# CHAPTER 3 GEOLOGY AND ECONOMIC GEOLOGY OF THE SURVEY AREA

## 3-1 General Geology

The Oman Mountains, forming part of the Alps-Himalaya orogenic belt, consist of autochthonous and allochthonous units. The autochthonous units form the Arabian Platform and consists of the Pre-Cambrian to Mesozoic formations. The allochthonous units, overthrusted onto the autochtonous units, consist of Hawasina Nappes and overlying Samail Nappe. The Hawasina Nappes consist of Hawasina Sediments and the Samail Nappe is divided into Samail Ophiolite and Supra-ophiolite Sediments. The study area is located on the Samail Nappe.

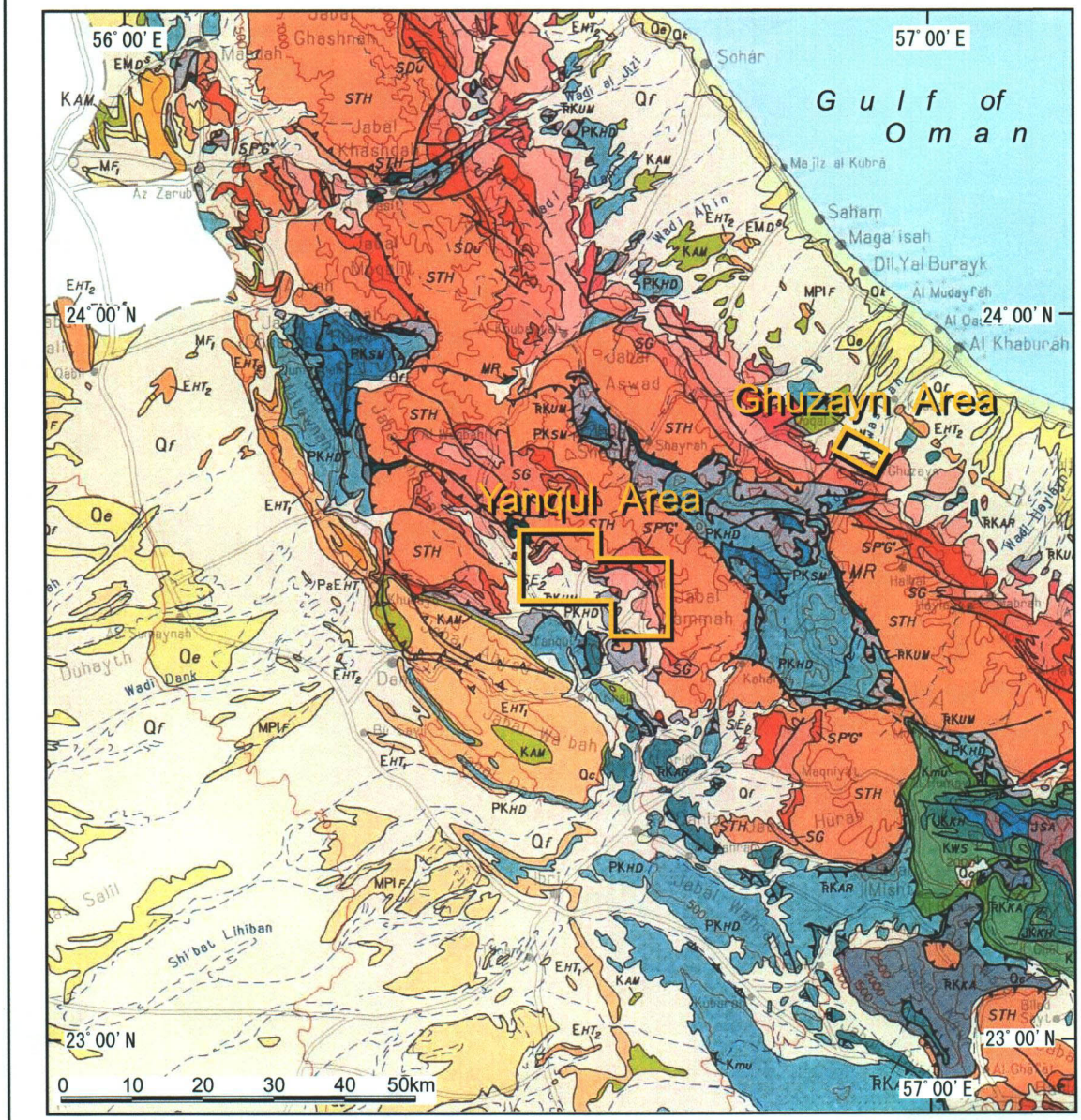
The Samail Ophiolite consists of Tectonites, Cumulate Sequence, High-level gabbro, Sheeted-dyke Complex and Samail Volcanic Rocks in ascending order. The Supra-ophiolite Sediments comprise mainly olistostroms. The geological map of the study area is shown in Fig. I -3-1.

