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Foundation for Ancient Research and Mormon Studies

Eugene E. Clark

A Preliminary Study of the Geology and Mineral Resources of Dhofar, the Sultanate of Oman

FARMS

Summary:

The area of Wadi Sayq has been identified as a location that appears to meet the criteria for the site named Bountiful by Lehi and his family. While Nephi mentions metal used in this area, researchers had not previously discovered deposits of ore near Wadi Sayq. In this report, Eugene Clark identifies recent geological findings of copper and iron ore, documenting the plausibility of Wadi Sayq as the site where the Nephites smelted ore for shipbuilding tools.

Preliminary Report
Book of Mormon, Geography

FARMS
Brigham Young University
P.O. Box 7113
University Station
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1-800-327-6715
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This FARMS preliminary report reflects substantial research but is not ready for final publication. It is made available to be critiqued and improved and to stimulate further research.

Introduction

Noel B. Reynolds

The efforts begun by Warren and Michaela Aston to identify important sites along the Lehi trail eventually evolved into a FARMS project and exploration to Southern Oman's Dhofar region in 1992. The remote area of Wadi Sayq on the western extremity of that region has been identified as a location that appears to meet all of the criteria one can infer from the text of the Book of Mormon for the coastal site named Bountiful by Lehi and his family, where they lived while building a ship for their ocean crossing.

The text also states that while they lived at Bountiful, the Lord showed Nephi where to go to locate ore with which to make tools for their boat-building project. While it is known that greater Oman was a famous source of abundant and high-quality copper during Lehi's time, commercial mining near Wadi Sayq is not documented. The ancient copper mines of Oman are hundreds of miles farther north and unlikely candidates for Nephi's ore.

Graciously responding to a FARMS request, Eugene Clark, former geologist for ESSO in Oman, has prepared a preliminary report of geological possibilities of mineral deposits in the Dhofar region, where Wadi Sayq is located. The report identifies a number of geological possibilities for copper or iron ore accessible to Wadi Sayq, based on published geological studies and surveys. An on-site survey is projected for later this year to explore the possibilities documented in this report.

Most promising among the published studies are reports of specular hematite found in small, random deposits on the Mirbat plain east of Salalah. Specular hematite is the most readily available form of high-quality iron and would have been most attractive as a low-tech smelting source for Nephi's tools. The report also notes that Dhofar irons would usually occur in mixtures with manganese and carbon, yielding higher-quality steel that would be superior for tools.

This preliminary report documents the plausibility of the Nephite account of ore being smelted for shipbuilding tools. It also defines a range of possible ore sources in the Dhofar area that can be verified through on-site exploration.

A PRELIMINARY STUDY OF THE GEOLOGY AND MINERAL RESOURCES OF DHOFAR, THE SULTANATE OF OMAN

E. E. Clark
Esso Exploration, Retired
Lehi, Utah

ABSTRACT--The Dhofar Region of Southern Oman consists of a broad monocline that gently dips to the north, and is composed of a thick sequence of deeply dissected Tertiary limestones and older sediments. The monocline is abruptly terminated in the south by a series of normal faults associated with the early stages of rifting of the Gulf of Aden. The up-dip highland area, known as the Dhofar Mountains, is cut by deep wadis and extensional faults that expose Mesozoic and Paleozoic sections along the coastal cliffs and in the wadis. At Mirbat, a peneplain of late Precambrian crystalline basement rocks has been exposed and it appears that these same units are found on the Kuria Muria Islands to the east.

Although copper mining has long been established in the Jabal al-Hajar, in Northern Oman, there is no documented history of mining in Dhofar. The nearest known mineral deposits are the massive sulfide (copper) mines located on Masirah Island to the northeast. However, in Mirbat, there is a tradition that that ancient seaport once supported a thriving metals industry, possibly using some ore from local mines.

Listed below are several conceptual leads for Dhofari mineralization.

- Associated with the Precambrian basement complex and subsequent intrusion of granitic dikes, hematitic staining has been observed, and samples of specular hematite are reported to have been collected in the Mirbat area.
- Within the Infracambrian to Lower Paleozoic sediments found north of Mirbat, deep hematitic staining has also been observed which may lead to the possibility of taconite deposits.
- Ferruginous oolitic limestones are found in Wadi Miaidin, in Northern Oman and in Iran, and could extend into the Dhofar and Eastern Yemen, in upper Cenomanian units along the southern flank of the Dhofar Mountains.
- Massive sulfide deposits (copper ores) are found in the Ophiolite complex on Masirah Island to the northeast. Ras Madratah to the southwest of Masirah also contains ophiolites but it is unknown if they contain massive sulfide deposits.
- Dripstones or travertine spring deposits associated with Tertiary limestones have been observed along the Dhofari and

Yemeni coasts. In places, these dripstones contain hematitic and limonitic staining.

