UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

SAUDI ARABIAN MISSION

TECHNICAL RECORD 20

(INTERAGENCY REPORT 377)

PRELIMINARY INVESTIGATION OF THE BAID AL JIMALAH TUNGSTEN DEPOSIT, KINGDOM OF SAUDI ARABIA

by

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and Michael D. Fenton

Open-File Report 81-1223

1981

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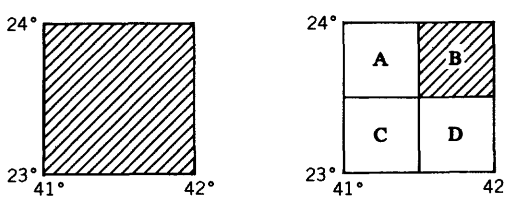

23/41

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PRELIMINARY INVESTIGATION OF THE BAID AL JIMALAH TUNGSTEN DEPOSIT, KINGDOM OF SAUDI ARABIA

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ABSTRACT

Significant tungsten mineralization is present within and marginal to a small irregular cupola and dike network of late Proterozoic, porphyritic, biotite-bearing microcline-albite granite in the Al Jurdhawiyah quadrangle (sheet 25/42 D), Kingdom of Saudi Arabia. The granite is highly enriched in lithium, fluorine, beryllium, tungsten, and tin, and has been heavily veined and greisenized, probably during an intense hydrothermal event related to the emplacement of the granite. Mineralization consists principally of very coarse crystals of wolframite, lesser cassiterite, and minor scheelite in stockworks and in dense, subvertical zones of vuggy quartz veins. Greisenized granite and country-rock hornfels contain some disseminated cassiterite, wolframite, and lesser pyrite. Composite outcrop samples of vein material, greisen, and relatively fresh granite contain up to 6400 ppm tungsten and 300 ppm tin. The outcrop extent of the mineralized area exceeds 700 m by 800 m and encloses four subparallel zones of closely spaced quartz veins. The southernmost of these zones is somewhat distinct, containing higher median concentrations of lithium, fluorine, tin, beryllium, and sulfides, and may have been formed at slightly lower temperatures.

The granite and veins were emplaced into fine-grained clastic rocks of the Murdama group, just below the subhorizontal unconformity that marks the base of the younger Al Jurdhawiyah group of continental andesitic volcanic and volcaniclastic rocks. Tungsten mineralization is most likely younger than the Al Jurdhawiyah group, and may be cogenetic with a vein- and fracture-controlled lead-zinc-silver deposit 2 km to the east.

The Baid al Jimalah tungsten deposit is similar in terms of its structural setting, chemistry, mineralogy, and paragenesis to deposits of tungsten, worldwide, and tin in association with granitoid plutonic rocks. The size of the mineralized area is comparable to that of producing, economic deposits elsewhere, but the depth and grade of the ore at Baid al Jimalah are unknown. We recommend additional mapping, trenching, sampling, and geophysical investigation of this deposit.

Analyzed samples of wadi sediments from the vicinity of the tungsten deposit show that the ore minerals have not been widely dispersed by surficial processes. Anomalous concentrations of tungsten and tin are only present within about 2 km of the mineralized area, and therefore, similar deposits could easily escape detection in geochemical surveys of low sample-density. Our study suggests that detection of anomalies could be improved by reducing the amount of magnetite and zircon in the analyzed panned concentrate.

INTRODUCTION

Tungsten mineralization, chiefly in the form of wolframite-bearing stockwork quartz veins in greisenized granite porphyry, was discovered by Cole in March 1980, during geologic mapping of the Al Jurdhawiyah quadrangle (sheet 25/42 D). The size of the mineralized area and the apparent grade of the deposit warranted a preliminary evaluation of the prospect. This report is based on reconnaissance plane-table mapping at 1:1000 scale and detailed sampling of outcrop by the authors during 14-17 May, 1980. Cole collected samples of wadi sediment in the vicinity during the preceding month.

All work was performed under a cooperative agreement between the U.S. Geological Survey (USGS) and the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. All new analytical results listed in this report were obtained by the chemistry laboratory of the Deputy Ministry for Mineral Resources (DMMR/USGS) or by the USGS petrographic services laboratory in Jiddah. Values determined by semi-quantitative emission spectrography are listed in parts per million (ppm) representing the approximate midpoint of concentrations in the series 1, 1.5, 2, 3, 5, 7, ... ppm. Total values were obtained for silver, gold, lithium, and zinc by atomic absorption spectroscopy, for fluorine by selective ion-electrode techniques, and for tungsten and arsenic by colorimetry. Individual credit for analytical work is listed in the appropriate figures of this report. Complete sample information and all analytical data from this project are tabulated in a USGS archive data file (available from the USGS, Jiddah, Saudi Arabia).

REGIONAL SETTING

The Baid al Jimalah tungsten deposit is located at lat 25°09'N., long 42°41'E. in the northeastern Proterozoic shield of Saudi Arabia (fig. 1). It is situated approximately 180 km west-southwest of Buraydah, and approximately 135 km north of Afif. There is a new paved highway that connects the Madinah-Riyadh highway near Wadi ar Rimah with

