GL015008

Mr Leggat comments

(1980?)



# FUTURE EXPLORATION OF THE SEMAIL OPHIOLITE COMPLEX, SULTANATE OF OMAN

## INTRODUCTION

As representatives of an Australian Technical Support Mission, we, Dr. R.G. Dodson, Bureau of Mineral Resources Department of National Development and Energy, and Mr. T.J. Ireland, Department of Mines and Energy, South Australia, were seconded to the Geological Section, Dept of Minerals, Sultanate of Oman for a period of seven weeks. The secondment was planned by Mr. R.M. Causlan, Consul-General and Senior Trade Commissioner, Abu Dhabi; travel financed by the Australian Department of Trade and Resources and internal travel and accommodation costs met by the Sultanate of Oman. The objectives of the Mission were:

1. To assess 'Reports of Field Investigations' prepared by Prospection Ltd., from January 1974 to 1978, thereafter prepared by Oman Mining and Company (OMCO).

2. To recommend the approach to investigation of areas considered prospective outside Mining Licences No.1 to 10 and Exploration Licences No 1 to 15, all held by the Oman Mining Company.

3. To assist and advise as far as possible on the future role of the Geological Section, Department of Minerals, Sultanate of Oman.

In this report objectives 1 & 2 are discussed. Objective 3 is discussed in another report.

We wish to acknowledge with thanks assistance and information received from staff of the Department of Minerals, Sultanate of Oman; thanks are particularly due to Mr. M. Kassim and Mr. Omer El - Amin. We also wish to express our appreciation to Mr. A.P. Leggat for his assistance in providing technical and background informaiton, and acting as guide for our two field trips.

## ASSESSMENT OF 'REPORTS OF FIELD INVESTIGATIONS'

Our assessment of the reports by Prospection Ltd commenced with a study of a considerable volume of scientific literature describing the geology of the Semail Ophiolite Complex. The two field trips undertaken were planned to familiarise ourselves with the geology of the Semail Ophiolite Complex and in particular to study the geological environment of the known mineral deposits in the complex. We also studied the quarterly exploration reports dating from June 1973, prepared by Prospection Limtied, to the most recent report, prepared by OMCO (Oman mining and Company), and various related documents.

As appraisal of future exploration activity on areas retained by OMCO ( as Mining Licences No 1 to 10 and Exploration Licences No. 1 to 15 - see Fig.2) is beyond the scope of this investigation, our assessment was designed:

a) to judge the effectiveness of methods used, and

b) to document the exploration progress and results in areas subsequently surrendered from the original concession, in order to formulate recommendations for future resource evaluation, by the Ministry of its agents, in the remaining or available lands (see subsequent section, and Fig.2)

To this end, each commodity which is prospective in the available lands is reviewed within the following framework:

-- type examples of documented deposits
-- mode of occurrence
-- distribution of prospective host rock units
-- exploration methods and limitations in their application
-- existing exploration coverage

Copper and chromium are discussed in some detail, while the status of eight subordinate commodities is more briefly summarised.

## 1. Copper

Basalt association

Examples include Lasail, Bayda, Aarja and others in the 'Alley' area 30 km west of Sohar, and Tawi Rakah 10 km north east of Yanqul.

The deposit type is well known in ophiolitic environments (e.g. Troodos Complex, Cyprus). Mineralisation typically consists of massive pyrite lenses with subordinate chalcopyrite. Deposits are generally conformable, accumulating at mid-oceanic spreading centres from volcanogenic or magmatic-hydrothermal emanations. They are shrongly stratigraphically controlled, occurring at the top of the lowest of the ophiolitic volcanic cycles. They tend to occur in clusters, with a degree of structural control, and in close proximity to younger plagiogranite plugs. Deposits which differ from the ideal model are commonly observed. Variations may be due to either differences in depositional environment or to post-depositional modification.

Reserves at Lasail, the alrgest of this type known in Oman, total 8 million tonnes, but comparable deposits in Cyprus may exceed 20 million tonnes. Ore tenor is typically moderate with grades of various deposits ranging between 1 and 6% Cu, and traces of zinc (up to 2%), gold (up to 2 gram/tonne), and silver. The most recent technical publication is that by Alabaster.*

Within the available lands there are limited, scattered exposures of the most commen hostrock sequence in the following:

a) Northern range-front, from south-west of Khabura to south-east of Khabura, and possibly further east.
b) South-western range-front from Yanqul to 30 km north-east of Ibri.
c) Southern range-front from Samad to north of Ibra Dome.

* Alabaster, T. et al; 1980; in Panayiotou, A.(ed). 'Ophiolites Proceedings International Ophiolite Symposium, Cyprus 1979' Pp 751-757.

The following observed characteristics of these deposits ((1a) (2a)...etc) may be considered, subject to the noted limitations ( (1b) (2b)...etc), in planning on exploration program.

(1a) Geological control and associations:

(1b) However, detailed geological documentation has not been available, and this approach has not been used outside the Lasail area as a basic exploration tool. These shortcomings are currently being remedied by the results of research, a regional mapping program, and changing approaches to exploration.

(2a) Conductivity contrast with enclosing rocks:

(2B) However, measurement of this parameter by electromagnetic (E.M.) techniques is frequently observed by conductive overburden and country rocks, and competing features (e.g. fault and alteration zones) which provide stronger responses.

(3a) Density contrast with enclosing rocks.

(3b) However, the gravitational effect of massive sulphide accumulation may be diminished by the alteration of enclosing country rocks, which reduces their specific gravity. Rugged terrain and the impracticability of applying adequate terrain corrections further limit the effectiveness of gravity survey. Nevertheless it has come to be regarded as the most reliable indirect exploration technique in use:

(4a) distinctive gossan development caused by reaction with host rocks of concentrated acid generated during oxidation of pyrite.

(4b) However all massive sulphide gossans are likely to have been identified by ancient miners, whose advanced Copper extraction technology and wide ranging mining activity is today indicated by slag dumps throughout the ophiolite belt. It is expected that prospecting during the past decade with helicopter support has located all significant ancient mining sites, and that some appraisal of potential has occurred at each such site.

(5a) Supergene alteration of enclosing rocks by acid ground water (Kaolinisation, silicification), accompanying gossan development:

(5b) However this is not observed in all cases:

(6a) Primary hydrothermal alteration, and deposition in footwall, of quartz-pyrite-chalcopyrite stringer mineralisation, associated with the accumulation of mineralisation:

(6b) However the primary silicate alteration is commonly difficult to distinquish in hand specimen. Microscopic examination may be required.

(7a) Stratigraphically and possibly genetically related 'Umbers' (laminated ferruginous mudstones).

(7b) However stratigraphic relationships between umbers and mineralisation are not yet well understood, and are obscured by the detailed structural complexity of the ophiolite;

(8a) Geochemical dispersion of Cu, Pb, Zn and possibly other metals in the supergene and surficial environment.

(8b) However primary geochemical patterns have not been documented, geochemical dispersion is patchy in the arid weathering environment of the region. While strong responses are recorded around major gossans and ancient metallurgical sites, weaker exposures apparently yield much less reliable results. Further systematic orientation work is required.

Prospection's exploration for these deposits in areas subsequently relinquished has consisted of:

a) throughout the complex.

1. sparse reconnaissance wadi sediment geochemical sampling
2. identification of visible gossans and ancient mining sites and evaluation of such prospects by the following procedure:
   - locate prospect using guides, traversing by vehicle or on foot, helivoper reconnaissance and air-photo interpretation.
   - inspect the occurrence and immediate environs

Produce sketch map and take grab samples of rock and sediment,

- Either a) reject as insignificant and abandon without further test

  or b) establish grid (restricted to the mineralised area only) for systematic geochemical sampling, and E.M., gravity and ground magnetic surveys.

- based on interpretation of the results of the above (with emphasis on E.M.)

  either a) abandon if no strong E.M. response

  or b) site drill hole(s) if conductor indicated.

- drill.

b) the north-eastern range-front, and much of the prospective stratigraphy along the south-western range-front was covered by an airborne INPUT (E.M.) survey. Many of the abundant anomalous responses identified in successive interpretations of the data have been investigated by ground E.M. survey (locate and refine anomaly definition) and then the procedure outlined above.

This first pass exploration of the whole of the available area has effectively removed the possibility that major subcropping massive sulphide deposits remain untested.

However, as follow up procedures tended to reject weak showings and responses at an early stage, and all indirect exploration techniques used can now be shown to be at least inconsistent and possibly unreliable in response to significant mineralisation, we believe that potential remains for weakly outcropping mineralisation, or mineralisation veneered by overburden to have escaped detection. Beyond this, there is a greater potential for blid deposits and off-set extensions to known deposits, at relatively shallow depth, but these present a more difficult exploration target. They may not yet justify the expense of detailed investigation outside of those areas which are most strongly favoured on geological grounds.

Another series of differentiated basaltic lavas is termed the Haybi Volcanics (Ph.D. Open University, M.P. Searle, 1980) and occurs within a narrow thrust slice between the Hawasina Allochthanous Unit and the Semail Ophiolite

There are small, widely scattered occurrences of these volcanic sequences, which include basic, intermediate and acid members, in association with larger blocks of Hawasina:

a) In the Hawasina Window, south-west of Khabura
b) South and north of Jebel Akhdar
c) north-west of Samad, and
d) possibly elsewhere.

The potential of these to host volcanogenic mineralisation deserves investigation,as they have been subjected to only the most preliminary phases of reconnaissance described in the previous section.

b) Gabbroic Association

Examples include Niba (20 km E of Ibra) Tabakhat (6 km WSW of Nizwa) and mulla2. (15 km SW of Samad). Descriptions can be found in Coleman etal* and Prospection Ltd prospect reprots of 1976 -77.

Chalcopyrite stringer and vein mineralisation, with minimal iron sulphides is typically scattered in schistosity planes of shear zones, at or close to the contact between peridotite and gabbro phases of the ophiolite. Evidence to date indicates that the deposits are likely to be small, and discontinous within the confining structure. However in some cases high grades have been intersected.

By analogy with the Limassol Forest deposits of Cyprus (Panayiotou: 1980 'Ophiolites' P 102-116) nickel and cobalt sulphide and orsenide mineralisation may also occur in this environment.

Both the oxidised and primary zones of many of these deposits in gabbro have been mined in ancient time, and some retain extensive copper-rich slag residuals as evidence of significant size and particularly grade. Abrupt p inch and swell of mineralised zones is implied by the absence of mineralisation in shear structures at the limits of old mine workings, accompanied by significant wallrock alteration , although in places, the deposits apparently lack any halo of disseminated mineralisation.

The favored peridotite-gabbro contact zone is widely exposed throughout all ophiolite masses of the available area. Apart from surface evidence at locations where mineralisation outcropped and was mined by the ancients, these deposits constitute a difficult exploration target. Gossan development is weak due to the lack of pyrite, and geophysical contrasts are subdued due to the patchy distribution of mineralisation. Induced Polarisation (I.P.) may be more responsive than E.M. to disseminated a stringer mineralisation, but the problem of discrimination between anomalies related to unmineralised shear zones and sulphide zones remains unsolved.

Exploration of these deposits has followed only the preliminary stages noted for the massive sulphide type, based mainly, on identification of ancient mining sites. The majority were rejected after initial inspection because they were thought to be totally mined out, too small, or because of the absence of additional gossans in the immediate vicinity. The shear zone containing mineralisation was not usually further tested. The ancient Mulluq deposit (10 km SW of Samad) is one of a few examples which lie wihtin the area of airborne E.M. survey. Drill testing of an E.M. anomaly resulted in an intersection of 6 metres averaging 4% Cu, without surface expression.

Although such deposits are likely to be small, we consider that limited testing is required on any structure which carried mineralisation.

## 2. Chromium

Examples include Nakhl (40 km W of Bid Bid) adn Far Far (40 Km WSW of Sohar). Podiform Chromite deposits occur as massive disseminated layers, lenses, pipes and irregular masses dunite segregations in peridotite. The host dunite body may be extensive relative to the size of the chromite or may only thinly envelope the deposit. Contacts between chromite and dunite are mostly diffuse. Due to specific gravity contrast, heavily disseminated chromite may be amenable to gravitational concentration processes.

* Coleman, R.G. & Bailey, E.H. 1974, 'Mineral Deposits and Geology Northern Oman'-Project Report (IR) OM-1 (interim) of the USGS.

Mineralisation is most abundant in and adjacent to the gradational contact zonw between massive peridotite and the base of the cumulate gabbro sequence. Chromite analyses recorded range from 26% to 50% $Cr_2O_3$ with most deposits qualifying as refractory grade, containing 38% to 45% $Cr_2O_3$ (subject to the elimination in many cases of gangue silica).

Less common segregations towards the core of the peridotite mass tend to contain higher tenor chromite of chemical or metallurgical grades. Reference to those deposits can be found in sources cited by Coleman etal and Panayiotou (ed: ' Ophiolites' Pp 714-721) and in the prospect reports of Prospection Ltd and OMCO.

Current research by a team of Ph. D. candidates from various European countries is directed towards obtaining a greater understanding of controls of ore genesis, chromite tenor and deposit localisation, and towards the derivation of more sophisticated exploration techniques. Other supportive reconnaissance documentation is being undertaken under a West German-sponsored assistance project.

To date, approximately 180 occurrences have been identified by surface and drainage prospecting. Although mostly of a few thousand tonnes or less, the largest, Far Far, contains reserves estimated (from surface measurements and conservative depth projections only) to be greater than 300,000 tonnes. Deposits ranging from 1 to 10 million tonnes are known in similar environments, as in Turkey.

Extensive parts of the Ophiolite Complex are prospective for chromite but their remoteness, the severity of terrain and the lack of water may preclude the economic development of chromite deposits identified.

Characteristics to be considered in planning exploraiton include the following:

(1a) the ubiquitous dunite host rock is visually distinctive in hand specimen, expands the geological tzrget and limits the areas of search:

(1b) however in weathered outcrop both dunite and chromite assume a dark-coloured surface induration which is similar to that of enclosing rocks. With practice, detection should be possible on detailed (1 : 20,000 scale) coloured photography.

(2a) In the local environment chromite is more resistant than enclosing rocks to weathering and is often exposed on positive topographic features and preserved as cobbles in drainage debris;

(2b) however conventional stream sediment geochemical sampling is rendered ineffective because:

- Chromtie is abundant in the host ultramafics, as an accessory so that abundance at a given sample site is more a measure of the effectiveness of heavy mineral concentration at that point than of the presence of actual chromite deposits in the watershed, and
- the exceptional resistance of the mineral to physical attrition prevents the disintegration of individual grains to the fine size-range necessary for statistically effective sampling.

Manual prospecting for chromite cobbles amongst coarse wadi sediments is a viable exploration technique. (Tracing boulder trains upstream and upslope to point of origin).

(3a) clustering of deposits and possibly localisation in response to deep seated structures visible on Landsat imagery:

(3b) however inadequate background data and poor stratigraphic control of the distribution of mineralisation limit the precision with which structural guidelines can be applied;

(4a) gravity contrast presented by larger deposits:

(4b) however rugged terrain in most peridotite-gabbro complexes restricts the effectiveness of gravity surveys.

Wadi prospecting has been undertaken in certain areas of peridotites, with some success. Other prospective areas are unexplored. Exploration by Prospection Ltd was limited by the lower priority afforded to chromium, compared with copper and by the difficulty of access. A few previously documented deposits were inspected and accessible prospects identified by indigenous population were visited

Over 90 new occurrences were identified in the Samad-Izki area by 4 west German prospecting teams during a recent 10 week period of wadi sampling and geological reconnaissance. Non-systematic scouting in the vicinity of the Nakhl deposit has located further occurrences in that area.

Potential elsewhere remains high. Previous reconnaissance (Japan International Cooperation Agency 1979) of potential for chromite placer deposits in wadi, Batinah Coastal Plain or beach environments proved disappointing. This is conceptually supported by the immaturity of the geomorphological and depositional environment and the sporadic but violent nature of sediment transport and distribution resulting from the modern arid climate.

## 3. Magnesite

The occurrence of a small proportion of magnesite is widespread in peridotite and serpentinised peridotite. Mineralisation occurs as interlocking vienlet stockworks and randomly oriented fracture fillings in deformed host rocks, and as major veins up to 1 metre in width in less imbricate ultramafics.

Research is required to determine economic aspects including marketability of the commodity, quality specificatins, price range and to test known occurrences.

Estimation of approximate quantities and grades required for successful large or small-scale mining could then provide the basis for an exploraiton effort, if justified.

The pale colour of magnesite is clearly discernable in outcrop or from aerial photogrpahy(black & white or colour 1 : 20,000 scale).

No serious effort has been made to locate and evaluate magnesite deposits in this country, although potential has usually been noted in generalised economic appraisal exercises.

## 4. Lead-Zinc, Barite

A single vein deposit of lead and zinc sulphides totalling at most a few thousand tonnes has been exploited by ancient miners. The Nujum deposit about 10 km SE of Bid Bid) is the only showing of any significance known in the ophiolite belt.

Set in an environment of highly deformed and metamorphosed rocks adjacent to and below the basal ophiolite thrust plane, it appears to be hosted in a melange of dislocated blocks of sediment of the Hawasina Allochthanous Unit. However, as emplacement probably occurred subsequent to thrusting, there may be greater significance in the structural control than in host rock type or statigraphic position.

Research is required to determine economic aspects including marketability of the commodity, quality specifications, price ranges, and to test known occurences.

Estimation of approximate quantities and grades required for successful large or small-scale mining could then provide the basis for an exploration effort, if justified.

The pale colour of magnesite is clearly discernable in outcrop or from aerial photography (black & white or colour, 1:20,000 scale). No serious effort has been made to locate and evaluate magnesite deposits in this country, although potential has usually been noted in generalised economic appraisal exercises.

## 4. Lead-Zinc, Barite

A single vein deposit of lead and zinc sulphides totalling at most a few thousand tonnes has been exploited by ancient miners. The Nujum deposit (about 10 km south east of Bid Bid) is the only showing of any significance known in the ophiolite belt.

Set in an environment of highly deformed and metamorphosed rocks adjacent to and below the basal ophiolite thrust plane, it appears to be hosted in a melange of dislocated blocks of sediment of the Hawasina Allochthanous Unit . However, as emplacement probably occurred subsequent to thrusting, there may be greater significance in the structural control than in host rock type or statigraphic position.

Very limited reconnaissance wadi sediment geochemical sampling and helicopter inspection traverses across the areas by the IGS Team (Carney & Welland, 1975) and Prospection Ltd, have failed to identify additional mineralisation. However, geochemical results indicate a general enhancement of background zinc levels in wadis draining sedimentary and metasedimentary units. Rock chip sampling in conjunction with the regional mapping program may confirm that this is an inherent feature unrelated to mineralisation.

In spite of the fact that only one small prospect is known, we consider the Hajar Supergroup Allochthanous Unit should be investigated as potential hosts of Mississippi Valley type base metal mineralisation, which is widespread in Upper Palaeozoic and Mesozoic sequences throughout Europe and the southern United States.

In exploration, zinc is the element which is most likely, due to its extreme chemical mobility, to be effectively detected by stream sediment geochemistry. However, orientation is required. Due to the possible absence of abundant pyrite in such mineralisation, and the carbonate-rich and vari-coloured host environment it is anticipated that goosan development would be much more subdued than in pyritic masses in ophiolite.

Rocks structurally and/or lithologically favourable for the occurrence of mineralisation of these types crop out extensively in the central core and southern range-front of the eastern half of the belt, and elsewhere.

## 5. Phosphate

No evaluation has been undertaken of potential for the deposition of rock phosphate in the shelf carbonate environment of the Hajar Super-group, or the shallower water carbonate evironment of the Tertiary cover sequence. This should be attempted in evaluation of regional mapping chip sampling, and conceptually as on adjunct to the investigations proposed in the previous section.

## 6. Gold

There are no records of production or occurence of the precious metal in Oman (except in the copper ore); nor is there evidence of any serious investigation of possible presence. Given the uncertainty of controls of gold mineralisation, there is justification for systematic reconnaissance of areas with significant quartz veining, by rock sampling and wadi sampling (panned concentrates), particularly in the under-explored basement windows in the core of the range.

## 7. Nickel - Iron

While potential for sulphide nickel is thought to be limited, there are in places through the ophiolites extensive laterites developed on mafic-ultramafic sequences. Examples include Fanjah (6 km NE of Bid Bid) and Ibra (20 km NE of Ibra).

Widespread lateritisation occurred between the time of ophiolite emplacement and the Uppermost Cretaceous transgression which allowed the widespread blanketing of the whole by Tertiary marine limestone. Subsequent uplift has allowed the stripping of the Tertiary, and surficial residuals from most of the ophiolite. However, outliers are preserved at the above locations and elsewhere.

Testing to date has indicated that at Ibra there are potential reserves of 150 million tonnes averaging less than 1% Ni.(Bull P. 1977; "Report on Ibra Laterite Project", Unpub. Prospection Ltd Report). The majority of this material is isolated below a sequence of indurated Tertiary limestones some tens of metres thick. Nevertheless, given the domestic availability of cheap energy (gas) and sulphuric acid (Lasail copper production) these and similar deposits deserve periodic evaluation.

## 8. Chrysotile Asbestos

A deposit located in Wadi Haybi (30 km SW of Sohar) is currently undergoing evaluation. A "Technical Evaluation" has been produced by Kilborn Ltd for the Ministry.

Cross-fibre asbestos veining is developed as a serpentinisation product in peridotite and dunite when serpentinisation is accompanied by shearing. Evidence to date indicates that these conditions were rarely met on any significant scale in the Semail Ophiolite. Chrysotile is only occasionally observed as a minor component of serpentinites.

More detailed information on its distribution should be generated in the course of the regional mapping project.

9. Platenoids

Although elements of the Pt series are characteristically associated with selected massive sulphide ores and especially with cumulate mafic-ultramafic intrusions, concentration of these elements has not been recorded elsewhere in the Alpine ophiolitic environment.

Analysis of the basalt-associated, massive pyritic copper ores has demonstrated their absence from that association.

Accordingly potential for these elements is thought to be negligible in the region.

10. Manganese

East of the ophiolite Belt (near Sur) the deep water cherts of the Hawasina Allochthanous Unit contain beds rich in manganese which are currently being assessed as potentially commercial.

While significant manganese occurrences are unknown in the Ophiolite Complex, equivalent rocks of the Hawasina Unit are widespread.

## Appraisal of Copper Exploration Strategy and Technology

In 1973 Prospection Ltd of Canada obtained mineral exploration rights to essentially the whole of the Semail Ophiolite Complex. Substantial reductions in the area held were required in 1975 and 1978 and exploration was arranged to complete prospecting of lands held, to allow these relinquishments.

Thus an economic appraisal of the whole of the area has been achieved, with the intensity of coverage naturally related closely to the perceived prospectivity of the area and the time spent on exploration by available staff. The results of these, and the continuing operations of retained lands, permit an assessment of the overall efficiency of copper exploration throughout the Ophiolite belt, and the effectiveness of the methods applied.

In undertaking the first modern exploration of an essentially virgin tract of land, with an extensive history of ancient copper mining, Prospection experienced rapid and continuing success in discovering prospects, locating mineralisation and in proving economically significant deposits. In an environment of excitement and technical success, their operations were evidently well organised, logically staged, competently and diligently conducted, and well documented. Limited resources were distributed amongst numerous competing high priority targets.

These operations were almost exclusively based upon surface prospecting and ground and eventually airborne E.M. surveys, to identify and screen out prospects, and then to site drillholes. With the benefit of hindsight, the following difficulties can be seen to limit the effectiveness of E.M. Surveys.

- in low lying areas, widespread conductive overburden masks response and limits effective depth penetration.
- competing features including abundant faults, conductive country rock types and conductive alteration zones, are as responsive as target mineralisation and discrimination of anomaly source is often impossible. Thus surveys generate a large proportion of anomalies unrelated to mineralisation.At some prospects drilling revealed no obvious anomaly source.

The continued introduction of upgraded E.M. technology to solve problems with that in use, and repeated resort to high-level consultancy implies that the difficulties relate to a basic in-applicability of the technique in this particular environment, and allows the suspicion that Oman was in part used as an arid testing ground for unproved technology. The operators' persistence may be attributed firstly to a basic faith in E.M. which has been so effectively proved in the Canadian environment, and secondly to the limited range of alternatives available within the exploration style adopted.

In favour of the E.M. approach it must be noted that the evidence suggests a great effectiveness as a primary screen. That is, if massive mineralisation is present even in small quantities, and shallow, an anomaly will be recorded. (If there is no anomaly, the particular surface feature is likely to be unrelated directly to mineralisation, and this would fulfil the operators' screening criteria during the early stages.) Other parameters, however, may indicate the need of deeper testing. There are also a few recorded exceptions where sulphides were not identified by the E.M. For example, the E.M. anomaly at Bayda is probably the response to an adjacent fault, with very weak response to the mineralisation. However, relatively new Australian and other technology is claimed to operate more effectively in the arid-saline surficial environment and further orientation studies are proposed.

Similarly the effectiveness of geochemical wadi sediment sampling may be seriously questioned on both technical grounds and the inconsistency of field results. While strongly developed gossans and ancient mining and smelting sites are sharply anomalous, with dispersion trains of the order of kilometers in length, response to smaller deposits is much less marked.

In an arid environment of predominantly mechanical weathering, where clay and residual soil development are negligible, chemical dispersion is slight. Furthermore, transport of rock fragments is effected by sporadic but violent sheet flow, grains containing mineralisation likely to be widely dispersed and enormously diluted by barren sediment, preventing the development of regular anomalous patterns.

Comments on other techniques were noted in the detailed description of copper occurrence and exploration.

It is considered that the combination of the foregoing factors is likely to have led to the rejection of concealed or weakly outcropping mineralisation on the basis of inadequate immediate response. Carlson, (H.D. 1977; "Geology of the Semdah - Lasail Area". Unpub. Rept. Prospection (Oman) Ltd), in an internal review of exploration strategy, stated in support of a more geologically sensitive and wider ranging approach to exploration, that "Past exploration practice ..... has been to establish narrowly restricted grids over precisely defined targets .... and to ignore even the immediately surrounding environment. This is short-sighted, wasteful and self-defeating practice".

We consider that this exploration practice, which attempted to define superimposed anomalies by a variety of exploration techniques and thereby a specific drilling target, was correct in the early phase of exploration. However, with the growth of knowledge of the environment of mineralisation and the declining success rate achieved by these means, it is now appropriate that exploration be directed towards geologically defined targets, supported by selected geophysical and geochemical surveys, in the search for concealed or very weakly exposed deposits.

This change in emphasis would be assisted, and greater drilling efficiency would be achieved, by the use of a percussion drill. Percussion drilling costs per metre are less than half diamond drilling costs, and a much greater rate of advance is possible. A percussion rig could be used for general tests of subsurface geology and, i.e. precollar diamond drill holes testing specific targets.

## Status of Copper Exploration Coverage

The situation has been reached where an effective first pass has been completed through all areas of higher prospectivity. It is unlikely that major ore bodies outcrop in the areas surveyed.

Abundant mineralisation has been identified particularly in the north-eastern range-front. The most attractive areas have been retained. However, parts of this belt relinquished in 1978 have not been re-evaluated in the light of current appreciation of the mineralised environment. In other areas the detail of prospecting is incomplete, as weak surface indications, low order anomalies, remote features and spot geochemical peaks have not been followed up satisfactorily. Consequently considerable potential remains.

However, it is in the north-eastern sector that the greatest potential is seen for successful detailed exploration, for the following reasons :

- density of mineral deposits known (almost 100 copper occurrences known outside of areas held by OMCO)
- incompleteness of detailed surface prospecting
- growing understanding of detailed geological controls and environments of mineralisation
- documented structural complexity which allows a strong possibility for the occurrence of blind deposits or structurally offset extensions to known deposits.

## Status of Exploration of Other Commodities

1. Exploration for chromite has been demonstrated to be most effectively carried out by simple drainage and outcrop prospecting. Current trial operations apparently confirm the ease of establishing small scale mining developments yielding clean direct-shipping ore.

   The spectacular success of recent undertakings in identifying new occurrences results from :
   - the abundance of occurrences, and
   - the limited extent of previous exploration. Accordingly the immediate, establishment of a compact, continuing chromite prospecting operation is proposed.

2. Low grade lateritic Ni-Fe concentrations are known and because of their extent, others are unlikely to be found. Local economic factors encourage the continued economic evaluation of these known resources.

3. Magnesite, chrysotile asbestos and man nese oxides are known to be locally concentrated in the ophiolites and associated sediments. While the favourablility of the environment is demonstrated, these occurrences are of subeconomic tenor and from present information we are not optimistic that economic deposits await discovery (possible exception magnesite).

4. Potential is seen for phosphate, lead-zinc, barite and gold mineralisation, but not supported by documented showings or significant exploration. Research is required in potential host rock sequences to confirm the favourability of the environment, before systematic exploration is undertaken.

Evaluation of data generated in the regional mapping project will considerably advance our knowledge of each of these commodity areas.

## RECOMMENDATIONS FOR FUTURE MINERAL EXPLORATION

### 1. OVERALL STRATEGY

It is clearly apparent that in the short term (5 to 10 years) the most significant mineral exploration priority facing the Sultanate of Oman is the upgrading of the Lasail Copper Project by increasing reserves of available copper, where possible by exploration and discovery.

The most prospective area for achievement of this goal, on purely technical grounds, is the belt of ophiolitic extrusive rocks extending along the northeastern range front. As second priority, smaller areas of equivalent rock units along the southern and south-western range fronts are also mineralised, but less abundantly, and carry a substantial logistic and infrastructure burden compared to areas adjacent to the Batinah Plain. However, for reasons noted in the previous section, the greatest economic potential to advance the Lasail project is considered to exist in the north-eastern range margin.

Accordingly it is recommended that the highest priority be given to acceleration of exploration effort in this zone. This may be achieved by the following courses of action :

- Letting of a contract for the detailed exploration of copper areas 1 and 2 of Leggat,(Leggat A.P. 1980; "Copper Exploration - A proposal for future work". Unpub. Ministry Report in support of 5

2300 sq.km, according to specifications defined in section 5 below

- Promotion of accelerated exploration expenditure on this target, by OMCO within their Mining Licences 1, 2, 3, 5, 6, 7 and 9.

In the longer term (5 - 15 years) planning of Ministry exploratory activities should be with the objective of comprehensive assessment mineral resources of the Nation, and promotion of mining developments where feasible. Recognising that no program or planned strategy can ever finally complete this task, we propose the following general approach as the most cost effective and time-efficient to reach an advanced stage of understanding.

During the current 5-year plan period it is recommended that operations be directed in a general area which can be described as upgrading the National economic geological date base. Specific programs are suggested below.

The regional mapping program will contribute enormously to this fund of geological and geochemical knowledge and should be supported by specific projects to provide over the next 3 to 4 years a sound basis for a wide range of commodity oriented exploration activities during the followng 5 year period. There will also of course be particular targets and prospects generated by the mapping and from other sources,to be evaluated over the whole period under discussion.

It is both technically and economically essential that systematic regional exploration projects be delayed until the completion of the mapping, for the following reasons :

- much of the value of geological and geochemical data acquisition of the mapping program will only emerge towards its conclusion, in the compilation, evaluation and interpretation of all data from the whole area.
- information required for effective exploration operations will be provided by the mapping program, and coordination of the timing and location of the two operations to avoid duplicating this work would be impossible.

- Given this region's attributes of abundant rock exposure and perceived uncertainties with most geophysical and geochemical techniques which have been used, it it envisaged that geological criteria of area and target selection will play on increasingly important role. Thus it is logical to await the substantial upgrading of this information from a project which is already committed.

Support of this data gathering phase is recommended in the following areas :

- Investigation of potential mineral environments.
- Upgrading of data organisation - maps, photos and bibliography.
- Acquisition of extended colour aerial photography.
- Extension of the mapping contractor's Landsat imagery interpretation, with emphasis on mineral occurrences.
- Documentation & recording of known mineral occurrences.

Means of support could include:

- field investigations
- support of Ph D and other research studies
- departmental organisation of existing data sources
- photogeological studies
- orientation studies of new exploration technology (particularly geophysical)
- organisation of technical assistance schemes.

Specific projects are suggested for various commodities in the Assessment of Exploration section, and many other such technical studies could be devised.

We emphasise our belief that, as one cannot plan for ore discovery - only for mineral search, equally the general program of resource evaluation must remain flexible to be able to response to changing economic conditions or to changing technical appreciation arising from the ever improving level of geological knowledge. Accordingly this longer term plan is coined in only general terms.

More specific recommendations for the immediate future are :

## 1. GEOLOGICAL SURVEYS, EXPLORATION RESEARCH

By 1985 the Semail Ophiolite Complex will have been completely mapped. New prospects and deposits of copper, chromite and possibly other commodities (asbestos, magnesite) will have been discovered. However, by the nature and scale of the survey it is impossible to guarantee the discovery of all deposits (for example, new discoveries continue to be made in the United Kingdom, which has been geologically surveyed in progressively larger scales for nearly a century).

The contract mapping of the complex should therefore be regarded as the starting point from which more specialised and detailed mapping of the most prospective parts of the region can be undertaken. Prospective potential of an area will be determined in the light of studies of the structural, lithological and regional distribution of known mineral deposits together with new data acquired during the planned regional surveys.

