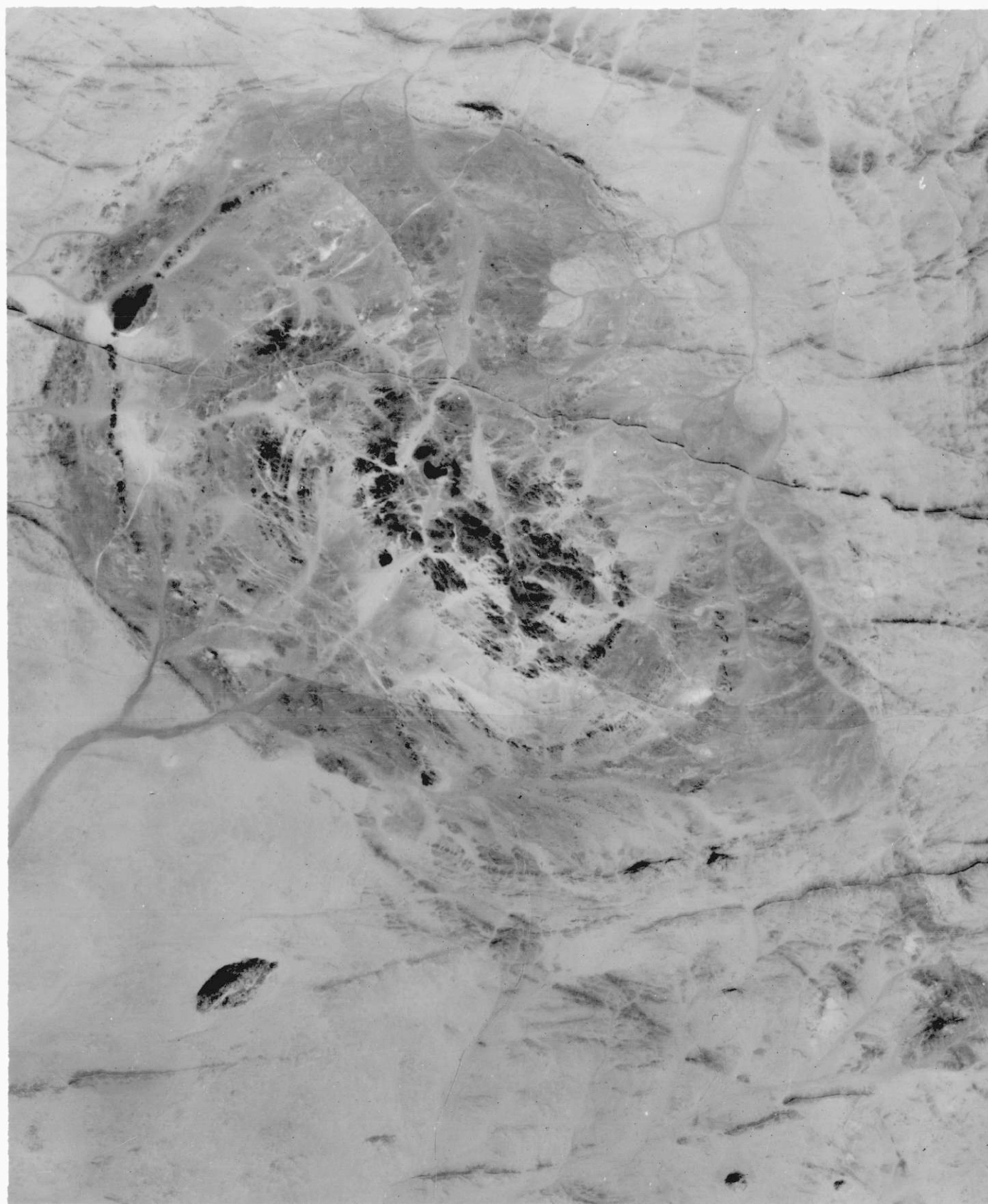
Work carried out previously has been at reconnaissance level with no attempt made to map the mass in detail.

1. Brankamp et al. (1963), included the layered intrusion on 1:500,000 geologic map (I-206A) as an amphibolite body.
2. Quin (1964), considered it to be a basin containing many conformable sills or bands of basic intrusive igneous rocks.
3. Theobald (1966), considered two ages for the rocks forming the ring complex, an older massive gabbro, and a younger amphibolite, formed as an alteration product of the pre-existing rocks.

Al Jealani layered mass

Figure 4-1

Aerial photograph (approximate scale 1 : 50,000) showing the elliptical Al-Jealani layered basic intrusion (dark grey) enveloped by granitic rocks (light grey). The dark coloured units are predominantly plagioclase-olivine cumulates intercalated with less resistant plagioclase-pyroxene cumulate layers.



4. Mytton (1966), considered the layered intrusion as an amphibolite complex.
5. Skiba and Al Shanti, (1971), the first to recognise the stratiform nature of the complex.

4.3.3 Airborne magnetic and radiometric survey

The layered intrusion has a marked aeromagnetic expression within the surrounding area of low magnetic relief. The radiometric levels over the layered mass are lower than the surrounding granitic rocks, as might be expected. Lambolez (1968) interpreted the magnetic pattern to indicate a deep rooted basic mass with a rather sharp and steeply dipping contact, and noted the presence of marked subsidiary anomalies within the structure. The suggested structure of a steep sided mass is important relative to the alternative possibility that the intrusion has a shallow lopolithic floor adjacent to the outermost ring of basic rock.

4.3.4 Nomenclature and sequence

The intrusion shows a layered structure such as is characteristic of the Skaergaard intrusion (Wager and Brown 1968) and it is composed of cyclic units in which the cumulus phases are represented in a regular manner. On the basis of the field relations fifteen rock units with a total thickness of 2,600 m forming the normal sequence from the margin to the centre of the intrusion were mapped. Within each unit many features such as distribution of cumulus plagioclase, pyroxenes and olivine, variable development of fine-scale rhythmic layering, variable grain size and degree of amphibolitization of pyroxene allow the subdivision of units into subunits. Continuity of units appears to be perfect and no significant mappable variation was noted along the strike.

The normal rock of the intrusion is a medium grained gabbro consisting of plagioclase and pyroxenes with olivine present in some units and displaying gabbroic texture. Several units display pyroxene

partially or completely replaced by secondary amphiboles. The layers are everywhere parallel to contact of the intrusion.

The layered units comprise a considerable variety of rock types ranging from gabbro and norite, through troctolite to anorthosite. These are believed to belong to a single fractionation series. Texturally and structurally there is a good evidence that these rocks are cumulates and rhythmic layering is found in many horizons (fig. 4-2,4-3). The light coloured layers of plagioclase cumulate (anorthosite) alternate with well laminated plagioclase-pyroxene cumulate (gabbro-norite).

The naming of rocks is based on cumulus minerals only listed in order of decreasing abundance, e.g. plagioclase-olivine cumulate corresponds to troctolite, etc. Such terms as cumulus, intercumulus are used in this thesis as defined by Wager and Brown (1968).

4.3.5 Field characteristics

The layered mass is oval in outline and funnel shaped with east and west contacts inclined inward at about 60° and north and south contacts at 50° . It is enclosed and intruded by granites. No evidence of a chilled phase is found in the marginal zone.

The intrusion contains a variety of structures and textures of a type which are normally attributed to crystal accumulation. Excellent examples of planar oriented plagioclase and pseudomorphed pyroxene, rhythmic layering and gravity stratification have been mapped. These layers are regularly disposed, parallel to each other and have low to moderate inward dips implying that no strong post-crystallization deformation has occurred.

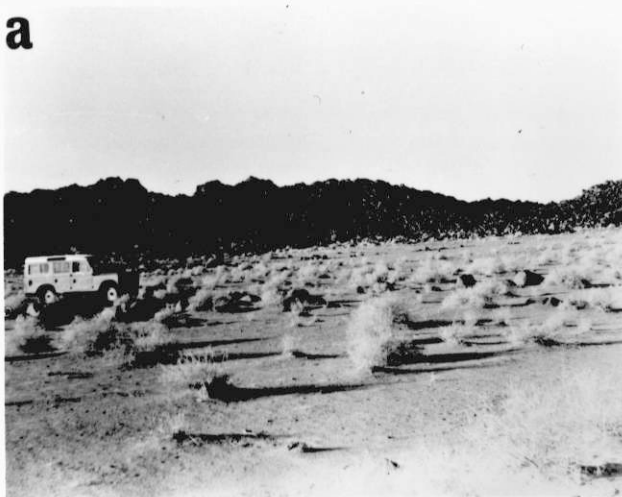
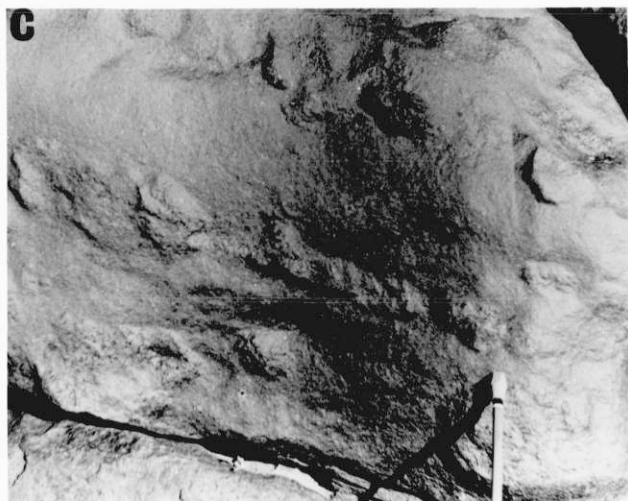
In addition to the small-scale rhythmic layering, a broad rhythm occurs which consists of plagioclase-pyroxene cumulates in which pyroxene is partly or entirely amphibolitized alternating with plagioclase-olivine cumulates. The generalized sequence is given in the vertical section (fig. 4-7).

Al Jéalani Layered Mass

Figure 4-2

Field characteristics

- a & b Plagioclase-olivine adcumulate of Unit II forming a prominent ridge. Large and small scale spheroidal weathering formed rounded boulders with characteristic "knobbly" surfaces (b). North side, looking northwesterly.
- c - Irregular layering in plagioclase-olivine cumulate, Unit VII, north side, looking easterly.
- d - Close view of "knobbly" structure on surfaces of boulders of Unit X, north side, looking northwesterly.
- e - Close view of closely packed lensoid knobs that consist predominately of calcic plagioclase. Base of Unit XII, north side, looking northwesterly.
- f - Well developed rhythmic layering in melanocratic plagioclase-olivine cumulate (thick layers) and leucocratic plagioclase rich thin layers. Unit V, east side, looking southerly.

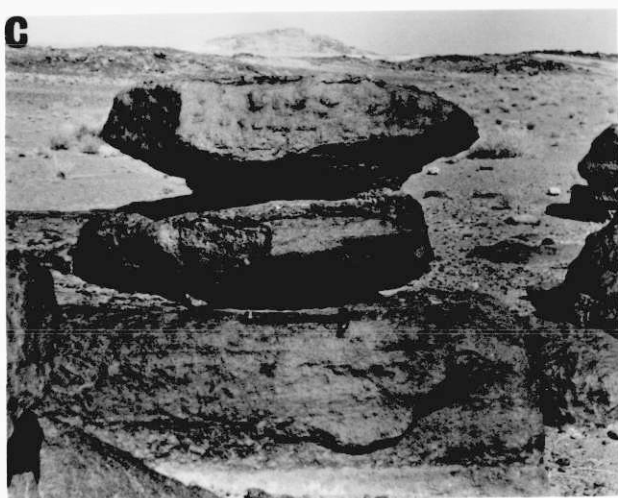
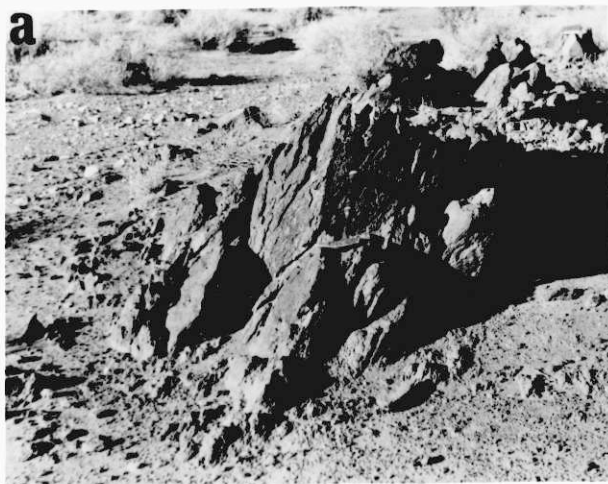
a**b****c****d****e****f**

Al Jéalani Layered Mass

Figure 4-3

Field characteristics

- a - Amphibolitized plagioclase-pyroxene cumulate showing fracture cleavage and surface weathering. Unit I, northern side, looking westerly.
- b - Amphibolitized plagioclase-pyroxene cumulate, showing easterly dip and a thin layer of plagioclase cumulate. Unit I, north side, looking easterly.
- c - Rhythmic layering expressed by regular and irregular layers (top), as well as by differential weathering in plagioclase-olivine cumulate. Unit VIII, east side, looking northeasterly.
- d - Rhythmic layering well developed, some layers exhibit cross lamination (bottom left). Unit VIII, west side, looking northerly.
- e - Amphibolitized plagioclase-pyroxene cumulate (eroded dark knobs) cut by gently dipping granite pegmatite dyke. Unit III, east side, looking easterly.



In a general way the sequence of rock types is duplicated in most of the zones with the amphibolitized plagioclase-pyroxene cumulates concentrated in the lower 2/3 divisions and the centre. The plagioclase-olivine cumulates occur at higher levels.

The most significant feature of the structures of the layering is a progressive decrease in dip towards the centre. The steepest dips (70° - 50°) occur around the margin and the strike of layering swings round to give a generally elliptical outcrop.

Because of this development and the olivine bearing horizons being most resistant to erosion, a series of parallel ridges dominate the landscape of the area. Approximate thicknesses of the zones, field characters and principal cumulus minerals from base to top are given in fig. 4-7.

Due to gravitational differentiation individual layered bands are characterized by lower more mafic and upper more feldspathic phases. The absence of ultramafic layers indicate a relatively high content of cumulus plagioclase. Extreme examples containing 95% plagioclase are present in thin layers and at about 1750 m. above the base a 20 m. thick layer of plagioclase cumulate occurs as a prominent anorthositic zone. The layered rocks locally appear to grade into massive non-layered plagioclase - olivine cumulates averaging 50 m. in thickness. These rocks are described as orthocumulates with plagioclase and subsidiary olivine as the only cumulus phases. These units are internally uniform in grain size and composition of cumulus minerals but are separated from underlying and overlying units by relatively sharp compositional differences. Individual layers, which vary from fraction of a centimeter to several meters in thickness, have never been observed to cut each other and in some outcrops a sharp transition from feldspathic to mafic layers was noted. The silicate grains are well oriented with their longer axes parallel to the plane of layering, thereby often imparting to the rocks a well laminated structure. Even when layering is absent the orientation of feldspar laths, amphiboles or olivines display linear parallelism.

In the field this layering simulates the rhythmic stratification of a sedimentary succession and in two dimensional outcrops it produces a striking effect of banding. The small scale rhythmic layering appears to be similar to that exposed in the layered series of gabbroic intrusions of the Bushveld complex (Hall 1932, and others), Stillwater (Hess 1960), Skaergaard (Wager and Dear 1939), Rhum (Brown 1957), Freetown (Wells 1962) and Aberdeenshire gabbro (Stewart 1947).

4.3.6 Mineralogy

3.6.1 Major constituents

The rock types are composed of various combinations of the five main minerals calcic plagioclase, magnesian olivine, titaniferous augite, orthorhombic pyroxene and secondary amphibole together with magnetite, ilmenite, brown amphibole, quartz, biotite and apatite as notable accessories.

Plagioclase

Plagioclase, the major component is present as light grey laths with abundant carlsbad-albite twins around which the other minerals have developed. The crystals are quite variable in size and generally euhedral in shape, the original straight edges being slightly modified by addition of a thin rim of feldspathic material deposited from intercumulus phase. Zoning is well developed in plagioclase which crystallized from intercumulus liquid (fig. 4-4a).

The shape of feldspars is related to its crystallization. The cumulus plagioclase is normally tabular on (010) and are roughly 3-5 times longer than wide. It is due to this habit that igneous lamination is so well developed. In contrast, the intercumulus feldspars which crystallized from pore-spaced trapped liquid are irregular in shape, (fig. 4-4a, c). Zoning is normally present, but in some plagioclase cumulate layers zoning is practically absent which may indicate a high degree of homogenisation as a result of adcumulus growth.

The composition of the feldspars was determined by the immersion method and chemical analyses of CaO content of the separated mineral

(fig. 4-10). The obvious oscillatory range in composition over the whole series of units is comparable to that in the Rhum intrusion (Brown 1956).

The most calcic plagioclases are unaltered and occur in the plagioclase-olivine cumulates. It is considered that this plagioclase was primarily in equilibrium with basic magma. The less calcic plagioclase is altered by sericitisation and epidotization and occurs in layers which were partly or entirely affected by amphibolitization.

Pyroxenes

Both clino- and orthopyroxenes occur as primary cumulus and intercumulus phases (fig. 4-4e, i and j), but data are not available for an adequate discussion of their nature and variation in composition.

In general appearance the clinopyroxene is uniform, purplish in thin sections and usually, shows tiny oriented brown exsolution inclusions and fine exsolution lamellae and is rarely twinned on (100).

As a cumulus phase it is mostly present in units which were amphibolitized. The crystals are prismatic, ranging from 0.5 to 4 mm. and averaging 2 mm. across. Composite grains are frequently observed in sections from the layered zones. As an intercumulus phase it forms large poikilitic crystals enclosing numerous grains of plagioclase (fig. 4-4e). The optical data on a few selected grains indicate a uniform composition of Ti-augite with 2V averaging $50-55^{\circ}$ and $\gamma = 1,713-1,715$.

Relict pyroxenes in amphibolitized rocks have the same shape and optical properties as the clinopyroxene in unaltered plagioclase-pyroxene and plagioclase-olivine cumulates.

Orthorhombic pyroxene is fairly pleochroic with X = pink, Y = very pale green and Z = very pale green. It occurs in some layers as primary cumulus minerals and more commonly it forms rims around olivines (fig. 4-4g and h).

Olivine

Crystals of olivine are widely distributed throughout the plagioclase-olivine layers in which they crystallized as a cumulus phase. In habit they are tabular (010) and aligned parallel to plagioclase imparting a distinct lamination to the rocks. Some olivines in the layered rocks cluster together to form characteristic chains in planes of lamination. The x-ray peaks of three separated olivines from unit IV and XI show range Fo 62-78.

The crystals are little serpentinised. They frequently contain small grains of magnetite (fig. 4-4f).

Amphibole

A brown primary hornblende forms usually thin rims around magnetite and clinopyroxene (fig. 4-4f). Several different amphiboles are however found in the rocks affected by amphibolitization. Most common is colourless tremolite forming fibrous aggregates within the pseudomorphs after clinopyroxene. The pleochroic blue-green actinolite surrounds the colourless amphibole in form of corona rim and in turn is patchily replaced by brownish-green amphibole (fig. 4-5b and c). Frequently amphibole occurs as narrow veins associated with fine fractures.

3.6.2 Accessories

Quartz occurs mainly as clear fine-grained (0.01 - 0.5 mm.) interstitial grains. Contacts between quartz grains are serrate and they usually display undulatory extinction.

Biotite

A minor quantity of brown biotite is found associated with magnetite or moulded on brownish-green hornblende (fig. 4-4f).

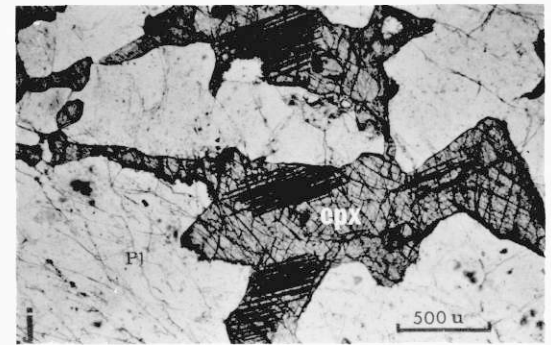
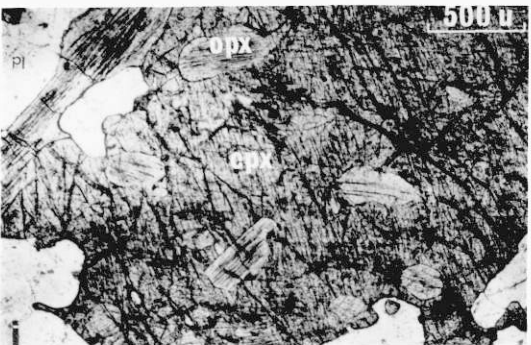
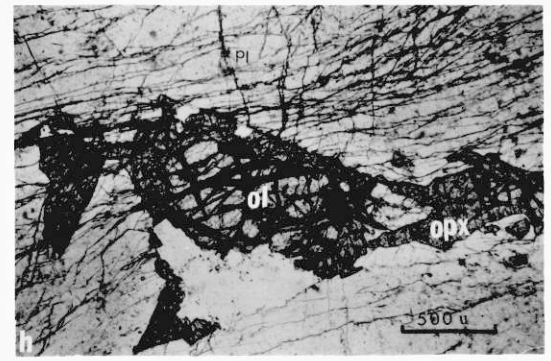
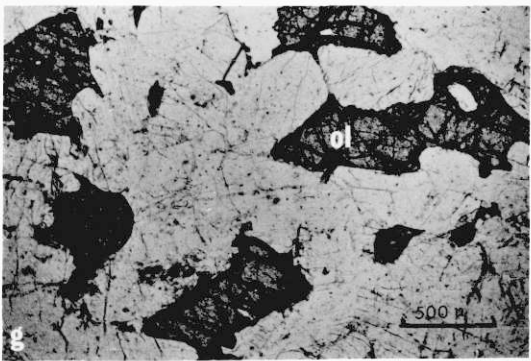
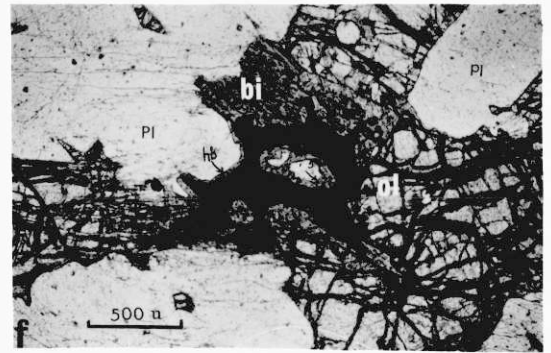
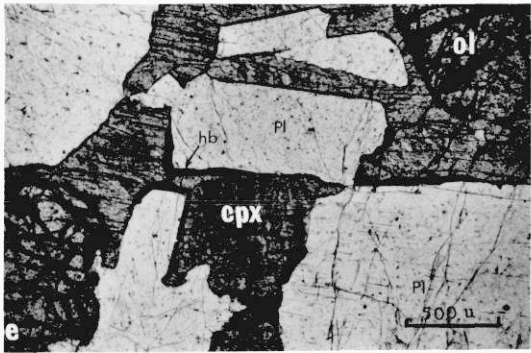
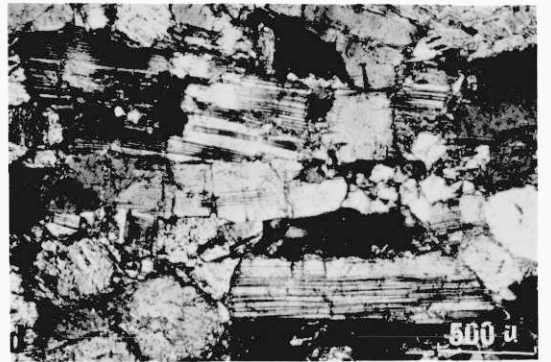
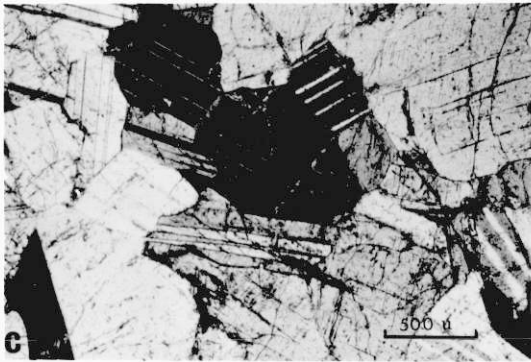
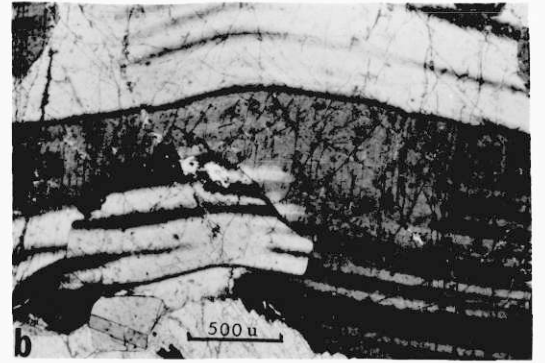
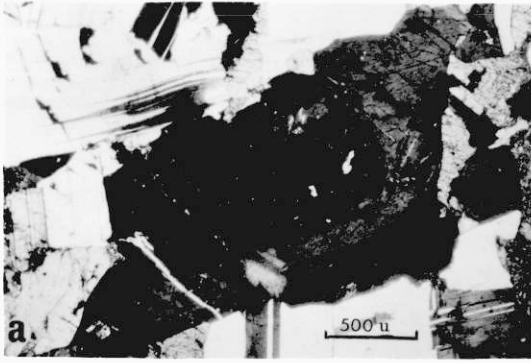
Other accessories include rare apatite.

Al Jéalani Layered Mass

Figure 4-4

(a to j taken in transmitted light)

- a - Plagioclase-olivine cumulate showing zoned plagioclase.
CN, As-300, Unit XIII.
- b - Plagioclase-olivine cumulate showing deformed (bent)
plagioclase grain. CN, As-258, Unit X.
- c - Plagioclase cumulate showing adcumulus texture in plagioclase
CN, As-322, Unit XI.
- d - Amphibolitized plagioclase-pyroxene cumulate showing well
developed primary planar fabric (igneous lamination).
CN, As-242, Unit V.
- e - Plagioclase-olivine cumulate showing intercumulus clinopyroxene
(cpx) rimmed by brown hornblende (hb). PPL, As-313, Unit XI.
- f - Plagioclase-olivine cumulate showing a reaction rim of brown
hornblende around the opaque mineral. Hornblende (hb) is
fringed by biotite (bi). PPL, As-302, Unit XIII.
- g - Plagioclase-olivine cumulate. Olivine (ol) grains show
reaction rims of orthopyroxene. PPL, As-230, Unit IV.
- h - Plagioclase-olivine cumulate, olivine partly serpentized
and rimmed by orthopyroxene (opx). Orthopyroxene is
interstitial. Plagioclase is cracked and partly saussuri-
tized. PPL, As-304, Unit XIV.
- i - Plagioclase-olivine-pyroxene cumulate showing cumulus
orthopyroxene grains enclosed within interstitial clinopyroxene.
PPL, As-313, Unit XIII.
- j - Plagioclase-olivine-pyroxene cumulate. Pyroxene with
exsolved opaque lamellae and rimmed with brown hornblende.
PPL, As-312, Unit XIII.



Al Jéalani Layered Mass

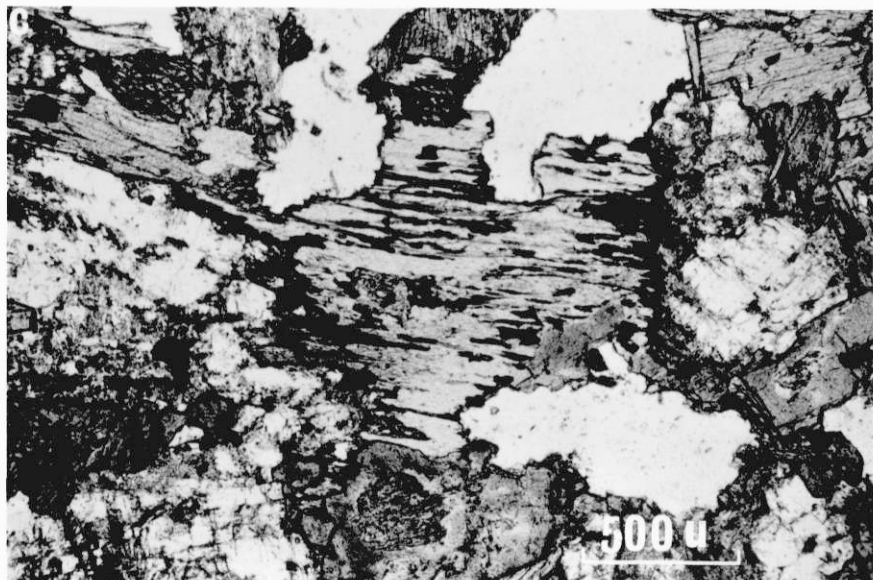
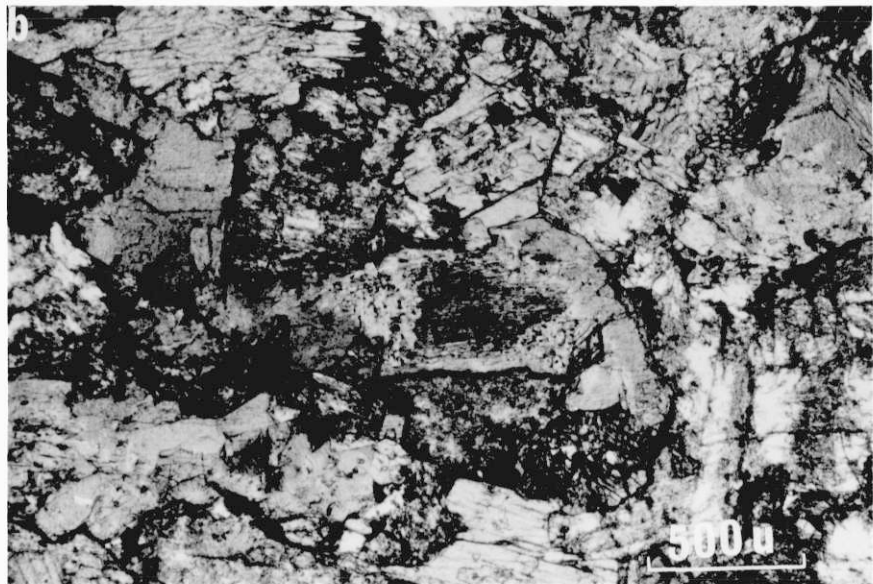
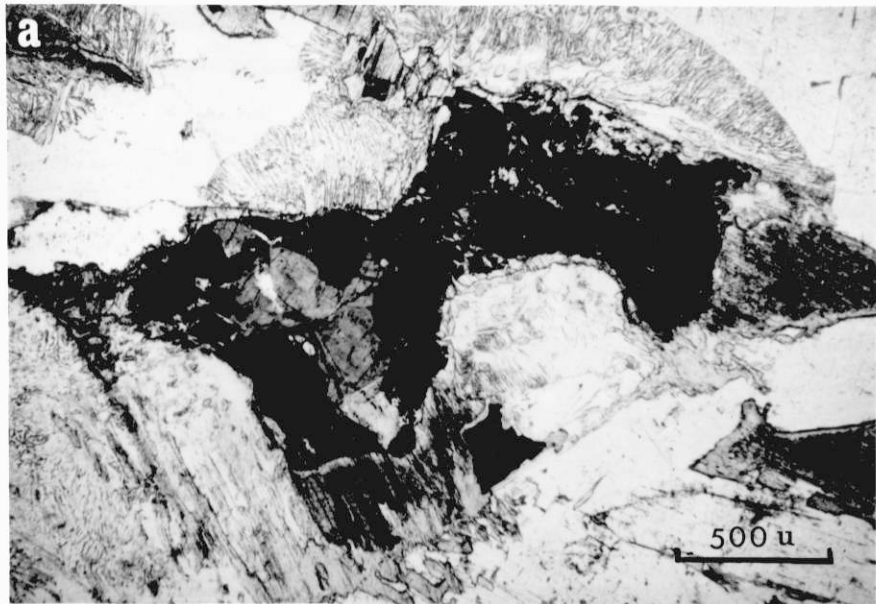
Figure 4-5

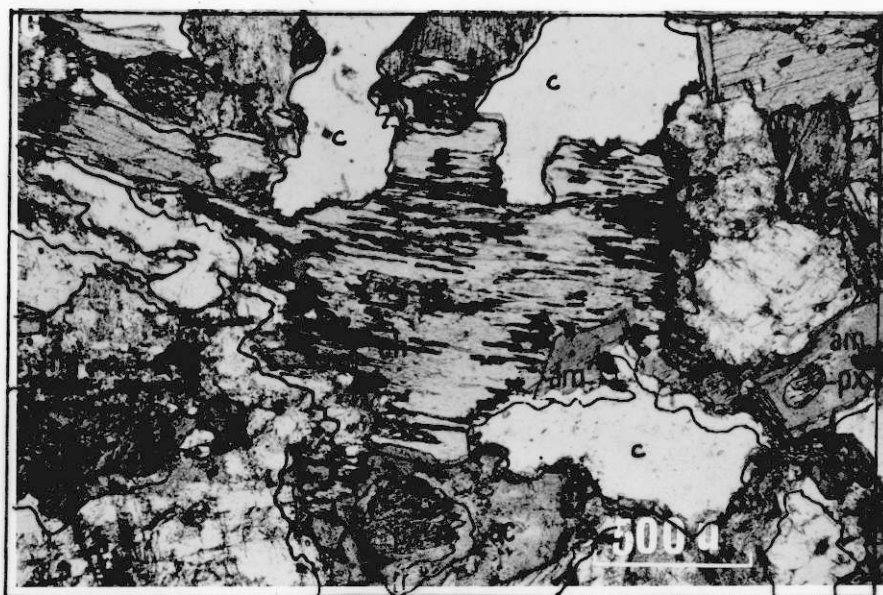
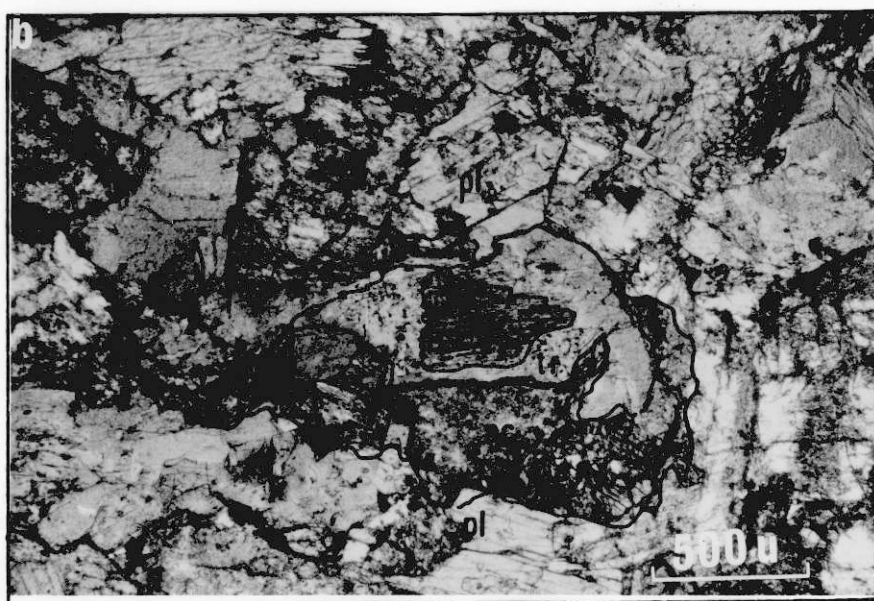
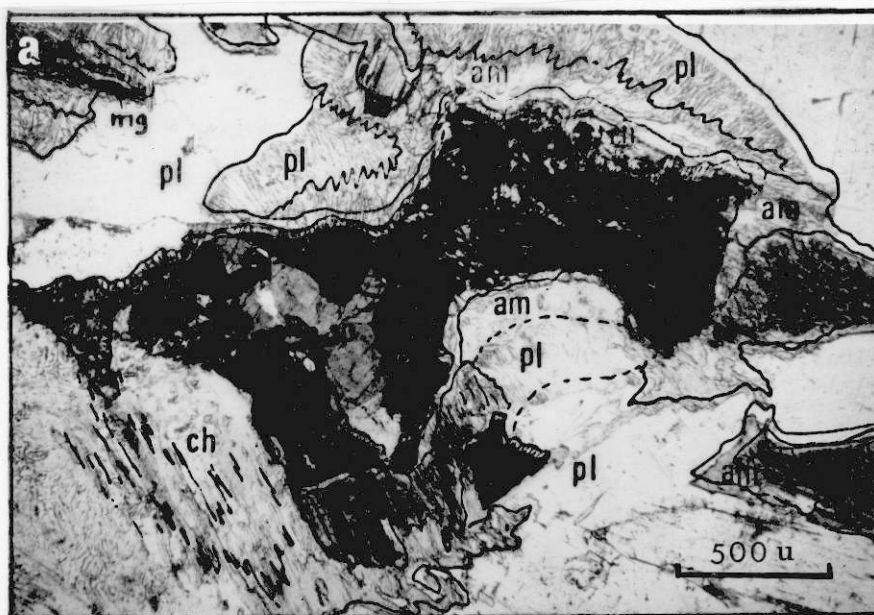
(a to c taken in transmitted light)

- a - Plagioclase-olivine cumulate showing symplectic intergrowth. Olivine is altered to magnetite (mg) and serpentine (sp). Well developed reaction rim of amphibole (am) and plagioclase (pl) produced by reaction of olivine with calcic feldspar. Amphibole and interstitial pyroxene (px) are altering to chlorite (ch). PPL. 15A-662. DHL Samrah prospect.

- b - Amphibolitized plagioclase-pyroxene cumulate showing stages of amphibolitization. Remnants of pyroxene (px) rimmed by light coloured tremolite (tr) which is in turn rimmed by light green actinolite (ac). Plagioclase is saussuritized and amphibole partly altered to chlorite. PPL, As-280, Unit XV.

- c - Two stages of amphibolitization, shown by light coloured tremolite (tr) around remnants of pyroxene (px), actinolite (ac) light green, is fringing the tremolite during the second stage of amphibolitization. The amphiboles are altering to chlorite (ch), (c) cavities in section. PPL, As-280, Unit XV.





Alteration products consist of sericite, chlorite, serpentine, calcite, epidote and prehnite.

3.6.3 Magnetic and related opaque minerals

The magnitude of the aeromagnetic anomaly of Al-Jéalani intrusion is attributed to the magnetic minerals in the rocks, mainly those in the system $\text{FeO-TiO}_2 - \text{Fe}_2\text{O}_3$. The Ulvo-spinel-magnetite series ($\text{Fe}_2\text{TiO}_4 - \text{Fe}_3\text{O}_4$) is most important magnetically, followed by less important phases in the ilmenite-hematite series. Maghemite and pyrrhotite also have significant magnetic susceptibilities.

The opaque minerals make up not more than 5% of the rocks and are represented by the primary magnetic oxide and sulphide minerals, magnetite, ilmenite, pyrrhotite and chalcopyrite and by secondary hematite, sphene and pyrite. The oxide minerals predominate.

Iron-Titanium oxides:

No concentrations of any kind have been found in this intrusion. Only disseminations of commonly coexisting ilmenite and magnetite grains are present attaining a maximum diameter of 1.0 cm. In polished section, the ilmenite and magnetite are in approximately equal amounts. The most common habit of both oxides is stumpy, anhedral, individual or intergrown grains, interstitial with silicate minerals (fig. 4-6a, b, d and f).

Magnetite:

In polished section magnetite is bluish grey or light pink, isotropic and non-pleochroic. It occurs in three characteristic forms:

- a) Interstitial and partly poikilitic magnetite is usually intergrown with ilmenite (fig. 4-6b, c and d). It occurs as an accessory mineral in plagioclase-olivine and plagioclase-pyroxene cumulates. Hematite develops within magnetite as an alteration product due to incipient weathering along octahedral cleavage planes, cracks and marginal holes (fig. 4-6b and c).

- b) Subhedral, small grains (0.2 = 0.5 mm.), (fig. 4-6b), occasionally intergrown with ilmenite. Martitization is developed at margins, cracks and octahedral planes. Poikilitic magnetite grains are rare. In As-245, 246 it makes up 2-3 percent of the rock.
- o) As fine coatings in cracks and margins of olivine grains as a result of incipient alteration (fig. 4-4f).

Ilmenite:

In polished section ilmenite is light brown, slightly pleochroic and strongly anisotropic. It commonly contains exsolved hematite along cleavage planes. Ilmenite occurs in two forms:

- a) Intergrown with magnetite in clusters of grains interstitial to other cumulus silicate minerals in amphibolitized and fresh rocks (fig. 4-6).
- b) As individual subhedral small grains or intergrown with magnetite (fig. 4-6e). In As-245 it makes up 2-3% of the rock.
- c) As minute blades possibly of exsolution origin in some pyroxene grains.

Hematite:

In polished section the mineral is white to light grey, non-pleochroic, anisotropic, with characteristic internal reflections. Hematite occurs as:

- 1) exsolved blebs and lamellae in ilmenite and in magnetite. (fig. 4-6 a and f).
- 2) secondary, due to incipient alteration of magnetite (fig. 4-6b and c).

Sphene:

In polished section, it is grey, anisotropic, non-pleochroic with strong internal reflections. Sphene occurs in ilmenite as a replacement mineral along the margins and cleavage planes (fig. 4-6d).

Table 4-1

Electron micro probe analyses of some co-existing magnetites and ilmenites

SAMPLE		1	2	3	4	5	6	7
Ilmenite FeWt%		36.7	37.0	40.9	40.4	37.3	39.0	38.8
	Ti	29.7	30.2	31.8	33.6	27.7	28.3	28.1
	Mn	0.4	0.4	0.2	0.2	0.5	0.5	0.5
TOTALS:		66.8	67.6	72.9	74.2	65.5	67.8	67.4
Equiva- lent oxides	FeO	47.2	47.6	52.6	51.9	48.0	50.2	49.9
	TiO ₂	49.5	50.4	53.0	56.0	46.2	47.2	46.9
	MnO	0.5	0.5	0.3	0.3	0.6	0.6	0.6
TOTALS:		97.2	98.5	105.9	108.2	94.8	98.0	97.4
Magnet- ites	FeWt%	73.4	72.5	70.5	71.6	72.8	69.9	70.7
	Ti	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Mn	0.05	0.05	0.05	0.05	0.05	0.05	0.05
TOTALS:		73.55	72.65	70.65	71.75	72.95	70.05	70.8

Equivalent oxides of FeO and Fe₂O₃ in (FeO.Fe₂O₃) are more or less identical to the published ratio 68.97% Fe₂O₃ and 31.03% FeO.

Sample 1 and 2 from Samrah hole No. 1 at depth of 632 feet, from plagioclase-orthoclino¹pyroxene cumulate.

Sample 3 and 4 are from (As-345) unit VII of Al-Jéalani intrusion in amphibolitized plagioclase-pyroxene cumulate.

Samples 5, 6 and 7 are from (As-220) Unit I, amphibolitized plagioclase-pyroxene cumulate.

The paucity of opaque oxidic minerals of economic interest was supported by panning concentrates from the weathered residue and stream wash within the area of outcrop of intrusion. Semi-quantitative spectrographic analyses of 18 heavy concentrates showed uniformly low levels of the ore metals as follows*:

V	400 to 800 ppm	Cu	20 to 40 ppm
Ni	50 to 150 ppm	Co	30 to 80 ppm

3.6.4 d. Sulphides:

The sulphide minerals are rare in both the fresh unaltered gabbros and the amphibolitized gabbros.

Pyrrhotite:

In the southern isolated parts of Al-Jéalani intrusion within the area of Samrah ancient mine, pyrrhotite occurs as small individual strongly anisotropic grains, or as remnants in secondary pyrite grains in the northern part of the intrusion.

Electron micro-probe analysis of pyrrhotite grain

Fe	60.3
Ni	0.4
S	38.2
Total	<u>98.9%</u>

Chalcopyrite:

Apart from its occurrence in the vein deposits of Samrah mine, it occurs as small blebs within secondary pyrite.

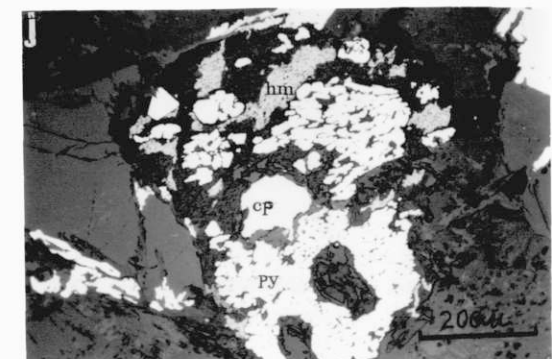
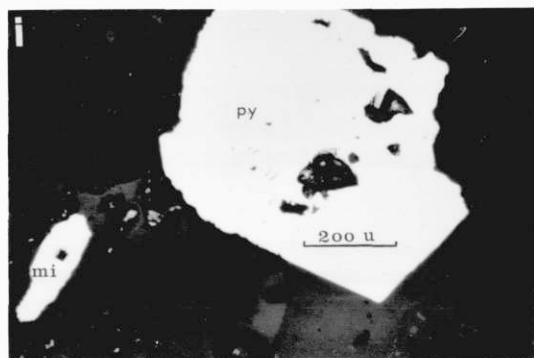
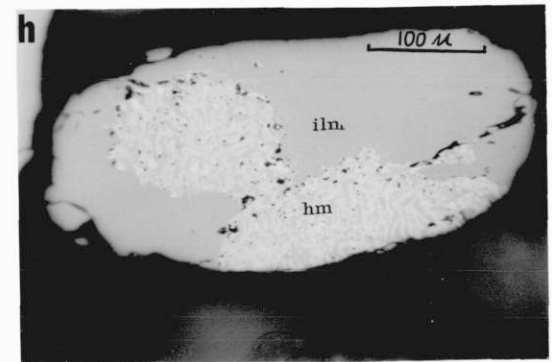
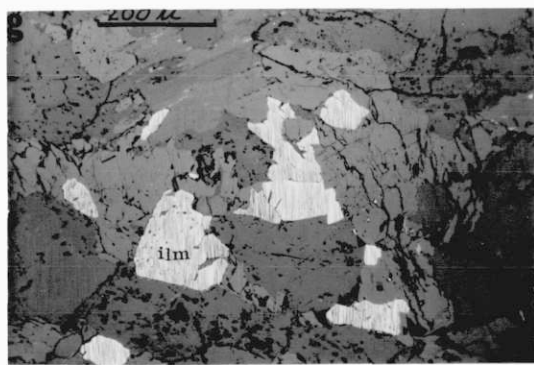
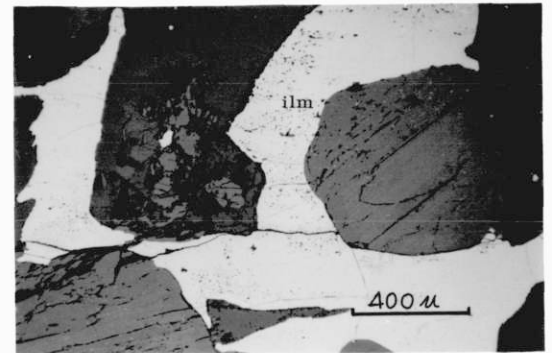
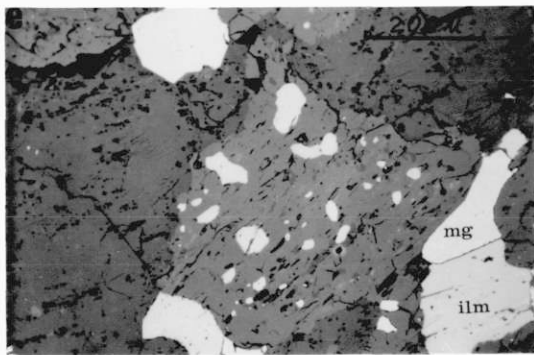
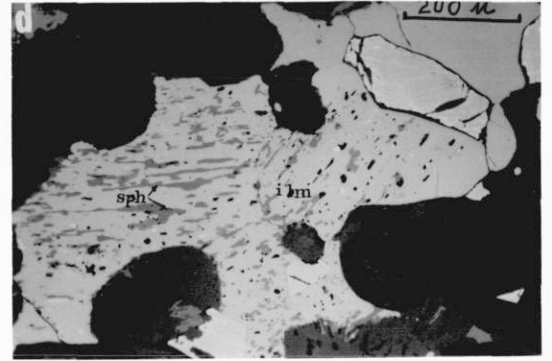
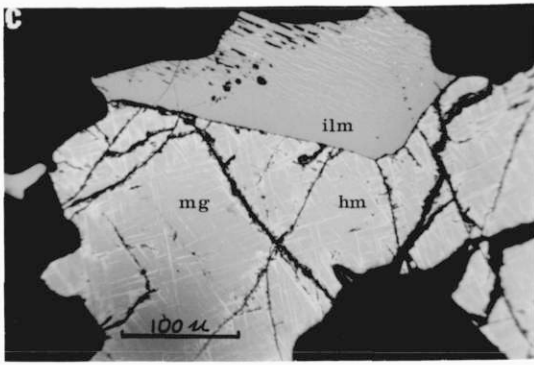
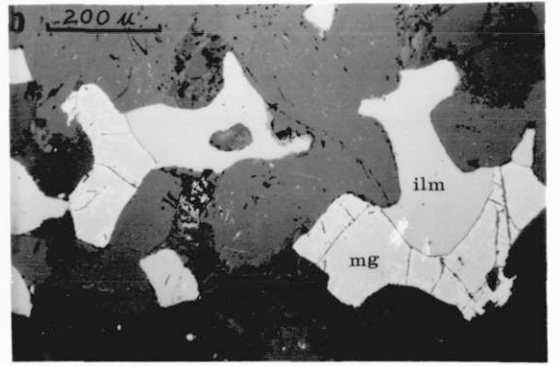
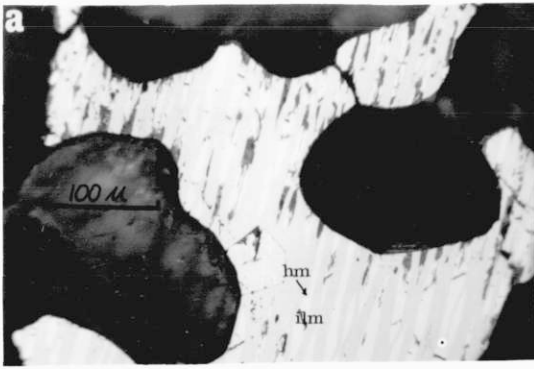
* See appendix 1 for the other elements.

Al Jéalani Layered Mass

Figure 4-6

(a to j taken in reflected light)

- a - Poikilitic ilmenite (ilm) with exsolved lamellae of hematite (hm). PPL, As-365, Unit VI.
- b - Compound grains of ilmenite (ilm) and magnetite (mg). The magnetite is replaced along cracks and octahedral planes by hematite (hm). PPL, As-245, Unit VII.
- c - Compound grain of ilmenite (ilm) and magnetite (mg). The ilmenite shows exsolved lamellae of hematite. The magnetite is replaced by hematite along octahedral crystal planes. PPL, As-365, Unit VI.
- d - Ilmenite (ilm), poikilitic, altering to sphene (sph). A
q small magnetite grain enclosed in the ilmenite is partially replaced by hematite. PPL, As-245, Unit VII.
- e - Ilmenite (ilm), cumulus, in variable grain sizes partly enclosed in a pyroxene grain. A compound ilmenite magnetite grain is shown. PPL, As-337, Unit V.
- f - Ilmenite intercumulus, showing interstitial growth with silicates. PPL, As-220, Unit I.
- g - Cumulus ilmenite (ilm) showing exsolved lamellae of sphene (dark grey). PPL, As-337, Unit V.
- h - Detrital ilmenite (ilm) grain from a stream draining Unit XII. The grain shows alteration to hematite (hm). PPL, SA-1.
- i - A grain of millerite (mi), NiS, and another of pyrite. PPL, LSA-485, DHL, Samrah prospect.
- j - Pyrite (py) replaced by gangue and hematite (hm), small chalcopyrite grains (cp) are present. PPL, As-220, Unit I.



Pyrite:

In the layered intrusion pyrite is rare. It occurs commonly in individual small grains relative to the opaque oxide minerals, or as microscopic veinlets interstitial to silicate minerals, or as anhedral aggregates (fig. 4-6i and j).

4.3.7 Textures

3.7.1 General textural characteristics

The textural features of the layered rocks are similar to those already described by Wager and Deer for Skaergaard and Brown for Rhum. It is considered that the textures of the basic intrusions are the result of crystal accumulation of cumulus minerals which crystallized from primary precipitate liquid followed by interstitial crystallization from the pore space trapped liquid.

Such textural relations of the rock reflect the process of accumulation of early formed crystals on the floor and sides of the conical magma chamber and the building up of a solid mass by the deposition of layer upon layer.

Both ferromagnesian and plagioclases display a well developed alignment of tabular grains which emphasises the lamination of the rock. For the most part, textures are typically igneous. Fine exsolution lamellae in pyroxenes and twinning in plagioclase are the same as in unmetamorphosed layered, basic masses. Blue-green amphibole is post consolidation in origin.

The textures of cumulates vary considerably (fig. 4-4) depending on the shape of cumulus grains and on the degree of post cumulus modifications.

Plagioclase is the dominant cumulus phase in all units and is the only cumulus phase in rocks with plagioclase as an essential mineral. Other cumulus minerals are clinopyroxene, olivine and rarely orthopyroxene. Post cumulus material includes plagioclase, opaque minerals, clinopyroxene and orthopyroxene (fig. 4-4a, i and j).

3.7.2 Textures of orthocumulates.

The characteristic cumulates represented by unaltered gabbroic rock horizons are predominantly orthocumulates invariably grading into mesocumulates. The prevailing plagioclase-olivine orthocumulates are characteristically developed in unit II; they also form thin horizons in units IV and V, and become predominant cumulates in the upper part of the layered mass forming numerous horizons in units VIII to XIV. Cumulus minerals are plagioclase, olivine, hypersthene, and augite. Intercumulus minerals include augite, hypersthene, brown hornblende and biotite.

The modal variation through the layered mass (fig. 4-8) show fairly uniform content of the cumulus minerals. A typical plagioclase-olivine orthocumulate from unit VIII (As-252) is perhaps the commonest rock type consisting of 60% plagioclase and 35% olivine. In most cumulates of this type, olivine amounts approximately to half of the feldspar content. Plagioclase grains are tabular, flattened parallel to (010), they range in length from 2 to 4 mm and display striking planar alignment (fig. 4-4d). The observed zoning in plagioclase (fig. 4-4a) indicates that the cumulus plagioclase may have amounted to no more than 35% of the total volume of the rock. As a result of rapid cooling, zones of lower temperature plagioclase were deposited over the early cumulus grains. In contrast, the intercumulus feldspar is irregular in shape and entirely interstitial.

Partly serpentized olivine forms single grains or clusters ranging in length from 1 to 2 mm. Most of the grains are aligned parallel to feldspars. Partial serpentization took place with increased volume causing a dense fracturing in plagioclase that surrounded olivine.

The clinopyroxene forms large poikilitic plates enclosing cumulus olivine and plagioclase (fig. 4-4e).

Slightly pleochroic orthopyroxene occurs in reaction rims around olivine. Few orthopyroxenes crystallized from intercumulus liquid and some display symplectic exsolution relation with iron oxide.

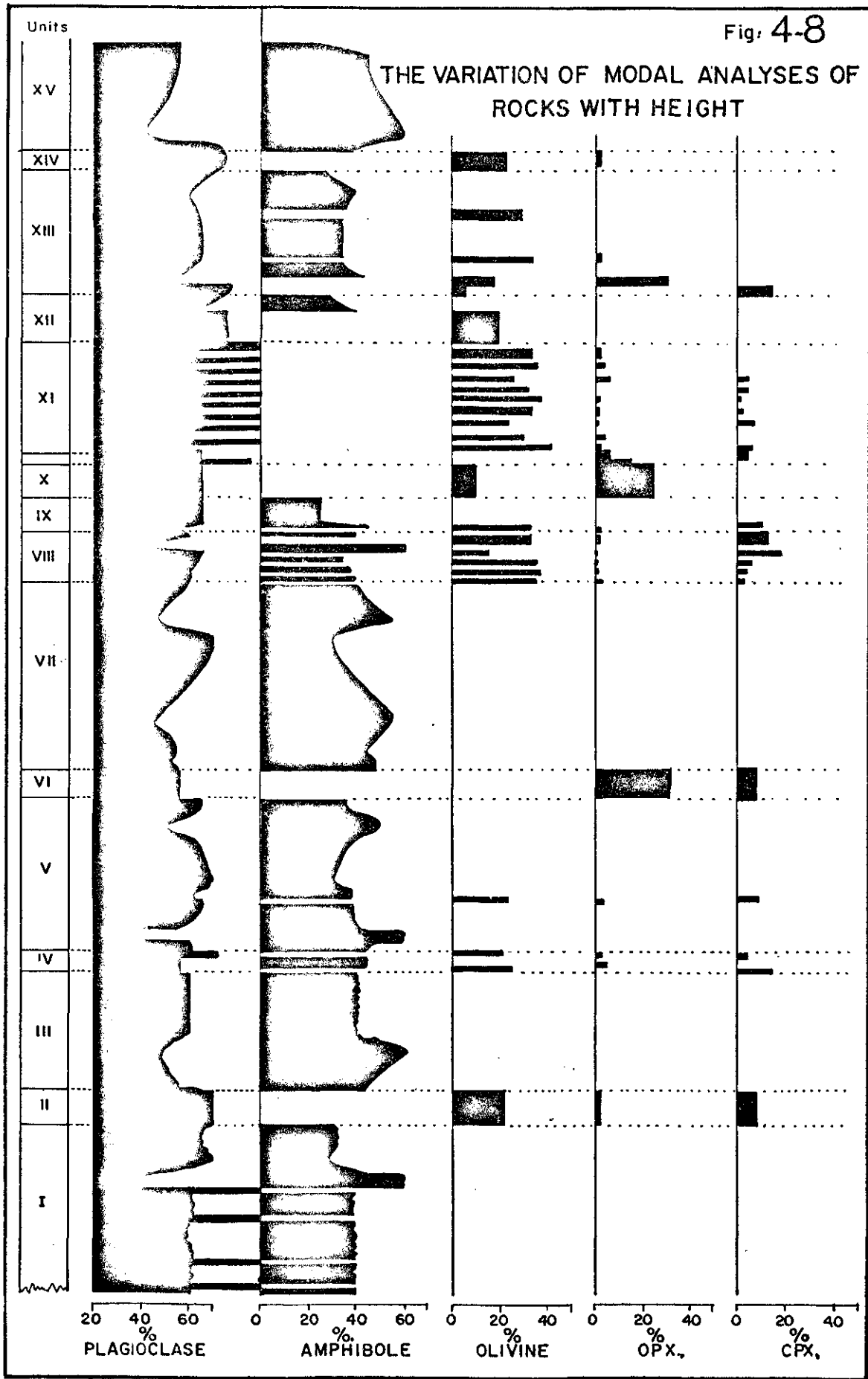
FIG. 4-7

GENERALIZED VERTICAL SECTION OF THE AL-JE'ALANI LAYERED SERIES

Unit No.	Sub-unit	Height meters	Plag. Composition	Field Characteristics Of The Rock Units And Cumulus Minerals	Intercumulus And Accessory Minerals
XV		2600	An 53	Amphibolized plagioclase-pyroxene cumulate, igneous lamination is partly developed. Pyroxene is partly or entirely amphibolized.	Brown amphibole, Magnetite and ilmenite in accessory amounts.
		2500	An 55		
		2400			
XIV			An 56	Plagioclase-olivine cumulate leucocratic, well developed ign. lamination	Accessory interstitial biotite, hypersthene 2%
XIII	4	2300	An 49	Amphibolized plagioclase-pyroxene cumulate, local thin bands of plagioclase cumulate.	
	3	2200		Plagioclase-olivine cumulate, well laminated.	Brown amphibole, biotite and opaque minerals
	2		An 54	Amphibolized plagioclase-pyroxene cumulate, spheroidal weathering, well developed igneous lamination	
XII	1	2100	An 58	Plagioclase-olivine-augite-orthopyroxene cumulate	Accessory brown amphibole and biotite
	2			Amphibolized plagioclase-clino-pyroxene cumulate, rhythmically layered	
	1	2000		Plagioclase-olivine cumulate, spheroidal weathering, irregular knobby texture on the weathered surfaces of lower part.	Clino and orthopyroxene. Brown amphibole
XI		1900	An 57	Plagioclase-olivine cumulate intercalated with plagioclase cumulate and amphibolized plagioclase-pyroxene cumulate.	
		1800	An 61		
		1700	An 60 An 57	Plagioclase-clinopyroxene cumulate	
X		1700	An 61	Plagioclase-olivine cumulate "Knobby" texture on weathered surfaces	Orthopyroxene and clinopyroxene
IX		1600	An 63 An 32	Plagioclase-pyroxene cumulate, pyroxene partly or entirely amphibolized in some horizons. Pythmic layering and lamination well developed.	Amphibole
		1500	An 47 An 61	Plagioclase-olivine cumulate alternating with bands of amphibolized rocks. Rhythmic layering well developed. Thin plagioclase cumulate layers occur within the upper part of the unit "Knobby" texture is well developed throughout this unit	Amphibole
VIII	5	1400	An 56	Amphibolized plagioclase-pyroxene cumulate, variation in mineral percentage, in texture, grain size & degree of igneous lamination. Fine scale rhythmic layering is well developed.	Disseminated magnetite and ilmenite, Locally sphere (As-245) Amphibole pseudomorphs after pyroxene.
	4				
	3	1300	An 47		
	2	1200			
	1	1100	An 43 An 50	Thin plagioclase cumulate intercalations occur in the upper part. Amphibolized plagioclase-pyroxene cumulate, coarse grained, no clearly defined orientation, spheroidal weathering intercalated at the base with fine grained variety	Amphibole replacing pyroxene
VI			An 59	Plagioclase-orthopyroxene-clinopyroxene cumulate. Tabular feldspars oriented in plane of igneous lamination	Accessory magnetite and ilmenite
V		1000		Amphibolized coarse plagioclase-pyroxene cumulate. No mineral orientations and little change in texture over middle and upper part, devoid igneous lamination	Amphibole pseudomorphs after pyroxene
		900		Amphibolized plagioclase pyroxene cumulate	
		800	An 54 An 57 An 60 An 50	Plagioclase-olivine cumulate Amphibolized plagioclase-pyroxene cumulate, early stages of amphibolization of pyroxene. Layering developed in lower part	Intercumulus augite and amphibole after pyroxene.
		700	An 49	Plagioclase-olivine cumulate Amphibolized plagioclase-pyroxene cumulate Plagioclase-olivine cumulate	Olivine & accessory pyroxene Amphibole pseudomorphing pyroxene. Pyroxene up to 15%.
III		600		Amphibolized plagioclase-pyroxene cumulate. Foliation parallel to the margin with unit II	Magnetite and ilmenite oxides. Amphibole pseudomorphing pyroxene
		500	An 48		
		400	An 44		
II		400	An 59	Plagioclase-olivine cumulate, spheroidal weathering, "Knobby" texture in the middle and upper parts. Well-developed igneous lamination	Poikilitic "heterocumulus" pyroxene and accessory opaques.
I	10	300		Amphibolized plagioclase-pyroxene cumulate of variable grain size and texture alternating with thin bands of plagioclase cumulate.	Magnetite and ilmenite are in upper part.
	9			Plagioclase cumulate rhythmically layered with plagioclase-pyroxene cumulate (amphibolized)	Amphibole is pseudomorphs after pyroxene
	8	200	An 55		
	7		An 40		
	6	100		Plagioclase cumulate alternating with thin bands of plagioclase-pyroxene cumulate	
	5				
	4				
	3	00	An 42	Base of the layered basic intrusion	
	Adamellite			Adamellite, gneissic	

Fig. 4-8

THE VARIATION OF MODAL ANALYSES OF
ROCKS WITH HEIGHT



Iron oxide and biotite present in accessory amounts appear to have crystallized from intercumulus liquid. In most plagioclase-olivine cumulates, late stage reaction rims are exceptionally well developed. The olivines rimmed by hypersthene, clinopyroxenes and iron oxides often display rims of primary brown hornblende and less commonly biotite. The plagioclase-ortho-, clinopyroxene cumulates form the unit 6. Both pyroxenes occur in tabular prisms orientated parallel to plagioclase. Narrow zoning and fingery outgrowths may represent addition of material from intercumulus phase. Iron oxide forms incomplete rims around pyroxenes.

