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# ORE CONTROLS AT THE MAHD ADH DHAHAB GOLD MINE, KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

Mahd adh Dhahab is the largest of numerous ancient gold mines scattered through the Precambrian shield of Saudi Arabia and the only one with recent production. Free gold and silver, tellurides, pyrite, galena, sphalerite, and chalcopyrite are in and associated with quartz veins and quartz veinlet stockworks. Country rocks consist of a sequence of pyroclastic and transported pyroclastic rocks of the Halaban Group that are locally highly silicified and potassium-feldspathized.

Two known ore zones occur in a north-trending zone of quartz veins and breccias, faults, alteration, and metallization approximately 400 m wide and 1,000 m long. The ancient and recent workings are located in the northern part of this zone, and a significant new discovery, the southern mineralized zone, is in the southern part. A potential resource of 1.1 million tons of 27 g/t Au and 73 g/t Ag ore is contained in the southern mineralized zone.

Geologic setting of ore bodies is similar in both zones. Significant mineralization occurs only within altered and fractured agglomerate directly beneath a cap of fine-grained tuff and sedimentary rock where the layered rocks are cut by metalliferous quartz veins. Ore was localized by four interacting controls;

depth, an impervious cap, metalliferous quartz veins and a receptive host rock.

## INTRODUCTION

Mahd adh Dhahab is an ancient and recent gold mine located in the central part of the Arabian Precambrian shield (fig. 1). Ancient mining activity is indicated by numerous narrow workings that extend to a depth of 50 m along major veins, several thousand tons of slag left from crude smelting operations, and a largely destroyed tell with attendant ruins and artifacts. The ancient operations predated 1,000 A.D. (Luce, et al., 1976). Recent operations were by the Saudi Arabian Mining Syndicate (SAMS, will be used throughout to designate the Saudi Arabian Mining Syndicate mining operations at Mahd adh Dhahab) during the period 1939-54.

This work is part of a study and evaluation of mineral deposits in the Mahd adh Dhahab district (Luce and others, 1976; Roberts and others, 1978; Bagdady and others, 1978 ~~in prep.~~; Worl, 1978) done by the U.S. Geological Survey in accordance with its work agreement with the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. Acknowledgment is due to the Deputy Minister of Mineral Resources and the Directorate General of Mineral Resources for providing the support that made these studies possible.

A second zone of metallization, the southern mineralized zone, occurs 700 m south of the ancient and recent workings. The significance of metallization in the lower agglomerate and the analogy to the geologic setting of the metallization in the SAMS mine area were recognized by Ralph J. Roberts, USGS mission

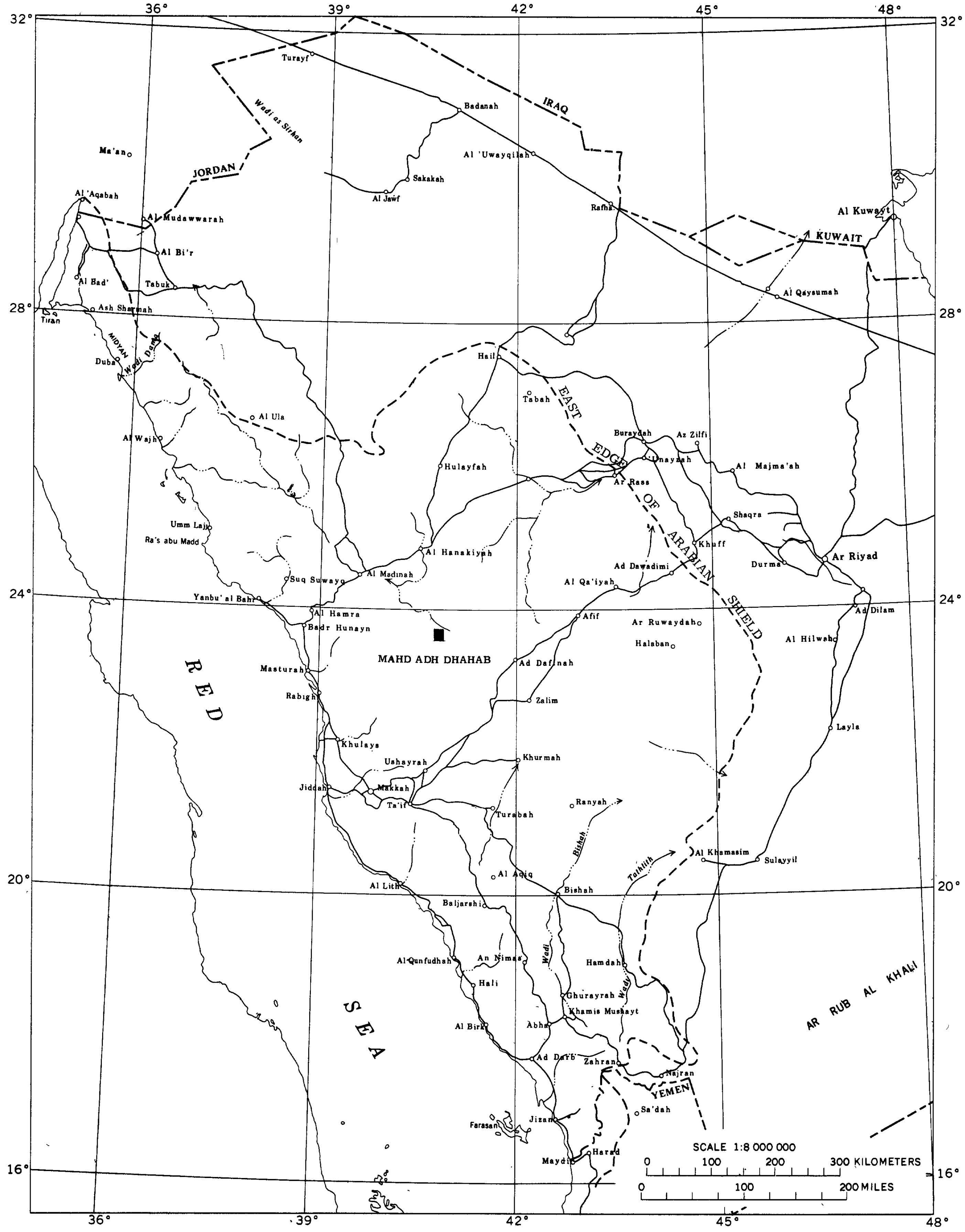


Figure 1. - Index map showing the location of the Mahd adh Dhahab district.

geologist, in early 1972 (Roberts, per commun., 1973). Subsequent mapping (Luce and others, 1976) and geochemical rock chip sampling (Roberts and others, 1978) confirmed the presence of significant values in this zone and a drilling program of four drill holes to explore the southern mineralized zone was recommended and laid out by Roberts, Luce, and Bagdady in mid-1973. The diamond drilling program in the district, including the southern mineralized zone, lasted from November, 1973, to June, 1975 (Worl, 1978).

