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MINERAL DEPOSITS IN WESTERN SAUDI ARABIA

by

Ralph J. Roberts, William R. Greenwood,
Ronald G. Worl, Franklin C. W. Dodge,
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ABSTRACT

Mineral deposits in Saudi Arabia include a variety of deposits which were formed in many geologic environments. These include magmatic and late magmatic deposits in igneous masses, contact metamorphic deposits along the margins of igneous bodies, and stratiform sulfide deposits and veins. Notable deposits of sedimentary origin include deposits of iron oxides and phosphate.

Strata-bound massive sulfide deposits containing copper, zinc, and nickel sulfides associated with pyrite and pyrrhotite in complexly deformed volcanic rocks in Saudi Arabia have been the subject of controversy. They are considered by some geologists to be of syngenetic or volcanogenic origin, and by others to be epigenetic.

The principal mineral deposits in western Saudi Arabia are localized in mineral belts within tectonic zones that trend northerly, northeasterly, and northwesterly. These belts contain the exploration target areas most promising for future exploration. Noteworthy among these are: 1) the northerly-trending Bidah copper-zinc belt; 2) the Sayid copper-zinc zone; 3) the northwest-trending Nuqrah copper-zinc-silver belt; and 4) the north-northwesterly-trending Al Amar belt. Gold and silver deposits are mainly localized in north-trending structural features of the Hijaz geotectonic cycle and northwest Najd trends.

Saudi Arabian metal deposits known thus far contain reserves in the 2 billion dollar range. Further exploration should result in discoveries that could significantly increase this amount; Saudi Arabia may well have workable metallic and nonmetallic mineral resources for industrial developments in many parts of the Kingdom.

In order to effectively carry on a search for new mineral deposits, the belts should be mapped in detail, with emphasis on the delineation of stratigraphic and structural features that control metallization. In addition, geochemical and geophysical studies should be made of promising areas to outline exploration targets. These targets could then be systematically explored.

INTRODUCTION

The mineral deposits of western Saudi Arabia include a wide variety of deposits that were formed in many geologic environments in Precambrian and Phanerozoic rocks during several metallogenic epochs. These include magmatic and contact metamorphic deposits in and associated with igneous bodies; strata-bound copper-zinc, iron, and nickel sulfide deposits; veins; and sedimentary deposits. Most of these deposits are of Precambrian age and have been metamorphosed; deposits of Phanerozoic age have not been metamorphosed.

The investigation of mineral deposits in Saudi Arabia has gone through three distinct phases. The first phase was identification of deposits worked during ancient times. The second phase was evaluation of these deposits and exploration of mineralized gossans. After these investigations proved to be only partially successful, a third phase, a detailed geologic mapping program, was begun so that the geologic and structural framework of the mineral deposits could be defined. This report includes a summary review of the framework and discusses the geologic and structural environment of the mineral deposits. The mineral deposits are mainly found in certain mineral belts that are stratigraphically and structurally controlled. The most favorable areas for prospecting are in the mineral belts, and geologic and genetic factors that might influence the planning and execution of exploration programs are discussed here briefly.

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GEOLOGY

The Arabian Shield is underlain by rocks that range from Precambrian through Phanerozoic (Brown and Jackson, 1960; Schmidt and others, 1973; Greenwood and others, 1973; Greenwood, Roberts, and Bagdady, 1974). The geology discussed herein is based on a report by Greenwood and others (unpub data) with several significant differences in interpretation favored by Roberts. The lithologic units, tectonism, plutonism, and metallogenic epochs are summarized in table 1.

Table 1.- Summary of Precambrian formations, tectonism, plutonism, volcanism, and metallogenic epochs in the Arabian Shield (modified after Schmidt and others, 1973; G.F. Brown, written commun., 1974; R.J. Fleck, written commun., 1974; Greenwood and others, 1973, 1974).

MAJOR PHASES	ASSEMBLAGES	ENVIRONMENTS	UNITS	MAJOR ROCK TYPES	VOLCANIC ROCKS		TECTONIC EPISODES	PLUTONIC ROCKS	RADIOMETRIC AGES (m.y.)[1]	METALLOGENIC EPISODES
LATE PHASE	Nonmetamorphosed assemblage	Postorogenic environment	Jubaylah Group	Conglomerate, sandstone, minor volcanic rocks; and marine marble and shale	Andesitic basalt and rhyolite		Najd Northwest left-lateral wrench faulting	Granite to granodiorite	~ 530	Najd (Au, Ag) Jabal Guyan Samrah
			U							
			Shammar Group	Rhyolite and minor clastic rocks	Mostly rhyolite tuff, rhyolite, and trachyte		Shammar subsidence	Granite to granodiorite	570 ?	
			U							
MIDDLE PHASE	Metaandesitic assemblage	Orogenic environment	Murdama Group	Clastic rocks and minor andesite, marble, and shale	Andesite and rhyolite	HIJAZ TECTONIC CYCLE	Bishah Northerly folds and faults	Quartz monzonite, subordinate diorite, gabbro and granite		Hijaz (Au, Ag) Mahd adh Dhahab (Au, Ag) Sayid and Nuqrah (Cu, Zn, Ag, Au) Samran (Cu, Zn) Bidah (Cu, Zn)
			U							
			Halaban Group	Upper: silicic volcanic rocks, tuff, and agglomerate	Rhyolite and trachyte		Yafikh Northerly folds and faults	Quartz monzonite, subordinate diorite, gabbro, and granite	650-600 ~ 690[2]	Wadi Sawawin (Fe)
				Middle: andesite, basalt, and tuff	Andesite and basalt					
				Lower: conglomerate, sandstone, and volcanic rocks	Andesite					
			U							
			Ablah Group	Conglomerate, sandstone, basalt, pyroclastic and volcaniclastic rocks, and marble	Andesite and rhyodacite		Ranyah Northerly and northeast folds and faults	Granodiorite gneiss, diorite, gabbro, quartz diorite	~ 800	Wadi Yiba (Cu)
			U							
			Jiddah Group	Andesitic to dacitic volcanic rocks and volcaniclastic rocks; minor slate and marble	Andesite, dacite, and basalt		Aqiq North and northeast folds and left-lateral faults	Diorite, gabbro to trondhjemite, and quartz diorite	~ 960	Wassat (Fe sulfide)
			?							
	Metabasalt-graywacke-chert assemblage	Oceanic environment	Bahah Group	Chlorite, graphite, and sericite schist, minor marble, quartzite, and chert	Minor basalt			Quartz porphyry orthoschist and diabase	> 960	
			Baish Group	Basalt and mafic tuff, graywacke, minor chert, and marble	Basalt and andesitic basalt					
EARLY PHASE	Biotite schist, amphibolite, and orthogneiss assemblage			SEQUENCE UNCERTAIN Schist, amphibolite, and orthogneiss. At least partly equivalent to early and middle phase assemblages	Basalt (?)		Tihama (?)			None recognized

1 - By K/Ar and Rb/Sr methods; the dates represent apparent ages and may in part reflect metamorphic events.

2 - K-feldspar in vein at Mahd adh Dhahab mine by Rb/Sr method; rhyolite 10 km north of mine gave 696 m.y. by Rb/Sr method.

Precambrian rocks

Greenwood and others (in prep.) have discussed the development of the Arabian Shield in terms of the Hijaz tectonic cycle. They have subdivided the cycle into three episodes: an early episode of mafic and intermediate volcanism and sedimentation (Baish, Bahah, and Jiddah Groups); a middle episode of intermediate to silicic volcanism and sedimentation (Ablah and Halaban Groups); and a late episode of silicic volcanism and sedimentation (Murdama Group).

The above subdivision of major rock groups places principal emphasis on episodes of deformation and is not followed in table 1 and plate 1 of this report. Instead, the rock units are grouped into four principal rock assemblages that were formed during major phases in the evolution of the Arabian Shield: an older assemblage of biotite schist, amphibolite, and orthogneiss; a second metabasalt-graywacke-chert assemblage; and a third metaandesitic assemblage that rests locally upon the middle assemblage. The fourth assemblage comprises unmetamorphosed clastic and volcanic rocks that rest locally on the third assemblage.

Biotite schist, amphibolite, and orthogneiss assemblage

An assemblage consisting of biotite schist, amphibolite, and gneiss crops out widely throughout the Shield. Rocks assigned to these units were initially assigned to the Hali Schist, Abt Schist, Khamis Mushayt Gneiss, and roughly correlative units (Brown and Jackson, 1960; Schmidt and others, 1973; Coleman, 1974), but recently Greenwood and others (unpub data) have suggested that though they may be higher in metamorphic grade than units commonly found in the lower and middle assemblages they are not necessarily older as had heretofore been assumed. Locally some units have been traced from biotite-amphibolite facies into greenschist facies. However, not all the high-grade metamorphic rocks in the Shield have been reexamined and reevaluated as yet, and Roberts feels that it is desirable and prudent to retain this metamorphic assemblage for the time being.

Some gneissic rocks are exposed in the cores of domal uplifts and were thought to be remobilized older basement by Schmidt and others (1973) and Coleman (1974). R. J. Fleck (written commun., March 1975) has dated some of these gneissic rocks by Rb/Sr methods and found them to be relatively young, in the range of 840-750 m.y. (table 1). These young dates may reflect the time of remobilization and do not necessarily represent the absolute ages of the rock units involved in doming.

Metabasalt-graywacke-chert assemblage

The second assemblage consists principally of metabasalt, metagraywacke, and metachert, and minor graphite schist and marble (Schmidt and others, 1973; Greenwood, in press a). Metabasalt and metagraywacke at the base of the assemblage which accumulated during submarine volcanism are assigned to the Baish Group. The associated graphitic schist, metachert, metatuff, and marble of the overlying Bahah Group indicate deposition in a moderately deep oceanic trough. Both units have been regionally metamorphosed to greenschist facies and have been intruded by a wide variety of plutonic rocks including extensive quartz porphyry sills. The Baish and Bahah are best developed in the southwestern part of the Shield. They have been metamorphosed to upper greenschist facies.

Metaandesitic assemblage

The third assemblage is predominantly made up of metamorphosed volcanic and pyroclastic rocks of andesitic to dacitic composition and associated volcaniclastic and clastic rocks with minor marble units. These have been assigned to the Jiddah, Halaban, Ablah, and Murdama Groups (plate 1, table 1). They are thought to have accumulated in subaerial to shallow marine evironments, and are now mostly metamorphosed to upper greenschist facies.

The Jiddah Group of Schmidt and others (1973) includes a wide variety of andesitic to rhyodacitic volcanic, pyroclastic and volcaniclastic rocks and minor slate, chert, and marble. The Jiddah Group has been extensively intruded by largely diorite bodies.

A predominantly clastic unit, the Ablah Group, rests unconformably on the Jiddah and on diorite that cuts the Jiddah (Greenwood and others, in press). The Ablah is characterized by a basal unit of conglomerate, sandstone, and minor shale and marble; a middle unit of andesite to rhyodacite volcanic and pyroclastic rocks; and an upper predominantly clastic unit.

The Halaban Group of Schmidt and others (1973) overlies folded rocks of the Ablah and Jiddah Groups and diorite that cuts these rocks. It consists of three units (Delfour, 1970b; Hadley, 1973, 1974a): a lower unit of metaconglomerate, shale, marble, and metavolcanic rocks; a middle unit of predominantly metaandesite, agglomerate, breccia, tuff, and metasediments; an upper unit largely of rhyolitic and trachytic metavolcanic flows and metapyroclastic rocks with locally significant clastic rocks and marble. Plutonic rocks ranging from diorite to granite cut the Halaban.

The Murdama Group of Schmidt and others (1973) unconformably overlies the Halaban Group. The lower part of the Murdama is made up largely of sedimentary and pyroclastic rocks including conglomerate, agglomerate, sandstone, shale, and minor marble beds. The upper part contains metaandesite and metarhyolite flows and pyroclastic rocks. Plutonic rocks that cut the Murdama include rhyolite porphyry to granite.

Unmetamorphosed assemblage

The youngest assemblage which includes two units, the Shammar and Jubaylah Groups (Delfour, 1970c; Schmidt and others, 1973; Hadley, 1973, 1974b), locally overlies rocks of the third assemblage. The Shammar consists mostly of andesitic basalt and rhyolitic volcanic and pyroclastic rocks and the Jubaylah of clastic rocks with minor limestone and stromatolite-bearing units. The volcanic and clastic units accumulated under subaerial conditions and the calcareous units in a shallow marine environment (table 1). These units are included with the third assemblage on plate 1.

Phanerozoic rocks

After a long period of erosion following the deposition of the Jubaylah, the Precambrian rocks of Saudi Arabia were overlapped by sedimentary rocks during the Phanerozoic (table 2). The oldest Phanerozoic unit is Cambrian-Ordovician quartz sandstone, followed by Ordovician and Silurian sandstone and shale and by Devonian limestone, shale, and sandstone (Powers and others, 1966).

The Devonian rocks are overlain unconformably by Permian limestone and shale; locally the underlying units have been eroded and the Permian rocks rest directly on the Precambrian. The Triassic rocks are sandstone and shale, mostly of continental facies, but locally contain marine limestone tongues. The Jurassic rocks are marine fine clastic rocks and carbonates; these are followed by Early Cretaceous clastic limestone; in late-Early Cretaceous continental sedimentation prevailed for a time, but marine deposition resumed again in the mid-Cretaceous (Powers and others, 1966).

Northwesterly subsidence across the Shield in the Late Cretaceous resulted in formation of a proto-Red Sea and subsequent accumulation of Upper Cretaceous to Paleocene sediments (Karpoff, 1957; Brown, 1970). Basaltic volcanism in Yemen, Ethiopia, and Saudi Arabia coincided with these events. During the same time span, sedimentation continued in the eastern part of Saudi Arabia (Powers and others, 1966).

Tertiary sedimentation in eastern Saudi Arabia was characterized by deposition of shallow-water marine clastic and calcareous rocks, whereas sedimentation in the west was characterized by clastic sedimentation and volcanism. During the late Tertiary the Red Sea became a deep trough in which thick saline and clastic deposits accumulated.

STRUCTURAL FRAMEWORK

The principal Precambrian tectonic events recognized in Saudi Arabia are summarized in table 1. The Tihama orogeny is the oldest orogenic event identified in the Shield (Schmidt and others, 1973). It was followed by the Hijaz tectonic cycle (Greenwood and others, 1973). The Hijaz is subdivided into four orogenic events: from oldest to youngest these are the Aqiq, Ranyah, Yafikh, and Bishah. The Bishah is followed by the Najd orogeny, the last major Precambrian event.