In the meantime we believe there is a strong case for continued research on geophysical techniques and geochemical surveys as applied to the local environment. Geophysical E.M. methods have proved to be highly sensitive to some conducting agents associated with orebodies, as at Lasail; and we believe that by further investigation it may become possible to distinguish those anomalies due to mineralisation from those caused by features unrelated to ore.

## 2. STAFF TRAINING

To ensure the most efficient participation in the next phase of geological investigation by the Government of the Sultanate of Oman, plans must be made as soon as possible to prepare staff of the Geological Section for this task. This can be done by utilising the agreement with the organisation responsible for the 1981-85 geological surveys to train Department of Minerals staff in field and laboratory techniques. Where considered necessary, staff can also be seconded to organisations willing to provide training, for example the Bureau of Mineral Resources,Australia. It cannot be emphasised too forcefully that successful participation in more detailed investigation of the Semail Ophiolite Complex will require a high degree of geoscientific knowledge and expertise.

## 3. SPECIALIST AIRPHOTOGRAPH SURVEY

The Semail Ophiolite Complex is magnificently exposed, and thus well suited to detailed photogeological interpretation. We strongly recommend acquisition of quality coloured air photographs at about 1:20,000 scale of the entire part of the Sultanate occupied by rocks considered prospective for non-hydrocarbon deposits.

A systematic appraisal of these photographs would require about six months and should be conducted independently, and irrespective of similar work undertaken during the regional mapping/exploration program. The objective would be to identify the following types of mineralisation : exposures of massive Fe-Cu sulphide gossans, chromite and dunite host rock bodies, magnesite veins, manganiferous beds other base metal gossans and associated structural features.

## 4. CHROMITE RECONNAISSANCE

We strongly recommend that systematic prospectingof all available peridotite areas be undertaken. We propose that this could be effectively carried out using prospectors,with geological supervision. Ideally, experienced prospectors may be available from amongst the Turkish miners currently engaged in the Nakhl mining operations. The The supervising geologist would be responsible for documentation and evaluation of discoveries, and direction of the project,based on photogeological area selection where colour photography was available. A prolonged, small scale operation is envisaged.

We support Leggat's comments (Leggat, A.P. 1980 "Chromite in Oman - A Review of Work Done and Proposals for Future Work". Unpub. Ministry Report) concerning deposit evaluation and beneficiation testing, although the division of responsibility between the Ministry and OMCO is a matter for resolution elsewhere.

## 5. CONTRACT EXPLORATION PROGRAM

Exploration on contract by consultants was reviewed by A.P. Leggat as a study of the 1981-5 five year plan cost schedules. The review is comprehensive and informative; we agree with it, and offer the following specifications for the program ;
It is strongly recommended that preference be given to organisations which include mining amongst their activities.

### (1) Terms of Reference :

Following the successful exploration of parts of the Sultanate of Oman, which led to the discovery of exploitable deposits of copper and chromite and prospects of asbestos, magnesite, manganese, and iron ore, it is the Government's intention to invite tenders to carry out an exploration of the parts of the Semail Ophiolite Complex shown in the accompanying map.

### (2) Timing :

The company awarded the contract will be expected to commence the reconnaissance phase of the project immediately after the contract is signed, completing field operations and submitting a preliminary report by the end of 1985.

### (3) Objectives of the Project :

(3) 1. To study the environment of the known copper deposits with particular reference to their structural relationships, spatial distribution and lithological affinities.

(3) 2. To apply knowledge acquired from this study to delineate the most prospective parts of the areas.

(3) 3. To continue limited orientation geophysical, and geochemical surveys to determine the most efficient exploration methods for the Semail Ophiolite Complex. Consideration of the applicability of Induce Polarisation (IP) and Self Potential (SP) and Sirotem type E.M. techniques over known orebodies is recommended. The research to be conducted in conjunction with a review of past work and in consultation with geoscience staff of the Oman Mining Company.

(3)4. To carry out a search for viable copper orebodies.

(4) Training of Department of Minerals Staff :

Provision to be made for the training of Omani geoscientists of the Department of Minerals in exploration methods with emphasis on field exploration techniques.

(5) Mineral Resource Assessment :

In the event of discovery of mineral deposits or the discovery of extensions of known deposits, investigations to be carried to a stage where a preliminary or provisional estimate of the indicated reserve tonnage and grade can be made. The contractor will not be required to make a final evaluation.

(6) Exploration Priority :

Copper is being mined at Lasail mine and a treatment plant and smelter are being constructed nearby. Top priority should be given to the search for copper deposits close to Lasail.

(7) Laboratory Facility :

The contractor will be required to make use of available Ministry facilities for sample preparation and analysis of geochemical samples, drill samples and petrographic samples (which will be charged at appropriate commercial rates) unless mutually satisfactory alternative arrangements are made. It is anticipated that a full range of services will be available.

(8) Reporting :

Quarterly and annual progress reports will be produced during the program. The quarterly reports will describe the areas investigated, the exploration techniques employed, and the results (if any) of the investigations; the annual report will present a comprehensive account of the year's work and an outline of the following year's proposed program.

(9) Program Management :

Throughout the project, exploration will be carried out to the satisfaction of a program coordinator appointed by the Ministry of Minerals and Energy. The contractor will be required to maintain close liaison with the program coordinator and a representative of the Oman Mining Company.

(10) Tender Procedure :

It is intended that detailed technical information be made available to prospective contractors. Communication with .................. is advised during preparation of the tender.

## CONCLUSION

The foregoing recommendations apply irrespective of whether exploration is conducted by mining companies in joint venture with the Government of the Sultanate of Oman, or by contractors on behalf of the Government. In either case interest in mineral potential is likely to be generated by the additional knowledge acquired during the regional geological survey, the exploration project and the photogeological survey.

This has been experienced in most mineral producing countries since the early 1950's when the era of modern mineral exploration commenced : areas investigated by Government geoscience surveys invariably attract mineral exploration interest.

T. J. IRELAND DR. R. G. DODSON

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA 22092

19 July 1981

H.E. Salim Mohammed Abdullah Shaaban,
Undersecretary
Ministry of Petroleum and Minerals
P.O. Box 551
Muscat, Sultanate of Oman

Your Excellency:

The U. S. Geological Survey would like to participate in the Department of Minerals of the Ministry of Petroleum and Minerals Mapping Program. Please find enclosed our preliminary proposal following the guidelines of your specifications accompanying your letter of February 8, 1981.

The proposal is not a complete document and so we would like you to accept it in that manner. We would hope to further negotiate our proposal until it meets with your satisfaction.

The U. S. Geological Survey has had a good working relationship with the Ministry of Petroleum and Minerals since 1973. We would like to continue this association and believe that it will be possible for the U.S.G.S. to carry out your mapping program following your specifications as modified in our proposal.

Sincerely yours,

Robert G. Coleman

Robert G. Coleman
Research Geologist

RGC/deb

Enclosure as cited

PROPOSED U. S. GEOLOGICAL SURVEY PLAN FOR PARTICIPATION IN THE DEPT. OF MINERALS FOR THE MINISTRY OF PETROLEUM AND MINERALS, SULTANATE OF OMAN

This is a work plan which could be undertaken by the U. S. Geological Survey to carry out the Ministry's objectives in mapping and evaluation of the Sultanate of Oman's mineral resources. Most of the objectives of the Mapping Program could be completed under the following guidelines:

## FIELD MAPPING

1st Stage. Area B (South Muscat Area) would be the first area to be mapped. During the first year, at least two field camps would be established and at least 3 to 4 senior geologists would attempt to map 6 1:100,000 sheets. Compilation of previous mapping and photogeology would be carried out on at least 5 1:100,000 sheets. Following the end of the field season, at least 10 sheets would be plotted on chronoflex greenline sheets and be ready for review by the end of the year.

2nd Stage. Area B (South Muscat). The same groups that started Area B (3 to 4 senior geologists) would complete the remaining 8 1:100.000 sheets during the second year. A second group (3 to 4 senior geologists) would set up two camps in Area A (Buraimi-Rustaq Area). During this second field season, at least 5 1:100,000 sheets will be mapped in the field. Following this field season, at least 13 sheets would be plotted on chronoflex greenline sheets and be ready for review by the end of the second year.

3rd Stage. All quadrangles in Area B would be given a final field check by the geologists working in the area. This could take up to half the field season. Following the final field check, one camp will be set up in Area C and mapping would continue until the four sheets in the area were finished.

3rd Stage (cont.)

The Area A group would complete the remaining 5 sheets of the Buraimi-Rustaq area. One camp would be set up in the Haushi Huqf area and at least 2 or 3 1:100,000 sheets completed. At least 11 sheets would be plotted on chronoflex greenline and be ready for editorial review.

4th Stage. All quadrangles in Areas A & C would be given a final field check during the first half of the season. Two field camps in Area D (Haushi Huqf Area) would complete the field mapping. A single camp would be set up in the Dhofar Area(e) and complete at least 3 sheets. At least 8 chronoflex greenline sheets would be ready for review.

5th Stage. Two or three field camps would be set up in Area E and the remaining 9 quadrangles would be mapped. Final field check on Area D would be made in the first half of the season. Kuria Muria Island would be mapped, personnel permitting. At least 10 sheets would be plotted on chronoflex greenline and be ready for editorial review by the end of the year.

6th Stage. Final field checking of all areas and completion of mapping left unfinished because of logistic problems. Completion of Dhofar Map 1:500,000. Area G would be checked by helicopter for ground truth. Nearly all of the sheets would be plotted on greenline chronoflex and be ready for review.

The plan for mapping is somewhat flexible and depends on availibility of people to carry out the mapping as well as the logistic support. Field support will require approximately 60-80 days of helicopter support. After the 1st stage, at least 3 to 4 field camps will be operating during the field season.

Base Materials for Mapping:

Uncontrolled mosaics 1:60,000 will be made from RAF photos now available.

Base Materials (cont.)

from this, negatives will be made and the mosaics reduced to 1:100,000. Map compilation will be made simultaneously on the photo mosaics and greenline chronoflex. Photo mosaics will be produced prior to field mapping where possible.

Landsat imagery of the 16 images covering Oman will be compiled at 1:100,000 and 1:250,000. Format for final compilation to be according to the Ministry's wishes.

All photogeological studies will be accompanied by ground truth in areas where it is lacking.

We expect to receive cooperation from the Directorate of Military Surveys, Great Britain, for base maps at 1:100,000 which will be converted to greenline chronoflex copies without air-brush topography.

## GEOCHEMICAL EXPLORATION

Systematic sampling of units will be made to establish background concentrations of important economic elements. Those igneous units of the Samail ophiolite will be carefully collected to establish Cu, Pb, Zn (Au, Ag) anomalies and their relationship to known massive sulfide deposits. Pt, Pd, Rh assays will be made on sulfide samples from the lower parts of the layered gabbros. Dunite areas with chromite concentrations will be assayed for Cr-Fe-Al ratios and geophysical methods employed to establish the size of the body. Sedimentary rocks will be carefully inspected for radioactivity by using vehicle-mounted detectors or hand-held scintillometers. Panned concentrates will be analyzed from stream samples to establish anomalous values by emission spectrography.

Where there are areas of anomalous values and surface expression of mineralization, detailed geochemical studies will be made to establish the presence of possible ore bodies.

General petrographic studies will be made of each unit to establish its physical nature and econmoic potential. Special studies of sulfide deposits by ore microscopy and microprobe will be undertaken. Work on presently mined sulfide ore bodies can help establish the nature of mineralization.

Age of sedimentary rock units will be established by careful micro and macro paleontological studies. Absolute ages on igneous rocks will be made by R/Ar techniques and where needed, supplementary determinations using Pb-U or Rb-Sv methods.

Analytical work for the geochemical exploration will be done in the laboratories of the U.S.G.S. in Denver and Menlo Park. Emission spectrography, x-ray spectroscopy, Rapid rock analyses (wet methods), fire assay, and flame Atomic Absorption spectroscopy will be used. In some special cases, we will also use neutron activation analyses.

We hope to have a geochemical exploration expert guide the sampling during the field season and he will help train Omanis to carry out this work in the future. During the 3rd Stage, a special team will carry out Geochemical Exploration of the Musandam Peninsula sediments and a separate report prepared.

Prior to commencing our geochemical work, we will compile all presently known information and establish the best procedures and collections for each quadrangle. Known deposits will be studied for background and target areas for intensive study and sampling. Before starting GX programs, we will consult with geologists in the Department of Minerals.

Geologists carrying out mapping will note interesting areas of mineralization or structural features that could control mineral deposition.

All potential mineralized areas will be tabulated and classified according to their potential. An experienced economic geologist will produce a synthesis of the geochemical exploration for Oman as a separate report with recommendations for future work.

## LABORATORY SUPPORT

Nearly all of the chemical work will be carried out in the U.S.G.S. laboratories at Denver or Menlo Park, U.S.A. We would hope to help the Department of Minerals set up a sample preparation laboratory and perhaps train an Omani technician to make thin sections. Some petrographic studies would be made in Oman, but the more exacting work would be accomplished in the U.S.A.

Final drafting of 1:100,000 maps would be carried out by the U.S.G.S. in Washington, D.C. under the supervision of experienced draftsmen. Drafting facilities will be needed in the U.S.G.S. office in Muscat to support work of the field mapping.

## TRAINING PROGRAM

The Department of Minerals will select Omanis with at least a B.S. degree for advanced training in the U.S.G.S. The training will be carried out at the Menlo Park, Denver, or Washington, D.C. centers under the supervision of OIC. Laboratory skills in mineralogy, petrology, geochemistry, and paleontology are available. Periods up to several months will be spent in the field working with U.S.G.S. geologists on structural geology, economic geology, igneous or metamorphic petrology. These same Omani geologists will work in the field with the U.S.G.S. team during the field season and contribute to the mapping. We will attempt to train technicians for field assistants, prospectors, or laboratory technicians The U.S.G.S. will provide help in selecting appropriately qualified candidates. We can also provide help in placing qualified students in U. S. A. universities to carry on advanced studies in geology.

## REPORTS & FINAL PRODUCTS

The Project Chief will provide a written monthly report to the Department of Minerals as well as infrequent discussions on progress and problems. A more detailed annual report will be produced to highlight progress in mapping and geochemical exploration.

For each quadrangle an inked chronoflex edited copy will be produced along with at least one colored ozalid copy to be used for final drafting. Each 1:100,000 sheet will have at least 25 typewritten pages of explanatory notes. We estimate at least 10 completed sheets with explanation will be produced each field season.

After the approval of the Department of Minerals, the sheets will be sent to Washington, D.C., for drafting and printing. Colored proofs will be reviewed by the Project Chief and designated expert in the Department.

Format of each sheet will follow that suggested in the Ministry's program specifications. All reports and maps will be reviewed to conform to the standards of the U. S. Geological Survey. Maps will be similar in quality to the attached copy. Detailed aspects of the format will be negotiated by the Project Chief and designated expert in the Department.

Special reports on remote sensing, mineral potential, geochemical exploration, and geologic framework will be developed in the final stages of the project. From time to time, other specialized reports will be produced.

Final printing and distribution of maps and reports will be controlled by mapping schedule and drafting schedules.

## PAST U.S.G.S WORK AND THE POTENTIAL FOR FUTURE STUDIES

Continued cooperation between the U. S. Geological Survey and the Ministry of Petroleum Minerals, Sultanate of Oman, will produce new and important geologic data relevant to the economic development of Oman and will provide a basis for training of Omani geologists as well as helping in the establishment of a technically strong Ministry of Petroleum and Minerals. For the U. S. Geological Survey, this would provide a continued opportunity to work on the world's best exposed ophiolite mass (ancient oceanic crust) as part of our interdivision program on metallogenic processes at spreading centers. The Oman field work could provide an excellent training ground for the future studies of spreading centers throughout the oceans. Participation by U.S.G.S. geologists in mapping within the Samail ophiolite in Oman would also provide another important tie to the present U.S.G.S. resources processes program on the study of massive sulfide deposits. The exchange made by this program would strengthen the friendship and cooperation between the U.S.A. and the Sultanate of Oman and would allow mutually beneficial cultural and scientific exchanges to take place.

The first agreement with Oman was carried out during the winter field season of 1973-1974 by a two-man U.S.G.S. team (R. G. Coleman and E. H. Bailey) as part of a short-term investigation of the mineral resources of northern Oman and totally funded by the Ministry of Development, Sultanate of Oman. Upon completion of this work agreement, a report was submitted to the Ministry (Coleman and Bailey, 1974). Within this report, recommendations were given for future development of the mineral potential related to the economy of the Sultanate of Oman as well as the organization of a geologic group in the Ministry.

As a result of our first geologic work in Oman, the U.S.G.S. and N.S.F. became very much interested in the scientific and economic problems related to the Samail ophiolite in Oman. A second period of field work during 1977-1978 was initiated under the financial sponsorship of the U. S. National Science Foundation and the Field Geochemistry and Petrology Branch of the U. S. Geological Survey. This project had scientific goals of petrologic, geochemical, and geophysical studies of the Samail ophiolite. A geologic transect through the Samail ophiolite from Muscat south to Ibra was the site for this work carried out by the Department of Geology, University of California at Santa Barbara (Prof. Clifford Hopson) and the U. S. Geological Survey (R. G. Coleman and E. H. Bailey). The work on this project is completed and includes a mapped strip 25 x 150 km (1:100,000 scale) between Ibra and Muscat (see enclosure). This multidiscipline project successfully integrated the work of 13 earth scientists from the U.S.A., Canada, and France which is published in a special issue of the Journal of Geophysical Research, Vol. 86, 1981. A symposium on these studies was held at the American Geophysical Union meeting in San Francisco in December, 1979. Some of these studies bear directly on the economic development of ore deposits with the Samail ophiolite. The present work plan will provide more integration of the past U.S.G.S. work into the mapping and geochemical exploration program now being considered by the Ministry of Petroleum and Minerals.

## Bibliography

Bailey, E. H., and Coleman, R. G., 1975, Mineral deposits in the Semail ophiolite of northern Oman, Geol. Soc. Am. Abst. 1, p. 293.

Boudier, F., and Coleman, R. G., 1980, Cross section through the peridotite in the Samail ophiolite, southeastern Oman mountains, Jour. Geoph. Res., (Special Issue).

Chen, J. H., and Pallister, J. S., 1980, Lead isotopic studies of the Samail ophiolite, Jour. Geophys. Res. (Special Issue).

Coleman, R. G., 1977, The Semail Ophiolite, Oman, a chapter in Ophiolites: Springer-Verlag, New York.

_____1979, Tectonic setting for ophiolite obduction in Oman, Jour. Geoph. Res., (Special Issue).

Coleman, R. G., and Bailey, E. H., 1974, Mineral deposits and geology of northern Oman, U.S. Geologic Survey Project Report (IR) OM-1 (Interim), 127 p.

Coleman, R. G., Huston, C. C., El-Boushi, I. M., Al-Hinai, K. M., and Bailey, E. H., 1979, The Semail Ophiolite and associated massive sulfide deposits, Sultanate of Oman, in Evolution and mineralization of the Arabian-Nubian Shield, Vol. II, (in press).

Donato, M. M., and Coleman, R. G., 1976, Sub-sea floor metamorphism of Saudi Arabian and Omani Ophiolite, Amer. Geophys. Union Trans., 57, p. 1022 (abst.).

Ghent, E. D., and Stout, M. Z., 1980, Metamorphism at the base of the Samail ophiolite, southeastern Oman Mountains, Jour. Geophys. Res. (Special Issue).

Hopson, C. A., and Coleman, R. G., 1980, Petrologic processes at oceanic crust-mantle boundary, southeastern Samail ophiolite, Oman, Jour. Geophys. Res. (Special Issue).

Hopson, C. A., and Pallister, J. S., 1978, Gabbro sections in the Samail ophiolite, southeastern Oman Mountains, Geol. Soc. Amer. Abstr. with program, v. 10, p. 424.

_____1979, Samail ophiolite magma chamber: I, evidence from gabbro phase variation, internal structure and layering, volume of Proceedings, International Ophiolite Symposium, Geological Survey Dept. Cyprus, p. 37.

_____1980, Samail ophiolite gabbro member: II, Implications for spreading ocean-ridge magma chambers, Jour. Geophys. Res. (Special Issue).

Hopson, C. A., Pallister, J. S., Coleman, R. G., Bailey, E. H., 1977, Geologic section through the Semail ophiolite, southeastern Oman Mountains, Sultanate of Oman, Geol. Soc. America, Programs with Abstracts, v. 9, no. 7, p. 1024-1025 (abst.).

Lanphere, M. A., 1980, K-Ar ages of metamorphic rocks at the base of the Samail ophiolite, Oman, Jour. Geophys Res. (Special Issue).

Lanphere, M., Coleman, R. G., and Hopson, C., 1980, Sr-isotope study of the Samail ophiolite, Oman, Jour. Geophys. Res. (Special Issue).

Luyendyk, B. P., and Day, R., 1980, Paleomagnetism of the Kadir transect through the Samail ophiolite, Oman, Jour. Geophys. Res. (Special Issue).

McCollugh, M. T., Gregory, R. T., Wasserburg, G. J., and Taylor, H. P., Sr., 1980, Sm-Nd, Rb-Sr, and $^{18}O/^{16}O$ isotopic systematics in an oceanic crustal section: evidence from the Samail ophiolite, Jour. Geophys. Res. (Special Issue).

Manghnani, M., Coleman, R. G., and Lau, W., 1980, Gravity studies in the Oman Mountains, Jour. Geophys. Res. (Special Issue).

Pallister, J. S., 1980, Samail ophiolite sheeted dike complex, Jour. Geophys. Res. (Special Issue).

Pallister, J. S., and Knight, R. J., 1980, REE geochemistry of the Samail ophiolite near Ibra, Oman, Jour. Geophys. Res. (Special Issue).

## U. S. GEOLOGICAL SURVEY PERSONNEL

The project will consist of one Project Chief, seven geologists, one administrative officer, and one secretary as permanent staff in Oman during the mapping program. Temporary duty geologists during the mapping season may be as many as eight. Draftsman?

All technicians, field assistants, cooks, and other helpers will be hired in Oman.

The U.S.G.S. will develop office space and living quarters for the staff in Oman. No permanent facilities will be established unless specifically requested by the Ministry.

## BUDGET ( PRELIMINARY)

| | | |
|---|---|---|
| Personnel | | $ 3,600,000 |
| Housing | | 5,184,000 |
| Office Space | | 576,000 |
| Travel | | 1,800,000 |
| Transport of Goods | | 900,000 |
| | Sub-total | 12,060,000 |

## FIELD EXPENSES

| | | |
|---|---|---|
| Camp Equipment | | 168,000 |
| Camp Operation | | 576,000 |
| Field Camp Personnel | | 288,000 |
| Helicopter Support | | 1,920,000 |
| | Sub-total | 2,952,000 |

| | | |
|---|---|---|
| Geochem & Other Lab Studies | | 1,031,000 |
| Map Base-Mosaics Landsat | | 900,000 |
| Drafting & Printing | | 1,100,000 |
| Admin. Support (overhead) | | 3,569,000 |
| | Sub-total | 6,600,000 |

| | | |
|---|---|---|
| Training of Omani Geologists<br>6 people - 1 yr. in U.S.G.S. | | 200,000 |
| | GRAND TOTAL | $21,812,000 |

by: Robert G. Coleman
"Bob" Coleman



## FINANCIAL ARRANGEMENTS

The U.S.G.S. work plan as outlined shall be carried out with funds in the amount of $21,812,000 United States dollars advanced by the Ministry of Petroleum and Minerals in accordance with the budget estimates in yearly increments. These funds shall be advanced by the Ministry in the form(s) of a check payable to the "U. S. Geological Survey" in accordance with the schedule cited below:

a. The Ministry will make an initial advance of $ covering the first year's estimated budget upon execution of the Project Plan.

b. U.S.G.S. will provide the Ministry, on a quarterly basis, a report of obligations and expenditures for the funds advanced by the Ministry.

c. The Ministry will advance funds for the ensuing years' activity at least (90) ninety days before the end of the then current year. Such advances will be in the amount as cited in the pertinent year's budget estimate.

d. Any unobligated balance of a prior year's advance will be utilized in the ensuing year. Such balance will be deducted from the ensuing year's budget estimate.

The U. S. dollar amounts specified, and amendments thereto, are based upon estimates of salaries, differential, allowances, expenses, equipment, supplies, material, and contractual services to be provided under this Project Plan and upon current prevailing costs; therefore, actual obligations and expenditures may differ from the budgeted amount. Should the actual cost increase over that stated in the budget estimates due to increase in staff or costs of equipment, materials, supplies, and expenses, budget allocations and scope of work will be renegotiated.

Oman
M.C.

# SULTANATE OF MUSCAT AND OMAN

Report by PS Bagnall
Feb. 1969.

## General Background Information

The Sultanate of Muscat and Oman is situated on the South Eastern coast of the Arabian Peninsula between 53° and 60° E., and between 16° and 25°N. It is bordered on the North by the Persian Gulf and the Gulf of Oman, on the East by the Arabian Sea, on the South-West by the Aden Federation and on the West by the Trucial States and Rub-al-Khali (or Empty Quarter). Its area, estimated about 1,30,000 sq. miles, includes the town of Muscat, and the districts known as the Ruus-al-Jebal, Batinah, Dhahirah, Central Oman, Sharqiyah, Ja'alan and the Dependency of Dhofar. Except for small stretches between Dibba and Khatmat Milahah in the Shumailiyah in the North East, the coast line extends nearly one thousand miles from Ras-al-Keer near Shaam on the West side of the Musandum Peninsula in the North to Ras Darbat Ali to the West of Dhofar in the South.

## Topography

Physically, the Sultanate of Muscat and Oman, except for the dependency of Dhofar, consists of three Divisions; a coastal plain, a mountain range and a plateau. The coastal plain varies in width from ten miles in the neighbourhood of Suwaiq to practically nothing near Muscat town where the hills descend abruptly to the sea. The Oman mountain range runs generally from North West to

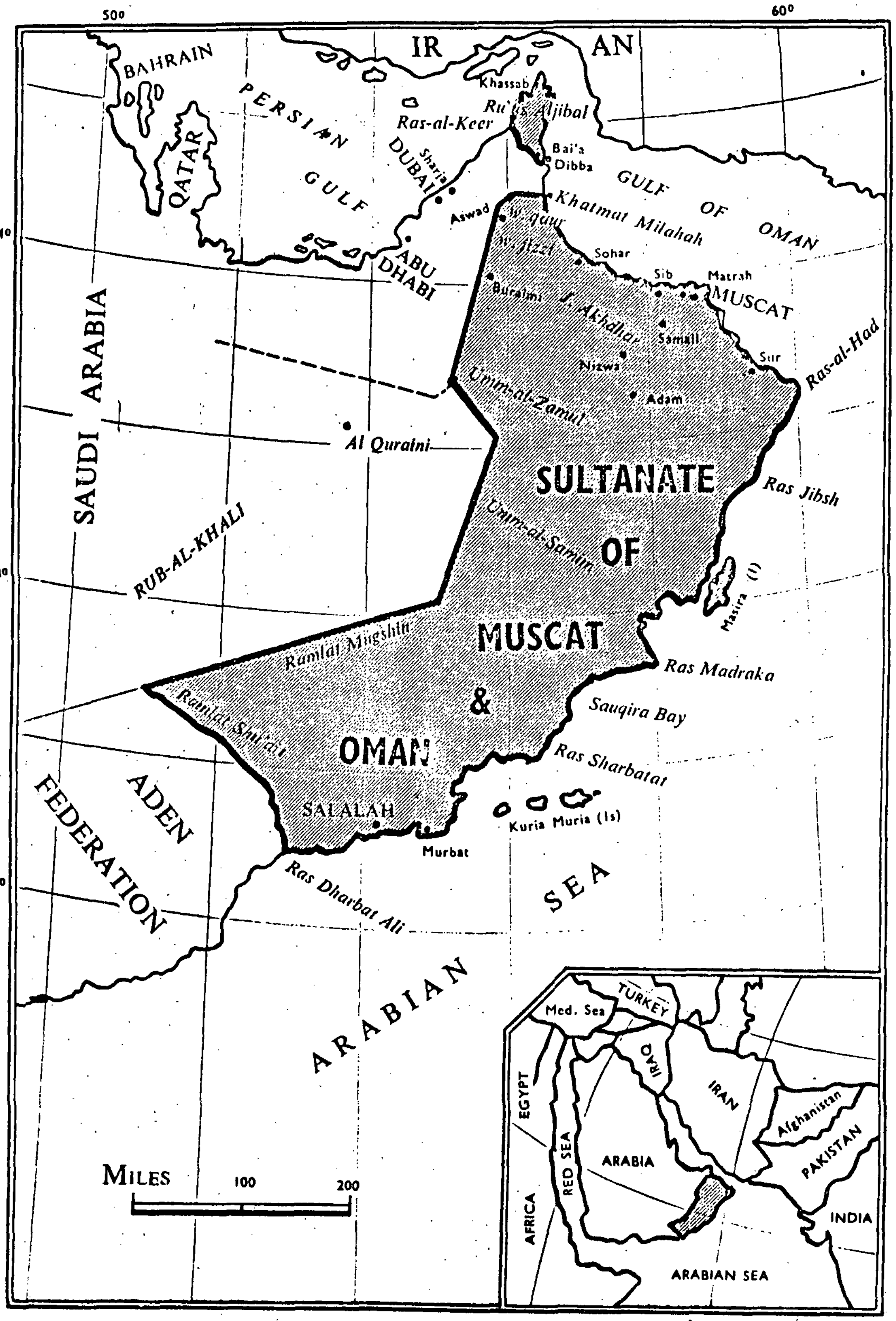

50°
60°
24°
20°
16°
IRAN
BAHRAIN
QATAR
PERSIAN GULF
Khassab
Ru'us Aljibal
Ras-al-Keer
DUBAI
Sharja
Bai'a
Dibba
GULF OF OMAN
Aswad
Khatmat Milahah
ABU DHABI
Sohar
Sib
Matrah
MUSCAT
Buraimi
J. Akhdhar
Samail
Nizwa
Sur
Ras-al-Had
Adam
Umm-al-Zamul
SAUDI ARABIA
Al Quraini
SULTANATE OF MUSCAT & OMAN
Ras Jibsh
Umm-al-Samim
RUB-AL-KHALI
Masira (I)
Ramlat Mugshin
Ras Madraka
Ramlat Shu'ait
Sauqira Bay
Ras Sharbatat
SALALAH
Kuria Muria (Is)
Murbat
ADEN FEDERATION
Ras Dharbat Ali
ARABIAN SEA
MILES
100
200
Med. Sea
TURKEY
IRAQ
EGYPT
IRAN
Afghanistan
PAKISTAN
RED SEA
ARABIA
AFRICA
INDIA
ARABIAN SEA

Fig 1

South East and reaches its greatest height in the Jebal Akhdar (or green mountain) whose summit is about 9,900 feet. The mountains are mostly barren igneous rock but there are numerous cultivated areas or oases where water is plentiful. The plateau has an average height of about a thousand feet and is mostly stony and waterless and extends to the sands of the desert area known as the Rub-al-Khali (the Empty Quarter). The coastline southward to Dhofar is barren and forbidding. The principal town of Dhofar is Salalah on the coast from which a semi-circular fertile plain extends to the foot of a steep line of hills, some two to three thousand feet high, which are grassy and wooded, and which form the edge of a stony plateau also extending to the sands of the Rub-al-Khali.

Climate

Annual rainfall is about four inches in Muscat, though it has varied from less than two inches in bad years to over twelve inches in good years. The fall is mostly in January though there are records of rain in any month. Dhofar is subject to the South West Monsoon and falls up to twenty five inches have been recorded in the rainy season which starts in late June and lasts till October. Whilst the mountain areas enjoy more plentiful rain, some parts of the coast, particularly near Masirah Island, sometimes receive no rain at all. The climate, generally, is very hot, with maximum temperatures averaging 115° Fahrenheit in the hot season which is from May to October. Temperatures seldom drop below 54° in the cold season.

## Population

The population of the Sultanate is estimated at five to six hundred thousand. A general estimate would be a total of one hundred thousand for the principal towns (Matrah 14000, Sur 8000, Nizwa 8000 and Muscat 5000); three hundred and fifty thousand for the smaller towns and villages and one hundred thousand nomadic or semi-nomadic tribes. The population is predominantly Arab except on the Batinah Coast where there are many Baluch and Negro elements. In Muscat and Matrah, Khojas, Hyderabadis, Hindus, and Baluch predominate.

## Communications

Motorable roads and tracks run from Muscat along the Batinah Coast to Sohar and thence to the Trucial Coast. There are unpaved motorable roads to Nizwa and Sur, whilst a number of feeder roads have been constructed and are still being developed. Dhofar can also be reached by a motorable land route. There is a landing ground for smaller aircraft near Muscat and a number of emergency strips elsewhere in the country. Larger aircraft can land at Adhaiba, Masirah and Salalah but the normal method of entry into the Sultanate is by sea or air via Muscat and permission is required for the use of other air fields or ports or to travel on roads beyond a certain distance of Muscat. Messrs. Cable & Wireless operate both a public telegraph and telephone service at Muscat, and there is also a Post Office with normal air and surface letter and parcel services to any part of the world.

