SA(IR)-375

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

SAUDI ARABIAN MISSION

TECHNICAL RECORD 19

GOLD PLACER AND QUATERNARY STRATIGRAPHY OF THE JABAL MOKHYAT AREA, SOUTHERN NAJD PROVINCE, KINGDOM OF SAUDI ARABIA

by

Dwight L. Schmidt, Willard P. Puffett,

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Open-file 82-414

PREPARED FOR

DIRECTORATE GENERAL OF MINERAL RESOURCES

MINISTRY OF PETROLEUM AND MINERAL RESOURCES

JIDDAH SAUDI ARABIA

1981

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The work on which this report was based was performed in accordance with a cooperative agreement between the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources.

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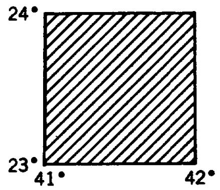

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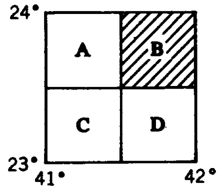
1-degree quadrangle



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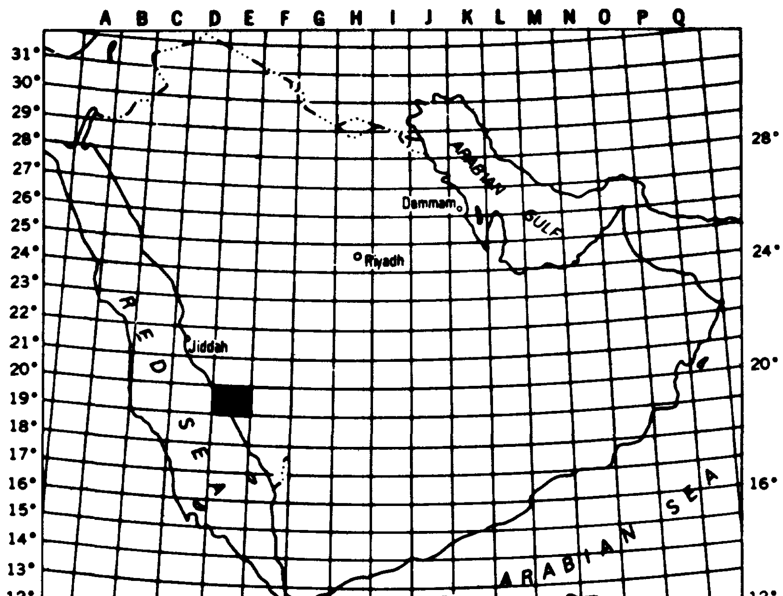

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GOLD PLACER AND QUATERNARY STRATIGRAPHY OF THE JABAL MOKHYAT AREA, SOUTHERN NAJD PROVINCE, KINGDOM OF SAUDI ARABIA

by

Dwight L. Schmidt1/, Willard P. Puffett1/, Wesley L. Campbell1/, and Ziad H. Al-Koulak

ABSTRACT

An ancient gold placer at Jabal Mokhyat (lat 20°12.2'N., long 43°28'E.), about 90 km east of Qalat Bishah in the southern Najd Province, Kingdom of Saudi Arabia, was studied in 1973. Seven hundred and twenty-eight samples in 25 measured sections were collected along trenches and pits 2.5 m in depth and 2,600 m in total length. Alluvium was thicker than the excavation depth along about 50 percent of the trench length. The average gold content was 4.4 mg per m^3, and the highest grade trench contained 40 mg gold per m^3. Because fine particulate gold is rare in the alluvium, a few large particles, 1 to 5 mm in diameter, greatly affected the sampling results. The ancient placer diggings are in small headwater wadis distributed over a 30-km^2 area, and the total dug area is about 1.2 km^2. The placer produced an estimated 50 kg of gold and was worked about 2,600 $\pm$ 250 years ago. The potential for a present-day placer operation is small.

The gold is sparsely distributed in locally derived, flood-deposited, immature gravels throughout a stratigraphic section that consists of 1) calichified, saprolitic bedrock of Precambrian age; 2) basal, intensely calichified, saprolitic gravel (0-3 m thick) of Pleistocene age; 3) disconformable, slightly consolidated gravel and sand (0-1 m thick) of late Pleistocene age containing sparse, disseminated caliche; 4) firm loessic silt (0-1 m thick) of early Holocene age; and 5) loose sand and gravel (0.3-1 m thick) of late Holocene age. The loessic silt accumulated during the Holocene pluvial. The top of the loessic silt unit is dated at about 6,000 years B.P. by using charcoal from hearths of ancient man. Following the Holocene pluvial, the climate became arid, and extreme desiccation resulted in abundant eolian sand that progressively diluted the late Holocene gravels. The remnants of the pre-Holocene stratigraphy suggest similar climatic cycles during the Pleistocene.

1/ U.S. Geological Survey, Denver, Colorado 80225

Abundant, sparsely mineralized, gold-bearing quartz veins (0-1 m wide) were the source of the placer gold. These late Proterozoic veins have hydrothermally altered wall-rock zones (1-5 m wide). The veins are dispersed over an area of 50 km^2. Though many veins were prospected in ancient times and some were slightly worked, only the Mokhyat ancient mine, located on a quartz-vein zone 30 m wide by 200 m long, was extensively worked. The quartz contains chalcopyrite, galena, sphalerite, tetrahedrite, an unidentified bismuth mineral, and small amounts of dispersed gold.

The fissure quartz veins lie at the complexly splayed, terminal end of a small northwest-trending Najd fault that elsewhere along strike has 11 km of left-lateral displacement. Most large veins are in north-trending vertical fractures where the stresses were distributed along an older, north-trending structural grain in andesitic greenstone terrane. Subhorizontal fracture sets contain conspicuous, well-developed gold-bearing quartz veins and associated alteration zones. These attest to the shallowness and youthfulness of mineralization during latest Precambrian time. Late Precambrian granitic plutons (625-600 m.y. old) had been deeply eroded before the gold minerals were emplaced; hence, the gold is not related to granitic plutonism. Abundant, widely distributed diabasic dikes associated with the Najd faulting event of latest Precambrian age were probably the heat source for the hydrothermal convection system and possibly the source of the gold.

INTRODUCTION

Discovery, location, and access

The only gold placers previously reported in Saudi Arabia are the ancient and modern workings at the Mahd adh Dhahab gold mine in central Arabia (Bagdady and others, 1978). During 1964-65, J. W. Whitlow (1966) discovered the ancient gold-quartz mine at Jabal Mokhyat and noted that nearby scree slopes had also been mined for gold. The discovery of extensive ancient placer workings at Jabal Mokhyat in 1968 by Louis Gonzalez, USGS, aroused much interest, and initially there was some disbelief that the subtle surface-viewed microrelief actually represented placer tailings. These placer workings are fairly uniformly distributed in small headwater drainages within an area of 30 km^2. From the air, the dimpled plains of tailings mounds are obvious only when the sun angle is low (figs. 14 and 15). On the ground, the innumerable, subdued tailings mounds, 0.5 to 1 m high, are detectable only if one drives among or very near them.

Jabal Mokhyat, at lat 20° 12.2' N. and long 43° 28' E., is near the eastern border of the Jabal al Qarah 30-minute quadrangle (fig. 1; Schmidt, 1981). The ancient placer area lies about 90 km east of Qalat Bishah and is accessible from Bishah on unmarked tracks over generally firm desert surface. Principal desert roads connect Qalat Bishah with At Taif and Ar Riyad to the north and with Khamis Mushyat to the south. Jabal Mokhyat is best approached from Jabal Abss, located about 30 km to the southwest along the southern side of Jabal Istan. It is relatively inaccessible over desert tracks from the north, east, and south because of extensive sand dunes.

Throughout this report the adjective "ancient" refers to the time during or prior to the Abbasid Caliphate (750-1,250 A.D.). Mining was a lost art in Arabia from about middle Abbasid time until modern time. In contrast, in the literature on gold placers, "ancient" refers to the gold itself and means gold deposited in alluvium of an older-than-present erosion cycle. At Jabal Mokhyat, and in the Najd Province in general, the alluvium lies along recent drainages. High-level erosion surfaces and gravels or buried alluvium in other than modern drainages are not to be expected.

Previous investigations

The ancient placer workings at Jabal Mokhyat were mapped by Louis Gonzalez in early 1968 during a reconnaissance exploration for gold (Gonzalez, written commun., 1970). Assisted by Ghazy Gafer and Abdul Malik A. Helaby, Gonzalez sampled a 50-km^2 area that contained both the ancient placer workings and abundant ancient diggings on small gold-bearing quartz veins. The area studied extends 7 km north

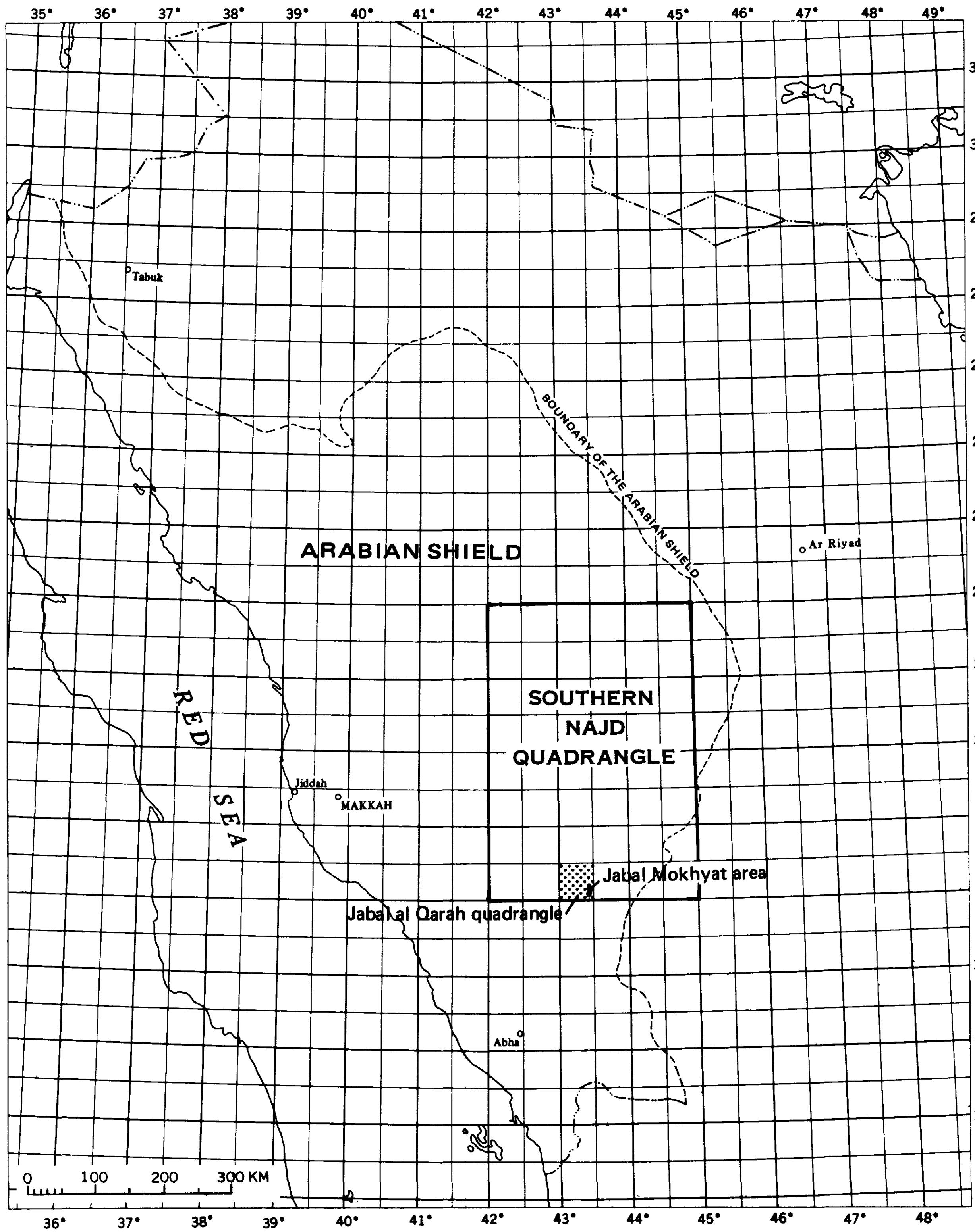

Figure 1.--Index map of the western part of Saudi Arabia showing the locations of the Southern Najd quadrangle (map scale 1:500,000), the Jabal al Qarah quadrangle (map scale 1:100,000), and the Jabal Mokhyat area.

and 9 km east of Jabal Mokhyat. About 40 samples of surface and near-surface debris, each measured in a 1/8-yd^3 container, were washed in a sluice and further concentrated by hand panning, and the resultant concentrates were fire assayed.

The gold values reported by Gonzalez suggest a wide range and erratic distribution. He reported that all tailings and dump samples contained variable amounts of gold and that, in general, the gold was coarse, some in "fairly large nuggets." Only 23 of the 40 samples are significant in the evaluation of the Jabal Mokhyat placer area. Nine samples were from placer tailings within the map area of plate 1. Three additional samples of placer tailings were from the eastern side of Jabal Sakhara, about 1 km east of the area represented in plate 1. Three samples from within the map area, which are recorded as tailings, were taken near ancient quartz-vein prospects and represent either dump materials or eluvium. Eight samples, all without visible gold, were from shallow wadi alluvium not worked by the ancient miners; four of these were close to placer workings within the map area of plate 1, and the lack of gold may reflect the sparsity of gold in recent alluvium.

Seventeen of the forty samples did not relate directly to the placer evaluation. Fourteen samples recorded as tailings apparently were taken from quartz-vein dumps or small diggings in eluvial material below quartz veins in the area east and north of the Jabal Mokhyat placer workings, a terrane too flat for significant concentration of alluvial gold. Most gold in these samples was probably in the eluvium, having weathered out of the nearby quartz veins. Three samples of wadi alluvium were from outside the gold-bearing area and contained no visible gold.

Gonzalez estimated that the placer tailings worked by the ancients covered about 400,000 to 600,000 m^2 at an average depth of 1.5 m and that 35 samples contained about one gram of gold per m^3. Indeed, we consider this estimate much too high because most of the higher gold assays of Gonzalez were of samples from quartz-vein dumps and from small eluvial workings adjacent to quartz veins, rather than from the alluvial placers.

Present investigation

An examination of the Jabal Mokhyat area was made in March, 1973, by T. H. Kiilsgaard, Puffett, and Schmidt. Trenching, sampling, and panning commenced on March 30, 1973, and was finished on April 30 of the same year. Fieldwork was done by all the authors.

Nearly 1,000 samples, each 0.01 m^3, were collected, and 728 of these were used to evaluate the placer (pl. 2). Marshud M. Alutaibi assisted in sample collecting. The samples were concentrated by panning in the field by Ibrahim Samyan, Hamed B. Al Mutayri, and Ali A. Juman, under the supervision of Campbell. These concentrates were then analyzed for gold and silver by use of atomic absorption methods in the DGMR-USGS Chemistry Laboratory in Jiddah.

The samples were collected from 25 trenches and lines of pits (pl. 1) across wadis. Some sample sites were representative of the placer alluvium worked by the ancient miners, others tested unworked alluvium adjacent to the ancient workings, and still others tested thicker alluvium downstream from the ancient placers. A backhoe with a 1 m-wide bucket capable of reaching 2.5 m deep was loaned by the Bureau de Recherches Geologiques et Minieres for the trenching and pitting. An aggregate length of 2,600 m of trench and pit line was systematically sampled.

Seven seismic refraction profiles adjacent to several trenches were made by use of a small, low-energy seismic method (thumper) to determine depth to bedrock.

ACKNOWLEDGMENTS

The investigation of the ancient placer in the Jabal Mokhyat area by the U.S. Geological Survey was in accordance with a work agreement with the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. We are grateful to Ghanim Jeri Al Harbi for his prospecting and discovery of native gold in many of the quartz veins. Ghufun Misfer Al Yami acted as guide and guard at the Mokhyat camp.

PHYSIOGRAPHY

The area around Jabal Mokhyat constitutes a north-trending block of greenstone, 7 to 14 km wide by about 15 km long, that is surrounded by an extensive terrane of younger plutonic rocks of late Precambrian age (Schmidt, 1981a). The greenstone crops out in two conspicuous north-trending ridges and numerous smaller ridges that reflect near-vertical layering. These ridges crest at about 900 m, and the highest peak of Jabal Mokyhat has an altitude of 943 m. They are surrounded by coalescing pediments, 1 to 2 km wide, that drain into several main wadis. The area is a headwater divide sloping both to the north and the south. The divide crosses the structurally controlled north- and south-draining, broad valleys at an altitude of about 850 m. The lowest altitude in the map area is 800 m, northwest of Jabal Mokhyat. Local relief is 50 to 100 m (pl. 1).

Large northeast-trending irqs, or longitudinal dune complexes, encroach on the northern part of the ancient placer area. These irqs are part of a series of northeast-trending dune complexes in the extensive plain adjacent to Wadi Tathlith east of Jabal Mokhyat (Jackson and others, 1963).

About half of the gold-bearing area (50 km^2) consists of alluviated pediments and wadis. Alluvial channels, the largest about 100 m wide, and fringing terraces, 0.2 to 0.5 m high, contain unconsolidated Holocene silt, sand, and gravel about 2 m thick and are underlain by consolidated Pleistocene gravel, 1 to 3 m thick. The total alluvial thickness exceeds 3 m in only a few places. The pediments are cut mainly on greenstone bedrock and are covered by a thin veneer of unconsolidated Holocene alluvium commonly less than 1 m thick; in places they are cut on consolidated Pleistocene gravel 1 to 2 m thick. The locally derived gravel of the wadis and pediments consists of subrounded clasts as coarse as 15 cm in diameter. Over half of the alluvium volume is composed of silt (mostly redeposited loess) and sand (mostly water-worked eolian sand). The surface of the pediments and terraces consists of a pavement of lag pebbles and cobbles that are coated with a black desert patina.

The broad alluvial channels and pediments lead abruptly upslope into hills where small headwater wadis, as wide as 20 or 30 m, are confined between steep bedrock slopes. In these confined wadis, small angular to subangular boulders, 20 to 30 cm in diameter, are common. The wadi gravel consists of greenstone and a disproportionate amount of vein quartz and hydrothermally altered greenstone that is more resistant to weathering than the unaltered greenstone.