The Tihama orogeny affected the Baish and Bahah Groups and the Hijaz the Jiddah, Halaban, and Murdama Groups. Plutonism during the Tihama resulted in emplacement of quartz porphyry bodies. Plutonism during the Aqiq orogeny culminated in the emplacement of major diorite batholiths at about 950 m.y. Folding during the Aqiq orogeny followed diverse trends, but north-striking folds and left-lateral wrench faults were characteristically developed. Complementary northeast-trending right-lateral wrench faults and northeast and northerly folds were formed at the same time.

The Ablah Group and underlying rocks were folded during the Ranyah orogeny along north and northeast trends. Granodiorite gneiss, diorite, gabbro, trondhjemite, and quartz diorite plutons were emplaced at this time.

The Yafikh orogenic trends followed those of the Aqiq and Ranyah orogenies and resulted in shearing and mylonitization of earlier emplaced diorite plutons (Greenwood and others, in press). In addition, an upright cleavage was developed in rocks of the Halaban Group and in older units. Quartz monzonite and subordinate diorite, gabbro, and granite plutons were emplaced in late stages of the Yafikh orogeny. The intrusive patterns in the northern part of the Shield appear to have been controlled by a strong north-south grain in the basement underlying the younger volcanics and sediments.

The Bishah orogeny was the final major tectonic event in the Precambrian Shield in Saudi Arabia. During this orogeny rocks of the Murdama Group were folded on trends established earlier in the Hijaz cycle.

Table 2.- Summary of Phanerozoic formations, tectonism, plutonism, and metallogenic epochs in Saudi Arabia.

EASTERN PROVINCE (modified after Powers and others, 1966)

AGE				FORMATION	LITHOLOGY	THICK-NESS	MAJOR STRATIGRAPHIC DIVISIONS
CENOZOIC	QUATERNARY AND TERTIARY			Surficial deposits	Gravel, sand, and silt		
CENOZOIC	TERTIARY	Miocene and Pliocene		Kharj	Limestone, lacustrine limestone, gypsum, and gravel	28 m	Miocene and Pliocene Clastic Rocks
				Hofuf	Sandy marl and sandy limestone; subordinate calcareous sandstone. Local gravel beds in lower part	95 m	
				Dam	Marl and shale; subordinate sandstone, chalky limestone, and coquina	91 m	
				Hadrukh	Calcareous, silty sandstone, sandy limestone; local chert	84 m	
		Oligocene					NOT REPRESENTED
		Eocene	Lutetian	Dammam	Limestone, dolomite, marl, and shale	33 m	Upper Cretaceous to Eocene Carbonate Rocks
			Ypresian	Rus	Marl, chalky limestone, and gypsum; common chert and geodal quartz in lower part. Dominantly anhydrite in subsurface	56 m	
		Paleocene	Thanetian / Montian(?)	Umm er Radhuma	Limestone, dolomitic limestone, and dolomite	243 m	
				Possible disconformity			
MESOZOIC	CRETACEOUS		Maestrichtian / Campanian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in north-western and southern areas of outcrop	142 m	
			Turonian(?) / Cenomanian	Wasia (Sakaka Sandstone of northwest Arabia)	Sandstone; subordinate shale, rare dolomite lenses	42 m	Middle Cretaceous Clastic Rocks
			Aptian / Barremian	Biyadh	Sandstone; subordinate shale	425 m	Late Lower Cretaceous Clastic Rocks
			Hauterivian	Buwaib	Biogenic calcarenite and calcarenitic limestone interbedded with fine sandstone in upper part	18 m	
			Valanginian	Yamama	Biogenic-pellet calcarenite; subordinate aphanitic limestone and biogenic calcarenitic limestone	46 m	Upper Jurassic and Early Lower Cretaceous Carbonate Rocks
			Berriasian	Sulaiy	Chalky aphanitic limestone; rare biogenic calcarenite and calcarenite limestone	170 m	
	JURASSIC		Tithonian	Hith	Anhydrite	90 m	
				Arab	Calcarenite, calcarenitic and aphanitic limestone, dolomite and some anhydrite. Solution-collapse carbonate breccia on outcrop due to loss of interbedded anhydrite	124 m	
			Kimmeridgian	Jubaila	Aphanitic limestone and dolomite; subordinate calcarenite and calcarenitic limestone. Lower part sandstone between 20° N. and 22° N.	±118 m	
				Hanifa	Aphanitic limestone, calcarenitic limestone, and calcarenite	113 m	
			Oxfordian / Callovian	Tuwaiq Mountain	Aphanitic limestone; subordinate calcarenitic limestone and calcarenite. Abundant corals and stomatoporids in upper part	203 m	
			Callovian(?) / Bathonian / Bajocian	Dhruma	Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22° N. and north of 26° N.	375 m	Lower and Middle Jurassic Clastic and Carbonate Rocks
			Toarcian	Marrat	Shale and aphanitic limestone; subordinate sandstone	103 m	
	TRIASSIC		Upper	Minjur	Sandstone; some shale	315 m	Permian and Triassic Clastic Rocks
			Middle	Jilh	Sandstone, aphanitic limestone, and shale; subordinate gypsum	±326 m	
			Lower	Sudair	Red and green shale	116 m	
PALEOZOIC	PERMIAN		Upper	Khuff	Limestone and shale; dominantly sandstone south of 21°N.	171 m	
			Lower	Wajid	Sandstone, gravel, and basement erratics (Recognized only in southwestern Saudi Arabia and northern Yemen)	950 m calculated	
	?		undated				
				Precambrian basement complex			
	DEVONIAN		Lower	Jauf	Limestone, shale, and sandstone	299 m	Lower Paleozoic Clastic Rocks
	ORDOVICIAN AND SILURIAN			Tabuk	Sandstone and shale	1,072 m	
	CAMBRIAN			Saq { Umm Sahm, Ram, Quweira, Siq }	Sandstone	+600 m	

Compiled by R. W. Powers and L. F. Ramirez, June 3, 1963

Table 2. - Continued.

WESTERN PROVINCE - ARABIAN SHIELD AND RED SEA TROUGH (modified after Brown and Jackson, 1960; Shanti, 1966, 1970; Ahmad, 1972; Meissner and Ankary, 1972; Girdler and Styles, 1974)							
FORMATION	LITHOLOGY	THICK-NESS	MAJOR STRATIGRAPHIC DIVISIONS	TECTONIC EPISODES	PLUTONIC ROCKS	VOLCANIC ROCKS	METAL-LOGENIC EPOCHS
		m				Mafic volcanism	Red Sea deposits
Unnamed unit	Reef limestone, gypsum, clay, marl, sand-stone	160	Miocene and Pliocene clastic rocks, clays, and evaporites	Major subsid-ence in Red Sea graben; rifting during last 5 m. y.	Dikes and sills related to mafic volcanism	do.	Zinc, lead, barite, and manganese deposits (Rabigh, Jabal Dhaylan)
Raghama and Baid Formations	Arkose, sand-stone, and shale	±140	Oligocene sandstone and shale	Initial rifting 41-36 m.y. in Red Sea graben	do.	do.	
Shumaysi Formation	Sandstone, shale, silt-stone, tuff, and basaltic andesite	163	Paleocene to Eocene clastic and volcanic rocks	Paleocene: initial subsid-ence along Red Sea graben	do.	Basaltic andesite and rhyolite in Hijaz	Oolitic iron ore
Usfan and Hibr Formations					do.	Mafic volcanism in Yemen	Phosphate deposits in northern Saudi Arabia
				Subsidence in southern Red Sea			
EROSION OF SHIELD				General epeirogenic uplift in northern Red Sea			
Local deposition of Saq and Tabuk equivalents				Carboniferous: initial subsid-ence in Gulf of Suez			
				Epeirogeny in Arabian-Nubian shield			

The northwest-trending Najd orogeny developed in response to postorogenic crustal adjustments and strike-slip faulting in latest Precambrian time. The left-lateral sense of movement can be seen by the displacement of intrusive outcrop patterns in the fault zone (plate 1). The magnitude of lateral transport has been estimated by Brown (1972) to be about 240 km. Large vertical displacements are also common in this fault zone. A few late granites were emplaced in the Najd zone and were sheared by late fault movement. Subsidiary northeast, east-west, and north-south trending faults were also developed in and adjacent to the Najd zone. Rocks involved in the Najd orogeny generally appear to be depressed with respect to old crustal rocks to the southwest and northeast. Narrow horst-like blocks rise in the more intensely faulted zones of the system. Similarly, narrow grabens preserve the youngest Precambrian-Cambrian deposits, the Shammar and Jubaylah Groups (Delfour, 1970c; Hadley, 1974b). The broad northwest-trending subsidence and deformation related to the Najd fault system appears to have accompanied and followed rhyolitic volcanism of the Shammar Group (table 1).

Geotectonic models

Greenwood and others (unpub. data) have postulated a plate tectonic model for the development of the Arabian Shield in Precambrian time, emphasizing similarities with other regions where this model has been applied (Dewey and Bird, 1970; Dickinson, 1971; Hsu, 1973).

Roberts, however, feels that the Shield lacks diagnostic rocks and features that are characteristic of the plate tectonic regime, such as ophiolite sequences, blue-schist rock facies, trench melanges, and identifiable suture zones (Meyerhoff and Meyerhoff, 1972; Maxwell, 1973; Wilson, 1974; Schermerhorn, 1974). In addition, the large amounts of potassic granites throughout the Shield suggest a sialic basement.

Roberts proposes an alternative model for the development of the Shield, based on a geosynclinal model (Roberts, 1972). This model includes sedimentation and mafic volcanism in and marginal to a seaway between the African and Arabian Shields which was underlain by oceanic crust (Baish-Bahah); this was followed by andesitic volcanism and sedimentation (Jiddah, Halaban-Ablah, Murdama); and by volcanism and clastic accumulation (Shammar and Jubaylah).

Major structural trends in Saudi Arabia

The generalized geologic map of western Saudi Arabia (plate 1) shows that a north-south grain dominates structural patterns of the southern part of the Arabian Shield. The north-south grain was imposed by folding, left-lateral wrench-faulting, and intrusion of diorite batholiths during the Aqiq orogeny. Complementary northeast-trending folds and right-lateral wrench faults were also developed during the Aqiq orogeny north and east of Jiddah. Subsequent tectonism during the Hijaz cycle followed the same north-south and northeasterly trends.

The map pattern shows a gradual increase in younger rocks from south to north with an abrupt change at the principal southernmost strand of the Najd fault system shown on plate 1 and on figure 1. From this fault strand northward, most of the layered rocks appear to be younger than the diorite batholiths of the Aqiq orogeny. Younger potassic intrusions clearly predominate in the north. High-grade basement rocks have been brought up along several strands of the Najd fault and crop out extensively in the Dawadami area on the east side of the Shield.

The distribution of Phanerozoic rocks is controlled by broad arching of the Arabian Shield in post-Precambrian time. East of the Shield Phanerozoic rocks dip gently eastward. Southwest of the Shield late Mesozoic and Tertiary rocks were deposited in the Red Sea downwarp and rift zone.

This distribution of major rock types and structural features exerts a fundamental control on the distribution of mineral deposits in western Saudi Arabia (table 3). Base metal deposits occur in faulted and folded rocks of the Baish Group in Wadi Bidah; in the Jiddah Group at Wadi Shwas and Samran; and in the Halaban Group at Nuqrah and Jabal Sayid. Precious metal deposits have been found in all the major assemblages except the youngest--the nonmetamorphosed assemblage.

Phanerozoic deposits at Rabigh and Jabal Dhaylan are found in Tertiary rocks or are controlled by Tertiary structural features. Recent ore deposits in the Red Sea zone are in Miocene to Holocene sediments.

TYPES OF MINERAL DEPOSITS IN WESTERN SAUDI ARABIA

The significant mineral deposits in Saudi Arabia occur in three principal geologic settings: in Precambrian rocks of the Shield; in Tertiary rocks that rest on the Shield or in fault blocks in the Red Sea coastal plain; and in Tertiary and Quaternary rocks in axial deeps of the Red Sea. Typical examples of each principal class will be described in the following account.

Table 3. - Characteristics of principal mineral deposits in Saudi Arabia.

Age	NAME AND TYPE	GEOLOGIC SETTING	STRUCTURAL SETTING	ORE CONTROL	PRINCIPAL ORE MINERALS	GANGUE MINERALS	SOURCE OF DATA
PRECAMBRIAN	JABAL SAYID - Massive base metal sulfide	Halaban Group pyroclastic rocks	N to N20°E steeply plunging anticline	Replacement of tuff beds below jasper envelope	Pyrite, pyrrhotite, chalcopyrite, sphalerite, tellurides, native gold	Jasper, quartz, carbonates, chlorite	Conraux and others, 1969; Delfour, 1970a, b; Alabouvette, 1974; Routhier and Delfour, 1975
PRECAMBRIAN	WADI BIDAH - Massive base metal sulfide	Rocks of Baish and Bahah Groups; quartz porphyry	Shearing along N-trending tight folds	Replacement of sheared calcaleous tuff beds and quartz porphyry	Pyrite, pyrrhotite, chalcopyrite, locally sphalerite, native gold	Carbonates, quartz, chlorite, barite, rhodonite	Earhart and Mawad, 1970; Earhart, 1971; Jackaman, 1972; Greenwood and others, 1974b
PRECAMBRIAN	WADI QATAN - Massive nickeliferous sulfide	Andesitic volcanic rocks of Jiddah Group	N and NW shearing along beds	Nickel minerals replace iron sulfides in pyroclastic units	Pyrite, pyrrhotite, magnetite, pentlandite, violarite	Carbonates, quartz, chlorite	Overstreet and Rossman, 1970; Dodge and Rossman, 1975, Greenwood, in prep.
PRECAMBRIAN	UYAIJAH - Disseminated Mo-W deposit; Mo-bearing quartz veins	Granitic rocks intrusive into Murdama Group	Circular and arcuate intrusive bodies; late-stage fracture zones	Mo-W minerals in contact zone; quartz-filled NW shear zones	Scheelite, powellite, and molybdenite, minor pyrite, chalcopyrite	Quartz, chlorite, sericite, K-feldspar	Whitlow, 1968a, b, 1971; Theobald, 1970a; Dodge, 1973, Theobald and Allcott, 1975 Dodge and Helaby, 1975
PRECAMBRIAN	MAHD ADH DHAHAB - Gold-silver-bearing quartz veins	Murdama Group pyroclastic rocks; rhyolite porphyry	Homoclinal rocks cut by NW, NE, NS striking faults	N, NW, NE quartz veins; disseminated	Pyrite, chalcopyrite, galena, native gold and silver	Quartz, K-feldspar, carbonates, chlorite	Dirom, 1946; Goldsmith, 1971; Goldsmith and Kouthier, 1971; Luce and others, unpub. data.
PRECAMBRIAN	SAMRAH - Silver-zinc-bearing quartz veins	Granitic rocks cut by mafic dikes	Veins in NE fault zones	NE faults of Najd system	Pyrite, sphalerite, galena, silver-bearing sulfosalts	Quartz, carbonates, chlorite, epidote, sericite	Kiilsgaard, 1970; Kiilsgaard and Martin, 1969; Shanti, 1973
PRECAMBRIAN	SAWAWIN - Banded hematite-jaspilite iron ore	Sandstone, shale, chert, and tuff of Halaban Group	NW-trending folds and faults	Syngenitic chemical deposition in lagoon environment	Massive and specular hematite, magnetite	Jasper, quartz, clay minerals	JGM, 1967; Bogue, 1953; Kahr and Agocs, 1962
TERTIARY	SHUMAYSI - Oolitic hematite-goethite ore	Oligocene sediments in NW basins marginal to proto-Red Sea	NW-trending early Miocene grabens	Marine near shore subtidal facies with high wave energy	Hematite, goethite, hydrohematite	Quartz and alumina gels	Richter-Bernburg and Schots, 1954; Shanti, 1966
TERTIARY	JABAL DHAYLAN - Base metal replacement and sedimentary deposits	Raghama Formation clastic rocks and limestone	Horizontal to gently dipping beds, cut by faults	Strata-bound, tabular; some steeply dipping bodies in fault zones	Galena, secondary zinc minerals, manganese oxides	Barite, calcite, quartz, jasperoid	Dadet and others, 1969; Dadet, 1970; Bigot, 1973; Delfour, 1973
TERTIARY	RABIGH - Barite veins	Jiddah Group andesite cut by diorite and granodiorite	Faulted zones parallel to Red Sea margin	Steep veins N25-60°W mostly in granitic rocks	Barite, minor chalcopyrite, galena	Jasperoid, quartz, carbonate	Brobst, 1966, 1972; Shanti, 1970
TERTIARY	THANIYAT TURAYF - Bedded phosphorite	Upper Cretaceous and Eocene sediments	Preserved in Sirhan-Turayf basin	Shallow marine shelf adjacent to deep water; upwelling currents	Apatite	Clay minerals, quartz sand, marl, chert, limestone	Powers and others, 1966; Sheldon, 1967; Meissner and Ankary, 1972
TERTIARY	RED SEA - Volcanogenic sedimentary	Sediments in Red Sea trough and in shelves	Grabens and rift zones on floor of Red Sea	Strata-bound, closed basins on sea floor	Marcasite, marmatite, manganite, chalcopyrite	Clay minerals, iron oxides, carbonates	Bischoff, 1969; Skipwith, 1973; Degens and Ross, in press