Thin layers of plagioclase-clinopyroxene cumulate (As-259) occur amongst the rhythmically layered succession of plagioclase-olivine cumulate in unit XI. A rare example of plagioclase-clino-orthopyroxene-olivine cumulate occurs at the base of unit XIII (As-271) with pyroxenes forming large aggregates (4 x 10 mm) and scattered olivines averaging 0.2 mm in length. Both are poikilitically enclosed by brown hornblende of late crystallization.

3.7.3 Texture of adcumulates

Most of plagioclase cumulates forming 'anorthosite' horizons display typical adcumulate to mesocumulate textures. Several of such layers occur in the lower part of unit I and through entire thickness of unit II. They range in thickness from 3 cm. up to 2 m and often display marked transitions to plagioclase-olivine or plagioclase-olivine-clinopyroxene cumulate. Generally, the plagioclase content is high within the range 90-97%. Accessory minerals include clinopyroxene or secondary amphibole in pseudomorphs after clinopyroxene, serpentinized olivine and iron oxides. Fine scale rhythmic layering is best developed where plagioclase is found forming monomineralic layers. The feldspar rich layers are usually lensoid and they are rarely followed along strike for long distances. Marginal zoning of plagioclase is well developed in most feldspar rich layers and it is attributed to adcumulus growth from the pore-space liquid.

The plagioclase is clouded with secondary alteration products such as sericite and numerous well orientated ultrafine rods of iron oxides. Other secondary products include epidote, chlorite, calcite, quartz, iron oxide, sphene and prehnite.

3.7.4 Textures of amphibolitized cumulates

The plagioclase-pyroxene cumulates were affected at post consolidational stage by a variable degree of amphibolitization. Nearly all textures of amphibolitized rocks display a conspicuous replacement of clinopyroxene by colourless and pale blue-green amphiboles. Amphibole crystals may form a replacement for either pyroxene and/or brown hornblende or plagioclase. This replacement is often pseudomorphous after the clinopyroxene so that the original orientation and poikilitic texture wherever present is preserved. The colourless amphibole, often developed in the centres of the grains, grades peripherally into a blue-green variety. The amphiboles occur as fibres of rugged prisms with irregular outgrowth which occasionally obliterate the original outlines of the pyroxenes.

3.7.4a Types of amphibole grains

1. Single crystal grains: In many of the rocks (As-223) a pale blue-green amphibole is developed marginally to the pyroxene. Primary brown amphibole is often left as a relict grain, separated from the pyroxenes which then appear as inclusions in optical continuity, entirely surrounded by amphibole. In some extreme cases of replacement the pyroxene retains its original appearance in ordinary light but loses its normal colour and shows the lower order of interference colours of amphibole. Spry (1969) states that single crystal pseudomorphs require a considerable degree of structural similarity between the primary and secondary minerals and probably a considerable retention of original structural units occur. This seems to apply to the replacement of brown amphibole and pyroxene by colourless or blue-green amphibole, all three of which are structurally similar.

2. Multilattice grains: In this type, the grains consist of a number of elongate sub-grains which may show a range of extinction angles indicating different orientations.

3. Disoriented aggregate-grains: They may show development of a large number of amphibole subgrains, elongate along cleavage, all showing identical extinction positions, though not necessarily of the host grain. A patchy type shows at random orientation. Relict textures and the original shape of the pyroxene are recognizable in all sections, except for the primary grain boundaries which become indistinct because the crystal mesh often appears to extend over what must have been several original grains with rather complex margins.

The aggregate-grains of amphiboles are also seen growing in plagioclase. The boundaries of many plagioclase grains appear to have been altered considerably by external prisms of amphibole which in part replace feldspars.

3.7.4b Grain boundaries

The most important grain boundaries are those between plagioclase and amphiboles. The regular boundaries are sharply defined and are either straight or more often consist of a small number of simple curves. Irregular or serrate grain boundaries consist of a series of sharply dentate contacts. Invariably in this type, the comb-like boundary is formed by growth of amphibole at the expense of feldspar.

In many cases of irregular feldspar-amphibole boundaries, the feldspar margin shows a certain amount of straining. Irregular boundaries are also associated with amphibole veinlets, where these pass through plagioclase.

Boundaries which are highly serrated and irregular are basically unstable and they must be preserved in a rock in metastable state.

3.7.4c Two stages of amphibolitization: In most amphibolitized cumulates, amphiboles occur in two generations (As-223). A fibrous colourless tremolite forms disoriented aggregate-grains well confined to pseudomorphs after pyroxene. Second blue-green pleochroic amphibole forms well defined rim around tremolite. The tiny prisms of amphibole in the rim are perpendicular to more centrally situated tremolite and they penetrate into plagioclase (fig. 4-5 b and c).

4.3.8 Petrography of the principal rock types

3.8.1 Modal data

Sixty specimens from the basic mass were examined modally to give some indication of the compositional ranges found within the intrusion. The volumetric mineral compositions of selected specimens are given in fig. 4-8.

Five essential minerals of both primary and secondary origin were measured using a Swift automatic point counter. The primary minerals include plagioclase, olivine, clino- and orthopyroxene. The amphiboles are predominantly secondary in origin and consists of colourless tremolite and blue-green actinolite in a conspicuous pseudomorphous replacement of clinopyroxene.

3.8.2 Amphibolitized plagioclase-pyroxene cumulates (amphibolitized-gabbro)

These cumulates are the most abundant rocks in the layered intrusion. They constitute over 60 percent of the exposed rocks.

Fractures parallel to layering and to primary igneous lamination developed after crystallization is a common feature for most of the layers.

Rhythmic layering is well represented by intercalations of leucocratic and melanocratic layers.

In thin section the rock is medium-grained, roughly equigranular and consisting of plagioclase and amphibole, the former generally being in excess of the latter, and making up about 55-65 percent of the rock. Plagioclase forms prominent parallel orientated tabular crystals with An content ranging from 50 to 60 though lower (An 40) and higher (An 70) values have been recorded. Coarse grained rocks are uncommon and only two layers were encountered. First layer containing over 5 percent by volume interstitial opaques, occurs in the lower part of unit I.

Second, forms the lower part of unit VII. It contains large anhedral-grains of plagioclase (5 to 10 mm in length) set in a groundmass of tremolite-actinolite pseudomorphs after pyroxene and cumulus opaques. (As-295, As-246).

Plagioclase is generally fresh with slight clouding, but sericitization and saussuritization is seen to have developed adjacent to contacts with local intrusives and in the lowermost layers. Strongly altered plagioclase show dull pale brownish areas in between fibrous aggregates of tremolite-actinolite and/or chlorite. Bent plagioclase laths are observed adjacent to amphibole aggregates. Local cataclasis was observed in rocks affected by dyke intrusions.

Throughout the amphibolitized plagioclase-pyroxene cumulates, the primary pyroxenes have been amphibolitized, small irregular relics of pyroxene remaining in the cores of small amphibole grains. Where the pyroxene has been completely amphibolitized its original outline has been retained and exsolved lamellae preserved. The colourless amphibole, often developed in the centres of the grains, grades peripherally into a blue-green variety. Dusty brown hornblende is a frequent interstitial mineral and in some instances it forms rims around the green fibrous actinolite.

Chlorite occurs in appreciable amounts with less abundant calcite and biotite often replacing amphibole in zones close to contacts with younger intrusions. Opaque minerals, are usually interstitial and poikilitic; they include magnetite, ilmenite, secondary hematite, pyrite (both euhedral primary grains and secondary interstitial veinlets) and locally minute blebs of pyrrhotite and chalcopyrite.

Apatite is an accessory interstitial mineral in certain layers and seldom exceeds 0.1 percent by volume. The relatively high values up to two percent have been found at the western margin of the layered mass (As 276)

3.8.3 Plagioclase-olivine cumulates (troctolite)

These cumulates form second most abundant rock type in the layered series. They occur either as discontinuous arcuate conformable layers

(unit II and IV), or as continuous concentric bands. Weathering has produced dark grey spheroidal boulders at the surfaces of their exposures. Typically, fresh plagioclase-olivine cumulate is composed of plagioclase (labradorite) $An_{70}-An_{55}$, averaging approximately 65 percent by volume of the rock. Small rounded to subrounded grains are included locally within olivine crystals or, rarely within interstitial pyroxene. Euhedral olivine is the second cumulus mineral averaging 25-30 percent. It occurs as large grains and as a rule is an early formed constituent

When in contact with plagioclase, often displays corona reaction rims, of orthopyroxene succeeded by an outer zone of brown hornblende. Symplectic intergrowth and myrmikitic magnetite is common. Incipient serpentinisation of olivine along cracks and around margins is widespread.

Pyroxene is present either as an accessory fringing olivine or forming an interstitial intercumulus phase which poikilitically encloses labradorite and/or olivine grains. Pyroxene amounts to 10 percent of the rock and usually orthopyroxene (hypersthene) is in excess of clinopyroxene (augite). Hypersthene is light pink, pleochroic, with exsolution lamellae and blebs probably of augite. Augite and titaniferous augite is either pink or brownish-green with well developed schiller texture.

Plagioclase-olivine cumulates are mainly massive, but igneous lamination is locally developed in units XIII and XIV (As 301, As 303). Rhythmic layering is lacking in the major part of the layers, fine banding on microscopic scale is due to variations in the relative proportions of plagioclase and olivine giving alternative layers of plagioclase and plagioclase-olivine cumulate of the order of only 0.5 to 1 centimeter in width.

3.8.4 Plagioclase-pyroxene-olivine cumulate (olivine leuconorite)

Plagioclase pyroxene-olivine cumulate is present as one distinct layer at the base of unit XIII (As 271).

In appearance and texture the rock is similar to the plagioclase-olivine cumulate, being medium to coarse-grained and consisting essentially of cumulus plagioclase, olivine and pyroxene. Due to spheroidal weathering, boulder strewn surfaces are characteristically developed in most of the outcrops. Plagioclase is the most abundant constituent in the rock, in places occurring as prominent parallel orientated laths, in others it is present as interstitial mineral. They are commonly fringed by brown hornblende and, more rarely, by biotite.

Olivine makes up about 20 percent of the rock, as anhedral, stumpy grains with incipient marginal and internal serpentinization. Some small grains of olivine (0.2 mm in diameter) are included in plagioclase or in pyroxene. Corona rims and symplectic intergrowths are locally developed.

A specimen (As 321) taken from B-B' traverse from the same layer, exhibited equal percentages by volume of both olivine and pyroxene, with both pyroxenes in equal amounts. Titaniferous augite is in cumulus occurrence while poikilitic hypersthene is intercumulus, with corona rims of brown hornblende.

3.8.5 Plagioclase-pyroxene cumulate (norites)

Plagioclase-pyroxene cumulate is characterised by its friable rock exposures, spheroidal weathering and a rusty dark grey surface. It is poorly exposed. The main mass of this cumulate forms Unit VI and some thin layers of the same composition are present at the base of Unit XI. Igneous lamination is well exposed in all exposures except in the south.

Plagioclase (volumetrically 50-65 percent) occurs as fine to medium grained tabular fresh laths. Occasional bent laths are observed in the neighbourhood of the pyroxene grains. Hypersthene (20-45 percent) occurs as small to medium grain sized grains, sub-rounded, pleochroic from pink to pale brown with exolved lamellae

locally developed. Clinopyroxene (up to 15%) is usually associated with hypersthene. Brown hornblende is a common accessory interstitial mineral. Green hornblende constitutes 2-3 percent of the rock and it appears to be confined to southern most exposures.

Brown biotite is also a minor accessory mineral, forming up to 2% of the rock in the south. Biotite and, more particularly, hornblende form rims around pyroxenes and opaque minerals.

Magnetite and ilmenite are interstitial accessory minerals which are locally poikilitic.

3.8.6 Plagioclase cumulates (anorthosites)

Commonly in thin layers (50-100 cm.), thicker layers up to 20 m in width are occasionally present in units I and XI. They also occur in inch scale layering alternating with mafic bands. Generally, they are pale-white, pale-brown or pale-grey in colour. They contain numerous dark spots of interstitial chlorite or amphibole pseudomorphs after pyroxene. These cumulates are of variable grain size, but coarse grained varieties are dominant. Primary igneous lamination is developed in a few thin layers in unit I, where the rocks are distinctly fissile and contain over 95% plagioclase.

Plagioclase cumulate layers are predominantly intercalated with mafic layers within the amphibolitized units. Orthocumulates, with few crystals showing primary zoning are in excess of adcumulate layers.

In thin section, labradorite and, in places, andesine form the principal cumulus mineral comprising volumetrically between 80-100 percent of the rock. The plagioclase is locally sericitized and/or saussuritized, along grain margins in small irregular patches and along prismatic planes. At contacts with younger intrusives, chlorite, irregularly shaped grains of quartz, prehnite, epidote, calcite and fine saussurite and sericite, are recognized as alteration products (As-263b).

The interstitial tremolite-actinolite is pseudomorphous after pyroxene, with chlorite associated in stages of more advanced alteration. The range of grain size for plagioclase is between 0.3 and 1 centimetre in length.

4.3.9 The characters of individual units of the layered series

Gneissic porphyroblastic adamellite envelopes the layered intrusion, thus obscuring the relationship between the intrusion and the primary country rock. The marginal gabbroic facies are partly the result of post-intrusive tectonic stresses and partly the result of initial emplacement into sedimentary succession which was already heated by regional metamorphism and, therefore, no chilled contacts are observed. Although the deformation of the whole intrusive mass has not been intense, there is a clear indication that the southernmost part was disrupted by advancing younger granitic magma that crystallized as porphyritic adamellite. Numerous inclusions of variable sizes, consisting of olivine gabbro and heavily saussuritized and chloritized gabbros, with primary textures preserved, have been recognized and mapped at several localities around the southern regions of the intrusive mass.

UNIT 1

Unit I, approx. 350 m thick as measured along traverse A-A' is fairly well exposed at this locality except for the uppermost 80 m which were studied outside the line of traverse. The rocks of this unit display mafic layers of variable grain size, composition and texture, alternating with narrower bands of anorthosite. The sequence of rocks forming the Unit I is divided into ten subunits:

I-1, 16.5 m. (As-212): Coarse grained with plagioclase and amphibole crystals ranging from 0.5 to 1.0 centimetre in length. The upper part of this layer grades into coarse grained, mottled plagioclase orthocumulate (An_{63}).

I-2, 7.0 m.: Medium grained amphibolitized rock, strongly foliated parallel to layering (fig. 4-3a), with plagioclase and amphibole present approximately in equal amounts.

I-3, 11.5 m. (As-213): Coarse grained, dark grey rock. Mineralogy and volumetric proportions similar to subunit I-2.

I-4, 41.0 m. (As-214, 216, 217, 218): Layered sequence, variable in grain size, thickness and foliation. As-216 is composed of about 60 percent plagioclase and 40 percent amphibole (tremolite-actinolite). Plagioclase is strongly sericitized. Three varieties of amphibole are recognised, colourless tremolite in centres of grains, pale green to green fibrous actinolite, usually rimming tremolite, and, locally, brown hornblende rimming the actinolite.

I-5, 23.5 m. (As-219): Mottled plagioclase-cumulate (anorthosite), massive medium to coarse grained. The zoned plagioclase which makes up about 97 percent of the rock, is partly sericitized and moderately saussuritized. Poikilitic and interstitial chlorite and calcite appear to pseudomorph pyroxene. Sub-poikilitic ilmenite and magnetite are present as minor accessories.

I-6, 28.5 m. (As-220): This subunit consists of fine scale rhythmically layered plagioclase cumulate and light-coloured amphibolitized plagioclase-pyroxene cumulate. Foliation is well developed in the latter. A one metre wide band of massive, medium-grained rock in the upper part of the subunit contains about 55 percent of opaque minerals (mainly poikilitic magnetite and ilmenite, with secondary hematite within the magnetite, with accessory pyrite grains enclosing small blebs of pyrrhotite and chalcopyrite). The contacts between layers are gradational. As-220 contains approximately 60 percent of plagioclase and 35 percent of amphibole. Relic textures are well preserved.

I-7, 19.0 m. (As-221): Medium to coarse grained amphibolitized plagioclase-pyroxene cumulate, moderately well foliated parallel to

layering. The central section contains a 0.5 m. wide mottled coarse grained plagioclase cumulate layer with about 98 percent plagioclase, slightly zoned and moderately sericitized. Poikilitic chlorite and calcite pseudomorphs after pyroxene, accessory subpoikilitic magnetite and apatite are also present. Contacts with anorthosite layer are gradational.

I-8, 98.0 m. (As-222, 223, 224, 225): Amphibolitized plagioclase-pyroxene cumulate, rhythmically layered with plagioclase cumulate layers ranging from 0.4 to 1.0 m. in width. The amphibolitized rocks in this subunit are foliated parallel to layering and show a higher amphibole content, and finer scale rhythmic layering than similar rocks in subunit I-7. A massive 2 m. wide layer which is found in the lower part of this subunit is composed of 60 percent amphibole and 40 percent plagioclase.

I-9, 18.0 m. (As-226): Massive leucocratic amphibolitized cumulate of uniform composition. Plagioclase makes up about 60-70 percent of the rock, amphibole approximately 30-40 percent. It becomes a plagioclase cumulate rock, where plagioclase is the only cumulus phase. Amphibole pseudomorphs are essentially poikilitic, rimmed by accessory brown hornblende.

I-10, 87.0 m.: Exposures of this subunit are rather scarce in the vicinity of the traverse, however, at the locality 300 m. to the west, it is formed mainly of foliated fine to medium grained amphibolitized cumulate layers, with interlayered thin anorthosites, rather similar to subunit 8.

UNIT II

This unit forms a semicircular ridge around the northern side of the intrusive body. It attains a thickness of 72 m. at the locality of the traverse. It forms a conspicuous landmark, rising up to about 70 m. above the more eroded underlying and overlying amphibolitized gabbros. Surface outcrops of the unit are characteristically strewn

by spheroidally weathered boulders with rough knobby surfaces (fig. 4-2b). The 'knobs' characterising the surfaces were formed as a result of differential weathering of areas with low content of intercumulus pyroxene. The rock is devoid of both rhythmic and igneous lamination. In thin section (As-227) the rock displays a characteristic plagioclase-olivine orthocumulate texture. The plagioclase (An 62) constitutes 70 percent, and olivine about 20 percent of the rock, both present as cumulate minerals. The olivine occurs as small rounded to subrounded stumpy grains, and nearly all are affected by slight internal and marginal serpentinization. Some very small rounded cumulus olivines are enclosed in large tabular crystals of plagioclase. Plagioclase adjacent to olivine grains is heavily fractured.

The intercumulus material is largely represented by titaniferous augite, which forms large, optically continuous, poikilitic crystals and interstitial grains. It makes up about 8 percent of the rock.

Hypersthene is an accessory mineral, mainly restricted to corona rims around olivine grains, but also forming an interstitial phase. There is local symplectic intergrowth between hypersthene and magnetite.

UNIT III

Outcrops of this unit are rare. The amphibolitized cumulates display foliation parallel to the margins of the unit. A secondary cleavage striking N 45°E and dipping 70°SE is superimposed on this unit. This cleavage is therefore at an angle of 15° with the N 60°E strike of the layering (as measured along this traverse).

In thin section the rocks are essentially composed of 45-50 percent cumulus plagioclase (An₆₀-An₅₈) and 50-55 percent amphibole e.g. (As-229). Colourless, fibrous tremolite commonly forms the cores of grains and is surrounded by pale green actinolite, in pseudomorph, after pyroxene. Accessory dusty brown hornblende rims actinolite. Opaque minerals include magnetite, ilmenite and secondary hematite. They poikilitically enclose cumulus grains.

UNIT IV

This unit is composed of two massive plagioclase-olivine cumulate layers separated by a layer of amphibolitized plagioclase-pyroxene cumulate. Exposures are sporadic. A prominent feature of the massive layers is their boulder strewn surface, which rises 1-2 m. above the surrounding ground. Small rounded 'knobs' are developed on the surface of the boulders. The plagioclase-olivine layers are well exposed around the northwestern part of the intrusion. They lens out to the south and to the east. This unit is subdivided into three subunits.

IV-1, 8.0 m. (As-230): Dark grey, massive, plagioclase-olivine mesocumulate (troctolite). Boulders characterizing exposure surfaces have small rounded to subrounded 'knobs' - averaging 3-7 cm. in diameter. This subunit is devoid of both rhythmic layering and igneous lamination. It is essentially composed of about 55 percent, fresh, unzoned, tabular plagioclase and approximately 25 percent of cumulus olivine forming small stumpy, subrounded grains. The olivines are commonly fringed by hypersthene and brown primary hornblende, more rarely by clinopyroxene. Incipient alteration to serpentine is seen at the margins and along the cracks of the grains. Myrmekitic magnetite is occasionally developed at contacts between pyroxene and plagioclase. Titaniferous augite with rims of hornblende and/or hypersthene forms intercumulus phase (15 percent). Hypersthene (up to 8 percent), also forms small interstitial grains. Accessory minerals include biotite, brown hornblende and opaque ore minerals. These generally occur as interstitial grains or as rims around plagioclase, olivine, and less commonly, titaniferous augite.

IV-2, 19.0 m.: Amphibolitized plagioclase-pyroxene cumulate, strongly foliated parallel to the contacts of the subunit. Plagioclase makes up 45-60 percent of the rock, amphibole the remainder.

IV-3, 14.0 m. (As-231): Dark grey, massive plagioclase-olivine orthocumulate (troctolite). Surface strewn with boulders which have rounded 'knobs' 5-10 cm. in diameter. This cumulate consists of about 65 percent cumulus plagioclase (An₅₈) (fresh, medium grained tabular crystals).

Locally small rounded olivine grains are included within the plagioclase, which also contain exsolved lamellae of rutile in some grains. Olivine (30 percent) is the second cumulus mineral. It occurs as small stumpy subrounded grains. Incipient alteration to serpentine is developed along margins and cracks. The rock contains up to 5 percent titaniferous augite forming large optically continuous grains poikilitically enclosing plagioclase and olivine. It is randomly distributed in the rock. Accessory opaque minerals occur as fine coatings along margins and cracks of olivine crystals, or as subpoikilitic grains.

UNIT V

This unit is 320 m. wide and is poorly exposed. It is made up of amphibolitized plagioclase-pyroxene cumulates in which rhythmic layering is well developed. There is a considerable variation in grain size and intensity of foliation. Two narrow concordant massive layers occur in the lower part of this unit. They are more resistant to erosion than the strongly foliated amphibolitized rocks and so form good marker horizons. The plagioclase content in this unit varies from 40 to 65 percent. This unit is subdivided into the following subunits:

V-1, 40.0 m. (As-232, 233): Amphibolitized plagioclase-pyroxene cumulate. Primary igneous lamination is well developed and imparts a strong foliation to the rock which consists of 50 percent of zoned cumulus plagioclase and about 30 percent amphibole. Pyroxene (15 percent) and chlorite are also present. Amphibolitization of pyroxene is clear and well represented. Pyroxene remnants, mainly green titaniferous augite, display irregular grains and patches, always rimmed by fibrous actinolite. Relics of exsolved lamellae are still present in the completely amphibolitized grains. Chlorite is secondary after pyroxene.

V-2, 15.0 m. (As-234): Identical to subunit 3, Unit IV.

V-3, 90.0 m. (As-235): Identical to subunit 1 of Unit V.

V-4, 15.0 m. (As-236): Identical to subunit 3 in Unit IV, and subunit 2 in Unit V.

V-5, 160 m. (As-237, 238, 239, 240, 241, 242): Most of the rocks in this subunit are banded. They exhibit strong primary foliation parallel to the banding which is composed of alterations of plagioclase-rich and amphibole rich horizons. There are a few narrow layers of massive amphibolitized gabbro and anorthosite.

UNIT VI

Plagioclase-hypersthene-clinopyroxene-orthocumulate (norite) forms outcrops of this unit ranging in width between 60-100 m. It is generally poorly exposed. Characteristic spheroidal weathering is developed and 20-30 cm. diameter annular holes are developed in the south. The rock is largely composed of plagioclase which varies from 50 percent in the west to 65 percent in the north (Table 4-2). Cumulus hypersthene constitutes between about 20-40 percent. Titaniferous augite is also present as a cumulus phase and is usually associated with the hypersthene in aggregates. In the south, the rock is massive, but elsewhere a primary igneous lamination on a fine scale is developed.

Table 4-2 Modal analyses of rocks from Unit VI

<u>Sample Number</u>	<u>Vol.% Plagio- clase</u>	<u>Vol.% Opx.</u>	<u>Vol. % Cpx.</u>	<u>Vol. % Hb.</u>	<u>Vol. % Biotite</u>	<u>Vol. % Opagues</u>	<u>Remarks</u>
As-243	65.0	30.0	4.0	-	-	1.0	North side of intrusion
As-365	62.0	20.0	14.0	accessory	accessory	4.0	East side of intrusion
As-369	60.0	38.0	2.0	"	-	acc.	East side of intrusion
As-418	55.0	25.0	15.0	1.0	3.0	1.0	Southeast side of intrusion
As-429	50.0	33.0	10.0	3.0	3.0	2.0	East side of intrusion
As-289	55.0	42.0	2.0	0.5	accessory	0.5	West side of intrusion

UNIT VII

In the north this unit forms the widest succession of rhythmically layered amphibolitized rocks (395 m.). It narrows towards both the eastern and western sides of the intrusion. The layers within this unit vary in thickness, grain size, intensity of foliation and in the relative proportions of essential minerals. Plagioclase and amphibole together make up over 95 percent of the rock.

VII-1, 133.0 m. (As-244, 245): Massive, coarse grained, amphibolitized plagioclase-pyroxene orthocumulate. Plagioclase occurs as large, tabular, euhedral-grains which show local zoning. It is moderately sericitized, and occasionally has corroded margins. Plagioclase is the main cumulus phase in the rock constituting 50-55 percent of the total volume. Amphibole, pseudomorphous after pyroxene forms the remainder. Small plagioclase grains are poikilitically included within the larger crystals of amphibole which also occur as smaller interstitial grains. Original pyroxene outlines and exsolution lamellae are preserved. Magnetite, ilmenite and secondary hematite are present as fine grains, mainly associated with amphibole. They form up to 5 percent of the rock.

VII-2, 15.0 m.: Thinly foliated cumulate without conspicuous rhythmic layering.

VII-3, 90.0 m. (As-246): Identical to subunit I.

VII-4, 69.0 m. (As-247, 248): Alternating bands of poorly exposed fine- and medium-grained plagioclase-pyroxene cumulate. Various stages of amphibolitization are well displayed. Compositionally almost identical to the subunits already described. Rhythmic layering is poorly developed.

VII-5, 88.0 m. (As-249, 251): The uppermost part, of this subunit shows inch scale rhythmic layering where narrow anorthosite bands become abundant. Primary igneous lamination imparts a planar fabric parallel to the layering. Plagioclase forms 60-70 percent of the

rock. Tremolite-actinolite pseudomorphs after pyroxene are common and display relic poikilitic textures. The amphibole is also interstitial to plagioclase. Accessory opaque minerals are poikilitic and are predominantly associated with amphibole.

UNIT VIII

This unit is 108 m. thick along traverse A-A'. It shows distinct rhythmic layering between narrow layers of plagioclase-olivine orthocumulate (5-10 m.), amphibolitized plagioclase-pyroxene cumulate and very narrow plagioclase - cumulate layers. Layering on a scale of 2-3 cm. is present between alternating leucocratic and melanocratic bands in the amphibolitized rocks. The fresh, unaltered rocks of plagioclase-olivine orthocumulate are coarser-grained than the underlying rocks of similar composition (As-252, 253). These are the predominant rock types and form continuous outcrops around the layered mass. They have characteristic 'knobbly' boulder strewn surface. In thin section, the essential cumulus minerals are coarse grained (0.2-0.5 cm.), and are laminated, with their long axes lying in a subparallel orientation e.g. (As-253). Slightly zoned plagioclase constitutes about 60 percent and olivine approximate 35 percent of the total volume of the rock. Pyroxene is restricted to corona rims around olivine crystals and to occasional small grains interstitial to plagioclase.

Plagioclase-amphibole rocks and plagioclase cumulate layers in this unit vary in grain size, in composition and in the development of foliation parallel to layering. They show advanced stages of amphibolitization of primary pyroxene, and are mineralogically identical to other rocks of this type within the intrusion.

UNIT IX

This unit is essentially formed of amphibolitized cumulate, intercalated with several layers of plagioclase cumulate rocks. Inch scale rhythmic layering is well developed particularly towards the top of the unit. The lower part of the unit is foliated parallel to layering, where rocks (e.g. As-256, 257) show an igneous lamination of aligned

plagioclase and amphibole. Plagioclase is a dominant mineral and forms 55-75 percent of the rock, amphibole forms 25-45 percent. Alternating coarse- and medium-grained rocks forming the upper part of the unit do not show any primary mineral orientation.

UNIT X

This unit is 67 m. wide and is mainly formed of coarse-grained (0.2-0.7 m.) plagioclase-olivine orthocumulate. Except for the coarse grain-size, it is identical to Unit II. In thin section the rock shows a very patchy distribution of pyroxene and olivine. This texture can be directly related to the 'knobbly' texture of weathered surfaces, where olivine-rich areas are found to be more readily decomposed. Zoned plagioclase (fig. 4-4b), makes up 65 percent of the rock and olivine about 10 percent (eg. As-258). Both are cumulus minerals. The olivine is extensively fringed by hypersthene and brown hornblende. Incipient serpentinization along margins and cracks is developed in some grains. Hypersthene and titaniferous augite are present, the former as large, optically continuous poikilitic grains which enclose both plagioclase and olivine. Pyroxene makes up approximately 20 percent of the rock (e.g. As-258), but this is probably anomalously high, as the mineral is so patchily distributed.

UNIT XI

Rocks in this unit are generally coarse-grained and rhythmically layered. They are mottled with sporadic patches of amphibole or chlorite. Anorthosite (plagioclase cumulate) is predominant and tend to form eroded areas in between layers of troctolite. Plagioclase-olivine orthocumulate, and more rarely, mesocumulate layers are the second most abundant rock types within the unit.

The lowest part of this unit forms a 10 m. wide plagioclase-hypersthene cumulate layer (e.g. As-259). It is exposed only at the northern and western sides of the intrusion, and may be lacking altogether in the south and east.

Plagioclase cumulate layers contain about 80-97 percent plagioclase. The slightly zoned, plagioclase is coarse-grained (0.3-1.0 mm.)

and is moderately to strongly saussuritized and/or sericitized along cleavage planes and along contacts with chlorite, prehnite and quartz (e.g. As-263)a). Epidote as an accessory mineral is associated with the interstitial chlorite or forms microstringers within plagioclase grains (As-265).

UNIT XII

This unit is divided into two subunits- a lower massive plagioclase-olivine orthocumulate and an upper massive plagioclase-olivine mesocumulate interlayered with plagioclase-amphibole rock.

XII-1, 52.0 m. (As-269): Leucocratic cumulate containing about 75 percent plagioclase and about 20 percent olivine. Clino- and orthopyroxene are present as intercumulus phases forming about 5 percent of the rock, the former is in excess of the latter. They occur as small interstitial grains or as corona rims around olivine. Accessory brown hornblende rims pyroxene and, occasionally, olivine. Accessory biotite and opaque minerals are also interstitial and are locally poikilitic.

XII-2, 50.0 m. (As-270, 378, 379): Dominantly plagioclase-amphibole rock. However, a narrow band of massive, fresh plagioclase-olivine cumulate layer outcrops in the central part of this subunit. Amphibolitization stages are well displayed (e.g. As-379) where relics of pyroxene are preserved. Plagioclase forms about 60 percent of the rock, amphibole most of the remainder.

UNIT XIII

This unit, 262 m. wide across the measured traverse, is divided into four subunits, a massive plagioclase-pyroxene-olivine orthocumulate underlies massive plagioclase-olivine orthocumulate which is interlayered with plagioclase-amphibole rock.

XIII-1, 15.0 m. (As-271): Massive, medium-grained, melanocratic plagioclase-pyroxene-olivine orthocumulate. Plagioclase forms 43 percent, hypersthene, 20 percent, titaniferous augite 15 percent, olivine 18 percent, biotite, and hornblende 2 percent by volume of the total rock. Plagioclase, pyroxene and olivine are the cumulus phases. Brown

hornblende and brown biotite are interstitial and commonly surround grains of pyroxene and olivine.

XIII-2, 136.0 m. (As-376): Plagioclase-amphibole rock is medium-grained and massive. Plagioclase forms between 40-55 percent of the rock.

XIII-3, 13.0 m. (As-301): Plagioclase-olivine orthocumulate, with primary igneous lamination. Plagioclase forms 65 percent of the rock, olivine forms about 35 percent, both as cumulus phases. Hypersthene, brown hornblende, biotite and opaque minerals are interstitial accessories.

XIII-4, 98.0 m. (As-377): Plagioclase-amphibole rock much injected by granitic dykes. Plagioclase averages between 50-60 percent of the rock. There are bands of plagioclase cumulate.

UNIT XIV

This unit is formed of leucocratic, fresh plagioclase-olivine orthocumulate 32 m. wide along traverse A-A'. Igneous lamination is well developed. Plagioclase makes up 75 percent, olivine 23 percent, and hypersthene 2 percent of the total volume of the rock. The hypersthene occurs both as coarse rims around olivine and as interstitial grains.

UNIT XV

This unit is formed of amphibolitized plagioclase-pyroxene cumulate and occupies the oval-shaped core of the intrusion. Its relief is lower in relation to the surrounding massive layers and exposures are scarce, being concealed by a thin alluvial gravel and sand cover. This central area is much affected by granitic and pegmatitic dyke intrusions. The rock is fine- to medium-grained and locally shows igneous lamination (e.g. As-380). Plagioclase makes up 35-60 percent, amphibole replacing pyroxene makes up the remainder.

4.3.10 Geochemistry

3.10.1 Whole rock analyses

Five rock analyses are represented in table 4-3 of which two are plagioclase - clinopyroxene cumulates which were amphibolitized. The plagioclase - olivine cumulates have the composition of a saturated basaltic magma with a high alumina content and tholeiitic affinities. It is similar to analyses of the Skaergaard chilled marginal gabbro (table 4-4) but differs from Stillwater in having more Na_2O and a lower $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio.

Both quartz and olivine are absent from the CIPW norm, so that the presence of these minerals in the layered rocks is indicative of strong crystal fractionation.

Table 4-3

	As-227	As-300	As-289	As-239	As-308
SiO_2 wt%	49.03	43.51	48.32	49.01	48.46
TiO_2	2.52	2.01	2.02	1.06	0.56
Al_2O_3	19.30	21.41	16.62	18.41	20.71
Fe_2O_3	1.05	22.37	3.32	1.39	2.15
FeO	6.00	5.20	9.34	4.03	5.02
MnO	0.23	0.25	0.18	0.19	0.32
MgO	7.05	5.89	3.90	4.42	4.73
CaO	11.60	13.00	13.30	11.80	11.90
Na_2O	3.37	5.63	3.37	2.97	4.10
K_2O	0.34	0.47	0.53	1.08	0.53
H_2O	0.60	0.70	0.30	7.00	2.00
P_2O_5	0.00	0.00	0.51	0.01	0.01

As-227 = Plagioclase-olivine-orthocumulate (Troctolite) Unit II

As-300 = " " orthocumulate (Troctolite) Unit XIII

As-289 = " Hypersthene orthocumulate (Norite) Unit VI

As-239 = " -clinopyroxene cumulate (Amphibolitized) Unit V

As-308 = " " " (") Unit XV

Table 4-4

	1	2	3
SiO ₂	48.01	49.70	50.55
TiO ₂	1.51	0.16	0.66
Al ₂ O ₃	19.11	22.04	15.23
Fe ₂ O ₃	1.20	0.66	1.04
FeO	8.44	4.02	10.07
MnO	0.12	0.09	0.23
MgO	7.72	7.03	8.30
CaO	10.33	13.59	11.30
Na ₂ O	2.34	1.79	2.24
K ₂ O	0.17	0.07	0.19
H ₂ O ⁺	0.55	0.82	0.24
H ₂ O ⁻	0.05	0.09	-
P ₂ O ₅	0.069	0.02	0.12
Total	99.62	100.11	100.18

1. Chilled marginal Skaergaard gabbro of Tranquil Division, Wager and Brown (1968 Table 7).
2. Composite sample of 40 specimens from the norite, anorthosite and gabbro zones, (Hess (1960) Table 32).
3. Fine-grained hypersthene gabbro, Bushveld Marginal Group (Wager and Brown (1968) Table 26).

3.10.2 Strontium in plagioclase

3.10.2a Introduction

The main purpose of these investigations was to establish:

1. The relationships between amphibolitized rocks and unaltered cumulates.
2. The derivation and genetic relations of the numerous xenoliths enclosed in the granite.
3. To delineate the disrupted southern margin of the intrusion.

The geochemical relationships between, Sr and Ca has been investigated by numerous geochemists. According to Goldschmidt (1954) there is a tendency for certain minor elements to follow major elements of similar ionic radius and bond type. This suggestion is exemplified by strontium which is concentrated in Ca-rich minerals.

Investigations into the relationship between Sr and Ca in both basaltic and gabbroic rocks have been carried out by Nockolds and Mitchell (1948), and by Wager and Mitchell (1951). Heier and Taylor (1959) have discussed the ability of Sr to replace Ca and K in the feldspar lattice.

Heier (1962) discovered that plagioclase in the range from oligoclase to labradorite contains the highest Sr values (898-1129 p.p.m.), and that more calcic and more sodic members have relatively low Sr content.

Turikian and Kulp (1956) suggested the hypothesis that the strontium content in basaltic or gabbroic rocks is dominated by the regional differences in strontium content of the source magma and the fractional crystallization and differentiation conditions.

Butler and Skiba (1962) pointed out that plagioclase from Somalian layered gabbros held the most of the strontium which varied between 1000 and 1850 p.p.m. and tended to increase as An decreases from An_{68} - An_{48} .

Skiba and Butler (1963) attempted to distinguish between amphibolites derived from gabbros and those of the country rock derived from impure lime-magnesia sediments. They found that the Sr content of plagioclase from the country rock amphibolites was almost invariably

below the range 1000 - 1450 p.p.m., which was characteristic of plagioclase from gabbro and metagabbro. Also, the distribution of Sr values for the country-rock amphibolites is so haphazard that they cannot be genetically related to the gabbro and metagabbro masses. With reference to amphibolitization of a gabbro mass the authors found that amphibolitization had little effect on the original Sr and An contents of the plagioclase which crystallized from the initial basic magma.

3.10.2b Strontium in plagioclase from Al-Jéalani intrusion

The intrusion is dominated by amphibolitized rocks interlayered with unaltered cumulates. Plagioclase separated from 38 representative samples, showed a fluctuating An content throughout. The Sr of the plagioclase was found to increase with decreasing An content, which ranged from An_{70} - An_{32} .

The Sr content varies between 840-1700 p.p.m., except for one anomalously high value (2225 p.p.m.) in an amphibolitized gabbro with An_{47} , (As-294). The mean average for Sr from all the investigated samples apart from the highly Sr-enriched one is 1405 p.p.m. For the plagioclase separated from fresh cumulates, the average Sr content was 1402 p.p.m., which is very close to the average Sr content, for the amphibolitized rocks (1407 p.p.m.). The anorthite content for fresh unaltered cumulates ranges between An_{70} - An_{58} , that for amphibolitized gabbros between An_{67} - An_{32} .

Table 4-5 Sr and An in plagioclase in Al-Jéalani intrusion

Sample No.	Rock type	An content		Sr (p.p.m.)
		Immer-sion	Chem. analyses	
As-214	Amphi-plagioclase-pyroxene cumulate	39		915
As-221	Plagioclase cumulate (anorthosite)	48	40	1405
As-391	Amphi-plagioclase-pyroxene cumulate	63	55	1195
As-392	" " "	56	42	84
As-226	" " "	67	56	1047
As-227	Plagioclase-olivine orthocumulate (troctolite)	62	59	950

Sample No.	Rock Type	An content		Sr (p.p.m.)
		Immer- sion	Chem. analyses	
As-235	Amphi. plagioclase-pyroxene cumulate	52	50	1270
As-239	" " "	62	57	1325
As-240	" " "	56	54	1343
As-247	" " "	55	50	1570
As-249	" " "	51	47	1721
As-253	Plagioclase-olivine orthocumulate (troctolite)	58	61	1260
As-257	Amphi. plagioclase-pyroxene cumulate	48	32	1370
As-261	Plagioclase-olivine orthocumulate (troctolite)	58	57	1518
As-264	" " "	58	60	1465
As-266	" " "	59	61	1660
As-377	Amphi. plagioclase-pyroxene cumulate	51	49	1420
As-379	" " "	55	52	1600
As-380	" " "	55	-	1660
As-276	" " "	57	66	1410
As-278	" " "	59	49	1340
As-284	" " "	56	49	1447
As-289	Plagioclase-hypersthene cumulate (norite)	59	58	1610
As-308	Amphi. plagioclase-pyroxene cumulate	57	56	1635
As-317	Plagioclase-olivine cumulate (troctolite)	66	68	1385
As-295	Amphi plagioclase-pyroxene cumulate	63	-	1195
As-304	Plagioclase-olivine cumulate (troctolite)	70	66	1372
As-271	Plagioclase-pyroxene-olivine cumulate (noritic troctolite)	66	-	1425
As-300	Plagioclase-olivine cumulate (troctolite)	63	-	1415
As-329	Amphi. plagioclase-pyroxene cumulate	56	-	1715
As-333	" " "	56	45	1590
As-269	Plagioclase-olivine cumulate (troctolite)	52	-	1380
As-236	Plagioclase " "	67	60	1138
As-283	Amphi. plagioclase-pyroxene cumulate	59	47	1425
As-319	Plagioclase-olivine cumulate (troctolite)	63	61	1367
As-394	Amphi. plagioclase-pyroxene cumulate	60	60	1235
As-241	" " "	52	51	1428
As-280	" " "	50	43	1382

Sample No.	Rock Type	An content		Sr (p.p.m.)
		Immer- sion	Chem. analyses	
As-453	Plagioclase-olivine cumulate (xenolith)	62	60	1250
As-455	Amphibolitized plagio. pyroxene cumulate (xenolith)	53	-	1430
As-456	Plagioclase-olivine cumulate (xenolith)	58	-	1520
As-464	Amphibolitized plagioc-pyroxene cumulate (xenolith)	55	-	1345
As-443	" " " (xenolith)	48	-	1190

Table 4-6 Sr and An in plagioclase from rocks in Arja basic intrusion

Sample No.	Rock Type	Plagioclase		Sr (p.p.m.)
		An % Wt. Immer- sion	Chem. anal.	
Ar-85	Plagioclase-olivine cumulate (troctolite)	67	42	1663
Ar-86	Amphibolitized plagioclase-pyroxene cumulate	60	51	1385
Ar-88	" " "	59	58	1130
G-301	Plagioclase-clinopyroxene (ti-augite) cumulate	56	46	2050
G-302	Amphibolitized plagioclase-pyroxene cumulate	56	45	1112
G-303	Plagioclase-clinopyroxene (titano-augite) cumulate	59	55	792
G-304	Amphibolitized plagioclase-pyroxene cumulate	56	47	1940
G-305	" " "	63	45	982
G-306	" " "	43	37	810
G-299	Plagioclase-clinopyroxene cumulate	43	35	1067
G-349	Plagioclase-cumulate (anorthosite)	59	56	1482

3.10.2 Strontium in plagioclase from xenoliths

Many large xenoliths have been mapped outside both intrusions. Some of them are concentrated towards the southern margin of the Al-Je'alani mass. Attention is directed to xenoliths with variable content of

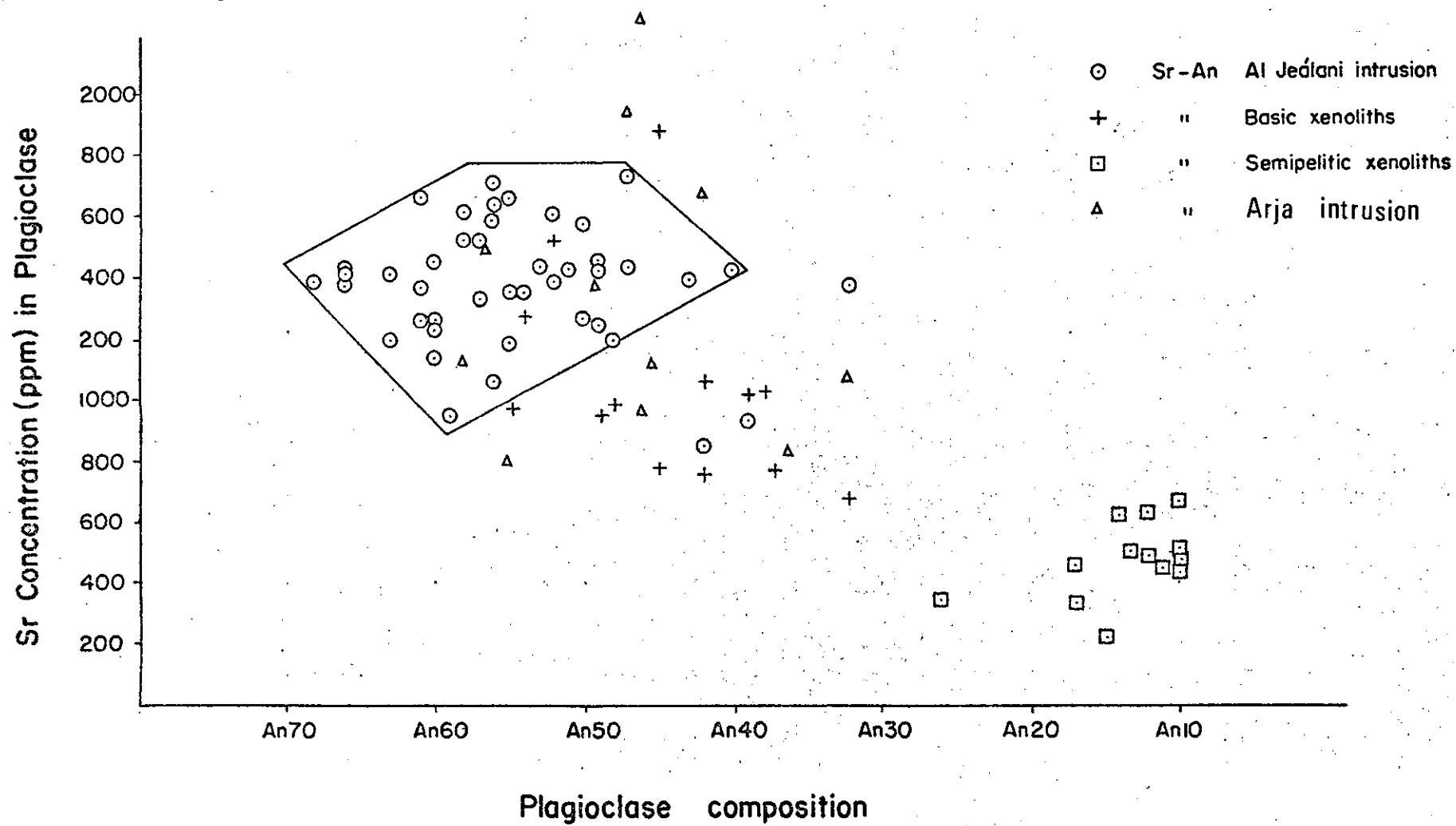
feldspar, biotite and/or hornblende. The field evidence alone is not sufficiently diagnostic to determine parentage of these xenoliths and define the disrupted southern contact of the intrusion. Although some of the xenoliths in the south exhibit similar petrography and texture to plagioclase-olivine cumulates of the intrusion, most have lost their primary texture and mineralogy.

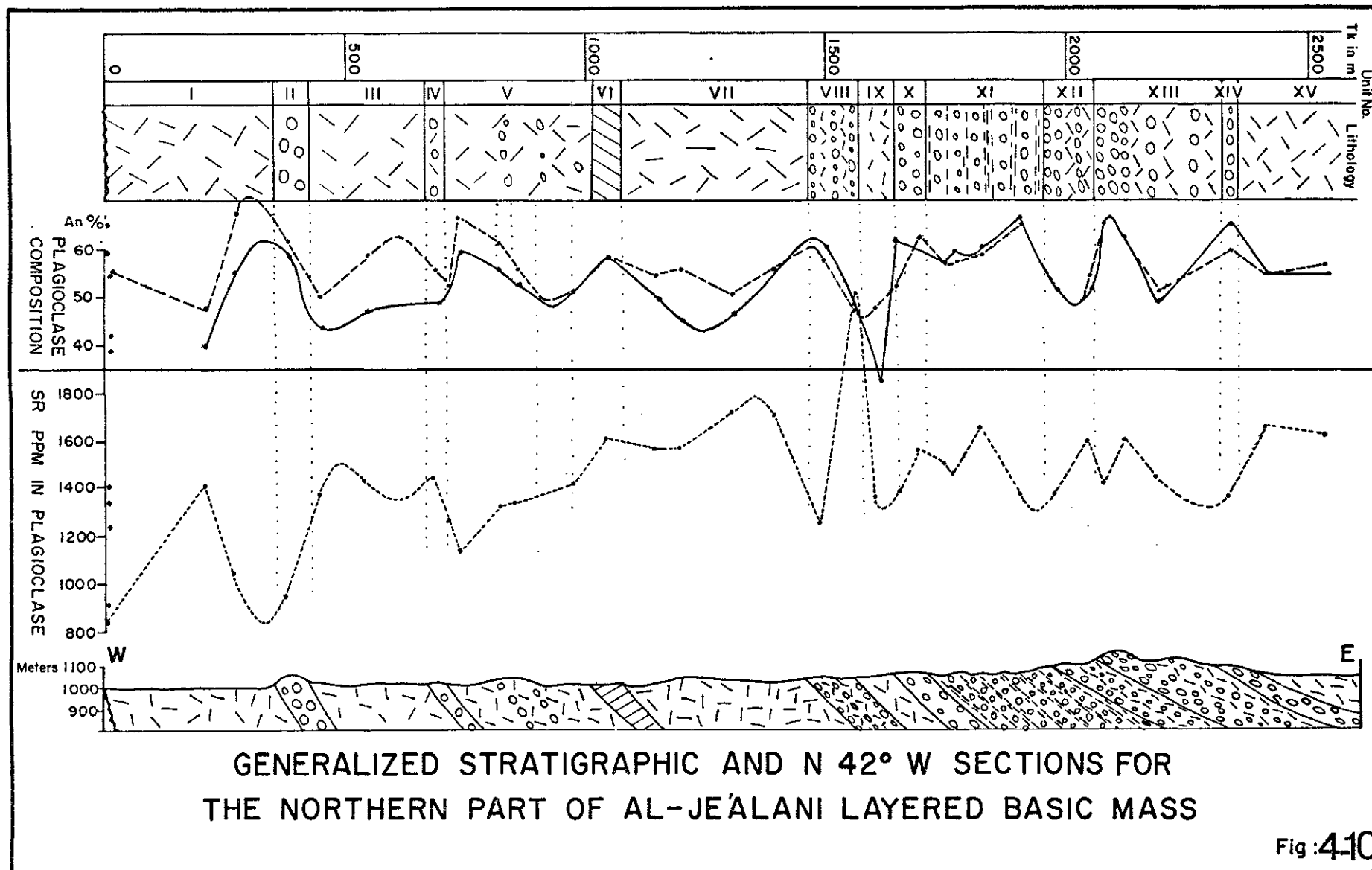
Tables 4-5, 6, 7 & 8 and (figs. 4-9 and 4-10) give the data which demonstrates a clear distinction between Sr-An values for plagioclase from the layered masses and from the xenoliths in the granite. Values in the polygon from the intrusions refer to fresh cumulates and amphibolitized rocks. Relatively high values and rather small variation of Sr with change of An content is observed in (fig. 4-9). Sr-An data from xenoliths are given in tables 4-7 and 8. There is a widespread of An values from An₁₀ to An₅₄ and the strontium varies appreciably from 205 to 1870 p.p.m. It is clear that these rocks are unconnected genetically with the intrusions on account of lower tenor of Sr and much greater variation of Sr with change of An content. By a co-ordination of Sr/An data with carefully field mapping it is possible to extend the boundary of the south main intrusive mass southwards to incorporate the large inclusions which are genetically related to the intrusion.

Table 4-7 Sr and An content in plagioclase from country rock xenoliths in the granitic rocks

Sample No.	Rock type	An content	Sr (ppm)
G-110	Biotite schist	17	450
G-136	" "	12	630
G-139	" "	14	612
G-164(b)	" "	10	473
G-180(b)	" "	12	485
G-216	Amphibole schist	25	344
G-209	Biotite schist	10	490
G-210	" "	10	660

Fig. 4—9





GENERALIZED STRATIGRAPHIC AND N 42° W SECTIONS FOR
THE NORTHERN PART OF AL-JE'ALANI LAYERED BASIC MASS

Fig: 410

Sample No.	Rock type	An content	Sr (ppm)
G-211	Biotite schist	17	330
G-215	" "	11	455
G-216	" "	13	495
G-218	" "	15	205
G-222	" "	10	455

Table 4-8 Sr and An content in plagioclase from the basic xenoliths in the granitic rocks

Sample No.	Rock type	An content	Sr (ppm)
G-114	Metadiorite	42	1060
G-116	Sheared microdiorite	37	765
G-153	Metagabbro	39	1010
G-163	"	45	766
G-164(a)	"	52	1505
G-204	"	48	880
G-207	Metadiorite	32	1675
G-212	Metagabbro	38	1025
G-214	"	54	1275
G-217	Metadiorite	45	1870
G-263	"	42	770
G-264	"	49	942
G-269	"	55	978

3.10.2d Summary and conclusions

From these measurements the following conclusions can be drawn:

- 1) Sr-An relationship in plagioclases from Al-Jéalani mass, is inversal i.e. the Sr content increases as the An content decreases (fig. 4-9, 10). This is comparable to results obtained from some Somalian (Skiba and Butler, 1963), and the Stillwater (Turikian and Kulp, 1956) intrusions.

- 2) Amphibolitized cumulates and fresh unaltered cumulates show almost identical Sr content of 1407 and 1402 p.p.m. respectively. This indicates that both rock types originated from one magmatic source.
- 3) The average Sr content of the rocks of the intrusion (1405 p.p.m.) is high relative to the average Sr content of the pre-existing basic country rocks (492 p.p.m.) included within the granitic rocks as xenoliths. This suggests that the amphibolitized rocks of the intrusion are not pre-existing amphibolite country rocks which have been injected by gabbroic ring dykes, as Quin (1964) concluded.
- 4) The plagioclase has a fluctuating An content (fig. 4-10) from bottom to top. In all the samples studied, the An content of plagioclase changes abruptly from about 60-70 percent in unaltered cumulates to approximately 40-60 percent in amphibolitized rocks. This change is associated with the equally abrupt appearance of epidote and sericite in plagioclase and also amphibolitization of pyroxene. The change of An content in plagioclase is, therefore, linked with secondary reaction as the result of interstitial water.
- 5) Samples collected from the marginal layers of the intrusion or nearby contacts with granitic intrusions, show low anorthite content. This low An ratio is probably due to localized intense saussuritization of plagioclase. Sr content (840-1410 p.p.m.) is slightly affected by saussuritization.
- 6) A very clear distinction is demonstrated between Sr-An values for plagioclase from the layered mass and from the xenoliths enclosed in the granite. Most xenoliths are unconnected genetically with the Al-Jéalani intrusion.
- 7) The southern intrusive boundary of the layered mass can be delineated on the basis of Sr-An ratio in plagioclase.

3.10.3 Variation of the trace elements

3.10.3a Introduction: The main purpose of this investigation was to evaluate the geochemical behaviour of minor elements during differentiation of the intrusion. A total of 38 samples from the Al-Jéalani layered intrusion were spectrographically analysed for 12 elements, 7 of which (Ni, Co, Ba, Zr, V, Cu, Cr) have been studied in detail, to see whether there is any significant variation between the component rock types, and especially between those that have been amphibolitized and those that are fresh.

13 samples from granitic rocks enveloping and intruding the mass were also analysed together with 3 samples from inclusions within the granite for comparison purposes.

Table 4-9 Fresh cumulates (gabbro) Al-Jéalani intrusion

Sample No.	ppm Nickel	ppm Cobalt	ppm Barium	ppm Zirconium	ppm Vanadium	ppm Copper	ppm Chromium
As-227	300	600	200	10	50	80	120
As-231	100	60	250	30	60	50	100
As-234	120	80	200	20	400	50	80
As-236	120	60	200	15	80	30	150
As-253	300	20	200	30	20	40	20
As-295	500	30	250	50	120	40	150
As-261	200	10	600	10	30	40	30
As-263	30	10	200	10	40	30	100
As-264	500	50	200	10	150	20	120
As-266	100	30	200	10	40	30	100
As-300	300	40	200	20	80	20	70
As-304	300	N.D.	200	10	30	15	30
As-269	200	16	200	10	30	20	30
As-271	700	40	200	30	100	20	2000
As-317	300	60	200	20	80	100	70
As-319	70	10	200	10	50	40	50
As-219	10	15	250	20	300	80	30
As-332	100	30	200	30	200	40	50

Table 4-10 Amphibolitized cumulates (metagabbro) - Al Jéalani
layered intrusion

Sample No.	ppm Nickel	ppm Cobalt	ppm Barium	ppm Zirconium	ppm Vanadium	ppm Copper	ppm Chromium
As-214	60	10	800	150	150	30	200
As-428	50	40	300	100	150	20	70
As-216	10	10	250	220	150	10	70
As-221	10	10	500	20	30	10	120
As-280	70	10	1000	20	80	40	400
As-226	400	40	1000	10	30	20	70
As-283	100	20	500	20	200	20	70
As-235	50	40	500	20	70	40	120
As-284	40	30	360	70	100	20	70
As-239	100	20	600	20	120	50	300
As-390	50	30	500	80	200	20	150
As-240	100	40	400	20	200	60	150
As-241	80	30	600	20	100	50	150
As-247	50	20	300	10	120	30	120
As-249	60	20	400	10	100	20	120
As-285	50	20	350	30	170	40	100
As-257	200	10	600	50	100	60	300
As-257	200	10	600	50	100	60	300
As-294	10	10	800	10	50	20	70
As-308	80	10	250	10	100	20	70

3.10.3b Nickel:

Vogt (1923), Wager and Mitchell (1951), Storm and Holland (1957), Turikian (1963) and others have shown that nickel exhibits a strong tendency towards enrichment in olivine and to a lesser extent, in orthopyroxene. The element is therefore depleted during early stages of differentiation of a basic magma.

In the Al-Jealani layered intrusion, the average nickel content is found to be higher in the unaltered rocks (228 ppm) than in the amphibolitized rocks (86 ppm). In the plagioclase-olivine cumulates with olivine averaging 35 percent and pyroxene approximately 18 percent, the nickel content may be as high as 700 ppm (As-271). In contrast, the amphibolitized rocks show low values for nickel and only rarely a value of 400 ppm is attained (As-226).

The sudden increase of the nickel content in units II, VIII, IX, X and XII demonstrates clearly a tendency for its concentration in plagioclase-olivine cumulates in the early and late stages of crystallization and therefore its sensitivity to processes of crystal differentiation.

It is interesting to note that their average value is similar to that of many other basic rocks elsewhere (Fleisher and Stevens, 1962), indicating that metamorphism of the original pyroxene did not cause mobilization of the element.

In granitic rocks associated with the intrusion, an average of 14 ppm nickel is present, which is normal for such rocks.

Table 4-11 Granitic rocks - vicinity of Al Jealani intrusion

Sample No.	ppm Nickel	ppm Cobalt	ppm Barium	ppm Zirconium	ppm Vanadium	ppm Copper	ppm Chromium
As-206	10	10	1500	170	40	10	400
As-215	10	10	500	80	20	10	400
As-255	10	10	2000	200	30	1000	150
As-314	15	10	1000	80	20	10	1500
As-372	60	10	1500	40	20	10	300
As-333	10	10	800	500	40	10	350
As-345	10	10	1200	700	50	30	300
As-406	10	10	1000	120	30	10	300
As-412	10	10	1000	500	40	10	200
As-415	10	10	500	10	20	10	200
As-449	50	40	300	100	150	10	170
As-473	10	10	1500	200	30	10	150
As-290	10	10	1200	100	20	10	120

Xenoliths in the granitic rocks contain an average nickel content of 25 ppm in two samples and 300 ppm in As-396 which is a biotite schist.