The alluvial system is divisible into three parts that are significant for the concentration of placer gold: 1) narrow headwater channel deposits confined between bedrock slopes; 2) alluvial pediments downstream from the bedrock hills; and 3) broad channel deposits of coalesced wadis below the pediments. Almost invariably the ancient placer workings are in the lower reaches of the headwater channels and the uppermost reaches of the pediments where the headwater channels debouch onto the pediment (pl. 1). This segment of the channel is ideal for concentration of particulate gold of moderate size in shallow alluvium and is well suited to the recovery method of the ancient miners. We expected to find dispersed, fine-grained gold in the lower reaches of the pediments, and especially in the larger-volume alluvium of the broad wadis downstream, but found none.

BEDROCK GEOLOGY

Andesitic greenstone

The bedrock in the ancient placer area consists of metavolcanic and metavolcaniclastic rocks (pl. 1), probably of the Halaban group of late Proterozoic age (Schmidt and others, 1973). The volcanic rocks consist predominantly of layered porphyritic andesitic flows, thick massive pyroclastic flows, and breccia flows. Basaltic and dacitic flows and tuffaceous units are subordinate. Sedimentary rocks are interlayered with the volcanic rocks and constitute somewhat less than half of the rock volume; the sedimentary rocks are commonly calcareous and are derived from the volcanic rocks.

The volcanic and sedimentary rocks are highly deformed and regionally metamorphosed to the greenschist facies. Layering is vertical or nearly vertical and generally parallels pervasive north-trending, vertical cleavage in the massive rocks and parallel schistosity in the sedimentary and tuffaceous rocks (pl. 1). The cleavage and schistosity are axial planar, and most of the rocks are isoclinally folded about north-trending, gently plunging axes.

The ancient placer area lies across a major regional shear zone that trends north and dips about vertical. Shearing was penecontemporaneous with folding but continued episodically after folding. Shears tended to develop in thick sections of metavolcaniclastic rocks, but some massive volcanic rocks are also intensely sheared, and their original character obliterated. These shear zones weather and erode more rapidly than the adjoining rocks, thus forming the broad north-south valleys in the area (pl. 1).

Intrusive rocks

Plutonic rocks of several ages (Schmidt, 1981a) intruded the metavolcanic and metasedimentary rocks near the ancient placer area. Hornblende diorite, biotite-hornblende quartz diorite, and tonalite (IUGS classification; Streckeisen, 1976) intruded the greenstone 5 km west of Jabal Mokhyat. These rocks were metamorphosed and deformed at the same time as the volcanic and sedimentary rocks. Most contacts between rock units are faults. After regional metamorphism, pink, medium-grained, biotite monzogranite intruded the greenstone 6 km east of Jabal Mokhyat. Obvious contact metamorphism extends 1 to 3 km into the greenstone. Red, coarse-grained, hornblende alkali-feldspar granite intruded the greenstone 10 km south of Jabal Mokhyat. These red granites are characteristic of the late plutonism in the Precambrian Shield and were probably emplaced between 650 and 600 m.y. ago (Fleck and others, 1979).

Abundant dikes and sills of mafic and intermediate composition intruded the greenstone, probably penecontemporaneously with volcanism. Leucocratic felsic dikes that intruded the greenstone are slightly younger in that they are deformed and tectonically fragmented to a lesser degree than the greenstone. Younger diabasic dikes are abundant outside the area, but none were recognized in the Jabal Mokhyat area.

Najd faulting

Major northwest-trending faulting occurred during the Najd faulting event of latest Proterozoic age. Several large fault zones have displacements of many tens of kilometers in the central and northern parts of the Arabian Shield; the nearest is 70 km north of the Mokhyat area. In the Jabal al Qarah quadrangle (Schmidt, 1981a), Najd faulting is represented by two northwest-trending faults that have a few kilometers of left-lateral displacement and by numerous additional northwest-trending fractures of lesser displacement. Many of these fractures are filled by diabasic dikes as wide as 5 to 10 m. Numerous small subsidiary shear faults and fractures of variable trends relieved stress between the northwesterly faults. These fractures are common in the Jabal Mokhyat area and are related to one of the small Najd faults that elsewhere along strike has left-lateral displacement of 11 km; in the northern part of the Mokhyat area this fault splays out and terminates in a zone many kilometers wide. In the Mokhyat area much of the stress was accommodated in the older, north-trending structural grain in the greenstone.

Quartz veins

Lenticular, white quartz veins that fill fractures cutting the greenstone are abundant in the Mokhyat placer area (pl. 1). However, they are not abundant or large enough to be much more conspicuous here than in other areas of the southern Najd Province. Those depicted on plate 1 are characteristic but represent only a few of the total number. The larger veins, about 1 m thick by 100 m long, lie in zones consisting of many small veins, lenses, and pods of quartz in sheared and highly altered greenstone. The zones are parallel with the north-trending cleavage and schistosity, and may be several tens of meters wide and continuous for several tens of kilometers between northwest-trending faults. Presumably these zones are nearly vertical, and the quartz veins within them dip from 60° to vertical (fig. 2). A second set of veins, dipping 0° to 15°, presumably is indicative of a shallow depth of fracture. In places, such as on the small peak 400 m southwest of trench F-5 (pl. 1), a conspicuous step topography is developed on subhorizontal quartz veins (fig. 3) and layers of altered wall rock. Elsewhere, as on the small peak east-northeast of trench F-5 and on the northern end of Jabal Mokhyat ridge, single subhorizontal

Figure 2.--Subhorizontal quartz veins (about 0.3 m wide) and alteration layers in greenstone on small peak 1.5 km north-northwest of Jabal Mokhyat peak. View looking northeast.

Figure 3.--Mokhyat ancient mine located on a complex vein and alteration zone consisting of lenticular, closely spaced quartz veins. The vein zone trends north and dips nearly vertically, parallel with the structural grain of the greenstone wall rock.

quartz veins are conspicuous for several hundred meters. Small quartz veins within the vein zones and elsewhere in the area are oriented in different directions depending on the complex pattern of minor fractures. All the quartz veins and vein zones are along subsidiary fractures related to Najd faulting.

The quartz veins contain cubic pyrite, carbonate minerals such as calcite, ankerite(?), and siderite, and sparse amounts of dispersed sulfides of copper, lead, and zinc, as well as gold. The sulfides are commonly localized in small, dispersed clots or along late fractures in the quartz. In most outcrops, copper carbonate stain is a good guide to gold. In places, the sulfides fill vugs in the quartz or have grown on quartz crystals in the vugs. The vein quartz was fractured and recrystallized many times. All metallization appears to have taken place during a late stage of quartz vein formation, and some gold was the latest mobile element. The latest gold occurs as thin films on the latest fractures.

Only the Mokhyat ancient mine (fig. 3) about 1 km south-southeast of Jabal Mokhyat (pl. 1) appears to have produced more than a very small amount of gold. Here a complex vein and alteration zone, about 30 m wide by 200 m long, contains lenticular, closely spaced quartz veins, 0.1 to 1 m thick by 5 m to 20 m long. The veins consists of microfractured, milky white quartz locally slightly stained by iron oxide or containing 1 mm-thick fractures filled with oxidized pyrite. Rarely a slight copper stain is found on specimens from the dumps, and more rarely such specimens contain tiny particles of gold, chalcocite(?), chalcopyrite, galena, tetrahedrite(?), and sphalerite.

The ancient workings consist of several dozen pits, 2 to 7 m across by 1 to 2 m deep; originally some may have been several meters deep but now are filled with sand. The dumps contain a few thousand cubic meters of rock. An ancient mill site on the pediment 150 m downslope to the west of the workings contains stone anvils and hammers, fragments of circular grindstones, and the ruins of the stone foundations of six small buildings. Very little gold was produced from the quartz veins because the grade is very low. Eluvial gold was probably recovered from the base of the eluvium that overlies the saprolitic wall rock close to the quartz veins.

Within the Jabal Mokhyat area, many other quartz veins were prospected and (or) mined by the ancients on a smaller scale. East of the map area (to as far as 6 km east of the area depicted in plate 1), many more gold veins were worked. Some of these veins are in pink biotite monzogranite.

Hydrothermal wall-rock alteration

The wall rock of the quartz veins and of many other non-quartz-bearing fractures is intensely hydrothermally altered. Wall rock within the vein zones is the most intensely altered. Alteration away from the vein zones extends for tens of meters into the adjacent greenstone. Along most fractures, alteration is divisible by color into two subzones, an inner red zone and an outer green zone. The green altered rock grades imperceptibly outward into the parent metavolcanic-metasedimentary rock.

Most alteration is propylitic, although the innermost red alteration zone closest to the fracture is commonly sericitic as well. In the outer, green altered zone, the wall rock is carbonatized and chloritized and may or may not contain disseminated cubic pyrite. The alteration was controlled by microfracturing, and original volcanic textures are commonly preserved. In the field, the green altered rock is distinguished readily from the unaltered greenstone by the presence of carbonate, and field testing for carbonate with dilute HCl provides a convenient method for estimating the degree of alteration. In the inner, red altered zone, the wall rock is variably intensely carbonatized, silicified, pyritized, and sericitized, and original volcanic textures are rarely preserved. The red color results from weathering of the abundant pyrite.

Alteration zonation is well displayed along a subhorizontal joint or fracture set in the northeastern part of the mapped area where a bench topography is developed on alternating resistant zones of red and green altered rock and intervening less-resistant greenstone; these zones are not related to bedding. The altered zones are about a meter thick and alternate with zones of greenstone several meters thick. Quartz segregation on these particular fractures is slight or nonexistent. The same distinct zonation, with or without quartz veins, is also seen nearby on steeply dipping fractures.

GEOCHEMISTRY OF HYDROTHERMALLY ALTERED WALL ROCK AND QUARTZ VEINS

Analyses of 49 samples of hydrothermally altered wall rock indicate little net addition or subtraction of most major and minor elements (table 1, in pocket) as a result of alteration, despite obvious changes in mineralogy and appearance. Analyses of 48 samples of mineralized quartz-vein material indicate a large, but highly localized, enrichment in gold, silver, copper, and lead contents (table 1), aside from an obvious gross increase in quartz. All samples of quartz-vein material were selected mineralized quartz (that is, "high-graded quartz"), and in this report are referred to as mineralized quartz.

Greenstone and green altered wall rock

The green altered wall rock, in the outer alteration zone, appears to differ only slightly from the unaltered greenstone country rock. Histograms (fig. 4) suggest that element abundances in the two rock types are largely confined within a single modal distribution; few or no values are anomalous, and no distributions are bimodal.

No hydrothermally altered greenstones were analyzed from the Jabal Mokhyat area. The only compositional comparison is with nonhydrothermally altered greenstones (andesitic rocks of greenschist facies) from the Wadi Qatan area about 200 km south of Jabal Mokhyat. Partial analyses of 20 samples of these rock are reported by Dodge and Rossman (1975, p. 44). These rocks are judged (by Schmidt) to be generally similar and probably of the same stratigraphic group as those at Jabal Mokhyat. For the minor elements that are compared (fig. 4), the unaltered rocks of Wadi Qatan are in fact similar to the green altered rocks of Jabal Mokhyat. Comparisons between unaltered andesitic rock from Wadi Qatan and the green altered wall rock from Jabal Mokhyat (table 2) indicate only small differences in cobalt, nickel, molybdenum, and manganese contents; the differences between the green altered rock and world-average andesite and basalt are only somewhat larger. Likewise, the average silver content in 11 samples of the green altered greenstone from Jabal Mokhyat (table 1; fig. 4) is comparable to the average silver content (ppm) in the 20 samples of unaltered greenstone from Wadi Qatan:

	Gold	Silver
Green altered wall rock from Jabal Mokhyat	0.14	0.73
Unaltered greenstone from Wadi Qatan	no data	.87
World-average andesite	.0046	.13

The average silver content in the Jabal Mokhyat and Wadi Qatan rocks is about six times higher than that of world-average andesite (Taylor and others, 1969). The average gold content in the green altered rocks from the Jabal Mokhyat area is about 30 times higher than that of world-average andesite (Gottfried and others, 1972, p. 21). The gold content was not determined for the Wadi Qatan rocks.

Red altered wall rock

Chemical differences exist between the green altered and the red altered wall rock. Comparison of the arithmetic means and geometric modes of the histograms of all 49 samples

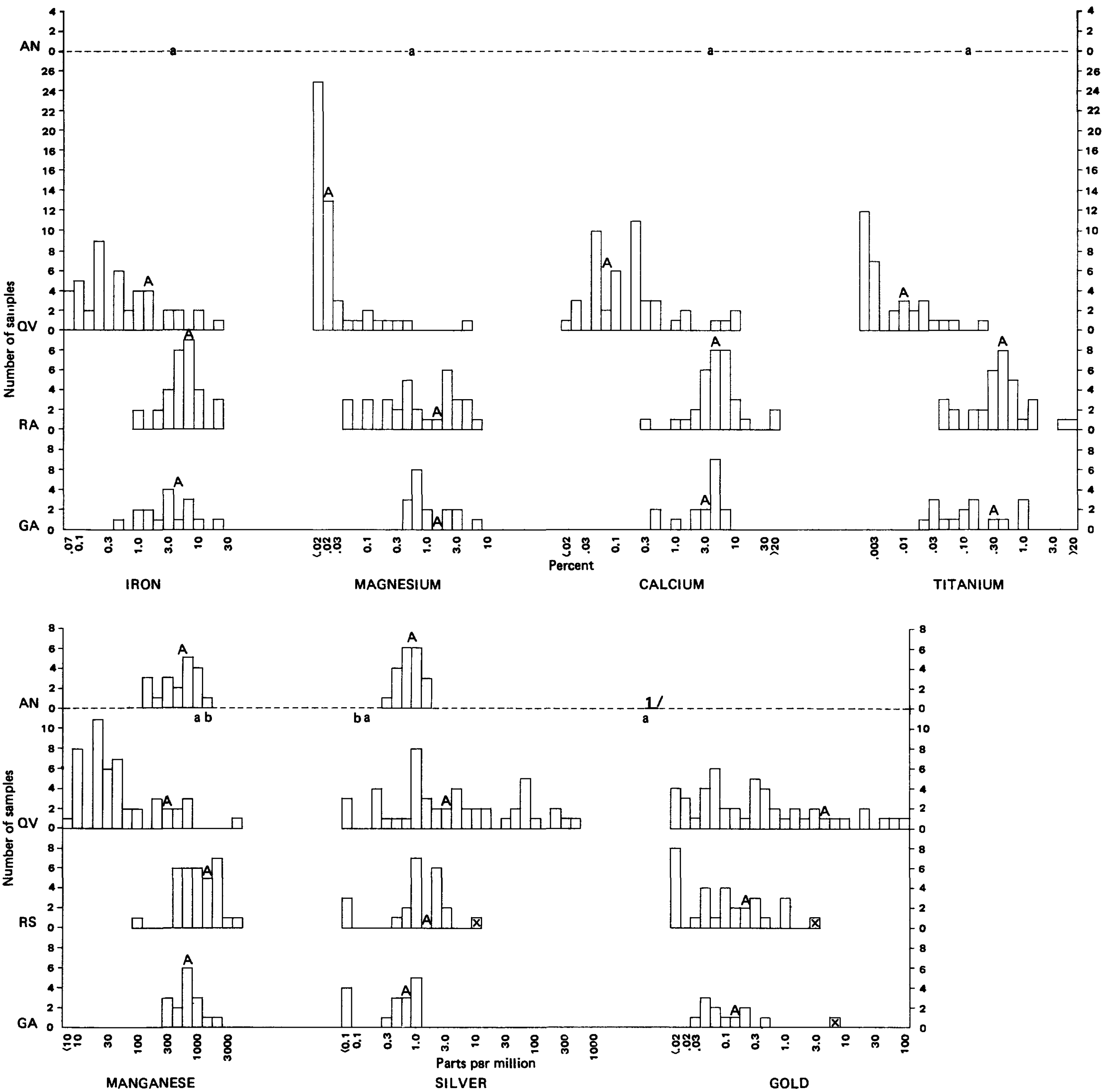

Figure 4.--Histograms of major and minor elements in altered greenstone wall rock and mineralized vein quartz from the Jabal Mokhyat area. AN, nonaltered andesitic bedrock from Wadi Qatan (Dodge and Rossman, 1975, p. 44); QV, mineralized quartz-vein samples (48 analyses); RA, red altered wall rock (33 analyses); GA, green altered wall rock (16 analyses); all data from table 1 except a, average element content for andesite (Taylor and others, 1969), and b, average element content for basalt (Turekian and Wedepohl, 1961). A, arithmetic mean; x, anomalous value excluded from mean.