At present Gulf Aviation, a BOAC subsidiary run a bi-weekly passenger air-service connecting Muscat with the International Air-port of Bahrain and with all the Shaikdoms in the Persian Gulf. British India Steam Navigation mail and passenger Steamers also call regularly entering and leaving the Gulf, whilst Strick Line and other cargo ships from Europe, Australia and the Far-East call at approximately monthly intervals.

Government

Oman is an independent monarchy and the Sultan, Said bin Taimur, born on 13th August 1910, excercises absolute power. The succession has been hereditary since the beginning of the present al-bu-said dynasty. The Sultan is assisted in the capital by a Minister of the Interior, a Personal Adviser and a number of Secretaries of Departments including External Affairs, Defence and Development. Walis (or Governors) are appointed by the Sultan for all the chief towns and districts throughout the Sultanate and the tribes supply guards or askars though not necessarily from the same district. A joint Municipality of Matrah and Muscat towns managed by an Executive Officer advised by a Commitee of leading business-men, under the general control of an official appointed by the Sultan takes care of local government.

**The Economy**

The economy is almost entirely dependent upon the cultivation and export of dates, but dried fish, limes, pomegranates and fire-wood represent other exports. Imports are mainly of wheat, rice and textiles, but with increasing wealth of the population, more so-called luxury goods are finding their way into the markets.

The Sultan is planning development of the country and hopes are chiefly vested in the exploitation of the countries oil reserves. He is also known to be favourably disposed to geological exploration providing the right approach can be made.

**Taxation**

There is no income tax, nor any Sultanate taxation other than the Customs import duty and zakat (religious tax on produce) which, in the Sultanate, is collected at 5% where irrigation is carried on through wells, and at 10% where it is by "falaj". A small Municipal Tax is also levied on the value of imports, and exports through the Ports of Muscat and Matrah, which provides the chief source of income for the joint Municipality of those two towns.

**Revenue**

The revenue of the Sultanate is almost entirely derived from customs levies, which vary from 7½% on essentials such as wheat, rice, sugar, coffee and cotton piece goods, to 75% on drugs such as opium. There is also a levy upon exports of locally produced commodities limited to 5%. There are no restrictions on export.

**Currency**

The Official currency is the Indian Rupee in notes of 1, 5, 10 and 100 Rupees of the Persian Gulf issue; the Indian Naya Paisa and Baizas in units of 3, 5, and 20. The Indian one Rupee coin is not used. The silver Maria Theresa Thaler or dollar is also still used in the Interior and Dhofar. Current exchange rates are approximately as follows:

18 Rupees = £1 sterling    7.50 Rupees = 1 dollar U.S.A.;

**Foreign Representation**

Great Britain and India, which have treaties with the Sultan, are the only two countries at present maintaining diplomatic representation in Muscat. This they do through Consulates General. There is also a treaty recently renewed with the United States of America, but no representation in the country at present, whilst treaties were also concluded with France and Holland many years ago.

**Travel to Oman**

A Muscat visa is required and this must be obtained in advance. As there are no hotels in Oman a visa applicant must have a local sponsor to guarantee accommodation. Before issuance of a visa the sponsor, normally a business agent, applies for a required No Objection Certificate in Oman and if given sends it to the Sultanate Consul, 7, Albert Court, Kensington Grove, London, S.W. 7, who will normally issue the Muscat Visa. It takes at least 3 to 4 months to complete visa formalities.

# GEOLOGY OF OMAN

## Previous Work

Little detailed work has been carried out within Oman and that which has been undertaken has been aimed largely at finding oil deposits. Lees (1928) was the first to formulate any substantial account of the geology of Oman. He recognised the Hawasina series overlain by the Semail Igneous series, the two rock formations that form the bulk of the Oman mountain range. Lees believed that the Hawasina and Semail rocks formed major components of a vast thrust nappe complex.

Further work of a stratigraphic and structural nature was carried out by members of the Iraq Petroleum company during the period 1940 to 1960. Published accounts of investigations in the Oman mountain range have been provided by Hudson McGugan and Morton (1954), Hudson Browne and Chatton (1954), Hudson and Chatton (1959) and Hudson (1960).

An excellent synthesis of the geology of Oman is recorded by Morton (1959) who gives evidence for believing that Lees' ideas of thrusting of the Hawasina and Semail onto the Arabian foreland from the east are no longer tenable and that these formations are autochtonous. Morton suggested that the chaotic structures typical of the serpentine and radiolarites of the Semail and Hawasina series derive through "effusion tectonics" associated with Upper Cutaceous serpentine extrusions.

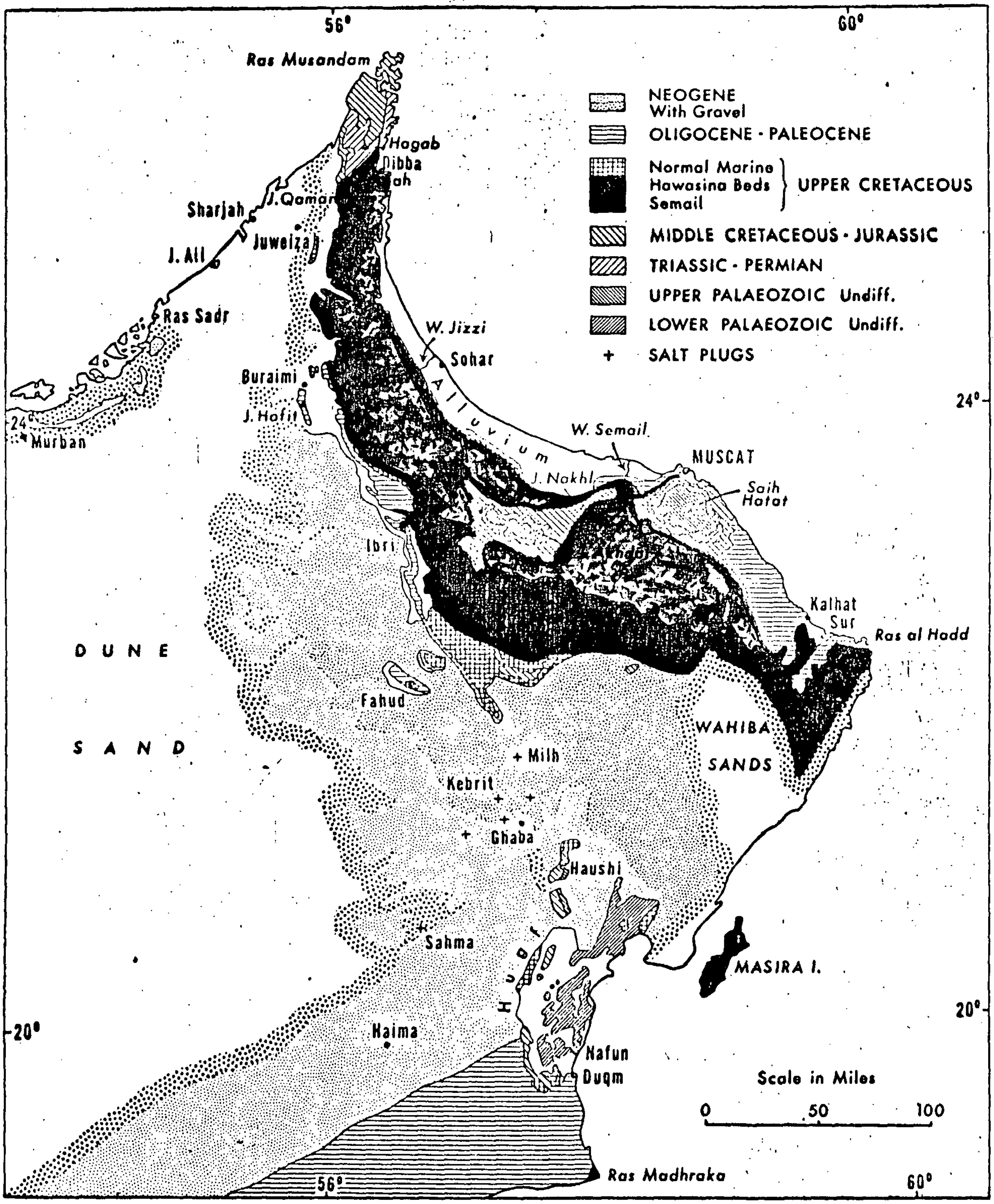



**Fig. 2—Geological Map of Oman.**

Lees regarded the Oman mountain ranges as a southern extension of the Zagros mountains nappe zone in Iran. Morton believes this theory to be incorrect and suggests that wrench faulting on a large scale may have caused "detachment of the Oman orogenic zone from former connections to the north and south".

Still more recent accounts of the structure and historical development are given by Kuendig (1959) and Tschopp (1967). Kuendig in particular criticises Lees' theories in favour of a process of engeosynclinal gravity gliding of the olistostrome and sheet type developing from the break up of a domal structure in the Persian Gulf area.

Information pertinent to the geology of Oman is also given in publications arising out of Greenwood and Loneys (1968) studies in the Trucial States and Berjdouns (1964) work in the E. Aden Protectorate.

Greenwood and Loneys' studies are of particular interest in that they offers the first comprehensive published account of the economic mineral potential of a part of the Oman mountain range. Small chromite deposits (less than 5000 metric tons) were discovered in Semail serpentinite. Oxidised copper deposits of economic tenor (3% W) but unknown tonnage are recorded from Hawasina metasediments intruded by quartz veins.

Their studies lend support to the thesis that the economic mineral potential of Oman is likely to be best developed in the in the Semail and Hawasina rock series.

Shell Oils activities in Oman leading to the development of productive oilfields were also instrumental in producing the most comprehensive geological map of Oman. Although much of their work was confined to the desert foreland their geologists traversed the Oman mountain range and carried out a photogeological interpretation of the mountain mass. This resulted in the accurate delineation of the Semail and Hawasina rock series. As the Semail forms the bulk of the mountainous area and is composed of serpentinite and ultrabasic rock types the Shell geologists were not too interested in the economic implications of such rocks. However Shells unpublished map of Oman remains the best effort to date and a copy of it would prove a most valuable basis to any mineral exploration programme.

## Regional Geology

Oman is divisible into a north east mountain range and a south west foreland adjoining the Arabian Shield.

## The Foreland

Oligocene to Miocene sediments cover most of the foreland together with recent dune sands and salty mud flats.

In the south west part of the foreland a core of Lower Palosozoic rocks forms the Hugf-Haushi swell. Here Cambrian dolomites shales and sandstones are intruded by rare basalt dykes and sheets and pierced by salt dome structures. Ordovician sandstones and shales

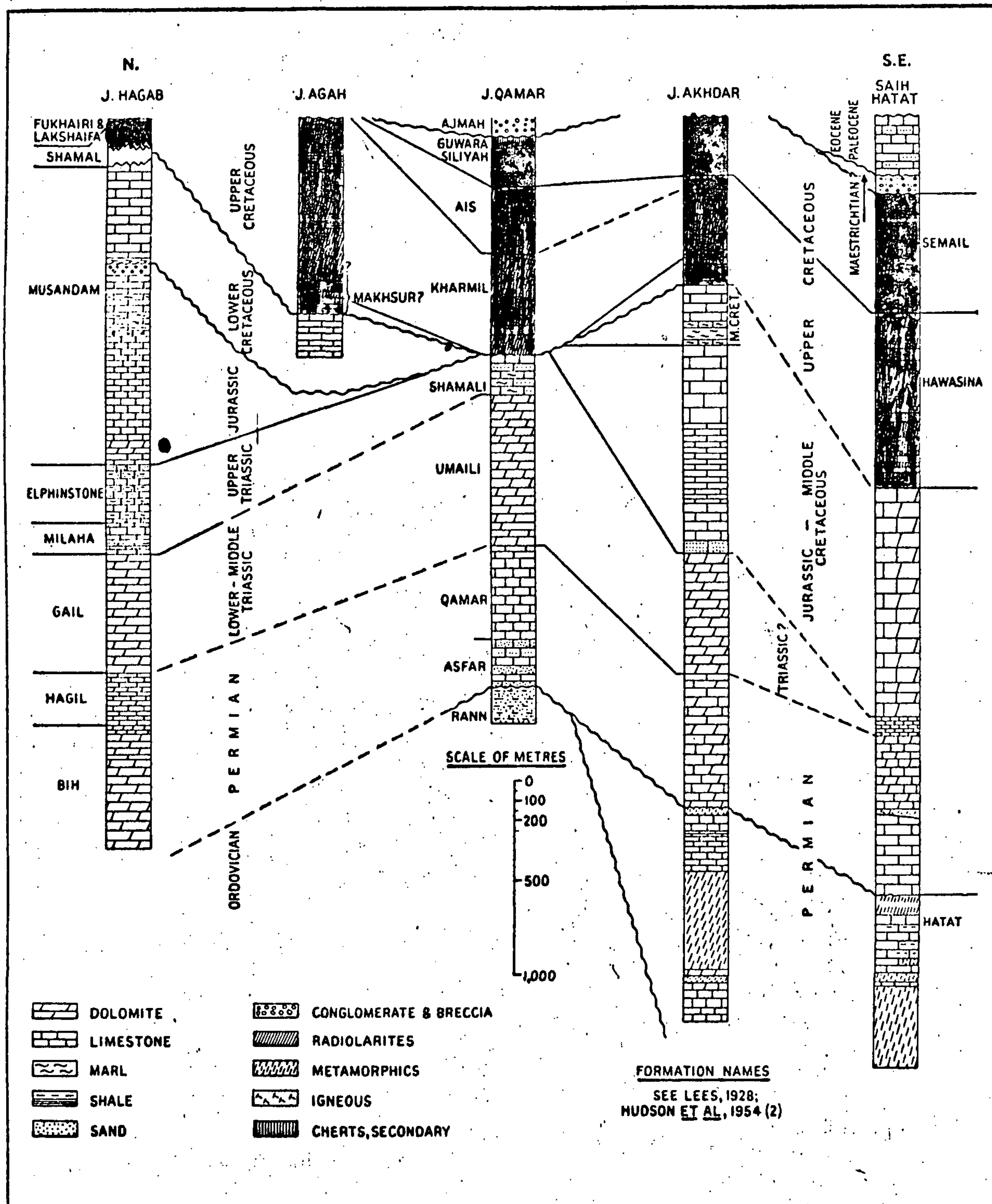



Fig. 3—Stratigraphic Sections of Oman.

overlie the Cambrian unconformably and geophysical investigations indicate salt dome structures at depth.

At Hausi Permian boulder beds supercede the Ordorician. The boulder beds appear to be derived from Basement rocks and contain subangular blocks of granite, gneiss and porphyry. The boulder beds transgress widely and grade upwards into sandstones and reddish marls.

Attenuated Triassic and Jurassic sequences are present locally not always forming surface outcrops. Cretaceous rocks rest unconformably upon Jurassic sediments although a similar lithology is maintained. Mid-Cretaceous rocks become more arenaceous whilst marly limestones dominate the calcareous rock series. Marls and limestones with pronounced lateral changes in facies and thickness continue into the Upper Cretaceous.

Maestrichtian limestones and marls crop out over much of the foreland particularly close to the Hugf-Haushi swell and the foothills of the Oman mountain range where their transgressive nature is well shown.

Tertiary limestones, chalks, marls and evaporite sequences also are widespread over the Oman foreland. It is the foreland areas that have provided the structures and rock types suitable for the development of producing oil fields. Little is known regarding their metallic mineral content but this is assumed to be rather poorly represented.

The Oman Mountain Range

In the Oman mountain range the oldest exposed formations are Permian phyllites, basic intrusives and quartzites overlain by Upper Permain limestones.

Questionable Triassic sediments continue the calcareous rock sequence and grade upwards into Jurassic marls and dolomites.

The Lower and Middle Cretaceous sections are represented largely by dolomitic, radiolarian and crinoidal limestones. The Upper Cretaceous is well developed and forms the bulk of the Oman Mountain range. According to Morton (1959) the Upper Cretaceous consists of the calcareous-metamorphic sequence of the Hawasina Series overlain by over 1,000 metres of the Semail igneous series. According to Dr. Hewellyn of University College, London, and formerly on Shells staff in Oman, the Semail underlie the Hawasina a view generally agreed with by Greenwood and Loney (1968). The Semail is composed of a suite of plutonic, ultramafic rocks together with their hypabyssal and extrusive representatives. Peridotites, dunites, pyroxenites, gabbros and diorites all occur. Generally they are subordinate to the vast mass of serpentinite, much of which has derived from the ultramafic rocks.

Greenwood and Loney (1968) believe that the gabbros, ultramafic rocks and serpentinites are all components of a pseudostratiform alpine peridotile-gabbro complex. They believe the serpentinite derives from plutonic ultramafic rocks rather than by extrusion directly from a peridotitic or serpentinic melt.

A characteristic feature of the Semail serpentinite is the random occurrence of chromite blocks and lens at different vertical levels. The Hawasina Series is closely associated with the Semail and the Lower Hawasina composed of cherts and radiolarites is inter-bedded with Semail intrusive sheets. The Upper Hawasina generally overlies the Semail and forms a distinct lithological group of low grade metamorphic rocks. Chlorite, epidote and garnet occur widely in either predominantly arenaceous or calcareous metamorphic rock suites.

Manganiferous cherts are characteristic of the Hawasina as is the widespread occurrence of oxidised copper minerals.

## Mineral Resources

Little is known of the economic mineral resources of Oman, the emphasis of its limited exploration being placed on petroleum prospecting. Apart from scattered travellers descriptions of coal deposits and historical archaeological accounts of ancient copper workings, little can be gleaned from published material.

Fortunately recent studies of the neighbouring Trucial Oman Range do allow a certain knowledge of the Oman mountain range by inference. As far as base metal mineralisation goes the Semail and Hawasina series are the obvious host rocks. As these make up the bulk of the Oman Mountain range then it is this mountainous area that offers the greatest prospects for discovery of base metal deposits.

Greenwood and Loneys (1968) reconnaissance of the mineral recources of Trucial Oman indicate the presence of substantial if isolated, tonnages of chromite, widespread traces of copper mineralisation some of economic tenor, manganiferous cherts, and several geochemically anomalous zones for nickel and molybdenum. They do however state that none of the mineral deposits so far found in Trucial Oman are economic propositions under present conditions. As their work was confined to approximately one fifth of the total area of Semail and Hawasina rocks the chances of discovering similar bodies in Oman is probabalistically much greater.

Chromite and nickel are likely to be present in the Semail ultramafies whilst copper and manganese may be expected in the Hawasina Series. The possibility of molybdenum occurring in economic proportions is not great but minor acid intrusions are known and the presence of diorite stocks does not preclude the development of porphyry copper type mineralisation.

The Oman mountain ophiolite suite probably corrolates with the ultrabasic belts of Cyprus and Turkey where similar rock types have given rise to economic chrome and asbestos deposits.

At Cyprus Chrome companys workings on Troodos, the extremely irregular shape and lack of constancy of the ore pockets, presented tremendous exploration and mine development problems and ore reserves never looked good. Even so over the period from 1931 to 1957 over 170,000 tons of chrome ore was mined.

These figures are given to indicate that Greenwood and Loneys estimates of individual deposits containing up to 5,700 metric tons of chrome ore in Trucial Oman might be much more encouraging than they supposed particularly as their estimates were not based on any drilling results and in view of the typically erratic distribution of chrome ore.

All that can be said, at the present state of knowledge in Oman, with regard to economic mineral potential is that considerable areas of rock types occur that are known to be favourable to chromite platinum, nickel, copper and asbestos formation but that the delineation of economic deposits could only come after a well developed and probably expensive exploration campaign.

Mineral Opportunities in Oman

Due to its relatively unexplored state and the presence of a vast mass of differentiated ultrabasics, Oman remains one of the most likely places to find economic deposits of chrome ore. Its known association in the past with copper smelting and the recorded presence of sub-marginal copper in Trucial Oman provide favourable pointers towards the search for copper in this region.

However in its present undeveloped state Muscat and Oman obviously provides extreme challenges to successful mining ventures. The lack of road and transport facilities, the lack of trained semi skilled labour force, the complete absence of any form of mining code and the lack of any formal governmental procedures might appear to militate against successful ventures in this territory. One could however argue that the complete lack of a mining code could allow favourable negotiations of an equable arrangement with the Sultan. The recent discovery and exploitation of commercial oil deposits has provided a source of revenue that could be the springboard for the development of Oman.

According to the Sultan's 1968 pronouncements and my discussions with his consul in London and several of his consultants the present is an extremely opportune time to discuss mineral exploration activities as the Sultan is particularly interested in raw material development, having at last the financial gains of the twenty years of oil exploration.

At present mineral concessions are held by Wendell Phillips for the Dhofar Province and the remainder of the Sultanate is covered by a concession granted to Shell Oil. Whether Shell Oil are interested in base metal prospection remains open but in view of diversification trends it is highly unlikely that they would willingly give up their mineral concessions.

They may, of course, be willing to cooperate in a joint exploration venture and should U.S. Steel continue its interest in Oman, then the possibilities of such a move should be carefully considered. Shell Oils expertise in Oman, the companies facilities for transport, storage and accommodation and its close ties with the Sultan would be extremely favourable features of any cooperative venture.

Conclusions and Recommendations

1. Oman is a relatively unknown, physically difficult area of some geological favourability for the discovery of chromite, nickel copper and possibly manganese deposits.

2. The next ten years are almost certain to witness the most rapid development of road, transport, medical and social facilities in the history of Oman.

3. Opportunities for mineral ventures do exist but the exploration programme required to delineate ore prospects is likely to be expensive.

4. As Shell Oil hold the mining concession over the most favourable areas, discussion as to the possibility of a joint base metal exploration programme should be considered.

5. A preliminary photogeological interpretation could delineate the most favourable areas of the Semail and Hawasina outcrops in the Oman mountain Range. Dr. R. Hewellyn of University College, London, a geologist who formerly mapped part of this range for Shell Oil, is the most authoritative person capable of carrying out such an interpretation. As he still retains much of the original Shell mapping a good photointerpretation could be prepared within a month's time.

6. Should U.S. Steel be interested in pursuing formal application for mineral exploration concessions then the course advised by the Sultanate consul in London is to write to him c/o 7, Albert Court, London W. 7. Upon receipt of a letter showing U.S. Steel'

interest in Oman the consul will inform the Sultan accordingly.

As the Sultan apparently is in daily Telex communication with his London advisers and spends from 3 to 6 months of the year in London, a prompt reply should be forthcoming.

Appendix A.

Geology and Mineral Resources of the Trucial Oman Range by I. Greenwood and P. Loney.

Stanton Hazzard [signature]

Feb. 1969

US Steel 24 Oct 83

Oman Concession

- 1000 km² in ophiolite belt ; 17 km x 60 km
- plant in center of Lasail deposit + prospect
- USGS published in JGR Ap 1981 about ophiolites – vol 86 B4 10 Ap 81 Ophiolites
- geol map avail by Oman University
- known deposits – pillow lavas near top of sequence

Aspects of Expl

1. work in each of 8 known prospect areas
2. Recon of rest of area.

Input ~~after~~ over
[1/3 km linespacing   av. + C 400 ft.
[Geotemex

June/July/Aug too hot to work

They feel its mostly a subsurface program – may propose mostly GP.

3 year prog – Exploration Services in Nature

→ Bid due 14 Nov 83

wells are uncored –

Team

4 geologists (incl geochem) over there, perhaps 2 groups - 1 N half, 1 S half.

map drag 1 km spaced lines + sampling outcrops + wadi sampling (streams) -

map geol, do air photos

scintrex: magnetometer + VLF portable - > I said "don't do it."

1 geol heading each team
1 on drilling

need geochemist to go over there, be on call in states.
do sample prep here, then bring samples back to US -

Proposal

$3 \times 10^6 \times 700 \times 10^{-9}$
$2100 \times 10^{-3}$
2.1 T gold
× 2000
4200
12
00
42000 oz
400
\$16800,000 AU

To provide geol services of 2-3 people @ monthly cost -!! then add equip cost, etc.
min equip requirements purchase and/or lease -
USS would buy equip, charge it off to project, give it to them @ end of project.

John will be going to Pittsburg 2 Nov -
for final form on 14 Nov.

Notes From RFP

1. Exploration program 3-yr period
start "1983"

2. Now developing Lasail, Aarjah, Bayda orebodies
- Lasail mining has given some idea of ore controls ; started 1980

3. Wadi sampling by Prospection Limited failed - -80 mesh fraction
used -- should have been -30 mesh.

4. INPUT in 1974 - guided almost all work
followup : surface mapping over INPUT anomalies
drill decision
- conductive overburden
- conductive country rock, faults, alt zones yield large #
anomalies as good as over ore

5. Sumail Ophiolite - thrust sheet
tectonized peridotite → peridotite → gabbro → sheeted dike swarm
→ pillow lava → pelagic seds
old slab of mantle + ocean spreading center, thrust
over Perm to Upper Cret in Late Cret
- Dips to E @ shallow angle, faulted
- Pillow lavas host Cyprus-type massive sulfides

Lavas are Geotimes, Lasail, Alley old to young
Geotimes is basalt pillow lavas, defined in field
and by geochem.

Lasail & Aarjah occur on top of Geotimes

8. <u>Required Components of Program</u>

(a) Color aerial photography 1:20,000 in strips over whole area, w/ 1:5000 in strips over 8 prospect areas

(b) Study of relations between Cyprus-type and Oman occurrences

(c) delineation of volcanic centers, use of plate tectonics, modern volcanology

(d) detailed geologic mapping "should constitute the primary exploration approach" -- volcanic centers, etc.

(e) gossan analysis - relationships to mineralization and evaluation using up-to-date techniques - multielement [illegible] analyses for this!

(f) Detailed geol map @ 1:50K (or 1:25K) + overlays showing other data -

(g) Geochemistry - wadi geochem orientation -- Prospection Ltd used -80 mesh
- Started at beginning of field work w/ detailed scheduling req.
- analyzed for 20-30 elements; computer processing
- Separate report.

(h) Geophysics -
- reassess INPUT & mag data
- post reassess our known orebodies w/ ground EM, IP, mag, logging
- separate report

9. Drilling –
- as approved by Dept of Minerals, using their gear
- all cores & cuttings logged geologically
- all mineralization analyzed

10. Staffing
- Number & discipline of experts
- Education & training
- Tech exp & background in minerals expl

use of gravity for deep deposits

Are there no grav mag anomalies?

11. Support – contractor to provide own facilities

12. Training – train a min of 4 geoscience graduates
- employment & training of Omani technicians

13. Reporting – mo, quarterly, annual reports

14. Management – contractor will carry out program to satisfaction of a coordinator from Dept Minerals -- Close contact w/ Chief Geol Oman Mining Co.

1. MO $q^{co}/A$ up and, Pichuch

2. Fred neon – Mary Cam $\overline{c}$ meeting

Ann MO $q^{co}/A$

3. budget for our operation
+ indirect – plan dredged – if don't spend, goes back

$\frac{1.50 \times 10^{3}}{2 \times 10^{6}}$

$7.5 \times 10^{-3}$

0.07%

Notes : "Future Exploration of the Semail Ophiolite - - - "
Dodson - BMR - Australia
Ireland DME - S Australia

- Deposits are of Cyprus & Troodos Complex type
  conformable, strata controlled, top of ophiolite volc sequences,
  clusters, some struct control, near younger plagiogranite plugs.

- Lasail 8 MT, but others of Cyprus type > 20 MT

- Exploration methods
  (1) geolog assoc
  - not enough known to apply this
  (2) Conductivity contrast
  false, competing anomalies
  (3) density contrast
  - rugged terrain, densification of host rocks
  lack good maps for terrain corrs.
  (4) Gossans
  all likely known since ancient times - numerous old slag dumps
  (5) Supergene alteration
  - not observed everywhere
  (6) primary hydroth alt + footwall stringers
  - hard to recognize w/out thin sections
  (7) Umbers - ferruginous laminated mudstones
  relation to ore not understood

  (8) Chemical dispersion
  - not documented

- Prospection Ltd's prog ← Canada

geology ↙ reject ↘ proceed - sampling EM gravity mag → reject if no EM ; → proceed

- Lots of EM anomalies (INPUT)
- Expl has eliminated possibility of major, shallow deposit
- Prosp. Ltd did first systematic exploration
- Limitations to EM
  - conductive overburden in low lying areas
  - anomalies due to faults, cond country rock, alt zones as responsive as orebodies.
- EM doesn't work very well here - its use continued due to faith and lack of good alternatives
- Authors recommend a program heavily guided by geol environ of selected use of geochem, geophys. Balls out recon days are over
- High degree of sophistication needed for further exploration to be successful.
- Exploration contractor should be mining Co.

at Tynagh, Ireland: Econ. Geol.,

Newcastle mineral district, New
, v. 51, no. 551, p. 150-155.
of sulphide mineralization in the
70, no. 1, p. 90-101.
of emplacement of the Brunswick
w Brunswick: Canadian Instit.

ine, Trinity County, California:

-most Norway (Finnmark): in
on: Geol. Survey Canada Paper

Canadian Cordillera: Canadian

: in Porphyry deposits of the
gy Spec. Vol. 15, p. 44-51.
ology at Parys Mountain, Ang-
gham, 1974): Abst. in Trans. of

y and lithogeochemistry of the
Econ. Geol., v. 70 no. 1,

copper deposits southwestern
p.
ng and other sulphide deposits,
. Geol. v. 73, no. 2, p. 192-206.
s and mode of subduction: in
neral Deposits: Geol. Assoc.

enstone terrains of shield areas
oc. South Africa Spec. Publ. 2,

ard, G.W. 197_ The geology

ntinents: John Wiley and Sons

The Continental Crust and Its Mineral Deposits, edited by D.W. Strangway
Geological Association of Canada Special Paper 20

# Cu-PYRITE MINERALIZATION AND SEAWATER CONVECTION IN OCEANIC CRUST – THE OPHIOLITIC ORE DEPOSITS OF CYPRUS

**E.T.C. Spooner**
Department of Geology, University of Toronto, Toronto, Ontario M5S 1A1

## ABSTRACT

One of the major discoveries of recent years about the physical and chemical behaviour of the solid Earth and the oceans is the scale of the phenomenon of convective seawater circulation within the upper 3 to 5 km of the oceanic crust at spreading ridges. Analysis of the discrepancy between observed conductive heat flow and that predicted on the basis of a purely conductive cooling model suggests that the total ocean mass may circulate through basaltic oceanic crust at ridges once every 3 to 10 Ma.

An important point concerning hydrothermal circulation to arise from studies of ophiolitic rocks is that the formation of economically significant (on land) cupriferous pyrite ore deposits appears to be a natural side effect of seawater convection. This suggestion has recently received considerable support from the discovery of massive sulphide mounds (Francheteau *et al.*, 1979) and turbulent, buoyant plumes of hot water at 380°C ± 30°C precipitating sulphides at 21°N on the East Pacific Rise (Spiess *et al.*, 1980).

The geometry of circulatory flow in the ophiolitic sequence of Cyprus appears to have consisted of axially symmetric cells containing central plumes of hot ascending fluid which were positionally fixed through time with respect to enclosing rock. Parmentier and Spooner (1978) have modeled such hydrothermal circulation by finite difference approximations. Fluid inclusion studies and theoretical models suggest that the principal factors which caused localized ore deposition were surface and near-surface cooling due to mixing, and conductive heat loss.

The possible effects of subduction of compositionally modified oceanic crust on the generation of magmas and associated mineral deposits at convergent plate boundaries are clear. For example, large quantities of reduced seawater sulphate, in association with hydroxyl and chloride, could be added to oceanic crust by seawater/rock interaction at ridges. Release of water from the descending slab at subduction zones might then cause wet melting of mantle material and could produce volatile rich siliceous magmas enriched in chloride and sulphur. Such a simple model could explain the amounts of magmatically released water, chlorine and sulphur required for the formation of porphyry Cu ± Mo ± Au deposits spatially associated with calc-alkaline intrusive rocks.

## RÉSUMÉ

Une des principales découvertes au cours des dernières années sur le comportement physique et chimique de la terre solide et des océans a été l'échelle du phénomène de circulation par convection de l'eau de mer dans les 3 à 5 km supérieurs de la croûte océanique le long des crêtes en expansion. L'analyse de l'écart entre le flux thermique convectif observé et celui qu'on prédit sur la base d'un modèle de refroidissement par convection uniquement suggère que la masse totale de l'océan peut circuler dans la croûte basaltique de l'océan le long des crêtes une fois tous les 3 à 10 Ma.

Un point important concernant la circulation hydrothermale qui a ressorti des études sur les roches ophiolitiques est que la formation de dépôts de minerais de pyrite cuprifère d'importance économique (sur terre) semble être un effet secondaire naturel de la convection de l'eau de mer. Cette suggestion a récemment reçu un support considérable par la découverte de monticules de sulfures massifs dans le glacis continental de l'est du Pacifique (Francheteau *et al.*, 1979).

La géométrie de l'écoulement circulatoire dans la séquence ophiolitique de Chypre semble avoir consisté en cellules axialement symétriques contenant en leur centre des panaches de fluide chaud ascendant dont la position s'est fixée au cours du temps par rapport à la roche encaissante. Parmentier et Spooner (1978) ont modelé une telle circulation hydrothermale à l'aide d'approximations par différences finies. Les études sur les inclusions fluides et les modèles théoriques suggèrent que les principaux facteurs qui sont responsables du dépôt localisé de minerai ont été le refroidissement en surface et près de la surface par mélange et la perte de chaleur par conduction.