It is unknown if any of these leads have accumulations of consequence, as yet there are no known assessments.

INTRODUCTION

Copper has been mined in Oman for nearly five thousand years but apparently there has been no commercial iron mining in the country. Most of the mining effort in Oman has been concentrated in the massive sulphide (copper) deposits in the Semail Ophiolite sequence and the Hawasina deep-sea allocthonous units (manganese) of the Jabal al-Hajar, in Northern Oman and on Masirah Island in the Arabian Sea.

The Dhofar Province, on the other hand, has no confirmed mining history. There are no ophiolite sequences found south of Ras Madrakah, some 450 kilometers northeast of Salalah. Mineral exploration in Dhofar must then take a different tack, metallic mineralization may be associated with Precambrian basement or Infracambrian to Tertiary sedimentary units.

GEOGRAPHIC AND GEOLOGIC SETTING

The Dhofar Province of Oman lies along the southeastern margin of the Arabian Plate which has been a stable carbonate platform from the Late Permian, almost continually, until the Miocene. Deformation from the emplacement of the Hawasina and Semail overthrusts during the Turonian did not reach the Dhofar. However, as the Tethys closed at "Zagros Crush time", gentle folding of the Dhofar began. Within a short time, rifting of the

Gulf of Aden brought about uplifting, tilting and major block faulting. Since this 13 Ma year event, continued extensional faulting and erosion have carved the deeply dissected momocline seen today in the Dhofar and eastern Yemen.

General Structure. The Dhofar Region consists of essentially one large gently folded and tilted block containing Tertiary and older sediments. The block is slightly arched and lifted in the south along the Salalah-Dhofari coast where it slopes gently northward. At the southern edge, the margin falls sharply to the coast by a series of "down-dropped" crustal blocks. These cliff faces and deep water cut courses (wadis or widyan) reveal sedimentary sections from the Tertiary limestones seen along the length and breadth of the Dhofar Mountains down to crystalline basement. These crescent-shaped mountains catch much of the summer monsoon rains and help produce the greensward of Southern Oman, an anomaly on the Arabian Peninsula.

The northern flank of this tilted Dhofari slab is dissected by finger-like dry watercourses or wadis which merge and flow to the north where they are lost in the sands of the Rub al-Khali. Here the topography is more even, and is often called a monotonous landscape when compared to the craggy coastal areas (Clarke, 1991).

Dhofar Mountains. The coastal mountain belt in the Dhofar which contains Jabal al-Qara, Jabal al-Qamar, and Jabal Samhan, consists of the block faulted eastern flank of the Hadramawt Arch. Faulting along the southern margin gives rise to the mountainous region and its rugged relief (over 1000 meters above sea level). The northern flank of this belt is relatively unfaulted and consists of a gently dipping north slope or Paleocene tableland capped by mesas and Eocene cuestas, (Beydoun, 1963).

<u>Najd al-Dhofar</u>. The northern gravel plain lies between the Rub al-Khali sand desert to the north and the gently dipping north flank of Handramawt Arch or Dhofar Plateau. This nearly flat gravel plain in places is broken by low eroded ridges, scree sloped hills, and small sand dunes. The plain is approximately 60 to 80 kilometers wide and rises from 250 to 550 meters above sea level.

<u>Rub al-Khali</u> (Empty Quarter). The Rub al-Khali is a barren desert that consists of active sand dune complexes (ramlats) and gravel strewn plains in northern Dhofar and of course into Saudi Arabia and Abu Dhabi. Along the northern margin of the Najd al-Dhofar, the dunes are subparallel longitudinal (uruq) with low, flat areas of gypsum, gravel, silt and clay in between (shuquq). These dunes are 100 to 150 meters high with occasional barchan or crescent dunes. Farther to the north, these dunes grade into classical transverse Sahara type dunes.

The slip faces of the dunes observed in the field point to the south indicating the primary north-northeast direction of the Shamal winds.

<u>Dhofar Coastal Plain</u>. The coastal plain varies from east to west through Dhofar. The al-Qamari coast in the west has a

variable width and consists of gravel flats, raised beaches, dunal areas, terraces, alluvial slopes, beaches, and wadi mouth soils that have been reworked by agriculture. The Salalah or Juraib Plain contains all of the above but also a broad (20 km) plain of arable soils which have been cultivated for centuries. The Mirbat Plain and Kuria Muria Islands contain little soil but instead are a peneplain exposing crystalline basement.