The ore bodies of the southern mineralized zone were explored by applying parameters of ore body control from the SAMS mine area to the south. Geologic setting of the ore bodies is similar in the two areas. Underground geology of the SAMS mine is well documented (Dirom, 1947) but the underground geology of the southern mineralized zone is based upon only limited diamond drilling and the exact size and shape of the postulated orebodies must await development work.

U.S. Geological Survey drill holes are designated throughout this report by the symbol MD- and the drill hole number; i.e. MD-5. Saudi Arabian Mining Syndicate (SAMS) drill holes are designated by SAMS- and the drill hole number; i.e. SAMS-5.

## GEOLOGIC SETTING

### Lithology

The Mahd adh Dhahab district is underlain by a complex of Precambrian pyroclastic, volcanic, and clastic rocks of the Halaban (Hulayfah) Group overlying a large body of diorite to granodiorite (Goldsmith and Kouther, 1971, pl. 1). The complex is described by Aguttes and Duhamel (1971, p. 17) as predominantly "rhyolitic pyroclastites" with interstratified andesite, fine-grained sedimentary rocks, "ignimbrite" and silicic tuff, none of which has regional extent except the "ignimbrite". They consider the complex in the mine area to be a succession of lenses several meters to 40 m thick and limited in areal extent by numerous facies changes. Alkalic granite and rhyolite cut the sequence north of Mahd adh Dhahab and andesite and rhyolite dikes and sills cut it throughout the district.

Exposures in the mine area (pl. 1) are composed of an intimate mixture of pyroclastic and transported pyroclastic and clastic detrital material. Volcanic flow rocks, welded tuff,and breccia are subordinate. Grain size and related parameters of sorting, grading, and bedding vary much more than lithic, pyroclastic,and mineral composition, which is relatively consistent through most units mapped. Most of the medium- to fine-grained rocks are bedded and commonly graded. The rocks exposed range from coarse agglomerate to very fine-grained tuff. Lithic and pyroclastic fragments in order of decreasing abundance are andesite to rhyodacite volcanic rocks, silicic tuff, and chert, with locally abundant broken feldspar grains, diorite, pumice, and glass shards. The common minerals are chlorite, plagioclase, potassium-feldspar, and quartz, with locally abundant epidote and minor amphibole.

The lithologic sequence of Luce and others (1976, p. 5), from oldest to youngest, of lower agglomerate, lower tuff, upper agglomerate, and upper tuff, with a further subdivision of units, is retained in this report (table 1). The lower agglomerate was subdivided into lower, middle, and upper units on the basis of

Table 1. Stratigraphy of the Mahd Dhahab mine area

| | | |
|---|---|---|
| UPPER TUFF | uta | AGGLOMERATE-CONGLOMERATE - Red to pale green, characterized by abundance of pale green, dacite fragments; white, gray, and red tuff; red chert; fragmental plagioclase; locally abundant fragmental quartz. Coarse layering. Intercalated waterlain tuff and argillite |
| | utt | ARGILLITE-CALCAREOUS TUFF - Fine bedded gray argillite intercalate with calcareous and talcose, brown, massive to fine bedded tuff and minor volcanic wacke. Local zones of massive talc |
| | | ----------------Unconformity or fault------------------ |
| UPPER AGGLOMERATE | uaa | GRAY AGGLOMERATE - Subrounded fragments of white, red, and gray chert, siliceous tuff, pyrite-rich tuff, andesite to rhyodacite volcanic rock, and chlorite and epidote-rich clots set in a gray siliceous and and pyritiferous groundmass. Local pink potassium feldspar scattered indiscriminately through groundmass and fragments |
| | | -----------------Local unconformity----------------- |
| | uat | CRYSTALLITHIC TUFF TO AGGLOMERATE - Pale to dark green, with gray chert, brown to gray tuff, whispy chlorite, gray siliceous lapilli, locally abundant fragmental plagioclase and andesite to rhyodacite volcanic rock set in siliceous gray groundmass. Generally bedded and locally graded. Intercalated fine-grained massive green tuff. Pink potassium feldspar is locally abundant as a partial to total replacement of the fragmental plagioclase and to a lesser extent as scattered crystals through groundmass and all fragments |
| LOWER TUFF | lt | TUFF AND SEDIMENTARY ROCKS - Fine-grained massive to finely bedded tuff, lapilli tuff, volcanic wacke, and sandstone. Highly potassium-feldspathized in the vicinity of the SAMS mine (pl. 1). |
| LOWER AGGLOMERATE | lau | UPPER UNIT - Mafic agglomerate, mostly andesite and chloritic fragments set in gray siliceous groundmass, and mafic lapilli tuff, plagioclase crystal tuff, and massive cherty tuff. Local fragments of massive sulfide(?) and pyrite-rich tuff |
| | lam | MIDDLE UNIT - Mafic agglomerate agglomerate with andesite, chloritic, red, gray, and black massive tuff, and diorite fragments in chlorite and epidote groundmass. Intercalated dense massive green to brown chert |
| | lal | LOWER UNIT - Massive to slightly bedded andesite tuff and lapilli tuff with minor intercalated mafic agglomerate |

drill core information. The subdivision is recognizable in outcrops at the surface, but is not readily mappable on the scree-covered outcrops.

The contact of the lower agglomerate and lower tuff is gradational across a wide zone of intercalated lapilli tuff, agglomerate, and massive tuff. The contact of the lower tuff with the upper agglomerate is sharp with no gradation or intercalation of the two.

The upper agglomerate is here divided into two units, crystallithic tuff to agglomerate and gray agglomerate. The crystallithic tuff conformably overlies the lower tuff and in the lower few meters is primarily a mafic pyroclastic rock that contains an abundance of flattened lapilli and possible shards. The remainder of the crystallithic tuff-agglomerate is generally well bedded and commonly graded. The gray agglomerate seems to be unconformable to the crystallithic tuff-agglomerate, as its outcrop pattern transects layering in the underlying crystallithic tuff-agglomerate and in some areas it directly overlies the lower tuff.

The upper tuff is largely agglomerate-conglomerate with a relatively thin unit of finely bedded waterlaid argillite and carbonate-bearing tuff at the base. It rests unconformably on the underlying upper agglomerate. Where penetrated by drill or mine workings the contact is seen to be a bedding plane fault, parallel to bedding in the upper tuff.