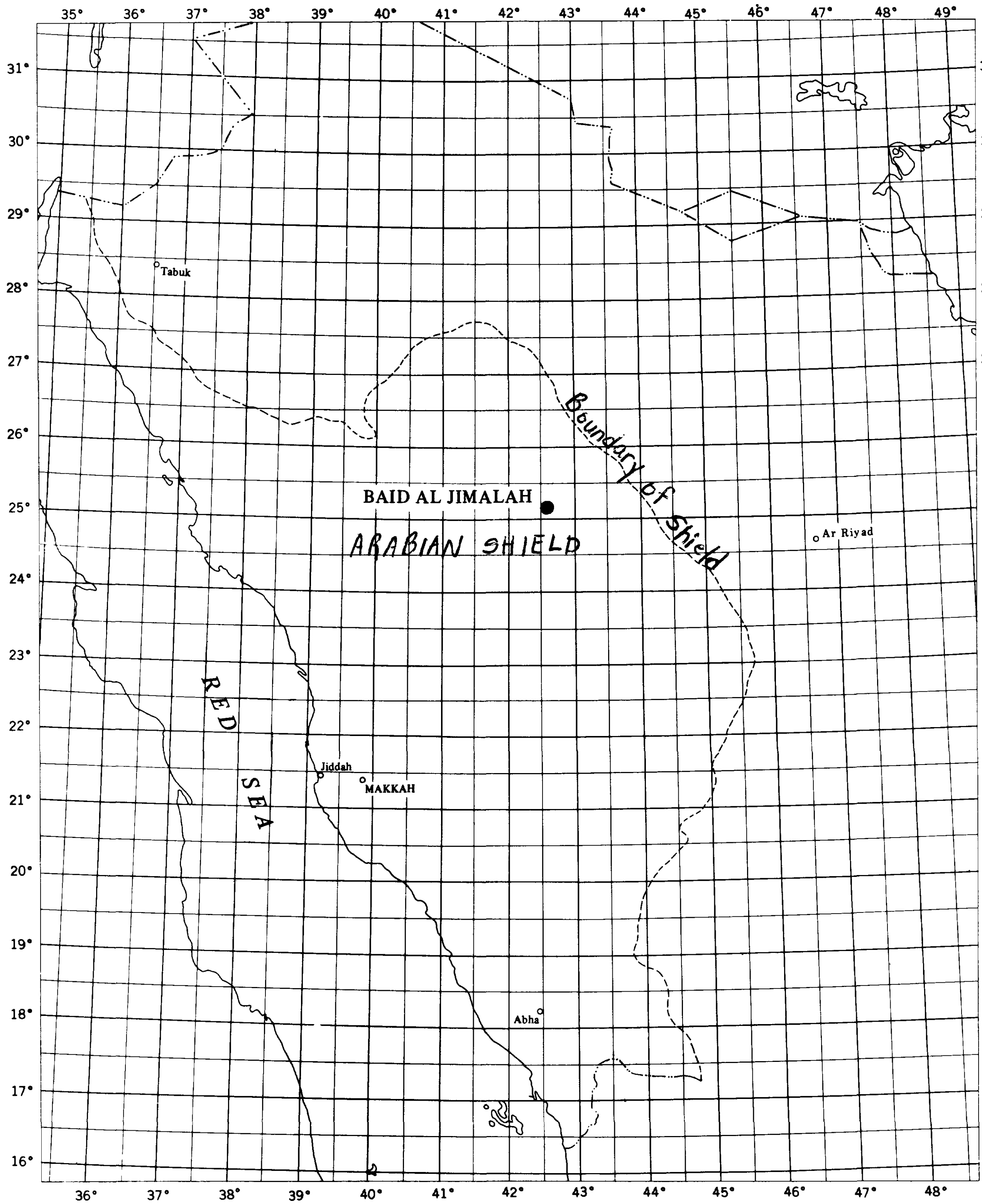


Figure 1.–Index map of western Saudi Arabia, showing the location of the Baid al Jimalah tungsten deposit.

the village of Al Jurdhawiyah, from which a good dirt road can be followed about 30 km south to the site. The nearest village is Al Aghar, 6 km to the southwest.

The name Baid al Jimalah refers to a small group of hills west of Nafud Kutayfah and east of Jabal Shawfan. Previous geologic and mineral-resource studies (Fakhry, 1941; Bramkamp and others, 1963; Mytton, 1970; Muller, 1975) have ascribed this name to an ancient lead-zinc-silver mine located 1.5 km east of this tungsten deposit.

Inasmuch as Baid al Jimalah is an established regional name, we use it in reference to the tungsten deposit and, where specifically stated, to the lead-zinc-silver deposit as well. The term "Baid al Jimalah district" is defined to include both deposits.

The tungsten mineralization is spatially and genetically related to a small irregular body of biotite-bearing microcline-albite granite porphyry that intrudes folded, regionally metamorphosed metasiltstone and metasandstone of the Murdama group. A poorly defined, superimposed contact-metamorphic aureole encloses the granite porphyry. The higher hills and mountains surrounding the tungsten deposit consist of the undeformed, flat-lying rocks of the Al Jurdhawiyah group, unconformably overlying the Murdama group (Cole, in press). We present evidence that implies the granite porphyry and its related tungsten mineralization are younger than the Al Jurdhawiyah group. Both the Murdama and Al Jurdhawiyah groups in the region are intruded by large ovoid plutons of calc-alkaline granodiorite and alkaline to peralkaline perthite granite. However, the granite porphyry at Baid al Jimalah is spatially, petrographically, and chemically distinct from these two classes of young granite. There is no evidence to suggest any genetic connection to other magmatic events. Therefore, the granite porphyry of Baid al Jimalah appears to be unique, although its age is not well known.

MURDAMA GROUP

In the southern part of the Al Jurdhawiyah quadrangle, the Murdama group consists of a monotonous assemblage of fine-grained, thinly bedded marine siltstones and sandstones with local sills or flows of diabasic subporphyritic andesite to quartz latite (Cole, in press). The clastic rocks are composed of very poorly sorted, subangular sand-sized fragments, consisting chiefly of feldspar, quartz, and very fine grained volcanic rock, in a fine-grained matrix. Primary textures in these rocks and in the interlayered igneous rocks are typically well preserved, although weak regional metamorphism has produced assemblages of chlorite, epidote, sericite, sodic plagioclase, calcite, and widely disseminated pyrite (now hematite). The structure of the Murdama group is a synclinorium with a general north-south axial trend. Deformation has produced large-scale folds and minor small-scale contortions without a pervasive cleavage or schistosity. In the general vicinity of Baid al Jimalah, bedding strikes in a northerly direction, and dips moderately to steeply to the west. There is no evidence at present to suggest that structures in the Murdama group exercized any control on the tungsten mineralization.

