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GEOCHEMICAL ORIENTATION FOR MINERAL EXPLORATION IN THE HASHEMITE KINGDOM OF JORDAN

by

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ABSTRACT

This report is a supplement to previous accounts of geochemical exploration conducted in the Hashemite Kingdom of Jordan by the Natural Resources Authority of the Royal Government of Jordan and the U.S. Geological Survey. The field work on which this report is based was sponsored by the U.S. Agency for International Development, U.S. Department of State.

Procedures used in collecting various kinds of rocks, ores, slags, eluvial and alluvial sediments, heavy-mineral concentrates, and organic materials for use as geochemical sample media are summarized, as are the laboratory procedures followed for the analysis of these sample materials by semiquantitative spectrographic, atomic absorption, fluorometric, and X-ray diffraction methods. Geochemical evaluations of the possibilities for economic mineral deposits in certain areas are presented.

The results of these preliminary investigations open concepts for further use in geochemical exploration in the search for metallic mineral deposits in Jordan. Perhaps the most desirable new activity would be hydrogeochemical exploration for uranium and base metals, accompanied by interpretation of such remote-sensing data as results of airborne radiometric surveys and computer-enhanced LANDSAT imagery. For more conventional approaches to geochemical exploration, however, several fundamental problems regarding proper choice

of geochemical sample media for different geologic and geographic parts of the country must be solved before effective surveys can be made.

The present results also show that such common geochemical exploration techniques as the determination of the trace-element contents of soils, plant ash, and slags have direct application also toward the resolution of several archaeological problems in Jordan. These include the relation of trace-elements chemistry of local soils to the composition of botanic remains, the trace-elements composition of slags to the technological development of the extractive metallurgy of copper and iron in the region, and the use of charcoal from slags for the C-14 dating of periods of archaeometallurgical activity. Less directly, interpretations based on the distribution in time and space of the archaeometallurgical activities of the region might add to the knowledge of early climatic conditions and vegetative cover of the area.

INTRODUCTION

Purpose of report

This report is a supplement to earlier accounts of geochemical orientation surveys conducted for mineral exploration in the Hashemite Kingdom of Jordan by personnel of the U.S. Geological Survey (USGS) in cooperation with and at the invitation of the Natural Resources Authority (NRA), Royal Government of Jordan, and sponsored by the Agency for International Development (AID), U.S. Department of State, under PASA No. IC/JOR-181-6-76. Those earlier accounts (Overstreet, 1978a; Grimes, 1978; Seitz, 1978) reviewed field and laboratory methods already in use by NRA for geochemical exploration for mineral deposits, recommended new or modified procedures, and suggested that a continuing program of orientation surveys be initiated to determine techniques of geochemical exploration combined with remote-sensing techniques most suited to the arid conditions that prevail in Jordan. The work that led to those earlier recommendations included the collection of samples of various geologic materials for trace-elements analysis. However, in late 1977 and early 1978 when the samples were obtained, the planning requirements of NRA and AID would not admit the delay of recommendations until analyses were completed. Those analyses, made in the laboratories of NRA in Amman, Jordan, and of USGS in Denver, USA, were finished in October 1978. The purpose of the present report is to give the results of those analyses and to discuss how those results affect problems in geochemical exploration for mineral deposits in the Hashemite Kingdom of Jordan.

Acknowledgments

The friendly assistance of officials in NRA is gratefully acknowledged. In particular, the writers wish to express their appreciation for the support of Ahmad Dakhgan, Vice President, NRA, Yousef F. Nimry, Director General, NRA, Muhamad Abu Ajamieh, Director, Geological Survey and Bureau of Mines, and Yousef Hamarneh, Laboratory Chief. In the field, the help of Riad Gharaibeh, geochemist, and Abdullah Bahdari, geologist, greatly facilitated the review of the areas visited. In the laboratory at Amman, the interest and cooperation of Mohamad Sha'aban, Chief Chemist, Omar Sawwan, Mineral Dressing Chief, Zuheir Issa, Chemist, and Abdel Wahhab, Chemical Engineer, contributed to the completion of the analyses.

By a congruence of interests, some ancient food plant materials and soils were brought by David W. McCreery, scientist with an expedition to the Southeast Dead Sea Valley, Jordan, to the Laboratory Division of NRA in Amman for analysis. The results of these analyses are of use in a discussion here of biogeochemical exploration. Through the permission of the Expedition, those results are released in this report.

The support of members of USAID is acknowledged with appreciation.

PROCEDURES

Field

The procedures used in the field for collecting and processing the samples for geochemical exploration, as well as the localities sampled, were discussed in a previous report (Overstreet, 1978a, p. 9- 10). Where necessary for clarity in the text below, additional details on the sites and the preparation of samples are given. Such data are particularly needed in connection with samples collected by D. J. Grimes and D. W. McCreery, which samples were not described in prior reports.

Laboratory

Division of work

Spectrographic analyses of the geologic materials collected in Jordan were done in the Laboratory Division of NRA in Amman, Jordan, and in the laboratories of the USGS in Denver, USA. The procedures followed for these analyses were the same at the two laboratories (Grimes, 1978). Other types of analysis were made in the USGS.

Methods

Semiquantitative spectrographic analysis.--The method of semiquantitative spectrographic analysis of geologic materials used in geochemical exploration by the USGS (Grimes and Marranzino, 1968) was introduced in the Laboratory Division of NRA by Grimes (1978). In this procedure, 31 elements are determined over wide ranges in concentration (table 1). The precision and

Table 1. Ranges in concentration for 31 elements determined by semiquantitative spectrographic methods on geologic materials from the Hashemite Kingdom of Jordan.

Element	Concentration range			Element	Concentration range		
	From		To		From		To
	NRA	USGS	[1]		NRA	USGS	[1]
Elements reported in percent							
Fe	0.05	0.05	50	Mg	0.02	0.02	10
Ca	.05	.05	20	Ti	.002	.002	1
Elements reported in parts per million (ppm)							
Ag	2	0.5	5,000	Nb	20	20	2,000
As	500	200	10,000	Ni	10	5	5,000
Au	20	10	500	Pb	50	20	20,000
B	20	10	2,000	Sb	200	100	10,000
Ba	50	20	5,000	Sc	5	5	100
Be	2	2	1,000	Sn	50	10	1,000
Bi	20	10	1,000	Sr	200	100	5,000
Cd	100	20	500	Th	200	100	2,000
Co	5	5	2,000	V	10	10	10,000
Cr	10	50	5,000	W	50	50	10,000
Cu	2	5	20,000	Y	20	10	2,000
La	50	20	1,000	Zn	200	200	10,000
Mn	50	10	5,000	Zr	20	10	1,000
Mo	10	5	2,000				

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[1] Upper limits are the same for NRA and USGS.

accuracy of the method are satisfactory for use in geochemical exploration (Motooka and Grimes, 1976; Myers and others, 1976; Allcott and Lakin, 1974; 1978).

Several slight differences in the lower limit of determination exist between the analyses made in NRA and those done in USGS (table 1). The lower limits of determination for Cr and Cu in the analyses done in NRA were below the values reported in USGS. For 10 elements, Ca, Co, Fe, Mg, Nb, Sc, Ti, V, W, and Zn, the lower limits of determination were the same in both laboratories: Slightly greater lower limits of determination were used for the other elements in the laboratory at NRA. The same upper limits of determination were used in both laboratories.

In this procedure of semiquantitative spectrographic analysis, 10 milligrams (mg) of a finely ground sample (<100 mesh) is mixed with 20 mg of pelletizing graphite powder and packed into the crater of a preformed graphite electrode. This mixture is burned to completion at 13 amperes (direct current arc) for 2 minutes with an electrode gap of 4 mm. The emitted light is diffracted by a grating and recorded on a set of photographic plates. The plates are developed for 3 minutes at 20C, fixed for 6 minutes, washed in cold water, and air dried. The resultant spectrum is compared visually to spectra on standard plates utilizing a 15x microphotometer, and the concentration ranges for the 31 elements are reported in six steps that are the approximate geometric midpoints of ranges as follows:

Approximate geometric midpoint (reporting value)	Ranges of values represented by each midpoint
1	1.2 - 0.83
0.7	0.83 - 0.56
0.5	0.56 - 0.38
0.3	0.38 - 0.22
0.2	0.22 - 0.18
0.15	0.18 - 0.12
0.1	0.12 - 0.08

The spectrographic analyses were made by David J. Grimes and R. T. Hopkins, USGS, and by Mohamad Sha'aban and Zuheir Issa, NRA.

Atomic absorption analysis.--Gold, indium, thallium, and tellurium were determined by atomic absorption analyses as follows:

Element	Sensitivity ppm	Method	Analyst
Au	0.05	Ward and others (1969)	J. G. Viets
In	0.1	Hubert and Lakin (1973)	Do.
Tl	0.1	Do.	Do.
Te	0.2	Modified Hubert and Lakin (1973)	R. W. Leinz

In some samples the lower limit of determination of tellurium was raised owing to the small amount of sample available.

Flameless atomic absorption analysis.-- Mercury was determined for this investigation by Reinhard W. Leinz, USGS using the flameless atomic absorption method of analysis described by Vaughn and McCarthy (1964). This instrumental method is sensitive to a lower limit of determination of 0.02 ppm, and the reported values are within ±50 percent of the actual amount present.

Fluorometric analysis for selenium.--Selenium was determined by R. W. Leinz using a fluorometric procedure described by Crenshaw and Lakin (1974). The lower limit of determination achieved by this method is 0.02 ppm selenium. The values for selenium are reported in intervals of 0.1 ppm and are within ±15 percent of the actual abundance of selenium in the sample.

Instrumental and fluorometric analyses for uranium.--Equivalent uranium (eU) was measured by John C. Negri, USGS, using an instrumental counting procedure that gave a lower limit of determination of 20 ppm. This value is 10 times greater than the crustal abundance of uranium, reported to be 2 ppm (Finch and others, 1973, p. 459); later, uranium was analyzed by Delmont M. Hopkins using a fluorometric method capable of detecting uranium in concentrations as low as 0.2 ppm (Huffman and Riley, 1970).

Isotopic analysis.--Isotopic analysis was used to determine the C-14 ages of several samples of charcoal from slags at ancient smelters located to the east of Wadi al'Arabah. These analyses were made by Meyer Rubin in the USGS geochronology laboratory in Reston, USA.

X-ray diffraction analysis.--X-ray diffraction patterns were made of several minerals and slags by Theodore Botinelly, USGS, Denver, using standard procedures of determinative mineralogy. The X-ray machine used for these analyses is a standard Phillips X-ray diffraction set with a graphite monochromator to remove all fluorescence from the patterns of iron-rich samples such as the concentrates and slags from Jordan.

Purpose of the atomic absorption and fluorometric analyses

Several volatile elements, particularly mercury, thallium, tellurium, and selenium, are of interest in exploration for hydrothermal mineral deposits, because they tend to form halos around ore deposits (Hawkes and Webb, 1962, p. 72-73; Ewers and Keays, 1977; Watterson and others, 1977). These halos constitute a larger target for exploration than the ore deposit itself. However, these elements cannot be readily determined by use of the semiquantitative spectrographic method described above; therefore, splits of the samples were analyzed variously by flameless atomic absorption, atomic absorption, and a fluorometric method for possible mercury, thallium, tellurium, and selenium.

Analysis of samples for gold by the atomic absorption procedure, which is sensitive to 0.05 ppm gold, permits the detection of gold where the quantity of the element present is significantly less than the lower limit of determination of 20 ppm by the semiquantitative spectrographic procedure (table 1).

Routine scanning of samples for the instrumental determination of equivalent uranium is a common practice in geochemical exploration. The routine is designed to detect unusual enrichment of a sample in radioactive elements. But as was mentioned above, special fluorometric analyses must be made to determine uranium where it is present in concentrations close to its crustal abundance.

Results

The conventional listing of the results of analyses after a discussion of procedures used in the analyses is abandoned in this report in the interest of keeping the results close to the interpretations. This form of presentation was chosen because geographically and geologically diverse localities are represented by the samples, and because the localities were selected to represent different kinds of sampling problems that are met in orientation surveys for geochemical exploration.

Throughout the reporting of the results of the analyses, use is made of alphabetic conventions to show certain forms of technically censored data. By censored data is meant values that fall above or below the analytical determination limits of particular methods for particular elements. These limits are listed in table 1 for the results of the semiquantitative spectrographic methods. For results by the other analytical procedures, only the lower limits of determination have been given, because none of these elements was found to be present in amounts greater than the upper limits of determination. The alphabetic conventions followed below are:

N = Not detected at the lower limit of determination, or at value shown.

L = Detected, but below the lower limit of determination, or below value shown.

G = Greater than upper limit of determination, or greater than value shown.

INTERPRETATION OF RESULTS OF ANALYSES

The interpretations are made by geographic region sampled, presented in an order based on the geologic materials used for geochemical sample media in a succession from rocks to alluvium to organic materials. In general, the geographic order is from north to south (fig. 1).

Barite deposit located to the northwest of Mahattat el Jufur

A vein deposit of barite in limestone was discovered by the German Geologic Mission to Jordan (Bender, 1974) at a locality (3247'26"N.; 3748'33"E.) about 90 km northwest of Mahattat el Jufur (fig. 1), the town at the abandoned petroleum pipeline pumping station numbered H-4. The deposit is in the Wadi Muqat area about 5 km south of the border with Syria. Exploration of the barite deposit (fig. 2) was done by NRA, and the conclusion was reached that the deposit was too small to mine. During a trip to the locality in November 1977, five samples of vein and wallrock material were collected (Overstreet, 1978a, p. 28-29) for analysis so that the results could be compared with the distribution of minor elements in the Tertiary barite vein deposit in Precambrian

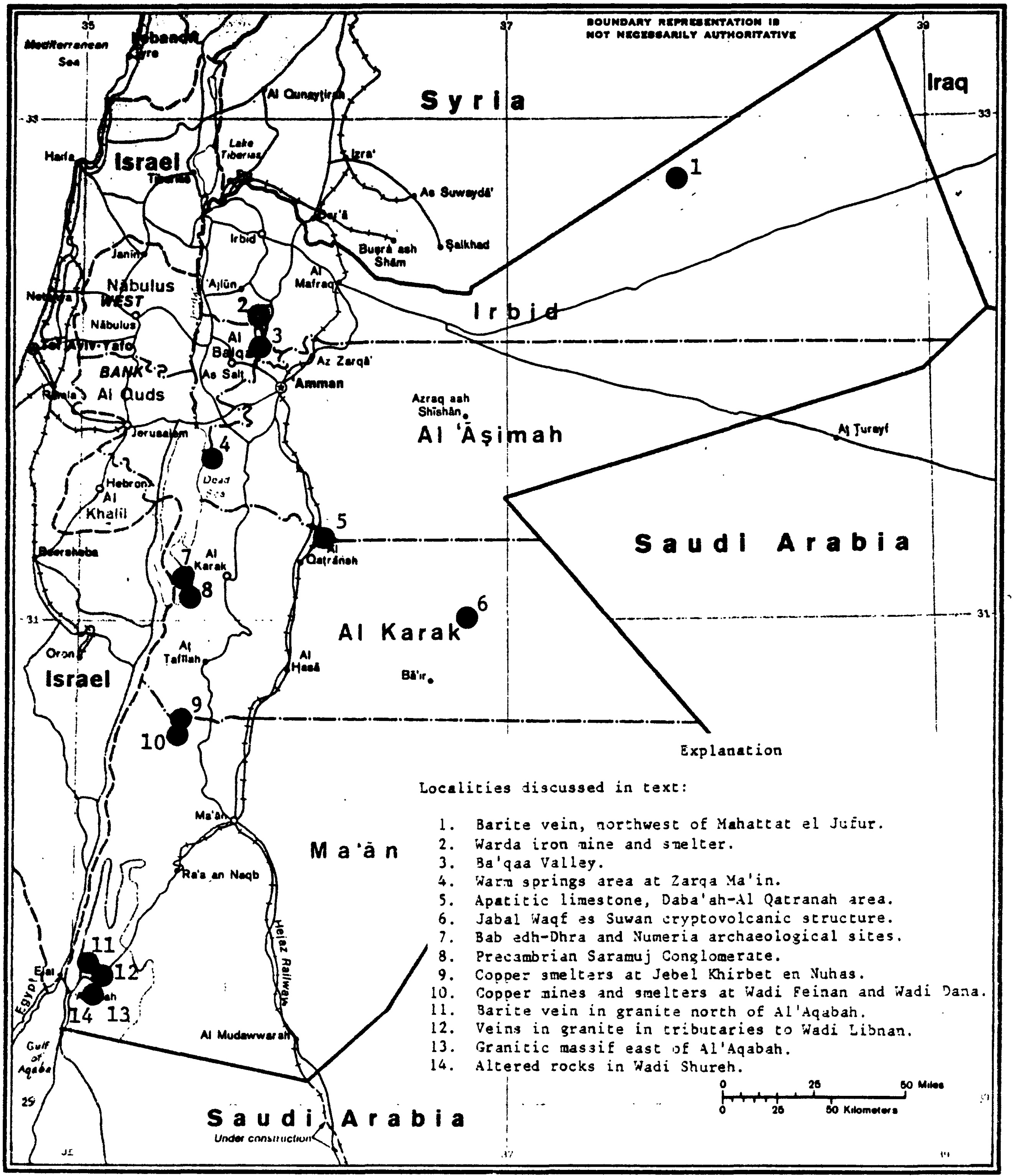

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Figure 1. Index map of Jordan.

Figure 2. Barite deposit in the Wadi Muqat area to the northwest of Qasr Burqu and Mahattat el Jufur, Hashemite Kingdom of Jordan. View shows exploration pit on barite vein.

granodiorite near Rabigh, Saudi Arabia, in the Red Sea rift system (Brobst, 1966, table 1; Shanti, 1970). An isotopic study of the lead in galena from the Rabigh barite deposit showed that it was similar to lead in metal-rich brine in the central Red Sea (Delevaux and others, 1967). At Rabigh, dark-brown jasperoid in the thicker parts of the barite veins contained unusual concentrations of Be, Pb, Y, B, Mn, and Fe that were interpreted by Brobst to indicate the possible presence of undiscovered hydrothermal sulfide ore deposits. Should comparable results be found for material from the barite vein deposit northwest of Mahattat el Jufur, then additional geologic reason would exist for further exploration at that locality.

The five smaples from the vein deposit in northeastern Jordan are:

Field number	Description
77-OT-622	Limestone.
-623	Clayey, limonite-rich alteration product of limestone in a zone 3-8 cm thick along footwall of barite vein.
-624	Gray barite vein in limestone.
-625	Dark brown, cryptocrystalline, slightly vuggy jasperoid from the barite vein.
-626	Gray barite vein in limestone.

Results of the analyses of these specimens are given in table 2.

The limestone and the limonite-rich, clayey alteration product along the footwall of the vein are richer in Fe, Mg, and Ca than the barite or jasperoid, and the alteration product contains more titanium than the other material (table 2). Both the limestone and the barite are remarkably pure. They have very low contents of all the minor elements sought in these analyses. The only exceptions to this observation are the high value for barium in the limestone (77-OT-622), and the high values for strontium in the barite (77-OT-624 and 77-OT-626), which is geochemically expectable. The

Table 2. Results of analyses of vein and wallrock materials from the barite deposit located to the northwest of Mahattat el Jufur, Hashemite Kingdom of Jordan.
[Analyses by D. J. Grimes, R. T. Hopkins, J. C. Negri, R. W. Leinz, J. G. Viets, and D. M. Hopkins, USGS.]

Element	77-OT-622 MAX-227 Limestone	77-OT-623 MAX-228 Footwall alteration	77-OT-624 MAX-229 Barite	77-OT-625 MAX-230 Jasperoid	77-OT-626 MAX-231 Barite
			Results in percent		
Fe	0.1	2	0.05	0.1	L(0.05)
Mg	.5	1	.05	.05	L(0.02)
Ca	G(20)	10	.5	1	.2
Ti	.007	.07	.015	.007	.005
			Results in parts per million (ppm)[2]		
Ag	N(0.5)	.7	N(0.5)	3	N(0.5)
Au[1]	L(0.05)	L(0.05)	L(0.05)	L(0.05)	L(0.05)
B	N(20)	50	N(20)	100	N(20)
Ba	G(5,000)	G(5,000)	G(5,000)	G(5,000)	G(5,000)
Co	N(5)	L(5)	N(5)	N(5)	N(5)
Cr	100	1,500	150	100	50
Cu	7	70	10	15	5
La	N(20)	20	N(20)	N(20)	N(20)
Mn	50	70	N(10)	100	N(10)
Ni	15	150	7	10	N(5)
Sc	N(5)	7	N(5)	N(5)	N(5)
Se	.1	.9	.5	.5	.1
Sr	500	G(5,000)	G(5,000)	1,500	G(5,000)
Tl	L(0.2)	L(0.2)	L(0.2)	L(0.2)	L(0.2)
eU	L(20)	30	L(20)	L(20)	L(20)
U	.6	21.8	.6	.6	4
V	70	700	150	70	15
Y	N(10)	70	N(10)	N(10)	N(10)
Zn	N(200)	200	N(200)	N(200)	N(200)
Zr	N(10)	70	N(10)	N(10)	N(10)

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[1] Gold by atomic absorption analysis.

[2] Looked for but not found at lower limits of determination as shown in ppm: As, 200; Be, 1; Bi, 10; Cd, 20; Hg, 0.02; Mo, 5; Nb, 20; Pb, 20; Sb, 100; Sn, 10; Te, 0.2; Th, 100; and W, 50.

largest anomalies in abundance of the minor elements are in the limonitic clayey alteration product along the footwall (77-OT-623) and/or in the jasperoid (77-OT-625), where higher values are found for Ag, B, Cr, Cu, La, Mn, Ni, Se, U, V, Y, Zn, and Zr, than are present in the limestone or barite.

Metal concentrations in barite and in jasperoid from the locality in northeastern Jordan are compared in table 3 with those reported for the deposit near Rabigh in Saudi Arabia (Brobst, 1966, table 1; Shanti, 1970, p. 56). The jasperoid described by Shanti (1970, p. 57) was said to be strongly contaminated by iron and manganese minerals. If allowance is made for contamination, if about three reporting intervals are permitted for acceptable variation in the results of the analyses, and if elements that were not detected are counted as being equivalent in the three sets of analytical results, then the samples of jasperoid from the two localities have similar concentrations of Mg, Ti, As, B, Bi, Cd, Cu, La, Mo, Ni, Sb, Sc, Sn, V, W, Zn, and Zr. The Jordanian material is enriched in Ca, Ba, Cr, and Sr compared to the Arabian jasperoid. The Jordanian jasperoid is also enriched in elements that were not reported for the Arabian material (Ag, Au, Se, Tl, and U). Of the elements in the Arabian jasperoid that were considered to be critical geochemical indicators for hidden hydrothermal sulfide deposits (Be, Pb, Y, B, Mn, and Fe), only boron is more abundant in the jasperoid from Jordan. The other elements assigned indicator roles for the Arabian jasperoid (Brobst, 1966) are less abundant, as is mercury, in the jasperoid from Jordan.

When the same parameters of allowable analytical variation are applied to the composition of the barite from the two countries as was used to compare the results of the analyses of the jasperoid, the barite samples are seen (table 3) to have similar contents of all reported elements except Cr, Pb, and

Table 3.--Comparison of metal concentrations in barite and jasperiod from barite vein deposits in northeastern Jordan and at Rabigh, Kingdom of Saudi Arabia.

[Data for Saudi Arabia from Brobst, 1966, table 1, and Shanti, 1970, p. 56. n d. = no data.]

Element	Northeastern Jordan		Rabigh, Saudi Arabia			
	Barite (2 samples)	Jasperiod (1 sample)	Barite (1 sample, Brobst)	Jasperiod (3 samples, Brobst)	Jasperiod (2 samples, Shanti)	
			Results in percent			
Fe	L(0.05)	0.1	<0.1	11	n.d.	n.d.
Mg	.03	.05	<.01	0.01	n.d.	n.d.
Ca	.3	1	<.1	.2	n.d.	n.d.
Ti	.01	.007	<.005	<.005	0.001	0.005
			Results in parts per million			
As	N(200)	N(200)	N[1]	N[1]	n.d.	n.d.
B	N(20)	100	<10	30	100	10
Ba	G(5,000)	G(5,000)	G(10,000)	1,100	n.d.	n.d.
Be	N(1)	N(1)	<1	15	100	7
Bi	N(10)	N(10)	N	N	20	N[1]
Cd	N(20)	N(20)	N	N	50	N
Cr	100	100	<5	<5	5	5
Cu	7	15	<2	50	100	1,000
Hg	N(0.02)	N(0.02)	.02	.12	n.d.	n.d.
La	N(20)	N(20)	N	N	10	N
Mn	N(10)	100	<20	3,000	2,000	10,000
Mo	N(5)	N(5)	<2	3	20	150
Ni	L(5)	10	<2	<2	15	30
Pb	N(20)	N(20)	150	700	2,000	10,000
Sb	N(100)	N(100)	N	N	200	N
Sc	N(5)	N(5)	N	N	10	10
Sn	N(10)	N(10)	N	N	10	10
Sr	G(5,000)	1,500	G(10,000)	<50	50	500
V	70	70	<10	50	200	300
W	N(50)	N(50)	N	N	50	N
Y	N(10)	N(10)	<5	40	30	20
Zn	N(200)	N(200)	N	N	500	500
Zr	N(10)	N(10)	N	N	10	20

[1] Lower limits of determination not given by Brobst (1966) and Shanti (1970) for elements looked for but not found.

V. Chromium and vanadium are more abundant in the barite from northeastern Jordan. Lead is more abundant in the Rabigh barite.

Some physical differences exist between the jasperoid in the two barite deposits. That from Jordan consists of small bodies of dark brown, cryptocrystalline, slightly vuggy jasperoid with small patches of limonite in the outer vugs. The pods of jasperoid at the Rabigh barite deposit are as much as 0.7 m wide and 2 m long, thus they are larger than the jasperoid bodies in Jordan. The Arabia jasperoid is dark golden brown, phaneric, and specked with particles of manganese oxide and iron oxide (Brobst, 1966, p. 188). Also, the wallrock limestone in Jordan is a more reactive rock than the wallrock granodiorite in the vein deposit at Rabigh. As a consequence, more profound alteration of the rock along the walls of the veins has taken place in northeastern Jordan than in Arabia (table 2, and Brobst, 1966, table 1). Interestingly, slight enrichment of silver was found by Brobst (1966, p. 188-189) in the altered wallrock, just as is shown for the alteration product along the vein walls at the barite deposit northwest of Mahattat el Jufur (table 2). Shanti (1970, p. 56) reported 1 and 30 ppm silver respectively for the two samples of jasperoid listed in table 3.

The chemical similarities of the barite from the two localities, the similar enrichment in silver of altered wallrock at the two deposits, and the similarity of abundances of many minor elements in the jasperoid from both localities (northeastern Jordan and from Rabigh in the Red Sea rift zone of Saudi Arabia,) may indicate some common features of origin despite the geographic separation of about 1,200 km.

In studies of the character, origin, and economic significance of jasperoid, Lovering (1972, p. 50) found it convenient to categorize jasperoid as "favorable jasperoid" if it was related to or associated with ore deposits, and as "unfavorable jasperoid" if it was not related to ore deposits. Chemical analyses of major and minor elements disclosed that certain elements were characteristically present and other elements were sparse (Lovering, 1972, p. 55):

Percent of specimens of jasperoid in which element is detectable	Term used for element by category of presence	Elements
>90	Characteristic	Fe, Mg, Ca, Mn, Ti, Ba, Cr, Cu
50-90	Common	Ni, Pb, Sr, V, Zr
10-50	Minor	Ag, As, B, Be, Bi, Mo, Sb, Sn, Y, Zn
2-10	Sparse	Cd, Co, La, Nb, Sc
<2	Very sparse	Nd, U, W

Among the characteristic and common elements, significant differences in abundances were noted for favorable and unfavorable jasperoids (Lovering and Hamilton, 1962; Lovering, 1972, p. 55-56). Abundances characteristic of favorable jasperoid were >1.5 percent iron, >30 ppm copper, and >15 ppm lead. A barely significant association with unfavorable jasperoid was found for magnesium in concentrations >0.015 percent. Also, favorable jasperoid more commonly contained Ag, As, Bi, Cd, Co, Mo, Sn, and Zn than unfavorable jasperoid. Lovering noted that sparse elements such as Cd and Co appeared only in jasperoid having high concentrations of Cu, Pb, Zn, or Ag, which ranked the jasperoid as favorable. The presence of very sparse elements such as U and W suggested areas in which these elements were abnormally concentrated, and the detection of sparse or very sparse elements in jasperoid could be highly significant if deposits of these elements were being sought (Lovering, 1972, p. 56). Summaries of significant concentrations and in significant concentrations of elements in jasperoid were tabulated by Lovering (1972, tables 12 and 14) to serve as geochemical guides to favorable jasperoids:

Significant concentrations (Lovering, 1972, table 14)		Not significant concentrations (Lovering, 1972, table 12)
Favorable jasperoid	Unfavorable jasperoid	
Fe $\geq$ 1.5 percent	Mg $\geq$0.015 percent	Ca
Cu $\geq$30 ppm		Mn
Pb $\geq$15 ppm		Ti
Ag $\geq$ 1.5 ppm		Ba
As $\geq$1,500 ppm		Cr
Bi $\geq$7 ppm		Ni
Mo $\geq$5 ppm		Sr
Sn $\geq$15 ppm		V
Zn $\geq$150 ppm		Zr

Lovering's research showed that certain colors, grain size, and textures in jasperoid also distinguished favorable from unfavorable jasperoid (Lovering, 1972, tables 9 and 10).

The jasperoid from northeastern Jordan fails in several critical ways to meet Lovering's criteria for favorable jasperoid, but in many less critical ways it satisfies the criteria, and in several ways it may exceed the demands for classification as favorable jasperoid. The dark brown color and slightly vuggy texture are somewhat significant in classing it as favorable jasperoid, but the cryptocrystalline character is notably against the classification as favorable jasperoid. The contents of Fe, Mg, and As are significantly unfavorable, but the content of Ag is highly significant for favorable jasperoid. High values for Ca, Ba, Cr, Mn, Ni, Sr, and V are not significant for classifying the jasperoid (Lovering, 1972, table 12). Only ambiguous interpretations arise from considerations of Cu, Pb, Bi, Mo, Sn, and Zn, because the lower limits of determination of the analyses of the jasperoid from Jordan are close to the significant concentrations related by Lovering

(1972, table 14) to favorable jasperoids:

Favorable jasperoid	Jasperoid from northern Jordan
Cu > 30	15
Pb ≥ 15	N(20)
Bi ≥ 7	N(10)
Mo ≥ 5	N(5)
Sn ≥ 15	N(10)
Zn ≥ 150	N(200)

A difference of one or two reporting units in the results of the analyses of the jasperoid from Jordan could have raised all these elements to the favorable concentrations. Equally as well, they could have been less. Evidently, additional samples of jasperoid from the locality northwest of Mahattat el Jufur need to be analyzed by methods giving lower limits of determination before the criteria based on these elements can be employed. From the published data, the significance of the small amounts of Au, Se, Tl, and U in classifying the jasperoid cannot be evaluated, except to recognize that they are very scarce elements which may show relation to metals in stratigraphic units through which the barium-bearing hydrothermal solutions passed (Se and U)or, may show the presence of sulfide deposits at depth (Au, Se, and Tl).

Rocks from the cryptovolcanic structure at Jabal Waqf es Suwan

One of the two cryptovolcanic structures recognized in Jordan (Bender, 1968a; 1975, pl. 1; Zagorac, 1969) is at Jabal Waqf es Suwan (3103'N.; 3648'E.) (fig. 1). It has the classic shape of an unbreached volcanic pipe capped by domed rocks--mainly Cretaceous sandstone, marl, phosphorite, silicified limestone, and chert--bounded by annular faults (Bender, 1975, pl. 1). Geophysical and geochemical investigations conducted by NRA and an United

Nations Special Fund Project (Zagorac, 1969) disclosed no surface evidence of mineralization. However, those investigations concluded with the recommendation that a vertical drill hole be sunk in the center of the structure to test it for possible ore deposits. Inasmuch as this hole had not been drilled as of 1977, and some cryptovolcanic structures have been proven to contain immense reserves of fluorite, barite, rare earths, beryllium, and zinc, as at Hicks Dome, Hardin County, Illinois, U.S.A. (Brown and others, 1954; Bradbury and others, 1955; Trace, 1960; 1976; Heyl and Brock, 1961; Heyl and others, 1965), a further recommendation was made that this hole be drilled to test the possibility of mineralization (Overstreet, 1978a, p. 18-19). A geochemical survey is said to have been made for base metals, barium, and strontium by NRA at Jabal Waqf es Suwan using augered soil samples for chemical analysis, but the results of the survey have not been available for the present discussion.

Field observations made November 18, 1977, at Jabal Waqf es Suwan disclosed no surface evidence for mineralization (fig. 3, A and B), unlike the cryptovolcanic structure at Hicks Dome, U.S.A., where dikes, veins, and intrusive breccia are exposed in the dome (Trace, 1976, p. 65). Nevertheless, 29 samples of rock were collected from Jabal Waqf es Suwan in the vicinity of geophysical station GM-146 (Zagorac, 1969). Chip samples were taken as close to the walls of joints and fractures as possible in order to include any imperceptible coatings that might be present along the openings. The decision to take chip samples of the walls of fractures instead of repeating the soil sampling of the earlier geochemical survey was based on the idea of a possible exhalation halo emerging through fractures above the buried intrusive. The central part of the dome over the intrusive would be the main channelway for fugitive constituents from the intrusive rocks below. Inasmuch as the core of

A. Chert in foreground; limestone and marl in background.

B. Fractured limestone.

Figure 3. Photographs of rocks exposed at Jabal Waqf es Suwan, Hashemite Kingdom of Jordan.

the dome is Cretaceous sandstone, and the immediate flanks are Upper Cretaceous chalk, marl, bituminous limestone, phosphorite, silicified limestone, and chert (Bender, 1975, pl. 1), the reactive carbonate rocks, phosphorite, and chert were selected for sampling (table 4). None of the rock chips prepared for analysis contained the slightest trace of fluorite, sulfide minerals, or barite.

The results of spectrographic and other analyses of the 29 rock specimens from Jabal Waqf es Suwan are shown in table 5. The minor elements most critically indicative of possible fluorite, rare-earth, or sulfide deposits, or of alkalic rocks at depth, as at Hicks Dome, are, if present, less abundant than their respective lower limits of determination (As, Be, Bi, Cd, Nb, Sb, Sn, Te, Th, W, and Zn), are rarely detected (Ag, Co, Cr, Hg, La, Mo, Pb, Sc, Y, and Zr), or are only sparsely present (B, Cu, Ni, Se, and Tl). Some common elements (Fe, Mg, Ca, and Ti) occur in geochemically expectable amounts. Specific rock types appear to be enriched in certain locally anomalously abundant elements (Ba, Mn, Sr, U, and V) and the presence of these elements more probably reflects the chemistry of their sedimentary deposition than that of exhalation halos related to a subjacent igneous source.

Distribution of elements

The distribution of the elements reported in table 5 is discussed below to compare the geochemistry of the rock samples from the dome at Jabal Waqf es Suwan with the abundances of these elements in surface materials and drill core from Hicks Dome, U.S.A., and with average geochemical abundances in limestone.

Hicks Dome, a circular structure 14 km in diameter having about 1,200 m of vertical stratigraphic uplift, is situated in a complexly faulted area in the

Table 4. Sedimentary rocks from Jabal Waqf es Suwan, Hashemite Kingdom of Jordan. [Field descriptions by Abdullah Bahdari, NRA.]

Field number	Field description
77-0T-592	Cream-colored, silicified, fossiliferous limestone.
-593	Do.
-594	Pink, fossiliferous, sandy clay marl.
-595	Same unit as 77-0T-592.
-596	Do.
-597	Do.
-598	Same unit as 77-0T-592, calcite veinlets present.
-599	Do.
-600	Brown, nummulitic limestone.
-601	Same unit as 77-0T-592.
-602	Calcite vein.
-603	Same unit as 77-0T-592.
-604	Do.
-605	Do.
-606	Tan, silicified limestone with hairline fractures coated with iron and manganese oxides.
-607	Silicified limestone.
-608	Brecciated, iron-stained chert.
-609	Do.
-610	Do.
-611	Do.
-612	Do.
-613	Do.
-614	Brown, silicified limestone.
-615	Brecciated, iron-stained chert.
-616	Massive, iron-stained chert.
-617	Do.
-618	Gray, phosphatic chert.
-619	Siliceous phosphate rock.
-620	Rosy, siliceous limestone.

Table 5. Results of analyses of sedimentary rock from the cryptovolcanic structure at Jabal Waqf es Suwan, Hashemite Kingdom of Jordan.

[Analyses by D. J. Grimes, R. T. Hopkins, J. C. Negri, R. W. Leinz, J. G. Viets, and D. M. Hopkins, USGS.]

Sample numbers		Results of analyses[1]														
Field	Laboratory	In percent				In parts per million										
		Fe	Mg	Ca	Ti	Au[2]	B	Ba	Cu	Mn	Ni	Se	Sr	Tl	U	V
77-OT-592	MAX-197	0.3	0.5	G(20)	0.02	L(0.05)	N(20)	1,000	70	1,500	L(5)	0.1	300	L(0.2)	0.4	20
-593	-198	2	.7	G(20)	.02	L(.05)	N(20)	5,000	50	1,000	10	.3	500	L(.2)	.6	50
-594	-199	5	7	20	.1	L(.10)	70	300	30	2,000	20	.1	700	L(.2)	4.9	50
-595	-200	.3	.3	G(20)	.015	L(.05)	N(20)	300	30	500	5	.3	300	.2	.4	15
-596	-201	.2	.7	G(20)	.015	L(.10)	L(20)	300	30	300	L(5)	.1	300	.2	1.0	15
-597	-202	.07	.5	(G20)	.007	L(.10)	N(20)	150	20	150	L(5)	.4	300	.2	.5	15
-598	-203	L(.05)	.3	G(20)	.005	L(.05)	N(20)	20	30	150	L(5)	.1	200	L(.2)	.8	10
-599	-204	.05	.5	G(20)	.007	L(.25)	N(20)	50	20	150	L(5)	.2	300	.2	.3	L(10)
-600	-205	5	.7	G(20)	.03	L(.10)	20	200	20	1,000	30	1.3	300	.4	.4	70
-601	-206	.2	.7	G(20)	.02	L(.10)	L(20)	70	20	150	7	.3	300	L(.2)	.4	20
-602	-207	.1	.3	G(20)	.002	L(.10)	N(20)	20	5	500	N(5)	.1	150	L(.2)	.4	L(10)
-603	-208	.1	.5	G(20)	.01	L(.10)	N(20)	300	10	100	L(5)	.2	200	L(.2)	.3	15
-604	-209	.07	.5	G(20)	.007	L(.10)	N(20)	100	7	100	L(5)	.4	200	L(.2)	.3	L(10)
-605	-210	.1	.7	G(20)	.007	L(.10)	N(20)	70	15	100	L(5)	.1	200	L(.2)	.6	10
-606	-211	.7	.5	G(20)	.01	L(.10)	N(20)	200	7	700	20	.2	150	L(.2)	.4	50
-607	-212	.07	.5	G(20)	.01	L(.10)	N(20)	100	7	100	L(5)	.1	150	L(.4)	.6	15
-608	-213	.1	.1	2	.01	L(.05)	100	100	15	100	10	.3	L(100)	L(.2)	.9	20
-609	-214	.1	.1	2	.005	L(.05)	100	200	7	150	L(5)	.1	L(100)	.2	.6	L(10)
-610	-215	.3	.2	5	.02	L(.05)	70	500	15	150	15	.7	100	.2	3.0	70
-611	-216	.3	.3	5	.02	L(.05)	70	3,000	20	200	15	.3	200	L(.2)	2.8	30
-612	-217	.2	.15	3	.015	L(.05)	70	500	10	300	7	.3	100	.2	.5	L(10)
-613	-218	.2	.2	3	.01	L(.05)	100	700	10	300	10	.5	100	.4	1.9	20
-614	-219	L(.05)	.3	G(20)	.005	L(.10)	N(20)	100	7	100	L(5)	.2	200	.2	1.9	20
-615	-220	.3	.2	3	.02	L(.10)	50	700	7	200	10	.3	100	.2	.9	20
-616	-221	.1	.15	3	.007	L(.05)	70	300	5	200	7	.2	100	L(.2)	2.0	20
-617	-222	.1	.1	1	.01	L(.05)	50	150	7	100	7	.2	L(100)	L(.2)	1.5	15
-618	-223	L(.05)	.3	20	L(.002)	L(.05)	70	300	20	30	5	1.4	1,000	.4	37.4	70
-619	-224	.1	.7	20	.01	L(.05)	N(20)	5,000	30	20	30	1.3	1,500	L(.2)	62.4	300
-620	-225	.07	.3	G(20)	.01	L(.05)	N(20)	100	15	50	15	.2	300	L(.2)	2.1	150

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[1] Looked for but not found at lower limits of determination as shown, in ppm: As, 200; Au (spectrographic analysis), 10; Be, 1; Bi, 10; Cd, 20; Nb, 20; Sb, 100; Sn, 10; Te, 0.2; Th, 100; W, 50; and Zn, 200. Elements rarely detected, abundances, and sample numbers where found include: Ag, 5 ppm, 77-OT-618; Co, 5 ppm, 77-OT-593 and -594, 15 ppm, 77-OT-600; Cr, 50 ppm, 77-OT-600, -610, -613, -614, -617, -618, 70 ppm, 77-OT-594, 100 ppm, 77-OT-611 and -620, 150 ppm, 77-OT-619; Hg, L(.02), 77-OT-593 and -599, 0.02 ppm, 77-OT-603; La, 30 ppm, 77-OT-594; Mo, L(5), 77-OT-610, 7 ppm, 77-OT-620, 10 ppm, 77-OT-619, 15 ppm, 77-OT-593, -594, and -600; Pb, L(20), 77-OT-592, 20, 77-OT-594, and 70, 77-OT-600; Sc, L(5), 77-OT-600, and 5, 77-OT-594; eU, L(20), 77-OT-592 through -617 and also -620, 90, 77-OT-618, and 100, 77-OT-619; Y, 10, 77-OT-592, 15, 77-OT-593 and -600, and 20, 77-OT-594, -618, and -619, and and Zr, L(10), 77-OT-593, 10, 77-OT-592 and -600, 50, 77-OT-594.

[2] Atomic absorption analyses.

central craton of the United States (Heyl and Brock, 1961, p. D3-D5; Heyl and others, 1965, p. B10; Trace, 1976, p. 68-70). Radial and concentric ring faults are present near the margin of the dome, mineralized explosion breccias are present in the dome, and the dome is intruded by strongly altered dikes of alkalic peridotite. Some of the breccias have been drilled, and material from the breccias and dikes have been analyzed mineralogically and chemically. Locally, surface exposures of fluorite in the breccias and of radioactive dikes in the dome have encouraged exploration and mining (Brown and others, 1954). Minerals in the breccia include rare-earth-bearing fluorite, sphalerite, galena, barite, monazite, bertrandite, florencite, pyrite, brookite, rutile, xenotime, and apatite (Trace, 1976, p. 68). Beryllium, niobium, and zirconium are enriched in the breccia, and these elements as well as F, Ga, Ba, Ti, Ni, Y and Ce are enriched in the dikes (Trace, 1976, p. 65). The mineralized breccias have been interpreted as diatremes, and Hicks Dome is thought to be a cryptovolcanic structure (Heyl and others, 1965, p. B11).

Elements less abundant than their respective lower limits of determination.--The elements shown in table 5 to be less abundant in the rocks from Jabal Waqf es Suwan than their respective lower limits of determination, and those limits in ppm, are: As, 200; Be, 1; Bi, 10; Cd, 20; Nb, 20; Sb, 100; Sn, 10; Te, 0.2; Th, 100; W, 50; and Zn, 200.

The presence of fluorite at depth might be indirectly indicated by the beryllium and several other elements at the surface, because F- serves as a complexing agent that forms water-soluble fluoride complexes of elements such as Be, Bi, Mn, Nb, Ti, and W (Griffitts, 1973, p. 89). Except for manganese and titanium, these elements are below their limits of determination in this set of samples. When the abundances of these elements are considered with the mineralogical observation that fluorite was absent on the joints and fractures that were sampled, the probability seems to be against the presence of fluorite at depth.

Beryllium, niobium, rare earths, and thorium are elements commonly associated with alkalic rocks. At Hicks Dome the peridotite dikes with alkalic affinities contain 10-50 ppm Be and 50-100 ppm Nb (Trace, 1976, p. 65), and the breccia is enriched in these elements (Grogan and Bradbury, 1968, p. 398) and has many rare-earth and thorium-bearing minerals. Of these elements, only the rare earths have been detected in the sedimentary rocks at Jabal Waqf es Suwan, and they were rarely found (see below). Their absence, within the limits of determination, in the fractured parts of the sedimentary rocks could be compatible with an absence of alkalic intrusives at depth, but the limits of determination of these elements are sufficiently high that they could be present in small quantities that would still exceed normal abundances in sedimentary rocks. For example, limestones typically contain <1 ppm Be, 0.3 ppm Nb, and 1.7 ppm Th (Bowen, 1966, p. 176- 205). Thus, it cannot be certainly said that the failure to detect beryllium, niobium, and thorium excludes the possibility of alkalic intrusives at depth. When taken with the absence of fluorite and the low values for other characteristic elements discussed below, such as Ba, La, Mn, Sr, Ti, Y, and Zr, the possibility for an alkalic intrusive is remote.

Elements generally associated with sulfide deposits, such as As, Bi, Cd, Sb, Te, and Zn, and commonly found in geochemical halos around sulfide deposits, are also below their limits of determination in these rocks. They typically are quite sparse in limestone, for example: 1 ppm As; 0.035 ppm Cd; 0.2 ppm Sb; 20 ppm Zn (Bowen, 1966, p. 174-209), and of these elements, only zinc has been reported at Hicks Dome, where 50-100 ppm were found in weathered peridotite dikes (Trace, 1976, p. 65). Such low levels of concentration are not reached by the analytical methods used. However, the presence of at least some of these elements, and particularly of tellurium (Watterson and others, 1977), might be expected in leakage halos associated with hidden sulfide deposits of base metals. The absence of these elements combined with the rarity of elements such as Ag, Au, Co, Cu, Hg, Mo, Ni, Pb, Se, and Tl, suggest that deposits of base metals are not present in depth at Jabal Waqf es Suwan.

Rarely detected elements.--Elements that are rarely detected in the samples of rocks from Jabal Waqf es Suwan are: Ag, Co, Cr, Hg, La, Mo, Pb, Sc, Y, and Zr (table 5). Out of this group, only mercury and zirconium have limits of determination in these analyses that are lower than the average abundances in limestone:

Element	Lower limit of determination for table 5, in ppm	Average abundance in limestone, in ppm (Bowen, 1966, p. 173-210)
Ag	0.5	0.07
Co	5	.1
Cr	50	11
Hg	.02	.04
La	20	6.2
Mo	5	.4
Pb	20	9
Sc	5	1
Y	10	4.3
Zr	10	19

Interestingly, the only samples of rock from Jabal Waqf es Suwan that contain detectable mercury (table 5) are from silicified limestone and fractured limestone, as if some connection existed between chemical and mechanical alteration of the limestone:

Sample number	Rock type	Mercury (ppm)
77-OT-593	Silicified limestone	L(.02)
77-OT-603	Do.	.02
77-OT-599	Limestone with fractures and veinlets	L(.02)

These amounts for mercury are just at the threshold of detection; thus, it may be assumed that the abundance of mercury in the whole suite of samples is somewhat less than 0.02 ppm, and the limestones at Jabal Waqf es Suwan are leaner in mercury than the average limestone, cited above. Samples 77-OT-599 and 77-OT-603 are leaner in all elements except mercury than most of the other rocks in table 5; thus, the slight rise in the abundance of mercury found for these two rocks is unmatched by rises in the abundances of other pathfinder elements for sulfide deposits. Sample 77-OT-593 is one rock that has a high content of these elements (Fe, Ba, Co, Cu, Mn, Mo, Ni, V, Y, and Zr). Indeed, when the average values for the abundance of each element are determined for the nine varieties of rock sampled at Jabal Waqf es Suwan (table 6), it is seen that characteristic assemblages of elements are present in greater than average amounts in specific rock types:

Rock type	Characteristic high-value element (Anomalously rich elements underlined)
Limestone	Fe,Co,Mn,Mo,Ni,Pb,Se,Tl,V,Y
Silicified limestone	Ba,Hg
Fractured limestone	Hg
Marl	Fe,Mg,Ti,B,Cr,Cu,La,Mn,Mo,Sc,Sr,U, Y,Zr
Calcite vein	None
Massive chert	B,U
Brecciated chert	B,Ba,U
Phosphatic chert	Ag,B,Se,Sr,Tl,U,V,Y
Silicified phosphate rock.	Ba,Cr,Cu,Mo,Ni,Se,Sr,U,V,Y

The presence of the mercury in rocks otherwise lacking in enriched elements, and the lack of mercury in the sample of calcite vein or samples of

Table 6. Average values for observed elements in nine varieties of rock from Jabal Waqf es Suwan, Hashemite Kingdom of Jordan.

[Compiled from data in tables 4 and 5 of this report; number of samples in average given below rock name.]