Two types of postdepositional alteration have affected all rock types: 1) hydrothermal alteration, mainly silicification, pyritization, and propylitization centered on the quartz vein zone, and 2) more widespread and pervasive potassium-feldspathization, in part contemporaneous with early quartz veining. The original mafic minerals have altered to chlorite and magnetite. Much of the plagioclase has been altered to either masses of sericite and quartz or to saussurite aggregates. Three types of secondary potassium-feldspar are found: randomly disseminated crystals, as a replacement of plagioclase, and as a minor vein and veinlet mineral. All three types are similar optically and X-ray diffraction patterns suggest they are compositionally similar, nearly maximum microcline. Randomaly disseminated potassium-feldspar crystals occur in all map units indiscriminately throughout the groundmass and in lithic and pyroclastic fragments of all types. The subhedral potassium-feldspar crystals commonly cut grain boundaries of metamorphic minerals. Fragmental plagioclase in crystal lithic tuff of the upper and lower agglomerates are partially to totally replaced by potassium-feldspar.

Rocks considered by previous investigators to be rhyolite (Dirom, 1947, and Luce and others, 1976) are considered by the author to be potassium-feldspathized tuff, wacke, and volcanic sandstone of the lower tuff unit (pl. 1). Rocks previously mapped as rhyolite are similar in texture, composition, and mineralogy to those mapped as lower tuff; however, locally abundant potassium-feldspar crystals and zones of sericitization(?) occur in the metasomatized rock. The gradation from unaltered to altered rock can be observed in core from drill holes MD-6, 9, and 10 and SAMS-1, 4, 5, and 13.

## Structure

Mahd adh Dhahab is within a zone of strong regional northeast-trending faults and folds, and the southwestern edge of the major northwest-trending Najd fault system is only a few kilometers to the northeast. Within the mine area, however, generally north-trending structures dominate while northeast- and northwest-trending structures are subordinate. A major northeast-trending right lateral fault system bounds the area on the southeast (Goldsmith and Kouther, 1971, pl. 1), but is covered by alluvium.

The most obvious structural feature in the mine area is the wide north 10° east-trending zone of quartz veins, alteration, and faults within which both the SAMS mine and southern mineralized zone are located. Several periods of faulting and quartz vein and andesite dike emplacement along north- to northeast-trending fractures and to a lesser extent along northwest- to west-trending fractures are evident (Luce and others, 1976). Latest faulting was along the northwest- to west-trending fractures, although lateral offset is minor. The low angle faults in the northern part of the zone (pl. 1 and fig. 2) are local features within or along the contacts of the crystal-lithic tuff-agglomerate unit of the upper agglomerate where it is strongly folded around the nose of a relatively tight fold.

Structure of the layered rocks is defined by primary sedimentary or volcanic bedding and lithologic layering in most units. Only the agglomerates lack measurable bedding and other primary layering features. Foliation and other metamorphic penetrative planar structures are not well developed, and where present are

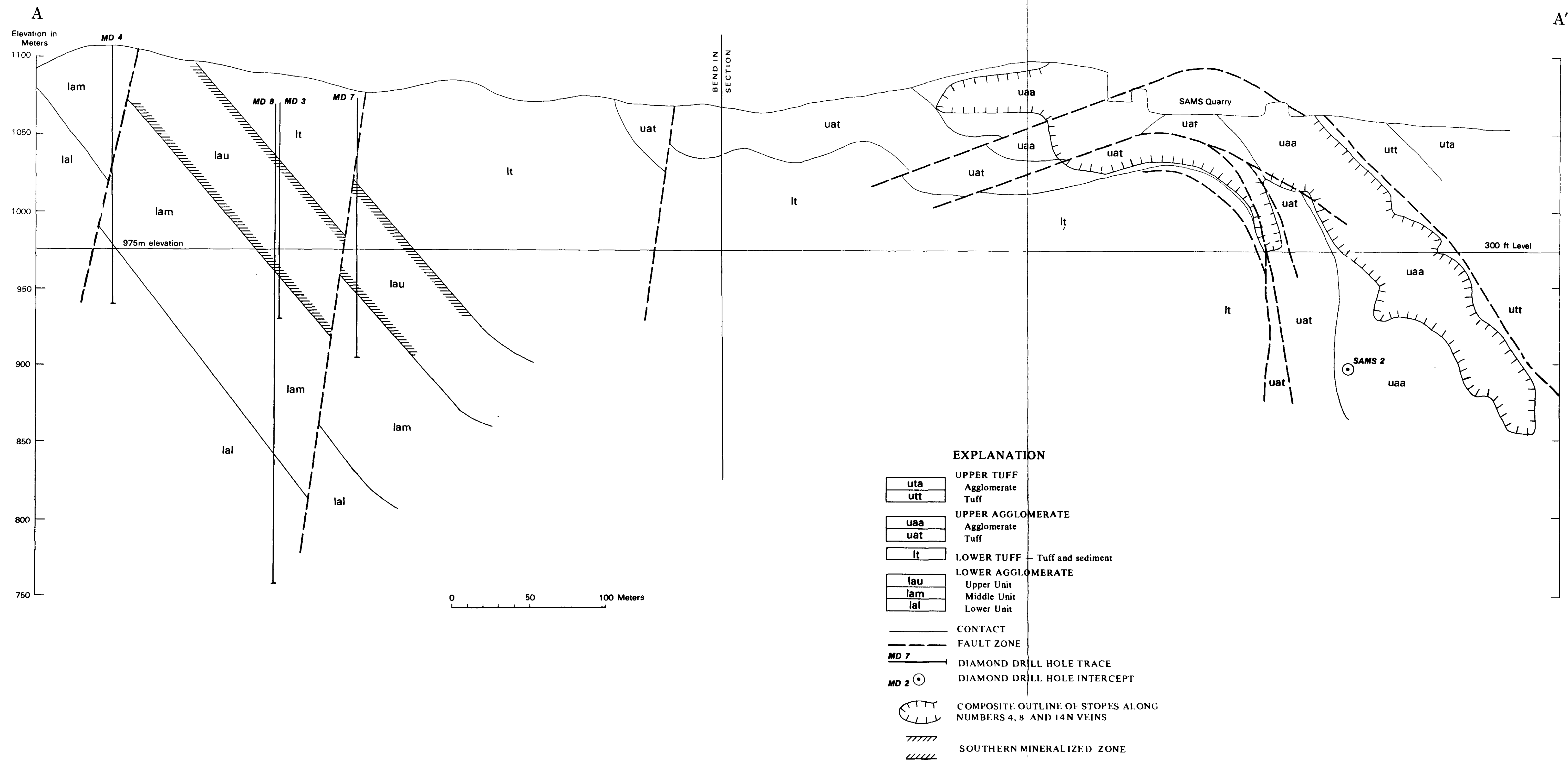


Figure 2. Geologic cross section along line A-A′

generally parallel to bedding or to an adjacent major shear zone. Minor fold axes and other measurable linear penetrative structures are lacking. Folds are open flexural types; shear folds and flow folds common in higher rank metamorphic rocks of the Arabian Precambrian shield area are not present.