Near the contact of the Baid al Jimalah granite porphyry, the Murdama clastic rocks have been recrystallized to structureless hornfels. The clastic fabric is virtually obliterated by the unoriented growth of pale reddish brown biotite and by the mosaic recrystallization of detrital quartz and feldspar grains. Feldspars are locally replaced by decussate aggregates of yellowish muscovite. Porphyroblastic patches of colorless to purple-tinted fluorite are common near the granite contact and, along with irregular clustering of biotite grains, produce a spotted or mottled texture in the hornfels. Accessory minerals include common 0.01 mm granules of cassiterite(?; hornfels contains as much as 200 ppm tin), traces of zircon, a few acicular, greenish, weakly pleochroic grains that are probably tourmaline, and irregular, hematite-bordered, unidentified opaque minerals.

The hornfelses are cut by fairly abundant quartz veins of several ages, but all the veins are apparently related to the mineralized granite. Thin early veins, 1 to 3 cm thick, typically consist of a symmetrical 1 to 4 mm selvage of yellowish muscovite (platelets grown at a high angle to vein walls) and an inner filling of mosaic quartz, unaltered albite, and fluorite. Other minerals identified in hand specimen include wolframite, carbonate, and local lenslike aggregates of very fine grained metallic minerals that probably include cassiterite, sphalerite, wolframite, and arsenopyrite. One sample of this metallic aggregate, analyzed by emission spectrography, contains 3 ppm silver, 700 ppm arsenic, 300 ppm copper, 3000 ppm lead, more than 1000 ppm tin, 500 ppm tungsten, and 1000 ppm zinc (sample 152515; A. B. Assegaff, analyst). Later veins typically do not have the characteristic muscovite selvage of the early veins, and generally do not contain albite. We believe the later veins are the same as veins in the granite, described in detail below, in the section on greisenization and veining.

GRANITE PORPHYRY OF BAID AL JIMALAH

The small body of granite that is host to the tungsten mineralization crops out discontinuously over an area of at least 700 m by 800 m, and has a highly irregular outline in plan (fig. 2). In the vicinity of triangulation station A and for several hundred meters to the east, granite is the only rock type exposed. However, west of station A and along the ridge west of station C, granite crops out chiefly as 1 to 10 m thick, subvertical dikes with a dominant west-northwest trend. Elsewhere, the trend of dikes is much more diverse, and dips range from vertical to subhorizontal. Contacts between granite and hornfelsic rocks of the Murdama group are typically sharp and planar. With the exception of large blocks of hornfels that are enclosed by dikes of granite, inclusions of hornfels in the granite were not found. The form of the granite exposed at Baid al Jimalah suggests that it represents a zone of closely spaced dikes adjacent to a small stock or cupola.

The granite itself has been highly altered subsequent to emplacement, but an examination of less altered samples demonstrates that the original rock was a porphyritic biotite-bearing microcline-albite granite. It is a very homogeneous granite, without obvious textural or compositional variation. The rock contains about 35 percent phenocrysts, of which 50 percent are equant quartz, 10 percent are unzoned lath-shaped albite, and 40 percent are rectangular to irregular, Carlsbad-twinned microcline with coarse, patchy perthitic textures. In some samples the potassium feldspar is weakly perthitic orthoclase displaying incipient inversion to microcline. Extinction angles for the albite indicate a composition of 5 to 10 mole percent anorthite, assuming the low-temperature structural state. However, partial chemical analyses of the granite indicate less than 0.5 weight percent CaO, almost all of which can be accounted for in fluorite and secondary carbonate. The plagioclase is therefore most likely sodic albite, and the rock logically is classified as microcline-albite granite in the scheme of Streckeisen (1976).

The overall rock texture is hypidiomorphic-inequigranular to subporphyritic with a grain-size range of 0.5 to 2.5 mm. A 1000-point mode of a very slightly altered granite sample (147489) defines the following volume percentages of minerals:

<u>Primary phases</u>

42.2 quartz
22.6 albite (including that exsolved from microcline)
22.8 microcline
trace zircon

Secondary phases

7.9 muscovite (dominantly replaces albite)
1.3 fluorite (intergrown with muscovite)
0.3 cassiterite (as granules in muscovite)
0.4 hematite (along grain boundaries)
1.0 illite(?) (replaces microcline)
1.5 carbonate (in veins; also replaces microcline)

By taking the secondary alteration products into account, the estimated essential-mineral composition of the original granite is about 43 percent quartz, 32 percent albite, and 25 percent microcline. Biotite relics are not present in this sample, and probably never exceeded 5 percent in the original granite. Where biotite is preserved, it exists only as small, euhedral, greenish-brown inclusions within magmatic quartz.

Radioactivity of the granite, on the basis of spot measurements with a total-count scintillometer, is high in relation to other granites of similar bulk composition. The highest levels of radioactivity correlate with areas of least altered granite.

GREISENIZATION AND VEINING

In the alteration of the granite at Baid al Jimalah, much of the original rock has been replaced by muscovite and quartz, and the altered rock is referred to as a greisen. Microcline has been replaced by illite(?) clay, abundant grains of muscovite, and by fluorite quartz having crystallographically controlled orientation, and disseminated patches of granular carbonate. Biotite has been almost wholly replaced by muscovite and thin films and grains of hematite. Albite has generally been completely replaced by decussate muscovite aggregates. Disseminated minerals within the greisenized granite include small anhedral patches of purple-tinted fluorite, small subhedral to anhedral grains of cassiterite, and rare irregular granules of opaque minerals with hematite rims (pyrite or pyrrhotite?). X-ray diffraction on heavy-mineral separates from crushed greisens confirms the presence of muscovite, a trioctahedral mica (lepidolite(?)), fluorite, wolframite, cassiterite, rutile, zircon, topaz, tourmaline, apatite, and scheelite.