Structural development in the area can be divided into three stages; formation of Samail Ophiolite (stage-1), obduction of Samail Ophiolite (stage-2), and after emplacement (stage-3). Samail Ophiolite was formed in the spreading ridge of Palaeo-Tethys sea from early to Middle Cretaceous (Lippard et al., 1986). In this stage, (stage-1), the Hawasina basin was situated between the ridge and the Arabian Plate and the Hawasina Sediments were deposited in the basin. The original structures of Ophiolite generally remain within the Tectonites, Cumulate Sequence and Sheeted-dyke Complex. The original structures observed in the Rakah area indicate similar trend to the general trend of ophiolite in the Oman Mountains region. Following the obduction of the Hawasina Nappes and deposition of the Supra-ophiolite Sediments, the Samail Nappe detached from sea floor and obducted onto the southwestern edge of the Arabian Plate (Oman Platform) in the stage-2. The obduction of Samail Ophiolite is considered to be the Late Cretaceous age (Coleman, 1981 and Lippard et al., 1986). Thrust faults and folds related to the obduction are widely found in the Oman Mountains. In the Rakah area, several thrust faults and folds in this stage are found and the thrust faults form an imbricated structure. The stage-3 corresponds to post-obduction and shows a variation in different localities. Several faults in this stage are found in the Rakah area.

## 3-2 Mineralization and Mining Activities

### 3-2-1 Mineralization

Massive sulphide deposits in the Oman Mountains are situated in the lower part of the Samail Volcanic Rocks and are classified into the Cyprus-type copper deposits. In general, it is understood that the Cyprus-type copper deposits are formed on the sea floor and accompanied with basic volcanic rocks.




## LEGEND

**SURFICIAL DEPOSITS**
Quaternary

- Qr — Alluvial deposits
- Qm — Coastal deposits

**SEDIMENTARY COVER**
End-Cretaceous - Tertiary

- $MPlF_3$ — MIOCENE-PLIOCENE, Upper Fars Group, Shelf facies
- $MF_2$ — MIDDLE MIOCENE, Middle Fars Group, Shelf facies
- $MF_1$ — EARLY-MIDDLE MIOCENE, Lower Fars Group, Shelf, fore-reef and slope facies
- EMD — LATE EOCENE - EARLY MIOCENE, Dhofar Group, Shelf facies
- $EHT_3$ — LATE EOCENE, Upper Hadhramaut Group, Shelf facies
- $EHT_2$ — EARLY-MIDDLE EOCENE, Middle Hadhramaut Group, Shelf facies
- $EHT_1$ — Lower Hadhramaut Group, Shelf facies
- KAM — END-CRETACEOUS, Aruma Group, Shelf, slope and basin facies

**SAMAIL OPHIOLITE**
Middle - Late Cretaceous

- $SE_2$ — LATE MAGMATIC UNIT, Upper extrusives
- SPG — Intrusives - Peridotite, gabbro
- $SDE_1$ — EARLY MAGMATIC SEQUENCE, Sheeted dyke complex and Lower extrusives
- SG — Cumulate and High level gabbro
- SDu — Dunite
- STH — MANTLE SEQUENCE, Tectonized harzburgite

**SUMEINI AND HAWASINA NAPPES**
Late Permian - Late Cretaceous

- TKUM — TRIASSIC-CRETACEOUS, Umar Group, Volcanic rocks, basin facies
- TKKA — TRIASSIC-CRETACEOUS, Kawr Group, Volcanic rocks, platform facies
- PKHD — LATE PERMIAN - LATE CRETACEOUS, Hamrat Duru Group, Volcanic rocks, basin facies
- PJBd — LATE PERMIAN - JURASSIC, Baid Formation, Shelf facies
- TKAR — TRIASSIC - LATE CRETACEOUS, Al Aridh Group, Volcanic rocks, slope facies
- PKSM — LATE PERMIAN - LATE CRETACEOUS, Sumeini Group, Slope facies

**Geological symbols**

- Contact
- Fault - Dashed where inferred
- Major thrust fault - Saw-teeth on upper plate
- Minor thrust fault, reverse fault

Ministry of Petroleum and Minerals (1993)

Fig. I -3-1 Geological map of the Yanqul - Ghuzayn area

Major Cyprus-type copper deposits in Oman Mountains consist of Lasail, Aarja and Bayda deposits in the Sohar area, Rakah and Hayl as Safil deposits in the Rakah area. Additionally, as a result of this cooperative mineral exploration survey, the Ghuzayn deposit has been discovered.