Structural analysis of measured attitudes available from all sources (unpublished SAMS data; Dirom, 1947; Goldsmith and Kouther, 1971; Luce and others, 1976; Worl, 1978) defined areas of broad open folds (Worl, 1978). Structure west of the north 10° east-trending vein zone (pl. 1) is a slightly folded homocline with northwest-strike and approximately 50° north dip. In the northeast part of the map area (pl. 1; figs. 2,3) generally north of drill hole MD-7, structure is defined as flexural folding around a northwest-trending, 25° plunging axis, although it seems from field data to be a doubly plunging fold with the opposite axis plunging east. In the southeast part of the map area, south of drill hole MD-7, structure is defined as flexural folding around an east-trending, 60° plunging axis. Folding in the eastern part of the map area is probably the result of drag along the major northeast-trending fault system just to the east. There is no evidence for multiple episodes of folding and the quartz veins are unfolded. Those quartz veins with curvilinear outcrop patterns are post-folding. They formed in older faults and breccia.

## Mineralization

Mineralization at Mahd adh Dhahab consists of gold, silver, copper, and zinc metallization in or associated with quartz veins. Although there are quartz veins throughout Jabal Mahd adh Dhahab they are most abundant in a north $10^{\circ}$ east-trending zone 400 m wide and approximately 1,000 m in length along the eastern edge of the jabal. This zone of faulting, veining, and metallization contains the SAMS mine, most ancient workings, and the recently discovered southern mineralized zone.

Quartz veins range in width from 1 mm to as much as 5 m for some composite veins, but most individual veins are 10 to 50 cm in width. Vein material is generally space filling of fractures, open breccias and fissures and commonly earlier vein material is brecciated and healed by later quartz. Postmineral (quartz vein) shears and faults occur within and along the edge of most of the major veins. The larger veins are invariably brecciated composite veins composed of quartz-healed breccias of previous vein material and wall rock fragments and sheeted veins 10 to 50 cm in width. Veins 10 to 50 cm wide are typified by banding, crystal-lined vugs, cockade structure, and comb structure of inwardly terminated zoned quartz crystals. The veins are mostly quartz with subordinate layers of sulfides and chlorite. Chalcedonic quartz and carbonate are late constituents in some veins. Potassium feldspar is locally abundant, especially in the SAMS mine area, as bands in the veins and as veinlets in altered wall rock. Metallization is highest where quartz veining and stockworking is most intense, but not all such zones are metallized.

Sulfides present in the veins are pyrite, chalcopyrite, at least two generations of sphalerite, minor galena, tetrahedrite, and argentite. Native gold and silver accompany the major sulfides. Preliminary petrologic and mineralogic studies of the USGS drill core indicate that much of the gold, and presumably also the silver, in the southern mineralized zone is in the form of tellurides. BRGM geologists have recognized hessite, empressite, and rare altaite and pezite in the ore samples from Mahd adh Dhahab (Delfour, 1975, p. 24). An occasional gold grain or wire can be found in quartz from the dumps or outwash plain.

The degree of wall rock alteration is variable. Most rock within the zone of veining and faulting (pl. 1) is pyritized and propylitized(?) while some zones are intensely silicified and other zones are potassium feldspathized, as shown by veinlets of potassium feldspar and pyroclastic fragments and plagioclase replaced by potassium feldspar. Highly fractured rock with a pervasive stockwork of 1 cm sized veinlets is the most strongly altered.

## ORE BODIES

### SAMS mine

The SAMS mine in the northern part of the main zone of quartz veins, alteration, and faults was the center of most ancient mining and all recent mining. Ancient mining was from surface pits and narrow stopes and shafts as much as 50 m deep. The SAMS operation was from a quarry and from 150', 300', 450', and 600' levels of the mine. Most ore came from four major vein systems, numbers 1, 4, 8, and 14 (pl. 1; fig. 3). Approximately 591,200 tons of ore averaging 1 oz of gold were taken from underground workings during the SAMS operation. An equal amount of gold was probably produced in ancient times.