Element	Limestone (1)	Silicified limestone (12)	Limestone with fractures (3)	Marl (1)	Calcite vein (1)	Massive iron-stained chert (2)	Brecciated iron-stained chert (7)	Phosphatic chert (1)	Siliceous phosphate rock (1)
Results in percent									
Fe	5	0.3	0.3	5	0.1	0.1	0.2	L(.05)	0.1
Mg	0.7	.5	.4	7	.3	.1	.4	.3	.7
Ca	G(20)	G(20)	G(20)	20	G(20)	2	3.3	20	20
Ti	.03	.01	.01	.1	.002	.008	.01	L(.002)	.01
Results in parts per million									
Ag	N(0.5)	N(0.5)	N(0.5)	N(0.5)	N(0.5)	N(0.5)	N(0.5)	5	N(0.5)
Au[1]	L(.10)	L(.10)	L(.15)	L(.10)	L(.10)	L(.05)	L(.05)	L(.05)	L(.05)
B	20	N(20)	N(20)	70	N(20)	60	70	70	N(20)
Ba	200	500	100	300	20	200	700	300	5,000
Co	15	N(5)	N(5)	5	N(5)	N(5)	N(5)	N(5)	N(5)
Cr	50	L(50)	N(50)	70	N(50)	L(50)	L(50)	50	150
Cu	20	20	20	30	5	5	10	20	30
Hg	N(.02)	L(.02)	L(.02)	N(.02)	N(.02)	N(.02)	N(.02)	N(.02)	N(.02)
La	N(20)	N(20)	N(20)	30	N(20)	N(20)	N(20)	N(20)	N(20)
Mn	1,000	300	300	2,000	500	150	200	30	20
Mo	15	L(5)	N(5)	15	N(5)	N(5)	N(5)	N(5)	10
Ni	30	L(5)	7	20	N(5)	7	10	5	30
Pb	70	N(20)	N(20)	20	N(20)	N(20)	N(20)	N(20)	N(20)
Sc	L(5)	N(5)	N(5)	5	N(5)	N(5)	N(5)	N(5)	N(5)
Se	1.3	.2	.2	.1	.1	.2	.4	1.4	1.3
Sr	300	300	200	700	150	L(100)	100	1,000	1,500
Tl	.4	L(.2)	L(.2)	L(.2)	L(.2)	L(.2)	.2	.4	L(.2)
U	.4	.8	.5	4.9	.4	1.7	1.5	37.4	62.4
V	70	30	20	50	L(10)	15	20	70	300
Y	15	N(10)	N(10)	20	N(10)	N(10)	N(10)	20	20
Zr	10	N(10)	N(10)	50	N(10)	N(10)	N(10)	N(10)	N(10)

Looked for but not found at lower limits of determination as shown in ppm: As, 200; Au (spectrographic analysis), 10; Be, 1; Bi, 10; Cd, 20; Nb, 20; Sb, 100; Sn, 10; Te, 0.2; Th, 100; W, 50; and Zn, 200.

[1] Atomic absorption analyses.

brecciated chert pretty much restrict the possible source of the mercury to slight variations in the abundance associated with specific beds of sedimentary deposition. Data are unavailable on the amount of mercury in rocks at Hicks Dome, U.S.A.

Zirconium, the other element in this group of rarely detected elements that has a limit of determination in the present analyses below its average abundance in limestone, was found in limestone (77-OT-600), silicified limestone (77-OT-592 and -593), and marl (77-OT-594). Only the value for marl, 50 ppm, exceeds the average abundance of zirconium in limestone, 19 ppm (Bowen, 1966, p. 210). Silty or clayey components of the marl are the most probable source for this small amount of zirconium, which would be in fine-grained detrital zircon deposited with the silt and clay during the sedimentation of the marl. This small amount of zirconium in one rock type out of the nine varieties sampled at Jabal Waqf es Suwan is unlikely to indicate the presence of subjacent alkalic intrusives, which at Hicks Dome contain from 100-500 ppm zirconium (Trace, 1976, p. 65).

Among the other rarely detected elements in the rocks at Jabal Waqf es Suwan, silver is present (5 ppm) in one specimen (77-OT-618, table 5), that consists of gray phosphatic chert. This amount of silver resembles the 1-5 ppm of silver reported for the alkalic peridotite dikes at Hicks Dome (Trace, 1976, p. 65). However, the phosphatic chert from Jabal Waqf es Suwan, like the silicified phosphate rock, marl, and limestone (table 6), is distinctly enriched in a number of elements over the other rocks. Although this is the only sample in which silver was observed, and its abundance is much greater than the average value for silver in sedimentary rocks (0.7 ppm, Bowen, 1966,

p. 173), the presence of this amount of silver is interpreted to be related to syngenetic processes of sedimentary deposition rather than to post-depositional alteration.

Cobalt is present at the lower limit of determination (5 ppm) in two samples and reaches a value of 15 ppm in one sample from Jabal Waqf es Suwan (table 5), but these abundances are considerably less than the 100-500 ppm cobalt found in the intrusive mafic dikes at Hicks Dome (Trace, 1976, p. 65). Each of the three cobalt-bearing samples of sedimentary rock from Jabal Waqf es Suwan is also richer in manganese and molybdenum than most of the other samples:

Sample number	Rock type	Elements (ppm)		
		Co	Mn	Mo
77-OT-593	Silicified limestone	5	1,000	15
-594	Marl	5	2,000	15
-600	Limestone	15	1,000	15

The slight rise in the abundances of cobalt and molybdenum above their lower limits of determination (5 ppm each) represent a considerable rise above their average values in limestone, said by Bowen (1966, p. 180 and 192) to be 0.1 ppm cobalt and 0.4 ppm molybdenum. For both elements, their slightly enhanced abundances in these three samples may relate to the increased content of manganese. Both elements are known to accumulate in manganese-rich sediments (Rankama and Sahama, 1950, p. 630 and 684). Although none of the analyzed rocks would be called manganese-rich, these three are among the samples that contain the most manganese in the suite. Two other molybdenum-bearing samples (77-OT-619, siliceous phosphate rock and 77-OT-620, siliceous limestone), however, are among the most manganese-poor rocks in the group (table 5). The sparse presence and small variation in the abundances of cobalt and molybdenum probably are products of slight variations in the chemical environment of deposition of the beds represented by these samples. The abundance of molybdenum in these samples is much closer to the 10-50 ppm molybdenum reported for the dikes at Hicks Dome (Trace, 1976, p. 65) than is the abundance of cobalt to the amount of cobalt at Hicks Dome.

Most of the chromium-bearing samples are chert and siliceous limestone, but the element was also detected in marl, limestone, and phosphate rock (tables 4 and 5). All the chromium-bearing samples also contain nickel, but the reverse relation is not found: some nickel-bearing samples lack chromium. Inasmuch as the threshold for determining chromium in the present analyses was about 5 times as great as the average abundance of chromium in limestone (11 ppm, Bowen, 1966, p. 181), and some of the samples contain 10-15 times that much, these samples must be regarded as enriched in chromium even though they contain about the average amount of nickel found in limestone (20 ppm, Bowen, 1966, p. 194):

Sample number	Rock type	Elements			
		Cr	Ni	Fe	Ti
		(ppm)		(percent)	
77-OT-594	Marl	70	20	5	0.1
-600	Limestone	50	30	5	.03
-610	Brecciated chert	50	15	0.3	.02
-611	Do.	100	15	.3	.02
-613	Do.	50	10	.2	.01
-614	Silicified limestone	50	L(5)	L(.05)	.005
-615	Brecciated chert	L(50)	10	.3	.02
-616	Massive chert	50	7	.1	.01
-618	Phosphatic chert	50	5	L(.05)	L(.002)
-619	Phosphate rock	150	30	.1	.01
-620	Silicified limestone	100	15	.07	.01

At Hicks Dome the dikes contain 100-500 ppm chromium (Trace, 1976, p. 65).

Most of the chromium-bearing samples contain more iron and titanium than the average samples, but the highest values for chromium do not correspond to the highest values for iron or titanium. Only the marl seems to have coincident high values for chromium, iron, and titanium. The chromium and titanium, like zirconium, may be present in the marl in resistate minerals such as ilmenite and chromite. However, other sources of chromium, including chromium silicate minerals, and of nickel have been reported by Bender (1974, p. 158-159) for marl elsewhere in Jordan. These occurrences are related to the chemistry of euxinic facies of sedimentary deposition. In the other sedimentary rocks at Jabal Waqf es Suwan, detrital grains are unlikely to be the source, and the chromium may be substituting for iron in the secondary iron compounds in the sediments.

The rare-earth elements lanthanum, scandium, and yttrium are sparingly present in a few samples from Jabal Waqf es Suwan (table 5):

Sample number	Rock type	Elements (ppm) La	Sc	Y
77-OT-592	Silicified limestone-----	N(20)	N(5)	10
-593	Do.	N(20)	N(5)	15
-594	Marl---------------------	30	5	20
-600	Limestone----------------	N(20)	L(5)	15
-618	Phosphatic chert---------	N(20)	N(5)	20
-619	Silicified phosphate rock	N(20)	N(5)	20

The average values for the abundances of these elements in limestone is given by Bowen (1966, p. 189, 201, and 208) as: La, 6.2 ppm; Sc, 1 ppm; and Y, 4.3 ppm. At Hicks Dome the dikes are reported to contain 100-500 ppm lanthanum, 10-50 ppm scandium, and 1,000-5,000 ppm yttrium. Enrichment in yttrium and the common presence of ordinarily rare yttrium and scandium minerals is also a characteristic of the explosion breccias at Hicks Dome

(Heyl and Brock, 1961, p. D-4). The restriction of the lanthanum and of the measurable scandium to the marl and of the highest tenors in yttrium to the marl and to the phosphatic rocks at Jabal Waqf es Suwan is interpreted to indicate normal sedimentary processes as the source for the rare earths.

Lead is present in small amounts in three of the rare-earth-bearing rocks sampled at Jabal Waqf es Suwan (table 5):

Sample number	Rock type	Lead (ppm)
77-OT-592	Silicified limestone	L(20)
-594	Marl----------------	20
-600	Limestone-----------	70

These values for lead are, for two of the samples, only slightly greater than the average abundance of lead in limestone (9 ppm, Bowen, 1966, p. 197), and for the three samples the values are about what has been reported for the dikes at Hicks Dome (10-50 ppm Pb; Trace, 1976, p. 65). Thus, no conclusion as to origin of the lead--whether sedimentary or not--can be drawn from these abundances, but the fact that the three lead-bearing samples also contain above-background amounts of many other elements, and these are interpreted to be syngenetic, suggests the same explanation for the lead. These three samples, as well as other metal-rich samples (77-OT-618 and 77-OT-619), may constitute examples of walls of joints affected by exhalation halos, and the other samples may be from the walls of unaffected fractures. This possibility seems to be overridden by the fact that the samples containing many high-value elements are from particular kinds of sedimentary rocks where such values are geochemically expectable.

Sparsely present elements.--The sparsely present elements are elements that show up in most of the samples in table 5, but their concentrations tend to be low except in a few rocks, where some of these elements are anomalously abundant. They are: Au, B, Cu, Ni, Se, and Tl.

Gold is the most unexpected element to show up in this group. In no sample is it sufficiently abundant to be measured, but in every sample its presence was reported as detected but below the lower limit of determination (L). For 15 samples the lower limit of determination of 0.05 ppm gold, but for 13 samples the lower limit of determination was 0.10 ppm gold, and for one sample it was 0.25 ppm (table 5). These differences were caused by variation in the amount of sample material available for analysis: the less the amount the higher the value for the lower limit of determination. The values reported for gold in table 5 are an analytical convention and do not reflect the amount of gold in the source rock. Even these values are rather high compared to the abundance of gold in carbonate rocks, given as 0.00n ppm by Beus and Grigorian (1977, table 3), and in sedimentary rocks, shown as 0.004 ppm by Bowen (1966, p. 175), which makes the conventionally reported gold content of every sample from Jabal Maqf es Suwan appear to be at least 10 times greater than the average value for the gold content of limestones. These values do not constitute geochemical evidence for mineralization at depth at Jabal Waqf es Suwan. They are an anomaly in analytical reporting convention. Data are lacking on the gold content of the intrusive rocks and breccias at Hick Dome.

Boron in the samples of rock from Jabal Waqf es Suwan gives some of the clearest geochemical evidence of affinity for a particular rock of any of the minor elements (tables 4 and 5). The highest values for boron, 50-100 ppm, are restricted to the ten samples of chert, except for the one specimen of marl (77-OT-594), which contains 70 ppm boron. One specimen of limestone

(77-OT-600) has 20 ppm boron and two samples of silicified limestone (77-OT-596 and -601) contain less than 20 ppm boron. The average boron content of limestone is reported to be 20 ppm (Bowen, 1966, p. 175); thus, most of the limestone represented by this set of samples contains less boron than the average. Data are lacking on the boron content of the dikes and breccia at Hicks Dome. Nevertheless, the clear association of boron at Jabal Waqf es Suwan with one type of sedimentary rock is interpreted to show that the element is not derived from emanations from an underlying igneous source.

Copper, nickel, selenium, and thallium were detected in small amounts in virtually every sample from Jabal Waqf es Suwan listed in table 5. The single exception is the sample of calcite vein (77-OT-602), which lacks nickel at a lower limit of determination of 5 ppm. That vein also has the lowest values for the three other elements. The massive chert, samples 77-OT-616 and -617, has almost as low a content of copper, nickel, selenium, and thallium as the calcite vein.

Copper, selenium, and thallium are more abundant in all samples in table 5 than their average concentrations in limestone, which are reported (Bowen, 1966, p. 182, 202, and 206) to be: 4 ppm, Cu; 0.08 ppm Se; and 0.05 ppm, Tl. Nickel is generally less common in the sedimentary rocks sampled at Jabal Waqf es Suwan than its average abundance in limestone of 20 ppm (Bowen, 1966, p. 194). Data are lacking for the concentrations of selenium and thallium in the intrusive rocks at Hicks Dome, but the dikes are reported to contain 100-500 ppm copper and 1,000-5,000 ppm nickel (Trace, 1976, p. 65).

If the average values for the concentrations of these four elements in the nine kinds of rocks sampled at Jabal Waqf es Suwan (table 6) are compared with the concentrations reported for individual samples (table 5) where several specimens of the same type of rock were analyzed, it can be seen that the range of abundances for a given element is greater within a single rock type than it is between types of rocks. Mostly, the differences in abundance for copper, nickel, and thallium in the average values for these elements in table 6 is only one or two laboratory reporting units.

Several distinctive highs are reached by selenium. The unsilicified limestone, phosphatic chert, and siliceous phosphate rock are enriched in selenium--respectively 1.3 ppm, 1.4 ppm, and 1.3 ppm--compared to the silicified limestone, fractured limestone, marl, and chert. A rise in the abundance of selenium in the two phosphatic samples (77-OT-618 and -619) is geochemically expectable, because phosphate rock commonly contains selenium in quantities exceeding crustal abundance (Lakin and Davidson, 1973, p. 575). The similar rise in the unsilicified limestone (77-OT-600) is unexplainable on present data. This limestone is also anomalously rich in Co, Mn, Mo, Pb, Tl, and V. Most of these elements might have been derived from the sedimentary environment, but when they are also accompanied by selenium, which is known in volcanic emanations (Lakin and Davidson, 1973, p. 575), the possibility arises for the sample to reflect an exhalation halo. The high value for selenium is unmatched by high values for As, Sb, Hg, or Ag, which might also be expected in volcanic emanations (Koljonen, 1977, p. 1). Therefore, the interpretation is tentatively made that the selenium in the limestone and in the phosphatic rocks is syngenetic. It does not indicate a halo.

Common elements.--The common elements iron, magnesium, calcium, and titanium, were determined in all the samples (table 5). For the most part the reported abundances are expectable for the kinds of rocks that were analyzed (table 6). Iron appears to be somewhat greater than would be expected in the limestone (77-OT-600) and marl (77-OT-594), and magnesium is high in the marl, but none of these values is sufficiently anomalous to merit further attention. Only titanium among the common elements would be influenced appreciably by an exhalation halo. The rise in titanium in the marl has been discussed above with chromium, where the titanium was interpreted to be in detrital resistate minerals in the marl.

Elements with strong local anomalies.--The elements showing strong local anomalies in the rock samples from Jabal Waqf es Suwan are Ba, Mn, Sr, U, and V. Interestingly, in many of the samples of limestone, the low values for these elements tend to be far below average values reported for limestone, which are, in parts per million: Ba, 120; Mn, 1,100; Sr, 610; U, 2.2; and V, 20 (Bowen, 1966, p. 176, 191, 204, and 207). In the dike rocks at Hicks Dome the concentrations of these elements are given by Trace (1976, p. 65) as (in ppm): Ba, 1,000-5,000; Mn, 500-1,000; Sr, 100-500, and V, 100-500. Data were not presented for uranium, but the deposit is radioactive, and in earlier accounts some radioactivity was attributed to uranium and some to thorium (Brown and others, 1954, p. 899-900), with 10 ppm uranium being uniformly present to depths of 900 m (Trace, 1960, table 30.2).

Barium is one of the enriched elements at Hicks Dome, and, together with strontium and the base metals, is one of the elements sought in the geochemical survey of Jabal Waqf es Suwan by NRA. Unfortunately, access to that report was not possible at the time the present text was prepared. A comparison of the results of the two surveys should be made before further work is undertaken by NRA.

The average contents for barium in the nine rock types represented by the samples from Jabal Waqf es Suwan are given in table 6. The calcite vein (77-OT-602) and the fractured limestone (77-OT-598, -599, and -606) contain less barium than average limestones: 20 ppm for the vein and 100 ppm for the fractured limestones. Both these rock types contain on average less Ba, Mn, Sr, and U than the average limestone, as cited by Bowen (1966):

Rock	Element (in ppm)				
	Ba	Mn	Sr	U	V
Calcite vein	20	500	150	0.4	(L10)
Fractured limestone	100	300	200	.5	20
Average limestone (Bowen, 1966)	120	1,100	610	2.2	20

These materials at Jabal Waqf es Suwan thus give no indication of anomalous enrichment that might be related to exhalation halos bringing Ba, Mn, Sr, U, or V from depth. Because these materials represent veins and cemented fractures, they might be expected to have been the most positively biased samples of the group toward the presence of elements migrating from depth.

Among the silicified limestones two samples (77-OT-592 and -593) are strongly anomalous, containing respectively 1,000 ppm and 5,000 ppm barium (table 5). Most of the remainder of the samples of silicified limestone contain about the same amount of barium as the average limestone (Bowen, 1966, p. 176), a little less, or a little more. Thus, the barium content of the other silicified limestones, the unsilicified limestone, and marl can be considered to be normal.

Rather erratic values for barium were found for the massive and brecciated chert. Only one can be regarded as anomalous: sample 77-OT-611 with 3,000 ppm barium (table 5). Both uranium and vanadium are a little more abundant in this specimen than in the other samples of chert.

The high value of 5,000 ppm barium was found in the single sample of silicified phosphate rock (77-OT-619) in the suite from Jabal Waqf es Suwan (table 5). Accompanying the anomalous content of barium are highly anomalous amounts of strontium, uranium, and vanadium. These latter three elements are also enriched in the other phosphatic specimen (77-OT-618).

The manganese content of the samples of sedimentary rocks reported in table 5 tend to be low; only four samples (77-OT-592, -593, -594, and -600) contain 1,000 ppm or more manganese. The two samples of silicified limestone with anomalous barium are among the four specimens with 1,000 ppm or more of manganese, but for both samples of silicified limestone this manganese content is about average for limestones (Bowen, 1966, p. 191). The lowest concentrations for manganese were found for the two phosphatic rocks (77-OT-618 and 77-OT-619), which are anomalously enriched in strontium, uranium, and vanadium. The distributon of manganese in the sampled rocks at Jabal Waqf es Suwan is more in accord with variations related to original sedimentary deposition than with subsequent addition from underlying igneous sources.

Strontium, uranium, and/or vanadium are anomalously enriched in the marl, brecciated chert, massive chert, phosphatic chert, siliceous phosphate rock, and one sample (77-OT-620) of siliceous limestone (table 5). They are characteristic elements of sedimentary deposition, and the geochemical association of uranium with vanadium in phosphate deposits is well known. Uranium for example, is commonly present in Jordanian phosphorites in abundances of 100-125 ppm (Bender, 1974, p. 159).

Geologic inferences.--None of the elements that was detected in the samples from Jabal Waqf es Suwan can be attributed with real assurance to sources in underlying igneous rocks. Many elements that can be expected to have migrated upward from igneous rocks are undetected in these samples, or if present, they are not unusually abundant for sedimentary rocks. So far as can be determined from the present geochemical data, the distribution and abundances of the elements reported for the suite of rocks from Jabal Waqf es Suwan are entirely compatible with sedimentary deposition from sea water under varied conditions resulting from changes in the physical, chemical, and biologic character of the marine environment (Cathcart and Gulbrandsen, 1973, p. 517).

Owing to a lack of published results of analyses of the carbonate rocks at Hicks Dome, only the trace-elements chemistry of mafic dikes and intrusive breccia could be cited to show abundances of elements. No direct comparison may be made, of course, between abundances of those elements in sedimentary and in igneous rocks. However, the purpose was served of showing what elements are enriched at a major, mineralized cryptovolcanic structure. The general failure of the more mobile of these elements to show up at Jabal Waqf es Suwan is thought to indicate a lack of mineralization at the cryptovolcanic structure in Jordan, either similar to the enrichments at Hicks Dome (beryllium, niobium, rare earths, barium, zinc, and fluorite), or different (as base metals).

Several of the samples from Jabal Waqf es Suwan might actually represent the walls of joints or fractures along which halo-induced metallization occurred, but this interpretation requires much additional sampling and analysis.

In the light of the results of the present geochemical orientation survey, the interpretation is proposed that Jabal Waqf es Suwan is a structural dome over a buried volcanic plug. This plug is probably related to the Neogene and Pleistocene basaltic flows and tuffs known elsewhere in Jordan (Bender, 1975, pl. 1).

Future exploration

Further geochemical exploration is needed at Jabal Waqf es Suwan, but in terms of national priorities for the operations of NRA, such exploration should be rather low in comparison with other investigations. Chip samples of rocks should be taken under careful stratigraphic control. The positions of the samples and the detailed sedimentary and structural geology of the structure should be mapped by plane table at 1:10,000 scale and the results should be compared with the existing geophysical and geochemical surveys on file in NRA. During this program, a drill hole should be sunk near the center of the structure to a depth of 500 m for additional geologic, geochemical, and mineralogical data.

Apatitic limestone from the Daba'ah-Al Qatranah area

Material analyzed

Crystalline brown, black, red, green, and white apatitic limestones have been quarried for ornamental stone, called marble, in the Daba'ah-Al Qatranah area (fig. 1) of the Hashemite Kingdom of Jordan since 1951 (Walid Hakki, written commun., 1978; Pressler, 1978). The ornamental character of this rock was appreciated as long ago as the Roman occupation (fig. 4, A and B). Daba'ah and Al Qatranah are stations on the railroad situated respectively about 50 km and

A. Mottled apatitic limestone.

B. Unfinished column probably dating from Roman time.

Figure 4. Photographs showing quarries in apatitic limestone used as a source for ornamental stone, Daba'ah-Al Qatranah area, Hashemite Kingdom of Jordan.

90 km south of Amman. Hakki noted that these apatitic limestones are at a sedimentary discontinuity in the uppermost part of the unit of Maestrichtian to Early Paleocene age shown as "chalky marls, bituminous limestones and marls, locally gypsum, locally crystalline limestones" on the geologic map of the Amman quadrangle (Bender, 1968b). The apatitic limestone was described by Hakki as forming strongly linear outcrop patterns following the trends of major east-striking faults that branch from the main Jordan Rift Valley faults, as well as following the trends of faults of lesser magnitude that strike toward the north-northwest. These apatitic limestones quarried for ornamental use are exposed in irregularly lenticular masses 20-100 m long, 20-40 m wide, and 3-5 m thick (Walid Hakki, written commun., 1978).

The so-called marble horizon in the apatitic limestone is regarded by Bender (1974, p. 80-82) as being restricted to an euxinic sedimentary facies stratigraphically younger than the main phosphorite-bearing rocks of Jordan. Bender describes the rocks as being multicolored owing to secondary mineralization and as being intersected by many fissures and joints that are recrystallized. The industrial demand to use the rock as marble results from its handsome colors and its ability to withstand sawing and to take a polish.

As early as 1963 a rare calcium-chromate mineral was described from the multicolored apatitic limestone quarried near Al Qatranah (Eckhardt and Heimbach, 1963, cited in Bender, 1974, p. 158). Several rare minerals characteristic of artificial compounds found in portland cement, as well as rare chromium minerals and minerals containing nickel, vanadium, and silver, have been described in similar rocks on the west side of the Jordan Valley (Bentor and others, 1963; Gross, 1977). These minerals include chromatite, spurrite, bayerite, vaterite, portlandite, tobermorite, thaumasite, and ettringite.

Various explanations have been offered for the origin of this unusual suite of heavy-metal bearing minerals in these euxinic facies sedimentary rocks. The most consistent explanation called upon a combination of oxidation and thermal metamorphism (Bentor and Vroman, 1960, p. 58-61). In its earliest form, this explanation proposed widespread oxidation of sulfide minerals and bituminous matter in the euxinic rocks by the post-depositional circulation of oxygen-rich ground water. The oxidation was thought to have occasioned considerble heating because of the low thermal conductivity of the overlying sedimentary rocks. The new minerals formed in response to this heating. The explanation as originally proposed was insufficient to account for the formation of a high-temperature mineral such as spurrite, and for the crystallization of portlandite and ettringite, which form under conditions of extremely high alkalinity (Bentor and others, 1963, p. 930; Bender, 1974, p. 158).

A varied range in temperature of formation of these minerals was thought to be required, from the high temperatures associated with spurrite to the low temperature (110C) at which ettringite loses most of its water and lattice shrinkage occurs (Taylor, 1973, p. 388). However, variations in pH and cation content of ground water can cause the crystallization of mineral assemblages that mimic suites generally thought to represent wide ranges in temperature and pressure (Ivan Barnes, written commun., 1980).

Elsewhere in Jordan, ground water having extremely high pH has been observed. Water from springs and wells in the Yarmouk River drainage north of Irbid was found by the USGS to have unusually high pH values of more than 12.5

(Ivan Barnes, written commun., 1980) where bituminous marls and chalky to cherty limestones were the aquifers. Heat from the oxidation of the bituminous marls, as earlier described (Bentor and Vroman, 1960; Bentor and others, 1963), was thought by Barnes to calcine the marl to lime which would rehydrate to portlandite and other minerals, depending upon the varied sedimentary components--in addition to calcite--capable of yielding a complex suite of heavy-metal-bearing minerals under a wide range of temperature of reaction (Mathews and Kolondy, 1978; Ivan Barnes, written commun., 1980). Thus, chemically active ground water of high pH would be able to cause the formation of the complex suite of heavy-metal-bearing minerals described for the multicolored apatitic limestone.

New studies of the rare minerals in this marble were begun in 1977 by members of USGS (Phoebe L. Hauff, written commun., 1979), who think that hydrothermal processes connected with the Lisan-Suwaqa fault (Bender, 1968b), instead of diagenetic processes in heavy-metal-bearing euxinic facies sedimentary rocks, may be the source of some of the barium- and chromium-enriched minerals found in veinlets and fracture fillings in the apatitic limestone.

The possibility that hydrothermal activity along the Lisan-Suwaqa fault yielded products having trace-element similarities to hydrothermal alteration at Zarqa Ma'in and the barite veins northwest of Mahattat el Jufur led the present writers to analyse a specimen of the crystalline limestone from a quarry (3130'00"N.; 3612'30"E.) to the north of Jebel al Suwaqa. The hand specimen used for analysis was banded red, red to white, white to green, and green. Seven samples were divided on a basis of color for semiquantitative spectrographic analysis:

Sample number	Description
78-MQ- 1	Dark red with minor dark green marble
- 2	Bright green marble with white streaks
- 3	Dull green marble
- 4	Red marble
-4A	Red to white marble
-4B	White to green marble
-4C	Green marble

Composition compared to other rocks and ores analyzed in the present study

The results of the analyses of these samples are given in table 7.

None of the other samples from Jordan analyzed for this investigation contains as large a suite of anomalously rich elements as this set of samples from the apatitic limestone. Elements clearly anomalously abundant in the apatitic limestone, compared to other rocks and ores sampled in Jordan (table 8), include: Ag, Cd, Cr, Mo, Ni, V, Y, and Zn. Possibly copper should also be listed with the anomalously abundant elements in the apatitic limestone, if the copper ores (table 8) are not used in the comparison.

The closest values to those of the anomalous elements in the apatitic limestone were found in three artificially prepared materials used in this study (table 8): (1) ash of pyritiferous lignite from Triassic (?) or Jurassic (?) sandstone in the Ba'qaa Valley; (2) oxalic acid leachate of sedimentary rocks in Wadi Shureh near Al'Aqabah; and (3) concentrate panned from the Precambrian Saramuj Conglomerate in Wadi Saramuj about 80 km southwest of the sample site in the apatitic limestone. None possessed all the anomalous trace-element characteristics of the apatitic limestone, and none had the unique enrichment found for cadmium in that rock.

able 7. *Results of semiquantitative spectrographic analyses of apatitic limestone from the Daba'ah-Al Qatranah area, Hashemite Kingdom of Jordan.*
[Analyses by D. J. Grimes and R. T. Hopkins, USGS, 1978.]

Sample numbers		In percent[1]			In parts per million[2]																
ield	Laboratory	Fe	Mg	Ti	Ag	B	Ba	Cd[3]	Cr[4]	Cu	La	Mn	Mo	Ni	Pb	Sc	Sr	V	Y	Zn	Zr
8-MQ-1	MAX-273	0.7	1	0.15	10	70	700	100	5,000	200	L(20)	70	300	300	N(20)	7	2,000	5,000	70	5,000	30
-2	-274	.15	1	.02	N(0.5)	L(20)	500	70	5,000	70	20	10	20	200	N(20)	5	2,000	500	70	700	10
-3	-275	.1	0.5	.015	N(0.5)	70	1,000	70	G(5,000)	50	20	L(10)	20	200	20	5	1,500	700	100	200	30
-4	-276	.7	3	.1	7	70	300	G(500)	500	500	20	50	30	500	50	7	1,500	500	70	5,000	50
-4A	-277	1	1.5	.15	7	30	300	G(500)	300	700	20	70	7	1,500	50	10	1,500	500	70	5,000	70
-4B	-278	.1	.7	.03	2	L(20)	200	G(500)	1,000	150	20	L(10)	5	200	N(20)	5	1,500	300	100	700	20
-4C	-279	.05	.5	.02	15	L(20)	300	500	G(5,000)	30	L(20)	L(10)	5	150	N(20)	L(5)	1,500	300	70	500	15

Calcium is greater than 20 percent, the upper limit of determination, in all samples.

Elements looked for but not found at lower limits of determination shown in table 1: As, Au, Be, Bi, Nb, Sb, Sn, Th, and W.

Elements rarely present at lower limits of determination shown in table 1, sample number, and abundance are: Co, 5 ppm, 78-MQ-4A.

Abundance of cadmium shown as G(500) reported by analysts to be in range of 700-1,500 ppm.

Abundance of chromium shown as G(5,000) reported by analysts to be 7,000 ppm.

Table 8. Comparison of trace-element content of apatitic limestone from the Daba'ah-Al Qatranah area with trace-elements in other rocks and ores from the Hashemite Kingdom of Jordan, in ppm

Element	Apatitic limestone (average of 7 from table 7)	Ash from pyritiferous lignite from Triassic(?) or Jurassic(?) sandstone in the Ba'qaa Valley (1 from table 32)	Altered sedimentary rocks, Zarqa Ma'in (average of 9 from table 9)	Wadi Shureh			Vein northwest of Mahattat el Jufur		Copper ore from Wadi Feinan, Wadi Dana, Wadi Khalid, and Jebel Khirbet en Nuhas (average of 6 from table 21)	Sedimentary rocks from Jabal Waqf es Suwan (average of 29 from table 5)	Concentrate from Precambrian Saramuj Conglomerate in Wadi Saramuj	
				Altered granite (average of 21 from table 16)	Altered sedimentary rocks (average of 10 from table 17)	Oxalic acid leachate of altered sedimentary rocks (average of 8 from table 17)	Barite (average of 2 from table 2)	Jasperoid (1 from table 2)			Magnetic fraction (1 from table 14)	Nonmagnetic fraction (1 from table 14)
Ag	7	N(0.5)	N(0.5)	N(0.5)	L(0.5)	50	N(0.5)	3	5	N(0.5)	N(0.5)	N(0.5)
B	50	300	70	50	20	200	N(20)	100	50	30	30	30
Ba	500	1,500	100	200	300	1,000	G(5,000)	G(5,000)	700	700	200	1,500
Be	N(2)	10	L(2)	L(2)	3	30	N(1)	N(1)	5	N(2)	N(2)	N(2)
Bi	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)
Cd	500	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)
Co	N(5)	100	15	L(5)	10	100	N(5)	N(5)	20	N(5)	100	70
Cr	3,000	300	50	10	L(20)	500	100	100	20	L(50)	2,000	1,500
Cu	200	150	10	10	30	300	7	15	G(20,000)	20	50	50
La	20	N(20)	30	50	30	20	N(20)	N(20)	20	N(20)	N(20)	70
Mn	30	150	500	300	500	5,000	N(10)	100	1,000	300	1,500	1,500
Mo	50	30	N(5)	N(5)	N(5)	15	N(5)	N(5)	L(5)	L(5)	N(5)	N(5)
Ni	500	300	20	5	20	300	5	10	30	7	150	150
Pb	20	150	50	L(20)	70	300	N(20)	N(20)	300	L(20)	50	100
Sc	7	7	L(5)	N(5)	15	15	N(5)	N(5)	L(5)	N(5)	20	20
Sr	1,500	N(100)	100	300	200	1,500	G(5,000)	1,500	150	300	N(100)	N(100)
V	1,000	3,000	100	30	70	2,000	70	70	70	30	7,000	1,500
Y	70	20	20	15	30	70	N(10)	N(10)	10	L(10)	20	50
Zn	2,000	N(200)	N(200)	N(200)	N(200)	2,000	N(200)	N(200)	L(200)	N(200)	N(200)	N(200)
Zr	30	500	100	500	150	150	N(10)	N(10)	100	L(10)	300	700

Distribution of elements

A clear preferred association of high values of elements for particular color phases of the apatitic limestone is seen in the data in table 7. The red (78-MQ-1 and -4) and red to white (78-MQ-4A) phases of the apatitic limestone tend to be enriched in Fe, Mg, Ti, Cu, Mn, Mo, Ni, Sc, V, and Zn. Chromium is least abundant in those phases, but it is most abundant in the white to green (78-MQ-2 and -4B) and the green (78-MQ-3 and -4C) phases. No essential differences in abundance by color phase of the rock can be seen for La, Sr, and Y. The distributions of Ag, B, Ba, Cd, Pb, and Zr are too variable to be related to color phases.

Chemical data on the common black and brown color phases (Walid Hakki, written commun., 1978) are lacking, but these data are obviously needed.

The observed associations of elements with color phases of the rock are probably controlled by differences in the mineral composition of the four color phases analyzed here. This is a subject that needs to be investigated, not only for an understanding of the origin of the so-called marble and of its suite of rare, heavy-metal-bearing minerals, but also for the significant role that color would have on the choice of rock chips for use as a sample medium in future geochemical studies. Should these color-related differences hold in general for the apatitic limestone, then great care would be needed in the selection of samples for analysis.

Possible sources of anomalous elements

The presence of anomalous amounts of Ag, Cr, Ni, and V in the crystalline apatitic limestone has long been known, and these metals have been interpreted as a typical enrichment associated with euxinic facies sedimentary rocks

(Bender, 1974, p. 158). The rare minerals incorporating these elements have been ascribed to secondary processes during diagenesis (Bender, 1974, p. 158), to oxidation and thermal metamorphism (Bentor and Vroman, 1960), or to hydrothermal activity associated with movement of fluids along the major, east-trending Lisan-Suwaqa fault (Phoebe L. Hauff, written commun., 1979). The observation that the lenticular bodies of the heavy-metal-bearing apatitic limestone tend to be most common where east-trending faults are intersected by north-northwest-trending faults (Walid Hakki, written commun., 1978) also suggests that some post-depositional structural control of migrating solutions was one aspect of the formation of these bodies. Thus, a combination of sedimentological, metamorphic, and structural factors may be involved in the origin of the rock, because the heavy metals that are enriched in the crystalline apatitic limestone are commonly enriched in phosphorites and euxinic sedimentary rock (Hawkes and Webb, 1962, p. 360-367; Rankama and Sahama, 1950).

The concept of Bentor and Vroman (1960) as modified by Ivan Barnes (written commun., 1980) to provide a flow of ground water of exceptionally high pH seemingly can account for the formation of the heavy-metal bearing minerals in the apatitic limestone from sources within the rock. Localization along the Lisan-Suwaqa fault could be caused by migration toward release through available fratures. Thus, the fault is not a channel for hydrothermal fluids from depth but a conduit for emerging gound water.

The only other phosphatic rocks analyzed in the present study are the stratigraphically lower phosphatic chert and siliceous phosphate rock from the area of Jabal Waqf es Suwan, samples 77-OT-618 and -619 in table 5. By comparison, the apatitic limestone from the Daba'ah-Al Qatranah area is greatly enriched in Cd, Cr, Cu, Ni, V, and Zn:

Element	Abundance in ppm		
	Daba'ah-Al Qatranah area apatitic limestone (average of 7)	Jabal Waqf es Suwan	
		Phosphatic chert (77-OT-618)	Siliceous phosphate rock (77-OT-619)
Ag	7	5	N(0.5)
Cd	500	N(20)	N(20)
Cr	3,000	50	150
Cu	200	20	30
Mo	50	N(5)	10
Ni	500	5	30
V	1,000	70	300
Y	70	20	20
Zn	2,000	N(200)	N(200)

The geochemical similarity of the apatitic limestone to euxinic facies sedimentary rocks is clear. What is uncertain is whether the original heavy-metal components of this sediment were mobilized mainly in the diagenetic stage or in a later hydrothermal stage. The high average value for cadmium (500 ppm) and the low Zn:Cd ratio of 4, as well as the low Co:Ni ratio of <0.05, suggest that low-temperature migration has occurred, but the controlling conditions cannot be determined from present data on the heavy metals in the apatitic limestone.

When the trace-elements suite in the hydrothermally altered rocks at Zarqa Ma'in or Wadi Shureh are compared with those of the apatitic limestone, no similarity can be seen except in the enhanced anomalies obtained at Wadi Shureh by the oxalic-acid leach technique (table 8). The lack of cadmium at both of these hydrothermal sites suggests that the cadmium in the apatitic limestone may be of original sedimentary origin.

Further studies

Further studies of the apatitic limestone and of other rocks exposed along the trace of the Lisan-Suwaqa fault are needed to determine whether this structure actually was a conduit for hydrothermal solutions and also to understand the possibility for blind ore deposits of hydrothermal origin in the Hashemite Kingdom of Jordan.

Altered rocks from Zarqa Ma'in

The thermal springs at Zarqa Ma'in (3136'25"N.; 3536'04"E.) emerge along the northern wall of Wadi Zarqa Ma'in about 4 km east of the Dead Sea (fig. 1). The geology and hydrogeology have been described by Bender (1974, p. 178- 180, table 12), and the springs were recognized by Abu Ajamieh (1974, p. 37-46) as the most radioactive areas discovered in Jordan to 1974. Wide discoloration and alteration of the sedimentary rocks, mainly sandstone, shale, and marl, in the north wall of the wadi (fig. 5, A and B), combined with the suggestion by Abu Ajamieh (1974) of possible unexposed sulfide mineral deposits at depth, led to a recommendation that the hydrothermally altered rocks be examined geochemically (Overstreet, 1978a, p. 17). The water of the warm springs was shown by Bender (1974, table 12) to be enriched in bromine and iodine, and thereby have a similarity to the Dead Sea water, and the source of heat was attributed to the geothermal gradient associated with the roots of basaltic extrusions of middle Pleistocene or younger age (Bender, 1974, p. 179-180). The interesting possibility exists that the regional geologic process giving rise to the warm springs might be analogous to that supplying the heavy-metal brines in the central Red Sea (Bischoff, 1969; Hendricks and others, 1969; Bischoff and Manheim, 1969; Shanks and Bischoff, 1977), and that possible heavy-metal sulfide deposits at depth in Wadi Zarqa Ma'in would have come from solution of Dead Sea evaporites. This possibility could be further tested by comparison of the distribution and abundance of minor elements at Zarqa Ma'in with published geochemical evidence from the

A. One of 18 warm springs at Zarqa Ma'in, showing

B. Warm stream fed by warm springs.

Figure 5. Photographs showing warm springs and warm stream at Zarqa Ma'in, Hashemite Kingdom of Jordan.

Broadlands geothermal field, New Zealand, where a crude zoning of metals was found in which Ag, Se, Te, Bi, Pb, Zn, Cu, and Co were concentrated at depth, and As, Sb, Au, and Tl were enriched in near-surface regions (Ewers and Keays, 1977). Thus, it was hoped that systematic analyses of alluvium, warm springs deposits, and altered wallrocks in Wadi Zarqa Ma'in might give geochemical clues to support the supposition that sulfide deposits were at depth (Abu Ajamieh, 1974, p. 37-46).

The necessary systematic sampling for this evaluation has not been done. However, one sample of alluvium was collected by W. C. Overstreet, USGS, in November 1977 from the warm stream in the bed of Wadi Zarqa Ma'in at the point where the road crosses the stream (sample 77-OT-621), and nine samples of hydrothermally altered sedimentary rocks (samples 78-ZM-1 through 78-ZM-9) were collected along the road into the wadi by D. J. Grimes, USGS, in February 1978:

Field number	Altitude in meters (mean sea level, Mediterranean Sea)
78-ZM-1	+91.4
-2	+54.9
-3	+24.4
-4	- 6.1
-5	-36.6
-6	-45.7
-7	-67.1
-8	-85.3
-9	-97.5

The sample of alluvium was dark mud. One sample (78-ZM-6) of the altered sedimentary rocks was a piece of float. The other samples were taken in place. Sample 78-ZM-8 included the walls of a vertical fracture with alteration.

All samples were analyzed in the USGS laboratories, Denver, Colorado. Prior to preparing the specimen of alluvium for analysis, it was studied mineralogically by Theodore Botinelly, USGS, for the possible presence of hokutolite, a gray, radium-bearing plumbian barite (Okamoto, 1911; 1912, p. 178-184; 1913; 1915, p. 27; Overstreet, 1971b, p. 13). Hokutolite is a rare mineral of the barite-anglesite isomorphous series. Evidently the term hokutolite has been abandoned as an invalid name for an intermediate member of a series, because it does not appear in recent lists of valid mineral names (Fleischer, 1975). As originally described in the early 1900's, hokutolite is found as botryoidal coatings on ledges and rocks in the bed of a stream supplied by thermal water issuing from a warm spring at Peitou in the Tatun volcanic area in Taiwan. Inasmuch as barium and radium are present in the waters of the Zarqa Ma'in warm springs, it was thought that this rare mineral might be found in the mud from the bed of the stream. X-ray diffraction analyses of various size fractions of the sample from the bed of the warm-water stream were reported (Theodore Botinelly, written commun., 1978) to show quartz, calcite, and clays. Upon leaching with 6N HCl, a split of the sample was cleared of the calcite, and the white residue (quartz and clay) disclosed only one-fifth of the radioactivity of the unleached sample. Thus, the radioactive elements may be in the calcite. Indeed, the unleached sample is rather lean in uranium, as determined fluorometrically (see below), but it has a fairly high instrumental equivalent uranium content. The difference between the chemically determined value for uranium and the value for instrumentally determined equivalent uranium shows other radioactive elements to be present despite the lack of hokutolite.

Only a small part of the radioactivity of the sample mud from the bed of the warm stream is due to uranium. The reported equivalent uranium is a measure of the amount of gamma radiation emitted by the sample, and the interpretation is that either uranium has been leached from the sample, or that daughter products have migrated to the sample site. The presence or absence of hokutolite has little significance, despite the fact that radium sulfate precipitates with barium sulfate.

The results of the various analyses on the raw samples are shown in table 9 and the results of spectrographic analyses on oxalic acid leachates from the hydrothermally altered sedimentary rocks are shown in table 10. Many of the elements particularly sought in the contexts of comparison with metal-rich Red Sea brines, or as indicators of deep-seated base-metal deposits associated with a geothermal field, proved to have abundances below the lower limits of determination available for the methods of analysis used. Interestingly, the results of the spectrographic analyses of the oxalic acid leachates showed that this technique greatly enhances the values obtained for a number of elements, particularly Fe, Ba, Co, Cr, Cu, Mn, Ni, and Pb. A similar leach was also used for the analysis of some samples from Wadi Shureh southeast of Al'Aqabah, with similar results.

Comparison with Red Sea metal-rich hot brine deposits

The metal-rich hot brine deposits of the central Red Sea (Bischoff, 1969; Hendricks and others, 1969; Bischoff and Manheim, 1969; Shanks and Bischoff, 1977) consist of unconsolidated sediments that have precipitated out of the superjacent layer of brine. The brine is seawater that has circulated through underlying Miocene evaporites and that rises when heated by geologically young intrusive rocks in the Red Sea rift zone. These deposits vary widely in physical appearance and chemical composition, and contain from 55 to 96

Table 9. Results of analyses of alluvium and of altered sedimentary rocks from Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan.
[Analysts: D. J. Grimes, R. T. Hopkins, J. C. Negri, J. G. Viets, D. M. Hopkins, and R. W. Leinz, USGS. n.d. = no data.]

Element	Sample numbers (field numbers followed by laboratory number)									
	77-OT-621 (MAX-226)	78-ZM-1 (MAX-249)	78-ZM-2 (MAX-250)	78-ZM-3 (MAX-251)	78-ZM-4 (MAX-252)	78-ZM-5 (MAX-253)	78-ZM-6 (MAX-254)	78-ZM-7 (MAX-255)	78-ZM-8 (MAX-256)	78-ZM-9 (MAX-257)
	Results in percent									
Fe	3	5	10	15	10	10	~30	1	2	15
Mg	5	10	.7	.03	.07	.2	.2	.2	.3	.03
Ca	20	20	20	.5	.7	.3	1.5	2	.3	.05
Ti	.15	.15	.03	.07	.1	.3	.03	.05	.07	.15
	Results in parts per million (ppm)[1]									
Au	L(.05)	N(.05)	N(.05)	N(.05)	N(.05)	N(.05)	N(.05)	N(.05)	N(.05)	N(.05)
B	70	70	30	70	70	50	300	L(20)	L(20)	70
Ba	300	20	L(20)	50	300	200	150	30	50	50
Be	2	N(2)	15	N(2)	N(2)	N(2)	N(2)	N(2)	N(2)	N(2)
Co	5	N(5)	150	N(5)	5	N(5)	N(5)	N(5)	N(5)	N(5)
Cr	100	100	30	50	50	70	150	N(20)	L(20)	70
Cu	10	5	30	15	5	20	20	5	7	10
Hg	N(.02)	N(.02)	.02	L(.02)	N(.02)	N(.02)	N(.02)	N(.02)	N(.02)	N(.02)
In	n.d.	N(.1)	.1	.1	N(.1)	N(.1)	.1	N(.1)	N(.1)	N(.1)
La	N(20)	L(20)	50	50	70	70	L(20)	50	L(20)	50
Mn	5,000	1,000	3,000	70	100	20	150	20	10	10
Ni	20	15	150	L(5)	5	L(5)	5	L(5)	L(5)	L(5)
Pb	L(20)	L(20)	L(20)	70	30	30	150	20	70	50
Sc	5	5	L(5)	L(5)	L(5)	5	L(5)	N(5)	N(5)	5
Se	.7	.7	.9	.7	.2	.2	.4	.2	.2	.3
Sr	1,500	100	N(100)	200	N(100)	N(100)	300	N(100)	100	100
Tl	N(0.2)	N(.1)	.3	.6	.2	.1	.2	N(.1)	.1	.7
eU	30	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)
U	.8	2.9	2.2	.8	1.2	.9	.8	.9	.7	1.0
V	50	70	30	100	100	70	150	15	15	300
Y	15	10	100	L(10)	15	10	L(10)	10	10	15
Zn	N(200)	N(200)	200	N(200)	N(200)	N(200)	N(200)	N(200	N(200)	N(200)
Zr	70	30	10	100	150	300	20	70	70	200

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[1] Looked for but not found at lower limits of determination, in parts per million, as shown: Ag, 0.5; As, 200; spectrographic Au, 10; Bi, 10; Cd, 20: Mo, 5; Nb, 20; Sb, 100; Sn, 10; Te, 0.2; Th, 100; and W, 50.

Table 10. Results of spectrographic analyses of oxalic acid leachates of hydrothermally altered sedimentary rocks from Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan.
[Analysts: D. J. Grimes and R. T. Hopkins, USGS.]

Element	Sample numbers (field numbers followed by laboratory number)								
	78-ZM-1X (MAX-288)	78-ZM-2X (MAX-289)	78-ZM-3X (MAX-290)	78-ZM-4X (MAX-291)	78-ZM-5X (MAX-292)	78-ZM-6X (MAX-293)	78-ZM-7X (MAX-294)	78-ZM-8X (MAX-295)	78-ZM-9X (MAX-296)
Results in percent									
Fe	30	30	50	50	50	50	30	30	50
Mg	20	5	1	3	5	2	7	5	0.15
Ca	1	10	5	3	5	5	3	2	.3
Ti	0.02	N(0.002)	0.07	0.07	0.07	0.07	0.07	.03	.02
Results in parts per million (ppm)[1]									
B	200	100	100	100	200	700	100	100	70
Ba	50	20	300	700	500	1,000	500	300	70
Be	7	30	2	7	L(2)	L(2)	L(2)	L(2)	L(2)
Co	20	1,500	10	150	7	5	15	L(5)	L(5)
Cr	100	50	300	300	500	300	200	100	300
Cu	300	150	70	70	300	100	70	70	150
Mn	1,500	G(10,000)	300	2,000	1,000	700	700	150	200
Ni	50	700	30	150	50	50	70	15	30
Pb	20	30	700	150	100	500	100	500	150
Sr	N(100)	N(100)	2,000	150	200	1,500	150	1,000	200
V	100	50	200	500	300	500	200	70	1,500

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[1] Looked for but not found at lower limits of determination in parts per million, as shown: As, 200; Au, 10; Bi, 10; Cd, 20; Nb, 20; Sb, 100; Sn, 10; Th, 100; and W, 50. Elements rarely detected, abundances in ppm, and sample numbers: Ag, 3, 78-ZM-8X, 30, 78-ZM-1X; La, 30, 78-ZM-2X; Mo, 100, 78-ZM-1X; Sc, 15, 78-ZM-9X; Y, 70, 78-ZM-2X; Zn, 1,000, 78-ZM-2X; and Zr, 30, 78-ZM-6X, 50, 78-ZM-3X and -7X.

percent interstitial brine. Deposits in the Atlantis II Deep have the highest average content of metals: Fe, 29 percent; Zn, 34,000 ppm; Cu, 13,000 ppm; Pb, 1,000 ppm; Ag, 54 ppm; and Au, ±0.5 ppm. Within the deposits, the greatest amounts of heavy metals are in dark sulfide-rich sediments.