Drainage System. As in nearly the entire Arabian Peninsula, the dry wadis normally flow only during heavy rains, which causes spectacular but dangerous flash flooding. Many of these wadis are deeply cut and reach depths of 200 to 300 meters. Two widyan systems are recognized in the Dhofar: coastal wadis flowing to the Arabian Sea are obsequent to the structure and the Dhofar Mountain-Najd al-Dhofar system which flows to the Rub al-Khali, and are consequent to regional dip.

The coastal widyan of Dhofar are short and a number contain water until they enter the Salalah or coastal plains. In the west, the wadis are controlled by faults and flow to the east-southeast, then cut back to the watershed as they reach the coast. These wadis usually have steep gradients which are difficult to traverse and when water flows, it often runs in torrents (Beydoun, 1963).

The northern widyan are long and shallow water courses that flow to the Rub al-Khali from the Dhofar Mountains. The head of these wadis lie along the axis of the Hadramawt Arch in Yemen and the highest portion of the Dhofar Plateau from Jabal al-Qamar to

Jabal Samhan (Bunker, 1953). This wadi system flows for several hundred kilometers to the north-northeast where they skirt to the northeast around the sand dunes of Ramlat Fasad to Ramlat Muqshiu near the Saudi border.

Climate and Vegetation. The Salalah Plain and the western Dhofari coast have regular summer monsoons unlike the coast of Yemen and the Sawqirah to Masirah coastal areas of Oman. This summer monsoon season lasts from June until August and consists of strong southwest winds (up to 120 km/hr) and rough seas. Salalah receives an average of 15 cm of rain each year but in the southern flanks of the Jabal al-Qara, 75 cm of rain often falls each year. The lush vegetation found in this crescent is not found to the northeast or southwest along the Arabian coast. The wadis often contain water and pools that only flow underground upon entering the coastal plain.

There are winter monsoons in the Dhofar Region but these consist of more gentle southeast winds that bring clouds but little rain to the region from October to April (Beydoun, 1963).

The Dhofar interior has a diurinal of 30° C. In winter, frost is not uncommon and daytime highs can reach above 30° C while in the summer, the daytime temperatures high can reach over 55° C. Along the coast, daily winter temperatures range from 10° - 30° C but in the summer, high humidity and heat with no breeze accompany the periods between monsoon storms.

In the interior, high winds, dust, and sandstorms are a problem. During the winter, the Shamal winds blow across the

Arabian Peninsula causing sandstorms that can last for days. In the hot summer months, dusty conditions of low visibility prevail.

The vegetation in the interior region is essentially barren except for the wadis where acacia, tamarisk, ilb, camel thorn, and bunch grass grow. In the coastal areas, date palms, millet, grains, cotton, vegetables, and tobacco have long been cultivated.

Frankincense has historically been grown not on the lush southern flank of the Al-Qara but on the north flanks of the Jabal al-Qamar to Jabal al-Samhan (Carter, 1852) where even though this area falls within the rain shadow, it receives sufficient precipitation.

STRATIGRAPHY

Precambrian. The metamorphic basement complex found in the Dhofar Province is exposed along most of the Mirbat Plain and on the Kuria Muria Islands to the northeast. This sequence of orthogneisses of granitic and granodioritic composition and schists has been cut by a series of pegmatitic or coarse crystalline granitic dikes. The metamorphic basement complex has been radiometrically dated at between 650 and 800 Ma (Clarke, 1991). This sequence may be coeval to the Aden series in Yemen (Greenwood and Bleachley, 1963) and the al-Hijaz series in Saudi Arabia (Brown and Coleman, 1972).

The dense pattern of subparallel dikes runs in a north-south direction, somewhat perpendicular to the steep westerly foliation dip observed by Fox (1947). He has also described a younger "Precambrian" series along the northwestern corner of the Mirbat Plain. Here the Jabal Ali consists of a sequence of dolomitic marbles, amphibolites and serpentinites that also appear to be cut by pegmatitic or coarse crystalline dikes. It is unknown if the meta-dolomites are Precambrian or are actually a lower member of the Infracambrian Huqf. Fox also describes this younger Precambrian unit as being found on the Kuria Muria Islands as well.