The greisenization is contemporaneous with or older than the emplacement of mineralized stockwork quartz veins. The geometry of the vein systems is complex, ranging from randomly oriented stockworks of thin veins (0.5 cm to about 3 cm), to continuous zones of anastomosing, thick veins (roughly 5 cm to 25 cm). A rough estimate of the vein density shows that, on the average, 15 percent of the volume of greisenized

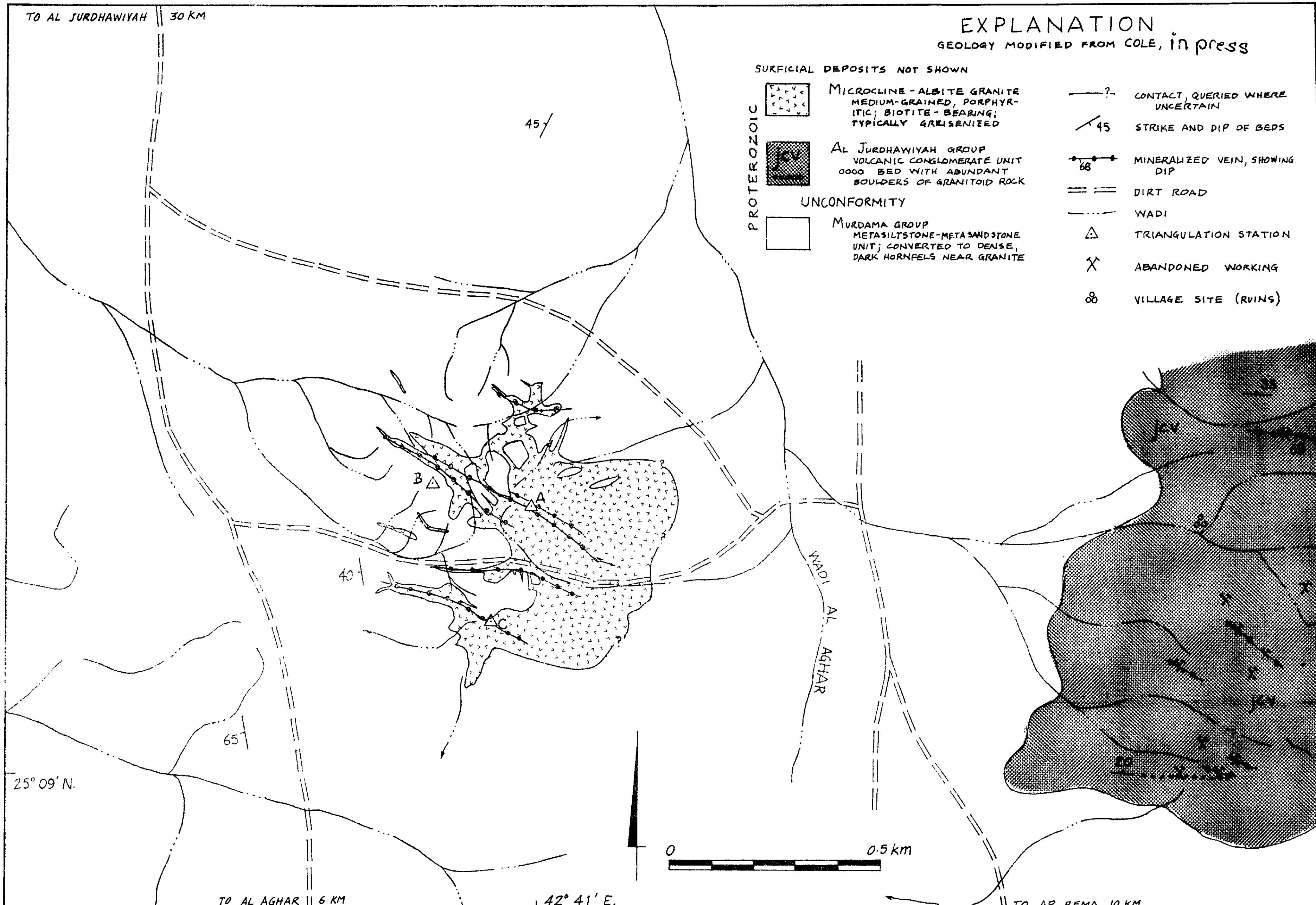


Figure 2.–Regional geologic map of the Baid al Jimalah district.