Based on the survey results around the Ghuzayn deposit, its geological structure and mineralization can be schematically described as shown in Fig. I -3-2. As indicated in this figure, the following characteristics in mineralization, geological structure and alteration about the deposit can be summarized as follows:

**Characteristics of the mineralization**

① Consists mainly of massive ore. Ore minerals are composed of pyrite and chalcopyrite accompanied by a slight amount of sphalerite, magnetite and hematite.

② The massive ore shows a brecciated texture and consists of pyrite breccia, fine grained matrix of pyrite and chalcopyrite and large crystals of anhedral chalcopyrite.

③ The massive ore shows sedimentary structure on its edge where the ore body grades laterally into metalliferous sediments that are rich in magnetite.

④ Under the massive ore body, stockwork ore consisting of chalcopyrite and pyrite is developed in places. This stockwork ore is accompanied by pyrite dissemination in many places and sphalerite dissemination in some places.

⑤ Above the massive ore, pyrite dissemination is widely distributed and stockwork consisting of chalcopyrite and pyrite can be seen in places.

**Characteristics of the geological structure**

① The ore body is situated in the lower part of the Samail Volcanic Rocks and occurs in the contact between Geotimes Unit and Lasail Unit.

② One side of the ore body is limited by the fault that formed before the ore body formation, for which the ore body shows its maximum thickness in the vicinity of this fault.

**Characteristics of the alteration**

① Alteration due to mineralization consists of silicification, chloritization (Clinochlore) and epidotization.

② These alterations show stronger intensity when closer to the ore body. At the footwall side this alteration is stronger than at the hanging wall side.

### 3-2-2 Brief history of mining

The Oman Mountains region in the northern part of Oman is known as a major producer of copper during the era of Mesopotamia. It has been said that the exploitation and smelting of copper in the ancient times continued up to around 940 AD of the early era of Islam. The copper deposits operated in that period are presumed to be in the same location as the Lasail mine and Rakah deposit and a great volume of slag and ancient smelter sites can be observed in these sites even at the present days.