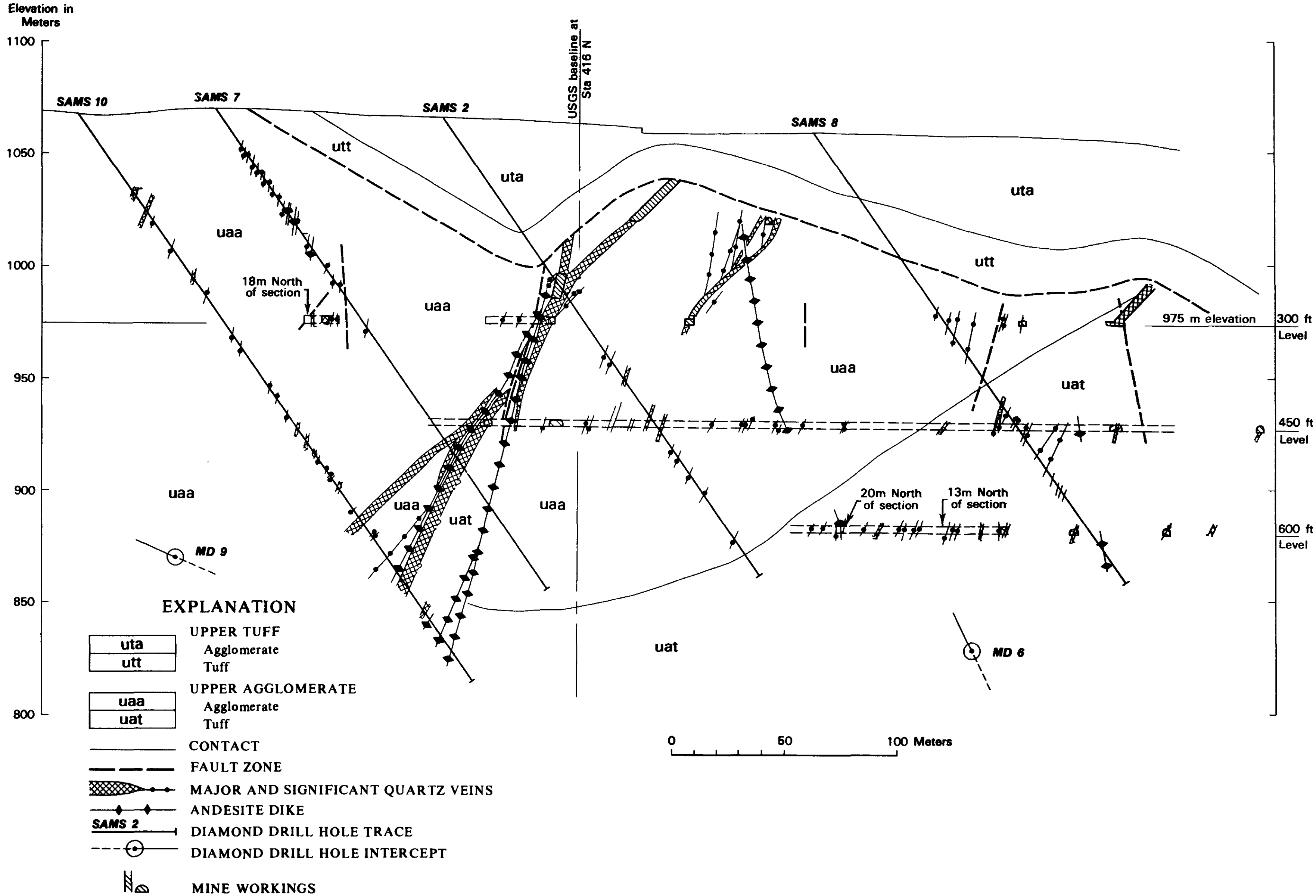


**Figure 3.** Geologic cross section through diamond drill holes SAMS 2, 7, 8, and 10

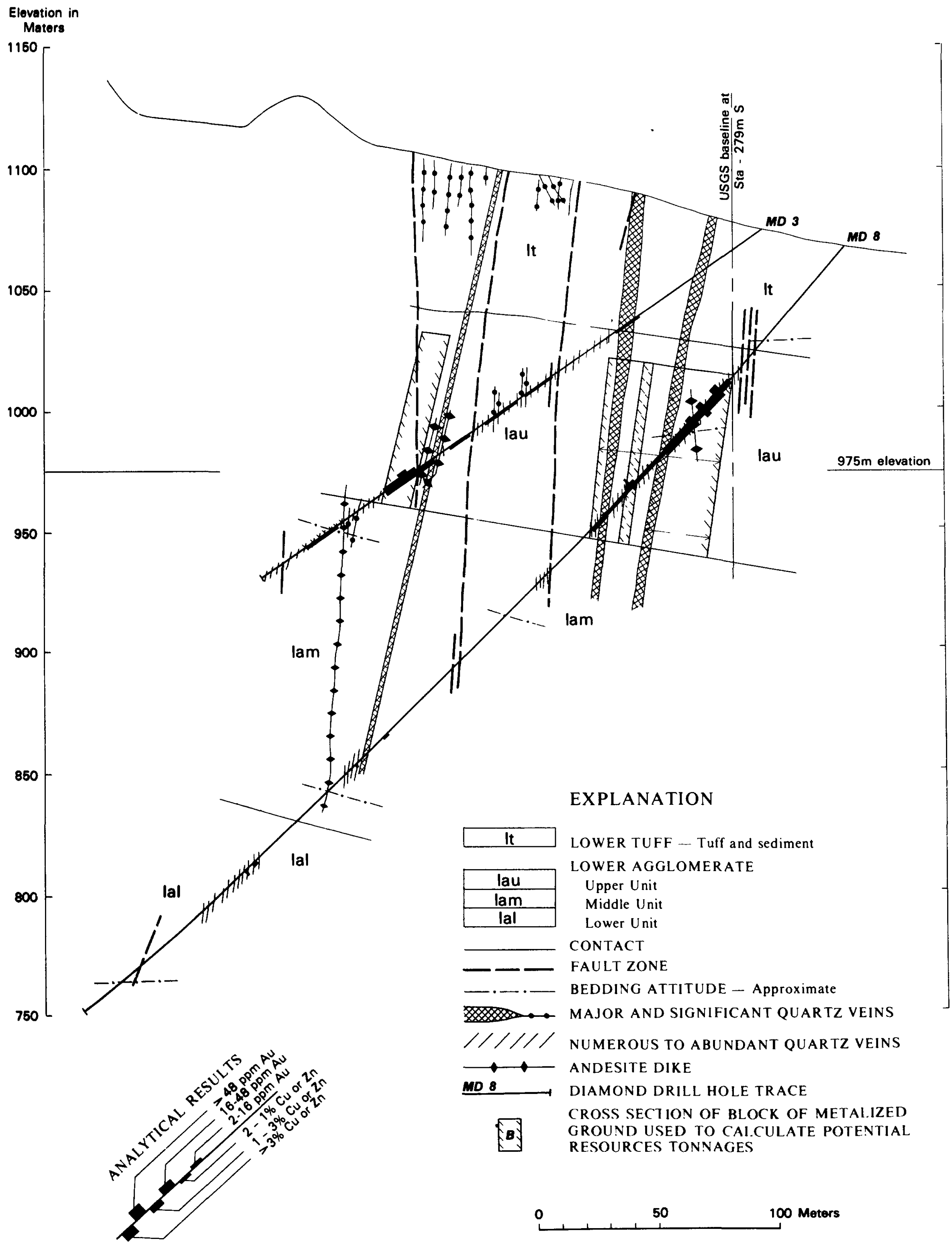


Figure 4. Geologic cross section through diamond drill holes MD 3 and 8

The number 1 vein system (pl. 1), the easternmost of the productive veins, is a north-trending system that was mined from the surface to the 450' level. It was most productive on and above the 300' level where 250 m of vein length in three ore shoots was stoped. Only 107 m of vein length in one ore shoot was stoped on the 450' level and there was no mining attempted on the 600' level because only narrow widths of low-grade ore were indicated by exploratory diamond drilling.

The number 4 vein is a northeast-trending vein system that southwestward turns south and becomes intertwined with the north-trending number 8 vein system (pl. 1). The number 4 system occupies faults and breccias along the contact of the lower tuff and upper agglomerate, and thus mimics folding. Excellent ore was mined above the 300' level from one ore shoot 165 m long; the same ore shoot on the 450' level was 130 m long, but was of very low grade. Only minor ore was taken from the number 4 vein on the 600' level. The south-trending portion of the number 4 vein system, before it joins the number 8 system, was a major producer at the surface but yielded no ore below the 150' level.