Infracambrian/Lower Paleozoic. Although typical Huqf Group sediments observed along the Huqf Arch and within the south Oman Salt Graben have not been observed in Dhofar, the Upper Dolomitic marble section at Jabal Ali and the Murbat Sandstone may represent the Infracambrian Huqf or Cambrian Lower Haima Group. Fox (1947) described these sandstones as brown and argillaceous, and recognized a possible relationship with indurated sandstones and phyllites in Wadi Nagar Ghaiz, near Raysut. It appears the core of the Dhofar Monocline from Jaba Qamar to Jabar Qara may be represented by these Infracambrian/Lower Paleozoic units.

Paleozoic. The Paleozoic section seen along the Huqf Arch, in well data from the Southern Oman Salt Basin, and along the coast of Dhofar consists of predominantly coarse continental clastics representative of the old Gondwana super-continent. Much of the Cambro-ordovician Haima and Permian Haushi are preserved in the record while nearly the entire Silurian, Deuonian, and Carboniferous sections are missing due to non-deposition and erosion (Tchopp, 1967). The early Permian Al-Khlata Formation contains thick sections of tillites and other clastic deposits associated with the Permian glacial epoch. The Upper Permian Khuff Formation represents the onset of the long lived carbonate shelf that dominated much of the Arabian Peninsula until the Miocene.

Mesozoic. The Mesozoic section in Oman is represented by a nearly continuous sequence of shelfal carbonates deposited on the stable Arabian Platform. These shelf carbonates extend from the Dhofar and Hadramawt in the south, northwest to Syria and Southeastern Turkey, and northeast into Iran. A portion of this carbonate shelf section is seen along the lower cliffs of the southern margin of the Dhofar Mountains. Fox (1947) and Hudson, et. al. (1953) have described this section as consisting of limestones, white dolomitic limestones, chalks, and thick carbonates with clastic and cherty interbeds. Wilson (1969) refers to these units as "the monotonous carbonate sequence."

A major hiatus during the Turonian is found over much of Arabian Platform and represents the emplacement period of the Hawasina section and Semail Ophiolite overthrusts, which temporarily brought to a close the long period of carbonate platform deposition. At Jabal Qusaibah in Wadi Miaidin and in several other locations along the Eastern Hajar, shallow water ferruginous carbonate deposits rest on top of the Cenomanian, the base of the unconformity. These iron rich units consist of a thin (3 meters) ferruginous oolitic limestone that caps the Wasia Group (Wilson, 1969). James and Wynd (1965) have recognized this same ferruginous unit capping the coeual Savak Formation in Khusestan, Iran. It would appear that this strata may be widespread and may even extend into the Dhofar, although it has not been observed by the author nor described in the literature.

Tertiary. The Tertiary and Upper Cretaceous strata found along the flanks and on the crest of the Dhofar Mountains would probably also be described by Wilson as more "monotonous limestones" and calcareous argillites. The entire dip slope of the Dhofar Monocline consists of a thick sequence of dissected Tertiary carbonates. The base of the Tertiary, the lowermost unit of the Hadramawt Group, consist of the Umm er-Radhuma sandstone which is exposed along the southern flank of the Dhofar Mountains. These sandstones are the main aquifer for not only Oman but for much of the Arabian Peninsula. The regional charging area for the Umm er-Radhuma aquifer lies along the southern flanks of the Oman Mountains where there is anomalously high rainfall (Clark, 1991).

Above the Umm er-Radhuma, the remainder of the Pliocene-Eocene Hadramawt Group consists of a thick sequence of carbonates with lesser amounts of interrelated shales, silts, sandstone, anhydrite, and gypsum (Beydoun, 1963). Unconformably resting on the Hadramawt group is the Oligocene-Miocene Fars Formation. Although in the Arabian Gulf Region to the north, these units consist of predominantly evaporite deposits with interbedded carbonate units, in Dhofar, the Far Formation contains mostly carbonates. These carbonates make up most of the strata on the crest and the north flank of the Dhofar Mountains.

STRUCTURAL AND TECTONIC HISTORY

Structure. As the northern Hadramawt Arch in Eastern Yemen plunges to the east across the al-Mahrah it apparently bifurcates or broadens and extends into the Dhofar, the southern axis running east-west through the Jabal al-Qamar, and the northern axis through Jabal al-Qara and possibly as far east as Jabal Samhan and even the Kuria Muria Islands. Within Dhofar, the main arch appears to behave more like a monocline, with a single but gentle northern flexure often described as a homocline.

The southern flank of the Dhofar monocline has been decapitated by 'down to the basin' extensional faults. These east-west trending faults, associated with the Gulf of Aden rifting, not only have severed the Arabin Plate but form the impressive cliffs and steep southern flanks of the Jabal al-Qamar and Jabal al-Qara. Wadi Shaghawat in Eastern Yemen and Wadis Sayq, Qamar, and Adawnib all appear to be fault controlled by the same east-west trending Gulf of Aden rift system. What is not understood is the structural relationship between Jabal Samhan and the Mirbat Plain. There, of course, are no 'down to the south' normal faults along the southern margin of Jabal Samhan and it would appear that the escarpment is either an erosional remnant from the Mirbat "Peneplain" or the structuring is yet unknown.