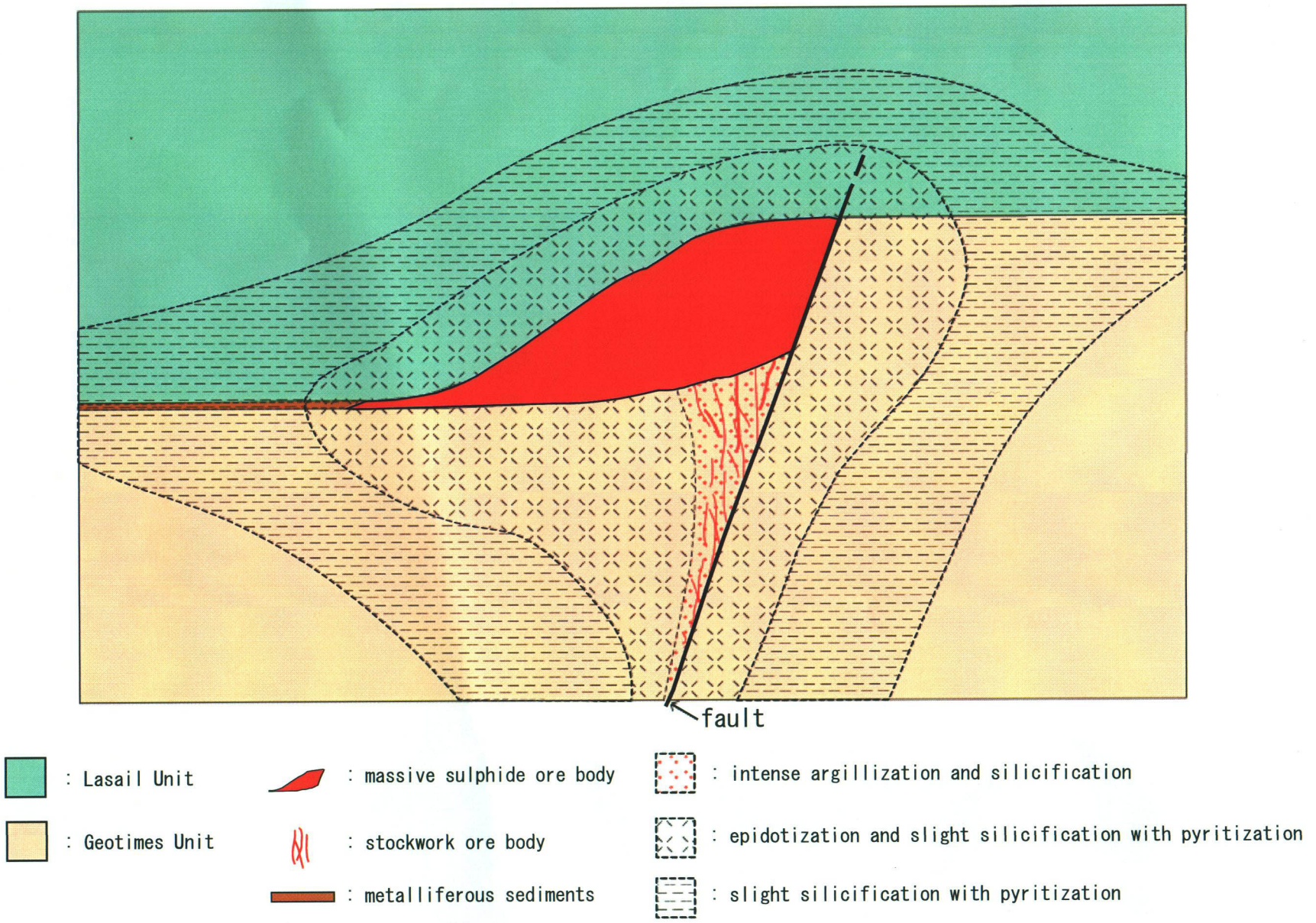



Fig. I -3-2 Schematic model of massive sulphide deposits in Ghuzayn area

The modern exploration activity, mainly aimed to copper deposits in the Oman Mountains, was commenced by Prospection Ltd. of Canada in the decade of 1960. Presently known deposits of Lasail, Bayda, Aarja in Sohar area and Rakah deposits in Rakah area, were confirmed by this exploration including drillings.

In the decade of 1970, the Government of Oman purchased the title of property owned by Prospection Ltd. and started the mine development in Sohar area. Consequently in 1983, the operations of Lasail and Bayda mines and Sohar copper smelter were commenced by Oman Mining Company (OMCO), which was established and fully owned by the Government of Oman. The capacity of this smelter has a copper metal production of 24,000 tons per year.

For the purpose of keeping a stable supply of raw material to the Sohar smelter, the Government of Oman awarded in 1984, through international tender, to Bishimetal Exploration Co., Ltd. a contract for a copper exploration program in an area of 8,000 $km^2$ surrounding the Sohar smelter. Investigations were carried out for a period of 4 years up to 1987 and during which some ore reserves were newly obtained in and around the known deposits, as well as many mineralized zones were confirmed.

On the other hand, BRGM of France was awarded in 1983, a project of geological mapping in the northern Oman Mountains region by the Government of Oman and carried out such works until 1985. During the course of their mapping program, a zone of large scaled gossan was discovered together with the confirmation of several mineralized zones near the village of Hayl as Safil, located at the western foothills of the Oman Mountains.

The Government of Oman awarded in 1985 to BRGM a contract until 1986 for the exploration of 13 major copper mineralized zones discovered in the course of mapping. As a result, the existence of massive sulphide deposits was confirmed in the gossan zone near the village of Hayl as Safil.

In 1988, the Government of Oman requested to the Government of Japan to investigate the possibility of developing the Hayl as Safil and the Rakah deposits. In response to such request, the Government of Japan carried out a Cooperative Mineral Exploration Program (Regional Development Plan) through Japan International Cooperation Agency (JICA) and Metal Mining Agency of Japan (MMAJ) in order to study the possibility of mining development in this area.

On the other hand, in 1988 OMCO commenced the mine development of Aarja deposit in Sohar area by supplying raw material to the Sohar smelter due to the exhaustion of ore reserves at Lasail and Bayda mines. However, the Aaja deposit was mined out in 1993 and as such, the smelter operates by using the purchased ore from abroad. The total production and grade of closed mines are as follows:

| | | |
|---|---|---|
| Lasail Mine | 9,183,677 tonnes | 1.42% Cu |
| Aaja Mine | 2,561,887 tonnes | 0.97% Cu |
| Bayda Mine | 790,891 tonnes | 1.60% Cu |
| Lasail West Mine | 434,478 tonnes | 1.02% Cu |

From the above-mentioned background, the Government of Oman and OMCO are aggressively continuing exploration activities for the development of the domestic mines. Especially in Hayl as

Safil deposit, intensive exploration works has been carried out and the three satellite ore bodies of Al Jadeed, Al Asghar and Al Bishara have been confirmed in the periphery of the main deposits. The ore reserves and grade obtained by these exploration are about 11 millions tons with 1.44% Cu and 0.73g/t Au including Hayl as Safil deposit, its satellite ore bodies and Rakah deposits.