Precambrian metal deposits in the Shield

Precambrian metal deposits in the Shield are divided into four major groups: base and ferrous metal sulfide deposits; disseminated tungsten-molybdenum deposits and molybdenum-bearing quartz veins; gold- and silver-bearing quartz veins; and sedimentary iron deposits. The base metal sulfide deposits have been subdivided into three subgroups: massive copper-zinc deposits, nickel-iron deposits, and disseminated sulfide deposits. Iron sulfide deposits are commonly strata-bound. The gold- and silver-bearing quartz veins are discussed separately. Deposits representative of these four major groups are summarized in table 3, and will be described briefly here to give a basis for discussing their genesis.

Base metal sulfide deposits

Base metal sulfide deposits in the Arabian Shield include massive copper-zinc deposits at Jabal Sayid and Wadi Bidah, nickel-iron sulfide deposits at Wadi Qatan, iron sulfide deposits at Wadi Wassat, and disseminated copper-zinc sulfide deposits at Kutam.

Massive copper-zinc deposits

Jabal Sayid

The Jabal Sayid copper-zinc sulfide deposit at lat 23°55'00"N. and long 40°56'30"E. consists of two principal ore bodies, the Main and East bodies, in pyroclastic rocks of the Halaban Group (Conraux and others, 1969; Delfour, 1970a, b; Alabouvette, 1974; Routhier and Delfour, 1975).

The Main ore body is an elliptical pipe-like body on the overturned northwest flank of a faulted anticline that trends north to N.20°E. and plunges steeply northeast (Delfour, 1970a). The East ore body may be an offset segment of the Main ore body, displaced about 400 m east on a right-lateral fault trending N.70°E. Ore minerals were formed during two stages: an early stage characterized by pyrite, magnetite, cassiterite (SnO_2), and pyrrhotite; followed by a late stage assemblage including chalcopyrite, sphalerite, stannite (Cu_2FeSnS_4), hessite (Ag_2Te), sylvanite ($AuAgTe_4$), krennerite ($AuTe_2$), electrum (AgAu), native gold (Au), coloradoite (HgTe), altaite (PbTe), cubanite ($CuFe_2S_3$), and mackinavite ($Cu_2Fe_4S_7$). The ore bodies are capped by a jasper zone, cut by quartz veinlets that replaces the rocks overlying the sulfide zone. Sericite, chlorite, quartz, and carbonates resulted from pervasive sericitic and propylitic alteration of the mineralized rock.

The Jabal Sayid deposit has been extensively explored by diamond drilling and trenching. Fifty-four holes aggregating about 20,000 m have been drilled thus far. Reserves are about 8,000,000 metric tons averaging 2.2 percent Cu, 1.4 percent Zn, 40 g/t Ag, and 0.5 g/t Au (Routhier and Delfour, 1975).

The sulfides that formed during the early stage of metallization commonly parallel bedding in the pyroclastic rocks. Likewise, the jasper envelope roughly parallels bedding, though locally fingers of jasper cut sharply across bedding. The late-stage minerals occur mostly in veinlets that cut the early-stage minerals and the jasperized wall rock.

Delfour (1970a, b) considered the Jabal Sayid deposit to be synorogenic with Halaban volcanism, and indicated that sulfide metallization lies between hydrothermally altered rock in the footwall and jasperized rock in the hanging wall.

Alabouvette (1974) more recently has emphasized that the alteration and mineralization were formed by hydrothermal solutions that came in contact with sea water, forming jasper during several cycles and precipitating the sulfide minerals during one cycle. Tectonic activity during and following this time caused erosion of the hydrothermally altered rocks and younger clastic rocks of the Murdama Group were deposited on the Halaban Group. Subsequent tectonic activity in post-Murdama time caused additional faulting and fracturing of the rocks.

Roberts has noted the close relationships of silicification, alteration, and sulfide metallization at Jabal Sayid. The silicification and alteration are partly developed in the rocks overlying the mineral deposits, and it is inferred that they formed in an environment below the sea floor. In addition, the early pyrite and pyrrhotite were fractured during early stages of metallogenesis, and later base metal sulfide minerals were introduced into the fractured rock. The base metals may therefore be younger, possibly even post-volcanic, and may have formed during plutonism related to the Bishah orogeny which terminated the Hijaz cycle.

Nuqrah

The Nuqrah deposit comprises two mineralized bodies, North Nuqrah at lat 25°38'30"N.; long 41°26'30"E., and South Nuqrah at lat 25°35'30"N.; long 41°26'30"E. The deposits are in north-striking pyroclastic rocks, andesite, and dolomitic marble which Delfour (1970a, b) assigned to the Halaban Group.

At North Nuqrah the beds strike northerly and are locally overturned and sheared parallel to bedding. Metallization is in graphitic and chloritic tuff and dolomitic marble between andesite and rhyolitic tuff (Bouladon, 1969; Delfour, 1970b; Routhier and Delfour, 1975). The mineralized bodies are pod-like, and parallel bedding.

At South Nuqrah the beds strike in general N.20°E. and dip 50°NW., but are locally complexly folded and broken on faults. Metallization is in the upper part of the dolomitic marble unit and in the lower part of a diabase unit. The mineralized bodies form lenticular pods along bedding.

The ore minerals consist of pyrite, sphalerite, chalcopyrite, galena, arsenopyrite, pyrrhotite, and minor amounts of altaite (PbTe), hessite (Ag_2Te), empressite (AgTe), tetradymite (Bi_2Te_2S), mackinavite ($Cu_2Fe_4S_7$), electrum (AgAu), bournonite ($PbCuSbS_3$), frohbergite ($FeTe_2$), and native gold.

According to Routhier and Delfour (1975) the reserves at North Nuqrah are 400,000 tons that average 2.5 g/t Au, 332 g/t Ag, 0.75 percent Cu, 1.22 percent Pb, and 6.0 percent Zn. At South Nuqrah a mineralized lens of 1,000,000 tons averages 4.3 g/t Au, 220 g/t Ag, 0.82 percent Cu, 1.83 percent Pb, and 5.6 percent Zn (Routhier and Delfour, 1975).

As Safra

The As Safra ancient copper mine is near lat 24°10'N. and long 41°54'E. on the Najd plateau (Schaffner, 1956; Kabbàni and Brown, 1956; Conraux and Delfour, 1970). The workings consist of many shallow trenches in a N.20°E. zone 4 km long and 0.5 km wide.

The workings are in the pyroclastic unit of the Halaban Group which here includes andesite, microdiorite, dolomitic marble, and rhyolitic tuff. These rocks have been propylitically altered and some units have been sericitized. They have been cut by many northwest-trending rhyolite and mafic dikes.

The copper metallization is mainly massive lenses and disseminations in the rhyolitic tuff and marble units. The ore minerals include early pyrite and pyrrhotite, and a later generation of chalcopyrite, sphalerite, and minor galena; accessory cubanite ($CuFe_2S_3$), hessite (Ag_2Te), tetradymite (Bi_2Te_2S), and native bismuth accompany the principal sulfides. Many quartz veins and stockworks cut the mineralized beds.

According to Conraux and Delfour (1970), the inferred reserves total 2,750,000 tons containing 2.13 percent Cu, and 4,500,000 tons averaging 1.29 percent Cu.

Wadi Bidah

The Wadi Bidah district includes several copper-zinc deposits and many untested gossans in two host rocks: in volcanic, pyroclastic, and sedimentary rocks of the Baish Group (Rabathan deposit); and in quartz porphyry sills that cut these rocks (Gehab deposit) (Earhart and Mawad, 1970; Earhart, 1971; Jackaman, 1972; Greenwood and others, 1974b).

The Rabathan ancient mine at lat 20°23'42"N. and long 41°22'59"E. is in calcareous mafic tuff and graphitic schist of the Baish Group on the sheared limbs and nose of a tight fold that trends northerly and plunges about 50°N. The ore minerals are chalcopyrite and sphalerite that cut brecciated early pyrite and pyrrhotite. Significant amounts of silver and gold locally accompany the late sulfides.

The Gehab deposit at lat 20°41'N. and long 41°24'E. is on the sheared flanks of an anticlinally folded quartz porphyry sill which conformably intrudes basalt breccia, tuff, ferruginous chert, and chert. The sulfide bodies are lenticular and replace the quartz porphyry along mylonitized shear zones that trend northerly, parallel to major structural features in this region.

The ore minerals are pyrite, chalcopyrite, sphalerite, and locally, native gold and are in rocks that have been propylitically altered. Chlorite, carbonate, quartz, pyrite, and epidote are common products of this alteration process; locally barite was introduced into the mineralized rock. Rhodonite and rhodochrosite are gangue minerals at the Gehab deposit.

These deposits were formed following a complex sequence of events, including regional folding, development of schistosity, metamorphism, and intrusion of quartz porphyry sills. Metallization took place during two stages: an initial replacement of favorable units (calcareous tuff and quartz porphyry) by pyrite and pyrrhotite; and a distinctly later replacement of brecciated pyrite and pyrrhotite, following an episode of refolding, brecciation, and shearing, by chalcopyrite, sphalerite, precious metals and associated carbonates, barite, and quartz. The paragenesis resembles that at the Killingdal Mine, Norway (Rui, 1973).

The reserves at Wadi Bidah are significant (Earhart and Mawad, 1970; Greenwood and others, 1974b): the Gehab deposit has been explored by 6 drill holes that prove the deposit is at least 300 m long, ranges from 4 to 7 m thick, and extends to a depth of at least 130 m. The reserves total 1,038,000 tons averaging 0.95 percent Cu, 0.81 percent Zn, 0.79 g/t Au, and 5.49 g/t Ag. The Rabathan deposit has also been explored by drilling. Six holes penetrate the ore body and indicate a strike length of 200 m, thickness 1 to 19 m, and depth of 220 m. The reserves total 1,500,000 tons averaging 2.14 percent Cu, 0.02 percent Zn, 0.15 g/t Au, and 2.45 g/t Ag.

The Sha'ab Eltare deposit is in the central part of the Wadi Bidah district at lat 20°35'N. and long 41°22'E. (Earhart and Mawad, 1970; Greenwood and others, 1974b). The deposit consists of seven discontinuous gossans in a zone 600 m long and 35 m or more wide. The deposit consists of closely spaced layers of massive and disseminated sulfides. Pyrite is the principal sulfide; it is accompanied by chalcopyrite, sphalerite, and a little native gold. Barite and quartz are the gangue minerals.

The deposit has been explored by four diamond drill holes along a 200-m zone to a depth of as much as 120 m. Reserves in this block total about 4,000,000 tons averaging 0.36 percent Cu, 1.09 percent Zn, 3.46 g/t Ag, and 0.55 g/t Au (Greenwood and others, 1974b).

Mahawiyah-Bahah area

Numerous ancient mines and gossan exposures occur in the Bidah belt, outside the main Wadi Bidah district described earlier. The ancient mines which were worked for their copper content are in malachite- and chrysocolla-bearing gossans in mafic tuffs of the Baish Group.

Gossans at the Ma'dan Mine (20°19'40"N.; 41°20'10"E.) and Wadi Mandhaha (20°19'05"N.; 41°20'55"E.) occur in tightly folded calcareous tuff along the contact of north-trending mafic dikes. Surface geochemical sampling indicates anomalous concentrations of copper and zinc in gossan and in altered and iron-stained quartz sericite schist. The Ma'dan mine area which has been tested by three drill holes, contains several zones of massive and disseminated sulfides less than 1 m thick (Allcott, 1970).

In the vicinity of Jabal al Azhar (20°09'40"N.; 41°27'10"E.) numerous gossan zones, 10 to 100 m in length, are scattered along a north-trending sheared zone for 2,200 m. The gossans are in mafic tuffs at or near the contact with a large diorite to gabbro intrusive body. Gossan occurs within fractures of the shear zone and as lenses that extend along minor beds in the tuff for a few meters from the mineralized fractures. Surface geochemistry indicates anomalous concentrations of copper, nickel, and silver.