On voit clairement les effets possibles de la subduction de la croûte océanique dont la composition a été modifiée sur la génération des magmas et des dépôts minéraux associés aux limites de plaques convergentes. Par exemple, de grandes quantités de sulfates d'eau de mer réduits, en association avec les chlorures et les groupes hydroxyles, pourraient s'ajouter à la croûte océanique par l'interaction eau de mer/roche le long des crêtes. La libération de l'eau provenant d'une plaque descendante dans les zones de subduction pourrait alors causer la fusion humide du matériel du manteau et ainsi produire des magmas siliceux riches en volatiles et enrichies en chlorures et en soufre. Un tel modèle simple pourrait expliquer les quantités d'eau, de chlore et de soufre libérées du magma qui sont requises pour la formation des dépôts porphyriques de Cu ± Mo ± Au associés dans l'espace avec les roches intrusives calco-alcalines.


## INTRODUCTION

One of the major discoveries of recent years about the physical and chemical behaviour of the solid earth and the oceans is the scale of the phenomenon of convective seawater circulation within the upper 3 to 5 km of the oceanic crust at spreading ridges (Lister, 1972; Spooner and Fyfe, 1973; Williams *et al.*, 1974; Wolery and Sleep, 1976; Anderson *et al.*, 1979). Analysis of the discrepancy between observed conductive heat flow and that predicted on the basis of a purely conductive cooling model (the "heat flow anomaly") suggests convective removal of about $50 \times 10^{18}$ cal/yr (Sleep and Wolery, 1978). This is equivalent to about 16% of the Earth's total heat loss of $32 \times 10^{19}$ cal/yr, as estimated by Williams and Von Herzen (1974). The estimate implies that the total ocean mass ($1.41 \times 10^{24}$g) may circulate through basaltic oceanic crust at spreading ridges once every 3 to 10 Ma, for an average hot water discharge temperature between 100°C and 300°C (mass fluxes from Sleep and Wolery, 1978). Fluid inclusion data obtained from identified discharge zones in the Upper-Cretaceous ophiolitic complex of Troodos, Cyprus suggest that 300°C is a reasonable

s sur le comportement physi-
hénomène de circulation par
océanique le long des crêtes
ectif observé et celui qu'on
uniquement suggère que la
océan le long des crêtes une

qui a ressorti des études sur
ninerais de pyrite cuprifère
é naturel de la convection de
dérable par la découverte de
u Pacifique (Francheteau *et*

hiolitique de Chypre semble
eur centre des panaches de
emps par rapport à la roche
circulation hydrothermale à
inclusions fluides et les mo-
sponsables du dépôt localisé
e par mélange et la perte de

a croûte océanique dont la
pôts minéraux associés aux
és de sulfates d'eau de mer
es, pourraient s'ajouter à la
ètes. La libération de l'eau
on pourrait alors causer la
s siliceux riches en volatiles
rait expliquer les quantités
pour la formation des dépôts
s intrusives calco-alcalines.

e physical and chemical
of the phenomenon of
of the oceanic crust at
iams *et al.*, 1974; Wolery
pancy between observed
urely conductive cooling
oval of about $50 \times 10^{18}$
16% of the Earth's total
Von Herzen (1974). The
circulate through basaltic
or an average hot water
from Sleep and Wolery,
rge zones in the Upper-
hat 300°C is a reasonable



figure (Spooner and Bray, 1977) and that, therefore, an estimate for the mean recirculation time of 10 Ma is likewise reasonable.

In a geological conceptual framework 10 Ma is, of course, a relatively short length of time. It implies that the total present ocean mass may have circulated through oceanic crust at least 400 times in the last 4000 Ma. Assuming that there is some relationship between the amount of convective heat transfer and total heat production, the mean recirculation time may have been about 3 Ma in early Archean time (3500 Ma ago). As noted by Fryer *et al.* (1979), it appears that a significant amount of intrusion of plutonic granitoids occurred in the submarine environment in the Archean, rather than in sub-aerial continental crust as at present. This effect may have lowered the recirculation time further.

Marked complementary chemical changes occur during basalt/seawater interaction at elevated temperatures (e.g., Mottl and Holland, 1978). Hence, compositionally modified oceanic crust returns to the mantle in subduction zones. The nature of these various phenomena and their implications with respect to the chemical composition and evolution of the oceans, the oceanic crust, the mantle and the continental crust are gradually beginning to be detected and appreciated (e.g., Wolery and Sleep, 1976). For example, Spooner (1976) developed and tested a possible quantitative model to explain the isotopic composition of strontium dissolved in ocean water. It involved a balance between strontium delivered by continental runoff and strontium derived from the oceanic crust by exchange during hydrothermal convection.

A side effect of fluid mass transfer associated with convective heat transfer at oceanic ridges appears to be the formation of sulphide mineral deposits. The suggestion that the oceanic crust might contain sulphide deposits was first made simply on the basis of an empirical comparison between ophiolitic complexes and the oceanic crust (Sillitoe, 1972; Spooner and Fyfe, 1973). The speculative hypothesis that such ore deposits may have been formed during seawater convection (Spooner and Fyfe, 1973) has been tested geochemically in some detail, and has essentially been validated (e.g., Spooner, 1977; Heaton and Sheppard, 1977; Spooner and Bray, 1977; Chapman and Spooner, 1977; Spooner *et al.*, 1977; Parmentier and Spooner, 1978). Similarly, the prediction that massive sulphide mineral deposits should be found actively forming on, and within, oceanic spreading ridges has recently been vindicated, firstly, by the discovery of fine grained sulphide mounds up to 10 m high on the East Pacific Rise about 240 km south of the entrance to the Gulf of California, with no associated active hot water discharge (Francheteau *et al.*, 1979), and, secondly, by the discovery recently announced (May 4, 1979) by the U.S. National Geographic Society of discharge of very hot water (300°C - 400°C) associated with mineral deposition in the same general area.

Spiess *et al.*, (1980) have now described the latter discovery in greater detail. Turbulent, conical plumes of very hot water at 380°C ± 30°C have been observed discharging at velocities of several metres/sec. from "chimneys" 1 - 5 m high and as much as 30 cm in diameter. The buoyant jets, referred to as "smokers", appear black because of entrained particles consisting mainly of aggregates of hexagonal pyrrhotite platelets, typically 20$\mu$ across, together with lesser amounts of pyrite, sphalerite and Cu-Fe sulphides. The chimneys occur on sulphide mounds having typical lateral dimensions of 15 x 30 m. Both consist mainly of pyrite-chalcopyrite-sphalerite, with minor amounts of such Fe-Cu-Zn sulphides as pyrrhotite, marcasite, wurtzite, bornite, cubanite and chalcocite. Ca, Ba sulphates (anhydrite, gypsum and barite), talc, amorphous silica and secondary iron hydroxyoxides (goethite, limonite) have also been identified.

## SEAWATER INTERACTION DURING DOWN-FLOW

Much information supporting the general hypothesis of seawater circulation within oceanic crust has now been obtained from the examination of ophiolitic complexes. For example, clear evidence for water/rock interaction is found in the non-isochemical, hydrothermal metamorphism of ocean-floor origin which has been reported from ophiolitic assemblages in Cyprus (Gass and Smewing, 1973; Spooner *et al.*, 1977), Newfoundland (Williams and Malpas, 1972; Coish, 1977), E. Liguria, Italy (Spooner and Fyfe, 1973), S. Chile (Stern *et al.*, 1976) and Taiwan (Liou and Ernst, 1979). Metamorphic mineral assemblages of the zeolite to amphibolite facies, which pseudomorph original igneous textures and which also occur as open-space fillings, have been observed in metabasic pillow lavas, metadolerite sheeted dykes and the upper parts of layered plutonic sequences. The use of isotopes (H/D; $^{13}C/^{12}C$; $^{18}O/^{16}O$; $^{87}Sr/^{86}Sr$) as geochemical tracers has confirmed that the interacting fluid was of seawater origin (Spooner *et al.*, 1974; Heaton and Sheppard, 1977; Spooner *et al.*, 1977).

*Example 1.* Zeolite to amphibolite facies metabasic rocks from the Troodos Massif, Cyprus are variably enriched in $^{87}Sr$ relative to fresh analogues (Spooner *et al.*, 1977). Initial $^{87}Sr/^{86}Sr$ ratios as high as $0.70760 \pm 0.00003$, for an interstitial zeolite sample, and 0.7069, for a metabasic rock, have been recorded. These compare with low values obtained for fresh gabbroic rocks of $0.70338 \pm 0.00010$ to $0.70365 \pm 0.00005$. Upper Cretaceous seawater, with a ratio of about 0.7076, was the only reasonable contaminant (Spooner *et al.*, 1977).

*Example 2.* Relative to a $\delta^{18}O$ value of about 6‰ for fresh basaltic rocks, the hydrothermally metamorphosed rocks of Cyprus show strong oxygen isotopic modifications which change from relative $^{18}O$ enrichments in the upper part of the sequence (e.g., + 12.40‰) to relative $^{18}O$ depletions in the lower part of the sequence (e.g., + 3.31‰). These changes indicate interaction with large volumes of hot water and are consistent with interaction with heated seawater (Spooner *et al.*, 1974).

*Example 3.* Heaton and Sheppard (1977) have shown that the isotopic composition of hydrogen in water in equilibrium with chlorite and amphibole samples from metadolerite dykes and metagabbros from Cyprus was indistinguishable from that of seawater.

Calculations based on the degree of oxidation of the basaltic rocks suggest that the bulk integrated water/rock ratio may have been as much as $10^3$:1 (Spooner *et al.*, 1977). In Cyprus, the degree of hydration decreases in the upper part of the plutonic sequence. This observation suggests that the depth of seawater penetration and circulation was about 2 to 3 km. Comparison of compressional wave velocities, shear wave velocities and Poisson's ratios measured at 1 kb for a variety of altered and fresh arcasite, wurtzite, bornite, gypsum and barite), talc, ethite, limonite) have also

WN-FLOW

is of seawater circulation nination of ophiolitic com- action is found in the non- origin which has been re- mewing, 1973; Spooner *et* sh, 1977), E. Liguria, Italy 1 Taiwan (Liou and Ernst, amphibolite facies, which cur as open-space fillings, rite sheeted dykes and the pes (H/D; $^{13}C/^{12}C$; $^{18}O/^{16}O$; e interacting fluid was of ard, 1977; Spooner *et al.*,

rocks from the Troodos h analogues (Spooner *et al.*, 3, for an interstitial zeolite orded. These compare with 8 ± 0.00010 to 0.70365 ± bout 0.7076, was the only

or fresh basaltic rocks, the ong oxygen isotopic modifi- upper part of the sequence art of the sequence (e.g., + olumes of hot water and are er *et al.*, 1974).

n that the isotopic composi- nd amphibole samples from distinguishable from that of

asaltic rocks suggest that the ch as $10^3$:1 (Spooner *et al.*, e upper part of the plutonic f seawater penetration and sional wave velocities, shear a variety of altered and fresh



ophiolitic lithologies with model profiles for in situ oceanic crust (Christensen, 1978) suggest that the equivalent penetration depth in "average" oceanic crust may be about 3 to 5 km.

## THE VOLCANOGENIC CUPRIFEROUS PYRITE ORE DEPOSITS

Whereas hydrothermal metamorphism occurred during in-flow and through-flow of seawater, it appears that, in Cyprus, sulphide ore deposits formed at the positions of discharge. In general terms these deposits consist of a lens of massive ore underlain by

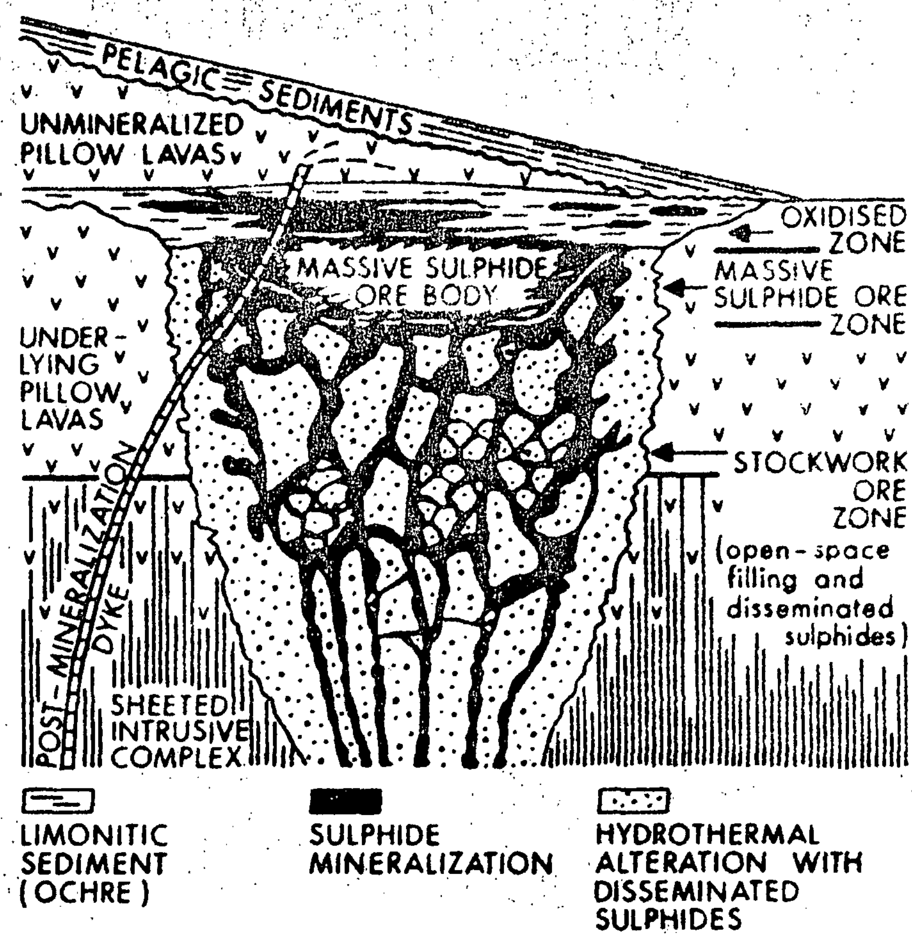



**Figure 1.** Schematic diagram of an ophiolitic (Cyprus-type) volcanogenic sulphide ore deposit (modified after Hutchinson and Searle, 1971).

The section shows the surficially oxidized massive pyritic lens, which is intercalated within the metabasic pillow lavas, the underlying pipe-shaped stockwork of hydrothermally metamorphosed and mineralized material which extends down into the dyke complex, and the fact that the sulphide ore bodies are usually overlain by unmineralized basaltic pillow lavas, which are in turn overlain by pelagic marine sediments.

an approximately pipe-shaped stockwork (Fig. 1). The massive ore consists of a porous, crudely colloform-textured mass of fine-grained pyrite and chalcopyrite, with accessory quantities of marcasite, sphalerite and galena. The voids in the massive ore are frequently partially filled with fine-grained, sooty pyrite. The lenses occur intercalated within the pillow lava sequence and their attitudes are conformable with the local stratigraphy. (Description summarized from Hutchinson and Searle, 1971: Constantinou and Govett, 1973.) A large lens, for example that at Skouriotissa, had a maximum thickness of about 50 m, and was approximately elliptical in plan (long axis about 500 m; short axis about 350 m) (Constantinou and Govett, 1973). It contained pre-production ore reserves of about 6 million tonnes at 2.3% Cu (Bear, 1963). An important point is that the evidence suggests that this massive ore actually formed *on* the ocean floor since it does not replace pre-existing rock, can show alteration near the top to a goethitic material (ochre), which has been interpreted as a submarine weathering product of ore (Constantinou and Govett, 1972), and is itself overlain either by unmineralized deep-water marine sediments, or by unmineralized pillow lavas which are, in turn, overlain by pelagic sediments (Robertson, 1975).

Stockworks, which occur beneath massive ore and which were clearly feeder zones, consist of highly altered and mineralized material of basaltic origin. Mineralization occurs as veins, veinlets and disseminated impregnations of sulphides. The alteration silicate mineralogy of the reconstituted pillow lava consists of quartz-chlorite-illite-sphene. Uneconomic alteration pipes characterized by pyritization penetrate 1 to 2 km down into the ophiolitic sequence. Stockworks are normally elliptical in plan. A good idea of dimensions is provided by the Limni deposit in western Cyprus, which has a long axis of about 800 m and a short axis of about 400 m (Trennery and Pocock, 1972; Adamides, 1975). This deposit contained pre-production reserves of around 4 million tonnes at 1.37% Cu (Bear, 1963) and has proved to be economically exploitable for about 200 m below the original ocean floor

Approximately 20 significant sulphide ore deposits have been mined in Cyprus. Along the 80 km long continuous northern pillow lava outcrop, 15 deposits occur in an imperfectly regular distribution (Fig. 2) which is characterized by a half-spacing of 2.6

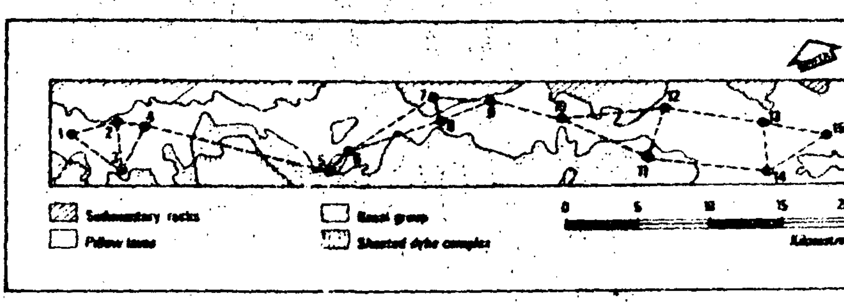
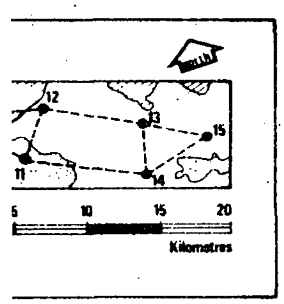



Figure 2. The imperfectly regular distribution of 15 cupriferous pyrite ore deposits along the northern pillow lava outcrop of the Troodos ophiolitic complex, Cyprus. The average of the 21 inter-ore deposit half-spacings is $2.6 \pm 1.4$ km (1 standard deviation).

1, Mavrovouni; 2, Lefka; 3, Apliki; 4, Skouriotissa; 5, Alestos; 6, Memi; 7, Kokkinoyia; 8, Kokkinopezoula; 9, Agrokipia; 10, Klirou district; 11, Kapedhes; 12, Kambia; 13, Mathiati; 14, Lythrodondha; 15, Sha.

nassive ore consists of a
·ite and chalcopyrite, with
e voids in the massive ore
. The lenses occur interca-
:onformable with the local
nd Searle, 1971; Constan-
ouriotissa, had a maximum
ı plan (long axis about 500
1973). It contained pre-
3% Cu (Bear, 1963). An
ve ore actually formed *on*
n show alteration near the
d as a submarine weather-
s itself overlain either by
ralized pillow lavas which
75).
which were clearly feeder
basaltic origin. Mineraliza-
ations of sulphides. The
lava consists of quartz-
acterized by pyritization
Stockworks are normally
by the Limni deposit in
short axis of about 400 m
contained pre-production
63) and has proved to be
al ocean floor.
ve been mined in Cyprus.
op, 15 deposits occur in an
ed by a half-spacing of 2.6




pyrite ore deposits along the
yprus. The average of the 21
n).
;, 6, Memi; 7, Kokkinoyia; 8,
12, Kambia; 13, Mathiati; 14,



**TABLE I**
**PRE-PRODUCTION RESERVES AND GRADES OF OPHIOLITIC AND OTHER VOLCANOGENIC MASSIVE SULPHIDE ORE DEPOSITS**

| Mine | Pre-production reserves (million tons) | Cu (%) | S (%) | Zn (%) | Pb (%) | Ag (ppm) | Au (ppm) | Source |
|---|---|---|---|---|---|---|---|---|
| Mavrovouni; Cyprus | 15 | 4 | 47 | 0.5 | — | 39 | 0.3 | Bear (1963) |
| Skouriotissa; Cyprus | 6 | 2.3 | 48 | 0.06 | — | — | — | Bear (1963) |
| Kalavasos; Cyprus | 2.3 | 1.5 | 33 | 0.7 | 0.01 | 5.7 | 1.6 | Bear (1963) |
| Limni; Cyprus | 4 | 1.4 | — | 0.29* | — | 2.7* | 0.51* | Bear (1963) *Trennery and Pocock (1972) |
| Lasail, Aarja, Bayda; Oman | 15 | 2.1 | — | — | — | — | — | Mining Journal, 22 July 1977, p. 63. |
| York Harbour; Newfoundland (ophiolitic) | 0.28 | 1.92 | — | 4.67 | — | — | — | Duke and Hutchinson (1974) |
| Arithmetic average Precambrian volcanogenic massive sulphide deposit in the Canadian Shield (n = 110) | 6.9 | 1.9 | — | 4.6 | (90% <1%) | 45 | 0.84 | Boldy (1977) *Sangster (1977) |
| Japanese Kuroko deposits (ave. 1976 production) | 2-35† | 2.0 | — | 4.2 | 1.3 | 63 | 0.7 | Hashimoto (1977) |

— indicates no data available to author.
† Range of pre-production reserves for Kuroko deposits (Lambert and Sato, 1974).

km ± 1.4 km (1 standard deviation; 28 inter-ore deposit measurements; Spooner, 1977).

In Cyprus, ophiolitic sulphide deposits have been worked principally for copper and for high-quality non-arsenical pyrite suitable for the manufacture of sulphuric acid (e.g., Spooner, 1975). Minor amounts of gold and silver have been produced from veins of "Devil's Mud" which occur in the flamboyant gossans (Bear, 1963). Examples of pre-production commercial reserves and grades of some attractive ophiolitic sulphide deposits in Cyprus and Oman are given in Table 1, together with comparative data for the small York Harbour ophiolitic deposit in Newfoundland, for Precambrian volcanogenic massive sulphide deposits in the Canadian Shield and for the Kuroko deposits of Japan.

Total pre-production reserve tonnages can be as high as 15 million tonnes (e.g., Mavrovouni). The average for eleven deposits in Cyprus listed by Bear (1963) and Constantinou and Govett (1973) is 3.6 ± 4.0 (1 standard deviation) million tonnes. This is similar to normal Kuroko type deposits (e.g., 2 to 35 million tonnes for those in Japan) and Precambrian volcanogenic massive sulphide deposits (e.g., an average of 6.9 million tonnes for 110 deposits in the Canadian Shield; Boldy, 1977). The copper contents of the ophiolitic deposits of Cyprus vary widely, ranging from low values (e.g., 0.24% Cu for Mathiati; Constantinou and Govett, 1973) to as much as 4% Cu (Mavrovouni). Zinc and lead contents in economic, not geochemical, terms are characteristically low for ophiolitic deposits (e.g., Table 1, Zn = 0.06% to 0.7%; Pb = 0.01%), in comparison wtih Kuroko and Precambrian deposits. An exception is the York Harbour, Newfoundland, deposit which contains 4.67% Zn. However, an important, but generally unremarked, characteristic of ophiolitic deposits is that they can contain quite significant concentrations of silver and gold. For example, Mavrovouni ore contained 39 g/tonne silver, which is comparable to the average 1976 Kuroko production grade (63 g/tonne) and the average Canadian Precambrian volcanogenic massive sulphide deposit (45 g/tonne). Kalavasos (Cyprus) ore contained 1.6 g/tonne gold, which exceeds both the average 1976 Kuroko production grade (0.7 g/tonne) and the average Canadian Precambrian volcanogenic massive sulphide deposit grade (0.84 g/tonne).

In on-land economic terms, the massive sulphide deposits recently discovered on the East Pacific Rise, 240 km south of the mouth of the Gulf of California (Francheteau *et al.*, 1979), are simply minor showings. They consist of partially hollow, sponge-like mounds up to 10 m high which are aligned along faults subparallel to the spreading axis. Active hot spring discharge has ceased, and the sulphide material is oxidizing to red, yellow, and brown amorphous iron hydroxyoxides (cf. ochre) and yellow native sulphur. The primary sulphide mineral assemblage consists mainly of sphalerite and pyrite with minor chalcopyrite and marcasite. Analysis of four small sulphide samples (26.5 g to 90.7 g) reveals both pyrite rich (14.9% to 29.6% Fe) and sphalerite rich (23 to 28.7% Zn) types with higher copper concentrations (0.2% to 6% Cu). Hence, this material shows chemical and mineralogical similarities to that from ophiolitic deposits.

## SEAWATER DISCHARGE DURING MINERALIZATION

The hypothesis of metal leaching and transport in convecting hot seawater (see Fig. 3), which was speculatively proposed to account for the formation of ophiolitic massive sulphide ore deposits (Spooner and Fyfe, 1973), has been tested by geochemical methods. Examination of fluid inclusion properties and the hydrogen, oxygen and strontium isotopic composition of mineralized material has revealed no evidence for a component of the hydrothermal fluid which was *not* of seawater origin (Spooner and Bray, 1977; Heaton and Sheppard, 1977; Chapman and Spooner, 1977; Spooner, 1977).

*Example 1.* Microthermometric examination of fluid inclusions in ore material from Cyprus has shown that samples of the ore forming fluid trapped in small cavities in quartz intergrown with sulphides have a freezing point indistinguishable from that of seawater. A mean fluid inclusion freezing point of $-1.9°C \pm 0.3°C$ (1 standard deviation) was obtained from 273 measurements from four mineralized localities (Spooner, in prep.; updated from Spooner and Bray, 1977). This freezing point is statistically identical to that of ordinary seawater. Since the freezing point of a solution is a reflection of its salinity, this information indicates a close similarity in bulk composition between the hydrothermal fluid, which was at temperatures between 300°C and 350°C (Spooner and Bray, 1977), and normal seawater.

*Example 2* Mineralized material from four deposits in Cyprus is significantly enriched in $^{87}Sr$ (Chapman and Spooner, 1977). Initial $^{87}Sr/^{86}Sr$ ratios as high as, but not higher than, upper Cretaceous seawater have been recorded (e.g., $0.7075 \pm 0.0002$).

*Example 3* The hydrogen isotope composition of the hydrothermal fluid has been shown to have been essentially the same as that of seawater (Heaton and Sheppard, 1977).

## THE NATURE OF THE CONVECTIVE PROCESS IN THE OPHIOLITIC ROCKS OF THE TROODOS MASSIF, CYPRUS

The evidence summarized above successfully traces the complete cycle of seawater circulation (Fig. 3). Several deductions can now be made about the nature of the convective process which occurred in the ophiolitic rocks of Cyprus. Although it is uncertain how representative of oceanic crust the Troodos complex is and, for that matter, how variable the oceanic crust itself is, some of these points may be relevant to an understanding of convective heat and mass transfer within spreading ridges.

1) As shown diagrammatically in Figure 3, the first-order geometry of circulatory flow appears to have consisted of axially symmetric cells containing central plumes of hot ascending fluid which were positionally fixed through time with respect to enclosing rock but not, therefore, with respect to the spreading axis (Spooner, 1977; Parmentier and Spooner, 1978). The explanation for this pattern is uncertain. It could either be a reflection of some periodicity in the distribution of discrete magma intrusions within the spreading ridge, or it might be a natural pattern of convection in a quasi-uniformly heated, unconfined, permeable layer. The latter explanation would appear less likely, however, since the geometry of flow would probably reflect the decrease in basal heat flow away from a ridge axis. It would then consist of linear two-dimensional rolls sub-parallel to the axis.

2) The distribution of major plumes, as deduced from the arrangement of the major

ore desposits in Cyprus, was imperfectly regular in a direction normal to the original spreading axis, and was characterized by a half-spacing (2.6 ± 1.4 km) comparable to the thickness of the permeable layer (2 to 3 km) (Spooner, 1977; Fig. 2).

3) In Cyprus, ore deposits are frequently cross-cut by unmineralized dykes and/or overlain by unmineralized pillow lavas (Fig. 1). This suggests that formation of the ore deposits occurred *within* the volcanically active zone at a spreading ridge. For a half-width of about 6 km and a spreading rate of about 5 cm/yr, the ore desposits may, therefore, have formed in a time on the order of $10^5$ years (Spooner, 1977). The mean internal upward flow rate may have been about $10^{-6}$ g/cm$^2$/s (Spooner, 1977). Later finite difference calculations have shown this rate to be reasonable (Parmentier and Spooner, 1978).

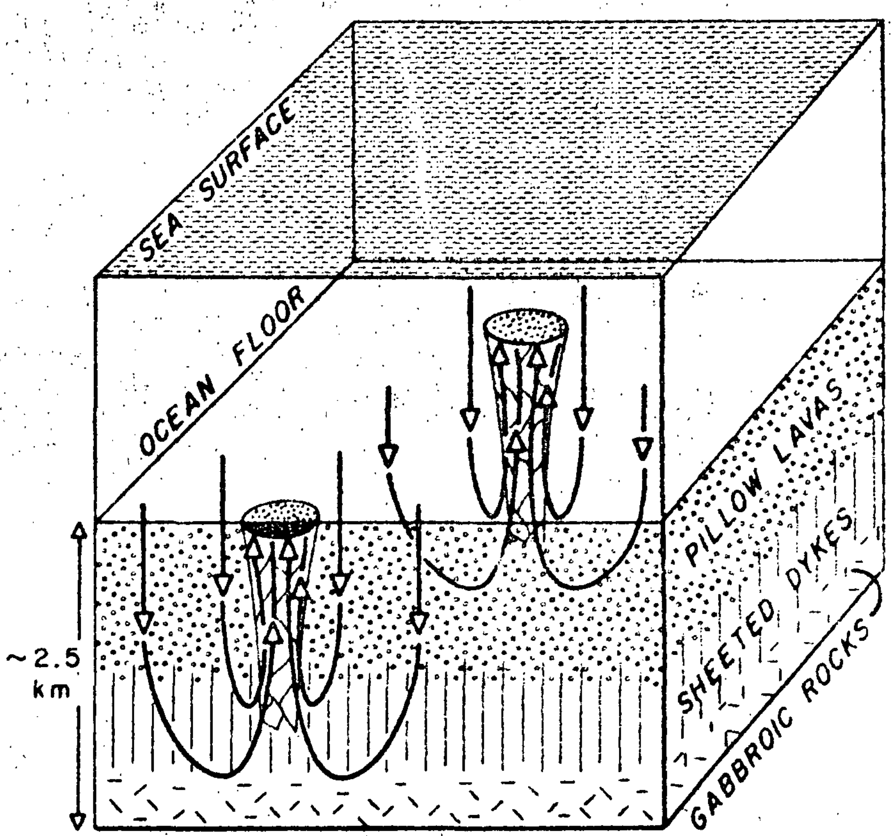
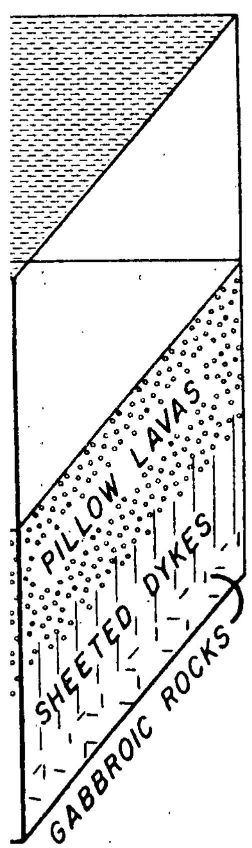



**Figure 3.** Schematic three-dimensional diagram of the geologically inferred mode of hydrothermal convection, metamorphism and mineralization within the upper Cretaceous ophiolitic sequence of the Troodos Massif, Cyprus.

*General metamorphism* is thought to have occurred in the zones of recharge flow, whereas the cupriferous pyrite ore deposits are thought to have formed at the positions of discharge of approximately axially symmetric plumes of rising hot fluid of sea water origin.

ı normal to the original
1.4 km) comparable to
977; Fig. 2).
ineralized dykes and/or
hat formation of the ore
spreading ridge. For a
the ore desposits may,
ɔoner, 1977). The mean
(Spooner, 1977). Later
ɔnable (Parmentier and




ɛrred mode of hydrothermal
aceous ophiolitic sequence

s of recharge flow, whereas
ıe positions of discharge of
vater origin.



4) The depth of the original ocean above the permeable oceanic crust has been derived from the filling temperatures of fluid inclusions which homogenize into the liquid phase, and which co-exist with aqueous inclusions homogenizing into the gaseous phase. This evidence indicates that boiling occurred during mineral deposition (Spooner, in prep.). The inclusions were found in quartz from quartz-sulphide veins within the high-level Mathiati stockwork, and were located only about 5 m below the original ocean floor, as indicated by the presence of massive ore. The equilibrium pressure for boiling at a measured temperature for a measured composition has been determined as 250 ± 30 bars. This is equivalent to an original ocean depth of 2.5 ± 0.3 km. This deduction is very reasonable, since the elevations of spreading ridge axes are typically between −2 km and −4 km.

5) Using the ocean depth discussed above and estimates of stratigraphic depth, fluid inclusion filling temperatures may be pressure corrected to yield mineralization temperatures (Spooner, in prep.). Data from four mineralized localities in Cyprus are presented in Table II.