Marine seismic in Kuria Muria Bay could help unravel this structural problem but in its absence it may be assumed that the islands are an eastern extension of the North Hadramawt Arch or a continuation of the southern Dhofar extensional fault system, or more likely both.

Tectonic History. Direct information on the Precambrian tectogenetic cycles in Dhofar is missing. The oldest phase of the Precambrian known in Saudi Arabia is the Kibarran cycle (Brown and Coleman, 1972; Brown, et. al., 1963). This cycle is composed of two tectonic events culminating at 1000 Ma and 725 Ma respectively. In Iran, Stocklin (1968), also differentiated two Precambrian tectonic events prior to the Infracambrian. Halsey (1980) suggests east-west compression in the al-Hijaz resulting in north-south trending folds and ophiolite emplacement. This event was culminated by a major intrusive phase at 620-660 Ma (Brown and Coleman, 1972; Schmidt, et. al., 1979).

Schmidt, et. al. (1979) recognized a younger event in the al-Hejaz during the Infracambrian which culminated at about 580 Ma. This event consists of an early north-northwest trend of granitic intrusions and a north-south system of normal faults, noted as the Najd event. Abbas and Masin (1975) have recognized the extension of this trend into Iraq, and Stocklin (1968) traced these same north-south trending Najd structures from Iran south into the Arabian Gulf to Qatar.

This divergence in the ancestral Arabian Plate during the Infracambrian created a system of north-south trending normal faults with associated horsts and grabens from the Dhofar Province north to Iran and northwest into at least the eastern flanks of the al-Hejaz. The Ghawar Field in Saudi Arabia and the North Gas Field in Qatar, the largest oil and gas fields in the world rest on the tilted horst blocks associated with this Najd event. Grabens and half grabens with clastics, minor carbonates, and evaporites (Hormuz salt) are found in the Southern Arabian Gulf, south through the Rub al-Khali, and into Southern Oman and the Dhofar.

In Dhofar, the South Oman Salt Basin is such an Infracambrian structure, filled with Infracambrian Huqf clastics and evaporites which are the source, seal, and reservoir units of most of the oil in Southern Oman. It appears that this same structural trend could extend south to the Mirbat Plain and the Kuria Muria Islands where the Precambrian basement has been extensively fractured in a north-south direction. These fractures were subsequently intruded by granitic dikes.

The Caledonian and Hercynian events (Silurian and Triassic) did not appreciably change the structural pattern of Dhofar. For most of the Paleozoic, the Caladonian and Acadian events are only represented by the absence of most of the Silurian, Devonian, and Carboniferous sections which was the result of erosion and nondeposition. The Hercynian is only represented by an unconformity in the Triassic and possibly into the Jurassic.

As a new spreading center temporarily formed in the closing Tethys, obduction of the Semail Ophiolite occurred in Northern Oman at about 90 Ma, at the end of the Cenomanian. In Dhofar, the only evidence of this event is the Turonian unconformity. At 18 Ma (Early Miocene), the last of the Tethys oceanic crust was consumed after 160 M.Y. of separation of the Eurasian and Arabian Plates. By 15 Ma, the Zagros suture was formed representing the final closure of Tethys, and Tethian marine sedimentation ceased on the Arabian Platform. Since "Zagros Crush Time," there has been approximately 400 km of convergence in the Asian and Arabian Plates. Seventy to 100 km of this convergence has been accommodated by folding and thrusting in the Zagros and 300 km of crustal shortening has been taken up by internal deformation in Iran and the Caucasus. A small portion of this shortening has apparently been taken up in the Dhofar and Eastern Yemen by gentle Hadramawt folding.

In the Middle Miocene (13 Ma), sea floor spreading began in the Red Sea and Gulf of Aden after an initial period of extensional faulting and uplift. Spreading, faulting, and uplift in the Gulf of Aden has continued since Mid-Miocene, separating the Yemeni Coast and Dhofar Region from Northeastern Somalia. The Island of Socotra off the Somali coast appears to have been rifted from a position opposite the Kuria Muria islands. Socotra has a similar Precambrian to lower Paleozoic sequence as do the Kuria Muria Islands.