Lead in the near-surface brine deposits of the Red Sea is dominantly of mantle derivation, but the metalliferous sediments are thought to have received at least some of their heavy metals through the solution of underlying evaporite deposits (Delevaux and Doe, 1977, p. 04). The indirect source of the mantle-derived lead appears to be the weathered young, mantle-derived volcanic rocks, the lead then being transported to the Red Sea instead of being directly introduced from the underlying mantle. Evaporite sequences in the Dead Sea might be a source for possible heavy metals at Zarqa Ma'in.

The interstitial brines are essentially saturated with sodium chloride (Hendricks and others, 1969) and are enriched in Ca, Mg, K, Fe, and Mn compared with the warm springs waters at Zarqa Ma'in (table 11). Interestingly, SO_4^{++} is nearly the same in both types of water, but most interesting is the large amount of bromine in the Red Sea interstitial brine. The bromine content, 2.9 ppm, of the warm springs waters at Zarqa Ma'in, was regarded by Bender (1974, p. 180) as sufficiently high to merit special consideration. The bromine content of the Red Sea brine is about 50 times greater (138 ppm) than the warm springs waters, and both are vastly less than the bromine content of the Dead Sea (3,850 ppm) at the mouth of Wadi Zarqa Ma'in (Bender, 1974, table 12).

The fact the bromine contents of the warm springs waters and the Red Sea interstitial waters are high is indeed one of the chemical similarities. Other similarities also exist. Because one is a brine and the other a weakly mineralized thermal water, the absolute abundances of the major constituents

Table 11. Comparison of dissolved solids and major components of the warm spring waters at Zarqa Ma'in, Jordan, and the interstitial brines from the heavy-metal deposits in the central Red Sea, in ppm
[Data for Zarqa Ma'in from Bender, 1974, table 12; data for Red Sea brines from Hendricks and others, 1969, tables 5 and 8.]

Constituents	Zarqa Ma'in water	Red Sea brine
Total dissolved solids	1734	260,000
Cl^-	659.8	155,000
SO_4^{--}	207.1	228.6
Ca^{++}	130.7	4,800
Mg^{++}	32.2	947
Na^+	422.6	89,000
K^+	51.0	3,100
Br^-	2.9	138
Fe	0.05	41
Mn	.19	75

(table 12) cannot be compared, but noteworthy similarities exist in a number of ratios for the two waters. For example:

Ratio	Zarqa Ma'in	Red Sea brine
$\frac{\text{Cl}}{\text{Dissolved solids}}$	0.38	0.6
$\frac{\text{Na}}{\text{Dissolved solids}}$	.24	.34
$\frac{\text{K}}{\text{Dissolved solids}}$	.03	.01
$\frac{\text{Mn}}{\text{Dissolved solids}}$	.00011	.00029
$\frac{\text{Mg}}{\text{Ca}}$	.25	.20
$\frac{\text{Mg}}{\text{K}}$	.63	.31
$\frac{\text{Fe}}{\text{Mn}}$	.26	.55
$\frac{\text{Br}}{\text{Ca}}$	.02	.03
$\frac{\text{Br}}{\text{Mg}}$	.09	.15

Table 12. Comparison of average amounts of minor elements in alluvium and hydrothermally altered rocks at Zarqa Ma'in, Jordan, with amounts in sediments and interstitial brines associated with deeps in the central Red Sea, in ppm

[n.d. = no data]

Element	Zarqa Ma'in		Red Sea deeps		Crustal abundances			
	Alluvium (1 sample)	Altered sedimentary rocks (9 samples)	Sediment (110 samples) (Hendricks and others, 1969, table 6)	Interstitial brine (50 samples) (Hendricks and others, 1969, table 5)	Continental lithosphere (Beus and Grigorian, 1977, table 3)	Average sedimentary rocks (Rankama and Sahama, 1950, table 5.52) Sandstone	Shale	Limestone
Au	L(.05)	N(.05)	0.01[1], 0.27[2], 0.44[3]	trace[4]	0.0017	0.028	n.d.	0.005-0.009
B	70	75	100	31	7	9-31	310	3
Ba	300	95	1,800	4	450	170	460	120
Be	2	L(2)	<0.1	N[4]	1.5	0	<3.6	0
Co	5	15	47	1[5]	34	0	8	0
Cr	100	60	27	<0.1	120	68-200	410-680	2
Cu	10	13	1,700	3	65	n.d.	192	20.2
In	n.d.	L(.1)	<0.1	N[4]	.23	.3	.5	n.d.
La	N(20)	40	3	N[4]	25	n.d.	n.d.	n.d.
Mn	5,000	487	13,000	70	900	trace[4]	620	385
Ni	20	20	20	.1	95	2-8	24	0
Pb	L(20)	50	200	<.9	9	20	20	5-10
Sc	5	L(5)	<10	N[4]	24	.7	6.5	0
Se	0.7	0.4	n.d.	n.d.	.1	n.d.	.6	<.1
Sr	1,500	100	800	75	380	<26	170	425-765
Tl	N(0.2)	.3	2	N[4]	.7	2	2	n.d.
U	.8	1.3	N(2,000)	N[4]	1.5	1.2	1.2	1.3
V	50	94	100	N[4]	190	20	120	<10
Y	15	20	8	N[4]	26	1.6	28.1	0
Zn	N(200)	L(200)	8,5000	10.3[5]	87	<20	200-1,000	>50
Zr	70	105	200	trace[4]	130	n.d.	120	n.d.
Minor elements below limit of determination at Zarqa Ma'in								
Ag	N(.05)		19	0.09	.09	.44	.05	.2
As	N(200)		100	N[4]	1.9	n.d.	5	n.d.
Bi	N(10)		N(2)	N[4]	.08	.3	1	n.d.
Cd	N(20)		38	N[4]	.19	0	.3	n.d.
Mo	N(5)		100	0.1	1.3	n.d.	n.d.	n.d.
Nb	N(20)		N(100)	N[4]	19	n.d.	n.d.	n.d.
Sb	N(100)		5	trace[4]	.2	1	3	n.d.
Sn	N(10)		.3	[4]	1.9	n.d.	40	n.d.
Te	N(0.2)		N(20)	N[4]	.001	n.d.	n.d.	n.d.
Th	N(100)		N(1,000)	N[4]	7.3	6.1	10.1	1.1
W	N(50)		.6	N[4]	1.1	n.d.	1-2	n.d.

[1] Average for 110 samples by spectrographic analysis (Hendricks and others, 1969, table 6).
[2] Average of four composites representing 51 samples by spectrographic analysis with chemical preconcentration (Hendricks and others, 1969, p. 414).
[3] Average of 87 samples by atomic absorption (Hendricks and others, 1969, table 8).
[4] Lower limit of determination not cited.
[5] Source: Hendricks and others, 1969, table 8.

The single sample of alluvium from the bed of the stream at Wadi Zarqa Ma'in also has some curious similarities in the abundances of the minor elements compared with those in the sediments from the deeps in the central Red Sea (table 12). Copper and zinc cannot be compared, because they are greatly enriched in the Red Sea sediment. However, at least ten elements have essentially parallel abundances in the two media: Au, B, La, Mn, Ni, Sc, Sr, V, Y, and Zr. Many of the elements that were below the limit of analytical determination in the sample of alluvium from Zarqa Ma'in are also very scarce in the sediment from the Red Sea deeps (table 12). In most samples the concentrations of the elements in the alluvium and in the sediments are significantly different from the normal crustal abundances associated with the continental lithosphere and average sedimentary rocks (table 12). Thus, the trace-elements chemistry of the alluvium and of the sediments more closely resemble each other than it does the crustal abundances of these elements.

The compositions of the hydrothermally altered sedimentary rocks at Zarqa Ma'in (tables 9 and 12), except for their decidedly lower contents of Ba, Mn, and Sr, are remarkably similar in content of trace elements to the alluvium at Zarqa Ma'in. Compared to crustal abundance, the altered sedimentary rocks are slightly enriched in B, Co, Pb, Ni, Se, and V, but they are depleted in most of the other elements. However, this comparison is poor, because the gain or loss attributable to the abundances of these elements in the altered rocks should be determined by analysis of unaltered rocks from the same stratigraphic units. Obviously, any further work requires that comparisons of the geochemistry of the altered and unaltered rocks in the same units be made. Also, the old values used for averages for the elements in the sedimentary rocks are inadequate for certain elements, particularly for As, Be, In, Mo, Sb, Se, Te, Tl, and U. Thus, from the available data it cannot be determined with any assurance which elements have been added and which have been subtracted by the passage of hydrothermal fluids through these rocks. No direct evidence of base-metal mineralization at depth is given by the results of the analyses of the alluvium and altered sedimentary rocks at Zarqa Ma'in.

Comparison with the Broadlands geothermal field, New Zealand

At the Broadlands geothermal field, New Zealand, gold and silver ores are being deposited at the surface from dilute hydrothermal waters. Pyrite, galena, sphalerite, and chalcopyrite are present in hydrothermally altered wallrocks at depths explored to 1,400 m (Ewers and Keays, 1977). Results of analyses of the thermal waters, warm springs deposits, and altered rocks were reported to show a crude zoning of elements in the deposits such that As, Sb, Au, and Tl are enriched in near-surface parts of the hydrothermal system, and Ag, Se, Te, Bi, Pb, Zn, Cu, and Co tend to be concentrated at depth (Ewers and Keays, 1977, tables 3 and 4). The source of these dissolved constituents is thought by Ewers and Keays (1977, p. 1339) to be the wallrocks, mainly volcanic rocks and graywacke, which were leached by downward percolating meteoric waters. When these waters were heated at depth by cooling magma, they ascended, and during ascent most dissolved constituents precipitated through the combined effects of decreasing temperature and boiling in permeable zones. Thallium appears to have deposited from the ascending thermal water entirely in response to decreasing temperature of the water. Thus, thallium was carried to the outermost and uppermost parts of the system, a role that indicates thallium to be a useful geochemical pathfinder element for hidden sulfide deposits.

The results of the analyses of the Jordanian samples are compared with those reported for the New Zealand geothermal area in table 13. The values shown in table 13 for alluvium and altered rock at Zarqa Ma'in are remarkably similar to the wallrocks at Broadlands for Co, Pb, Se, and Tl. The values are possibly very similar for Ag, Bi, Cu, Te, and Zn within the lower limits of determination used for the samples from Zarqa Ma'in. The abundances of gold and iron are dissimilar. Those for arsenic and antimony cannot be evaluated, because the high values for the lower limits of determination of the method of analysis used for the Zarqa Ma'in samples are too great to permit valid comparison. However, the values for arsenic and antimony at Zarqa Ma'in may well be substantially less than their respective lower limits of determination, which would bring them in their direction of the abundances of these elements in the Broadlands rocks.

Lack of samples of calc-sinters and other warm springs deposits from Narqa Ma'in prevents any direct comparison with the pool precipitates at Broadlands (table 13), but inasmuch as the alluvium from the bed of Wadi Zarqa Ma'in lacks the huge values for As, Sb, Tl, Se, Au, and Ag shown by the pool precipitates from New Zealand, the warm springs deposits at Zarqa Ma'in are not as metalliferous as the New Zealand deposits.

The similarities in the abundances of the pathfinder elements in samples of rock from the two areas support Abu Ajamieh's idea that sulfide deposits may be present at depth in the Zarqa Ma'in area (Abu Ajamieh, 1974, p. 37-46).

Oxalic-acid leach technique

Oxalic-acid leaching of rocks and other geochemical sample media has been introduced in geochemical exploration as a technique to accentuate anomalies (Alminas and Mosier, 1976). The technique as described by Alminas and Mosier (1976, p. 5) was applied to the 78-ZM series of samples from Wadi Zarqa Ma'in.

Table 13. Comparison of the abundances of pathfinder elements in alluvium and hydrothermally altered rocks at Zarqa Ma'in, Jordan, with those reported for the Broadlands, New Zealand, geothermal field, in ppm [Data for New Zealand from Ewers and Keays, 1977, tables 3 and 4.]

	Zarqa Ma'in		Broadlands	
Element	Alluvium (1 sample)	Altered rock (9 samples)	Whole rock (10 samples[1])	Pool precipitates (2 samples)
As	N(200)	N(200)	5.6	7,550
Sb	N(100)	N(100)	1.5	77,200
Tl	N(.02)	0.3	0.8	1,405
Bi	N(10)	N(10)	1	2.3
Se	0.7	.4	.4	128.2
Te	N(0.2)	N(0.2)	.18	<20
Au	L(.05)	N(.05)	1.6	48
Co	5	15	6.4	<25
Ag	N(.05)	N(.05)	.09	135.5
Fe	30,000	110,000	28,000	3,100
Pb	L(20)	50	40	N[2]
Zn	N(200)	L(200)	300	100
Cu	10	13	<20	N[2]

[1] Five samples for Fe, Pb, Zn, and Cu.

[2] Lower limit of determination not given.

The results of the spectrographic analyses of the leachates (table 10), when compared with the results of the analyses of the raw samples (table 9), show strong increases in the contents of Fe, Mg, Ba, Co, Cr, Cu, Mn, Ni, Pb, Sr, and V, as well as less strong increases in the abundances of B and Be. prevents an evaluation of the contribution of the rock itself to the elements enriched in the coatings, but the presence in the coatings of rather large quantities of such elements as Be, Co, Cu, Mn, Ni, Pb, and V appear to favor Little change in the contents of Ca, Ag, Mo, and Zn took place, and four elements were less concentrated in the leachate than in the rock: La, Sc, Y, and Zr.

The oxalic acid leach removes various iron, calcium, and manganese coatings on the grains of the hydrothermally altered rocks. These coatings tend to concentrate various elements. The high contents of these elements may be a function of the coating and of the source rock or may be caused by the presence of elements transported by the hydrothermal fluids moving through the sedimentary rock. Lack of comparison samples from the unaltered rocks prevents an evaluation of the contribution of the rock itself to the elements enriched in the coatings, but in the coatings the presence of rather large quantities of such elements as Be, Co, Cu, Mn, Ni, Pb, and V appear to favor Abu Ajamieh's (1974) interpretation of hidden sulfide deposits at depth. Where several of these elements are enriched in the same sample, as are Be, Co, Cu, Mn, Ni, and Zn in sample 78-ZM-2X, the source of the enrichment is a suitable geochemical problem for further investigation, particularly when the enriched elements in the hydrothermally altered rocks at Zarqa Ma'in are nearly identical to the elements enriched in altered rocks at Wadi Shureh near Al'Aqabah and in possibly hydrothermally altered apatitic limestone in central Jordan (see above).

Further investigations needed

The comparisons of the trace-element composition of thermal water, alluvium, and hydrothermally altered sedimentary rocks at Zarqa Ma'in, Jordan, with interstitial brines and metal-rich sediment from the central Red Sea and with altered rocks at the Broadlands geothermal field affords some geochemical basis for postulating the possible presence of deep-seated sulfide deposits at Zarqa Ma'in. Thus, the geochemistry is in agreement with the geologic and geophysical interpretation to that effect made by Abu Ajamieh (1974, p. 37-46). Nevertheless, the geochemical agreement is tenuous and requires further work to permit a firm interpretation.

Further geochemical investigations should include systematic new sampling to obtain suites of fresh and altered rocks throughout the area of effluence of the warm springs, suites of sinter and other warm springs deposits, alluvium from the bed of the wadi, and samples of water. All these materials should be analyzed by methods permitting lower limits of determination for the various elements sought than were yielded by the methods used for this orientation.

Further geophysical exploration of the Zarqa Ma'in area should be done to determine the possible presence of sulfide bodies at depth. Parts of the proposal made by Andreasen (1978) for geophysical surveys in Jordan could accommodate the work at Zarqa Ma'in.

The results of the geochemical and geophysical investigations should be interpreted in the context of sulfide deposits. Physical exploration would normally be required if the interpretation of the geochemistry and geophysics favored the presence of sulfide ores. At this juncture, before any test drilling was undertaken for sulfide bodies, consultation with the scientists considering the geothermal potential of the Zarqa Ma'in site would be mandatory, because of the effects of possible sulfide ores on the planning of the geothermal investigations, and because of the effects of deep drilling on both the conduct of the geothermal investigation and the future economic development of the site. Indeed, from the outset a detailed investigation of possible sulfide ore deposits at Zarqa Ma'in should be conducted in close cooperation with the geothermal project, and should be considered in the feasibility study related to the development of geothermal energy at Zarqa Ma'in. Exploitation of a base metal deposit at depth under Wadi Zarqa Ma'in would face formidable engineering hazards from faulted and fractured rock, inflow of thermal water, and high geothermal gradient.

Weathered Precambrian conglomerate at Wadi Saramuj

The Saramuj Conglomerate, a Precambrian pebble to boulder conglomerate (fig. 6), is exposed over a width of as much as 1 km (Bender, 1974, p. 36-37) in Wadi Saramuj (31°02'N.; 35°1'E.) at the southeastern end of the Dead Sea and extends north-northeastward for 9 km. In response to reports reaching NRA that the conglomerate is gold-bearing, a composite sample of weathered conglomerate weighing about 100 kg was taken in November 1977. The composite sample was reduced to a heavy-mineral concentrate (77-OT-591) by panning, and the panned concentrate was examined by hand lens for gold, which was not detected. A summary of this investigation was made (Overstreet, 1978a, p. 27-28), which included a recommendation for a more detailed examination of the concentrate. The results of the further examination are given below.

The crude concentrate was processed in USGS by Theodore Botinelly to obtain heavy-liquid and magnetic fractions which were then analyzed mineralogically by Botinelly and spectrographically by D. J. Grimes and R. T. Hopkins.

Gold was not detected in the mineralogical examination.

The results of the spectrographic analysis of the raw concentrate and of various separates prepared from it are given in table 14, where it can be seen that gold was not detected at a lower limit of determination of 10 ppm in any fraction of the concentrate. Further confirmation for the low abundance of gold is given by the absence of silver at a lower limit of determination of 0.5 ppm. Native gold generally is alloyed with small amounts of silver.

The values for iron and titanium in the raw concentrate and the magnetic and nonmagnetic fractions having densities greater than 2.8--the part of the concentrate that sank in the heavy liquid--reflect the abundance of magnetite and the sparsity of ilmenite and rutile in the concentrate. The extraordinarily high value for barium in the raw concentrate is poorly matched by the amount in the nonmagnetic fraction, where the element could be expected

Figure 6. Photograph of the Precambrian Saramuj Conglomerate exposed in the wall of Wadi Waramuj, Hashemite Kingdom of Jordan.

Table 14. Results of semiquantitative spectrographic analyses of a heavy-mineral concentrate from the Saramuj Conglomerate, Hashemite Kingdom Jordan.
[Analyses by D. J. Grimes and R. T. Hopkins, USGS.]

	Fractions of concentrate			
	Raw concentrate	Heavy-liquid and magnetic separations		
Element	(77-OT-591; MAX-272)	Magnetic fraction (77-OT-591M; MAX-188)	Nonmagnetic fraction (77-OT-591N; MAX-189)	Float in heavy-liquid (77-OT-591L; MAX-240)
Results in percent				
Fe	50	50	50	7
Mg	0.7	1	1	2
Ca	1	0.3	0.7	1.5
Ti	G(2)	2	2	1
Results in parts per million (ppm)				
B	70	30	30	70
Ba	7,000	200	1,500	700
Be	L(2)	N(2)	N(2)	N(2)
Co	100	100	70	10
Cr	700	2,000	1,500	150
Cu	100	50	50	50
La	100	N(20)	70	50
Mn	1,500	1,500	1,500	700
Nb	20	N(20)	N(20)	N(20)
Ni	100	150	150	70
Pb	150	50	100	50
Sc	20	20	20	10
Sr	100	N(100)	N(100)	300
V	2,000	7,000	1,500	300
Y	150	20	50	20
Zr	2,000	300	700	300

Looked for but not detected at lower limits of determination as shown, in ppm: Ag, 0.5; As, 200; Au, 10; Bi, 10; Cd, 20; Mo, 5; Sb, 100; Sn, 10; Th, 100; W, 50; and Zn, 200.

to appear in even greater amount than in the unseparated concentrate if the barium is in barite, which is nonmagnetic. These relations are interpreted to indicate that the barium is in feldspar in the raw concentrate. Processing the raw concentrate through heavy liquids removed the feldspar and thereby reduced the barium content of the nonmagnetic fraction.

Both cobalt and nickel are rather scarce in the concentrate and tend to be in the heavy fraction, although more nickel than cobalt persists in the light fraction (table 14). Much of the cobalt and nickel is probably in the magnetite, but a small amount of nickel is in some unidentified mineral that is in the light fraction. Neither element has any economic significance at the reported concentrations.

The division of high values for chromium into nearly equal amounts between the magnetic and nonmagnetic fractions indicates the presence of chromite in part intergrown with magnetite.

The sparse amounts of lanthanum and yttrium, combined with low values for thorium (table 14) indicate that exploitable amounts of monazite are lacking. Zircon and garnet are the most likely sources for these elements (Overstreet and others, 1970).

Lack of segregation of the manganese into a single fraction of the concentrate (table 14), and equal values for manganese in the raw concentrate and in the two heavy fractions indicate the presence of manganese in several minerals and also shows a problem with the splitting of the concentrate for analysis. The quantity of manganese shown by the analyses is expectable for concentrates.

The extremely high values for vanadium in the concentrate and in the heavy magnetic and nonmagnetic fractions pretty well identify the souce to be magnetite (table 14). If magnetite is the major source for the vanadium, and is also the source for some of the chromium, cobalt, and nickel as well, these geochemical data indicate that an important source for the magnetite in the conglomerate was mafic rocks. The crustal abundances of chromium cobalt, nickel, and vanadium are about 120 ppm, 20 ppm, 80-200 ppm, and 100-150 ppm respectively (Beus and Grigorian, 1977, table 3; Vhay and others, 1973, p. 145; Cornwall, 1973, p. 438; Fischer, 1973, p. 681). During magmatic differentiation of igneous rocks these four elements tend to decrease in abundance so that high average values are characteristic of mafic rocks and low average values are found in felsic rocks. In magnetites derived from igneous rocks, cobalt and vanadium tend to exceed crustal abundances, nickel is equal to or less than crustal abundance, and chromium is generally less (Frietsch, 1970, p. 67-81). The trend in concentration of these elements in magnetite of igneous origin is similar to the trend of these elements in the host rocks. Each of the elements is progressively depleted in magnetite from mafic rocks to magnetite from felsic rocks. Although considerable variation in the abundances of these elements in magnetite has been recorded from one igneous complex to another, in a general way the composition of the magnetite reflects its sources (Overstreet and others, 1978, p. 349- 350):

Dominant source	Co (ppm)	Cr (ppm)	Ni (ppm)	V (ppm)
Mafic rocks	>200	>5,000	>200	>1,000
Felsic rocks and hydrothermal deposits	<50	<500	<100(?)	<500

Nickel tends to be more abundant than cobalt in magnetite from early differentiated mafic rocks, but the greatest differences are shown in the abundances for chromium and vanadium in magnetite from mafic and felsic rocks. Also, where vanadium is more abundant than zinc in magnetite of magmatic origin, the parent rock for the magnetite is mafic. Applying these observations to the distribution of Co, Cr, Ni, and V in the magnetic fraction of the concentrate from the Saramuj Conglomerate, an important source for the detrital magnetite appears to have been mafic rocks:

Element	Detrital magnetite from the Saramuj Conglomerate (ppm)	Magmatic magnetite from mafic rocks (ppm)
Co	100	>200
Cr	2,000	>5,000
Ni	150	>200
V	7,000	>1,000

Zinc in the magnetic fraction of the concentrate from the Saramuj Conglomerate was not detected at a lower limit of determination of 200 ppm; thus, the abundance of zinc is less than that of vanadium, which supports the interpretation based on Co, Cr, Ni, and V.

Zirconium, like barium and manganese, is more abundant in the raw concentrate than in the fractions derived from the concentrate. Zirconium would be expected to be present in zircon, which is a nonmagnetic mineral. Hence, the highest value for zirconium would be expected in the nonmagnetic fraction (77-OT-591N in table 14). Although the amount of zirconium reported for this fraction is unexpectedly lower than that found in the raw concentrate, the amount is, properly, greater than those in the magnetic fraction and in the float from the heavy-liquid separation.

The elements that were looked for but not found at the given lower limits of determination include important ore metals or indicator elements for ore deposits: Ag, As, Au, Bi, Cd, Mo, Sb, Sn, Th, W, and Zn. When to this group is added the list of low-value elements reported in table 14, such as Be, Co, Cr, Cu, Nb, Ni, and Pb, it appears that the Precambrian rocks from which the sampled part of the Saramuj Conglomerate was formed were unmineralized at the time of the deposition of this part of the conglomerate. Of course, that does not mean that all the rest of the Saramuj Conglomerate, which has not been sampled, lacks gold, other possible ore minerals, or pathfinder elements. This possibility can only be determined by a systematic sampling of the Saramuj Conglomerate, as was discussed elsewhere (Overstreet, 1978a, p. 27-28).

If the report of gold in the Saramuj Conglomerate, as it reached NRA, was in some way confused between Wadi Saramuj and the Saramuj Conglomerate, then the possibility would exist for detrital gold to be in the sand and gravel of the wadi floor instead of in the conglomerate. Provision to test this possibility should be made by the processing of bulk smaples of alluvium for heavy-mineral concentrates and examining the concentrates for gold.

Altered rocks in Wadi Shureh

Exposed in a part of Wadi Shureh (fig. 1) about 6 km east of the coastal highway leading south from Al'Aqabah and in the vicinity of sample locality 2565 established earlier by Dr. Riad Gharaibeh (1969, plate 1) is an area of altered red porphyritic biotite granite (29°28'30"N.; 35°03'E.). Mafic dikes are common in the granite. The rock is part of the Precambrian unit mapped as granodiorite and quartz diorite by Bender (1968c), and as older granite by Hakki (1971). Faults and shear zones are common in the granite on the north side of Wadi Shureh at this locality, and on the south side of the wadi, narrow north-trending fault troughs are filled with loosely consolidated white to brown sandstone. The basal unit of the sandstone is a pebble-to-cobble conglomerate partly cemented by clay and limonite. This sedimentary sequence rests unconformably on the altered granite. It may be as young as Pliocene or Quaternary. The variegated colors of the sandstone and conglomerate--white, yellow, buff, orange, red, purple, and brown--make it distinctive.

Surface exposures of the granite and mafic dikes are in part weathered to saprolite, which is decomposed but undisturbed crystalline rock (Becker, 1895, p. 289-290). The term saprolite is applied to the products of chemical weathering where those products are still in place. Indeed, to a large degree, saprolite retains the texture and structure of the original unweathered rock despite the fact that saprolite is loose enough to be dug by pick and shovel. Saprolite is produced mainly by the chemical weathering of the feldspars and mafic minerals of the rock, the stability of which during weathering is the reverse of the Bowen reaction series. Under the conglomerate the granite is also weathered locally to saprolite.

Secular weathering that produces saprolite is a process that, in fact, mimics hydrothermal alteration. Clayey end products of the two processes tend to resemble one another. However, if the hydrothermal alteration introduces new elements or causes a marked rise in some elements already present in the unaltered rock, the action of the hydrothermal process can be identified by the trace-elements geochemistry of the altered rocks. Rocks that were altered hydrothermally can in their subsequent history, when exposed at the earth's surface, be further modified by weathering. Inasmuch as the products of weathering tend to be distributed regionally and the products of hydrothermal alteration tend to be restricted to rather narrow zones, the present appearance of the Wadi Shureh area is one of a complex sequence of weathering and possible hydrothermal alteration. The first interpretation of possible hydrothermal alteration in the sheared granite of Wadi Shureh was made by Gharaibeh (1969) on the basis of the results of geochemical analyses of the minus-80-mesh fractions of wadi sand from this area. These samples showed low but distinct enrichment of the base metals.

Two series of samples were collected in the area (table 15). The samples in the 77-OT-series were screened to three sieve sizes to permit evaluation of the possible concentration of certain elements in selected sieve sizes. These samples were analyzed spectrographically at the NRA laboratory in Amman by Mohamad Sha'aban and Zuheir Issa (table 16). Samples in the 78-DG series were ground to the conventional <100-mesh size, then split into two fractions, one of which was analyzed directly, and the other of which was leached in oxalic acid and the leachate was analyzed (table 17).

Granite

The results of the analyses of the granite are shown in table 16, samples 77-OT-563A through -563C, and in table 17, samples 78-DG-1 through 78-DG-4.

Composition related to size of fraction analyzed.--No significant changes in the trace-element composition of the sieve fractions can be detected in the analytical results shown in table 16, except for a moderate tendency for calcium to be enriched in the <9+32 mesh fraction and for boron and zirconium to be enriched in the <80-mesh fraction. The magnitudes of these enrichments, in terms of analytical reporting intervals between the value for a given element in the <9+32 mesh fraction and for the same element in the <80-mesh fraction, are generally so small that they are within the range of accepted

Table 15. Descriptions of altered biotite granite and sandstone sampled in Wadi Shureh to the southeast of Al'Aqabah, Hashemite Kingdom of Jordan.

Field number	Description of material sampled
	Altered biotite granite
77-OT-563A	Middle part of strongly altered zone; sample sieved to <9 + 32 mesh
-563B	Do.; <32 + 80 mesh
-563C	Do.; <80 mesh
78-DG-1	70 m north of middle part of strongly altered zone
-1A	Basic dike near altered granite
-2	Middle part of strongly altered zone
-3	Specimen of iron oxide from quartz-calcite vein in middle part of strongly altered zone
-4	30 m south of middle part of strongly altered zone
	Wadi sand from point 40 m downstream from southern edge of exposed altered granite
77-OT-565A	Wadi sand; sieved to <9 + 32 mesh
-565B	Do.; <32 + 80 mesh
-565C	Do.; <80 mesh
	Altered, poorly consolidated sandstone and conglomerate
77-OT-567A	White sandstone; sieved to <9 + 32 mesh
-567B	Do.; <32 + 80 mesh
-567C	Do.; <80 mesh
-569A	Pink to red sandstone; sieved to <9 + 32 mesh
-569B	Do.; <32 + 80 mesh
-569C	Do.; <80 mesh
-571A	Brown sandstone; sieved to <9 + 32 mesh
-571B	Do.; <32 + 80 mesh
-571C	Do.; <80 mesh
-573A	Yellow sandstone; sieved to <9 to 32 mesh
-573B	Do.; <32 + 80 mesh
-573C	Do.; <80 mesh
-575A	Yellow basal gravel; sieved to <9 + 32 mesh
-575B	Do.; <32 + 80 mesh
-575C	Do.; <80 mesh
78-DG-5	Fe-Mn stained sandstone
-6	Fe-stained sandstone
-7	Bleached sandstone
-8	Poorly sorted, altered sandstone
-8A	Do.

Table 16. Results of semiquantitative spectrographic analyses of altered biotite granite and sandstone from Wadi Shureh to the southeast of Al'Aqabah, Hashemite Kingdom of Jordan.

[Analyses by Mohamad Sha'aban and Zuheir Issa, NRA, Amman.]

Sample numbers		Results in percent				Results in parts per million[1]											
Field	Laboratory	Fe	Mg	Ca	Ti	B	Ba	Be	Cr	Cu	La	Mn	Ni	Sr	V	Y	Zr
77-OT-563A	SPL- 89	3	0.7	1.5	0.3	N(20)	1,000	2	N(10)	15	50	700	N(10)	300	30	30	500
-563B	- 90	2	.5	1.5	.2	N(20)	700	2	N(10)	5	50	700	N(10)	300	20	N(20)	300
-563C	- 91	3	.7	1.5	.3	N(20)	1,000	N(2)	N(10)	7	100	700	N(10)	500	30	30	>1,000
-565A	- 92	3	1.5	2	.5	N(20)	1,000	3	15	10	50	1,000	10	500	70	30	200
-565B	- 93	3	1.5	2	.3	N(20)	1,000	3	15	15	50	700	15	300	70	30	150
-565C	- 94	3	1.5	3	.3	20	700	3	30	20	70	700	15	300	50	50	1,000
-567A	- 95	0.05	.02	0.07	.15	30	N(50)	N(2)	10	N(2)	50	150	N(10)	200	15	20	150
-567B	- 96	.07	N(.02)	.05	.15	70	N(50)	N(2)	N(10)	N(2)	50	N(50)	N(10)	200	15	N(20)	70
-567C	- 97	.07	.02	.07	.2	150	N(50)	N(2)	N(10)	N(2)	50	N(50)	N(10)	300	15	N(20)	300
-569A	- 98	.7	.05	.1	.15	50	N(50)	N(2)	N(10)	N(2)	50	N(50)	N(10)	N(200)	20	N(20)	70
-569B	- 99	.7	N(.02)	.07	.15	50	N(50)	N(2)	N(10)	15	50	N(50)	N(10)	N(200)	20	20	100
-569C	-100	1	.02	.05	.2	150	N(50)	N(2)	N(10)	5	50	N(50)	N(10)	200	20	30	700
-571A	-101	1.5	.07	.15	.2	50	N(50)	N(2)	15	15	50	100	N(10)	300	30	20	500
-571B	-102	.7	.02	.1	.15	50	N(50)	N(2)	10	7	50	50	N(10)	300	15	N(20)	300
-571C	-103	1	.05	.15	.3	100	N(50)	3	15	15	50	70	N(10)	300	30	30	>1,000
-573A	-104	1.5	.5	.15	.3	100	N(50)	3	15	15	50	70	N(10)	300	30	30	>1,000
-573B	-105	1	N(.02)	.05	.05	20	N(50)	N(2)	10	5	50	50	15	500	10	N(20)	150
-573C	-106	1	N(.02)	.03	.07	30	N(50)	N(2)	10	5	N(50)	50	15	300	10	N(20)	100
-575A	-107	2	N(.02)	.07	.2	70	50	N(2)	10	10	50	70	30	1,000	30	30	500
-575B	-108	1.5	.5	10	.1	70	100	N(2)	20	7	N(50)	500	10	N(200)	30	N(20)	200
-575C	-109	1.5	.3	10	.1	70	100	N(2)	30	7	N(50)	300	10	N(200)	30	N(20)	150

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[1] Elements looked for but not found at lower limits of determination shown in table 1: Ag, As, Au, Bi, Cd, Mo, Nb, Sb, Sn, Th, W, and Zn. Elements rarely present at lower limits of determination shown in table 1, abundances, and sample numbers are: Co, 5 ppm, 77-OT-565B; 7 ppm, 77-OT-565A and -565C; Pb, 50 ppm, 77-OT-563A, -565C, -575B, and -575C; Sc, 5 ppm, 77-OT-563A and -563C; 7 ppm, 77-OT-565A, -565B, and -565C.

Table 17

Results of analyses of altered rocks and of oxalic leachates from Wadi Shureh to the southeast of Al'Aqabah, Hashemite Kingdom of Jordan

[Spectrographic analyses by D. J. Grimes; instrumental eU analyses by J. C. Negri; fluorometric analyses for U by D. M. Hopkins; atomic absorption analyses for In and Tl by J. G. Viets, and for Au and Te by R. W. Leinz; flameless atomic absorption analyses for Hg by R. W. Leinz; USGS; oxalic acid leachates shown by "X" suffix to sample numbers; n.d. = no data.]

Sample numbers		In percent				Results in parts per million[1]																					
eld 3DG-	Laboratory	Fe	Mg	Ca	Ti	Ag	B	Ba	Be	Co	Cr	Cu	In	La	Mn	Mo	Nb	Ni	Pb	Sc	Se	Sn	Sr	Tl	U	V	Y	Zn	Zr
	MAX-241	0.7	0.2	0.5	0.02	N(.5)	N(20)	150	3	N(5)	N(20)	5	N(.1)	N(20)	150	N(5)	N(20)	7	50	N(5)	L(.1)	N(10)	N(100)	0.3	3.9	10	10	N(200)	30
A	-297	20	3	5	1	N(.5)	20	700	2	50	N(20)	70	n.d.	70	1,500	N(5)	20	20	20	50	n.d.	N(10)	1,000	n.d.	n.d.	300	70	N(200)	200
X	-280	50	5	3	.3	N(.5)	500	700	30	150	700	300	n.d.	N(20)	10,000	N(5)	300	300	300	30	n.d.	50	700	n.d.	n.d.	150	20	1,000	200
2	-242	5	.3	10	.01	N(.5)	N(20)	700	5	N(5)	N(20)	20	0.5	N(20)	500	N(5)	N(20)	10	200	100	.1	N(10)	N(100)	.5	7.2	30	150	N(200)	10
2X	-281	50	5	1.5	1.5	N(.5)	500	2,000	70	50	1,500	300	n.d.	N(20)	10,000	50	700	70	100	20	n.d.	50	200	n.d.	n.d.	200	N(10)	3,000	30
3	-243	3	.5	5	.15	N(.5)	N(20)	500	N(2)	N(5)	N(20)	15	.1	N(20)	300	N(5)	N(20)	L(5)	30	L(5)	.7	N(10)	150	.2	4.0	30	20	N(200)	70
3X	-282	7	1.5	1.5	.05	N(.5)	L(20)	300	3	15	N(20)	15	n.d.	N(20)	1,500	N(5)	N(20)	30	30	N(5)	n.d.	N(10)	500	n.d.	n.d.	100	N(10)	L(200)	N(10)
4	-244	5	1	3	.2	N(.5)	N(20)	1,000	2	N(5)	N(20)	7	.1	50	1,000	N(5)	N(20)	L(5)	50	7	.1	N(10)	300	.2	4.5	50	30	N(200)	150
4X	-283	30	10	1.5	.3	N(.5)	50	700	15	50	100	150	n.d.	N(20)	10,000	N(5)	N(20)	30	50	N(5)	n.d.	N(10)	500	n.d.	n.d.	200	N(10)	1,000	100
5	-245	20	L(.02)	.07	.02	N(.5)	N(20)	30	30	50	N(20)	200	.1	50	700	N(5)	N(20)	200	70	5	.1	N(10)	150	.2	10.9	100	10	N(200)	50
5X	-284	50	1.5	7	.1	3	200	500	100	300	300	1,000	n.d.	N(20)	7,000	N(5)	N(20)	2,000	700	30	n.d.	N(10)	500	n.d.	n.d.	3,000	200	7,000	200
6	-246	1	L(.02)	L(.05)	.3	N(.5)	50	20	N(2)	N(5)	N(20)	10	N(.1)	50	10	N(5)	N(20)	L(5)	30	N(5)	L(.1)	N(10)	100	.1	1.8	30	20	N(200)	200
6X	-285	20	5	5	.02	5	300	700	2	20	200	150	n.d.	70	1,500	20	N(20)	100	700	30	n.d.	N(10)	2,000	n.d.	n.d.	1,000	200	2,000	300
7	-247	.2	.02	.07	.15	N(.5)	50	20	N(2)	N(5)	N(20)	N(5)	N(.1)	50	10	N(5)	N(20)	L(5)	20	N(5)	.1	N(10)	200	N(.1)	2.0	30	15	N(200)	200
7X	-286	20	5	10	.2	300	300	1,[illegible]00	7	30	300	300	n.d.	100	500	30	N(20)	200	1,000	20	n.d.	50	7,000	n.d.	n.d.	700	150	1,500	300
8	-248	1.5	.3	1	.2	.5	50	100	N(2)	5	100	20	N(.1)	50	200	N(5)	N(20)	L(5)	200	7	L(.1)	N(10)	200	N(.10	3.1	70	20	N(200)	300
8A	-298	1.5	.3	5	.15	.5	30	200	N(2)	L(5)	30	15	n.d.	20	200	N(5)	N(20)	10	70	5	n.d.	N(10)	200	n.d.	n.d.	70	15	N(200)	150
8X	-287	30	5	1.5	.15	15	50	1,000	2	70	1,000	150	n.d.	N(20)	1,500	30	N(20)	150	300	5	n.d.	N(10)	2,000	n.d.	n.d.	1,500	N(10)	300	70

Elements below limits of determination as shown in table 1 and accompanying text: As, Au, Bi, Cd, Sb, Te, Th, and W; Hg was detected at L(.02) in sample 78-DG-7; eU was reported as L(20) in samples 8-1 through 78-DG-8; Au was not detected at 0.05 ppm and Te was not detected at 0.2 ppm by atomic absorption in all samples not treated with oxalic acid; the oxalic acid leachates were analyzed by pectrographic methods only, as were samples 78-DG-1A and -8A. Note: The values for chromium in samples 78-DG-1X and -2X may reflect contamination introduced during the grinding of the samples in eparation for analysis.

analytical variation for the method of semiquantitative spectrographic analysis used:

Element	Number of analytical reporting intervals of enrichment between coarsest and finest sieve fractions where samples show enrichment between fractions			
	<9+32-mesh fraction enriched		<80-mesh fraction enriched	
	Total samples showing enrichment in given element	Reporting intervals represented by enrichment in each such sample	Total samples showing enrichment in given element	Reporting intervals represented by enrichment in each such sample
Fe	3	1, 1, 1	2	1, 1
Mg	2	1, 10	1	9
Ca	3	2, 4, 13	1	1
Ti	3	1, 4, 1	3	1, 1, 1
B	1	2	4	2, 2, 4, 3
Ba	1	1	1	2
Be	2	2, 2	1	2
Cr	2	2, 1	2	2, 3
Cu	3	2, 2, 1	2	2, 3
La	2	2, 2	2	2, 1
Mn	4	1, 5, 1, 1	1	4
Ni	1	3	2	1, 2
Sr	2	1, 6	3	1, 1, 2
V	2	1, 2	0	0
Y	3	1, 2, 2	3	1, 2, 1
Zr	2	>6, 3	5	2, 4, 2, 6, >2

Where values for a given element exceed the accepted range of analytical variance for that element in two samples, as is seen for magnesium (ten and nine reporting intervals) and for manganese (five and four reporting intervals), and in one sample the coarsest-grained fraction is enriched, whereas in the other sample the finest-grained fraction is enriched, no preference can be made by grain size for use as a sample medium.

Elements with unchanged values between the coarsest and the finest sieve fractions are: Ag, As, Au, Bi, Cd, Co, Mo, Nb, Sb, Sc, Sn, Th, W, and Zn. These elements mostly were reported as below the limits of determination (table 16).

These results are quite different from those reported by Theobald and others (1977, p. 10) for trace elements in sieved fractions of granitic rock debris sampled at the Uyaijah ring structure in the Kingdom of Saudi Arabia. From the results of the analyses of five sieve fractions of each of 25 samples used in their orientation survey, the coarsest-grained (<10+32-mesh) fraction was found to give the greatest variation for the 14 minor elements detected spectrographically in all analyzed samples. On the other hand, the finest-grained fraction (<200-mesh) lacked measurable natural variation in the spectrographic results. The lack of variation in the <200-mesh fraction was interpreted "...to result from thorough aeolian introduction of fine debris from a huge area of Saudi Arabia" (Theobald and others, 1977, p. 12).

Measurable natural variation in the elements determined in sieved fractions of granitic rock debris was shown by Theobald and associates (1977, (fig. 2) to be a more important factor in geochemical exploration than the median values obtained for the elements. A spread in values is needed to identify positive anomalies. In the Saudi Arabian samples, the finest grained fractions tended to have a spread of only three or four reporting units for the elements, whereas the spread of the coarsest-grained fractions was twice as great, but the median values for the elements were somewhat lower than the medians reported for the finest-grained fractions. The increase in scatter of the abundances of the elements found with increase in grain size of the material analyzed was interpreted by Theobald and associates (1977, p. 12) to show that the coarser the fraction used for analysis, the closer the sample comes to representing a local source.

A meaningful test of those observations cannot be made with the present data from Wadi Shureh in Jordan, because of the small number of sized fractions analyzed, and because the analyzed materials are mainly poorly consolidated, iron-stained sandstone and granite saprolite. Only one sample is wadi sand, and none is gruss. Nevertheless, it is of interest to see how the composition of these materials differs by size fraction from the results reported for granitic gruss in Saudi Arabia. At Wadi Shureh the finest-grained fraction tends to have the greatest natural variation, owing possibly to an increase in the amount of iron oxides in that fraction:

Element	Measured natural variation in reporting units for elements in sized fractions from Wadi Shureh, Hashemite Kingdom of Jordan (number of reporting units)	
	<9 + 32 mesh	<80 mesh
Fe	12	11
Ca	10	16
Ti	4	5
B	6	7
Ba	9	10
Be	3	3
Cr	3	5
Cu	6	7
La	1	4
Mn	10	9
Ni	5	3
Sr	6	4
V	5	5
Y	3	4
Zr	7	8

from saprolite, which is untransported rock material lacking intermixed fine-grained aeolian debris. Inasmuch as the fine-grained fraction of the saprolite is from the same rock as the coarse-grained fraction, no large differences in composition are to be expected.

Even the nearby alluvium from Wadi Shureh (tables 15 and 16, samples 77-OT-565A through -565C) shows only slight variation in contents of trace elements by sieve fraction of the sample:

Enriched element	Sieve fraction enriched (mesh size)	Number of analytical reporting intervals in enrichment between coarsest and finest sieve fractions
Ca	<80	1
Ti	<9+32	1
B	<80	2
Ba	<9+32	1
Cr	<80	2
Cu	<80	2
La	<80	1
Mn	<9+32	1
Ni	<80	1
Sr	<9+32	1
V	<9+32	1
Y	<80	1
Zr	<80	4

Zirconium has the greatest variation in the wadi alluvium, as it is also in saprolite. No geochemical significance can be attached to these small differences, which are within the accepted range of analytical variation for the semiquantitative procedure used.

Composition of unleached samples and of oxalic acid leachates.--The results of the spectrographic analyses of the unleached altered granite ground to minus-100 mesh and the oxalic acid leachate from the granite are given in table 17. The method of using oxalic acid to leach iron oxides and manganese oxides from geologic materials, and then to analyze the leachate for minor elements of interest in geochemical exploration for ore deposits, has been described by Alminas and Mosier (1976) and by Watts and associates (1978). The procedure provides an anomaly-accentuation technique to emphasize the presence of those elements that tend to precipitate in nature with the iron and manganese oxides.

As described by Alminas and Mosier (1976, p. 5), the oxalic acid leach technique requires that 5 g of ground rock be placed in a beaker with 50 ml of

1.5N oxalic acid and the mixture be brought to a low boil. After boiling for five minutes the oxalate solution thus formed is filtered and dryed. The leachate is further heated to remove free oxalic acid, then the leachate is placed in a crucible and heated to 450C to convert the oxalates to oxides and to drive off water. When cool, the leachate is ground and analyzed spectrographically.

Elements clearly enriched in the oxalic acid leachates (samples 78-DG-1X, -2X, and -4X) over their abundances in the untreated samples of altered granite (samples 78-DC-1, -2, and -4) are:

Enriched element	Number of analytical reporting intervals in enrichment (average of three analyses)
Fe	7
Mg	7
Ti	7
B	7
Be	6
Co	8
Cr	10[1]
Cu	9
Mn	8
Ni	7
Sr	4
V	5
Zn	7

[1] May result from contamination.

Four elements are enriched in the oxalic acid leachate in two-thirds of the granite samples analyzed: Ba, Nb, Sn, and Zr (table 17). Eleven elements are essentially unaffected in abundance between the untreated sample and the oxalic acid leachate within the limits of determination of the analytical procedure: Ag, As, Au, Bi, Cd, La, Mo, Pb, Sb, Th, and W.

Three elements tend to be depleted in the oxalic acid leachate compared to their abundances in the untreated samples: Ca, Sc, and Y.

The degree of enrichment in the abundances of the elements in the leachates compared to the untreated samples, in terms of number of analytical reporting intervals, is significantly greater than in the procedure using sieved fractions. As yet untested in the orientation survey is a combination of sieving to coarse and fine sizes, then splitting the sieve fractions for analyses of the untreated sample and the oxalic acid leachate for each sieve fraction. Where altered but untransported rock materials are the sample medium, this further step evidently would be of little practical value, because admixed aeolian debris of fine size is lacking. However, the attractive possibility exists that in saprolite and hydrothermally altered rocks, a far greater proportion of actual clay minerals--in contrast to clay-size particles of rock-forming minerals--is present than in wadi sediment, in which the finest particles consist of less than 1 percent of clay minerals (Overstreet, 1978b, p. 32). The presence of clay minerals in the altered rock should cause some enrichment of metals in the finest fraction, whether analyzed as an untreated sieve fraction or as a leachate, owing to adsorption of elements on the surfaces of the clay minerals in the altered rocks.