Except for information from the Mathiati mine, which applies to the near-surface cooling and mixing environment, the data suggest that the temperature of the rising plume, as defined by the range of mean ± standard deviation values for the three other stockworks, was about 300°C to 370°C. This range is in good agreement with a value of 300°C estimated for the temperature of last equilibrium with quartz of end-member hydrothermal fluid from the Galapagos Ridge axis (Edmond, 1978), is consistent with a maximum value of 285°C estimated by Crane and Normark (1977) for hydrothermal activity on the East Pacific Rise at 21°N and corresponds closely with the discharge temperatures of 380°C ± 30°C measured at 21°N on the East Pacific Rise (Spiess *et al.*, 1980).

**TABLE II**

Trapping temperatures (pressure corrected filling temperatures) for fluid inclusions from ophiolitic sulphide ore deposits in Cyprus (Spooner, in prep.)

| Locality | Range (°C) | Arithmetic Mean (°C), standard deviation and number of measurements | Mode(s) (°C) |
|---|---|---|---|
| Mathiati Mine (very high level stockwork) | 212 - 321; 109 | 286 ± 22 (93) | 298 |
| Limni Mine (high level stockwork) | 283 - 372; 89 | 320 ± 18 (95) | 325 |
| Limni Mine; Mineralized Basal Group (deep stockwork) | 271 - 368; 97 | 336 ± 19 (80) | 341 |
| Alestos Mine (deep stockwork) | (274) 323 - 394; 71 | 352 ± 21 (61) | 335 and 370 (poorly defined) |

6) The temperature immediately below massive ore was high during mineralization. Fluid inclusion studies of material from the Mathiati Mine, Cyprus and the Lasail deposit, Oman give a temperature range of 264°C to 348°C and indicate mixing with overlying cold seawater (Spooner, in prep.). These data confirm discharge of very hot seawater, and also confirm that discharge of hot seawater may be an effective heat removal mechanism (see Ribando *et al.*, 1976 for discussion).

## NUMERICAL FLUID DYNAMIC MODELLING OF CONVECTION RELEVANT TO THE ORIGIN OF THE OPHIOLITIC SULPHIDE ORE DEPOSITS OF CYPRUS

Parmentier and Spooner (1978) have carried out numerical modelling by finite difference approximations on a 21 X 21 grid of convection in a permeable layer relevant to the origin of the ophiolitic massive sulphide deposits of Cyprus (see Fig. 4). The model parameters chosen to be appropriate include a cylindrical geometry: an aspect ratio (height:radius) of 1:1, a cell top open to inward and outward flow, constant bottom heat flux and a constant upper boundary temperature. For mathematical reasons the model did *not* allow discharge of *hot* water. This assumption is known to be incorrect, but it should not affect the gross aspects of flow. It should only be relevant to boundary layer phenomena in the discharge zone. (For further mathematical and computational aspects see Parmentier and Spooner, 1978.)

A solution for a Rayleigh number of 50 was dimensionalized by choosing a cell height (radius) of 2 km, a maximum basal temperature of 450°C, derived from basal metamorphic mineral assemblages, and an upper boundary temperature of 0°C (see Fig. 4). The principal geological findings may be summarized as follows:

1) The flow geometry inferred to have existed naturally, which was characterized by axially symmetric rising plumes, was experimentally found to be stable at Rayleigh numbers of 50 and 100 for a cell aspect ratio of 1:1.

2) The overall zone of rising fluid contains a hot core which is dimensionally comparable to mineralized stockworks observed in Cyprus.

3) The water in the hot core of the rising plume remains essentially isothermal at a temperature of 350°C to 400°C for much of its upward transit. The temperature of the rising plume is in reasonable agreement with that found independently from fluid inclusion studies of deep-level stockworks (317°C to 373°C; see Table II).

4) The rising plume cools conductively only within the topmost 200 m of the permeable layer. This depth corresponds to the economically exploitable depth of mineralization within the Limni stockwork (about 200 m).

5) The upward fluid flux of the hot plume is on the order of $10^{-6}$ cm/sec. This corresponds closely to the flux estimated crudely on the basis of geochemical arguments (Spooner, 1977).

6) The model has reproduced several factors necessary for the successful formation of an economically exploitable mineral concentration. In this case, three principal factors may be identified: a dimensionally restricted hot core zone, a hot core zone which also contains the maximum fluid flux and a dimensionally restricted surface boundary layer within which cooling occurs. Thus, a theoretical volume of maximum mineralization may be defined as that volume through which fluids flowed which had been at temperatures greater than 350°C, and which cooled below a temperature of 300°C (volume 'a' in Fig. 4). The leaching and depositional threshold temperatures

high during mineraliza-
e, Cyprus and the Lasail
nd indicate mixing with
rm discharge of very hot
nay be an effective heat
1).

CTION RELEVANT TO
EPOSITS OF CYPRUS

ical modelling by finite
ermeable layer relevant
Cyprus (see Fig. 4). The
cal geometry, an aspect
outward flow, constant
ture. For mathematical
assumption is known to
flow. It should only be
(For further mathemati-
1978.)
lized by choosing a cell
0°C, derived from basal
emperature of 0°C (see
d as follows:
which was characterized
to be stable at Rayleigh

which is dimensionally

sentially isothermal at a
The temperature of the
dependently from fluid
see Table II).
topmost 200 m of the
ly exploitable depth of

er of $10^{-6}$ cm/sec. This
is of geochemical argu-

r the successful forma-
his case, three principal
zone, a hot core zone
nally restricted surface
al volume of maximum
luids flowed which had
below a temperature of
hreshold temperatures



were chosen in the light of experimental solubility work by Crerar and Barnes (1976). It can be seen that this volume ('a') is comparable in dimensions to the Limni mine stockwork (volume 'c' in Fig. 4).

7) A theoretical volume of maximum leaching may also be defined as that for which the temperature was greater than 350°C (volume 'b' in Fig. 4). This is comparable in size to a volume of basaltic material which would contain all the copper contained in the Limni deposit (volume 'd' in Fig. 4).

8) Absolute values of average permeability (0.1 millidarcies) and basal heat flux

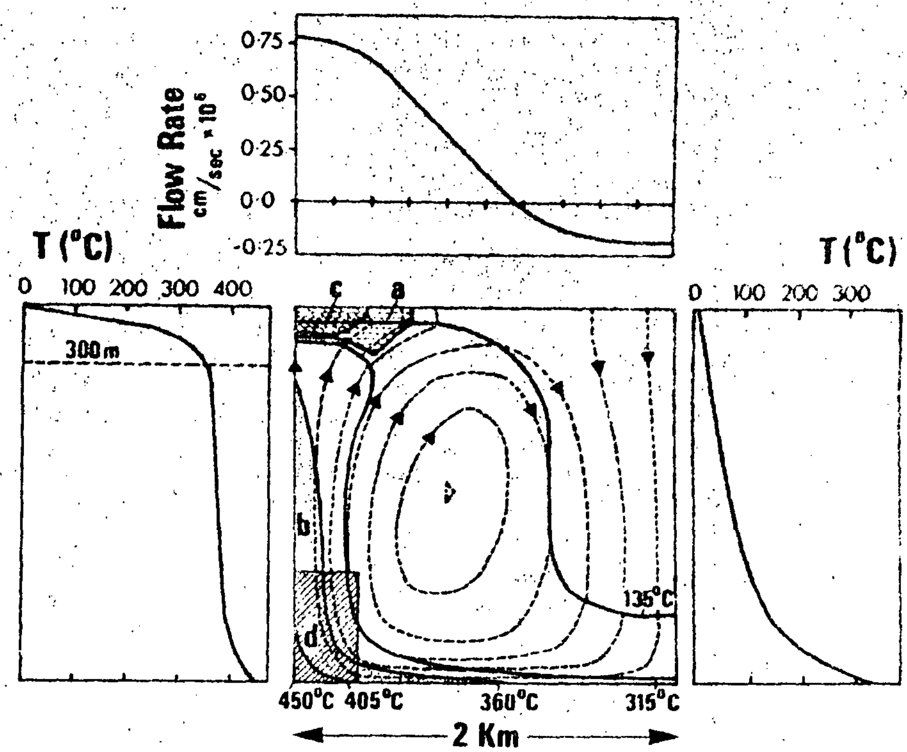



**Figure 4.** The central part of the diagram shows streamlines and isotherms for steady-state convection of aqueous fluid with temperature dependent viscosity and coefficient of thermal expansion in a permeable medium at a Rayleigh number of 50 in a cylindrical cell with an open top and a constant bottom heat flux (from Parmentier and Spooner, 1978). The solution has been dimensionalized by choosing realistic values of cell height/radius (2 km), maximum basal temperature (450°C) and upper boundary temperature (0°C).

Area a = a theoretical volume of most intense mineralization. Area b = a theoretical volume of maximum leaching. Area c = approximate dimensions of the Limni mine stockwork. Area d = approximate volume of basalt which would contain the copper contained in the Limni ore deposit. (For further discussion see text.)

Temperature profiles along the vertical boundaries of the cell are shown on the left- and right-hand sides of the central diagram, and the vertical flow rate through the open upper boundary is shown above the central diagram.

(50.4 HFU) obtained by dimensionalizing the model are reasonable (Parmentier and Spooner, 1978).

In conclusion, it can be stated on the basis of the above discussion that a seawater convection model for the origin of the ophiolitic sulphide deposits, which had already been shown to be qualitatively reasonable, has also been shown to be semi-quantitatively satisfactory.

## THE MECHANISM OF SULPHIDE ORE PRECIPITATION

By combining information from the fluid dynamic modeling discussed above with results from microthermometric examination of fluid inclusions in material immediately below massive ore in Cyprus (Mathiati deposit) and Oman (Lasail deposit) (Spooner, in prep.), it is possible to begin to discuss the actual mechanism of mineral precipitation both below and on the original ocean floor.

### Conductive Cooling

The fluid dynamic model (Fig. 4) indicates that strong conductive cooling may start within 200 m to 300 m of the seawater/rock interface. This is the approximate maximum depth of the economically exploitable Limni stockwork. Microthermometric examination of fluid inclusions in this stockwork shows that inferred trapping temperatures have a well-defined symmetrical statistical distribution with a low coefficient of variation of only 6% and an arithmetic mean of 320°C (see Table II). This type of distribution, which exhibits no negative skewness, is consistent with conductive cooling without significant mixing with variable quantities of cooler, overlying seawater. The information suggests, therefore, that the principal factor in mineral precipitation in the deeper parts of stockworks was simple conductive cooling.

### Cooling by Mixing

If the effect of dilution on precipitation is outweighed by the effect of cooling by mixing on solubility, then it is possible for temperature decrease induced by mixing with a cooler fluid to be an effective mechanism for exceeding mineral solubility products. This can be demonstrated by using data on copper solubility in equilibrium with the sulphide assemblage chalcopyrite-pyrite-bornite at 350°C and 250°C, in near-neutral solutions of 1.0 molal chloride ion content (Crerar and Barnes, 1976). Between 350°C and 250°C, the copper concentration of the solution drops by two orders of magnitude, from about 1000 ppm to about 10 ppm. It is possible to lower the temperature of a fluid from 350°C to 250°C by mixing with 0°C seawater in the ratio of 1:0.4. While dilution alone would lower the copper concentration to 714 ppm, the temperature drop would lower it to 10 ppm. Hence, it can be seen that the effect of temperature decrease on solubility far outweighs the counteracting effect of dilution; therefore, cooling by mixing can be a very effective precipitation mechanism. It is worth noting that the temperatures discussed above are *exactly* those which fluid inclusion studies have shown to have occurred during formation of the ophiolitic sulphide ore deposits of Cyprus.

That this mechanism does occur is shown by the fact that volcaniclastic sediments in a bay of the island of Vulcano in the Tyrrhenian Sea are being actively cemented by reasonable (Parmentier and

ve discussion that a seawater
deposits, which had already
been shown to be semi-

RECIPITATION

deling discussed above with
inclusions in material im-
) and Oman (Lasail deposit)
actual mechanism of mineral

ng conductive cooling may
ce. This is the approximate
ockwork. Microthermomet-
hows that inferred trapping
distribution with a low coef-
20°C (see Table II). This type
consistent with conductive
s of cooler, overlying seawa-
l factor in mineral precipita-
uctive cooling.

d by the effect of cooling by
decrease induced by mixing
xceeding mineral solubility
per solubility in equilibrium
at 350°C and 250°C, in near-
and Barnes, 1976). Between
ion drops by two orders of
ssible to lower the tempera-
awater in the ratio of 1:0.4.
to 714 ppm, the temperature
at the effect of temperature
effect of dilution; therefore,
echanism. It is worth noting
which fluid inclusion studies
iolitic sulphide ore deposits

hat volcaniclastic sediments
being actively cemented by



pyrite and marcasite in shallow water submarine fumaroles (Honnorez *et al.*, 1973). The recent observations on the chemistry and temperature of hot springs on the Galapagos spreading ridge (Edmond, 1978) provide similar evidence of mixing. Although measured discharge temperatures only rise as high as 17°C (15°C above ambient), it can be calculated from the point of intersection of the dissolved silica temperature dilution line with the quartz solubility curve that the end-member hydrothermal fluid was at a temperature of at least 300°C. Two other important points in this study are, firstly, that mixing with overlying seawater can occur *below* the ocean floor in hot spring regions and, secondly, that despite the extreme dilution with oxygenated ocean water, the warm water still contains dissolved reduced sulphur species. The latter are metabolized by sulphide oxidizing bacteria which form the base of a complex ocean-bottom food chain with essentially no connections to the photic zone (Corliss and Ballard, 1977).

Microthermometric determination of fluid inclusion filling temperatures and freezing points in material immediately below massive sulphide ore indicates that shallow sub-surface mixing also occurred during formation of ophiolitic sulphide deposits. In the Mathiati deposit (Cyprus), the distribution of fluid inclusion filling temperatures shows a pronounced negative skewness (Pearson measure of skewness derived from data in Table II is − 0.55), with values as low as 212°C relative to a modal value of 298°C. A similar relationship, combined with a drop in salinity from high values produced by boiling, has also been detected immediately below massive sulphide ore in the Lasail deposit, Oman (Spooner, in prep.).

Hence, cooling caused by mixing of hot hydrothermal fluid with cold seawater combined with pH increase caused precipitation immediately beneath the original seawater/basalt interface, in the upper parts of stockworks and, especially, during discharge into overlying seawater.

## SPECULATIONS ON THE IMPLICATIONS OF SUBDUCTION OF COMPOSITIONALLY MODIFIED OCEANIC CRUST WITH RESPECT TO THE ORIGIN OF CALC-ALKALINE IGNEOUS ROCKS AND SPATIALLY ASSOCIATED PORPHYRY CU ± Mo ± Au DEPOSITS

The geochemical effects of subduction of compositionally modified, in particular hydrated and $^{87}$Sr-enriched, oceanic crust (Spooner, 1976; 1978) are just beginning to be detected and appreciated. It is possible that the phenomena of hydrothermal metamorphism and mineralization of oceanic crust could be quantitatively important aspects of the geochemical evolution of the crust and the mantle. The various possible connections and processes are shown diagrammatically in Figure 5.

The precise mechanism of generation of calc-alkaline igneous rocks and associated mineral deposits which occur spatially related to subduction zones has long been a matter of dispute. Recent geochemical work, in particular that involving combined analysis of the neodymium and strontium isotopic compositions of calc-alkaline lavas (Hawkesworth *et al.*, 1977, 1979) may be pointing towards a resolution of the problem. For andesitic lavas associated with subduction zones in the Scotia Arc, Ecuador, Chile, the Marianas and the Lesser Antilles, $^{87}$Sr/$^{86}$Sr ratios have been determined which are anomalously high relative to the well-defined $^{143}$Nd/$^{144}$Nd –

$^{87}Sr/^{86}Sr$ antipathetic correlation which has been observed for mid-ocean ridge basaltic rocks. On the basis of a variety of arguments, Hawkesworth *et al.* (1979) suggest that this effect, combined with the major and trace element chemistry of the lavas, may be best explained not by partial melting of the subducted oceanic crust, but by devolatilization which produced an alkali (K, Rb, Sr)-rich, high $^{87}Sr/^{86}Sr$ aqueous fluid phase which activated partial melting of the overlying mantle wedge (see Fig. 5). Devolatilization would occur because the upper 3 to 5 km of oceanic crust are hydrated by seawater/basalt interaction during hydrothermal circulation within spreading ridges. For example, the $H_2O+$ contents of nine ophiolitic metabasalts and metadolerites reported by Spooner *et al.* (1977) range from 0.6% to 4.5 wt.% and average 2.5

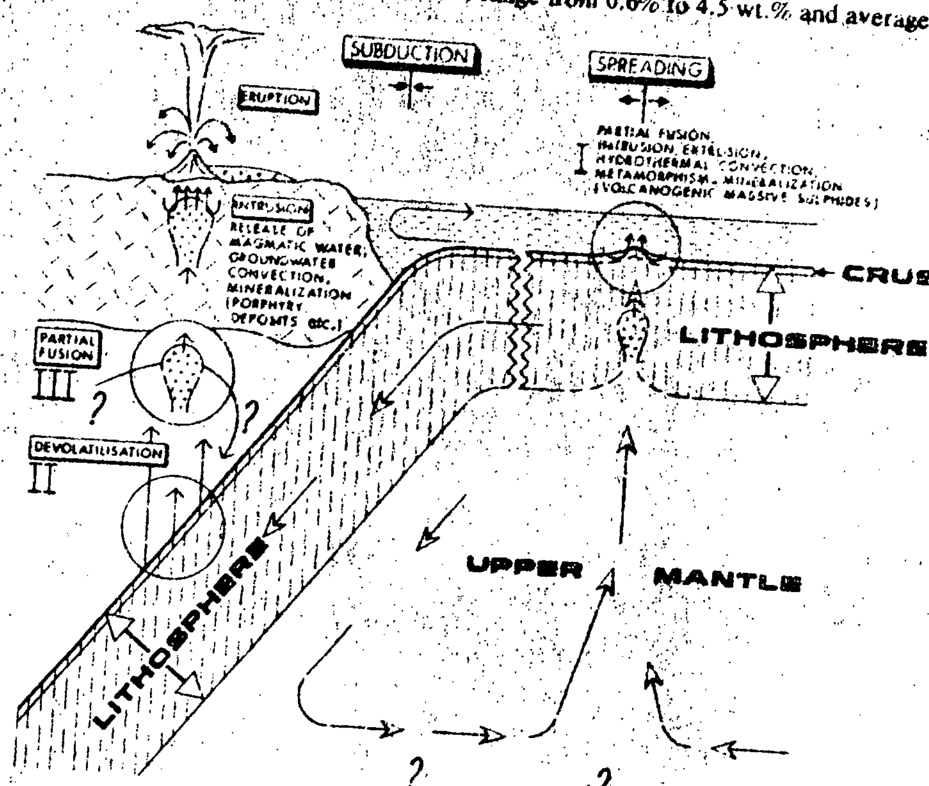



**Figure 5.** Highly schematic cartoon showing possible geochemical connections which may occur related to the processes of sea-floor spreading and subduction. The principal objective of the diagram is to portray a technically feasible series of linkages between seawater sulphate, massive sulphide deposits in hydrated oceanic crust produced by seawater convection within spreading ridges, devolatilization of hydrated oceanic crust in subduction zones, partial fusion of the overlying mantle wedge and formation of porphyry copper deposits spatially related to high level, sub-volcanic, calc-alkaline plutons of intermediate composition.

It is interesting to note how convective phenomena manifest themselves in a wide variety of media, forms and locations. The media include solid mantle material, silicate magma, seawater in oceanic crust, groundwater in continental crust, the oceans and the atmosphere.

wt.%. These data compare with a mean water content for fresh deep-sea basaltic material of about 0.30 wt.% (Moore, 1970), and suggest an increase in water content of about 2 wt.%.

If this figure is representative, then at the present rate of subduction of hydrated oceanic crust (about 4 x $10^{16}$ g/yr; Spooner, 1976), the total ocean mass could be recycled through the mantle in about 1.8 x $10^{9}$ yr.

A closely related implication concerns the possible presence of sulphide deposits in oceanic crust, which could be comparable in size and density of occurrence to those in Cyprus. The isotopic composition of contained sulphur suggests that the ore sulphide is mainly of reduced seawater sulphate origin (Bachinski, 1977; Spooner, 1977; Heaton and Sheppard, 1977). Hence, large quantities of sulphide, in association with hydroxyl and chloride, could be added to the oceanic crust during seawater/rock interaction at ridges (Fig. 5). Release of water from the descending slab at subduction zones may cause wet melting of mantle material, as suggested by the arguments of Hawkesworth *et al.* (1979), and could produce volatile rich siliceous magmas enriched in chlorine and sulphur (Fig. 5). Such a simple model could begin to explain the amounts of magmatically released water, chlorine and sulphur required for the formation of porphyry Cu ± Mo ± Au deposits. Water is needed as the transport medium, chloride for metal complexing and sulphur for fixing the metals as solid phases (Spooner, 1978).

An oceanic crust depleted in volatiles and associated elements to an unknown extent is then returned to the active mantle where it may become involved in subsequent ocean ridge and other melting events in the slow, continuous cycle of mantle convection and partial fusion.

## CONCLUSIONS

Further implications of the subduction of chemically and isotopically modified oceanic crust remain to be evaluated. Many difficult geochemical problems are encountered, particularly if semi-quantitative models are attempted. Some examples are given below:

1) What is the bulk average change in the chemical composition of the upper part of the oceanic crust affected by seawater circulation?
2) How much of the modified material returned to the mantle during subduction is returned irreversibly to the continental crust by the processes which occur in and above subduction zones?
3) How much of the modified material is, therefore, completely returned to the mantle?
4) How much of the mantle is, and has been, involved?
5) How is the mantle changing in composition now as a result of these processes?
6) What sort of elemental and isotopic heterogeneities may be produced in the mantle?
7) If the combination of processes is important now, then how much more important may it have been in the early stages of the chemical evolution of the Earth, when radiogenic heat production was approximately three times what it is today?

These geochemical questions arise from the realization by several people, including J. Tuzo Wilson, that the Earth is a rather complex dynamic system.

## ACKNOWLEDGEMENTS

Receipt of NSERC grant no. A6114 is very gratefully acknowledged since it helped significantly in the preparation of this work. I would also like to express my thanks to Subhash Shanbhag (draftsman), Brian O'Donovan (photographer) and Sylvia Skinner (secretary) for invaluable assistance.

## REFERENCES

Adamides, N.G., 1975, Geological history of the Limni concession, Cyprus, in the light of the plate tectonics hypothesis: Trans. Instit. Mining and Metallurgy (Section B: Applied Earth Science), v. 84, p. B17-B23.

Anderson, R.N., Hobart, M.A. and Langseth, M.G., 1979, Geothermal convection through oceanic crust and sediments in the Indian Ocean: Science, v. 204, p. 828-832.

Bachinski, D.J., 1977, Sulfur isotopic composition of ophiolitic cupriferous iron sulfide deposits, Notre Dame Bay, Newfoundland: Econ. Geol., v. 72, p. 243-277.

Bear, L.M., 1963, The mineral resources and mining industry of Cyprus: Bull. Geol. Survey Department of Cyprus, v. 1, 208 p.

Boldy, J., 1977, (Un)certain exploration facts from figures: Canadian Instit. Mining Bull., v. 70, no. 781, p. 86-95.

Chapman, H.J. and Spooner, E.T.C., 1977, $^{87}$Sr enrichment of ophiolitic sulphide deposits in Cyprus confirms ore formation by circulating sea water: Earth and Planetary Sci. Letters, v. 35, p. 71-78.

Christensen, N.I., 1978, Ophiolites, seismic velocities and oceanic crustal structure: Tectonophysics, v. 47, p. 131-157.

Coish, R.A., 1977, Ocean floor metamorphism in the Betts Cove ophiolite, Newfoundland: Contrib. Mineralogy and Petrology, v. 60, p. 255-270.

Constantinou, G. and Govett, G.J.S., 1972, Genesis of sulphide deposits, ochre and umber of Cyprus: Trans. Instit. Mining and Metallurgy (Section B: Applied Earth Science), v. 81, p. B32-B46.

————————, 1973, Geology, geochemistry and genesis of Cyprus sulfide deposits: Econ. Geol., v. 68, p. 843-858.

Corliss, J.B. and Ballard, R.D., 1977, Oases of life in the cold abyss: National Geographic Magazine, v. 152, p. 441-453.

Crane, K. and Normark, W.R., 1977, Hydrothermal activity and crustal structure of the East Pacific Rise at 21°N: Jour. Geophys. Research, v. 82, p. 5336-5348.

Crerar, D.A. and Barnes, H.L., 1976, Ore solution chemistry V. Solubilities of chalcopyrite and chalcocite assemblages in hydrothermal solution at 200°C and 350°C: Econ. Geol., v. 71, p. 772-794.

Duke, N.A. and Hutchinson, R.W., 1974, Geological relationships between massive sulfide bodies and ophiolitic volcanic rocks near York Harbour, Newfoundland: Canadian Jour. Earth Sci. v. 11, p. 53-69.

Edmond, J.M., 1978, Chemistry of the hot springs on the Galapagos ridge axis (abst.): The Second Maurice Ewing Memorial Symposium (Abstracts), p. 13.

Francheteau, J., Needham, H.D., Choukroune, P., Juteau, T., *et al.*, 1979, Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise: Nature, v. 277, p. 523-528.

Fryer, B.J., Fyfe, W.S. and Kerrich, R., 1979, Archean volcanogenic oceans: Chemical Geol., v. 24, p. 25-33.

Gass, I.G. and Smewing, J.D., 1973, Intrusion, extrusion and metamorphism at constructive margins: evidence from the Troodos Massif, Cyprus: Nature, v. 242, p. 26-29.

y acknowledged since it
d also like to express my
ı (photographer) and Syl-

ı, Cyprus, in the light of the
;y (Section B: Applied Earth

thermal convection through
204, p. 828-832.
iferous iron sulfide deposits,
-277.
Cyprus: Bull. Geol. Survey

ın Instit. Mining Bull., v. 70,

phiolitic sulphide deposits in
ınd Planetary Sci. Letters, v.

anic crustal structure: Tec-

e ophiolite, Newfoundland:

eposits, ochre and umber of
lied Earth Science), v. 81, p.

prus sulfide deposits: Econ.

abyss: National Geographic

crustal structure of the East
5-5348.
lubilities of chalcopyrite and
350°C: Econ. Geol., v. 71, p.

ps between massive sulfide
wfoundland: Canadian Jour.

agos ridge axis (abst.): The
13.
al., 1979, Massive deep-sea
ature, v. 277, p. 523-528.
ic oceans: Chemical Geol., v.

etamorphism at constructive
, v. 242, p. 26-29.



Hashimoto, K., 1977, The Kuroko deposits of Japan – geology and exploration strategies: Asociacion de Ingenieros de Minas Metalurgistas y geologos de Mexico Memoria Tecnica, v. 13, p. 25-88.

Hawkesworth, C.J., O'Nions, R.K., Pankhurst, R.J., Hamilton, P.J. and Evensen, N.M., 1977, A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea: Earth and Planetary Sci. Letters, v. 36, p. 253-262.

Hawkesworth, C.J., Norry, M.J., Roddick, J.C. and Baker, P.E., 1979, $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and incompatible element variations in calc-alkaline andesites and plateau lavas from South America: Earth and Planetary Sci. Letters, v. 42, p. 45-57.

Heaton, T.H.E. and Sheppard, S.M.F., 1977, Hydrogen and oxygen isotope evidence for sea-water-hydrothermal alteration and ore deposition, Troodos complex, Cyprus: Geol. Soc. London Special Publ., no. 7, p. 42-57.

Honnorez, J., Honnorez-Guerstein, B., Valette, J. and Wauschkuhn, A., 1973, Present day formation of an exhalative sulphide deposit at Vulcano (Tyrrhenian Sea), part II: active crystallization of fumarolic sulphides in the volcanic sediments of the Baia di Levante: in Amstutz, G.C. and Bernard, A.J., eds., Ores in Sediments: Berlin – Heidelberg – New York, Springer-Verlag, p. 139-166.

Hutchinson, R.W. and Searle, D.L., 1971, Stratabound pyrite deposits in Cyprus and relations to other sulphide ores: Soc. Mining Geol. of Japan Special Issue, no. 3, p. 198-205.

Lambert, I.B. and Sato, T., 1974, The Kuroko and associated ore deposits of Japan: a review of their features and metallogenesis: Econ. Geol., v. 69, p. 1215-1236.

Liou, J.G. and Ernst, W.G., 1979, Oceanic ridge metamorphism of Taiwan ophiolite: Contrib. Mineralogy and Petrology, v. 68, p. 335-348.

Lister, C.R.B., 1972, On the thermal balance of a mid-ocean ridge: Geophys. Jour. Royal Astron. Soc., v. 26, p. 515-535.

Moore, J.G., 1970, Water content of basalt erupted on the ocean floor: Contrib. Mineralogy and Petrology, v. 28, p. 272-279.

Mottl, M.J. and Holland, H.D., 1978, Chemical exchange during hydrothermal alteration of basalt by sea water – I. Experimental results for major and minor components of sea water: Geochim. et Cosmochim. Acta, v. 42, p. 1103-1116.

Parmentier, E.M. and Spooner, E.T.C., 1978, A theoretical study of hydrothermal convection and the origin of the ophiolitic sulphide ore deposits of Cyprus: Earth and Planetary Sci. Letters, v. 40, p. 33-44.

Ribando, R.J., Torrance, K.E. and Turcotte, D.L., 1976, Numerical models of hydrothermal circulation in the oceanic crust: Jour. Geophys. Research, v. 81, p. 3007-3012.

Robertson, A.H.F., 1975, Cyprus umbers; basalt-sediment relationships on a Mesozoic ocean ridge: Jour. Geol. Soc. London, v. 131, p. 511-531.

Sangster, D.F., 1977, Some grade and tonnage relationships among Canadian volcanogenic massive sulphide deposits: Geol. Survey Canada Paper, v. 77-1A, p. 5-12.

Sillitoe, R.H., 1972, Formation of certain massive sulphide deposits at sites of sea-floor spreading: Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science), v. 81, p. B141-B148.

Sleep, N.H. and Wolery, T.J., 1978, Egress of hot water from midocean ridge hydrothermal systems: some thermal constraints: Jour. Geophys. Research, v. 83, p. 5913-5922.

Spiess, F.N., Macdonald, K.C. Atwater, T., Ballard, R., *et al.*, 1980, East Pacific Rise: hot springs and geophysical experiments: Science, v. 207, 1421-1433.

Spooner, E.T.C., 1975, Cyprus pyrite today: Sulphur, no. 121, p. 23-27.

————————, 1976, The strontium isotopic composition of seawater and seawater-oceanic crust interaction: Earth and Planetary Sci. Letters, v. 31, p. 167-174.

————————, 1977, Hydrodynamic model for the origin of the ophiolitic cupriferous pyrite ore deposits of Cyprus: Geol. Soc. London Special Publ., no. 7, 58-71.

———————, 1978, Ophiolitic rocks and evidence for hydrothermal convection of sea water within oceanic crust (abst): The Second Maurice Ewing Memorial Symposium (Abstracts), p. 36-37.

Spooner, E.T.C., Beckinsale, R.D., Fyfe, W.S. and Smewing, J.D., 1974, $^{18}O$ enriched ophiolitic metabasic rocks from E. Liguria (Italy), Pindos (Greece) and Troodos (Cyprus): Contrib. Mineralogy and Petrology, v. 47, p. 41-62.

Spooner, E.T.C. and Bray, C.J., 1977, Hydrothermal fluids of sea water salinity in ophiolitic sulphide ore deposits in Cyprus: Nature, v. 266, p. 808-812.

Spooner, E.T.C., Chapman, H.J. and Smewing, J.D., 1977, Strontium isotopic contamination and oxidation during ocean floor hydrothermal metamorphism of the ophiolitic rocks of the Troodos Massif, Cyprus: Geochim. et Cosmochim. Acta, v. 41, p. 873-890.

Spooner, E.T.C. and Fyfe, W.S., 1973, Sub-sea-floor metamorphism, heat and mass transfer: Contrib. Mineralogy and Petrology, v. 42, p. 287-304.

Stern, C., De Wit, M.J. and Lawrence, J.R., 1976, Igneous and metamorphic processes associated with the formation of Chilean ophiolites and their implication for ocean floor metamorphism, seismic layering and magnetism: Jour. Geophys. Research, v. 81, p. 4370-4380.

Trennery, T.O. and Pocock, B.G., 1972, Mining and milling operations at Limni Mine, Cyprus: Transactions of the Institution of Mining and Metallurgy (Section A: Mining Industry), v. 81, p. A1-A12.

Williams, D.L. and Von Herzen, R.P., 1974, Heat loss from the Earth: new estimate: Geology, v. 2, p. 327-328.

Williams, D.L., Von Herzen, R.P., Sclater, J.G. and Anderson, R.N., 1974, The Galapagos spreading centre: lithospheric cooling and hydrothermal circulation: Geophys. Jour. Royal Astronomical Soc., v. 38, p. 587-608.

Williams, H. and Malpas, J., 1972, Sheeted dikes and brecciated dyke rocks within transported igneous complexes, Bay of Islands, Western Newfoundland: Canadian Jour. Earth Science, v. 9, p. 1216-1229.