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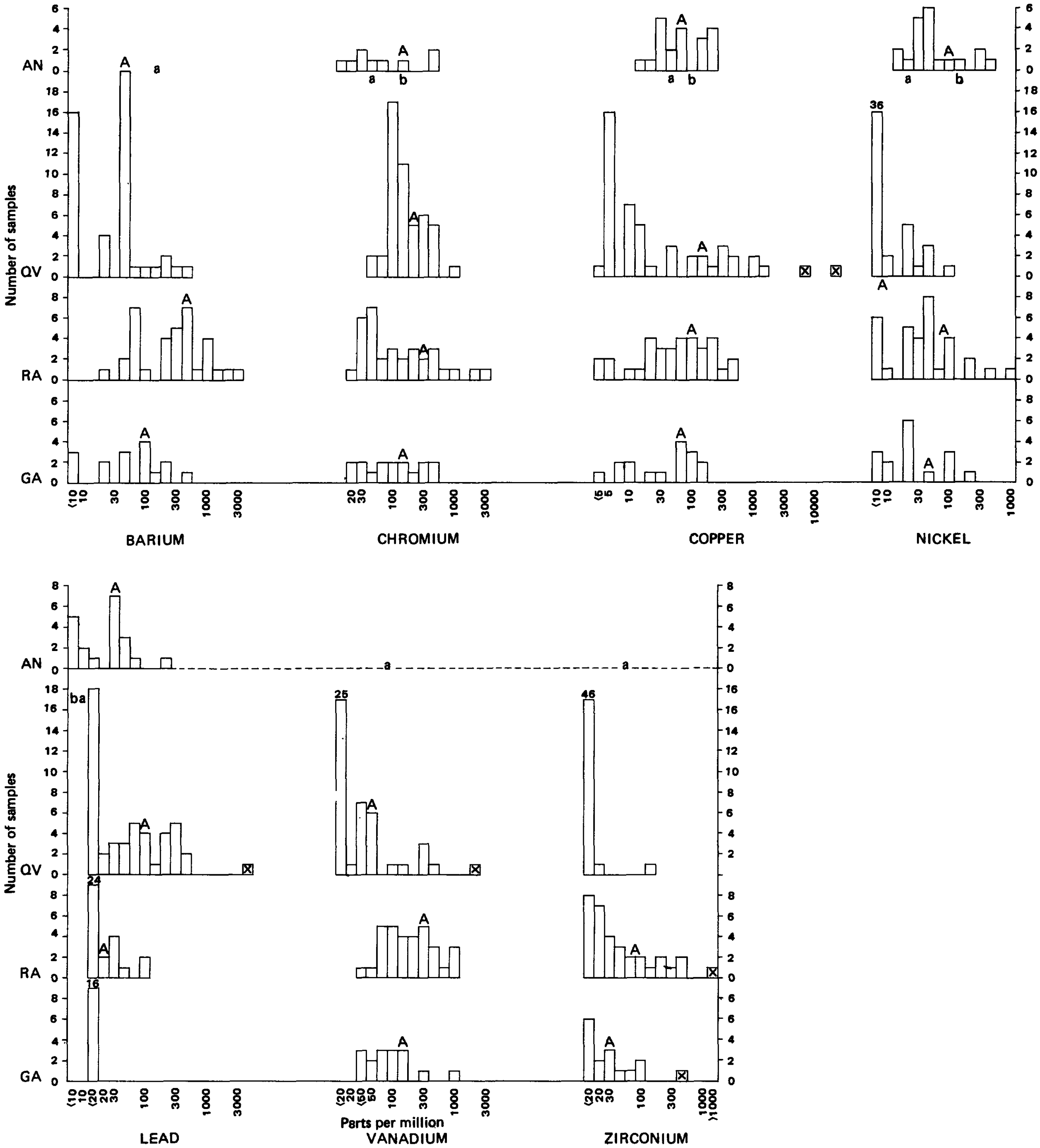

Figure 4.-- Continued

Table 2.--*Comparison of arithmetic means for cobalt, nickel, molybdenum, and manganese in samples of altered wall rock and mineralized vein quartz, Jabal Mokhyat area*

[Results in parts per million]

Metal	Mineralized vein quartz	Red altered wall rock 1/	Green altered wall rock 1/	Unaltered andesitic bedrock 2/	World-average andesite 3/	World-average basalt 4/
Number of analyses	48	33	16	20		
Co	<20 (20)	37	30	46	24	48
Ni	8 (10)	90	43	92	18	130
Mo	2 (10)	2 (10)	<10 (10)	2.5	1.1	1.5
Mn	220	1,250	800	610	1,200	1,500

1/ Data from table 1; lower limit of detectability in parentheses, where significant
2/ Atomic absorption analyses, Dodge and Rossman (1975)
3/ Taylor and others, 1969
4/ Turekian and Wedepohl, 1961

of green and red altered wall rock (fig. 4) is made in table 3. As alteration increases from the green altered to the red altered rock, the iron content increases about 2 times, calcium content remains about constant, and magnesium content decreases 1 to 2 times. Presumably the silicon content decreases in the altered rocks in order to balance the decreased content of silicate minerals, increased content of iron, and the formation of the vein quartz. Among the minor metals, silver content increases about 2 times, gold content increases about 1.5 times, and barium content increases about 6 times. In addition, manganese, nickel, lead, titanium, and vanadium contents increase variably with increased alteration. In general, silver, gold, nickel, lead, vanadium, and perhaps manganese move as chalcophilic elements with sulfur and iron (Fleischer, 1955, p. 971; Krauskopf, 1967, p. 582). The abundances of most translocated elements can be approximately accounted for across the alteration zone if the parent rock is considered to be average andesite (Taylor and others, 1969). For instance, barium appears to be depleted in the green altered rock relative to average andesite and is enriched in the red altered rock, so barium may nearly balance across the alteration zone.

As indicated in table 1, many of the analyzed samples were collected as sample pairs exhibiting visible, progressive alteration from green to red. In general, individual sample pairs show elemental trends similar to those of the modal trends (fig. 4), though exceptions occur and the amount of element change may differ appreciably. For emphasis, another specific example is cited. Analyses of 10 samples across a quartz vein (1 m wide) and its alteration zone (6 to 20 m wide) on an outcrop 100 m north of trench A-2 show that iron contents increase, magnesium contents decrease, and calcium contents are variable to constant toward the vein; silver, gold, and copper contents increase toward the vein; barium contents increase 10 to 20 times; and chromium contents decrease toward the vein.

Mineralized quartz veins

The chemistry of the quartz veins is represented by analyses of 48 samples of conspicuously mineralized vein quartz (table 1). All these samples are of rocks judged in the field to be those most likely to contain gold. Most contain abundant oxidized pyrite, many contain conspicuous traces of copper stain, a few contain nonoxidized sulfides of iron, copper, lead, and zinc, and six contain a little visible gold. These samples represent only a very small fraction of the vein at any given outcrop; most of the vein is barren white quartz with or without calcite, ankerite(?), and possibly siderite. The analyses show that the metals are locally enriched; however, that enrichment may be quantitatively insignificant relative to the entire vein.

Table 3.--*Element change with increased hydrothermal alteration in the wall rock of the quartz-vein system in the Jabal Mokhyat area*

[Column 1 is the change from green altered to red altered wall rock expressed as a multiple; column 2 lists elements for which the multiple was visually estimated from modal distributions in histograms of figure 4; and column 3 lists elements for which the multiple was derived from change in arithmetic means (table 1)]

1 Multiple factor	2 From mode	3 From arithmetic mean
+6x	Ba	Ba
+5x	(?)Pb	(?)Pb
+4x	Ti	
+3x	Ni, V	Mn, Cr, V, Zr
+2x	Au, Fe, Mn	Fe, Ca, Au, Ag, Cu, Ni
+1x	Ag	
0	Ca, Cu	Mg, Ti
-1.5x	Mg, Cr, Zr	

According to the histograms (fig. 4), gold, silver, copper, and chromium contents generally show anomalous values, that is, values distinctly above regional thresholds (Overstreet, 1978, p. 46-50) for the respective elements and generally above the element content in the altered wall rock.

Bismuth, zinc, antimony, molybdenum, and boron show local erratic anomalous contents (table 1). Histograms were not made for these elements, but the following numbers of samples contained more than the analytically detectable amounts, which probably are well above the regional threshold.

Element	Number of anomalous samples of the 48 samples	Fraction of anomalous samples of the 48 samples
Gold	20	1/2
Silver	19	1/2
Lead	15	1/3
Copper	8	1/6
Chromium	6	1/8

Element	Number of anomalous samples of the 48 samples analyzed
Bismuth	16
Zinc	7
Antimony	6
Molybdenum	1
Boron	1

The histograms for gold, silver, lead, and barium show distinct secondary modes; those for manganese and copper show less distinct secondary modes; and those for titanium and vanadium show weak secondary modes. This bimodal character suggests that these elements may occur in two different minerals in the mineralized quartz vein material.

Visually identified ore minerals in the mineralized quartz veins in the Jabal Mokhyat area include pyrite, gold, galena, chalcopyrite, sphalerite, specularite, chalcocite(?), and tetrahedrite(?). Antimony in tetrahedrite and as an accessory element in galena (Fleischer, 1955, p. 979) may account for the anomalous antimony in six samples (12 percent). All other anomalous metals are accounted for in the ore-minerals list above, except bismuth and chromium. The chromium is perhaps associated with minor gangue minerals in the vein. The occurrence of anomalous boron in one sample and anomalous molybdenum in another sample is not considered significant.

Bismuth was detected in 16 samples (33 percent) and is 5 to 35 times more abundant than the analytical detectability in six samples (12 percent). We have not identified a bismuth-bearing mineral in the Jabal Mokhyat area. The only bismuth mineral found associated with native gold in a quartz vein anywhere near Jabal Mokhyat is at the Jabal Wahdon ancient gold prospect, located 80 km to the west in the Al Junaynah quadrangle, where gruenlingite (Bi_4Te S(?); Fleischer, 1975, p. 47) was identified by Mohammed Naqvi and J. J. Matzko using X-ray diffraction (Schmidt, 1980a). Some bismuth may be associated with galena (Fleischer, 1955, p. 979). Tellurium was not looked for in the semiquantitative spectrographic analyses. However, tellurium minerals have been reported from many deposits of several different types of mineralization in the shield, including the gold-quartz-vein type of deposit of Mahd adh Dhahab and Al Amar (Sabir, 1979).

Weathering

Some of the chemical changes that have been interpreted as indicating migration of elements during hydrothermal alteration may instead have resulted from weathering and the action of ground water. Major-element abundances for the green altered rocks are probably reliable, as these abundances correspond reasonably well with those from the fresh samples of unaltered rocks from Wadi Qatan. On the other hand, major-element abundances for the red altered rocks may have been considerably changed by the presence of the sulfate ion that resulted from the thorough oxidation of pyrite. Minor-element contents of all rocks, and certainly of the completely oxidized red altered rocks, may have been significantly changed by weathering. For example, Dodge and Rossman (1975, p. 58) demonstrated that surface gossans are depleted in nickel, cobalt, copper, lead, and zinc by factors of 5 to 10 relative to nonoxidized drill-core samples; however, the same surface gossans were slightly enriched about two times in silver.

ORIGIN OF GOLD IN QUARTZ VEINS

The hydrothermal system in the Jabal Mokhyat area, which consists of gold-quartz veins and hydrothermally altered wall rock, formed locally in numerous shear and tensional fractures at a shallow crustal level. Hence, it is of latest Precambrian age relative to the late Precambrian age of the greenstone wall rock and nearby granitic plutons. Convective circulation was energized by heat from mafic intrusions not exposed at the surface in the Jabal Mokhyat area but regionally well represented by diabase dikes. Most compositional differences between unaltered greenstone and quartz veins can be accounted for by chemical changes within the intervening wall-rock alteration zone. Small amounts of a few elements, such as gold, antimony, and bismuth, and possibly silver, copper, lead, and zinc, may have been added from outside the wall-rock part of the system, perhaps from diabasic magma. Everywhere the chemistry of the hydrothermal alteration and quartz veins has a probable association with mafic rock or mafic magma, and nowhere are components of granite or particularly of the late alkalic granite identified. A magmatic source for the gold is suggested by a consistent, average 30-fold enrichment of gold in both the green altered and red altered wall rocks relative to the gold abundance in world-average andesite.

The age and origin of the gold-quartz veins are better defined in the adjacent Jabal Yafikh quadrangle, where gold-quartz veins, identical to those at Jabal Mokhyat, formed at the end of the Najd faulting event as the youngest deformational event involving the shield rocks (Schmidt, 1981b). In the Jabal Yafikh quadrangle, gold-quartz veins were emplaced in all major rock units of widely differing compositions and age without change in the character of the associated, hydrothermally altered wall rocks or of the vein metallization. The quartz veins and hydrothermal alteration are clearly associated with small subsidiary shear and tensional fractures that in places are filled with diabase, trachyte, and rhyolite dikes. The rhyolite magma was dry and viscous and not a likely source of gold, whereas the much more abundant, associated diabase is commonly hybridized and highly deuterically altered and is a likely source of a sulfurous mineralizer and of gold.

The small, slightly mineralized quartz veins and their altered wall rocks at Jabal Mokhyat and Jabal Yafikh are physically, mineralogically, and geochemically similar to gold-quartz veins throughout much of the southern Najd Province, an area larger than 100,000 km^2. The veins occur in many plutonic, volcanic, and sedimentary rock units including the youngest rocks associated with the Najd faulting event. Such a distribution requires a widespread source of low-level energy, as well as a uniform source of gold; the latest Precambrian diabase dikes of Najd fault age are such a regionally extensive source of both heat and gold.

The regional hydrothermal system of small convective cells was activated wherever water was available and permeability in fractured rock allowed circulation. Within these convective cells, movement of fluid along both vertical and horizontal permeable pathways resulted in hydrothermal alteration in zones a meter to several tens of meters wide. Convection was limited by the low overall permeability of the greenstone terrane and the availability of water. Alteration tended to reduce or eliminate permeability, except where the precipitated quartz was fractured under continued stress allowing the alteration to proceed. In the Jabal Mokhyat area, subsidiary fracturing at the terminus of a small primary Najd fault resulted in closer spaced convective pathways and more intense mineralization than in the region as a whole. The situation is somewhat similar to the splayed faulting and mineralization in the Ad Dawadimi district (Moore and Al Shanti, 1974).

QUATERNARY STRATIGRAPHY

A Quaternary section of cyclically bedded rocks is well exposed in the trenches at Jabal Mokhyat (pl. 1). Geologic sections along the trench walls are shown on plate 2, and a diagrammatic stratigraphic column is shown on figure 5. The four principal Quaternary units are, from oldest to youngest, 1) reddish-brown Pleistocene alluvium that is highly calichified and saprolitic; 2) gray late Pleistocene gravel and sand, slightly consolidated; 3) buff Holocene loessic silt, firm; and 4) tan late Holocene sand and gravel, unconsolidated.

Carbon dates of about 6,000 years B.P. (see later section, "Earlier man") on charcoal from near the top of the loessic silt unit clearly dates the silt and overlying unconsolidated alluvium as Holocene. The highly indurated, calichified, and saprolitic alluvium beneath must be pre-late Pleistocene, and the gray, but slightly consolidated gravel and sand between the two units is late Pleistocene.

A weakly developed humic layer in the upper part of the loessic silt, together with the loessic deposit itself, indicates the existence of a pluvial period that ended about 6,000 years B.P. The overlying late Holocene alluvium contains dune-sand deposits and abundant washed eolian sand, which indicates that extreme aridity followed the pluvial period. Since about 6,000 years ago, most stream and pediment activity has been confined to narrow dissection channels, with little lateral channel migration. The extensive ancient placer workings adjacent to these channels are dated at 2,600 ± 250 years B.P. and have been only slightly disturbed since that time (see later section, "Ancient diggings").

The cyclical Quaternary deposits are of two types, fluvial and eolian: 1) fluvial gravel and sand related to arid climate; and 2) loessic silt and eolian sand related to pluvial and extremely arid climates, respectively. The fluvial deposits are the result of bedrock erosion, wadi transport, and wadi deposition by ephemeral, turbulent floods characteristic of an arid climate. Thus, the overall ratio of gravel to sand is about the same in all three fluvial units (fig. 5). The alluvium is locally derived from the greenstone and quartz veins, is immature, and was transported

Climate	Geologic time	Carbon dates (years B.P.)	Thickness (in meters)	Description
		2,620±250		Placer mining
				Stone monuments (Early Dilmun(?) 5,000-3,800 yrs B.P.)
Extremely arid	--		0-0.05	Black desert patina, cobble pavement. Trace caliche
Arid	Late Holocene		0.25-1.0	Gray, washed sand and gravel, nonconsolidated. Reddish-buff, washed eolian sand, abundant
		5,930±300		**Hearthsite, ancient man.** **Medium, buff gray humic soil, weakly developed**
Pluvial 9,000-6,000 B.P.	Holocene (altithermal)	--	0.5-1.0	Buff loessic silt, washed, coherent
Arid	Late Pleistocene	--	0.5-1.0	Gray to buff gravel and sand, slightly consolidated, some white calcite-coated cobbles
Cyclical pluvial and arid	Pleistocene	--	1.0-3.0	Red and white calcified, saprolitic gravel and sand. Semicalcified red sand on top is washed eolian sand
				White and drab-green saprolitic bedrock, calcified

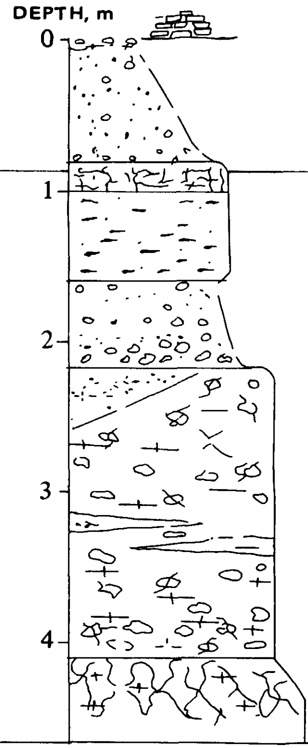

Figure 5.--Quaternary stratigraphic column for the Jabal Mokhyat area. (Carbon-14 dating by Meyer Rubin, USGS.)

no more than 2 km except in Wadi F, which is 4 km long. Estimated cobble size decreases from 10 to 30 cm for the largest cobbles (1 to 5 cm median size) in the headwater wadi deposits to about 5 to 10 cm for the largest cobbles (1 cm median size) 2 to 4 km downstream.

As the climate became more arid, the upper part of each of the three fluvial units was greatly diluted by reworked, washed, and redeposited eolian sand. This dilution is particularly apparent in the uppermost late Holocene alluvium, on which active sand dunes are conspicuous evidence of extreme aridity. The tops of the two older fluvial units are cut by disconformities, suggesting that much of the diluted upper parts have been removed by erosion. Remnants of older dune sand overlying the two older fluvial units are rarely preserved (pl. 2).

As the climate became more pluvial, stream action produced channeling, disconformities, and marked hiatuses. Loess was draped over the valley floors, and washed silt derived from the loess formed an aggradational deposit on the flood plain. Most loess and silt deposits were subsequently washed away as the climate became more arid, and a basal gravel marks the end of the pluvial period.

Calichified gravel and sand

The oldest Quaternary unit consists mostly of coarse gravel that is intensely calichified and saprolitic. The gravel is reddish brown where the detritus is derived from propylitic bedrock containing abundant oxidized pyrite but elsewhere is white or light gray owing to caliche. The presence of "red caliche" might be used cautiously as a guide to placer gold. The formation of caliche and saprolite in the unit obscures and obliterates internal sedimentary structures, so that no subdivision was attempted except for an upper red sand, which is especially well developed in trench G-1 (pl. 2). The red sand is only moderately cemented by carbonate and is probably a Pleistocene eolian sand that had been slightly reworked by water in the ancestral wadi. This process is illustrated at trench G-1, where thick eolian sand is presently accumulating adjacent to the northern end of the trench.

The thoroughly calichified and saprolitic character of the gravel and sand unit suggests that the unit is older than late Pleistocene. The total thickness of caliche is estimated to be 3 m in places, which is also the estimated maximum thickness of the unit itself. In most places, the bedrock is calichified and saprolitic as well, so that its contact with the alluvium is obscured and even obliterated. In eastern Saudi Arabia, only 0.3 to 0.4 m of duricrust (caliche) developed on the oldest of three Pleistocene terraces (Chapman, 1974, p. 122-123); however, the age of these duricrust layers within the Pleistocene is not known. In contrast, a maximum thickness of 3 m of caliche developed nearby on the sandy limestone of the Hofuf Formation of late Miocene or Pliocene age. Chapman suggested that the 3 m of caliche is pre-Pleistocene. Elsewhere in the world, the literature on caliche suggests that 3 m of pedogenic caliche represents maximum development and thickness and that such caliche formed on deposits older than Pleistocene. A 2.5- to 3-m-thick pedogenic caliche layer on the Ogallala Formation in the western United Stated (Miocene and Pliocene age) formed during and since late Pliocene time (Bachman, 1976). At Jabal Mokhyat we do not know that the caliche is related to soil formation and therefore that its thickness is a measure of age, but certainly the estimated 3 m of caliche implies a considerable length of time for development. We regard the deposit as pre-late Pleistocene, although it is probably early Pleistocene or older.