Geochemical evidence for hydrothermal alteration.--The results of the analyses of the untreated samples of altered granite, as well as of the mafic dike (table 16, sample 78-DG-1A) and the iron oxide from the quartz-calcite vein in sheared granite (table 17, sample 78-DG-3), disclose only low values for elements that are typically enriched in hydrothermally altered rocks. Here the values resemble those found in unaltered rocks (table 18). Significant enrichments are absent except for Co, Cu, Mn, Sr, and V in the mafic dike. These rises are normal in mafic rocks:

Element	Mafic dike at Wadi Shureh	Average abundance in mafic rocks (ppm)	
		Hawkes and Webb, 1962	Beus and Grigorian, 1977
Co	50	45	48
Cu	70	140	87
Mn	1,500	2,200	1,200
Sr	1,000	No data	470
V	300	200	250

The many minor elements reported in tables 16 and 17 as not detected include some of the most notable associated with hydrothermal enrichment: Ag, As, Au, Bi, Cd, Hg, Mo, Sn, Te, and W. Some of these, for example Au, Sn, and W, could be expected even to be somewhat enriched during weathering, if the saprolite was developed after a hydrothermal event. Several other elements, particularly In, Sc, Te, and Tl, might also be expected to be somewhat concentrated in weathering products, but the amounts reported in table 17 are rather low for the granite and the iron oxide from the quartz-calcite vein:

	Abundance in ppm			
	In	Se	Te	Tl
Altered granite				
78-DG-1	N(.1)	L(.1)	N(.2)	0.3
-2	0.5	0.1	N(.2)	.5
-4	.1	.1	N(.2)	.2
Iron oxide from vein				
78-DG-3	.1	.7	N(.2)	.2

Low as these values are, they resemble values reported for altered wallrock at the Broadlands geothermal field in New Zealand (Ewers and Keays, 1977, tables 3 and 4).

Many critical elements for use in an interpretation of possible hydrothermal alteration at Wadi Shureh are enriched in the oxalic acid leachates from the altered granite (table 17). The composition of these

Table 18. -Comparison of the content of minor elements in altered rocks from Wadi Shureh, Hashemite Kingdom of Jordan, and the content of the same elements in the average granitic rock, in ppm.
[n,d. = no data.]

Element	Wadi Shureh			Average granite	
	Altered granite (6 samples)	Mafic dike	Iron oxide from vein	Hawkes and Webb, 1962	Beus and Grigorian, 1977
B	L(20)	20	N(20)	15	15
Ba	750	700	500	830	840
Be	2	2	N(2)	5.5	3.5
Co	N(5)	50	N(5)	5	1
Cu	10	70	15	30	10
Mn	700	1,500	300	600	400
Ni	L(5)	20	L(5)	8	4.5
Pb	50	20	30	48	19
Sr	200	1,000	150	n.d.	110
U	5	n.d.	4	3.5	3
V	30	300	30	40	44
Zn	N(200)	N(200)	N(200)	60	39

leachates resembles that reported for leachates from hydrothermally altered rocks exposed in Wadi Zarqa Ma'in (table 19), except that the iron oxide crust from the quartz-calcite vein in sheared granite at Wadi Shureh is too lean in B, Co, Cr, Cu, Ni, and Pb to be interpreted as having any genetic connection with base-metal bearing hydrothermal solutions. The abundances of these elements in the leachates from the altered granite may be interpreted as a slight indication of possible hydrothermal alteration modified by subsequent weathering. However, the collateral geochemical evidence from the altered, poorly consolidated sandstones in Wadi Shureh needs to be evaluated before a conclusion can be reached.

Table 19. Comparison of the abundances of selected elements in leachates from altered granite at Wadi Shureh with elements in hydrothermally altered sandstone at Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan.

Element	Wadi Shureh		Wadi Zarqa Ma'in
	Altered granite (average of 3)	Iron oxide from quartz-calcite vein	(average of 9 from table 10 of this report)
	Values in percent		
Fe	50	7	50
Mg	7	1.5	5
Ca	2	1.5	3
Ti	0.7	0.5	0.05
	Values in parts per million		
B	350	L(20)	200
Ba	1,000	300	300
Be	30	3	5
Co	N(20)	N(20)	200
Cr	700	N(20)	200
Cu	200	15	150
Mn	10,000	1,500	2,500
Ni	150	30	100
Pb	150	30	250
Sr	500	500	500
V	200	100	100

Sandstone

Descriptions of the altered sandstones samples taken on the south side of Wadi Shureh are given in table 15. Results of the analyses of sieved fractions of the sandstones are presented in table 16, and the results of analyses of oxalic acid leachates are given in table 17.

Composition related to size of fraction analyzed.--No consistent enrichment was found for any element in any size-fraction analyzed (table

16). All results are within one or two analytical reporting intervals, or. where changes in the abundance of an element are clearly related to size fraction of the sandstone, there is no consistent relation between abundance and particle size. Boron, manganese, strontium, and zirconium are the only elements that show increases in concentration related to sieve fraction analyzed. However, the direction of the changes in concentration shows no consistency by particle size. These differences do not relate to the color of the sandstone. Thus, no improvement in geochemical identification of possible anomalies was achieved by the use of coarse size fractions over the use of the conventional <80-mesh fraction.

Composition of unleached samples and of oxalic acid leachates.--The oxalic acid treatment, in contrast to the sieving technique, clearly enhances the values obtained for many of the elements sought in the sandstone.

A comparison of the values reported in table 17 for samples of unleached sandstone (78-DG-5, -6, -7, -8, and -8A) with values for derived leachates (78-DG-5X, -6X, -7X, and -8X) makes immediately apparent that similar elements in the sandstone are enriched in the oxalic acid leachate as were enriched in the leachates from the altered granite:

Enriched element	Number of analytical reporting intervals in enrichment (average of four analyses)
Fe	8
Mg	11
Ca	10
Ag	11
Ba	8
Be	3
Co	6
Cr	8
Cu	7
Mn	8
Ni	9
Pb	6
Sr	6
V	8
Zn	7

Elements more enriched in the leachates from sandstone than in leachates from the granite are Fe, Mg, Ca, Ag, Ba, Ni, Pb, Sr, and V. Less enriched elements in the leachates from the sandstone than in leachates from the granite are: Ti, B, Be, Co, Cr, Cu, and Zn. Whether an element is more or less enriched in the leachates from the sandstone compared to the leachates from the granite, the number of analytical reporting intervals in the difference is generally only one or two. In actual amounts, these elements are about equally abundant in the leachates from the sandstone and from the granite, except that Cu, Ni, Pb, Sr, V, and Zn are slightly more abundant in the leachates from the sandstone.

Six elements are enriched in three-fourths of the leachates from sandstone: Ti, La, Mo, Sc, Y, and Zr. Eight are unchanged in abundance in the untreated samples of sandstone and in the leachates: As, Au, Bi, Cd, Nb, Sb, Th, and W. Thus, the elements Ag, La, Mo, and Pb, tend to be enriched in the leachates from sandstone compared to the leachates from granite. This indicates that those four elements, as well as Cu, Ni, Sr, V, and Zn, are more abundant in the materials in the sandstone that are attacked by the oxalic acid than they are in the leachable material in the granite.

Geochemical evidence for hydrothermal alteration.--As was true for the data from the granite at Wadi Shureh, the geochemical data from the sandstone are based on far too few samples to demonstrate the possible presence of a positive geochemical anomaly for the base metals. The data may as well be background abundances as anomalous abundances. However, the amounts of Be, Cu, and Pb in both the sandstone and the leachate, U in the sandstone, and Ag, Mo, Ni, V, and Zn in the leachate are sufficiently high to suggest that the sandstone has been affected by hydrothermal alteration similar to that presently taking place at the warm springs in Wadi Zarqa Ma'in, or that secondary oxides and hydroxides of iron have precipitated from ground water in the sandstone and added scavenged metals (Canney, 1966; Jenne, 1968). At Wadi Shureh the values determined for In, Se, Te, Tl, and U in the sandstone and granite are similar to those determined for hydrothermally altered sandstone at Wadi Zarqa Ma'n:

Element	Abundance (ppm)		
	Wadi Shureh		Wadi Zarqa Ma'in
	Sandstone	Granite	Sandstone
	(Average of 4)	(Average of 3)	(Average of 9)
In	L(.1)	0.2	L(.1)
Se	L(.1)	L(.1)	.4
Te	N(.2)	N(.2)	N(.2)
Tl	L(.1)	.3	.2
U	4.4	51	1.2

[1] Six samples in average for U in granite.

The extremely small quantities of In, Se, Te, and Tl in the sandstone seemingly do not indicate an episode of hydrothermal alteration at Wadi Shureh, but these low abundances cannot be interpreted negatively, because they are similar to the abundances of these elements in sandstone at Wadi Zarqa Ma'in.

Interestingly, uranium, though near crustal abundance, is richer in both sandstone and granite from Wadi Shureh than it is in sandstone at Wadi Zarqa Ma'in where radioactivity attains a regional high (Abu Ajamieh, 1974). Inasmuch as the greatest quantity of uranium, 10.9 ppm, was found in the sample of sandstone (78-DG-5) containing the most iron--20 percent--at Wadi Shureh, the possibility exists that the uranium is associated with secondary iron minerals in the sandstone. Uranium-bearing iron oxides are reported in the geologic literature (Lovering, 1955; Lovering and Beroni, 1959; Mckelvey and others, 1956; Karkhanavala, 1958; and Pan and others, 1980). The close association of hematite with certain uranium deposits has been used as a guide in geologic prospecting (Nininger, 1956, p. 116). Generally, however, uraniferous hematite and limonite contain more than 100 ppm uranium, which is 20 times or more the quantity of uranium in the rocks at Wadi Shureh.

These geochemical data do not present positive evidence for a former hydrothermal event at Wadi Shureh. The trace-elements geochemistry is not unlike what would be expected from iron oxides precipitated from normal ground water. However, the geochemical similarities to other localities in Jordan where hydrothermal alteration is known are so strong that the area deserves further investigation for possible hydrothermally formed base metal deposits at depth.

Ores and slags

Background

A few grab samples of copper ore from old mines and of slags from ancient copper smelters were taken at sites of former mining in eastern tributaries to Wadi Arabah, and several samples of ore and slag were collected from the Warda ancient iron workings in the Ajlun District of Jordan (fig. 1, table 20). The purpose in taking these samples was to determine if the slags from the copper smelters contained traces of economically valuable elements not present in the ores (Overstreet, 1978a, p. 26-27). Had such elements been detected, then the interpretation could be drawn that ores from distant and geologically different sites were also processed in antiquity at these copper smelters. This interpretation would have afforded justification for a search for other sources of ore other than the nearby mines. The results of the analyses

Table 20. Description of rocks, ores, and slags from ancient mines and smelters in the Hashemite Kingdom of Jordan.

Sample number	Description
	Wadi Feinan-Wadi Dana (30°37'N.: 35°29'E.)
77-OT-579	Malachite in sandstone.
-580	Malachite in manganese-bearing dolomitic shale.
-581	Slag from ancient copper smelting from pile crossed by road 5.5 km by road down Wadi Dana from NRA camp; black, massive, slabby to
-582	Charcoal in slag represented by sample 77-OT-581.
-584	Heavy-mineral concentrate panned from talus on a plug of spherulitic dacite exposed 1 km to the east of Jebel Feinan. Coordinates of sample locality are 30°37'32"N.; 35°30'24"E.
-585	Sieved fractions of talus from same locality as sample 77-OT-584.
-586	Slag from heap 300 m southwest of pile represented by sample 77-OT-581. Specimen 77-OT-586 is apparently younger than 77-OT-581, because the slag pile from which 77-OT-586 was taken overlaps dark slag like 77-OT-581, and at this locality the slag from which specimen 77-OT-586 came was poured against a ruined wall of dressed sandstone blocks constituting part of a building and retaining an arched doorway and semicicular wall, possibly of Roman (?) age. The slag is light olive brown in color, glassy, scoriaceous, and blocky. This slag may be Byzantine or Islamic in age.
78-DG-18	Copper ore from small dump near mine openings.
	Wadi Khalid
78-DG-13	Iron-stained sandstone (30°38'36"N.; 34°29'33"E.)
-19	Copper ore (30°38'36"N.; 34°29'00"E.)
	Jebel Khirbet en Nuhas (30°40'50"N.: 35°26'13"E.)
77-OT-587	Dark brown to black, massive, slabby to slag in piles covering area at least 200 m by 500 m; color, texture, and structure resembles sample 77-OT-581.
-588	Charcoal from slag represented by sample 77-OT-587.
-589	Copper carbonate in sandstone.
-590	Friable, pulverulent, dark gray to black slag that resembles manganiferous sandstone.
78-DG-14	Ferruginous sandstone 10 cm below slag represented by sample 77-OT-590.
-15	White sandstone 5 cm below slag represented by sample 77-OT-590.
-16	Slag like 77-OT-590 from position in pile 5 cm above contact with white sandstone.
-17	Copper ore in sandstone at Byzantine slag site near Jebel Khirbet en Nuhas.
JoSz32	Charcoal from slag similar to 77-OT-587; located 30°41'50"N.:35°26'10"E.
	Warda iron mine and smelter, Ajlun District (32°14'N.; 35°43'E.)
78-DG-9	Travertine from inside of mine.
-10	Iron ore.
-11	Do.
-12	Slag from pile 50 m from mine.

support a contrary conclusion: the trace-element composition of the slags conforms with that of the local ores, and the ancient copper smelter sites evidently did not engage in the custom smelting of ores traded from presently unrecognized distant and geologically different mineral deposits.

Owing to the presence of charcoal in the slags, pieces could be handpicked from broken slag. Fragments of charcoal thus recovered had been sealed in the slag since it solidified; thus, the age of the charcoal, as determined by C-14 analysis, dates the maximum age of operation of the furnace from which the slag was derived. Three samples of charcoal were successfully recovered and analyzed for carbon-isotope age determinations. The results show that vastly more significant archaeological, geochemical, and pyrometallurgical investigations could be conducted at the ancient mines and smelters in Jordan than have yet been done. If slags were recovered in systematic stratigraphic sequences in archaeological digs, they could be searched for charcoal and the charcoal could be dated. Major- and minor-element analyses of the charcoal-dated slags could be combined with mineralogical, petrographic, and metallurgical study of the slag (Milton and others, 1976) to yield considerable new insight into the sources of the ores, kinds and sources of the fluxes and furnace linings, and state of the pyrotechnological arts during the long period of metallurgical evolution represented by the ancient slags of Jordan. Most of the requisite laboratory procedures following archaeologic excavation of the slags are essentially geologic, but the resulting data would be of use to the archaeo-metallurgist and archaeologist as well as to the exploration geochemist and economic geologist.

The few samples and analyses acquired in the present orientation survey contribute to data already published on the copper deposits in eastern tributaries to Wadi Arabah (Bender, 1974, p. 147-154; Nimry, 1973) and on the Warda iron mine (Bender, 1974, p. 157-158). Additionally, as many as 150 samples of ore and slag from the ancient copper mines and smelters situated in the valleys east of Wadi Arabah were collected and analyzed spectrographically in the 1960's by members of the Geological Survey of the Federal Republic of Germany's Geologic Mission to Jordan, but the results of the analyses have not been published (Friedrich Bender, oral commun., 1978). The Mission had analyzed examples of all the ores and slags for trace elements, and from these results, the slags appeared to have been derived from ores mined from nearby deposits. Dr. Bender indicated that the unpublished data were available for use by interested scientists.

More is presently known of the techniques of copper mining and smelting in antiquity, based on the mine workings, ruined furnaces, and slags on the west side of Wadi Arabah than has been determined from sites on the east side (Rothenberg, 1972; Rothenberg and others, 1978; Wilson, 1977). This unfortunate absence of geographic balance in the examination of ancient sites of mining and smelting is certainly reflected in interpretations of the rise and progress of pyrotechnology in the Wadi Arabah area, because the sites straddle the wadi and constitute together a metallurgical province in which exploitation was evidently not entirely synchronous on the eastern and the western sides of the valley. Indeed, mining and smelting in one area might have taken place whilst these activities were in abeyance on the other side of the wadi. For example a hiatus in mining at the western sites is reported from the 12th century B.C.--when Egyptian mining ceased in that locality--to Roman times nearly 1,500 years later (Rothenberg, 1972, p. 14). The three new isotopic ages for charcoal from slags at smelter sites on the eastern side of Wadi Arabah, obtained during the present investigation, give a record of metallurgical activity between 3,200 ± 200 years and 2,540 ± 200 years before the present (Meyer Rubin, written commun., 1978; 1980):

Sample numbers		Locality	Radiocarbon ages determined by the U.S. Geological Survey Radiocarbon Laboratory, Reston, Va., and based on the Libby half-life (5568 ± 30 yr) referenced to the year 1950
Field	Laboratory		
77-OT-582	W-4054	Wadi Feinan-Wadi Dana area (3037'40"N.; 3539'00"E.)	3,000 ± 300 yr B.P.
77-OT-588	W-4051	Jebel Khirbet en Nuhas (3040'50"N., 3526'13"E.)	2,540 ± 200 yr B.P.
JoSz32	W-4456	Jebel Khirbet en Nuhas (3041'02"N.; 3526'10"E.)	3,220 ± 200 yr B.P.

If these ages are corrected according to the calibration table of Hans Seuss (1979), the oldest age has a corrected value of 1,540 B.C. (Meyer Rubin, written commun., 1980) and the youngest age a corrected value of 800 B.C. (Meyer Rubin, written commun., 1979):

Sample numbers		Radiocarbon ages	
Field	Laboratory	Measured	Corrected
77-OT-582	W-4054	3,000 ± 300 B.P.	1,310-1,390 ± 70 B.C.
77-OT-588	W-4051	2,540 ± 200 B.P.	800 B.C.
JoSz32	W-4456	3,220 ± 200 B.P.	1,540 B.C.

Such ages indicate continuance of smelting enterprises associated with the copper deposits on the eastern side of Wadi Arabah when smelting on the west side is said to have been abandoned.

The abandonment of metal mines and smelters at given sites, and the activation or re-activation of mining and smelting at other localities, was caused by a spectrum of geologic, climatic, human, economic, and political factors. Only the first two of these factors are within the purview of geochemical exploration.

Re-establishment of mining on either side of Wadi Arabah after a lengthy interval of inactivity can only be interpreted to mean that geologic factors--such as mineralogy, tenor, accessibility of the ore, and availability of fluxing agents--were not the prime determinants controlling renewed exploitation of these deposits, even if re-activation necessitated some change or improvement in technology. Climate and the human factors must have been decisive in where and when metallurgical enterprises were opened or re-opened on the copper deposits in the area.

The climatic factor is always of interest in geochemical exploration, because the exposed parts of the earth's surface are modified by the chemical response of rocks and soils to rain and to variations in temperature and vegetation. Climatic factors affect the selection of suitable geologic or botanic materials to serve for geochemical sample media. These same factors may have intervened at mining sites adjacent to Wadi Arabah by influencing water supply and plant growth over long periods.

Charcoal made from local acacia trees and brushwood was the main fuel used at the smelter sites along the western side of Wadi Arabah, supplemented possibly by dry donkey dung (Rothenberg, 1972, p. 232). Elsewhere in Western Asia various trees, desert bushes, dried vine, and dung have been used as fuels (Wertime, 1968, p. 932).

The amount of fuel consumed in smelting operations in the Wadi Arabah region may have equalled about one-half of the weight of the ore that was processed, though fuel:ore ratios could have ranged from 1:1 to 1:3 (Rothenberg and others, 1978, p. 43). Larger amounts of fuel were required for equal weights of ore to smelt copper than to smelt iron, because copper smelting produced more slag (Rothenberg and others, 1978, p. 44). Lead ore smelted quite recently in Iran in small furnaces somewhat similar to those used during antiquity for copper smelting in the Wadi Arabah area is said to have required 35 kg of charcoal for a single charge of 30 kg of lead ore and 30 kg of flux (Wertime, 1968, p. 931). The consumption of trees and brushwood over a long period of smelting could, in a region where renewal of forests was slow, result in denudation of forests and loss of sources for fuel within a practical economic radius of transport. When this condition was reached, the operation of the furnaces would cease for lack of fuel.

Examples of recent deforestation caused by the use of trees for firewood are well known in Jordan. Several sources confirm the extent of deforestation during World War I to supply fuel for the narrow-gauge railroad. One account notes that by 1917 many of the ancient oak forests had disappeared for this purpose (Vester, 1950, p. 272). Another states that the eastern hills and tributaries to Wadi Arabah in the vicinity of Shaubak were deforested during the few years of World War I to supply fuel for locomotives, and the upper parts of Wadi Dana have lost most of their juniper and oak since the turn of this century (Mountfort, 1965, p. 102 and 104). Smelting-related deforestation was noticed in Iran by Wertime (1968, p. 935), who commented that as late as 1918 wild pistachio trees provided a reasonably thick forest in the Heneshk area, but the smelting of iron ore during the ensuing 50 years had caused the loss of all except one or two trees.

That the vegetation of Wadi Arabah was seriously depleted by ancient smelting practice seems certain (Rothenberg, 1972, p. 232). If the rapid depletion of vegetation in one area as a result of smelting was imposed on a regional long-term climatic cycle trending toward desiccation, the period in which forest cover was lacking and pyrotechnology was in abeyance could become quite extended. Such a period might be measured in a time span approaching that of the historic control of the area by one nation. The possible local unavailability of acacia for charcoal in the western part of Wadi Arabah has been cited by Milton and associates (1976, p. 24) for the appearance of three important periods of copper smelting in that area--Chalcolithic, Egyptian, and Roman-Byzantine time. A closer study of the ages of slags, as determined by C-14 analyses of charcoal therefrom--should show more clearly the relation of smelting activities to particular times and should allow a sounder evaluation to be made of the relative roles of climatic and human factors on smelting in the Wadi Arabah area.

Because climatic cycles are regional in extent, and because there were many centers of pyrotechnology in the Middle East, the combined effect of regional desiccation and local deforestation would extend far beyond the smelting sites in Wadi Arabah. This effect should be observable in the Arabian Peninsula and adjacent areas through the rise and decline of ceramics, glassmaking, and agriculture as well as extractive metallurgy.

Climatic cycles of varied rainfall extending farther back in time than the historic record have been inferred from the soils of Jordan and other parts of the Arabian Peninsula (Stevens, 1978, p. 269). Combined desiccation and deforestation has been cited as one cause for the decline of ancient mines and smelters in the area of the Kingdom of Saudi Arabia (Overstreet, 1971a, p. 28-29).

From the point of view of the exploration geochemist, the slags from the smelting of copper and iron during antiquity in Jordan can be regarded as composite samples of ore and flux slightly modified by some addition from the furnance lining (generally clay) and fuel (generally charcoal) and greatly modified by the subtraction of molten metal, by the loss of elements removed in the molten metal, and by elements lost in flue products. Clearly, these unknown additions and subtractions are so complex that the relations of the minor elements in the slag to those in the ores are tenuous at best. Despite these unknowns, some interesting results emerge from the analyses (table 21). Traditional fluxes for copper smelting were iron oxide and limestone (Wertime, 1968, p. 934; 1973a, p. 676-677; 1973b, p. 881-882; Milton and others, 1976, p. 25; Rothenberg and others, 1978, p. 28-29). Limonite or gossan was used as the source of the iron oxides, and the proportion of copper ore to iron oxide was about 1:2 (Rothenberg and others, 1978, p. 40). Workable, low-melting slags from this combination of ore and flux consisted of skeletal fayalitic olivine in a matrix of skeletal ferro-hedenbergite, anorthite, and minor magnetite in glass (Milton and others, 1976, p. 26). The composition of the slag is consistent with pouring temperatures of 1,350-1,400C (Milton and others, 1976, p. 28). Early fluxes are said to have made more use of iron oxide, but later fluxes employed manganese oxides, and in the western smelters of the Wadi Arabah area, Chalcolithic slags are said to contain less manganese than later slags (Rothenberg and others, 1978, p. 21). Old slags from that area were reported (Milton and others, 1976, table 2) to have from 26.5-33.6 percent iron and 1.3-5.9 percent manganese.

Other factors than the relative age of copper slags may be operative in affecting the tenors in iron and manganese of the slags. The geologic presence of readily exploitable sources for, say, iron oxides as contrasted to manganese oxides, could be a major determinant in the compounding of a flux: preference would be accorded the most readily available oxide. Another factor could be the intrusion into the long trend of development in smelting of a retrogressive pyrometallurgical technique. That is, a poorly perfected smelting process employed at a late date could yield slags with metal contents resembling those of early slags. For example, of the five specimens of copper slag from the Wadi Feinan-Wadi Dana area and the Jebel Khirbet en Nuhas area in Jordan analyzed for total contents of iron and manganese, the youngest slag--probably Byzantine or Islamic in age (sample 77-OT-586, table 20)--was found to contain the most iron, and the older slags had the most manganese (R. W. Leinz, written commun., 1980):

Sample number	Locality	Possible relative age	Metal content (percent)	
			Fe	Mn
77-OT-586	Wadi Feinan-Wadi Dana	Byzantine (?) Islamic (?)	21.0	9
-581	Do.	Egyptian (?)	5.5	26
-587	Jebel Khirbet en Nuhas	Do.	2.0	24
-590	Do.	Pre-Egyptian (?)	2.8	21
78-DG-16	Do.	Do.	1.7	19

Large manganese deposits long have been known in Wadi Dana, and the copper ores of the Wadi Feinan-Wadi Dana and Jebel Khirbet en Nuhas areas are closely associated spatially with these manganese ores (Bender, 1974, p. 154-156). Nodules of copper ore and diffused copper minerals are reported to be present in the manganese-bearing deposits (Bender, 1974, p. 156). These geologic associations may well have critically influenced pyrometallurgical development in the copper mining and smelting sites on the eastern side of Wadi Arabah. Analyses of these slags collected in the context of archaeological stratigraphy are needed to clarify this problem.

Copper mines and smelters at Wadi Feinan and Wadi Dana

Ruins of smelter sites, villages, and slag piles mark the course of Wadi Feinan below the confluence of Wadi Dana (3037'N.; 3529'E.), a northerly tributary to Wadi Feinan. These ruins are downstream from the openings of ancient copper mines in white sandstone of Middle Cambrian age (fig. 7, A and B). The main copper deposits in the sandstone consist of small nodules of copper minerals surrounding grains of quartz (Bender, 1974, p. 149-154). Less common ores are thin beds of copper-impregnated sandstone. The main copper minerals are malachite and cuprite, of which malachite is the more common. Several other copper minerals have been reported in the ore, but they are said to be rare: chalcocite, bornite, chalcopyrite, and azurite (Bender, 1974, p. 149-150). In the Wadi Feinan area a partly sandy dolomite is reported to laterally replace the lower part of the white sandstone (Bender, 1974, p. 150). Traces of copper minerals are present in the uppermost parts of the dolomite. From Wadi Feinan to the middle reaches of Wadi Dana, manganese becomes an important constituent of the dolomite, and thin-bedded copper-bearing manganese ores are also found in the sandstone over the dolomite. Unusual minerals associated with high-grade copper ores in the sandstone just above the dolomite are reported to include plancheite and chrysocolla (Bender, 1974, p. 153). The Wadi Feinan-Wadi Dana area is the largest ancient mine and smelter site in Jordan, and its ore reserves have been investigated in detail (Nimry, 1973).

Samples of ore from the Wadi Feinan-Wadi Dana area (77-OT-579, -580, and 78-DG-18, table 20) analyzed in the USGS (table 21) resemble in most respects the trace-element composition reported by Bender (1974, p. 148-153) for Ag, As, Au, B, Ba, Be, Bi, Co, Cr, Ni, Pb, Sb, Sn, Ti, and Zn. The present data extend the published compositions by showing the sparseness of other trace elements: Cd, Hg, La, Mo, Nb, Sc, Se, Sr, Te, Th, Tl, U, V, W, and Zr. These low values conform to abundances that are expectable for copper ores of

A. Portal of ancient copper mine at Wadi Dana.

B. Interior of mine at Wadi Feinan showing galleries.

Figure 7. Photographs of ancient copper mines in the Wadi Feinan-Wadi Dana area, Hashemite Kingdom of Jordan.

Table 21. Results of analyses of rocks, ores, and slags from ancient mines and smelters in the Hashemite Kingdom of Jordan

[Analyses by D. J. Grimes, R. T. Hopkins, J. C. Negri, R. W. Leinz, J. G. Viets, and D. M. Hopkins, USGS; field numbers are in the 77-OT and 78-DG series; laboratory numbers are in MAX series; n.d. = no data.]

Element	Wadi Feinan-Wadi Dana					Wadi Khalid		Jebel Khirbet en Nuhas							Warda iron mine			
	77-OT-579 MAX-190	77-OT-580 MAX-191	77-OT-581 MAX-192	77-OT-586 MAX-193	78-DG-18 MAX-308	78-DG-13 MAX-303	78-DG-19 MAX-309	77-OT-587 MAX-194	77-OT-589 MAX-195	77-OT-590 MAX-196	77-DG-14 MAX-304	78-DG-15 MAX-305	78-DG-16 MAX-306	78-DG-17 MAX-307	78-DG-9 MAX-299	78-DG-10 MAX-300	78-DG-11 MAX-301	78-DG-12 MAX-302
	Results in percent																	
Fe	L(0.05)	0.7	10	G(20)	20	1	0.7	5	0.3	10	3	0.2	5	0.7	0.3	G(20)	G(20)	G(20)
Mg	.1	.2	0.7	0.07	0.05	0.15	.1	1.5	.15	0.7	0.3	1	1.5	.15	1	0.3	0.15	1
Ca	.5	.5	5	7	.7	1	.3	10	.7	10	.05	1	10	.2	G(20)	5	.1	10
Ti	.15	.1	.07	.1	.03	.3	.015	0.07	.1	.15	.3	.5	.1	.5	.03	.02	.03	0.07
	Results in parts per million[1]																	
Ag	30	.5	30	20	L(.5)	N(.5)	1.5	30	L(.5)	50	N(.5)	N(.5)	2	N(.5)	N(.5)	N(.5)	N(.5)	N(.5)
B	N(20)	100	150	150	50	70	20	150	70	150	50	30	150	150	N(20)	N(20)	N(20)	L(20)
Ba	300	1,500	G(5,000)	G(5,000)	200	1,500	500	G(5,000)	1,500	G(5,000)	100	100	G(5,000)	500	30	50	70	150
Be	N(1)	3	15	15	10	2	7	10	5	15	5	2	15	10	N(2)	N(2)	N(2)	N(2)
Co	N(5)	7	100	500	50	L(5)	20	100	7	200	5	L(5)	150	50	N(5)	N(5)	L(5)	L(5)
Cr	50	N(50)	50	100	70	20	N(20)	50	N(50)	50	50	L(20)	50	L(20)	N(20)	20	30	70
Cu	G(20,000)	G(20,000)	7,000	7,000	G(20,000)	500	G(20,000)	5,000	G(20,000)	15,000	1,500	700	10,000	G(20,000)	5	20	10	20
La	N(20)	30	50	30	L(20)	50	L(20)	30	20	50	70	70	100	100	L(20)	L(20)	L(20)	L(20)
Mn	100	500	G(5,000)	G(5,000)	700	150	5,000	G(5,000)	1,500	G(5,000)	300	200	G(5,000)	300	30	L(10)	150	300
Ni	10	15	15	70	100	10	20	10	15	50	10	5	70	30	L(5)	7	L(5)	L(5)
Pb	30	70	3,000	3,000	150	20	1,500	2,000	L(20)	5,000	200	200	7,000	150	N(20)	N(20)	N(20)	N(20)
Sc	5	5	7	10	N(5)	L(5)	L(5)	7	L(5)	10	15	7	10	5	N(5)	N(5)	N(5)	5
Sr	300	200	1,000	1,000	100	200	L(5)	1,500	300	1,000	150	500	1,000	200	200	N(100)	N(100)	300
eU	L(20)	L(20)	20	30	n.d.	n.d.	n.d.	20	L(20)	20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	.7	1.8	.9	4.1	n.d.	n.d.	n.d.	.6	3.0	.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
V	70	30	200	200	300	50	70	200	15	200	100	20	200	50	20	100	70	150
Y	15	20	50	50	10	20	L(10)	50	10	70	30	30	70	30	N(10)	10	10	10
Zn	N(200)	N(200)	300	1,000	300	N(200)	200	300	N(200)	500	N(200)	N(200)	700	N(200)	L(200)	N(200)	N(200)	N(200)
Zr	150	150	100	100	70	200	10	100	100	150	300	500	150	300	20	N(10)	N(10)	30

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[1] Looked for but not found at lower limits of determination as shown, in ppm: Au (spectrographic), 10; Sb, 100; Sn, 10; Te (77-OT series only), 0.2; Th, 100, and W, 50. Elements rarely detected, abundances, and sample numbers where found include, in ppm; As, 700, 78-DG-11; Au (atomic absorption, 77-OT series only), L(0.05), all specimens; Bi, 15, 78-DG-16; Cd, 20, 78-DG-16; Hg, L(0.02), 77-OT-580 and -586; Mo, 10, 78-DG-12, 15, 77-OT586, 20, 78-DG-18; Nb, L(20), 78-DG-16, 20, 78-DG-13 and -14, 30, 78-DG-15 and -17; Se, L(0.1), 77-OT-589, 0.4, -581, -586, and -589, 0.4, 77-OT-580, -587, and -590.

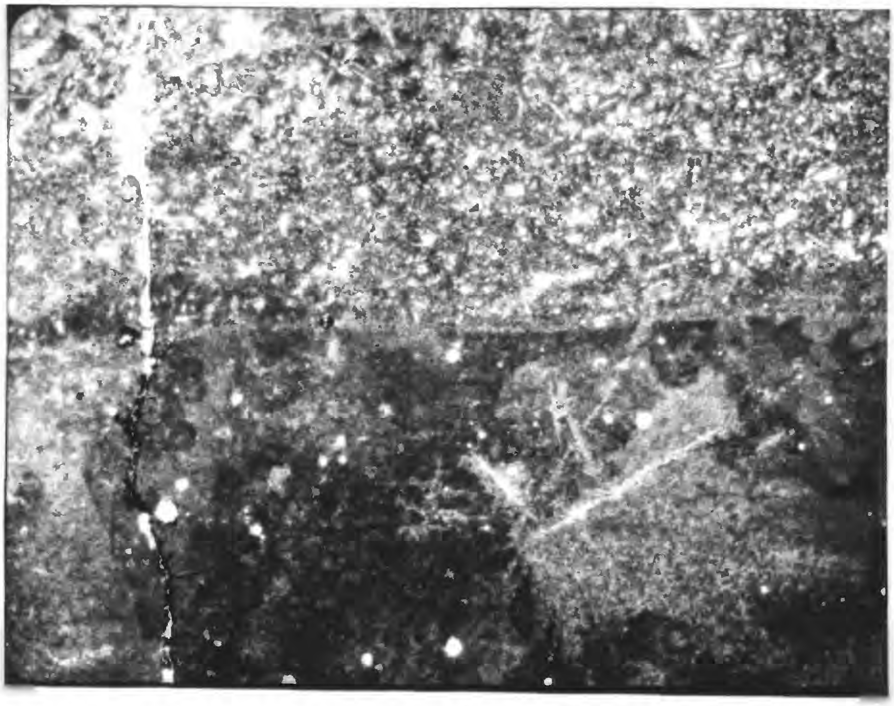
synsedimentary origin or remobilized sedimentary origin.

Among the numerous smelting sites of Wadi Arabah, the sites of Wadi Feinan, according to Glueck (1970), included Early Bronze or Middle Bronze I sherds (Robin Brown, written commun., 1980). However, fragments of pottery scattered on the ground at the ruins of the smelting and mining sites along Wadi Feinan are said to encompass such a mixture of different ages that without careful archaeological excavation it is not possible to assign adjacent slag piles to their proper ages on the basis of artifacts (Dr. James Sauer, American School of Oriental Research, Amman, oral commun., 1978). One of the two samples of slag taken at Wadi Feinan (77-OT-581) seemed to be older than the other (77-OT-586) on a basis of the relation of the supposedly younger slag to ruined buildings (table 20). The two slags are also different in physical appearance. The "older" slag at Wadi Feinan resembles that of slags from the western side of Wadi Arabah variously assigned to Egyptian, Roman, and Byzantine periods of smelting (Milton and others, 1976, p. 24). If, indeed, the slags of different ages in the western side of Wadi Arabah are so similar in physical appearance, which is belied by the presence on the eastern side of Wadi Arabah by slags of at least three distinctive physical types, then the C-14 ages of included fragments of charcoal would form the only certain basis for dating. The trace-elements composition of the slag ordinarily would also be thought to give a gross indication of the age, because improvements through time in the practice of extractive metallurgy would cause less of the wanted metal--copper--to persist into the slag. Also, if at different periods of smelting, other ores than the local ones were used, or major changes in fluxes were made, these variations would show up in the slag.

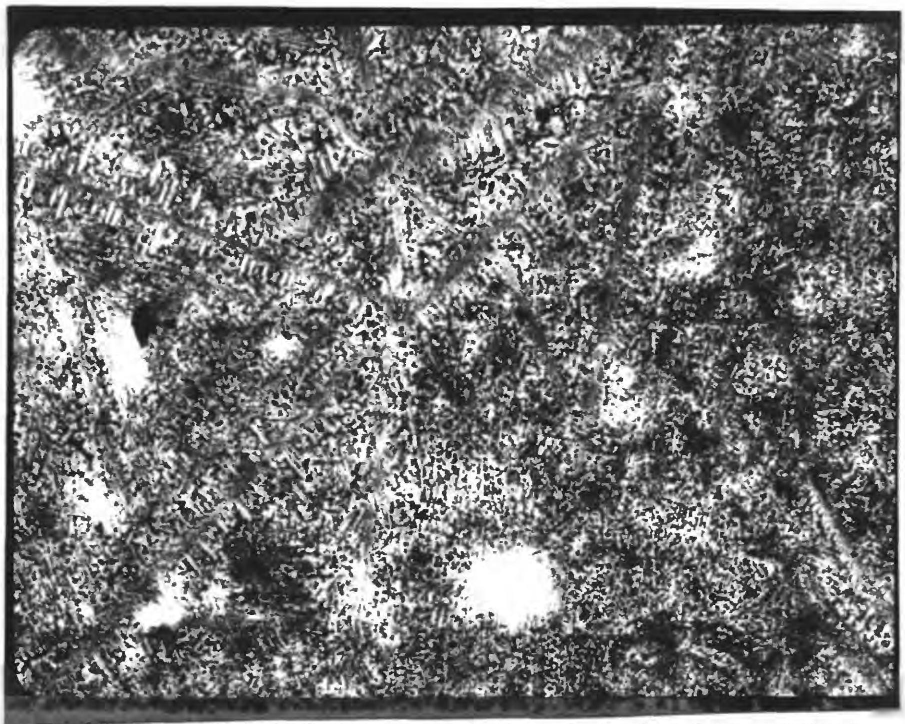
Charcoal (77-OT-582) handpicked from freshly broken pieces of the "older" slag was reported by Meyer Rubin (written commun., 1978), USGS, to have an age of 3,000 ± 300 years before present. Its corrected (Seuss, 1979) age is 1,370-1,310 ± 70 years B.C. This black, massive, slabby to ropy slag has scattered, round to flat and irregular-shaped gas bubbles. Most of the charcoal is found in these openings. Physically identical slag from Jebel Khirbet en Nuhas (see below) was also dated by C-14 analysis to be about 400 years younger.

Under the microscope the slag from Wadi Dana is seen to consist of prismatic skeletal crystals of tephroitic olivine (pure tephroite is manganese orthosilicate), iron oxide minerals, and glass (fig. 8, A and B). Slags described from ancient smelters on the western side of Wadi Arabah contained skeletal fayalitic olivine (pure fayalite is ferrous orthosilicate) (Milton and others, 1976). These relations of the olivine are confirmed by the differences between the contents of iron and manganese of the slags from the two areas. X-ray patterns of the slags from the east side of Wadi Arabah are reported (Theodore Botinelly, written commun., July 21, 1980) to show olivine as the dominant mineral, and to show that the olivine is near tephroite in composition. Spectrographic analyses indicate that chemically the olivine has sufficient calcium, magnesium, and iron to be regarded as mixed olivine.

The light olive brown, scoriaceous, blocky slag (table 20, sample 77-OT-586) from Wadi Feinan, thought to be younger than the black slag, has not been dated. The "older" slag contains appreciably less iron, a factor that may be related to differences in the fluxes or in pyrotechnology, but the measurable trace elements are present in nearly identical abundances in the two slags (table 21), and the mineral composition is similar (fig. 9, A and B).



A. Layered skeletal tephroite crystals, sparse iron oxides, and glass; 40X.



B. Prismatic skeletal crystals of tephroite; white areas are gas bubbles; 170X.

Figure 8. Photomicrographs of thin sections of black, massive, ropy to slabby copper slag (77-OT-581, table 20) from Wadi Dana, Hashemite Kingdom of Jordan. Mineralogical and textural features resemble slag at Jebel Khirbet en Nuhas (fig. 12). Photomicrographs by Theodore Botinelly, USGS.

A. Prismatic skeletal crystals of tephorite and small grains of iron oxide set in glass; layering reflects cooling history; 40 X.

B. Prismatic skeletal crystals of tephorite, small black grains of iron oxides; white area is gas bubble; 100X.

Figure 9. Photomicrographs of thin sections of light olive brown, glassy, scoriaceous, blocky copper slag (77-OT-586, table 20) of possible Byzantine or Islamic age from the Wadi Feinan-Wadi Dana area, Hashemite Kingdom of Jordan. Photomicrographs by Theodore Botinelly, USGS.

Thus, the trace-elements chemistry is an inadequate basis for separating the two slags in a time/technique context. Indeed, the similarity in the contents of trace elements may indicate that chronologically young but technically equivalent operations could have yielded a "younger" slag having the chemical characteristics of an "older" slag.

When the trace-elements composition of the slags are compared to the ores (table 21), the abundances of Ag, B, Cr, La, Ni, Sc, Ti, U, V, and Zr are seen to be about the same. Copper is less abundant in the slag than in the ore. Increases are found in the Be, Ca, Fe, Mg, and Y, and strong increases occur in the amounts of Ba, Co, Mn, Pb, Sr, and Zn. The actual amounts of barium and manganese in the slags cannot be determined from these results because both elements are more abundant than can be measured by the upper limits of determination, but manganese and iron were re-determined by another procedure (see above). Compared to the slags from the western side of Wadi Arabah, these slags must be called manganese-rich, a characterisitc of post-Chalcolithic slags (Rothenberg and others, 1978, p. 21). The question must be raised, however, whether absolute age of the slag is the controlling factor in relative contents of iron and manganese, or whether access to geologically different fluxes and/or recapitulation of earlier evolutionary stages of pyrometallurgical development are overriding controls?

Components of the slag that have clearly entered from the fluxes are Ba, Ca, Fe, Mg, Mn, and Sr, because of their chemical association with limestone (Ca, Mg, and Sr) and with iron oxides or manganese oxides (Ba, Fe, and Mn). As much as 2.3 percent of barium has been observed in the manganese ores from this part of Jordan (Bender, 1974, p. 156). Cobalt and zinc may also have entered with the fluxes, because they increase in abundance together in the more iron-rich slag. The noticeable rise in the concentration of beryllium in the slag may also be caused by the flux, particularly if weathered, limonitic iron oxides were added, because beryllium during weathering is enriched in the hydrolyzates (Rankama and Sahama, 1950, p. 446). For the same geochemical reasoning, the beryllium might equally as well have come from clay in the walls of the furnace. The small rise in the amount of yttrium in the slag may be no more important geochemically than slight variations in its abundance in the ores. However, the yttrium phosphate mineral weinschenkite has been reported to form crusts on manganese ores and manganiferous limonite in the United States (Milton and others, 1944). Admittedly, the geochemical cycle leading to the development of weinschenkite on the manganese ores in the United States is exotic. It is not at all likely to have been duplicated in Jordan. However, the fluxes might be a source for yttrium.

The great increase in the amount of lead in the slag over that in the ore (table 21) is of prime interest to the exploration geochemist, because the quantity of lead equals or exceeds amounts found in ancient furnace products from complex deposits of base and precious metals in the Kingdom of Saudi Arabia (Overstreet and others, 1969, tables 2 and 5). Almost half as much lead as copper is present in the two samples of slag from the Wadi Feinan-Wadi Dana area, and at Jebel Khirbet en Nuhas specimens of slag contain as much as 7,000 ppm lead (samples 77-OT-587, -590, and 78-DG-16; table 21). Five of the six samples of ore from eastern tributaries to Wadi Arabah shown in table 21 (77-OT-579, -580, -589, 78-DG-17, -18, and -19) have from L(20) to 150 ppm lead. One sample of copper ore from Wadi Khalid (78-DG-19) has 1,500 ppm lead. Chalcolithic and later slags from the western side of Wadi Arabah are reported to contain from approximately 1,000 to 10,000 ppm lead, and 450 ppm lead is found in some copper ore from there (Rothenberg and others, 1978, tables 1 and 3). Copper ores and copper-bearing minerals from the eastern tributaries to Wadi Arabah were shown to contain 100 to 1,000 ppm lead (Bender, 1974, p. 151-153), but manganese ores in this region have from 2,000 to 8,000 ppm lead (Bender, 1974, p. 156). The most probable source for the lead in these slags appears to be the fluxes, not the ore.

Ancient slags from the smelting of complex sulfide ores typically are enriched in base metals and contain small amounts of precious metals. For example, slags from the ancient mines at Esh Qay'ib and Avala in the Kingdom of Saudi Arabia are enriched in these elements (Overstreet and others, 1969, tables 2 and 5):

	Sample number	Elements in ppm				
		Ag	Au	Cu	Pb	Zn
Esh Qay'ib zinc-copper mine	22301	1.4	trace	15,000	2,000	31,000
	30150	Nil	Nil	21,000	1,000	35,000
Avala gold mine	22453A	10	0.3	4,000	3,000	10,000

The slags from these ores are more enriched in Ag, Au, Cu, and Zn than slags from the Wadi Feinan-Wadi Dana area.

Thus, even the large amount of lead in the slag from Wadi Feinan and Wadi Dana--a chemical characteristic that suggested introduction into these furnaces of ores from other, as yet unrecognized, sources--conforms to the composition of locally available material used for fluxes. All the trace-element data supports the interpretation that the ores smelted at these sites were locally derived.

One of the questions regarding the copper ores in the Wadi Feinan-Wadi Dana area is the possible role of post-Cambrian intrusive and extrusive rocks in the origin of the deposits. Late Proterozoic to Cambrian age quartz porphyry in the area has been shown to contain disseminated copper minerals, and analyses showed high values for nickel (Bender, 1974, p. 147-148, 159). At a locality about 1 km east of Jebel Feinan (table 20), a small plug of spherulitic dacite intrudes the Precambrian rocks. Primary flow banding is defined by flattened gas bubbles filled with chlorite. Other filled gas bubbles or spherules in the fine-grained gray-green matrix of the rock are composed of: (1) radial fibrous epidote; (2) quartz and epidote; (3) quartz and chlorite; (4) quartz, red feldspar, and chlorite, and (5) calcite. Inclusions of Paleozoic sandstone are present in the plug. From the presence of the sandstone inclusions, the age of the plug must be post-Cambrian, probably Lower Cretaceous or younger, because the earliest post-Cambrian intrusive rocks in the region are rhyolite of Lower Cretaceous age (Bender, 1968c).

Neither primary nor secondary copper minerals were observed in exposures of the spherulitic dacite. However, samples were taken of the talus on the dacite to provide three sieved fractions of the talus sand and one heavy-mineral concentrate (table 20). These materials were analyzed by semiquantitative spectrographic procedure with results that are shown in table 22. Copper is quite sparse (50-70 ppm) in both the talus and the concentrate, which is in notable contrast to the copper content of the Late Proterozoic-Early Cambrian quartz porphyries of the area, which were shown by Bender (1974, p. 148) to contain 7,700 ppm copper. Other differences are also apparent between the composition of talus from the plug and the rock sample of quartz porphyry:

Table 22. Results of semiquantitative spectrographic analyses of sieved fractions of talus and a heavy-mineral concentrate from a plug of spherulitic dacite exposed 1 km to the east of Jebel Feinan, Hashemite Kingdom of Jordan.

[Analyses of the talus by Mohamad Sha'aban and Zuheir Issa, NRA, Amman, Jordan, 1978; analyses of concentrate by D. J. Grimes and R. T Hopkins, USGS, 1978.]

Element	Sieved fractions of talus			Concentrate
	<9 + 32 mesh	<32 + 80 mesh	<80-mesh	
	Field and laboratory number of samples			
	77-0T-585A	77-0T-585B	77-0T-585C	77-0T-584
	SPL-113	SPL-114	SPL-115	MAX-271
Results in percent				
Fe	10	7	7	10
Mg	5	3	3	2
Ca	10	15	15	20
Ti	0.7	0.3	0.5	0.7
Results in parts per million[1]				
B	20	20	50	50
Ba	700	300	500	500
Be	N(2)	N(2)	N(2)	L(2)
Co	50	30	30	20
Cr	300	200	300	200
Cu	70	50	70	70
La	70	50	50	70
Mn	1,000	1,000	1,000	1,500
Ni	100	70	70	100
Pb	50	200	50	150
Sc	30	15	15	20
Sr	700	300	300	700
V	200	150	150	300
Y	50	30	30	30
Zr	200	150	300	500

---

[1] Elements looked for but not found at lower limits of determination shown in table 1: Ag, As, Au, Bi, Cd, Mo, Nb, Sb, Sn, Th, W, and Zn.

Element	Metal content in parts per million	
	Talus from spherulitic dacite 1 km east of Jebel Feinan (average of three)	Rock sample of quartz porphyry (Bender, 1974, p. 148, 159)
Ag	N(2)	10
As	N(500)	N[1]
Ba	500	200
Be	N(2)	10
Co	30	N
Cr	300	N
Mn	1,000	100
Mo	N(10)	N
Ni	70	1,000-7,000
Pb	100	100
Sb	N(200)	N
Sn	N(50)	10
Ti	5,000	500
V	150	10
Zn	N(200)	N
Zr	200	Trace

[1] Element was not detected at unspecified lower limits of determination.

More geochemical study of the plug near Jebel Feinan is needed, as recommended by Bender (1974, p. 159), to determine if, indeed, it might be a source of copper and, particularly, nickel, as recommended by Bender (1974, p. 159). The results of the rock sampling of the quartz porphyry suggest that this older rock is more mineralized than the younger dacite plug.

Copper mines at Wadi Khalid

The Wadi Khalid ancient copper mines are about 1.8 km north of the Wadi Feinan-Wadi Dana mining and smelting sites. Two grab samples were taken at that locality. Specimen 78-DG-13 is iron-stained sandstone from tailings at the remarkable ancient triple shaft on the hillside above the wadi (fig. 10, A and B). Sample 78-DG-19 is copper ore from a seam in the open gallery of the mine on the west-facing cliff about 1 km west of the triple shaft.