Table 4-12 Biotite schist xenoliths in granitic rocks

Sample No.	ppm Nickel	ppm Cobalt	ppm Barium	ppm Zirconium	ppm Vanadium	ppm Copper	ppm Chromium
As-209	20	10	500	150	100	20	150
As-396	300	20	1000	200	150	60	600
As-397	30	20	700	70	200	15	50

3.10.3c Cobalt:

Wager and Mitchel (1951), Cornwall and Rose (1957), McDougall and Lovering (1963) and others, have shown that cobalt enters the same mineral phases as nickel but in lesser amounts and with more constant values. They have also shown that there is a gradual decrease in the cobalt content with crystallization differentiation.

In the Al-Jealani layered mass (fig. 4-13) the cobalt content is generally low. Although both the fresh rocks and the amphibolitized gabbros show varying values, the former have a slightly higher average (34 ppm) than the latter 23ppm). Thus the olivine rich rocks of units II, IV, V and XI show high Co values compared to the other units.

The granitic rocks and xenoliths have average contents of 10 and 15 ppm respectively which are normal for such rocks.

3.10.3d Barium:

In gabbroic and basaltic rocks, barium is generally restricted to plagioclase feldspar. In plagioclase of oligoclase to labradorite composition, barium averages 315-390 ppm (Heier 1962), and decreases in the more sodic or more calcic end members, the total range as reported by Martin Prinz (1967) is 220-303 ppm.

Barium fluctuates throughout the Al-Jealani layered mass and no trend emerges, but it appears to be concentrated in the amphibolitized gabbros in which it attains more than double its value in the unaltered rocks (fig. 4-11, 13 and 15). In the former rocks, barium ranges from 300-1000 ppm with a mean value of 535 ppm; in the latter rocks, it ranged from 200-250 ppm. Ba. with a mean of 215 ppm.

It is possible that in the amphibolitized rocks barium enrichment was produced by hydrothermal solutions which accompanied the partial saussuritization and sericitization of the plagioclase.

Felsic rocks and xenoliths show mean barium contents of 1169 ppm and 700 respectively. These high values are to be expected for potassium rich rocks in which barium can substitute for potassium in the K-feldspar lattice.

3.10.3e Zirconium:

Apart from its presence in zircon, the element is found in pyroxene and apatite lattices, generally replacing calcium ions. Its value tends to increase with differentiation (Wager and Mitchell 1951). Chao and Fleisher (1960) found a wide regional variation of zirconium in basaltic rocks and were unable to give an average figure.

In Al-Je'alani mass, a slight fluctuation is noticed, where it averages 36 ppm for pyroxene-rich and amphibolitized rocks and 20 ppm for olivine-rich rocks.

This is in accordance with previous investigations and findings that zirconium tends to enter pyroxene more readily than other minerals.

In the granitic and xenolithic rocks there are high average zirconium contents 212 ppm and 140 ppm respectively. In samples As-255, As-395 zirconium ranges from 500-700 ppm. These particularly high values are probably due to the presence of zircon.

3.10.3f Copper:

The average copper content (37 ppm) in rocks of the Al-Je'alani layered intrusion, is lower than the value for basic rocks of 100 ppm given by Martin Prinz (1967). It

is rather higher in the marginal layers (50-80 ppm) than the upper layers (20-40 ppm). The mean copper content for the unaltered gabbroic rocks is 40 ppm., compared with the slightly lower average value of 33 ppm in the amphibolitized rocks.

In granitic and xenolithic rocks copper content is 10 ppm and 32 ppm respectively, but in a dacite dyke (As-255), 100 ppm copper is encountered, this is probably due to presence of copper sulphides in the rock.

3.10.3g Vanadium:

Vanadium in basaltic rocks has a pronounced regional variation. Turikian and Wedepohl (1961) have stated that olivine basalts contain an average of about 140 ppm. The element is mainly concentrated in magnetite (300 ppm), and to a lesser extent in pyroxene. Usually, vanadium enters these minerals during the middle stages of fractionation and decreases during late fractionation (Martin Prinz, 1967).

In the Al-Jealani intrusion the vanadium content is low in both fresh and amphibolitized rocks, 93 and 115 ppm respectively. It is commonly enriched in rocks containing a relatively high content of magnetite and biotite, such as As-234 and 264 which contain 400 and 150 ppm respectively or in rocks with appreciable amounts of cumulus pyroxene such as As-289 with 300 ppm.

Vanadium is enriched in amphibolitized rocks (115 ppm) relative to fresh cumulates (93 ppm). This may be due to the retention of vanadium in amphibole pseudomorphs after pyroxene and to the higher magnetite content in these rocks. Occasionally however, plagioclase-olivine cumulate (e.g. As-234) is enriched in vanadium which may be due to a relatively high amount of magnetite

and interstitial pyroxene. Felsic rocks and xenoliths contain 36 and 150 ppm respectively, this difference is attributed mainly to the differing magnetite content.

3.10.3h Chromium:

Chromium has a tendency to be enriched in pyroxene, magnetite and chrome spinel, (Wager and Mitchell 1951; Turikian, 1963; McDougall and Lovering, 1963).

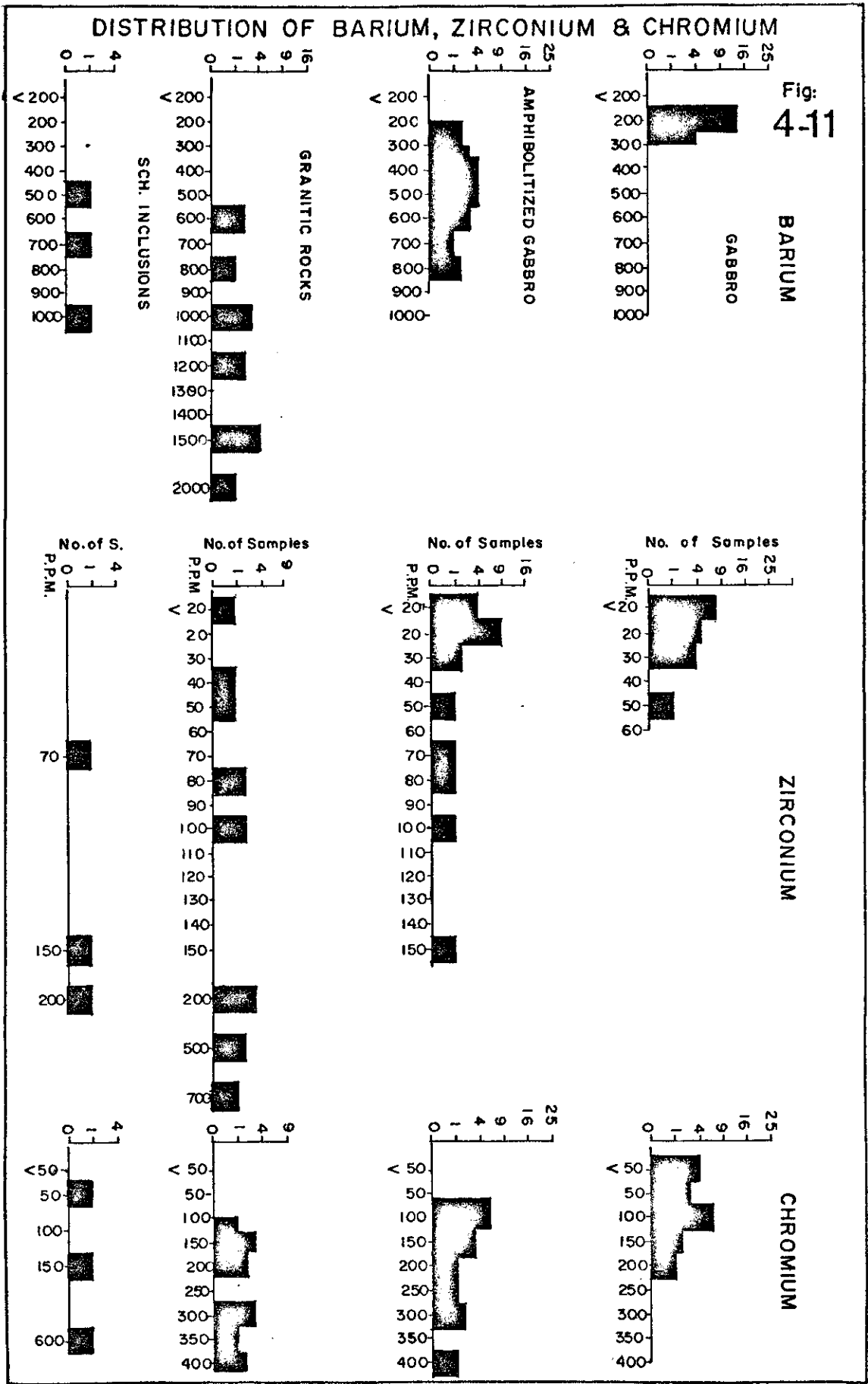
In the Al-Jealani layered intrusion, chromium varies erratically throughout. The amphibolitized gabbros with an average of 150 ppm have considerably higher content of the element than the fresh gabbros (average 86 ppm), (fig. 4-11, 14). This difference between the two types of rocks is in accordance with the tendency for chromium to enter a crystal lattice of pyroxene more readily than any other mineral. It also indicates that amphibolitization of pyroxene has not affected the original content of chromium which is still retained in the amphibole pseudomorphs.

In felsic rocks, the average chromium content is 253 ppm which is probably contained in the opaque minerals. Samples As-209 and As-379 from biotite schist xenoliths in the granitic rocks average 100 ppm., whereas the biotite schist xenolith (As-396) contains an abnormally large value (600 ppm) which is probably due to a high opaque mineral content.

3.10.3i Summary and conclusions

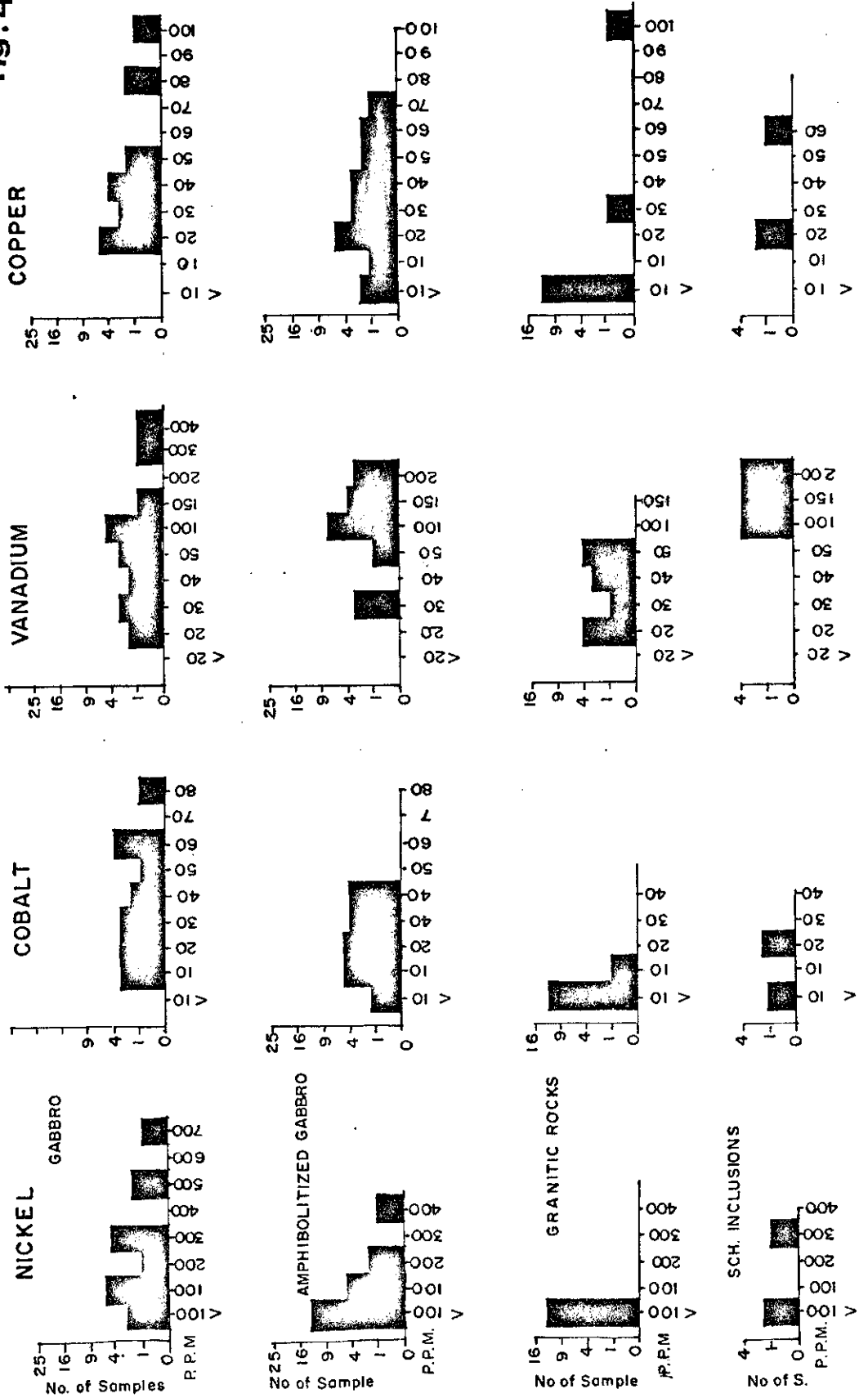
Some important conclusions can be drawn from the distribution of trace elements in the intrusion. Considering the tendency of Ni, Co, Cr, V, Zr to enter the lattice of olivine and/or pyroxene in variable amounts it was possible to differentiate between the unaltered gabbro and the amphibolitized gabbro.

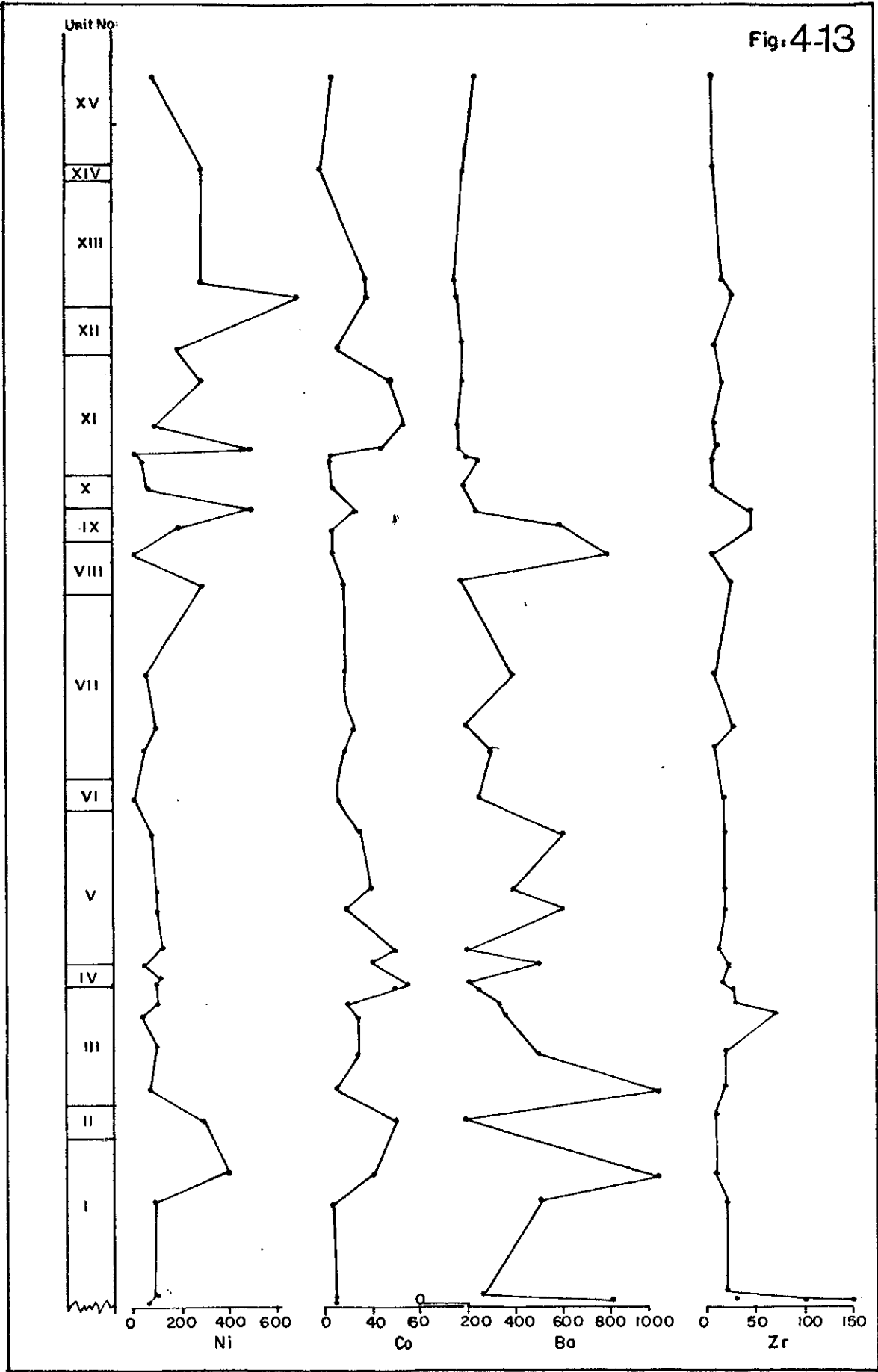
Ni and Co are depleted from the amphibolitized gabbro relative to the fresh olivine gabbro. (Table 4-9, 10 figs. 4-12, 13, 16) Cr, V, Zr,



Distribution of Ni, Co, V & Cu

fig:4-12





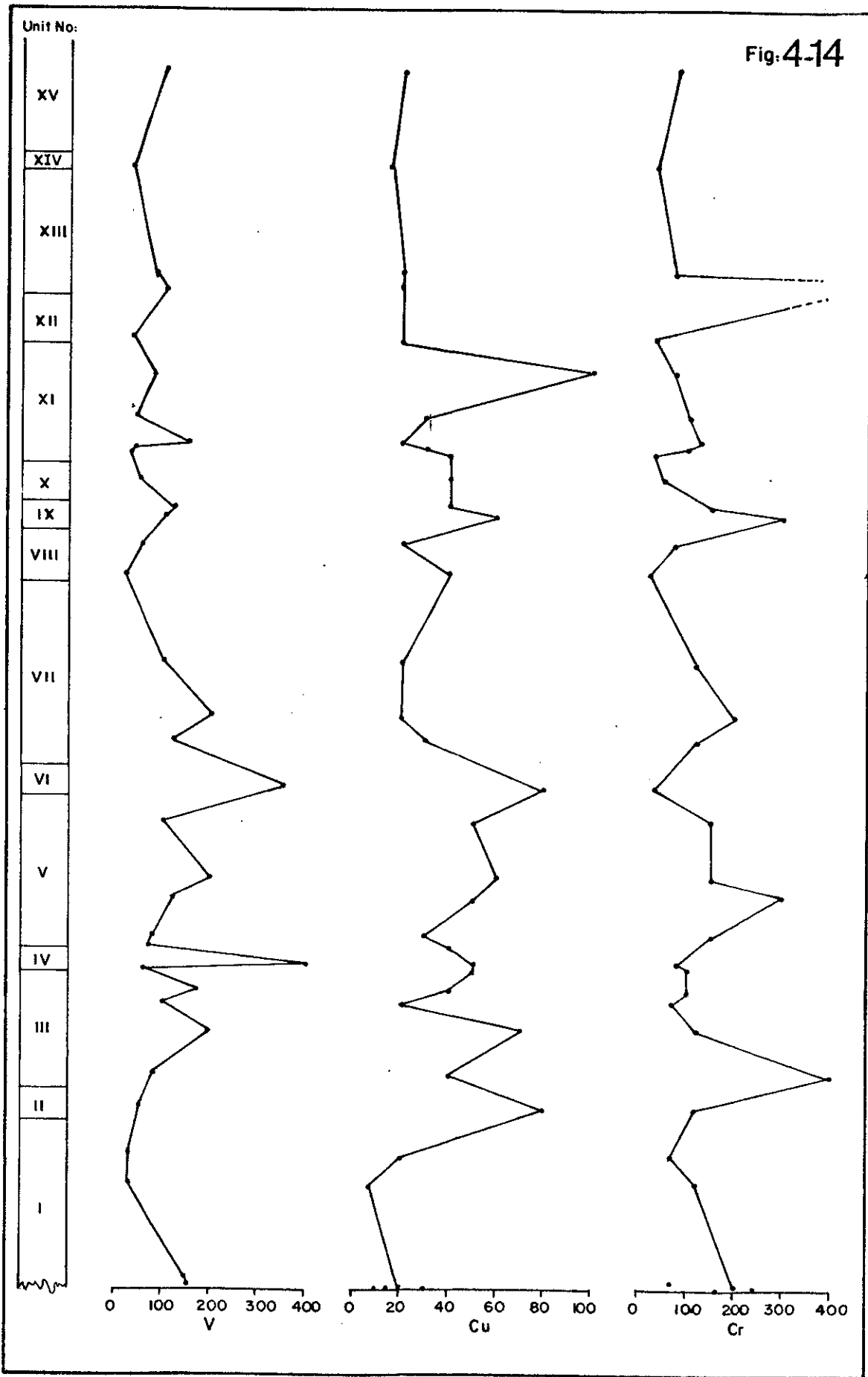


Fig. 4-15

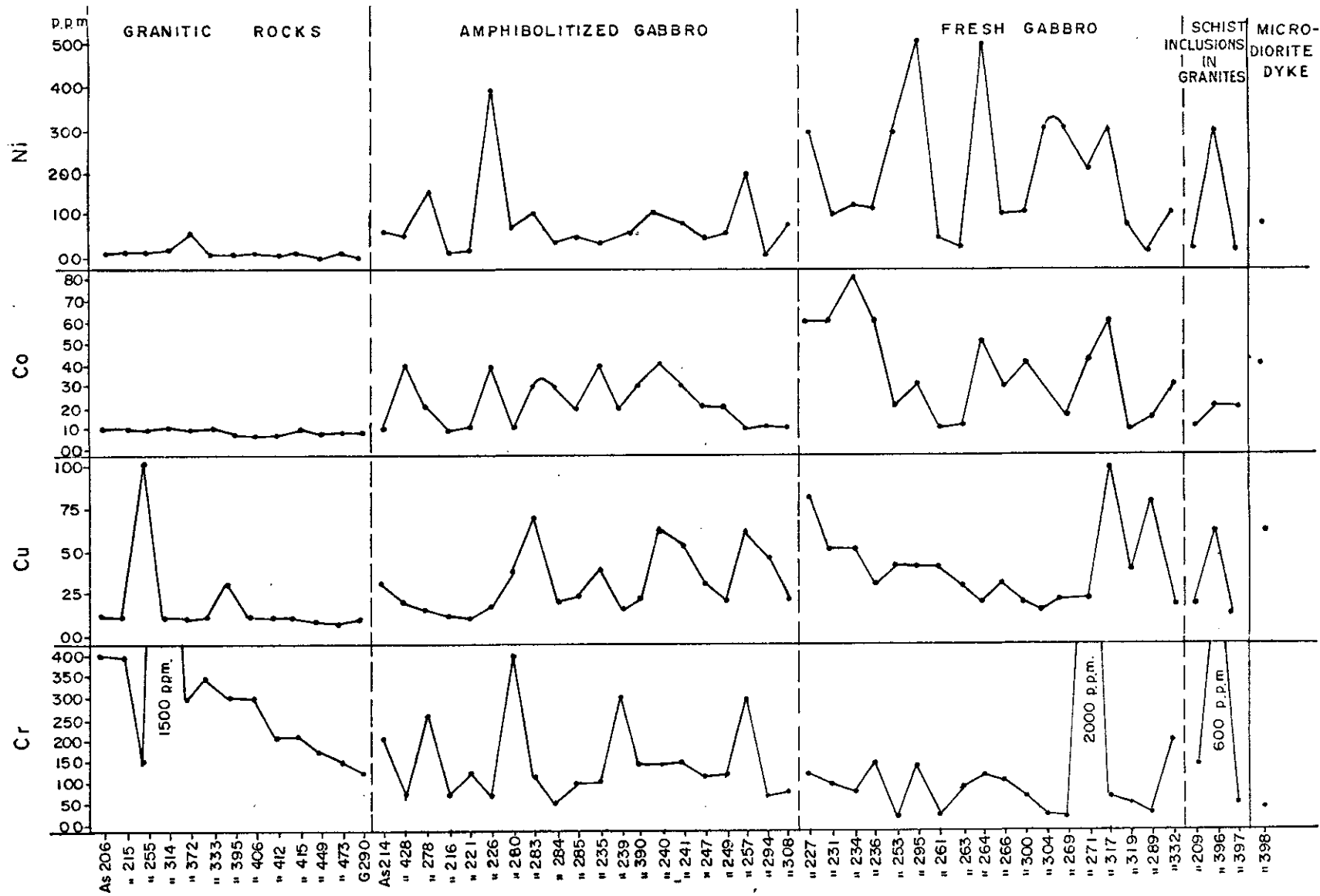
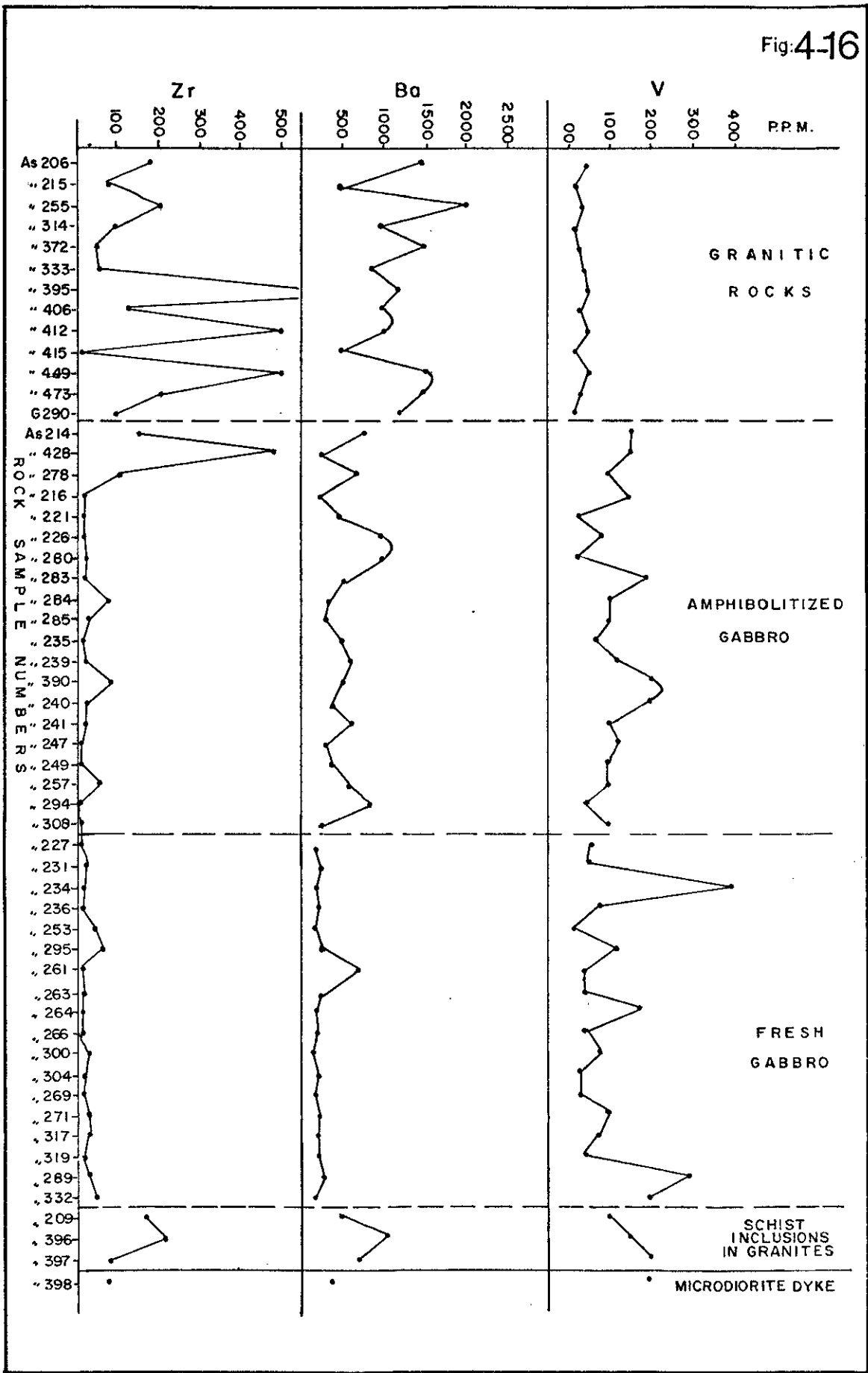


Fig. 4-16



are enriched in the amphibolitized gabbro relative to the olivine gabbro.

Ba which tends to substitute K^+ in the feldspar lattice is enriched in the amphibolitized gabbros relative to olivine gabbro. This is possibly due to partial sericitization and saussuritization of the plagioclase during metamorphism.

Amphibolitization has probably not mobilized the trace elements from the pre-existing pyroxene, as indicated by the enrichment of Cr, V, and Zr which tend to enter pyroxene lattice in the amphibolitized rocks. This conclusion is in accordance with the petrographic evidence that the amphibolitized gabbros are derived from plagioclase-pyroxene cumulates.

4.4 ARJA LAYERED BASIC INTRUSION

This intrusion, 1.5 x 6 km. is intruded into a succession of biotite and quartz-chlorite schist. An aureole (20-50 m.) plagioclase-orthopyroxene hornfels was formed along the contact; and in the incorporated xenoliths within the intrusion. Outcrops of this intrusion are rare and are in form of small dark exposures or exfoliated in situ boulders uncovered along local streams or protruding from the alluvial cover. The hornfels xenoliths are better exposed over the enveloping basic rocks.

Although scarcity of exposures did not allow further detailed work to be carried out; several rock cumulates were recognized. In one of these exposures, rhythmic and phase layering is exhibited between plagioclase and amphibolitized plagioclase-pyroxene cumulates.

The following are comparisons between Arja and Al Jealani intrusion:

1. Both intrusions are oval in shape and occur 30 km apart along a north-south line with their long axes approximately parallel.

2. Both intrusions consist of cumulates with characteristic textures. Plagioclase is the dominant cumulus phase, followed by pyroxene (both ortho- and clino-), and olivine. The pyroxenes suffered variable degrees of amphibolitization. In Arja, the effects of metamorphism were stronger and much of the pyroxene was altered to chlorite. The olivine, which is almost fresh in Al-Jéalani, suffered serpentinization in Arja mass.
3. In Al-Jéalani, pre-existing country rock inclusions are entirely absent, and the mass is enveloped by younger syn-kinematic adamellite; while in case of Arja the mass is enveloped by the pre-existing pelitic rocks which have been affected by thermal metamorphism.
4. The spectrographic analysis of the heavy mineral concentrate from both layered intrusions revealed no economic mineral deposits.
5. The An content of the plagioclase from Arja mass showed a fluctuation between An_{58} and An_{35} (chemical analysis); the amphibolitized rocks have generally a lower content. The same applies to Al-Jéalani mass (see page 154). This is attributed to amphibolitization where it is believed that part of CaO of feldspars was utilized by amphiboles.
6. The Sr content of the plagioclase in Arja mass ranges from 742-2050 (table 4-6). This shows scattering when plotted against the An content (fig. 4-10). In case of Al-Jéalani mass the Sr content increases with the decrease of An content and the plot exhibits grouping in a pentagon (fig. 4-10). This difference is possibly either due to the limited number of analyses performed in case of Arja, or to the degree of intensity of metamorphism it suffered.

4.5 GENERAL SUMMARY AND CONCLUSIONS

The following observations made in the course of this research have an important bearing on the origin and differentiation of the intrusions:

4.5.1 The primary features of the intrusion:

- 4.5.1a Shape: The elliptical outline and the inwardly decreasing dips of the layered series suggest an inverted funnel shape of the intrusion. However Lambolez (see page 107) has interpreted the aeromagnetic anomaly as indicating steeply dipping contacts. The fact that Al-Jealani and Arja intrusions (30 km north of Al Jealani) show an elliptical shape with their long axes striking N 40°W, suggests that both have originated through emplacement of basic magma along pre-existing north westerly fractures.
- 4.5.1b Contacts: The marginal facies may be partly the result of post intrusive tectonic effects and partly the result of initial emplacement into a sedimentary succession which was already heated by regional metamorphism and, therefore displays no chilled contacts.
- 4.5.1c Synopsis of petrography and textures. The intrusion consists of cumulates ranging from predominant orthocumulate (gabbro, amphibolitized gabbro, troctolite, norite) to plagioclase-adcumulate (anorthosite); all textures of the rocks from base to top are the characteristic textures of cumulates; plagioclase is the dominant cumulus phase in all layers; other cumulus minerals are olivine, clino- and ortho-pyroxene; post cumulus material includes plagioclase, opaque minerals, clino- and orthopyroxene.
- 4.5.1d Layering: Rhythmic macro and micro layering is well developed. The layered rocks are made up of 15 regular cyclic repetitious units; elongated minerals in the banded rocks and some uniform horizons have their long axes within the plane of layering; no significant cryptic layering from base to top of the intrusion is recorded; phase layering is present in all parts of the intrusion indicating that

cumulus minerals such as olivine, ortho- and clino-pyroxene show entry and exit at different horizons within the intrusion to define distinct and mostly continuous units.

4.5.1e Variations in mineral composition: The ferromagnesian minerals tend to show repeated and abrupt changes down the reaction series from more common olivine and clino-pyroxene to less abundant orthopyroxene, brown hornblende and biotite; the plagioclase shows oscillatory range of An content from base to top of the intrusion; its variation in composition within the intrusion is not so pronounced as it is from one unit to the next; the upper part of a layered unit tend to have more sodic plagioclase than the lower part but commonly a unit with more calcic-plagioclase overlies one with more sodic feldspar; the mineralogical variation in grain size and composition within single cycle units, e.g. in unit II (As-1010-1015) and Unit VI (As-1016-1019) is rather small but noticeable and considerably more work will be necessary for statistical demonstration.

4.5.2 The metamorphic features:

4.5.2a Grade of metamorphism: The intrusion was subjected to greenschist facies of metamorphism which mainly affected the plagioclase-clinopyroxene cumulates with primary igneous lamination.

4.5.2b Mineralogical changes: The pyroxene was replaced by amphibole with preservation of relic textures; plagioclase-olivine cumulates in general are unaffected apart from local serpentinization of olivine; plagioclase in the basal unit is extensively sericitized and epidotized, the metamorphism was most intense towards the contacts of the intrusion with the enveloping adamellite and younger intrusive granites; the pyroxenes are altered to chlorite and

tremolite and plagioclase breaks down to epidote and/or sericite, quartz and locally prehnite.

4.5.2c Features of amphibolitization: Amphibolitization affected the intrusion after the crystallization of the rocks; augite is partly or entirely replaced by secondary amphibole varying in composition from tremolite to actinolite.

4.5.3 Geochemical considerations

4.5.3a Original composition: The composition of the parental magma is not certain. The olivine gabbro is assumed to be closest in composition. In general, the tholeiitic affinities are indicated as those of Bushveld.

4.5.3b Sr-An ratio in plagioclase: Plagioclase shows an oscillatory range of An content from base to top of the intrusion and Sr increases with decreasing An content; amphibolitized units and fresh unaltered cumulates show almost identical Sr/An ratio in plagioclase; the southern intrusive contacts of the layered mass can be delineated on the basis of Sr/An ratio in plagioclase - most of the basic xenoliths in the granites are unconnected genetically with the Al-Jéalani intrusion.

4.5.3c Minor elements: The characteristic peaks of some minor elements (Ni, Cr, V, Zr) demonstrate their sensitivity to processes of crystallization differentiation.

4.5.3d Relationships of the Zn-Pb-Ag vein mineralization and the layered basic masses: The following facts suggest that the Zn-Pb-Ag mineralization in the district is probably related to a north-south belt in the granite extensively enriched in pelitic and semi-pelitic country rock xenoliths.

1. The Zn-Pb-Ag vein mineralization is structurally controlled along fractures predominantly concentrated in granitic rocks.

2. All the 150 ancient Zn-Pb-Ag prospects in the district are located out of the layered basic intrusions which were passive and did not respond to fracturing.
3. The majority of these mineralized sites are situated along a north-south belt within the granite enriched with xenoliths of pelitic and semi-pelitic rocks.
4. Spectrographic analysis of rocks and heavy concentrates from the layered masses did not show any anomalous amounts of zinc, lead or copper.

4.6 DISCUSSION

The interpretation of features like rhythmic layering, mineral and rock variation, and the relationship of the margin and structure of the intrusion is based on petrographic and geochemical data and on observed field relationships.

The composition and structure of the layered mass is believed to represent surges of magma along the oval structure synchronous with the waning stage of regional metamorphism and deformation. The layered rocks originated through undercooling combined with convection currents in the magma. Density stratification in rhythmically layered rocks has been attributed to gravitative process. The well layered sequences which are separated by essentially non-rhythmically layered plagioclase-olivine cumulates suggest that the process of rhythmic layering operated intermittently. Intrusions of this type are normally found to form basic masses with steep walls which were emplaced near the end stage of the regional metamorphic cycle. The succession of cumulus phases that make up cyclic units is the same as that expected during cooling and crystallization of basaltic magma (fig. 4-10).

Layering in large gabbroic masses has been studied intensively by Wager and Deer (1939) and Hess (1961), who clearly distinguished between cryptic layering and rhythmic layering. The absence of cryptic layering in the Al-Jéalani intrusion is not unique. Wells (1962) has clearly pointed out that despite the great thickness of the Freetown

layered rocks and the evidence of formation by bottom accumulation of crystals, there is a remarkable absence of any cryptic layering. This feature has normally been encountered in layered ultramafic rocks but it appears to be rare in mafic rocks.

The diversity of compositions in the sequence of cyclic units may represent successive inflows of magmas Jackson (1970). However, the gradational contacts between the cyclic units may also indicate the intermittent changes in water and perhaps oxygen fugacity operating in a simple body of magma (Wager and Brown 1968).

Features of amphibolitization have formed after the complete solidification of the rocks and are interpreted as being formed at the end stages of regional metamorphism and subsequent to emplacement and solidification of the gabbro mass. The patchy amphibolitization of the pyroxenes is principally related to introduction of water (Yoder^{et al}, 1962) under relatively high PT conditions.

As already indicated the amphibolitized units have lower An content than the unaltered cumulates. It is probable that amphibolitization is also linked with decrease of An content in plagioclase. Amphiboles commonly penetrate deeply into plagioclase, so that the plagioclase would become more albitic than its original composition. If the oscillations of An content are primary then the problem needs further study. Abbott (1962) and Brown (1956) indicated that minor pulses of fresh magma would account for oscillations of An content. This feature may equally be due to minor variations in water vapour pressure causing undercooling at some horizons.

The monomineralic plagioclase cumulates may indicate slow crystallization at certain stages which prolonged diffusion and led to the origin of plagioclase adcumulates.

The lack of any concentration of ore minerals is disappointing, and it is clear that down to the outermost exposed layer the intrusion is barren. However, if the walls of the intrusion are steep-sided, then the possibility is not excluded that further layering exists below the visible limit with the associated possibility of accumulations of ore minerals.

CHAPTER 5

GRANITES

5.1 INTRODUCTION

Rocks of granitic composition form part of a large northwesterly trending batholith. They make up over 70% of the exposed basement rocks in the area mapped (2425 sq. Km.). The batholith is situated near the eastern margin of the Arabian shield and is unconformably overlain in its east-central part by a little-deformed Palaeozoic sedimentary succession. The granitic rocks are shown as one unit of synkinematic granite gneiss on the 1:500,000 scale geological map 206A (Bramkamp et al., 1963) (Fig. 1-3). Eijkelboom (1966 a and b), recognized six varieties of granitic rocks in the district: Syntectonic granodiorite, syntectonic granite, syn- to late- tectonic granite, syn- and late- tectonic granite, post tectonic granite and granite of uncertain age.

Greenwood and Brown (1972), divided the Arabian shield in relation to the magmatic differentiates of plutonic rocks, into three compartments, following Peacock's (1931) classification of igneous rocks. According to this division, the Ad-Dawadmi batholith, which is situated within the northeastern compartment is a calc-alkalic magmatic differentiate.

Detailed field and laboratory studies were carried out on the granitic rocks of Ad-Dawadmi, in order to determine the mode of emplacement, as well as to investigate the origin of the magma.

For the most part, the area underlain by granitic rocks is a pediment from which protrude bare steep-sided elliptical hills. Exfoliation or cavity weathering are characteristic of these hills. Long east-west trending dark grey to tan ridges follow the outcrops of dacite and rhyolite dykes. Shear zones are present in the granitic area and usually make prominent linear features, which are difficult to distinguish from dykes. Rainwater is held within the upper weathered zone of the granitic rocks, and a limited supply of water is available from wells hand dug or drilled in the main valleys crossing the granite.

5.2 THE META-SEDIMENTARY ENVELOPE

The granitic batholith has been emplaced within previously metamorphosed sedimentary country rocks which flank the batholith to the east and west. Within the mapped district (Plate 1) these metamorphic rocks are exposed in the south-east and in the north, where they make up about 20% of the exposed rocks. These metamorphic successions were assigned to Ar-Ridaniyah and Abt Formations.

Exposures of the latter Formation are predominant. They make the principal country rock inclusions in the granite and in the north. Rocks of Ar-Ridaniyah Formation form the major rock types in the south-east. They underlie rocks of Abt Formation.

The base of Ar-Ridaniyah Formation comprises a quartzo-feldspathic schist unit that grades westwards into quartzo-feldspathic gneiss. This quartzo-feldspathic unit is overlain by a thick calcareous unit made up of marble, dolomite, amphibole schist with rare thin intercalations of chlorite-biotite and chlorite-sericite schist.

The Abt Formation is essentially a pelitic Formation composed of quartz - chlorite - sericite and quartz - biotite - chlorite schist with local quartzite, and quartzo-feldspathic schists.

Rocks of both Formations have been intruded by pre-, syn- and post-kinematic minor intrusions of acidic, basic and intermediate compositions and have suffered regional metamorphism of greenschist grade. Progressive metamorphism is exhibited in the north where quartz-chlorite-sericite schist grades southwards into gneissose biotite schist. Garnetiferous biotite hornfels with cordierite occurs at the contact with granitic rocks.

In the north, the strike of the schistosity in the abundant xenoliths swings from 070° in the east to 110° in the west. In the extreme north the schistosity in the quartz-chlorite-sericite schist is 135° . In the south-east the schistosity of the metamorphic successions is about 010° and the dip is $50-70^{\circ}$ E. The xenoliths of country rock within the batholith also strike approximately N-S.

5.3 THE GRANITIC BATHOLITH

The granitic batholith is about 200 Km, in length and 70 Km. in width and has been emplaced subparallel to the general strike of the bedding of the metamorphic host rocks. Elongation of xenoliths, foliation, and primary flow direction of magma conform with its contacts with the country rocks. Lead-zinc-silver vein mineralization occurs along a northerly trending zone situated in the central sector of this batholith. This mineralization is structurally controlled along north-easterly shear zones and at their intersections with easterly trending tension fractures.

Within this batholith, there are also well developed fracture sets related to the final orogenic event.

5.3.1 The major units of the batholith

The batholith consists of two clearly separated components: an earlier foliated, coarse-grained, porphyritic variety in the west and a later even-grained variety in the east. The latter contains inclusions of the former variety. Together, these two types constitute over 95 percent of the granitic rocks exposed in the area. Other younger granitic rocks occur as small intrusions within both major types.

5.3.2 Petrography and internal variation

The major components of the batholith exhibit diversified composition, texture and structure. They range from quartz-monzonodiorite to alkali-granite in composition (Fig. 5-1), and in texture, from being coarse-grained, foliated and porphyritic to being homogeneous, even-grained and non-foliated. Both composition and texture were affected by the pre-existing country rocks, as can be seen in the marginal zones close to contacts with the inclusions.

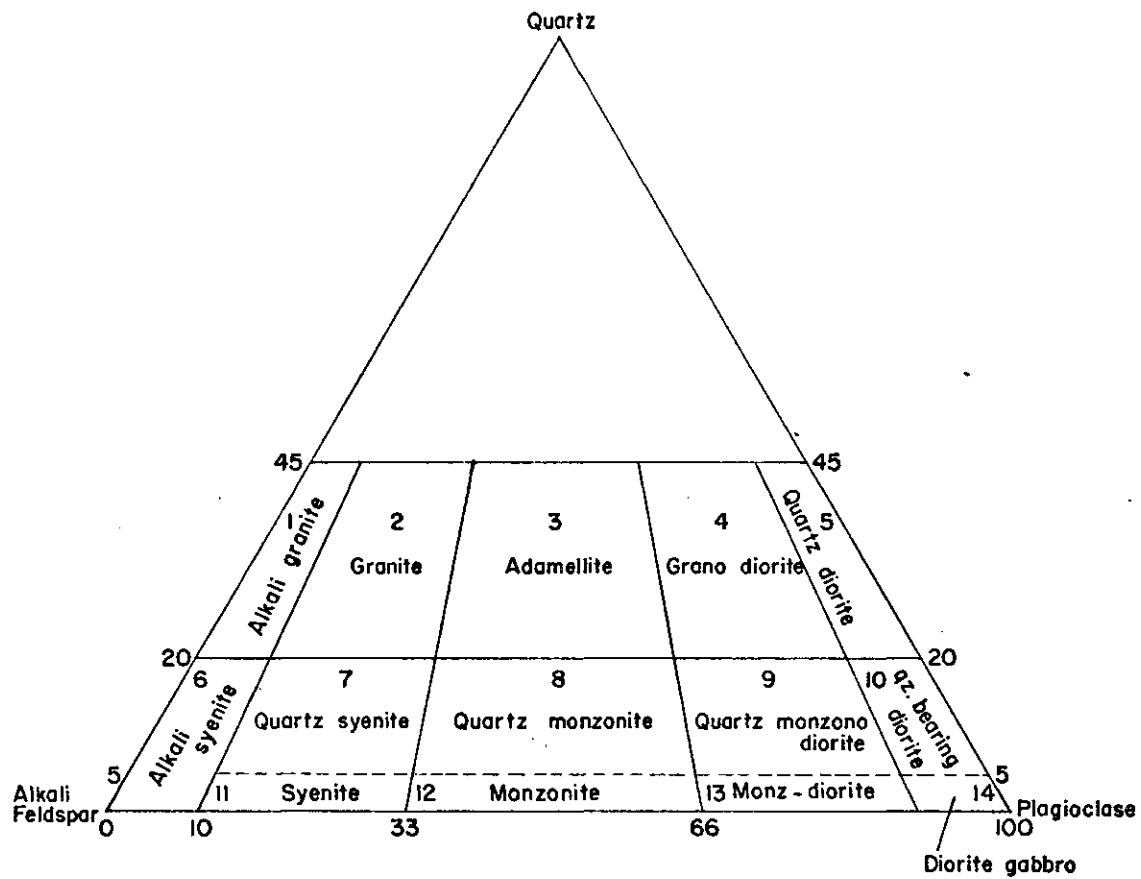


Fig. 5 -I Classification of igneous rocks

5.3.3 The relict masses of amphibolitized gabbro and metadiorite

Abundant scattered melanocratic inclusions are present in both early and late granitic rocks. In the latter, they have been more affected by metamorphism than those in the early granitic rocks, and consist of metamorphosed gabbro, tonalite, diorite and quartz-diorite. Important remnants of these rocks occur in a strip between Ad-Dawadmi and Sidriyah hills. Smaller xenoliths and more widely scattered are aligned in northeasterly direction between Wadi Magrass and Wadi Wasset approximately 10 Km. south of Ad-Dawadmi. These relict masses show great variation in composition, coarseness and sizes. They vary from few cms. to 2 Kms. in length, they are generally elongated parallel to the strike of their planar structure. The large xenoliths appear to have been little affected by the flowage of magma while the small remnants are sometimes disorientated presumably due to flow of the enclosing granitic magma. The contacts with the granitic rocks are often sharp and as a rule steeply dipping. In general the inclusions have been contaminated by granitic material and easily responded to amphibolitization.

Occasionally, large phenocrysts of microcline have grown in these xenoliths close to their contacts (Fig. 5-2c) which are transitional with the granite. A planar structure is visible in some of the larger basic inclusions, which may be relict igneous lamination, possibly with later foliation induced parallel to it. Many of the basic inclusions are themselves enclosed in large xenoliths of early granitic rock within the later one. The jointing in the latter is continuous through the basic inclusions.

In thin section, the original sub-ophitic texture typical of gabbro is preserved. The three principal constituents plagioclase, amphibole and biotite show characteristic changes, with increasing metamorphism. The plagioclase is often altered to zoisite and/or sericite and albite. The amphibole commonly pseudomorphs pyroxene. In the transitional contact, amphibole is altered to biotite and chlorite.

5.3.4 Relict masses of the pelitic and semi-pelitic rocks

Large relict masses of pelitic composition are not as common as remnants of basic composition. The early granitic rocks contain fairly abundant relics of biotite schist in the area south of Wadi Arjah. Abundant garnet and less common cordierite in these indicate that they have been affected by thermal metamorphism.

The contacts with the enveloping granitic rocks are gradational with a development of alternating white and dark bands (Fig. 5-2e). Sharp contacts are also developed. The schistosity within the xenoliths is essentially north-north-westerly in the major part of the mapped area, except in the north, where it swings from 070° to 110° . Locally these xenoliths have been rotated in later deformational shear zones. The primary flow direction of the granitic magma was parallel to schistosity. Xenoliths have numerous aplite and pegmatite veins parallel to schistosity.

It has been demonstrated that the large relict masses that are enclosed entirely within the granite batholith show considerable difference in composition but they are conformable with the structures of the country rocks. It is therefore that the xenolithic masses are not far removed from their original position and display analogy to ghost structures of the Older migmatitic granodiorite at Donegal (Pitcher 1953).

5.4 CLASSIFICATION

It is difficult to construct a satisfactory classification for the wide range of granitic rocks in the area because individual rock types form part of a gradational series.

Comprehensive petrographic systems of classification (Johannsen, 1931, Streckeisen 1967) are useful and quantitative but they are too mechanical and inflexible for employing in petrogenetic discussions.

The following systems of rock classifications are adopted in this thesis:- 1) A quantitative mineralogical and/or chemical system that is used in describing the petrography, and 2) a flexible genetic system

that groups together those igneous rocks that appear to have evolved under broadly similar conditions. The latter system is used in petrogenetic discussion.

The field data, the mode of emplacement of various granitic rocks and the age relationships with each other and with the country rocks and the variation in their megascopic characteristics support and justify this two fold classification.

The triangular diagram (Fig. 5-1) shows the mineralogical classification adopted. From this diagram and from (Plate 1), it is noticed that adamellite is the most abundant rock type, granodiorite, granite and quartz-monzono-diorite are also present.

Genetically, the rock types are classified into synkinematic, late kinematic and post-kinematic. Geographic locality names are used along with this genetic classification.

5.4.1 The synkinematic granitic rocks

Rocks included within this grouping are typically coarse-grained, foliated and porphyritic (Fig. 5-2c). They are adamellite, granodioritic and quartz-monzono-dioritic in composition. They occupy the western part of the area. Inclusions of biotite schist and biotite-plagioclase-cordierite hornfels are abundant and grade in size from small clots about 1 cm. in diameter (Fig. 5-2 a and b) to large elongated xenoliths about 7 Km. in length and 100-150 m. in width (Plate 1). Inclusions of metadiorite and amphibolitized gabbro are also common. Remnants from pre-existing country rocks are also represented by trails of orientated biotite bands conforming with flow banding (Fig. 5-2h).

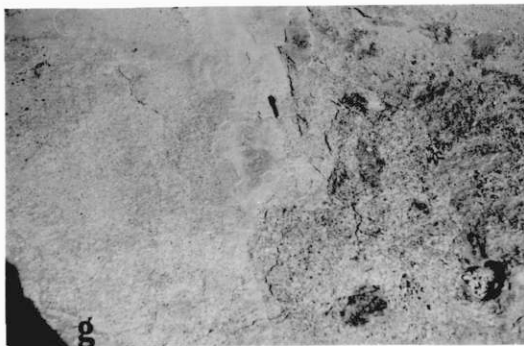
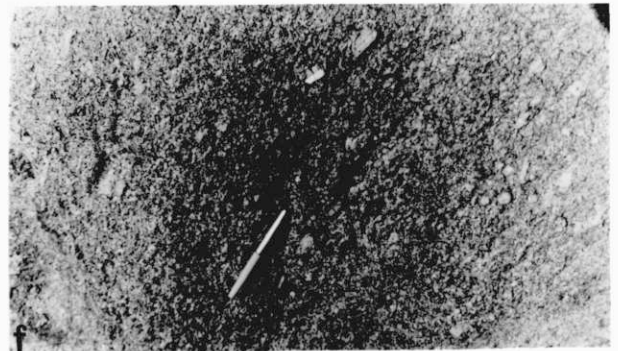
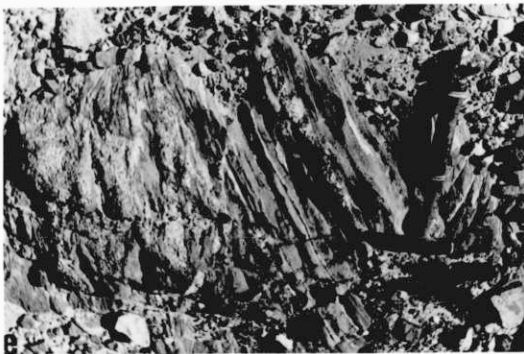
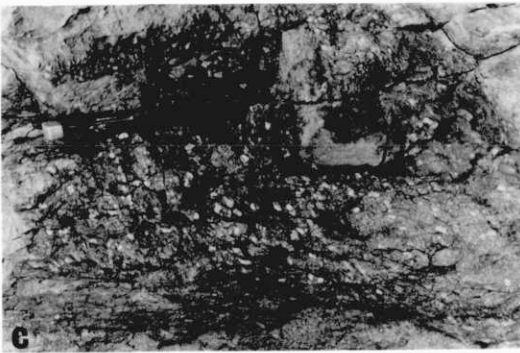
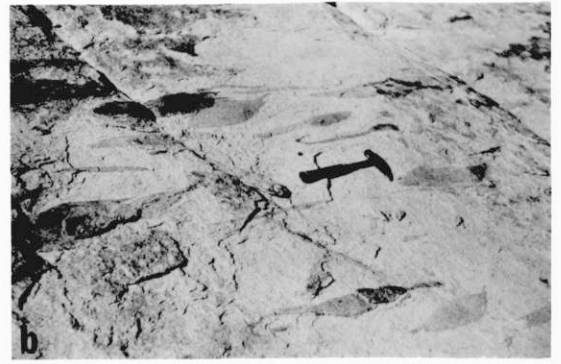
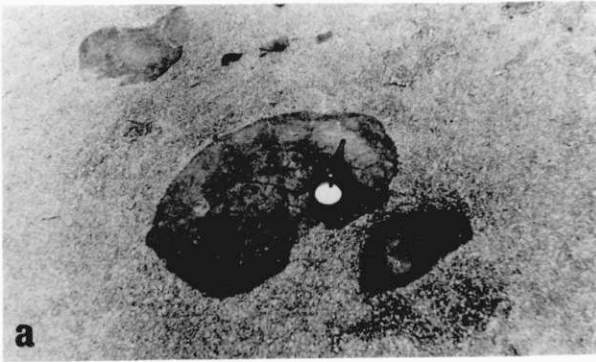
4.1.1 The Sidriyah quartz-monzono-diorite: This rock type comprises only a small fraction of the synkinematic rocks. It is mainly found in the mid-western area where large inclusions of pelitic-semipelitic country rocks are particularly common. It is also present as lenses within the adamellite and granodiorite. The rock is characterized generally, by its overall darker colour relative to the granodiorite and adamellite, by the small white plagioclase phenocrysts and by the scarcity

Granites

Figure 5-2

Field characteristics

- a & b Ar-Ridaiyah. porphyritic adamellite with inclusions of plagioclase-biotite hornfels. Long axes in xenoliths are orientated parallel to flowbanding in adamellite.
a - locality Ar-32, b - locality G-290 (Plate 5).
- c - Microcline megacrysts grown in quartz-diorite xenolith in Ar-Ridaiyah adamellite. Locality, As-750 (Plate 5)
- d - Sharp contact between the earlier synkinematic Ar-Ridaiyah adamellite (grey) and the late-kinematic adamellite (light grey). Locality G-290 (Plate 5).
- e - Granitized biotite schist (migmatite), gradational contact of a xenolith. Locality G-110 (Plate 5).
- f - Flow banding as displayed by orientation of the long axes of alkali-feldspar phenocrysts and mafic minerals.
Ar-Ridaiyah adamellite. Locality G-307 (Plate 5).
- g - Sharp chilled contact of post-kinematic pink granite (left) against earlier synkinematic adamellite. Locality G-221. (Plate 5).
- h - Trails of parallel orientated bands of biotite conforming with the flow banding of Ar-Ridaiyah adamellite.
Locality G-279 (Plate 5).



of alkali feldspar phenocrysts. 30-40% of the quartz-monzonodiorite is made up of tabular to sub-rounded phenocrysts of oligoclase (An_{29-23}), 3-10 mm. in diameter. Megacrysts of light pink to white alkali-feldspar, 1-6 cm. in length are locally present.

The phenocrysts are set in a dark matrix of biotite, plagioclase, quartz and minor alkali-feldspar grains. Accessory constituents include sphene, apatite and magnetite.

Table 5-1 Modal analyses of the Sidriyah quartz-monzonodiorite

Sample no.	K-feldspar	Plagioclase	Quartz	Mafic minerals
As-701	9.9	54.7	10.8	24.6
As-703	8.9	52.4	13.3	25.4
As-704	9.2	55.0	8.7	27.1
As-705	7.7	57.1	13.5	21.7
As-708	15.0	49.0	14.7	21.3
Range :	7.7 - 15.0	49.0 - 57.1	8.7 - 14.7	21.3 - 27.1
Average :	10.1	53.6	12.0	24.0

4.1.2 The Sidriyah granodiorite:- This rock type surrounds the main outcrop of quartz-monzonodiorite, and occurs also as lenses within both the Sidriyah quartz-monzonodiorite and the Ar-Ridaihah adamellite.

In hand specimen the granodiorite is coarse-grained and grey in colour. The white oligoclase phenocrysts are common and are smaller than those of pink alkali-feldspars which also range in length between 1-6 cm.

In thin section the phenocrysts of oligoclase and alkali feldspars are randomly distributed in a quartz-diorite groundmass of plagioclase, biotite, quartz and alkali feldspar with accessory amounts of magnetite, apatite, chlorite and sphene.

Table 5-2 Modal analyses of the Sidriyah granodiorite

Sample No.	K-feldspar	Plagioclase	Quartz	Mafic minerals
As-702	14.4	43.1	17.2	25.3
As-706	10.3	51.7	17.4	20.6
As-710	17.0	49.3	21.4	12.3
As-716	18.2	47.7	18.0	16.1
As-717	13.3	47.5	25.9	13.3
As-451	20.3	51.2	22.6	5.9
As-490	18.0	48.0	18.0	16.0
Range :	10.3 - 20.8	43.1 - 55.1	17.2 - 27.2	12.3 - 25.3
Average :	16.0	48.9	22.7	15.6

4.1.3 The Ar-Ridaihah adamellite

4.1.3a Field characteristics: The Ar-Ridaihah adamellite is characterized by large phenocrysts of pink alkali feldspars. In the field the rock is seen to be poorly foliated, but in hand specimen, this foliation is generally difficult to distinguish. The rock has a coarse-grained groundmass of microcline and/or perthite, plagioclase, quartz, biotite and rarely secondary chlorite in which are set well shaped tabular and prismatic phenocrysts of pink potash feldspar. These phenocrysts show a good preferred orientation parallel to the foliation (fig. 5-2f). They measure 2-6 cm. in length and 1-2 cm. in width. Often they enclose portions of groundmass. Commonly the composition of the rock is transformed to that of granite, when a noticeable increase in the ratio of potash feldspar relative to plagioclase is attained.

A strongly gneissic porphyritic adamellite crops out around the Al-Jealani layered complex (fig. 5-3a, b and c). The gneissic structure gradually becomes weaker away from the margin of this complex, and is restricted to a zone that ranges in width from 50-100 m. It is probably the result of marginal shear during the emplacement of the granitic

material along the contact with the older rigid basic intrusion. Fragments of the outer layers of this basic intrusion are enclosed in this zone as xenoliths.

4.1.3b Petrography: In thin section the gneissic adamellite is seen to be composed of a granular mosaic of microcline, perthite, quartz, oligoclase and biotite. The microcline forms large phenocrysts segregated locally into bands with a finer grained darkish groundmass of feldspar, quartz and biotite. The phenocrysts commonly form augen which are elongated parallel to the foliation (fig. 5-3a). The gneissic adamellite shows cataclastic effects as quartz is crushed into a fine grained mosaic in which the mineral shows undulose extinction. The grains of quartz are rounded to subrounded in shape. Biotite grains are segregated into roughly parallel bands (fig. 5-3a); some flakes are bent.