It should be noted that ophiolites found on Masirah Island are not associated with the Semail but have been dated at Late Jurassic-Early Cretaceous (126-158 Ma). It appears that the ophiolites found at Ras Jibsh, Ras Madrakah, and Masirah Island represent uplifted blocks of Indian Ocean crust, not right-laterally displaced fragments of the Semail Ophiolite (Smewing, et. al., 1991). These blocks are related to the 132 Ma breaking away of India from Antarctica. Counterclockwise rotation in the Early Cretaceous triggered partial closure of Late Jurassic-Early Cretaceous proto-Owens Basin. Obduction of the ophiolites caused crustal thickening of the basement complex. A shallow marine carbonate platform was re-established until the Late Cretaceous when transcurrent movement of the Masirah fault incorporated the platform derived blocks into the ophiolites.

ECONOMIC GEOLOGY

Although there is oil production in Northeastern Dhofar, in its long history, the Dhofar Province and Eastern Yemen have no record of mining metals. Stories told in Mirbat of an ancient mining center there have not been verified and ore types or locations are unknown (Fox, 1947; Beydoun, 1963). Copper has been mined in Oman for more than five thousand years (Clarke, 1991) from the massive sulfide deposits within the Semail Ophiolites in Northern Oman in the Bayda and the new Sohar districts. These complex ophiolites consist of serpentinites, gabbroic intrusions, sheeted dikes, pillow basalts, and mineral rich deep water sediments (Pearce, et. al., 1979). The upper portion of the sheeted dikes and the pillow lavas with heavy hematitic staining have produced and continue to produce most of Oman's copper. Associated with these sulfide deposits, chromium has been mined, in recent years, from units deeper within the ophiolite sequence, with the gabbros and cumulates (Clarke, 1991).

It appears that although the massive sulfide deposits within the Semail Ophiolite contain an appreciable quantity of iron (massive pyrite with chalcopyrite), it has not been suitable as an ore and is yet to be developed (Clarke, 1991). A new occurrence of "native" iron has recently been discovered in serpentinized peridotites near Maqsad, on the Semail Massif, to the southwest of Muscat (Lorand, 1987) but they too have not been exploited because of their poor quality and limited quantity.

In the Hawasina allocthonous units, in the fine-grained sediments, nodules of manganese oxides are found which have been mined on a small scale and the Ministry is preparing more extensive mining operations for export (Clarke, 1991). These red manganese concentrations and nodules are associated with radiolarian cherts found within the Hawasina, particularly in the eastern al-Hajar.

It appears that copper has been, in the past, mined from complex ophiolites found on Masirah Island where a highly dismembered but complete sequence is found including: hartzburgites, serpentinites, layered and isotropic gabbros, sheeted dike complexes, pillow lavas, and associated fine-grained sediments (Moseley and Abbots, 1979). Ophiolites are also recognized at Ras Jibsh and Ras Madrakah as well but those localities have no history of copper mining. It should be noted that the ophiolites found along the Arabian Sea are not coeval with the Semail Ophiolites nor are they a part of that tectonic event. They have been dated by Smewing et. al. (1991) as Late Jurassic to Early Cretaceous (126-158 Ma). Although the serpentinites on Masirah are high in Fe_2O_3 (10% hematite), it does not appear that an attempt has been made to mine the iron. Associated with the massive sulfide deposits within the Semail and Masirah Ophiolites, minor amounts of nickel, lead, zinc, gold, silver, and arsenic are reported but there is no record of their being exploited (Clarke, 1991).

Wilson (1969) and many others have long recognized iron rich units which cap the Wasia Group in Northeastern Oman. These beds consist of ferruginous oolitic limestones which are seen at the top of the Cenomanian section in Wadi Miaidin along the road to the Saiq Plateau. Although it has been generally recognized that this ferruginous layer is too thin to exploit (three meters), the Ministry is studying several recent proposals for development (H.E. Said bin Ahmed al-Shanfari, Minister of Petroleum and Minerals, pers. comm., 1992).

Lignite has also been found intercalated with sandstones and shales within the Tertiary near Sur. These coal seams are as thick as two meters but have been considered sub-commercial even though they have been used for local consumption for some time.

ECONOMIC LEADS

Although there apparently are no recognized economic mineral assemblages in the Dhofar Region, there are however, several exploration leads which may be of local interest that are listed as follows:

Iron

- Hematitic mineralization associated with Precambrian metamorphic basement and subsequent intrusion of pegmatitic dikes.
- "Iron Formation" or taconite deposits associated with the Precambrian, Infracambrian, or even the Cambro-Orduoician Mirbat Formation, which can contain high iron concentrations.
- Ferruginous oolitic limestone at the top of the Wasia Group which can have high concentrations of iron minerals, normally hematitic ooids comprising most of the oolitic ore (Park and MacDiarmid, 1970).
- Hematitic or limonitic dripstone (spring deposits) associated with Tertiary and Cretaceous limestones along the south facing cliffs of the Dhofar coast. The Kuchan mine in Hakkaido, Japan, has extracted over five million tons of limonitic dripstone ore.