Late Pleistocene gravel and sand

Gray, slightly consolidated gravel and sand overlie the calichified gravel and sand and bedrock. The contact between consolidated and slightly consolidated alluvium is a conspicuous disconformity and suggests a long depositional hiatus. The lower half of the unit is predominantly gravel and the upper half is predominantly sand. The sand in the upper half is probably reworked eolian sand, the gravel and sand sequence representing the arid and extremely arid parts of a climatic cycle. Carbonate is sparse throughout; generally, it is a thin coating on cobbles and pebbles. The alluvial layer is probably latest Pleistocene and earliest Holocene, that is, later than the late Pleistocene pluvial (about 36,000-17,000 years B.P. in Arabia; McClure, 1976). A late Pleistocene loessic deposit presumed to have underlain the alluvial layer was removed by erosion.

Holocene loessic silt

The loessic silt unit is composed mostly of reworked and redeposited loess; that is, loess deposited on wadi flood plains and adjacent slopes, then washed and subsequently redeposited on the flood plains. We chose for convenience to call it loessic silt to denote both its ultimate eolian origin and its silty, slightly washed character. Caton-Thompson and Gardner (1939, p. 25) used the term "aeolian silt," partly alluvial and partly aeolian, for similar material in the Hadhramaut of Yemen. In the lower reaches of Wadis F and G (trenches F-7, F-8, F-9, and G-1; pl. 2), the loessic silt is well displayed and buries irregular microrelief on an older valley floor. In most places, after the deposition of the silt unit, the silt was removed by stream erosion and pediment washing. In a few places, parts of the silt are preserved and in fewer places the top is preserved. The top consists of a gray, probably slightly humic layer, in which some organic carbon was preserved during the ensuing arid climate. Similar organic carbon presumably initially in the buff silt below the top of the silt section must have been removed by oxidation during the pluvial climate itself. A vigorous vegetative growth was necessary for deposition, protection, and preservation of the loessic silt during the pluvial, but slight evidence of that vegetation remains. The silt contains a few pulmonate gastropods and a few carbonate-lined tubules that are relicts of plant rootlets and stems.

No mineralogic study of the Jabal Mokhyat loessic silt was made, but a loessic silt at the same stratigraphic level in Wadi Bishah near Hazim, 100 km west-southwest of Jabal Mokhyat, was studied by C. L. Hummel (written commun., 1964). Results of a mechanical and mineralogical analysis (table 4) of the Hazim loessic silt indicate that it consists of unconsolidated, partly weathered rock debris, of which 55 percent is clay size (less than 44 micrometers, -325 mesh) containing less than 10 percent montmorillonite and only a trace of kaolinite; rock minerals are about equally distributed in both the less than 44 micrometer and greater than 44 micrometer fractions.

Bedrock weathering with little clay alteration produced a fine-grained mineral assemblage that, except for calcite and gypsum, differs little from that of average Precambrian bedrock. Such weathering is characteristic of arid climates, and the aridity is further emphasized by the presence of gypsum and calcite in the Hazim silt sample. The sample has all the normal characteristics of a desert loess (C. W. Sweetwood, U.S. Bureau of Mines, written commun., July 21, 1965) that was ultimately derived from diverse parts of the Arabian Shield.

Late Holocene sand and gravel

Unconsolidated, buff sand and gravel (0.25-1 m thick) is confined to active wadi and pediment channels. These channels did not migrate laterally to any degree during the late Holocene. Most sand in the active channels is reworked and redeposited eolian sand that has been mixed with locally derived gravel. A thin layer of washed sand, commonly from 0.25 to 0.5 m thick, underlies the wadi flood plains, terraces, and older pediment surfaces. On older surfaces most of the layer is concealed beneath a capping lag pavement of black, desert-varnished pebbles.

The proportion of washed eolian sand increases both upward in any given section and downstream in any given wadi. The former is a function of increasing aridity during the late Holocene, and the latter is a function of wind dynamics relative to physiographic position. Small amounts of eolian sand accumulate in the narrow headwater parts of wadis

Table 4.--*Mineralogical analysis of loessic silt from Hazim area on Wadi Bishah, 16 km south-southwest of Qalat Bishah crossing*

[Sample collected by C. L. Hummel, USGS. Analyses by x-ray diffraction of sample number 217-Cn-2206, 29 April 1965; analyst, Paul D. Blackmon, USGS]

	Size fraction	
	>44 micrometers (+325 mesh) 45 percent	<44 micrometers (-325 mesh) 55 percent
Mineral	Estimated amount (parts in ten)	
Gypsum	<1	
Calcite	<1	1
Quartz	1+	1
Feldspar	2+	<1
Chlorite	1	2
Mica	1+	
Mica (highly weathered)		2
Amphibole	1+	<1
Iron oxide		trace
Montmorillonite		<1
Vermiculite (aluminum interlayered)		<1
Kaolinite		trace
Bassanite ($2CaSO_4 \cdot H_2O$)	trace	
Zeolite(?)	trace	

incised in bedrock, whereas large amounts of eolian sand accumulate in the broader, lower parts of wadis and on open pediments. Generally, the more open parts of wadis contain small sand dunes, which indicate that eolian sand is accumulating faster than surface water can wash and redeposit it. For example, Wadi F (pl. 2) contains late Holocene gravel deposits and small amounts of admixed eolian sand (trenches F-2, F-3) in its upper, bedrock-confined part and primarily washed eolian sand (trenches F-7, F-8, F-9) in its lower, open part. Between the upper and lower parts, the wadi is as wide as 0.5 km and contains abundant sand dunes; the wadi is choked with dune sand that is only partly reworked as alluvial sand (trench lines F-4, F-5).

LOESSIC SILT DEPOSITION

The loessic silt of Arabia is a desert loess ultimately derived from the weathering of Precambrian rocks under arid climates. The Holocene loessic silt is a composite deposit derived largely from older Pleistocene loess through fluvial and eolian recycling. On a regional scale and under arid conditions, the weathered rock debris was transported downstream by water, and the finer fractions of sand and silt were recycled and transported by wind in the opposite upslope direction, which coincides with the prevailing wind direction (southeasterly winds). Thus, fluvial debris from the Precambrian shield was transported eastward toward the Rub al Khali, and the sand and silt fraction was blown back northwestward into the shield drainage area. The volume of recycled eolian sand and silt increased with time as the major drainage basin closed during the Pleistocene, and sand and silt was no longer lost by fluvial transport to the sea (Arabian Gulf via the Rub al Khali). With closed drainage in the Rub al Khali, pluvial lakes acted as large temporary sinks for the fluvial debris, as well as sinks for the precipitation of calcite and gypsum (Powers and others, 1966, p. 99; McClure, 1976). Therefore, the recycling loess, blown in part from the pluvial lakes, has a large component of calcite and gypsum.

Regionally, eolian sand and silt was transported upslope (northwestward to the shield) throughout the Quaternary. During arid climates, only the sand fraction accumulated appreciably, forming dunes in the Precambrian shield area. During the pluvials, with a changed rainfall pattern, desert loess accumulated as silt deposits. But with return of aridity and an arid rainfall pattern, large flash floods flushed out the wadi accumulations of loessic silt. During each pluvial-arid cycle, some silt was preserved on the margins of the flood plains of the wadi systems, and, after the many cycles of the Pleistocene, the amount of loessic silt in the wadi system actually increased. This residual silt, as a local, partial source, greatly supplemented the silt available for deposition during any subsequent pluvial. Thus, during the Holocene pluvial, which was a minor pluvial, a large deposit of loessic silt accumulated in the wadis of the shield. Much of this deposit has already washed out during the past 6,000 years of the current arid cycle.

In the Jabal Mokhyat area during the Holocene pluvial, loessic silt accumulated and aggraded only where it was protected by a vegetative cover. On wadi flood plains the protective cover was dense enough to choke stream flow and thus prevent any influx of sand and gravel. During the pluvial, a more even distribution of rainfall throughout the year also greatly reduced the transportion of sand and gravel. Modern examples of this type of silt aggradation without sand and gravel deposition are the Jordan River in Jordan and the Sudd on the Nile River of southern Sudan, where the change in the river depositional regime is related to dense vegetative cover (Whiteman, 1971, p. 112).

As the climate became more arid, the protective vegetation was lost and most loess and silt deposits were washed away. A basal gravel marks the passing of the pluvial period. The change from pluvial to arid climate may more reflect a change in the distribution of rainfall than a change in the amount of rainfall; the more even rainfall of the pluvial changed to a few violent storms causing flash floods during the arid climate.

SAPROLITIC WEATHERING

Saprolitic alluvium and bedrock

The oldest (pre-late Pleistocene) unit of figure 5 is a complex, composite deposit of calichified gravel and sand. This alluviual unit and the underlying bedrock were probably saprolitized prior to calichification, suggesting a long climatic period more humid than the arid-pluvial cycles of the Quaternary. Though thick saprolitic gravels and tills are common in old glacial deposits of the early Pleistocene in more northerly and more humid areas of Europe and Asia, it is doubtful that a thick saprolite could have formed even during the presumably numerous pluvial cycles of the Pleistocene in Arabia. On the other hand, extensive saprolite, tens of meters thick, formed on rocks as young as the Miocene basalts in western Arabia (Madden and others, 1979; p. 14, 26), which suggests that sometime during late Tertiary time Arabia had a more humid climate. Therefore, the saprolite at Jabal Mokhyat is probably a relict of late Tertiary time.

Deep saprolitic weathering of the bedrock greatly facilitated the release of gold from the quartz veins and thus the concentration of gold in placer gravels. Therefore, the old saprolitic gravel should have a greater potential for placer gold than the young unconsolidated alluvium, but this potential was not satisfactorily evaluated in this study. The preservation of a thin saprolitic veneer of old gravel coincides with the regional location of the Jabal Mokhyat area on a stable divide between major drainages. Other old gravels in similar physiographic divide areas are worthy of examination in the search for potential gold placers.

Depth of weathering by seismic profile

Since the alluvium below 2.5 m (depth of trenches, pl. 2) is potentially gold bearing, it was desirable to determine the thickness of this alluvium to calculate reserves. Our intent in using a seismic method was to locate the contact between alluvium and bedrock where this contact was below the depth of trenching. The seismic method did not distinguish between calichified saprolitic gravel, shallow calichified saprolitic bedrock, or deeper saprolitic bedrock, because apparently these materials lack a seismic velocity contrast; consequently, the thickness of the alluvium could not be measured. However, the seismic work did suggest the total depth of saprolitic weathering.

An attempt to determine alluvial thicknesses using a "thumper" seismic refraction method was made by V. J. Flanigan, assisted by Hisham Gazzaz, Habib Merghelani, and A. R. Gazzaz. A 12-channel portable seismograph with 12 detectors was used to record data, and a 400-pound weight, dropped about 2.5 m, was used to create the seismic energy. Seven seismic lines, each from 107 to 137 m long, were run adjacent to and parallel with several sample trenches. The computed profiles are shown on figure 6. The unconsolidated alluvium at 1 to 2 m depth was not accurately delineated by this method at the detector spacing used, and the seismic depths computed from endpoint-intercept times are too deep by a factor of about two; shorter detector spacing is necessary to measure such very shallow refractors.

Seismic refraction profiles in the Jabal Mokhyat placer area reveal a significant refractor at 10 to 20 m depth, where velocity increases from about 1,500 to 4,000 m/sec. This change is interpreted as marking the depth of intensive saprolitic weathering in the greenstone bedrock beneath the pediment area (table 5; cols. 2, 3, and 4). As weathering to such a depth cannot be attributed to the climatic conditions during Quaternary time, it probably occurred during late Tertiary time.

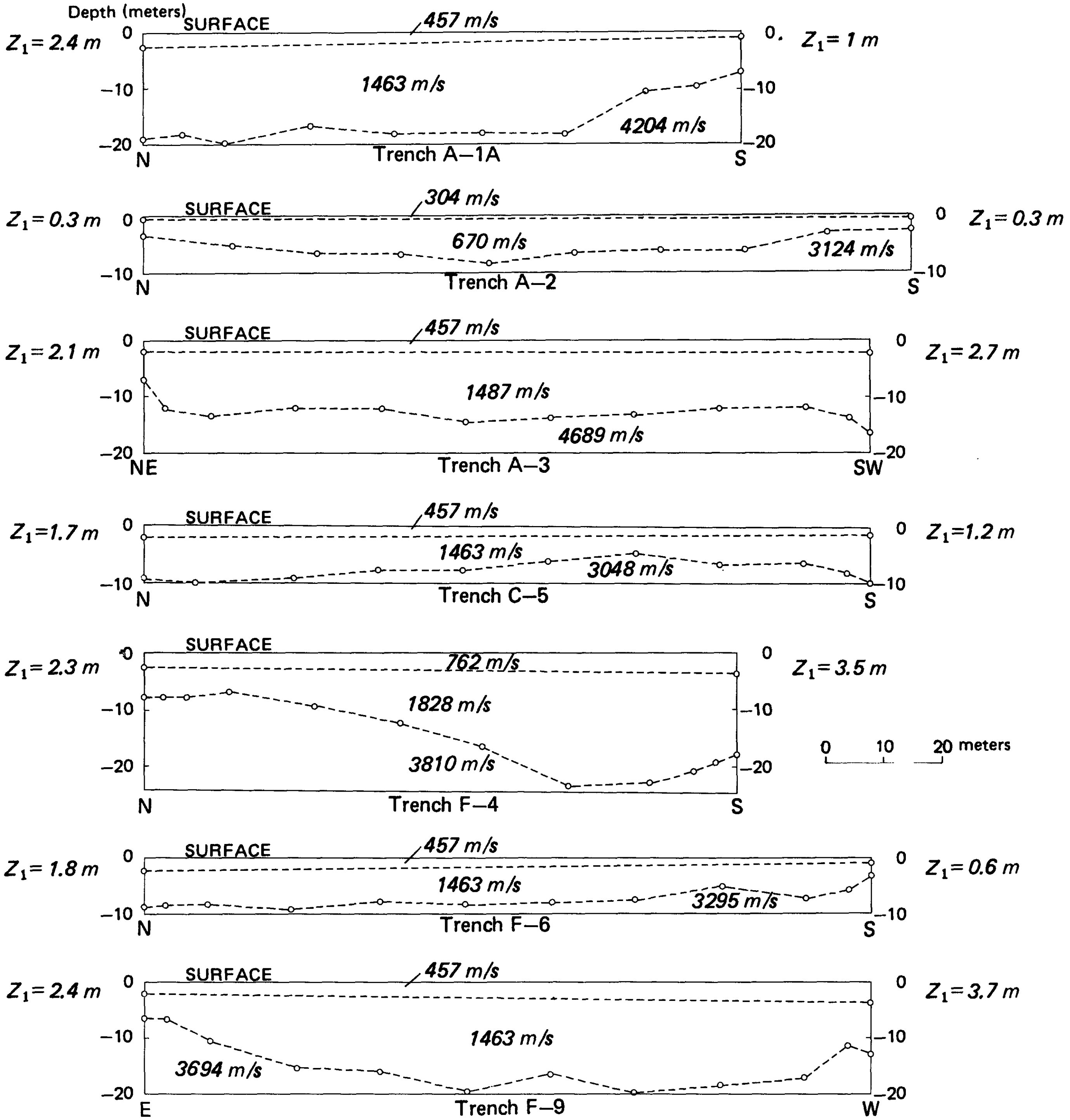

Figure 6.–Seismic profiles across small wadis and pediments in the Jabal Mokhyat area. Profiles are parallel with sample trenches (pl. 1) and are designated by trench number. The refractor at 10 to 20 m depth is interpreted as the base of intensive saprolitic weathering in the greenstone bedrock: ∘, computed depth point to seismic refractor; Z_1, computed depth of unconsolidated alluvium. 304-762 m/s, seismic velocity in unconsolidated sand and gravel; 1463-1828 m/s, seismic velocity in compact gravel and weathered (saprolitic) bedrock; 3048-4204 m/s, seismic velocity in bedrock. Survey by V. J. Flanigan, 1973.

Table 5.--*Seismic velocities and computed depths along seismic profiles parallel to sample trenches in the Jabal Mokhyat area*

[Survey by V. J. Flanigan, USGS]

1	2	3	4	5	6	7
Seismic profile and trench line	Nonsaprolitic bedrock	Saprolitic bedrock and alluvium		Unconsolidated alluvium		
	Velocity (m/s)	Velocity (m/s)	Computed depth (m)	Velocity (m/s)	Computed depth (m)	Measured depth (m)
A-1a	4,204	1,463	18	457	1-2.4	1-1.5
A-2	3,124	670	7	304	.3	1 (1.5 max.)
A-3	4,689	1,487	13	457	2.1-2.7	1
C-5	3,048	1,463	8	457	1.7-1.2	.1 (.5 max.)
F-4	3,810	1,828	8-20	762	2.3-3.5	>1
F-6	3,295	1,463	8	457	1.8-0.6	2
F-9	3,694	1,463	18	457	2.4-3.7	>2.2

PLACER GOLD

Field method

Samples were collected along 25 sections totaling about 2,600 meters in length (pl. 1 and 2): 1,100 m was explored by trenches and 1,500 m by a series of pits; the actual digging totaled about 1,500 linear meters. Where panning showed a given area to contain very little gold, trenching was changed to pitting. In many trenches, calichified gravel proved too difficult to dig in a reasonable time, and so the bedrock contact was not reached for sampling in many places.

Samples were taken systematically in vertical channels spaced 5 m apart along the trench walls. Each sample represents 50 cm of vertical section, except across the bedrock-alluvium contact, where each sample represents only 25 cm of alluvium and includes a few centimeters of the bedrock itself. The volume of each sample, measured in a bucket, is 0.01 m^3 (10 liters). About 1,000 samples were collected, but only 728 samples were used for evaluation; the additional samples were used to test special situations such as bedrock and internal contacts for localized concentrations of gold.

Panning was done at the field camp by Ibrahim Samran, Hamed B. Al Mutayri, and Ali A. Juman, using steel gold pans 16 inches in diameter. Water was obtained by tank truck. Samples were wet-sieved directly into the pans, and the minus 1.25 cm fraction, commonly a heaping panful, was panned in water in tubs consisting of the halves of standard 55-gallon steel barrels. About 30 samples were panned per 8-hour man-day, about 16 minutes per pan. Tailings were panned from time to time to check for particulate gold, but none was found.