Table 5-3 Modal analyses of Ar-Ridaiyah adamellite

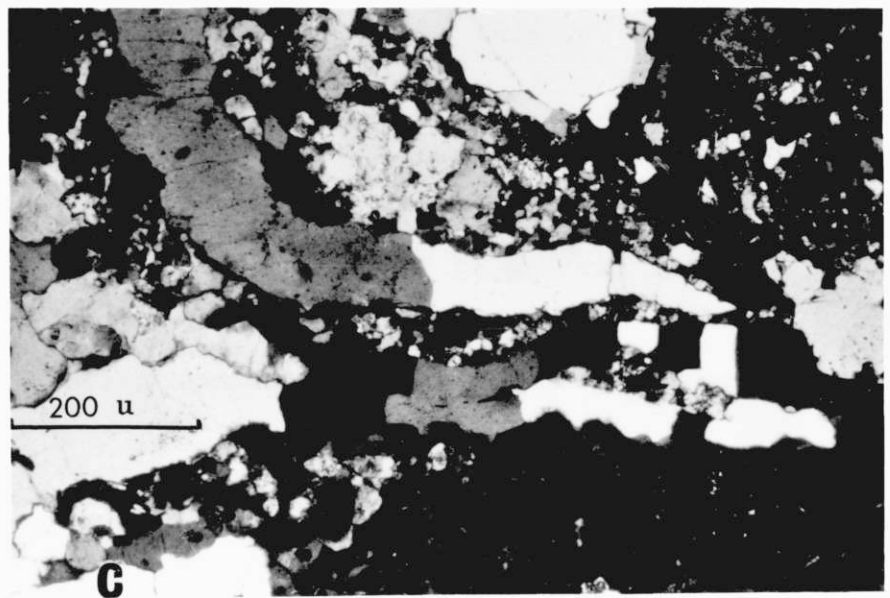
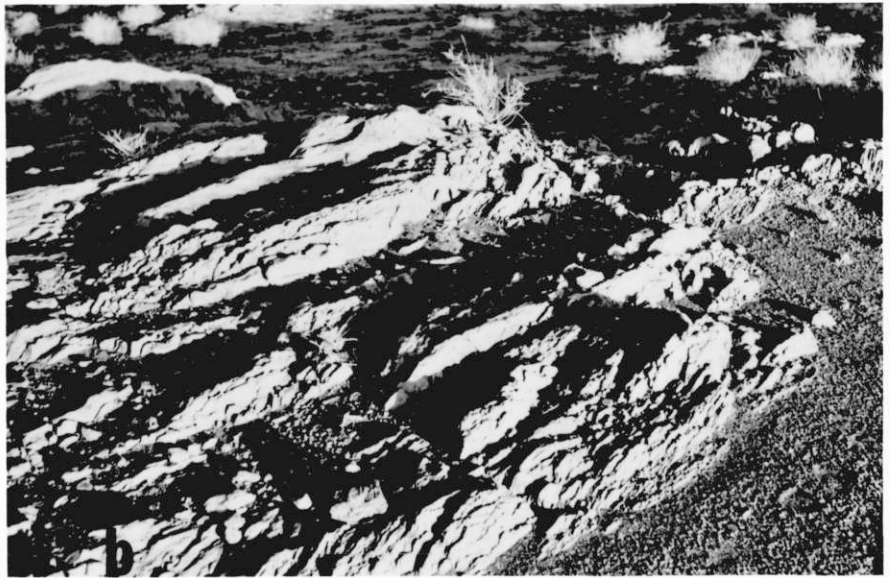
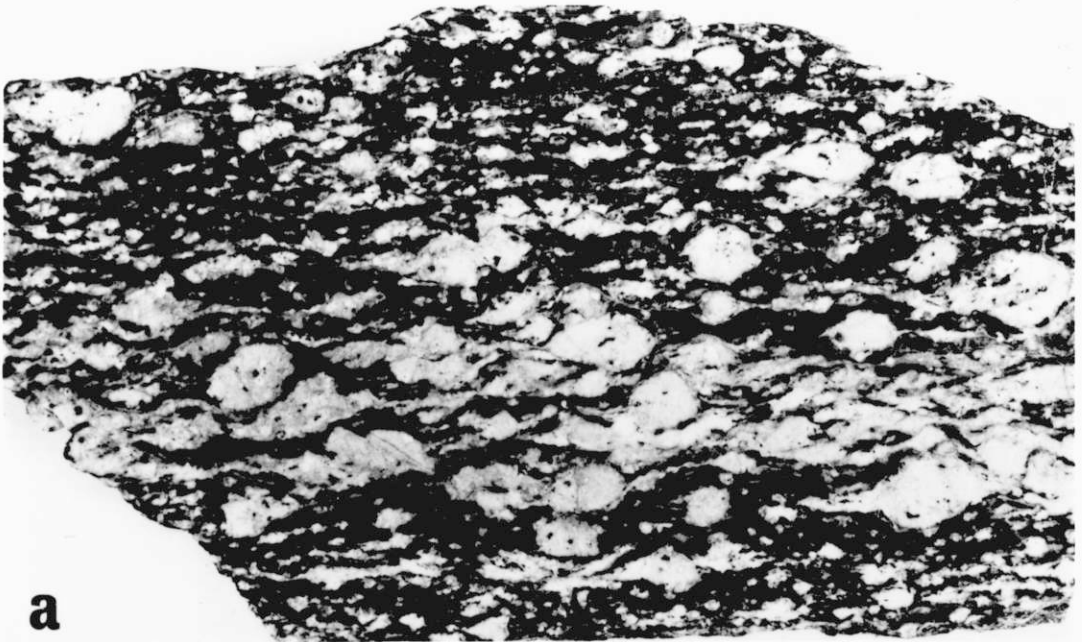
Sample no.	K.-feldspar	Plagioclase	Quartz	Mafic minerals
As-372(b)	37.6	35.0	24.6	2.8
As-438	35.2	31.9	25.7	7.2
As-470	29.2	35.8	23.0	12.0
As-473	33.2	24.2	29.1	13.5
As-481	37.6	28.8	28.0	5.6
As-482	36.9	30.2	24.0	8.9
As-432	40.1	41.1	14.0	5.8
As-714	33.3	33.1	24.0	9.0
As-709	41.5	34.5	19.6	4.4
Range :	29.2 - 41.5	24.2 - 41.1	14.0 - 29.1	2.8 - 13.5
Average :	36.2	33.1	23.5	7.3

Quartz: Quartz occurs in two forms; as rounded and subrounded relatively small individual grains enclosed within later microcline and plagioclase, and as coarse granular clusters. Strain effects are common in the

Granites

Figure 5-3

- a - Polished surface of porphyritic gneissose adamellite, marginal to Al Jéalani layered mass. Foliation is well developed and alkali-feldspar phenocrysts deformed parallel to planar fabric. x 1, As-487 (west contact).
- b - Schistose Ar-Ridaiyah adamellite, east contact with the Al Jéalani layered mass. Looking southerly.
- c - Thin section of deformed Ar-Ridaiyah porphyritic adamellite, quartz is in elongated and lenticular aggregates. North contact of Al Jéalani mass. Transmitted CN. As-482.



granular quartz, but cataclasis is rare, except in the gneissic adamellite surrounding the Al-Jéalani layered complex. The quartz grains enclosed as inclusions in plates of alkali feldspars or oligoclase, have a characteristically rounded outline. In many instances the quartz shows signs of strain and crushing while the rest of the minerals are unaffected.

Plagioclase: The plagioclase feldspar also occurs in two generations: as earlier phenocrysts of oligoclase ($An_{23}-An_{29}$), and as later smaller grains in the groundmass. Crystals are usually poorly shaped. Microcline is seen to replace oligoclase (fig. 5-4d) and often at the contacts a zone of myrmekite is developed (fig. 5-4b and e). Sericite inclusions are abundant but are cleaned up on replacement by microcline.

Albite developed at later stages of crystallization forms narrow rims around the oligoclase (fig. 5-4a, b and c). It is usually clear and free from sericite inclusions.

Alkali feldspar: Microcline and microcline perthite occur in two forms; as large phenocrysts which show replacement relationships towards earlier formed minerals, especially the oligoclase (fig. 5-4b, d and e), and as small grains in the groundmass.

The phenocrysts usually have irregular margins extending into the groundmass and the earlier formed plagioclase (fig. 5-4b, c and d). Myrmekitic intergrowth is well developed (fig. 5-4e). Cross hatching, simple Carlsbad twinning and perthitic intergrowths are common. Inclusions of biotite, rounded droplets of quartz, albite and oligoclase are also common. The phenocrysts, in outcrops close to the contact zone with other granitic rocks are reddened perhaps due to the impregnation of hematite dust by later hydrothermal solutions.

Biotite: Biotite is the most abundant mafic mineral of the granitic rocks of the district. It is usually dark brown in colour with greenish tint locally. In some cases, where inclusions of older rocks are in close proximity, the biotite flakes show a ghost directional orientation. Biotite alters to chlorite. Marmo (1971) suggested that biotite is a typical mineral of the synkinematic rocks and that its presence is easily

understood if the general formation of synkinematic granite due to the granitization of mainly pelitic and arkosic sediments is accepted. In Ad-Dawadmi, biotite is the principal mafic mineral in all generations of the granitic rocks.

Hornblende occurs locally and in subordinate accessory amounts in the synkinematic adamellite intrusions within the layered basic mass or in proximity of older amphibolitized gabbro and metadiorite inclusions.

Sphene is invariably associated with biotite, when present it is in accessory quantities, brown to yellowish-brown in colour, occurs in granules, as well as wedge-shaped crystals.

Allanite, epidote and apatite occur as accessory minerals.

4.1.3c History of crystallisation. It is suggested that the first silicate minerals to separate from the melt were plagioclase and biotite; oligoclase locally reacted with the melt to give a reaction rim of albite. Crystallization of alkali feldspars followed. Quartz was the final mineral to crystallize as it occupies interstitial spaces. A post-crystallization alkali metasomatism formed the second generation of alkali feldspars in the form of large anhedral crystals of microcline, which replaced the original constituents of the rock, especially the oligoclase. It also enclosed relics of the groundmass represented by oligoclase, quartz and little biotite. Due to late stage albitization the microcline was replaced by microcline perthite.

Chlorite, sphene, allanite and epidote are most likely secondary deuteric minerals. Sericitization of feldspars is probably a near surface hydrothermal action.

4.1.4 Summary:

The synkinematic granitic rocks are characterized by:

- 1) Coarse grained, foliated, porphyritic, inhomogeneous differentiates of quartz-monzonodiorite, granodiorite, adamellite and granite.

- 2) Scattered masses of variable altered inclusions of biotite schist or biotite-plagioclase hornfels that range in size from clots to long belts are included.
- 3) The contacts with the country rocks are migmatitic but there are many cases of sharp contacts.
- 4) The contacts with the younger granitic rocks are sharp.
- 5) In the marginal zones of xenoliths, it is highly contaminated with mafic minerals and tends to become dioritic.
- 6) The alkali feldspar phenocrysts away from the Al-Jéalani layered basic intrusion indicate a 155° - 170° flow direction of the granitic magma. This is parallel or sub-parallel to structural trends of the country rock xenoliths or their elongation. The foliation was induced along the same trend.
- 7) The marginal zone to Al-Jéalani layered mass exhibits a flow direction of the granitic magma parallel to its contact, with persistently inward dip. This marginal zone displays an extensive shearing of the granite at the contact, which gradually decreases at some distance from it. The zone affected by this deformation is 50-100 m. wide. The schistosity is consistently parallel to the margin of the layered basic mass with a steep inward dip (60° - 70°).

5.4.2 The late-kinematic granitic rocks (Al-Masloukhah adamellite)

4.2.1 Field characteristics. The late-kinematic rocks included in this study cover about 50% of the part of the granitic batholith mapped by the author. They are characterized by fine to medium grained texture, grey colour and absence of any planar structure. They are of fairly uniform composition, essentially consisting of albitic oligoclase, quartz, microcline, perthite and biotite (fig. 5-4h). Feldspar is white to pale grey in colour; phenocrysts of this mineral are absent. Biotite is locally segregated into clots.

In the central part of the mapped area, inclusions of amphibolitized gabbro, metadiorite, quartz-diorite and tonalite within the adamellite are abundant (plate 1). The adamellite close to these inclusions is characterized by the presence of basic patches rich in amphibole. Transitional rocks at the margins of these xenoliths show gradations between the adamellite and the xenolith material (As-1009). The Al-Masloukhah adamellite also contains numerous inclusions of the older porphyritic synkinematic foliated granitic rocks, into which it has been intruded (plate 4). A 'ghost' gneissose structure visible locally in the adamellite is derived from inclusions of foliated synkinematic granitic rocks.

4.2.2 Petrography: In thin section, oligoclase with rims of albite and alkali feldspars are almost equally abundant (Table 5-4); the oligoclase locally forms larger crystals than the alkali feldspar and is almost always sericitized.

Quartz occurs in large grains many of which show undulose extinction. It also occurs as small rounded and subrounded grains enclosed within the oligoclase or alkali feldspars.

Table 5-4 Modal analyses of Al-Masloukhah adamellite

Sample no.	K-feldspar	Plagioclase	Quartz	Mafic minerals
G-13	40.0	29.0	25.6	5.4
G-290	29.1	41.7	20.2	8.0
As-471	37.7	31.3	26.8	4.2
As-372(a)	39.1	31.8	25.8	3.3
As-466	34.7	33.2	27.0	5.1
As-476	27.8	37.0	33.2	3.0
As-477	36.8	32.0	29.0	2.2
As-479	41.0	30.7	28.0	5.6
As-711	34.8	40.3	23.4	1.5
As-731	31.4	36.3	28.7	3.6
As-732	38.4	38.1	22.6	0.9
As-718	40.7	34.7	19.4	5.2
As-719	39.4	31.3	20.7	8.6
As-727	40.4	27.8	30.0	1.8
As-729	30.2	35.0	27.1	7.7
As-726(a)	30.4	32.4	30.3	6.9
As-726(b)	37.9	36.6	20.8	4.7
As-820	36.0	38.2	19.3	6.5
As-821	37.8	33.9	22.9	5.4
As-822	31.8	38.7	28.2	1.3
As-823	23.4	37.9	20.5	18.2 (contaminated)
Range	: 27.8 - 41.0	29.0 - 41.7	19.3 - 33.2	0.9 - 18.2
Average	: 34.6	36.1	25.0	5.1

Microcline and perthite are intergranular and appear to replace oligoclase and portions of the groundmass. Locally, it occurs in small phenocrysts enclosing idiomorphic plagioclase. Myrmikitic intergrowths are sparingly developed at borders between plagioclase and microcline.

Biotite is the main ferromagnesian mineral present. It is locally altered to chlorite. Muscovite is occasionally associated with biotite. Hornblende occurs in areas close to xenoliths. Sphene, apatite, allanite, muscovite are the common accessory minerals.

4.2.3 History of crystallization: From thin section examination it appears that the first to crystallize from the melt are plagioclase and biotite. Some of the plagioclase reacted with the melt to form an albitic rim. Orthoclase followed, but a change in the physical conditions of crystallization led to the crystallization of microcline also. The first generation of quartz occurs as small crystals in the groundmass or rounded embayments in the feldspars. And the second, larger interstitial grains was the last mineral to form.

A post-consolidation soda metasomatism is possibly responsible for the perthitic intergrowth with microcline to form microcline perthite.

Chlorite, sphene, allanite and epidote are most likely secondary deuteric minerals. Sericitization is probably a near surface hydrothermal action.

4.2.4 Summary:

The Al-Masloukhah adamellite is characterized by the following:

- 1) Homogeneous composition, massive, fine to medium even-grained texture.
- 2) An absence of inclusions of the biotite schist derived from the country rocks.
- 3) An abundance of inclusions of the syn-kinematic granitic rocks which contain xenoliths of original country rocks.

- 4) An abundance of inclusions of pre-existing basic rocks in the central area.
- 5) Approximately equal amounts of potash-feldspar and plagioclase, with the former tending to embay the latter.
- 6) An absence of foliation.
- 7) The sharp discordant contacts with synkinematic granitic rocks. (fig. 5-2d, 4j).

5.4.3 The post-kinematic granitic rocks

Two types of granitic rocks occurring in the area have been assigned to this grouping.

- 1) Al-Hadbah medium-grained "patchy" adamellite.
- 2) Coarse-grained pink granite.

Both are intruded into the syn- and late-kinematic granitic rocks in the form of small stocks and dykes covering an area of about 15 Km², the contacts with other rocks are usually chilled, discordant and sharp (fig. 5-2g).

4.3.1 The Al-Hadbah Adamellite

This adamellite is finer-grained than the Al-Masloukhah type and is characterized by an abundance of dark biotite-muscovite rich patches, $\frac{1}{2}$ -1 cm. in diameter. These patches are uniformly distributed throughout the rock and are 5-10 cm. apart. Weathered surfaces usually have a pitted appearance where these patches have been weathered away into rounded dark hollows (fig. 5-4i). Inclusions of both the syn-kinematic and the late-kinematic granitic rocks are abundant.

In thin section both microcline and orthoclase are found in association with albitic oligoclase and quartz. Biotite, occurs dispersed throughout the rock locally biotite and muscovite aggregates form dark patches. Chlorite, sphene, apatite and magnetite are the main accessory minerals.

4.3.2 The coarse-grained pink granite

This granite occurs as small stocks near the contact between synkinematic and late-kinematic granitic masses. Rarely it occurs in smaller bodies away from this contact.

This leucocratic granite is characterized by its pinkish to pinkish-red colour, coarse grain-size and the presence of some alkali-feldspar phenocrysts. In thin section, potash feldspar, both orthoclase, orthoclase perthite (fig. 5-4f) and microcline (fig. 5-4g) are dominant over plagioclase (table 5-5), which is of oligoclase composition (An_{27-18}). The oligoclase is sericitized along cracks and in the cores of grains. Biotite is the only mafic mineral present (0.4 - 5.0 percent).

Table 5-5 Modal analyses of the postkinematic pink granites

Sample no.	K-feldspar	Plagioclase	Quartz	Mafic minerals
G-2	47.1	19.3	29.4	4.2
KP-62	51.7	16.0	25.6	6.7
As-459	55.4	18.1	23.4	3.1
As-468	44.1	18.0	35.3	2.6
As-700	44.1	17.5	36.8	1.6
As-713	45.5	20.1	34.0	0.4
As-819	51.3	20.0	24.3	4.2
As-831	41.2	23.8	30.0	4.97
Range :	41.2 - 55.4	16.0 - 23.8	23.4 - 36.8	0.4 - 6.7
Average :	47.5	19.1	29.9	3.5

4.3.3 Summary

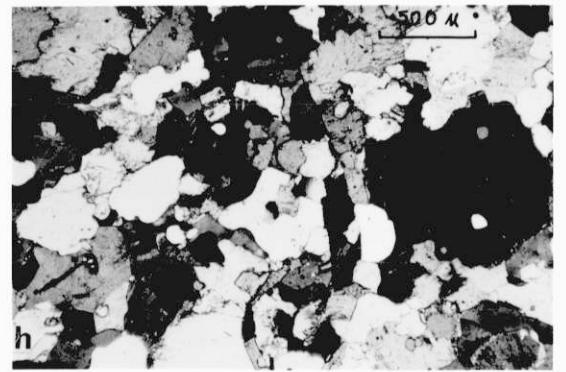
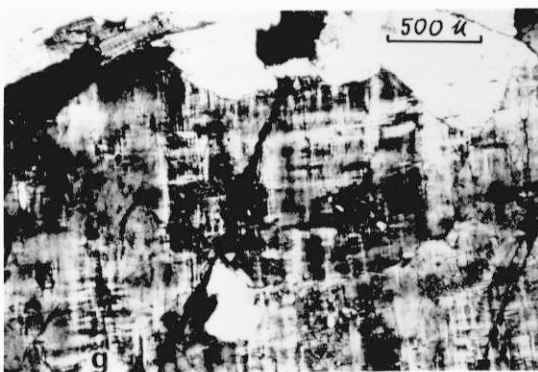
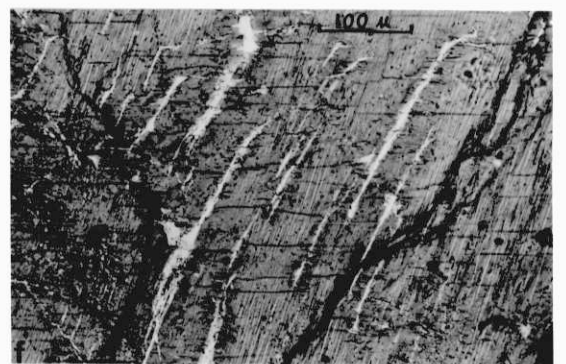
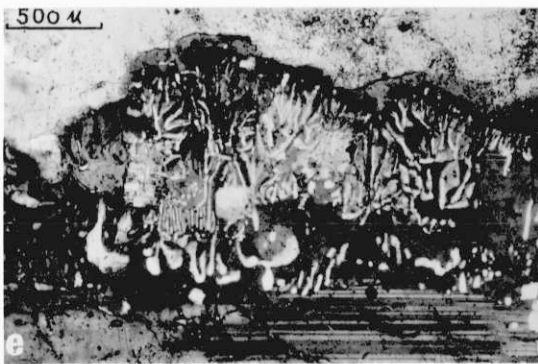
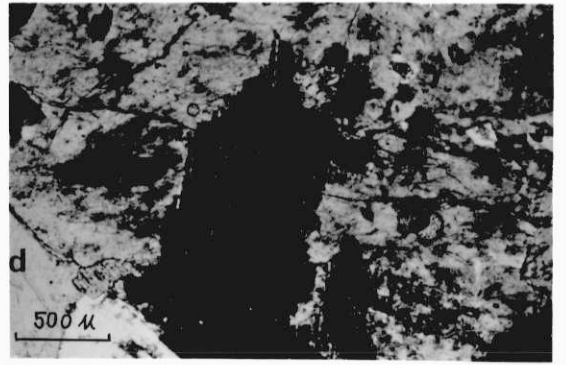
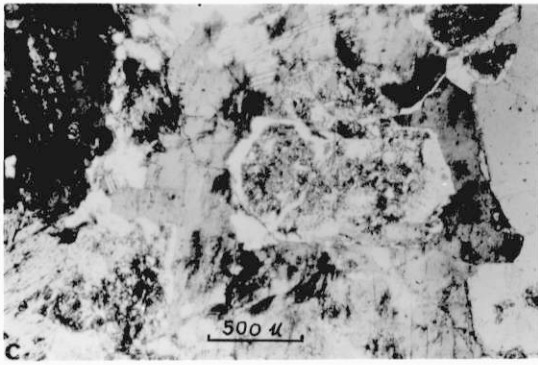
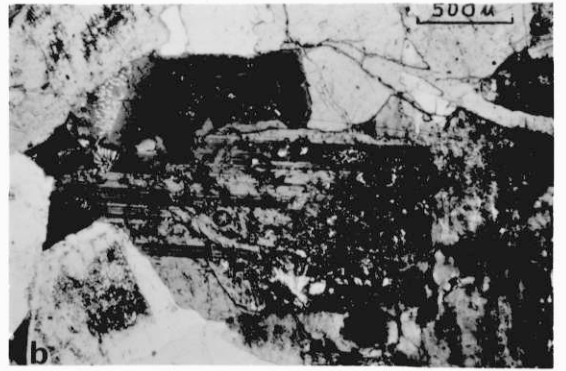
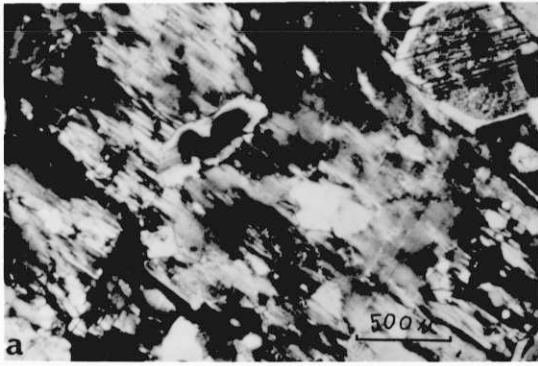
The post-kinematic rocks are homogeneous, unfoliated, even-grained and pink but locally porphyritic. They occupy only 15 sq.Km. of the total granitic area. They occur in small stocks and dykes with sharp chilled contacts against both the syn- and late-kinematic granitic rocks. They are either adamellite in composition, (Al-Hadbah adamellite) characterized by their uniform spotted texture of the mica

Granites

Figure 5-4

(a to h taken in transmitted light)

- a - Perthitic microcline phenocryst enclosing plagioclase crystals with albite rim. Small inclusions of quartz and biotite are also present. Post-kinematic granite, CN, G-218.
- b - Plagioclase crystals enclosed in a large microcline phenocryst. Plagioclase grains sericitized and saussuritized, zoned, and with albite rim. Myrmikitic intergrowth is developed at contact with the alkali-feldspar. Ar-Ridaiyah adamellite, CN, As-395.
- c - Microcline phenocryst enclosing sericitized plagioclase crystals with albite rim. Note the irregular grain boundary with quartz (right) and biotite (left). Ar-Ridaiyah adamellite, CN, As-395.
- d - Microcline phenocryst replacing plagioclase. Ar-Ridaiyah adamellite, CN, As-395.
- e - Myrmikitic intergrowth at contact of earlier plagioclase (bottom) and younger alkali-feldspar (top). Ar-Ridaiyah adamellite, CN, As-395.
- f - Orthoclase-perthite, abundant exsolved lamellae of perthite with variable dimensions. Post-kinematic granite, CN, G-218.
- g - Well-developed cross-hatching in microcline crystal. Post-kinematic granite, CN, G-218.
- h - Equigranular adamellite. Al-Masloukhah adamellite, CN, As-820.
- i - Uniformly distributed patches of biotite and muscovite in post-kinematic patchy adamellite. Locality G-266 (Plate 5).
- j - Dykes of late-kinematic granite in earlier synkinematic porphyritic adamellite. Locality As-467 (Plate 5).



patches, or coarser grained and granitic in composition. They are devoid of inclusions of earlier rocks and are not contaminated.

5.5 MINOR INTRUSIONS

5.5.1 Pregranite intrusions

5.1.1 Microdiorite dykes

These are narrow dykes ($\frac{1}{2}$ -2 m. across) which strike approximately 160° . They occur predominantly cutting the layered basic rocks of Samrah Mine area. These are the oldest dykes present in the area and are cut by younger basic and acidic dykes. They are usually porphyritic with large euhedral plagioclase phenocrysts set in a groundmass of approximately equal amounts of feldspar and pyroxene and/or amphibole. In some of these dykes up to 10% of quartz is present. In thin section the plagioclase and pyroxene frequently show subophitic intergrowth. Small zoned euhedral to subedral laths of plagioclase range in composition from An_{35} to An_{42} . The pyroxene forms stumpy euhedral grains which are marginally altered to amphibole. Apatite, opaque ore minerals, biotite and hematite are present in accessory amounts. Alteration of the main constituents is extensive, plagioclase being altered to sericite and pyroxene to amphibole, chlorite and locally carbonate.

5.5.2 Postgranite intrusions

5.2.1 Aplites and pegmatite

Veins and lenses of leucocratic, pink pegmatite, usually associated with aplite, range in width from less than 1 cm. up to 10 m., generally they are 1-3 m. across. They are extremely abundant in the granitic rocks of the area and are randomly orientated. They are also abundant in the Al-Jéalani basic intrusion, where they have consistently outwards dips of 10° - 50° which contrast markedly with the inward dips of the layered mass.

The aplites are fine grained, hololeucocratic rocks which, in thin section are seen to be mainly composed of quartz, orthoclase, albite, biotite and/or muscovite.

Some pegmatites exhibit zonal differentiation, for example in the white plugs in the vicinity of Samrah ancient mine, where the core is occupied by quartz and is rimmed by pink orthoclase with subordinate muscovite; others, usually dykes, exhibit no zonal differentiation. Quin (1964) found a lithium-bearing mica float (Lepidolite) in the white plug west of Samrah mine. Eijkelboom (1966) reported the occurrence of large crystals of andalusite in an orthoclase-rich zone in one of these pegmatite plugs. Pockets of tourmaline and muscovite are present in pegmatites injected into the layered intrusion.

5.2.2 Granitic dykes

These dykes are formed of fine grained pink rock of adamellitic or granitic composition. They cut all types of rock and are occasionally randomly orientated. They are most abundant in the areas SSE of Musiddah village and south of Hamrur village (plate 1). In both areas they generally trend east-west.

The modal variation in these dykes is shown in (table 5-6). Most of the dyke rocks analysed indicated adamellite composition. The rest are either granodiorite, granite or even quartz monzonite in composition (fig. 5-7b).

Table 5-6 Modal analyses for granitic dykes in the area

Sample no.	K-feldspar	Plagioclase	Quartz	Mafic minerals
G-10-b	45.2	21.8	32.0	1.0
G-10-c	41.7	24.0	33.0	1.3
As-433	38.0	38.2	21.6	2.2
As-461	47.3	17.0	34.8	0.9
As-707	24.8	37.9	34.3	3.0
As-720	51.8	30.7	13.8	3.7
As-721(a)	27.6	35.8	31.8	4.8
As-721(b)	34.8	34.8	26.7	3.7
As-722	31.2	39.6	24.9	4.3
As-724	12.6	46.9	29.3	11.2
As-725	23.7	41.7	28.0	6.6
As-730	35.2	29.1	34.6	1.1

5.2.3 Dacite, microdiorite, quartz microdiorite and Rhyolite dykes*

These dykes generally occur infilling en-echelon tension fractures which are locally sigmoidal and which run east-west to east - northeast west - southwest over long distances (plate 1). Clear sharp chilled contacts with country rocks are characteristic.

The dacite dyke swarm is more abundant and forms four groups in the south part of the area, a fifth group occurs in the central part. These dykes show good flow banding and closely developed jointing parallel to the walls. There is local primary microfolding of the flow banding, usually parallel to irregularities in the walls.

The dacite dykes are porphyritic with phenocrysts of potash feldspar, zoned plagioclase and more rarely quartz set in a fine grained groundmass of quartz, feldspar, biotite and amphibole.

The microdiorite and quartz microdiorite dykes are dominant in the mid-western and northern parts of the mapped area (plate 1), where they infill west - northwesterly trending tension fractures. Towards the south, they are less abundant and run in an east - west direction. They are composed of plagioclase phenocrysts set in a groundmass of andesine, pyroxene, amphibole and chlorite. Up to about 5% quartz is present in some of these dykes.

The Rhyolite dykes are most common in the northern part of the mapped area where they trend 110° . They range from 2-5m. in thickness and are intruded into biotite and sericite schists. They infill tension fractures in en-echelon pattern. The rhyolite dykes are locally in contact with microdiorite dykes without any cross-cutting relationships. These dykes are pale grey or pink in colour and are porphyritic, with phenocrysts of potash feldspar, set in a groundmass of chlorite, quartz and accessory opaque minerals. Other rhyolite dykes are spherulitic in which the spherulites are locally fringed with amphibole.

* Volcanic terms are used because these dyke rocks exhibit textures similar to those of volcanics, the groundmass is cryptocrystalline.

5.6 GEOCHEMISTRY AND MODAL VARIATION OF THE GRANITIC ROCKS

5.6.1 Modal Variation

Modal analyses for the various granitic rocks in the whole plutonic complex (tables 5- 1,2,3,4,5) have been plotted onto ternary diagrams using potash feldspar (F), quartz (Q) and plagioclase feldspar (P) as co-ordinates after recalculating the modes to 100%, ignoring the mafics. The coarse grained synkinematic granitic rocks show a wide range of modal variation than the fine grained granitic rocks (fig. 5-6 a and b). Rock types vary from quartz-monzonodiorite to granodiorite to adamellite and locally to granite, thus forming a heterogeneous group of granitic rocks. The finer grained Al-Masloukhah adamellite, however, shows a concentration in the adamellite compartment of the diagram (fig. 5-6 b).

The post-kinematic granite (fig. 5-7a) shows a close group of plots in the granite zone of the ternary diagram, except for three out of ten samples, two of which have adamellite composition and one quartz-monzonite.

The ternary diagram (fig. 5-5) for quartz, total feldspars and total mafic minerals shows a similar spread for the synkinematic rocks towards the mafic corner, while both late- and post-kinematic types show clusters with much less mafics, with the post- still less than the late-kinematic. This suggests that the synkinematic rocks were contaminated by the more basic country rocks.

5.6.2 Normative and chemical variation

6.2.1 Introduction: A total of 16 complete major-element analyses was done by atomic absorption methods (table 5-7). Electronic computing techniques were employed, using these results, to derive the C.I.P.W. norms for the samples (table 5-8) and to calculate a differentiation index based on the total of normative minerals quartz + orthoclase + albite + leucite + nepheline + kaliophilite (table 5-9). The norms were also used in the triangular plots of the $\text{NaAlSi}_3\text{O}_8 - \text{KAlSi}_3\text{O}_8 - \text{SiO}_2 - \text{H}_2\text{O}$ experimental system, projected on the anhydrous base (Tuttle and Bowen 1958),

Table 5-7

	Synkinematic - granitic rocks						Latekinematic - granitic rocks				Postkinematic - granitic rocks			Granitic dykes		
	As-701	As-704	As-706	As-206	As-372	As-395	As-726 (a)	As-729	As-822	As-823	As-700	As-819	G-266	ISA-39'	ISA-16'	ISA-39'0 6"
SiO ₂	69.50	64.32	63.83	69.00	73.18	75.20	76.14	75.45	70.83	69.20	79.62	70.83	76.64	63.80	71.30	71.69
TiO ₂	0.38	0.30	0.67	0.30	0.26	0.42	0.12	0.67	0.05	0.17	0.02	0.13	0.08	0.68	0.35	0.09
Al ₂ O ₃	12.66	13.82	13.50	13.06	12.80	11.10	11.45	10.39	13.40	10.01	8.71	13.64	10.17	16.00	14.93	15.50
Fe ₂ O ₃	2.48	3.19	3.46	1.22	0.62	0.28	0.43	1.11	0.56	2.94	0.54	0.61	0.93	1.84	0.56	0.53
FeO	3.46	4.55	5.30	1.56	1.95	1.10	0.73	1.64	0.80	3.92	1.73	3.40	1.14	3.76	1.76	1.03
MnO	0.06	0.08	0.09	0.04	0.02	0.09	0.03	0.03	0.01	0.07	0.01	0.02	0.03	0.12	0.03	0.02
NgO	1.24	1.99	1.62	0.66	0.23	0.61	0.13	0.38	0.33	2.14	0.09	0.07	0.17	2.80	0.26	0.27
CaO	2.75	3.27	5.15	2.24	1.26	1.26	0.83	0.95	1.33	2.70	0.71	0.81	0.84	1.79	0.00	0.51
Na ₂ O	4.08	4.53	3.96	6.87	5.10	5.12	4.41	4.48	4.50	4.15	2.89	4.30	4.31	3.82	4.44	4.16
K ₂ O	4.04	3.01	2.61	4.90	4.14	3.75	4.51	4.66	7.80	3.88	4.91	5.78	4.36	2.50	5.03	4.63
H ₂ O ⁺	0.68	0.53	1.02	0.62	0.14	0.50	0.25	0.54	0.24	0.98	0.22	0.10	0.50	3.10	0.50	1.52
H ₂ O ⁻	0.07	0.05	0.06	0.08	0.06	0.10	0.07	0.13	0.03	0.03	0.05	0.08	0.02	0.40	0.07	0.06
P ₂ O ₅	0.07	0.09	0.14	0.04	0.01	0.07	0.02	0.02	0.01	0.09	0.02	0.01	0.02	0.14	0.05	0.02
Total	101.47	99.73	101.41	100.59	99.77	99.60	99.12	100.45	100.04	100.28	99.52	99.77	99.21	100.77	99.28	100.03

Analysts: A. Al Shanti and S. Farouki

Table 5-8 Normative analyses

	Synkinematic - granitic rocks						Latekinematic - granitic rocks				Postkinematic - granitic rocks			Granitic dykes		
	As-706	As-701	As-704	As-206	As-372	As-395	As-726 a	As-729	As-822	As-823	G-266	As-700	As-819	ISA-39'	ISA-16'	ISA-39'06"
Qtz	17.91	22.95	15.83	14.91	24.81	31.98	33.16	33.81	18.83	22.75	36.22	45.10	20.02	22.35	24.95	27.72
C														4.09	2.30	2.77
Or	15.43	23.88	17.79	28.96	24.47	22.16	26.66	27.54	46.10	22.93	25.77	29.02	34.16	14.78	29.73	27.37
Ab	33.51	34.52	38.33	39.90	42.79	36.22	33.79	27.50	25.50	29.89	28.04	17.47	36.38	32.32	37.57	35.20
An	11.36	4.30	8.49										00.85		0.33	2.40
Ne																
Dj	11.13	7.40	5.93	8.14	5.37	4.79	2.95	3.88	4.41	10.64	3.50	2.99	2.75			
Wo				0.48			0.24		0.54							
Hy	4.38	3.18	7.38		0.56	0.64		0.94		5.97	0.62	1.81	4.28	11.46	2.89	2.01
Ol																
Mt	5.02	3.60	4.62		0.74					1.96			0.88	2.67	0.81	0.77
Hm																
Il	1.27	0.72	0.57	0.57	0.49	0.80	0.23	1.27	0.09	0.32	0.15	0.04	0.25	1.29	0.66	0.17
Hap	0.33	0.17	0.21	0.09	0.02	0.17	0.05	0.05	0.02	0.21	0.05	0.05	0.02	0.33	0.12	0.05
Ac				3.53	0.31	0.81	1.24	3.21	1.62	4.60	2.69	1.56				
Ns				3.31		1.44	0.49	1.57	2.50		1.25	1.21				
H ₂ O	1.07	0.75	0.58	0.70	0.20	0.60	0.32	0.67	0.27	1.01	0.52	0.27	0.18	3.49	0.57	1.58
Total	101.41	101.47	99.73	100.59	99.77	99.60	99.12	100.45	99.89	100.28	99.21	99.52	99.78	100.75	99.28	100.03

Table 5-9 Differentiation index - granitic rocks

Sample No.	D. Index*	Average	Remarks
As-706	66.85	81.05	Synkinematic granitic rocks
As-701	81.35		
As-704	71.95		
As-206	83.77		
As-372	92.07		
As-395	90.36		
As-726(a)	93.61	87.11	late kinematic granitic rocks
As-729	88.85		
As-822	90.43		
As-823	75.57		
G-266	90.43	90.86	post kinematic granitic rocks
As-700	91.59		
As-819	90.56		
ISA-39'	69.45	83.99	granitic dykes
ISA-16'	92.25		
ISA-39'6"	90.29		

* Differentiation index

i.e. the Q - Or - Ab diagram (fig. 5-8b). Other triangular diagrams plotted were Or - Ab - An (fig. 5-9a). It should be noted that the components in each case were converted to total 100%, and as such are taken as indicators of relationships, rather than exact representation of the relative positions of the samples in the individual systems. These methods of plotting also tend to be selective as only a limited number of components is used.

The composition of the granitic rocks with respect to the minerals quartz, albite and orthoclase is restricted to a relatively small range and are clearly grouped when plotted on a ternary diagram (fig. 5-8b).

The A.F.M. diagram, exhibits an approximately linear trend (fig. 5-9a) and is in accordance with the alkali - lime index of Peacock (1931) (fig. 5-10).

Greenwood and Brown (1972) concluded that the plutonic granitic rocks in the north-east compartment of the Arabian shield in which the Ad-Dawadmi batholith is situated is formed from calc-alkaline magma.

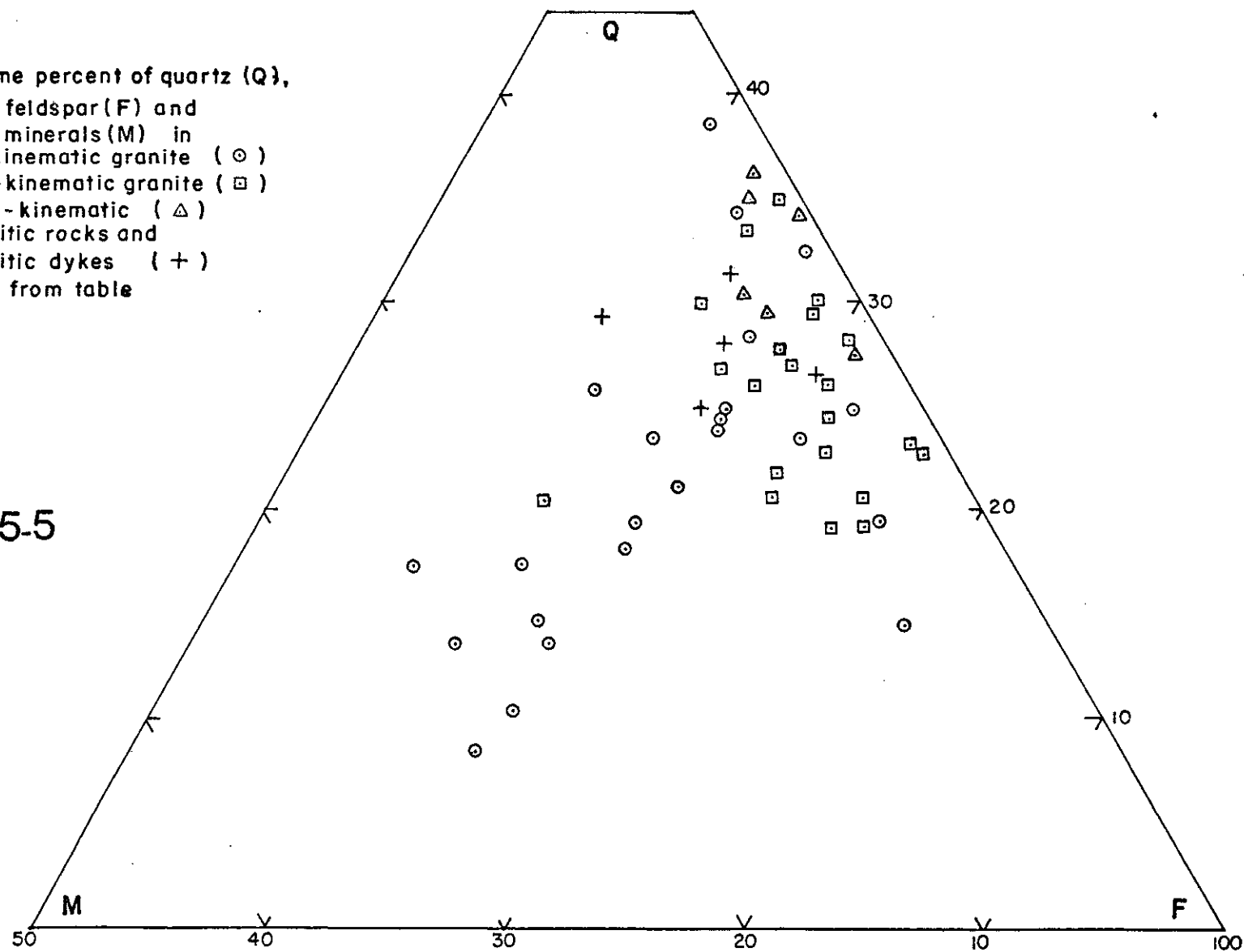
In the following the chemistry of the various granitic rocks syn-, late- and post-kinematic is discussed separately.

6.2.2 The synkinematic granitic rocks which are of wide modal variation ranging from quartz-monzonodiorite to granite in composition, exhibit on the ternary diagrams (fig. 5-8 and 9) clustering towards the sodic or (Ab) corner.

The $\text{CaO} - \text{Na}_2\text{O} - \text{K}_2\text{O}$ diagram (fig. 5-8a) shows a trend extending from calcic towards low calcic with more soda enrichment relative to potash. The A.F.M. diagram (fig. 5-9) shows a variation from low alkalic towards higher alkalic. This chemical variation is in accordance with the modal variation. Both point out the wide range of contamination. (fig. 10) gives an alkali - lime index of 57.5% SiO_2 indicating origin from a calc-alkaline melt (Peacock, 1931).

Volume percent of quartz (Q),
total feldspar (F) and
dark minerals (M) in
Synkinematic granite (○)
late-kinematic granite (◻)
post-kinematic (△)
granitic rocks and
granitic dykes (+)
data from table

Fig. 5-5



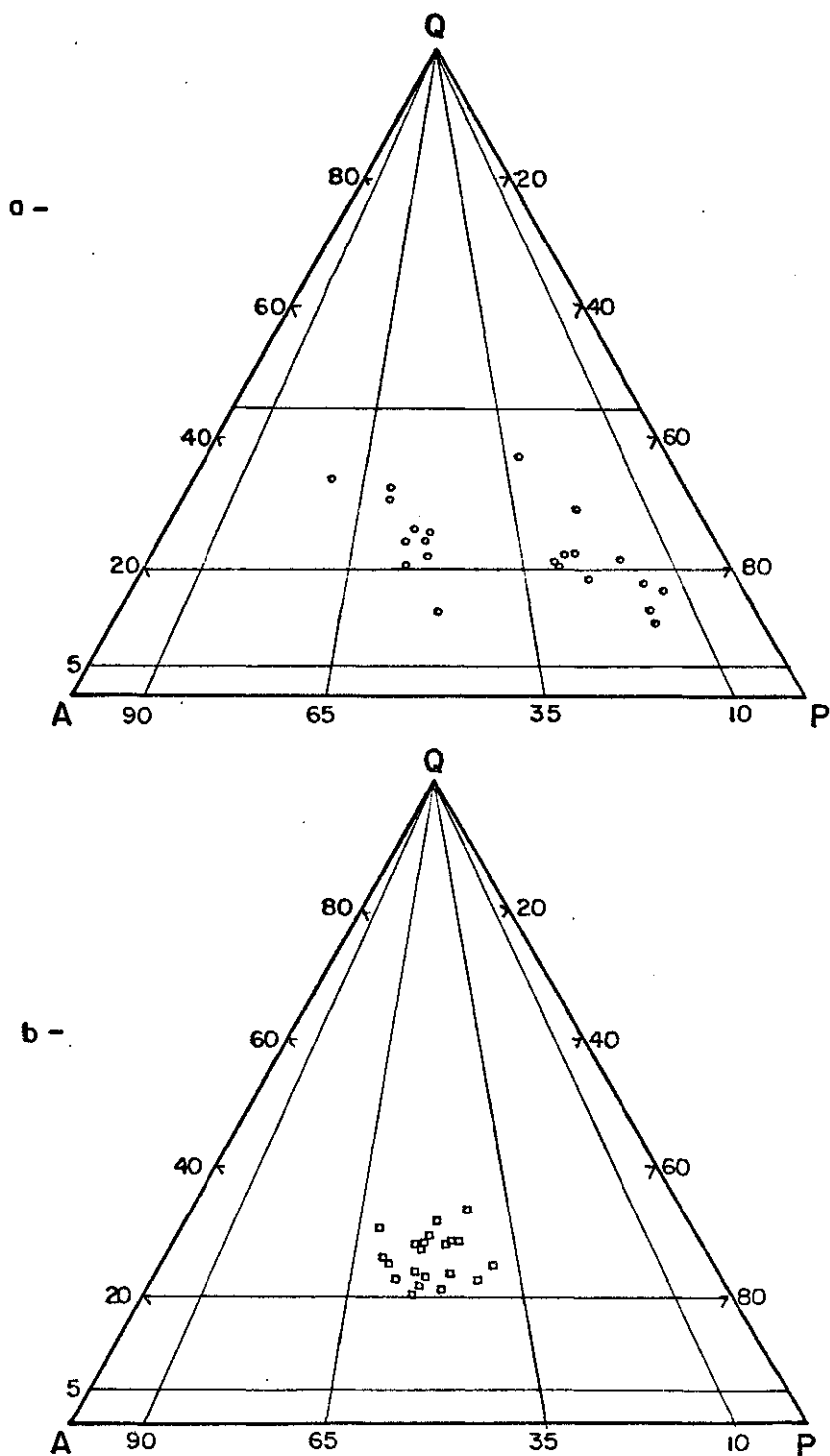


Fig. 5-6

Volume percent of Quartz (Q), plagioclase feldspars (P) and alkali feldspars (A) for "a" Synkinematic and for "b" late Kinematic granitic rocks

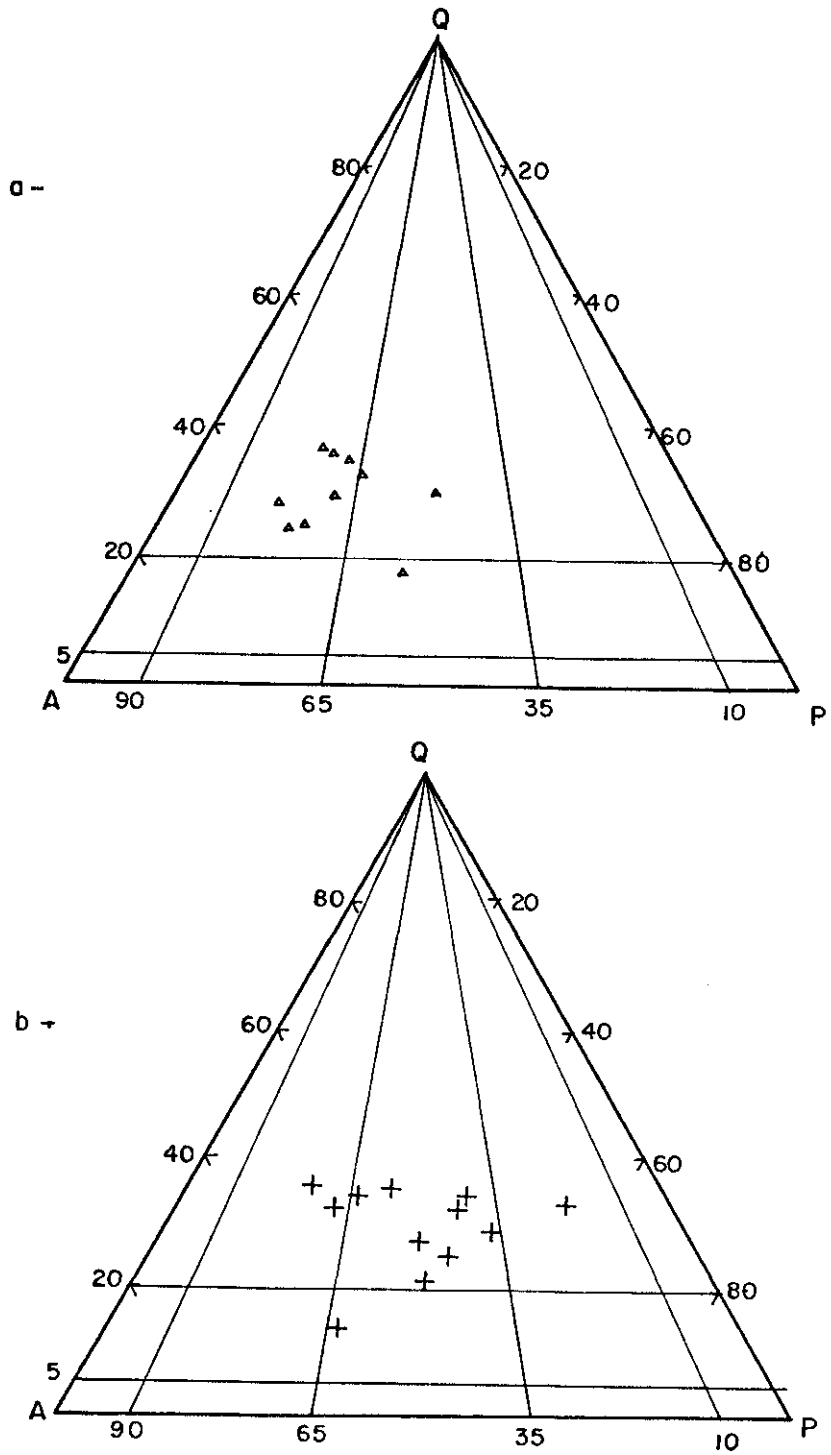
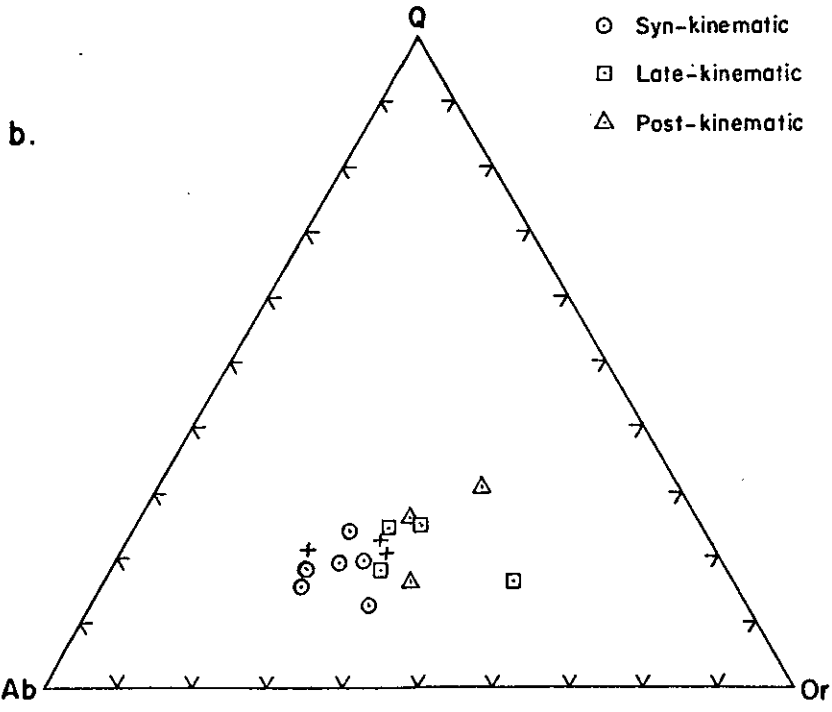
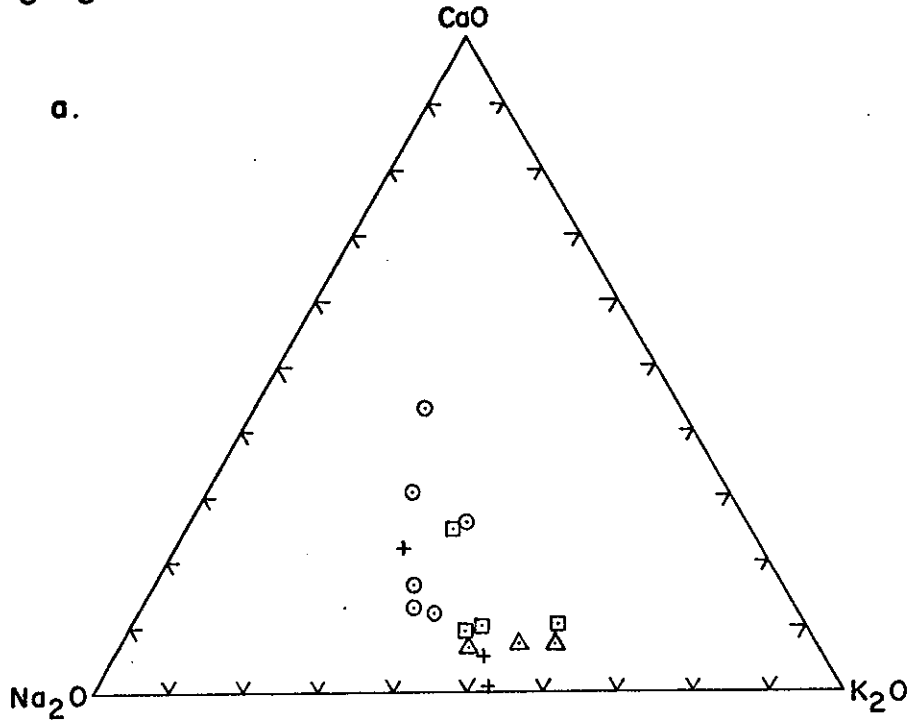


Fig: 5-7

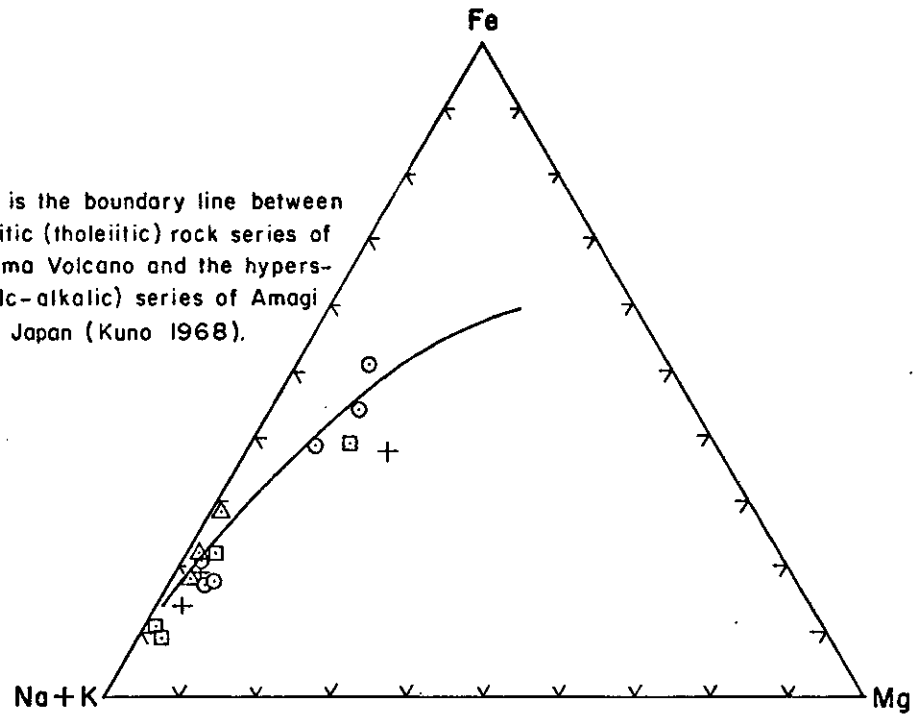
Volume percent of Quartz (Q) plagioclase feldspars (P) and alkali feldspars (A) for "a" Post Kinematic granitic rocks, "b" granitic dykes.

Fig: 5-8



a.

The curve is the boundary line between the pigeonitic (tholeiitic) rock series of Hatizyo-zima Volcano and the hypers-thenic (calc-alkalic) series of Amagi Volcano in Japan (Kuno 1968).



b.

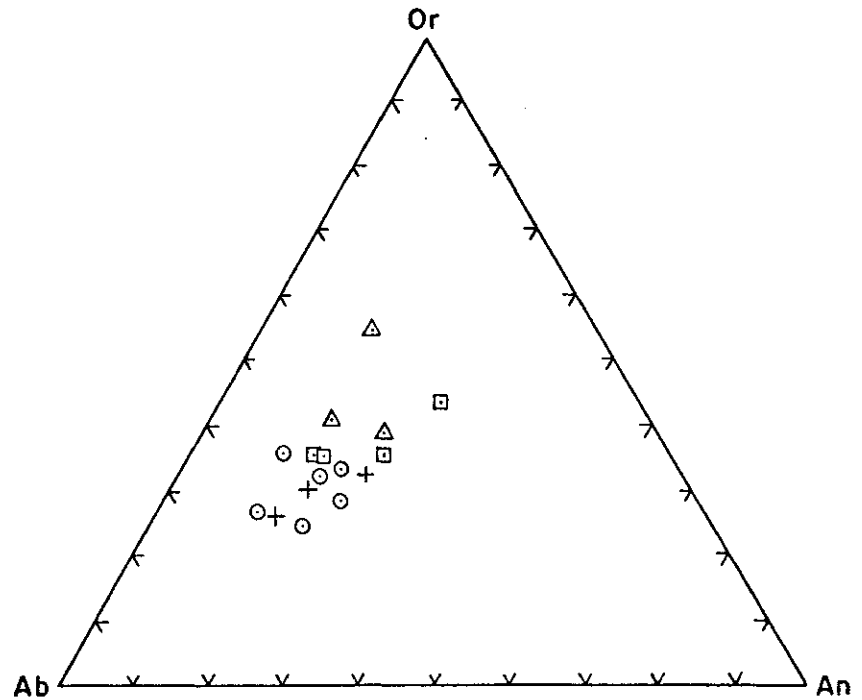


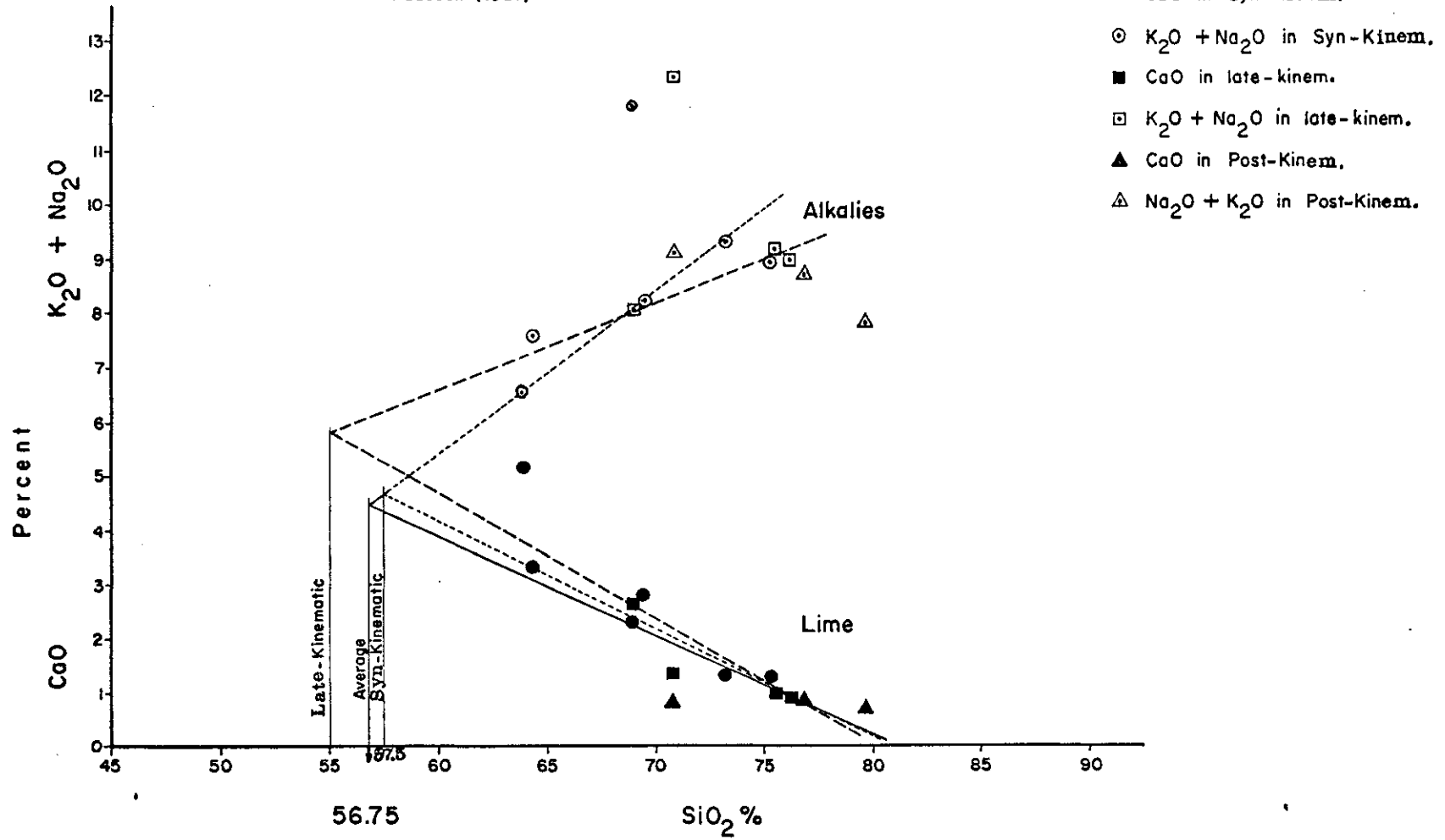
Fig: 5-9

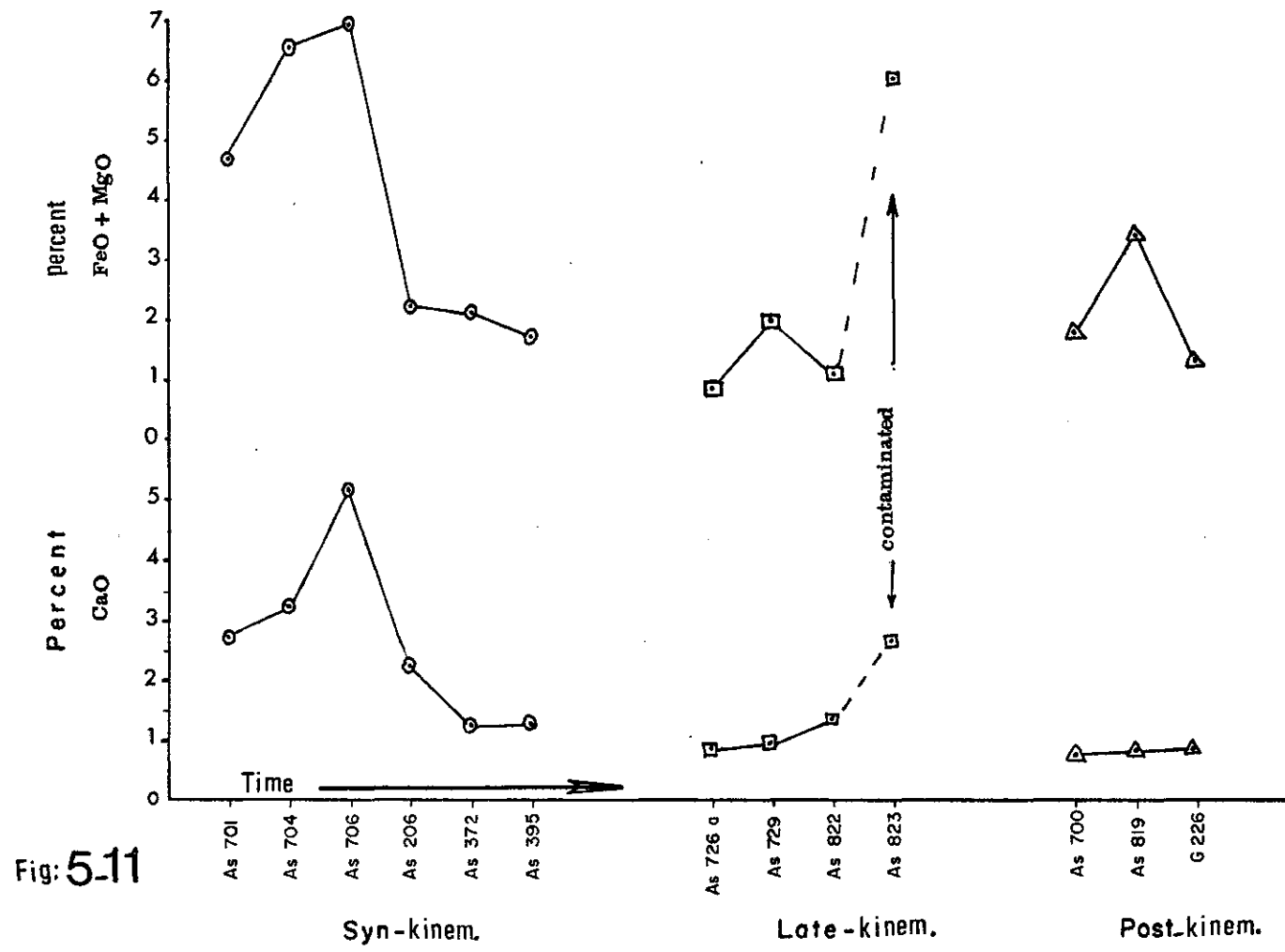
Alk-F-M and Normative diagrams

- a) Alk-represents alkali oxides, Fe-total iron, and Mg-Magnesium oxide.
b) Or-Ab-An.