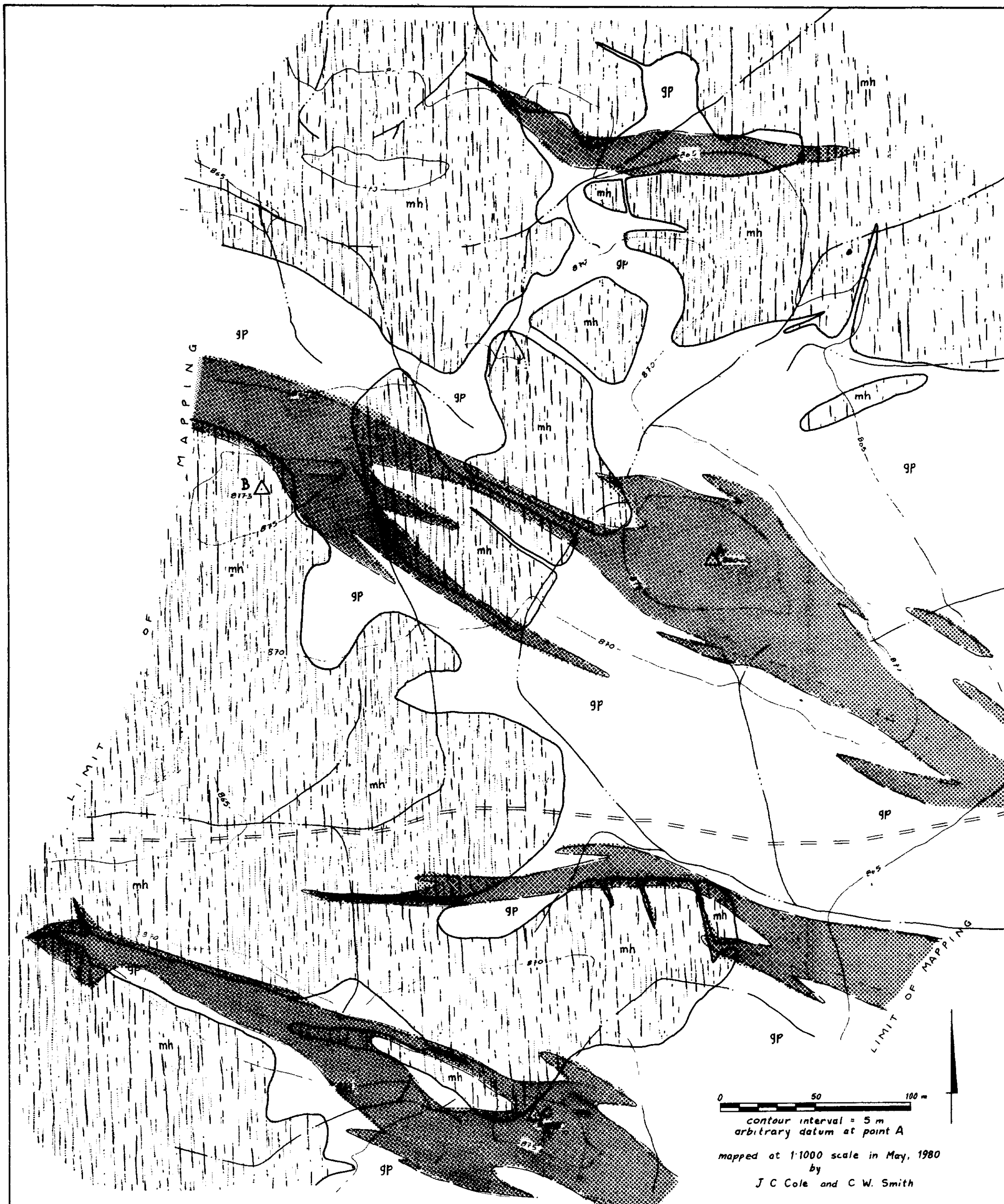
granite consists of vein material. All evidence to date suggests that the veins in the granite are roughly of the same age and possess a similar mineral assemblage. However, individual veins can locally be traced from the granite into the hornfels, where a muscovite selvage is present between hornfels and vein quartz, and white feldspar accompanies quartz as a gangue mineral. These muscovite-selvaged veins are typically cut by other quartz-wolframite veins lacking the selvage, and therefore may be slightly older.

The continuous zones of dense, thick quartz veins have a general west-northwesterly trend. Four prominent zones have been identified (figs. 2, 3, 4, and 6) that coincide with subparallel swarms of granite dikes in the hornfels (individual dikes not shown on fig. 3). The zones range in breadth from 20 m to 80 m and are continuous over distances of 200 m to 800 m. The thicker veins in these zones are roughly parallel to the granite dikes, trend in a west-northwesterly direction, and are vertical or dip steeply to the south. In the vicinity of station A (fig. 3), contemporaneous vein sets strike approximately N.30°W. and N.80°W., forming a dense intersecting network.

It appears that veins are neither as thick nor as abundant in the hornfels as in the greisenized granite. The zones of dense veining diminish in breadth where they cross blocks of hornfels as, for example, on the ridge between stations A and B, or at the western end of the ridge west of station C (fig. 3). However, even in these areas of wall rock, mineralization is persistent along thin, muscovite-selvaged veins of diverse orientation. These observations probably reflect the difference in mechanical response of hornfels and granite to the fracturing that produced the conduits for vein deposition.

Typical veins consist of coarse-grained quartz crystals that have grown perpendicular to vein walls, 0.5 cm to 4 cm subhedral to anhedral crystals of wolframite locally coated with scheelite, and lesser muscovite, fluorite, pyrite, carbonate, and possibly topaz. Hematite pseudomorphs of pyrite or pyrrhotite(?) are common in some veins, especially near station C (fig. 3) where disseminated pyrite is also common in the greisen. Though cassiterite is rarely present in most veins, it forms a significant part of the assemblage in several wolframite-cassiterite veins near stations A and C. These veins appear to be of the same age as the more common quartz-wolframite veins.

Wolframite is the dominant ore mineral in all of the veins and, on the average, makes up a few percent of the vein volume. Intervals of a few meters length along some veins contain over 30 percent wolframite by volume. Crystals are typically dark metallic black, twinned on the (100) face, and



EXPLANATION

SURFICIAL DEPOSITS NOT SHOWN

gp — MICROCLINE-ALBITE GRANITE
MEDIUM-GRAINED, PORPHYRITIC; FORMS DIKE SWARMS
CONTACTS ENCLOSE AREAS CHIEFLY OF GRANITE

mh — MURDAMA GROUP
FINE-GRAINED, MASSIVE FLUORITE-BIOTITE HORNFELS;
GRADES AWAY FROM GRANITE INTO METASILTSTONE
AND METASANDSTONE

CONTACT, GENERALIZED

ZONE OF DENSE QUARTZ-WOLFRAMITE VEINS (SEE TEXT FOR DESCRIPTION)

WADI

DIRT ROAD

A 880.0 — TRIANGULATION STATION AND ALTITUDE, IN METERS

Figure 3.--Geologic map of the central portion of the Baid al Jimalah tungsten deposit.

form tabular groups that are locally arranged in fan-shaped sets anchored to the vein wall. Wolframite is partially coated and replaced by later scheelite and appears to be locally etched and replaced by hematite.