The number 8 vein system was the focus of extensive ancient near-surface mining. That portion of the number 8 system north of the intersection with the number 4 vein was also a major SAMS producer. Above the 300' level one ore shoot approximately 100 m long was stoped to the surface. On the 450' level this ore shoot was only 30 m long and it did not extend to the 600' level. South of the intersection with the number 4 vein the number 8 system splits into a multitude of minor mineralized fractures. One stope in this zone mined from the 300' to the 150' level produced ore of very erratic grade and low average gold content.

The number 14 vein system (pl. 1) in part occupies low angle west-dipping faults and breccias in and along the contacts of the crystallithic tuff to agglomerate unit of the upper agglomerate and in part occupies nearly vertical north-trending fractures. The low-angle and vertical portions were probably formed contemporaneously although there are later north-trending vertical veins that cut all mineralized veins. According to mining records several stopes along the number 14 footwall vein stopped abruptly against faults, mafic dikes or barren quartz veins of north-trend and nearly vertical attitude.

Two major ore shoots were mined along the number 14 footwall vein; a southern ore shoot approximately 100 m in length was stoped from the surface to the 300' level and a northern ore shoot approximately 100 m in length was stoped from the 300' level to the 600' level.

Ore shoots of the ancient and SAMS operation are all close to the contact of the upper agglomerate and the overlying upper tuff and the majority occur within the upper agglomerate; only a few ancient stopes occur within altered lower tuff. The ore bodies as shown by a composite outline of stopes from the numbers 4, 8, and 14N vein systems occur in a zone approximately 50 m thick directly beneath the north-dipping upper agglomerate (fig. 2). Stopes from the other vein systems show similar alignment and differ only in actual elevation and dip of the upper tuff unit. The stopes below and directly south of the SAMS quarry (pl. 1;

fig. 2) are in a zone of highest brecciation along the nose of a fold. Mineralization in this zone extends as much as 100 m below the inferred upper tuff contact. Much of this ore zone was probably removed by erosion with the mined ore bodies representing the lower tails.

Mine data suggesting that significant metallization does not extend below the 600' level of the mine was confirmed for the number 8 through 15 vein systems by diamond drilling (Worl, 1978). Most of the ore shoots quit with depth, mostly as a function of distance from the overlying upper tuff. In addition there seems to be general decrease in amount and grade of mineralization with actual depth.

Southern mineralized zone

The southern mineralized zone is at the intersection of the north-trending zone of faults, alteration, and quartz veins and the generally east-striking, north-dipping upper unit of the lower agglomerate (pl. 1; fig. 4). This zone is outlined by diamond drill holes MD-3, 7, and 8, and by anomalous surface geochemical samples (Roberts and others, 1978; Worl, 1978). Metallization is mainly gold and silver, but copper and zinc are also important constituents. Although metals are most abundant next to the major quartz veins, anomalous gold and silver occur throughout the inter-vein areas penetrated by drilling. The entire zone of quartz vein-upper unit intersection can be considered as potentially metallized. Several major veins cut the upper unit and the rock is sufficiently fractured and filled with quartz veins and veinlets to constitute a stockwork throughout the zone. High precious metal values in the core and surface samples are in altered and quartz veinlet zones next to major quartz veins, or within major quartz veinlet stockworks. More importantly, all of the high gold and silver values and most of the high copper and zinc values are restricted to a distinct stratigraphic horizon; the upper unit of the lower agglomerate.

This suggests that the upper unit is either a source bed for the metals with slight remobilization by quartz veining or that it is a receptive and selective host because of undefined physical or chemical parameters.

Although similar in hand specimen lithology, the upper and middle units of the lower agglomerate differ markedly geochemically (table 2). The upper unit is higher in $SiO_2$ and distinctly lower in K and possibly lower in Al than the middle unit. Metal values are higher in the upper unit even when the few anomalously high values are removed from consideration (Worl, 1978).

Chemistry of the lower agglomerate was determined from 128 lithologic character samples from diamond drill holes MD-1, -2, -3, and -4 taken according to a nested hierarchical sampling plan. The purpose was to test element concentration variation within and between the three lithologic units. These 20-30 gram samples were taken by sawing out a 1 to 2 cm disk before the core was split. Since this size is the equivalent of a chemical split, no variation in analytical results was introduced by sample splitting or sample preparation. The total sample was used in the analysis. An attempt was made to include only wall rock in the sample disk, but in some sample zones the wall rock contained a pervasive network of mm-sized quartz veinlets that could not be avoided.

Table 2. - Means, standard deviations, and high, medium, and low population mode values of bimodal and trimodal distribution curves. Value representing dominant population is underlined. h = high, m = medium, l = low, o = overall mean, ( ) standard deviation.

| Number of samples | | (32) | (80) | (16) |
|---|---|---|---|---|
| Element | | Upper unit | Middle unit | Lower unit |
| K% | h | | 4.00 | 3.50 |
| | m | | 1.75 | 2.00 |
| | l | .50 | .50 | .25 |
| | o | .36 (.42) | 2.90(1.68) | 1.72 (1.3) |
| $SiO_2$% | h | 90 | 87 | 92 |
| | m | 67 | 67 | 68 |
| | l | 48 | | 45 |
| | o | 75.69(13.70) | 70.25 (9.93) | 63.38(20.87) |
| Na% | h | 3.8 | | 4.5 |
| | m | 1.5 | 2.2 | 2.2 |
| | l | .50 | .25 | .50 |
| | o | 0.66 (1.13) | 0.84 (1.40) | 2.30 (2.17) |
| Al% | h | 9.0 | 7.00 | 9.50 |
| | m | 5.5 | 4.75 | 4.25 |
| | l | 1.25 | 1.00 | 1.25 |
| | o | 3.72 (2.42) | 4.22 (2.10) | 6.07 (3.58) |
| Ca% | h | 2.1 | | 2.8 |
| | m | .9 | .9 | .9 |
| | l | .3 | .3 | .3 |
| | o | .49 (.51) | .43 (.36) | 1.56 (1.16) |
| Mg% | h | 5.7 | 5.5 | |
| | m | 3.2 | 3.8 | 3.5 |
| | l | .4 | 1.2 | .75 |
| | o | 2.53 (1.79) | 2.35 (1.43) | 2.48 (1.30) |
| Mn ppm | h | 2400 | 3200 | 2400 |
| | m | 1400 | | 1800 |
| | l | 400 | 800 | 700 |
| | o | 1100(800) | 1500(700) | 1600(800) |
| Au ppm | h | | | |
| | m | .35 | | |
| | l | .1 | .02 | .02 |
| | o | 1.25 (5.19) | .20 (.62) | .06 (.05) |
| Specific gravity | o | 2.70 (0.12) | 2.68(0.08) | 2.77 (0.08) |

Analyses performed on the lithologic character samples included gold, silver, copper, lead, zinc, bismuth, cadmium, cobalt, manganese, sodium, potassium, silica, aluminum, and calcium by atomic absorption methods and molybdenum, tungsten, arsenic, and antimony by colorimetric methods. Values for molybdenum, tungsten, arsenic, antimony, and bismuth were generally low, at or below detection limits. Values for copper, lead, and zinc were erratic and generally corresponded to values obtained from split core samples.