Each sample was panned to a concentrate of about 100 g, and any visible gold particles were noted; however, a specific search for gold was not encouraged in order to maintain panning efficiency, and because the panned concentrate was purposely kept relatively large. Even so, 53 panned concentrates were reported to have visible gold, representing 80 percent of the samples (65 samples) in which a significant gold content was found by laboratory analysis.

Laboratory analysis

All 728 panned concentrates were analyzed for gold and silver by W. L. Campbell in the DGMR-USGS chemistry laboratory in Jiddah. For most samples, the entire concentrate was dissolved, and an aliquot of 10 ml was analyzed by atomic absorption; this procedure assured that all particulate gold in the sample was reported. Concentrates of samples 88055 through 88122 were mechanically split in half, so that the gold and heavy minerals in these samples could be examined in the laboratory. Each split was then analyzed separately, and the sum of their gold contents was reported. The use of the phrases "gold content" or "silver content" in this report refers to analytically determined gold and silver contents unless stated otherwise.

The splitting of samples containing particulate gold is unsatisfactory, in that the sparse gold particles do not split evenly (the "particle sparsity effect," Clifton and others, 1967). This is shown in the following tabulation from the 67 samples that were split; only those samples containing significant amounts of analyzed and weighed gold are listed.

	Split A		Split B		Analytical
	µg Au	µg Au	µg Au	µg Au	fineness
88082	0.6	8.5	37.5	7.4	832
88083	128.0	2.0	<0.2	3.7	986
88089	284.0	15.5	0.9	1.5	947
88105	.4	5.5	3,220+<0.2[1]	3.7	940[2]
88114	---	6.2	1,140+<0.2[1]	4.9	---
88116	.4	5.0	16.5	0.8	957

1/ Weight of single particle of gold handpicked from sample before analysis.
2/ Fineness by analysis of gold particle (see table 8).

The limit of detectability of the atomic absorption analysis method is 0.2 µg (micrograms) gold (0.02 ppm of the aliquot). The reported results of the analyses may vary as much as ±20 percent (precision and accuracy) of the indicated gold content. Check analyses on five samples with known contents of particulate gold produced gold values 2 to 24 percent less than the known amounts (Bagdady and others, 1978, p. 11).

Nature of the placer gold

Because the gold content of the placer deposit was analytically determined, it is necessary to determine what gold is free and recoverable by panning or other simple mechanical methods and what gold is nonrecoverable by such methods. Some of the analytically determined gold is certainly not free gold but is bound up in the various iron-oxide minerals of the panned concentrates. From the available data, the amount of free gold at low analyzed gold contents can be reasonably estimated by an examination of the analytical fineness.

Fineness

An average analytical fineness of 950 is suggested for the placer gold in the Jabal Mokhyat area. This is determined from figure 7, where analytical fineness is defined as ("apparent fineness" of von Rahden, 1965)

$$\frac{\text{analytical Au}}{\text{analytical Ag + Au}} \times 1{,}000$$

and is plotted against the analytically determined gold content for each sample. A plot of the gold content in each sample against the corresponding silver content (fig. 8) indicates that above about 10 μg gold, most silver varies systematically with gold. Contents of gold and silver at a gold content greater than 10 μg follow a trend indicating two phases of silver: 1) that silver associated with 950 fine gold, and 2) that silver bound in other minerals of the panned concentrate, that is, an independent silver content averaging 7 μg silver. This two-phase relationship is indicated by the reasonable fit of the scatter trend (fig. 8) to calculated curves (dashed) for constant background contents of 7 and 10 μg silver per sample, respectively, using a gold fineness of 950. The scatter in figure 8 is probably largely analytical error plus a natural variation in gold and silver bound in the iron oxides of the panned concentrates.

Below about 10 μg gold, most silver is associated with minerals other than native gold. This silver content is visually estimated (fig. 8) at about 7 μg. Likewise, because very fine grained gold was not observed in panning, it is assumed that most of the gold contents of less than 10 μg do not represent free gold recoverable by panning. Most gold and silver below 10 μg gold is probably associated with iron oxides (oxidized pyrite and magnetite) in the panned concentrate.

Size and shape

Table 6 lists the size and weight of 15 particles of panned gold that have been examined and in part photographed (fig. 9). Their color is uniformly bright yellow. The largest particle weighs 66.05 mg and the smallest 0.06 mg. Most particles are compact, elongated, and flattened. A length of 1 mm is common for the coarser particles, and the longest is 4.5 mm. Most particles are angular, many have partly rounded smooth surfaces, and a few are amoeboidal. Some angular particles are highly indented, which suggests that quartz has been dissolved from the angular voids without subsequent shape modification of the voids. The gold is free of attached quartz or other minerals, indicating that quartz was highly susceptible to solution during weathering in the nearby outcrops. All the apparent smooth surfaces are microscopi-

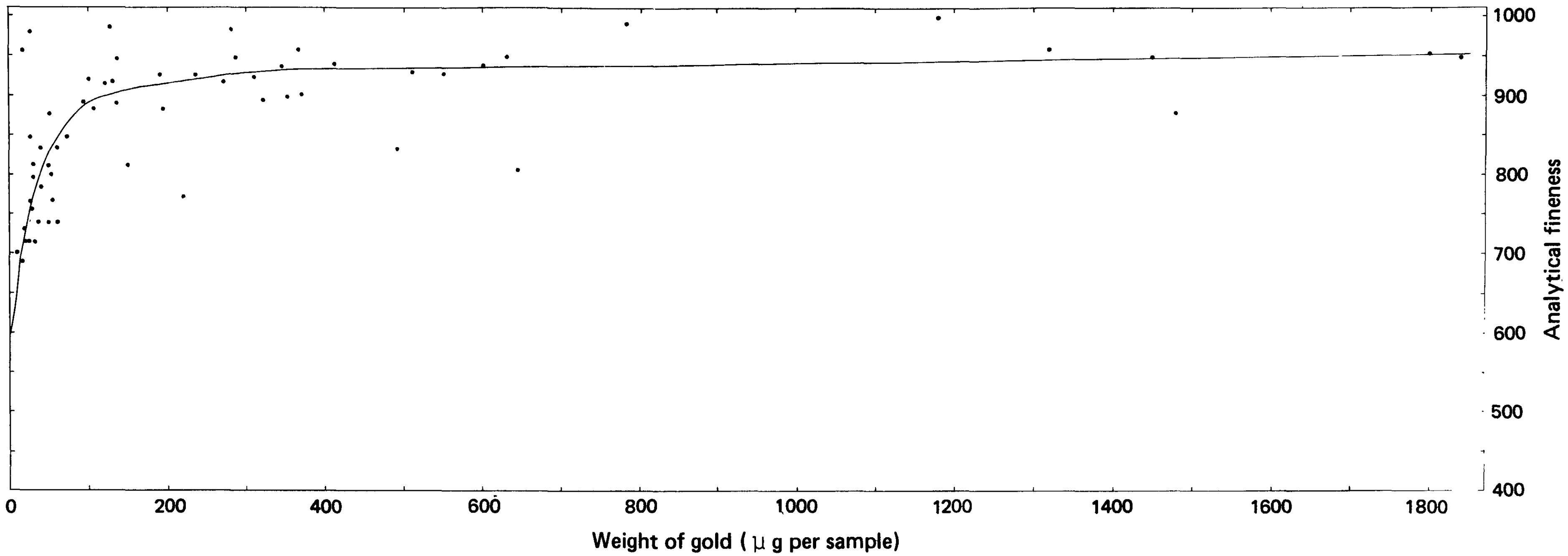

Figure 7.–Analytical fineness of gold plotted against analytically determined gold content in panned concentrates from the Jabal Mokhyat ancient placer area. Only gold contents greater than 10 µ g (65 samples out of 728 samples) are plotted. The estimated curve is visually drawn through the scatter of points and is asymptotic to an analytical fineness of 950.

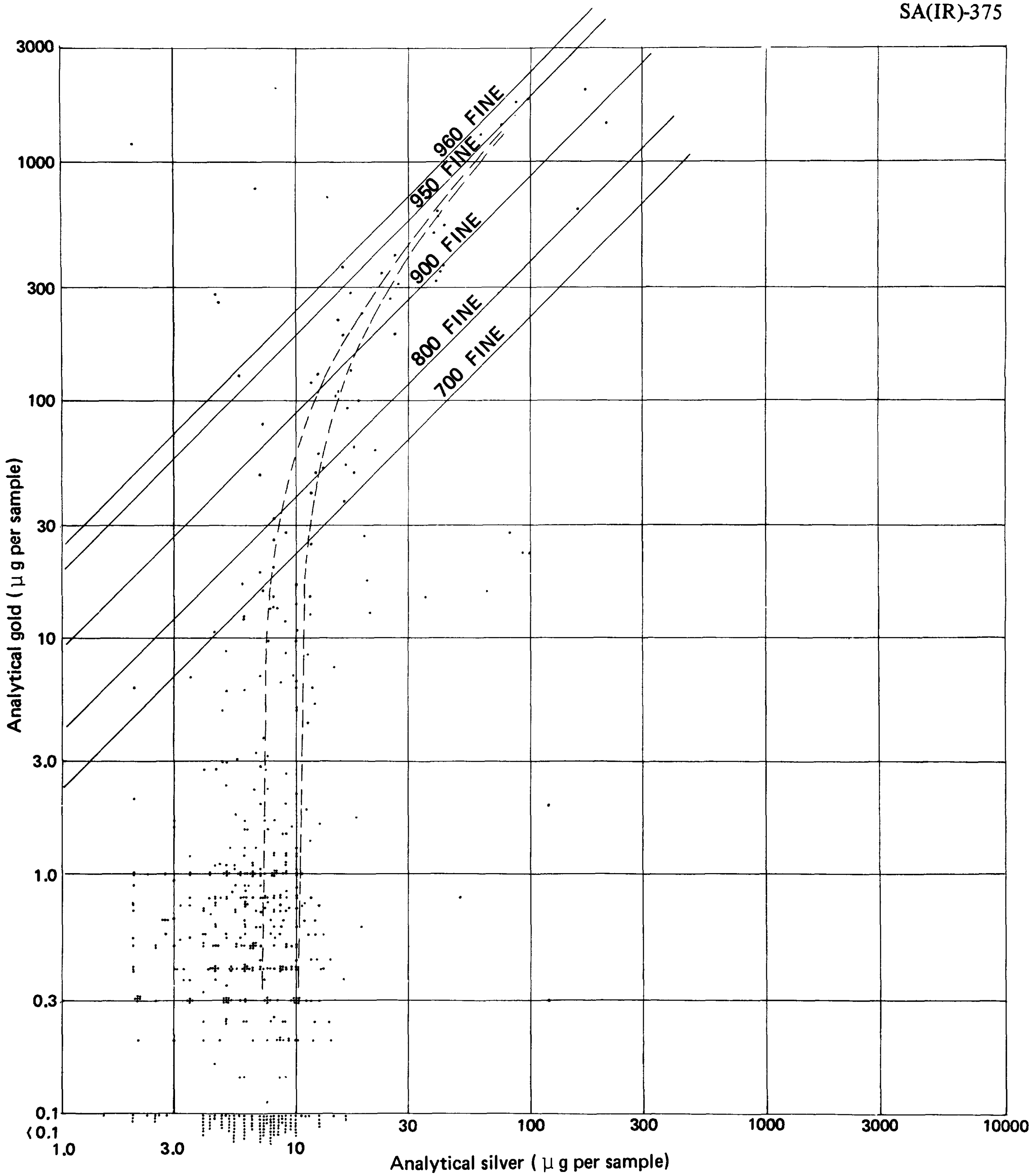

Figure 8.--Analytically determined gold content plotted against analytically determined silver content in panned concentrates from the Jabal Mokhyat ancient placer area. Gold fineness curves at 960, 950, 900, 800, and 700 are superimposed on the plot. The fineness of the gold is visually estimated to be about 950. Two dashed curves are calculated assuming constant contents of 7 µg silver and 10 µg silver that are independent of free gold that has a fineness of 950. These curves reasonably fit the scatter trend above 10 µg silver and by calculation are asymptotic to the 950 fineness curve.

Table 6.--*Size and weight of selected gold particles from Jabal Mokyat area*

[Samples 88105, 88114, and 88720 used in placer evaluation. Asterisks mark gold particles analyzed for minor-element content, table 7]

Trench and(or) sample number	Total weight gold (mg)	Number of particles	Weight of individual particles (mg$\pm$0.02)	Value in cents ($500/troy oz.)	Size (mm)
88034	98.35	3	---	---	---
88034*			66.05	106.5	4.5x3.0x0.5
88033*			32.00	51.5	2.5x2.0x0.5
---			0.30	0.5	0.75x0.5x0.5
D-4	29.12	3	---	---	---
88001*			16.00	26.0	3x2x0.5
88000*			12.76	20.5	1.5x1.5x0.5
---			.36	0.6	1.0x0.5x0.25
88720*	6.05	1	6.05	10.0	1.5x1.0x0.75
88105*	3.22	1	3.22	5.0	1.25x0.75x0.5
A	2.64	4	---	---	---
			large 1.70	2.75	1.5x0.6x0.5
			small .13	0.2	0.75x0.5x0.25
B-3	1.34	6	---	---	---
			large .11	0.2	1.0x0.5x0.25
			small .06	0.1	0.5x0.25x0.25
88114	1.14	1	1.14	1.85	1.0x0.75x0.5
B-2	.33	1	.33	0.55	0.6x0.5x0.25
F-2	.20	1	.20	0.3	0.5x0.25x0.25

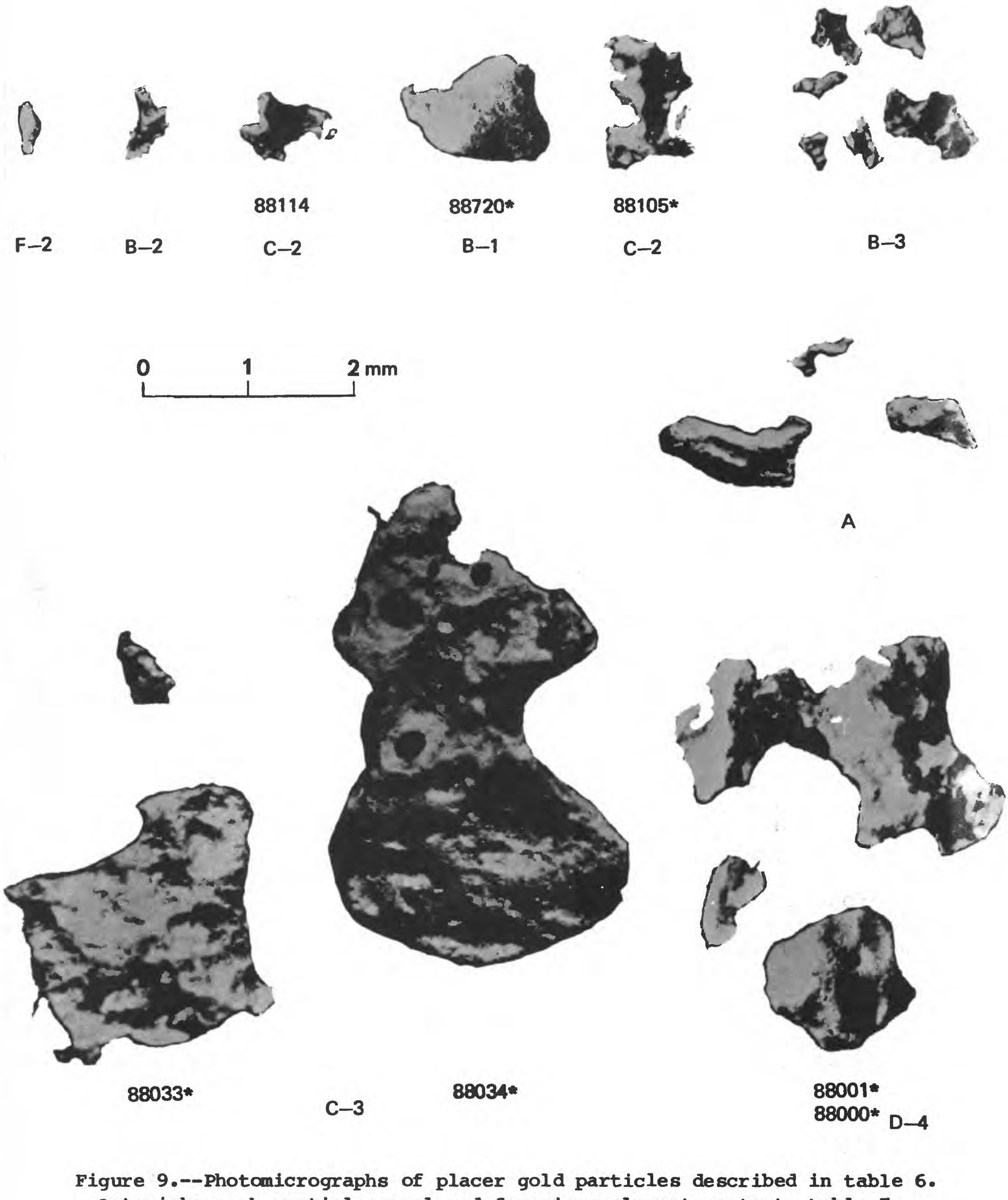

Figure 9.--Photomicrographs of placer gold particles described in table 6. Asterisks mark particles analyzed for minor element content, table 7. Letter and number indicates wadi and trench from which particle was collected. Photos by J. J. Matzko, USGS.

cally rough (fig. 10); this roughness is probably related to the original gold precipitation process rather than to weathering.

The wide variety of shapes of the gold particles must reflect a wide variety of shapes of primary gold in the quartz veins. Most of the gold has not moved mechanically more than a few hundred meters from its outcrop source; therefore, mechanical transport cannot be a factor in producing rounded particles, and the round shape must be original. Although small particles and films of gold in selected vein quartz from the Jabal Mokhyat area are readily visible under hand lens, these very small particles and flake gold were not seen in the placer. Particles less than 0.1 mm long are sparse in the placer, and particles less than 0.01 mm long are apparently absent.