In 1994, Rakah gold mine started the operation utilizing gold rich gossan near surface and has been produced about 500kg gold annually. Ore of about 0.7 million tons has been mined and processed, and gold of about 4.2 tons and silver of about 2.0 tons have been produced by the end of 2001. A gold rich gossan was also confirmed in Al Bishara ore body with an approximate ore reserve and grade estimated by OMCO as 0.5 million tons with 6.35 g/t Au.

In response to a request made by the Government of Oman, JICA/MMAJ carried out in the Batinah Coast area, a Cooperative Mineral Exploration Program that consisted of a Mineral Exploration Project during 1995 to 1996 in the Central Batinah Coast Area followed by another Mineral Exploration Project during 1997 to 1999 in the South Batinah Coast Area. These projects resulted in the discovery of three massive sulphide bodies in Ghuzayn with an approximate ore reserve and grade of 14 million tons and 1.64%Cu, respectively.

# CHAPTER 4 EXPLORATION RESULTS

During Phase I, the geological survey carried out in Yanqul area delimited the distribution of the host rock within the area, i.e., Geotimes and Lasail units of Samail volcanic rocks. The geophysical survey (TDIP method) was carried out within this area delimited by the geological survey and detected 5 anomalous areas including the known mineralized zone. These areas are as follows:

a. Quron Al-Akhbab area
b. Tawi Rakah mineral showing
c. Rakah deposits
d. Najaid area
e. Hayl as Safil deposits

During Phase I, the TEM survey was carried out in Quron Al-Akhbab area, Rakah deposits and Hayl as Safil deposits. During Phase II, a detailed TDIP survey was carried out in all the 5 above-mentioned areas. On the basis of the geophysical survey results, drilling survey was conducted at 8 boreholes during Phase I and at 19 boreholes during Phase II. Promising copper mineralization of stockwork type was confirmed in Quron Al-Akhbab area.

## 4-1 Quron Al-Akhbab area

This area is located 2.5km to the east of Rakah deposits. Ground surface shows dark-brown color, which is in general, weakly gossanized. Gossanized quarts veinlets accompanied by copper oxide are recognized at many parts. Testimony of ancient exploration activities such as galleries, depressions and waste dump are observed in several places.

During Phase I, drilling survey was carried out within a remarkable chargeability anomaly detected by TDIP survey. All of the 5 holes intersected a stockwork zone with core ranging from 17.70m to 89.70m in depth at MJOY-2 and showing relatively higher Cu grade of 0.83% in average. During Phase II, a rather detailed TDIP survey was carried out in order to quantify in more detail the extension of the mineralized zone. Drilling survey was also carried out at 13 locations within the detected high chargeability anomaly zone. As a result of drilling survey, 6 boreholes intersected stockwork zone with core length over 10m and a grade over 0.5%Cu. Furthermore, it was clarified that the distribution of high chargeability anomalies correspond to the distribution of a mineralized zone that extends about 300m along the EW direction and about 150m along the NS direction (see Fig. I -4-1). The area within the mineralized zone is wide but with a high-grade part that is distributed uncontinuously, resulting in a low average grade of copper. Gold mineralization is scarcely distributed. An approximate ore reserve in this area is estimated in 2 million with an average grade is 0.71%Cu and less than 0.1g/tAu.