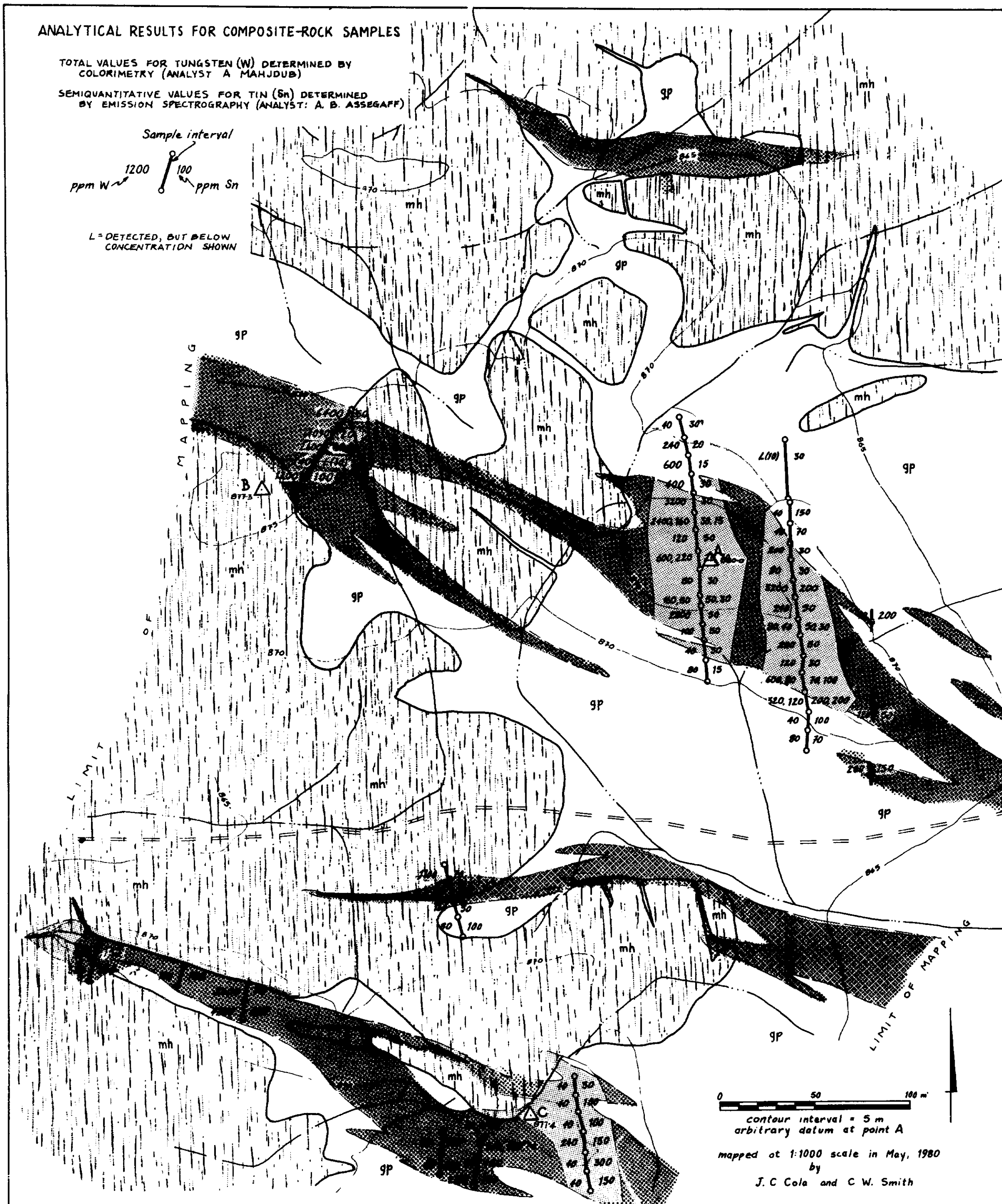
Microscopically, the vein quartz differs from quartz in the greisen in several ways. The vein quartz is an open-space filling in which well-terminated crystals project into voids; the outer few hundredths of a millimeter of the crystals are charged with irregular, minute solid inclusions, a feature not noted in greisen quartz. Two-phase fluid inclusions are much more common in vein quartz than in greisen quartz. These fluid inclusions form planar or irregular groups and consist of a liquid phase and a vapor bubble. The ratio of liquid to vapor appears, on the basis of very limited reconnaissance observations, to be roughly constant in the vein quartz (about 3:1). Fluid inclusions are also present in vein fluorite, and probably in greisen fluorite as well.

The limited amount of work accomplished to date has determined only the most basic features of the greisenization and vein emplacement. What seems clear is that the granite porphyry at Baid al Jimalah was shattered and altered by highly volatile enriched fluids, probably a short time following emplacement. Much is yet to be learned about the complete mineral assemblage of the veins, the paragenetic sequence, the chemistry of the mineralizing fluid, and the chemistry of the solid phases.

ANALYSIS OF OUTCROP SAMPLES

A rock-sampling program was devised by Fenton and performed by him and by Smith to assess element distribution and concentration at Baid al Jimalah. Ten traverse lines, oriented roughly at right angles to the dominant vein trends in the granite (fig. 4), were subdivided into 10-m intervals. Within each interval along these lines, the samplers obtained about four kg of composite rock by chipping material from outcrop near and along the traverse line. A total of 56 intervals was sampled in this manner, and seven intervals were sampled in duplicate in order to assess the chemical variability arising from sampling. A 10-kg sample of mixed granite, greisen, and vein material was crushed, pulverized, homogenized, and split into eight aliquots for use as a geochemical reference in order to evaluate analytical precision.