The Jabal Murryyi deposit at 20°06'50"N.; 41°34'10"E. is the largest of several copper-rich lenses in volcanic wacke exposed in the general area; this unit may be correlative with the Ablah Group. The copper-bearing rock is a dense siliceous material that weathers camel tan. The rock contains malachite and chrysocolla as disseminations and along minute fractures, but contains only minor amounts of iron oxides. The largest lens is 150 m long and 5 m wide and contains an average of 1.9 percent Cu. Most of the lenses are in contact with a hydrothermally altered fault zone.

Umm al Khabath (20°10'10"N.; 41°17'30"E.) is an ancient mining and smelting area that contains thousands of tons of copper-bearing slag. A north-trending shear zone has several areas of gossan, ancient workings, and locally malachite-rich caliche capping. Country rocks are mafic tuffs, calcareous mafic tuffs, and mafic dikes of the Baish Group. Quartz sericite schist is extensively developed along the shear zone. Three diamond drill holes indicated a wide zone of alteration with abundant fine-grained pyrite and local zones of talc, but only minor concentrations of copper.

Wadi Yiba

Several oxidized copper deposits are known in and near Wadi Yiba in the region bounded by lats 18°50' to 19°15'N. and longs 41°15' to 41°50'E. The principal deposits are near Wadi Yiba and at Jabal Sarbon (Earhart, 1969a, 1969b, 1969c).

Copper deposits near Wadi Yiba (lat 19°10'N.; long 41°49'E.) are in siliceous dolomite, tuff and mafic tuff, and sericite and chlorite schist that have been assigned to the Ablah Formation by Bayley (1970). These rocks have been metamorphosed to greenschist facies and folded into a tight syncline that strikes and plunges north. A major fault that trends north cuts the eastern flank of the syncline; westerly-trending minor faults end against the major fault (Earhart, 1969c).

Metallization in the siliceous dolomite is best developed along shears parallel to the strike of the folds. According to Earhart (1969c), the pattern of ore bodies in the dolomite suggests an overall stratigraphic control but the copper minerals have been locally mobilized and redeposited in shear zones.

Metallization in tuff and mafic tuff can be traced for about a kilometer (Earhart, 1969c). The tuff averages about 1.5 m thick and contains disseminated malachite and chalcocite. The copper minerals are in beds 1-2 cm thick separated by barren beds of similar thickness; these copper minerals are considered by Earhart to be volcanogenic; we concur in this interpretation.

Quartz and carbonate veins containing copper minerals also cut the rocks in the Wadi Yiba area (Earhart, 1969c; Bayley, 1970). The veins are generally less than a meter wide and contain disseminated pyrite and chalcopyrite; the pyrite is commonly altered to iron oxides and the chalcopyrite to chalcocite, chrysocolla, and malachite.

A program of detailed mapping, sampling, and diamond drilling was carried on by Earhart (1969c) following geophysical studies by Davis and Akhrass (1969). Nine diamond drill holes totalling 1,180 m were drilled. The grade of mineralized rock ranged from one to two percent copper over thicknesses of 1-3 m. The grade, thickness, and extent of metallization are significant and should be further evaluated by more detailed field study and exploration.

Other significant deposits are found to the south of Wadi Yiba at Jabal Sarbon (Sa'ban) (lat 18°52'N.; long 41°57'E.). Earhart (1969b) noted discontinuous copper metallization for about 4 km along a ridge crest. The metallization is in chloritic garnetiferous amphibolite which strikes north-northwest and dips steeply. Interbedded siliceous dolomite, volcanic rocks, and quartzite are associated with the amphibolite; granitic rocks cut the sequence in places.

The copper metallization consists of malachite and chalcocite with a little iron oxide and smithsonite(?) (Earhart, 1969b). These minerals occur as disseminations and as massive gossan zones in the amphibolite. Sampling showed copper values in the range of 0.37 to 10.55 percent, zinc 0.04 to 1.64 percent, and gold as much as 0.05 oz/ton (1.56 g/t). Two holes were subsequently drilled (Earhart, written commun., 1971) to test downdip extensions of the ore. Hole No. 1 was 190 m long; it encountered narrow zones containing pyrite and chalcopyrite(?). Hole No. 2 penetrated only low-grade mineralized zones.

Other copper prospects were examined by Earhart (1969a) in the area west of Wadi Yiba. One of these prospects (Wadi Sishah) at lat 19°13'N. and long 41°33'E. is controlled by a north-northwesterly shear zone that cuts schistose, siliceous, and calcareous metasedimentary rocks. The deposit consists of malachite, chalcocite, and chalcopyrite in quartz-carbonate veins 2 cm to 1 m wide separated by 3 to 50 m of wall rock in a shear zone 150-200 m wide and about 1 km long.

At Suq al Khamis (lat 19°13'N.; long 41°32'E.), oxidized copper shows in a rhyolitic volcanic sequence are scattered over a strike length of 1,200 m.

Thirteen kilometers west of Suq al Khamis at lat 19°10'N. and long 41°24'E. a zone of pyroclastic rocks 700 m wide and 2 km long contains disseminated pyrite and anomalous copper mineralization. Malachite is the most abundant copper mineral; copper sulfides were found locally in quartz veins.

Lead-silver and copper shows are found at Jabal Zahwa (Al Muckahal), lat 19°17'N.; long 41°41'E., in marble and chlorite-sericite schist on the nose of a north-plunging anticline (Earhart, 1969a; Bayley, 1970). The sulfide minerals are disseminated and pod-like zones of galena, sphalerite, and chalcopyrite in narrow shear zones that strike north and dip steeply. The metallization has been traced for about 200 m along strike; the metallized zones range from a centimeter to half a meter wide.

Ash Sha'ib

The Ash Sha'ib zinc-copper deposit is in the southeastern part of the Shield at lat 19°15'N. and long 43°40'E. (Allcott, 1970). The deposit comprises several lenses of disseminated and massive zinc and copper sulfides in metasedimentary host rocks that form an east-west septum between granitic and gabbroic plutons. The metasedimentary rocks include dolomite and schist which have been metamorphosed to hornfels and tactite near intrusive contacts. The rocks have been folded along east-west trends and have been cut by faults that strike east-west, northwest, and northeast.

The ore minerals are pyrite, sphalerite, chalcopyrite, and galena which replace calcareous rocks and tactite; the gangue minerals are barite, quartz, and fluorite(?). Sphalerite is by far the most abundant sulfide; it is commonly dark brown.

Six diamond drill holes explore the deposit in depth. The reserves total 1,348,000 tons averaging 4.58 percent Zn, 0.43 percent Cu, 21 g/t Ag (calculated by Thor H. Kiilsgaard from data in Allcott, 1970).

Wadi Shwas

The Wadi Shwas copper-zinc zone includes several mineralized areas, the most important of which are the Jabal Jadmah near lat 20°00'N. and long 41°58'30"E. and the Al Hajal near lat 19°58'N. and long 42°03'E. (Ozawa, 1970; Igarashi, 1970; Fujii and others, 1973; Fujii and Kato, 1974; Greenwood, in press b; Anderson, in press).

Jabal Jadmah is underlain by a sequence of metamorphosed volcanic, pyroclastic, and sedimentary rocks which have been intruded by rhyolite sills (Fujii and Kato, 1974). Greenwood (in press b) has assigned these rocks to the Jiddah Group. The primary ore minerals are pyrite, pyrrhotite, chalcopyrite, and sphalerite with accessory galena, tetrahedrite, hessite, altaite, tetradymite, covellite, and digenite which occur as massive sulfide lenses in and disseminated throughout the host rocks. The host rocks are propylitically altered to chlorite, jasper, quartz, and carbonate aggregates. Fujii and Kato (1974) noted that the pyrite is commonly brecciated and the interstices are filled with chalcopyrite. They consider that metallization is mainly submarine exhalative, but ascribe copper mineralization in a glassy mafic rock to hydrothermal processes.

Al Hajal is in altered porphyritic dacite which is interpreted by Anderson (in press.) to be intrusive and part of the An Nimas batholith. The dacite has been cut by faults that trend N.30°-50°W., N.20°E., and east and has been propylitically altered. Jasper and carbonate pods occur along the N.20°E. fault zone; gossans of iron oxides and iron-stained opaline silica mask the relationships of ore to the host rock. Pyrite and sparse chalcopyrite are the only primary ore minerals found in drill cores. Traces of lead and zinc were also reported in the cores. Fujii and others (1973) consider the mineralization to be hydrothermal.

Preliminary estimates of reserves at Jabal Jadmah total 1,200,000 metric tons averaging 2.13 percent copper and 1.57 percent zinc (Fujii and Kato, 1974).

Ar-Ridaniyah deposit

The massive zinc sulfide deposit at Ar-Ridaniyah (lat 24°22'N.; long 44°38'E.) is in mica, chlorite, and amphibole schist and marble and dolomite which are intercalated with metamorphosed dacite, rhyodacite, and rhyolite of the Ar-Ridaniyah Formation (Letalenet and Quinet, 1969; Letalenet, 1970; Shanti, 1973). We tentatively correlate this unit with the Jiddah Group.

Metallization at Ar-Ridaniyah consists of massive sulfide bodies that parallel bedding and are therefore strata-bound. The bodies consist mainly of pyrite, pyrrhotite, and sphalerite. A little arsenopyrite, chalcopyrite, cassiterite, stannite, and galena accompany the other sulfides.

Shanti (1973) suggests that the iron sulfides were originally deposited as pyrite; regional desulfurization during metamorphism later changed part of the pyrite to pyrrhotite. The sphalerite formed subsequent to the pyrrhotite, though Shanti considers that zinc may have been present as an original constituent of the rock. The sphalerite also occurs in veins which cut the strata-bound sulfides.

The deposit has been explored by four diamond drill holes. Two of these cut several pyritic zones that contained significant sphalerite, ranging as high as 4.60 percent Zn.

Al Masane (Wadi Hizmah)

Al Masane deposit is near lat 18°02'N.; long 43°59'E. Ancient workings explore a north-striking belt of tuffaceous rocks along which is a mineralized shear zone that is subparallel to the strike of the bedded rocks (Meaton and Assiri, 1970). The zone may be traced to the south for about 5 km. It is about 30 m thick where it crops out in the southern wall of Wadi Hizmah. On the eastern footwall side it consists of massive gossan 8 m thick, above which is about 15 m of iron-stained sericitic schist, which originally was a volcanic tuff. Strands of gossan in schist form the hanging wall part of the gossan. Three samples across the 8 m footwall part of the zone average 2.6 g/t gold, .79 g/t silver, .62 percent copper, trace lead, and .71 percent zinc (Greenwood, written commun., 1975). A sample taken from an ancient pit, about 2 km to the south, across a 1.5 m width of a mineralized zone which is offset about 150 m to the west from the northern zone, contained 4.16 g/t gold, 10.2 g/t silver, .7 percent copper, and .3 percent zinc. Another sample about .5 km farther south, taken from another ancient pit in the same zone and across a mineralized width of .70 m, contained .17 g/t gold, 8.40 g/t silver, 1.22 percent copper, and 2.68 percent zinc. The total width of the mineralized zone, in the southern part of the area may be as much as 30 m. Thin beds of marble interbedded in the schist along the shear zone indicate that mineralization follows the bedding and is, in part, strata-controlled. A parallel but smaller zone is about .5 km west.

A diamond drilling program was carried on in 1974 in the northern part of the mineralized zone in Wadi Hizmah by the Arabian Shield Development Co. Two holes were drilled, both at an acute angle to the strike and dip of the zone. Hole 1 intersected two mineralized intervals a sample from one of which assayed 0.013 oz/t (0.4 g/t) gold, 0.55 oz/t (17.1 g/t) silver, 1.79 percent copper, and 4.00 percent zinc. A sample from the second interval assayed 0.22 oz/t (6.8 g/t) gold, 1.29 oz/t (40.1 g/t) silver, 2.13 percent copper, and 8.59 percent zinc. A sample from the second hole assayed 0.017 oz/t (0.5 g/t) gold, 0.58 oz/t (18.0 g/t) silver, 2.02 percent copper, and 4.51 percent zinc (Hatem Khalidy, written commun., 1974). Further exploratory work in the mineralized zone is planned by the Arabian Shield Development Co. in 1975.

Nickel-iron sulfide deposit

Wadi Qatan

The Wadi Qatan nickeliferous iron sulfide deposits at lat 18°08'40"N. and long 44°07'10"E. are in volcanic and pyroclastic rocks (Overstreet and Rossman, 1970) which are correlated by us with the Jiddah Group. The sulfide bodies are strata-bound bodies in laminated tuff units 20-50 m thick which are intercalated with massive volcanic breccias. The tuff contains disseminated to massive pyrite and pyrrhotite zones which enclose grains of pentlandite (NiS) and other nickel minerals such as violarite (Ni_2FeS_4).

The nickeliferous deposits were being explored by the Arabian Shield Development Co. in 1973-74 and their grade and extent are not yet fully known. Preliminary results of diamond drilling reported by Hatem Khalidy, however, indicate average values of 1.5 percent Ni over widths of as much as 100 ft (31 m) and length of 200 ft (62 m). The highest value reported was 3.9 percent Ni over a width of about 1 m (Min. Journal, Sept. 7, 1973; Min. Record, Sept. 5, 1973).

The Wadi Qatan nickel deposits have been recently studied by many workers (Overstreet and Rossman, 1970; Jackaman, 1972; Dodge and Rossman, 1975; Greenwood, unpub. data). These workers disagree in their interpretations of the genesis of the deposits. Overstreet and Rossman considered the Wadi Wassat and Wadi Qatan deposits to be polygenetic, formed of original syngenetic pyrite which was remobilized by igneous intrusions and replaced the tuffaceous host rock. Jackaman considered that the deposits were originally formed as fumarolic deposits on the sea floor and were subsequently sulfidized. Kiilsgaard and Greenwood view the iron sulfides as syngenetic or diagenetic, but consider that the iron and nickel were remobilized during a metamorphic event. Dodge and Rossman interpret the Wadi Qatan deposits to be a syngenetic sulfide deposit to which nickel was added during a late-stage hydrothermal event; Roberts concurs in this interpretation.

Iron sulfide deposit

Wadi Wassat

The Wadi Wassat massive iron sulfide deposit is centered near lat 18°21'N. and long 44°12'E. in the southeastern part of the Shield. The deposit consists of several lenticular bodies of sulfides which replace a laminated tuff unit in andesitic breccia that we have correlated with the Jiddah Group. A similar unit contains the sulfide deposits in Wadi Qatan. The mineralized unit has been isoclinally folded and broken by faults trending northerly and northwesterly (Overstreet and Rossman, 1970; Martin, 1970; Jackaman, 1972; Greenwood, unpub. data).