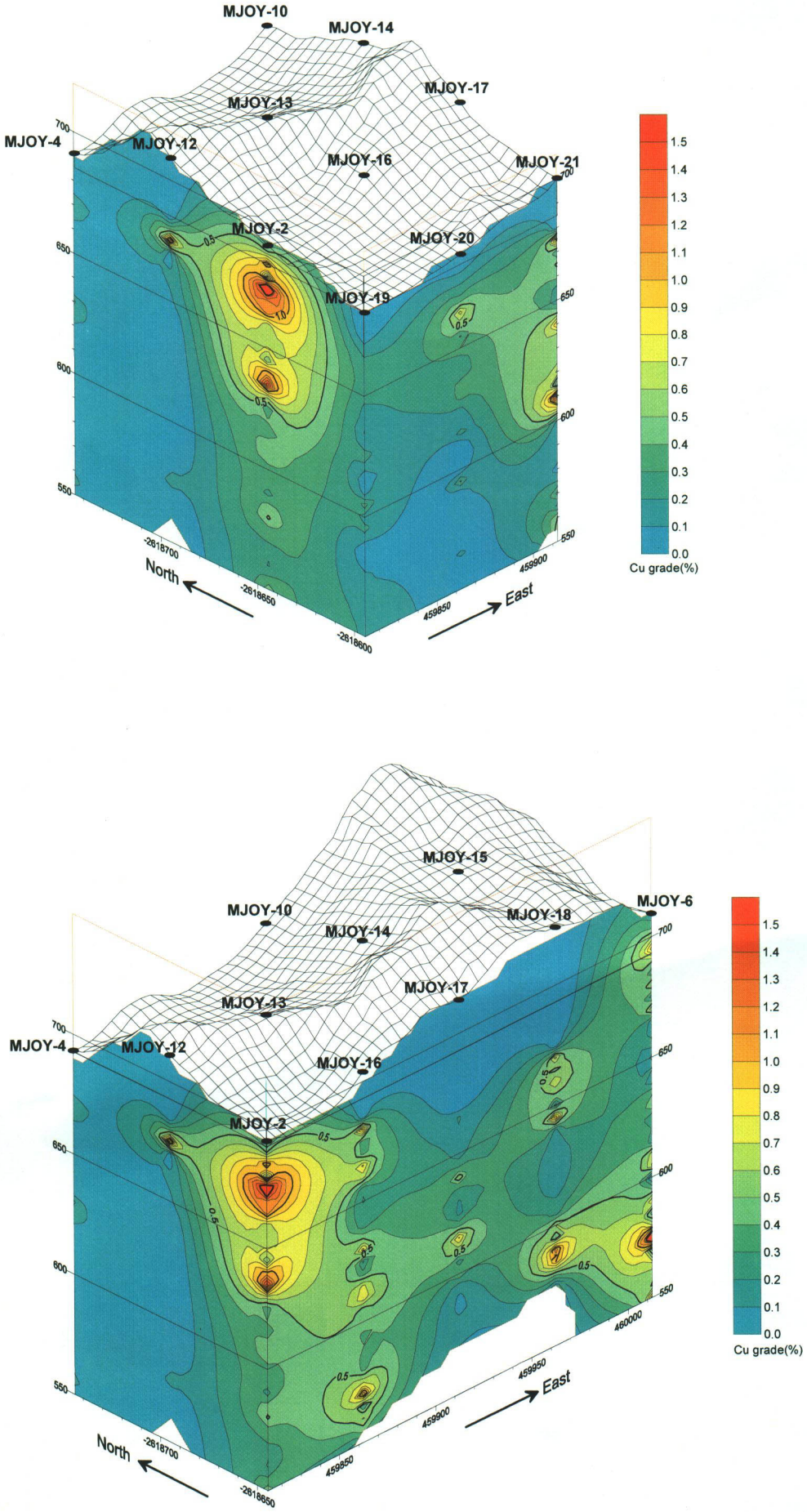



Fig. I -4-1 3-D copper assay in Quron Al-Akhbab

### 4-2 Tawi Rakah Mineral Showing

In this area, many exploration works were conducted in the past detecting a low grade copper mineralized zone.

During Phase I, a chargeability anomaly was extracted to the north of the known mineral showing, which is similar to that of Quron Al-Akhbab. Low resistivity was also detected in the shallow part of the showing. To confirm these results, drilling survey carried out at the northern anomaly intersected a stockwork zone of low Cu grade with strong pyrite dissemination from 14.90m to 107.00m. Copper mineralization is weak but continues to 140m in depth. During Phase II, a detailed TDIP survey was carried out in and around the anomaly zone detected during Phase I, and it was clarified that there is no promising place for further exploration.

### 4-3 Rakah Deposits

High chargeability zone was detected to the southeast of Rakah open pit by TDIP survey during Phase I. Drilling survey was carried out on the high TEM response zone detected by the TEM survey conducted on the above mentioned high chargeability zone. As a result of the drilling survey, low grade stockwork ore accompanied partly by chalcopyrite veinlets was intersected below -171.35m. In previous survey, stockwork ore was intersected to the northeast of the Rakah open pit, while IP anomaly zone was detected to the south of the open pit during Phase I. Subsequent to this result, a detailed TDIP survey was carried out during Phase II to study the possibility of finding another ore body to the south of the existing ore body. As a result of this survey, drilling survey, consisting of one borehole, was carried on a remarkable chargeability zone detected to the southwest of the open pit and intersecting stockwork ore consisting of chalcopyrite with gold mineralization in 2 shallow parts. Total length of ore was 18.20m with average grade of 0.48%Cu and 0.46g/tAu. This result open a good possibility of finding another stockwork ore to the southwest of the open pit.