Wolery, T.J. and Sleep, N.H., 1976, Hydrothermal circulation and geochemical flux at mid-ocean ridges: Jour. Geol., v. 84, p. 249-275.

wRl 6447

To: W. L. Anderson
File

United States Steel Corporation

Interorganization Correspondence

Date: May 24, 1982

From: E. I. Bloomstein

Subject: Proposed Geochemical Exploration Program in Northern Oman

Contents:

I Geologic Setting of Northern Oman

II Volcanic-hosted Cu-Zn massive sulfide deposits of northern Oman
1) Characteristics of the deposits
2) Hydrothermal alteration
3) Genetic model
4) Exploration consequences

III Suggested Geochemical Exploration Program
1) Advantages of using rock geochemistry as a principal method
2) First step - regional rock geochemical survey of northern Oman
3) Target areas
4) Second step - detailed rock geochemical surveys of the target areas
5) Third step - assessment of geochemical anomalies
6) Use of wadi sediments for geochemical exploration

IV Computer Data Processing


## I. Geologic Setting of Northern Oman

The Semail ophiolite complex forms a 400-km long, arcuate belt with an exposed cross sectional width of up to 80 km coincident with the Oman Mountains. Areal exposure of ophiolitic rocks encompasses 20,000 km$^2$, thus representing one of the largest sections of intact on-land oceanic crust (Coleman, 1977). This slab of oceanic crust reached its present position by thrusting in a southwestern direction over the northeast part of the Arabian continental margin (Carry and Welland, 1974; Stonely, 1975). The Semail ophiolite was produced during a Late Cretaceous period of sea-floor spreading beneath the Hawasina ocean, which was part of the great Tethys seaway. The Semail ophiolites are believed to have formed at a fast-spreading ridge system where 130 to 150 km of new ocean crust was produced within two million years (Tilton, 1981). The direction of the former spreading axis is defined by the sheeted dike complrx and runs N20$^o$W $\pm 25^o$ along the entire length of the Oman Mountains.

The six major elements of the Semail ophiolite complex recognized and mapped from the lowermost member up are: (1) the mantle sequence of harzburgite and dunite; (2) the cumulative intrusives of gabbro and peridotite; (3) the high-level intrusives of diorite and plagio-granite; (4) the sheeted intrusive complex of diabase dikes; (5) the basaltic pillow lavas, sills and massive basaltic flows; and (6) the ophiolitic sediments of mostly mudstones. These six members have a total stratigraphic thickness of at least 15 km. As commercial Cu-Zn massive sulfide deposits are localized within pillow lavas of member 5 of the above sequence or at the contact between those basalts and the sheeted dikes of member 4, an understanding of the rather complex volcanic stratigraphy of member 5 is particularly essential for the exploration for these deposits. The most attractive stratigraphic scheme in our opinion was developed by the geologists of London's Open University ophiolite group (Alabaster, 1981). They mapped in detail the Lasail mining district in northern Oman, which contains three commercial massive sulfide deposits and conducted a reconnaissance survey to see the extent to which the stratigraphy of that district applied to the 400 km along strike exposure of the basaltic unit. There can be no doubt that their stratigraphy will be amended and modified by further work but we also believe that the stratigraphy is based on sound plate tectonic evidence and will hold in principle.

Three distinct mappable units termed, in order of eruption, the Geotimes, Lasail and Alley are recognized. The Geotimes Unit, with a thickness of about 1500 m, is predominantly basaltic pillow and massive lavas formed at a spreading axis. It consists of several individual flow units. In many places basalts are quite altered with montmorillonite, chlorite and zeolite as main alteration minerals. Small massive cupriferous sulfides, gossans and ochres are found within the Geotimes Unit (for example, in the Wadi Salahi tectonic block). They were formed by sulfide precipitation within saucer-shaped depressions on the sea floor.

The Lasail Unit (thickness 1000 m) consists of a differentiated series of basalt-andesite-rhyolite and does not occur throughout the sequence. It is restricted to some kind of volcanic centers spaced at 25-30 km intervals along the strike of the ophiolite belt. These centers are considered to be "seamounts", having formed by eruption onto oceanic crust in the "oft-spreading axis" environment. Geochemically these volcanics are similar to island-arc basalts and andesites. Pillow lavas of the Lasail Unit may directly overlie the "spreading axis" pillow lavas of the Geotimes Unit with no intercalated sediment. Andesites are mapped as dikes and lava flows. Rhyolites form felsite sheets or massive flows and often occur on the periphery of the plagiogranite plugs, which are also mapped in the "seamount" volcanic centers. Basalts are often propylitically altered; amphibolization of andesites and epidotization of rhyolites have been recorded. Almost all significant massive sulfide deposits occur in seamount areas and are localized within the pillow lavas of the Lasail Unit erupted directly onto the Geotimes pillow lavas.

The Alley Unit, about 500 m thick, is a second basalt-rhyolite differentiation sequence. It may overlie the Lasail Unit in seamount areas or directly overlie the "spreading axis" Geotimes basalt between the seamount areas. The Alley Unit rocks are strongly altered in the zeolite facies. Rhyolites of the Alley Unit form small domes and volcanic centers 0.5-1.0 km in diameter. These centers are more numerous than those belonging to the Lasail Unit. Pillow and massive basalt lavas of the Alley Unit can be found throughout the length of the ophiolite. The

Alley Unit volcanics are particularly well-developed inbetween "seamount" areas which are interpreted as faulted depressions or grabens. This unit, therefore, is considered to have erupted in a post-seamount rifting environment. One massive sulfide deposit is associated with the Alley Unit.

## II. Volcanic-Hosted Cu-Zn Massive Sulfide Deposits of Northern Oman

### 1. Characteristics of the Deposits

Three substantial massive sulfide deposits--the Lasail, Bayda and Aarja--occur in the volcanic part of the northern Oman ophiolite terrain. A number of major gossans and about 150 sulfide occurrences are also known in the area or are undergoing exploration.

The Lasail deposit has reserves of 12 million tons of 2.4% Cu. The orebody is elongated and disk-shaped, and is 450 m long and 280 m wide. It dips at a shallow angle and is cross-cut and displaced by small faults. The deposit has the basalts of the Geotimes Unit as a footwall and basaltic pillow lavas of the Lasail Unit as a hanging wall. There is an underlying stockwork of silicified, chloritized and brecciated rocks which is restricted to the Geotimes Unit. In the stockwork pyrite and chalcopyrite occur as stringers, bands and blebs. The orebody lies within 30 meters of the surface.

The Bayda deposit with 1 million ton reserves has a similar stratigraphic position. Pyrite-chalcopyrite-sphalerite mineralization is found in two pipes, the first 1 $km^2$ in area and the second 500 $m^2$.

geology

The Aarja deposit, 3 million tons of reserves, also has the Geotimes basalts as a footwall but the hanging wall is formed by zolitically altered basalts of the Alley Unit. Mineralization is found as a pipe-like mass 70 m by 40 m in area. Some gold (0.018 oz/t, 700 ppb) and silver (0.10 oz/t, 3.4 ppm) are found at Aarja.

geology

All the above deposits exhibit the main features of Cyprus-type massive sulfide mineralization: (1) pyrite and chalcopyrite as predominant sulfide minerals with minor sphalerite and negligible galena in both massive ore and vertically extensive stringer zones; (2) an underlying quartz-chloride-sulfide stockwork; (3) abundant Fe and Ti oxide inclusions in pyrite; and (4) orebodies which are pipeline or mushroom-shaped are generally massive.

Structure

Similar to Cyprus, most of the Omani deposits and prospects lie within the pillow lava sequence of the ophiolite affinity. Many of the orebodies sit immediately adjacent to steep normal faults.

Massive sulfide deposits of northern Oman are poorly zoned because they are copper-rich, have only minor zinc, and are deficient in lead. From very limited data it appears that sphalerite-rich pods are distributed erratically within the massive ore and the Cu/Zn ratio therefore does not decrease upward as in other deposits.

At Aarja and Lasail gold and silver constitute minor byproducts. There is no indication that the deposits carry significantly higher proportions of gold relative to silver.

Massive sulfide deposits of the Cyprus type similar to Lasail, Bayda and Aarja are known in other parts of the world, for example Troodes massif, Cyprus; Notre Dame Bay, Newfoundland; Ergani district, southeastern Turkey; Balabac and Hixbar deposits, Philippines; Oxec district in Guatemala; the Island Mountain deposit, California; Lokken district, Norway; and Sevan-Akeron mining district, Armenia, USSR. The geology of these deposits has been described by Hutchinson, 1973, and Franklin et al., 1981.

2. Hydrothermal Alteration

The northern Oman Cu-Zn deposits typically contain three alteration assemblages--a gossan or an ochre horizon capping the massive ore, a basal zone of silicification, and an alteration pipe below the massive ore.

Umbers vs ochres
Geol. + geochem

The ochre horizon may serve as an exploration guide. The Zuka prospect in the Wadi Salhi block was discovered due to a brilliantly colored massive ochre. Ochres were recognized at Rakah, Lasail, Bayda and Aarja deposits. The ochre horizons are composed predominantly of brown and orange-yellow, massive or layered sediment containing goethite and silica (quartz) with some illite and jarosite and also some corroded fragments of pyrite (Bear, 1963). They are interpreted as the accumulated product of submarine oxidative leaching of the sulfide ore that was exposed on the sea floor. Ochres are rich in iron and poor in manganese.

Ochres as ore-related alteration must be distinguished from manganese-rich umbers which indicate hydrothermal activity on the ocean floor not necessarily related to sulfide mineralization. Umbers are sedimentary deposits of Fe-Mn oxides admixed with variable amounts of biogenic material. In the Geotimes Unit umbers are minor, laminated, brown deposits. Most show no spatial relationship with the sulfide mineralization. At the Lasail deposit, however, umbers were mapped very close to mineralization. In the Lasail and Alley units lenses of umber up to 5 m long and 1 m thick are widespread. Fleet and Robertson (1981) describe them as finely laminated and silicified sediments, which are underlain by altered lavas and sometimes are brecciated and cut by ferruginous veins. This indicates that umbers form directly above the discharge zone of submarine hydrothermal vents and therefore mark the syn-eruptive fault zones.

Gossans are mentioned in all publications and exploration reports on northern Oman, but very little information is given on their size, type, mineralogy or geochemistry. Gossans, as is well known, are iron-rich, weather cap rocks over massive sulfide bodies (Blain and Andrew, 1977). Ideally, the orebody grades upwards into a more oxidized secondary sulfide zone. This zone is overlain by an oxide zone, leached of ore metals, which is capped by gossan at the surface. The enriched pyrite-chalcopyrite gossans vary in appearance from massive steely gray to powdery black geol. [illegible] mapping

accumulations. Reports contain sketchy mentions of both types at the Lasail and Bayda deposits. Iron contained in gossans is most commonly in the form of goethite and hematite. Most sulfide gossans are variably silicified. Iron sulfide gossans (and to some extent, ochres) derived from "barren" pyrite are difficult to distinguish in the field from base-metal gossans. It is felt that true gossans, ironstones, ochres and umbers have not been properly distinguished and mapped by exploration geologists in northern Oman. It must be done in the course of a successful mineral exploration program.

alt. halo

Alteration pipes below Cu-Zn orebodies constitute another important alteration type. In a typical Cyprus Cu-Zn deposit this alteration is well defined and, in some cases, is very extensive vertically (1000 m and more). There is no data on the vertical extent of alteration in Oman deposits. Alteration mainly consists of an Mg-rich chlorite core surrounded by a sericite-quartz-rich halo (Lasail deposit). The central Mg-rich core is expected to be depleted in silica, whereas the outer sericite zone may be enriched in $SiO_2$. Another chemical feature of alteration in basalts below the Cu-Zn mineralization is pervasive $Na_2O$ and CaO depletion.

3. Genetic Model

These deposits are considered to be formed at or near the discharge vents of submarine hydrothermal systems. The hydrothermal system is thought to be a convective cell which consists mainly of seawater (see review by Franklin, Lydon and Sangsten, 1981). The driving energy of the convective cell is believed to be either the oceanic crustal heat flow, especially above the spreading ridges, or local intrusive bodies such as plagiogranite plugs associated with the seamounts and the Lasail Unit. During its descent in the convection cell, seawater becomes heated and modified in chemical composition. The major chemical change is the reduction achieved by reaction with Fe components of the basalt (activity of $H_2O$ is greater than activity of $SO_4$). The net result of this heating and interaction is reduced, slightly alkaline saline solution that contains copper and zinc leached from the basalt sequences along the flow path of the solutions. Lead is immobile in alkaline solutions. The hydrothermal solution rises along a fault or fracture zone carrying Cu and Zn as bisulfide complexes. Initial precipitation takes place near the ocean floor surface forming the alteration pipe and stringer zone ores and is characterized by magnesium (chlorite) metasomatism and silicification. At the seawater-rock interface, the precipitation is much more rapid and results in the accumulation of a sulfide mound around the vent. ~~Most of the deposits are characteristically zoned with the Cu/Zn ratio decreasing upward and outward from the central part of the mound.~~ This can be explained as remobilization of previously deposited sulfides by the action of continued hydrothermal flow through the mound. An alternative explanation is that ores with the highest Cu/Zn ratios were deposited at higher temperatures and lower $P_{O_2}$ than those with lower Cu/Zn ratios. ~~Barite, if present, tends to concentrate where the Cu/Zn ratio is lowest. Silica and iron or manganese oxides may be precipitated in distal, or stratigraphically higher, positions relative to the sulfide body.~~

4. Exploration Consequences

[illegible] used

The first exploration consequence of this theory is that sites of formation of volcanic massive sulfide deposits are controlled by the geometry of the convective cell and are spaced regularly. Solomon (1976) noted that the Cyprus deposits appeared to occur in groups, with a spacing between individual deposits of 2 to 4.5 km and between groups of 7.5 to 12.5 km. Because of the difficulty in leaching sufficient copper and zinc from a convection cell 1-1.5 km deep, as calculated from the spacing of the deposits, he suggested that the main hydrothermal convection cell should have a diameter of about 10 km and a depth of about 3.5 km, i.e., the between-group spacing. That seems to be the case with the Lasail seamounts.

photogeology used

The second consequence is that volcanic-hosted massive sulfide deposits have very limited lateral extent and were deposited very close to the exact site of discharge by a fault or a fracture zone. Therefore, boundaries of fault blocks, circular features and fault intersections should be sought out in photo interpretation and in the course of detailed mapping.

III. Suggested Geochemical Exploration Program

1. Advantages of Using Rock Geochemistry as a Principal Method

Rock geochemistry became a popular and widely accepted technique in the search for blind ore deposits. The presence of broad Cu and Zn geochemical dispersion halos in wallrocks significantly enhances the chances of exploration success in the general area of mineralization. ~~As the study of many deposits shows, the Cu-Zn mineralized areas have a definite geochemical signature. In major oxides, for example,~~ ~~$Na_2O$ is found to be strongly depleted in the vicinity of ore deposits. This is accompanied by MgO enrichment and CaO depletion.~~ Of the most commonly examined trace elements, Cu, Zn, Cd, Pb, Mo and Ag are capable of showing enhancement related to massive sulfide mineralization.

geochem

The basic rationale for use of rock geochemistry as an exploration tool comes from the genetic model of Cu-Zn massive sulfide mineralization (see Section II-4). These deposits are considered to have been formed as a result of the activity of submarine hydrothermal systems. As the fluids involved percolate through the seafloor basalts, they alter the mineralogy and bulk chemistry of the host rocks. This creates distinctive zones which constitute much wider target areas in the search for mineralization than the mineralization itself. ~~The geochemical halos are significantly (two or three times) wider than the obvious mineralogical halo and often anomalous geochemical values are found in rocks which have merely background alteration or no apparent alteration at all (for instance, Noranda massive sulfide deposit, Pirie and Nichols, 1981). On a wider scale, copper and zinc dispersion patterns are related to the mineralized faults and fracture systems of the area and could help to locate favorable ground.~~

used

One of the most significant conclusions which could be drawn from regional rock geochemical studies is that on a regional scale (10-20 $km^2$) it is the ore elements, mainly Cu and Zn, that give the most definitive patterns in relation to the distribution of sulfide deposits; whereas on the mine scale (1 $km^2$ of the mineralization) the major elements, such as $Na_2O$, MgO, and CaO, give the most well-defined halos.

used

Another important conclusion, reached during the Cyprus rock geochemical study (Govett and Pantazis, 1971), is that massive sulfide deposits occur in the areas of low Cu and high Zn content. It was confirmed later that the Newfoundland and New Brunswick massive sulfide deposits also lie in Cu-deficient zones (Govett and Piva, 1981). These authors calculated that the changes in the metal content of the rocks around mineralization compared to the average rocks of the region require a loss of more than 30% of Cu. This is probably due to leaching of metals from basalts to form sulfides.

2. <u>First Step - Regional Rock Geochemical Survey of Northern Oman</u>

It is suggested that a low-density regional rock geochemical survey of the volcanic province of northern Oman be conducted, using five geologists for two months. The objective would be to determine Cu, Zn and Pb variations attributable to: (1) proximity to sulfide mineralization and alteration; (2) stratigraphic position in the Geotimes, Lasail or Alley units; (3) plate tectonic position relative to spreading axis, off-axis seamount, or post-seamount graben; and (4) petrographic (rock type) differences as to tholeitic basalts, andesites, rhyolites, etc.

It is proposed that 15-20 traverses be located over the volcanic belt and in the Ibra region, in such a manner that the traverses will cross main rock groups at right angles to the strike. Geographically, traverses should be spaced more or less equidistantly. It is necessary that some traverses cross the Bowling Alley, Lasail and Ibra mining districts in order to determine geochemical changes as a function of proximity to mineralization. To assure this, some miscellaneous (radial) traverses could be planned in these districts.

Rock samples along traverses may be taken at regular intervals of 200 m. At each sample location several samples may be required, for example from obviously different rock types, from rocks with various degrees of alteration, etc.

It is anticipated that 2000-3000 samples would be collected in this regional geochemical survey. All samples should be analyzed for Cu, Zn and Pb; a certain number of samples should be analyzed for 10 major oxides and additional trace elements such as V, Ni, Co, Cr, Ti, Mn, Ba, Ag, Cd, Zr and Y.

In addition to identifying the mining districts and regional trends geochemically, these analyses will provide a systematic, reliable data base for the recognition of background and anomalous populations by use of computer processing of the analytical results. They will serve also as an important aid to mineral exploration.

3. Target Areas

Target areas should be defined by the analysis of geology and mineral belts, by photogeological interpretation of structural features and color (alteration) anomalies, and by reconnaissance geological mapping. These matters are outside the scope of this report. A regional geochemical survey could be of some help in locating target areas, supplementing the above methods, but it should not be a principal tool.

4. Second Step - Detailed Rock Geochemical Surveys of the Target Areas

Once a target area is outlined it is recommended that detailed rock geochemical sampling in conjunction with detailed geological mapping be used as a potent method in the search for blind massive sulfide orebodies. Two types of settings for Cu-Zn deposits are envisioned--exposed or thinly concealed, and concealed by post-ore cover such as ophiolite-sedimentary rocks, eolic sand or alluvium. Outcrop samples are recommended for the detailed geochemical prospecting. Desert soils are thin and alkaline, with poorly developed profiles in which abundant, partly weathered fragments of bedrock are common. On ridge crests and steep slopes where outcrops and "float" are abundant, soil samples would not be as informative as bedrock samples. Therefore, soil samples should be used for grid sampling in small areas of known or suspected mineralization.

In detailed prospecting for massive sulfide deposits, the following group of elements is particularly serviceable: copper, zinc, lead, cadmium, silver, molybdenum, and cobalt. In addition, the major oxides such as $Na_2O$, $K_2O$, MgO and CaO should be determined (see Section III-1). The appraisal of proven geochemical anomalies may be facilitated occasionally by the use of bismuth, arsenic and barium as supplementary indicator elements.

Analyses for lead are especially necessary in the areas where the acidic volcanic rocks of the Lasail and Alley units are exposed as there is a chance for discovery of Kuroko-style Cu-Zn-Pb deposits.

During the rock geochemical survey of the target area, some halos of increased concentration of certain elements such as Zn and Ag or decreased concentrations of Cu would be discovered. Such halos are more likely to develop in the footwall of massive sulfide orebodies, and as previously discussed, the halos could be several times larger than the orebodies. In general, halos of large pyrite-chalcopyrite orebodies are broader and longer than halos of small ones. Small orebodies are known to develop a multitude of small halos.

The main problem in the rock geochemical surveying of a target area for a blind massive sulfide deposit is not the discovery and mapping of the Cu-Zn halos. The halos are a considerable size and could be found easily. The problem is the interpretation of the halos and estimation of the potential size and grade of the blind mineralization. The size of the halos is merely an indication of the span of massive sulfide mineralization. Although proven criteria have not been fully developed to differentiate between economic and uneconomic ore deposits by their halos, some preliminary suggestions can be made. One is to pay special attention to geochemistry of altered rocks. High values of copper, zinc, and lead generally correspond to quartz-sericite-chlorite alteration. High values of cobalt and molybdenum generally are found in basal silicified zones. Gossans and ochres are particularly indicative; in copper-zinc gossans, a high Cu, Pb, Ba, Au and Ag-low Mn, Ni, Cr and Co association is diagnostic of economic mineralization. In some cases, small, low-grade copper-zinc orebodies exhibit lower Ba and higher Zn and Mn contents in the gossans.

One final comment is that in conducting rock geochemical sampling in conjunction with detailed geological mapping, it is not mandatory to do it on a grid basis. Bedrock samples could be taken along mapping traverses and from key outcrops where principal stratigraphic units and alteration assemblages are exposed.

5. Third Step - Assessment of Geochemical Anomalies

After halos of ore elements have been mapped and a geochemical anomaly identified, an assessment of this anomaly and definition of drill targets should be performed. Such assessment is usually done by conducting a grid soil geochemical survey and taking "fill-in" rock samples over the identified anomaly. Soil samples must be closely spaced along traverses normal to the trend of the geochemical anomaly, which presumably reflects the concealed massive sulfides. The grid should have an interval only slightly greater than the dimensions of the minimum-sized massive sulfide deposits. Considering the surface expressions of known deposits in northern Oman, grid lines 50 m apart with samples taken every 25 m are recommended. The lithology should be mapped on every sample line.

Such a grid soil geochemical survey would define drill targets on the basis of the metal's absolute value, the Cu/Zn ratio and field relationships. If additional indicator elements are used, the idea of vertical geochemical zonation should be utilized. For example, high values of cobalt and molybdenum are typical for a zone beneath the ore; high copper and zinc are obviously characteristic of the deposit itself; lead, barium and silver are indicative of an above-ore (overburden) zone.

6. Use of Wadi Sediments for Geochemical Exploration

Wadi sediments could be used for geochemical exploration in spite of the negative factors, such as a very low level of precipitation, an absence of permanent water courses, an abundance of eolin sand in the wadi sediment, and poor sorting of the wadi alluvium. The critical factor is what size fraction should be sampled.

The theory of epigenetic geochemical mobility shows that ore minerals could be transported in the weathering environment either by mechanical dispersion (solid phase) or as a metal-salt soluble phase. In the desert areas mechanical dispersion plays a far greater role than hydromorphic dispersion (on a 20:1 ratio). It may follow from this that coarse fractions of wadi sediments reflecting a mechanical dispersion should be more indicative of mineralization than the traditional -80 mesh fraction. Indeed, results obtained by Solovov (1959) in the Kara-Kum desert, USSR; Bugrov (1974) in the Eastern Desert, Egypt; Theobald, et al. (1979) in the Sonora Desert, Mexico; and Theobald, et al. (1977) in the Rub-al-Hali Desert, Saudi Arabia, demonstrate very clearly that geochemical data from the conventional -80 mesh sediment showed no correlation with the geology and mineralization. This reflects the inability of silt and argillaceous materials in wadi alluvium to absorb much metal from the surface and temporary underground streams. The above studies also showed that -30 mesh fraction proved to be the most satisfactory for analysis. At times, material as coarse as -20 mesh proved most useful. Discrete, heavy, relatively coarse detrital minerals contributed most of the anomalous metals. The -30 mesh fraction had the added advantage of being easier and faster to collect than the conventional -80 mesh fraction.

It is recommended, therefore, that a coarse-fraction wadi sediment survey be utilized for district-level prospecting. Sample spacing and sample arrangement with regard to minor wadi channels should be the same as in any other stream sediment survey.

## IV. Computer Data Processing

Rock and soil geochemistry data should be computer processed, using visual display, statistical and graphic interpretation techniques.

USSC has state-of-the-art computer programs combined into such packages as STATPACK, SURFACE II, and PACKAGE FOR INTERPRETATION OF RECONNAISSANCE AND PROPERTY EVALUATION DATA. The hardware configuration at U. S. Steel's exploration office includes two Tektronix visual display terminals, large digitizer, minicomputer PDP-1123 and main frame computer CDC CYBER-175.

USSC has a staff of experienced geologists and programmers who work with similar rock and soil geochemical data on a routine basis and would be in a position to handle the northern Oman data quickly and efficiently.

Edward I. Bloomstein, Ph.D.
Senior Geologist

EIB/cwb

# وجود الكبريتيدات المتكتلة الحاملة النحاس في أفيوليت سميل بسلطنة عمان

ر.ج. كولمان، س.س. هستون ، أ.م. البوشي، ك.م.الهنائي، أ.هـ.بيلي


## الخلاصة

ان أفيوليت سميل بعمان جزء من سلسلة جبال الشرق الأوسط الألبية حيث يكون الجزء الجنوبي من "الهلال الأفيوليتي القبل العربي" وهو يتكون من أطباق دفع تدل بنيتها الداخلية على استقلال كل منها عن الأخرى في أثناء التكرار البنائي لتتابع الأفيوليت كما تشير الى انقلاب القطاع في بعض الحالات . وحدات خليط في قاع التتابع تغطيها بيريدوتيتات مسربنتنة تشمل ٦٠ ٪ من منكشف الصخور. والهارزبرجيت هو أهم صخر أصلي في تكون البيريدوتيت مع أجسام من الدونيتات متخالفة توجد في أعاليها كتل من الكروميت ويعلو الهرزبرجيتات والدونيتات نطاق انتقال ذو أنسجة تراكمية يتدرج علويا الى صخور من الجابروطباقية ثم كتلية نادرة التطبق وفوق الجابرو توجد البلاجيوجرانيتات والتماس بين الجابرو مايعلوه من جدد الدياباز الفريشية تخالف بالغ .

هذا وإن الجدد الفريشية دقيقة التحبب وذات نسيج احتوائي نما بين البلاجيوكلاز (أن ٤٠-٨٠) والكلينو بيروكسين (ح ر٩٠ مغ ٤٥ر٥ كا ٤٥ر٥) - أما البركانيات (وهي قرابة ٣٠٪ من المنكشف) فهي تحوي الوسائد والفتات الزجاجية بين الوسائد وقد تحولت بالحرارة الى تجمعات من الزيوليت والشست الأخضر ، وتبين الدراسات الصخرية أن تكون الأفيوليت كان متعدد الأصول وأن أحداث هذا التكون ربما كانت قد جرت في مركز انفراج في بحر التيثيس (البحر الأوسط) لا على حافة قارية لشبه الجزيرة العربية .

كشف أكثر من ١٥٠ موضع كبريتيد النحاس الكتلي خلال الأفيوليت أعظمها تلك التي في لابات الوسائد قرب القمة بعضها مع الصدوع في مركز التمعدن والبعض الآخر على طول الصدوع في اتجاه الشمال الغربي المتعلقة بالبنائيات الحدث .

وعلى طول التماس بين تراكمات الجابر والبيريدوتيت تتعدد شواهد النحاس الصغيرة . وهي بوضعها هذا مع خبثها القديم الغني بالنيكل توحي بأن هذه الكبريتيدات وقد تكون مرتبطة بتاريخ الجابرو التراكمي . والكبريتيدات الكتلية تتكون أساسا من البيريت والكالكوبيريت هذا دائما يكون أحدث تكونا وغالبا مايصحبه الاسفاليريت في الكسور - هذا وفي ألباب الحفر يوجد قليل من البورنيت والكالكوسيت .

والتحول الحراري الواطئ الدرجة الذي يعتري البركانيات والأجزاء العليا من الجابرو ربما يعزى الى مياه المحيط الدوّارة الساخنة الناتجة عن التدفق العالي الحرارة قرب مركز الانفراج. وهذا الحدث الحراري قد يكون المسئول عن قرارات النحاس كما هي الحال في قبرص . هذا وإن التصدع الدافع المتراكب داخل الأفيوليت والتشوه الشديد على طول حافته الأمامية والتشوه الخفيف عند حافته الخلفية توحي كلها بوضع الأفيوليت في مكانه الحالي نتيجة الانزلاق بالجاذبية .


# THE SEMAIL OPHIOLITE AND ASSOCIATED MASSIVE SULFIDE DEPOSITS, SULTANATE OF OMAN


R. G. COLEMAN[1], C. C. HUSTON[2], I. M. EL-BOUSHI[3], K. M. AL-HINAI[3] and E. H. BAILEY[1]

[1]U.S. Geological Survey, Menlo Park, California, U.S.A.
[2]*President of Prospection Limited, Toronto, Ontario, Canada*
[3]Directorate General of Petroleum and Minerals, Muscat, Sultanate of Oman



**Abstract**—The Semail ophiolite is part of the Middle East alpine mountain chain and forms the southern part of the "Pre-Arabian ophiolite crescent". It is made up of thrust plates whose internal structure suggests interplate independence during tectonic repetition of the ophiolite sequence and in some instances overturning of the section. Melange units at the base are overlain by serpentinized peridotites which comprise 60% of the outcrop. Harzburgite is the most important original rock of the peridotite with discordant bodies of dunite. Chromite bodies occur at the top and in these dunites. A transition zone overlies the harzburgites and dunites. It exhibits cumulate textures and grades upwards into layered, and finally massive, gabbros exhibiting rare layering. Plagiogranites are found at the top of the gabbro. The contact between gabbro and overlying sheeted diabase dikes marks a major unconformity. The sheeted dikes are fine grained and have ophitic texture developed by plagioclase and clinopyroxene. The volcanics contain pillows and inter-pillow hyaloclastics. They have been thermally metamorphosed to zeolite and greenschist assemblages. Petrologic reconstruction shows that ophiolite formation was polygenetic and that these processes probably took place at a spreading center in the Tethys Sea and not on a continental margin of the Arabian Peninsula.

Over 150 massive sulfide Cu prospects have been discovered throughout the ophiolite, but those in the pillow lavas close to the top are the largest. Some show association to faults central to the mineralization. Others lie along N.W.-trending faults related to younger tectonics. Along the contact between cumulate gabbro and cumulate peridotite are numerous small Cu prospects. Their occurrence and their Ni-rich ancient slags suggest that these sulfides may be related to the history of the cumulate gabbros (of the Duluth gabbro). The massive sulfides consist mainly of pyrite and chalcopyrite. The chalcopyrite is always late and often accompanied by sphalerite in fractures. Minor bornite and chalcocite occur in drill cores.

The low grade thermal metamorphism of the volcanics and the upper parts of the gabbro is probably related to hot circulating oceanic waters produced by high heat flow near the spreading center. This thermal event (as in Cyprus) may be responsible for the Cu deposits. The imbricate thrusting within the ophiolite, combined with strong deformation along its leading edge and mild deformation at its trailing edge, suggest emplacement by gravity sliding.

## INTRODUCTION

New sulfide deposits have been discovered within the Semail ophiolite which is located in the northern part of the Sultanate of Oman. A mineral exploration program started in 1973 by Prospection (Oman) Ltd., under agreement with the Sultanate of Oman has led to these new discoveries. Archaeological research on the Island of Baharain by a Danish group (Bibby, 1969) described possible shipments of copper during the Third Millenium originating from "Makan or Magan" which is believed to be the mountainous part of Oman. A literature search and geologic comparison of northern Oman with Cyprus persuaded C. C. Huston that the Semail ophiolite was an excellent exploration target for copper. Early in the exploration program, evidence of ancient copper mining was found in many areas of Oman. Ancient slag heaps showing traces of copper and charcoal inclusions were clear indications of smelting by early man. Carbon 14 age measurements on charcoal from these slag heaps indicate these deposits had been worked as late as 1500 A.D., but archeological evidence shows that these deposits were also worked as early as the Third Millennium, thus confirming the earlier archeological studies on Baharain (Bibby, 1969).

Most of the ore bodies have large slag heaps associated with them as well as conspicuous brightly colored gossans, so their recognition was easily accomplished. However, airborne electromagnetic surveys were also carried out over selected areas of the Semail ophiolite. Promising anomalies were followed up by ground geochemical and geophysical surveys that included electromagnetic, gravity, and magnetic intensity methods. The outcome of the combined geological, geochemical, and geophysical methods has led to over 100 mineral prospects, mostly copper but also including chromite, nickel, lead, zinc, silver, and gold as by-products. Three of the more promising massive sulfide bodies have been drilled in sufficient detail for evaluation and the aggregate drilling indicates proven and/or probable ore reserves of the order of 20 million metric tons at approximately 2 percent Cu. Feasibility studies have been completed on the Lasail, Aarja, and Bayda prospects, and production is contemplated in the near future. The purpose of this paper is to provide a geologic description of these deposits and to relate their occurrence to the Semail ophiolite. This work was carried out under an agreement with the Ministry of Agriculture, Fisheries, Petroleum, and Minerals of the Sultanate of Oman and the U.S. Geological Survey.