A. Three circular coalescing mine shafts 11.8 m deep. Similar shafts are described from the Timna mining area where they are considered to be Egyptian in origin and are attributed to the Nineteenth Dynasty (Wilson, 1977, p. 69).

B. Another view of the same shaft.

Figure 10. Photographs of triple circular shaft at Wadi Khalid ancient copper mine, Hashemite Kingdom of Jordan

These workings are in sandstone copper deposits like those at Wadi Feinan and Wadi Dana. Iron, calcium, and barium are enriched in the sandstone (table 21). Copper and niobium are slightly enriched. Slight enrichment in niobium seems to be characteristic of the sandstone represented in table 21 for Jebel Khirbet en Nuhas also (78-DG-14 and -15). Like the other copper ores in table 21, that from Wadi Khalid has moderate amounts of barium, but it is much richer in manganese and lead than the other samples of ore. This relation suggests a geochemical affinity of barium and lead with manganese in copper ore as well as with manganese ore in this district.

The unusual design of the ancient copper mine at Wadi Khalid may be a clue to the period of mining activity at this site and to who may have been responsible for its excavation. In contrast to the tunnel entrances in cliff faces characteristic of mines in the Wadi Feinan-Wadi Dana area (fig. 7, A and B), the Wadi Khalid mine has been excavated as a cluster of circular shafts sunk vertically into the bedrock floor of the valley (fig. 10, A and B). The entrance is a circular opening about 4 m in diameter and excavated to a depth of about 2 m. From the irregular bottom of this opening, three equally spaced circular shafts, from 60-80 cm in diameter, have been excavated vertically downward. Two of the shafts coalesce within 2 m of their top, and the third coalesces farther down so that the bottom, about 11.8 m below the ground surface, consists of a single chamber.

The distinctive features of this mine are the nearly perfect cylindrical shapes and the remarkably smooth finish on the walls of the smaller shafts. Because smooth, cylindrical shafts offer no functional advantage in mining over rough, irregular ones, and yet require far more effort and skill to produce, it is apparent that the design of this mine was controlled by some strong tradition.

The method of construction of the circular shafts at Wadi Khalid was also used about 100 km to the south, and on the western side of Wadi Arabah, at Timna where, during the 14th to the 12th centuries B.C., intensive mining was practiced by the Egyptians. Among the extensive mine workings developed by the Egyptians during this period are numerous circular, smooth-walled vertical shafts (Wilson, 1977). As these are virtually identical to the shafts at Wadi Khalid, the same tradition was apparently dictating the methods of mining practiced in the two areas. These observations, coupled with the evidence of the older C-14 ages from the slags at Wadi Feinan and Jebel Khirbet en Nuhas, leads to the interpretation that the circular shafts at Wadi Khalid were excavated during Egyptian mining activity on the east side of Wadi Arabah.

Copper smelters at Jebel Khirbet en Nuhas

Jebel Khirbet en Nuhas is the name given to the extensive ancient ruins of a copper-smelting community (3040'50"N.; 3526'13"E.) in Wadi Ghuweib about 7.5 km northwest of the mines and ruins at Wadi Feinan. What is immediately noticeable at Jebel Khirbet en Nuhas is the vastly larger slag piles than at Wadi Feinan, and the absence of ancient mine openings in the immediate vicinity of the slag piles. Thus, remains are lacking of ancient mines sufficient to have supplied the ore needed to have yielded the impressive piles of slag at Jebel Khirbet en Nuhas (fig. 11, A and B; fig. 12, A). On the other hand, the mines in the Wadi Feinan-Wadi Dana area seem to be much larger than would be required to have furnished sufficient ore to account for the local piles of slag. Can it be that much of the ore mined in the Wadi Feinan-Wadi Dana area was hauled by pack animals to the site at Jebel Khirbet

A. View toward the northeast; dark piles are ancient copper slag.

B. View eastward; dark piles are slag.

Figure 11. Photographs of slag piles from copper smelting in the area of Jebel Khirbet en Nuhas, Hashemite Kingdom of Jordan.

en Nuhas for smelting, because the site at Jebel Khirbet en Nuhas possessed better facilities for smelting, such as natural draft for the furnaces, or sources for water, fuel, and flux, than the area around Wadi Feinan and Wadi Dana? Should this possibility prove upon detailed investigation to be the fact, then it would bear importantly on the proposals made in NRA for a large exploration program at Jebel Khirbet en Nuhas.

The smelting site at Jebel Khirbet en Nuhas in Wadi Ghuweib is bordered by cliffs of Cambrian sandstone and manganiferous dolomitic shale in which small nodules and disseminated particles of malachite are present. The area is regarded by Bender (1974, p. 149) as being in the richer part of the cupriferous sediments.

Owing to the sparsity of evidence for mining at Jebel Khirbet en Nuhas, a program of sampling and evaluation cannot be based on the distribution of ancient mines, as it was at Wadi Feinan and Wadi Dana (Nimry, 1973). Possibly the most satisfactory results of preliminary field work at Jebel Khirbet en Nuhas would be obtained by geologic mapping at 1:10,000 scale and sampling of the sedimentary rocks. Then the sites for the proposed trenching could be located from an analysis of the geologic data.

Grab samples of copper ore in sandstone from this vicinity of Jebel Khirbet en Nuhas were analyzed for minor elements, and the results are shown in table 21 (samples 77-OT-589 and 78-DG-17). Most elements are similarly abundant within two reporting intervals, but one sample, 77-OT-589, contains calcite in the matrix and is therefore slightly enriched in Ca, Ba, and Mn, and somewhat lean in Ti, La, and Zr (elements characteristic of detrital accessory minerals in sandstone). The calcite-bearing sandstone has traces of

A. Slag pile.

B. Close-up view of dark brown to black, massive slabby to ropy slag similar to sample 77-OT-587, table 20.

Figure 12. Photographs of slag pile and slag at ancient copper smelter site near Jebel Khirbet en Nuhas, Hashemite Kingdom of Jordan.

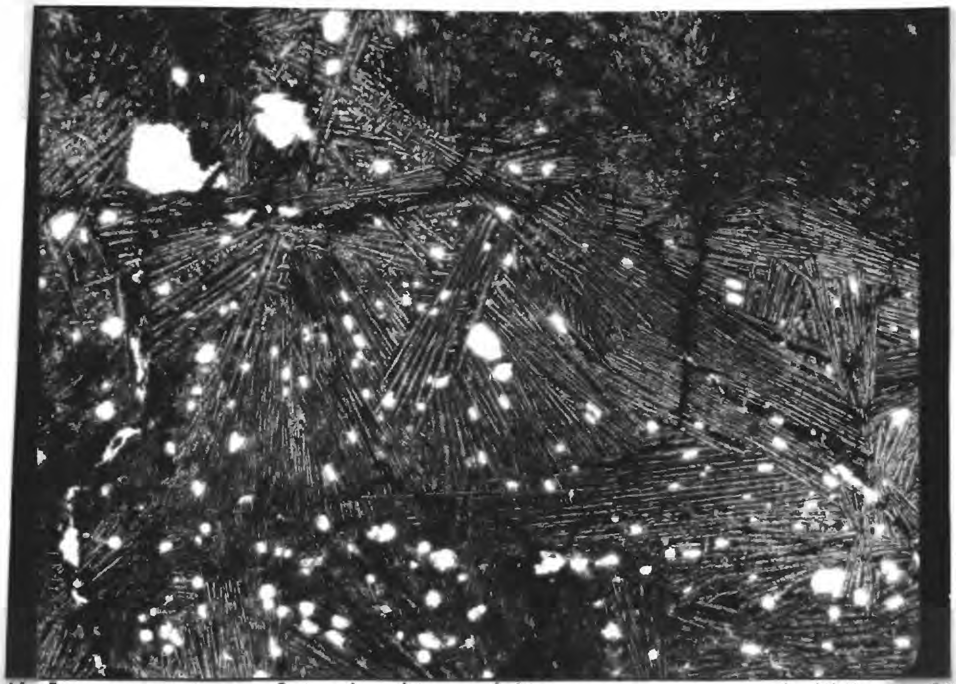
selenium and thallium that are lacking in the cleaner sandstone, which is unexplainably slightly richer in cobalt and lead. Although these ores are less manganiferous than that from Wadi Khalid (table 21, sample 78-DG-19), they are otherwise quite similar in trace-element content. The similarity in abundances of trace elements is even more striking between the ores from Jebel Khirbet en Nuhas and those from the Wadi Feinan-Wadi Dana area (table 21, samples 77-OT-579, -580, and 78-DG-18). These similarities are sufficiently great to preclude the possibility of relating ores from specific localities to slags on a basis of trace-element contents.

Three samples of slag from piles in the Jebel Khirbet en Nuhas area were analyzed (tables 20 and 21, samples 77-OT-587, -590, and 78-DG-16). Six elements yielded identical values in the three samples, and ten elements were found to be within two reporting intervals:

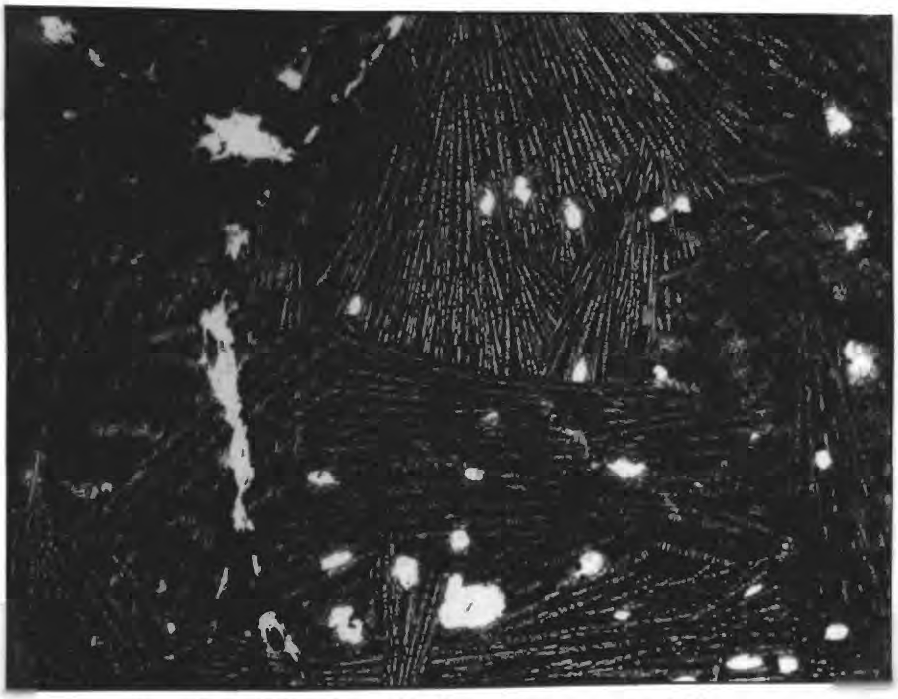
Elements with identical abundances	Elements within two reporting intervals
Ca, B, Ba	Fe, Mg, Ti, Be, Co,
Cr, Mn, V	Sc, Sr, Y, Zn, Zr

Both Ba and Mn are censored values at G(5,000); thus, their true abundances may not be identical. The most notable chemical differences are the lower amounts of Cu, La, Ni, Pb, and Zn in the massive slabby to ropy slag (77-OT-587) compared with the amounts of these elements in the friable dark gray slags (77-OT-590 and 78-DG-16). Indeed, the chemical differences are as distinctive as the physical differences in the two types of slag.

The physical differences in the two types of slag are interpreted to indicate technical differences in the smelting and probably result from higher temperatures being attained in the pyrometallurgical processes associated with the production of the massive ropy slag (fig. 13, A and B). Even so, the temperature attained in the smelting that gave the pulverulent slag was high, because tephroite (Mn2SiO4) was identified by X-ray diffraction study of that



A. Radial aggregates of tephroite; white area are gas bubbles; 40X.



B. Detail of radial aggregates; 80X.

Figure 13. Photomicrograph of thin section of dark brown to black, massive, slabby to ropy slag (77-OT-587, from 20) from Jebel Khirbet en Nuhas, Hashemite Kingdom of Jordan. Specimen was taken from a piece of slag like that shown in figure 12B. Photomicrographs by Theodore Botinelly, USGS.

slag as well as the ropy slag (Theodore Botinelly, written commun., 1978). If pure, tephroite has a melting point of 1,345C. This interpretation of probable melting point is in remarkably good agreement with observations made by Milton and others (1976, p. 28) on ancient copper slag from the western side of Wadi Arabah. They concluded that completely molten slag commenced to crystallize at about 1,350-1,400C.

The great pile of massive ropy slag lies on alluvium and exposed rock of the main terrace at Wadi Ghuweib, but the pulverent gray slag is scattered over only small parts of the terrace. The principal sites for the pulverulent slag are the steep hillsides. Wherever present, the pulverulent slag has been partly eroded and partly moved into dispersion trains toward the floors of small tributaries to Wadi Ghuweib. Similar erosion of the massive ropy slag was not observed. Contacts between the massive ropy slag and the pulverulent slag were not discovered, but they are probably present. Excavation may be needed to show the stratigraphic relations of the two slags. It is thought by the present writers that the massive ropy slag is younger than the pulverulent slag, because it is less eroded than the pulverulent slag and it may partly overlie pulverulent slag.

The massive ropy slag at Jebel Khirbet en Nuhas resembles in texture, color, and chemical composition the older and more widespread of the slags sampled in the Wadi Feinan-Wadi Dana area (figs. 8 and 13). Two samples of charcoal were obtained from the massive ropy slag at Jebel Khirbet en Nuhas (table 20), and C-14 isotopic analyses were made of them by Meyer Rubin, USGS. Ages of 2,540 ± 200 years and 3,200 ± 200 years B.P. were reported (Rubin, Meyer, written commun., 1978), which when corrected, are 800 and 1,540 years B.C. (Rubin, Meyer, Written commun., 1978, 1979, 1980).

The pulverulent slag as presently exposed has somewhat the appearance of a manganese-cemented sandstone such as might form through the deposition of manganese oxides from groundwater emerging in seeps. However, the bottom contact of the pulverulent slag with underlying sandstone is extremely sharp and discordant, and the change in trace elements is equally sharp. Ferruginous sandstone (78-DG-14) and white sandstone (78-DG-15) were sampled respectively 10 cm and 5 cm below the pulverulent slags represented by samples 77-OT-590 and 78-DG-16 (table 20). Great differences between the compositions of the sandstones and the slags (table 21) are interpreted here to show that the pulverulent slag is not a manganiferous springs deposit, because in the short distance of 5-10 cm beneath the slag, the sandstones lack enrichment in elements like Fe, Ca, Ag, B, Ba, Co, Cu, Mn, Ni, Pb, Sr, or Zn, which are all abundant in the slag and could not be expected not to have migrated into the underlying sandstone if springs had been active at these sites.

Three ages of slag having different physical and chemical properties are therefore identified at the Wadi Feinan-Wadi Dana and Jebel Khirbet en Nuhas sites. The slag of intermediate age has been dated (table 23).

Lack of sufficient C-14 ages from the slags, and absence of an archaeologically determined time sequence for the slags from these areas prevent the certain correlation of the late, middle, and early slags of table 23 with the dominant Roman-Byzantine, Egyptian, and Chalcolithic periods of smelting activity identified at sites on the western side of Wadi Arabah (Rothenburg, 1972, p. 14; Milton and others, 1976, p. 24). Certainly at the Wadi Feinan, Wadi Dana, and Jebel Khirbet en Nuhas sites in Jordan, the largest slag piles are associated with dates from 3,220 ± 200 to 2,540 ± 200

Table 23. Relative ages, appearance, and characteristic abundances of minor elements in copper slags from the Wadi Feinan-Wadi Dana area and the Jebel Khirbet en Nuhas area, Hashemite Kingdom of Jordan

Probable relative age	Area where present	Properties	
		Physical (Sample numbers cited)	Chemical (Characteristic elements)
Late: post-Roman, probably Byzantine or Islamic	Wadi Feinan and Wadi Dana	77-OT-586; light olive brown, glassy, scoriaceous and blocky	Fe, G(20%); Ca, 7%; Ag, 20 ppm; Co, 500 ppm; Cu, 7,000 ppm; La, 30 ppm; Ni, 70; Pb, 3,000 ppm; Zn, 1,000 ppm
Middle: C-14 ages of 2,540 ± 200 years to 3,220 ± 200 years BP (corrected to 800 years B.C. to 1,540 years B.C. respectively), possibly Egyptian, Late Bronze Age	Wadi Feinan, Wadi Dana, and Jebel Khirbet en Nuhas	77-OT-581, 77-OT-587, and JoSz32; and dark brown to black, massive, slabby to ropy	Fe, 7%; Ca, 7%; Ag, 30 ppm; Co, 100 ppm; Cu, <7,000 ppm; La, <50 ppm; Ni, <15 ppm; Pb, <3,000 ppm; Zn, 300 ppm.
Early: probably before 3,220 ± 200 years BP; possibly Chalcolithic	Jebel Khirbet en Nuhas	77-OT-590 and 78-DG-16; dark gray to black, dull, friable, pulverulent, granular	Fe, 7%; Ca, 10%; Ag, 25 ppm; Co, >150 ppm; Cu, >10,000 ppm; La, 70 ppm; Ni, >50 ppm; Pb, >5,000 ppm; Zn, >500 ppm

years before the present (corrected to 1,540 years B.C. to 800 years B.C., Suess, 1979), when smelting was in abeyance on the other side of Wadi Arabah.

The Khirbet en Nuhas slag yielding the radiocarbon age of 1,540 B.C. provides a date within the Late Bronze Age for mining and smelting activity in Wadi Arabah (Robin Brown, written commun., July 25, 1980). The question whether this site was an Egyptian enterprise or was controlled by Levantines was thought by Brown to be speculative until further data are available, but the combination of radiocarbon ages and the design of the circular shaft at Wadi Khalid suggests that the Khirbet en Nuhas site was controlled by Egyptians, Therefore, the "Middle slags" of table 23 are tentatively attributed to Egyptian metallurgical techniques of the Eighteenth (1, 567-1,320 B.C.) and Nineteenth (1,318-1,200 B.C.) Dynasties in the Late Bronze Age.

About the only chemical evidence for improvement in pyrometallurgical techniques, as shown by these samples, is a reduction of Cu, Pb, and Zn in the slag from the early to middle periods of operation.

The difference in ages of the samples of charcoal from the otherwise similar slags from the Wadi Feinan-Wadi Dana area and the Jebel Khirbet en Nuhas area possibly shows that a shift in smelting activity took place from the Wadi Feinan-Wadi Dana area to the Jebel Khirbet en Nuhas area in that period. However, one determination only from the Wadi Feinan-Wadi Dana area is insufficient to establish the length of operation. Also possible is the transport of ore from the Wadi Feinan-Wadi Dana area to Jebel Khirbet en Nuhas for smelting in later years. Perhaps this represented a reactivation of the Jebel Khirbet en Nuhas area for smelting after dormancy from the close of the early stage (table 23).

Warda iron mine and smelter in the Ajlun District

The ancient Warda iron mine (fig. 14, A and B) and smelter (32°14'N.; 35°43'E.) in the Ajlun District of Jordan is said by Bender (1974, p. 157-158) to date back to the time of the Crusades and to be in the only deposit of iron ore in Jordan that affords a possibility for present-day exploitation (fig. 1). The ore deposit is said to consist of aggregates of hematite and limonite in Cretaceous limestone. Although sulfide minerals are not reported in the ore, the deposit has been interpreted to have formed from late-magmatic epithermal metasomatism (Bender, 1974, p. 158). Calculated and proved reserves are given as 561,000 metric tons (Bender, 1974, p. 158)

Several samples of wallrock, ore, and slag (table 20) were taken at the deposit for analysis to determine if the abundances of the minor elements might in any way show whether the iron minerals were connected with hidden base-metal hydrothermal deposits. The results of the analyses (table 21) show extremely low values for all indicator elements except one specimen of ore that contains 700 ppm As. That value alone is sufficient to suggest that further analysis of the iron ore is needed for As, Sb, Se, Te, and Tl to determine the possible presence of these hydrothermal indicator elements.

The results of the analysis of the iron slag (78-DG-12) are strikingly different from the results for the copper slags (table 21). The chemical composition clearly distinguishes between the two types of slag.

The distribution of minor elements in the iron slag from the historic Warda furnace is not greatly different from that found for iron slag from historic furnaces at Sa'dah in the Yemen Arab Republic (table 24), despite the fact that the geologic relations of the iron ores are quite different at the two sites. In the Sa'dah area the material used for iron ore is gossan

A. Setting

Figure 14. Entrance to the Warda iron mine, Ajlun District Hashemite Kingdom of Jordan.

Table 24. Composition of iron slags from historic smelting sites at Warda in the Hashemite Kingdom of Jordan and at Sa'dah in the Yemen Arab Republic.

[Data on Yemen slag are average of four analyses from Overstreet and others, 1976, table 2.]

Element	Slags from historic iron furnaces Warda (1 analysis)	 Sa'dah (average of 4 analyses)
	In percent	
Fe	G(20)	G(20)
Mg	1	1
Ca	10	5
Ti	0.07	0.15
	In parts per million	
Ag	N(.5)	N(.5)
As	N(200)	N(200)
Au	N(10)	N(10)
B	N(20)	20
Ba	150	500
Be	N(2)	15
Bi	N(10)	N(10)
Cd	N(5)	N(20)
Co	L(5)	30
Cr	70	50
Cu	20	20
La	L(20)	N(20)
Mn	300	G5,0000
Mo	N(5)	N(5)
Nb	N(20)	N(20)
Ni	L(5)	30
Pb	N(20)	L(10)
Sb	N(100)	N(100)
Sc	5	10
Sn	N(10)	N(10)
Sr	300	1,000
V	150	100
W	N(50)	N(50)
Y	10	150
Zn	N(200)	N(200)
Zr	30	50

developed over massive barren pyrite of Precambrian age (Overstreet and others, 1976, p. 33-55). The similarities in the trace-element composition of these slags give further reason to investigate the Warda deposit for indicator elements of possible concealed sulfide deposits.

Wadi sand and concentrates from the Al'Aqabah region

The <80-mesh fraction is the classic sample medium of the humid temperate regions where the science of geochemical exploration evolved (Hawkes and Webb, 1962). The same sample medium was utilized by the NRA prior to 1977 for geochemical exploration in the region east of Al'Aqabah, where Precambrian granitic rocks are exposed (Gharaibeh, 1969). The conceptual basis for its use is that the <80-mesh fraction of stream sediments contains clay derived from rocks in the drainage basin. Under conditions of secular weathering, the feldspars and femic minerals of rocks are chemically altered in part to clay minerals, and elements of interest in geochemical exploration enter into chemical solution in ground water permeating weathered rocks. The clay minerals adsorb these elements on their surfaces. Thus, clays become enriched in the wanted elements, and the results of chemical analyses of the <80-mesh fraction, compared to coarser-grained fractions of alluvium, are biased in favor of the wanted elements because of the abundant clay in the fine-grained fraction. Such bias is desirable in geochemical exploration, because only small amounts of these elements are generally present. However, even in temperate humid regions, the <80-mesh medium may be locally unsatisfactory as a sample material for geochemical exploration, and other media are used.

Under arid and semiarid conditions, he weathering of rocks tends to be mechanical instead of chemical, owing to the sparsity of water to dissolve minerals in the rocks. Thus, the rocks break into fragments, the fragments become more and more finely divided, but clay minerals do not make up much of this debris. The <80-mesh material is, therefore, a flour of rock particles not particularly adapted to adsorbing ions of metals from solutions contacting them. Furthermore, <80-mesh particles are the major component of windborne dust, which may originate scores or hundreds of kilometers from the sample locality, yet may make up a significant part of a sample of alluvium sieved to <80 mesh. At the locality sampled, the <80-mesh material is likely not to be representative of the adjacent rocks. Also, windborne particles tend to be mixed from many sources, which causes them to display similar chemical characteristics over wide areas (Theobald and others, 1977, p. 12). In arid regions, the <80-mesh medium may not yield the distinctive pattern of positive anomalous metal values needed to identify a mineral deposit by geochemical methods.

These considerations were recognized in NRA as early as 1969 when geochemical exploration in the granitic massif east of Al'Aqabah was completed by Gharaibeh (1969). He recommended that future geochemical surveys in Jordan, when based on the analysis of wadi sand, include studies of the relative effectiveness as sample media of other sizes of wadi sand than the conventional <80-mesh fraction. Such orientation had not been done by NRA as of 1977, when Gharaibeh's recommendation was supported by other geochemical observations concerning Jordan (Overstreet, 1978a, p. 9) and in the Kingdom of Saudi Arabia (Theobald and others, 1977). The procedure used in central Saudi Arabia is a model geochemical orientation survey for arid regions. Its results showed that coarse-grained fractions of wadi sand, and heavy-mineral concentrates from wadi sand, are superior to conventional <80-mesh alluvium as geochemical sample media for use in that arid region. Similar observations have been made in the deserts of southern Africa (Coetzee, 1980) and in New Mexico, U.S.A. (Griffitts and Alminas, 1968).

Heavy-mineral concentrates were used in a small way by Gharaibeh (1969, p. 23) in his geochemical survey of the Al'Aqabah granite region. They yielded notable results. Two heavy-mineral concentrates were panned from wadi sand. Spectrographic analysis outside Jordan disclosed the presence of such elements as beryllium, molybdenum, rare earths, thorium, tin, tungsten, and zirconium. The further use of this medium was recommended by Gharaibeh (1969, p. 23) for follow-up surveys, but analytical capability for these elements was then lacking in Jordan. With the introduction of semiquantitative spectrographic analytical methods for the determination of 30 elements in the laboratory at NRA in 1978 (Grimes, 1978), the opportunity to develop orientation surveys using heavy-mineral concentrates as the geochemical sample medium was realized.

In the original geochemical survey of the Al'Aqabah granite massif, the only elements determined, except for the 35 elements reported for the two concentrates analyzed outside of Jordan, were copper, lead, and zinc (Gharaibeh, 1969). The results of the analyses for the base metals did not give distinct indications of ore deposits, although several areas of small veins or of locally altered rocks showed above-background values for the base metals.

The NRA had long realized that the use of conventional sample media, coupled with the determination of only copper, lead, and zinc, have prevented geochemical exploration surveys from achieving positive results. Resolution of those factors was recognized as being necessary before geochemical exploration could make a useful contribution to the discovery of mineral deposits in Jordan. Therefore, as a preliminary trial, in November 1977, a few samples of wadi sand were collected from various areas in the granitic massif east of Al'Aqabah (table 25) by personnel from NRA and USGS for analysis in the spectrographic laboratory at NRA during the introduction of new analytical methods in January 1978 (Overstreet, 1978a; Grimes, 1978). These samples were divided in the field into three sieve fractions (<9 + 32 mesh, <32 + 80 mesh, and <80 mesh), and 10 kg of unsized wadi sand from several localities was panned to recover heavy-mineral concentrates (fig. 15). Semiquantitative spectrographic analyses of the sized fractions of wadi sand were made for 30 elements in the laboratory of NRA. The concentrates were analyzed by the USGS.

The results of analyses of the sieved fractions of talus and wadi sand from the area of the granite massif to the east of Al'Aqabah, like the results from Wadi Shureh described above, failed to give a clear indication that the coarsest size fractions were superior as a geochemical sample medium in this area. However, the results from the Al'Aqabah area are more similar to the observations made in Saudi Arabia (Theobald and others, 1977, p. 9-14) than the results from Wadi Shureh:

Element	Measured natural variation in reporting units for elements in sized fractions from the area of the granitic massif to the east of Al'Aqabah, Hashemite Kingdom of Jordan (number of reporting units)	
	<9 + 32 mesh	<80 mesh
Fe	9	7
Ca	11	8
Ti	6	5
B	5	9
Ba	8	12
Be	5	5
Cr	8	5
Cu	11	7
La	6	5
Mn	7	11
Ni	7	6
Sr	5	4
V	11	7
Y	7	7
Zr	8	8

Table 25. Descriptions of samples of wadi sand and concentrates from the Al'Aqabah region, Hashemite Kingdom of Jordan.

Field number	Description
	Granitic massif east of Al'Aqabah
77-OT-578A	Talus sample of late Precambrian leucocratic granite exposed in highway cut near new harbor and warehouse installations on southeast side of Al'Aqabah; the leucocratic granite has been evaluated as a possible source for feldspar for ceramic use (Gharaibeh, 1969), aplite granite of Bender (1968c); located at 29°30'N.; 35°00'E.; sample sieved to <9 + 32 mesh.
-578B	Do.; sieved to <32 + 80 mesh.
-578C	Do., sieved to <80 mesh.
-545A	Wadi sand derived from late Precambrian, white to pink, porphyritic granite with feldspar phenocrysts; intruded by dikes of diabase and andesite; granodiorite of Bender (1968c) but called youngest Precambrian granite by Hakki (1971); located at 29°30'45"N.; 35°07'00"E.; sample sieved to <9 + 32 mesh.
-545B	Do.; sieved to <32 + 80 mesh.
-545C	Do.; sieved to <80 mesh.
-544	Do.; panned concentrate.
-517A	Talus sample of late Precambrian pink, porphyritic biotite granite with quartz phenocrysts; possibly somewhat older granite than the granites represented by samples 77-OT-578 and -545; mapped as granodiorite by Bender (1968c); located at 29°31'50"N.; 35°07'00"E.; sample sieved to <9 + 32 mesh.
-517B	Do.; sieved to <32 + 80 mesh.
-517C	Do.; sieved to <80 mesh.
-516	Do.; panned concentrate.
-518	Concentrate panned from wadi sand derived from granite represented by sample 77-OT-517.
-521A	Wadi sand sample derived from unit mapped as Precambrian granodiorite by Bender (1968c) and described as an older granite by Hakki (1971); many gabbro and diabase dikes present; rare, small copper- and lead-bearing quartz veins reported (Gharaibeh, 1969) in the granite but not observed at these exposures in Wadi Ruwerithii, a tributary to Wadi Imran; located at 29°32'N.; 35°07'E.; sample sieved to <9 + 32 mesh.
-521B	Do.; sieved to <32 + 80 mesh.
-521C	Do., sieved to <80 mesh.
-523A	Wadi sand sample derived from coarsely porphyritic Precambrian granite (granodiorite of Bender, 1968c) intruded by dikes of gabbro, diabase, and red quartz porphyry exposed in Wadi Ruwerithii; copper-bearing quartz vein reported (Gharaibeh, 1969) to be in granite upstream, but vein was not seen; located at 29°31'30"N.; 35°06'30"E.; sample sieved to <9 + 32 mesh.

Table 25. Descriptions of samples of wadi sand and concentrates from the Al'Aqabah region, Hashemite Kingdom of Jordan.--Continued.

Field number	Description
77-OT-523B	Do.; sieved to <32 + 80 mesh.
-523C	Do.; sieved to <80 mesh.
-522	Concentrate panned from wadi sand represented by sample 77-OT-523.
-535A	Wadi sand sample from older granite (granodiorite of Bender, 1968c) intruded by younger granite, and by dikes of diabase, quartz porphyry, and felsite; located at 29°30'35"n.; 35°05'50"E.; sample sieved to <9 + 32 mesh.
-535B	Do.; sieved to <32 + 80 mesh.
-535C	Do.; sieved to <80 mesh.
-537A	Wadi sand sample from older Precambrian granite (granodiorite of Bender, 1968c) intruded by younger granite, and by dikes of red felsite, quartz porphyry, gabbro, and diabase; located at 29°31'10"N.; 35°04'45"E.; sample sieved to <9 + 32 mesh.
-537B	Do.; sieved to <32 + 80 mesh.
-537C	Do.; sieved to <80 mesh.
	Granite and sandstone in the Wadi Rum area to the northeast of Al'Aquabah
77-OT-547A	Talus slope sample with considerable windblown sand taken on younger red granite (the Precambrian alkali granite of Bender, 1968c) overlain by Cambrian brown sandstone exposed at junction of Wadi Rum road and first crossing of railroad immediately south of Qa'Um Salab; located 29°42'N.; 35°18'E.; sample sieved to <9 + 32 mesh.
-547B	Do.; sieved to <32 + 80 mesh.
-547C	Do.; sieved to <80 mesh.
-546	Do.; panned concentrate from talus.
550A	Wadi sand sample derived from pink younger Precambrian biotite granite overlain by Cambrian sandstone exposed 8 km north of Wadi Rum Police Fort; the biotite granite is coarse-grained, massive, and lacks mafic dikes although a few felsite dikes are present; mapped as aplite granite by Bender (1968c); located at 29°39'N.; 35°25'E., sample sieved to <9 + 32 mesh.
-550B	Do.; sieved to <32 + 80 mesh.
-550C	Do.; sieved to <80 mesh.
-549	Do,; concentrate panned from wadi sand.
-553A	Wadi sand sample taken near Jabal Rum at Wadi Rum Police Fort where Precambrian granite and granodiorite are overlain by Cambrian and Ordovician sandstones (Bender, 1968c); source of wadi sand is mainly the sandstone; gold is rumored to have been found at this locality (29°34'N.; 35°25'E.); sample sieved to <9 + 32 mesh.
-553B	Do.; sieved to <32 + 80 mesh.
-553C	Do.; sieved to <80 mesh.

Table 25. Descriptions of samples of wadi sand and concentrates from the Al'Aqabah region, Hashemite Kingdom of Jordan.--Continued.

Field number	Description
77-OT-556A	Talus (gruss) and windblown sand from crevices in late Precambrian, gray to pink, massive, medium-grained, porphyritic biotite granite (Precambrian aplite granite and calc-alkali granite of Bender, 1968c) overlain by Cambrian sandstone; last eastward exposure of granite (29°40'N.; 35°28'E.); along road from Wadi Rum to Qa'Disa; 200-300 m to north of exposure (upwind) is the broad salt-clay dry lake surface of Qa'Disa; sample sieved to <9 + 32 mesh.
-556B	Do.; sieved to <32 + 80 mesh.
-556C	Do.; sieved to <80 mesh.
	Barite vein in granite northeast of Al'Aqabah
77-OT-558A	Wadi sand sample taken from small, deeply entrenched wadi where wadi crosses small veins of barite in older Precambrian coarse-grained porphyritic biotite granite (mapped as aplitic granite by Bender, 1968c) exposed on east side of Wadi Arabah (29°38'N.; 35°04'E.); sample sieved to <9 + 32 mesh.
-558B	Do.; sieved to <32 + 80 mesh.
-558C	Do.; sieved to <80 mesh.
-557	Do.; concentrate panned from wadi sand used for sample 77-OT-558.
-560A	Wadi sand taken 150 m down-stream from outcrops of barite veins; sample sieved to <9 + 32 mesh.
-560B	Do.; sieved to <32 + 80 mesh.
-560C	Do; sieved to <80 mesh
-559	Do.; concentrate panned from wadi sand used for sample 77-OT-560.
	Veins in the granitic massif east of Al'Aqabah
77-OT-527A	Wadi sand sample adjacent to milky quartz vein in older granite (granodiorite of Bender, 1968c); located at 29°31'15"N.; 35°06'10"E.; sample sieved to <9 + 32 mesh.
-527B	Do.; sieved to <32 + 80 mesh.
-527C	Do.; sieved to <80 mesh.
-529A	Wadi sand sample taken 75 m downstream from 77-OT-527; sample sieved to <9 + 32 mesh.
-529B	Do.; sieved to <32 + 80 mesh.
-529C	Do.; sieved to <80 mesh.
-528	Do.; concentrate panned from wadi sand used for sample 77-OT-529.
-532A	Same quartz vein as represented by samples 77-OT-527 through -529, but here vein is pegmatitic; wadi sand sample taken 50 m downslope from exposed vein; sample sieved to <9 + 32 mesh.
-532B	Do.; sieved to <32 + 80 mesh.
-532C	Do.; sieved to <80 mesh.

Table 25. Descriptions of samples of wadi sand and concentrates from the Al'Aqabah region, Hashemite Kingdom of Jordan.--Continued.

Field number	Description
77-OT-541A	Wadi sand below exposure of calcite-quartz vein in brecciated fault zone in diabase dike that intrudes Precambrian red granite with rounded quartz phenocrysts (granodiorite of Bender, 1968c); located at 29°30'20"N.; 35°06'40"E.); sample sieved to <9 + 32 mesh.
-541B	Do.; sieved to <32 + 80 mesh.
-541C	Do.; sieved to <80 mesh.
-543A	Do.; 200 m downstream from sample 77-OT-541; sample sieved to <9 + 32 mesh.
-543B	Do.; sieved to <32 + 80 mesh.
-543C	Do.; sieved to <80 mesh.

Figure 15. Photograph showing the panning of a 10-kg sample of wadi sand from the granitic massif east of Al'Aqabah to recover a heavy-mineral concentrate for chemical analysis; site is at the shore of the Gulf of 'Aqabah, Hashemite Kingdom of Jordan.

Histograms were constructed for 18 pairs of <9 + 32-mesh and <80-mesh fractions of sediments to show the variation in abundance of 15 elements by size of the fraction analyzed (figs. 16-20). From these histograms it can be seen that the greatest natural spread in variation of abundances of Fe, Ca, Ti, Cr, Cu, La, Ni, Sr, V, and Zr is associated with the coarse-grained fration (<9 + 32-mesh), and that each of these elements reaches its highest concentration in the fine-grained sediment (<80-mesh). These results are very similar to the observations reported for Saudi Arabia (Theobald and others, 1977, fig. 2). For three elements (B, Ba, and Mn) the greatest spread in variation of abundances is associated with the fine-grained fraction, and for boron and manganese the greatest abundances are also in the fine-grained fraction. The spread in variation is the same for beryllium and yttrium in both size fractions, but their greatest concentrations are in the fine-grained fraction. Only barium has its greatest concentration in the coarse-grained fraction.

When the analytical results are considered for individual areas, as below, instead of regionally, the relation of spread in variation of concentration and maximum concentrations of the elements to the size fractions is less clear. Such lack of clarity is caused by too few samples. When a larger number of samples from Jordan are analyzed, the relations of variation and abundance observed in Saudi Arabia will be found to apply to wadi sediments in Jordan.

The concentrates were analyzed without prior removal of quartz, feldspar, and magnetite, with the result that values for elements associated with nonmagnetic minerals of high density were obscured by these mineral contaminants.

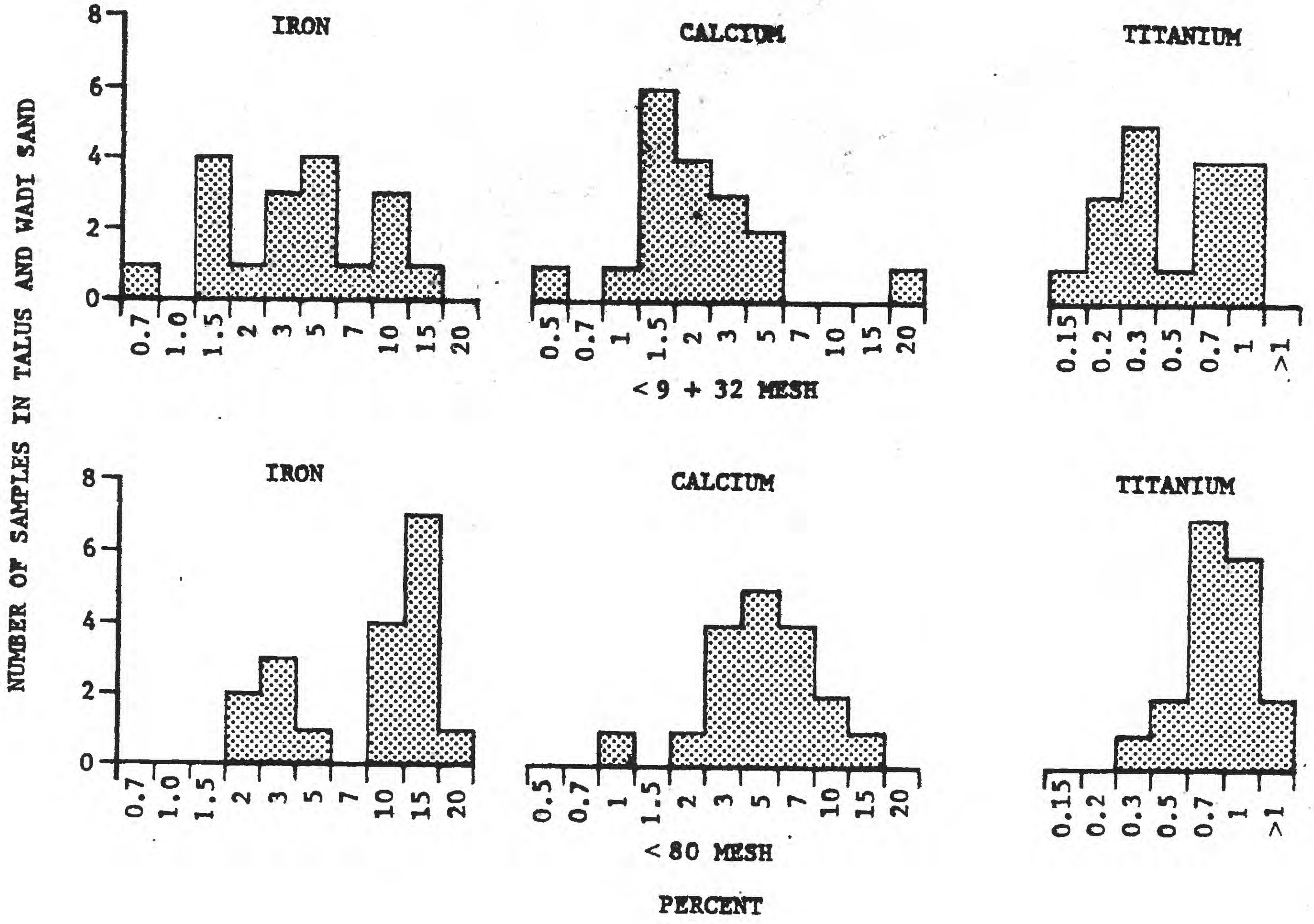


Figure 16. Histograms of iron, calcium, and titanium showing variation in content of metals as a function of the grain size of the fraction of the sediment used for analysis, granitic massif east of Al 'Aqabah, Hashemite Kingdom of Jordan.

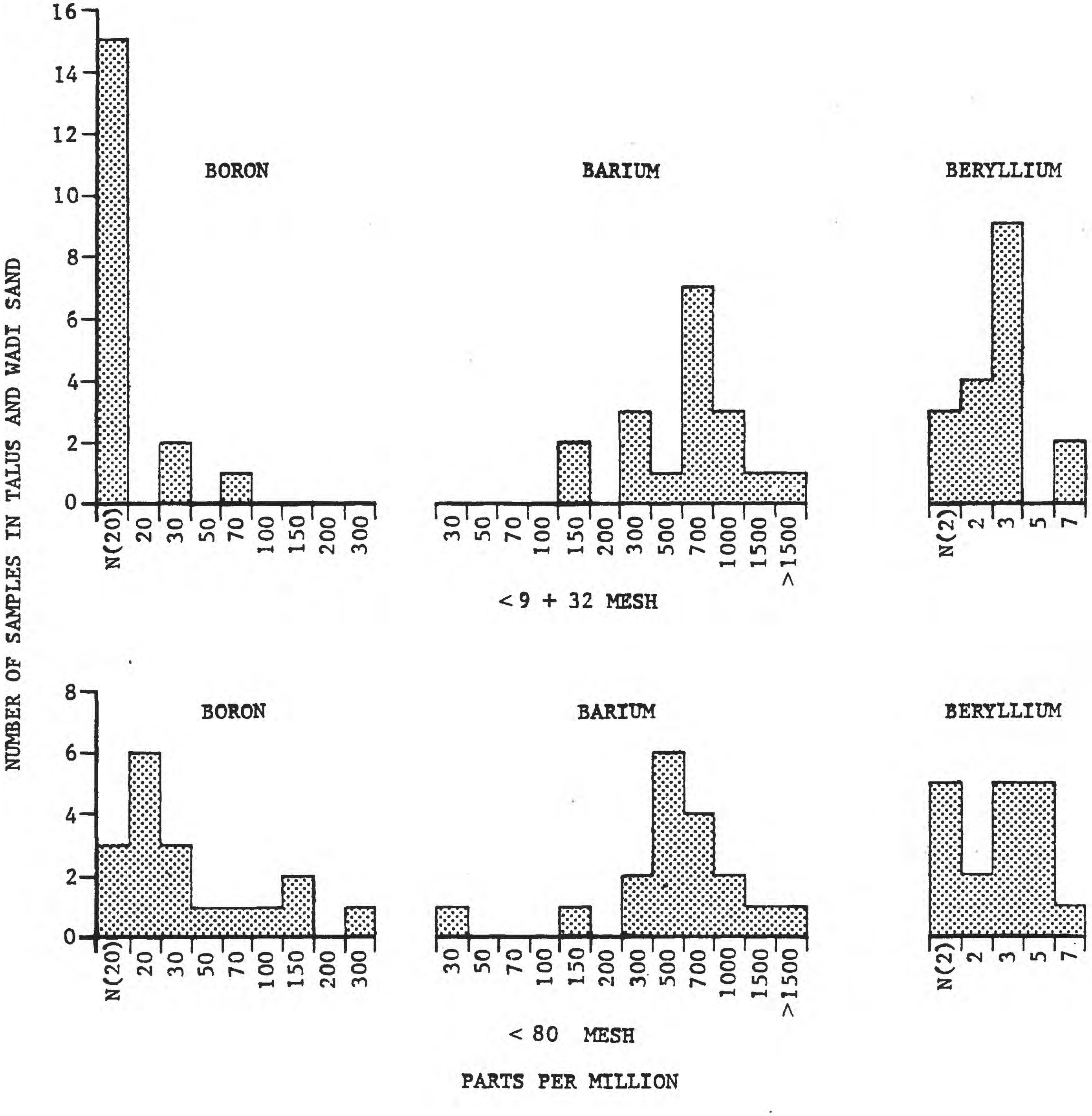


Figure 17. Histograms of boron, barium, and beryllium showing variation in content of metals as a function of the grain size of the sediment used for analysis, granitic massif east of Al 'Aqabah, Hashemite Kingdom of Jordan.

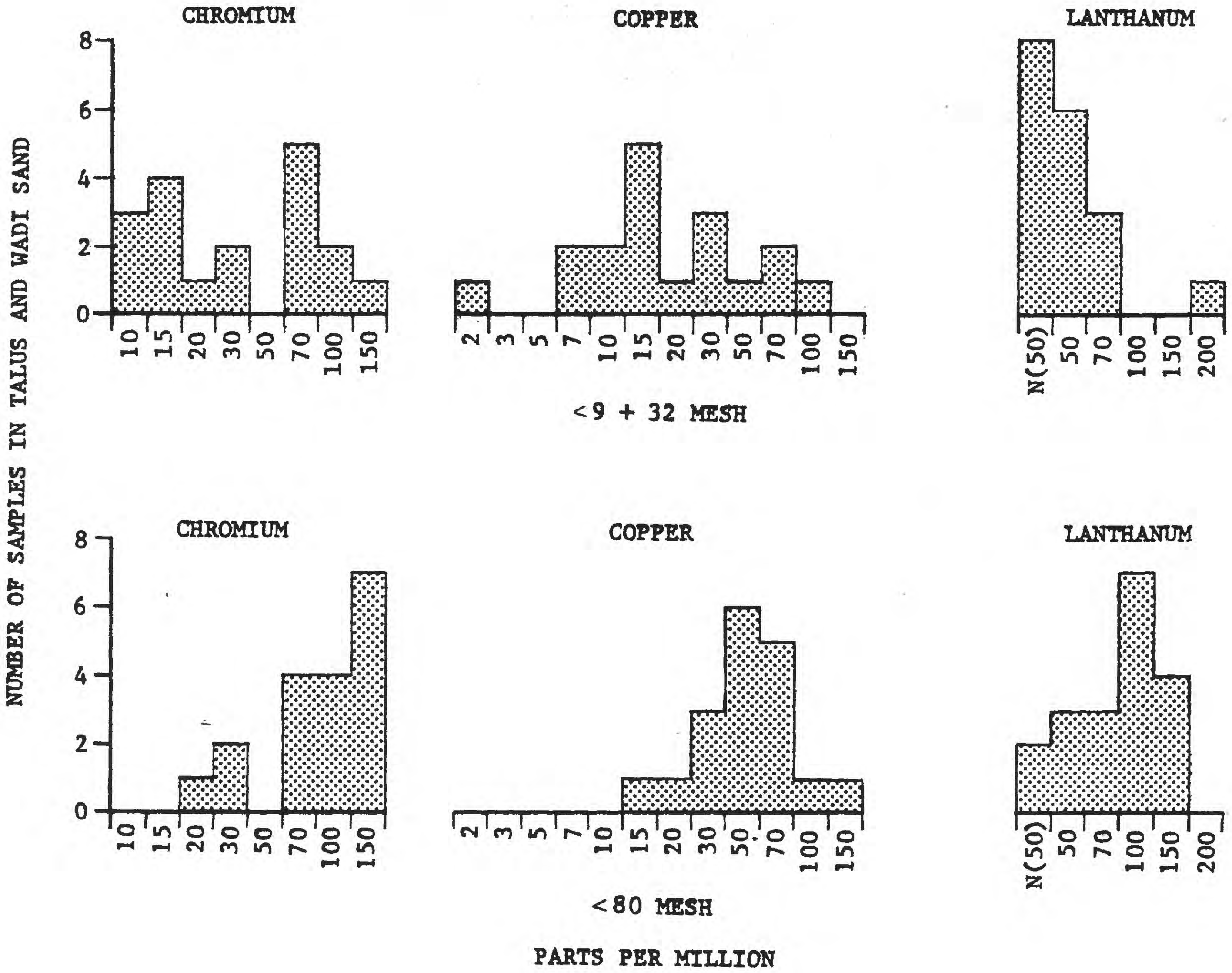


Figure 18. Histograms of chromium, copper, and lanthanum showing variation in content of metals as a function of the grain size of the sediment used for analysis, granitic massif east of Al 'Aqabah, Hashemite Kingdom of Jordan.