The sulfide minerals are pyrite and pyrrhotite, with occasional grains of chalcopyrite and sphalerite (Jackaman, 1972). These sulfides mainly parallel laminations presumed to be bedding, but locally cut sharply across the laminations on shear zones. The deposit is thought by most workers to have been formed syngenetically with the enclosing sediments, though pyrite was locally mobilized and partly converted to pyrrhotite during later metamorphism and plutonism.

Weissenborn and Earhart (1969) have estimated that the reserves over a strike length of 6 km totalled 84 million tons of material averaging 80 percent massive sulfides to the depth of drilling which ranges from 80 to 125 m.

Disseminated sulfide deposits

Kutam

The Kutam mine is in the southern part of the Shield at lat 17°36'N. and long 43°34'E. about 140 km southeast of Khamis Mushayt. The Kutam area has recently been mapped by R. E. Anderson and M. R. Dehlavi; the following account has been summarized from Anderson (in press).

The Kutam area is underlain by sedimentary and volcanic rocks that have been intruded by quartz porphyry bodies and mafic dikes. These rocks were metamorphosed during an orogeny that began with the development of a N.60°W. schistosity, followed by a thermal event coinciding with the emplacement of quartz monzonite plutons. During this event the metamorphic rocks were converted to hornfels; in the mineralized area, biotite, tourmaline, gahnite (zinc spinel, $ZnAl_2O_4$), garnet, muscovite(?), quartz, and chlorite were formed. This assemblage indicates a depletion of calcium and possibly of sodium; quartz was introduced.

Later, during N.45°W. shearing and hydrothermal alteration, the gahnite was partly replaced by a white mica and sphalerite, chalcopyrite, and a little pyrite were introduced. The sulfides mostly occur as pods and veinlets, though in part they are disseminated throughout the ore zone. Anderson (in press). interprets the mineralization and associated silicification as

> "the final events in a long and complex continuous process of metamorphism and alteration stemming from regional metamorphism. The area in which sulfides were eventually deposited had been maintained as an important channelway for the passage of metasomatic and hydrothermal solutions over much of the period of metamorphism".

The Kutam deposit was explored by diamond drilling in 1974-75. Six holes aggregating about 1,510 m in length have been drilled (C. W. Smith, oral commun., 1975). The exploratory work shows metallization for 450 m along strike and 250 m down dip. The mineralized zone cut in hole KA-1 is as much as 65.6 m wide; mineralized widths and copper percent are: 27.8 m, 2.04; 11.8 m, 3.82; 13.9 m, 2.99; 3.6 m, 4.12.

Jabal ash Shizm

The Jabal ash Shizm ancient copper mine is at lat 26°27'N. and long 37°32'E., about 40 km west of Al Ula (Ange, 1974; Pellaton, in prep.). The mine is in rhyolite, andesite, tuff, breccia, marble, and jasper which have been assigned to the Halaban Group. These rocks strike east-west and dip 40°-70°N.; they are cut by numerous dikes and small granitic bodies.

The workings are pits and shallow shafts in an area 500 m long and about 300 m wide along northwest-striking faults that dip 40°-70°NE. Exploratory drilling in 1975 has shown pyrite, chalcopyrite, and sphalerite in pods and disseminated throughout the wall rock in zones as much as 30 m wide (M. Bertucat, oral commun., July 1975). Minerals in the oxidized zone include malachite and chrysocolla; copper and zinc sulfates occur locally along fractures and in sulfurous spring sinter. Alteration products recognized by Ange (1974) include chlorite, epidote, calcite, and jasper; the deposits are considered by him to be of hydrothermal origin.

Disseminated tungsten and molybdenum deposits and molybdenum-bearing quartz veins

Reconnaissance geochemical sampling and heavy mineral studies of wadi sediments in the Arabian Shield in the 1960's (Whitlow, 1971, 1968a, b; Theobald, 1970a; Theobald and Allcott, 1975) disclosed the presence of many tungsten- and molybdenum-bearing areas. One of these areas, the Uyaijah ring structure, was selected for detailed mapping and study during 1972-73 (Dodge, 1973).

Tungsten and molybdenum deposits of the Uyaijah ring structure

The Uyaijah ring structure is an elliptical multiple-injection granitic complex about 16 by 19 km, whose center lies near lat 22°48'N. and long 44°22'E. and which cuts metamorphic rocks of the Murdama and Halaban Groups. Two zones within and adjacent to this structure contain significant amounts of tungsten- and molybdenum-bearing minerals, the southeast area and the west-central area.

In the southeast area, scheelite ($CaWO_4$) and powellite ($MoWO_4$) are in lenses and pods along bedding in calc-hornfels of the Murdama(?) Group at the margin of the ring structure

a. , a zone about 300 m long and as much as 20 m wide. The scheelite and powellite were also localized in quartz veins and pods, and in narrow fractured zones. Metallization is sporadic within this zone.

The west-central part of the Uyaijah ring structure is underlain by quartz monzonite that is cut by many closely-spaced quartz veins (Whitlow, 1968a, b; Theobald, 1970a). Many of these veins contain molybdenite, powellite, pyrite, and minor bismuthinite, scheelite and chalcopyrite (Dodge and Helaby, 1975).

The quartz veins crop out in a zone about 1500 m long and 300 m wide. Two generations of veins have been recognized: the older veins are more abundant and are cut by mafic dikes. The younger veins cut the dikes. The older veins are commonly larger and more persistent and occur in en echelon swarms; they are as much as 2 m wide and pinch and swell along strike for hundreds of meters. The quartz is generally massive and milky or translucent. Locally it is granulated. Potassium feldspar and muscovite are minor constituents of the veins in places.

Mineralization consists principally of scattered cubic pyrite crystals and hexagonal molybdenite plates; bismuthinite, chalcopyrite, galena, and scheelite are rare accessories. The molybdenite is generally peripherally altered to powellite, the pyrite to limonite and specular hematite, and the chalcopyrite to malachite and other secondary copper minerals.

Analyses of 190 vein samples from the west-central area show an average molybdenum content of 80 parts per million, though locally values up to 1600 ppm were recorded. This material is well below present-day ore grade (4000 ppm at Climax, Colorado) (Wallace and others, 1968).

Gold- and silver-bearing quartz veins

Gold-bearing quartz veins and their associated placer deposits were extensively worked in ancient times in many parts of Saudi Arabia. Three principal periods of activity are known: in the 21st century B.C. when gold from Arabia was shipped to Lagash, a city between the Tigris and Euphrates Rivers in Mesopotamia (Lutz, 1924); about 1000-921 B.C. during the reigns of King David and King Solomon (The Bible, Genesis, X, 29; I Kings, X, 11; Isaiah, XIII, 12). and intermittently during the late years of the Ommayed Caliphate (661-750 A.D.) and during the early years of the Abbasid Caliphate (750-1258 A.D.). Thereafter mining went into a decline that lasted nearly 750 years until the Saudi Arabian Mining Syndicate began operations at Mahd adh Dhahab in 1939. These modern operations continued until 1954 when the easily accessible high-grade ore on which the operation was based became too costly to mine at the gold price prevailing at that time. Silver-bearing veins also were worked in ancient times in Arabia, but at a later date than the beginning of gold mining. Charcoal in slag from early operations at Samrah gave Carbon-14 dates of about 700 to 726 A.D. (report to Harold Quinn dated Sept. 29, 1964 by Kaman Instruments, Austin, Texas).

The gold- and silver-bearing deposits cut layered rocks of the Baish, Bahah, Jiddah, Halaban, and Murdama Groups and dioritic to granitic intrusive rocks. The Mahd adh Dhahab, Jabal Guyan, and Al Amar mines will be described as typical of the gold-bearing quartz vein deposits. The Samrah mine will be described as typical of the silver-bearing vein deposits.

Mahd adh Dhahab mine

The Mahd adh Dhahab mine, 275 km north-northeast of Jiddah at lat 23°30'N. and long 40°52'E. was worked at two periods during ancient times (about 950 B.C. and 750-1258 A.D.) and during modern times from 1939 to 1954 by the Saudi Arabian Mining Syndicate (SAMS). The early production is not known, but SAMS production totalled 765,768 ounces fine gold and 1,002,029 ounces silver (Goldsmith, 1971; Luce and others, unpub. data), which was produced chiefly from a zone 85 to 200 m below the surface. Ancient stopes reached about 85 m below the surface; assuming the grade of ore in that interval was comparable to the grade mined by SAMS below 85 m, it is reasonable to infer that the ancient production was between 750,000 and 1,500,000 ounces.

The mine area is underlain by a conformable sequence of pyroclastic and clastic rocks which rest on red granite and which have been assigned to the Murdama(?) Group. In ascending order, the units are basalt conglomerate, andesite, lower agglomerate, lower tuff, upper agglomerate, and upper tuff. Rhyolite porphyry intrusive bodies and andesite dikes cut the layered rocks. The two agglomerate units and the rhyolite porphyry contain the principal ore bodies in the district. The rocks have been affected by potassic and propylitic alteration, and silicification, especially near quartz veins. Potassium feldspar in the veins gave a date of 690 ± 35 m.y. by Rb/Sr methods (R. J. Fleck, written commun., 1973).

The rocks in the Mahd adh Dhahab district have been tilted northward and broken by six sets of faults. Three of these sets, which strike N.25°-30°W., N.30°-60°E., and N.10°W.-N.20°E. contain productive quartz veins.

The principal ore minerals are pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, minor pyrargyrite, and native gold and silver. The gold and silver occur finely disseminated in the veins and in the altered wall rock in selvages along veins. In addition, stockworks of small quartz veins occur in the wall rock adjacent to the major veins. The gangue minerals include quartz, chlorite, K-feldspar, calcite, and iron- and manganese-carbonates.

Mineralized zones at the surface were geochemically sampled during 1972-73; of 781 samples analyzed, about 322 indicated significant gold metallization (>2.5 ppm). Exploratory work was begun during late 1973 to evaluate mineralized areas in the northeastern and southeastern parts of the district. This work was continuing in July 1975.

Al Amar mine

The Al Amar gold-zinc deposit is near lat 23°47'N. and long 45°04'E. in the eastern part of the Shield. The deposit consists of a series of quartz veins that form a stockwork striking north-northwesterly in pyroclastic rocks of the Halaban Group (Eijkelboom, 1966, 1968; Smith, 1967). The veins are composed of milky quartz, commonly crustified, and range from thin seams to 5 m or more wide.

The ore minerals are pyrite, sphalerite, chalcopyrite, and gold. The gold is sporadically distributed throughout the vein system.

According to Eijkelboom (1968) the reserves at Al Amar total 5,670,000 tons averaging 5.0 percent Zn, 0.75 percent Cu, and 9.2 g/t Au. Recent work at Al Amar (Chiron, 1974) has resulted in reevaluation of the reserves. Chiron (1974) estimates that the stockwork contains probable reserves of 25 million tons containing 1.5 percent zinc; of this tonnage 3.75 million tons may average 5 percent zinc.

Jabal Guyan mine

The Jabal Guyan ancient gold mine is at lat 18°10'N. and long 43°55'E. in the southern part of the Shield near Wadi Qatan. The mine workings extend along three northwest-striking fault zones for a length of about 2 km (Helaby and Dodge, unpub. data). The workings are in sericite and chlorite schist and greenstone which have been correlated with the Jiddah Group (Helaby and Dodge, unpub. data). In places these rocks have been cut by dacite dikes.

The workings explore quartz veins along shear zones that mostly strike northwest though some veins strike northeast. The northwest veins commonly dip steeply southwest to vertical; the northeast veins dip gently southeast. Two generations of quartz have been recognized in the veins: an older dark gray vitreous quartz which contains disseminated gold and iron oxides and is strongly sheared; and a younger massive milky quartz. The veins range in thickness from a few centimeters to more than

4 m, and pinch and swell along the strike and down dip. The stopes are mostly shallow, but some extend 25-35 m below the surface. Helaby and Dodge (unpub.data) estimate that about 9,500 m^3 of material has been removed from the workings and is now mostly piled on the dumps. The average grade of this material is 6.5 ppm gold (0.185 oz/t). Samples taken in and along the veins indicate that the ore mined may have averaged about an ounce to the ton. The total production may therefore have been as much as 25,000 ounces which at the present gold price ($160 an ounce in May 1975) would be worth about $4,000,000.

Samrah mine

The Samrah silver deposit, 15 km south of Dawadami at lat 24°22'N. and long 44°22'E., was productive on a small scale during the Abbasid Caliphate (750-1258 A.D.). The deposit was explored by the U. S. Geological Survey in 1966-67 when 18 diamond drill holes aggregating 3,624 m were put down (Kiilsgaard, 1970; Kiilsgaard and Martin, 1969).

The deposit is in an east-northeast curving fault zone between two strands of the Najd fault system (Shanti, 1973; Moore and Shanti, 1973). Ore shoots in this zone are considered by Theobald (1970) to be related to intersections of northerly- and northeasterly-trending fractures with faults of the Najd zone.

The ore minerals include sphalerite, galena, pyrite, arsenopyrite, chalcopyrite, magnetite, tetrahedrite, polybasite, pyrargyrite, stromeyerite, gold, and silver. The gangue minerals are quartz, calcite, and chlorite, epidote, sericite, and serpentine (Shanti, 1973).

The vein has a strike length of 400 m. Indicated and inferred reserves based on diamond drilling total about 301,000 tons of mineralized rock (Kiilsgaard, 1970) which is calculated to average 452 g/t Ag, 1.13 percent lead, and 4.99 percent zinc.

Sedimentary iron deposits

Deposits of sedimentary iron oxides in Wadi Sawawin are typical of sedimentary iron deposits in many parts of the world (Bogue, 1953; Japanese Geol. Mission, 1967; Marsden, 1972).

Wadi Sawawin

The Wadi Sawawin sedimentary iron deposits in northwestern Saudi Arabia near the Gulf of Aqaba lie in a zone about 110 km long and 55 km wide, between lats 27°50' and 28°38'N. and longs 35°18' and 36°00'E.

The iron-bearing unit is red jaspilite, hematite, and magnetite in cherty and tuffaceous rocks informally named the Silasia Formation by Bogue (1953). According to D. G. Hadley (oral commun., 1975), this unit closely resembles the Halaban Group of the Wayban quadrangle (Hadley, 1974a). These rocks have been divided into two units by the Japanese Geological Mission (1967): the lower unit, about 1,100 m thick, consists of andesite tuff breccia and metaandesite flows and minor amounts interbedded green tuff, rhyolite tuff breccia, crystal tuff, sandstone, and slate; the upper unit, about 1,160 m thick, is composed mainly of sandstone, slate, and argillite, and minor jaspilite, tuffaceous sandstone, tuff breccia, conglomerate, and limestone. The iron-bearing jaspilite is near the top of the upper unit and is about 50 m thick. It contains thin seams of interbedded sandstone and slate.