### 4-4 Najaid Area

This area is located about 2.5km to the east of Rakah deposits. Small-scale gossanized zone is observed with scattered quartz-epidote veinlets accompanied in places by copper oxide.

To further investigate this area, the borehole MJOY-27 was drilled on a remarkable high chargeability zone detected in the shallow part. As a result of the drilling survey, copper mineralization (chalcopyrite veinlets of 1 to 4 mm width) was detected, however it is quite local. As a consequence of these results, it can be concluded that only weak mineralization is distributed in this area.

### 4-5 Hayl as Safil Deposit

Remarkable high chargeability zone was detected around the gossan during Phase I. The south edge of this zone is also a high metal factor zone because of its low resistivity. To investigate this zone where no drilling has been done yet, one borehole (MJOY-8) was drilled on this high metal factor anomaly detecting strong silicification but mineralization was rarely recognized. Drilling survey (borehole MJOY-22) was also carried out on a small but remarkable IP anomaly detected 300m to the north of gossan, but mineralization was not recognized.

As a result of geophysical survey in Phase I, the distributions of the high metal factor anomalies at shallow level (N=1) indicated a good correspondence with the locations of already-known ore bodies. TEM high response anomaly zone appears in places where massive sulphide ore bodies have been found. During Phase II, a detailed TDIP survey was carried out around the gossan, detected in more detail the extension of the high chargeability distribution, for which a drilling survey was carried out at 2 places where a high chargeability zone was detected to the north of the gossan. As a result of the drilling survey, low-grade stockwork ore containing hematite (specularite) and pyrite was recognized. Although drilling survey was not carried out at the center of the high chargeability anomaly zone because of steep topography and date tree plantation, it is inferred that stockwork ore body may exist at the high chargeability anomaly zone because copper mineralization is recognized at the edge of the anomaly zone.

### 4-6 Considerations on the Exploration Results

#### 4-6-1 Geological Characteristics

The geological and drilling surveys in Yanqul region indicated several differences on the geology and mineralization as compared to Batinah coast area. The geological characteristics in Yanqul region are as follows:

a. The formations and ore bodies show repeated stratigraphies due to thrust faults.
b. Ore deposits in Yanqul area consist mainly of stockwork ores. Massive sulphide ore does not develop well.
c. Stockwork ore is mainly developed in the Lasail unit.
d. Metalliferous sediments in the lower part of Lasail unit are developed only in Hayl as Safil deposit area. They are rarely seen in other parts of Yanqul area with the exception of some places in Rakah deposit.
e. Breccias of sulphide ore and pillow lava of Lasail unit are observed in the metalliferous sediments of the Lasail unit in and around Hayl as Safil deposit area. This evidence indicates that the volcanism already started during the deposition of metalliferous sediments and massive sulphide ore.

These facts can be considered as important guidelines for further exploration surveys in Oman.

### 4-6-2 Exploration methods

The same exploration methodology that were used for the exploration in the South Batinah Coast area during 1995 ~ 1999 was applied to the exploration investigations in Yanqul area.

As a result of the exploration, the TDIP survey was able to detect new mineralized zones and to extract existing ore bodies by detecting remarkable IP anomaly zones. The TEM survey showed also remarkable anomalies in places where massive sulphide ore bodies are located. Ore deposits in this area consist mainly of stockwork ore, while massive sulphide ore does not develop well. It was clarified from this survey that stockwork ore could be detected as IP anomaly zone.

Taking into account the results mentioned above, the exploration flow is summarized as follows (Fig.I-4-2):

1) The selection of potential areas for this type of deposits can be achieved by first selecting the most suitable zones by means of geological and airborne magnetic methods. The airborne magnetic method is useful to delineate demagnetized zones associated to mineralization.
2) The areas selected by the above methodology can be further investigated by appropriate ground geophysical methods in order to delineate zones with high potentiality. The TDIP method is adopted in order to detect mineralized zones in the first step. In the second step, the TEM and the precise TDIP methods are used to extract massive sulphide ore bodies and stockwork ore bodies from the mineralized zone.
3) A suitable exploratory drilling program is conducted on the anomaly area detected by geophysical survey in order to confirm the exploration results.

### 4-6-3 Potentiality of increasing ore reserve in Yanqul area

Geophysical survey carried out in areas where favorable horizons could be found distributed in Geotimes and Lasail Units of Samail Volcanic Rocks, detected the most promising anomaly zone in Quron Al-Akhbab area. The drilling survey conducted on this anomaly zone, confirmed predominant mineralized zone extending about 300m along the EW direction and about 150m along the NS direction. However, the drilling intersected low average Cu grade and gold mineralization scarcely distributed. An estimated ore reserve in this area indicates 2 million tons with an average grade of 0.71%Cu and less than 0.1g/tAu. And concluding that the potentiality of discovering new mineralization zones which can be developed in this area is very low.