Copper

- Copper mineralization associated with pegmatitic intrusions of Precambrian basement complex.

Coal

- Lignite beds within the Tertiary clastic section may be similar to those coal beds found near Sur. These of course would only be of local interest and use.

Petroleum

- Associated oil with coastal seeps where oil is trapped in Tertiary half-grabens offshore. Seeps have long been recognized at Marmul prior to production and along the tidal channel near Mirbat (Fox, 1947).

LOCAL AREAS OF INTEREST

Mirbat Plain. The Mirbat Plain lies south of the abrupt southern flank or escarpment of Jabal Samhan just east of Salalah. The plain is nearly 60 km long and 20 km wide, and consists predominantly of Precambrian metamorphic basement rocks containing gneisses and schists that have been radiometrically dated at 650-800 Ma (Clarke, 1991). This basement complex would appear to be the same age as the continental crystalline basement near Muscat and in Southern Yemen. The gneisses and schists along the Mirbat Plain have been subsequently cut by a great many coarse crystalline (pegmatitic) dikes which form parallel and elongated ridges. In the western portion of the plain, Infracambrian to Cambro-Ordovician dolomitic marbles and sandstones outcrop north of Mirbat.

Specular hematite samples have been reported to have been collected from the Mirbat area (Fox, 1947). It is not known if these samples came from Precambrian/Infracambrian metamorphics and intrusives or the early Paleozoic Mirbat Sandstone section but in either case, if the report is accurate it would be of extreme interest, since hematite is the most important iron ore in the world (Park and MacDiarmid, 1970).

In the field, red hematitc staining has been recognized by the author in both the metamorphic basement complex and the Cambro-Orodovician Mirbat sandstones but in limited concentrations. It would appear there could be small amounts of hematite along the Mirbat Plain which may have been of local interest in the past but probably of no commercial value today.

Little (1925) reports cupriferous iron ore associated with weathered intrusives near Fakhida, Yemen, which was used by the bedouin near Makalla. This cupriferous iron ore may be chalcopyrite which has also been observed in small mineralized veins associated with the dike system near Mirbat. It is not known if copper has been extracted in even small quantities from these deposits.

Kuria Muria Islands. The Kuria Muria Islands consist of an east-west trending chain of five small islands that lie approximately 50 km offshore, in the Kuria Muria Bay to the northeast of the Mirbat Plain. These islands which range in length from one to ten km are composed of Late Precambrian metamorphics and intrusives. This basement complex has also been cut by similar dikes found at Mirbat. No radiometric dates have been obtained for these units but they would appear to be coeval with the Mirbat Complex dated at 650-800 Ma (Clarke, 1991). No mining has been recorded on these islands but hematitic staining has been noted to be associated with the dikes (M. Kassim, pers. comm., 1992). It would appear that prior to the main opening of the Gulf of Aden, Kuria Muria was rifted from Socotra by early divergence in the Oligocene-Miocene (Cockran, 1981). Iron oxides on the Island of Socotra have been reported to have been mined over the centuries in this same Precambrian basement complex.

Ras ash-Shuaymiah. Shuaymiah point lies along the head of Kuria Muria Bay where Tertiary limestones outcrop to form a low escarpment along the coast. As water flows through the limestone hills above Shuaymiah, it picks up dissolved minerals and salts, which, when redeposited, build up an assortment of forms. Dripstone deposits from these springs in the limestones along the escarpment create "icicle-shaped" deposits which have heavy hematitic staining in some places (Clarke, 1991). Park and MacDiarmid (1970) refer to these travertine deposits as "spring deposits" where iron rich waters may deposit iron oxides in commercial quantities, in terrace-like embankments.

Wadi Darbat. About 40 km east-northeast of Salalah, near or above Khor Ruri, travertine deposits have actually formed terraced dams across the wadi. These extraordinary accumulations of travertine (dripstone) are highly mineralized and could be of interest due to their hematite content and close proximity to the Salalah Plain. There are, however, no known mines along these embankments or in similar deposits along the Dhofar Mountains.