## GEOLOGIC SETTING

The Semail ophiolite is part of the Middle East alpine mountain chain forming the southern-most part of the "peri-Arabian ophiolite crescent" that can be followed westward from Oman through Neyriz and Kermanshah in Iran, along the Turkish-Iran border fold belt and finally into Hatay and Cyprus (Ricou, 1971). It is now considered that the ophiolites of the peri-Arabian crescent represent oceanic crust formed in the "Paleo-Tethys" Sea as described by Stocklin (1974). The Semail ophiolite is perhaps the largest (30,000 cubic kilometers) and the best exposed section of ancient oceanic crust in the world (Fig. 1). Recent studies of the Oman mountains have provided new insights on the geology (Glennie *et al.*, 1974; Glennie *et al.*, 1973; Reinhardt, 1969; Allemann and Peters, 1972). Earlier reports on the Oman mountains were of

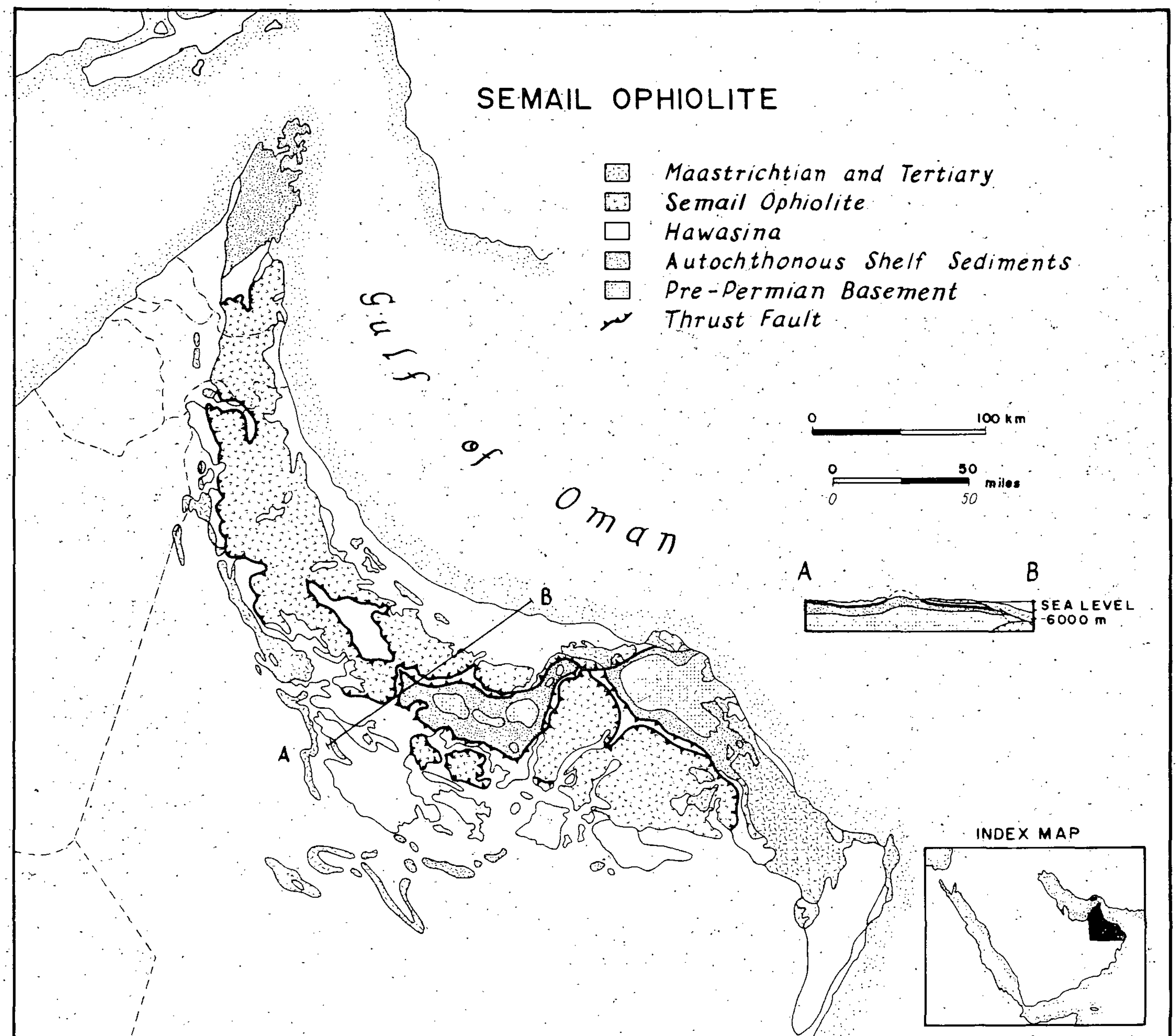



FIG. 1. General geologic setting of the Semail ophiolite in Oman.

reconnaissance nature and provide only sparse information on the Semail ophiolite (Hudson *et al.*, 1954; Morton, 1959; Hudson and Chatton, 1959; Hudson, 1960; Tschopp, 1967; Wilson, 1969; Greenwood and Loney, 1968) and, up to now, there are no published detailed and systematic studies of the ophiolite.

The geologic setting of the Oman mountains can best be understood by dividing the rock units into four groups in sequence from the basement upwards (Fig. 1).

(I) Basement autochthonous rocks represented by Paleozoic and possible Precambrian rocks unconformably overlain by a thick sequence of shallow shelf carbonates (Hajar Super-Group, Mid Permian to Cenomanian), which are characteristic for the whole eastern Arabian continental margin and the Zagros fold belt in Iran. Continental edge and slope deposits consisting of supratidal and open marine reefal facies (Sumeini Group, Permian to Cenomanian).

(II) Hawasina unit of deep water chert, shales, and limestones deposited during the same time span (Permian to Cenomanian) as the Group I autochthonous sediments. These sediments were deposited in an environment representing a continental rise and ocean basin situated N.E. of the present east Arabian continental margin (Glennie *et al.*, 1974).

(III) The Semail ophiolite, a thick sequence of ultramafic and mafic rocks thought to represent ancient oceanic lithosphere (Cenomanian). The Semail ophiolites and Hawasina units are allochthonous units tectonically emplaced during the Late Cretaceous above the Group I autochthonous sediments with the ophiolites being the highest structural slice. Emplacement of the Hawasina and Semail ophiolite has produced chaotic masses of melange underlying the ophiolite and containing mountain-size exotic blocks of Permian reefal limestone. Metamorphic zones formed at the base of the Semail ophiolite may be related to earlier hot detachment of these ophiolites in the Tethys trough.

(IV) Thick, shallow water marine limestones of Late Cretaceous to Middle Tertiary age represent a transgressive sequence following the tectonic emplacement of the Semail ophiolites.

All of the units in Groups I to IV have been involved in simple compressional up-folding sometime during the Oligocene and Miocene. This up-folding was followed by Late Tertiary normal faulting and recent uplift along the axis of the Oman mountains. Thus the emplacement of the Semail ophiolite coincides with Eo-Alpine orogenesis and marks the closing of the Tethyan Sea during the Late Cretaceous. Since the Semail ophiolite contains all of the copper deposits within the Oman mountains and these copper-rich massive sulfides appear stratabound within the pillow lavas of the ophiolite, it appears reasonable to assume that these deposits formed on the sea floor during volcanogenic processes developed at spreading centers (Sillitoe, 1972, 1973; Spooner *et al.*, 1974; Duke and Hutchinson, 1974) prior to the emplacement of the Semail ophiolite on the Arabian shelf carbonate platform.

## SEMAIL OPHIOLITE

It is possible to divide the Semail ophiolite into the following units (Reinhardt, 1969) that form a superposed sequence starting from the bottom to the top:

(1) Metamorphic zone including garnet amphibolites and greenschist assemblages.
(2) Peridotite section including both tectonized and cumulate ultramafic rocks.
(3) Transition zone referred to as PG by Reinhardt.
(4) Gabbro section including both cumulate and massive rocks as well as plagiogranites and encompassing Reinhardt's G and HG units.
(5) Diabase dike section.
(6) Pillow lavas and interbedded umbers.

The Semail ophiolite does not consist of a continuous sheet or nappe, but is made up of individual thrust plates whose internal structures suggest interplate independence during tectonic emplacement. Internal low angle thrust faults have led to tectonic repetition of the ophiolite sequences and, in some instances, overturning of the section. Post-emplacement vertical faults have offset sequences, but some offsets within the gabbro-peridotite do not extend into overlying diabase and gabbro, suggesting pre-emplacement deformation at the Tethys spreading ridge. In a general way, there appears to be more deformation and serpentinization of the peridotites on the leading edge of the nappes (west and south) than on their trailing edges (east and north).

Melange units are more common than the garnet amphibolites and greenschists at the base of the Semail ophiolite and consist mainly of Hawasina units immersed in matrix consisting of fine-grained broken fragments from the same unit. It is rare that these melange units have a serpentinite matrix or other broken fragments of the ophiolite.

The peridotites comprise 60 percent of the outcrop area of the Semail ophiolite and form a characteristic topography of sharp peaks with a fairly low relief. These rocks have been pervasively serpentinized (60–100 percent) under static conditions so that the present appearance is of a very dark-colored, friable, and fractured rock.

Harzburgite is the most important original rock type and consists of 60–80 percent olivine ($Fo_{90}$) and 10–25 percent orthopyroxene ($En_{90-91}$) with accessory chromite. The harzburgites show a faint layering and, in some instances, a strong tectonic fabric can be seen. Discontinuous lenses and larger (2–4 km) discordant bodies of dunite are present within the harzburgite, and chromite bodies are found in these dunite masses. Orthopyroxene and gabbro dikes, from one centimeter to 1/2 meter thick, commonly cut the harzburgite. Up to now, there is very little known about the internal structures of the peridotite, and it is difficult to establish boundaries between cumulate layering and metamorphic peridotite.

The transition zone marks the first appearance of rocks clearly exhibiting cumulate igneous textures and containing plagioclase. It is characterized by alternating white and dark bands. The dark bands consist of cumulate olivine and clinopyroxene, whereas the light bands consist of anorthosites, troctolites, gabbros, and norites. Below this zone, extending 200 meters or more, are cumulate olivine rocks (dunite) some of which contain zones of chromite that also have cumulate structures. The banded rocks of the transition zone show a more iron-rich olivine ($Fo_{85-88}$) than found in the underlying harzburgite, and the associated plagioclase is very calcic ($An_{81-92}$) as is the clinopyroxene ($Fe_{58}Mg_{50}Ca_{44.2}$). The transition zone exhibits complex relationships with dikes of gabbro, anorthosite, or troctolite cutting the layered sequence.

The transitional zone grades gradually upward into layered gabbros and finally into massive gabbros exhibiting only rare layering. The main rock types in this zone are plagioclase ($An_{92-65}$)-rich gabbros containing various proportions of calcic clinopyroxene, olivine ($Fo_{72-85}$), and orthopyroxene. The layering in these gabbros seems concordant with the underlying transition zone but with fewer cross-cutting dikes. Higher in the section, as the diabase contact is approached, zones of brecciated meta-gabbro are invaded by leucogabbros. Quartz appears in some gabbros with granophyric textures developing. The sequence from the transition zone to the upper parts of the gabbro demonstrates progressive differentiation of these rocks from meta-gabbros on up to leucogabbros. Small individual masses of plagiogranite at the top of the gabbro represent the end product of the differentiation and consist essentially of quartz and sodic plagioclase with minor hornblende. The plagiogranites form irregular bodies that cross-cut the massive and layered gabbros and, where extensive brecciation is present, this same plagiogranite has infiltrated the gabbroic breccia.

The contact between the gabbros and overlying sheeted diabase marks a major unconformity in the Semail ophiolite. At the contact, diabase dikes with chilled margins extend downward into the gabbro and cross-cut all existing structures. Large-scale mapping has shown that widespread folding of the gabbros had taken place prior to dike emplacement. The sheeted dikes of Semail ophiolite are sub-parallel, ranging in width from five centimeters to several meters, and exhibiting chilled margins against one another. There are no country rock screens yet reported from these dike swarms, and both asymmetric and symmetric chill zones are present, suggesting a mechanism of emplacement similar to that postulated for Cyprus (Moores and Vine, 1971). The sheeted dikes are fine grained and have ophitic texture developed by plagioclase ($An_{40-80}$) and clinopyroxene ($Fe_9Mg_{45.5}Ca_{45.5}$). Generally, the diabase shows an overprint of greenschist facies thermal metamorphism with quartz, albite, actinolite, epidote, and chlorite replacing the original minerals. Leucocratic dikes having compositions similar to the underlying plagiogranites may have extensive development within the dike swarms and locally predominate over the more mafic dikes.

The volcanics of the Semail ophiolite are the least abundant rocks (~3 percent) and generally form low rounded hills with poor exposures. The dike swarm contact with the overlying pillow lavas is marked by increasing screens of lava between the dikes and anastomosing of the dikes into cross-cutting relationships demonstrates that they acted as feeders for the pillow lavas. Nearly all of the volcanics exhibit pillow structures and contain interpillow hyloclastites. Where the attitude of the pillows can be ascertained in relationship to the strike of the sheeted dikes, the angle is approximately 90°. Thus, there seems to be no tectonic break or unconformity between the pillows and diabase dike swarm. Near the top of the Semail pillow lavas, interlayered ironstones (umbers) are present in many areas and resemble those described from Cyprus (Robertson, 1975). Sediments in a normal sequence above the pillows are of Cenomanian and Coniacian age and provide a minimum age on the formation of the ophiolite (Glennie *et al.*, 1974).

The volcanics have all undergone a thermal metamorphism producing zeolite and greenschist assemblages. The preserved textures are dominantly intersertal with some porphyritic and variolitic varieties. The feldspar is typically albite associated with chlorite, epidote, quartz, and unaltered augite and ilmenomagnetite. Actinolite replaces the pyroxene, and the vesicles contain varying proportions of calcite, quartz, and laumontite. The degree of alteration in the volcanics is similar to that described in the Cyprus pillow lavas (Gass and Smewing, 1973), and there also appears to be a downward increase in metamorphic grade into the diabase and gabbro units, but terminating downward somewhere in the gabbro section.

The petrologic reconstruction of the Semail ophiolite shows that its formation was polygenetic, and that these processes probably took place at a spreading center in the Tethys Sea and not on the continental margin of the Arabian Peninsula. The basal peridotite has an apparent uniform composition and exhibits evidence of having been deformed under subsolidus conditions. Estimation of temperature and pressure expressed by partition coefficients and pyroxene compositions within the peridotite indicate that temperatures attending peridotite formation were in excess of 1200°C, and pressures approached 7 kb (Reinhardt, 1969). The creation of such a large mass of uniform peridotite at these temperatures and pressures requires that this part of the Semail ophiolite formed within the upper mantle. It seems most probable that the Semail peridotite represents a refractory residue formed during a partial melting event in the mantle.

The overlying transitional and gabbro zones are more obviously derived from a fractionating mafic melt. Precipitation of cumulate olivine and chromite signals the beginning of this fractionation. Decreasing $Mg/Mg + Fe$ ratios in the olivines of the gabbros indicates a progressive trend; however, sharp reversals in the cumulate sequence into more mafic layers on top of less mafic layers indicates cyclic events. These cyclic events combined with brecciation, peculiar dike sequences, and pre-diabase faulting, all point to the transient nature of the fractionating magma source. The overlying sheeted dike sequence and pillow lavas, apparently formed at a spreading center, developed after the deformation of the transient underlying cumulate sequence. Thus, there is evidence of three distinct penecontemporaneous events taking place at the spreading center: (1) production of a partial melt residue and its plastic deformation in the mantle; (2) formation of a magma chamber and development of cumulate sequences by cyclic and random invasions of magma having undergone variable degrees of fractionation; and (3) invasion of basaltic and differentiated magmas along vertical tension fractures and out-pouring of lavas on the ocean floor. The low-grade thermal metamorphism present in the pillow lavas, diabase dikes, and upper parts of the gabbro is related to hot circulating ocean waters produced by the high heat flow near the spreading centers as has been described on Cyprus (Gass and Smewing, 1973; Spooner and Fyfe, 1973). The discovery of widespread copper deposits within the hydrothermally altered Semail pillow lavas further strengthens its analogy with Cyprus ophiolite and associated massive sulfide deposits (Huston, 1975; Bailey and Coleman, 1975).

## OCCURRENCE OF COPPER IN THE SEMAIL OPHIOLITE

Copper prospects occur throughout the vast thickness of the Semail ophiolite, but those developed in the pillow lavas, especially those near the top of the pillow lavas, contain the largest tonnages of ore. The position of some of these deposits within the ophiolite is shown diagrammatically on Fig. 2. The ore bodies proved out by drilling within the pillow lavas consist mainly of massive sulfide (pyrite). Through oxidation, the pyrite has given rise to acid waters that have produced brightly colored, extensively leached, gossan outcrops. These gossan zones with their underlying ore bodies are small in areal extent, being generally elliptical in plan with major axes from 30 to 150 m. Downward extension of these ore bodies to at least 200 meters has been proved by drilling (Fig. 3). Certain ore bodies are not elliptical, but elongate and apparently fault controlled. Typically the pillow lavas associated with these ore bodies have undergone zeolite facies alteration, but extensive veins or fractures showing alteration products or mineralization are not present.

The bright orange, red, brown, or yellow colors of the gossan make the exposed deposits easy to find. However, distinguishing gossans over sulfide deposits that contain copper from those that are barren is difficult. Where there are secondary copper minerals in the outcrop, the deposits have invariably been found and worked in ancient times. Black slag piles dot the landscape surrounding the deposits, and in some places there are extensive ruins of old reduction furnaces. But, where the leaching of the gossan has been most intense, the original copper sulfides have been dissolved, and no secondary copper minerals are left behind. As a result, in some deposits, secondary copper minerals can be seen in the less altered periphery but not in the most mineralized core. The surface shape of the gossan generally mimics the subsurface extent of the massive sulfide body. The oxidation of the massive sulfides in the gossans has produced a loss in volume, so much so, that in some gossans depressions develop. Generally, the gossans extend less than 10 m below the surface forming a very porous and incoherent mass. In some places, copper leached from a gossan is redeposited at the base of the leached zone but no zone of secondary enrichment has been noted. The oxidation of the pyrite appears to have formed

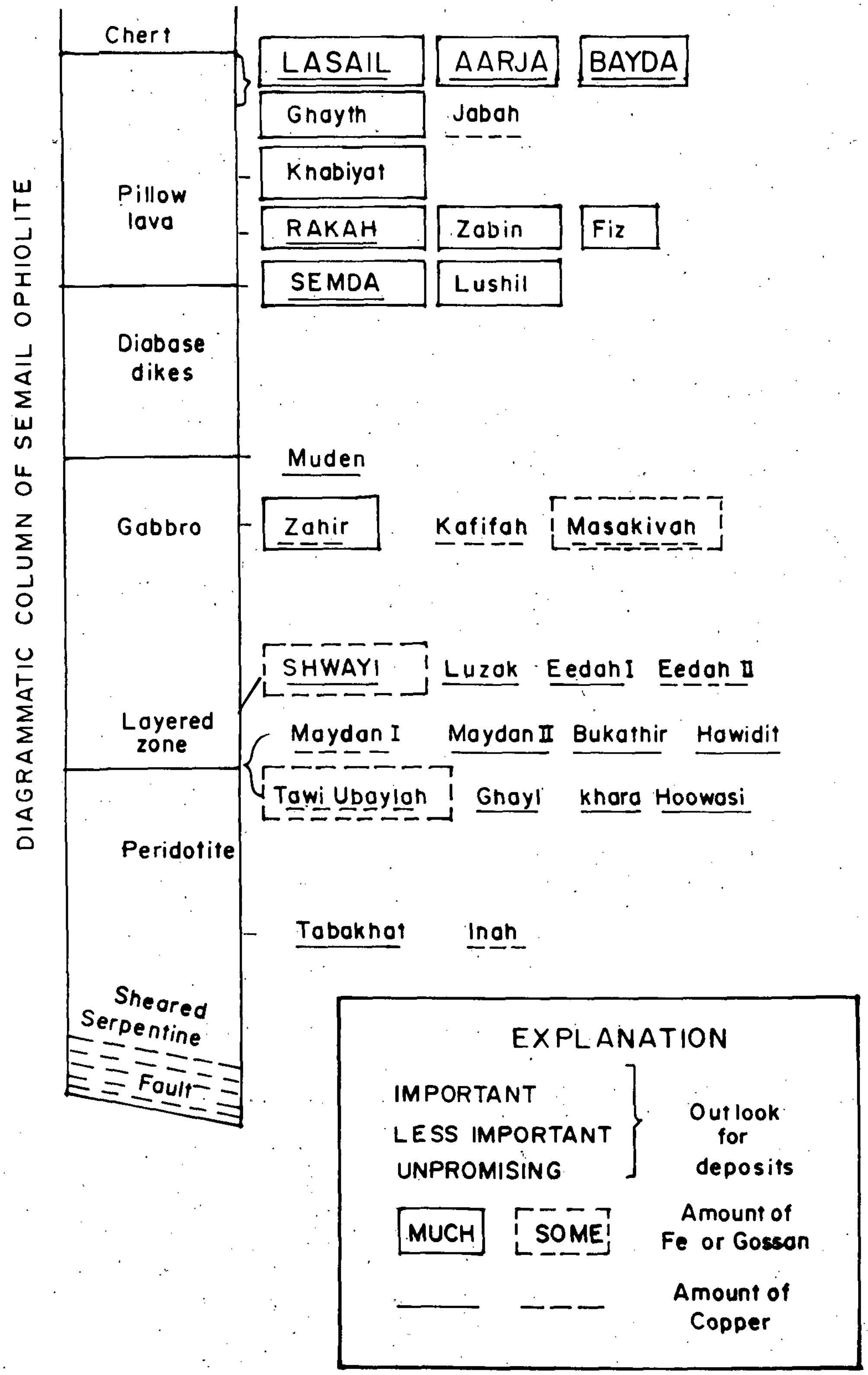



FIG. 2. Diagram showing distribution and other features of 29 copper-iron sulfide deposits in the Semail ophiolite.

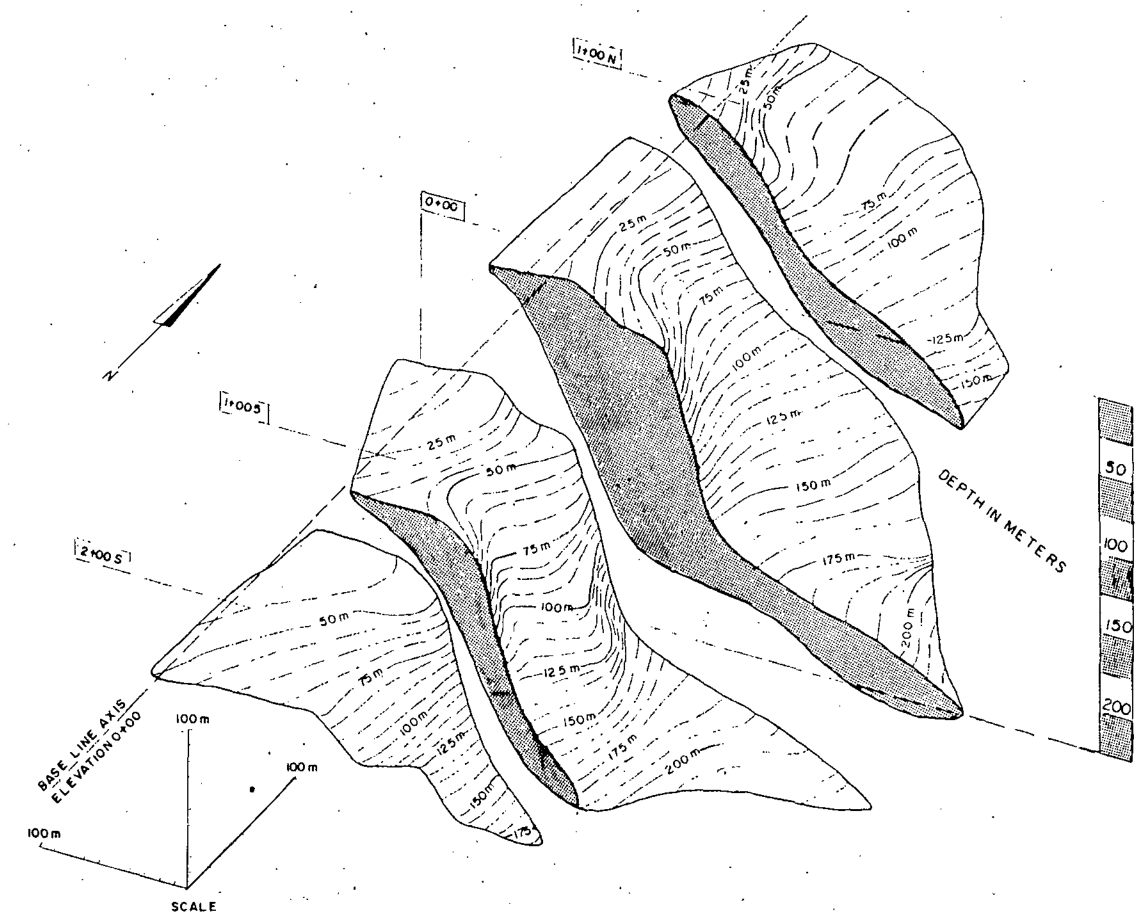



FIG. 3. Isometric diagram of the Lasail ore body.

strong solvents such as sulfuric acid and iron sulphate. The most important secondary minerals that make up these gossans are goethite, jarosite, hematite, gypsum and, more rarely, natroalunite.

The most important massive sulfide deposits are located in an area referred to as the "Bowling Alley" 35 km west of Sohar and terminated on the south by Wadi Jizzi (Fig. 4). By their shape, some deposits in the Bowling Alley indicate fault control to the mineralization. Others seem to lie along N.W.-trending faults related to younger tectonics. It is worth noting here that there are no deposits within the sheeted dikes except for two gossans that are found at the very top of the sheeted dike section.

The lower gabbro and peridotite parts of the Semail ophiolite contain numerous copper prospects, but none of these has proven large tonnages of massive sulfide (Fig. 2). Many of these were mined in ancient times. Most of these deposits are along the contact between cumulate gabbro and cumulate peridotite that localized steep faults along this boundary. The mineralized zones are narrow, usually less than 8 m wide, have lengths of less than 300 m, and generally are poorly exposed. Primary chalcopyrite was found in some places as discrete grains within the gabbro, but the usual ore in outcrop contains only secondary copper minerals. In contrast to the ores in the lavas, these deposits typically contain minor amounts of pyrite,

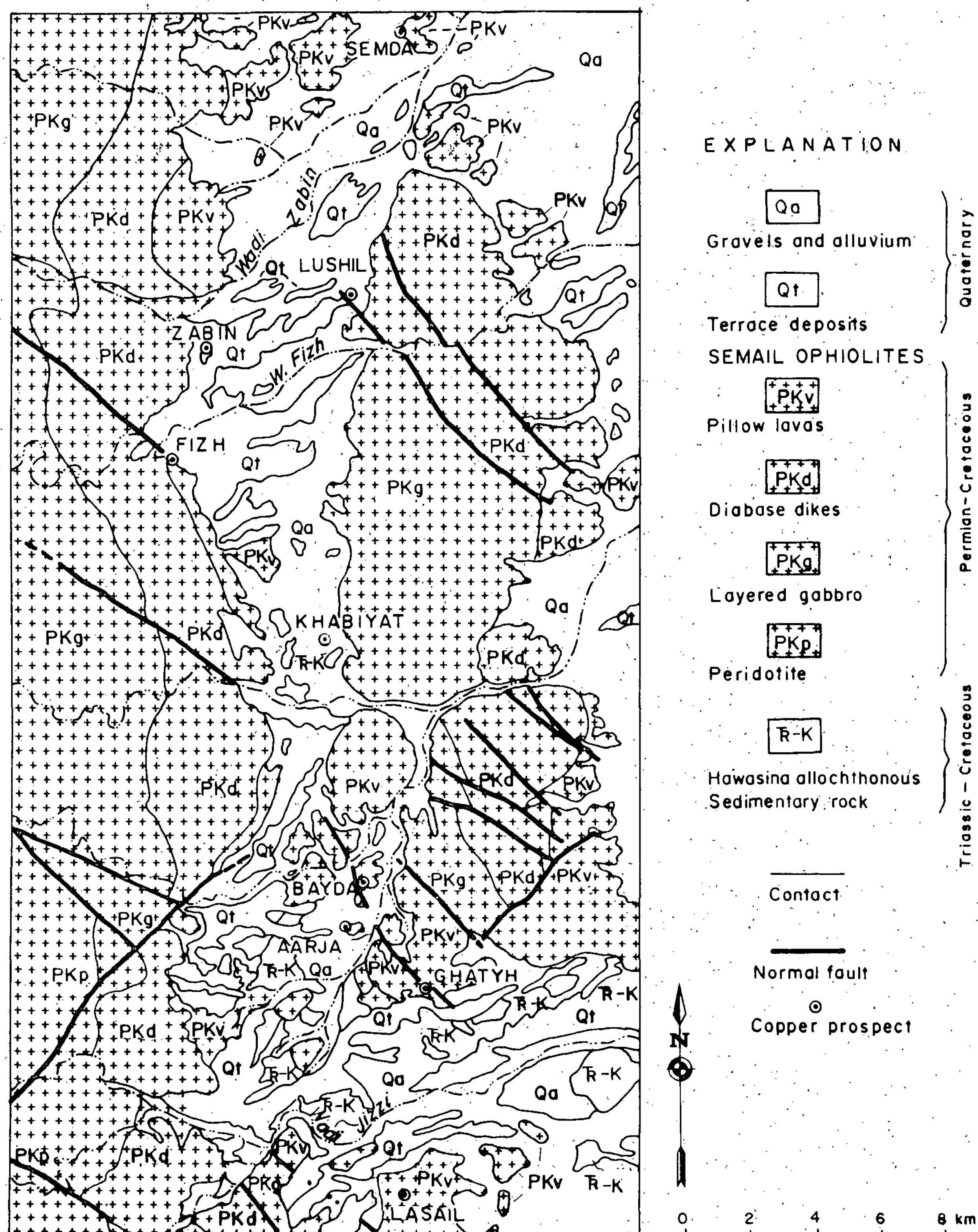



FIG. 4. Geologic map of the "Bowling Alley" area showing the relation of copper-iron sulfide deposits in volcanic rock in the upper part of the Semail ophiolite to N.W.-trending faults.

and they generally exhibit only a little iron staining rather than a heavy gossan. Their consistent occurrence at the base of the cumulate gabbros and the high nickel content of their ancient slags strongly suggest that these sulfides may be related to the igneous history of the cumulate gabbros similar to the sulfide deposits of the Duluth gabbro.

## ORE MINERALOGY

The massive sulfide ore zones consist mainly of pyrite (>95 percent) which exhibits no relict structures of the host basalt that bounds the deposits. The pyrite assumes various habits within these zones. Euhedral to subhedral pyrite forms a compact ore having bright color both in hand specimen and in polished section. This type of ore invariably has been fractured with infilling of quartz, chalcopyrite, and gypsum. Some zones of massive pyrite are very porous and friable breaking down into sulfide sand. This pyrite is usually dull and has a low reflectivity and is much more susceptible to oxidation when exposed to the atmosphere after drilling. Occasionally, colloform textures have been recognized, but it is difficult to establish the relationship of this layering to the more massive sulfides.

Chalcopyrite is the main ore mineral in the massive sulfide bodies and varies from less than 1 percent to more than 30 percent in some drill cores. The chalcopyrite is always late and is found in fractures or veins replacing pyrite. The chalcopyrite is often accompanied by sphalerite in the fractures. In those specimens where chalcopyrite is the dominant mineral, it encloses anhedral pyrite grains. The drill core data on the various deposits does not allow any generalization as to the distribution of chalcopyrite within the massive sulfide bodies. Minor amounts of bornite and chalcocite have been observed in the drill cores. Up to now, neither marcasite nor pyrrhotite have been reported in the massive sulfide bodies.

Drill core penetration below the massive sulfide bodies have intersected vein structures and strongly altered rock which may represent a stock-work system similar to those described from Cyprus (Searle, 1972). These veins consist mainly of euhedral pyrite associated with quartz, gypsum, and only very minor chalcopyrite.

Mineralogical and chemical analyses of massive sulfide drill-core samples from Lasail and Aarja are given in Table 1. The mineralogy of all samples is quite simple as explained above, and the distribution of copper is very erratic. Minor and trace elements provide some insight to these deposits. The nickel:cobalt ratios suggest that these deposits are enriched in cobalt relative to nickel and, in the case of the Lasail deposit, the Co averages more than 800 ppm. The enrichment of cobalt in the Cyprus iron sulfides as well as in pyrite from most hydrothermal deposits is characteristic. However, cobalt in the Aarja deposit does not show this same pattern and has an average cobalt less than 15 ppm. This striking difference in minor elements between Lasail and Aarja is further reinforced by arsenic. No arsenic was detected in Lasail whereas the Aarja deposit has significant amount (~ 1000 ppm As). Minor but consistent differences in Mo and Pb further strengthen the idea that these deposits were formed by ore fluids of distinct history.