Fig. 5-10 Alkali-lime index diagram.

Peacock (1931)





6.2.3 The late kinematic granitic rocks show grouping with little separation, or small area overlap with the previous rock types on the ternary diagrams (fig. 5-8b and 9b). These rocks are more on the potassium rich side. The A.F.M. diagram (fig. 5-9) shows high alkalies.

The homogenous nature of this granitic rock exhibited by the modal analysis (fig. 5-6b) does not appear so clearly here. This is probably due to the limited number of chemical analyses performed on these rocks.

The alkali - lime index for the late-kinematic rocks is 55.0% SiO_2 (fig. 10) indicating origin from an alkali-calcic melt (Peacock, 1931).

6.2.4 The post-kinematic granitic rocks show on the ternary diagram (fig. 5-8a and 9b) a high (Or) and a constant low lime. This indicates a homogeneous non-contaminated magma more on the alkalic side than both syn- and late-kinematic rocks. This is in accordance with the modal analysis, diagram (fig. 5-7a).

5.7 GENERAL DISCUSSIONS AND CONCLUSIONS

1. The three granitic rock units, syn-, late- and post-kinematic are derived from one magmatic source of average calc-alkaline composition. The lack of associated large amounts of basic intrusive rocks suggests that this magmatic source originated from a crustal melt.

2. The values (fig. 5-9a) appear to fit a simple differentiation trend with time, along which alkalies are progressively concentrated relative to iron and magnesium. Rocks of the synkinematic quartz-monzonodiorite and granodiorite plot towards the Fe-Mg rich end of the trend and are separated from the rocks of adamellite composition. This suggests that magma followed one path of differentiation, with the synkinematic more calcic first, followed by granodiorite, adamellite and finally granite (fig. 5-11).

3. The contamination with ferromagnesian minerals from the pre-existing country rocks is extensive and decreases towards the more alkalic rocks, i.e. following the same differentiation trend.

4. The synkinematic intrusive rocks show extensive enrichment with xenoliths at the present level of erosion. This suggests some contamination of magma by partial assimilation of xenolithic material.

5. The primary flow fabric defined by the preferred orientation of the alkali-feldspar grains, and less distinct, the mafics, suggests that the granite melt had been generated below this present level. Structures in the pre-existing rocks appear to have controlled this flow direction.

The prevailing gradational contacts and the inhomogeneity of the synkinematic granitic rocks indicate an undisturbed region in the upper low liquid portion of the zone of melting, Tuttle and Bowen (1958). The late kinematic rocks which are homogeneous and unfoliated represent the more fluid portions of the zone of melting. These were intruded into higher levels giving rise to sharp contacts with the synkinematic rocks.

The post-kinematic granitic rocks were emplaced last and have sharp chilled contacts against both older intrusive rock types. They are also less contaminated and more alkalic.

CHAPTER 6

FRACTURES AND JOINTS

6.1 INTRODUCTION

Well exposed linear features attract the attention in aerial photographs of Ad-Dawadmi district. These are surface expressions of extensive faulting in the area. The shear zones in the granitic batholith are loci of the zinc - lead - silver mineralization.

The complex fractures pattern is related to the transcurrent sinistral Najd Fault System (Brown et al. 1972, a series of major lineaments extending for over 1200 Kms. (fig 6-1) in a northwesterly direction.

Study of the fracture patterns in the district shows that the fractures can be explained as a result of modification of a regional stress field by movements on a series of wrench faults which are considered to be part of the Najd fault system.

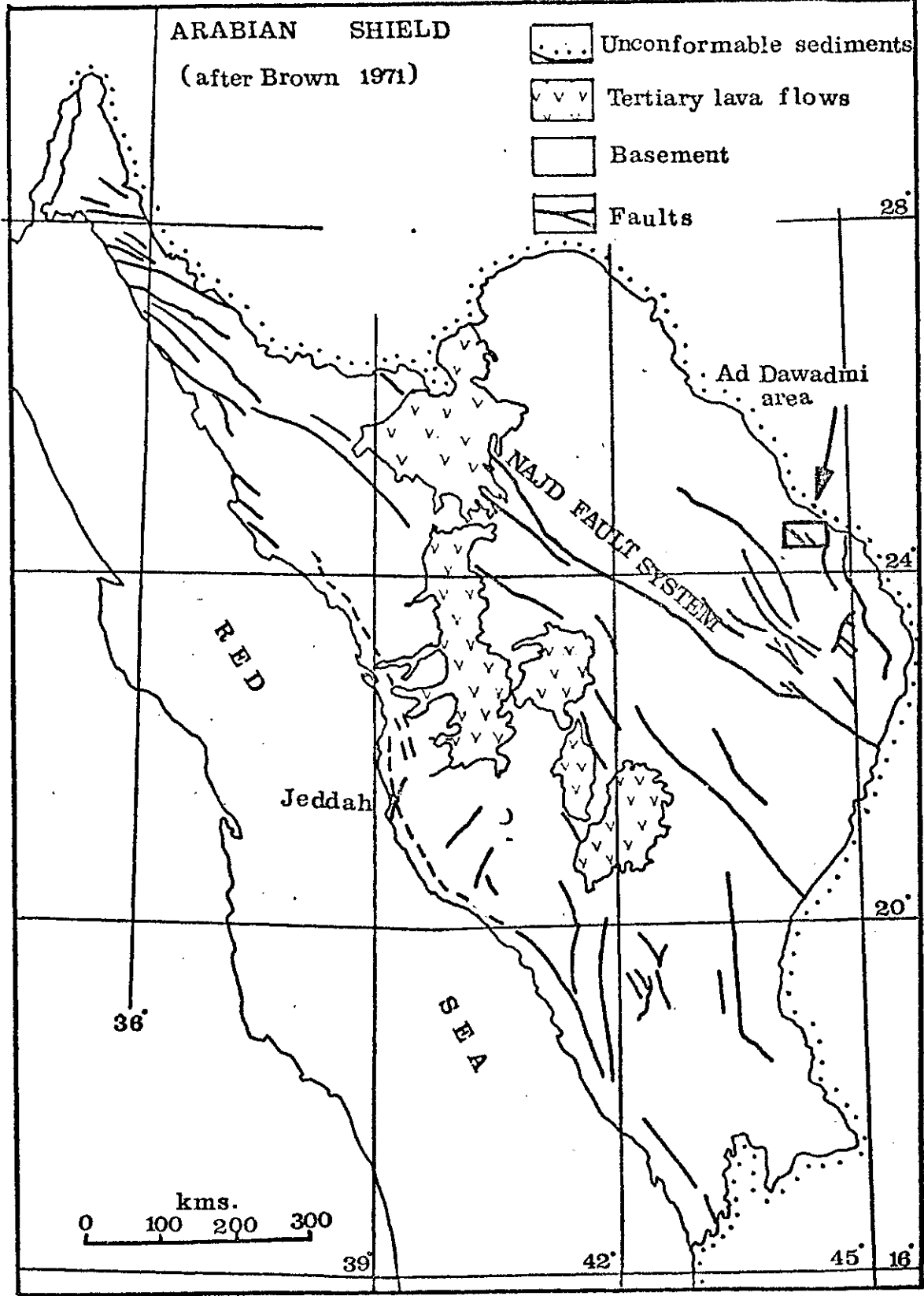
6.2 GEOLOGICAL HISTORY OF THE FRACTURE SYSTEM

After the Hejaz Orogeny (1000 - 660 m.y), the district was affected by faulting during the Najd Orogeny (660 - 570 m.y). The northwesterly wrench faults were the first to form, followed by the secondary fault systems. The faulting was accompanied by intrusion of the numerous dykes predominantly of dacitic and microdioritic composition in the south, and rhyolitic and microdioritic in the north. At a later stage fluids which deposited quartz, sulphides with chlorite and carbonates invaded the fractures. Renewed movements along these fractures during and after mineral deposition caused extensive brecciation. Three generations of hydrothermal solutions are indicated by quartz overgrowths. Displacements of the early granite pegmatite dykes commonly indicate the direction and amount of the strike-slip on the faults.

6.3 FIRST ORDER WRENCH FAULTING

The prominent sinistral shear zones comprising close en echelon fractures trending $135^{\circ} \pm 5^{\circ}$ are part of the Najd fault system. The

fig:6-1



width of the shear zone in these faults ranges from 15 - 30 metres. The rocks within the shears are strongly fractured, brecciated and cemented by quartz, carbonate and chlorite gangue and generally stained brown and standing prominently above the surrounding ground. The Hamrur, Saffaga and Um Ergaba in the south (Fig. 6-2) are the best exposed major faults.

6.4 SECOND ORDER FAULTING

The second order faulting is associated with the first order wrench movements in the form of shear fractures with strike-slip movements, and extension fractures which have suffered dilation only.

6.4.1 Shears

At most localities one member of a pair of shear fractures dominates to the exclusion of the other. The northeasterly trending components have a strong parallelism and are approximately at equal separations. They are characteristically curved near to first order faults. In the area between the Hamrur and Um Ergaba faults they form a sigmoidal pattern (fig. 6-2).

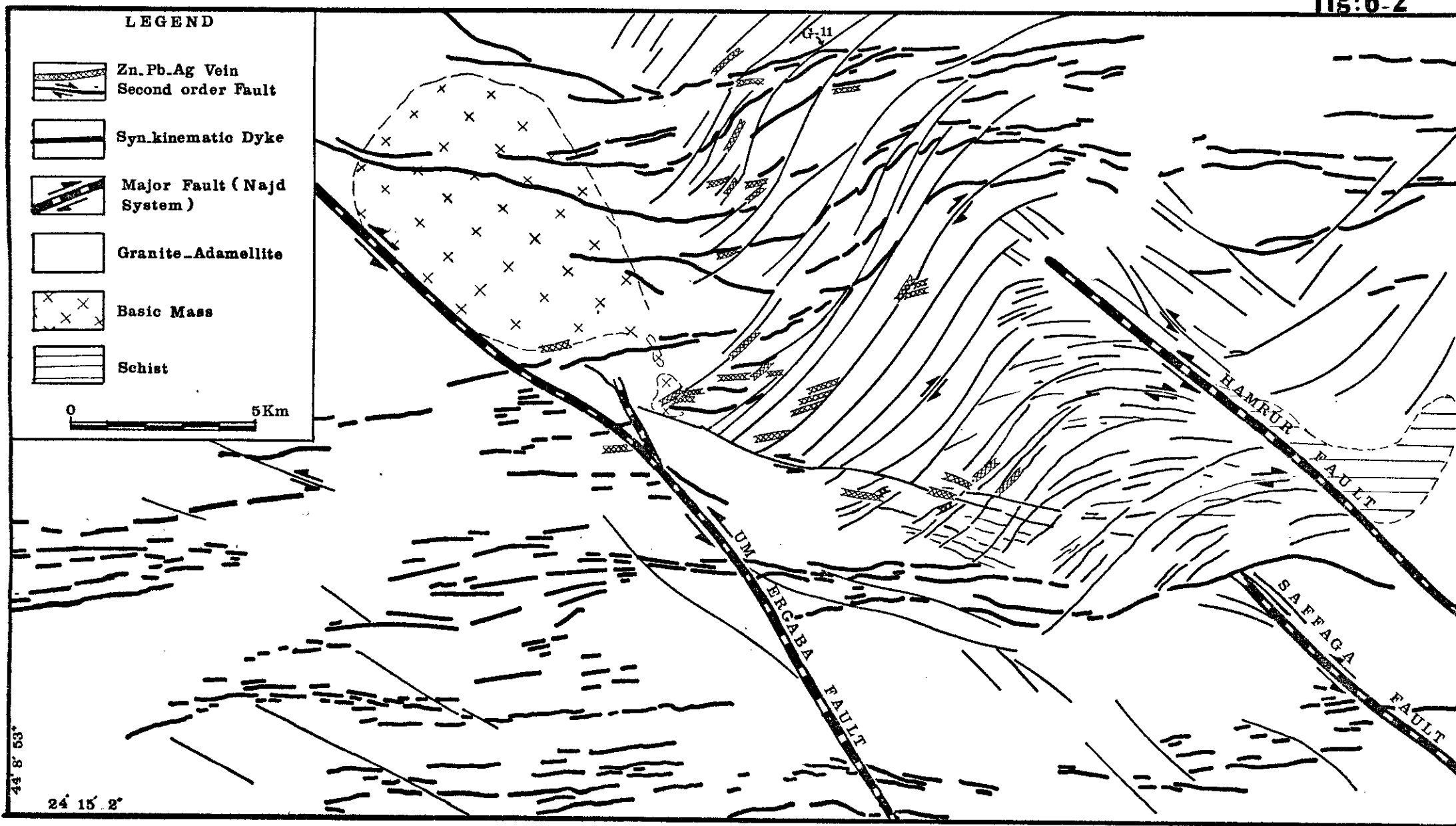
These shear fractures are prominent at their outcrops due to post-movement silicification and alteration of bedrock which has produced differential resistance to weathering between shear zones and country rocks. The width of individual shears ranges from 7-20 m., with outcrop relief generally between 1-3 m., but locally up to 10 m. with a dyke-like appearance.

Mineralizing fluids and subsequent oxidation have coloured the shear zones amber or brown. Complex fracture cleavages and extensive brecciation were developed within the shear zones indicating repeated deformation.

6.4.2 Extension fractures

East-west trending sets of en echelon extension fractures formed synchronously with the second order shears are filled by a swarm of

fig:6-2



dacite, microdiorite and rhyolite dykes (see section 6.4.7). The dykes show chilling against the wall rocks. Quartz-sulphide vein deposits invaded the extension fissures adjacent to second order shears.

6.4.3 Consideration of fracture analysis implications

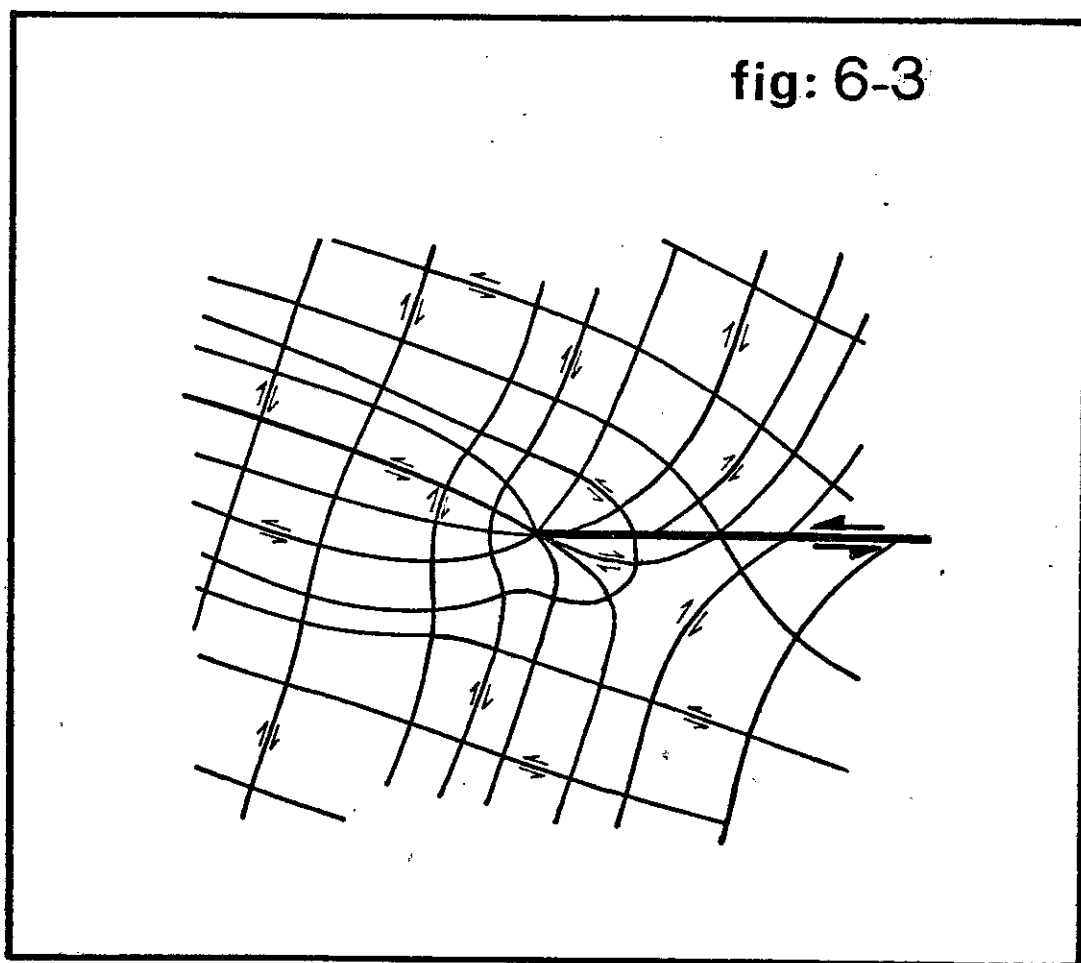
McKinstry (1953) suggested an explanation for some of the structures based on a two dimensional analysis of the stresses which caused secondary faulting. Moody and Hill (1956) proposed that as a result of reorientation and partial relief of the regional stress field during movements on the wrench faults, second and third order faults are expected to form. Stress trajectories for this complex fracture system were constructed at the suggestion of (J. McM. Moore) and helped in the analysis and interpretation of the fault system.

Stress trajectories are defined as sets of orthogonal lines representing the orientation of the principal stresses, compressive, extensive and maximum shearing stresses at a specified point. This concept of stress trajectories permits the representation of progressive changes in the orientation of the principal stress axes within a stress field, while maintaining their orthogonal relationships one to another.

The formation of a major wrench fault by the failure of a previously isotropic medium in a compressive stress field results in local distortion of that field. The distortion is at a maximum in the vicinity of the tip of the fault and is reduced away from the end, as the regional field re-establishes itself across the moving fault, modified only by frictional drag on the fault plane.

Chinnery (1966) considered the conditions apertaining around a moving wrench fault under (a) pure shear and (b) uniaxial compressive stress, and constructed maximum shearing stress trajectories for each of the two models (fig. 6-3). Theoretical considerations render the pure shear model unacceptable as a mechanism for wrench faulting (N.J. Price, personal communication).

Theoretical maximum shearing stress trajectories at the end of a sinistral wrench fault (after Chinnery)



6.4.4 Comparison with theoretical models

In order to reconstruct a palaeo-stress system that is comparable with the theoretical models like those of Chinnery from a fracture pattern, the following conditions must be fulfilled:

- (a) failure should have happened before any significant ductile deformation took place.
- (b) The country rocks of the area should be approximately isotropic i.e. devoid of any planar fabric discontinuities, sedimentary or tectonic.
- (c) The area should be near or include the ends of one of the major wrench faults caused by the stress system.

The area represented in (fig. 6-2) of the Ad-Dawadmi district fulfils the above requirements, where

- (a) There is no field evidence of ductile behaviour in the rocks of this area.
- (b) The igneous fabric in the Al-Masloukhah adamellite which comprises over 90% of the area is homogeneous and isotropic.

Despite minor shearing of its contact, the Al-Jealani layered basic intrusion behaved as an integral part of the otherwise isotropic adamellite during faulting. This is shown by the lack of distortion of the dacite dyke traces (σ_1 trajectories) which cut the batholith and basic mass.

Contraction joints were formed during cooling of the granitic magma, but these joints did not influence the later Najd stress field.

- (c) The three major wrench faults in the south area have at some period terminated there, although subsequent movements have caused the Um Ergaba fault to propagate a further 16 Kms. north-westward, diverging from its previous course and termination at X (fig. 6-4).

Evidence of a distorted stress field around the tip of the Hamrur and Um Ergaba faults has been preserved by a freakish

fig: 6-4

FORCAST SHEAR ORIENTATIONS



Anticipated conjugate shear fractures.



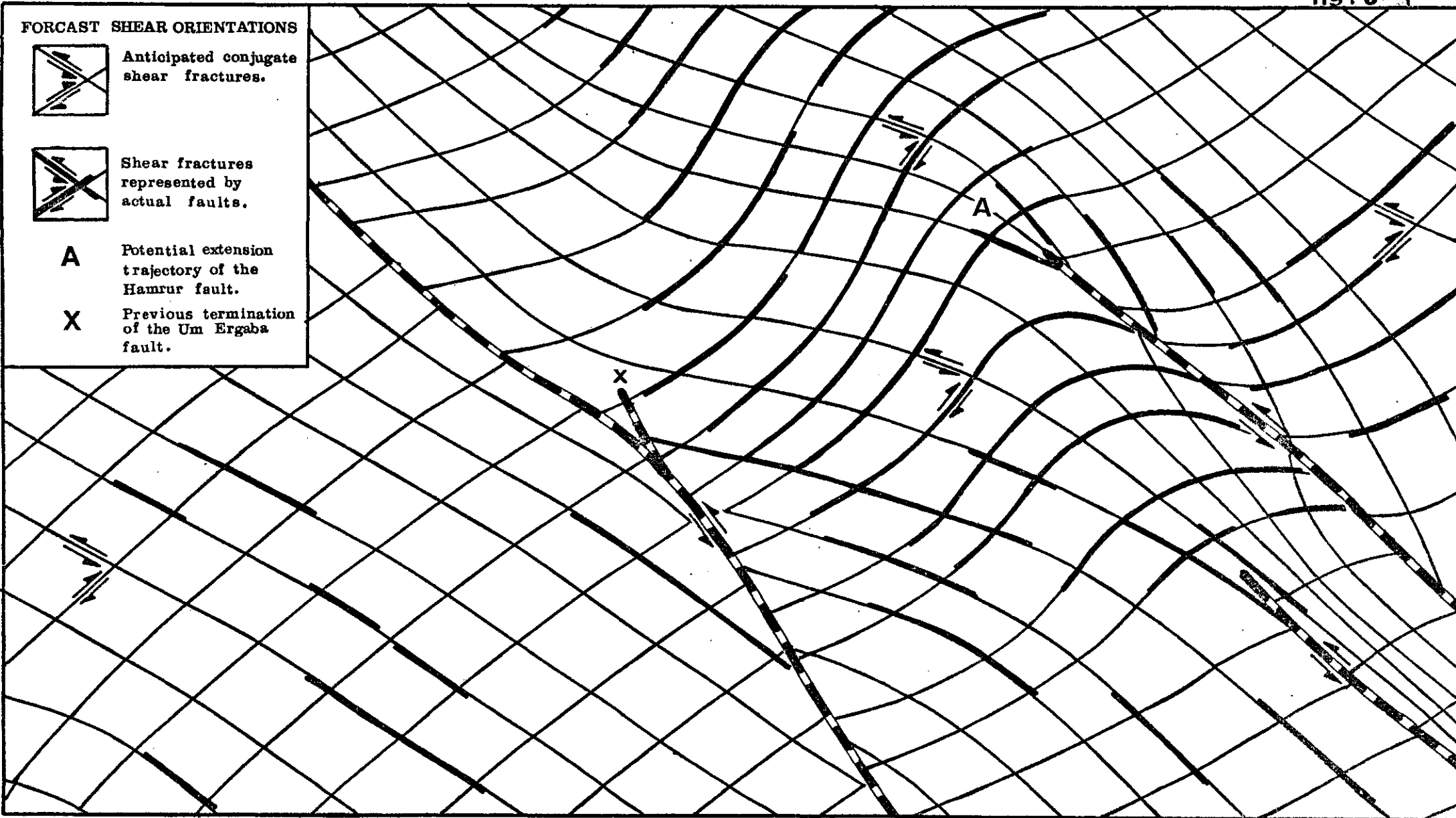
Shear fractures represented by actual faults.

A

Potential extension trajectory of the Hamrur fault.

X

Previous termination of the Um Ergaba fault.



combination of second order faulting and the simultaneous intrusion of dykes into the related, tension fractures.

6.4.5 Relationships of joints and the second order fractures

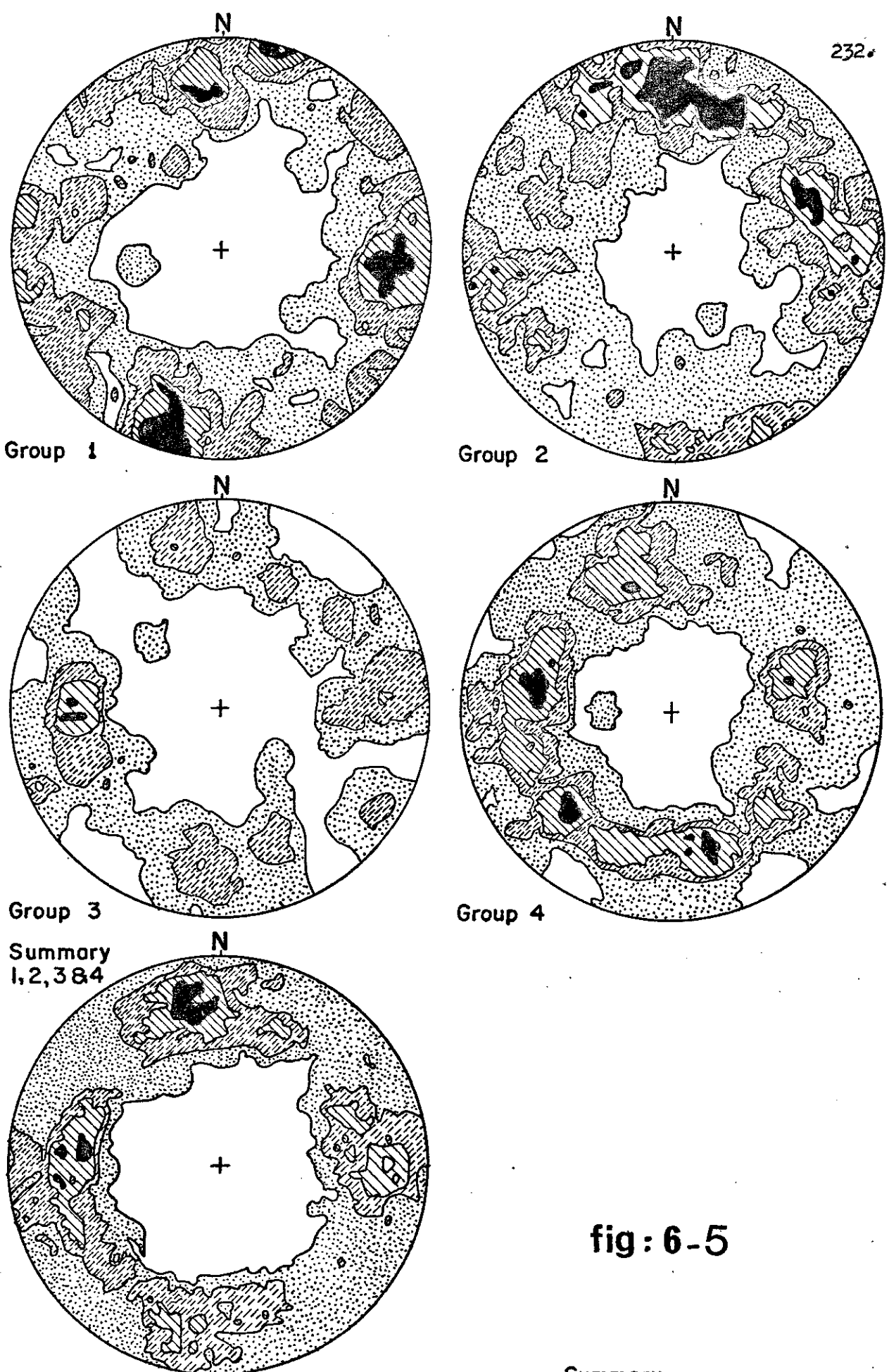
Figs. 6-5 and 6-6, show the stereographic plots and the rose diagram for the joint sets in four separate areas of the district (plate 5). The compound diagram in both figures shows that four main sets of joints occur. Three of the main joint sets coincide with the later Najd east-west tension fractures and conjugate shears. The fourth joint set is a strong set normal to the regional compressive stress orientation during the Najd faulting. It seems possible that this set originated partly as cooling joints in the granite batholith and partly as relaxation joints after the faulting. In the former case the orientation normal to the maximum compressive stress would mean that they remained passive during the east-west Najd compression. Many of the cooling joints in the granite batholith were intruded and "sealed" by granite pegmatites.

6.5 STRESS TRAJECTORIES

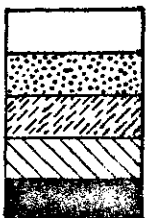
6.5.1 Principal stresses

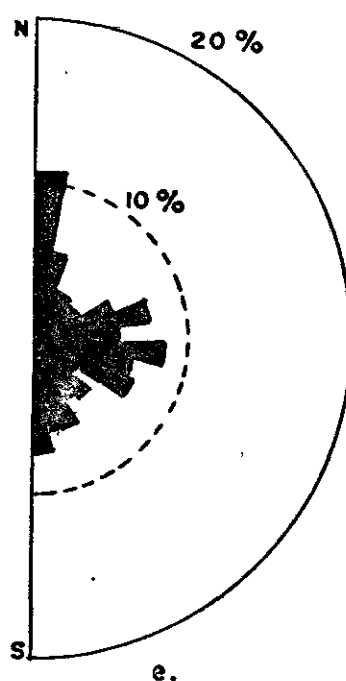
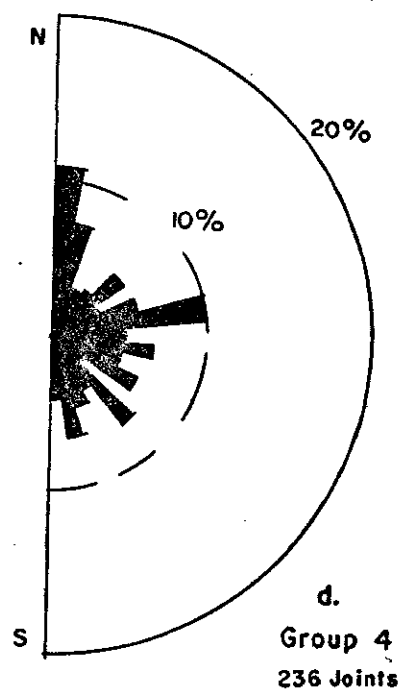
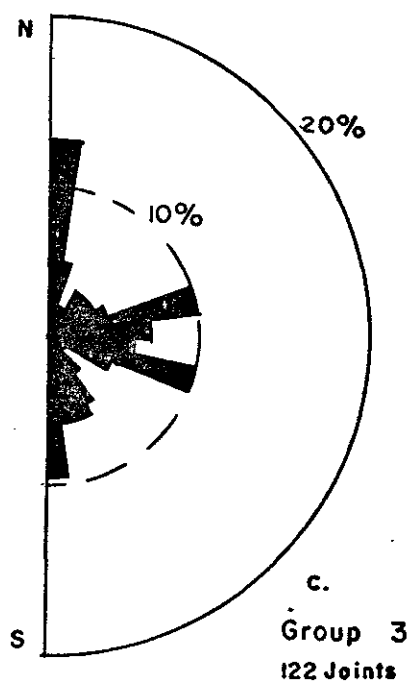
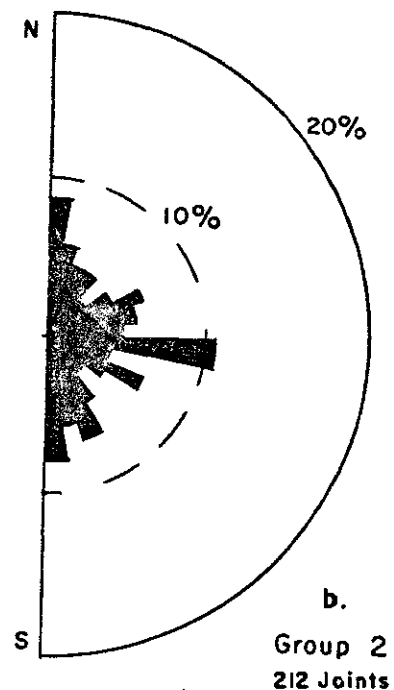
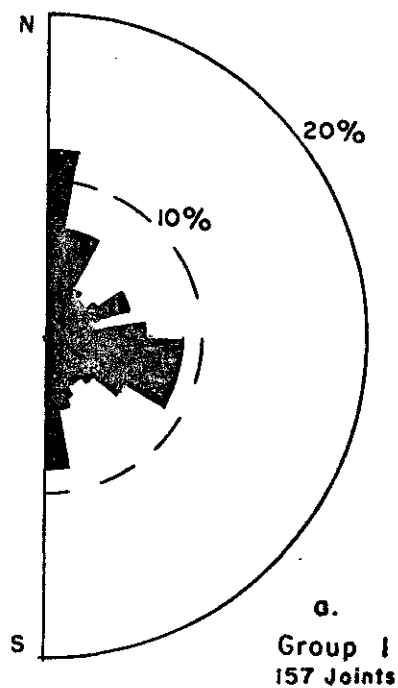
There are three sets of principal stresses, (compressive or extensive) which are orthogonal, and one pair of maximum shearing stresses are oriented at 45° to the maximum and minimum principal stresses.

In the upper crust one of the three principal stresses acts normal to the earth's surface and two parallel with it. In flat or subdued topography one principal axis is therefore approximately vertical and two horizontal. Wrench faults form under conditions in which the maximum and minimum compressive stresses are horizontal



Group 1	Group 2	Group 3	Group 4	Summary Grs. 1 2 3 4
0 - 1/2 %	0 - 1/2 %	0 - 1 %	0 - 1/2 %	0 - 1 %
1/2 - 2 %	1/2 - 2 %	1 - 3 %	1/2 - 2 %	1 - 2 %
2 - 4 %	2 - 3 %	3 - 7 %	2 - 3 %	2 - 3 %
4 - 6 %	3 - 4 %	7 - 11 %	3 - 5 %	3 - 4 %
6 - 10 %	4 - 7 %	11 - 13 %	5 - 7 %	4 - 5 %





Summary, groups 1, 2, 3 and 4
727 Joint readings

Fig: 6- 6

(fig. 6-7).

Thus the four sets of trajectories of σ^1 , σ^3 and the two maximum shearing stresses can be represented in plan.

6.5.2 Construction of stress trajectory in Ad-Dawadmi district

In Ad-Dawadmi, the southern map area where the fracture systems are very well exposed, a palaeo-trajectory system has been constructed from the fracture pattern (fig. 6-8). The plane normal to the least principal compressive stress (σ^3) is the orientation for potential extensional fissures. In this area the extensional fractures have been intruded by a dyke swarm.

Since the maximum compressive stress (σ^1) is horizontal under wrench fault conditions, the traces of the dykes are parallel to the trajectories of the maximum compressive stress. The maximum compressive stress also bisects the angle between related conjugate shears. It is therefore possible to locate σ^1 in localities where two complementary conjugate shears are observed. The average angle between the conjugate shear planes in Ad-Dawadmi is 72° . The angle between σ^1 and each shear plane is therefore 36° (fig. 6-7). Using only the angular relationships of the tensional fractures, whose only movement was dilation, and shears whose sense of displacement is known, it is possible to reconstruct a map of the palaeotrajectories of maximum compressive stress (σ^1), minimum compressive stress (σ^3) (fig. 6-8) and maximum shearing stress (τ) (fig. 6-9).

Using the angle between the maximum shearing stress (τ) and failure surface (S) (9°) and between the maximum compressive stress (σ^1) and failure surface (S) (36°) a map of the anticipated orientations of secondary faults throughout the area was constructed

fig:6-7

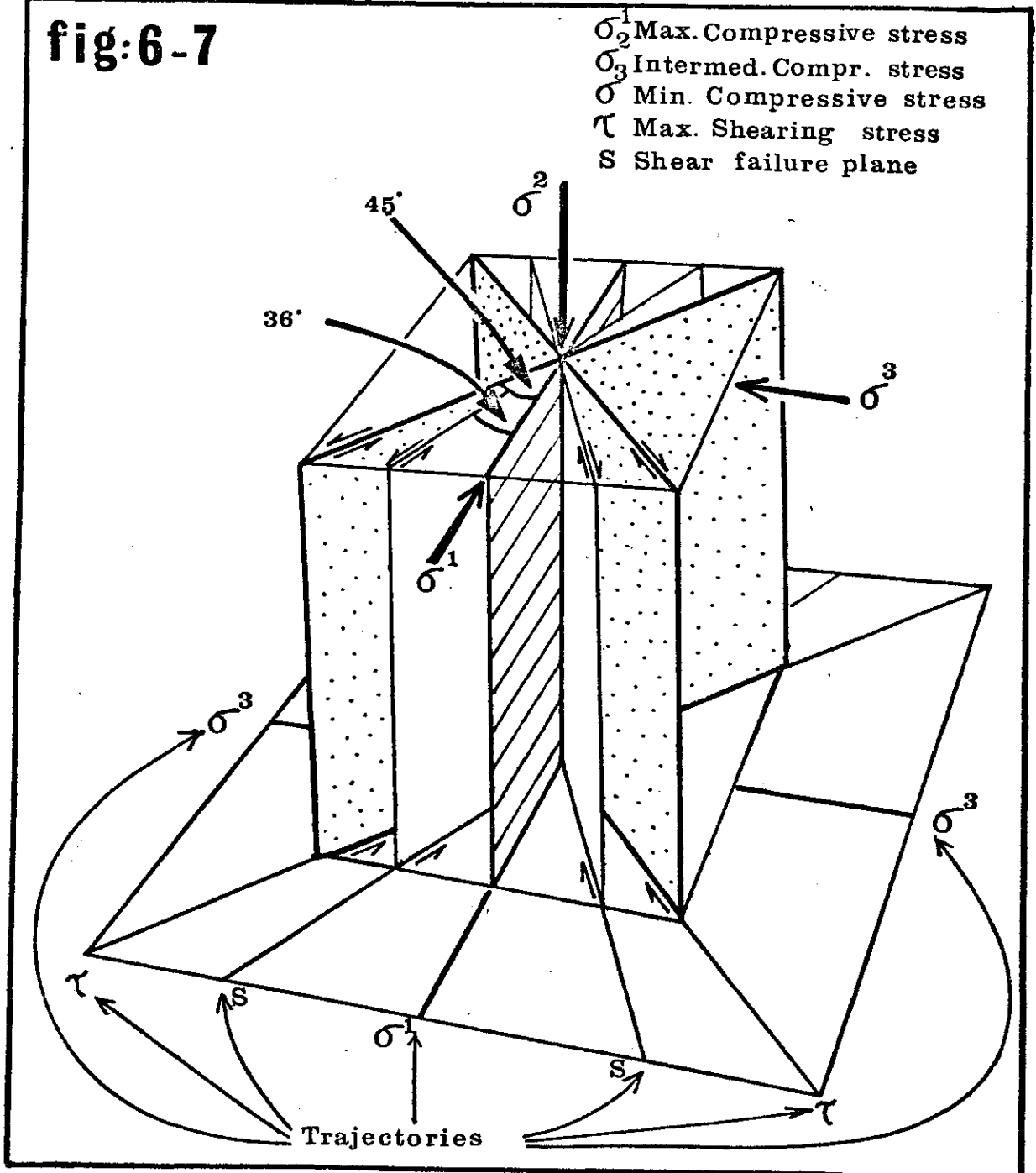


fig. 6-8

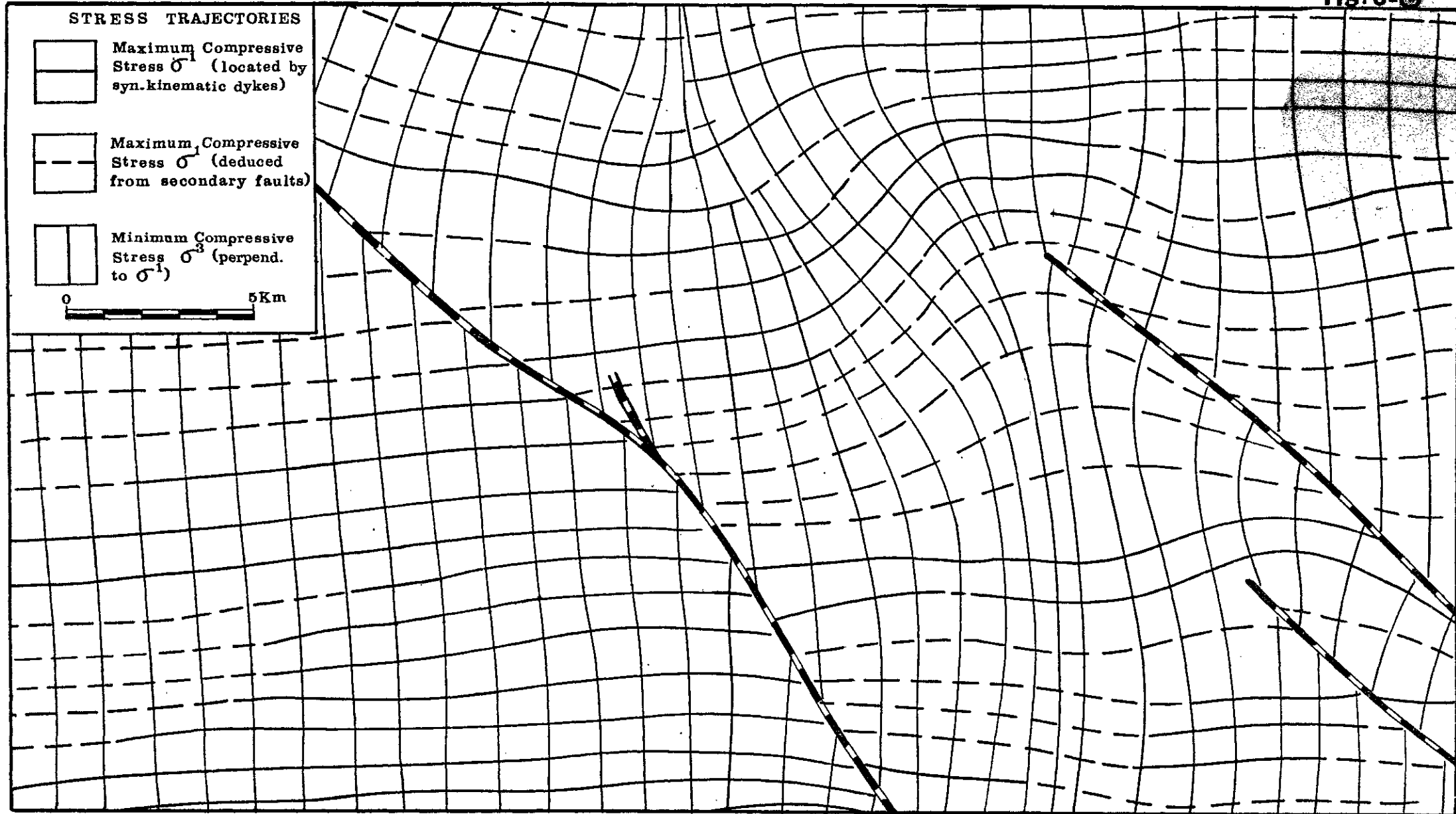
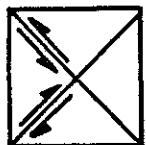


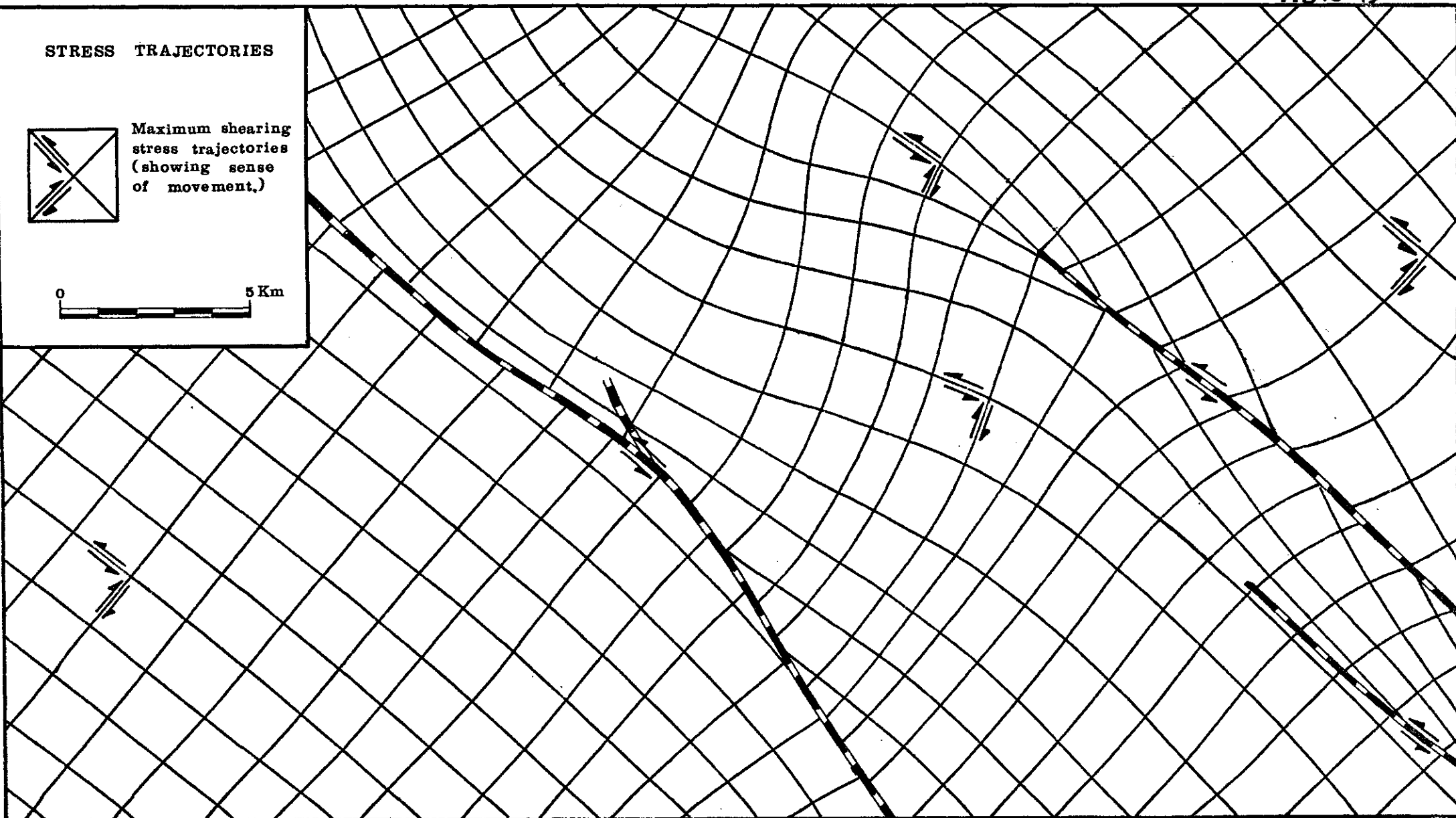
fig:6-9

STRESS TRAJECTORIES



Maximum shearing
stress trajectories
(showing sense
of movement.)

0 5 Km

A horizontal scale bar with alternating black and white segments, representing a distance of 5 kilometers.

(fig. 6-4). This should be compared with faults shown on the geological map (fig. 6-2) with which there is a good correlation.

6.6 RELATIONSHIPS BETWEEN FIRST AND SECOND ORDER FRACTURES

The complex secondary fault system is mainly related to the Hamrur and Saffaga faults, but not the Um Ergabah. The three faults are part of a larger zone of en echelon wrench faults associated with the Najd fault system. Both Hamrur and Saffaga faults end in the area and it seems likely that at some stage the Um Ergabah fault also terminated at X, where it shows localised splay branching and a sudden change of direction.

The sinusoidal northwesterly trending trajectories emanating from the tips of the Hamrur (A) (fig. 6-4) and Saffaga faults represents probable trends for the extension for the two faults. In the event of continued propagation the two faults would take lines diverging or curving from their previous course (fig. 6-3).

It is probable that the north-west deflection of Um Ergabah fault was influenced by the presence, in its path, of the basic mass. No secondary faulting occurred as the Um Ergabah fault extended along the new northwesterly course.

In contrast, stress conditions at the tips of the Hamrur and Saffaga faults were very complicated and resulted in piecemeal failure of the adamellite, perhaps as a result of higher confining pressures. This fracturing may have happened either during the movement of the Hamrur and Saffaga faults or in response to later renewed compression which, under lower confining pressures might otherwise have induced further propagation of the main faults.

It is not possible to deduce the exact age relations of the three faults but since the dykes which are synchronous with the Hamrur and Saffaga secondary fractures are not displaced by the Um Ergabah fault and locally intrude the fault plane, it seems likely that it is older than the Hamrur and Saffaga faults and already crossed the area at the time of dyke intrusion. The Um

Ergaba fault did not disturb the regional stress field indicating that this field was re-established after the extension of the fault had stabilized and before the dyke intrusion.

The main disturbance of the regional stress field was by the Hamrur and Saffaga faults during the intrusion of dykes.

The three first order wrench faults are almost certainly the products of the same east-west compressive stress system, each periodically moving independently to temporarily relieve the stress increase. The concentration of the stress at the tips of the faults as the stresses built up provided a strong inducement for the further propagation (Hamrur and Saffaga) and the deflection (Um Ergaba) of the faults.

6.7 RELATIONSHIPS BETWEEN FAULTS OF THE SECOND ORDER AND DYKES

The dykes invaded the tensional fissures before the relaxation of the compressive stresses and are therefore synkinematic (in relation to this last deformational phase). Locality G-11 illustrates the relationships (fig. 6-10).

The second order shear zone was formed by failure in a local stress system in which σ^1 plunged westward at 10° . Movement on the shear was extral as shown by the displacement of the pre-existing granite-pegmatite dyke. In the vicinity of the shear the orientation of the stress system was modified during movement and the dacite magma utilized the curved extension fracture ($\sigma^1 - \sigma^2$ surface) normal to the least compressive stress σ^3 to gain access. The curvature of the dyke therefore demonstrates the distorted (σ^1) stress trajectory. The magma failed almost completely to intrude the shear indicating that the confining pressure σ^n acting across the shear was greater than the hydraulic pressure of the magma. The only dacite in the shear itself is a series of small lenticular pods which have chilled margins like the dyke. These pods represent the aborted efforts of the magma to enter the shear plane under hydraulic pressure (P^m) against the resistance of σ^n .

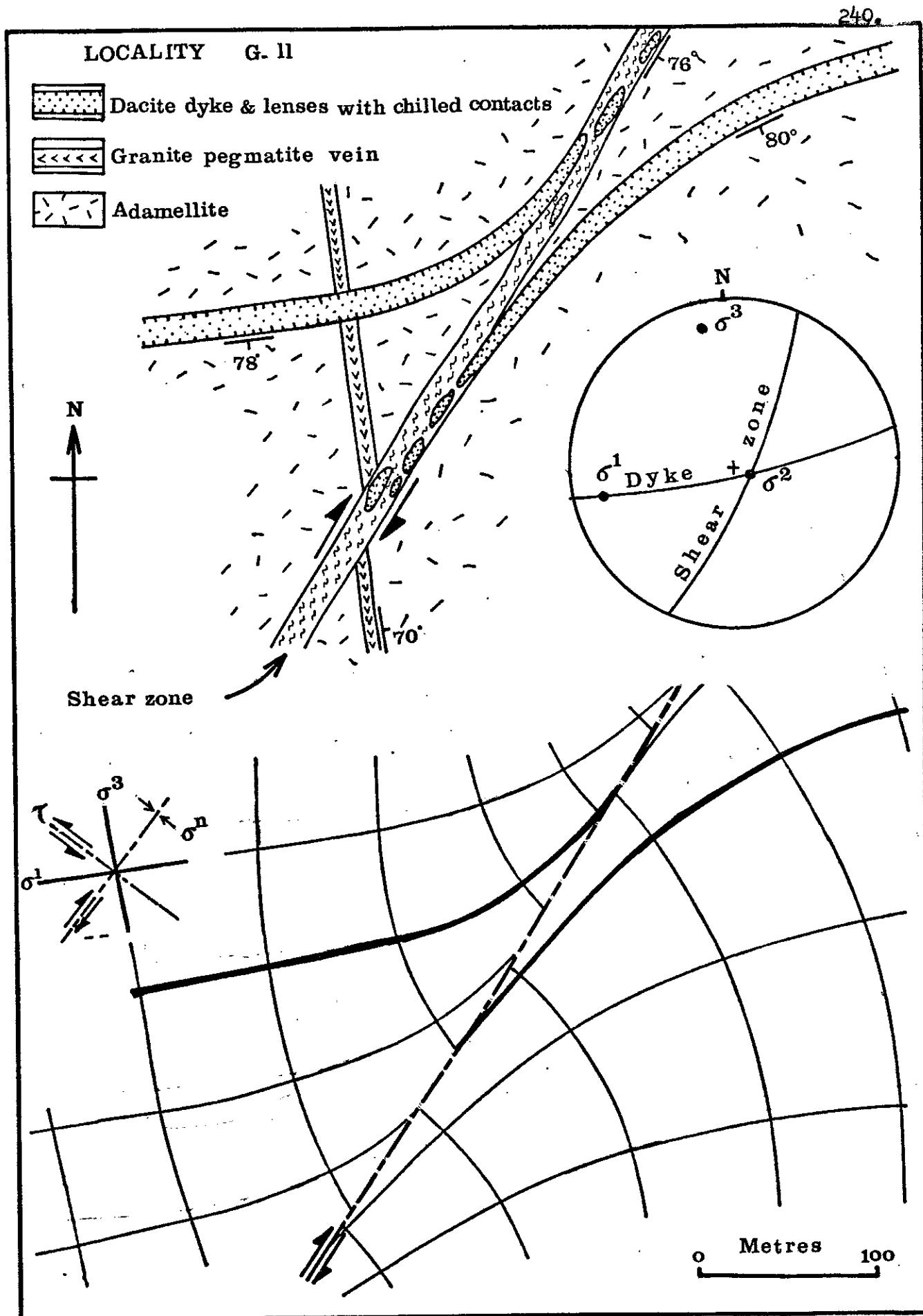


fig:6-10 Stereogram showing principal compressive stress orientations

It can therefore be concluded:

since $\sigma^1 > \sigma^2 > \sigma^3$

and $p^m > \sigma^3$ (dilation of the tension fractures by the intruding magma),

but $p^m \leq \sigma^n$ (component of the σ^1 acting normal to the failure to intrude the shear)

therefore $\sigma^1 > \sigma^n \geq p^m > \sigma^3$.

In addition to the tension fractures formed by the faulting, the dacite magma may have intruded pre-existing joints oriented normal to 3.

6.8 RELATIONSHIPS OF VEIN ORE DEPOSITS TO SECOND ORDER FRACTURES

The hydrothermal ore bearing fluids invaded the fault and fracture systems under hydraulic pressure after the relief of the confining stress σ^n . The fluids, were not therefore subjected to the same constraints as the dyke magma and as a result they entered the shears and extension fractures un-occupied or only partly filled by dykes. En echelon extension veins mainly on the northeasterly trending shears also contain ore bodies (Samrah prospect). The dominant control on the movement of these fluids was the permeability of shears and extension fractures unfilled by dykes. Fig. 6-11 shows the rose diagrams for all ancient workings in the district. The summary rose diagram (e) shows that all the orebodies of the ancient workings occupy the conjugate pair of shears as well as the E-W tension fractures.

6.9 SCALE FACTOR

The construction of trajectories in Ad-Dawadmi was carried out on maps of 1 : 100,000 scale. The results illustrate the disturbance of the regional stress field by the major faults in the area, in particular the Hamrur fault. Movements on the second order faults in turn disturbed local stress fields in their vicinity (locality G-11, fig. 6-10), in the same way as the regional field was affected by the first order faults. This disturbance led to minor third order

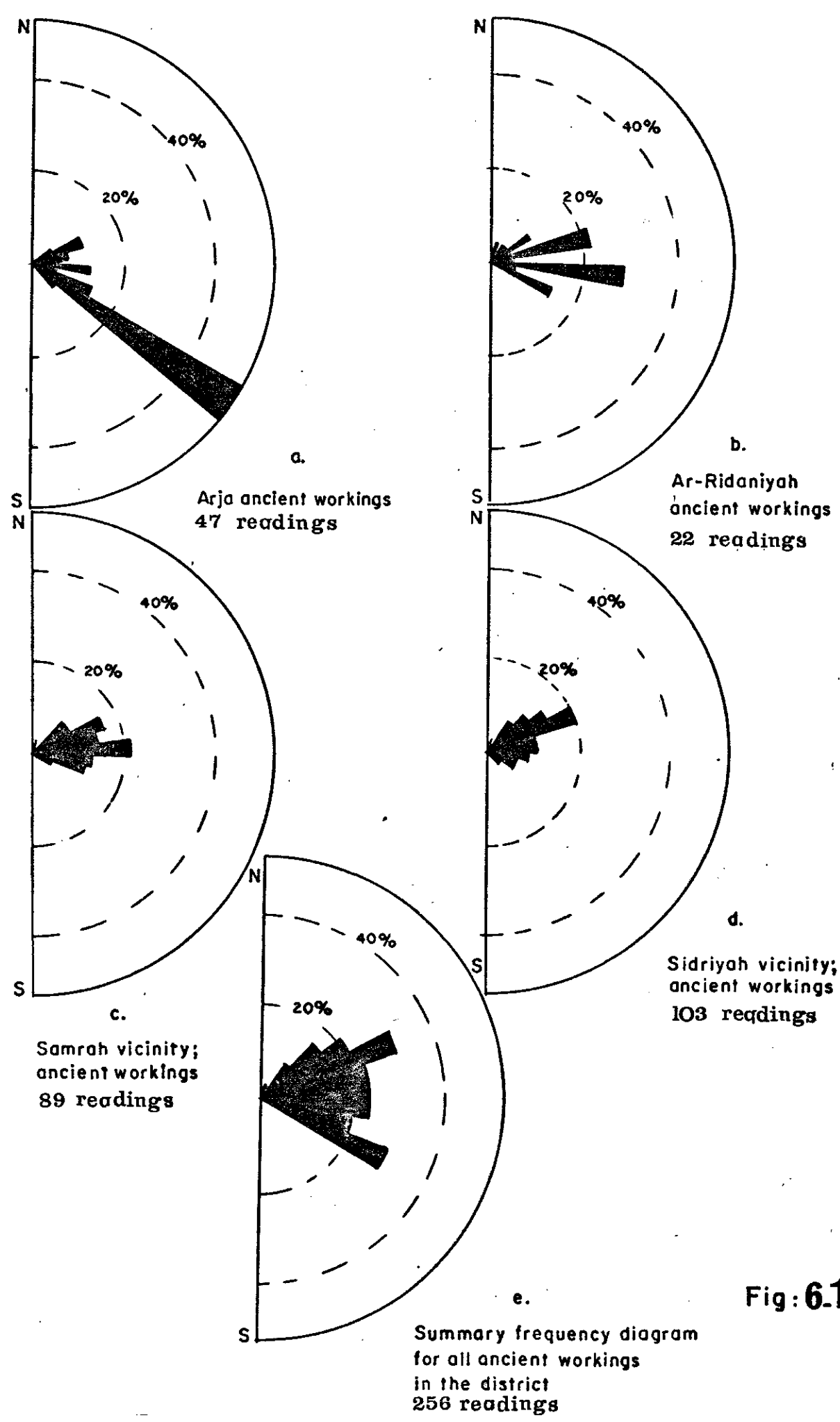


Fig: 6.11

fractures adjacent to second order faults.