Recoverable free gold

During panning we were surprised at the paucity of visible gold in the panned concentrate, particularly after considering the extensive work by the ancient placer miners. This was simply an unexpected indication of a very low grade placer deposit. We were further impressed by the lack of very fine grained gold in the panned concentrate. A single particle, or less commonly particles, of gold was observed during panning in 53 of the 728 panned concentrates, or about 1 pan out of 14 (7.5 percent). From the distribution of analytically determined gold and silver contents (fig. 8), we conclude that most recoverable free gold has an analyzed content greater than about 1 mg per m^3 (10 µg/sample). This means that most single particles of gold weigh 10 µg or more, since most panned concentrates that contain visible gold contain only a single particle. Using a gold content of 10 µg as a cutoff for recoverable free gold, 65 panned concentrates (9 percent) of the 728 samples analyzed contained recoverable placer gold. Only these 65 gold analyses were used to evaluate the placer.

Fourteen of the 53 panned concentrates in which gold was observed in the field panning contained less than 10 µg of analytical gold. Perhaps a few flat particles of gold observed in the pan actually weighed less than 10 µg, although some recording error cannot be excluded. It must be concluded that very fine grained gold, that is, flake and flower sizes of gold, is disproportionately sparse as compared to coarse gold in the Jabal Mokyat placer.

Analysis of gold particles

Analyses of single particles of gold from the Jabal Mokhyat area show silver and copper contents that suggest a hypothermal origin for the gold (Antweiler and Campbell,

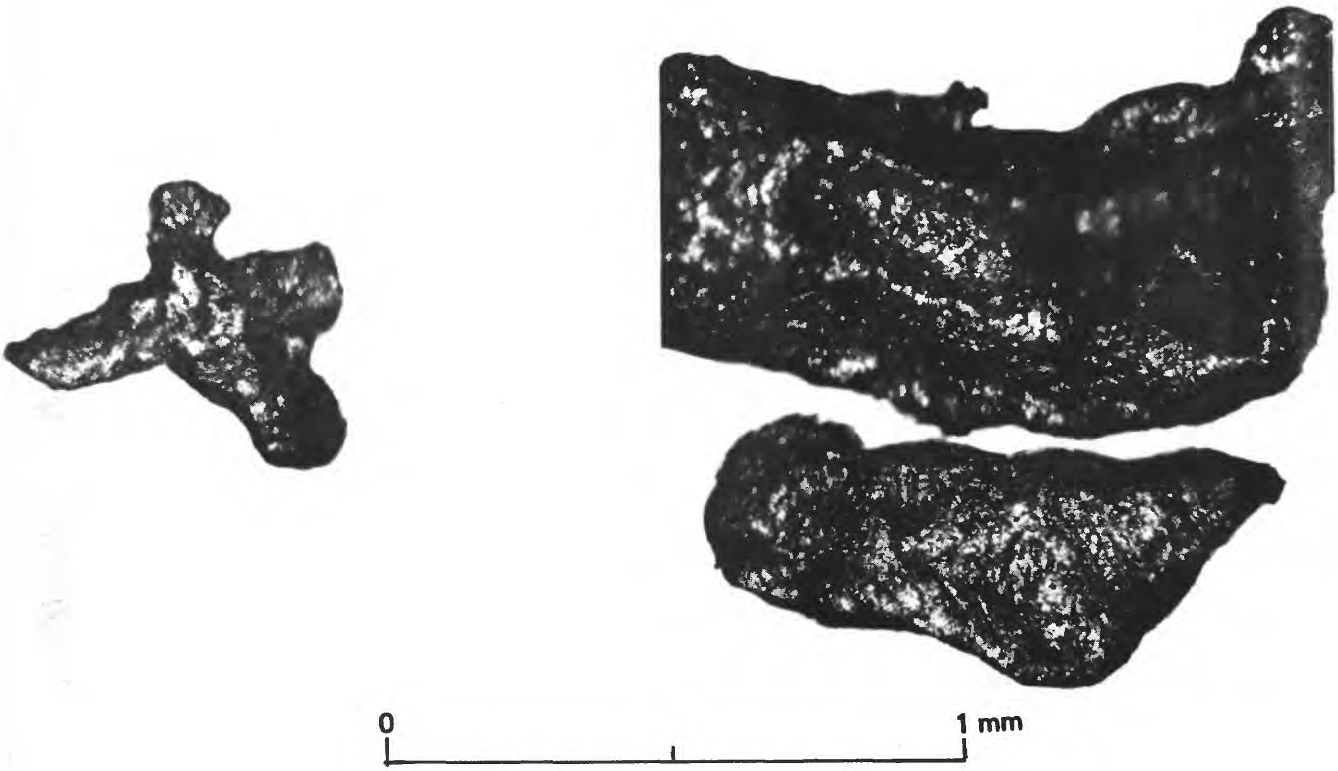

Figure 10.--Photomicrographs of placer gold particles showing microscopically rough surfaces. Particles from wadi A; the two larger particles are shown in figure 9, labeled A. Photo by J. J. Matzko, USGS.

1977). Six single particles were analyzed (table 7) by semi-quantitative emission spectrography (Mosier, 1975). The particles are described in table 6, and their photographs are shown on figure 9. All the analyzed particles were collected in the alluvium of Wadis B, C, and D and originated from a common bedrock source area, about 1 km long, at the heads of these wadis on the southwestern flank of Jabal Mokhyat. None of the particles were transported more than 500 m, and some moved less than 100 m. They range in shape from extremely angular to well rounded and in weight from 3 to 66 mg.

The average fineness of five particles is 916 (table 7), which is lower than the analytical fineness (figs. 7 and 8), possibly owing to the analytical differences in measuring large and small contents of silver. Sample number 88720 has a fineness of 790 and a minor-element content very different from the other five; it is considered nonrepresentative of Jabal Mokhyat gold and is not used in the averages.

The average Au/Ag ratio of five particles is 11.5, and the average Au/Cu ratio is 1,170; both correspond closely to hypothermal gold in the classification of Antweiler and Campbell (1977). Other minor elements such as arsenic, bismuth, nickel and lead, which are characteristic of gold from hypothermal quartz veins, were not detected in the analyses; apparently concentrations of these characteristic minor elements in the ore solutions were very low, which also is suggested by the sparsity of sulfides in the quartz veins. The presence of high silver and low copper contents and the minor elements lead and antimony in particle number 88720 is characteristic of lower mesothermal or epithermal gold.

Supergene processes apparently have not affected the gold. The composition of the gold particles is nearly constant despite variations in size, shape, and weight. Rinds formed by either supergene leaching or growth should have a much different composition from that of the particle cores (Antweiler and Campbell, 1977), and the small, large-surface-area particles should differ compositionally from large particles. No such analytical trends are noted (table 7).

Absence of very fine grained gold

The sparsity of gold particles less than 0.1 mm long and the apparent absence of particles less than 0.01 mm long in the placer indicate that the very fine grained gold, seen in abundance in the vein quartz, was removed by some natural process.

Chemical processes such as thiosulfate solution (Lakin and others, 1974, p. 28, 73), operative during the weathering and release of gold from vein quartz or during weathering of gold-bearing gravel in place, might be expected in a semiarid

Table 7.—*Semiquantitative spectrographic analyses of single particles of placer gold from Jabal Mokhyat area*

[Gold particles analyzed are shown on figure 9 and described in table 6. Results are in parts per million. -, indicates not detected at limit of detectability. Limit of detectability shown in parentheses at top of column. The following elements were looked for but not found; lower limit of detectability shown in parentheses in ppm: As(200), B(10), Ba(20), Bi(10), Cd(20), Co(5), Ga, Ge, In, La(20), Nb(20), Ni(5), Pd, Pt, Sc(5), Sn(10), Sr(100), Ta, Te, V(10), W(50), Y(10), Zn(200), and Zr(10). Analyst: E. L. Mosier]

Sample number	Weight (mg)	Fe (500)	Mg (200)	Ca (500)	Ti (20)	Ag (0.5)	Be (1)	Cr (10)	Cu (5)	Mo (5)	Pb (10)	Sb (100)	Si	Hg	Fineness	Au/Ag	Au/Cu
88001	16.00	90	19	70	-	90,000	-	-	940	-	-	-	200	3,000	910	10.1	968
88034	66.05	100	30	100	-	70,000	-	10	700	-	-	-	500	5,000	930	13.3	1,330
88720	6.05	160	70	50	5	210,000	-	-	100	2	150	30	500	5,000	790	3.8	7,900
88105	3.22	210	60	60	10	60,000	3	-	1,000	2	-	-	600	4,000	940	15.7	940
88033	32.00	50	10	15	-	90,000	-	-	920	-	-	-	150	3,000	910	10.1	989
88000	12.76	11	8	60	-	110,000	-	-	550	-	-	-	60	2,200	890	8.1	1,620
													Average[1/]		916	11.5	1,170

1/ Averages exclude sample 88720

or arid climate. However, at Jabal Mokhyat such solution can be excluded, because analysis of the gold particles indicates that the placer gold is characteristic of unmodified hydrothermal gold. Complete differential solution of very fine grained particles relative to coarser grained particles can be discounted, because the analyses do not indicate any gold enrichment in the weathering rinds; gold fineness in table 7 actually increases with increased particle size in all but one particle. If weathering rinds existed, the analyses of small particles would show a preferential enrichment of gold over silver.

Mechanical eolian removal of very fine grained gold particles during weathering at the quartz-vein outcrop or in the eluvium below the outcrop is not likely, because gold particles are rarely exposed at the surface. It is most likely that differential hydraulic action has removed the very fine grained particles. The high, turbulent flow of flash flood water that has deposited all the placer alluvium may have differentially removed nearly all the smaller particles of gold. Thus, under the long-term arid climatic conditions of Arabia, all the very fine gold particles were removed from the placer area and thoroughly dispersed and diluted in the downstream alluvial system.

Wadi gradients and placer gold

Most of the placer gold is in wadi reaches with gradients from 9 to 15 m/km (fig. 11); the richest concentration of gold is found at a gradient of about 14 m/km (fig. 12). The average gold content of samples from four trenches on Wadi A suggests a possibly characteristic curve to the concentration of gold as a function of gradient. Gold concentrations along this curve (fig. 12) peak at a gradient of about 12 m/km and fall sharply to zero downstream. The placer gold at Jabal Mokhyat occurs along gradients much steeper than the 6 m/km at which most large-scale mechanized gold placering is done elsewhere in the world, and the potential for large-volume placer mining at Jabal Mokhyat is slight indeed.

Most of the ancient placering at Jabal Mokhyat was done at wadi gradients between 10 and 30 m/km (figs. 11 and 12), though in places it was done at gradients well over 50 m/km, where alluvial and eluvial mining merge. All samples containing recoverable gold are from trenches located on wadi reaches with gradients between 8 and 30 m/km (fig. 12). Samples from wadi reaches with gradients less than 8 m/km do not contain gold at the recoverable level of 0.1 mg gold per m^3. Fine-grained particulate gold is absent in the Jabal Mokhyat area; the coarse gold found along the steeper gradients of 9 to 15 m/km is not succeeded downstream by the fine-grained gold normally expected at lower gradients of

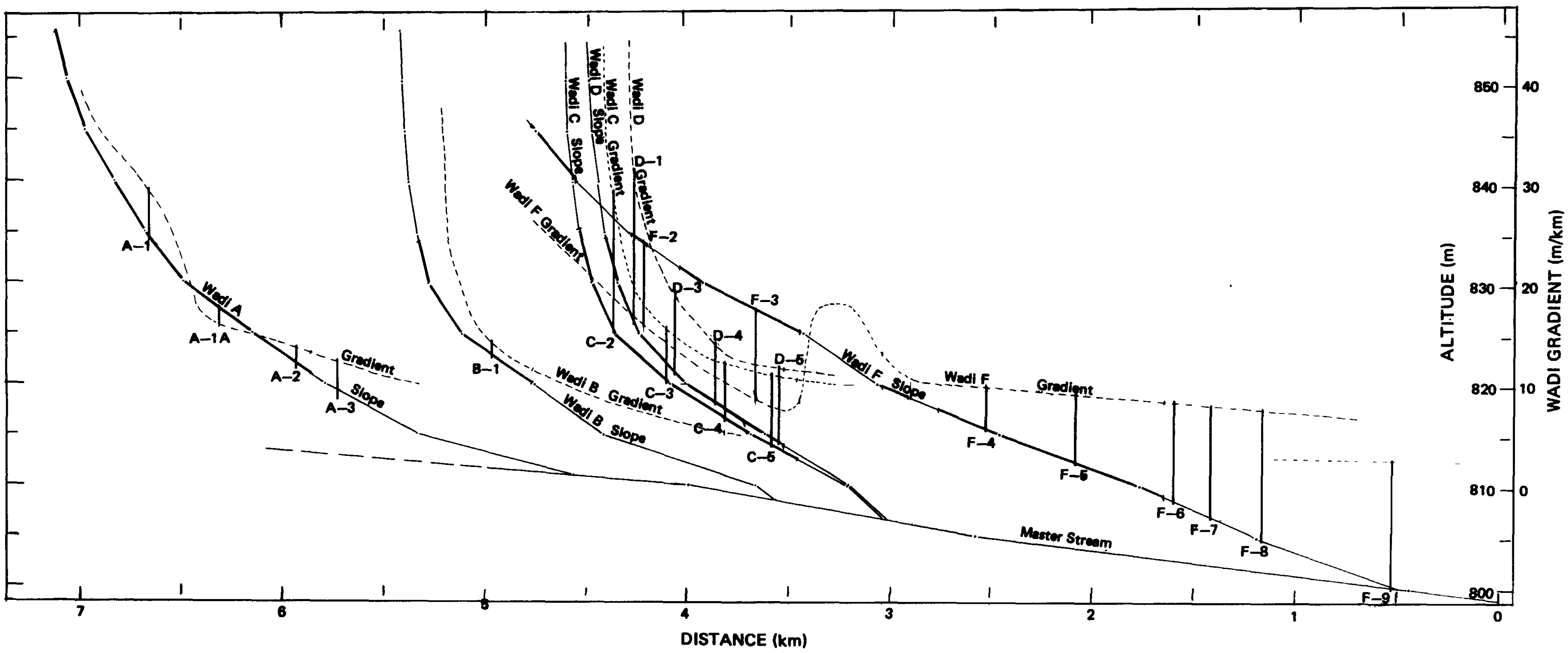

Figure 11.--Channel slopes and gradients of wadis sampled for placer gold. Vertical tielines locate sample trenches and connect the respective gradient and slope curves. Double line on channel-slope curves shows reaches of wadi that were placered by ancient miners. Most ancient placering was done on slopes between 10 and 30 m/km.

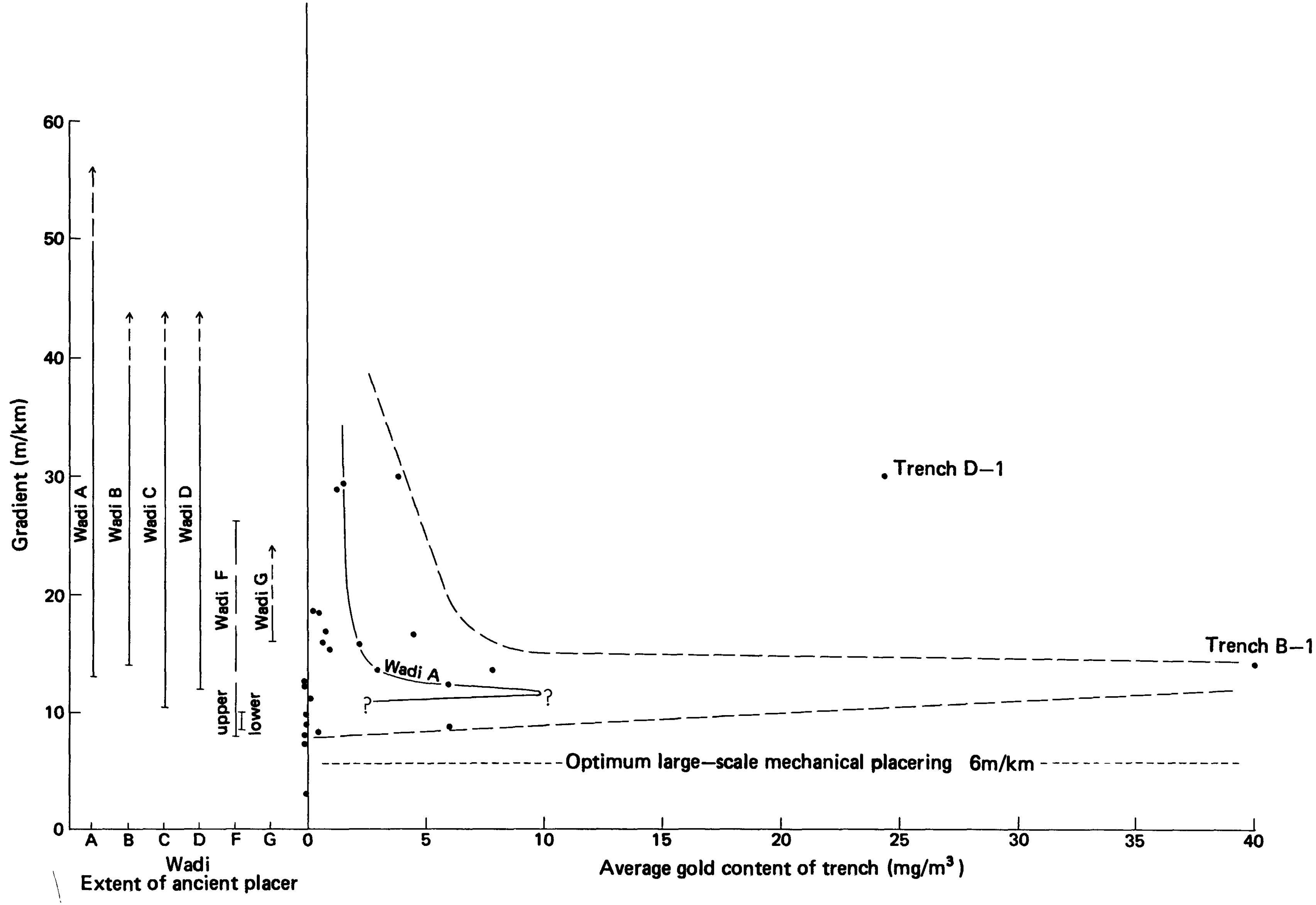

Figure 12.--Average gold contents of trenches relative to wadi gradients and position of ancient placers relative to wadi gradients. Optimum placers at Jabal Mokhyat are at gradients between 9 and 15 m/km (to left between wide-dashed lines). The curve for Wadi A (solid line) is probably a characteristic shape for gold distribution relative to gradient.

about 6 m/km. Because fine-grained gold does occur in the quartz veins, we conclude that it has been hydraulically removed from the placers.