## DISTRIBUTION OF Cu, Ni, Co, AND Zn

We have tried to establish the background content of S, Cu, Ni, Co, and Zn for the pillow lavas, diabase, and gabbros within the Semail ophiolite. Samples used for analyses were not mineralized and are considered to be representative of the rock types; however, it must be borne in mind that these rocks have undergone a certain amount of hydrothermal alteration. Therefore, the values for these elements cannot be considered representative of the original igneous rocks (Table 2). The basalts and diabase have nearly the same average values for Cu and Ni, but S and Co increase from basalts to diabase and Zn decreases. The gabbro average shows a much higher Ni content than the diabase or basalt, whereas S, Cu, and Co are nearly the same. If the average values from the Oman basalt and diabase are compared with various basalt averages from Cyprus, we find that Cu is nearly three times higher in Cyprus with Zn, Co, and Ni nearly the same. Assuming that both the Cyprus and Oman rocks have been affected by oceanic hydrothermal metamorphism, it is worth comparing the average amounts of these transitional elements in unaltered basalts and their glasses from the oceans (Table 2). The Cu concentrations in these unaltered basalts and their glasses are 2 to 4 times greater than in similar rocks from Oman and Cyprus. The relationships with Ni and Co are not quite as clear. There seems to be some depletion of Co, but Ni is somewhat erratic because of the strong influence olivine has on its distribution in basalts.

Comparing the ratios of Cu:Zn, Cu:Co, and Ni:Co in the pillow basalts and diabase dikes from Oman with the same ratios in the massive sulfide ores, we can immediately see that Fe, Cu, Zn, and Co are the main transition elements enriched in the massive sulfide ores. If the ore forming fluids that produced the massive sulfide deposits were derived by circulation of hot oceanic waters within the basalts and diabase of Oman, there is every indication that those elements enriched in the ore deposits have been depleted in the Oman ophiolite itself.

TABLE 1. MINERALOGICAL AND CHEMICAL COMPOSITION OF SELECTED DRILL CORE SAMPLES OF THE LASAIL AND AARJA MASSIVE SULFIDES[2].

| Sample No. | Hole No. | Depth m | Minerals[1] | % | ppm | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Cu | Ti | Mn | Ag | As | Ba | Co | Cr | Mo | Ni | Pb | Sc | Sr | V | Zn | Cu:Zn | Cu:Co | Ni:Co |
| | | | | | | | | | Lasail | | | | | | | | | | | | |
| OM-1 | 2-2 | 89.0 | Py, Cp | 7.36 | 0.002 | 100 | 5 | — | 50 | 700 | 2 | 105 | 2 | 5 | — | 2 | 20 | 70 | 105 | 10.5 | 0.003 |
| OM-2 | 2-2 | 140.7 | Py, Q | 0.24 | 0.005 | 50 | 3 | — | 10 | 1500 | 3 | — | 7 | 10 | — | 2 | — | 150 | 16 | 1.6 | 0.005 |
| OM-3 | 2-2 | 226.0 | Py, Q | 0.19 | 0.005 | 20 | 7 | — | 10 | 500 | 5 | 30 | 3 | 20 | — | 1 | — | 300 | .6 | 3.8 | 0.006 |
| OM-4 | 2-3 | 60.3 | Py, Q, Cp | 1.74 | 0.100 | 70 | 3 | — | 300 | 1000 | 5 | — | 7 | 10 | 5 | 3 | 30 | 200 | 87 | 17.4 | 0.007 |
| OM-5 | 2-5 | 147.5 | Py, Cp | 11.10 | 0.002 | 300 | 15 | — | 5 | 150 | 2 | — | 15 | 30 | — | 2 | 15 | 1000 | 111 | 740.0 | 0.100 |
| OM-6 | 2-6 | 94.0 | Ry, Q, Cp | 0.71 | 0.001 | 30 | 5 | — | 15 | 1000 | 2 | 300 | 2 | 20 | — | 2 | 7 | 200 | 36 | 7.1 | 0.002 |
| OM-7 | 2-6 | 127.0 | Ry, Q | 0.01 | 0.050 | 50 | 7 | — | 150 | 500 | 3 | — | 3 | 7 | — | 3 | 10 | — | — | 0.2 | 0.006 |
| OM-8 | 2-7 | 52.0 | Cp, Q, Gy | 14.30 | 0.100 | 700 | 2 | — | 30 | 3000 | 7 | — | 7 | — | 7 | 3 | 20 | 100 | 1430 | 48.0 | 0.002 |
| OM-9 | 2-9 | 167.6 | Py, Cp, Q | 12.30 | 0.005 | 100 | 30 | — | 300 | 70 | 3 | 70 | 2 | 30 | — | 3 | 50 | 5000 | 24 | 172.0 | 0.020 |
| OM-10 | 2-9 | 303.3 | Py, Cp, Q | 0.04 | 0.020 | 100 | — | — | 5 | 1500 | 1 | — | 10 | 7 | — | 1 | 7 | 30 | 13 | 0.3 | 0.006 |
| OM-11 | 2-9 | 377.6 | Py, Q, Cp, Gy | 0.61 | 0.100 | 200 | 1 | — | 30 | 500 | 5 | 20 | 15 | 7 | 7 | 10 | 50 | 70 | 87 | 12.2 | 0.030 |
| OM-12 | 2-10 | 99.0 | Py, Cp, Q | 2.40 | 0.002 | 50 | 15 | — | 3 | 200 | 3 | 20 | 7 | 50 | — | 1 | — | 1000 | 24 | 120.0 | 0.035 |
| | | | | | | | | | Aarja | | | | | | | | | | | | |
| OM-13 | 10-2 | 66.4 | Py, Cp, Q | 1.57 | 0.020 | 300 | 15.0 | 700 | 30 | 20 | 7 | — | 5 | 150 | 3 | 2 | 30 | 2000 | 7.9 | 785.0 | 0.250 |
| OM-14 | 10-3 | 134.7 | Py, Q | 0.41 | 0.002 | 150 | 10.0 | 1000 | 15 | — | 2 | — | 5 | 100 | — | 2 | 10 | 3000 | 1.4 | — | — |
| OM-15 | 10-9 | 99.0 | Py, Cp, Q | 5.50 | 0.002 | 200 | 30.0 | 1000 | 3 | — | 3 | — | 7 | 150 | — | 1 | 20 | 2000 | 27.5 | — | — |
| OM-16 | 10-10 | 99.0 | Py, Cp, Q | 1.14 | 0.010 | 50 | 10.0 | 1000 | 15 | 10 | 5 | — | 5 | 150 | — | 2 | 20 | 3000 | 3.8 | 1140.0 | 0.500 |
| OM-17 | 10-13 | 123.1 | Py, Q | 0.03 | 0.003 | 500 | 1.5 | — | 100 | 10 | 3 | — | 5 | 30 | — | 30 | 15 | 500 | 0.52 | 26.0 | 0.500 |

[1]Py = pyrite; Cp = chalcopyrite; Q = quartz; Gy = gypsum; determined by X-ray diffraction.
[2]Total Cu determined by M. Cremer, spectrographic analyses by C. Heropoulos, Menlo Park, CA.

TABLE 2. DISTRIBUTION OF S, Cu, Ni, Co, AND Zn IN BASALTS, DIABASE, GABBRO IN OMAN COMPARED TO SIMILAR ROCKS*.

| Samples | S | Cu | Zn | Co | Ni | Cu:Zn | Cu:Co | Ni:Co |
|---|---|---|---|---|---|---|---|---|
| | | | | Oman | | | | |
| Pillow basalts (19) | 180 | 23 | 87 | 28 | 35 | 0.26 | 0.82 | 1.25 |
| Diabase dikes (42) | 410 | 28 | 63 | 45 | 39 | 0.44 | 0.62 | 0.87 |
| Gabbro (18) | 210 | 70 | 39 | 43 | 164 | 1.8 | 1.63 | 3.78 |
| | | | | Cyprus-Pillow Lava(1) | | | | |
| Olivine basalts IV | — | 68 | 51 | 37 | 248 | 1.3 | 1.8 | 6.7 |
| Basic basalts III | — | 71 | 59 | 34 | 107 | 1.2 | 2.1 | 3.2 |
| Basalts II | — | 64 | 56 | 29 | 52 | 1.1 | 2.2 | 1.8 |
| Altered basalts I | — | 82 | 74 | 34 | 27 | 1.1 | 2.4 | 0.8 |
| | | | | Red Sea(2) | | | | |
| Oceanic basalt (4) | — | 110 | — | 48 | 100 | — | 2.29 | 2.08 |
| | | | | Mid-Atlantic Ridge(3) | | | | |
| Basaltic glass (1) | 910 | 100 | — | 68 | 193 | — | 1.47 | 2.8 |
| | | | | Average Tholeiite(4) | | | | |
| Tholeiites | — | 127 | — | 39 | 84 | — | 3.25 | 2.2 |

*Number of analysed samples are given in two parentheses.
(1) After Govett and Pantaziz, 1977.
(2) After Coleman *et al.*, 1974.
(3) After Bryan and Moore, 1977.
(4) After Mason, 1968.

## ALTERATION TRENDS

The pillow lavas and sheeted dikes all have undergone pervasive hydrothermal alteration with apparent increasing thermal gradient downward into the upper gabbros and plagiogranites where it appears to die out (Donato and Coleman, 1976). The altered rocks retain their primary igneous textures even though the grade of metamorphism reaches amphibolite facies. The location of the massive sulfide ore bodies does not seem to be related to the intensity of the alteration.

The hydrothermally altered pillow lavas have a typical brownish color and are characterized by the presence of zeolites (Brown Zone). In a general way, the plagioclase is altered to albite with the glassy material being replaced by chlorite. Relict igneous clinopyroxenes are commonly present within the altered pillow lavas. Laumontite is the most common zeolite but often is associated with natrolite, dachiardite, and analcite. The brownish color results from the breakdown of the primary magnetite to hydrated iron oxides and hematite. Smectite has not yet been identified in any of the samples X-rayed. It is estimated that the thickness of the pillow lavas is probably less than 1 km, and only rarely does the Brown Zone alteration extend downward into the sheeted dikes which are about 2 km thick.

The altered dikes have a greenish color (Green Zone) and have typical mineral assemblages that include chlorite, albite, epidote, actinolite, and sphene. Transitional rocks into the Brown Zone may contain prehnite-pumpellyite in place of epidote. The igneous textures are retained with plagioclase altering to albite + epidote or pumpellyite-prehnite. Clinopyroxene is partly replaced by actinolite and chlorite. The ilmeno-magnetite is replaced by sphene.

Chemical analyses of these altered rocks when compared to unaltered diabase and pillow lavas show marked changes in $Na_2O$, CaO, and MgO (Donato and Coleman, 1976). These chemical changes are apparently brought about by a high degree of chemical mobility of these elements during the hydrothermal alteration.

Some of the diabase lower in the section and the upper gabbros have mineral assemblages that indicate that the hydrothermal metamorphism reached low amphibolite facies. In these rocks, the primary calcic plagioclase ($An_{45-60}$) is stable retaining its igneous zoning, and clinopyroxene is completely replaced by fibrous blue-green to green amphibole (uralite). Temperatures indicated by the assemblage actinolite + calcic plagioclase are probably in excess of 400°C. Miyashiro *et al.* (1971) have found calcic plagioclase and actinolite assemblages from the Mid-Atlantic ridge. They also consider this assemblage to represent amphibolite facies metamorphism.

If seawater within the hydrothermal system is responsible for alteration of the upper part of the Semail ophiolite, it provides a potential fluid to bring about large scale seawater–basalt interactions. Hydrothermal brines developed during the alteration of the upper 3 km of the Semail ophiolite must then have had the potential of forming metalliferous concentrations within the ophiolite or at the interface between ocean water and points of brine discharge.

## DISCUSSION

The tectonic setting of the Semail ophiolite demonstrates that it is an allochthonous mass that has been transported southward (Glennie *et al.*, 1973, 1974). Associated sediments show that the Semail ophiolite was probably formed within a Paleo-Tethys Sea (Glennie *et al.*, 1974). Petrological reconstruction of the Semail ophiolite indicates that its formation was polygenetic and that these processes probably took place at a spreading center in the Tethys Sea and not along the continental margin of the Arabian Peninsula (Coleman, 1977).

The low-grade thermal metamorphism present in the pillow lavas, diabase dikes, and the upper parts of the gabbro is related to hot circulating oceanic waters produced by the high heat flow near the Tethyan spreading centers. Geochemical evidence shows that hot seawater brines can leach and transport metals from basalts and diabases that form the upper parts of ophiolite complexes (Spooner and Fyfe, 1973). The Cu-bearing massive sulfide bodies in the pillow lava sections associated with iron-rich sediments (umbers) in the Semail ophiolite probably represent metalliferous concentrations deposited by those hot circulating brines.

The important sulfide deposits are located within the upper parts of the pillow lavas, are stratabound and there is no compelling field evidence of large scale replacement of the host volcanics. The apparent fault control of the sulfide deposits within the Semail ophiolite may represent ocean-ridge faults that have concentrated hydrothermal brines along favorable zones of movement (Smewing *et al.*, 1977). The source of the metals in the massive sulfide deposits appears to be the surrounding hydrothermally altered pillow basalts and diabase dikes.

The field and geochemical evidence so far gathered on the Cu-bearing massive sulfide deposits from the Semail ophiolite strongly support the concept that these deposits were formed at a divergent plate margin in the ancient Tethyan Sea. Formation of the massive sulfides is connected to metalliferous brines formed beneath the sea floor during submarine volcanism related to spreading ridges and cannot be connected to subsequent intracrustal hydrothermal replacements on the Arabian platform.



## REFERENCES

ALLEMAN, F., and PETERS, T. 1972. The ophiolite-radiolarite belt of the North Oman mountains. *Eclogae Geol. Helv.* 65, 657–697.

BAILEY, E. H., and COLEMAN, R. G. 1975. Mineral deposits in the Semail ophiolite of northern Oman. *Geol. Soc. Am. Abst.* 1, 293.

BIBBY, G. 1969. *Looking for Dilmun.* Alfred Knopf, New York.

BRYAN, W. B., and MOORE, J. G. 1977. Compositional variations of young basalts in the Mid-Atlantic Ridge rift valley near lat. 36°99'N. *Geol. Soc. Am. Bull.* 88, 556–570.

COLEMAN, R. G. 1977. *Ophiolites.* Springer-Verlag, Berlin, 229p.

COLEMAN, R. G., TATSUMOTO, M., COLES, D. G., HEDGE, C. E., and MAYS, R. E. 1974. Red Sea basalts. *Am. Geophys. Union Trans.* 54, 1001–1002.

DONATO, M. M., and COLEMAN, R. G. 1976. Sub-sea floor metamorphism of Saudi Arabian and Omani ophiolite. *Am. Geophys. Union Trans.* 57, 1022.

DUKE, N. A., and HUTCHINSON, R. W. 1974. Geological relationships between massive sulfide bodies and ophiolitic volcanic rocks near York Harbour, Newfoundland. *Can. J. Earth Sci.* 11, 53–69.

GASS, I. G., and SMEWING, J. D. 1973. Intrusion, extrusion and metamorphism at constructive margins: evidence from the Troodos massif, Cyprus. *Nature* 242, 26–29.

GLENNIE, K. W., BOEUF, M. G. A., HUGHES-CLARKE, M. W., MOODY-STURAT, M., PILLAR, W. F. H., and REINHARDT, B. M. 1973. Late Cretaceous Nappes in Oman mountains and their geologic evolution. *Am. Assoc. Petroleum Geol. Bull.* 57, 5–27.

GLENNIE, K. W., BOEUF, M. G. A., HUGHES-CLARKE, M. W., MOODY-STURAT, M., PILLAR, W. F. H., and REINHARDT, B. M. 1974. The geology of the Oman mountains. *Konink Nederlands Geol. Mijnbouwkundig Genootschap. Verh.*, 423.

GOVETT, G. J. S., and PANTAZIS, M. 1971. Distribution of Cu, Zn, Ni, and Co in the Troodos Pillow lava series. *Inst. Min. Met. Trans.* 80, B, 27–46.

GREENWOOD, J. E. G. W., and LONEY, P. E. 1968. Geology and mineral resources of the Trucial Oman Range. *Great Britain Inst. Geol. Sci. Overseas Div.*, 108.

HUDSON, R. G. S. 1960. The Permian and Trias of the Oman Peninsula, Arabia. *Geol. Magazine*, 97, 299–308.

HUDSON, R. G. S., and CHATTON, M. 1959. The Musandam Limestone (Jurassic to Lower Cretaceous) of Oman, Arabia. *Paris Mus. Nat. d'Histoire Naturelle Notes et Memoires Moyen-Orient.* 7, 69–93.

HUDSON, R. G. S., MCGUGAN, A., and MORTON, D. M. 1954. The structure of the Jebel Hagab area, Trucial Oman. *J. Geol. Soc. Lond.* 110, 121–152.

HUSTON, C. C. 1975. Canadian expertise sparks discovery of three copper ore bodies in Oman. *Northern Miner* 61, 61.

MANSON, V. 1968. Geochemistry of basaltic rocks: Major elements. Pp 2–270 in *The Poldervaart Treatise on Rocks of Basaltic Composition.* (eds. HESS, H., and POLDERVAART, A.). Interscience, New York.

MIYASHIRO, A., SHIDO, F., and EWING, M. 1971. Metamorphism in the Mid-Atlantic Ridge near 24° and 30°N. *Phil. Trans. R. Soc. Lond.* A268, 589–603.

MOORES, E. M., and VINE, F. J. 1971. Troodos Massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. *Phil. Trans. R. Soc. Lond.* A268, 443–466.

MORTON, D. M. 1959. The geology of Oman. *5th World Petroleum Cong. Proc.*, New York. Sec. 1, 277–294.

REINHARDT, B. M. 1969. On the genesis and emplacement of ophiolites in the Oman mountains geosyncline. *Schweiz. Min. Petrog. Mitt.* 49, 1–30.

RICOU, L. E. 1971. Le croissant ophiolitique per-Arabe, une ceinture de nappes mises en place au Crétace Supérieur. *Revue de Geographic Phys. Geol. Dyn.* 13, 327–349.

ROBERTSON, A. H. F. 1975. Cyprus umbers: basalt-sediment relationships on a Mesozoic ocean ridge. *J. Geol. Soc. Lond.* 131, 511–531.

SEARLE, D. L. 1972. Mode of occurrence of the cupriferous pyrite deposits of Cyprus. *Inst. Min. Met. Trans.* 81, B189–B197.

SILLITOE, R. H. 1972. Formation of certain massive sulphide deposits at sites of sea-floor spreading. *Inst. Min. Met. Trans.* 81, 141–148.

SILLITOE, R. H. 1973. Environments of formation of volcanogenic massive sulfide deposits. *Econ. Geology.* 68, 1321–1336.

SMEWING, J. D., SIMONIAN, K. O., ELBOUSHI, I. M., and GASS, I. G. 1977. Mineralized fault zone parallel to the Oman ophiolite spreading axis. *Geology* 5, 534–538.

SPOONER, E. T. C., BECKINSALE, R. D., FYFE, W. S., and SMEWING, J. D. 1974. $O^{18}$-enriched ophiolitic metabasic rocks from E. Liguria (Italy), Pindos (Greece), and Troodos (Cyprus). *Contr. Mineral. Petrol.* 47, 41–62.

SPOONER, E. T. C., and FYFE, W. S. 1973. Sub-sea-floor metamorphism, heat and mass transfer. *Contr. Mineral. Petrol.* 42, 287–304.

STOCKLIN, J. 1974. Possible ancient continental margins in Iran. Pp 873–887 in *The Geology of Continental Margins* (eds. BURK, C. A., and DRAKE, C. L.). Springer, New York.

TSCHOPP, R. H. 1967. The general geology of Oman. *7th World Petroleum Cong. Proc.*, Mexico. Sec. 2, 231–242.

WILSON, H. H. 1969. Late Cretaceous eugeosynclinal sedimentation, gravity tectonics, and ophiolite emplacement in Oman Mountains, southeast Arabia. *Am. Assoc. Petroleum Geol. Bull.* 53, 626–671.

w/ RI Cott

RESOURCE DEVELOPMENT
REC'D OCT 1 ? 1983
TO | | 
FILE

# MELANO - PYXIS

*Geophysical Equipment*

October 19, 1983

Mr. John W. Tremaine, Sr. Geologist
U. S. STEEL CORPORATION
Resource Development
540 Arapeen Drive
Suite 201
Salt Lake City, Utah 84108

RE: Our meeting on October 12, 1983 concerning geophysical techniques and equipment for use in a copper exploration program in the northern part of the Oman Mountains, Oman

Dear John:

From our discussions at the meeting and from reading over a good part of the technical literature, I have come up with the following recommendations on geophysical techniques and type of equipment for each technique.

1. IP-Resistivity

Because of the success of detecting and distinguishing between disseminative and massive mineralization in the ophiolites on the Island of Cyprus, IP-resistivity should be a good tool to use in Oman.

Cost complex resistivity gear ≈ #82k w/7.5kw generator (portable)

I would like to recommend the Elliot IP-resistivity equipment manufactured by the Melano-Pyxis Co. because of its high degree of reliability, and the system would probably do well in many of the areas, however, due to the low resistivities in the host rock and overlying sediments in the Oman area, I think you should use the best system available for reading low signals within high noise that is typical in this kind of environment.

My recommendation would be:

Zonge Engineering and Research Organization, Inc.
3322 E. Fort Lowell Road
Tucson, Arizona 85716
(602)327-5501; Telex 165532 CEERHO TVC
Attention: Mr. Van Reed

Receiver Equipment: GDP-12 Geophysical Data Processor
XMT-12 Transmitter Controller - necessary for IP
CAP-12 Cassette/Printer

Transmitter Equipment:

They have a 5kw and a 20kw transmitter with associated engine-generator sets. I believe the 5kw system (GGT-5) would be satisfactory.

They can also supply you with reels, wire, etc. if you don't already have these items.

The Zonge System can be programmed for either the time domain or frequency domain mode of IP operation or both. I suggest both. In a discussion with Van Reed of their organization, he stated that the frequency domain is better for reading through noise so I suggest this as the mode of operation.

You might want to consider doing a more sophisticated type of survey termed "Complex Resistivity" by the Zonge organization. It is a more detailed, spectral study of IP-resistivity that will require additional equipment and the collection of a lot more data. You certainly don't need to run this kind of survey to explore for massive sulphides however, you might want to consider it for detailed studies over selected known deposits for a more thorough study of rock properties.

2. <u>Ground Magnetics</u>

It doesn't appear as if magnetics has been too helpful in the past exploration work. However, I read in one case where a "low" was associated with mineralization. Perhaps not enough has been run or the results have not been examined carefully enough. I would suggest that magnetics be run on every survey line.

There are several good magnetometers on the market. Scintrex just recently came out with a unit that incorporates their MP-3 proton magnetometer with their VLF-3 electromagnetic unit. This would enable you to do a VLF-EM survey and magnetics survey at the same time. They might have an availability problem, however, since it is so new.

Scintrex
Mr. Jack C. Webster
1973 West North Temple
Salt Lake City, Utah 84116
(801)532-2448

With the Scintrex System you would want to use thin base station recording magnetometer Model MBS-2.

I have heard one good report from field use of the proton magnetometer built by EDA Instruments, Inc. It is their Model PPM-350 total field magnetometer. The base station unit is their Model PPM-400. I understand it is a little heavier than other comparable magnetometers.

EDA Instruments, Inc.
5151 Ward Road
Wheat Ridge, Colorado 80033
(303)422-9112

Another consideration would be the Geometrics units. This would be their Model G-856 Proton Memory Magnetometer and their Model G-866 base station recording magnetometer. I have no information as to how well these units perform. I used their previous unit (Model G-816) for several years with good results.

EG&G Geometrics
395 Java Drive
Sunnyvale, California 94086
(408)734-4616

3. Ground EM

Apparently the EM surveys in Oman have not been too successful in trying to sort the many conductors detected in this environment. They used standard EM techniques termed VLEM (Vertical loop dip-angle EM); HLEM (Horizontal loop EM); Crone shootback (both vertical and horizontal loop); VLF (Very low frequency EM - Radem and probably EM-16); and the more recent technique PEM (Pulse EM). I understand there has been considerable progress made in equipment design and data interpretation of the PEM technique. I also understand that PEM has a better chance of success in a conductive environment. A contractor told me that the reason PEM is not used more than standard EM in North America is its higher cost. We stated that it is the standard EM tool in Australia which has a lot of highly conductive environments. From this, I would suggest that the only tool needed for EM surveys in Oman would be the PEM tool. Of course, you would have VLF results if you use the Scintrex magnetometer-VLF System.

CCS
EM37 - $73,100 Basic Tx, Rc Wire Reels
HP85A Package complete, - $50,800
Includes programs.
rental or lease purchase +5% for next year

The system I recommend is the Geonics Model EM37 ($73,100) along with their Model DDP37 Digital Data Pak. The digital data pak is used to assist in the editing and interpretation of the large volume of data gathered by EM37 system. It consists of a Geonics DAS40 ($10,100) Digital Data Acquisition Unit, a Data LPR16 tape recorder, a ($~~4,700~~ 4200) Hewlett Packard HP85 desk-top computer, and a variety of Geomics computer programs. ~~$57,040~~ 50,800 comes w/complete package, ROM's, paper etc.

Geonics Limited
1745 Meyerside Drive, Unit 8
Mississanga, Ontario, Canada L5T1C5
(416)676-9580

4. Drill-Hole Logging

There are all kinds of logging techniques as you know but, I believe you would mainly want to be concerned with EM and IP-resistivity.

Small winch cable & Dummy probe 3400
winch — 7620
Sensor & Cable $10.8k
900 m –
1800 m – – $13,634
winch 7,970
Dummy 3,730

a. EM

I would recommend the Geonics Model BH43 Borehole Logging Attachment which works with the EM37 PEM System. I believe with this system you can also determine anomaly bearing from the drill hole. Additional inquiries with Geonics should be done as to this feature.

Snelgrove Frank

Costs

. IP

Since you will already have a surface IP-resistivity system, all you need is the draw-works and cable. Scintrex has a Model DHIP-2 Drill Hole IP-resistivity Logging System that will probably do the job. You would not need their optimal IP equipment since your surface equipment could be used. They have three standard cable lengths of 250, 500, or 1,000 meters. Three sizes of winch are provided depending on cable length selected. It looks like the maximum diameter of the probe are the potential electrodes of 27 mm (1.06 in).

With this system you can not only do drill-hole logging, but determine bearings to detected anomalies. In addition, this system will enable mise-a-la-masse type surveys to be carried out if this type survey comes under consideration.

5. Gravity

From reading it does not appear that gravity measurements have been helpful in Oman. However, in the Oman specification report, they suggest gravity as a possibility for investigating the down-thrown block in the Semdah No. 7 area (appendix No. 1, 2.4.2).

For a gravity meter, I would recommend the LaCoste & Romberg Model G with the electronic readout option which aids in taking readings. $26k approx. 3yr delivery

Cost

LaCoste & Romberg, Inc.
6606 North Lamar
Austin, Texas 78752

Airborne Surveys

As we discussed, there is no need to consider additional airborne surveys until the existing input EM and magnetic data has been examined.

It should be mentioned that the U.S. Government is very touchy about micro-processors going out of the country. Most of the geophysical tools mentioned have micro-processors in them and this matter should be looked into.

I would suggest the use of a magnetic susceptibility meter for use in logging core and testing outcrop to support the magnetics as well as to support the geology. The unit to use is the one sold by Scintrex (originally designed and built by the Elliot Geophysical Company).

Sincerely,

B. R. O'Toole
Geophysicist

BRO'Toole:bsp

MIKE WRIGHT
U. of U Research

WRIGHT

# APPLICATION OF GEOPHYSICS IN OMAN

## General Discussion

About 350 gossans and/or mineral showings have been documented by previous workers in the ophiotite sequence that is known to contain Cyprus-type massive sulfide deposits in Oman. Only about 100 of these showings have received detailed evaluation and only 33 were drill tested. More work would have been done were it not for time and perhaps financial constraints. We therefore conclude that there is still substantial potential for occurrence of undiscovered orebodies in Oman.

The geophysical program consisted of airborne INPUT EM surveying followed by ground EM and gravity. Numerous problems apparently beset this program, mainly due to electrically conductive overburden that limited the effective exploration depth of the electrical techniques. It was late in the program when measures were implemented to mitigate these problems, and presumably many of the showings and/or INPUT anomalies followed up with ground geophysics early in the program were incorrectly or incompletely evaluated. There is thus ample room for improvement in the geophysical program.

## Approach

In prospecting a large region such as the Cretaceous ophiotite sequence one must be able quickly and with minimum expense to narrow the region down to those prospects on which more detailed exploration has the highest chance of success. In Oman there are two primary and presumably reliable methods of identifying prospects using existing data, namely 1) location of known gossans and 2) mapping INPUT anomalies. We propose to do an independant review and interpretation of the available INPUT data to establish that all valid INPUT anomalies have been located. Simulaneously we will carry out the geological program described elsewhere in this proposal to make certain that all gossans of interest have been located. Once a complete list of such prospects has been made it will be prioritized for detailed application of surface exploration methods then detailed exploration work will be carried out to further prioritize these prospects for drill testing. The gossans will be initailly ranked for surface exploration by geological and geochemical means, discussed elsewhere in this proposal, and by assigning a higher priority to gossans which have an associated INPUT anomaly. The INPUT anomalies will be ranked by quality (shape of the EM signature and number of INPUT recording channels that show the anomaly) and by association with a known gossan.

The followup process will be directed toward detecting and locating sulfide mineralization using geology, geochemistry and geophysics. Prospects showing evidence of occurrence of sulfides in the subsurface will be drill tested. Two primary geophysical techniques will be used to rank prospects for drill testing and to locate appropriate drill sites. These are the EM and IP techniques, discussed separately.

EM Techniques

EM followup of gossans and/or INPUT anomalies will require great care, as previous workers have discovered. A modern time-domain EM system such as the Crone Pluse EM system or perhaps SIROTEM, which is being developed in Australia for use in conditions of high surface conductivity, will be used. Careful interpretation of data using the latest available computer algorithms and careful testing over areas of known sulfide occurrence are proposed. We anticipate that all electrical conductors except those in the overburden will be of interest because graphitic conductors apparently do not exist (and would not be expected) in the ophiolites. We further propose to do a computer-based evaluation of all survey results to determine the effective depth of EM exploration. This will facilitate decisions on drill testing of areas which have no EM anomaly but have instead other evidence, such as geochemistry, that drilling might be warranted.

Experienced geophysicsts will be used both for the field work and for the interpretation. A certain amount of field interpretation of the data will be possible, but it will be necessary to get field results transmitted to our offices where sophisticated computer interpretation can be done. Data will be interpreted in terms of conductivity-thickness and location (including depth) of conductors.

Induced Polarization (IP) Techniques

Induced polarization is a method best known for its ability to detect small quantities of disseminated sulfide minerals in porphyry copper/molybdenum and similar deposits. It is not generally appreciated that IP can be successfully used in massive sulfide exploration because, in the general, case ground EM followup of airborne EM anomalies is the modus operandii and IP is not as often used in this way. However, massive sulfide deposits do yield an IP response, and in Oman the IP technique may well prove to be very valuable in followup of gossans and INPUT anomalies, especially given the problems that past application of EM techniques have had. There probably will be no need to use both EM and IP in a routine manner on each prospect, although for certain applications use of both may be wise. We propose to compare results of IP with EM over the best test areas available and using the best obtainable field data. Then one method will be chosen for routine field followup application.

Previous workers discarded the IP technique, presumably after some testing, because of the conductive overburden and highly varied landscape morphology. It is unlikely that Crone had IP equipment equal to the task in Oman.

In a highly conducting environment, electromagnetic (EM) coupling effects seriously contaminate IP measurements, and most conventional IP gear cannot measure and eliminate these EM coupling effects. They look on the instrument just like valid IP effects. IP instrumentation specifically designed to eliminate EM coupling does exist, however, and would be used in Oman in the proposed exploration program. In areas where EM coupling is a serious problem, one needs to make IP measurements at frequencies as low as possible (preferably down to 0.03 Hz) because EM coupling effects decrease linearly with frequency. But at frequencies below 1 Hz the natural electrical noise field increases rapidly, and so in some areas such as Western Australia, accurate IP measurements are difficult to obtain because of electrical noise problems.

The utility of the IP technique could only be determined after tests using the highest quality field data we can obtain. We propose to test the IP technique, using equipment that mitigates the EM coupling effects, over known sulfide bodies and over typical gossans and INPUT anomalies. We anticipate that IP responses will be found with careful survey techniques, appropriate equipment and skillful interpretation. If tests over known deposits appear successful, routine surveying of prospect areas would be used to help screen those prospects worthy of drilling and to help locate drill sites.

## Gravity

Although in a few select cases we may want to employ gravity, we do not propose to make extensive or routine use of the gravity method. Gravity is useful in massive sulfide exploration to distinguish sulfide conductors from non-sulfide conductors only in certain cases where the conductor is shallow (less than about 30 m) and has certain geometric shapes. In many cases ore bodies are found that have an associated gravity anomaly that is too small to detect in routine field surveys. The drill is a much surer way to test conductors for metal-bearing sulfide minerals.