On a regional scale, the entire Najd Fault System across the Arabian shield might be amenable to approximate stress trajectory analysis. The system shows many of the characteristics of major wrench faults in other parts of the world. These include the truncations and direction changes which are thought to represent pauses during episodic propagation and spasmodic movements on the fault lines. One of these is seen in Ad-Dawadmi on the Um Ergaba fault.

A suitably exposed fault system in isotropic rocks is amenable to stress trajectory analysis of fracture traces from a regional scale to the scale of a single exposure.

6.10 CONCLUSIONS

The hydrothermal Zn-Pb-Ag vein mineralization in Ad-Dawadmi district is structurally controlled along faults and fractures developed in the granitic batholith. The fracture systems, particularly those which are well exposed in the south on a terrain of subdued relief are amenable to fracture analysis.

The stress trajectory analysis provides a useful analytical method for the elucidation of the fracture systems at all scales from regional to those of individual exposures.

The second order faults and extensional fractures, usually curved, are most commonly developed near the ends of major wrench faults. Not all major wrench faults, however, have second order faults associated with them.

The secondary fracture systems associated with the Hamrur and Saffaga faults correspond closely to the theoretical model for stress conditions in the vicinity of the end of a wrench fault formed under uniaxial compressive stress. In making comparison with the model, allowance must be made for the (9°) angle between the maximum shearing stress (τ) and failure surfaces (S) which are represented by the actual faults.

In any one locality one member of each conjugate shear pair dominates to the exclusion of its complement. Locally, the complementary shear later took over and displaced its predecessor as movement on the major fault continued.

The regional stress field in Ad-Dawadmi has been re-oriented near the tip of a first order wrench during the fault movements. The whole fault pattern of the district can be explained by the local disturbance of a single regional stress field in which the compressive stresses acted east-west. The three major wrench faults entered the area from the south.

The Hamrur and Saffaga terminated in the area while the Um Ergabah now ends 16 kms northwestward, but its movements and propagation were spasmodic, and a previous termination from which it diverged can be seen south of the layered basic mass.

The homogeneous fracture pattern confirms that the adamellite and the incorporated basic mass behaved as an isotropic medium during faulting, the pre-faulting joints being passive or sealed by granite pegmatite veins.

Outside the batholith fault patterns have been influenced by the rock fabrics in the schists and trajectory construction is not possible.

The dyke swarms were "syn-faulting" and intruded the tension fractures because the confining stresses across the second order shears (σ^n) were in most cases greater than the hydraulic pressure of the magma.

The hydrothermal quartz-sulphide veins were emplaced post-faulting. The mineralizing fluids used the faults and the extension fractures to gain access and veins have formed in shears and extension joints unoccupied by dykes.

CHAPTER 7

VEIN-TYPE MINERALIZATION IN GRANITE

7.1 INTRODUCTION

The vein-type mineralization within the granite in Ad-Dawadmi district is restricted to a belt about 10 Km wide trending N-S. It lies approximately in the central portion of the batholith and extends from Arja mines in the north to (PL-100) in the south. The total number of ancient prospects is about 150 (Plate 1).

The majority of workings in these ancient mines are in the form of longitudinal caved-in trenches 1-6 m in depth. Deep shafts and stopes are present only in few of these ancient mines, particularly in Samrah where a depth of over 70 m was reached by the ancients with linking crosscuts and narrow stopes. All the ancient mines are localized along fractures which controlled the mineralization. These show a dominant northeasterly trend, but an east-west trend is also present. Intersections of both types of fractures commonly provide the loci for mineralization.

Brecciation is ubiquitous along zones of fracturing throughout the whole district. Three generations of quartz were introduced in these zones. The second generation was associated with the main bulk of ore deposition together with chlorite, calcite and sericite. Both the first and last quartz generations were practically barren. The last is a white comb quartz that cements fragments of the former two stages of quartz, the wall rock, and the shattered sulphide minerals (fig. 7-1 a, b and c). Occasionally microdiorite dykes were intruded in the fracture zones prior to quartz-1 and mineralization, subsequently they were brecciated and behaved as host for the sulphide and gangue minerals (Samrah).

The predominant ore minerals as identified by ore microscopy, X-ray diffraction and EPMA are Zn-Pb-Ag sulphides and sulphosalts, including sphalerite, galena, polybasite, pyrargyrite, argentian tetrahedrite (freibergite), acanthite, stromeyerite and native silver.

Other sulphides associated are: pyrite, chalcopyrite and minor amounts of arsenopyrite, while pyrrhotite and individual grains of millerite occur in the basic rocks of Samrah mine. The iron oxides magnetite and hematite are of localized occurrence.

The mineralized veins show brown stained outcrops which are prominent against the surrounding ground. Within the leached oxidized zone hematite, limonite, hemimorphite, malachite, cerrussite (minor, identified in hand specimen) and black manganese oxides were identified.

The common gangue minerals in order of decreasing abundance are quartz, chlorite, calcite/carbonates, epidote, sericite and serpentine.

7.2 HISTORY OF MINING

Remains of the ancients, apart from dozens of workings, are represented by ruins of villages, tailing dumps, pottery, grinding stones, charcoal and slag dumps.

Carbon 14 activity of charcoal collected by Quin (1964) from the slag left by the ancients and analyzed by the radiocarbon dating lab. of Kaman Instrument Inc. in Austin, Texas, gave ages before A.D. 1950 of 1214 ± 68 and 1188 ± 57 years. Fragments of glass studied by the Corning Museum of Glass (1965) indicated an Islamic period which could date anywhere from the 8th to the 13th century A.D.

Ancient slag samples analysed spectrographically showed a high lead content. Globules of native lead 1 mm in diameter could be seen in the slag, which may suggest that the ancients recovered only the silver and not the lead.

A pre-Islamic mining period in the district is possible, but the evidence is lacking.

7.3 PREVIOUS WORK

Several geologists investigated the main ancient mines, particularly Samrah, and accounts are given by: Twitchell (1932), Bogue (1954), Quin (1964), Theobald (1966 a and b) and (1972), Mytton (1965) and Kiilsgaard (1968).

Eijkkelboom (1966) located, investigated and sampled all the ancient prospects in the district.

The geology of Samrah mine and the vicinity was mapped from aerial photographs by Theobald. He logged and carried out trace element geochemical investigations of the drill cores from DHL. He also investigated the wadi sediments in Samrah and the vicinity for trace elements. Kiilsgaard carried out an evaluation study of Samrah mine based on 18 boreholes drilled on the mine by the U.S.G.S.

Regarding the other ancient mines in the district, Meaton (1971) carried out an exploration program consisting of surface trenching and sampling. This was followed by drilling 12 holes on nine favourable sites.

During 1971/72 an economic feasibility study of the Samrah ancient mine was conducted under the guidance of Prof. G.R. Davis. Mineralogical examination on ten fresh drill cores from deflections in existing holes was conducted by Al Shanti (1971) and Morrissey (1971), followed by metallurgical bench tests at the laboratories of Warren Spring in England and Metallgesellschaft A.G. in Germany. The work was co-ordinated by Northgate Exploration Ltd. at Dublin, Ireland, into an economic feasibility study by Schultz (1972).

7.4 PRESENT WORK

The examination of the mineralization at Samrah and other ancient workings was undertaken to fulfill the following objects:

1. To prepare a detailed map of Samrah prospect of a scale of 1 : 1000.
2. To log the drill holes and study the cores megascopically and petrographically.
3. Study the environment of ore deposition and to work out the genetic control.
4. To study the distribution of silver.
5. To make a systematic study of all the ore and gangue minerals from the textural and chemical point of view.

7.5 GEOLOGICAL SETTING

The well developed fracture system within the granitic rocks in the central portion of the batholith, furnished favourable channel-ways and sites for hydrothermal ore deposition. The predominantly brecciated granitic rocks within the zones of fracturing are generally the host for the ore deposits. However, within the mineralized belt, inclusions of the pre-existing country rocks were frequently transected during drilling. Younger, pre-mineralization basic dyke intrusions were also encountered. All these rocks have been brecciated in zones of fracturing and have participated as hosts to ore deposits. Many ancient mines are localized at sites of intersection of fractures with country rock inclusions (Pl-107, Pl-108, Pl-77, Pl-54, Pl-91 etc.). Occasionally the ore deposits are localized along fractures which form the boundary between the granite and the layered basic rocks, (Samrah, XL-34 and XL-45).

The three quartz generations within zones of fracturing form a characteristic hydrothermal quartz-sealed breccia. In situ fragments of a particular wall rock are numerous with extensive hydrothermal alteration. Commonly a halo of fine chlorite fringes such fragments (fig. 7-1b). Breccia fragments are of variable size, from microscopic to about 5 cm., angular or subangular to rounded depending on transportation within shear zones and subsequent hydrothermal corrosion.

After its deposition, the mineralization suffered deformation and subsequent partial mobilization. Mineral textures have been complicated by this later tectonism.

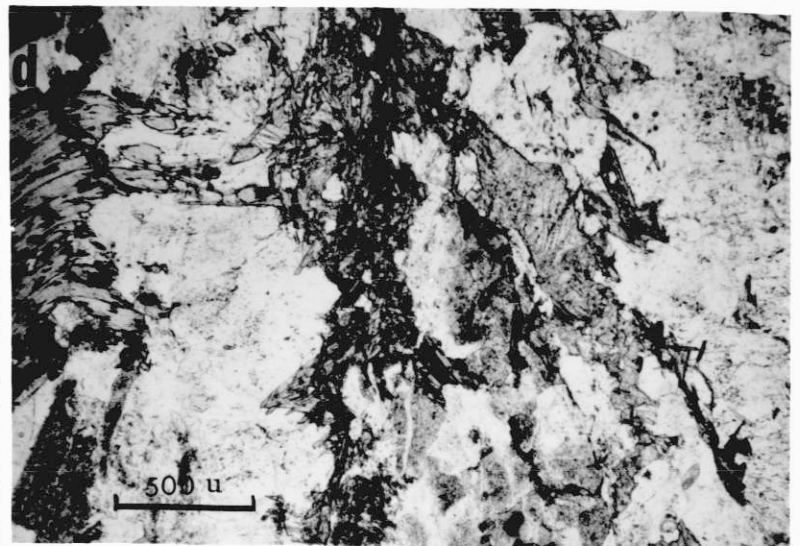
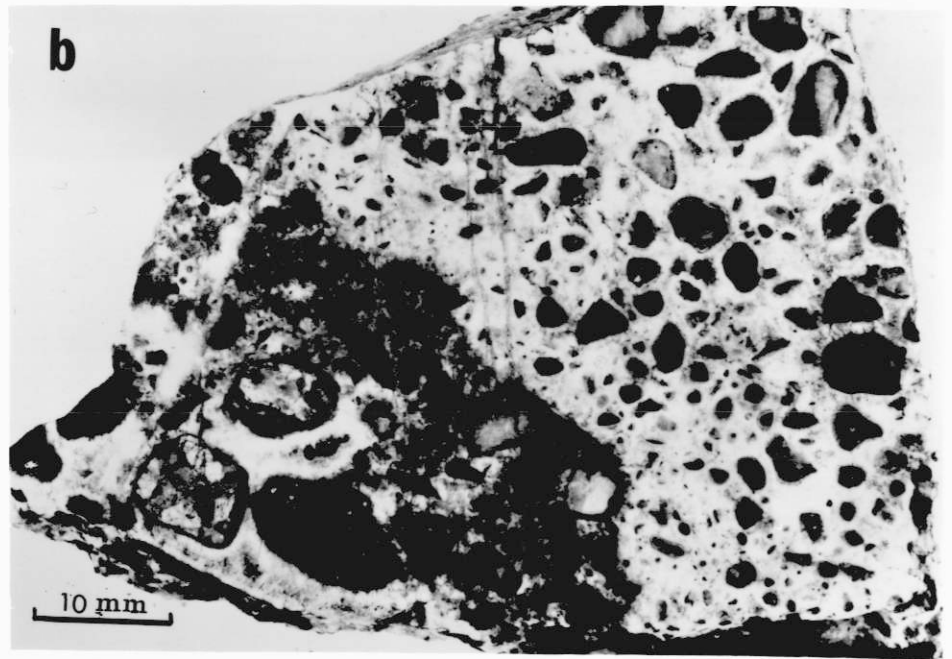
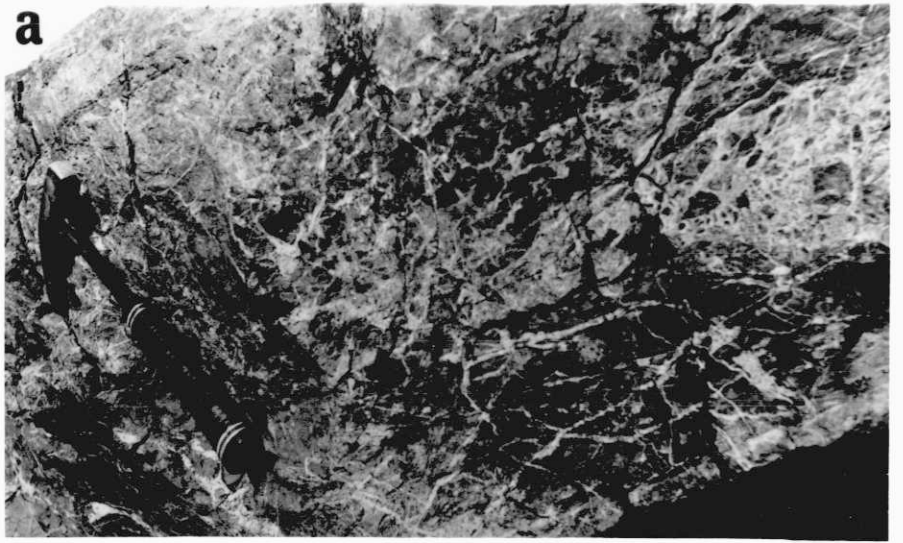
The fracture zones exhibit a width of 15-50 m of hydrothermal alteration of the wall rocks. The rocks are laced with a network of quartz veins and stringers that are commonly associated with chlorite and calcite. Extensive epidotization and sericitization of the feldspars and chloritization of the biotite is exhibited by the granitic rocks in the fracture zones.

Vein-Type Mineralization

Figure 7-1

Brecciation

- a - Typical brecciation on vein outcrops within the fracture zones. Brecciated wall rock fragments and adamellite in the central part (light) and microdiorite (dark). The first and last quartz generations (white) are shown. The second quartz generation is grey mixed with the wall rock fragments. Locality, Samrah prospect.
- b - Polished surface of a quartz sealed breccia. Fragments of the earlier breccia including quartz, chlorite, calcite and sericite, cemented by second generation of quartz and gangue. The third quartz generation (white) formed the last cementing material. The fragments of the second breccia are surrounded by an aureole of chlorite. Locality, Sumairah (PL-98) prospect.
- c - Northeast face of ancient slope in Samrah prospect. The central portion (light coloured) is quartz rich breccia, both hanging and foot walls consist of microdiorite dyke rocks cut extensively by thread-like stringers of the third quartz generation (hardly seen in the photograph).
- d - Thin section in brecciated rock. Quartz, chlorite and calcite occur in microveinlets. Samrah DHL at depth of 39 feet from the surface.



7.6 THE MINERALIZED SITES

A total of 150 mineralized sites occur within this belt. All have been explored by the ancients, but only several were mined, as indicated by extension and depth of ancient workings, mine tailings, ancient ruins and slag dumps.

Ten mines have been investigated recently by drilling, where a total of 30 holes were drilled, totalling 4867 metres. These are:

<u>Mineralized site</u>	<u>No. of drill holes</u>	<u>Metres drilled</u>
1 - Samrah	18	3624
2 - Materah (GV-19)	3	327
3 - Ulow (GV-21)	1	80
4 - Sumairah (PL-98)	2	174
5 - PL-44	1	110
6 - Sidriyah (PL-107)	1	120
7 - PL-108	1	120
8 - PL-77	1	101
9 - PL-59	1	106
10 - PL-24	1	105
Total	30	4867 metres

Only four of these, namely, Samrah, Materah, Sumairah and PL-44 showed silver mineralization as indicated by the chemical analyses on the cores. Microscopically, silver minerals were recognized in all four prospects. All other cored prospects showed disseminated or veined pyrite with localized specks of other sulphides: galena, sphalerite and chalcopyrite.

Detailed mineralogical studies were carried out essentially on Samrah because of the availability of abundant core and the relative abundance of ore and other minerals. Comparison of the mineralogy and textures of the mineralized zones in all these prospects demonstrates that they exhibit similar paragenesis and textural relationships.

The structural setting is identical for all prospects, Mineralization is structurally controlled in quartz veins and bodies of quartz-

sealed breccia occurring within northeasterly trending fracture zones and less commonly in easterly trending ones.

7.6.1 Samrah Mine

6.1.1 Lithology and structure

Samrah ancient mine is situated at the extreme south edge of a disrupted segment of the Al-Jéalani layered basic mass, in contact with younger late- and post-kinematic granitic rocks. The mineralization is structurally controlled along a $70^{\circ}/65^{\circ}$ - 70° shear zone with E-W tensile fractures branching from the south side of the main shear. The shear zone shows dextral strike-slip movement with a horizontal displacement of about 80 metres. This is shown by dislocation of the intermediate and basic dykes in the mine area (Plate 4). The tension fractures are emphasized by dolerite and fine grained microdiorite dykes commonly in a sigmoidal en echelon pattern.

These dykes were emplaced predominantly in the tensile fractures, but suffer diversion into the shear fractures at intersections. Within the mineralized zone, these dykes were strongly brecciated and cemented by quartz, calcite, chlorite and the associated sulphide minerals (fig. 7-1 b,d).

The primary lithology of the basic rocks is composed of plagioclase-pyroxene, plagioclase-pyroxene-olivine and plagioclase cumulates which have suffered hydration and amphibolitization in differing degrees. In the contact zone with granite these rocks are feldspathized to intermediate rocks of diorite and granodiorite composition (ISA 39 and 52). In the fracture zones, quartz, calcite, chlorite and the associated sulphides cement fragments of these basic and intermediate rocks.

The granitic rocks are even-grained alkali-calcic and brecciated in the fracture zones. The plagioclase is strongly saussuritized and has a light green colour, the alkali feldspar is strongly clouded. Biotite is altered to chlorite and the altered rock fragments are sealed with stringers of quartz, calcite, chlorite and sulphides.

Summary of geological history of Samrah

Time	Igneous activity	Metasomatic changes	Tectonic products	Vein filling	Alteration products
young				Comb quartz	
				Fracturing	
				Galena	
				Fracturing	
				Galena and silver	
				sulphosalts,	
				Sphalerite,	Chlorite,
				Magnetite + Hematite	
				pyrite	
	Microdiorite and			Quartz, carbonate, chlorite.	sericite and epidote.
7	Dolerite in tension en echelon fractures		All rocks have undergone brecciation within the zones of fracturing		Local serpentine
6	Aplite-pegmatite				
5	Microdiorite and quartz microdiorite dykes.		producing quartz and carbonate sealed breccia		
4	Post-kinematic granite stocks and dykes				
3	Late-kinematic adamellite				
2	Syn-kinematic adamellite & granodiorite	Only inclusions left within younger granitic rocks			
1	Basic layered rocks	Amphibolitization & possible granodioritization			
Old					

The loci of intersection of shear and tension fractures probably furnished the favourable conduits for mineralizing fluids as indicated by extensive ancient stoping at these locations and by drilling. The mineralization along tension fractures gradually decreases away from the main shear.

The repeated movement along the northeasterly shear fractures is indicated by the various generations of quartz and by the strong brecciation of the early two generations. Mutual replacement textures are common.

6.1.2 Ancient Workings

These constitute two main stopes 90 x 15 and 40 x 30 m at a depth of about 15 m as well as many shafts, stopes and trenches, the deepest of which reaches a depth of 75 m. These workings are surrounded by about 20,000 tons of waste in the form of dumps which conceal the bedrock (Plate 4).

An ancient village is situated at the southeast side of the mine workings where ruins of houses and mine dumps are extensive. Slag heaps lie a few hundred metres to the southwest of the mine where the ancients possibly smelted the ore.

6.1.3 Geophysical Survey

Resistivity, self-potential and induced polarization survey methods were carried out by Argas (1966) on the mine area. In conclusion no indication of a shallow ore body was given except for a conductive axis which roughly conforms to the main shear zone, and in part with the ancient workings situated along the tension fractures.

6.1.4 Geochemical Investigations

The geochemical investigations carried out on the wadi sediments of Samrah mine and the vicinity by Theobald and Thompson (1971) exhibited anomalies for lead, zinc and silver over the ancient workings, the ancient ruins, waste dumps and the ancient slag areas (fig. 7-2).

The zirconium depletion in the mine area was interpreted as due to alteration of rocks especially over the west mine workings. The

present author believes that the zirconium depletion over the west workings and other places is largely due to primary lithological compositions.

The trace element study of the Al-Je'alani layered basic intrusion indicated a prevailing low zirconium content for basic rocks (fig. 4-11, 13, 16) relative to granitic rocks. The zirconium content in the basic rocks of Samrah mine and those in the mass are of similar range. This is confirmed by the fact that the area showing the minimum zirconium content correspond to the areas covered by the layered basic rocks (fig. 7-2 and Plate 4).

6.1.5 Exploration drilling

A total of 18 drill holes and 10 deflections off some of these drill holes have been sunk under the ancient workings. These explored the 400 m length of the mineralization to a vertical depth of about 200 m from the surface. All the holes ended in basic rocks after crossing the mineralized veins (figs. 7-3, 4, 5 and 6) from collar positions in either basic or granitic rocks (Plate 4).

(Fig. 7-3, 4, 5 and 6) show deflection logs across the mineralization zones.

6.1.6 Mineralogy

The primary sulphide mineral assemblage comprises sphalerite, pyrite, galena and less common chalcopyrite. Arsenopyrite is rare. The main silver minerals are polybasite, pyrargyrite and argentian tetrahedrite. Acanthite, stromeyerite and native silver are of subordinate amounts. Magnetite and hematite occur in minor amounts in addition to the sulphides.

The main non-metallic gangue minerals are quartz, calcite and chlorite. The paragenetic sequence is illustrated in page 282.

1.6.1 Silver minerals

The silver minerals identified in Samrah ores are the antimony rich sulphosalts: argentian tetrahedrite (freibergite), polybasite

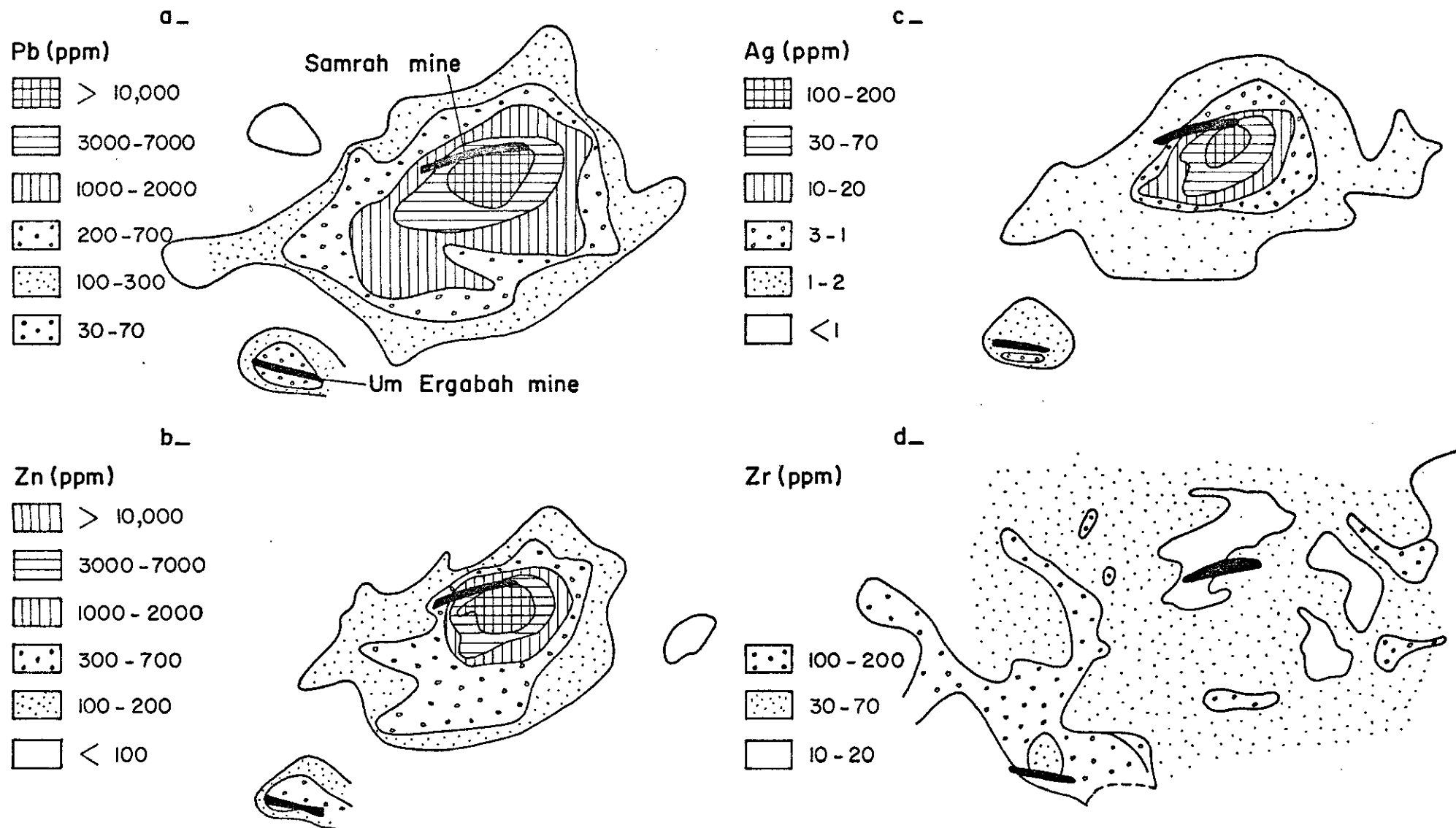


Fig:7-2 Geochemical Maps of Samrah mine and vicinity showing the distribution Pb, Zn, Ag, and Zr in the Wadi Sediment (30—80 mesh).Theobald (1971)

SAMRAH MINE
WEST DEFLECTIONS
DDH NO 1

By
A. M. AL SHANTI

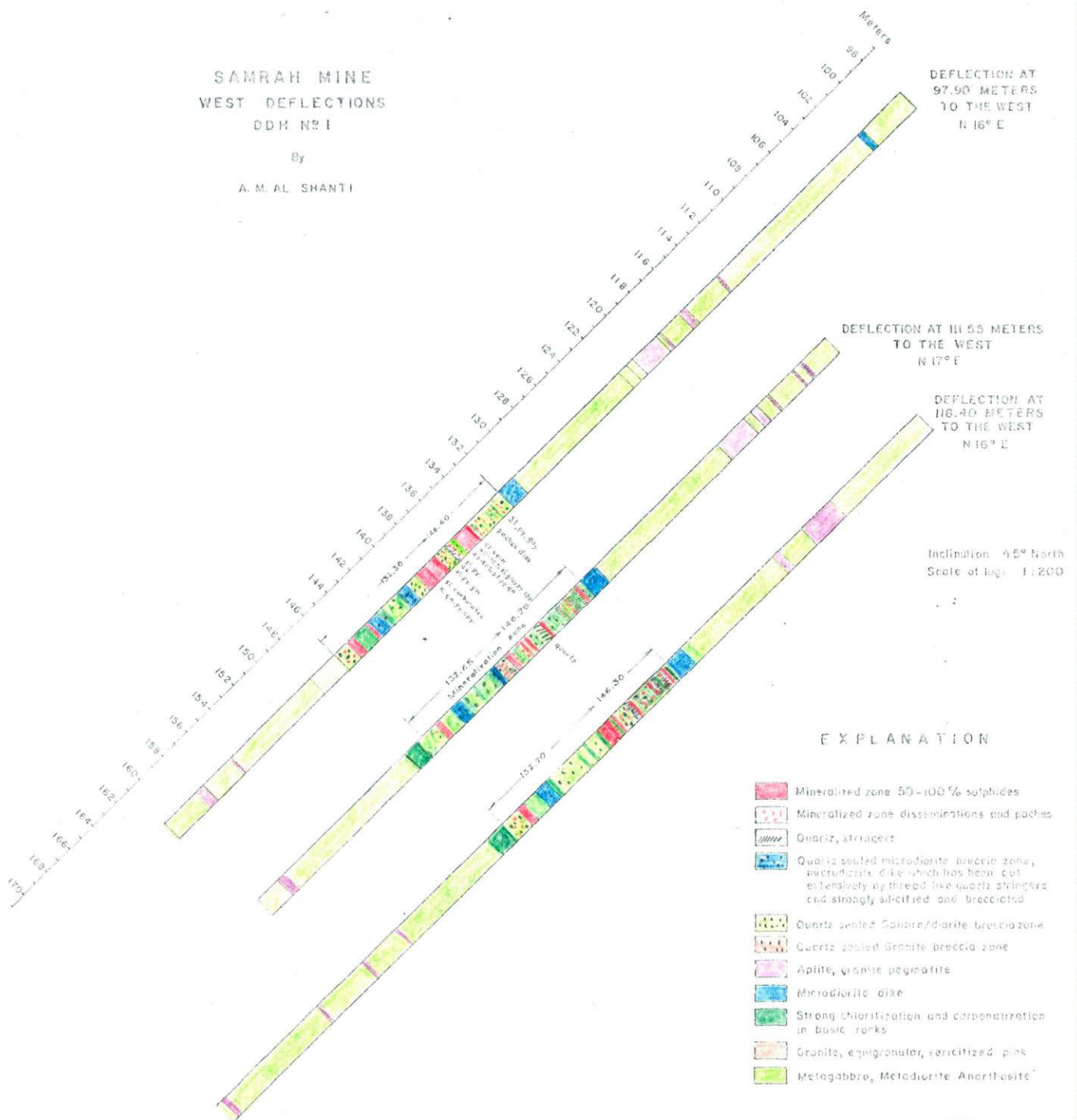


Fig: 7.3

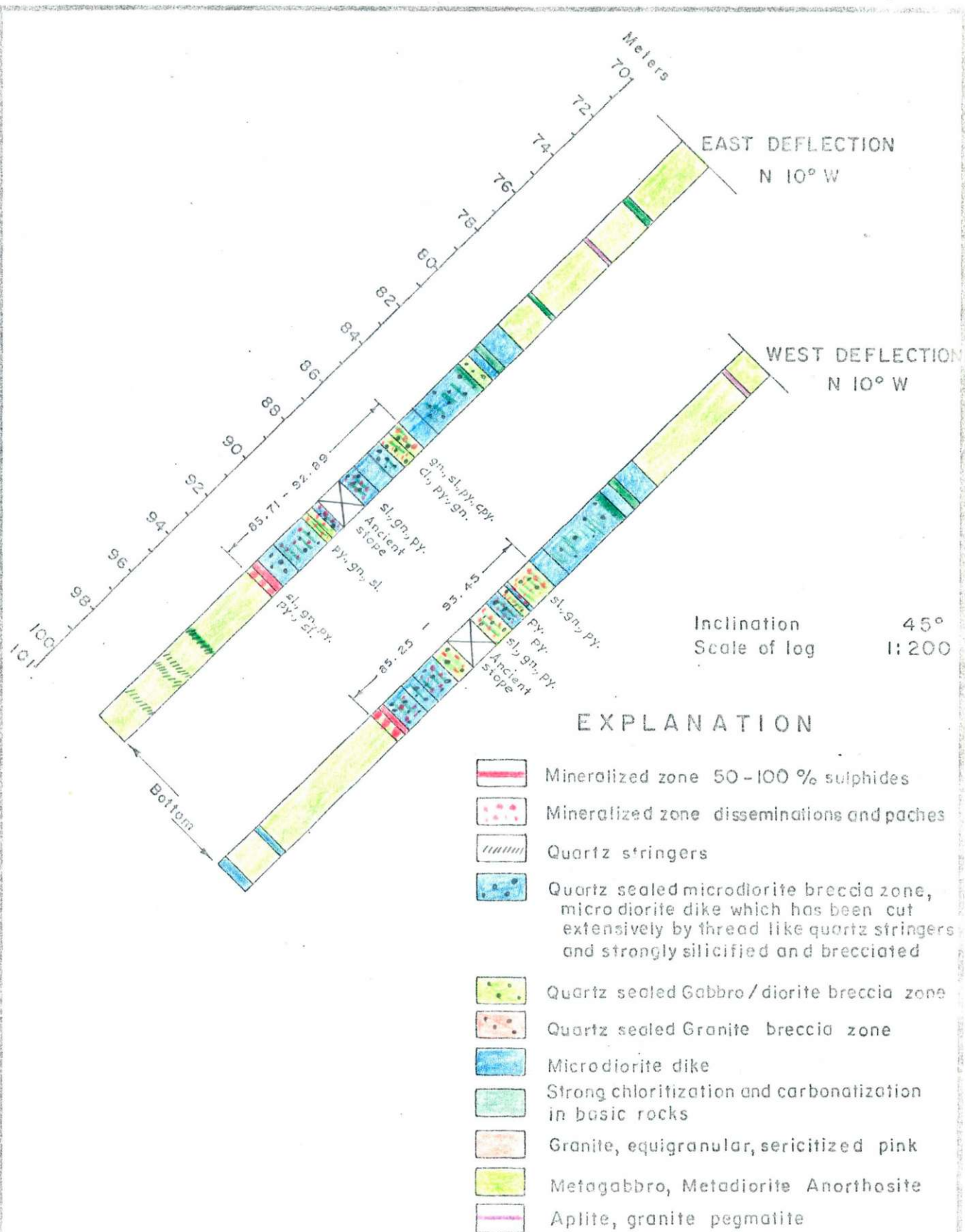


Fig: 7-4

SAMRAH MINE

EAST AND WEST DEFLECTIONS

DDHN: S-5

By

A. M. AL SHANTI

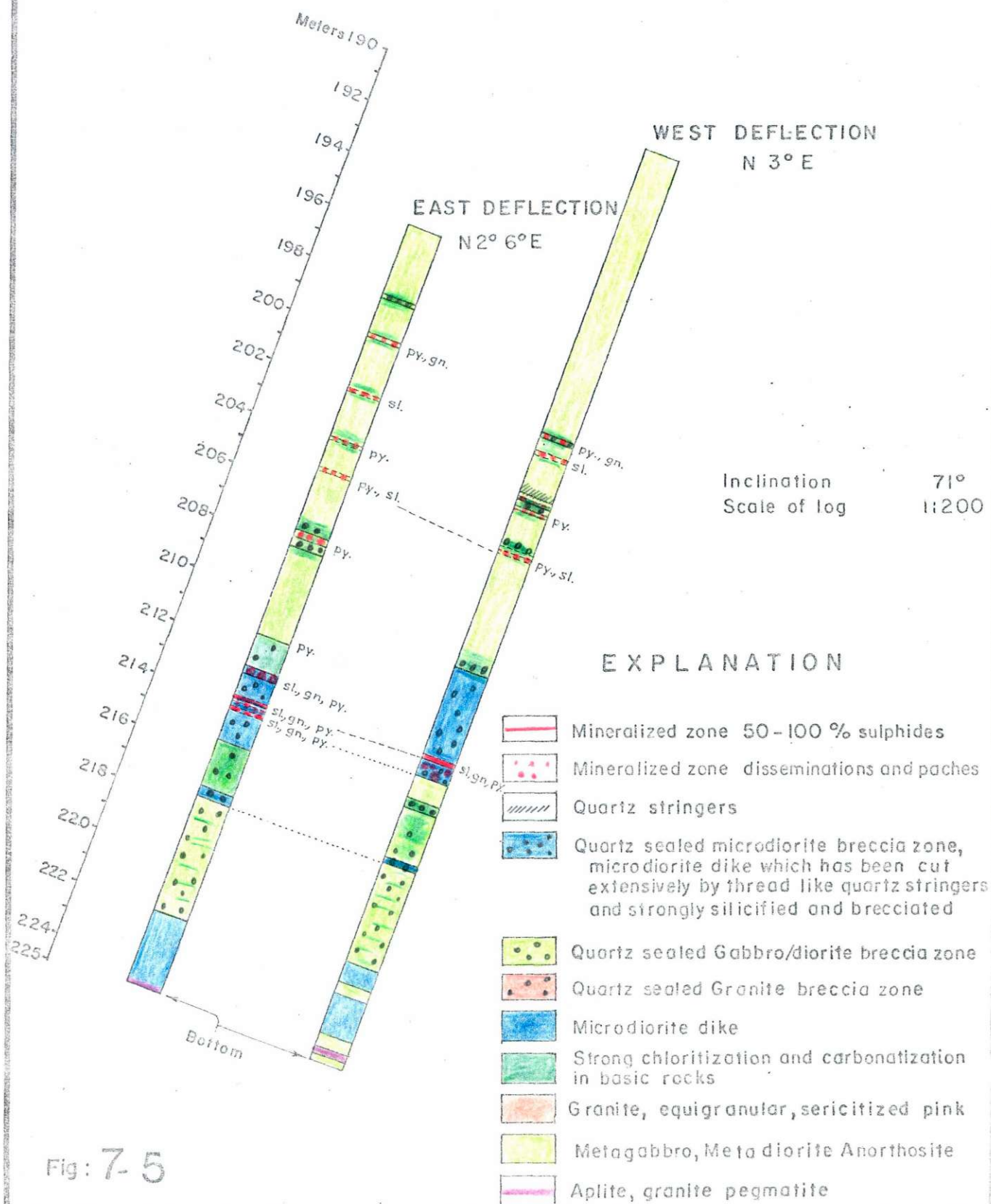
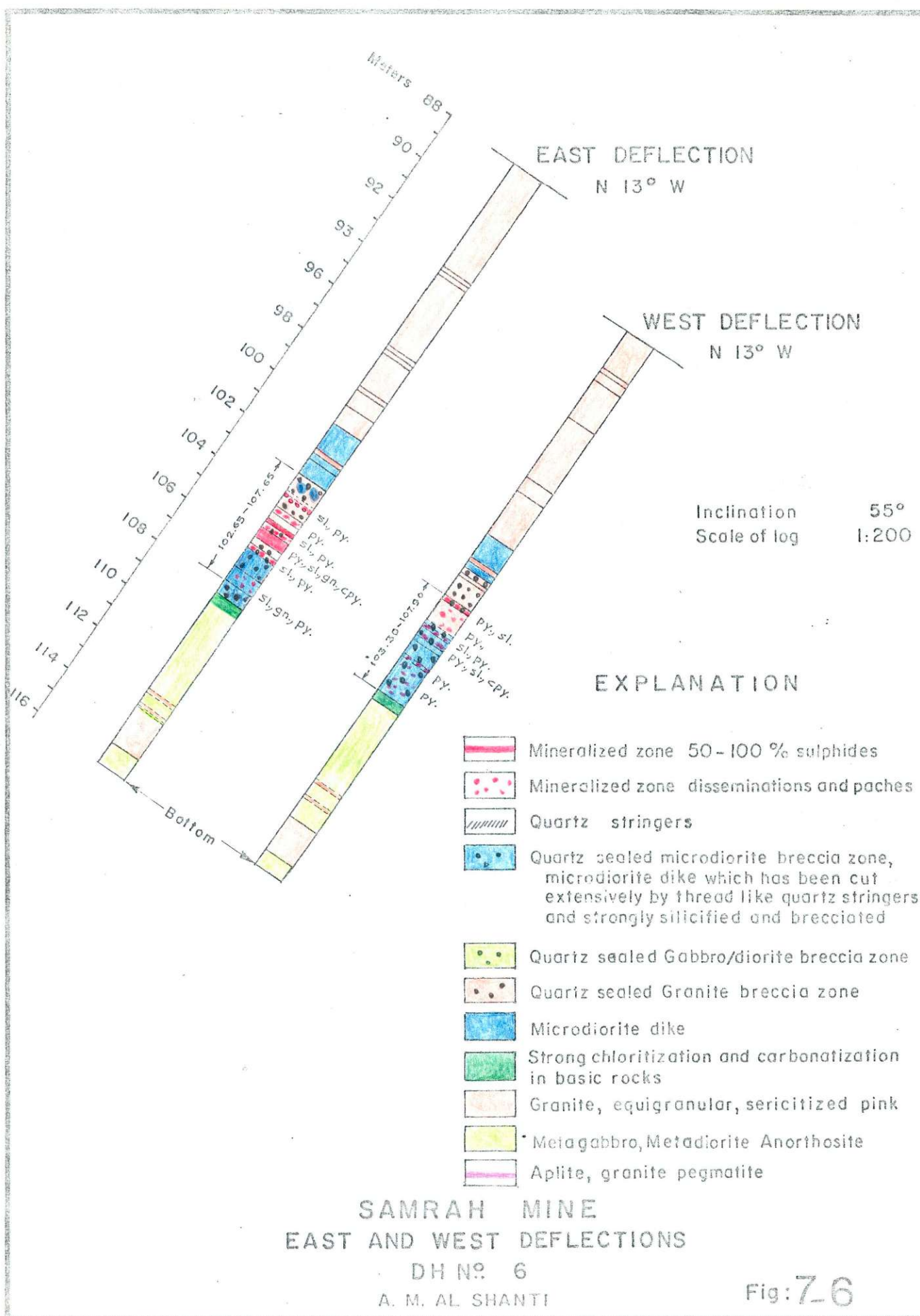


Fig: 7-5



and pyrargyrite. The sulphides present are acanthite and stromeyerite. Minor amounts of native silver are also present. The silver minerals are associated with the main ~~silver~~ sulphides of the ore, chiefly with galena and to a lesser extent with sphalerite. Association of silver minerals with pyrite is less common. Silver, predominantly present in native form as grains up to 1.5 mm in size disseminated in gangue specially calcite. The size range of the silver minerals is from about 200 μ m to 10 μ m with most of the grains 50 - 100 μ m.

1.6.1a Polybasite $(\text{Ag, Cu})_{16}(\text{Sb, As})_2\text{S}_{11}$

Polybasite is the dominant silver mineral throughout Samrah mineralization. It was detected by microscopic study and confirmed by electron probe microanalysis and by X-ray diffraction.

Polybasite is associated with galena, and less commonly with sphalerite and pyrite.

In the composite aggregates of sulphides where galena occurs as a major sulphide in the form of a granulated and irregular interstitial phase; polybasite commonly replaces it marginally. Polybasite grains in this type of occurrence attain their maximum grain size (up to 1200 μ m) and show distinct associations with acanthite, in which polybasite is always external. Minute "dendritic" stringers of chalcopyrite, usually separates the two silver phases (fig. 7-7 a and c) and frequently cross-cut the acanthite in all directions. The fringing polybasite is copper impoverished and one grain analysed contained 3% Fe. This mineral association and textural relationships suggests that polybasite is breaking down to give acanthite and chalcopyrite.

Polybasite is also observed to fill fractures and cracks developed within other sulphides and associated gangue (fig. 7-8 g).

Polybasite occurs also in massive coarsely crystalline galena (S-7, As-633, As-634) in the form of rounded, oval, or elongated grains which range in size from 10 μ m to 100 μ m, with the majority of grains less than 50 μ m. Compound grains of two silver sulphosalts are common (fig. 7-8b). The relatively large grains of polybasite are usually segregated along galena grain boundaries (fig. 7-9b) in contrast to

the small rounded ones which are included within the grains (fig. 7-9 a and b).

In sphalerite, polybasite occurs as inclusions of $30\mu\text{m}$ size or fills in fractures, where it is frequently associated with other silver minerals (fig. 7-8h). In pyrite, polybasite also occurs in fractures and inclusions (fig. 7-7f) but in smaller grains relative to those in sphalerite (fig. 7-8g).

In polished section, polybasite is light grey with a greenish tint ($R_{540} = 31.2$ approximate mean), moderately to strongly anisotropic, with localized red internal reflections in air and in oil. It invariably decomposes in the microscopic light beam or electron probe beam to give minute ($\sim 3\mu\text{m}$) rounded blebs or short wires of native silver (fig. 7-8 a and b). Simultaneously, polybasite is converted to a very soft, grey, poorly reflecting substance, that appears to be isotropic and lacking in internal reflections. The end products of the decomposition are thought to be acanthite and native silver. Al-Shanti (1971), Morrissey (1971). This is in accordance with the observations of Stephens (1931).

The textural relationships of polybasite towards other non-silver sulphides indicate its later formation and replacement of them (fig. 7-7 b and c).

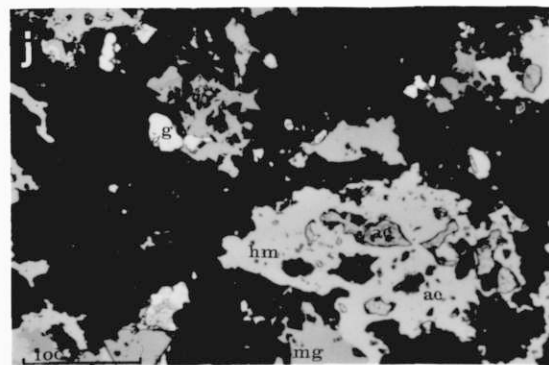
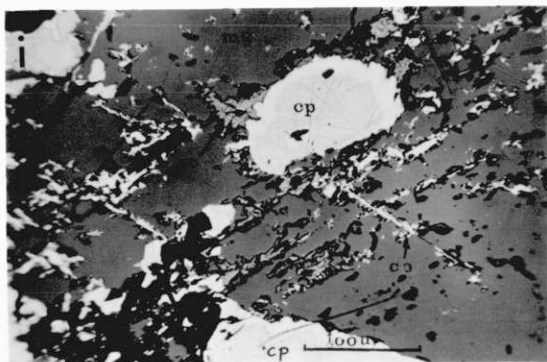
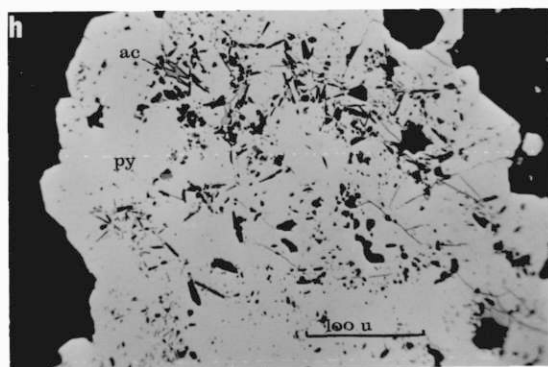
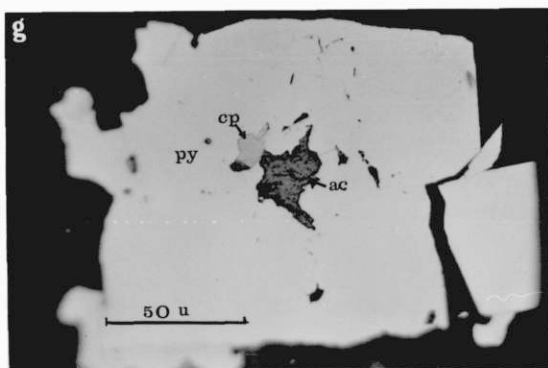
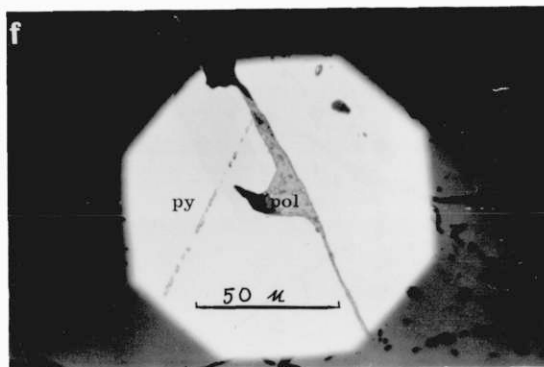
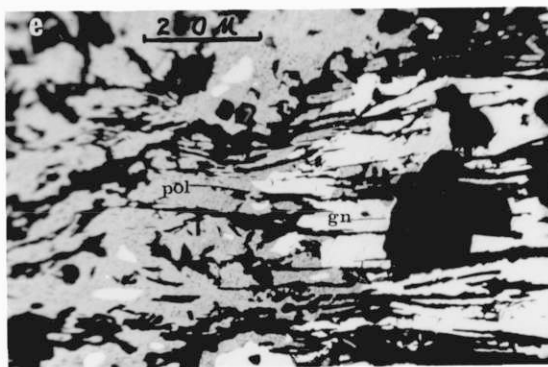
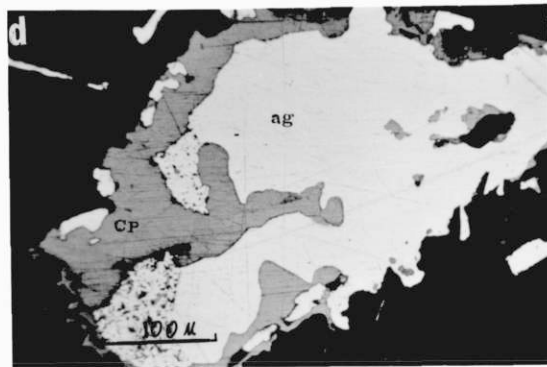
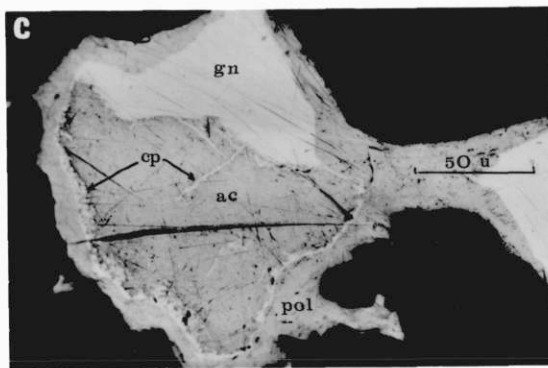
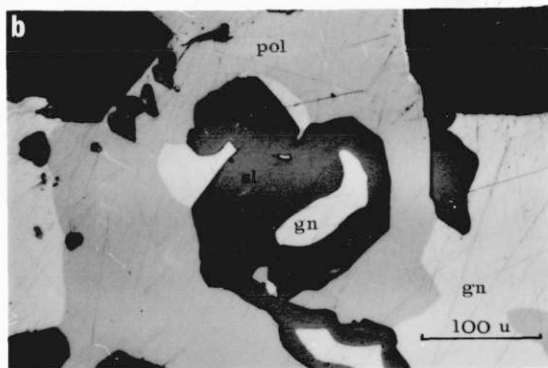
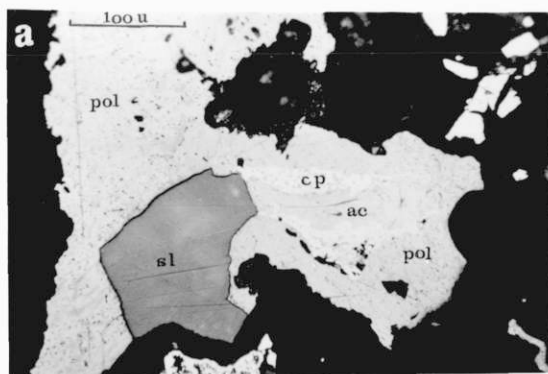
The chemical variation in polybasite is given in (Table 7-1 and fig. 7-10) in which the copper content ranges between traces and 1.66% and the arsenic from traces to 0.89%. It is the antimony rich member of the series polybasite - pearceite ($(\text{Ag}, \text{Cu})_{16}\text{Sb}_2\text{S}_{11}$ and $(\text{Ag}, \text{Cu})_{16}\text{As}_2\text{S}_{11}$). This variation is explained by the work conducted by Peacock and Berry (1947) where they concluded that in both end members copper replaces silver in considerable and varying amounts and in polybasite there may be also a substantial replacement of Sb by As. They indicated also that there is no complete solid solution from arsenian polybasite to pearceite and proposed two distinct species rather than end members of one series.

Vein-Type Mineralization

Figure 7-7

(a to j taken in reflected PPL from polished sections from Samrah prospect DH.1 and 6)

- a - Polybasite (pol) embaying sphalerite grain (sl) and probably replacing it. The polybasite in the centre decomposed to acanthite (ac) and chalcopyrite (cp). Chalcopyrite forms a rim around acanthite. 1SA-437, depth 143 mrs.
- b - Polybasite (pol) replacing galena which in turn replaced sphalerite (sl). 1SA-455, depth 148.0 mrs.
- c - Galena (gn) with marginal polybasite (pol) probably replacing it. Polybasite is breaking down to acanthite (ac) and chalcopyrite (cp). Chalcopyrite forms microstringers bordering both silver phases and crossing the acanthite. 1SA-437, depth 143.0 mrs.
- d - Native silver (ag) with marginal chalcopyrite (cp). S-8 depth 103.85 mrs.
- e - Polybasite (pol) extensively replacing galena (gn), both occupy parallel microfractures. 1SA-437, depth 143 mrs.
- f - Polybasite (pol) filling cracks in deformed pyrite (py). S-9, depth 105.20 mrs.
- g - Acanthite (ac) and chalcopyrite (cp) inclusions in pyrite (py). S-9, depth 105.20 mrs.
- h - Abundant inclusions of sphalerite, chalcopyrite, acanthite and gangue enclosed in pyrite. The inclusions have variable shapes and sizes. S-9, depth 105.20 mrs.
- i - Extensively fragmented magnetite (mg) and cemented by chalcopyrite (cp), gangue (black) and acanthite (ac). 1SA-444, depth of 146 mrs.
- j - Magnetite (mg) extensively replaced by hematite (hm) and gangue. The hematite contains inclusions of acanthite (ac). Native silver grains occur in the gangue. 1SA-454, depth of 150 mrs.



Vein-Type Mineralization

Figure 7-8

(a to h are taken in reflected PPL
from samples from Samrah prospect)

- a & b A grain of polybasite (pol) in galena matrix before (a) and after (b) breaking down to blebs of native silver (black) by the light beam of the microscope. As-634, DH.1, depth 132 mrs.

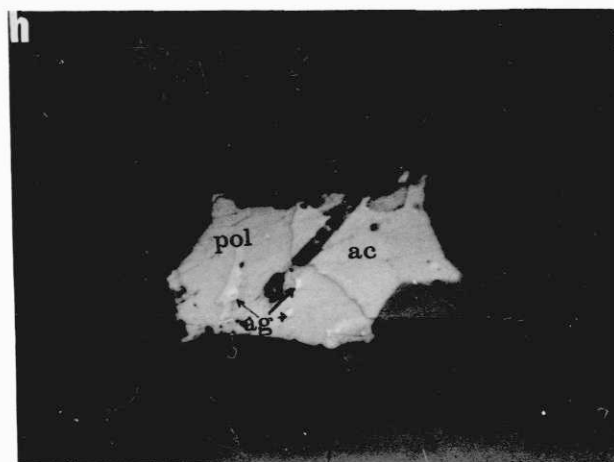
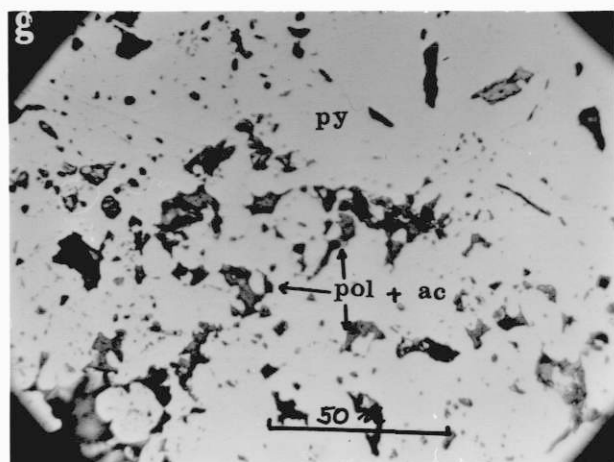
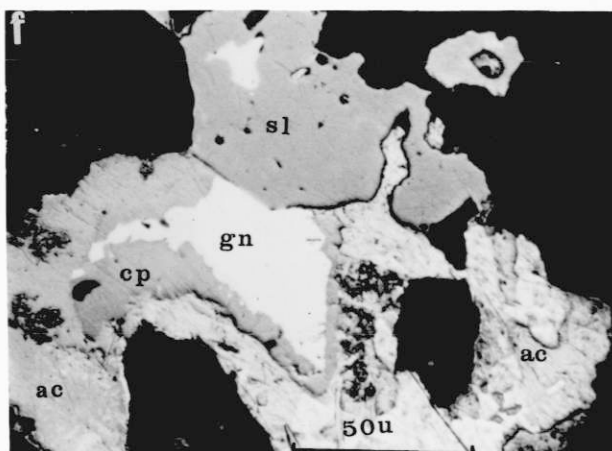
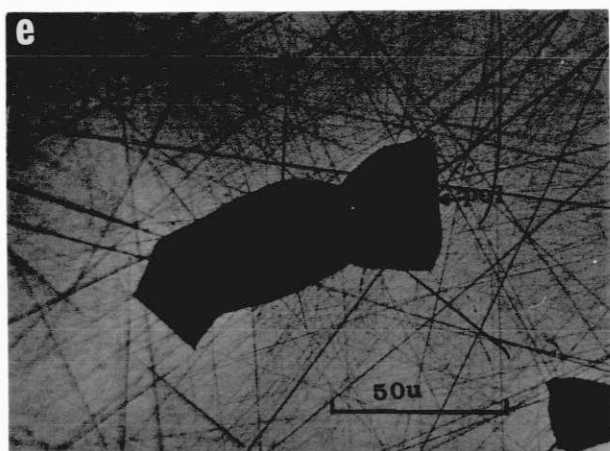
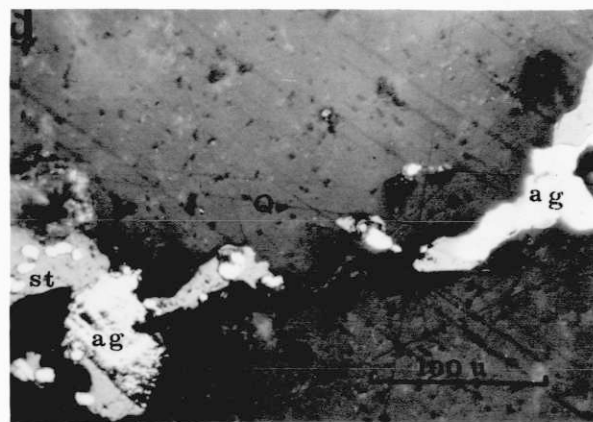
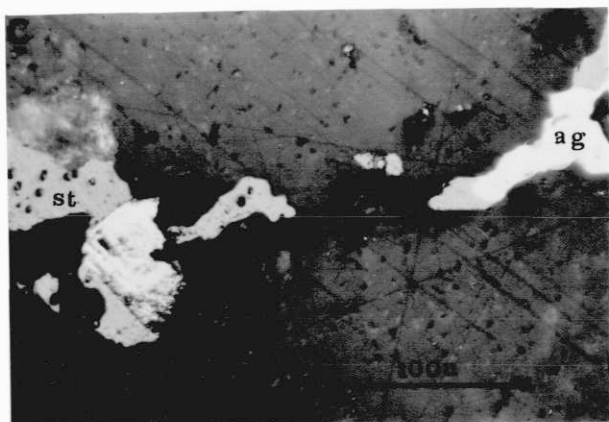
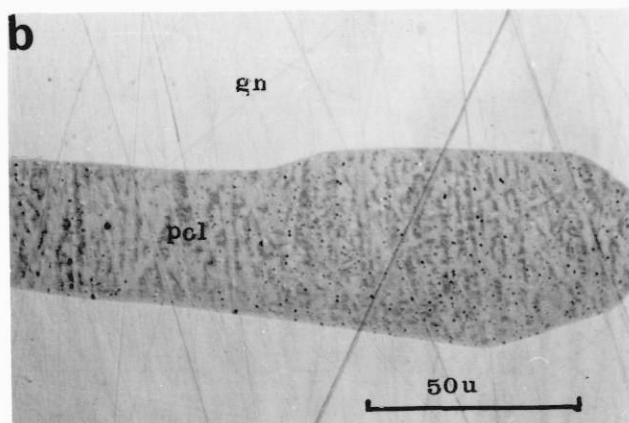
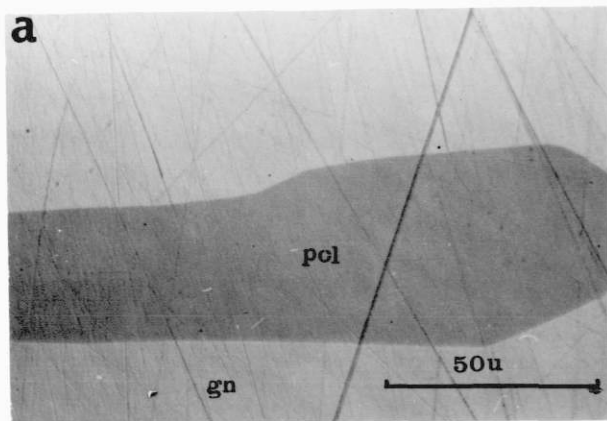
- c & d Compound grain of native silver (ag) and stromyerite (st). The stromyerite in (a) is breaking down by the effect of the microscopic light beam to native silver (b). As-628 DH.6, depth 104.30 mrs.

- e - A compound grain of polybasite (pol) and pyrargyrite in a matrix of massive galena (gn). The polybasite shows etching by the microscopic light beam of the microscope, but pyrargyrite is not yet affected. As-634, DH.1, depth 132 mrs.

- f - Metal sulphide aggregate of sphalerite (sl), chalcopyrite (cp), galena (gn) and acanthite (ac) showing grain boundary replacement relationships. Galena replacing sphalerite and chalcopyrite. Sphalerite galena and chalcopyrite are replaced by acanthite. As-628, DH.6, depth 104.30 mrs.

- g - Abundant inclusions of polybasite (pol), acanthite (ac) and gangue minerals in pyrite. S-9, DH.6, depth 105.20.

- h - A compound grain of polybasite (pol), acanthite (ac) and native silver enclosed in sphalerite (sl). Notice the decomposition of the silver phases by the electron probe beam (black spots). 1SA-455, DH.1, depth 150.50 mrs.