Distribution of placer gold in alluvial units

Gold is generally well dispersed in all the alluvial units (fig. 13) and is not significantly concentrated at either the bedrock contact or on internal contacts between consolidated and less consolidated units ("false bedrock"). Table 8 summarizes the distribution of gold in the various units for each trench, and table 9 shows the distribution of the 10 richest samples. Our sampling procedures were not detailed enough to allow precise evaluation of the gold distribution (fig. 13), and perhaps the red calichified gravel unit (Prcg) contains a slightly higher concentration of gold than other units. One might expect gold to be somewhat concentrated along contacts, particularly the bedrock-alluvium contact and the unconsolidated alluvium (Hgs)-consolidated alluvium contact (Prcg), but none of the more than 200 samples specifically collected at contacts contained gold. These samples were not used in the placer evaluation.

The generally even dispersal of gold throughout the alluvium suggests that alluvial deposition took place rapidly during brief floods; the marked immaturity of all the alluvium supports this conclusion. As the climate was arid, the area lacked perennial streams that would have concentrated gold more effectively. Gold was not transported during the deposition of the loessic silt.

The ancient placer tailings in most places contain a disproportionately large amount of gold (pl. 2), indicating that the ancient miners worked the highest grade alluvium and that their recovery was low. The trenches clearly demonstrate that the ancient miners went to great effort to mine the calichified alluvium. They sank shafts through calichified gravel to bedrock, mined along the bedrock contact, and left the bulk of the overlying calichified gravel in place (figs. 17 and 18). Apparently the ancient miners did find some concentration of gold at the base of the alluvium, but none was revealed by our sampling.

We had no difficulty disaggregating the calichified gravel and recovering its gold in our wet-panning operation; the inferred poor recovery of gold by the ancient miners strongly suggests that they did not use water in their primary concentration. They probably sifted the alluvium by hand, perhaps with reed sieves, and panned only the fine fraction; however, we have not found any direct evidence for this. Because the calichified gravel is very tough when dry, it is likely that much of this gravel could not be broken

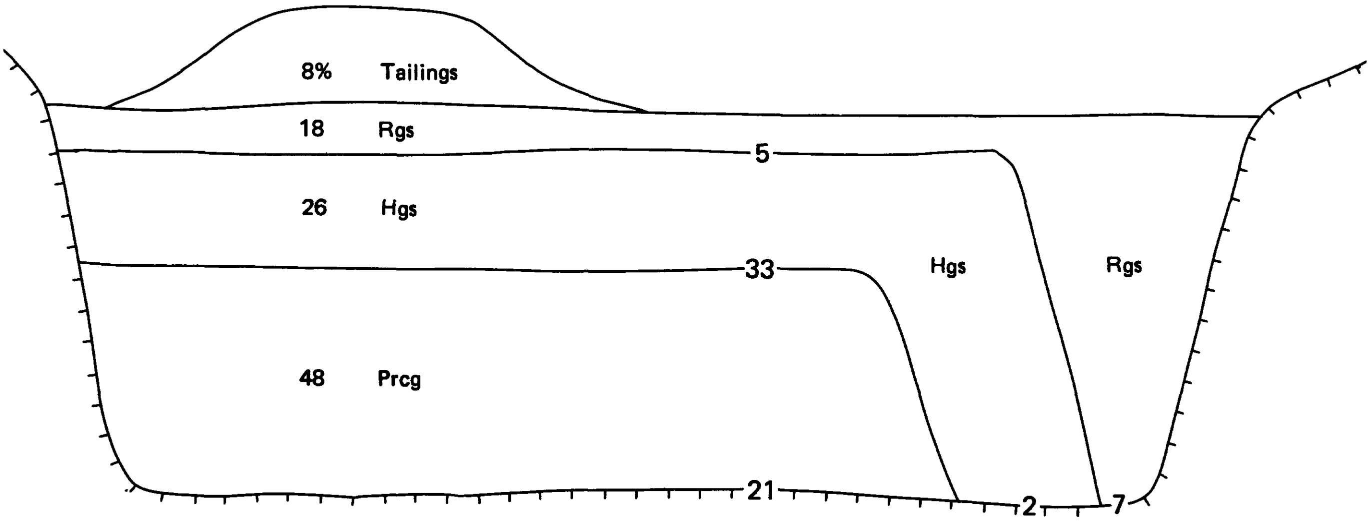

Figure 13.--Distribution of placer gold in alluvial units and at contacts (symbols as in pl. 2). Gold is well dispersed in all units so that the total amount of gold in any unit is approximately proportional to the volume of that unit. Percentages on left total 100 percent and represent all the gold used to evaluate the placer; the gold from any given interval (50 cm of vertical section per sample) was assigned to the specific alluvial unit sampled. However, many sample intervals included parts of two units, and the gold of the sample was assigned to either unit or proportionally divided between units. Percentages on the right total to 68 percent and represent gold from those sample intervals taken across internal contacts (50-cm vertical interval) or across the bedrock contact (25-cm interval). The percentage of gold at any contact is therefore inexact, and it is not known that the gold was actually on the contact.

Table 8.--*Distribution of gold in samples from the various alluvial units for each trench*

[Unit letter symbols refer to those used on trench section, plate 2]

Trench	Number of samples	Number of samples containing recoverable gold	Distribution
A-1	54	5	All gold in Prcg, mostly at or near bedrock contact
A-1a	30	6	80 percent of gold is in Prcg, bedrock contact not exposed; 20 percent in Rsg-Rs(g)
A-2	45	5	All gold-bearing samples in Prcg; 65 percent across Rgs-Prcg contact
A-3	25	1	Across Hgs-Prcg contact
B-1	40	16	Gold well dispersed in all units (Prcg, Hg, Rg, Rs); 45 percent of gold is in samples including bedrock contact with Prcg, Hg, Rg; 63 percent of gold is in samples containing Prcg; 62 percent of gold is in samples including an internal contact
C-1	38	3	In several units
C-2	18	3	Mostly in ancient placer tailings
C-3	54	1	Across Rgs-Prcg contact
C-4	13	0	Alluvium mostly worked by ancients
C-5	32	1	At surface in lag pavement
D-1	27	4	In Prcg only; no gold across Prcg-bedrock contact
D-2	8	1	In Prcg
D-3	9	1	In Rgs, possibly on bedrock
D-4	22	5	Gold well dispersed in Prcg, Hg, Rgs; all samples include bedrock contact; 22 percent of gold is in sample of ancient tailings
D-5	6	0	
F-2	34	1	Across Hgs-bedrock contact
F-3	49	5	Gold well dispersed in Rgs, Hgs, Pwcg; 5 percent of gold is in sample across Pwcg-bedrock contact
F-5	4	0	
F-6	40	2	In Hgs and Prcg, possibly at their contact
F-7	25	0	
F-8	76	0	
F-9	4	0	
G-0	9	0	
G-1	66	5	63 percent of gold is in Prcg, 37 percent is in samples across Hgs-Prcg contact

Table 9.--*Distribution and gold content of the 10 highest grade samples from the Jabal Mokhyat area*

[Letter symbol refers to those used on trench section, plate 2]

Sample number	Trench number	Alluvial unit	Weight Au in sample (mg)	Value of sample (cents) 1/	Percentage of total gold evaluated 2/	Grade (mg/m) 3/	Value (dollars per meter)
88720 4/	B-1	Hg-Prcg contact	6.05	9.75	19.	605	9.75
88105 4/	C-2	(?tailings?)	3.22	5.20	10.	322	5.20
88215	B-1		2.06	3.30	6.4	206	3.30
88197	B-1	Prcg-bedrock contact	1.84	2.95	5.6	184	2.95
88204	B-1		1.80	2.90	5.6	180	2.90
88462	A-3	Hgs-Prcg contact	1.48	2.40	4.6	148	2.40
88330	F-3		1.45	2.35	4.5	145	2.35
88199	B-1	Hg-Prcg contact	1.32	2.15	4.1	132	2.15
88324	F-3		1.18	1.90	3.7	118	1.90
88114 4/	C-2	(?tailings?)	1.14	1.85	3.6	114	1.85
Total			21.54	34.75	67.3		

1/ Calculations based on gold value of $500 per troy ounce or 1 mg = 1.613 cents
2/ Total gold used to evaluate placer was 31.985 mg from 728 samples
3/ Milligrams gold in 0.01 m^3 sample times 100 = mg per m^3
4/ Sample known to contain only one particle of gold; most other samples probably also contain only a single particle

down by the ancient miners. Some calichified gravel in the tailings has since weathered and disaggregated, releasing its few gold particles.

Summary evaluation

The economic potential of the Jabal Mokhyat placer area is exceedingly low (table 10). The overall average gold content is about 4.4 mg gold per m^3 (7.1 cents per m^3) if all 728 samples from the 25 trenches are included. (Values are given at U.S. $500 per troy ounce.) This calculation does not allow for a "swell factor" (Peele, 1950, p. 10-537). Most alluvium expands about 1.33 times when it is dug or sampled; hence, all the gold contents in this report must be multiplied by a factor of 1.33 to give the content of gold in the undisturbed alluvium. Volumetric calculations of the gold-bearing alluvium have not been made because the content of gold in the alluvium is so small. Volume can be estimated from the cross sections of plate 2 and the map of plate 1. The gold content per sample (in micrograms per 0.01 m^3 sample, as recorded on plate 2) must be divided by 10 and multiplied by 1.33 (total factor, 0.133) to give the gold content in the alluvium in place in mg/m^3.

Trench B-1 has the highest average gold content, 40 mg per m^3 for 40 samples. Trench C-2 has the second highest average content, 24 mg per m^3 for 18 samples. All other trenches averaged gold contents from 0 to 8 mg per m^3. Trenches B-1 and C-2 represent very small volumes of alluvium, as they are located in the headwater parts of their respective small wadis, B and C. For example, Trench B-1 contains an estimated 1.5 m thickness of alluvium across a width of 60 m, so that each meter of wadi length contains about 90 m^3 of alluvium containing about 3.6 gm of gold ($60 per meter of wadi length).

Most of the gold in the deposit is in a few particles that weigh more than 1.0 mg and is contained in only a few samples. About 67 percent of the total gold was contained in 10 samples (table 9) that represent only 1.4 percent of the 728 samples used to evaluate the placer (table 10). Each of these 10 samples contained more than 1.0 mg gold, and most had only a single particle of gold; in three of the samples the gold is known to occur as a single particle, and in the other seven most of the gold was probably in one or perhaps two particles. In the 53 panned concentrates in which gold was seen, the gold occurred most commonly as single particles, less frequently as two particles, and rarely as three or more particles.

The highest gold content in any one sample was contained in a single particle of gold weighing 6.05 mg and representing 19 percent of the total value of gold evaluated in the

Table 10.--*Averaged gold content for each of 24 trenches and pit lines in the Jabal Mokhyat area*

Trench 1/	Total weight of gold 2/ (μg)	Number of samples	Average gold per sample (μg)	Average gold per cubic meter 3/ (mg/m)	Average value 4/ (cents/m)
A-1	731	54	13.5	1.35	2.20
A-1a	633	30	21.1	2.11	3.40
A-2	1,312	45	29.2	2.92	4.70
A-3	1,480	25	59.2	5.92	9.55
B-1	16,050	40	401.0	40.10	64.70
C-1	451	38	11.9	1.19	1.90
C-2	4,377	18	243.0	24.30	39.20
C-3	490	54	9.1	.91	1.45
C-4	---	13	---	---	---
C-5	50	32	1.6	.16	0.25
D-1	1,035	27	38.3	3.83	6.20
D-2	60	8	7.5	.75	1.20
D-3	26	9	2.9	.29	.45
D-4	1,714	22	77.9	7.79	12.55
D-5	---	6	---	---	---
F-2	220	34	6.5	.65	1.05
F-3	2,923	49	59.7	5.97	9.65
F-5	---	4	---	---	---
F-6	154	40	3.9	.39	0.65
F-7	---	25	---	---	---
F-8	---	76	---	---	---
F-9	---	4	---	---	---
G-0	---	9	---	---	---
G-1	279	66	4.2	.42	.70
Total all trenches	31,985	728	43.94	4.39	7.10

1/ Trench F-4, a line of pits in eolian sand was not sampled

2/ Includes all analytical gold greater than 10 μg in each sample plus gold particles actually weighed

3/ Average gold per cubic meter (mg/m^3) = $\frac{\text{average gold } (\mu g)}{0.01\ m^3 \text{ sample}} \times \frac{1\ mg}{1000\ \mu g}$;
no correction for expansion of alluvium during sampling (results x 1.33)

4/ U.S. cents calculated at $500 per troy ounce or 1 mg = 1.613 cents sampling program (table 9). Still larger particles by a factor of 10 are known to exist. One eluvial sample, not used in the evaluation, contained a particle weighing 66.05 mg (table 6), worth twice the value of gold used to evaluate the placer. This sample was taken above the southern end of trench C-3.

THE ANCIENT PLACER

Gold production

Gold production from the ancient placer may be estimated optimistically at 50 kg gold (worth about U.S. $800,000 at $500 per troy ounce). This estimate is exceedingly uncertain and is based on an area of 1.2 km^2 of ancient diggings with an average depth of about 1 m and an average gold content of 40 mg per m^3. The area was estimated by point counting the placered areas on an aerial photograph enlarged to 1:20,000 scale. The ancient placer diggings cover a rectangular area of 30 km^2, of which 1.2 km^2, or 4 percent, is estimated to have been placered.

The estimated gold content is our determined value for trench B-1 and is about 10 times greater than the average of 4.4 mg per m^3 for the entire sampled area. Trench B-1 is located in a wadi headwater area, as are most of the ancient placers on other wadis. Wadi B was not worked as extensively as Wadis A, C, and D, and its gold content may have been lower. However, our data suggest that placer sites outside the area of Wadis A through D were not as rich. About 35 percent of the gold from our trench B-1 was in samples of ancient placer tailings, and the ancient miners presumably recovered more than we did. Hence, after considering these various factors, we arrived at 40 mg/m^3 as a reasonable, though optimistic, value for the average gold content recovered by the ancients.

Gold recovery by ancient miners may have been greater if they found, followed, and mined local remnant pay streaks in the basal saprolitic gravel. Some basal gravel may have been deposited during a more humid climate and erosion cycle than the present, and, during such a cycle, gold from even a sparse gold-bearing source might have been concentrated in narrow pay streaks along the bedrock-gravel contact. The shaft-mining technique used by the ancient miners does suggest that they sought a specific, restricted concentration of coarse placer gold. Most such pay streaks probably would be slightly deeper than our maximum depth of trenching (2.5 m); in any case, we did not find any pay streaks. Even if the ancient miners did mine some basal pay streaks, they would have been discontinuous and of small volume; their gold contents would not greatly change our conclusion that the potential for modern placer mining at Jabal Mokhyat is exceedingly small.

The ancient placer mining was done about 2,620 ± 250 years B.P., or 645 ± 250 years B.C., according to a charcoal date (Meyer Rubin, USGS Carbon Lab sample number W-2947, January 9, 1974; field sample number 88034, trench C-3, pl. 2). We have no evidence for more than one period of mining. The charcoal was collected in situ from a fire site at the bottom of an ancient shaft, 1.25 m deep, cut in calichified Pleistocene alluvium. The shaft was filled with unsorted placer tailings near the bottom and with stratified washed tailings above; this clearly indicates that the charcoal represents the time of mining.

Gold mined at this time probably was moved to south Arabian centers where the Sabaean and Qataban Kingdoms thrived during the first millenium B.C. (Bowen, 1958, p. 43, 65; Van Beek, 1969, p. 367). It seems likely that the southern Arabian kingdoms probably controlled the area at least as far north as Jabal Mokhyat. The Jabal Mokhyat area is about 500 km north of the ancient cultural centers at Marib and Ma'in, but is 1,500 km south of northern Arabian cultural centers. It was probably cheaper and easier to move the gold south than to pay for passage and protection through the tribal areas in other directions from Jabal Mokhyat. Through direct trade with the southern Arabian Kingdoms, the Jabal Mokhyat gold probably eventually contributed to the wealth of the eastern Mediterranean region.

Ancient diggings

The surface of the ancient placer diggings forms a smooth and unevenly mounded microrelief (figs. 14 and 15) that is recognizable only when standing on the tailings themselves. The tailings piles are mostly less than 1 m high and spaced 2 to 6 m apart (fig. 16). The tops of the piles consist of a lag deposit of coarse cobbles concentrated through wind deflation and rainwash during the past 2,500 years. The cobbles are from the bottom gravel of the oldest gravel unit and are coated with a thin rind of relict calcite. Only a few chunks of the calichified gravel remain intact after 2,500 years of weathering; in contrast, chunks of cemented gravel are abundant in the debris piles from our trenches. The areas between the ancient gravel piles are filled with rain-washed sand and silt, but in places a fill of well-sorted coarse sand indicates that the ancient miners probably screened their placer alluvium during concentration.

Most of our trenches cut ancient diggings (pl. 2). Alluvium of unconsolidated Holocene deposits was simply excavated by the ancient miners. Where the tough, calichified gravel was more than about 1 m thick, the ancient miners commonly sank shafts through the consolidated gravel to the calichified, saprolitic bedrock 1.5 m or more below (figs. 17 and 18). The shafts were about 1 m in diameter and spaced about 4 m apart. On bedrock the miners dug small stopes and "dog holes" about 0.5 m deep in the cemented gravel between the shafts. This exceedingly difficult work was done in extremely cramped quarters in calichified gravel so tough that in places our backhoe had difficulty excavating it. We presume that, in order to justify such laborious digging, placer gold was found at the base of the gravel.

No copper or iron tools or other artifacts were found, nor were traces of oxidized metal seen in the ancient workings intersected by our trenches or in panned concentrates of the ancient tailings. Angular, elongated, sharp-pointed, naturally cleaved cobbles of siliceous greenstone are abundant on the pediment surfaces adjacent to the placers, but no man-worked edges or workworn points were noted.

We believe that stone implements, skin buckets, and perhaps reed sieves were used to mine and beneficiate the alluvium. The nature of the final gold concentration process is not known; perhaps wet panning was used. If only coarse gold were recovered, as suggested by the 1 to 5 mm size of the particles of gold found in the tailings, it is possible that the entire concentration process was dry. However, despite the apparent arid dryness, morning dew is common most of the year, and the ancient miner would have had to carefully sun-dry his fine alluvial fraction before winnowing.

A small amount of slag was found around the stone ruins of three small houses on the east valley side, 1.6 km northeast of Jabal Mokhyat peak (200 m east of the suq described below). It suggests that metallurgical experimentation was attempted on a very small scale by the ancient miners, perhaps in testing for gold in heavy concentrates. A composite sample of several pieces of this slag (table 1) contains 160 ppm gold, high iron and calcium, and only traces of other elements. This analysis more closely resembles that of a panned concentrate (table 1) than vein quartz or mineralized wall rock.