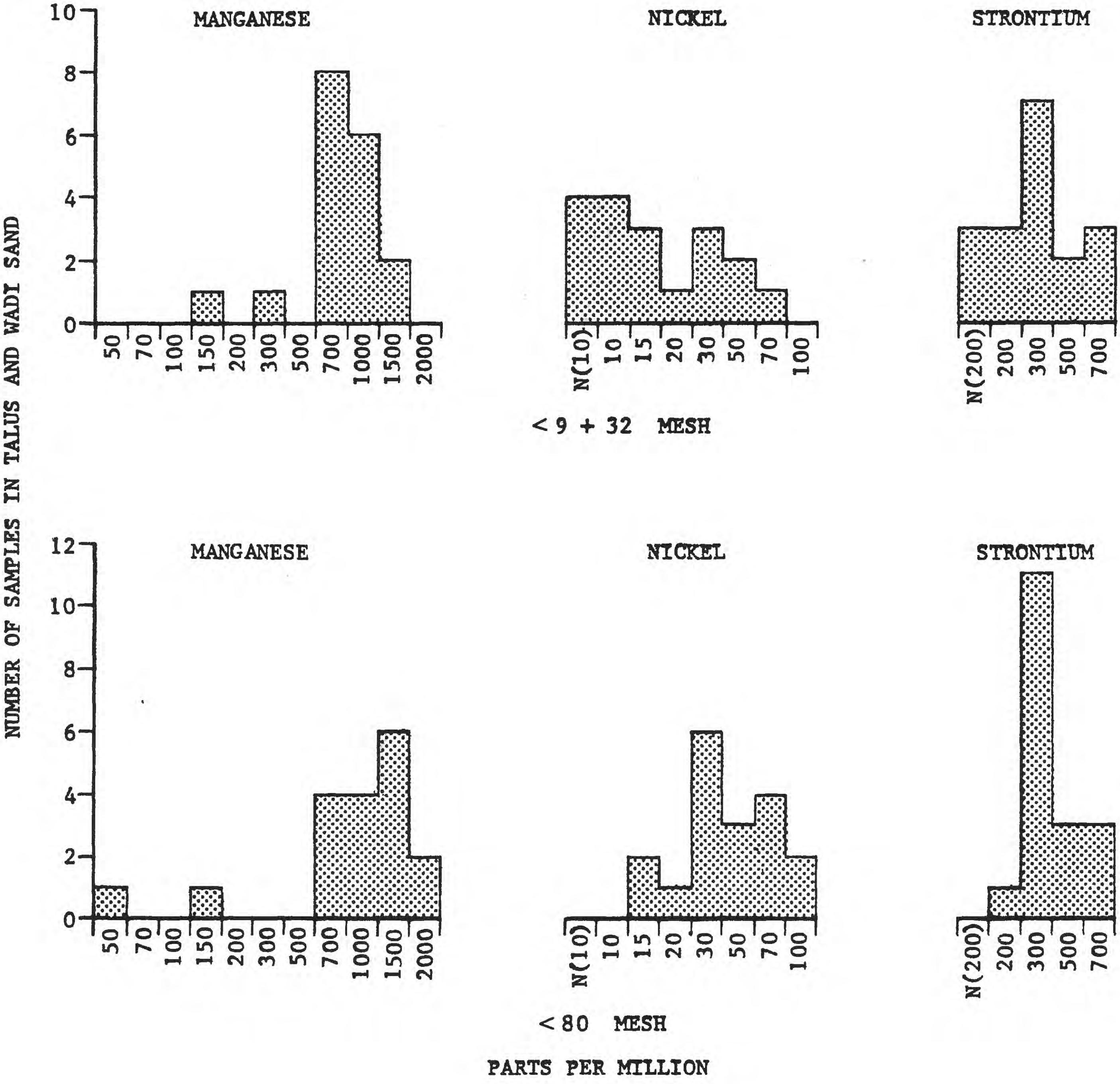


Figure 19. Histograms of manganese, nickel, and strontium showing variation in content of metals as a function of the grain size of the sediment used for analysis, granitic massif east of Al 'Aqabah, Hashemite Kingdom of Jordan.

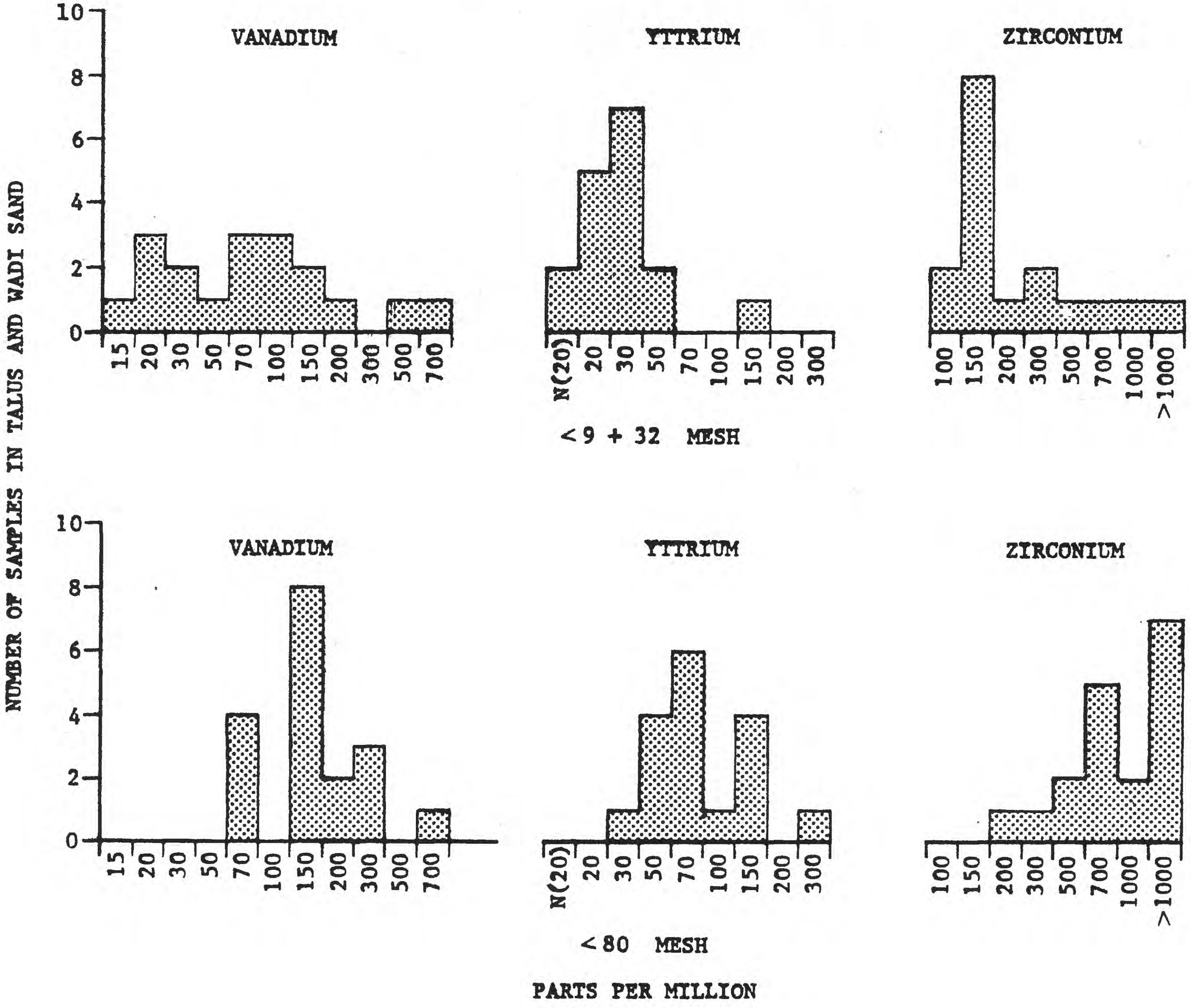


Figure 20. Histograms of vanadium, yttrium, and zirconium showing variation in content of metals as a function of the grain size of the sediment used for analysis, granitic massif east of Al 'Aqabah, Hashemite Kingdom of Jordan.

Granitic massif east of Al'Aqabah

The results of semiquantitative spectrographic analyses of sieved fractions of wadi sand and talus from the area of the granite massif exposed to the east of Al'Aqabah are given in table 26. Results from the analyses of the concentrates from this area appear in table 27.

Composition related to size of fraction of wadi sand or talus used for analysis.--A comparison of the number of reporting intervals for a given element as listed in table 26 between the coarsest grained (the A fraction, <9 + 32 mesh) and the finest grained (the C fraction, <80 mesh) components of the seven samples of wadi sand or talus shows a consistent pattern of higher values from the finest grained fraction:

Element and average algebraic difference[1] in reporting interval for each element between coarsest grained and finest grained fractions in seven samples

Fe = -2
Mg = -1
Ca = -2
Ti = -2
B = -2
Ba = 0
Be = -1

Co = -3
Cr = -3
Cu = -3
La = -2
Mn = -1
Nb = -1
Ni = -3

Pb = -2
Sc = -2
Sr = 1
V = -2
Y = -2
Zn = -1
Zr = -2

[1] Where the higher value of a given element is associated with the coarsest grained fraction, the difference in reporting intervals is called positive; where the higher value of a given element is associated with the finest grained fraction, the difference in reporting intervals is called negative; where no difference exists, the value of zero is assigned.

The results of these preliminary orientation surveys are discussed in the sections below, where it is shown that, contrary to the reasoning and experience cited above to favor coarse-grained fractions of wadi sand for use as the preferred sample medium in arid regions, the finest grained fraction (<80-mesh) was indeed the most metal-rich of the fractions and tended to have

Table 26. Results of semiquantitative spectrographic analyses of wadi sand and talus from the granitic massif in the region east of Al'Aqabah, Hashemite Kingdom of Jordan
[Analyses by Mohamad Sha'ahan and Zuheir Issa, NRA, Amman, Jordan, 1978.]

Sample numbers		In percent				Results in parts per million																
Field	Laboratory	Fe	Mg	Ca	Ti	B	Ba	Be	Co	Cr	Cu	La	Mn	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Zr
77-OT-578A	SPL-110	3	0.7	20	0.3	70	150	N(2)	10	70	15	N(50)	700	N(20)	15	70	7	200	70	30	N(200)	>1,000
-578B	-111	3	1.5	7	.3	50	700	3	10	70	50	50	1,000	N(20)	30	70	10	700	70	30	N(200)	200
-578C	-112	3	2	15	.5	70	500	3	15	100	70	70	700	N(20)	30	70	15	700	70	50	N(200)	300
-545A	-68	15	1.5	5	1	N(20)	1,000	N(2)	70	100	70	200	1,500	20	50	100	30	200	700	150	N(200)	>>1,000
-545B	-69	15	1.5	5	>1	N(20)	700	N(2)	70	100	150	300	2,000	50	100	50	30	700	700	300	N(200)	>1,000
-545C	-70	15	1.5	7	>1	N(20)	700	N(2)	50	150	150	150	2,000	30	70	70	20	300	700	150	200	>>1,000
-517A	-38	1.5	.7	1	.2	N(20)	700	2	N(5)	10	7	50	300	N(20)	N(10)	N(50)	N(5)	300	30	15	N(200)	100
-517B	-39	1.5	1	1.5	.2	N(20)	700	3	N(5)	15	10	70	500	N(20)	N(10)	50	5	300	30	20	N(200)	100
-517C	-40	3	1.5	7	.3	30	700	5	10	70	20	150	700	N(20)	20	70	10	500	70	30	200	500
-521A	-41	7	1.5	3	.7	N(20)	300	3	20	70	15	50	1,000	N(20)	30	N(50)	15	300	150	30	300	150
-521B	-42	10	1.5	3	.7	N(20)	300	5	30	100	30	70	1,500	20	30	50	15	300	150	50	200	150
-521C	-43	15	1.5	7	1	50	300	3	30	150	50	100	1,500	30	70	100	20	300	150	70	300	700
-523A	-44	1.5	1	1.5	.3	N(20)	300	3	N(5)	15	7	70	700	N(20)	10	N(50)	20	300	30	20	200	100
-523B	-45	15	2	3	1	N(20)	500	5	30	100	30	100	1,500	30	50	70	20	300	150	70	300	150
-523C	-46	15	1.5	5	1	20	300	5	30	150	50	150	1,500	30	70	70	30	300	200	100	300	1,000
-535A	-56	10	1.5	3	.7	N(20)	1,000	3	20	70	30	70	1,000	20	30	50	15	500	100	50	N(200)	150
-535B	-57	10	2	10	1	30	700	5	30	150	50	70	1,500	20	100	100	20	500	150	70	N(200)	1,000
-535C	-58	15	2	3	1	N(20)	1,000	3	30	100	50	70	1,000	20	50	50	15	300	150	70	200	200
-537A	-59	2	.7	1.5	.3	N(20)	700	3	N(5)	10	10	50	700	N(20)	10	N(50)	5	200	50	20	N(200)	150
-537B	-60	10	1.5	2	1	N(20)	700	5	30	70	30	70	1,500	30	30	70	15	300	150	70	200	150
-537C	-61	20	2	5	<1	20	500	5	30	150	70	100	2,000	30	100	100	20	300	300	100	300	700

[1] Elements looked for but not found at lower limits of determination shown in table 1: As, Au, Bi, Cd, Mo, Sb, Th, and W.
Elements rarely present at lower limits of determination shown in table 1, sample numbers, and abundances are: Ag, 2 ppm, 77-OT-521C, -523C, -535B, and 537C; and Sn, 500 ppm, 77-OT-523C.

Table 27.--Results of semiquantitative spectrographic analyses of concentrates panned from wadi sand and talus in the area of the granitic massif east of Al'Aqabah region, Hashemite Kingdom of Jordan
[Analyses by D. J. Grimes and R. T. Hopkins, USGS, 1978]

Sample numbers		In percent				In parts per million[1]																	
Field	Laboratory	Fe	Mg	Ca	Ti	B	Ba	Be	Co	Cr	Cu	La	Mn	Nb	Ni	Pb	Sc	Sn	Sr	Th	V	Y	Zn	Zr
77-OT-516	MAX-262	20	1	2	2	50	500	5	15	150	20	300	2,000	70	7	200	20	N(10)	300	100	500	200	N(200)	2,000
-518	-263	20	1	3	2	50	500	5	20	300	30	300	3,000	70	30	100	30	N(10)	200	100	500	200	N(200)	1,000
-522	-264	30	1	3	2	50	500	2	30	500	50	300	3,000	70	50	100	50	30	200	L(100)	1,000	300	500	1,500
-528	-265	30	1	3	G(2)	30	300	L(2)	70	300	100	200	3,000	50	50	70	70	N(10)	100	100	1,500	200	500	700
-544	-266	50	0.7	2	G(2)	50	300	N(2)	70	300	100	300	3,000	50	50	50	50	N(10)	100	N(100)	1,500	200	500	2,000
-546	-267	20	1.5	3	2	50	300	N(2)	30	300	50	70	2,000	30	50	30	30	N(10)	300	L(100)	700	70	300	700
-549	-268	15	.5	0.7	1.5	500	5,000	2	L(5)	300	30	150	10,000	50	10	30	20	70	200	200	200	300	N(200)	G(2000)[3]
-557	-269	10	.5	1.5	0.5	N(20)	G(10,000)[2]	2	15	30	7	70	1,500	20	7	100	15	30	10,000	N(100)	150	100	N(200)	1,000
-559	-270	50	.7	2	2	N(20)	10,000	3	20	500	50	150	3,000	50	20	100	20	N(10)	1,000	L(100)	700	300	N(200)	G(2,000)

[1] Elements looked for but not found at lower limits of determination shown in table 1: Ag, As, Au, Bi, Cd, Mo, Sb, and W.
[2] Barium content reported by analysts to be at least 10 percent.
[3] Zirconium content reported by analysts to be at least 2 percent.

the greatest range in variation in the high-value tail of the determinations. Windborne particulates appear to be less of a contaminant in wadi sands in the Al'Aqabah area than they were in the eastern part of the Precambrian Shield in Saudi Arabia. But what appears to be the main reason for the highest values for the metals being in the <80-mesh fraction may be a considerable presence in this fraction of micron-sized or larger particles of secondary iron and manganese oxides and hydroxides. These secondary products are precipitated from surface moisture and ground water under aerated conditions (Jenne, 1968; Chao and Theobald, 1976) and scavenge large quantities of other metals from the water as they form. Some chemical evidence in the present set of samples has been interpreted here to show that the process is more effective near the coast, where spray and fog are present, than farther inland, where less precipitation occurs. Mineralogical study of the various size fractions of wadi sand will be required to determine what processes are causing the enrichment in wanted metals of the finest-grained fractions of wadi sand. Also, future geochemical orientation surveys in central and eastern Jordan are required to determine if the coarsest- or the finest grained fraction of wadi sand serves better as a sample medium under different environmental conditions.

The heavy-mineral concentrates were analyzed without separation in bromoform to remove the 10-20 percent of quartz and feldspar in the crude concentrate and without magnetic separation to remove the magnetite. The presence of the feldspar and magnetite are reflected in the results of the analyses. Therefore, in further geochemical exploration in Jordan using heavy-mineral concentrates for the sample medium, it is recommended that the crude concentrates be cleaned in bromoform and separated magnetically before analysis. Future orientation surveys should also consider the use of independent analyses of the magnetic separates (Pan and others, 1980) and of the nonmagnetic separates (Overstreet and others, 1978) from the concentrates. From present data, the nonmagnetic separate may be the most useful. Despite these constraints on the present work, the value of heavy-mineral concentrates as a geochemical sample medium to identify secondary dispersion trains of high-density ore minerals was clearly shown in the vicinity of the small barite vein situated to the northeast of Al'Aqabah.

These results are opposite what would be expected from general considerations of aeolian contamination in the arid environment. They are also opposite the results reported by Theobald and associates (1977) for an orientation survey in the Kingdom of Saudi Arabia. Of the 147 pairs of determinations for the 21 elements listed in table 26 for the coarsest grained and finest grained fractions of the seven samples, 96 pairs have differences within two reporting intervals; that is, they are within expectable laboratory variance of each other:

Variance in reporting interval for coarsest- and finest grained fractions (+ fractions + = coarsest grained fraction has the greater value; - = finest finest grained fraction has greater value)	Number of pairs showing given variance
+3	1
+1	8
0	33
-1	31
-2	24
-3	22
-4	13
-5	7
-6	5
-7	3
	147

However, when the variance is so biased toward higher values in the finest-grained fractions, as it is here even for one and two reporting intervals, the variance seemingly must be attributed to changes in composition related to decreasing grain size of the fraction analyzed. Even a variance by three reporting intervals could be accepted as representing factors related to the precision of the analyses, if they were not so strongly restricted to the finest grained fractions. Through three reporting intervals the variance affects all the elements listed in table 26, but variance of four reporting intervals or more is restricted to 12 elements--Fe, Ca, B, Co, Cr, Cu, Ni, Pb, Sc, V, Y, and Zr:

Element	Number of pairs of size fractions displaying variance (+ = coarsest grained fraction has the greater value; - = finest grained fraction has the greater value)									
	+3	+1	0	-1	-2	-3	-4	-5	-6	-7
Fe	0	0	2	1	2	0	0	0	2	0
Mg	0	0	2	2	1	2	0	0	0	0
Ca	0	1	1	1	1	2	0	1	0	0
Ti	0	0	0	5	0	2	0	0	0	0
B	0	0	3	0	2	1	1	0	0	0
Ba	0	2	4	0	0	1	0	0	0	0
Be	0	0	3	2	0	2	0	0	0	0
Co	0	1	0	2	1	0	1	0	0	2
Cr	0	0	0	3	1	0	0	1	1	1
Cu	0	0	0	1	1	2	1	2	0	0
La	0	1	1	0	3	2	0	0	0	0
Mn	0	0	0	2	2	1	0	0	0	0
Nb	0	0	3	1	0	3	0	0	0	0
Ni	0	0	0	2	2	0	1	1	1	0
Pb	0	1	2	0	0	2	2	0	0	0
Sc	0	1	1	2	1	0	2	0	0	0
Sr	0	1	2	2	1	1	0	0	0	0
V	0	0	3	1	1	0	0	2	0	0
Y	0	0	1	2	2	0	2	0	0	0
Zn	0	0	2	1	3	1	0	0	0	0
Zr	1	0	1	1	0	0	3	0	1	0

Mineralogical study to determine the host grains for these 12 elements has not been done. Until the mineral composition and sources of the various size fractions of the wadi sand and talus have been determined, no explanation for the increased abundance of these elements in the finest grained fraction can be sustained. However, in the following section on the chemical composition of the sieved fractions of wadi sand and talus, the enrichment of trace elements in the <80-mesh fraction is tentatively identified with an increase in the amount of secondary iron and manganese minerals in that fraction. An alternative possibility, not as yet studied, may be that in this area the wadi sand has been contaminated by floods of metal-poor, coarse-grained quartz sand recycled from the Paleozoic sandstones to the north and east through aeolian transport. This would result in a reduction in the amount and the spread of the metal values observed in the coarse fraction.

Also, it is clear that a larger number of samples of wadi sand must be sieved and analyzed than was done in this investigation to determine the most satisfactory size of sand to use for geochemical exploration in Jordan.

Composition of wadi sand and talus related to source rocks.--Inspection of table 25 shows that the source rocks for the seven samples of wadi sand and talus listed in table 26 were classed by Bender (1968c) as aplite granite and granodiorite. However, various differences in mineral composition and texture of the rocks as well as the relative abundance of dikes of different sorts, and the reported presence locally of sulfide-bearing veins permits a somewhat broader classification adapted from Hakki (1971) for use here than that employed in the earlier geologic mapping:

Bender (1968c)

Aplite granite
77-OT-578
Granodiorite
77-OT-545
77-OT-517
77-OT-521
77-OT-523
77-OT-535
77-OT-537

Hakki (1971)

Late Precambrian granite
77-OT-578
77-OT-545
77-OT-517
Older Precambrian granite

With sulfide mineralization	Without sulfide mineralization
77-OT-521	77-OT-535
77-OT-523	77-OT-537

Compared to the composition of the average granite or granodiorite (table p 28), these sieved fractions of wadi sand and talus are generally enriched in Fe, Mg, Ti, Cr, Mn, Ni, and Pb. Locally the sediments are enriched in Ca, B, Co, Cu, V, Y, and Zr.

The general enrichment in iron and manganese, as well as the local enrichment in calcium (77-OT-578), may be caused by the presence of secondary iron and manganese oxides and hydrous oxides, and by calcium carbonate, that precipitated from surface and pore water under aerated conditions in intermittently saturated sand and talus (Canney, 1966; Jenne, 1968; Carpenter and others, 1975; Alminas and Mosier, 1976; Nowlan, 1976; Carpenter and Hayes, 1979). The secondary iron and manganese oxides and hydrous oxides are widely observed elsewhere to form coatings, discrete particles of colloidal size, or concretions in sediments. Likewise, calcium carbonate (caliche) precipitates as coatings, cement, or concretions in sediments in arid and semiarid regions. These secondary products, particularly the iron and manganese minerals, have a well-known capacity for scavenging trace elements in solution in the water from which they precipitate (Taylor and McKenzie, 1966; Neuerburg and others, 1971; Whitney, 1975; Chao and Theobald, 1976; Butt and others, 1977; Gatehouse and others, 1977). The tendency toward enrichment of the trace elements in the finest-grained fractions of the sediments from the

Table 28. Comparison of the content of elements in wadi sand and talus from the area of the granitic massif east of Al'Aqabah, Hashemite Kingdom of Jordan, with the contents of these same elements in average granite and granodiorite (in ppm)

Element	Granitic massif east of Al'Aqabah					Average granite[3]	Average granodiorite[3]
	77-OT-578[1]	77-OT-545[1]	77-OT-517[1]	77-OT-521 77-OT-523[2]	77-OT-535 77-OT-537[2]		
Fe	30,000	150,000	20,000	100,000	100,000	18,300	33,000
Mg	15,000	15,000	10,000	15,000	15,000	3,300	11,000
Ca	150,000	50,000	30,000	30,000	50,000	24,000	46,000
Ti	3,000	>10,000	2,000	7,000	10,000	1,700	3,800
B	70	N(20)	L(20)	L(20)	L(20)	15	12
Ba	500	700	700	300	700	840	450
Be	2	N(2)	3	5	5	3.5	2.5
Co	10	70	L(5)	20	20	1	7
Cr	70	100	30	100	100	10	22
Cu	50	100	10	30	30	10	26
La	50	200	100	100	70	55	40
Mn	700	2,000	500	1,000	1,500	400	700
Nb	N(20)	30	N(20)	20	20	21	20
Ni	20	70	10	50	50	4.5	15
Pb	70	70	50	50	50	19	15
Sc	10	30	5	20	15	7	14
Sr	500	500	300	300	300	110	440
V	70	700	50	150	150	44	88
Y	30	200	20	50	70	40	34
Zn	N(200)	L(200)	L(200)	300	200	39	56
Zr	700	>1,000	200	300	300	180	160

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[1] Average of three determinations, to nearest reporting interval.

[2] Average of six determinations, to nearest reporting interval.

[3] Beus and Grigorian, 1977, table 3.

Al'Aqabah area, noted above, may be related to the increased presence of these secondary minerals with decreasing grain size of the sieved factions of the samples of wadi sand and talus, because the secondary iron and manganese minerals not only precipitate as particles of colloidal size, but coatings and crusts of these minerals are readily abraded into dust-like products. As mentioned above, a mineralogical study of the <80-mesh fraction is required to determine the host minerals for the trace elements. Without this study, the interpretations given below, which are based on chemical composition related to grain size of the analyzed samples and the lithologic variations in the granitic rocks, are speculative. They are intended to identify some of the problems that will require solution by a comprehensive orientation survey.

Concentrations of iron and manganese tend to vary sympathetically, that is, where iron has a high value, manganese also has a high value, and where the abundance of iron is low, so is the abundance of manganese. For example, in sample 77-OT-578, from the area of the leucocratic granite considered by NRA to be a possible source for ceramic-grade feldspar, the sieved fractions of talus contain only 3 percent iron and 700-1,000 ppm manganese. In Sample 77-OT-517, of sediment derived from pink porphyritic granite lacking mafic dikes, the iron content of the talus ranges in percentage from 1.5-3, the manganese content is a low 300-700 ppm, and the highest values for both iron and manganese are in the <80-mesh fraction. Where the granitic rocks are intruded by mafic dikes, as in the areas furnishing samples of wadi sand numbered 77-OT-545, -521, -535, and -537, the quantity of iron and manganese picks up to about 4-5 and 3-4 times their respective abundances in the areas of granitic rocks lacking mafic dikes.

Other chemical evidence in table 26 does not support the concept that the contents of iron and manganese in the samples of talus and wadi sand reflect the presence or absence of mafic dikes in the granitic rocks in this part of the massif at Al'Aqabah. Elements typically enriched in mafic rocks compared to their abundances in granitic rocks, such as Ca, Mg, Ti, Co, Cr, Cu, Ni, Sc, Sr, V, and Zn (Beus and Grigorian, 1977, table 3), are no less abundant in sediments from the areas lacking mafic dikes (represented by samples 77-OT-578 and -517) than they are in the other areas, except titanium (table 26). Titanium is notably less abundant in the talus from areas of granitic rocks lacking mafic dikes than it is in wadi sand from areas where mafic dikes are present. The possibility that this exception may be caused by differences in mechanical winnowing, rather than by the chemistry of the source rocks, is discussed below. Elements typically enriched in granitic rocks compared to mafic rocks, such as B, Be, La, Nb, Pb, Y, and Zr (Beus and Grigorian, 1977, table 3), are no more abundant in the talus derived from the granitic rocks than they are in the wadi sand derived from granitic rocks intruded by mafic dikes. Indeed, the area of white to pink porphyritic granite intruded by dikes of diabase and andesite, represented by sample 77-OT-545 of wadi sand, is enriched in zirconium compared to the other samples listed in table 26.

The lower values for iron and manganese in samples from areas of granite lacking mafic dikes may be caused by factors other than the original chemical composition of the source rocks. Should this prove to be the fact, then additional care must be exercised in selecting sites in which to take erosional debris for sieving and analysis. The two samples of talus (77-OT-578 and -517) contain the least iron and manganese. If these elements are present mainly in fine-grained oxides and hydrous oxides, their relative sparsity in the sieved fractions from the talus of the valley walls may be the effect of high porosity and slope, whereby surface water moves down the gradient of the talus slope so rapidly that precipitation of these oxides and hydroxides is much less pronounced than it is in the wadi sands of the lower-gradient valley floors. Similarly, mechanical disaggregation and winnowing of the talus are far less advanced than in the wadi sand. Eluvial concentration of heavy minerals has progressed less in the talus than alluvial concentration in the wadi sand. Thus, titanium would tend to become more concentrated in wadi sand than in adjacent talus.

What source for water to promote the precipitation of iron and manganese oxides and hydroxides can be proposed for the area of the Al'Aqabah massif in Jordan that would not have been present in the area of Saudi Arabia studied by Theobald and others (1977)? An obvious source in the Al'Aqabah area is sea spray and coastal fog that are lacking in central Arabia hundreds of kilometers from the coast, and dew that is more copious in the coastal area at Al'Aqabah than it is in the interior of the Arabian Peninsula. The presence of these sources of water in other coastal deserts has been described (Grolier and others, 1974, p. 128). If, indeed, such sources of water promote the development of iron and manganese oxides and hydroxides in wadi sediments near the coast of the Arabian Peninsula, in contrast to the interior deserts, then some precaution is needed to insure that anomalies detected for wanted elements are not spurious, owing to the scavenging of these elements from unmineralized rocks (Canney, 1966; Horsnail and others, 1969; Carpenter and others, 1975; Chao and Theobald, 1976; Carpenter and Hayes, 1979).

Neither of the samples (77-OT-521 and -523) of wadi sand from areas in the granite where copper- and lead-bearing quartz veins are locally reported is in any way distinguishable chemically from the other samples on the basis of content of copper or lead (table 26). A slight rise of one reporting interval in zinc is evident, but this minor difference is too small to serve as a certain geochemical indicator of the local presence of sulfide-bearing veins. The finest grained fraction of each sample contains 2 ppm silver, but such low quantities of silver were also found for two other samples, neither of which is near known mineralized areas. Sample 77-OT-523C also contains 50 ppm tin, but this amount is at the threshold of detection and cannot be said to characterize these samples, because the tin was detected in only one out of six fractions from possibly mineralized areas. No chemically distinguishing characteristic was reported (table 27) for the concentrate (77-OT-522) from this area. Thus, these few samples do not identify the presence of the reported base-metal-bearing veins.

The high values for zirconium in wadi sand (77-OT-545) from an area underlain by porphyritic granite intruded by diabase and andesite are distinctive (table 26). The analysts, Mohamad Sha'aban and Zuheir Issa, note that the symbols >1,000 ppm and >>1,000 ppm used in table 26 indicate respectively about 1,500 ppm and 2,000 ppm zirconum. These values are also accompanied by high values for Fe, Ti, La, Mn, and Y, but the value for Nb is low. The concentrate from the same locality (77-OT-544, table 27) is also enriched in Fe, Ti, and Mn, but its contents of La, Y, and Zr are not increased over those of the raw sand. Other concentrates are notably richer in zirconium than sample 77-OT-544, and contain more Be, Nb, and Th than sample 77-OT-544. For these reasons the high values for zirconium in the wadi sand derived from Late Precambrian porphyritic granite in the massif east of Al'Aqabah probably do not indicate the presence of a Nb-Zr-U deposit such as the Ghurrayyah deposit in young alkaline to peralkaline granite in Saudi Arabia. The possibility for a similar kind of deposit, however, in the granitic massif east of Al'Aqabah is reason for attention, particularly of the composition of the concentrates.

Geochemical indication of other anomalous elements in the samples of wadi sand and talus listed in table 26 is lacking.

Composition of concentrates.--Three of the concentrates listed in table 25 are from wadi sand and one concentrate is from talus taken in conjunction with the sieved samples of sediment from the granitic massif near Al'Aqabah:

Sample number	Material sampled	Kind of sample
77-OT-516	Talus	Concentrate
-517	Talus	Sieved fractions
-518	Wadi sand adjacent to talus used for 77-OT-516 and -517	Concentrate
-522	Wadi sand	Concentrate from sand used for 77-OT-523
-523	Wadi sand	Sieved fractions
-544	Wadi sand	Concentrate from sand used for 77-OT-545
-545	Wadi sand	Sieved fractions

The results of the analyses of these concentrates are listed in table 27. Several elements that in themselves are ore metals, or are indicators of possible complex ore deposits, were not detected at their respective lower limits of determination, which are, in parts per million: Ag, 0.5; As, 200; Au, 10; Bi, 10; Cd, 20; Mo, 5; Sb, 100; and W, 50.

Two concentrates from adjacent parts of a valley, one prepared from talus on the valley wall (77-OT-516) and the other made from wadi sand (77-OT-518) at the toe of the wall, are quite similar in composition. Twenty-two of the 23 reported elements are within normal limits of analytical variation:

Number of reporting intervals in variation[1]	Elements with given variation
0	Fe, Mg, Ti, B, Ba, Be, La, Nb, Sn, Th, V, Y, Zn
1	Ca, Co, Cu, Mn, Sc
-1	Sr, Zr
2	Cr
-2	Pb
4	Ni

[1] Where larger of two values for a given element is determined for the concentrate prepared from wadi sand, a positive number is used; where the larger number is for the concentrate from talus, a negative number is used.

Panning the raw eluvial and alluvial sediment in these two examples led to a reduction of the chemical dissimilarity observed above between eluvial and alluvial sediments. Therefore, some homogenization in chemical composition is obtained by going from the raw sediment to a concentrate for the geochemical sample medium.

A comparison of the chemical composition of these two concentrates with the average composition of the sieved fractions of talus sample 77-OT-517 (table 28) from the same locality shows identical values in the abundances of Mg, Ca, Ti, Sr, and Zn, and quite similar values for B, Ba, Be, Co, Cu, Ni, and Sc. Values are enhanced in the concentrates for Fe, Cr, La, Mn, Nb, Pb, V, Y, and Zr. The elements whose abundances are enhanced in the concentrates are ones for which enhancement can be expected in such heavy minerals as magnetite, chromite, allanite, monazite, garnet, apatite, and manganese oxides (Theobald and others, 1967; Fischer and Fisher, 1968; Overstreet and others, 1978). The unusual relations of titanium, however, defy explanation because the mineralogical composition of the samples, needed to identify the titanium carriers, is not known. The most likely mineralogical hosts for the element are ilmenite, magnetite, rutile, biotite, and augite. Except for the biotite, these minerals should be more abundant in the concentrates than in the sieved fractions of raw sediment. However, the abundance of titanium was not increased by panning the raw sediment to a heavy-mineral concentrate.

Another unexplainable feature is the similarity in the contents of calcium between the raw sediment and the concentrate, unless the mineral grains of the concentrate have coatings of caliche or contain some feldspar. Such coatings were not a notable aspect of the heavy minerals as seen by hand lens after panning, but about 15-20 percent of the panned concentrate consisted of feldspar and quartz. These rock-forming minerals were not removed from the concentrate before analysis. Possibly the presence of feldspars in the concentrate accounts for the calcium as well as for barium and strontium, which are also about equally abundant in the raw sediment and in the concentrate.

Both lanthanum and yttrium could be in the heavy mineral zircon, which is evidently more abundant in the concentrates than in the sieved fractions of talus. Lanthanum and yttrium might also be associated with manganese, either in secondary oxides or in garnet, or with monazite, a mineral whose presence may be indicated by the small amount of thorium in concentrates 77-OT-516 and -518. In any event, these concentrates do not indicate the presence of any unusual concentrations of La, Mn, Th, Y, or Zr.

Low values for Be, Mo, Nb, Sn, and W in samples 77-OT-516 and -518 can be interpreted to indicate the lack of nearby sources for these elements. Abundances of Mo, Nb, Sn, and W would rise to hundreds or thousands of parts per million in concentrates derived from mineralized sources.

Vanadium is clearly more abundant in the concentrates than in the raw talus, reflecting perhaps the tendency for vanadium in igneous rocks to occur preferentially in magnetite. Values of 500 ppm vanadium or less are typically reported for magnetite from felsic igneous rocks, with greater amounts in magnetite from mafic igneous rocks (Sen and others, 1959; Frietsch, 1970). However, vanadium may precipitate with the secondary iron oxides, which would also be found in the concentrates, but the large increase in the content of vanadium in the concentrates compared to the content of the sieved fractions of talus--500 ppm to 50 ppm--is here interpreted to show that the vanadium is probably in the magnetite. Interestingly, but less likely, the rise in abundance of lead in the concentrate compared to lead in the sediment--100-200 ppm to 50 ppm--in conjunction with the rise in vanadium might be explained by the presence of small amounts of secondary lead vanadate minerals, such as descloizite or vanadinite, in the concentrate.

The chemical character of concentrates numbered 77-OT-516 and -518 are those of ordinary crude concentrates from unmineralized areas. No metals of economic importance, whose abundances would be enhanced in a heavy-mineral concentrate over their abundances in sediments or source rocks, are indicated by the composition of these two concentrates.

Concentrate number 77-OT-522 comes from an area where a copper-bearing quartz vein has been reported (table 25), but no significant enrichment of copper, or of the other base metals, was detected in the concentrate (table 27). Copper, lead, and zinc are more abundant by one (Cu and Zn) or two (Pb) reporting intervals in the concentrate than in the sieved sediment (77-OT-523). However, these differences are within acceptable analytical variation, and do not signify that degree of enrichment of a concentrate over a sieved fraction of sediment needed to indicate a positive anomaly (Newberg, 1967; Chaffee, 1975; Christensen and Friedrich, 1975; Chaffee and others, 1976). Indeed, the differences are mainly due to the contents of quartz and feldspar in the two materials.

Nearly identical or identical contents were determined for the concentrate amd wadi sand sample 77-OT-523 for Mg, Ca, Ti, B, Ba, Be, Co, La, Ni, Sc, Sn, and Sr. The finest grained sieved fraction of the wadi sand even contained 2 ppm silver, not noted in the concentrate, which was reported to have <0.5 ppm Ag. Expectable enrichments of Fe, Cr, Mn, Nb, Th, V, Y, and Zr were found in the concentrate, explainable by the factors noted above. The rise of vanadium to 1,000 ppm is worthy of note, particularly where it is associated with a rise of 500 ppm of chromium in the concentrate. Both increases suggest a greater quantity of mafic rocks in the drainage basin than in the source area for concentrates numbered 77-OT-516 and -518, because vanadium increases in abundance in magnetite from mafic rocks and chromium is a typical constituent in heavy minerals from mafic rocks. However, none of the geochemical data for the concentrate is indicative of any abnormal enrichment or of possible mineral deposits.

Concentrate sample number 77-OT-544 (table 27) departs less in composition from that of wadi sand from the same locality (sample 77-OT-545, table 28) than any concentrates in this group. Identical values were determined for Be, Co, Cu, and Y in the concentrate and in the raw sand. Nearly identical values were found for Mg, Ca, Ti, Ba, Cr, La, Mn, Nb, Ni, Pb, Sc, Sn, V, and Zr. For most of these elements, the values determined for the concentrate are the greater where there is a difference, but Ca, Ba, and Sr are more abundant enough in the wadi sand than in the concentrate to support the interpretation that these elements are hosted mainly by detrital feldspar or secondary caliche. The values for the elements in the concentrate are normal for ordinary granitic sources lacking mineral deposits.

Granite and sandstone in the Wadi Rum area northeast of Al'Aqabah

Several samples of wadi sand and talus were taken in the Wadi Rum area at the eastern edge of the massif of granitic rocks to the northeast of Al'Aqabah (table 25). The granitic rocks there are overlain by sandstone strata of Cambrian and of Ordovician age (Bender, 1968c) that thicken eastward. Wadi Rum affords the most easterly exposures of the massif in Jordan (fig. 21). Large mudflats lie upwind from two of the sampled localities. Their presence was thought to provide an opportunity to determine if aeolian transported saline particulates from the mudflats affected the chemical composition of samples of wadi sand and talus.

Sieved fractions of the wadi sand and talus (fig. 22, A and B) were analyzed (table 29) to determine if significant geochemical differences existed between coarse- and fine-grained fractions of the sand and talus, again using three fractions called A (<9 + 32 mesh), B (<32 + 80 mesh), and C (<80 mesh) for this test. Two concentrates, samples 77-OT-546 and -549, were prepared in order to compare their composition (table 27) with that of wadi sand and talus at the same localities.

Composition related to size fraction of wadi sand or talus used for analysis.--Here also in the far eastern part of the granitic massif the coarsest grained fractions of wadi sand and talus contain on average lower values for the reported elements than the finest grained fractions:

Figure 21. Photograph showing the easternmost exposures of the granitic massif to the east of Al Al'Aqabah as seen from the road leading eastward to Wadi Rum, Hashemite Kingdom of Jordan.

A. Talus of Precambrian granite intruded by felsite.

B. Wadi sand from Paleozoic sandstone.

Figure 22. Photographs showing the preparation of sieved samples of talus and wadi sand in the Wadi Rum area, Hashemite Kingdom of Jordan.

Table 29. Results of semiquantitative spectrographic analyses of wadi sand and talus from granite and sandstone in the Wadi Rum area to the northeast of Al'Aqabah, Hashemite Kingdom of Jordan.

[Analyses by Mohamad Sha'aban and Zuheir Issa, NRA, Amman, Jordan, 1978]

Sample numbers		In percent				In parts per million[1]												
Field	Laboratory	Fe	Mg	Ca	Ti	B	Ba	Be	Co	Cr	Cu	Mn	Ni	Sc	Sr	V	Y	Zr
77-OT-547A	SPL-71	10	2	5	1	N(20)	700	2	70	150	100	1,500	70	20	700	500	50	500
-547B	-72	15	3	7	1	N(20)	700	2	70	70	150	1,500	70	50	700	500	100	700
-547C	-73	5	1.5	7	0.7	100	500	2	15	100	50	700	30	15	300	150	50	>1,000
-550A	-74	1.5	0.3	1.5	.2	30	300	2	N(5)	15	70	700	N(10)	N(5)	N(200)	20	N(20)	300
-550B	-75	1	.2	1	.3	70	200	N(2)	N(5)	15	50	300	N(10)	N(5)	N(200)	30	20	>1,000
-550C	-76	3	.7	3	.7	300	500	N(2)	5	70	30	700	30	70	200	150	150	>>1,000
-553A	-77	0.7	.1	0.5	.15	N(20)	300	N(2)	N(5)	10	2	150	N(10)	N(5)	N(200)	20	N(20)	200
-553B	-78	.3	.07	.15	.1	N(20)	N(50)	N(2)	N(5)	N(10)	N(2)	70	N(10)	N(5)	N(200)	10	N(20)	100
-553C	-79	2	.3	1	.7	150	150	N(2)	N(5)	30	15	150	30	100	300	70	150	>>>1,000
-556A	-80	1.5	.5	1.5	.2	30	150	7	N(5)	15	10	700	N(10)	N(5)	N(200)	15	20	700
-556B	-81	1.5	.3	.7	.3	70	150	N(2)	N(5)	30	15	150	N(10)	N(5)	200	30	N(20)	1,000
-556C	-82	2	.7	3	.5	150	300	N(2)	N(5)	20	30	500	15	N(5)	300	70	50	>1,000

[1] Elements looked for but not found at lower limits of determination shown in table 1: As, Au, Bi, Cd, Mo, Sb, Sn, Th, and W.
Elements rarely present at lower limits of determination shown in table 1, abundances, and samples numbers are: As, 2 ppm, 77-OT-550C, 3 ppm, 77-OT-553A; La, 50 ppm, 77-OT-553C and -556C; Nb, 20 ppm, 77-OT-550C and -556C, 30 ppm, 77-OT-553C; Pb, 50 ppm, 77-OT-547B and -547C, 70 ppm, 77-OT-556A; Zn, 1,000 ppm, 77-OT-556A.

Element and average algebraic difference in[1] reporting interval for each element between coarsest grained and finest grained fractions, four samples

Fe = -1
Mg = -1
Ca = -2
Ti = -2
B = -6
Ba = -1
Be = 2

Co = 0
Cr = -2
Cu = -1
La = -1
Mn = 1
Nb = -2
Ni = -4

Pb = 0
Sc = -5
Sr = -1
V = -2
Y = -4
Zn = 1
Zr = -4

[1] Where the higher value of a given element is associated with the coarsest grained fraction, the difference in reporting intervals is called positive; where the higher value of a given element is associated with the finest grained fraction, the difference in reporting intervals is called negative; where no difference exists, the value of zero is assigned.

For all elements except B, Ni, Sc, Y, and Zr, the variance is within 1 or 2 reporting units, which is an acceptable range in variance. However, most of these variations are toward higher values in the finest grained fraction of the sediment, and all five elements with variance of 4 to 6 reporting intervals have higher values for the finest grained fractions. Therefore, even the variance of 1 or 2 reporting intervals confirms that the finest grained fraction is the more metal-rich material.

Several differences in variance of reporting intervals are evident between samples from the Wadi Rum area in the eastern part of the massif and samples from the western part of the massif; a few may be geochemically significant:

Wadi Rum area

Less than western part of massif	More than western part of massif	Same
Fe	B	Mg
Co	Ba	Ca
Cr	Be	Ti
Cu	Nb	Sr
La	Ni	V
Mn	Sc	
Ni	Y	
Pb	Zn	
	Zr	

The lesser variance in iron toward the finest grained sediment from the Wadi Rum area combined with manganese being more abundant in the coarsest grained fraction suggests that fine-grained particles of secondary iron and manganese oxides and hydroxides are less common in the Wadi Rum area than in the coastal part of the massif near Al'Aqabah. Average abundances of these two elements in the two areas supports this contention: 3 percent iron and 700 ppm manganese in wadi sand and talus from the Wadi Rum area, versus 7 percent iron and 1,000 ppm manganese in the sediments from the coastal area. Derivation of part of the wadi sand and talus at Wadi Rum from sandstones, where detrital mafic minerals are less common than primary mafic minerals in the granite, as shown below, may be the most likely cause of these differences in iron and manganese, instead of lesser development of secondary oxides in the drier environment of the Wadi Rum area. A study of the mineral composition of the sieved fractions of sediments will be needed to clarify the reason for the lesser amounts of iron and manganese in the sieved sediments from the Wadi Rum area.

The variance in the reporting intervals for boron in the wadi sand and talus from the Wadi Rum area is the greatest of any element reported for the area (table 29). In each sample the finest-grained fraction is enriched in boron. The quantity of boron in the coarsest fractions of two samples is below the lower limit of determination. The boron content of the finest grained fractions of the four samples from the Wadi Rum area is consistently greater (table 29) than the boron content of the fractions of wadi sand and talus from the western part of the granitic massif near Al'Aqabah (table 26).

A possible cause for the presence of boron in the samples from Wadi Rum is the fine-grained saline particulates borne by wind from the surfaces of the mudflats to the north of the sample localities (Bender, 1968c). This process has been recognized in the Precambrian Shield in the Kingdom of Saudi Arabia. Locally, boron was found to be anomalously abundant in windborne sand deposited on pediment surfaces downwind from parts of the Rub'Al-Khali. That rise in the abundance of boron was attributed to the deposition with the sand of windborne borate salts (Overstreet, 1978b).

Elsewhere in the Arabian Shield some anomalously high values for boron in samples of sand were interpreted to result from the movement of ground water (Theobald and others, 1977).

The samples from the Wadi Rum area closest to the Mudflats are: 77-OT-556, which is from a site 200-300 m south of Qa'Disa, and 77-OT-547, which was taken at a locality about a kilometer south of Qa'Um Salab. Samples 77-OT-550 and 77-OT-553 were collected at sites in Wadi Rum respectively 4 km and 12 km south of the mudflat at the mouth of Wadi Rum, which deposit lies between Aq'Disa and Qa'Um Salab. No general change in content of boron with distance from the mudflats can be seen:

Sample number	Distance from mudflats (km)	Boron content of finest-grained fraction (ppm)
77-OT-556	0.2-0.3	150
-547	1	100
-550	4	300
-553	12	150

The two closest localities were favorably situated to receive ablation products from the surface of the mudflats. Both localities were on north-facing hillsides which would have received aeolian saline particulates from Qa'Disa and Qa'Um Salab. However, the values for boron in the finest grained fractions of sand and talus from these sites are not greater than the amounts in the finest grained fractions of wadi sand from the localities farthest from the mudflats.

None of the other elements reported in table 29 for the finest grained fractions of the wadi sand shows an increase in concentration with decrease in distance of the sample site from the mudflats. Thus, no strong positive evidence for aeolian contamination through deflation of the mudflats was found. Inasmuch as the sample sites are upstream from the mudflats, the possibility that ground water or surface water draining toward the flats might have caused some enrichment in boron or other elements toward the flats, is also contraindicated by the geochemical data.

Nickel, scandium, yttrium, and zirconium are the other elements enriched in the finest grained fraction of wadi sand and talus, but mineralogical data are lacking for an interpretation.

Zinc is strongly enriched in the coarsest grained fraction of talus represented by sample 77-OT-556, which came from a locality close to Qa'Disa (table 25 and 29). However, mineralogical data are lacking to show the source of the zinc. This is the greatest quantity of zinc in any sample of wadi sand from the granitic massif east of Al'Aqabath, therefore its source should be identified.

Composition of wadi sand and talus related to source rocks.--The most evident influence on the chemistry of the sized samples of wadi sand and talus from the Wadi Rum area is from the increasing abundance of Cambrian and Ordovician sandstones in the source areas for samples at the eastern margin of the granitic massif. Samples 77-OT-547 and -556 have as their greatest sources the Precambrian granites. Samples 77-OT-550 and -553 are dominated by sources in the sandstones. These two samples are characterized by slightly more Ag, B, Sc, and Zr than the samples from the granitic sources. The other elements reported in table 29 are more abundant in the samples from granitic sources. For eleven elements, however, the difference is equal to only one or two analystical reporting units: Ag, Be, CA, Ba, La, Nb, Ni, Pb, Sc, Sr, and Ti.