These rocks have been regionally metamorphosed to greenschist facies and are cut by diorite, gabbro, diabase, quartz porphyry, granitic rocks, and many varieties of dikes. The rocks have been tightly folded along northwest trends and are locally overturned to the southwest and south. In part these folds are characteristic of those formed by slumping while the sediments are still unconsolidated, but mainly they appear to be related to northeast-southwest forces.

The jaspilite unit is composed of hematite, magnetite, martite, specular hematite, jasper, and a little chlorite and calcite. Commonly the iron oxides are interlayered with jasper and quartz-rich beds. The ratios of iron oxides to silica range from 60:40 to 40:60. The average grain size of the magnetite is about 0.05 mm and the hematite from 0.002 to 0.05 mm (<400 mesh).

The reserves calculated by the Japanese Geological Mission total about 350,000,000 tons of iron-bearing material that averages about 42 percent iron (Japanese Geological Mission, 1967). This material has been upgraded under laboratory conditions; a product containing 58% Fe and 13-16% SiO_2 can be made with a 90% recovery; a 65% Fe product can be made with a recovery of 65%. The products contain about 0.2% P_2O_5 (report by Min. Resources Research Center, Univ. Minn., Dec. 1973).

Tertiary deposits

Metallic mineral deposits in rocks of the Red Sea coastal plain include oolitic iron oxides of the Shumaysi Formation and lead-zinc deposits in the Raghama Formation at Jabal Dhaylan. Nonmetallic deposits include barite deposits at Rabigh and phosphate deposits in the northern part of Saudi Arabia.

Metallic mineral deposits

Oolitic iron oxides in the Shumaysi Formation

The Shumaysi Formation of Oligocene age is well exposed in Wadi Fatima and Wadi Shumaysi in a block bounded by lats 21°15' to 21°45'N. and longs 39°25' to 39°45'E. (Shanti, 1966). The unit ranges from 75 to 187 m thick and consists of interbedded sandstone, siltstone, shale, pebbly sandstone, chert, volcanic tuff, and oolitic iron deposits. The iron-bearing beds are near the middle of the unit.

Shanti (1966) reports that the oolitic iron deposits range from 1 to more than 5 m thick and average 41 to 48.5 percent Fe; the silica content ranges from 8.2 to 15.6 percent; phosphorous ranges from 0.27 to 0.76 percent. The reserves to a depth of 200 m total 48.4 million tons averaging 46.2 percent iron.

The Shumaysi Formation is regarded by Shanti (1966) to be of shallow-water marine origin and to have been formed along a coastal zone subjected to strong wave action. This interpretation is consistent with textures and structures of the ore beds and associated units.

Jabal Dhaylan zinc-lead deposits

The mineral deposits at Jabal Dhaylan are in beds of Tertiary age in the coastal plain of the Red Sea near Umm Lajj, about 500 km northwest of Jiddah at lat 25°31'N. and long 37°10'E. (Dadet and others, 1969; Dadet, 1970; Bigot, 1973).

The Tertiary rocks in the area have been assigned by Brown and others (1963) to the Raghama Formation. At Jabal Dhaylan the section consists of three units of intertongueing sandstone, arkose, sandy limestone, shale, clay conglomerate, marl, gypsum, reef limestone, and dolomite (Bigot, 1973). The units were considered by Brown and others (1963) to be Miocene, but Bigot (1973) thought that the oldest units might be Oligocene and the middle and upper units Miocene.

The mineralized bodies consist mostly of zinc, lead, and copper silicates, sulfides, carbonates, and oxides in sandstone, shale, and reef limestone. The bodies are lenticular and commonly parallel bedding. Pods of barite and nodules of manganese oxide are present locally; in places sooty manganese oxides flood porous beds. The zinc-bearing ore minerals are calamine (hemimorphite), smithsonite, and hydrozincite; the lead minerals are galena and cerussite; the copper minerals are malachite and chrysocolla; and the manganese minerals are wad, pyrolusite, cryptomelane(?), and psilomelane. In places the manganese minerals are interlayered with chalcedony and quartz in steeply-dipping zones. These may be fault zones filled with hypogene ore minerals.

Exploration carried out by the B.R.G.M. during 1969-72 indicated reserves of about 300,000 tons, averaging about 4.9 percent zinc and 1.39 percent lead (Bigot, 1970, 1973).

Nonmetallic mineral deposits in western Saudi Arabia

Noteworthy nonmetallic mineral deposits in western Saudi Arabia are the barite deposits at Rabigh and the phosphate deposits at Thaniyat-Turayf and Turayf.

Rabigh barite deposit

The barite veins near Rabigh, 150 km north of Jiddah at lat 23°00'N. and long 39°10'E. are of interest because they occur in fault zones of Tertiary age parallel to the Red Sea rift zone.

The veins strike N.25°-60°W. and dip steeply in greenstone of the Jiddah Group; they are commonly lenticular and pinch and swell along strike and down dip (Brobst, 1972, 1966; Shanti, 1970). The veins range in width from a few centimeters to 3 m. They are mostly filled with barite containing scattered crystals of chalcopyrite and galena and with pods of dark-golden-brown jasperoid containing manganese oxides. The chalcopyrite is generally altered to malachite and the galena to cerussite.

Shanti (1970) supervised an exploratory program in 1968 which indicated that 100,000 tons assaying more than 90 percent $BaSO_4$ could be mined to a depth of 30 m.

Thaniyat-Turayf and Turayf phosphorite deposits

The Thaniyat-Turayf and Turayf phosphate deposits are in northern Saudi Arabia between lats 29°15' and 32°00'N. and longs 37°00' and 40°00'E. In the Thaniyat-Turayf area the principal deposit is at the top of the Upper Cretaceous Aruma Formation (Meissner and Ankary, 1972). A thin lower-grade deposit is in the overlying lower Hibr Formation (Paleocene to Eocene). In the Turayf area the phosphorite beds are in three zones, all in the Eocene phosphate member of the Hibr Formation.

The phosphorite at Thaniyat-Turayf is in two beds in the Aruma Formation which are best developed at West Thaniyat: the upper bed is 10-80 cm thick and is separated from the 1-2.6 m thick lower bed by 0.35-1.65 m barren to low-grade material. The phosphorite is soft and friable and consists of apatite pellets, quartz sand, and clay. The phosphorite zone crops out for more than 10 km and has been proved by drilling to extend at least 10 km northward in the subsurface. Phosphorite in the unit averages 1.65 m thick containing 23 percent P_2O_5. The phosphorite reserves in this block are about 190,000,000 tons. A feasibility study by the Tennessee Valley Authority indicated that near surface material from the lower bed could be beneficiated; material in the subsurface zone contains a good deal of clay which interferes with the beneficiation process, and the feasibility of use of the material has not been proved (Meissner and Ankary, 1972).

The phosphorite in the Turayf area underlies 2,000 sq km. The upper zone contains one to six phosphorite beds whose combined thickness ranges from 0.25 to 8.09 m under an average of 12 m overburden; grade ranges from 11 to 23 percent P_2O_5. In one area, the Select area of Meissner and Ankary (1972), the combined thickness of beds is 4 m and the average grade is 18 percent P_2O_5. The Select area embraces 78.5 sq km and reserves are estimated to be 722,200,000 tons phosphorite. Most of the phosphorite in the Turayf area is firmly cemented by silica or calcite. Tests by CERPHOS, a French phosphate research organization, have shown that the hard calcareous phosphate can be upgraded by calcining, screening, and washing. On crude material containing 20.5 percent P_2O_5 phosphate, recovery was about 88 percent and the concentrate contained 37 percent P_2O_5 with a 1.5:1 $CaO-P_2O_5$ ratio.

Red Sea metal deposits

Metal deposits were discovered in deeps (>2000 m) in the Red Sea near lat 21°25'N. and long 38°03'E. between Sudan and Saudi Arabia in 1965 during oceanographic investigations (Miller and others, 1966). Further sampling was carried on during 1967-69, indicating about 50,000,000 tons of metalliferous bottom sediments (Bischoff, 1969).

According to Bischoff (1969) and Hackett and Bischoff (1973) the sediments contain eight distinct lithologic and mineralogic facies: 1) detrital; 2) iron-montmorillonite; 3) goethite-amorphous; 4) sulfide; 5) mangano-siderite; 6) anhydrite; 7) manganite; and 8) magnetite. The sulfide facies consists mostly of sphalerite, but also contains chalcopyrite, pyrite, and amorphous iron sulfide. The three major facies, iron montmorillonite, goethite, and sulfide, average 4, 3-1/2, and 1 meter thick, respectively, totalling 8.5 meters.

There has been some controversy as to the origin of the deposits. They are considered by Craig (1969) to have been leached from saline deposits in the Red Sea trough. Bischoff (1969) suggests that though the deposit falls in the syngenetic category, the metals could have been derived from fracture zones that tap metal sources beneath the ocean floor and are therefore of hydrothermal origin. He visualizes transport of the metals as chloride complexes and suggests that precipitation took place by cooling of the ore-bearing fluids and by reaction with sea water in the deeps.

Analyses of cores from the Atlantis II Deep deposit averaged as follows: Zn 3.4 percent, Cu 1.3 percent, Pb 0.1 percent, Ag 54 ppm, and Au about 0.5 ppm (Bischoff and Manheim, 1969). The value of contained metals is summarized in the following table:

Table 4. Value of the Atlantis II Deep heavy metal deposits (Hackett and Bischoff, 1973)

Metal	*Price (Dollars/ Ton)	Total Tonnage	Value (Dollars x 10^7)
Zn	360	32.2×10^5	116
Cu	1,060	8.05×10^5	85
Pb	310	0.8×10^5	2.5
Ag	51,200	45×10^2	23
Au	1.56×10^6	45	7
Total			233.5

*Prices from Wall Street Journal, 11 April 1972, v. 86, no. 71.

No estimates of the recovery costs can be made at this time; Walthier and Schatz (1969) emphasize that mining and processing the deposits presents many difficulties.

The Red Sea metal deposits are slightly closer to Sudan than to Saudi Arabia (Griffin, 1969) but they are well beyond the 200-m contour which is commonly considered to be the continental shelf. Currently discussions are underway between Saudi Arabia and Sudan concerning the investigation of Red Sea maritime wealth (News from Saudi Arabia, May 21, 1974).

DISTRIBUTION OF MAJOR MINERAL DEPOSITS IN SAUDI ARABIA

Eleven major districts in Saudi Arabia have been investigated during the last 10 years by the Saudi Arabian Directorate General of Mineral Resources, the French Bureau de Recherches Géologiques et Minières, the Japanese Geological Mission, and the U. S. Geological Survey. These include the Jabal Sayid, Nuqrah, Mahd adh Dhahab, Al Amar, Samrah, Wadi Bidah, As Safra, Jabal Dhaylan, Wadi Shwas, Sawawin, and Wadi Fatima districts. The salient facts concerning reserves and grade of these ore bodies are shown in table 5.

It is noteworthy that nine of these districts are in the northern half of the Arabian Shield. Although evidence is seen of much ancient prospecting for gold and copper in the southern part of the Shield, with the exception of the

Table 5.- Reserves in principal mineral deposits in Saudi Arabia.

NAME	LOCATION	TONNAGE (METRIC)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	P_2O_5 %	Fe %	SOURCES OF DATA
JABAL SAYID	23°55'N 40°57'E	8,000,000	.5	40.	2.2		1.4			Routhier and Delfour, 1975
NUQRAH										
North Nuqrah	25°38'N 41°26'E	400,000	2.5	332.	.75	1.22	6.			Routhier and Delfour, 1975
South Nuqrah	25°35'N 41°26'E	1,000,000	4.3	220.	.82	1.83	5.6			Routhier and Delfour, 1975
AS SAFRA	24°10'N 41°54'E	2,750,000 4,500,000			2.13 1.29					DGMR Mineral Resources Activities 1969-70
WADI BIDAH										
Gehab	20°41'N 41°24'E	1,038,000	.79	5.49	.95		.81			Greenwood and others, 1974b
Sha'ab Eltare	20°35'N 41°22'E	4,000,000	.55	3.46	.36		1.09			Greenwood and others, 1974b
Rabathan	20°24'N 41°23'E	1,500,000	.15	2.45	2.14		.02			Greenwood and others, 1974b
ASH SHA'IB	19°15'N 43°40'E	1,348,000		21.	.43		4.58			Calculated by T. H. Kiilsgaard from Allcott, 1970
WADI SHWAS										
Jadmah	20°00'N 41°58'E									Fujii and Kato, 1974
Ore body 1		336,000			4.6		1.2			
Ore body 2a		512,000			.88		1.24			
Ore body 2b		192,000			1.49		3.58			
Ore body 3		160,000			1.7		1.			
Inferred ore		1,048,000			Grade unknown					
MAHD ADH DHAHAB	20°30'N 40°52'E									Goldsmith, 1971
Tailings		726,000	2.23	8.08	.51	.60	1.89			
Quarry		56,700	16.98							
AL AMAR	23°47'N 45°04'E	5,670,000	9.2		.75		5.			DGMR Mineral Resources Activities 1969-1970
SAMRAH	24°22'N 44°22'E	301,000		452		1.13	4.99			Kiilsgaard, 1970
SAWAWIN	28°00'N 35°40'E	350,000,000						.2	42.	Japanese Geol. Mission, 1967; Marsden, 1972
SHUMAYSI	21°30'N 39°37'E	48,428,000						.5	46.2	Shanti, 1966; Marsden, 1972
JABAL DHAYLAN	25°31'N 37°10'E	300,000				1.39	4.9			Bigot, 1970; DGMR Mineral Resources Activities 1969-1970
THANIYAT-TURAYF	29°45'N 37°55'E	190,000,000						23.		Meissner and Ankary, 1972
TURAYF	31°35'N 39°13'E	722,200,000						18.		Meissner and Ankary, 1972
RED SEA										
Atlantis II Deep	21°25'N 38°03'E	50,000,000	.5	54.	1.3	.1	3.4			Bischoff and Manheim, 1969

Wadi Bidah, Wadi Shwas, and Kutam districts, most workings are small and shallow, and do not appear to have yielded significant tonnages of ore.

The reasons for this difference between the northern and southern parts are not completely understood. However, we can suggest two factors that may help explain the preponderance of major deposits in the northern part of the Shield: 1) the deposits in the northern part are mostly in or associated with younger stratigraphic and structural features which are best developed in that part; and 2) on the whole, deeper erosion in the southern part has removed the younger units which in the northern part contain the principal ore deposits.

Deposits in the northern part of the Shield such as Mahd adh Dhahab, Jabal Sayid, Nuqrah, and Al Amar are mainly in the Halaban and Murdama Groups and are controlled by northerly structural trends of the Hijaz tectonic cycle and northwesterly fault zones of the Najd system. These younger structural features apparently permitted ore-forming solutions to rise into upper stratigraphic and structural levels where mineral deposits were formed.