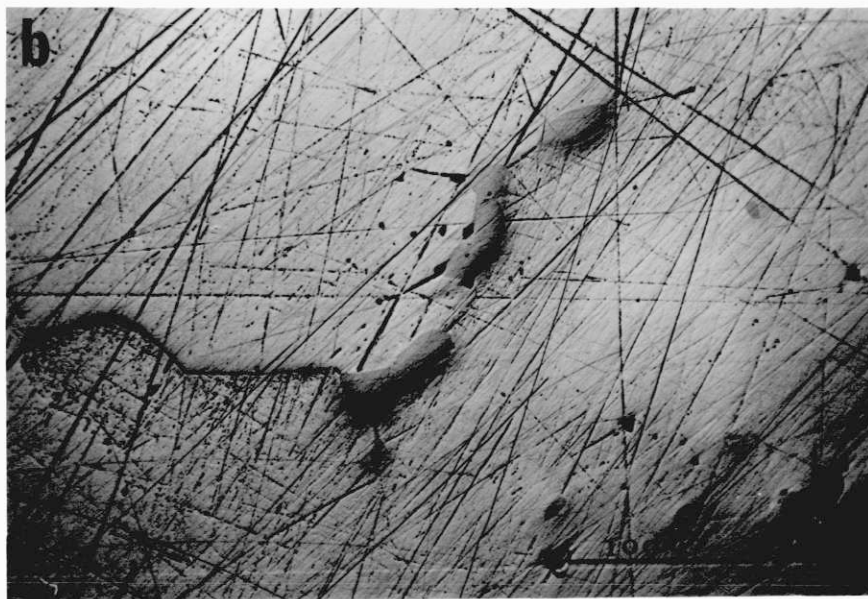
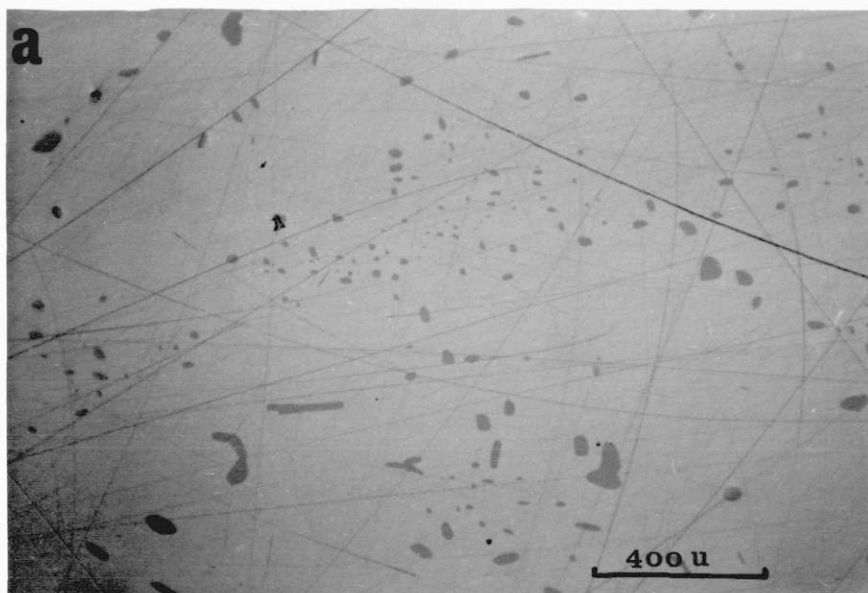


Vein-Type Mineralization

Figure 7-9

(a to c taken in reflected PPL)

- a - Silver sulphosalts, tetrahedrite (freibergite), pyrargyrite and polybasite in individual or compound grains included in a matrix of massive galena. As-634, DH.1 Samrah prospect, depth of 132 mrs.
- b - Etched massive galena showing grainboundary relationships and segregation of silver sulphosalts along them. Smaller sulphosalt inclusions occur in the galena grains probably as exsolved phases. As-634, DH.1, Samrah prospect, depth 132 mrs.
- c - Etched galena, showing recrystallization and annealing texture. Locality GV-19 depth of 80.50 mrs. DH.1.

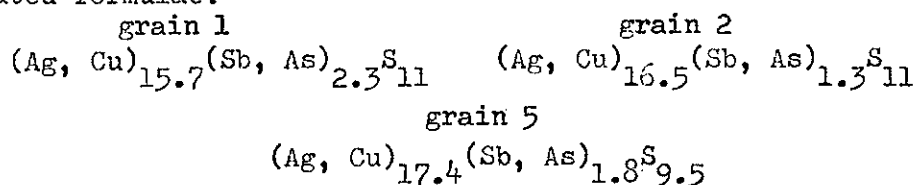


Fron del (1963) and Hall (1967) also suggested two distinct series Pearceite - antimonopenceite and polybasite - arsenopolybasite. Harries and others (1965) however, on the basis of the similarity in basic structural unit and external crystal form for all polybasite - pearceite minerals, preferred the classification into one series with polybasite as the Sb > As end member and pearceite as the As > Sb analogue, depending upon the simple multiplicity of fundamental cell dimensions.

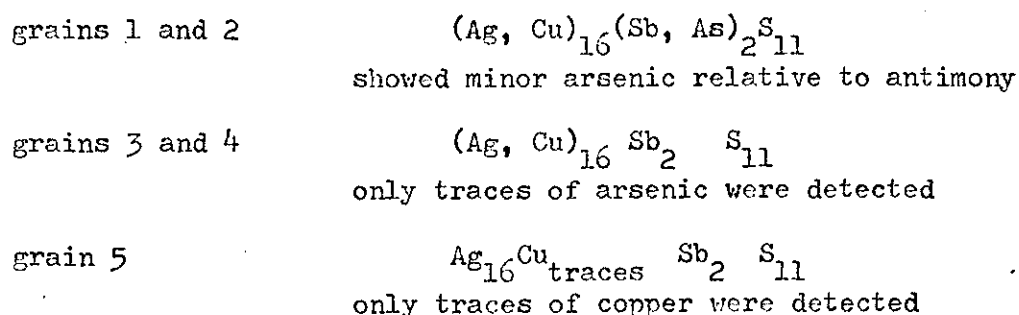
Table 7-1 Electron probe microanalysis of five grains of Polybasite from Samrah mine,^{*1} grain 1 and 2 after Warren Spring (1972).

Element	grain 1	grain 2	grain 3	grain 4	grain 5
	<u>W.S.</u>	<u>W.S.</u>	<u>As-634</u>	<u>ISA455</u>	<u>ISA437</u>
	wt%	wt%	wt%	wt%	wt%
Ag	73.45	74.05	75.0 ^{*2}	75.0	81.35
Cu	0.74	1.66	1.3	1.0	traces
Sb	9.65	6.05	9.8	9.0	10.4
As	0.89	0.46	---	---	---
S	15.85	15.25	14.8	14.5	13.46
Total	<u>100.58</u>	<u>97.47</u>			<u>105.21</u>

Calculated formulae:



The calculated formula for the above five grains indicated the silver sulphosalt polybasite,



*1 EPMA analyses listed in this chapter were conducted by J. Steed and N. Wilkinson, Imperial College. See appendix 3.

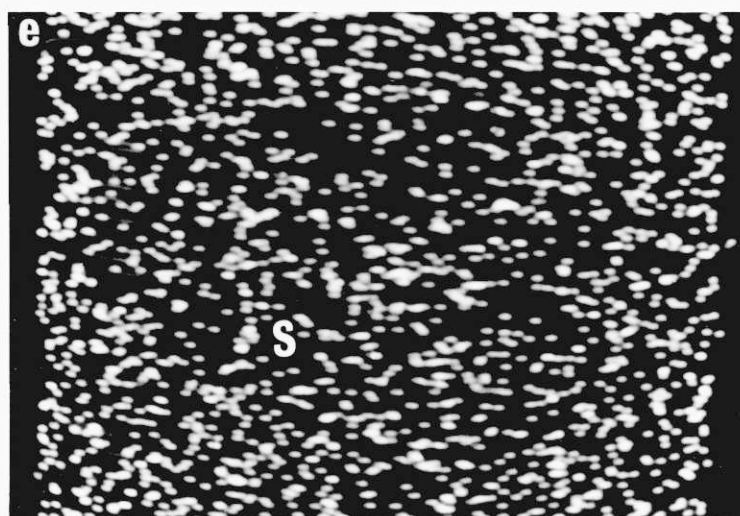
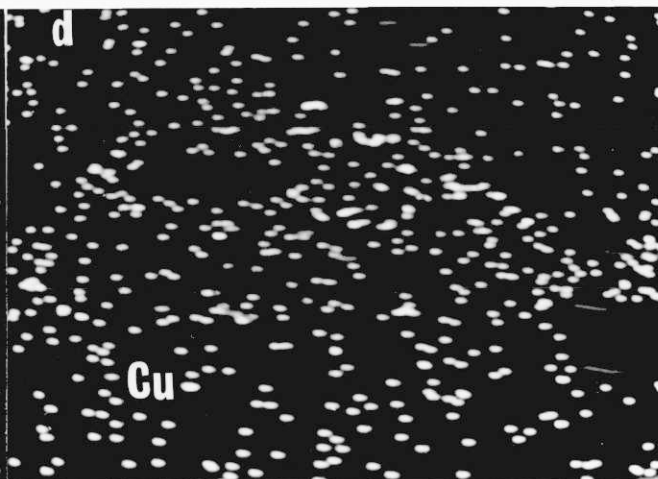
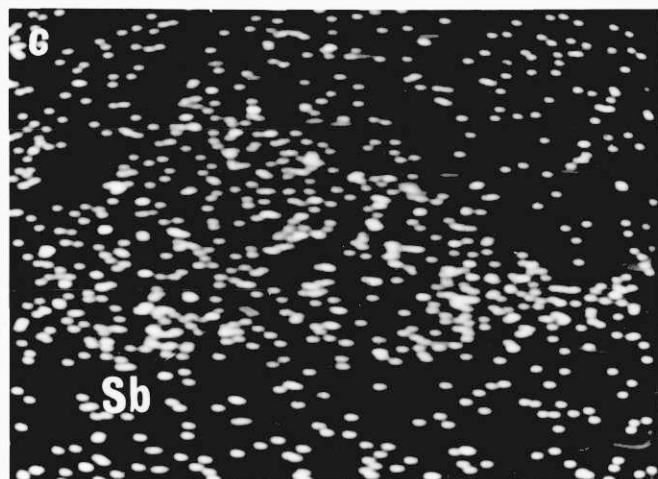
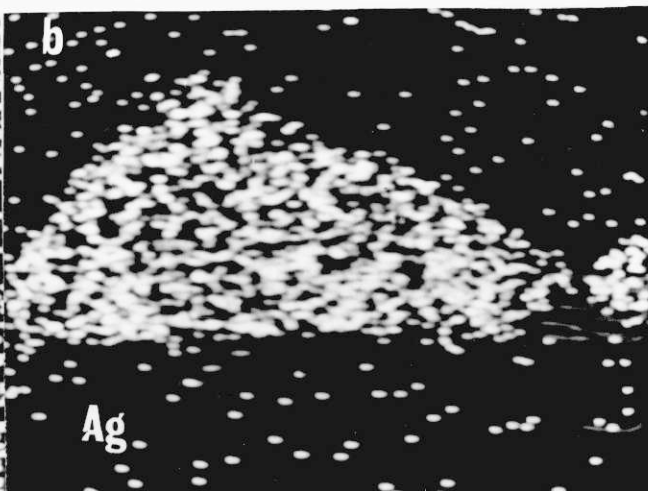
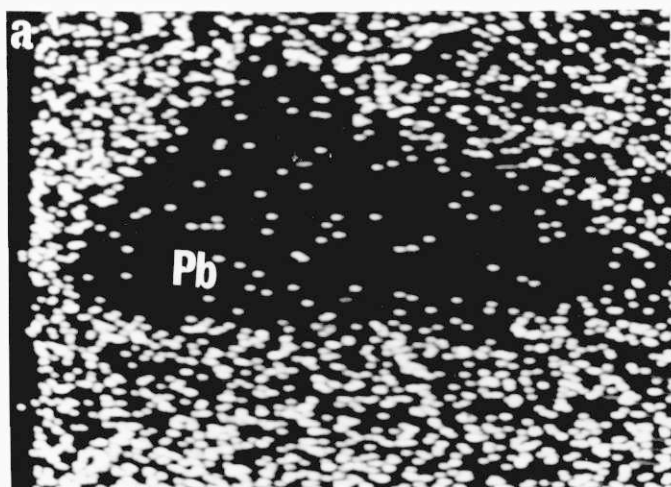
*2 Ag estimated, the phase decomposes and the analysis is unsatisfactory for silver.

Vein-Type Mineralization

Figure 7-10

(element distribution in polybasite)

Electron probe x-ray scanning images for lead (pb), silver (ag), antimony (sb), copper (cu) and sulphur (s) for a grain of polybasite included in massive galena. The symbols indicate the element represented by the bright areas of the photographs, As-634, DH.1. Samrah prospect depth 132.0 mrs. Scale 1 cm = 50.



1.6.1b Pyrargyrite (Ag_3SbS_3)

Pyrargyrite is a minor silver sulphosalt in Samrah mineralization. It was detected by microscopic study and confirmed by microprobe analysis. Its main occurrence is within massive galena (As-634, As-633, S-7) commonly associated with other silver sulphosalts, polybasite and tetrahedrite, (fig. 7-9a). It occurs in form of inclusions of rounded, subrounded, oval or elongate forms that range in size from about $100\mu\text{m}$ to less than $10\mu\text{m}$ with the majority of grains less than $50\mu\text{m}$. Pyrargyrite occasionally occurs intergrown with other silver sulphosalts (fig. 7-8e). In polished section, pyrargyrite is grey in colour with bluish tint, strongly anisotropic with or without red internal reflections in air and oil. The mineral does not decompose in the microscope light beam or under low current density during its analysis by the electron microprobe.

Table 7-2 Electron probe microanalysis of three Pyrargyrite grains from Samrah mine, grains 2 and 3 after Warren Spring (1972).

Element	grain 1	grain 2	grain 3
	wt%	wt%	wt%
Ag	57.25	59.4	59.95
Cu	-----	0.24	0.27
Sb	22.55	21.00	19.45
As	-----	3.82	0.47
S	20.77	18.6	17.7
Total	100.57	103.1	97.84

The chemical variation in pyrargyrite is given in table 7-2 in which the copper occurs up to 0.27% and arsenic varies from traces to 3.82%.

Copper as in the case of the polybasite - pearceite series, replaces silver in varying amounts. While arsenic substitutes for antimony.

The investigations carried out by Jaeger and Van Klooster (1912) on the melting relations in the system Ag_3AsS_3 - Ag_3SbS_3 by the method of cooling arrests, and by the X-ray diffraction studies, Toulmin (1963),

indicated the existence of a continuous solid solution series between proustite (Ag_3AsS_3) and pyrargyrite (Ag_3SbS_3). According to Toulmin, the miscibility becomes complete at 300°C between both end members.

1.6.1c Tetrahedrite (freibergite) $(\text{Cu,Ag,Fe,Zn})_8\text{Sb}_2\text{S}_7$

The argentian variety of tetrahedrite (freibergite) is the second abundant silver sulphosalt after polybasite in Samrah mineralization. It occurs mainly in the massive galena where it is associated with both polybasite and pyrargyrite (fig. 7-9a). However, occasional inclusions occur also in sphalerite associated with other silver minerals. It always forms rounded, subrounded, oval or irregular inclusions that range in size from 10 to $150\mu\text{m}$. Tetrahedrite grains in galena tend to cluster in separate zones from those of pyrargyrite and polybasite. Compound grains with other sulphosalts are common. Small amounts of chalcopyrite are observed to be in close association with tetrahedrite in the galena.

In sphalerite, tetrahedrite is associated with polybasite, acanthite and native silver (S-4) filling cracks and cavities, where it is believed to be breaking down by supergene alteration to give a sequence of other minerals.

In reflected light tetrahedrite is grey with brownish tint, ($R_{540} = 29.7 - 31.0$), isotropic, with no red internal reflections.

The electron probe microanalysis indicated argentian tetrahedrite (freibergite) composition (Table 7-3).

Table 7-3 Electron probe microanalysis of two grains of argentian tetrahedrite, Samrah mine

Element	As-634 <u>grain 1</u> wt%	As-634 <u>grain 2</u> wt%
Ag		
Ag	21.03	28.7
Cu	15.14	17.4
Sb	47.15	24.1
Zn	2.44	2.7
Fe	1.53	2.9
S	15.8 *	22.1 *
Total	<u>102.87</u>	<u>97.9</u>

* Indicating that S in the analysis is lower than the theoretical 24% - 27% given for tetrahedrite by Dana (7th Edition).

Warren Spring (1972), semiquantitatively analyzed three tetrahedrite grains from Samrah mine composite sample using the electron probe. They were found to contain about 20% silver, 34% Cu* and 23% Sb in addition to the presence of sulphur and iron.

From the above analyses we notice a great variation in Ag, Cu and Sb content of the various grains.

The electron probe microanalysis of two tetrahedrite grains showed that copper, iron, zinc, silver, antimony and sulphur were present, though in varying amounts. Arsenic was not detected in any of the tetrahedrites, and if present, it would be below 1% of the detection limit of the EPMA. The silver distribution is markedly variable.

In all samples analysed the sulphur value is low. Dana (7th Edition) gives the sulphur content of tetrahedrite as between 24 - 27 per cent.

Fig. 7-11 includes X-ray photographs of elemental distribution in a tetrahedrite-pyrargyrite compound grain. Qualitatively copper, zinc, iron, silver antimony and sulphur are all present in tetrahedrite though in varying amounts.

This high silver-bearing tetrahedrite has been called freibergite, and Dana (7th Edition) shows a maximum silver content of 18 per cent but usually less than 5 per cent. In the present study values from 20 to 29% Ag were detected.

1.6.1d Acanthite Ag_2S

Acanthite is a minor silver sulphide in Samrah mineralization. It is usually associated with polybasite in composite sulphide aggregates (fig. 7-8 f).

It is very closely intergrown with chalcopyrite and with native silver. The chalcopyrite forms minute branching veinlets, cross-cutting acanthite and separating it from marginal polybasite (fig. 7-7 a and c). This relationship between the three closely associated

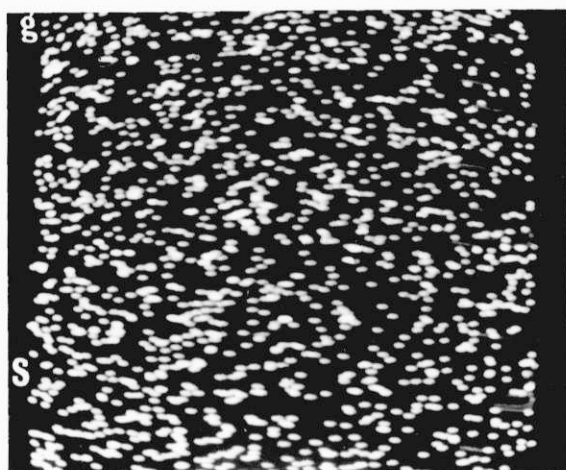
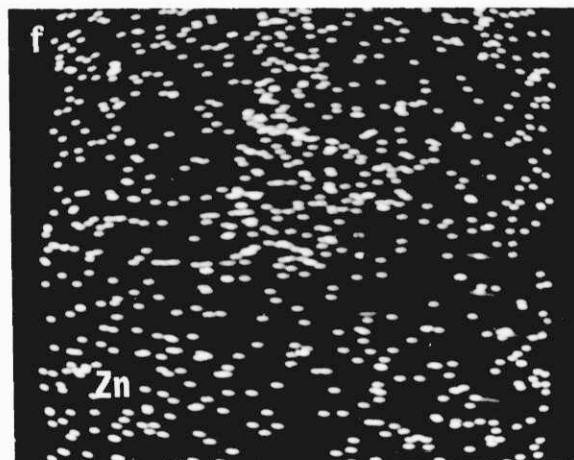
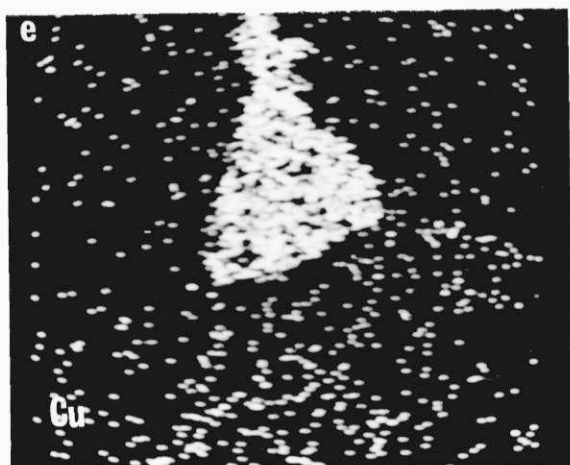
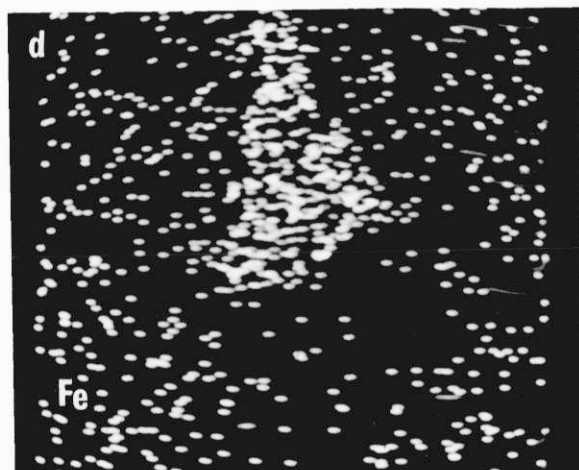
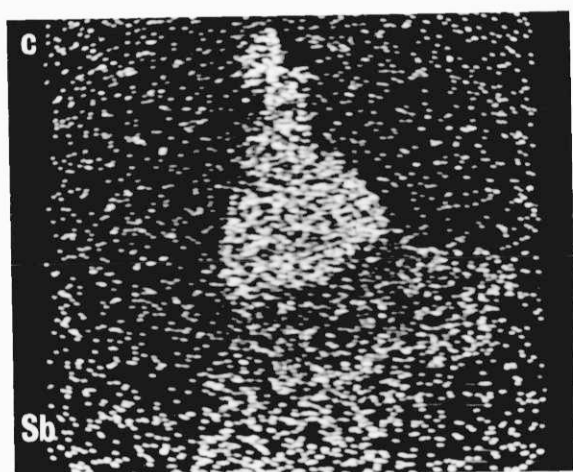
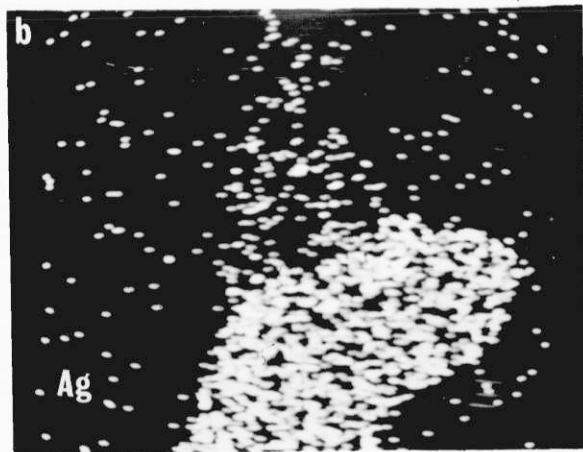
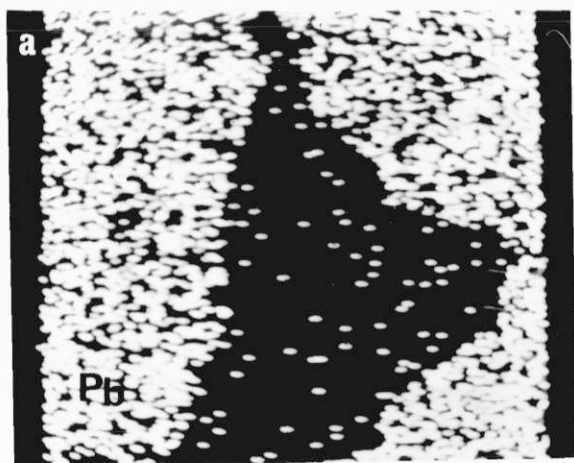
* Cu percentage is high and probably faulty analysis.

Vein-Type Mineralization

Figure 7-11

(element distribution in freibergite and pyrargyrite)

Electron probe x-ray scanning images for lead (pb), silver (ag), antimony (sb), iron (fe), copper (cu), zinc (zn) and sulphur (s) for a compound grain of tetrahedrite, (freibergite) (top) and pyrargyrite (bottom). The symbols indicate the element represented by the bright areas of the photographs. The intensity of brightness reflects the amount of the relevant element in the phase. Notice that pyrargyrite does not contain Fe or Zn. As-634, DH.1, Samrah prospect, depth 132.0 mrs. Scale 1 cm = 50



phases points out the possibility of polybasite breaking down to acanthite and chalcopyrite. In larger grains of polybasite, lensoid compound inclusions of acanthite, chalcopyrite and native silver occur.

Acanthite occurs also, as small individual or irregular compound inclusions in sphalerite, in pyrite and in magnetite (fig. 7-7 g, h, i and j) or it occurs as fracture filling within these minerals. The grain size in pyrite and in sphalerite ranges from $10\mu\text{m}$ - $50\mu\text{m}$.

In galena larger grain sizes $100\mu\text{m}$ were observed.

In polished section acanthite is either grey with greenish tint or grey, soft, usually shows scratched surfaces. The scratches occlude all anisotropy effects. It decomposes more rapidly than polybasite under the microscopic light beam to give minute blebs of native silver ($\sim 2\mu\text{m}$).

Due to its rapid decomposition under the electron beam of the microprobe, the following analyses only were possible (Table 7-4).

Table 7-4 Electron probe microanalysis of three acanthite grains from Samrah mine.

Element	As-618 grain 1	ISA-437 grain 2	ISA-455 grain 3
	wt%	wt%	wt%
Ag	82.3	84.9	78.4
S	10.7	11.4	13.0
Total	93.0	96.3	91.4

1.6.1e Stromeayerite $(\text{Ag Cu})_2\text{S}$

The stromeayerite is a minor phase in the Samrah assemblage. It was identified by electron probe. It is restricted to highly brecciated and chloritized parts of the ore body, where it is invariably rimmed by chalcopyrite (fig. 7-8 c and d).

In polished section it is grey, soft with scratched surfaces, but the anisotropy was difficult to detect owing to polishing damage. It is more readily etched by microscopic light than polybasite or acanthite. It decomposes to native silver in larger grains 10 μ m (fig. 7-8 c and d). No satisfactory quantitative analysis could be carried out due to its rapid decomposition in the electron beam.

From the mode of occurrence and its mineral association it is suggested that it is a secondary mineral formed from the decomposition of other silver sulphosalts.

1.6.1f Native silver

Native silver occurs in subordinate amounts in the Samrah mineralization. It is mainly associated with quartz and calcite veinlets (S-8) in which grains up to 1.5 mm occur. Its occurrence is erratic and acanthite is commonly in association. Chalcopyrite is also present and partially or entirely encloses native silver grains (fig. 7-7d).

Native silver grains 50 μ m are occasionally included in pyrite, in sites close to the centre of grains.

In brecciated sphalerite, native silver grains 150 μ m, occur as inclusions or along fractures commonly with complex assemblage of silver minerals (fig. 7-8h).

A few native silver grains were checked for Au, Hg, Cu and Bi by electron probe microanalysis, but nothing was detected.

The mode of occurrence of the native silver and its mineral association suggests that it is a secondary mineral formed by the decomposition of pre-existing silver sulphosalts, notably tetrahedrite, polybasite and pyrargyrite.

1.6.2 Sphalerite

The textural relationships of sphalerite depends largely on its reduced ductility and mobility relative to galena and chalcopyrite. Textural evidence suggests that sphalerite is of older generation.

than chalcopyrite and galena but obviously later than the first generation of pyrite (fig. 7-12g). The body colour in hand specimen varies from light brown to brown to steel grey, reflectivity measurements range ($R_{546} = 16.2 - 17.0$), paler colours being characteristic of remobilized sphalerite. The characteristic internal reflections are quite common from yellowish brown to reddish. Megascopic zoning is exhibited in core specimens where the colour grades from resinous brown on the margin to deep brown in the centre of the coarse crystalline grains. No colloform texture occurs.

Sphalerite is the most abundant base metal sulphide in the Samrah mineralization. It occurs throughout the mineralized zones as deformed coarsely crystalline (fig. 7-12b, c, and d) brecciated aggregates with quartz (fig. 7-12d, 7-13), calcite and chlorite in the form of veinlets together with other sulphides including galena, chalcopyrite and silver minerals which show replacement relationships against it.

In relation to pyrite, sphalerite is interstitial, infilling open spaces and commonly replacing the first pyrite generation (fig. 7-12g). Pyrite veinlets cross cutting sphalerite exhibit anhedral granular texture, and thus interpreted as second generation of pyrite. Often this pyrite is replaced by galena. Small euhedral pyrite grains 2 - 4 μ m occur embedded in sphalerite either associated with chalcopyrite inclusions or in zones where chalcopyrite is lacking. Their distribution is erratic and occasionally they concentrate along cracks or grain boundaries (fig. 7-12a, 7-13c).

Galena is of later generation, filling fissures and cavities and embaying sphalerite (fig. 7-12h and i). Replacement textures are very well developed and commonly commence in marginal zones by irregular extensions of galena into sphalerite. Remnant sphalerite grains are common in galena (fig. 7-12h).

The structure of sphalerite is closely related to that of chalcopyrite. Both oriented and non oriented intergrowths are common.

Solid solution takes place at least to a limited extent at elevated temperatures, and exsolution is therefore possible during falling temperatures (Edwards, 1954, Ramdohr, 1969). The exsolution of chalcopryrite from sphalerite in the Samrah mineralization takes the following forms:

1. Minute spherical droplets of various sizes arranged in cloud-like aggregates, with a size range from submicroscopic to $2\mu\text{m}$. These are commonly concentrated in particular areas of the grains, either occupying central positions of the grains (fig. 7-12e) or concentrated at the grain boundaries (fig. 7-12f).
2. Tabular or lens-like form embedded parallel to the crystallographic directions (fig. 7-12a).
3. Irregular ragged grains ($\sim 2\mu\text{m} - 10\mu\text{m}$) disseminated in sphalerite but more concentrated at grain boundaries.

The remobilized sphalerite contains no inclusions of chalcopryrite (fig. 7-12a). Generally, sphalerite where associated with chalcopryrite includes a large amount of exsolved chalcopryrite relative to that associated with other minerals or gangue.

Chalcopryrite replacing sphalerite at grain boundaries is a common feature (fig. 7-14a).

Table 7-5 Electron microprobe analysis of Samrah Sphalerite

<u>Element</u>	<u>ISA-477</u>	<u>As-633</u>
	wt%	wt%
Zn	64.2	56.4
Fe	4.6	5.4
S	32.8	33.1
Total	101.6	94.9

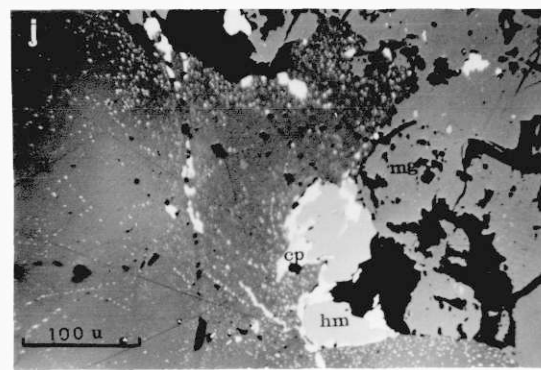
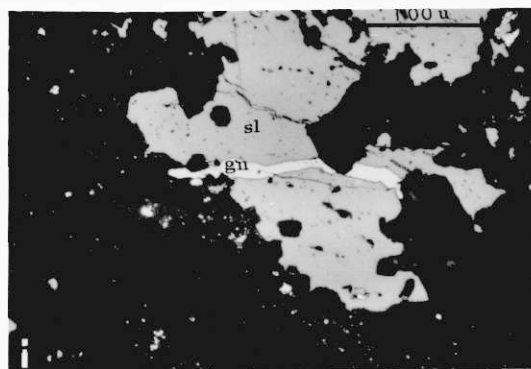
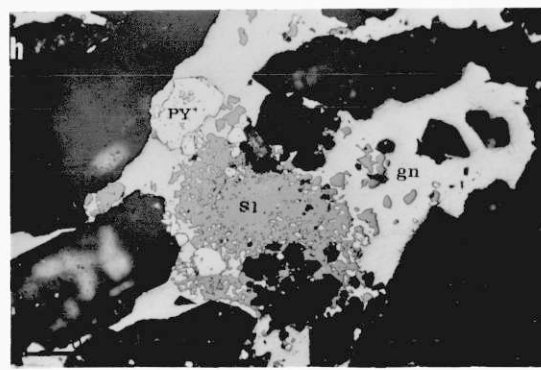
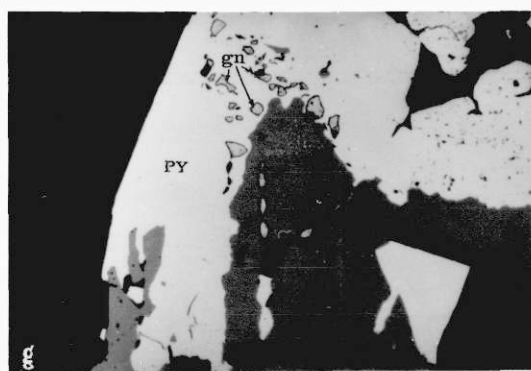
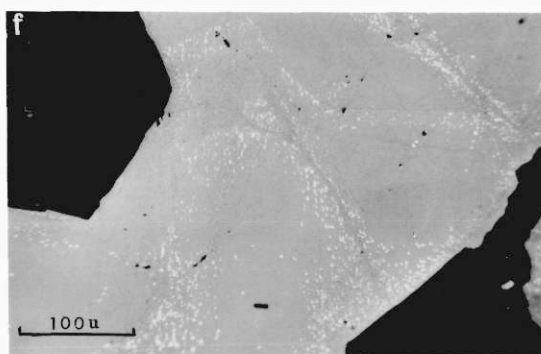
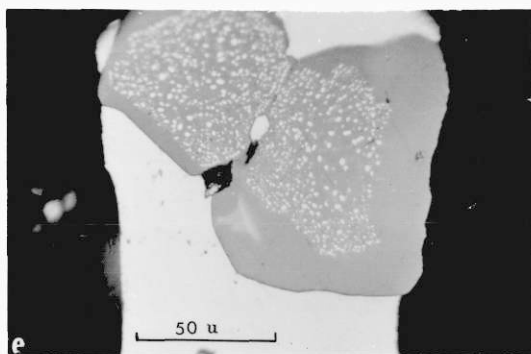
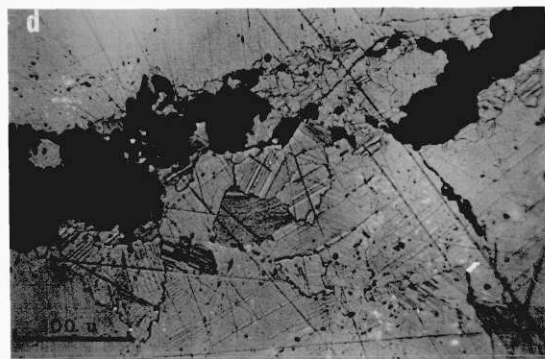
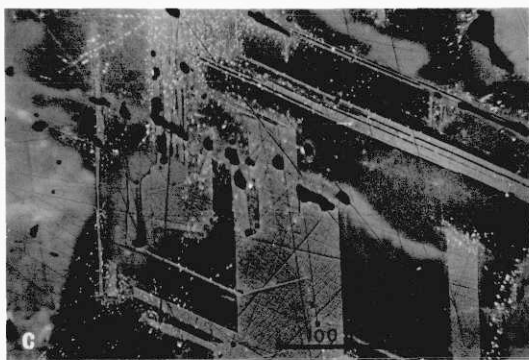
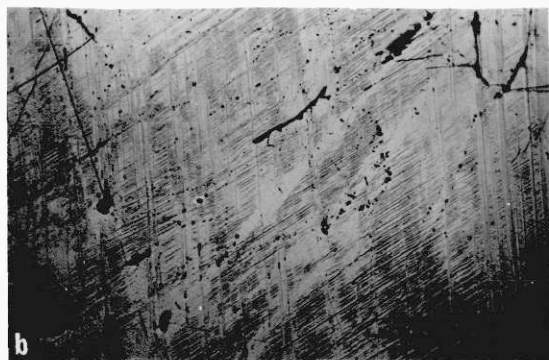
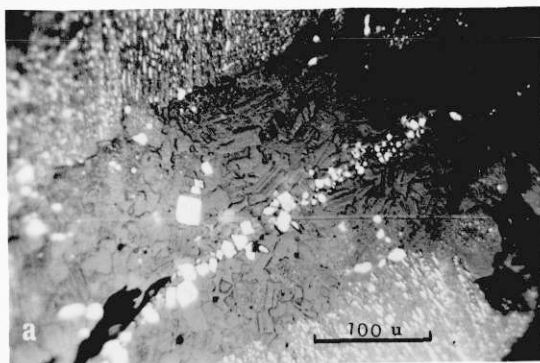
Several grains of sphalerite were checked for Mn and Cd by EPMA and proved to be below their detection limit of 1% and 0.5% respectively.

Vein-Type Mineralization

Figure 7-12

(a to j taken in reflected PPL)

- a - Deformed sphalerite, recrystallized to small untwinned crystals along walls of a fracture and became depleted from chalcopyrite which is enriched as exsolved phase in the undeformed parts. Fine euhedral pyrite crystals occur along the fracture. S-1, DH.1, depth 138.65 mrs. Samrah prospect (etched section).
- b - Deformed sphalerite showing large number of fine twin lamellae. GV-19 prospect, DH.1, depth of 80.5 mrs. (etched section).
- c - Sphalerite showing coarse twinning and irregularly distributed patches of exsolved chalcopyrite. GV-19 prospect, DH.1, depth of 80.5 mrs. (etched section).
- d - Well developed twinning in deformed and recrystallized sphalerite along a fracture. The fracture has been sealed later by quartz. GV-19 prospect, DH.1, depth 80.5 mrs. (etched section).
- e - Fine exsolution of chalcopyrite in sphalerite in emulsion texture. The grain boundaries of sphalerite are depleted. S-3, DH.1, Samrah prospect, depth 132.75 mrs.
- f - Fine exsolved chalcopyrite along grain boundaries of sphalerite aggregate. The sphalerite grains are clear away from the margins. As-614, DH.S-5W, Samrah prospect depth of 201.0 mrs.
- g - Pyrite (py) replaced by sphalerite (sl), both pyrite and sphalerite are replaced by galena (gn). 1SA-449, DH.1, Samrah prospect, depth of 148 mrs.
- h - Allotriomorphic galena (gn) replacing pyrite (py) and sphalerite (sl). S-3, DH.1, Samrah prospect, depth of 132.75 mrs.
- i - Galena (gn) veinlets cutting sphalerite (sl). 1SA-449, DH.1, Samrah prospect, depth of 148 mrs.
- j - Grain boundary relationships of sphalerite (sl) and magnetite (mg). Sphalerite is replacing magnetite. Chalcopyrite (cp) is marginal to hematite suggesting replacement texture. S-1, DH.1, Samrah prospect depth of 138.65 mrs.



Vein-Type Mineralization

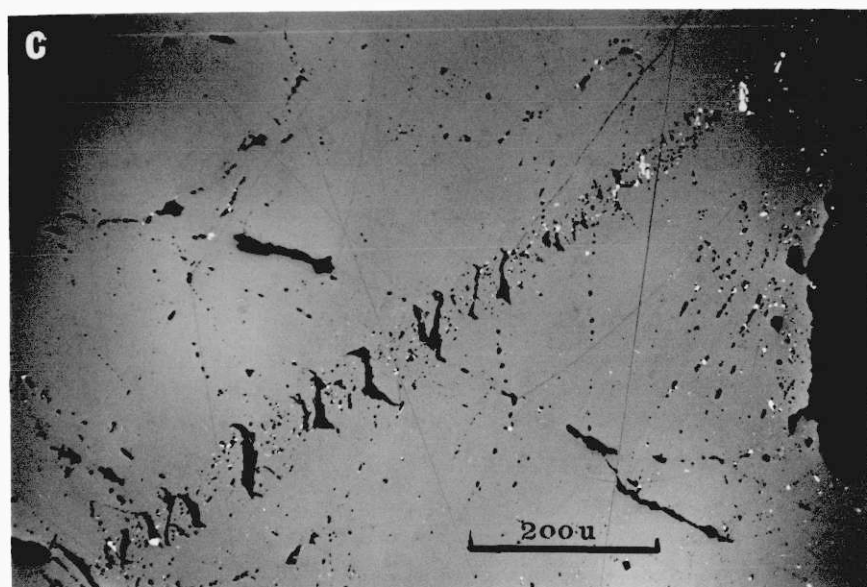
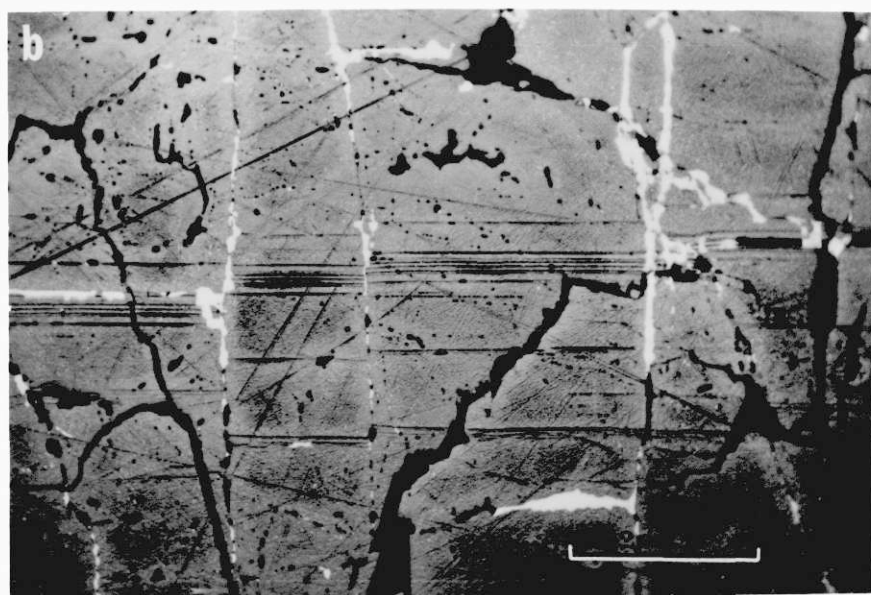
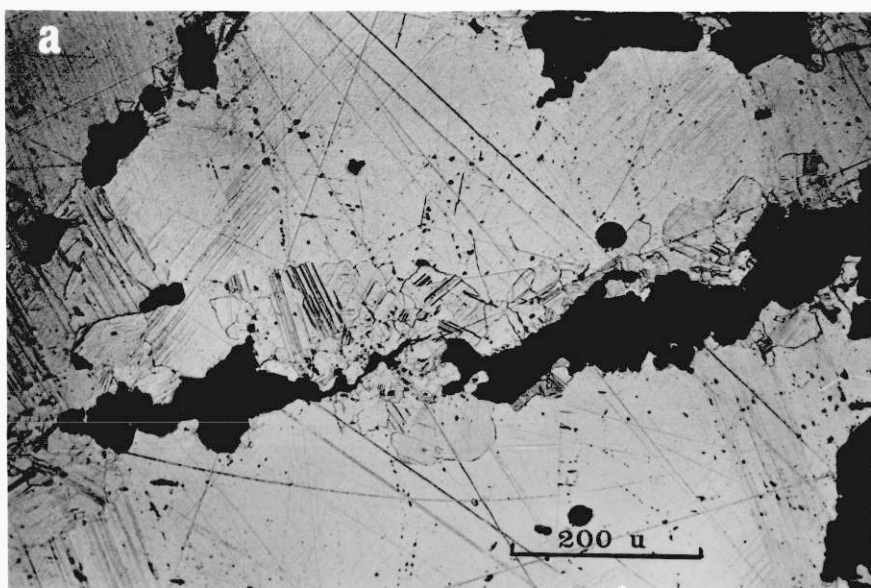
Figure 7-13

(a to c taken in reflected PPL)

- a - Etched sphalerite, showing recrystallization into fine twinned sphalerite grains along post-mineralization fractures. Fractures are sealed by quartz. The sphalerite away from the cracks is not affected. GV-19 prospect, DH.1, depth of 80.5 mrs.

- b - Etched sphalerite showing displaced twin lamellae by step micro-faults and later introduction of chalcopyrite along the fractures and twin lamellae. S-1, DH.1, Samrah prospect depth of 138.65 mrs.

- c - Microscopic sigmoidal tension gashes developed in sphalerite. The gashes are sealed by quartz and partly by pyrite. 1SA-442, DH.1, Samrah prospect, depth of 146 mrs.



1.6.3 Galena (PbS)

Galena is the second most abundant base metal sulphide after sphalerite in the Samrah mineralization. It is not as widespread but more restricted to central parts of the veins. It is commonly coarsely crystalline and compact and almost invariably contains inclusions of silver sulphosalts (described under their headings).

The habit of the galena in the mineral aggregates suggests that this mineral has responded to the later stages of brecciation and hydrothermal activity by readily recrystallizing and migrating to interstices around the latest generation of comb quartz (fig. 7-14b). This late (remobilized) galena contrasts with the earlier inclusion-rich galena in having fine annealed grain texture (fig. 7-9c) from which silver minerals are exsolved.

The primary intra-galena sulphosalt inclusions (tetrahedrite, polybasite and pyrargyrite) are replaced by grain rim complexes consisting of polybasite, acanthite, (fig. 7-7 a and c) and chalcopryrite which are apparently the stable low temperature phases representing the complex sulphosalts initially fixed as inclusions in the galena.

The galena shows a tendency to vein and replace pyrite, (fig. 7-15 c, d and e) sphalerite and chalcopryrite and textural evidence also suggests that it was still mobile and being recrystallized after the formation of the later gangue minerals (quartz, carbonates and chlorite).

Few grains of galena were checked for silver by EPMA but proved to be below its detection limit (0.5%).

1.6.4 Chalcopryrite CuFeS_2

Chalcopryrite is not as abundant as other mineral sulphides of Fe, Zn or Pb. It is of irregular distribution throughout the mineralized zones, most commonly as aggregates or clusters within the composite sulphide aggregates, or in thin seams cutting through the gangue, pyrite or sphalerite. The common minerals with which it is associated in decreasing order of abundance are sphalerite, magnetite, pyrite, acanthite, native silver and stromeyerite.

In the paragenetic sequence it is of younger age of crystallization than pyrite (1) and sphalerite. It always follows cataclastic fractures in both as replacement veinlets (fig. 7-15 a and b). Grain boundary segregation is common, but more dominant in sphalerite (cf sphalerite) where the segregation is often due to unmixing from the sphalerite. Replacement of both sulphides by chalcopryrite is illustrated in (fig. 7-12j and 7-15a and b). Exsolution textures of chalcopryrite in sphalerite are common and take various forms. (discussed under sphalerite).

Galena, which is of later crystallization tends to replace it, but this is not as extensively developed as in the case of pyrite or sphalerite. Native silver, stromeyerite and acanthite are commonly associated with chalcopryrite, (fig. 7-7d, 7-9f). The stromeyerite is almost always rimming and replacing chalcopryrite. Such veinlets are developed in calcite-chlorite gangue. In the case of acanthite thin "dendritic" chalcopryrite stringers cross-cut acanthite and form a zone separating it from the polybasite (fig. 7-7c). This chalcopryrite is thought to result from the decomposition of polybasite (discussed under the heading acanthite).

In the rare occurrences of magnetite-hematite, chalcopryrite is closely associated. It follows cracks in the magnetite and replaces it. Hematite occurs as tabular inclusions within chalcopryrite.

1.6.5 Pyrite FeS_2

Pyrite is widespread throughout the mineralization. It possesses variable characteristics and is evidently not all of the same period of crystallization.

Pyrite occurs in massive, polygonal, loosely bonded aggregates (fig. 7-15g). Usually, pyrite masses are fractured brecciated and healed with gangue, chalcopryrite, sphalerite or galena (fig. 7-15). This strongly shattered, corroded and strained pyrite does not have definite outlines. Pyrite also occurs as irregular or rounded residual grains in the gangue or enclosed in sphalerite and galena. Euhedral or subhedral pyrite grains host numerous inclusions of acanthite,

polybasite (S-9), native silver, galena, chalcopyrite, arsenopyrite, sphalerite and gangue.

Pyrite stringers also occur cutting other sulphides, usually sphalerite. Euhedral disseminations of pyrite crystals are also common throughout the mineralization with no evident cataclasis.

The mode of occurrence of pyrite and its relationship with other sulphides indicate that it formed during three distinct stages. Some older, where extensive fracturing took place after its crystallization causing brecciated fabrics and subsequent replacement by other sulphides, and some younger; the third stage was deposited along with the other sulphides.

Microscopically pyrite is not zoned and shows anomalous weak anisotropism with yellowish brown to light blue polarization colours. The microprobe investigations on pyrite gave no indication of significant minor elements in the pyrite lattice.

1.6.6 Arsenopyrite (FeAsS) (As-608)

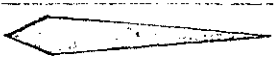
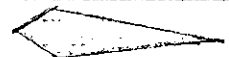
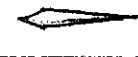
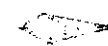
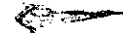
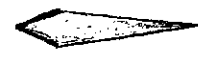
Arsenopyrite is a minor mineral in the Samrah mineralization, seen only in two polished sections taken from the foot wall of the main shear zone. Arsenopyrite occurs as euhedral to subhedral crystals or aggregates (fig. 7-15j) embedded in a quartz-chlorite-caronate and epidote matrix. Small corroded grains of variable sizes also occur, rimmed either by galena, sphalerite, chalcopyrite or acanthite.

Arsenopyrite is of later age than pyrite, it is seen rimming it or in form of minute inclusions within pyrite grains.

1.6.7 Magnetite ($\text{FeO} \cdot \text{Fe}_2\text{O}_3$)

Magnetite is associated with the sulphide minerals in subordinate amounts, commonly with chalcopyrite. It is deposited earlier than sphalerite following pyrite-1, as evidenced by its replacement of it (fig. 7-15f). The magnetite grains were shattered and re-cemented by chalcopyrite and quartz and less abundant galena or acanthite (fig. 7-14 c, d and e). Chalcopyrite occurs in the form of interstitial filling,

Paragenetic table illustrating sequence of minerals occurring in the
Zn-Pb-Ag vein deposits. Ad-Dawadmi District.

Minerals	1	2	3	4
<u>Sulphides and Oxides</u>				
Pyrite				
Magnetite				
Hematite				
Arsenopyrite				
Sphalerite			 	
Chalcopyrite				
Galena				
Tetrahedrite				
Polybasite				
Pyrargyrite				
Argentite				
Stromeyerite				
Native Silver				
<u>Gangue</u>				
Quartz				
Calcite				
Chlorite				
Epidote				
Sericite				
Serpentine				

veinlets or tongues in magnetite aggregates. Acanthite is less common; it infills fractures in partly martitized magnetite or forms small inclusions (fig. 7-7i). Sphalerite also replaces magnetite (fig. 7-12j).

1.6.8 Hematite (Fe_2O_3)

Hematite is less abundant than magnetite with which it is intimately associated as a primary hematite (fig. 7-14d) or a secondary hematite (fig. 7-7j) replacing it. Chalcopyrite is again observed at mutual grain boundaries tending to replace both minerals (fig. 7-14d).

The grain boundary relationships of hematite, magnetite and chalcopyrite suggest that both magnetite and primary hematite crystallized simultaneously before chalcopyrite.

6.1.7 Phase relationships between Iron Oxides and the Associated Iron Sulphides

The iron oxides at Samrah mine are closely associated with chalcopyrite and pyrite in the zones of mineralization within the fractures. This paragenesis occurs in a large number of epigenetic sulphide deposits in other parts of the world.

Schwartz and Ronbeck (1940) tabulated 130 deposits and showed that the minerals normally associated with the iron oxides are: chalcopyrite, pyrite, pyrrhotite, sphalerite, galena, arsenopyrite, bornite and chalcocite. The most common are those that can exist in equilibrium or under F_0 conditions favourable to the simultaneous formation of Fe_3O_4 - Fe_2O_3 . At Samrah these are pyrite and chalcopyrite and the formation of magnetite and primary hematite was preceded by that of pyrite.

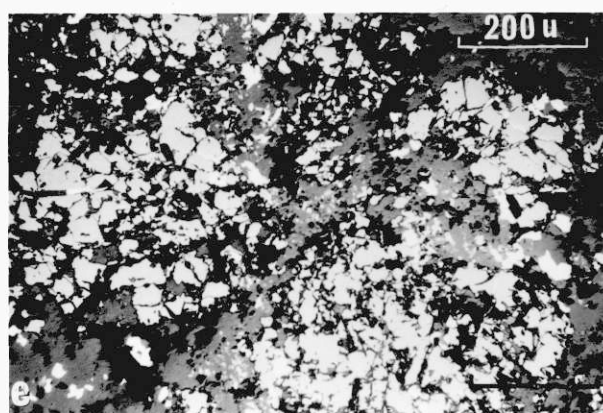
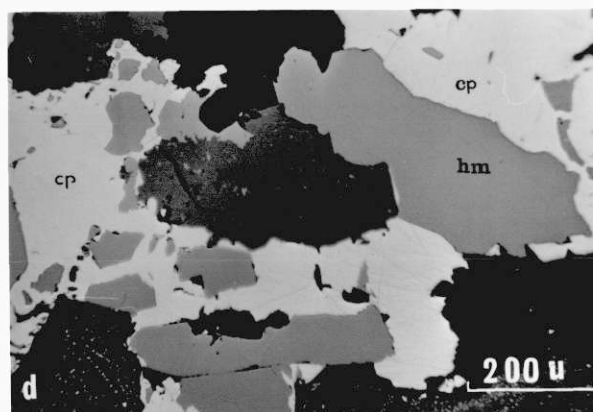
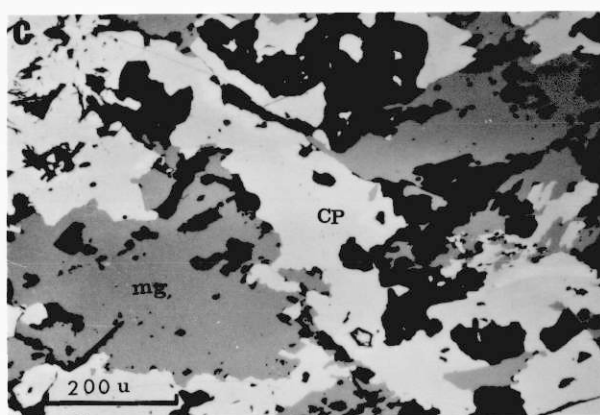
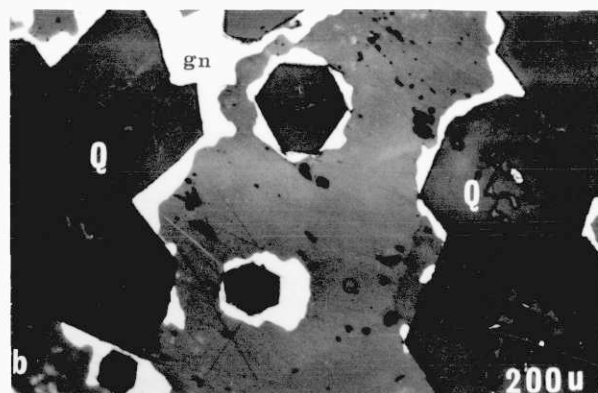
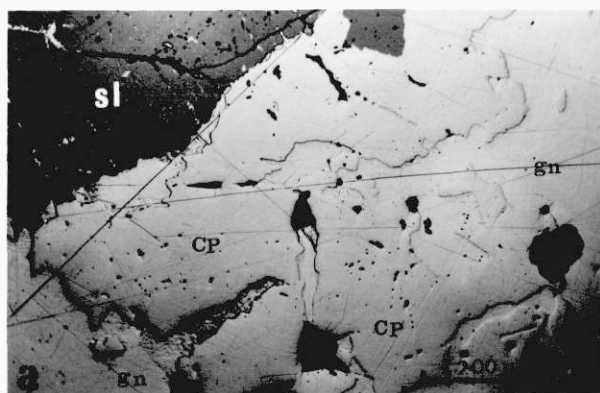
Taylor and Kullerud (1971) observed that the most common mineral assemblages that can occur with magnetite are those of the Cu-Fe-S system notably chalcopyrite, pyrrhotite and pyrite. They conducted experimental studies to show the phase relations in the Cu-Fe-S-O system at 300°C , from which it was deduced that if a copper-iron

Vein-Type Mineralization

Figure 7-14

(a to e taken in reflected PPL)

- a - Tongue-like protuberences of galena (gn) in chalcopyrite (cp) suggesting replacement of the latter by the galena. The sphalerite (sl) and chalcopyrite show a mutual even grain boundaries. S-1, DH.1, Samrah prospect, depth of 138.65 mrs.
- b - Galena mobilized into the interstices of the comb-quartz of the third generation and partly replacing the earlier quartz. 1SA-437, DH.1, Samrah prospect, depth of 143.0 mrs.
- c - An aggregate of magnetite (mg) and chalcopyrite (cp). The chalcopyrite is interstitial to magnetite replacing it. Residual magnetite is seen in chalcopyrite. S-1, DH.1, Samrah prospect, depth of 138.65 mrs.
- d - Sulphide-oxide aggregate of chalcopyrite (cp), magnetite (mg) and hematite (hm). Chalcopyrite appears to replace both iron oxides with residual grains left in a matrix of chalcopyrite. S-1, DH.1, Samrah prospect, depth of 138.65 mrs.
- e - Extensively brecciated magnetite (dark grey) replaced by hematite (light grey) and gangue (black). Minute veinlets of chalcopyrite cut the oxide minerals. 1SA-444, DH.1, Samrah prospect, depth of 144.0 mrs.

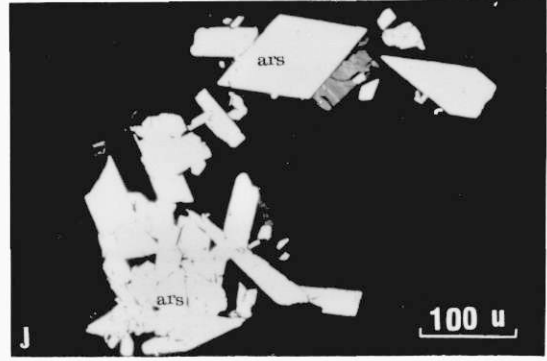
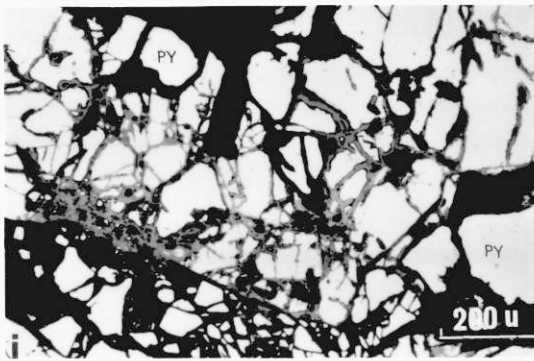
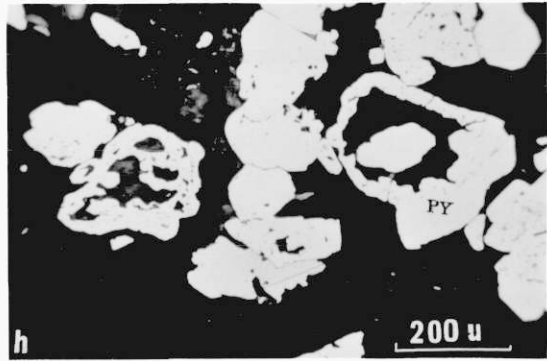
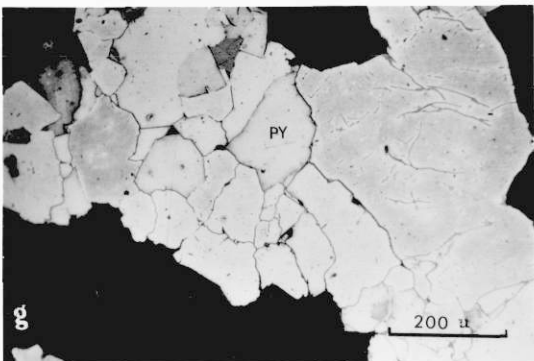
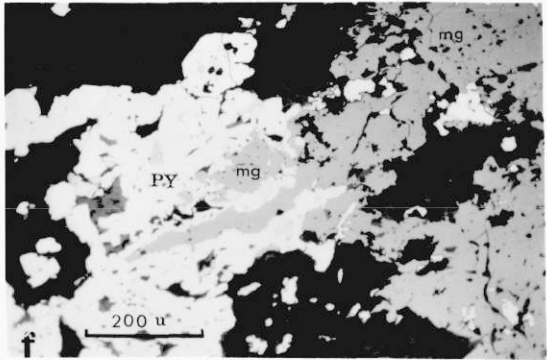
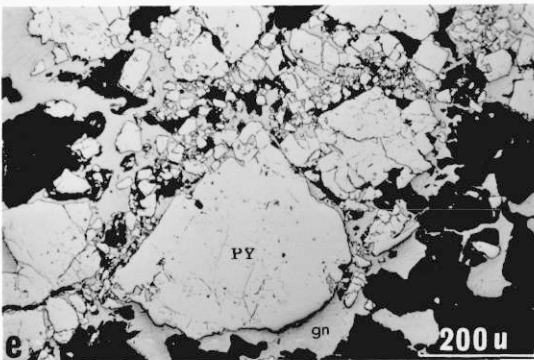
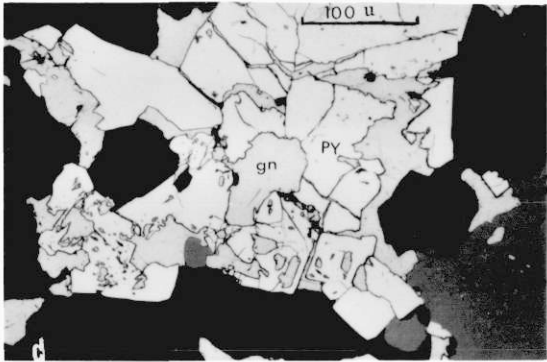
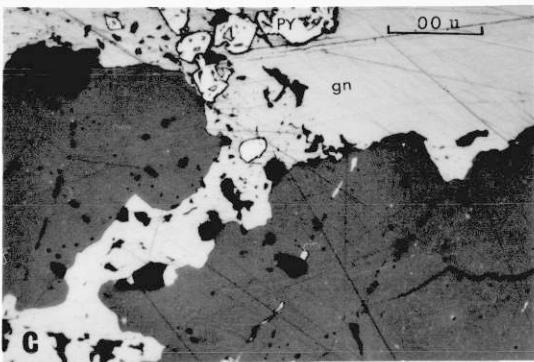
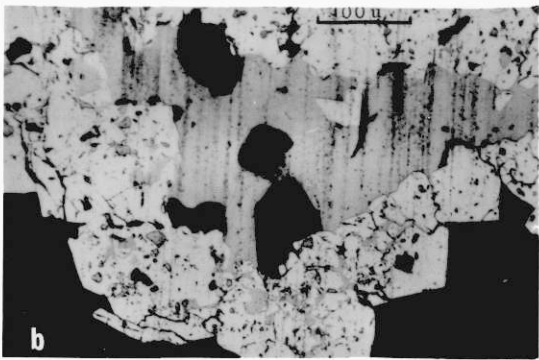
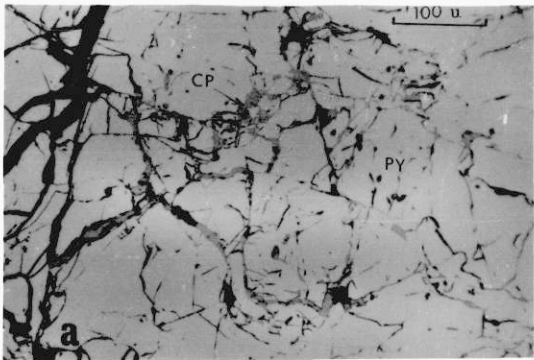


Vein-Type Mineralization

Figure 7-15

(a to j taken in reflected PPL)

- a - Pyrite (py) strongly deformed, cracks are sealed with chalcopyrite (cp) and quartz. GV-19 prospect, DH.1, depth of 80.70 mrs.
- b - Pyrite (py), brecciated, cemented and replaced by chalcopyrite (cp). DH.1, GV-19 prospect, depth of 80.70 mrs.
- c - Remnants of pyrite (py), corroded and replaced by galena (gn) 1SA-437, DH.1, Samrah prospect, depth of 143.0 mrs.
- d - Pyrite corroded and replaced by galena (gn), caries and atoll replacement textures are shown. 1SA-437, DH.1, Samrah prospect, depth of 143.0 mrs.
- e - Brecciated pyrite (py), cemented and extensively replaced by galena (gn), S-3, DH.1, Samrah prospect, depth of 132.75 mrs.
- f - Pyrite aggregate showing replacement by gangue and by magnetite (mg). S-1, DH.1, Samrah prospect, depth of 138.65 mrs.
- g - Pyrite aggregate, weakly deformed, showing grain boundary relationships. Air etched section. S-5, DH.3, Samrah prospect, depth of 92.85 mrs.
- h - Corroded pyrite grains, showing zonal and core replacement by gangue. S-9, DH.6, Samrah prospect, depth of 105.20 mrs.
- i - Pyrite, strongly deformed cemented and replaced by hematite (grey) and gangue (black). DH.1, PL-44, at depth of 56.0 mrs.
- j - Euhedral crystals of arsenopyrite in aggregates. 1SA-480, DH.1, Samrah prospect, depth of 158.0 mrs.



sulphide assemblage has a bulk composition situated on the sulphur side of an approximate composition line running from chalcocite through bornite and chalcopyrite to pyrite, it cannot coexist with magnetite alone and hematite must appear as a phase.