The authors wish to stress the limitations of these samples. Only outcrop material was included; in all cases, this consisted solely of granite, greisenized granite, and vein. Inclusions and screens of Murdama wall rock are present beneath colluvium in some sample intervals, but were not



EXPLANATION

SURFICIAL DEPOSITS NOT SHOWN

gp	MICROCLINE-ALBITE GRANITE MEDIUM-GRAINED, PORPHYRITIC; FORMS DIKE SWARMS. CONTACTS ENCLOSE AREAS CHIEFLY OF GRANITE		CONTACT, GENERALIZED
			ZONE OF DENSE QUARTZ-WOLFRAMITE VEINS (SEE TEXT FOR DESCRIPTION)
mh	MURDAMA GROUP FINE-GRAINED, MASSIVE FLUORITE-BIOTITE HORNFELS; GRADES AWAY FROM GRANITE INTO METASILTSTONE AND METASANDSTONE		WADI
			DIRT ROAD
		△A 980 o	TRIANGULATION STATION AND ALTITUDE, IN METERS

Figure 4.–Geologic map of the central portion of the Baid al Jimalah tungsten deposit, showing values of tungsten and tin in composite rock samples.

sampled. Further, no attempt was made to balance the samples to reflect the proportion of vein and greisen cropping out within each interval, and so these data cannot be used to firmly estimate the true concentration of tungsten or other elements in the deposit. The sampling scheme was designed only to test for chemical zonation, to check for correlations among groups of elements, to establish the rough concentration of metals, and to delineate areas for future detailed work and systematic sampling.

Quantitative values for tungsten and arsenic were determined colorimetrically. The replicate analysis of eight aliquots of a reference powder indicates a low analytical precision, with coefficients of variation (CV) of 0.14 for tungsten and 0.31 for arsenic. Similarly, fluorine analysis by the selective ion-electrode technique was relatively imprecise (CV=0.26). Atomic absorption proved to be a more reproducible analytical technique; lithium (CV=0.05), silver (CV=0.09), and gold (CV=0.10) were determined by this method. Reproducibility of semiquantitative values determined by emission spectrography for 30 elements was generally quite good for this technique; highest and lowest values were separated by no more than two reporting intervals.

Although precision is low, the analytical accuracy of tungsten values is believed to be good. Colorimetric values correspond well with the spectrographic values, and with reconnaissance determinations by X-ray fluorescence using internal standards (J. Curry, USGS, oral commun. 1980).

The distribution of ore minerals is highly variable over short distances in the quartz veins and greisen, as reflected in the analytical data. Sampling error, or the variation in elemental concentration within a sample interval, is high. In the seven intervals sampled in duplicate, the pairs of tungsten values differed by no less than a factor of two, and by as much as an order of magnitude. This variation is significantly greater than the analytical error and demonstrates that the sample material does not truly represent the average tungsten content within an interval. The coarse size of the wolframite crystals is principally responsible for this sampling error; greater initial sample mass or continuous-channel sampling would help to smooth out the effect of accidental inclusion or omission of large wolframite grains. Sampling error is much lower, and roughly equivalent to analytical error, for elements that are carried by finer grained and more disseminated minerals. Thus, interval-to-interval differences in fluorine, lithium, bismuth, tin, beryllium, and the like probably represent real differences in the chemistry of the rock in the interval.

The analytical data demonstrate that Baid al Jimalah is a mineral deposit that formed in a system highly enriched in arsenic, beryllium, bismuth, fluorine, lithium, tin, and tungsten. Other granitophile elements present in slightly anomalous amounts as indicated by maximum values include molybdenum (20 ppm), niobium (50 ppm), gold (0.4 ppm), and silver (2.0 ppm). Of the highly enriched elements, no patterns of covariation are apparent in the data. This may result in part from large sampling error, but may also indicate that each enriched element is chiefly carried by a single mineral phase, and that the proportions of these phases do not vary systematically within the deposit. The sample lines and the values for tungsten and tin are shown in figure 4, from which it is clear that no sympathetic relation exists between these elements.

The data do support a chemical distinction between samples collected from the veined zone that makes up the ridge connecting stations A and B, and those from the ridge that trends westerly from station C (fig. 4). As depicted in the histograms in figure 5, the 21 samples from the C ridge (including samples from the traverse line just south of the dirt road) are significantly enriched in lithium, fluorine, tin, and beryllium, and slightly depleted in bismuth with respect to the 42 samples from the AB ridge. The C ridge also has a somewhat distinct surface geology and mineralogy. Both the veins and greisens contain common hematite pseudomorphs after pyrite, which are uncommon on the AB ridge, and coarsely crystalline wolframite seems to be less abundant. The veins on the C ridge also tend to have more vugs and contain more coarsely crystalline fluorite than those on the AB ridge. The unusual veins in the Murdama hornfelses that contain thick nodular masses of metallic minerals, including sulfides, are only present near station C. These observations may indicate that the vein system on the C ridge formed at lower temperature, but additional work is necessary to determine the extent and significance of these areal variations in mineralogy and chemistry.

ANALYSIS OF WADI-SEDIMENT SAMPLES

Immediately following the discovery of the tungsten deposit, Cole collected 19 wadi-sediment samples within about 1200 m of the exposed granite to search for peripheral areas of mineralization, and to evaluate the dispersion and dilution of tin- and tungsten-bearing heavy minerals. Prior to discovery, Rashid Samater collected one sample of wadi sediment within 1 km of Baid al Jimalah as part of a regional geochemical reconnaissance program of the USGS; subsequent analysis showed an anomalous amount of tungsten. Had the mineralized area not been located as a result of routine geological mapping, follow-up studies based on the regional geochemical reconnaissance survey would probably have led to discovery.