To find zirconium more abundant in samples derived largely from sandstone is expectable, because the sandstone serves as an intermediate host in the concentration of detrital zircon from the granite. Titanium might be expected to behave similarly. However, the difference, one reporting unit in favor of the granitic source areas, is too small to show a trend.

The amounts of the other elements in the sized fractions of wadi sand and talus do not indicate any unusual sources of metals. Interestingly, a small amount of silver (3ppm) was reported for the coarsest grained fraction of wadi sand (77-OT-553A) from the vicinity of the Wadi Rum Police Fort, where rumor had it that gold was present. The lower limits of determination of the two metals--Ag, 2 ppm, and gold, 20 ppm (table 1)--are so different that small quantities of gold would escape detection although the silver would be detected. Silver is commonly alloyed with native gold, as are copper and lead (Mertie, 1940); thus, an undetected amount of gold might be the source of a little silver, copper, and lead. In view of the fact that the silver was detected in the coarsest grained fraction of the sample, the mineral grains that yielded it would have been large enough to have given a positive indication of gold if native gold had been the source (Fischer and Fisher, 1968). Similarly, the small amount of copper--only 2 ppm--and the absence of lead in sample 77-OT-553A argue against the presence of both coarse-grained native gold and base-metal sulfide minerals. The small amount of silver detected is probably camouflaged in some common mineral such as pyrite or limonite.

Composition of concentrates.--Samples 77-OT-546 and -549 are concentrates panned respectively from talus at the site of sample 77-OT-547 (table 25) and from wadi sand at the site of sample 77-OT-550. The crude concentrates were analyzed spectrographically, and the results are given in table 27.

Higher values were observed for Fe, Ti, Cr, La, Mn, Nb, and V in both concentrates than in the average values for the three fractions of each matching sample of wadi sand or talus:

Element	Concentrate (77-OT-546)	Talus[1] (77-OT-547)	Concentrate (77-OT-549)	Wadi sand[1] (77-OT-550)
		(In percent)		
Fe	20	10	15	2
Ti	2	1	1.5	0.3
		In parts per million		
Cr	300	100	300	30
La	70	N(50)	150	N(50)
Mn	2,000	1,000	10,000	500
Nb	30	N(20)	50	L(20)
V	700	300	200	70

[1] Average of three determinations.

Although several of these elements are only 1 or 2 reporting intervals more abundant in the concentrate than in the raw sediment, the direction of increase is toward the concentrate. Most of the greatest increases of these elements are in the concentrate made from wadi sand that was quite lean in each element. For the obvious reason of mineralogical host, each of the elements Fe, Ti, Cr, La, Mn, Nb, and V would be expected to increase in quantity in concentrates.

The behavior of barium, however, is quite different in the two concentrates. In the pair of samples 77-OT-546 and -547, barium is less abundant in the concentrate (300 ppm) than its average value in the sediment (500 ppm). In the other pair, 77-OT-549 and -550, barium reaches 5,000 ppm in the concentrate but averages only 300 ppm in the wadi sand. The most likely reason for these differences is that at the locality represented by samples 77-OT-546 and -547, the barium is in the feldspars, and its source minerals are not enriched in the concentrate. At the locality represented by samples 77-OT-549 and -550, in contrast, the barium is in a mineral of high density, such as barite, that is typically more enriched in concentrates than it is, where present, in sand. When the great enrichment in manganese in concentrate

77-OT-549 is considered--10,000 ppm in contrast to 500 ppm average in the matching wadi sand sample 77-OT-550--the possible presence of a hydrothermal source for barium and manganese in the granitic rocks near this locality needs present. In the other pair of samples where barium behaved as if it is in feldspars, the enrichment of manganese in the concentrate was only to 2,000 ppm from 1,000 ppm in the talus. Inasmuch as the contents of Cu, Pb, and Zn are low in both the concentrates and the raw sediments, a possible hydrothermal source yielding local enrichment in barium and manganese would not also be enriched in base metals.

Both lanthanum and yttrium are also more abundant in concentrate number 77-OT-549 than they are in the other concentrate or in the raw sediments. This rise may be associated either with the already noted rise in barium and manganese, or with the strong rise in the amount of zirconium reported for the concentrate (table 27). Possibly a little monazite is the source for these rare earths as well as the small quantity of thorium, and apatite or garnet may supply the yttrium, but mineralogical examination of the concentrates is needed to determine the host mineral, or minerals, for these elements. A little rise in the abundances of tin and niobium occurs in concentrate number 77-OT-549; indeed, the amount of tin in the concentrate is the greatest recorded in this set of samples.

Nothing in the geochemistry of these concentrates, except the high values recorded for Ba, Mn, and Zr in 77-OT-549, are in any way indicative of mineralization.

Calcium is less abundant in the concentrates (table 27) than it is in the sieved fractions of the raw sediments (table 29), from which it may be inferred that feldspars and particles of calcium carbonate in the raw sediments are the major source of this element.

Barite vein in granite northeast of Al'Aqabah

A short, narrow vein and small lenticular masses of barite are exposed in older Precambrian coarse-grained porphyritic biotite granite on the east side of Wadi Arabah about 10 km northeast of Al'Aqabah (table 25). The area was mapped as aplite granite by Bender (1968c). Two vertical drill holes were sunk by NRA to explore the vein, which is too small to be exploited (Overstreet, 1978a). However, the site is suitable for an evaluation of the barium content of a short secondary dispersion train of detrital barite from the vein and for a comparison of the trace-element geochemistry with barite veins in northern Jordan at the locality to the northwest of Mahattat el Jufur.

A small steep wadi heads uphill from the barite vein. The wadi crosses a 2-4 m wide exposure of the vein on a downhill course over uninterrupted exposures of granite. Several small vertical dikes of metabasalt intrude the granite in the vicinity of the barite vein. The largest of these dikes, which is 1.4 m thick, crosses the little wadi about 40 m downstream from the vein. Two samples of wadi sand (77-OT-558 and -560) and two concentrates (77-OT-557 and -559) were collected from the bed of the small wadi. The pair 77-OT-557 and -558 was taken adjacent to the vein on its downstream side, and the other pair (77-OT-559 and -560) was collected 150 m downstream from the vein and 110 m downstream from the mafic dikes. The samples of wadi sand were sieved in the field to three fractions (table 25): <9 + 32 mesh, <32 + 80 mesh, and <80 mesh. About 10 kg of wadi sand was panned to recover each heavy-mineral concentrate. These materials were analyzed by semiquantitative spectrographic methods, and the results are shown in tables 27 and 30.

Nearly every detected element in the sieved fractions of the two samples of sediment is enriched in the finest grained fraction (table 30), although the amount of enrichment is commonly only one or two reporting intervals. Elements thus enriched are: Fe, Mg, Ca, Ti, B, Co, Cr, Cu, La, Mn, Nb, Ni, Sc, V, Y, and Zr. Of these, the greatest enrichment in the finest grained size is for yttrium and zirconium, reflecting the probable presence of fine-grained zircon from the granite.

The concentrations of barium in the coarsest and finest grained fractions at the vein (>>5,000 ppm) are above the upper limit of determination, and reflect the great quantity of barite present in the wadi sand. However, at the locality 150 m downstream from the vein, the actual abundances of barium are less, 1,500 ppm, but the amount in the coarsest and finest grained fractions is the same. This uniform relation in the abundance of barium suggests that the winnowing effect upon the grain size of the barite through alluvial transport, with a relative reduction in the coarsest grains compared to the finest grains, is still imperfect over the short distance of 150 m where the gradient is steep. With increasing distance from the source and with decreasing gradient of the wadi, the coarsest grained fraction of wadi sand may be expected to become depleted in barium compared to the finest grained fraction, owing to alluvial deposition and lag of coarse grained barite. Neither this change in barium content related to alluvial transport, nor the decrease in barium content in the finest-grained fraction owing to aeolian contribution of barium-poor dust from outside the drainage basin has

Table 30.--Results of semiquantitative spectrographic analyses of wadi sand from the area of the barite vein in granite northeast of Al'Aqabah, Hashemite Kingdom of Jordan

[Analyses by Mohamad Sha'aban and Zuheir Issa, NRA, Amman, Jordan, 1978.]

Sample numbers		In percent				In parts per million[2]													
Field	Laboratory	Fe	Mg	Ca	Ti	Ba	Be	Co	Cr	Cu	Mn	Nb	Ni	Pb	Sc	Sr	V	Y	Zr
77-0T-558A	SPL-83	3	0.7	1.5	0.3	>>5,000	3	N(5)	15	15	700	N(20)	10	70	N(5)	700	70	30	150
-558B	-84	7	1	2	.5	>5,000	3	5	30	50	700	20	15	70	10	700	100	100	1,000
-558C	-85	10	1	5	.7	>>5,000	3	15	70	70	1,000	30	30	70	50	700	200	300	>>1,500
-560A	-86	5	.7	1.5	.3	1,500	3	5	20	15	700	N(20)	10	50	5	700	70	30	700
-560B	-87	7	1	1.5	.7	1,500	2	10	30	30	1,000	20	30	50	7	500	150	70	700
-560C	-88	10	1	3	.7	1,500	3	5	70	50	1,000	20	30	70	20	700	150	150	>1,000

[1] Elements looked for but not found at lower limits of determination shown in table 1: Aq, As, Au, Bi, Cd, Mo, Sb, Sn, Th, W, and Zn.
Elements rarely present at lower limits of determination shown in table 1, sample numbers, and abundances are: B, 20 ppm, 77-0T-560C, 30 ppm, 77-0T-558C; La, 50 ppm, 77-0T-558B and -560C, 100 ppm, 77-0T-558C.

been identified here, but the locality seems well suited to such an orientation survey.

The concentration of strontium in the wadi sand is unchanged between size fractions at each locality and between localities. The implication is that the strontium is camouflaged in another mineral well represented in these various sources. As shown in the comments on the concentrates, strontium may be in barite.

The contents of beryllium and lead are also remarkably constant among the various size fractions at the two localities. No explanation is apparent for this behavior of beryllium, but the lead may be substituting for barium in the barite.

No significant differences are present among the values for Mg, Ca, Be, Co, Cu, La, Nb, Ni, Pb, Sc, and Y in the wadi sand at the barite vein or at the locality 150 m downstream from the vein. Also, in both the samples of the raw sand and in the concentrates, many elements commonly enriched in sulfide mineral deposits, or other ores associated with granitic rocks, were not detected at lower limits of determination shown in table 1: Ag, As, Au, Bi, Cd, Mo, Sb, and W.

In one concentrate, 77-OT-559 from the downstream locality, the content of iron rises sharply, accompanied by clear increases in the abundances of Ti, Cr, Mn, and V, all of which may be attributable to a relative increase in magnetite, ilmenite, and other mafic heavy minerals owing to a decrease in the content of barite compared to the concentrate from the source adjacent to the vein. This decrease is indicated by the decline in the content of barium between the upstream and downstream concentrates.

In a distance of 150 m over which the wadi drops about 20 m, the dispersion train of detrital barite is noticeably depleted, as measured by the barium content of both the raw sand and the concentrates Thus, from the concentrates, particularly, the drainage basin would be identified as anomalous. The strontium content of the samples follows concentration patterns similar to those of barium:

Spatial relation of sample to barite vein, and kind of sample	Tenor of the samples (ppm)	
	Ba	Sr
Adjacent, wadi sand	>>5,000	700
adjacent,concentrate	G(10,000)[1]	10,000
150 m downstream, wadi sand	1,500	700
150 m, concentrace	10,000	1,000

[1] The quantity of barium is at least 10 percent (100,000 ppm).

The relations of barium and strontium in the wadi sand and concentrates suggest that the strontium is in the barite, but mineralogical studies of the concentrates and chemical studies of the barite are needed to determine the relation. Strontium is known to be present in barite (Rankama and Sahama, 1950, p. 477).

Doubtless the dispersion train of barium and strontium caused by the intermittent alluvial transport of detrital barite downstream from the exposure of the vein persists for at least several hundred meters farther than the locality 150 m from the vein. The heavy-mineral concentrate is the preferred geochemical sample medium in which to trace these two elements. A small source thus can be identified from concentrates panned from alluvium in small wadis that intersect the source, even if the sample locality is 0.2-0.5 km downstream from the source. Identical principles apply for ore deposits of many other metals whose main hosts are minerals of high density.

The little rises in the contents of lanthanum and yttrium in concentrate number 77-OT-559 (table 27) may be related the abundance of zirconium, which reaches at least 2 percent (20,000 ppm). These three elements could be present in zircon.

No direct comparison can be made between the chemical composition of the barite in this little vein northeast of Al'Aqabah and the veins to the northwest of Mahattat el Jufur in northeastern Jordan, because the barite near Al'Aqabah was not analyzed. But certain gross similarities are seen if the composition of the concentrates from the Al'Aqabah area is compared with that of the barite from northeastern Jordan (table 3). Strontium is enriched and boron is below the limit of determination at both localities. Most of the other elements below the limit of determination in the concentrates from the vicinity of the small barite vein near Al'Aqabah were not detected in the barite from the exposure northwest of Mahattat el Jufur. The chemical similarity should be investigated in detail to assist in an interpretation of the geologic age of the vein near Al'Aqabah.

Veins in the granitic massif to the east of Al'Aqabah

Two veins in the Precambrian granodiorite unit of Bender (1968c), exposed in the granitic massif east of Al' Aqabah, had previously been shown to contain traces of chalcopyrite (Hakki, 1971), but neither vein was regarded by NRA as a source for base metals. Each afforded an opportunity to determine if the sparse presence of chalcopyrite would be reflected in the trace-elements geochemistry of samples of various types of alluvial materials in source areas obviously dominated by erosional debris from the granodiorite. Therefore, several samples of alluvial materials were collected from small wadis in the vicinity of the two veins. Locations and descriptions of the source materials are given in table 25. The chemical composition of the single concentrate from these areas (sample 77-OT-528) is given in table 27, and the composition of the sieved samples of wadi sand is reported in table 31.

Pegmatitic quartz vein.--A quartz vein that strikes N.10°E. and dips vertically is intermittently exposed for more than 1,300 m in the northern wall of a main northeast-striking tributary valley to Wadi 'Imran between Jebel Um Jurfan and Jebel as Sinat. The northern exposure of the vein was sampled (specimens 77-OT-527, -528, and -529 in table 25) at a point about 4 km southwest of Khashm el Qatra. Sample 77-OT-532 was taken 1,300 m farther southward. The full extent of the vein was not traced.

At the northern sample locality the vein consists dominantly of milky quartz which grades into clear gray, greasy-appearing quartz containing septa and inclusions of the wall rock. This rock is the Older Granite of Hakki (1971), mapped as granodiorite by Bender (1968c), which is intruded by an altered diabase dike as much as 8 m thick. The vein follows the contact between the dike and the granite, filling fractures over a zone 2-3 m wide in both rocks. Individual quartz veins in the fracture zone are rarely more than 30 cm thick, but the vein is irregular in width, and one segment about 5 m long thickens to a mass of solid quartz 3 m across. The whole fracture zone contains about 30 percent of quartz. Mostly the vein appears to be barren of sulfide minerals, although a small amount of limonite after pyrite is present, and Hakki (1971) reported seeing a little chalcopyrite in the vein. Vugs in the vein rarely contain a little limonite after siderite.

At the southern sample locality the vein is about 1 m thick and horsetails into fractures in the granite. Inclusions of altered diabase and of granite are in the vein. Here the vein grades from milky quartz into a

Table 31. Results of semiquantitative spectrographic analyses of wadi sand from the vicinity of two veins in the granitic massif east of Al'Aqabah, Hashemite Kingdom of Jordan

[Analyses by Mohamad Sha'aban and Zuheir Issa, NRA, Amman, Jordan, 1978.]

Sample numbers		In percent				In parts per million[1]															
Field	Laboratory	Fe	Mg	Ca	Ti	Ba	Be	Co	Cr	Cu	La	Mn	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Zr
77-OT-527A	SPL-47	3	1.5	2	1	500	3	10	30	15	70	1,000	N(20)	15	50	10	300	20	20	N(200)	150
-527B	-48	15	1.5	5	0.5	500	7	30	70	30	150	1,500	30	30	100	20	300	150	100	200	300
-527C	-49	15	1.5	10	1	500	5	30	100	50	150	1,500	20	50	70	15	500	150	70	200	700
-529A	-50	5	1.5	2	.7	700	7	20	70	30	50	1,000	N(20)	20	50	15	300	100	30	N(200)	150
-529B	-51	15	2	3	.7	700	3	30	100	70	100	1,500	30	50	50	30	300	300	70	200	200
-529C	-52	15	1.5	5	1	700	5	30	150	100	100	1,500	20	100	70	30	300	300	70	200	700
-532A	-53	10	2	3	1	700	3	30	100	50	50	1,000	20	50	50	30	500	150	50	200	150
-532B	-54	15	2	5	>1	500	3	30	150	70	70	1,500	30	70	70	30	300	200	70	300	200
-532C	-55	15	2	10	1	500	7	30	150	70	100	1,500	30	50	150	20	300	150	70	300	500
-541A	-62	5	1.5	2	.5	700	2	15	70	20	50	700	N(20)	30	150	15	300	100	30	200	150
-541B	-63	7	1.5	3	.7	1,000	2	20	100	30	70	1,000	N(20)	50	70	15	300	150	50	200	150
-541C	-64	10	2	5	.7	1,000	2	30	150	30	100	1,000	L(20)	70	150	15	300	150	70	N(200)	1,000
-543A	-65	5	1.5	2	.7	1,000	3	15	30	30	N(50)	1,000	N(20)	15	50	10	300	200	30	N(200)	300
-543B	-66	15	1.5	3	1.2	1,000	N(2)	30	100	100	200	1,500	30	70	70	15	300	700	150	N(200)	>1,000
-543C	-67	10	1.5	2	.7	700	N(2)	30	30	70	100	1,500	20	15	50	15	500	300	50	N(200)	700

[1] Elements looked for but not found at lower limits of determination shown in table 1: As, Au, Bi, Cd, Mo, Sb, Sn, Th, and W.
Elements rarely present at lower limits of determination shown in table 1, sample numbers, and abundances are: Ag, 2 ppm, 77-OT-527B, -529C, -532B, and -532C; B, 20 ppm, 77-OT-527B, -529B, -541C, 30 ppm, 77-OT-532C, and 70 ppm, 77-OT-527C.

pegmatitic phase containing abundant phenocrysts of potassium feldspar and books of chloritized biotite that are as much as 4 mm across. Much of the feldspar is weathered, and some of the weathered feldspar resembles dull white to tan scheelite, but the results of analyses, discussed below, show that scheelite is absent.

At the northern locality one sample of wadi sand was taken adjacent to the quartz vein (77-OT-527), and a second sample of wadi sand was taken about 75 m downstream from the vein. At the southern locality a sample of wadi sand (77-OT-532) was made about 50 m downhill from the outcrop of the vein. One sample of wadi sand from the northern locality was panned to recover a heavy-mineral concentrate.

The trace-element content of the sieved fractions of the wadi sand (table 31) afford no clear-cut evidence for the presence of base metals in the vein despite the fact that the 150 ppm lead found for the finest grained fraction of sample 77-OT-532 is among the highest values determined for lead in wadi sands from the granitic massif east of Al'Aqabah. A slight rise in zinc is seen in the same sample, but these values cannot be regarded as anomalous because they are within two analytical reporting intervals of all values found for these metals in sands from the area of the massif, with the exception of sample 77-OT-556A from the vicinity of Qa'Disa, which contained 1,000 ppm zinc and for which no source was identified. Except for the sample near Qa'Disa, all samples of wadi sand from the granitic massif contain at most only 300 ppm zinc, 200 ppm lead, and 150 ppm copper. Also, other elements commonly associated with base metal sulfides in vein deposits are below their respective limits of determination (table 1) in the samples of wadi sand from the vicinity of this quartz vein (table 31): As, Au, Bi, Cd, and Sb.

About half of the detected elements in the sized fractions of the wadi sands are slightly more abundant in the finest grained fraction than in the coarsest grained fraction:

Element	Sieved samples of wadi sand					
	77-OT-527A	77-OT-527C	77-OT-529A	77-OT-529C	77-OT-532A	77-OT-532C
			In percent			
Fe	3	15	5	15	10	15
Ca	2	10	2	5	3	10
			In parts per million			
Cr	30	100	70	150	100	150
Cu	15	50	30	100	50	70
La	70	150	50	100	50	100
Mn	1,000	1,500	1,000	1,500	1,000	1,500
Nb	N(20)	20	N(20)	20	20	30
Pb	50	70	50	70	50	150
Y	20	70	30	70	50	70
Zn	N(200)	200	N(200)	200	200	300
Zr	150	700	150	700	150	500

Where this relation--the tendency for the finest grained fraction of wadi sand to have slightly higher values--does not obtain for the three samples, then the finest grained fraction either has metal contents greater than the coarsest grained fraction in two out of three of the sample pairs (B, Be, Co, Ni, Sc, Sr, and V), or essentially identical values (Mg, Ti, Ba, and Sr). Thus, at one more locality in the granitic massif east of Al'Aqabah the greater metal contents were found in the finest grained fraction of wadi sand.

A comparison of the composition of wadi sand immediately adjacent to the quartz vein (77-OT-527) with that collected 75 m downstream from the vein (77-OT-529) shows small differences in the abundances of the elements that are attributable to allowable laboratory variance. Evidently the presence of the quartz vein is not reflected geochemically, and the composition of the sands reflect that of the Older Granite of Hakki (1971).

The concentrate (77-OT-528) from the northern locality displays the expected rise in the abundance of elements associated with common heavy detrital minerals such as magnetite, ilmenite, monazite, apatite, and garnet as well as the secondary oxides of iron and manganese (table 27): Fe, Ti, Co, Cr, La, Mn, Nb, V, Y, and Zn. The barium and strontium contents of the concentrate, respectively 300 ppm and 100 ppm, are significantly lower than the contents of these elements in the raw sands (table 31), which identifies feldspar as the probable host of barium and strontium. Zinc and vanadium are more abundant in the concentrate than in the raw sand. This relation is attributable to the tendency for these two elements to be enriched in magnetite (Carstens, 1943; Theobald and others, 1967; Frietsch, 1970) and in hydrous oxides of iron and manganese (Canney, 1966; Jenne, 1968; Chao and Theobald, 1976). Molybdenum and tungsten were reported to be below their respective limits of determination in the concentrate (table 27); therefore, scheelite is absent in the vein.

None of the chemical characteristics of the concentrate can be attributed to the presence of this vein.

Although the geochemical evidence of these few analyses indicates a quartz vein lacking in base and precious metals, appropriate channel samples of the vein itself need to be made to determine the actual metal content of the vein. This is particularly true for gold, which has a relatively high lower limit of determination in the method used for analysis.

<u>Calcite-quartz vein.</u>--A calcite-quartz vein is exposed on the eastern flank of Jebel As Sinat in western tributaries to Wadi Libnan and along faults extending to the southwest (Gharaibeh, 1969, pl. 9; Overstreet, 1978a). This locality is about 1.5 km east of the southern part of the pegmatitic quartz

vein described above, and about 4 km south-southwest of Khashm el Qatra.

The vein strikes N.55°E. and dips 80°S. in a metamorphosed diabase dike in Precambrian red granite containing rounded quartz phenocrysts (mapped as granodiorite by Bender, 1968c). The vein occupies a fault zone in the dike. Where the fault was open the vein is a well-developed fracture filling about 1 to 2 m thick that consists mainly of calcite with quartz and sparse galena. Where the fault produced a brecciated zone in the dike, the vein fills the interstices of the breccia and forms a stockwork at least 30 m thick. Inclusions of the dike and of the granite are common in the stockwork. These inclusions range in size from a few centimeters to 3 m across. Parts of the exposed vein and stockwork are crusted with limonite, but thick gossan is absent. Within the vein small grains of limonite after pyrite were noted, but the pyrite is too sparse to have been the source of the limonite crusts on the exposures of the vein. Possibly the source for the limonite crusts was iron in carbonate minerals in the vein, but neither ankerite nor siderite was observed.

A channel sample of the stockwork part of the vein was analyzed on May 6, 1969, by the Laboratory Division of NRA with results as follows (Hakki, 1971, encl. 1):

Element	Abundance (ppm)
Cu	90
Zn	445
Pb	1,415
Co	50
Ni	140
Ag	Nil

The vein and stockwork form a nearly vertical scarp; the south wall of the host rock is removed to heights of 10-20 m, resulting in the exposure of the vein for a distance of about 200 m. The south side of the vein is separated from the metamorphosed dike to the south by a trench that grades into a shelf as much as 4 m in width, but the deepest part of the trench only reaches a depth of 1.5 m. Although this exposure may be natural and may have been caused by the preferential weathering of the fault-weakened wall rock, the elongate exposure has a certain similarity to trenches seen in Saudi Arabia that were the sites of ancient mining. Neither tailing piles nor slag piles were seen at this site to support the contention that the trench is man-made. Owing to the ruggedness of the site, however, the tailings from mining could readily have been swept away by sheet wash. Slag piles would be absent if the ore had been smelted at some other site.

Two samples of wadi sand from the vicinity of the calcite-quartz vein (77-OT-541 and -543, table 25) were sieved and analyzed. The results are shown in table 31, where it is immediately apparent that the enrichment in lead and zinc found in the vein (Hakki, 1971) is lacking in wadi sand derived in part from the vein:

Source	Pb (ppm)	Zn(ppm)
Vein (Hakki, 1971)	1,415	445
Wadi sand (average of three determinations for each sample)		
77-OT-541	100	200
77-OT-543	50	N(200)

The sample of wadi sand taken closest to the vein contains slightly more lead and zinc than the one farther from the vein, but these differences are within acceptable analytical variance. Copper is also less abundant in the wadi sand than in the vein material. Indeed, the values obtained for the elements in the wadi sand in no way indicate the presence of galena in the nearby vein.

As has been characteristic of the results of all the analyses of wadi sand from the area of the granitic massif east of Al'Aqabah, the finest grained fraction of the sand tends to yield higher values for the elements than the coarsest grained fractions. At this site the finest grained samples are the richest in Fe, Co, Cu, La, Mn, Nb, V, Y, and Zr. However, except for zirconium, the differences are small. Most of the other elements reported follow this pattern in one sample and show equal abundances of the element in the finest and coarsest grained fractions in the other sample: Mg, Ca, Ti, B, Cr, Ni, Sc, and Sr. These differences are also within the acceptable range of analytical variance. In sample 77-OT-543 the finest grained fraction yielded slightly lower values for barium and beryllium than the coarsest grained fraction, but the differences are nominal (table 31).

The analyses of one channel sample and two samples of wadi sand constitute insufficient data to form the basis for an appraisal of this calcite-quartz vein. What is needed are core samples from drill holes sited outside the vein to rake through the vein and wall rock on either side, as earlier proposed (Overstreet, 1978a).

Organic materials

Two sets of analyses were made of organic materials: (1) lignite from a bore hole in the Ba'qaa Valley (fig. 1), and (2) carbonized plant materials from archaeological sites at Bab edh-Dhra and Numeria (fig. 1). Analyses were made of the ash of these substances to determine the possible presence of uranium and vanadium in the lignite as a guide to exploration for sedimentary deposits of uranium, and to determine if the plant food products afforded an example of the biogeochemical exploration technique recommended in a prior report (Overstreet, 1978a, p. 16). Interestingly, both sets of analyses resulted in data worth following up despite the very few samples represented.

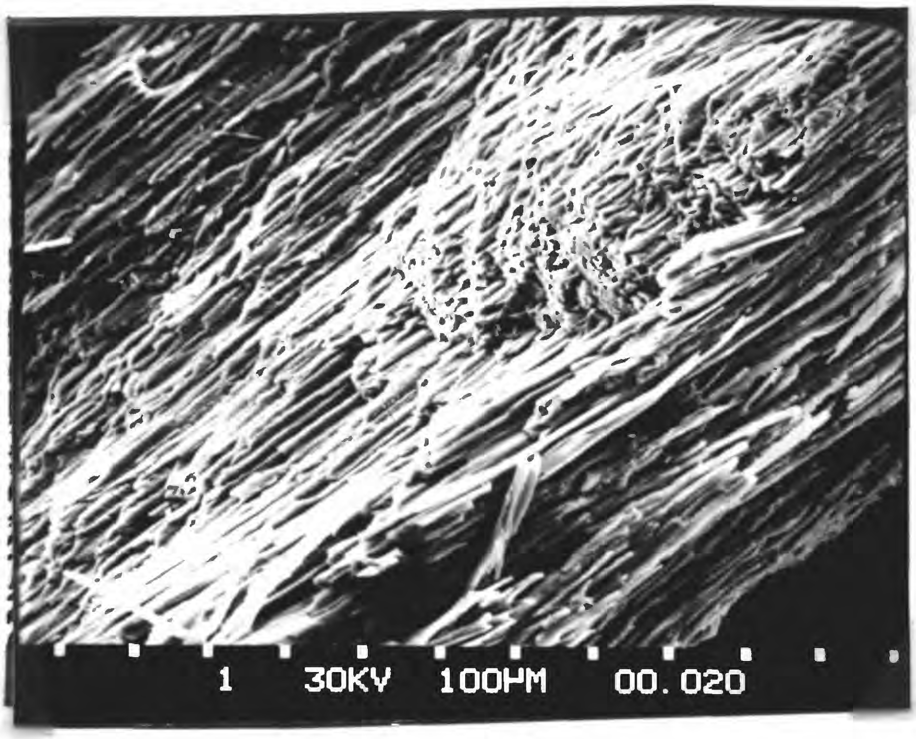
Lignite from the Ba'qaa Valley

Sample 77-OT-627 of Triassic(?) or Jurassic(?) pyritiferous lignite (fig. 23, A-C) was provided by Mr. Muhamad Abu Ajamieh, Director of the Geological Survey and Bureau of Mines, NRA. The sample is from a depth of 150 m below the collar of a borehole in the Ba'qaa Valley (32°04'N.; 35°50'E.). The host rock for the lignite is sandstone. Under the binocular microscope the lignite is seen to contain extensive zones of fine-grained, pale yellow to silvery colored pyrite that fills cells in, and replaces, woody parts of the lignite. The pyrite also fills cracks in the lignite, and replaces the lignite both parallel to and athwart the layering. The pyrite is here interpreted to be a secondary mineral formed during or after the deposition of the woody part of the lignite.

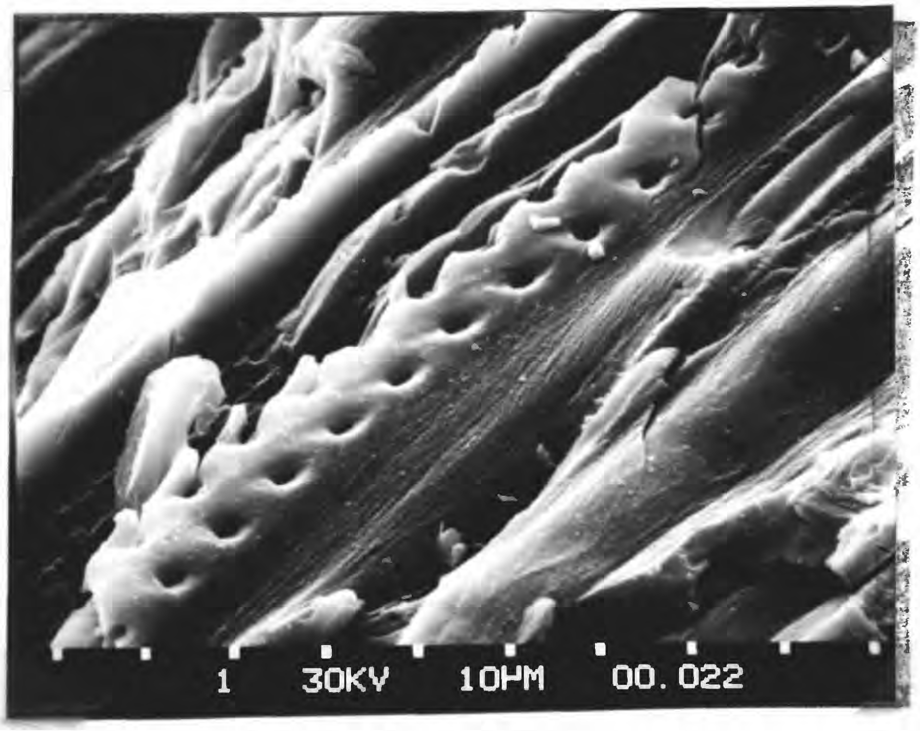
The lignite was reduced at 450°C to ash in a muffle furnace, and the ash was analyzed. Results are listed in table 32. The outstanding compositional anomalies of the ash are the large amounts of Fe, V, U, Ba, and Be, contrasted to the sparsity of most other elements.

Iron.--The large amount of iron in the ash reflects the presence of abundant pyrite in the lignite. It may also indicate that the presence of the pyrite has had an important effect on the abundances of the other elements reported in table 32; therefore, the trace elements must be considered both as components of pyrite and of lignite.

Vanadium and uranium.--The vanadium content of pyrite from different geologic environments has been extensively investigated, and distinctive differences have been reported for the vanadium content of pyrites of sedimentary and of hydrothermal origin (Carstens, 1942, table 1; 1943, p. 3),

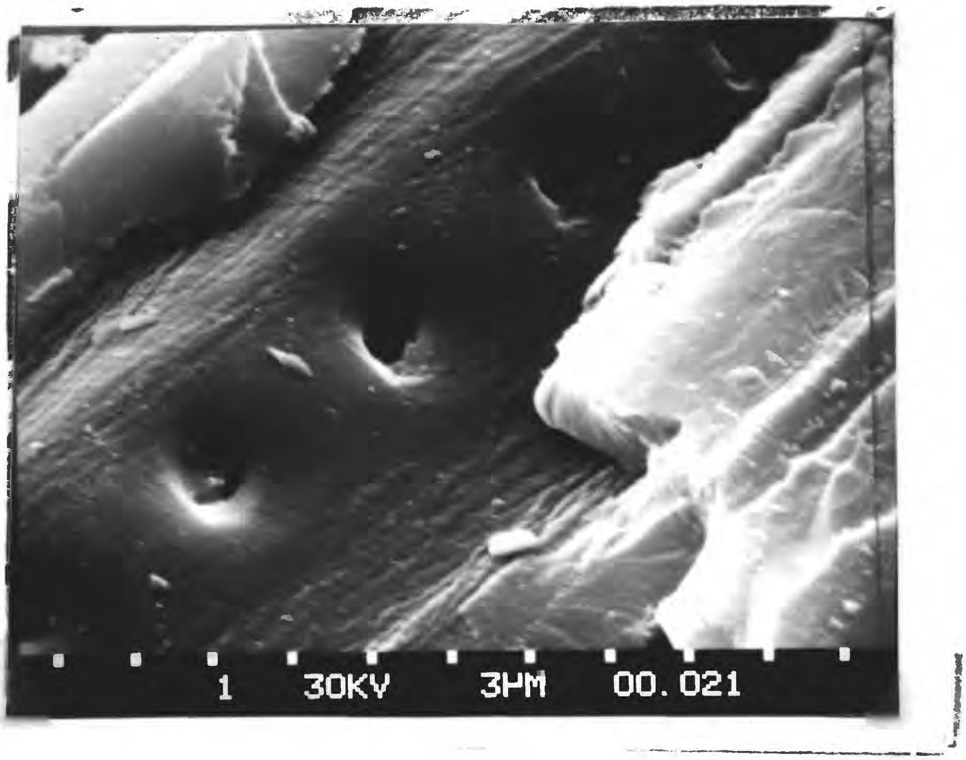


A. Texture at 100X.



B. Detail at 800X

Figure 23. Scanning electron micrographs of lignite from a borehole in the Ba'qaa Valley, Hashemite Kingdom of Jordan. Micrographs by James M. Nishi and James Jude, USGS.



C. Detail at 2,400X.

Figure 23. Continued. Scanning electron micrographs of lignite from a borehole in the Ba'qaa Valley, Hashemite Kingdom of Jordan. Micrographs by James M. Nishi and James Jude, USGS.

and Mitchell (1968, p. 76, tables 2-4) listed vanadium as one of the elements that can be used to distinguish hydrothermal and magmatic pyrites from marine sedimentary pyrite. However, the reported values for vanadium in pyrite are much lower than the 3,000 ppm observed in the sample of pyrite-bearing lignite: analyses of 894 pyrites of various origin showed that less than 0.5 percent of the specimens contained as much as 1,500 ppm vanadium and most pyrite had less than 100 ppm vanadium (Cambel and Jarkovský, 1967, table 51). Pyrite from marine clay has been reported to lack vanadium (Ignatius and others, 1968, table 2), and pyrites from shale and mudstone were found to contain only 7.6-115 ppm vanadium (Mohr, 1960, table 1). Thus, the vanadium in the ash appears to be from the lignite itself, and the quantity suggests a concentration therein of vanadium precipitated from aqueous solutions under reducing conditions (Rankama and Sahama, 1950, p. 600).

The uranium content of pyrite has received scant discussion in the literature, and where mentioned, the element has been reported to be absent (El Shazly and others, 1957, p. 244; Mitchell, 1968, p. 67) or less than 2 ppm (Wampler and Kulp, 1964). In the ash from the lignite, the 6.3 ppm uranium most likely was contributed by the organic material, and the pyrite acted as a dilutent.

Barium, strontium, calcium, and magnesium.--Among the three geochemically coherent alkaline-earth metals barium, calcium, and strontium, as well as magnesium, only the tenor in barium is anomalous for the ash of lignite. Although barium is one of the minor elements seldom reported in analyses of pyrite (Fleischer, 1955, table 8), small amounts of barium (generally <100 ppm) are commonly present in authigenic sedimentary pyrite owing to the incomplete expulsion of sediment from the pyrite during its growth, and the included sedimentary material is the source of the barium (Mitchell, 1968, p. 70-71; Mohr, 1960, p. 9). Thus, the barium is probably in the lignite. The low value for strontium suggests that the waters from which barium deposited were not enriched in strontium.

Beryllium.--The beryllium content of 10 ppm in the ash of the lignite is about four times the crustal abundance (2-3.5 ppm) of that element (Griffitts, 1973, p. 88); thus, it must be regarded as anomalous. In the literature on trace elements in pyrite, the presence of beryllium is not mentioned (Fleischer, 1955, table 8; Hegeman, 1943; Hawley and Nichol, 1959; Cambel and Jarkovský, 1967; Mitchell, 1968; and Itoh, 1971). Probably the beryllium is incorporated with detrital clays, micas, or feldspars in the lignite, because of the tolerance of these minerals for beryllium, and because the average concentration of beryllium in organic material such as plant ash is only 0.7 ppm (Brooks, 1972, p. 211).

Arsenic, bismuth, mercury, antimony, selenium, tellurium, and thallium.--This group of elements, except selenium, was undetected in the ash of the lignite (table 32). Whatever mercury may have been present in the pyritic lignite was driven off by ashing at 450C. The pyrite was not enriched in As, Bi, Sb, and Te, which further confirms the origin of the pyrite as attributable to sedimentary, diagenetic, or low-temperature replacement processes. The average abundance of thallium in pyrite from all sources is 24 ppm (Ivanov, 1969, table 1), but pyrite of sedimentary origin commonly lack thallium (El Shazly and others, 1957, table 7). The low value for thallium (table 32) further supports the sedimentary origin of the pyrite.

Table 32. Results of analyses of the ash of lignite from the Ba'qaa Valley, Hashemite Kingdom of Jordan.
[Analyses by D. J. Grimes, R. T. Hopkins, J. C.Negri, R. W. Leinz, J. G. Viets, and D. M. Hopkins, USGS, 1978.]

Element	Abundance	Element	Abundance
	In percent		
Fe	50	Mg	0.3
Ca	1	Ti	0.3
	In parts per million		
Ag	N(.5)	Ni	330
As	N(200)	Pb	150
Au[1]	N(10)	Sb	N(100)
Au[2]	N(0.2)	Sc	7
B	300	Se	0.2
Ba	1,500	Sn	N(10)
Be	10	Sr	N(100)
Bi	N(10)	Te	N(1.0)
Cd	N(20)	Th	N(100)
Co	100	Tl	N(0.2)
Cr	300	eU[3]	L(20)
Cu	150	U[4]	6.3
Hg	N(0.2)	V	3,000
La	N(20)	W	N(50)
Mn	150	Y	20
Mo	30	Zn	N(200)
Nb	N(20)	Zr	500

[1] Spectrographic.
[2] Atomic absorption.
[3] Instrumental.
[4] Fluorometric.

Selenium was determined as 0.2 ppm in the ash. This value for selenium would be confirmed by the low value for tellurium if both elements were confined to the pyrite, because the literature shows that the amount of selenium is consistently greater than the amount of tellurium in pyrite: Se:Te ratios of pyrite are variously cited as 2.4 (Ivanov, 1969, table 1), 8 (Chizhikov and Shchastlivyi, 1970, p. 41), or 10 (Vlasov, 1964, p. 593). However, the mode of occurrence of the selenium is not known. It may be in pyrite or in other minerals in the lignite.

An interesting relation exists between the abundances of selenium and uranium in samples of sedimentary rocks from Jordan that were analyzed for both elements. In 15 samples of sedimentary rocks having 1 ppm uranium or more, the amount of selenium tends to increase with a rise in the amount of uranium. Samples containing 1.0-3.9 ppm uranium averaged 0.25 ppm selenium, whereas samples with 4.0 ppm uranium or more averaged 0.78 ppm selenium. The three samples with more than 20 ppm uranium have an average of 1.2 ppm selenium. Therefore, some as yet unknown geochemical connection exists between a rise in the selenium content of the rock and a rise in the amount of uranium present.

Silver, gold, copper, lead, zinc, and cadmium.--Values for silver, gold, zinc, and cadmium in the ash are below their respective lower limits of determination (table 32) and afford further confirmation of the sedimentary, diagnetic, or low-temperature origin of the pyrite associated with the lignite, because substantially larger quantities of these elements are characteristic of pyrite of hydrothermal origin (Fleischer, 1955, p. 1005). Copper and lead in the ash may have come from pyrite in the lignite, but pyrites of sedimentary origin characteristically are lean in both elements (Hegemann, 1943, table 1; Cambel and Jarkovsky, 1967, table 48, p. 343-344; Mohr, 1960, p. 9; Wampler and Kulp, 1964, p. 1421), having generally less than 100 ppm of each element. Possibly these metals are in other authigenic sulfide minerals in the lignite.

Cobalt and nickel.--The amounts of cobalt and nickel (table 32) in the ash of the lignite are slightly greater than the quantities usually found in pyrite of marine or fresh-water sedimentary origin (Mitchell, 1968, p. 76), but the Co:Ni ratio is appropriate for pyrite of sedimentary origin. These relations suggest that much of the cobalt and nickel in the ash are from the pyrite.

Chromium, manganese, and titanium.--The source of the chromium in the ash of the lignite (table 32) is probably not the pyrite, because chromium is generally present in pyrite in amounts of less than 50 ppm, and pyrites of sedimentary origin commonly contain less than that (Fleischer, 1955, p. 1007; Minguzzi and Talluri, 1951, p. 106-107, 118; Einaudi, 1968, p. 1751; Mohr, 1960, table 1; Ignatius and others, 1968, table 2; and Mitchell, 1968, tables 2-4). Inasmuch as chromium is known to be notably enriched in coal ash (Rankama and Sahama, 1950, p. 624), the presence in the ash of the lignite from Jordan of 300 ppm chromium cannot be regarded as anomalous; however, it should be noted that chromium along with iron, molybdenum, and selenium may be precipitated from circulating ground water in sandstone where they are brought in contact with organic material (Finch and others, 1973, p. 459).

Manganese has been commonly reported in pyrites of sedimentary origin, and pyrite of marine sedimentary origin is said to be slightly leaner in manganese than sedimentary pyrite of fresh-water origin (Keith and Degens, 1959, fig. 4). The variations in the reported manganese content of pyrite are so great (Fleischer, 1955; Cambel and Jarkovsky, 1967, p. 341-342), however, that there is no way to evaluate the relative contributions of the pyrite and the other components of the lignite toward the 150 ppm manganese observed in the ash (table 32). In any event, the amount of manganese is not unusual.

The amount of titanium found in the ash (0.3 percent = 3,000 ppm; table 32) is in the upper range of the abundance of titanium in sedimentary pyrite (Keith and Degens, 1959, fig. 4, p. 53), but because of the presence of the lignite in a sequence of sandstone, a partial source for the titanium may be resistate detrital minerals. Only a small amount of detrital rutile or ilmenite in the lignite would be sufficient to insure a high value for titanium in the ash. Some support for an interpretation of the titanium content being at least partly attributable to detrital minerals is given by the tenor of the ash in zirconium.

Lanthanum, yttrium, thorium, and zirconium.--Lanthanum and thorium were both found to be below their respective limits of determination (table 32) in the ash from the lignite. The small amounts of yttrium (20 ppm) and zirconium (500 ppm) are probably attributable to detrital zircon in the lignite, or to the presence of these elements in the original plant materials, because yttrium and zirconium have seldom been reported in pyrite and have not been observed in pyrite of sedimentary origin (Mitchell, 1968, tables 2-4).

Tin, tungsten, molybdenum, and niobium.--Only molybdenum was detected in the ash from the lignite; tin, tungsten, and niobium were below their respective lower limits of determination (table 32). Values as high as 13 ppm molybdenum have been reported for pyrite from coal in Poland (Michalek, 1958,

p. 782-783). The molybdenum content of pyrite increases with a decrease in the temperature of formation of the pyrite. The element tends to be concentrated in pyrite of sedimentary origin, especially in pyrite from concretions in clay and carbonate rocks, where 60-90 ppm molybdenum have been reported (Cambel and Jarkovsky, 1967, table 31). Inasmuch as molybdenum is present in plant materials, is found in coal ash, and occurs in sedimentary pyrite, the present data are inadequate to establish the source for the element in the sample of lignite from Jordan.

Boron.--The ash of coals has long been known to be enriched in boron (Rankama and Sahama, 1950, p. 488). This pattern is shown by the 300 ppm boron in the ash of the lignite from Jordan (table 32). Evidently the principal source for the boron is the organic material in the sample, because pyrite is generally reported not to contain boron (Fleischer, 1955, table 8), and where the element is present, the boron-bearing pyrite formed in complex polymetallic sulfide deposits (Minguzzi and Talluri, 1951). A possible source other than the organic material may be detrital tourmaline in the lignite. Although the amount of tourmaline present originally in the lignite would have been very little, ashing would tend to concentrate the tourmaline. Inasmuch as the mineral composition of the lignite was not studied, no observations are available to support this contention, but the possibility of the presence of small amounts of detrital minerals in the lignite is raised by the amounts of titanium, zirconium, and boron detected in the ash.

Scandium.--Scandium is chemically similar to yttrium, but it is mentioned separately here because its geochemical behavior is different (Rankama and

Sahama, 1950, p. 516). The element may more likely be present in detrital tourmaline in the lignite than in other associations. Pyrite generally lacks scandium (Fleischer, 1955, table 8).

Geologic implications of the anomalous elements.--The principal geologic implications of the anomalous elements relate to the significance of the vanadium and uranium in the ash of the pyrite-bearing lignite from the Ba'qaa Valley. These two elements are here considered to constitute geochemical evidence for the possible presence of uranium deposits in the sandstone from which the lignite was taken. The association of selenium with the vanadium and uranium in the ash is further geochemical support for this inference. The concept is geologically attractive because the pyrite-bearing lignite is from sandstones deposited under continental and near-shore marine conditions in a marginal cratonic environment (Bender, 1974, p. 60-70; Powers and others, 1966, pl. 2). The regional geologic setting thus accords with that under which peneconcordant uranium deposits form (Finch and others, 1973, p. 460), and the geochemical composition of the ash from the lignite shows enrichment of those elements that are associated with uranium during deposition from circulating ground water under reducing conditions in locally carbonaceous sandstone: iron, vanadium, selenium, copper, chromium, and molybdenum (Fischer, 1973, p. 684; Finch and others, 1973, p. 459). These peneconcordant uranium deposits have received a great deal of study, because they are a major source of uranium ore (Gruner, 1956; Shawe and Granger, 1965; King and Austin, 1966; Finch, 1967; Fischer, 1968; Motica, 1968; Granger and Warren, 1969; 1974). The carbonaceous material ordinarily present in small amounts in unaltered sandstone of the roll-type uranium deposits is geochemically similar to coal or humates. It is generally destroyed in the altered sandstone (Granger and Warren, 1974, p. 191). Pyrite is invariably present in the unaltered sandstone in the roll-type uranium deposits, and anomalous amounts of selenium are associated with the interface between the altered and unaltered sandstone (Granger and Warren, 1974, p. 191).

The lignite is not thought to have come from a uranium deposit. The sandstone from which the lignite was taken appears to have geologic and geochemical characteristics favorable for the formation of peneconcordant uranium deposits. Therefore, the sandstone should be explored for uranium by use of procedures additional to those already employed by NRA (Abu Ajamieh, 1974). A proposal for a natural gamma radiation survey has been made (Andreasen, 1978, p. 3) as part of what USGS regards as an important countrywide aeromagnetic survey. This would aid in defining the Ba'qaa Valley as a site for possible uranium deposits of the sandstone type. However, ground-based surveys are also needed. Of these, the most suitable procedure would be a hydrogeochemical survey. This should be based on water samples from wells, springs, and streams. Various elements would be sought in addition to uranium and its daughter products (Cadigan and Felmlee, 1977; Miller, 1979; Seitz, 1978, p. 26-31).

Inasmuch as the sample of lignite was recovered from a borehole sunk to establish a supply of water for domestic and agricultural use, and uranium and selenium were detected in the ash of the lignite, the abundances of these elements in the water should be investigated to insure that toxic concentrations of these and other elements are not present. Should some of these elements be present in forms available to plants and animals, these elements might present local hazards to health (Lakin, 1972; Dorn and others, 1973; Shacklette and others, 1974, p. 2-3).