The variance of element concentration values within each unit is high for most elements (table 2), too high to allow direct comparison of element concentration between units. Of the elements listed in table 2, only the values for specific gravity and background metals have normal or lognormal distribution; the other distributions are mostly bimodal or trimodal. The lack of normal distributions, reflected in the high variance values, makes comparison of chemistry between the units difficult. Only the differences in potassium values between the upper unit and the other two units has statistical significance. The mode of individual populations within obviously bimodal or trimodal distribution curves can be approximated. The modes for all significant elements were determined by visually fitting curves to a histogram of values and they are listed in table 2.

The generally trimodal nature of element value distribution reflects the genetic history of the lower agglomerate. Using the modes listed in table 2 and petrography as a guideline it can be inferred that the source of elements in the lower agglomerate was in part andesite volcanic rock and in part diorite to granodiorite plutonic rock and dacite to rhyodacite volcanic rock. This is consistent with the geologic history of the region. Imposed upon the agglomerates were later hydrothermal alterations reflected by the high or low K, high $SiO_2$, high Na, low Al, high Mg(?), and high metal modes. The modes (table 2) suggest that the upper unit is more highly altered than either the middle or lower unit. If the upper unit was originally composed largely of andesitic components, similar to the lower unit, alteration involved the introduction of $SiO_2$ and metals and removal or dilution of Ca, Mn, Al, and Mg. If the upper unit was originally composed largely of diorite-dacite component, similar to the middle unit, alteration involved the introduction of $SiO_2$ and metals and removal or dilution of K, and possibly Al and Mg.

In conclusion it seems that the upper unit of the lower agglomerate does not have unique primary parameters, such as initial high metal content. Instead, the chemical parameters derive from hydrothermal alteration of a volcaniclastic rock similar to the middle or lower unit of the lower agglomerate. The alteration was without doubt associated with the quartz vein and stockwork formation. The upper unit was selectively altered and mineralized, over similar lithologies because it is directly beneath the relatively impermeable lower tuff unit. This had the effect of restricting upward movement of the ore-forming solutions that instead went through the easily fractured more competent agglomerate.

Tonnages and grades given for the southern mineralized zone are not reserve calculations, but are estimates of potential resources; only geologic presence and perspective of metallization is given in this report. Determination of size, distribution, and grade of ore bodies must await development work.

The potentially metallized rock includes all of the upper unit of the lower agglomerate within the main zone of faults, alteration, and quartz veins. The exposed width of this zone is approximately 300 m, but an additional 100 m or more of width under wadi fill to the east of the exposures can be inferred by southward projection of veins from the mine area (pl. 1). Depth of metallization is postulated to extend 250 m downdip of upper unit. This is only 50 m below the deepest ore intercept in drill hole MD-7 and is the downdip extent of mineralization in the SAMS mine area. The potentially metallized rock can be visualized as a north-dipping tabular sheet 40 m thick, 250 m wide (downdip of upper unit), and 400 m long (along strike of upper unit). North-, northwest-, and west-trending faults break this block into wedges that are slightly offset from one another. This idealized block contains 17,210,000 tons of potentially metallized rock. Eastward the layered rocks probably bend southward against a major northeast-trending fault. The upper unit of the lower agglomerate may be stretched parallel to the vein zone, in which case the total tonnage of potentially metallized rock would increase, or, it may be eliminated completely by offset, in which case the total tonnage of potentially metallized rock would decrease.

Five blocks of high-grade metallization can be defined within the zone tested by drilling. The size and grade of each of the five blocks is given in table 3. Various combinations of the high-grade blocks are used to calculate estimated potential resources, also given in table 3. The potential resources compare favorably to the grade determined from production figures of the SAMS operation where approximately 591,200 metric tons of underground ore containing an average 37 g/t gold and 58 g/t silver were produced during the SAMS operation. The portion of the southern mineralized zone tested by USGS diamond drilling has a potential resource of 783,000 metric tons of 31 g/t gold and 68 g/t silver ore or 1,107,000 metric tons of 27 g/t gold and 73 g/t silver ore. Because only 150 m of the possible 400 m width of vein-upper unit intersection has been explored, it is tempting to increase all potential resource figures 2.7 times. However, the geologic perspective does not warrant this; much of the untested zone is not exposed, is inferred to begin with, and metallization along the untested veins is unproved.

## SUMMARY AND CONCLUSIONS

Ore bodies in the SAMS mine area occur in a 50 to 100-m thick zone in the upper agglomerate directly beneath the upper tuff. The host rock is fractured and altered and is cut by metalliferous quartz veins. Gold and silver occurs within and next to quartz breccia veins and within quartz-veinlet stockworks. Significant metallization does not extend below a downdip depth of 250 m or actual depth of 180 m. Significant mineralization in the southern mineralized zone occurs in a similar geologic setting; within a

Table 3. Potential resource grades and tonnages (metric), southern mineralized zone

| BLOCK | SIZE (meters) | TONNAGE (metric) | GRADE (gold g/ton) | (silver g/ton) |
|---|---|---|---|---|
| Total potential metallized rock | 40x250x400 | 17,210,000 | | |
| Total metallized rock tested by drilling program | 40x250x150 | 4,050,000 | 6 | 22 |
| A | 40x250x40 | 675,000 | 28 | 68 |
| B | 40x250x04 | 108,000 | 47 | 68 |
| C | 40x250x12 | 324,000 | 17 | 84 |
| D | 40x250x07 | 189,000 | 11 | 57 |
| E (includes A, B, and intervening rock) | 40x250x50 | 1,350,000 | 13 | 38 |
| Potential resources | | | | |
| C, D, and E | | 1,863,000 | 13.5 | 48 |
| A and B | | 783,000 | 31 | 68 |
| A, B, and C | | 1,107,000 | 27 | 73 |

50 m thick zone directly beneath the lower tuff where a host rock of highly fractured and altered agglomerate is cut by metalliferous quartz veins.