The primary assemblage magnetite, hematite, pyrite and chalcopyrite observed in the Samrah mineralization can be regarded as a typical univariant assemblage formed in a sulphur rich system with a fixed f_{O_2} determined by the buffering effect of the rock silicates. It probably indicates an equilibrium temperature of 300°C or less (Taylor and Kullerud 1971).

6.1.8 Ore Reserve Estimation

Kiilsgaard (1968) reported the following estimate of indicated and inferred ore reserves calculated at a cut-off grade of \$ 25 per ton gross metal value and mineralized material with a grade of \$ 23 per ton, taking metal prices at \$ 2.45/oz. Ag, \$ 0.13/lb Pb and \$ 0.13/lb Zn:

Classification	Tonnage (metric)	Gross value per ton	Total gross value
Indicated ore	133,300	\$ 81	\$ 10,800,000
Inferred ore	71,100	\$ 41	\$ 2,900,000
	<u>204,400</u>	<u>\$ 67</u>	<u>\$ 13,700,000</u>
Indicated material	76,300	\$ 23	\$ 1,700,000
Inferred material	20,600	\$ 23	\$ 470,000
	<u>96,900</u>	<u>\$ 23</u>	<u>\$ 2,220,000</u>
Total ore and mineralized material	301,300	\$ 53	\$ 15,920,000

The actual metal content of the above as calculated from Kiilsgaard report is:

<u>Classification</u>	<u>Oz. Ag/ton</u>	<u>%Pb</u>	<u>%Zn</u>
Indicated ore	23.61	2.28	5.89
Inferred ore	10.17	0.55	5.14
	<u>18.93</u>	<u>1.68</u>	<u>5.63</u>
Indicated and inferred material	5.21	Nil	3.64
Total ore and mineralized material	14.52	1.14	5.00

Holzem (1969) considered that the 18 drill holes in Samrah which gave a total drill core of 3624 m to have explored a mineralized panel over 400 m long and 200 m deep. The reserves of this panel have been estimated at about 300,000 tons averaging 1% Pb, 5% Zn and 15 oz. Ag/ton.

Schultz (1972) estimated the reserves indicated by drilling to be 230,000 metric tons containing 13.2 oz. Ag/ton, 0.9% Pb and 5.3% Zn.

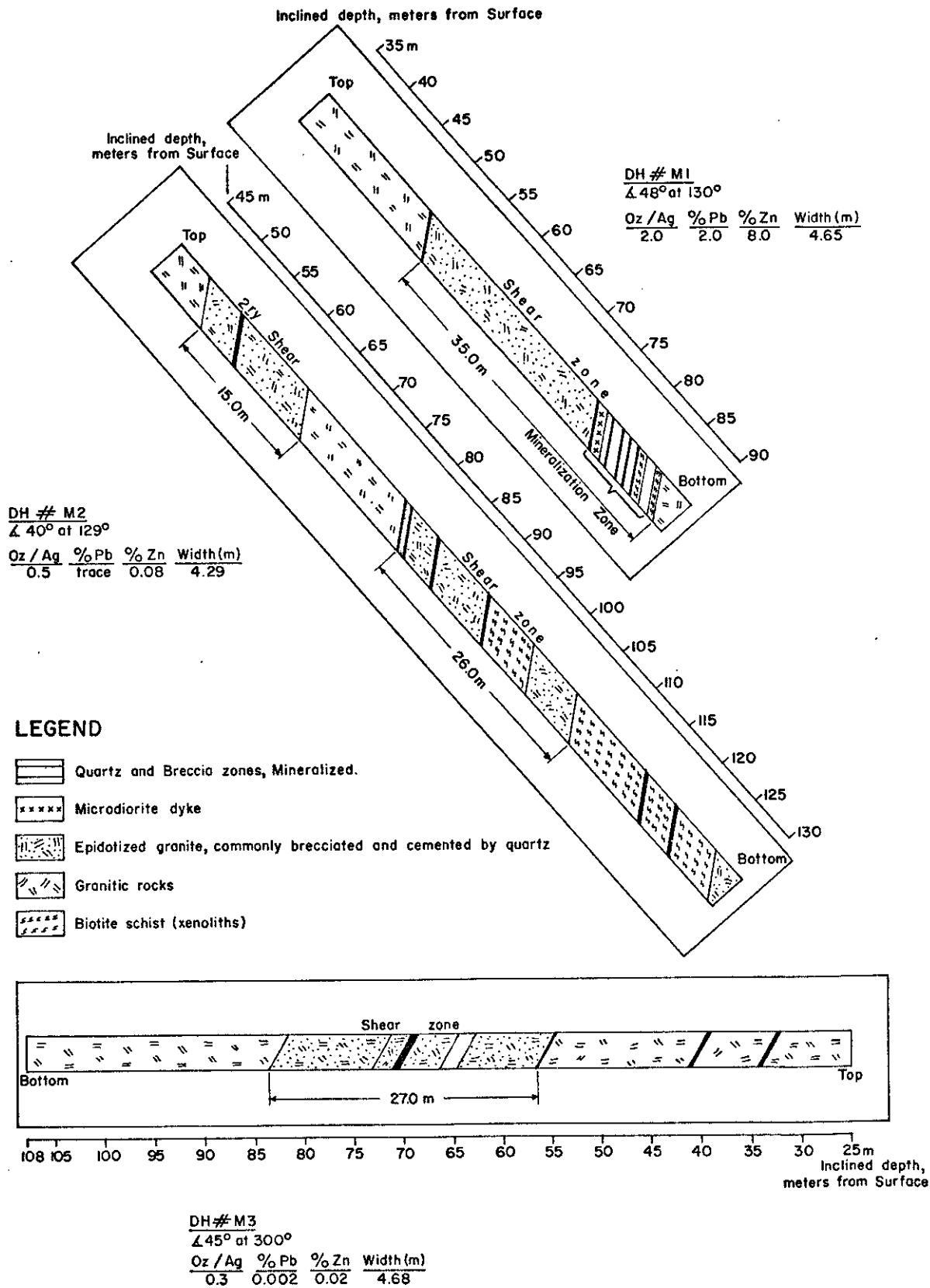
The estimation used by Schultz (1972) for the feasibility evaluation carried out on Samrah as 330,000 metric tons containing 13.6 oz. Ag/ton, 0.9% Pb and 4.5% Zn. He concluded that the reserves, the grade and the remoteness of this prospect renders it uneconomic.

7.6.2 Materah (GV19) prospect

Materah ancient mine is situated 5 Km. south of Ad-Dawadmi town, on a series of quartz sealed adamellite breccia and quartz veins localised along two parallel closely spaced shear zones trending 045°. The host rock is predominantly adamellite. Wall rock alteration as in the case of Samrah is very strong. The plagioclase of the adamellite is altered to light green clinozoisite and the potash feldspars clouded and stained red. Biotite schist inclusions are abundant, partly migmatized and invariably thermally metamorphosed to hornfels. Thin local microdiorite dyke intrusions preceded the mineralization.

The two mineralized shear zones are prominent over the surrounding ground, forming two longitudinal ridges. The ancient workings consist of discontinuous 5-10 m deep stopes. The workings extend intermittently for 700 m along the northern vein and 200 m along the southern one.

Fig. 7-16Materah (GV-19) Drill holes.



The zone showing shearing and hydrothermal alteration is 25-35 m wide. Sulphide mineralization is associated with grey quartz of the second stage infilling. The first stage quartz is barren white quartz which became brecciated and cemented by the second stage gangue and sulphide minerals. A third stage white barren comb quartz has cemented the former brecciated gangue and sulphide mineralization.

The sulphides present in Materah are pyrite, sphalerite, galena and chalcopryrite. The silver minerals present are polybasite and acanthite in minute inclusions in sphalerite.

The oxidized zone contains hematite, limonite, malachite and hemimorphite. Manganese staining is also abundant.

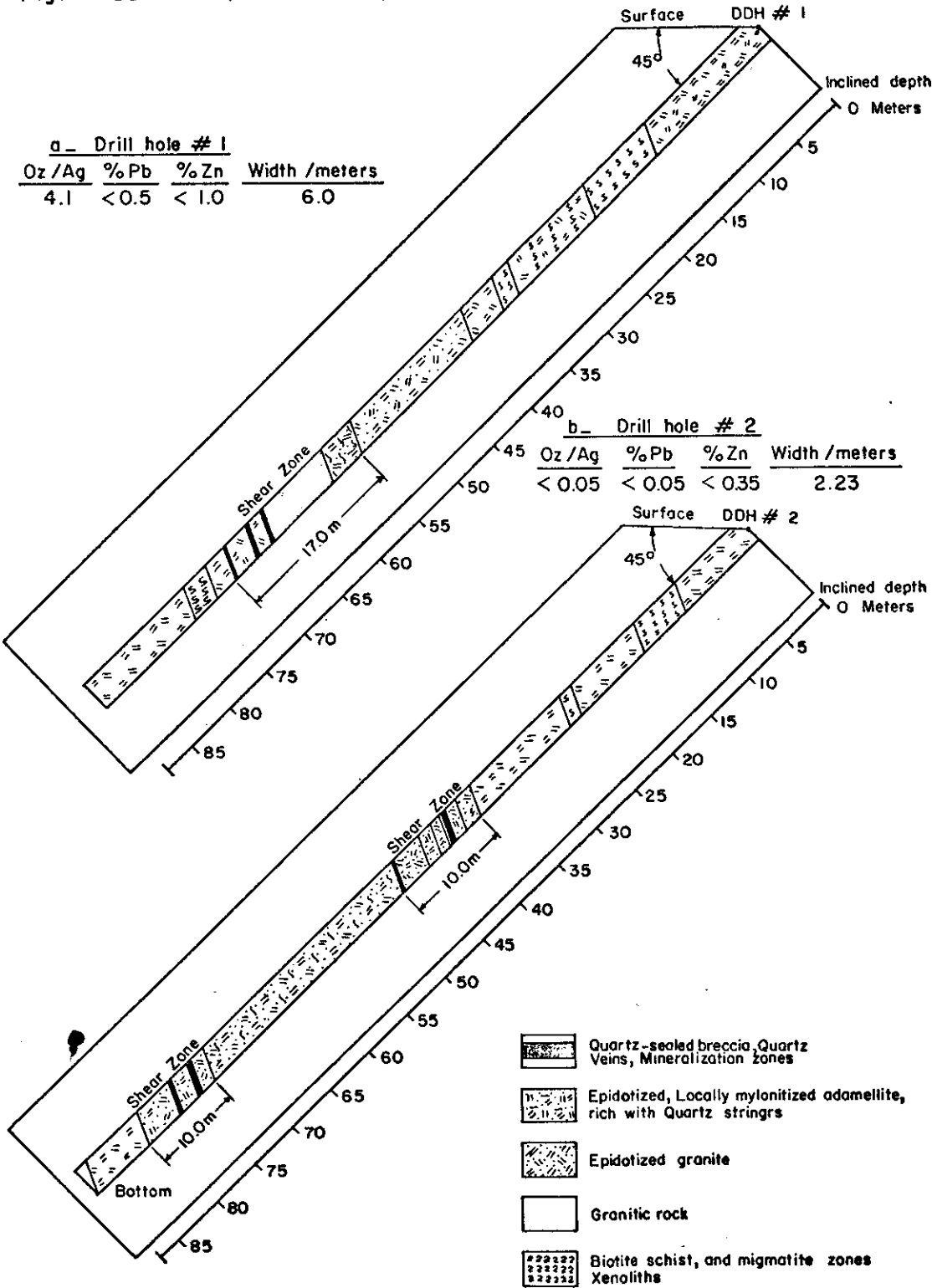
Three drill holes were carried out on the northern vein (fig. 7-16). These holes intersected disseminated sulphide mineralization associated with quartz veins. One hole intersected a 1.3 m zone with 11 oz of silver, but the average silver content in the whole thickness (4.65 m) of this zone is only 2 oz.

The textural relationships and paragenetic sequence of the ore minerals are comparable to those at Samrah. Pyrite was formed first, followed by sphalerite, then chalcopryrite. Galena is of later crystallization and tends to replace pyrite, sphalerite and chalcopryrite. Polybasite and acanthite are the last minerals formed as interstitial veinlets and minor inclusions in other sulphides, particularly sphalerite.

7.6.3 Sumairah (PL 98 west) prospect

Sumairah ancient workings are localized 2 Km on the north east extension of Samrah mine. The workings extend for a distance of 250 m. in the form of stopes and circular, inclined and vertical shafts. The depth reaches 15 m. The width of individual veins varies from 0.3 to 3.0 m. They consist of quartz-sealed granitic breccia and quartz veins. The host rocks are dominantly granitic and country rock inclusions. The granitic rocks are extensively saussuritized and sericitized and extensively cut by a network of white quartz veinlets commonly associated with calcite and chlorite.

Fig.7-17 Sumairah (PL 98 West)



Two holes were drilled on this mineral prospect (fig. 7-17). Both intersected sulphide mineralization within the quartz and the quartz breccia veins. The thicknesses and average analyses are given in fig. 7-17.

The sulphide minerals present are disseminated pyrite, sphalerite and galena. Chalcopyrite is less common, acanthite in minute inclusions and veinlets is rare. The textural relationships among the ore minerals as well as the paragenetic sequence are analogous to those of Samrah and Materah ancient mines.

7.6.4 PL 44

This ancient prospect is situated 3 Km north of Ad-Dawadmi town along a 057° trending shear zone.

The host rocks are predominantly porphyritic granodiorite intruded by equigranular Al-Masloukhah adamellite. Pre-existing rock inclusions are abundant. Alteration is identical to the former mineral sites. The ancient workings extend for 250 m as shallow filled-in pits.

One hole was drilled on this mineral prospect. It intersected the mineralized veins below the deep workings at an angle of 48° and 328° azimuth. A total of five quartz veins were intersected within a zone of country rock inclusion. The width of the veins ranges from 45 cm to 1.45 m within an 8.0 m wide zone. The silver values range from 0.1 - 2.8 oz/ton and average 4.6% zinc in a total lode width of 1.08 m.

The sulphide minerals pyrite, sphalerite, chalcopyrite and galena are disseminated throughout the zone of mineralization. Textures and paragenetic sequence are similar to the previously described vein deposits.

7.7 SUMMARY AND CONCLUSIONS

1. The zinc-lead-silver vein deposits of Ad-Dawadmi district are mostly situated within the granitic batholith. A few other vein deposits cut the metasediments near the granite contacts. These veins were extensively worked by the ancients.

2. The mineralization in the granitic rocks forms a distinct north-south belt in the central part of the district mapped. This belt contains many xenoliths which are predominantly pelitic and semi-pelitic. Many of the xenoliths are large and retain their original structure and orientation. There are several ancient prospects located in xenoliths, or at their faulted contacts with granite.
3. There is an obvious structural control of the mineralization throughout the district, along northeasterly trending shear zones and less commonly along east-west fractures. The intersections of the two provide favourable loci for mineralization.
4. The mineralization is controlled more by the availability of voids than by lithological variations in the wall rocks, i.e. the mineralized quartz breccia is found in granitic rocks (predominant), dyke rocks, basic inclusions or pelitic xenoliths. On a regional scale the mineralization is related to the belt previously occupied by a north-south trending pelitic horizon before the granite intrusion.
5. The hydrothermal fluids of residual magmatic origin related to the post-kinematic granite intrusions were responsible for the deposition of the sulphide minerals in fractures along a belt in the batholith which had been replaced by the granitic rocks.
6. Brecciation is ubiquitous along zones of fracturing throughout the district. The mineralization consists dominantly of a breccia of granitic fragments cemented by quartz with sulphide minerals. The brecciation and deformation were reactivated by repeated movements.
7. There were three generations of quartz deposition along the fractures. Base metal sulphide minerals were deposited with the second quartz generation. The first and the last generations of white quartz were barren. The earlier quartz is brecciated, but the last generation consisting of comb-like quartz crusts is more widespread and with the associated chlorite and calcite, cemented the fragmented sulphides and the gangue minerals.
8. The westerly trending fractures were intruded by dacite, microdiorite and rhyolite magma. The northeasterly shear fractures were locally intruded by this magma in the form of lenticular patches,

some of which were brecciated and mineralized during the latest fault movements which accompanied the mineralization (Samrah).

9. The predominant ore minerals are zinc, lead and silver sulphides (sphalerite, galena, acanthite and stromeyerite) and sulphosalts, (polybasite, pyrargyrite and tetrahedrite). Native silver is not uncommon and is associated with gangue and pyrite. Some other sulphides occur and include pyrite, chalcopryrite and minor amounts of arsenopyrite. Pyrrhotite and individual grains of millerite occur in the gabbroic wall rocks of Samrah prospect. Magnetite and hematite are uncommon and were only found in two drill hole intersections.

The sequence of mineral deposition was pyrite first, followed by magnetite, hematite then sphalerite. The pyrite, magnetite and sphalerite were extensively brecciated and cemented by later gangue and sulphide minerals. Chalcopryrite was deposited after sphalerite and replaced it and the earlier sulphides and iron oxides. Galena, the last mineral to be deposited, contains inclusions of silver phases and has been deformed and recrystallized, with well developed annealed textures. The silver phases related to this mobilized galena, predominantly as polybasite, migrated to the vicinity of grain boundaries and later were transformed to acanthite and chalcopryrite.

10. Supergene enrichment is weak and has formed small quantities of native silver, acanthite and stromeyerite.

11. Zoning: The mineral zoning across the veins is only slightly developed. The galena tends to occupy the central parts of the veins, which is probably due to its tendency to flow under conditions of high pressure temperature into new open spaces caused by renewed fracturing.. The sphalerite is almost ubiquitous but tends to be more concentrated on the hanging wall parts of the veins. Chalcopryrite, magnetite and hematite occupy positions near the foot walls of veins. The pyrite is widespread and does not show preference for any particular zone. Lateral and vertical mineral zoning other than the above is not observable and assumed to be insignificant.

12. Lateral extension of mineralization: DH8 and DH10 which traversed the west-south-west and the east-north-east strike extensions of Samrah mineralization respectively, did not detect

any significant mineralization. The surface exposures at both these extensions appear to be barren.

13. Mineralization at depth: Mineralization below the zone drilled probably decreases with depth as fracture zones become tighter.

CHAPTER 8

CONCLUSIONS

8.1 OROGENESIS

The Ad-Dawadmi district, as part of the east-central segment of the Arabian Shield, has been affected by few mountain building movements (the multicyclic Hejaz and Najd orogenies). These were responsible for the emplacement of various granitic, basic and ultrabasic rocks, as well as the folding, faulting and metamorphism of the older sedimentary successions. Bloomfield (1970) and Kazmin (1971) believed that the multicyclic Mozambique Orogeny may have extended northward into the Arabian shield. However Brown (1971) was reluctant to apply the African orogenic cycle nomenclature to the Arabian shield until more detailed correlation is made. Many radiometric datings appear to be correlatable.

In the Ad-Dawadmi district the conformable Ar-Ridaniyah and Abt Formations have been folded and metamorphosed to low grade greenschist facies during the widespread Hejaz orogeny which was active in the period of 1000 - 660 m.y. B.P.

An ultrabasic suite now comprises chloritite and serpentinite, which are schistose in the north. These, together with amphibolite, were emplaced in the Ar-Ridaniyah Formation during the earliest phase of the Hejaz orogeny.

Layered basic masses were emplaced during the waning stage of folding and were followed by syn- and late-kinematic granitic intrusions. The ultrabasic suite is strongly metamorphosed compared with the layered gabbros. This is probably due to the intrusions of the layered masses at a later and less intense stage of the Hejaz orogeny.

The Najd Orogeny followed the Hejaz Orogeny.. It is characterized by northwest tectonic trends and probably culminated at the end of the Precambrian. The effects of this orogeny on the district are restricted

to the intrusion of the post-kinematic granite and later the development of northwest strike-slip faults. Probably some of the retrograde metamorphism observed in the area is related to the Najd Orogeny. This orogeny is synchronous with the Pan-African tectonothermal event marking the end of Precambrian in Africa (Brown, 1971).

Following the Najd orogeny, the shield was a stable shelf throughout the Palaeozoic. Evidence of this is the occurrence of the undeformed Saq Sandstone which was deposited unconformably over the shield during Cambrian-Ordovician period.

8.2 THE METAMORPHIC SUCCESSIONS

The Ad-Dawadmi district contains two metasedimentary Formations, Ar-Ridaniyah and Abt. These were intruded by Pre-, syn-, late- and post-kinematic intrusions which range from ultrabasic to acidic. These metasediments were deposited in a transgressive probably marine environment with impure sandstones at the base and pelitic/semi-pelitic units at the top.

8.2.1 The Ar-Ridaniyah Formation is the basal formation. It consisted originally of 1500 - 2000 m thick impure sandstone horizon at the base. This is overlain conformably by a 2000 - 3000 m thick calcareous horizon intercalated with limestone, dolomitic limestone, pelitic bands and possibly thin tuffaceous layers. The Ar-Ridaniyah Formation is exposed only in the southeast part of the district.

8.2.2 The Abt Formation is composed essentially of a thick series of pelitic and semipelitic rocks which conformably overlie the Ar-Ridaniyah Formation. They were deposited in a relatively deeper environment than the sediments of Ar-Ridaniyah Formation.

8.2.3 The Ultrabasic Suite at the contact of the impure sandstone and the overlying calcareous horizon forms roughly concordant intrusive sheets in the Ar-Ridaniyah Formation.

8.2.4 The Deformation and Metamorphism related to the early Hejaz orogeny raised, deformed and metamorphosed both the sedimentary

successions and the intrusive ultrabasic suite. Metamorphism reached the greenschist grade facies (Bl.1-Bl.2). The metamorphic minerals which dominate both Formations are: albite, epidote/clinozoisite, tremolite/actinolite, biotite-chlorite-muscovite, calcite and quartz.

The ultrabasic suite was metamorphosed to serpentinite and chloritite which became schistose in the northern outcrops. The basic rocks became amphibolites.

8.3 LAYERED INTRUSIONS

The layered basic intrusions were intruded during the waning stages of the Hejaz orogeny. This is indicated by the absence of folding and by incipient amphibolitization.

The Al-Jealani intrusion is an elliptical mass with a steeply inward dipping margin that exhibits no chilled contacts against the enveloping granitic rocks. The intrusion is probably an inverted cone shape as interpreted from the aeromagnetic map and the dips at outcrop in the outer units. The dips of the fifteen units that comprise this intrusion at outcrop decrease gradually inwards from 60° to 20° or less.

The Al-Jealani layered mass probably formed from one surge of basaltic magma along an elliptical structure. The layered rocks originated through undercooling combined with convection currents in the magma. Density stratification in rhythmically layered rocks are attributed to a gravitative process.

The well layered sequences which are commonly separated by essentially non-rhythmically layered plagioclase - olivine cumulates suggest that the process of rhythmic layering operated intermittently.

8.4 GRANITIC ROCKS

The granitic rocks were emplaced during the late cycles of the multicyclic Hejaz orogeny, and after the emplacement of the layered basic masses. The long northwesterly axis of the granitic batholith is subparallel to the general strike of the fold axes in the enveloping metamorphic host rocks.

The batholith is comprised of three genetically separated components, an earlier foliated, coarse-grained and porphyritic variety in the west, termed synkinematic, a later equigranular homogeneous variety in the east termed late-kinematic and a post-kinematic type which is homogeneous, non-contaminated, pink, locally porphyritic and shows sharp chilled contacts against the previous two varieties. Syn- and late-kinematic components constitute about 95% of the granitic rocks exposed, whereas the post-kinematic type rocks constitute only 5% of the total granite and occur in small stocks and dykes.

The three granitic varieties are derived from one magmatic source of average calc-alkaline composition from a crustal melt. The magmatic differentiation followed one path from more calcic synkinematic to less calcic post-kinematic.

The syn-kinematic variety shows primary flow fabric suggesting generation of the granite melt below the present level. Their prevailing gradational contacts and inhomogeneity indicate an undisturbed region in the upper low liquid portion of the zone of melting.

The late-kinematic variety represents the more fluid portion of the zone of melting. It exhibits sharp contacts against earlier rocks.

The post-kinematic rocks were emplaced last and show chilled contacts against older granitic varieties.

8.5 SYN-SEDIMENTARY MINERALIZATION

The upper part of the Ar-Ridaniyah Formation contains concentrations of iron and zinc sulphides in the form of lenses parallel to bedding. At outcrop these are capped by brown gossan that extends about 20 m downwards with no apparent supergene base metal enrichment.

A syngenetic-diagenetic origin is postulated for these sulphide lenses. The sulphides may have been deposited either as sedimentary accumulations or as submarine hydrothermal exhalations or possibly by both processes.

The metals are thought to have been derived from a land surface by erosion and subsequently transported by currents in streams into an environment of sulphidation. Alternatively the source of metals could have been distant hydrothermal subaqueous exhalations. The sulphide deposits probably formed when the metal ions encountered H_2S generated from rotting organic material below the sediment/water interface, or more likely by the reduction of the sea water sulphate. The reduction of the sulphate may have been biogenic or inorganic.

According to Rickard (1968), the form of iron that reacts with sulphide species to form iron sulphides in the natural aqueous environment is mainly goethite. The diagenesis and the early stages of metamorphism were possibly the important factors which induced remobilization and concentration of the ore sulphides into lenses.

When the temperature exceeded $200^{\circ}C$ during regional metamorphism the non-equilibrium iron sulphides if present should have been converted into the equilibrium components pyrite and pyrrhotite (Rickard, 1968). As the pressure and temperature became higher the pyrite-pyrrhotite transformation possibly would have released large amounts of sulphur. This possibly leached the remaining zinc, lead, copper and silver ions adsorbed on the non-sulphide components to form further ore sulphides.

Supergene oxidation is marked by the peripheral breakdown of pyrrhotite grains or aggregates to marcasite and secondary pyrite. This presumably is promoted by either descending or ascending acidic solutions.

8.6 HYDROTHERMAL VEIN TYPE MINERALIZATION

The Ad-Dawadmi district is an ancient silver mining district. Ancient workings are widespread along quartz breccia veins. These veins are structurally controlled within a north-south trending belt in the central part of the granitic batholith. It seems possible that this mineralization was disseminated in a north-south trending pelitic and semi-pelitic horizon before the intrusion

of the granite and was therefore lithologically controlled. This pre-granite pelitic horizon is now represented only by xenoliths which commonly retain their original structures and orientations. The intrusion of post-kinematic granites was followed by the development of a fracture pattern related to the Najd orogeny.

The residual hydrothermal magmatic fluids of the post-kinematic granite probably played the main role in leaching the metals from the host rocks, mobilized and deposited them along these fractures. It is possible that the mineralized fluids were partly deep seated magmatic and partly metamorphic. Repeated shearing along mineralized fractures was associated with further deposition of gangue minerals, with brecciation of brittle minerals and with mobilization and recrystallization of other less brittle minerals.

Alteration is extensive within the fracture zones as well as in the walls. For example, feldspars of both granitic and basic rocks are strongly epidotized and sericitized, pyroxenes amphibolitized or altered to biotite and/or chlorite. Minute veinlets of quartz, carbonate minerals and chlorite are common.

A detailed exploration program carried out at Samrah, the main prospect in the district, proved that the deposit is uneconomic. The probable reserves are estimated by Kiilsgaard (1968) at 330,000 tons of ore with average 13.0 oz silver, 1% lead and 4.5% zinc.

The ancient miners won 60,000 tons of ore from surface and underground mining.

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APPENDIX 1

Semiquantitative Spectrographic Analysis of Heavy Concentrates in Al-Jealani Layered Complex

(B & Li were analyzed but not detected)
(Cr analysed by X-ray Fluorescence)

Sample No	Ba wt.%	Co wt.%	Mn wt.%	Cu wt.%	Cr wt.%	Ni wt.%	Ti wt.%	Sr wt.%	V wt.%	Pb wt.%	Zn wt.%	Fe wt.%	Zr wt.%	Ca wt.%	Na wt.%
SA-2	.02	.006	.25	.002	.07	.015	1.0	.02	.08	.005	.05	10.	.005	.3	.05
SA-6	.02	.003	.15	.002	.05	.006	1.0	.02	.06	.005	.05	10.	.015	.3	.05
SA-9	.02	.004	.2	.002	.04	.008	1.0	.02	.06	.005	.05	10.	.01	.6	.05
SA-14	.02	.003	.15	.002	.04	.006	1.0	.02	.06	.005	.05	10.	.015	.2	.05
SA-20	.02	.003	.2	.002	.016	.005	1.0	.02	.06	.005	.05	10.	.005	.6	.05
SA-24	.02	.004	.2	.002	.04	.005	1.0	.02	.05	.005	.05	10.	.015	.6	.05
SA-27	.02	.004	.2	.002	.04	.006	1.0	.02	.06	.005	.05	10.	.005	.6	.05
SA-30	.02	.006	.15	.003	.02	.006	1.0	.02	.08	.005	.05	10.	.008	.1	.05
SA-38	.02	.008	.12	.002	.03	.01	1.0	.02	.08	.005	.05	10.	.04	.1	.1
SA-44	.02	.006	.12	.002	.04	.01	1.0	.02	.035	.005	.05	10.	.02	1.5	.1
SA-46	.02	.006	.12	.003	.06	.01	1.0	.02	.06	.005	.05	10.	.025	.1	.05
SA-49	.02	.008	.15	.004	.14	.012	1.0	.02	.07	.005	.05	10.	.03	.3	.05
SA-51	.02	.008	.15	.003	.05	.015	1.0	.02	.07	.005	.05	10.	.02	1.	.05
SA-53	.02	.006	.12	.004	.06	.01	1.0	.02	.08	.005	.05	10.	.05	.2	.05
SA-55	.02	.008	.15	.003	.04	.01	1.0	.02	.08	.005	.05	10.	.05	1.5	.1
SA-57	.02	.007	.5	.003	.07	.015	1.0	.02	.06	.005	.05	8.	.02	.5	.05
SA-60	.02	.007	.4	.003	.06	.01	1.0	.02	.05	.005	.05	8.	.02	.5	.05
SA-62	.02	.006	.4	.003	.06	.008	1.0	.02	.05	.005	.05	8.	.02	.3	.05

APPENDIX 2

Field and Laboratory Methods
(Al-Jealani basic intrusion)

1. Two detailed chain and brunton compass traverses were carried out.

(a) A-A' traverse, N 42° W, started 200 metres away from the northern margin of the intrusion to the centre.

(b) B-B' traverse, N 48° E, ran across the intrusion from west to east.

These traverses were chosen to ensure best exposures of various units. However, many contacts between units were either inferred or checked in localities away from the traverse line.

2. 213 rock samples and 70 heavy concentrates were collected, the latter from the small tributaries draining particular rock units.
3. 160 thin sections were prepared from the rocks of the basic intrusion, the younger dyke rocks, the enveloping granitic rocks, the xenolithic outcrops in the vicinity of Samrah mine, and from drillhole 1 of the mine.
4. Plagioclase was separated, using Frantz isodynamic magnetic separator, from 40 rock samples of the basic intrusion.
5. An content of plagioclase was determined optically on cleavage fragments by the Tsuboi method. Ca was determined on the same material chemically. Sr was determined using X-ray Quantometer.
6. 5 whole rock analyses were made on rocks of the layered intrusion.
7. 60 rock samples were determined semiquantitatively by spectrographic analyses for trace elements, and other elements that are related to this study, Cr was checked by X.R.F.

8. 18 heavy concentrates were investigated semiquantitatively by spectrographic analyses for trace and other elements that relate to the study. Fe, Ti and Cr were checked by X.R.F.
9. 15 polished sections were prepared from the heavy concentrates.
10. 10 polished sections were prepared from the rocks of the basic intrusion which showed relatively high concentration of opaques.
11. The field data were plotted on 1 : 10,000 scale photo enlargement for the intrusion and the vicinity.
12. A final map (plate 3) 1 : 10,000 scale is made on the basis of (a) field work, (b) laboratory work, and (c) photogeologic interpretation.

APPENDIX 3

Procedure

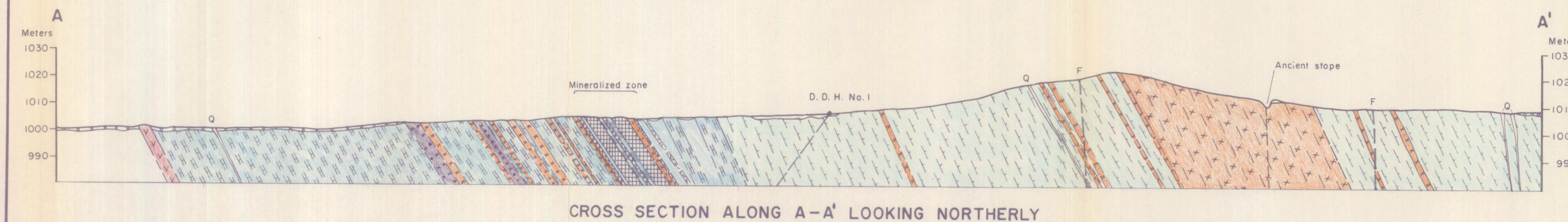
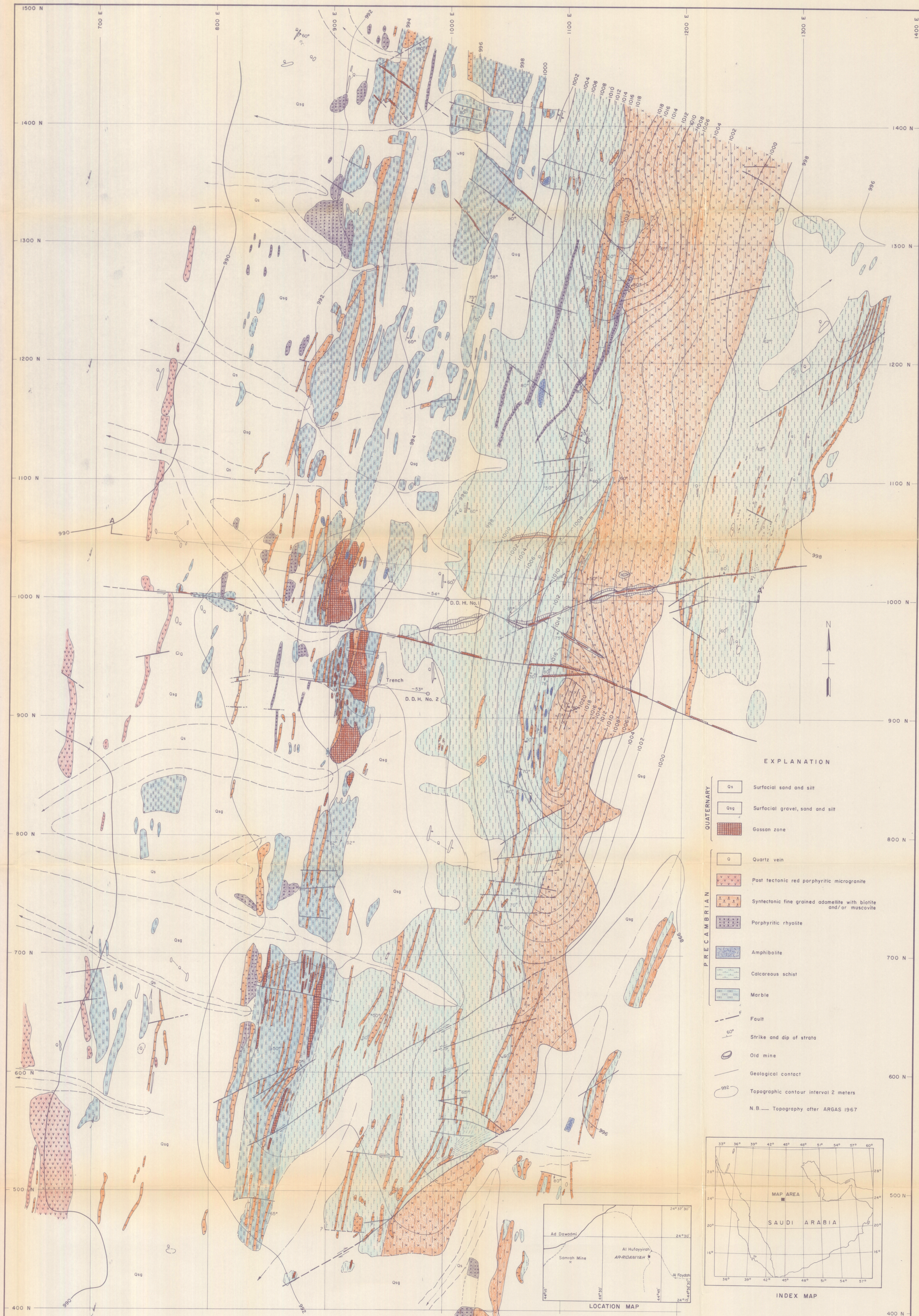
The mineral identification was carried out by using the combined technique of ore microscopy, electron microprobe analyses and X-ray powder diffraction.

The physical features and optical properties of the minerals were examined in reflected light using a Reichert Zetopan ore microscope.

A Cambridge Microscan Mk.1 was employed to analyse carbon-coated polished mineral surfaces. A constant accelerating voltage of 25 kv was used throughout. Average counts per ten seconds from the sample were compared with the count rate from standards which were pure metals or analysed samples. The detection limit is 1.0% or better, and the precision of analyses is within $\pm 5\%$ of the relative value.

Quantitative data were corrected for errors due to instrumental effects: absorption, over voltage, atomic number and fluorescence, using a semi-empirical method (T.K. Kelly and G.M. Steed pers. comm.).

Small amounts of silver sulphosalt polybasite were excavated from polished sections using a fine steel needle and incorporated in a small ball of rubber solution. The ball was mounted on a drawn glass fibre and inserted in a Philips 11.46 cm (dia.) Debye-Scherrer powder camera. Either Fe filtered Co K α ($\lambda = 1.7889 \text{ \AA}$) or Ni filtered Co K α ($\lambda = 1.5405 \text{ \AA}$) radiation was used. Interplanar spacings were determined with the line spacings being read on a scale, and the relative intensity of the lines was visually estimated. X-ray diffraction angles were tabulated and the d values obtained from tables.



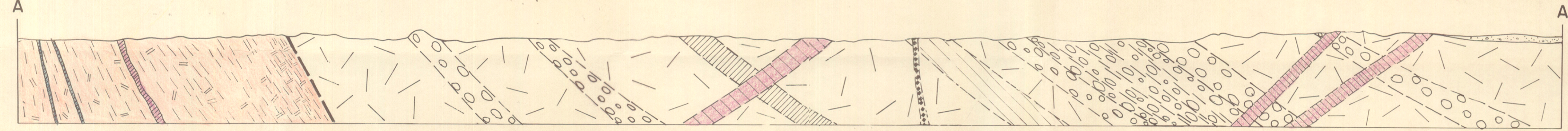
AR-RIDANIYAH AREA

BY

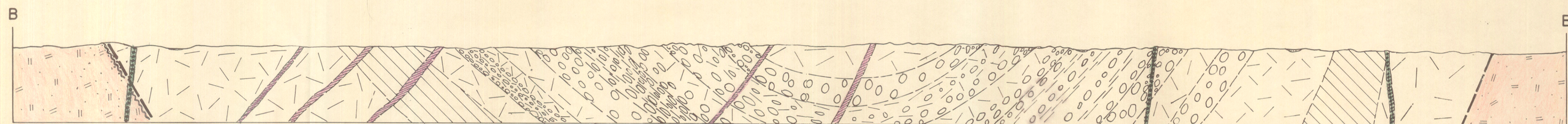
A. M. ALSHANTI

SCALE 1:1000

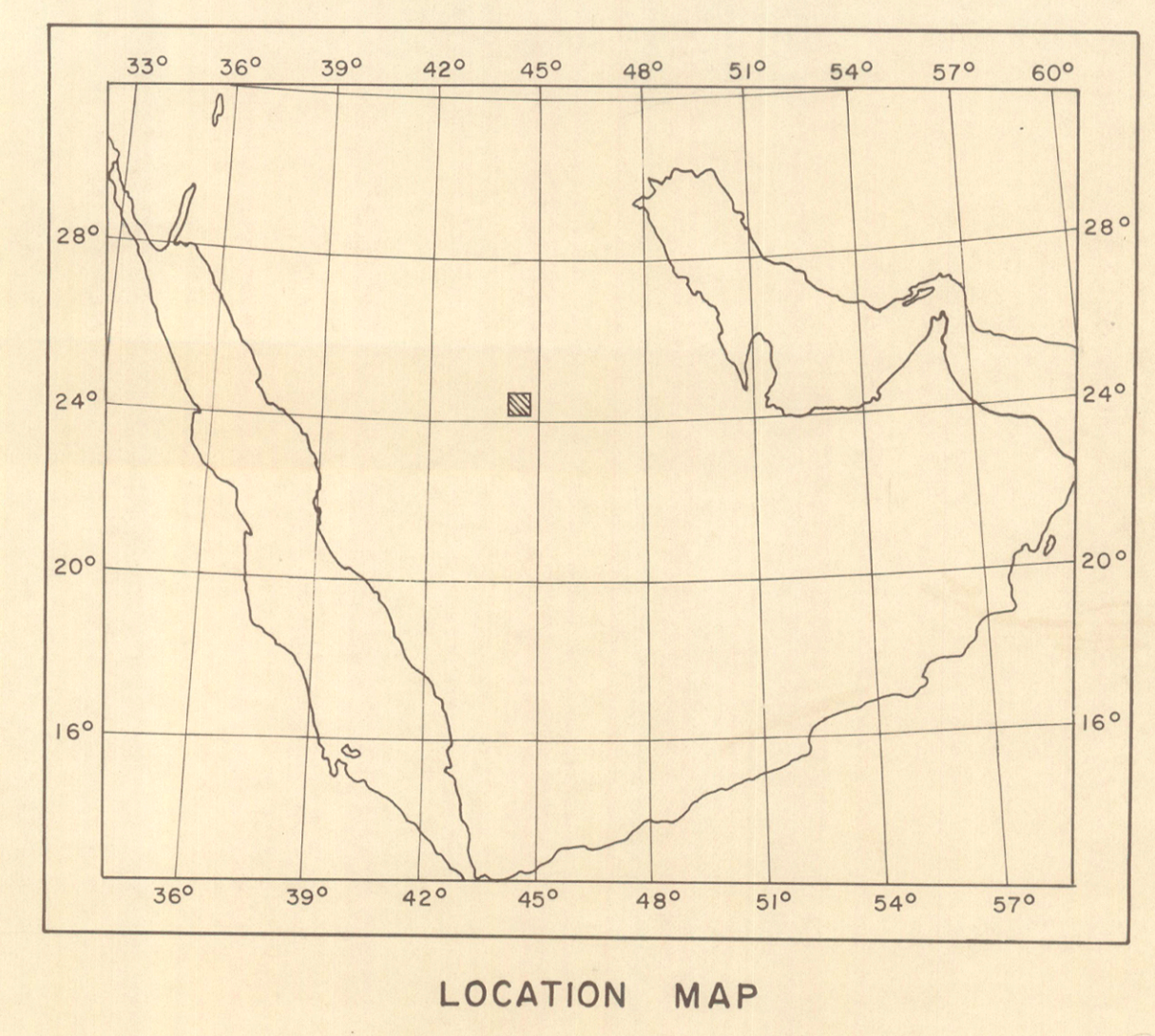
20 0 20 40 60 80 100 Meters



GEOLOGIC SECTION ALONG A-A' LOOKING N 42° W



GEOLOGIC SECTION ALONG B-B' LOOKING N 48° E



LOCATION MAP

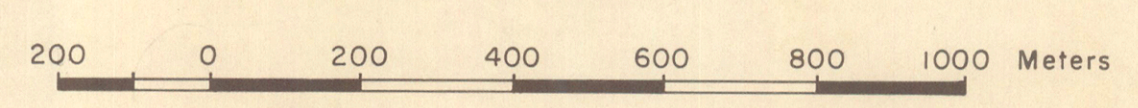
E X P L A N A T I O N

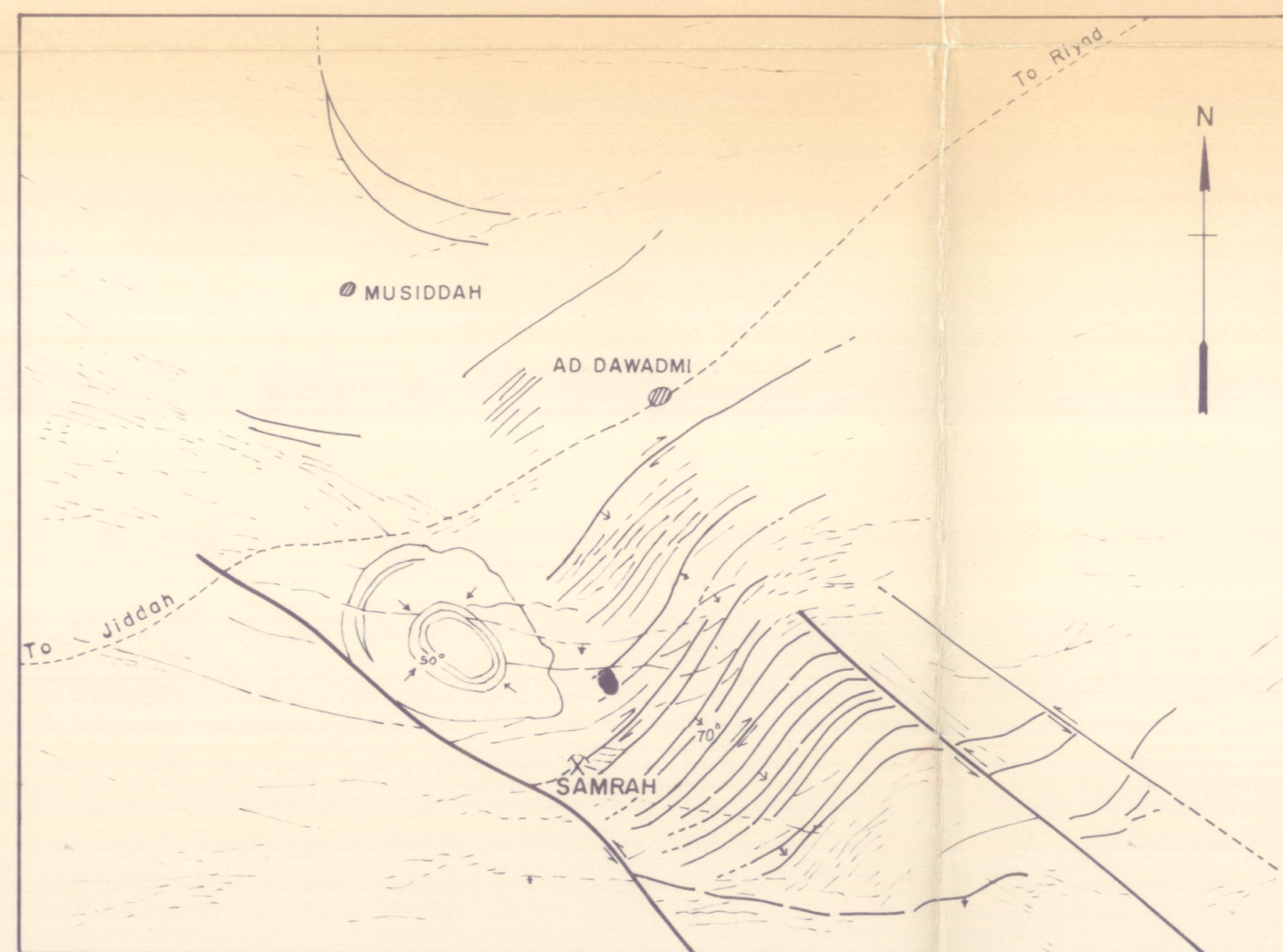
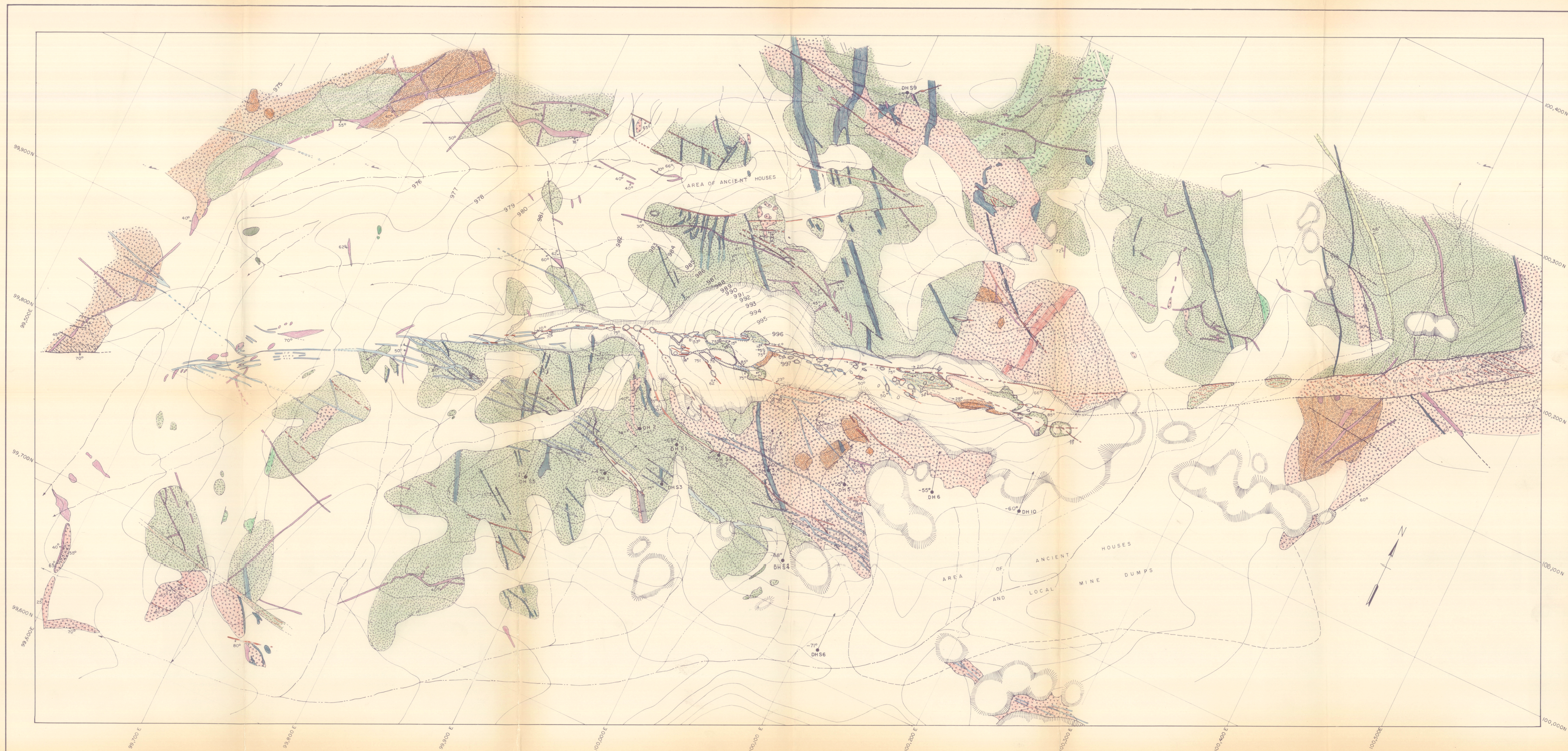
- | | |
|-----------------------|--|
| QUATERNARY | Alluvium |
| DYKES | Dacite |
| | Microdiorite and quartz microdiorite |
| | Aplite, pegmatite, microgranite, small plugs and dikes |
| GRANITIC ROCKS | Pink granite equigranular |
| | Al Masloukha adamellite |
| | Adamellite porphyritic |
| | Adamellite gneissic porphyritic |
| PRECAMBRIAN | Plagioclase cumulate interlayered with metagabbro and plagioclase-olivine pyroxene cumulate layers |
| | Plagioclase orthopyroxene cumulate, local intercalations of metagabbro layers |
| | Plagioclase-pyroxene-olivine cumulate, intercalated with metagabbro layers |
| | Plagioclase-olivine-pyroxene cumulate |
| | Metagabbro, thin layers of plagioclase cumulate, plagioclase-olivine-pyroxene cumulate occur in the middle zone layers |
| | Shear zone with dip |
| | Trend lines - (Schistosity) |
| | Layering of basic rocks |
| | Geologic contact definite and inferred |
| | Fault - indicated and inferred |

AL-JE'ALANI LAYERED MASS

BY
A. M. ALSHANTI

SCALE 1:10,000





EXPLANATION

- Main north westerly shear zones with horizontal component dislocation
- North easterly "S" Shears with horizontal component dislocation
- Tension open fractures - where no horizontal dislocation is involved filled in with dikes of Dacite, Rhyolite, Andesite and Microdiorite usually forming an echelon pattern
- Layered gabbro complex

REGIONAL TECTONIC SETTING

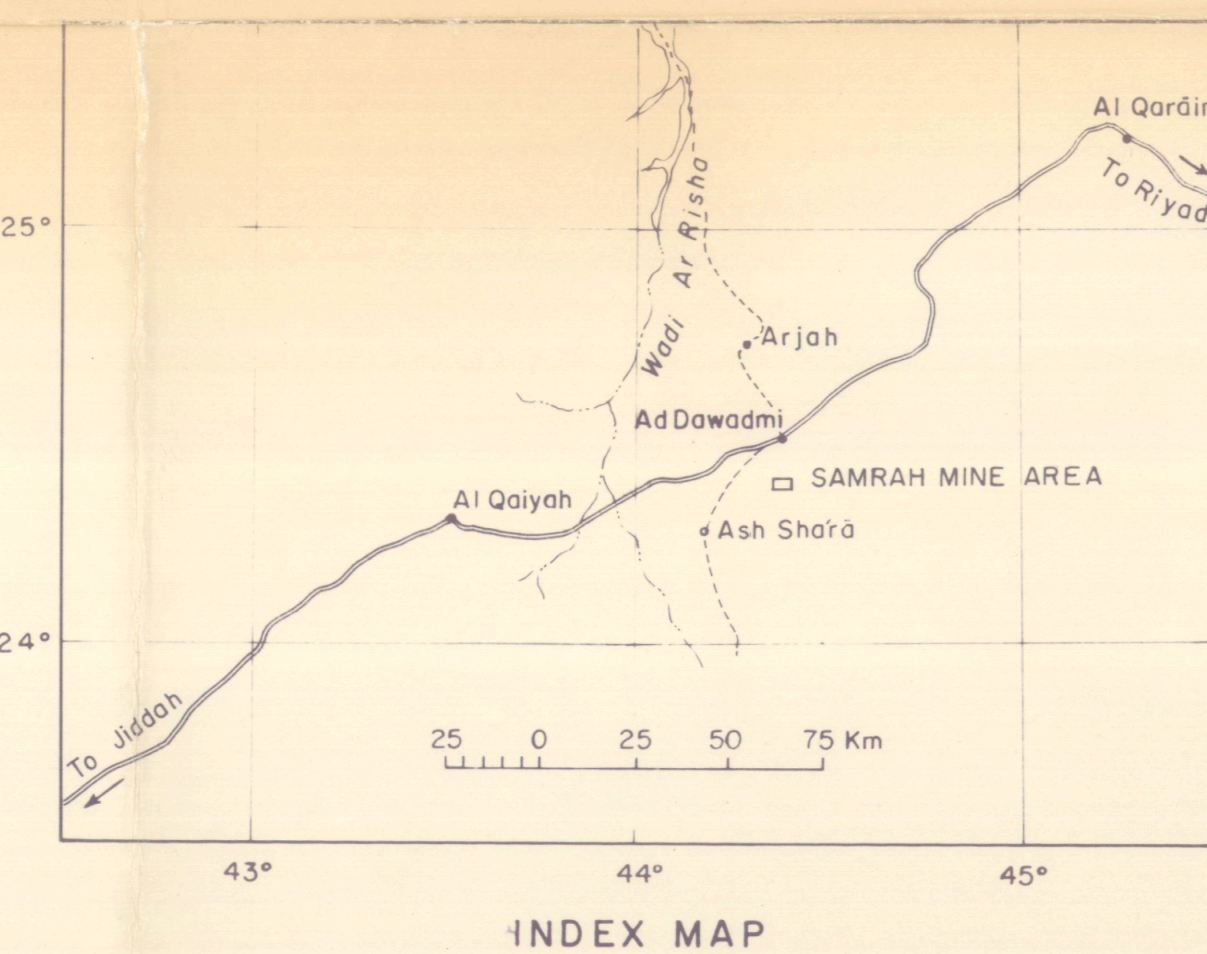
Appr. Scale 1:250,000

EXPLANATION

- Alluvium, gravel sand and silt
- FRACTURE ZONE FILLINGS**
 - Quartz - sealed granitic breccia - locally mineralized and extensively cut by later white quartz thread like stringers
 - Quartz - sealed metagabbro or metadiorite breccia locally mineralized and extensively cut by later quartz thread - like stringers
 - Quartz Vein - mineralized - usually hematized, silicified and brecciated
- DYKES**
 - Andesite: usually filling tension shears in form of an echelon pattern and dipping steeply southward
 - Pegmatite and aplite - usually dipping gently southward as most of tectonic elements in the area dip
 - Microdiorite porphyritic transformed or passing to amphibole schist
 - Microdiorite; trending N 20°-30° W, porphyritic, ranging from very fine grained andesitic to medium grained dioritic, margins leucocratic when in granitic rock
 - Biotite microgranite, equigranular, pink

- COUNTRY ROCKS**
 - Biotite granite; equigranular, leucocratic
 - Biotite adamellite equigranular, leucocratic
 - Biotite adamellite coarse grained, porphyritic, foliated, locally gneissic usually with inclusions of older rocks; (Paraschist inclusions), occurs as Xenoliths and inclusions in the younger equigranular, leucocratic biotite granite and fine grained biotite adamellite (Ar. Ridahah type)
 - Anorthosite, massive - usually in relatively thin layers
 - Gabbro, melanocratic, massive, weathered to individual large boulders
 - Metagabbro; metadiorite and local anorthosite, fine, medium and coarse grained pyroxenes strongly altered to actinolite - tremolite, and chlorite, usually massive but sheeting, fracture cleavage and spheroidal weathering are developed locally

- Fault, dashed when inferred usually marked with presence of later quartz and calcite
- Plunge of lineation
- Layering in basic rocks
- Dip of vein or dike
- Fracture cleavage showing strike and dip
- Joints in granitic rocks
- Geological contact dashed when inferred
- Mine dumps
- Outline of ancient stopes and shafts
- Diamond drill hole
- Topographic contour line - interval of one meter



SAMRAH MINE AREA

BY
A. M. AL SHANTI

Scale 1:1000
0 20 40 60 80 100 120 Meters

(Plane table Survey using autoreducing Keuffel & Esser alidade.
Considering Base station C as 997.2 meters above sea level)
Instrument used: W. DAWISH
MAY 1971
Coordinates represent geographic directions based on astronomic observation by Mr. Kuwagata of JGM 1971

AD-DAWADMI DISTRICT

SAMPLE LOCATION MAP

SHOWING GROUPING OF THE JOINTS
AND DRAINAGE PATTERN

BY

A. M. ALSHANTI

SCALE 1:50,000