On the other hand, small but clear IP anomaly zones were detected in the southwestern side of Rakah open pit and in the northern side of gossan in Hayl as Safil area where drilling exploration were not conducted before. Drilling survey at these IP anomaly zones intersected Stockwork ore bodies; thereby increasing slightly the potentiality of ore reserves in this area.

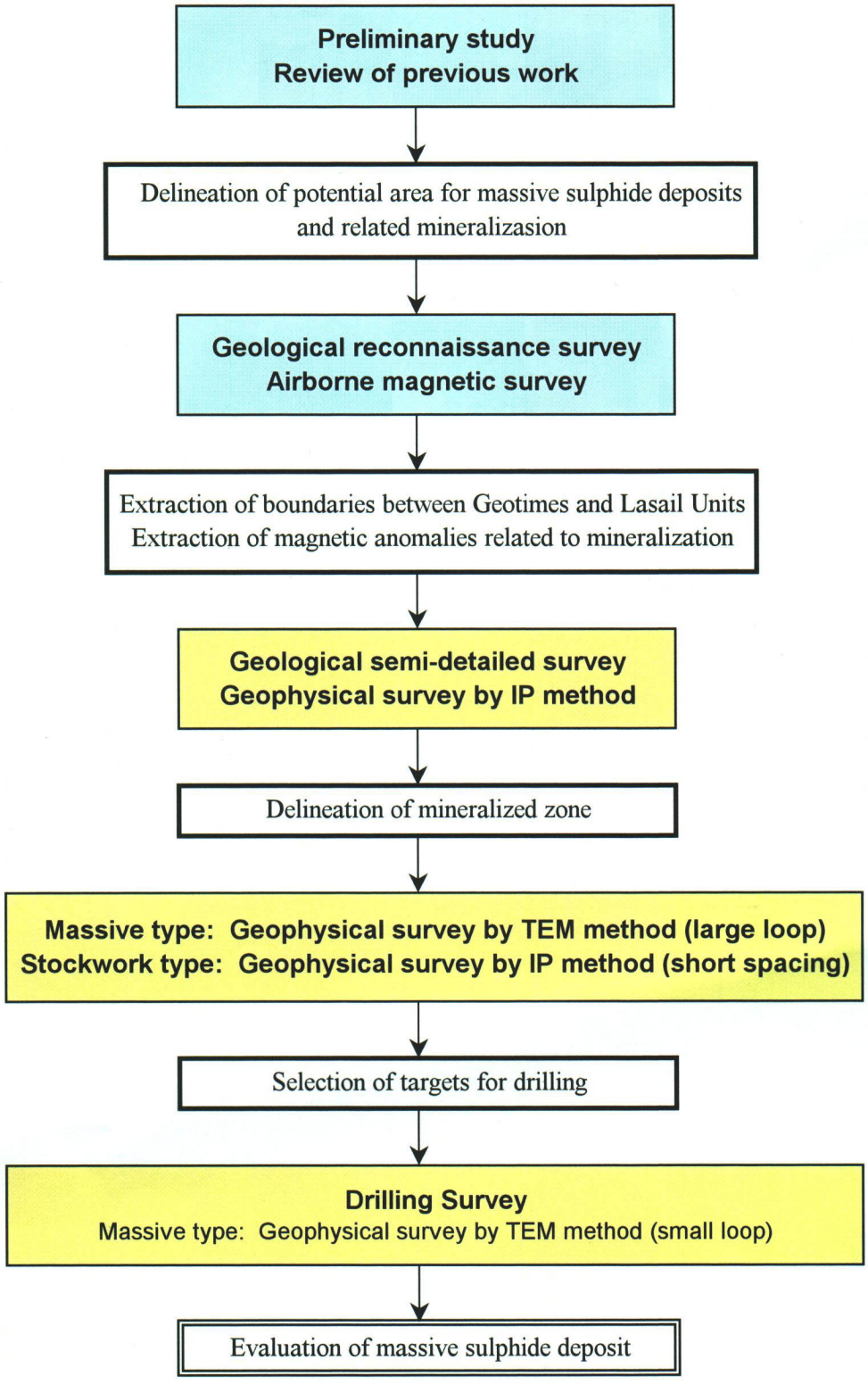



Fig. I -4-2 Flow for massive sulphide deposits exploration