Ancient quartz mining

The Mokhyat ancient mine, located 550 m east of trench A-1A, was mined, though not necessarily at the same time as the placer mining. Many shallow pits and trenches, 1 to 2 m deep, and corresponding dumps indicate that although most digging was in weathered wall rock, some was on quartz pods and stringers (fig. 3). On the pediment 150 m below the mine a few stone anvils and hammer stones and fragments of circular grindstones (fig. 19), as well as the ruins of several

Figure 14.--Ancient placer tailings along Wadi B. Tailings piles, about 0.5 m high, form a hummocky surface of low relief, here easily seen shortly before sunset; aerial view looking west.

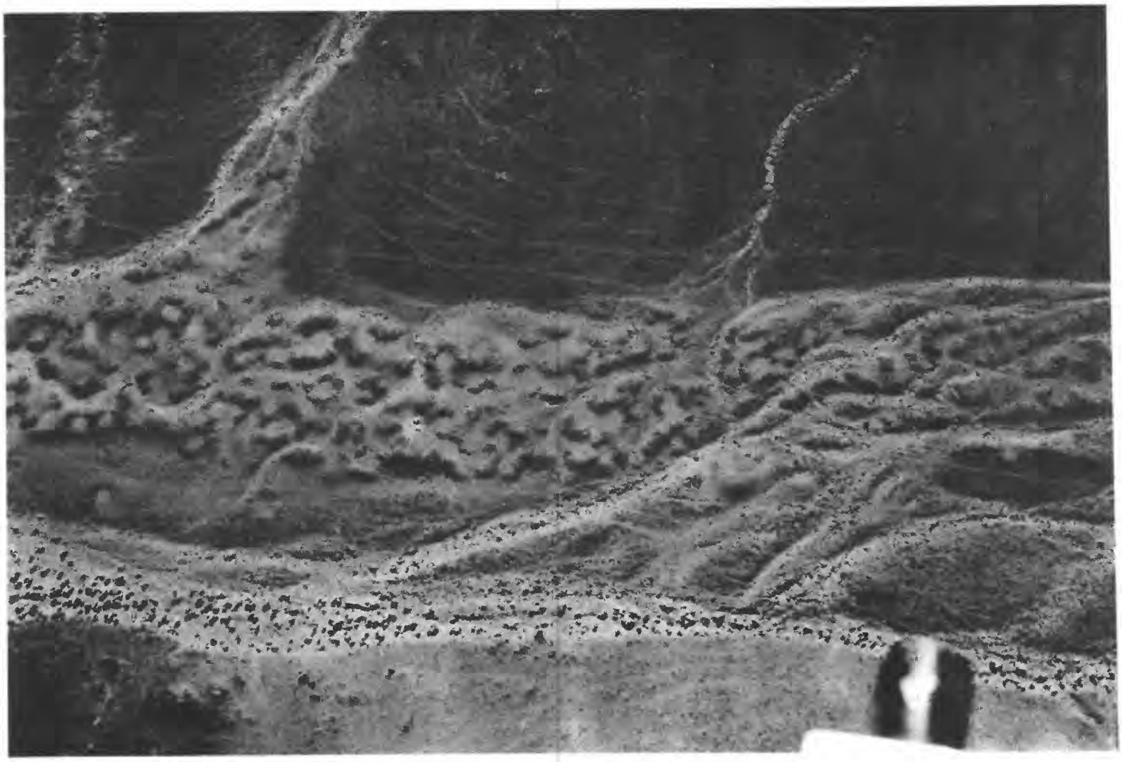

Figure 15.--Ancient placer tailings along Wadi A seen shortly before sunset. View looking west, several tens of meters upstream from Trench A-1.

Figure 16.--Tailings piles of the ancient placer at Jabal Mokhyat. Debris from modern trench C-2 is seen above the man's head.

Figure 17.--Ancient circular shaft, 1 m in diameter, sunk in tough, consolidated, calichified, and saprolitic gravel. The overlying unconsolidated alluvium, 0.5 m thick, is late Holocene sand and gravel and tailings. The shaft is filled with loose tailings that slumped into the modern trench A-2.

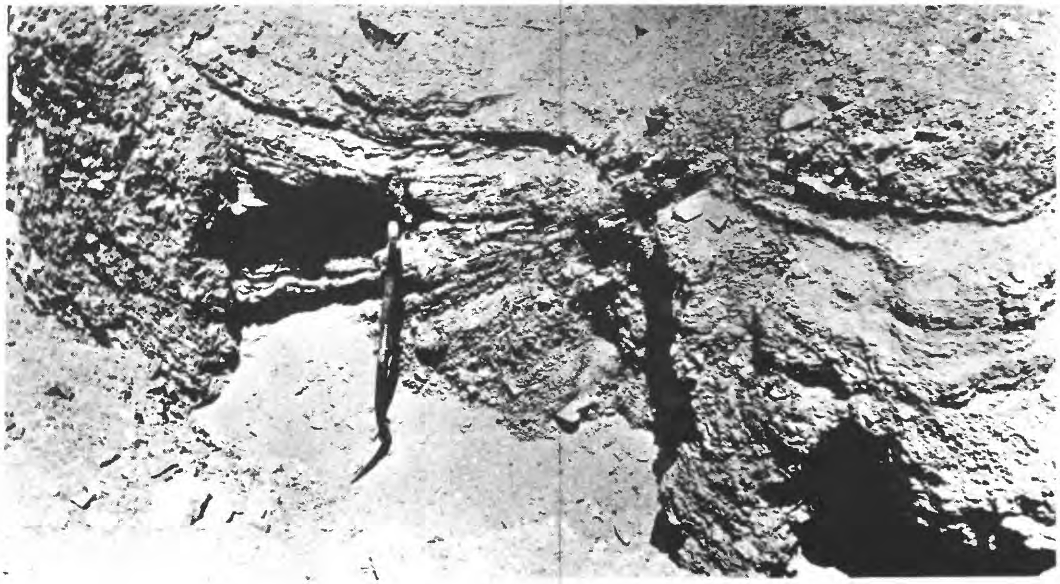

Figure 18.--Ancient shaft, 1.5 m diameter, sunk in consolidated, calichified, and saprolitic Pleistocene gravel and filled with stratified placer tailings. The shaft and gravel are overlain by more stratified tailings. Part of a second shaft is seen to the right. Trench C-3.

Figure 19.--Circular grindstones used by ancient miners to grind gold-quartz ore. Grindstones are made of red or white coarse-grained granite. These stones are at a mill site on Wadi Mahazul, 46 km south of Jabal Mokhyat, but are similar to the broken fragments at the Mokhyat ancient mill site.

stone wall foundations, indicate an ancient mill site at which hardrock quartz was processed for gold. Much of the disturbed surface among and immediately downslope from the quartz veins indicates that eluvial placer mining was done here as well as elsewhere in the Jabal Mokhyat area. Eluvial placering downslope from quartz veins was a prospecting method, but it obviously was used also to mine gold.

Small-scale eluvial mining was practiced at and immediately below hundreds of gold quartz-vein prospects worked by the ancients throughout the Najd Province. This is apparent upon examination of the ancient placer workings at Jabal Mokhyat or smaller ones in the Jabal Yafikh quadrangle, 50 km north-northeast of Jabal Mokhyat (Schmidt, 1981b). The eluvial workings rarely extend far below the quartz outcrop, probably because of the low gold contents in both the quartz and the eluvium. The ancient miners prospected by testing the eluvium at visibly favorable quartrz veins; only after favorable recovery of eluvial gold did hard-rock prospecting proceed, perhaps even at a much later time. From the large Najd Province of Arabia, much gold was probably recovered by such purposeful eluvial mining without a concerted effort to mine the quartz.

Gold-quartz veins were mined during several periods through the early Abbasid Period (750-950 A.D.) in the southern Najd Province. The late period is indicated by charcoal dated 950 ± 300 years B.P. (Meyer Rubin, USGS Carbon Lab, sample number W-2239, June 9, 1969; collected by T. H. Kiilsgaard) from the Chaim ancient mine (Gharb Hadad, No. 2 of Louis Gonzalez, written commun., 1970), 50 km north-northwest of Jabal Mokhyat (Worl, 1979). There is little evidence of mining in Arabia after the Haroun Al Rashid rule (784-809 A.D.) of the Abbasid Period, so the range for the carbon date is more likely 720 to 950 A.D.

Ancient copper mining

Copper was mined and locally smelted on a small scale in the Jabal Mokhyat region during the early Islamic period a-about 660 A.D. A small ancient copper mine, 32 km south-southeast of Jabal Mokhyat (lat 19°55.3' N., long 43°29.8' E.) in the Al Hassir 30-minute quadrangle, has two crude furnaces built into an adjacent south-facing slope. A nearby slag pile of about 10 tons contains several dozen earthen protectors for air tubes used to force air on the furnace fires (fig. 20). Coarse charcoal in some of the slag was dated 1,315 ± 250 years B.P. (Meyer Rubin, USGS Carbon Lab., sample number W-2946, January 9, 1974).

Living quarters

The impressive ruins of a small suq (market) consisting of 25 small shops lies on the desolate, broad divide, 1.5 km east-northeast of Jabal Mokhyat peak (pl. 1; fig. 21). Many well-worn trails can still be seen radiating from this abandoned market. One such winding trail leads 430 m east from the suq to the stone ruins of a small village built deep in the rugged bedrock hills probably for protection against the cold winter winds. These stone ruins are well camouflaged in the rocky surroundings and were found by following the ancient trail from the suq.

The stone ruins of many small house foundations lie scattered throughout the Jabal Mokhyat area (pl. 1). Some are isolated, single dwellings (fig. 22), but others consist of two or three dwellings suggestive of family units. Most are located against the bedrock hills in places protected from wind. Some alluvial mine shafts were probably used for temporary shelter against winter cold and wind; undoubtedly the charcoal found in these shafts is from warming and cooking fires.

The systematic distribution of the ancient placer mines, small village, scattered stone houses, and small neatly laid-out ancient cemetery 200 m west of the suq, and the persistent and uniform pattern of tailings all imply methodical mining by a small number of miners, at most less than 100, working for many years.

The dwellings suggest that the miners were accompanied by their families and, as the bedouin today, subsisted largely on the surrounding desert, gathering fuel, and bringing water from established wells. Today, wells exist within the granite inselbergs of Jabal ash Shawhatah al Hamrah, 10 km south of Jabal Mokhyat, and the largest group of perennial wells in the area lies on Wadi Mellah, 26 km to the south. The Wadi Mellah wells, dug in the active channel, are protected from most floods by a broad accumulation of dung and sand, 4 m high, that has been well compacted by man and animals over many centuries. The climate during the period of placer mining was extremely arid, and the availability of water and food alone must have limited the mining force. The placer stratigraphy clearly indicates that the eolian sand accumulated during and before the ancient placering, as it does today. Extreme desiccation came to Arabia before the ancient placering.

It has been argued that the placer mining was done by a large expeditionary force during a short period of time. If true, only a few of the expedition would have lived in stone houses; acquisition of sufficient food, water, and fuel would have posed serious problems; and the death rate, judging by

Figure 20.--Earthen protectors used in smelting copper ore at a small ancient copper mine, 32 km south-southeast of Jabal Mokhyat. The earthen tips protected the furnace end of wooden air-blast tubes. The air tube holes are about 2 cm in diameter. The fire end of the protectors is partly fused and covered with slag. In the left foreground is a fragment of slag, 8 cm long. Charcoal from slag dates about 660 A.D.±250 yr.

Figure 21.--Stone ruins of an ancient suq or market located 1.5 km east-northeast of Jabal Mokhyat peak. About 25 shop stalls can be seen.

Figure 22.--Stone ruins of a single dwelling built on a short beheaded segment of a wadi next to a cliff, 1.8 km northeast of Jabal Mokhyat and 0.45 km north-northeast of the suq. The old gravels of this wadi were thoroughly placered as indicated by the tailings piles seen behind the stone house.

the size of the cemetery, would have been high. Examination of many other ancient mining sites in the southern Najd Province has never suggested that any were large operations.

Earlier man

Dates on charcoal from fire sites suggest that many nomadic hunters roamed the southern Najd about 6,000 years B.P. (4,000 B.C.) during the period when the Al'Ubaid agrarian culture, 7,300-5,500 years B.P., was well developed on the Arabia Gulf coast of eastern Arabia (Bibby, 1969, p. 376; Masry, 1974, p. 23). This corresponds to the end of a pluvial period (9,000-6,000 yrs B.P.) dated in the Rub al Khali by H. A. McClure (1976).

In the Jabal Mokhyat area, five ancient campfire sites were found in the 1,500 meters of trenching. Each fire site was located near the top of the loessic silt unit, which in places has a humic upper part preserved that is indicative of more abundant vegetation than today. The high density of fire sites suggests a substantial human population during a more optimum climate. Charcoal from a fire site in trench F-8, pit no. 8 (pl. 1) beneath a broad pediment, has been dated at 5,830 $\pm$ 300 years B.P., or sometime between 4,300 and 3,700 B.C. (Meyer Rubin, USGS Carbon Lab sample number W-2949, January 9, 1974). The site consists of a hearth 25 cm in diameter, crudely lined with 12 baked and angular cobbles. It lies about 20 cm below the top of the loessic silt unit, and its contents consist of a mixture of charcoal and silt about 10 cm thick.

Charcoal from a fire site in a similar stratigraphic setting in the Nafud Hanjaran, 125 km northwest of Jabal Mokhyat, gives a similar date of 6,350 $\pm$ 350 years B.P. (Meyer Rubin, USGS Carbon Lab, number W-3282, December 3, 1975; Schmidt, 1980b).

Stone monuments

Ancient stone monuments and tumuli are abundant in the Jabal Mokhyat area and represent a more sophisticated and philosophical man than the nomadic hunter of about 4,000 years B.C. The monuments were disturbed, locally destroyed, and presumably nonrespected by the later ancient placer miner of about 650 B.C. These monument builders may have been nomadic correlatives of the Dilmun Culture (3,000 B.C. to 1,800 B.C.) of eastern Arabia (Bibby, 1969, p. 378). In fact, the stone monuments may be a rock-desert adaptation of the "Mound Builders" of Dilmun of about 2,600 B.C. (Bibby, 1969, p. 378). The stone monuments and tumuli are no more abundant at Jabal Mokhyat than elsewhere in the southern Najd and do not suggest a correlation with an earlier search for placer gold.

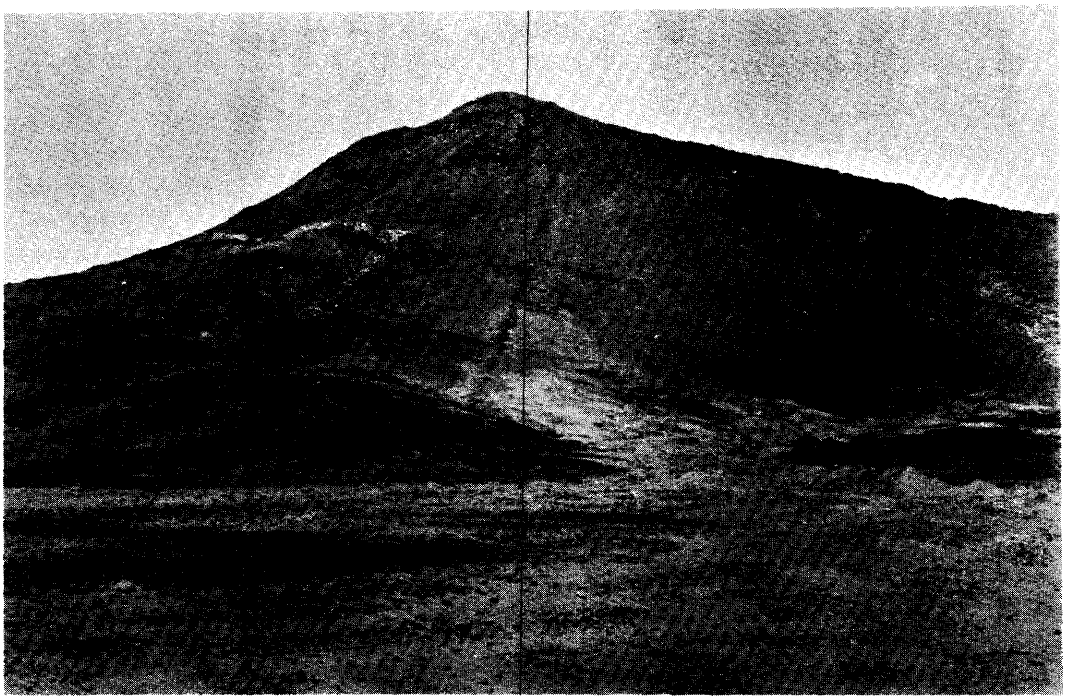

Figure 23.--Ruins of a stone fence leading from stone monuments and tumuli (out of view) on Jabal Mokhyat peak down to the pediment below. The ruins of a small stone mound lie to the left of the fence low on the slope. Ancient placer workings (light colored area, lower right) in the upper part of Wadi C intersect and displace some of the stone fence. Very little desert patina has formed on the rotated stones in the 2,600 years since the ancient placer mining. A subhorizontal quartz vein (white) is seen on the left flank of Jabal Mokhyat.

The stone monuments or tumuli are well constructed of a local stone on peaks and ridges, and some, as on Jabal Mokhyat peak, have stone fences leading from the peaks and ridges to the pediments below (pl. 1; fig. 23). In places, these fences are built in the style of a giant staircase, with 1 to 2 m rises and 2 to 3 m flats. Commonly the circular monuments on the peaks are 8 to 10 m in diameter, about 2 m high, and have an open core suggestive of a burial site. Lesser stone mounds and monuments commonly lie at the bases of the monumented peaks and ridges, especially where stone fences lead out on the pediments.

The exposed surfaces of the rocks of all monuments have a black desert patina that is nearly as dense as the patina on rocks on hill slopes and on cobbles on old pediment surfaces. The lower end of the stone fence on the southwestern side of Jabal Mokhyat (fig. 23) was disturbed by the ancient placer mining, and only a small amount of desert patina has formed on the rotated stones since they were moved. This suggests that most of the dark desert patina on the stone monuments formed before placer mining took place, probably before 3,000 years B.P. and after the end of the pluvial period (about 6,000 years B.P.); that is, the patina formed in a relatively short period of about 3,000 years or less, during an advancing stage of desiccation. If the stone monuments were built about 4,000 to 5,000 B.P., then the patina on them formed in an even shorter length of time. By 3,000 years B.P., most desert patina formation had stopped under conditions of extreme desiccation similar to today. This climatic change, inferred from the nonuniform development of desert patina with time, further supports the suggestion that the climate during the placer mining operation was similar to the climate today.

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