Carbonized plant materials from archaeological sites at Bab edh-Dhra and Numeria

Through the interest and courtesy of Dr. Walter E. Rast and Dr. R. Thomas Schaub, co-directors of The Expedition to the Southeast Dead Sea Valley, Jordan, which began in the 1970's, sponsored jointly by the American Schools of Oriental Research and the Jordanian Department of Antiquities with funding from the National Endowment of the Humanities and private individuals, samples of carbonized plant materials and soils from the archaeological sites at Bab edh-Dhra (31°15'N.; 35°32'E.) and Numeria (31°07'30"N.; 35°32'30"E.) were made available for analysis in Amman (fig. 1). Botanical remains were identified by David W. McCreery of the Expedition, and analyses of the plant materials and soils were performed in the laboratory of NRA by David J. Grimes, USGS, and Zuheir Issa, NRA.

The plant samples are reported by D. W. McCreery (written commun., 18 October 1978) to be from Early Bronze Age parts of the sites and to date generally between 3,100-2,300 B.C. The samples of soils are from present-day surface exposures and are, of course, parts of profiles much younger than the soil surface exposed when the plant materials were harvested. Erosion and deposition since the Early Bronze Age has changed the land surface and removed the soils in which the plants grew. Thus, direct comparisons between the trace-element composition of the plants and of the soils in which they grew cannot be made. However, some general relations appear in the analytical data.

The plant materials comprise (fig. 24, A-C):

Sample number	Locality	Plant material
1.	Bab edh-Dhra	Seeds of *Zizyphus spina-christa* (Christ-thorn seeds, locally called cedar seeds). Ca. 3,100 B.C.
2.	Bab edh-Dhra	Pits of *Olea europaea* (olive pits). Ca. 2,300 B.C.
3.	Bab edh-Dhra	*Hordeum distichum* (2-row barley). Ca. 2,300 B.C.
4.	Numeria	*Vitis vinifera* (cultivated grapes). Ca. 2,400 B.C.
5.	Numeria	*Cicer arietinum* (chickpea). Ca. 2,400 B.C.

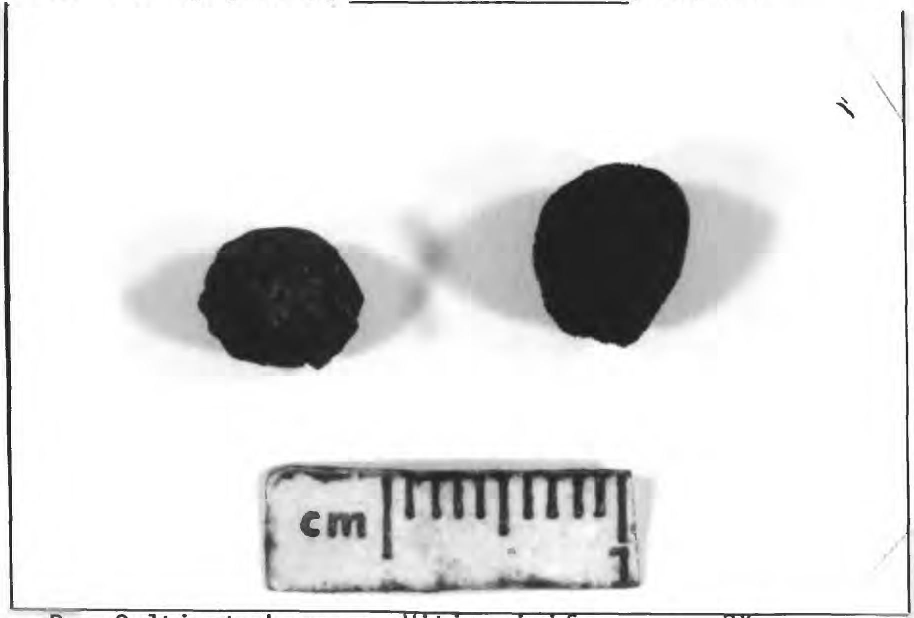
The soils collected in these areas are described in table 33.

The plant material was ashed and the ash was analyzed spectrographically (table 34). The soil was ground to a powder and analyzed spectrographically (table 35).

Major elements in plant ash.--Calcium and magnesium are the only major elements determined in the plant ash (table 34). The plants evidently were concentrators of both elements, because the ash contains more of each element than the present-day soils, and the old, relatively undisturbed soils in which these plants were grown probably contained less calcium than the present soils, owing to longer near-surface leaching (table 35). The differences in the magnesium content between present and ancient soils may not have been large. These relations are shown by a comparison of the average calcium and magnesium contents of the old eluvial soils (samples 25 and 26, table 35) with those of the rest of the soils:

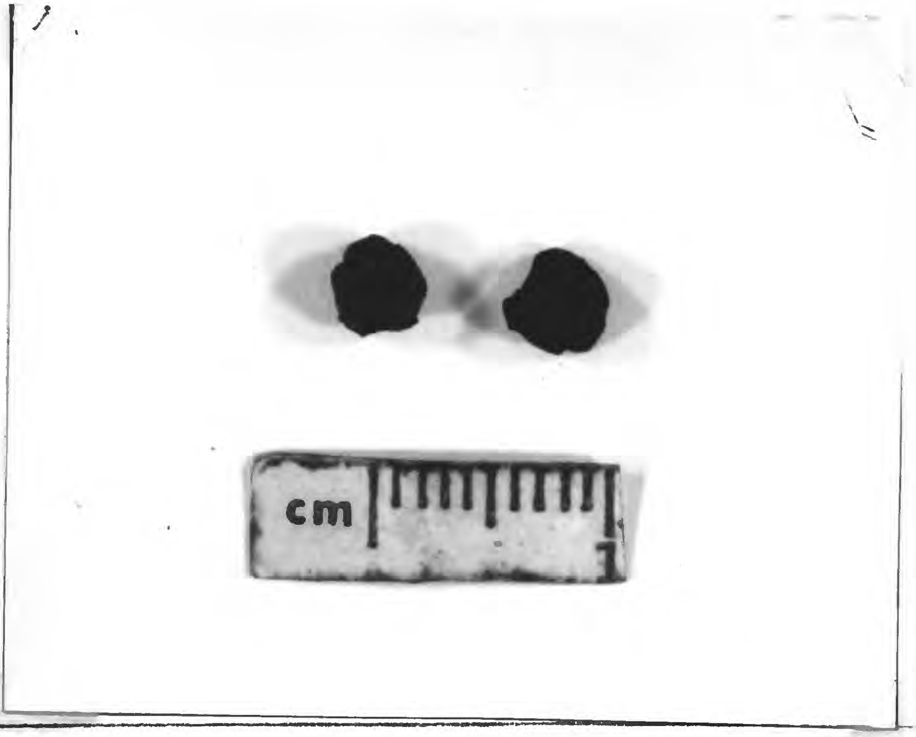
	Ca (percent)	Mg (percent)
Old eluvial soil	12.5	0.85
Other soils	15	1.3

A. Barley grains, Hordeum distichum, ca. 3X.



B. Cultivated grape, Vitis vinifera, ca. 3X.

Figure 24. Photographs of carbonized plant materials from Bab edh-Dhra and Numeria, Hashemite Kingdom of Jordan. Photographs by Theodore Botinelly, USGS.



C. Chick pea, *Cicer arietinum*, ca 3X.

Figure 24. Continued. Photographs of carbonized plant materials from Bab edh-Dhra and Numeria, Hashemite Kingdom of Jordan. Photographs by Theodore Botinelly, USGS.

Table 33. Sources of samples of soil from the vicinity of the Bab edh-Dhra and Numeria archaeological sites, Hashemite Kingdom of Jordan.
[Soil sampled by David W. McCreery, The Expedition to the Southeast Dead Sea Valley, Jordan, in March 1978.]

Field number	Locality
1	Irrigated field northwest of Bab edh-Dhra by the irrigation canal.
2	Cultivated field next to Wadi Kerak and 75 m east of Bab edh-Dhra spring.
3	Upper cultivated field next to Wadi Kerak and 75 m east of Bad edh-Dhra spring.
4	Middle of Wadi Kerak about 75 m east of Bab edh-Dhra spring.
5	North side of Wadi Kerak about 75 m east of Bab edh-Dhra spring.
6	Near Bab edh-Dhra spring.
7	Cultivated field, no crop, east of Arab Potash Company township site.
8	Cultivated field, no crop, 0.75 km east of Bab edh-Dhra spring.
9	Cultivated field, no crop, 2 km northwest of Majali house.
10	Edge of fallow cultivated field 0.5 km east of Bab edh-Dhra townsite.
11	Fallow field directly south of Bab edh-Dhra city near B cemetery area.
12	Field IX of Bab edh-Dhra city site.
13	Formerly cultivated field near acacia tree at east access road entrance to Arab Potash Company township site.
14	Cultivated field just west of Bab edh-Dhra at the southeast corner of Majali and the southeast corner of Byzantine site.
15	Irrigated field under cultivation for tomatoes at Mazra'a 100 m north of road crossing Wadi Kerak.
16	Same field as 15, at point 25 m north of road crossing Wadi Kerak.
17	Fallow cultivated field in Majali farms, at east end 0.25 km north of old checkpoint at Al-'Thra spring.
18	Cultivated field in Majali farms near farmhouse.
19	Next to Bab edh-Dhra spring 50 m south of point where stream from spring is crossed by road.
20	From H section of Arab Potash Company township site.
21	From F2 section of Arab Potash Company township site near probes F 2/1 and 2 on long wall.
22	Fallow cultivated field along Kerak road 100 m west of Musa's house.
23	Cultivated field on north bank of Wadi Numeria near Siq.
24	Numeria at a point 25 m east of weathervane.
25	Old eluvial deposit near entrance to Siq.
26	Old eluvial deposit about 50 cm above wadi floor at entrance to Siq.
27	Fallow cultivated field on south bank of Wadi Ibn Hammed beside irrigation canal.
28	Newly irrigated fallow field next to Baleida.
29	Ashy soil in same field as 28.
30	From middle of cultivated field directly west of Bab edh-Dhra city (Byzantine).
31	Ashy soil from middle of same field as 30.
32	Numeria, cultivated unplanted field across road from Arab Potash Company township site.

Table 34. Results of semiquantitative spectrographic analyses of the ash of carbonized plant materials from archaeological sites at Bab edh-Dhra and Numeria, Hashemite Kingdom of Jordan. [Analyses by David J. Grimes, USGS, in NRA laboratory, Amman, Jordan.]

Elements	Sample numbers and materials				
	1 (Christ-thorn seed)	2 (Olive pit)	3 (Barley)	4 (Grape)	5 (Chickpea)
	Results in percent				
Fe	0.2	1	0.1	0.5	0.2
Ca	30	30	30	30	30
Mg	3	5	1	3	5
Ti	.015	.005	.003	.03	.03
	Results in parts per million (ppm)[1]				
Ag	20	3	N(2)	3	15
B	3,000	2,000	1,000	1,000	500
Ba	N(50)	300	N(50)	2,000	N(50)
Cr	10	300	200	30	100
Cu	100	200	100	150	1,000
Mn	N(50)	N(50)	100	N(50)	70
Pb	150	150	N(50)	200	100
Sr	5,000	5,000	5,000	5,000	5,000
V	10	30	100	10	20
Zn	300	N(200)	N(200)	N(200)	500

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[1] Looked for but not found at lower limits of determination shown: As (500), Au (20), Be (2), Bi (50), Cd (100), Co (5), La (50), Mo (10), Nb (20), Ni (10), Sb (200), Sc (5), Sn (20), Th (200), W (50), Y (20), and Zr (20).

Table 35. Results of semiquantitative spectrographic analyses of soils from the vicinity of the Bab edh-Dhra and Numeria archaeological sites, Hashemite Kingdom of Jordan.
[Analyses by Zuheir Issa, NRA.]

Field	Laboratory	Results in percent				Results in parts per million (ppm)[1]									
number	number	Fe	Ca	Mg	Ti	B	Ba	Cr	Cu	Mn	Ni	Sr	V	Y	Zr
1	SPL-216	1	20	1.5	0.3	70	700	70	20	300	30	500	70	N	200
2	-217	1.5	20	1.5	.3	30	300,	100	30	300	30	700	70	20	200
3	-218	1.5	20	1.5	.3	70	200	70	15	300	30	1,500	70	20	100
4	-219	0.7	20	0.7	.15	20	150	30	7	150	N	300	30	N	N
5	-220	1	20	.7	.3	N(20)	150	100	7	150	N	300	50	N	100
6	-221	.7	20	1	.15	20	150	30	30	150	N	300	30	N	30
7	-222	2	20	1.5	.5	150	300	150	20	300	30	2,000	100	30	500
8	-223	1	20	1	.3	50	150	50	15	200	20	300	70	N	200
9	-224	3	20	1.5	.5	100	200	100	30	300	50	700	70	20	200
10	-225	1.5	>20	1.5	.3	20	1,500	200	20	200	100	1,000	70	20	70
11	-226	1.5	20	1.5	.5	50	500	100	15	300	30	700	70	20	200
12	-227	1	20	1.5	.3	70	300	100	20	300	20	1,500	50	N	150
13	-228	1	20	1.5	.3	70	150	70	50	300	20	1,000	70	20	300
14	-229	1.5	>20	1.5	.3	700	300	150	15	200	30	700	100	20	150
15	-230	.7	20	1	.2	100	150	70	15	200	20	700	70	N	150
16	-231	.7	20	1	.15	30	700	100	30	200	30	700	50	20	70
17	-232	1.5	20	1.5	.2	70	300	70	15	500	50	500	70	20	150
18	-233	1.5	15	1.5	.2	50	300	70	700	300	20	300	50	20	150
19	-234	1.5	15	1.5	.15	150	200	100	30	300	30	300	50	20	150
20	-235	1.5	20	2	.2	70	700	100	30	300	30	700	70	20	300
21	-236	1	20	1.5	.15	70	700	150	15	300	20	1,500	50	N	200
22	-237	1	20	1.5	.2	70	300	70	20	200	15	700	50	20	300
23	-238	1	2	.7	.3	200	1000	50	30	200	15	200	50	N	150
24	-239	.3	7	.5	.1	300	150	20	30	150	N	700	20	N	300
25	-240	.7	10	1	.07	50	500	20	7	200	N	200	20	N	500
26	-241	.7	15	.7	.07	70	300	20	15	150	N	200	20	N	1,000
27	-242	1	20	2	.2	50	150	150	20	300	50	300	100	30	150
28	-243	1	>20	1.5	.15	20	500	150	50	300	70	1,500	70	20	200
29	-244	1	20	1.5	.2	30	200	100	20	200	50	700	70	20	100
30	-245	.5	15	.7	.1	70	200	50	15	150	15	700	50	N	70
31	-246	.7	1.5	1	.1	100	150	50	70	200	20	1,000	50	N	100
32	-247	.7	7	.7	.07	50	300	30	3	150	N	200	20	20	300

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[1] Looked for but not found at lower limits of determination shown: Ag (2), As (500), Au (20), Bi (20), Cd (100), La (50), Mo (10), Nb (20), Pb (50), Sb (200), Sn (50), Th (200), and W (50).
Elements rarely detected, abundance, and sample numbers, in ppm: Be, 2, #9 and #27, 3, #17; Co, 5, #11, #19, and #27, 7, #7, 15, #9 and #17; Sc, 5, #28 and #29, 7, #7 and #27, and 10, #9; and Zn, 700, #18.

The extent to which the plants from which these carbonized remains were derived actually concentrated calcium and magnesium is uncertain. These samples of ash are richer in calcium than the geometric mean cited by Shacklette and Connor (1973, table 3) for calcium in plant ash from the United States, and they have about the same mean content of magnesium as the ashes from plants in the United States. Both elements are within the ranges of abundance found for them in plant ashes from the United States (Connor and Shacklette, 1975, tables 13 and 18):

Element	Abundance in plant ash (percent)		
	Jordan	U.S.A.	
	(Table 34)	(Shacklette and Connor, 1973, table 3)	(Connor and Shacklette, 1975, tables 13 and 28)
Ca	30	12	0.2-40
Mg	3.4	3	.4-24

The values for the amounts of calcium in the plant ash from Jordan (table 34) are unusually high and remarkably uniform. As pointed out by Connor and Shacklette (1975, p. F17), a "large compositional diversity [is] to be expected routinely in ordinary materials." The content of magnesium shows such diversity (table 34), but the content of calcium does not. Several possible interpretations can account for the uniformly high tenor of the carbonized plant remains in calcium: (1) while living, the plants absorbed calcium to their tolerance levels; (2) soluble calcium salts may have been added naturally to the soils in which the plants grew; and (3) the carbonized plant remains absorbed calcium from the strata in which they are preserved. The archaeological observations needed to support or reject an interpretation are unavailable. Variation in the contents of magnesium and barium, which could be geochemically associated with calcium, tend to detract from the interpretation, but the uniformly high values for strontium (table 34), an element that is geochemically coherent with calcium, tend to support the interpretation. Should this interpretation, in fact, conform to the real processes at the archaeological sites, then the concentrations of the other elements would respond as well to such external influences. However, in the comments that follow, the concentrations of the other elements are discussed as if the ash of the carbonized plant remains actually reflects the original composition of the plants.

Minor elements in plant ash.--A comparison of tables 34 and 35 shows that the plant ash tends to be depleted in Fe, Ti, Mn, and V compared to the abundances of these elements in the present soils. The ash is generally enriched in Ag, Cu, and Pb, and is very strongly enriched in B and Sr compared to the present soils. The plant ash is variably depleted or enriched in Ba, Cr, and Zn compared to the present soils (table 36).

Data by which to compare the minor elements in the ash of these botanical remains with the ash of similar present-day plants grown on the present soil are lacking. Owing to the fact that different species of plants, and even different parts of the same plant, take up unlike quantities of the inorganic constituents of the soils and groundwater (Hawkes and Webb, 1962, p. 296-300), and to the fact that soils developed on different kinds of source rocks contain different concentrations of available inorganic constituents, a comparison between the specific contents of trace elements in the ash of plant remains from Bab edh-Dhra and Numeria with average values for the ash of plants grown elsewhere gives a rough indication of specific enrichment of elements in the botanical remains from Jordan (table 37). Compared to the world and U.S.A. averages for concentrations of elements in the ash of land plants, the averages of the plant remains from Jordan are depleted in Ti, Mn,

Table 36. Relation of detected elements in plant ash to soils from the Bab edh-Dhra and Numeria archaeological sites, Hashemite Kingdom of Jordan.

Element	Plant ash depleted or enriched compared to present soils[1]				
	1. Christ thorn seed	2. Olive pit	3. Two-row barley	4. Grape	5. Chick-pea
Fe	<	~	<<	<	<
Ca	>	>	>	>	>
Mg	>	>	<	>	>
Ti	<<	<<	<<	<	<
Ag	>>	~	=	~	>>
B	>>	>>	>>	>>	>
Ba	<<	~	<<	>>	<<
Cr	<	>	>	<	~
Cu	>	>>	>	>	>>
Mn	<	<	<	<	<
Pb	>	>	=	>>	>
Sr	>>	>>	>>	>>	>>
V	<<	<	>	<<	<
Zn	>>	=	=	=	>>

[1] The symbols used are:

= The ash and soil are the same.
~ the ash and the soil have about the same abundance of the element.
< the ash has less of the element than the soil.
<< the ash has much less of the element than the soil.
> the ash contains more of the element than the soil.
>> the ash contains much more of the element than the soil.

Table 37.--Comparison of the partial composition of the ash of botanical remains at Bab edh-Dhra and Numeria, Hashemite Kingdom of Jordan, with average values for the chemical composition of land-plant ash from other sources.
[n.d. = no data.]

Element	Average abundances reported for the ash of land plants (ppm)							
	Bab edh-Dhra and Numeria, Jordan	World averages	Russia		USA			
		Brooks (1972)	Beus and Gregorian (1977, table 46)		Cannon (1960)	Connor and Shacklette (1975)	Shacklette and Connor (1973)	Shacklette, Erdman, Harms and Papp (1978)
			Grown on soil over unmineralized granitic rock	Grown on soil over mineral deposits				
Fe	4,000	6,700	6,700	n.d.	n.d.	50-50,000	3,600	n.d.
Ca	300,000	n.d.	30,000	n.d.	n.d.	2,000-400,000	120,000	n.d.
Mg	34,000	n.d.	70,000	n.d.	n.d.	4,000-240,000	30,000	n.d.
Ti	200	n.d.	1,000	n.d.	n.d.	<2-3,000	260	<10-15,000
Ag	8	1	1	0.04-60	n.d.	<0.5-20	<1-70	0.4-20
B	1,500	700	400	n.d.	n.d.	5-50,000	240	<30-1,000
Ba	460	280	600	n.d.	n.d.	15-1,500	390	5-1,500
Cr	130	9	90	n.d.	9	<2-150	9.6	<1-700
Cu	310	180	20	50-1,000	183	10-7,000	100	5-1,500
Mn	40	4,800	7,500	n.d.	n.d.	15-50,000	1,100	30-70,000
Pb	120	70	10	40-1,000	70	<10-3,000	86	<7-7,000
Sr	5,000	30	300	n.d.	n.d.	<7-20,000	880	<10-15,000
V	35	22	61	n.d.	22	<5-700	11	<7-300
Zn	200	1,400	900	300-3,000	1,400	100-10,000	450	<25-5,800

and Zn and are similar in contents of Fe and Mg. Elements that are enriched in the Jordan plant ash over abundances given as averages in the literature are Ba, Cu, Pb, and V; very strongly enriched elements in the Jordan plant ashes are Ag, B, Cr, and Sr. This distribution of depleted, similar, and enriched elements identified by comparison with the literature confirms the enrichments identified by comparison with the composition of present-day soils at the archaeological sites.

The data in table 34 show that specific plants in the Bab-Dhra and Numeria areas have selectively concentrated certain elemtns compared to the soils: Christ-thorn seed and chickpeas concentrated silver; Christ-thorn seed and olive pits concentrated boron; grapes concentrated barium; and grapes and chickpeas concentrated titanium. By comparison with the barium contents of the ash of European and American grapes, reported to be respectively 62 and 90 ppm (J. A. Erdman, oral commun., 1978), the grapes from the archaeological site are truly enriched in this element. The sample of ash from two-row barley from Jordan (3, table 34) is depleted in FE, Mg, BA, and Zn in comparison to the ash of barleys from the Northern Great Plains of the United States (J. A. Erdman and L. P. Gough, written commun., 1978). The barley ash from Jordan has similar contents of Ti, Ag, Cu, and Mn with those reported for ash of barley from the Great Plains, but the barley ash from Jordan is enriched by comparison in Cr and V, and strongly enriched in Ca, B, and Sr. Thus, compared to various averages for plant ash from other sources (table 37, and above cited correspondence), the average plant ash from the botanical remains in Jordan is notably enriched in Ca, Ag, B, Cu, Pb, and Sr, and the ash is deficient in Ti, Mn, and Zn. Probably in large part, the differences shown in table 37 result from growth of the Jordanian plants on soils derived from calcareous sedimentary rocks further influenced by additions of boron and strontium by wind-borne salts from evaporite deposits of present or former shores of the Dead Sea. Although the average value for barium is low in most of the botanical remains, the grape is greatly enriched at 2,000 ppm (table 34). Ash from grapes in other regions contains only small amounts of barium (table 37); thus, it is possible that the water used to irrigate the grape vines was enriched in barium compared to other waters used for irrigation in the area.

The data in table 35 show that the present soils from the Numeria area tend to be leaner in Fe, Ca, Mg, Ti, Cr, Sr, and V than those from Bab edh-Dhra. Only a partial reflection of the differences in the trace-element composition of the soils is found in the compositions of the ash from the two plants from Numeria compared with the ash from the three plants from the Bab edh-Dhra area. In part this may be caused by chemical differences between the older soils in which the plants grew and the present soils. However, selective concentration of certain elements by specific plants may be the more likely cause. The clearest correlation is with chromium: the Numeria soils and plant ash are leaner in this element than those of Bab edh-Dhra, but even for chromium, one plant from Bab edh-Dhra yields ash that has less chromium than the Numeria plant ash. Despite the lower abundance of iron, calcium, and magnesium in the soils at Numeria, the plant ashes from both localities have about the same contents of these elements. Although the soils around Numeria contain slightly less titanium than the soils at Bab edh-Dhra, the ash of the grape and chickpea from Numeria has more titanium than that from the plants around Bab edh-Dhra. The soils at Numeria are a little leaner in strontium than those at Bab edh-Dhra, but the plants are such strong accumulators of strontium at both localities that the difference in the strontium content of the soils is overridden, and the ash from all the plants is enriched in strontium. Soils near Numeria contain less vanadium than the soils at Bab edh-Dhra, and the ash of the plants from Numeria may be slightly leaner in vanadium than the plants from Bab edh-Dhra.

Silver is strongly concentrated in the ash of one plant each from the two areas--the Christ-thorn seed and the chickpea--which are the same plants whose ash is enriched in zinc. No detectable variation was noted for silver in these soils (table 35), and the only variation found for zinc is the greatly anomalous 700 ppm from the cultivated field at the Majali farmhouse, which may be caused by contamination.

Despite the absence of any appreciable difference between the boron content of the soils from the two areas, the amount of boron in the ash from the grape and chickpea at Numeria is less than that in the ash of the Christ-thorn seed and olive pit from Bab edh-Dhra.

Most of the plant species yielded ash that was depleted in barium compared to the soils (tables 34 and 35). The exception is the grape, noted above.

Although no appreciable difference exists in the copper content of the ash from four varieties of plant, the ash of the chickpea is greatly enriched in copper (table 34). The greater amount of copper in the chickpea ash is matched by greater quantities of zinc and silver. None of the soils have large amounts of copper except the soil at the Majali farmhouse. Inasmuch as this soil (table 35) was enriched in zinc, possibly from contamination, perhaps the same source that is responsible for the zinc is responsible for the rise in the amount of copper in the soil. It would be interesting to learn if the copper- and zinc-rich soil at the Majali farmhouse overlies artifacts of copper or brass (not ignoring the hazardous possibility of historically recent ordnance). The extent of the anomaly could be defined geochemically in the field through the use of rapid analyses of the soil by the acid extractable copper test (Ward and others, 1963, p. 25-27).

No variation in the contents of lead and manganese in the ash of the plants is sufficiently large to be attributed to a capacity for concentration by one species or to variations in the abundances of these elements in the soils.

Geochemistry of the soils.--Through use of the field descriptions in table 33, the 32 samples of soil from the area of the archaeological sites were divided into six groups based on topographic setting, origin, texture, and use: (1) old eluvial soil, (2) wadi soil, (3) ashy soil, (4) cultivated soil, (5) irrigated soil, and (6) the soil of city sites. No basis for fitting these soils into Bender's classification of the soils of Jordan was available (Bender, 1974, p. 187-193). Average values for the various elements were determined for these groups. The results disclosed some small geochemical differences among the groups (table 38), and five elements--Be, Co, Sc, Y, and Zn--dropped out of all groups, because their average values were below their respective limits of determination.

Compared to average values for elements in the soils of the United States and to world averages, the soils from the Bab edh-Dhra and Numeria archaeological sites in Jordan are greatly enriched in Ca, B, and Sr (table 38). The soils at this locality contain less Fe, Ti, and Mn than the regional and world averages.

Table 38. Average values for the concentration of elements in groups of soils from the vicinity of Bab edh-Dhra and Numeria, Hashemite Kingdom of Jordan,[1] compared with regional average values for soils in the United States and world averages.

Element	Jordan						USA	World
	Old eluvial soil	Wadi soil	Ashy soil	Cultivated soil	Irrigated soil	Soil at city sites	Shacklette and others (1971, table 1)	Vinogradov (1959)
	In percent							
Fe	0.7	1	0.9	1.4	0.9	1	2.5	3.8
Ca	12	19	11	19	>20	17	2.4	1.37
Mg	.8	1	1.2	1.4	1.2	1.4	0.92	.63
Ti	.07	0.2	.15	.3	.2	.2	.3	.46
	In parts per million (ppm)							
B	60	49	65	112	55	176	34	10
Ba	400	163	175	384	512	463	554	500
Cr	20	65	75	93	98	93	53	200
Cu	11	19	45	63	29	24	25	20
Mn	175	188	200	262	250	263	560	850
Ni	N(10)	12	35	32	38	18	20	40
Sr	200	300	850	720	850	1,100	240	300
V	20	40	60	68	65	48	76	100
Zr	750	74	100	200	155	238	240	300

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[1] As quoted in Shacklette and others, 1971, table 1.

The most geochemically distinctive soil is the old eluvial soil (samples 25 and 26), which is characterized by the lowest contents of all elements except Ca, B, Ba, and Zr. The tenor in calcium (12 percent), is only 1 percent greater than the lowest value in Jordanian samples (table 38). Thus, the eluvial soil fulfills the prior expressed interpretation that old original soils on which were grown the plants found at the archaeological sites were leaner in calcium than the present soils. This old eluvial soil is also the richest in zirconium (750 ppm), which may reflect the gravity concentration of zircon in the eluvial soils. However, titanium, which could be expected to concentrate with heavy minerals in eluvium, is at its lowest abundance (0.07 percent) in this soil. The other soils display very little difference in the abundance of titanium.

It is not understood why the soils from the present city sites (table 38) are richer in boron than the other soils, unless the sites are closer to sources of airborne salts from the Dead Sea. An explanation is also lacking for the notable deficiency in barium found for the so-called ashy soils and wadi soils compared with the barium content of the other soils.

Rather little variation was found for the amounts of magnesium and manganese in the soils. Copper also would have shown scant variation in abundance among these groups of soils except for the presence of the highly anomalous sample 18. Without it, the cultivated soils would have had an average content of only 20 ppm copper.

Chromium, nickel, and vanadium are pretty well leached out of the eluvial soil, but they are present in greater amounts in the other soils.

The rise in the abundance of strontium in the soils from the city sites is parallel to the increase in boron content compared with the other soils. This rise may be caused by proximity to shoreline features of the Dead Sea.

Implications for biogeochemical exploration.--The trace-element composition of the ash of the old plant materials from the archaeological sites at Bab edh-Dhra and Numeria clearly shows the factor that must be evaluated during orientation surveys preparatory to the use of biogeochemical exploration in Jordan: selective concentration of elements by plant species and possibly by part of the plant. Observations on the use of various species of *Acacia* for biogeochemical exploration in Saudi Arabia have already shown that one species, *A. hamulosa,* accumulates more molybdenum than three other species of *Acacia* (Allcott, 1970, p. 123), and the use of acacia trees in biogeochemical exploration in Egypt has been described (El Shazly and others, 1971). The services of a botanist are needed to identify the plants having the most general distribution in any area chosen for biogeochemical exploration. A selection of deep-rooted species should be made for study. Various parts, such as leaves, twigs, and fruit should be sampled for ashing and analysis of the ash. When the plants are sampled, the soils in which the plants grow should also be collected for analysis. The results of the analyses of ash and soil should be compared to determine what parts of which plants give the most useful biogeochemical data (Overstreet, 1978a, p. 16).

CONCLUSIONS

The results of these brief geochemical orientation surveys in the Hashemite Kingdom of Jordan have disclosed five areas for future investigation from which useful contributions can be made for improving knowledge of concealed ore deposits in the country. These orientation surveys have also shown that a clear contribution to the archaeology of Jordan can be made through the field and laboratory techniques of geochemical exploration. These areas for future investigation are:

1. Problems in the identification of possible concealed base-metal deposits related to hydrothermal activity along faults connected with the Jordan Rift Valley.
2. Evaluation of possible concealed rare-metal deposits associated with the cryptovolcanic structure at Jabal Waqf es Suwan.
3. Possible presence of peneconcordant sandstone-type sedimentary uranium deposits in the Ba'qaa Valley.
4. Consideration of size fractions of wadi sand most suitable for use in geochemical exploration in Jordan.
5. Use of heavy-mineral concentrates as a geochemical sample medium.
6. Interface of geochemical exploration and archaeology.

Identifying possible concealed base-metal deposits related to hydrothermal activity along faults connected with the Jordan Rift Valley

Four localities briefly observed in the present orientation survey in Jordan have been the sources of geochemical indications of hydrothermal activity from the Tertiary to the Quaternary periods. All appear to be controlled, at least in part, by faults associated with the Jordan Rift Valley. Most of these sites were the sources of tenuous geochemical data that have been interpreted as possibly indicating the presence of concealed base-metal deposits. Only the southernmost of these four areas will be covered by proposed airborne electromagnetic surveys (Andreasen, 1978; Seitz, 1978,

p. 10-12), which will be of major use in evaluating results of future geochemical exploration in the southern area. However, thorough surface study of the geochemical characteristics of the four areas is needed, supported by further airborne or ground electromagnetic surveys. From north to south these four areas are (fig. 1): (1) barite veins in northeastern Jordan; (2) apatitic limestone (marble) in the Daba'ah-Al Qatranah area; (3) hydrothermal alteration at the thermal springs in Wadi Zarqa Ma'in; and (4) altered granite and sandstone at Wadi Shureh in the granitic massif east of Al'Aqabah.

Barite veins in northeastern Jordan

Chemical and physical similarities were noted between barite and jasperoid from veins in northeastern Jordan, exposed about 90 km northwest of Mahattat el Jufur, and Tertiary veins of barite with jasperoid at Rabigh in the Red Sea Rift Zone on the coast of the Kingdom of Saudi Arabia. Despite the fact that these two hydrothermal deposits are 1,200 km apart, the observations by Brobst (1966) that the composition of the jasperoid from the barite veins at Rabigh was an indicator of possible concealed base-metal deposits can also be applied to the veins in northeastern Jordan. Favorable criteria at the Jordanian deposit include the assemblage of trace elements in the jasperoid, the color and texture of part of the jasperoid, and the geochemical enrichment of silver in the wall rocks of the veins.

Further samples of jasperoid should be collected from the barite veins in northeastern Jordan for textural and chemical study to determine how closely this material meets Lovering's (1972) category of texturally and chemically favorable jasperoid as an indicator of hidden, hydrothermal sulfide deposits of possible economic interest.

Apatitic limestone (marble), Daba'ah-Al Qatranah area

Apatitic limestone quarried for marble in the Daba'ah-Al Qatranah area contains anomalously large amounts of Ag, Cd, Cr, Mo, Ni, V, Y, and Zn, and possibly anomalous amounts of copper. These chemical characteristics of the rock have long been known. Mostly, they are attributable to processes of sedimentary deposition under euxinic conditions. Some metal concentrations, such as that of cadmium, are highly anomalous. Many of the anomalous elements are associated with distinct color phases of the rock, but where the rock is fractured, rare, heavy-metal-rich minerals fill the fractures and evidently represent secondary concentrations of these elements (Bender, 1974, p. 82, 158). Outcrops of the apatitic limestone (marble) tend to be linearly arranged along prominent east-striking faults, such as the Lisan-Suwaqa fault, associated with the tectonics of the Jordan Rift Valley (Walid Hakki, written commun., 1978), which leads to the possibility of remobilization or secondary enrichment of the anomalous elements by alkaline hydrothermal fluids moving in these faults. However, when the anomalous trace-element suite in the apatitic limestone (marble) is compared to suites in other hydrothermally altered rocks in Jordan, as at Wadi Zarqa Ma'in for example, no similarities in enriched elements are found. Any direct connection of these heavy metals with rifting seems unlikely.

Further studies of the geochemistry of the apatitic limestone (marble) and of other rocks exposed along the trace of the Lisan-Suwaqa fault, and other major faults, are needed to determine if these structures actually served as conduits for mineralizing hydrothermal fluids. Interpretation of new geochemical data should be made in concert with newly available remote-sensing data from the regional airborne magnetic survey of Jordan (Andreasen, 1978) and LANDSAT imagery, particularly the experimental analysis of computer-enhanced imagery (Chidester, 1975; Seitz, 1978, p. 35-41; Blodget and others, 1978; Raines, 1978), to help understand the possibility for concealed mineral deposits of hydrothermal origin in Jordan.

Hydrothermal alteration at the thermal springs in Wadi Zarqa Ma'in

The thermal springs at Wadi Zarqa Ma'in are marked by wide discoloration and hydrothermal alteration of the sedimentary rocks in the northern wall of the wadi. The thermal springs are the most radioactive area in Jordan, and the possibility for unexposed sulfide deposits at depth has been entertained by NRA (Abu Ajamieh, 1974). Results of the present geochemical analyses of the altered sedimentary rocks at Wadi Zarqa Ma'in show some similarities to characteristic assemblages of trace elements from the metal-rich hot brines of the Red Sea (Bischoff, 1969; Hendricks and others, 1969; Shanks and Bischoff, 1977) and to sulfide-bearing altered rocks at the Broadlands geothermal field, New Zealand (Ewers and Keays, 1977). However, many of the minor elements particularly sought for comparison with the Red Sea brines and the Broadlands geothermal field as indicators of deep-seated base-metal deposits proved to have abundances below the lower limits of the methods of determination used in the present study (tables 12 and 13). The values for these metals are similarly low in the Red Sea brines and hydrothermally altered rocks at Broadlands, therefore true comparisons can only be made by achieving lower limits of determination for Ag, As, Bi, Cd, Mo, Sb, Sn, and W. The methods used to determine Au, In, Se, and Tl are just barely able to detect these elements at the very low abundances reported for the Red Sea brines and the Broadlands altered rocks.

In the present study, most attention was paid to the altered rocks in the northern wall of the wadi. Unaltered sedimentary rocks were not collected nor were calc-sinters or other warm springs deposits collected; just one sample was taken from the bed of the warm stream in Wadi Zarqa Ma'in. Further work requires that analyses be made of both the altered and unaltered rocks in the walls of the wadi to determine gains and losses of elements attributable to hydrothermal alteration. Direct comparison with the huge values for Ag, As, Au, Sb, Se, and Tl in the pool precipitates at Broadlands could not be made, but the alluvium from the bed of Wadi Zarqa Ma'in lacks high values for these elements. Thus, no direct evidence of base or precious metals at depth has been indicated by the present data on the altered rocks at Wadi Zarqa Ma'in, but the site deserves close investigation.

Further geochemical investigations at Wadi Zarqa Ma'in should be undertaken by systematic new sampling. The new samples should include representative fresh and altered rocks from the area of effluence of the warm springs, suites of sinter and other warm springs deposits, alluvium, water, and gases. Analytical methods should permit lower limits of determination to be achieved for the indicator elements listed above than was attained in the present work. Electromagnetic surveys of the area are needed.

Following an interpretation of the results of geochemical and geophysical surveys at Wadi Zarqa Ma'in, a program of drilling may be needed to test the interpretations. Any test drilling to explore for hidden sulfide deposits should be conducted in close cooperation with the geothermal energy project at this site. The possibility of concealed metallic mineral deposits should be considered as a factor in feasibility considerations related to the development of geothermal energy at Wadi Zarqa Ma'in.

Altered granite and sandstone at Wadi Shureh in the granitic massif east of Al'Aqabah

The geochemical data from the altered granite and sandstone at Wadi Shureh in the granitic massif east of Al' Aqabah do not present positive evidence for a former hydrothermal event at Wadi Shureh. Increased values for indicator elements, particularly those associated with the varicolored sandstones, may indeed be caused by the scavenging action of secondary iron oxides and hydroxides (Canney, 1966; Jenne, 1968) precipitated from groundwater in the rocks. However, the geochemical similarities with the area at Wadi Zarqa Ma'in are so strong that the locality in Wadi Shureh deserves some more attention for possible hydrothermally formed base-metal deposits at depth.

The proposed airborne electromagnetic survey (Andreasen, 1978; Seitz, 1978) covers this area. Further geochemical investigations at Wadi Shureh should be coordinated with interpretations of the results of that survey.

Evaluation of possible concealed rare-metal deposits associated with the cryptovolcanic structure at Jabal Waqf es Suwan

The general failure of the more mobile rare metals and minerals associated with mineralized cryptovolcanic structures elsewhere in the world to appear in surface fractures in the sedimentary rocks at Jabal Waqf es Suwan may be interpreted to indicate that this cryptovolcanic structure is not mineralized. None of the elements detected in the suite of rocks from Jabal

Waqf es Suwan can be clearly attributed to sources in underlying igneous rocks, whereas in some mineralized cryptovolcanic structures, for example Hicks Dome in Illinois, USA, (Heyl and others, 1965; Trace, 1976) the elements Be, Ce, Ga, Nb, Ni, Ti, Y, and Zr as well as the minerals barite, fluorite, and sphalerite are anomalously abundant. Many elements that could be expected to be present in an exhalation halo above a buried igneous intrusive rock were not detected at Jabal Waqf es Suwan. The group of elements detected in the rocks at Jabal Waqf es Suwan is entirely compatible with processes of sedimentary deposition under varied conditions caused by changes in the physical, chemical, and biologic conditions of marine waters.

The structure at Jabal Waqf es Suwan is thought to be a dome over a buried volcanic plug probably related to the Neogene and Pleistocene basaltic flows and tuffs that are prominent surface features in parts of Jordan. Further geochemical exploration at Jabal Waqf es Suwan should have a low priority and might well be delayed until the results of airborne magnetic and radiometric surveys (Andreasen, 1978; Seitz, 1978) have been interpreted. When a new geochemical survey is instituted, it should be based on chip samples of rocks taken under careful stratigraphic control and geophysical guidance. During this program a vertical drill hole should be sunk to a depth of 500 m near the center of the structure for additional geological, geochemical, and mineralogical data (Overstreet, 1978a, p. 18-19).

Possible presence of peneconcordant sandstone-type sedimentary uranium deposits in the Ba'qaa Valley

High values for uranium, vanadium, and selenium in the ash of lignite from sandstone intersected by a water well in the Ba'qaa Valley constitute geochemical evidence for the possible presence of peneconcordant sandstone-type sedimentary uranium deposits in the region. This concept is supported by the environment of deposition of the sandstone host for the lignite: continental and near-shore marine conditions in a marginal cratonic position (Bender, 1974, p. 60-70; Finch and others, 1973, p. 460). The ash from the lignite shows enrichment of elements that are associated with uranium during deposition from circulating ground water under reducing conditions in locally carbonaceous sandstone: Fe, V, Se, Cu, Cr, and Mo (Fischer, 1973, p. 684; Granger and Warren, 1974).

The specimen of lignite itself is not from a uranium deposit, but the geologic setting from which it was derived and the geochemical character of the lignite constitute features that are elsewhere associated with the formation of peneconcordant uranium deposits in sandstone. Further investigation for uranium in the sandstone should receive a high priority in mineral exploration in Jordan. Results from the proposed airborne radiometric survey (Andreasen, 1978, p. 3; Seitz, 1978, p. 4-9) will give the first firm evidence if uranium-bearing formations crop out in the area. However, ground-based surveys are also necessary. Of these, the most suitable ground-based survey for the Ba'qaa Valley would be a hydrogeochemical survey using samples of water from wells, springs, and streams to measure the distribution of uranium, uranium daughter products, and other elements (Cadigan and Felmlee, 1977; Miller, 1979).

The possibility also exists that water from sources enriched in the elements found in the ash of the lignite could constitute a hazard to health (Lakin, 1972; Dorn and others, 1973; Shacklette and others, 1974). The results of a hydrogeochemical survey would also contribute to the identification of sources of unsafe water.

Consideration of size fractions of wadi sand most suitable for use in geochemical exploration in Jordan

Experience in geochemical exploration in Jordan had questioned whether the conventional sample of other regions, the <80-mesh fraction of alluvium, is suitable for use in exploration in arid regions (Gharaibeh, 1969). In central Saudi Arabia, much coarser grained fractions (<10+30-mesh) of wadi sand had proven to be superior to the finer grained fractions in geochemical exploration (Theobald and others, 1977) owing to the broad variation in the abundances of the elements in coarse fractions. Tests of three size fractions of wadi sand in the area of the granitic massif east of Al'Aqabah during the present investigation showed that in the area of the massif the finest grained fraction (<80-mesh) was the most metal-rich but that the coarsest fraction displayed the broadest variation. These observations conform to the findings in Saudi Arabia and in part to preliminary findings in desert regions elsewhere in western Asia (Domenico and others, 1978) where the <80-mesh fraction of sediment was shown to be richer in metals than coarser grained fractions. In the wadi sands of the area east of Al'Aqabah, wind-borne particulates appear to be less of a contaminant than they are in central Arabia.

Enrichment of metals in the finest grained fraction of wadi sand appears to be more pronounced close to the coast of the Gulf of 'Aqabah than farther inland in the area of the granitic massif. This relation may be caused by the greater moisture content of the air--more dew and fog--close to the coast than farther inland. Larger amounts of surface moisture would favor an increase in chemical weathering of rocks close to the coast, and also favor an increase in the formation of micron-sized or larger particles of iron and manganese oxides and hydroxides from solution in intermittent surface water. These secondary oxides are capable of scavenging large quantities of other metals from the water as they precipitate (Jenne, 1968; Chao and Theobald, 1976). Indeed, this scavenging effect is so great that precaution must be taken in geochemical exploration against the possibility of false metal anomalies that are caused by scavenging from unmineralized rocks instead of a real anomaly caused by a rise in metal content related to mineralization (Canney, 1966; Carpenter and others, 1975).

The need to understand what processes are affecting the distribution of metals in wadi sands (and soils, as shown by the orientation survey at Bab edh-Dhra and Numeria) in various parts of Jordan is thus clear. To achieve this, further studies of the chemistry, combined with detailed mineralogical analyses, must be made of various size fractions of wadi sand and of soil from selected geographic sites in Jordan to define the effects of relief, geology, and meteorology on sedimentary materials used for geochemical sample media. Results of these investigations would eliminate the old empirical approach to the selection of sample media, and place geochemical exploration in arid lands on a sounder scientific base (Bradshaw, 1979).

Use of heavy-mineral concentrates as a geochemical sample medium

Barite vein exposed to the northeast of Al'Aqabah

The value of heavy-mineral concentrates in effectively enlarging the size of a potential target in an area being explored geochemically was shown at the small barite vein in Precambrian granite exposed about 10 km to the northeast of Al'Aqabah. Although the vein is only 2-4 m wide, a strongly pronounced secondary dispersion train of detrital barite was followed for 150 m downhill from the vein by preparing heavy-mineral concentrates from wadi sand. Barite was clearly visible in the concentrates, and barium and strontium were strongly anomalous. Both the mineralogical and chemical anomalies were so strong at 150 m from the outcrop of the vein that these anomalous features would be seen in concentrates made from wadi sand as much as several hundred meters farther away. Thus the target area for the exploration geochemist was enlarged, on the downhill side, from a mere 2-4 m outcrop width to at least 150 m of highly anomalous dispersion train, and the width of the target train probably reaches as much as 500 m. Other ore minerals of high density could be detected in the same fashion where they are present in the rocks and are exposed to erosion and alluvial transport.

Saramuj Conglomerate

The reported occurrence of gold in the Saramuj Conglomerate in Wadi Saramuj was not supported by the results of mineralogical and chemical analyses of various magnetic and density separates from one heavy-mineral concentrate panned from 100 kg of weathered rock. Wadi alluvium would provide more meaningful samples than the rock itself, because auriferous parts of the rock could be missed in sampling. Wadi alluvium, particularly gravel where gold would tend to accumulate (Griffith, 1960), is derived from all exposed parts of the conglomerate; hence, alluvium represents the whole rock. Future investigations of the Saramuj Conglomerate for gold should be based on bulk samples of wadi alluvium that would be processed for heavy-mineral concentrates. Mineralogical and chemical analyses of the concentrates would disclose the gold if it is present. Follow-up exploration upon the discovery of gold in alluvium might proceed along lines previously suggested (Overstreet, 1978a, p. 27-28).

Interface of geochemical exploration and archaeology

The multiple interfaces of geology, geomorphology, and geochronology with archaeology are long established and fundamental, but the interface of the techniques of geochemical exploration and archaeology are not so fully perceived or used. The clearest examples of the use of geochemical exploration methods in archaeology are seen in archaeometallurgical investigations (Cooke and others, 1972; Rothenberg, 1972; Wertime, 1968; 1973a; 1973b; Milton and others, 1976) and in the tracing of sources and routes of trade in tin (Muhly, 1973; Franklin and others, 1978). Several aspects of this interface have been touched in the present investigation in orientation surveys of slags from copper smelters in Jordan and of soils and botanic remains at Bab edh-Dhra and Numeria.

Slags

The results of geochemical investigations of copper ores and slags in the Wadi Feinan-Wadi Dana, Wadi Khalid, and Jebel Khirbet en Nuhas areas on the eastern side of Wadi Arabah show that the copper smelters exploited local ores and fluxes. The possibility of a source for complex sulfide ores elsewhere, that were brought to these smelters in antiquity, but have been undiscovered in modern times, is unlikely. Isotopic age determinations on charcoal from the slags identifies metallurgical activity on the eastern side of Wadi Arabah when this industry is said to have been in abeyence on the western side of the valley (Rothenberg, 1972, p. 14).

The concept of C-14 ages of charcoal from slags, and the mineralogical and chemical composition of the slags, is most worthy of investigation at these sites in eastern tributaries to Wadi Arabah. Fragments of charcoal completely encased in slag can be recovered by breaking the slag and looking for pockets containing charcoal, which can then be picked for analysis. Botanic examination of the charcoal would classify the source vegetation for fuel used in smelting. At a site or, preferably, sites where archaeological excavation is done and the stratigraphic succession of the slag piles is worked out, the C-14 ages of slags assigned to difference episodes of smelting could be determined. These isotopically dated slags could then be studied mineralogically and chemically to give dated evaluations of technological progress in extractive metallurgy.

Botanic remains and soils at Bab edh-Dhra and Numeria

Geochemical studies of botanic remains and present soils at the archaeological sites at Bab edh-Dhra and Numeria defined a clear common interest in the applications of trace-elements analyses in geochemical and archaeological techniques. Problems inherent in comparing anomalous accumulations of trace elements in botanic remains were identified. Some exploitation of the trace-element composition of soils was possible for interpreting source and age. More interesting, however, is the possibility that the results of simple colorimetric analyses of closely spaced samples of soils will assist in locating hidden artifacts composed of copper or brass. Evidently, further use of the methods of geochemical exploration will be of advantage to Jordanian archaeologists.

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