Ore was localized by four interacting controls; a) depth, b) a relatively impervious capping of fine-grained tuff and sedimentary rock, c) large metalliferous quartz breccia veins and stockworks, and d) a physically and chemically receptive host rock. Gold and silver metallization accompanied one and possibly two of four stages of quartz vein formation (Luce and others, 1976, p. 25). Silicification and pyritization preceeded and probably helped prepare the agglomerate for gold and silver deposition. Folding and several generations of faulting preceeded mineralization. The ore-forming, vein-forming, and alteration solutions moving upward along steep north-trending and active fractures were restricted under the relatively plastic and impervious cap of a fine-grained tuff or sediment and spread laterally through the more competent, fractured, permeable, and altered agglomerates. The most favorable sites for metallization were the highly fractured areas such as the noses and steep flanks of tight folds.

Diamond drilling directly below surface gold anomalies in the southern mineralized zone failed to find mineralization. After it was noted that most of the anomalous surface values were relatively close to the lower agglomerate-lower tuff contact it was postulated that ore control here was the same as in the SAMS mine. Subsequent drilling downdip from the surface indication, directly below the lower tuff outlined the zones of mineralization.

Other sites in the area that fit the criterias of limited depth, impervious cap, metalliferous quartz veins, and receptive host below the cap are excellent exploration targets. There are two possibilities, both unfortunately covered by alluvium. The first is an eastward to southeastward extension of the southern mineralized zone. The overlying lower tuff here seems to turn south towards the east, and structural analysis of the area suggests folding around an eastward $60^{\circ}$ plunging axis. If the lower tuff is folded into an anticline it would make a convenient cap over the upper unit of the lower agglomerate, which would probably be highly fractured, and mineralized, in the axial zone. East-trending faulting and east-trending quartz veining in the vicinity of the southern mineralized zone support this. However, the presence of metalliferous quartz veins under the alluvial cover is unknown.

The second unexplored site is southeast of the SAMS mine. If the fold in the mine area is doubly plunging, as geologic relations shown on SAMS mine maps (Dirom, 1947) suggests, then a fold nose with upper agglomerate draped around lower tuff should plunge east to southeast. Whether the upper tuff also continues around to form an impervious cap is unknown as is the presence of metalliferous veins east of the number 1 vein. Both of these sites are worthy of investigation because they have the potential for shallow east-dipping ore bodies similar to numbers 14 and 4 in the SAMS mine area.

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MINISTRY OF PETROLEUM AND MINERAL RESOURCES
DIRECTORATE GENERAL OF MINERAL RESOURCES

# KINGDOM OF SAUDI ARABIA

78-778

SA(IR)232
PLATE 1


## EXPLANATION

| | |
|---|---|
| Qu | QUATERNARY COVER – Includes debris from mine workings |

### UPPER TUFF

| | |
|---|---|
| utt | TUFF – Finely bedded gray argillite intercalated with carbonate and talcose, brown, massive to finely bedded tuff and minor volcanic wackes. Local zones of massive talc. |

*UNCONFORMITY OR FAULT CONTACT*

### UPPER AGGLOMERATE

| | |
|---|---|
| uaa | GRAY AGGLOMERATE – Subrounded fragments of white, red, and gray chert, andesite, siliceous tuff, pyrite-rich tuff, andesite to rhyodacite volcanic rock and chlorite and epidote-rich clots set in a gray siliceous and pyritiferous groundmass. Local pink K-feldspar scattered indiscriminately through groundmass and fragments |

*LOCAL UNCONFORMITY*

| | |
|---|---|
| uat | CRYSTALLITHIC TUFF TO AGGLOMERATE – Pale to dark green, with gray chert, brown to gray tuff, whispy chlorite, gray siliceous lapilli, locally abundant fragmental plagioclase and andesite to rhyodacite volcanic rock set in siliceous gray groundmass. Generally bedded, and locally graded. Intercalated fine grained massive green tuff. Pink K-feldspar is locally abundant as a partial to total replacement of the fragmental plagioclase, and to a lesser extent as scattered crystals through groundmass and all fragments |

### METASOMATIZED LOWER TUFF

| | |
|---|---|
| m | K-FELDSPATHIZED TUFFS AND SEDIMENTS – Mostly fine- to medium grained tuffs to volcanic wackes and sandstones with local zones of mafic lapilli. Indiscriminately distributed pink K-feldspar as replacement of fragmental plagioclase and as discreet crystals that commonly cut meta morphic grain boundaries. This is the metasomatized equivalent of the lower tuff described below |

### LOWER TUFF

| | |
|---|---|
| lt | TUFFS AND SEDIMENTS – Fine-grained massive to finely bedded tuffs, lapilli tuffs, volcanic wackes, and sandstones |

### LOWER AGGLOMERATE

| | |
|---|---|
| lau | Upper Unit – Mafic agglomerate, mostly andesite and chloritic fragments set in gray siliceous groundmass, mafic lapilli tuff, plagioclase crystal tuff and massive cherty tuff. Local fragments of massive sulfide (?) and pyrite-rich tuff |
| lam | Middle Unit – Mafic agglomerate with andesite, chloritic, red, gray and black massive tuff, and diorite fragments in chlorite and epidote groundmass. Intercalated dense massive green to brown chert |
| lal | Lower Unit – Massive to slightly bedded andesite tuff and lapilli tuff with minor intercalated mafic agglomerate |

| | |
|---|---|
| 60 | Major and minor quartz veins showing direction and amount of dip |
| | Andesite dikes and sills |
| | Contact |
| | Fault zone |
| | Local thrust faults |
| MD 2 | Diamond drill hole trace |
| 60 | Strike and dip of beds |
| 14 | Vein system numbers |
| | Surface workings - Ancient and SAMS |
| 1062.3 × | Spot elevations |
| A — A' | Line of cross-section (see figure 2 for cross-section) |

Topographic base adapted from KLM photogrammetric compilation. Elevation data adjusted to Kingdom net

SCALE 1:2500

100 50 0 100 200 METERS

200 100 0 200 400 600 800 1000 FEET

Mapped in 1976-77
Geology north of 8000N modified after Dirom, 1947

# GEOLOGY OF THE MAIN METALLIZED QUARTZ VEIN ZONE, MAHD ADH DHAHAB AREA, KINGDOM OF SAUDI ARABIA

By

Ronald G. Worl

1978