Deeper erosion in the southern part of the Shield has largely stripped these younger rock units, except where they were deeply infolded, as in Wadi Yiba where rocks of the Ablah Group contain copper mineralization.

GENESIS OF SAUDI ARABIAN MINERAL DEPOSITS

Successful programs for exploration of mineral deposits must be based on an understanding of the shape of the deposits and their genesis. It is therefore necessary to carefully consider both of these factors at an early stage in the evaluation of a mining district or mineral deposit, for they may affect not only the cost, but the ultimate success of the program. Broadly speaking, ore deposits can be divided into two main classes: epigenetic, formed later than the enclosing rock; or syngenetic, formed at the same time as the enclosing rock.

Most workers agree that gold- and silver-bearing quartz veins are epigenetic, that is, they are formed by hydrothermal solutions carrying silica and metal ions from an external source. Likewise, there is general agreement as to the origin of magmatic and tungsten-molybdenum contact metamrophic deposits. However, strata-bound deposits, those confined to a certain bed, may be interpreted in a variety of ways (Stanton, 1972; Hutchison, 1973). They may have been deposited in a sedimentary or volcanic environment and thus may be syngenetic (Anderson and Nash, 1972). Or, alternatively, they may have replaced a favorable bed for chemical or physical reasons and thus may be epigenetic

(Bain, 1973). Exploration of strata-bound deposits is clearly dependent upon the interpretation of their origin.

For example, if the strata-bound deposits are stratiform and therefore syngenetic, the mineralized zone will be confined to a certain stratigraphic unit. The search for continuations of the zone beyond the outcrop area is then primarily dependent upon a knowledge of the stratigraphy and structure so that the continuation can be predicted. Examples in Saudi Arabia are the stratiform iron deposits in Wadi Sawawin.

On the other hand, if the deposit is epigenetic, then it may have been formed by replacement of a favorable bed in or near a fault or shear zone. The deposit may thus be strata-bound, but its position may have been controlled primarily by the local structure. Commonly such ore bodies occur in a variety of host rocks in a district. Examples in Saudi Arabia are deposits in the Wadi Bidah, Jabal Sayid, and Nuqrah districts.

Several tools may be employed in evaluating the genesis of mineral deposits and discriminating between syngenetic and epigenetic deposits: 1) syngenetic deposits commonly do not have widespread alteration haloes whereas epigenetic deposits are generally characterized by haloes of alteration; 2) syngenetic deposits are confined to a certain stratigraphic unit or host rock whereas epigenetic deposits may occur in a variety of host rocks and structural features in any one district; 3) certain mineral assemblages are characteristic of syngenetic deposits and distinctly different assemblages are found in epigenetic deposits. Each of these tools will be discussed briefly below.

Alteration

Syngenetic deposits which accumulate in marine basins form at low temperatures and therefore do not have characteristic alteration mineral assemblages. Secondary minerals may develop during diagenesis and later metamorphism, but these are of the same assemblage as those of the associated metamorphic facies.

Epigenetic deposits generally are characterized by haloes of alteration that extend into the wall rocks. In Saudi Arabia the haloes are generally characterized by low-temperature propylitic alteration, but higher temperature potassic alteration has been recognized locally. The propylitic alteration is marked by alteration of feldspars and micas to chlorite, clay minerals, and minerals of the epidote group, and formation of carbonates, quartz, and chalcedony, e.g. Wadi Bidah. Potassic alteration may be characterized by formation of K-feldspar or sericite, and absence of clay minerals, as at Mahd adh Dhahab.

Hydrothermal alteration is in places difficult to distinguish from the effects of regional metamorphism, and detailed mapping is required to delineate altered zones in metamorphic terranes.

Host rocks and structural control

Syngenetic deposits are restricted to certain stratigraphic units. Continuations of the mineralized bodies in concealed areas can therefore be predicted on the basis of knowledge of the local stratigraphy and structure. In complexly folded and faulted areas the ore bodies may be fragmented into small disconnected slices, making search for continuations nearly hopeless.

Epigenetic deposits commonly occur in folded and faulted rocks. Ore-forming solutions that ascend along major structural zones may react with a variety of host rocks and the ore minerals may be precipitated by reaction with calcareous beds, with sheared rocks in fault zones, and with propylitically altered rock units as at Wadi Bidah. Downward continuations of these mineralized bodies are likely; thus pervasive fracturing may aid in making a favorable block of ground more permeable to ore-forming solutions.

Mineral assemblages

Syngenetic base metal deposits commonly have simple mineral assemblages, consisting of pyrite, chalcopyrite, and sphalerite with minor amounts of other constituents. The metals that form these simple assemblages were deposited in a sedimentary or sedimentary-volcanic environment concurrently with accumulation of the enclosing units. Wadi Wassat is an example of this kind of ore deposit. Recrystallization during diagenesis and subsequent metamorphism may change the mineralogy of the deposit, but does not generally greatly alter the metal content.

Epigenetic base metal deposits are characterized by complex mineral assemblages which commonly form in a consistent paragenetic sequence as at Nuqrah, Jabal Sayid, and Mahd adh Dhahab. The early minerals are generally pyrite, pyrrhotite, magnetite, and hematite; fluorite occurs locally. These minerals are followed by chalcopyrite, sphalerite, and galena in varying proportions, along with native gold in places. Minerals late in the sequence are low-temperature sulfosalts, gold- and silver-tellurides, and native gold and silver. In general this sequence represents a falling temperature sequence, but other factors including variations in pressure, composition of mineralizing solutions, and changes in pH and oxidation potential of solutions may also influence the paragenesis.

The principal mineral assemblages found in Saudi Arabian mineral deposits have been listed in table 6. The minerals

Table 6. - Minerals from some mineral deposits in Saudi Arabia.

	Genesis	Gahnite $ZnAl_2O_4$	Stannite Cu_2FeSnS_4	Cassiterite SnO_2	Magnetite Fe_3O_4	Hematite Fe_2O_3	Pyrrhotite $Fe_{1-x}S$	Cubanite $CuFe_2S_3$	Pyrite FeS_2	Arsenopyrite FeAsS	Chalcopyrite $CuFeS_2$	Sphalerite (Zn, Fe)S	Galena PbS	Tetrahedrite $(Cu, Fe)_{12}Sb_4S_{13}$	Bournonite $PbCuSbS_3$	Mackinavite $Cu_2Fe_4S_7$	Stibnite Sb_2S_3	Tetradymite Bi_2Te_2S	Coloradoite HgTe	Hessite Ag_2Te	Empressite AgTe	Tellurobismuthite Bi_2Te_3	Altaite PbTe	Sylvanite $(AuAg)Te_2$	Frohbergite $FeTe_2$	Krennerite $AuTe_2$	Electrum (Au, Ag)	Native gold Au	Native silver Ag	Acanthite Ag_2S	Polybasite $(Ag, Cu)_{16}Sb_2S_{11}$	Marcasite FeS_2	Pyrargyrite Ag_3SbS_3	Stromeyerite CuAgS
Jabal Sayid			x	x	x		x	x	x	x	x	x	x	x		x			x	x		x	x	x		x	x	x						
Nuqrah							x	x	x	x	x	x	x		x	x		x		x	x		x		x		x	x						
Wadi Bidah					x		x		x		x	x	x															x	x					
Jadmah (Wadi Shwas)									x		x	x	x	x				x		x			x											
Ar Ridaniyah			x	x	x	x	x		x		x	x	x																x		x	x		
Wadi Wassat							x		x		x	x																						
Kutam	E	x							x		x	x																						
Mahd adh Dhahab	E						x		x		x	x	x	x			x											x	x				x	
Al Amar	E						x		x		x	x	x							x			x											
Samrah	E				x				x	x	x	x	x	x															x	x	x		x	x
Mamilah	E								x		x	x	x																					
An Nimas	E								x		x	x	x															x						
Materah									x		x	x	x																	x	x			

E - Epigenetic

are arranged from left to right in the table in general order of decreasing temperature of formation. Certain sulfide mineral species such as pyrite, chalcopyrite, and sphalerite are common to all the deposits, but the minor sulfosalts and tellurides have been recognized in only a few deposits. The reason for this may be that not many epigenetic deposits in Saudi Arabia have been studied in sufficient detail to permit recognition of all mineral species present.

The symbol "E" in the table indicates that a deposit is considered to be epigenetic by everyone who has expressed an opinion. The remaining deposits are considered by geologists who have studied them to be syngenetic or volcanogenic.

Discussion of specific deposits

The genesis of some mineral deposits in Saudi Arabia has been the subject of controversy during recent years. Among these are the copper-zinc deposits at Wadi Bidah and the copper-zinc-silver deposits at Nuqrah. The pertinent points that have been presented in these controversies will be summarized below.

Wadi Bidah

The copper-zinc massive sulfide deposits at Wadi Bidah were first described in detail by Earhart and Mawad (1970), by Earhart (1971), and by Jackaman (1972). These workers assigned the deposits to the syngenetic-volcanogenic class.

Earhart and Mawad (1970) and Earhart (1971) thought that the contained metals were first precipitated as syngenetic sulfides in a marine environment, and were later recrystallized and remobilized into their present form.

Jackaman (1972), however, was puzzled by the presence of a hematitic chert zone that was closely associated with some of the units containing sulfide minerals. In order to account for the simultaneous deposition of the hematite and base metals, he suggested initial precipitation of the base and ferrous metals as oxides and hydroxides; later the metal oxides and hydroxides were sulfidized, forming pyrite, chalcopyrite, sphalerite, and other sulfide minerals.

Greenwood and others (1974b) reinvestigated the mineral deposits in Wadi Bidah in 1973 and found that the ore deposits are in shear zones. The Rabathan deposit is in a sheared volcani-sedimentary sequence on the nose and flanks of an anticline. The mineralized zone is mostly a replacement body in a calcareous tuff, but associated shear zones are also mineralized. The Gehab deposit is on the flanks of an anticlinally folded and propylitized quartz porphyry sill. The quartz porphyry was considered by Earhart (1971) and Jackaman (1972) to be volcanic, but it is interpreted by

Roberts, Greenwood, and Worl to be intrusive and to have been emplaced during the Aqiq orogeny, long after volcanism.

The Wadi Bidah deposits were formed after a complex sequence of events that included 1) regional folding, 2) development of schistosity, 3) metamorphism, and 4) intrusion of quartz porphyry sills. The metallization, 5), then took place during two distinct stages: pyrite and pyrrhotite formed during an early stage; following an episode of refolding, shearing, and brecciation, chalcopyrite, sphalerite, and a little gold and silver were introduced.

Kiilsgaard and Greenwood suggest that the metals were derived from depth by the following processes: 1) water released during metamorphism dissolved metals and vein-forming constituents from the enclosing rocks; 2) the solutions moved upward along shear zones where they reacted with the wall rocks and formed epigenetic mineral deposits by replacement of favorable units and filling open spaces.

Roberts and Worl agree that these metamorphic processes may account for many deposits, but suggest that metals in some deposits may have been largely derived from sources in the mantle and lower crust during the rise of magmas into the upper crust.

Nuqrah

The Nuqrah copper-zinc-silver-gold deposits were first studied genetically by Hummel and others (1970) and more recently by Delfour (1970a, b) and Routhier and Delfour (1975).

Delfour (1970b) stated that the sulfide bodies at Nuqrah are interstratified with pyroclastic and sedimentary rocks in the lower part of the upper Halaban Group. The bodies are in sericitized graphitic and chloritic tuff and marble along with black jasper and a little fluorite. Pyrite, sphalerite, galena, and chalcopyrite are the principal sulfides, accompanied by minor tellurides and native gold and silver. Delfour (1970b, 1973) considers that the mineralization and alteration were caused by hydrothermal activity contemporaneous with volcanism on the sea floor.

In contrast, Hummel and others (1970) emphasized that the Nuqrah deposits are in marble associated with tuff in and near a well-defined, northwest-trending fault zone of the Najd wrench fault system. They also noted that the deposits are transected by northwest-striking faults which are subsidiary features of the wrench-fault system. Hummel and others (1970) therefore considered that the Nuqrah deposits are structurally controlled. In addition they pointed out that the deposits contain a hydrothermal mineral assemblage and are therefore epigenetic. Roberts has visited the Nuqrah deposits and concurs with the interpretation of Hummel and others (1970).

Conclusion

The massive sulfide deposits at Wadi Bidah and Nuqrah are controlled by major structural zones and favorable host rocks. The mineral assemblages and alteration envelopes in these deposits are similar to those of hydrothermal epigenetic deposits found in other parts of the world. By implication, the sulfide deposits at Jabal Sayid, As Safra, Ar-Ridaniyah, Wadi Shwas, and Kutam which have similar mineral assemblages and comparable alteration patterns are considered to be epigenetic.

The ultimate source of the metals in the deposits is uncertain. The metals may have been derived from the wall rocks during metamorphism as indicated by White (1965, 1968, 1974), Rye and Rye (1974), and J. McM. Moore (oral commun., 1974), or they may have been derived from deep sources related to melting in the lower crust and mantle. At any rate, the metallic minerals formed later than the enclosing rocks and are therefore epigenetic with respect to their present environment.

Lead isotopic investigations

Lead isotopic investigations are another potentially useful tool in evaluating the genesis and significance of ore deposits. Delevaux and others (1967, fig. 2) have shown that three principal categories of lead isotopic ratios can be distinguished in this region: one in Red Sea brine and Tertiary veins; another in Jurassic limestone; and the other in Precambrian deposits.

The isotopic composition of leads in galena from seven mineral deposits of Precambrian age in western Saudi Arabia are shown in table 7 (after Delevaux and others, 1967); the deposits include gold quartz veins, quartz-barite veins, a pegmatite, and silver-bearing veins. The isotopic ratios are broadly similar, indicating derivation of the leads from a uniform source.

Studies of lead isotopic ratios are continuing, and leads from a wider variety of genetic types of deposits in Saudi Arabia are being analyzed. Preliminary results (Bruce R. Doe and Maryse Delevaux, written commun., 1975) indicate that the leads in deposits like Wadi Wassat, Jabal Sayid, Nuqrah, and Wadi Bidah are similar to those of Mahd adh Dhahab.