Southern Dhofar Mountains. Jabal al-Qamar, Jabal al-Qara, and Jabal Samhan extend for nearly 250 km in an east-west orientation across southern Dhofar. Near the coast, large extensional faults associated with Gulf of Aden rifting create impressive cliffs. Along and at the base of these cliffs and in associated wadis, Cretaceous to Early Paleozoic rocks are exposed. The top of the Cenomanian Wasia Group is of primary concern due to the reports of ferruginous oolitic limestones in Wadi Miaidin in northern Oman (Clarke, 199) and in Iran. It is unknown if these thin beds extend this far to the south nor what concentrations of iron could be expected.

Across the base of the Dhofar cliffs and in adjacent wadis, exposures of Lower Paleozoic and possibly Infracambrian sediments are reported (Wilson, 1969). These same units have hematitic staining north of Mirbat but it is unknown if the concentration of iron is great enough to equate with "iron formation" and further study would be of interest.

Fox (1947) has reported carbonaceous material being found in Wadi Ghaiz near Ansarit which is suggestive of lignite with volatile percentages greater than fixed carbon but with high concentrations of ash and silica. It is not known if these beds would be considered bituminous siltstones or poor grade lignite coal, but poor quality lignites may be found in the Tertiary section along the Dhofar Mountains and the northern Dhofar flank. Such deposits would only be of historic interest if ever used.

CONCLUSIONS
AND THEIR BEARING ON MINERALIZATION

The Dhofar Region has been tectonically stable from at least the Infracambrian to the Miocene. Precambrian crystalline basement was fractured in the Late Precambrian and subsequently intruded along the fractures by granitic magma and covered by clastic and evaporitic sedimentation. This deposition that began in the Infracambrian continued in the form of continental clastic sedimentation on the stable Gondwana Continent until early signs of continental break-up in the Permian. From the Mid-Permian until the Miocene, nearly continual stable carbonate platform conditions persisted, interrupted only by distant tectonic events such as the Turronian emplacement of the Hawasina and Semail Ophiolite complex and closure of the Tethys in Mid-Miocene. Divergence of the African and Arabian Plates began in the Miocene with actual rifting beginning at 13 Ma and continuing to the present. This rifting of the Gulf of Aden caused uplift, block faulting, and an end of carbonate deposition in Dhofar.

<u>Precambrian/Infracambrian Leads</u>. Precambrian crystalline basement rocks were fractured and intruded by granitic dikes in the Late Precambrian or Infracambrian. Iron and possibly copper

mineralization appear to be associated with this event but there is no record of their being commercially exploited. However this mineralization may be of local and historic significance on the Mirbat Plain and Kuria Muria Islands.

Infracambrian/Cambro-Orduoician Lead. The Infracambrian to possibly Ordovician sections have been observed, north of Mirbat, to have traces of hematitic strain. The extend of this mineralization is unknown but "iron formation" or taconite deposits are known to be associated with the Late Precambrian to Lower Paleozoic along the margins of the Indian Ocean.

Ferruginous Cenomanian Limestones. At the top of the Cenomanian, during the inception of the Hawasina and Semail Ophiolite overthrust event, a thin layer of ferruginous oolitic limestones was deposited as a cap on the Wasia Group in northern Oman and in Iran. It is unknown if this thin zone of iron mineralization occurs in Dhofar but the Cretaceous section is present along the lower cliffs of the Dhofar Mountains. At best these deposits would be thin but could extend some distance.

Massive Sulfide Deposits. The nearest ophiolite outcrops are at Ras Madrakah to the northeast of Mirbat some 400 km. It is unknown if massive sulfide deposits similar to those found on Masirah Island or in the Semail Ophiolites of the Jabal Hajar exist at Ras Madrakah but if they do, this would represent a source of copper and minor amounts of zinc, nickel, manganese, arsenic, and chromium that could have been available in Southern Oman. The importance of these additional metals to any ancient metallurgy process in Dhofar is that if the technology were available, then brass (Copper 65-90% and Zinc 10-35%), stainless steel (Iron 70-80%, Chromium 15-20%, and Nickel 5-10%), and other alloys could be made.

Spring Deposits. Travertine dripstones or spring deposits which are stained by hematite and limonite have been observed along the Tertiary limestone cliffs of the Dhofari coast. The concentration of iron in these deposits is not known but spring deposits are known to produce useable iron ore and could possibly have produced small quantities in the Dhofar Region.

Recommendations. Since none of the above leads have been well documented, it is recommended that a field party secure any available satellite imagery, low level aerophotographs, topographic cuadrangles, and geologic maps of the Dhofar Region in preparation for a field season of mapping and collecting in each of the lead areas. Samples, of course, would need to be returned to the lab and analyzed.

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