Table 7. Lead isotope analyses of galenas from Saudi Arabia* (modified after Delevaux and others, 1967)

Locality	Location	Type of analysis	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Description
Abu Bier	19°56'N. 41°49'E.	Surface emission	17.96	15.65	37.74	Quartz vein in Precambrian andesite
Mukahal - B7	19°17'N. 41°41'E.	Surface emission	17.84	15.64	37.70	Quartz-barite vein in Precambrian marble
		Tetra-methyl	17.826	15.612	37.584	
Muckahal-B8	19°17'N. 41°41'E.	Surface emission	17.93	15.74	37.99	Quartz-barite vein in Precambrian marble, 1 mile from Muckahal-B7
Ardayat	24°22'N. 44°38'E.	Surface emission	17.87	15.68	37.92	Galena-quartz vein mined in Abbasid Dynasty (700-800 A.D.)
Jabal Hadb	23°31'N. 41°10'E.	Surface emission	17.84	15.63	37.64	From pegmatite 590 m.y. old
		Tetra-methyl	17.848	15.626	37.635	
Ta'if	21°13'N. 40°18'E.	Surface emission	17.75	15.63	37.56	In Precambrian quartz vein
		Tetra-methyl	17.746	15.622	37.488	
Samrah	24°23'N. 44°20'E.	Surface emission	17.57	15.61	37.60	In Precambrian granite a few km from Ardayat
		Tetra-methyl	17.592	15.618	37.638	
Mahd adh Dhahab	23°30'N. 40°50'E.	Surface emission	17.51	15.62	37.41	In upper Precambrian pyroclastic rocks and rhyolite

* All surface emission data are normalized to compare directly with data obtained on Tantalum (lot 1) filament material

MINERAL BELTS IN WESTERN SAUDI ARABIA

The mineral deposits in western Saudi Arabia (van Daalhoff, 1974) are mostly distributed in belts that can be defined geologically and tectonically (table 8). Eight principal mineral belts and zones have been recognized: 1) the Bidah copper-zinc belt; 2) the Samran copper-zinc belt; 3) the Sayid copper-zinc zone; 4) the Nuqrah copper-zinc belt; 5) the Al Amar copper-zinc belt; 6) the Wassat iron-nickel belt; 7) gold-silver belts of the Hijaz tectonic cycle; and 8) gold-silver deposits of the Najd zone. These belts are summarized in table 8, and are delineated on figure 1.

Copper-zinc belts

Bidah belt

The north-trending Bidah belt extends from lat 18°50' to 20°50'N. and long 41° to 42°10'E. It includes two zones of copper-zinc massive sulfide deposits, an easterly one in volcanic rocks of the Jiddah Group, and a westerly one in mafic tuffs and intrusive rocks of the Baish and Bahah Groups. The Bidah belt is bounded on the east by the An Nimas batholith and on the west by a fault contact with the early phase assemblage. The copper-zinc deposits in the belt are thought to have been formed during the Aqiq orogeny.

The Bidah belt has major potential for future discoveries of mineral deposits. The deposits in the northern part of the belt (Rabathan, Sha'ab Eltare, and Gehab) have only been explored to shallow depths, and many gossans have not been sampled or explored. A program of mapping, geochemical sampling, and diamond drilling was carried on in the southern part of the belt in 1974. Studies are continuing in 1975.

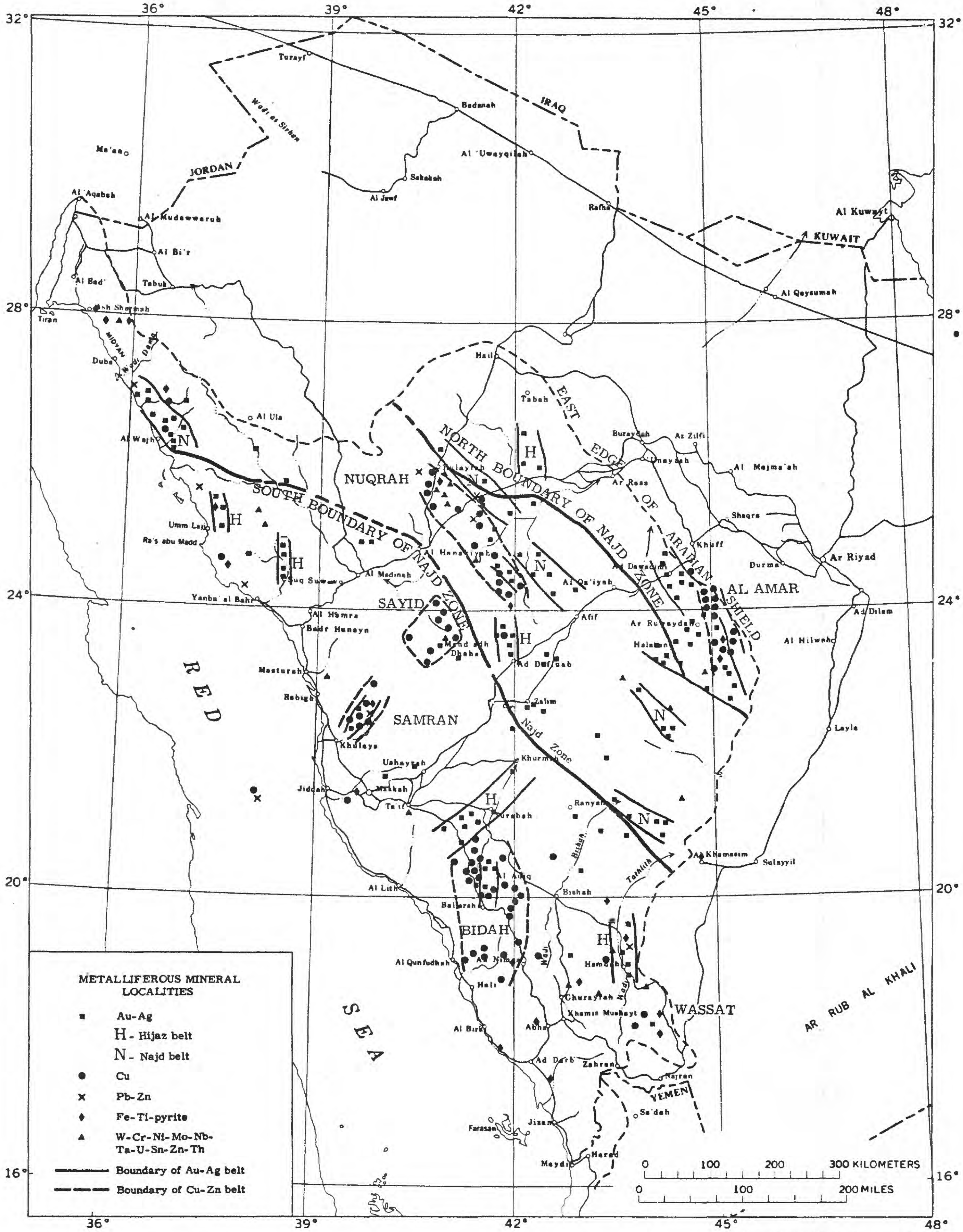
The southern continuation of the Bidah belt beyond the Hijaz-Asir escarpment is in extremely rugged terrain which has not been prospected in modern times. This zone should have good potential for future discoveries as the relief is high and rock exposures are excellent.

Samran belt

The northeast-trending Samran copper-zinc belt, about 75 km long and 30 km wide, extends from lat 22°25'N. and long 39°30'E. to about lat 23°00'N. and long 40°00'E. It is separated from the Sayid belt by a Tertiary to Holocene basalt field. The copper-zinc metallization in the belt (Liddicoat, 1971) is in dacitic pyroclastic rocks and interbedded marble which has been assigned by us to the Jiddah Group. The belt is bounded on the southeast by a diorite batholith; the nature of the northwestern boundary is unknown.

Table 8. - Precambrian mineral belts and zones in Saudi Arabia and suggested exploration target areas.

NAME	GEOLOGIC ENVIRONMENT	TECTONIC ENVIRONMENT	PRINCIPAL COMMODITIES	AGE (OROGENIC EVENT)	SUGGESTED EXPLORATION TARGET AREAS
1. Bidah	Baish-Jiddah	Northerly fracture zones	Cu, Zn	Hijaz	Within belt and to S and N of productive areas
2. Samran	Jiddah	Northeasterly fracture zone	Cu, Au, Ag, Zn	Hijaz	Within belt and to NE beneath lava
3. Sayid	Murdama-Halaban	Northerly fracture zone	Cu, Zn, Au, Ag	Hijaz	Near Jabal Sayid and to SE and NW of Jabal Sayid
4. Nuqrah	Murdama-Halaban	Northerly fracture zones	Cu, Zn, Au, Ag	Hijaz	Within belt and to S and N
5. Al Amar	Hali-Halaban	North-northeasterly and northwesterly fracture zones	Zn, Au Cu, Ag	Najd	Within belt and to S and N
6. Wassat	Jiddah	Northerly folds, locally crenulated and cut by northwesterly faults	Fe, Ni	Hijaz	Gossans in mineralized tuff
7. Hijaz	Baish-Murdama	Northerly and north-easterly fracture zones	Au, Ag	Hijaz	Gossans and quartz veins in belts
8. Najd	All units	Northwesterly fracture zones	Au, Ag	Najd	Gossans and quartz veins in belts



Compiled by W. R. Greenwood and R. J. Roberts. Mineral localities after Van Dahlhoff (1974)

Figure 1. - Mineral belts in western Saudi Arabia.

Exploration thus far in the Samran belt has not yielded major mineral deposits. Many mineral shows are known, however, and further prospecting is warranted, both within the belt and in the projection of the belt under volcanic cover to the northeast.

Sayid zone

The Sayid copper-zinc zone extends from about lat 23°15' to 24°10'N. and long 40°30' to 41°10'E. It is bounded on the southwest by a Tertiary to Holocene basalt field; the southeastern boundary is a depositional contact of the Murdama and Halaban Groups on older plutonic rocks. The nature of the other boundaries is not known.

The Sayid deposit includes disseminated and massive sulfide deposits in pyroclastic rocks of the upper part of the Halaban Group (Delfour, 1970a; Alabouvette, 1974). The mineralized zone was localized on the overturned northwest flank of an anticlinal arch that trends north to N.20°E. (Delfour, 1970a). Metallization was probably related to the Ranyah or Bishah orogeny.

The Sayid zone contains the largest ore deposits thus far discovered in Saudi Arabia. Continued exploration in the vicinity of the principal mineralized bodies is recommended, with emphasis on deep drilling in promising target areas.

Nuqrah belt

The Nuqrah copper-zinc belt includes three north-trending en echelon groups of deposits. The belt as a whole trends northwesterly and extends from lat 23°30'N. and long 42°00'E. to about lat 26°00'N. and long 40°30'E. The northeastern and southwestern boundaries are controlled by faulting, intrusion, and deposition of the Jubaylah Group. The deposits are in septa of pyroclastic rocks between plutons of young granite; the pyroclastic rocks were assigned to the Halaban by Delfour (1970b). The copper-zinc ore is in disseminated to massive sulfide bodies in sheared limbs of tight folds that trend north to N.20°E. The deposits were formed late in the Hijaz cycle, possibly during the Bishah orogeny.

Al Amar belt

The Al Amar north-northwesterly-trending copper-zinc belt extends from about lat 23°15'N. and long 45°10'E. to lat 24°30'N. and long 44°45'E. The eastern boundary is the unconformity with overlying Paleozoic sedimentary rocks. The western boundary is the north-striking Al Amar-Idsas fault (Eijkelboom, 1966). Metallization in the belt is mostly in pyroclastic and volcanic rocks, marble, and granite, and consists of veins, stockworks, and mineralized breccia and shear zones. The deposits are in northwest- and north-northeast-trending faults that cut north-south folds and the Al Amar-Idsas fault. Mineralization is apparently related to movements in the Najd zone following the Bishah orogeny.

Iron-nickel belt

Wassat belt

The Wassat iron-nickel belt includes a nickeliferous iron sulfide zone that extends from lat 18°10'N. and long 44°10'E. to lat 18°30'N. and long 44°10'E. The nickel-bearing deposits are in bedded tuff units interlayered with massive andesitic volcanic breccia assigned to the Jiddah Group.

The ore minerals are pyrite and pyrrhotite and intergrown pentlandite; violarite (NiS) is found in the supergene zone. The nickel deposits are abnormally low in most other base metals, particularly copper, but contain several hundred ppm molybdenum. The pyrite and pyrrhotite may be syngenetic, but the nickel-bearing minerals and associated copper-, zinc-, and molybdenum-bearing minerals are considered by us to be epigenetic. The ore-bearing units are cut by dioritic intrusive rocks similar to rocks which have been dated at 950-1050 m.y. and the nickel metallization is presumed to be related to the Hijaz tectonic cycle.

Many gossan zones in the Jiddah Group in the Wadi Wassat and Wadi Qatan area have not been explored. The potential for discoveries of additional nickeliferous sulfide bodies in this region is good.

Gold and silver belts

Gold and silver deposits are found in many parts of the Arabian Shield. The deposits are mostly in or near quartz veins in a variety of rock types including the Baish, Bahah, Jiddah, Halaban, and Murdama Groups and in dioritic to granitic plutonic rocks. The gold deposits commonly do not occur in clear-cut belts, but are scattered over extensive areas. In places, however, significant alinements can be discerned, such as the northerly and northeasterly trends of the Hijaz cycle, and the northwesterly trends of the Najd fault system (Okumi and others, 1965).

Hijaz belts

Gold and silver deposits that lie in or parallel to structural features of the Hijaz cycle are designated on figure 1 by the letter "H". Most of these trend north but some trend northeast.

Najd belts

Many of the gold and silver deposits occur in faults of the northwest-trending Najd fault system. Some deposits follow northwesterly-trending faults and others are in contemporaneous northeasterly faults. They are designated on figure 1 with the letter "N".

SUGGESTED EXPLORATION TARGET AREAS IN SAUDI ARABIA

In ancient times the most extensive mining operations in Arabia were carried on in the following belts and zones: Sayid, Nuqrah, Al Amar, Bidah, and the Hijaz and Najd. As far as we can determine, these belts and zones offer the greatest potential for future production, and it is recommended that particular attention be given to their evaluation and exploration. The principal characteristics of these belts and zones are summarized in table 8. In order to adequately evaluate this potential, much geologic, geophysical, and geochemical work remains to be done.

Although the belts have been geologically mapped in a general way at a scale of 1:100,000, this mapping was not done with the specific objective of tieing the ore deposits into the stratigraphic and structural framework. These major belts should now be reexamined at appropriate scales, e.g. 1:50,000 or larger; the geologic maps of each belt should then be integrated into a compilation designed to emphasize the controlling rock units and structural features.

After this work has been completed, geophysical and geochemical studies should follow, first on reconnaissance scales, then on selected detailed scales. The geochemical studies should emphasize bedrock sampling, but in places wadi sediment sampling on reconnaissance scales might yield valuable data.

Such a program, logically planned and properly carried out, should result in the discovery of many other significant ore bodies in Saudi Arabia which could form the basis for a broadly based program of industrial development.

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