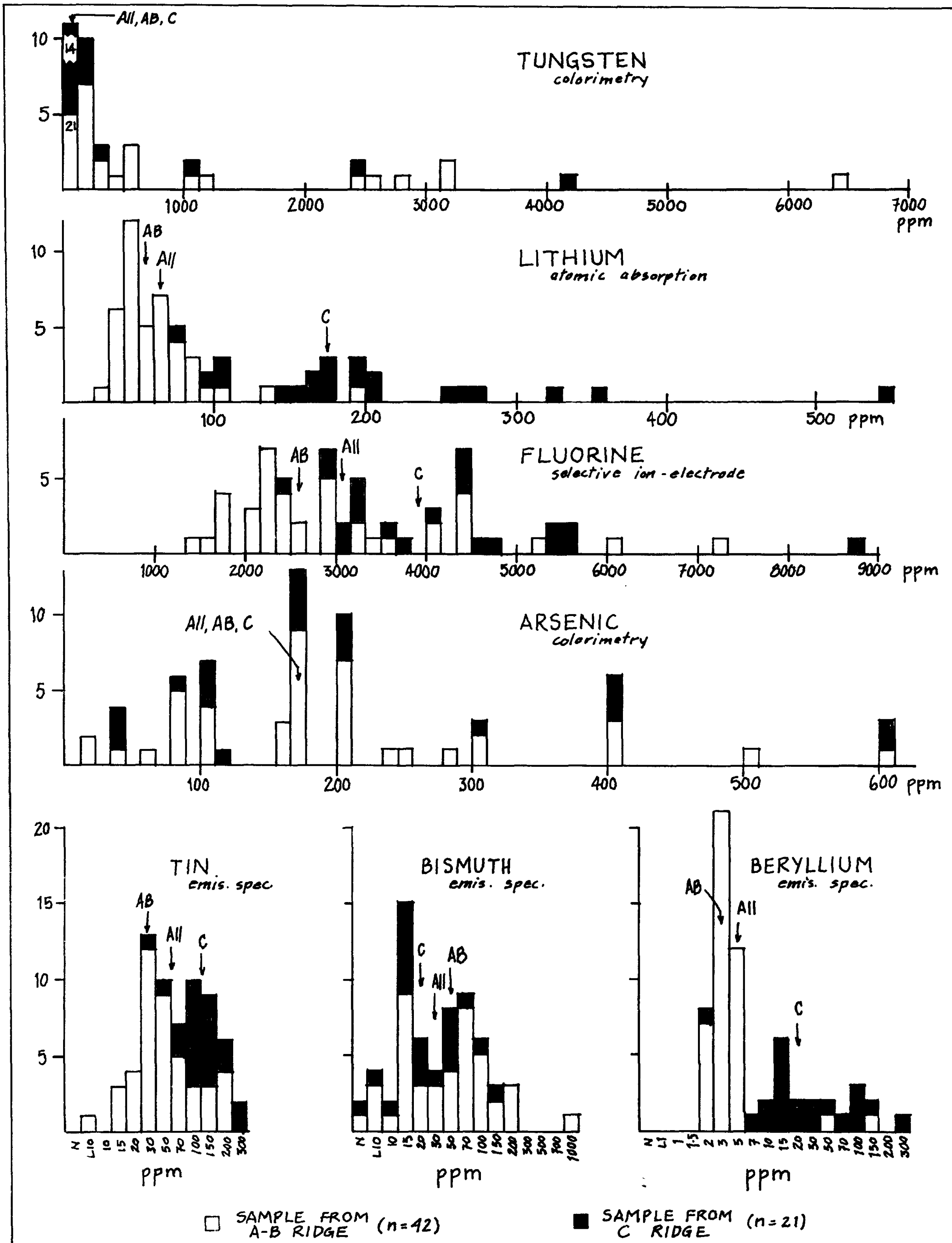


Figure 5.–Histograms of analytical values for highly anomalous elements in composite rock samples. Total values shown for tungsten and arsenic (A. Mahjoub, analyst), fluorine (I. Baraja, analyst), and lithium (A. Baabdulla, analyst). Semiquantitative values shown for tin, bismuth, and beryllium (A. B. Assegaff, analyst). L=detected, but below concentration shown; N=not detected. Arrows indicate median value for samples from the AB ridge, from the C ridge, and for all samples. See text for discussion.

Low topographic relief and slight rainfall in the vicinity of the deposit have led to the development of a poorly integrated drainage network. Runoff channels are broad and shallow and contain only thin deposits of very poorly sorted, pebble- to sand-sized detrital clasts and an undetermined amount of wind-transported fine sand and silt. Sample sites were selected to obtain the most recent water-transported material from well-defined wadis.

A sample of approximately 5 to 8 kg from each site was sieved to obtain four size fractions. The +10 mesh fraction (U. S. Sieve Series) was briefly examined for macroscopic wolframite and scheelite. The -10+30 and -30+80 mesh fractions were reduced by panning to heavy-mineral concentrates. The -80 mesh fraction was discarded to reduce the effect of contamination by wind-transported material. The central two size fractions were checked with an ultraviolet light, and a rough quantitative estimate of the amount of scheelite was recorded. Following removal of magnetite with a hand magnet, these two size fractions were pulverized to -140 mesh grain size, and semiquantitatively analyzed by emission spectrography (I.M. Naqvi and M. Husain, analysts).

The analytical results for tungsten and for tin in both size fractions are shown in bar-graph form on figure 6. Highest values for both elements occur in the -10+30 mesh (coarse) fraction, due to the large size of wolframite and cassiterite crystals, and the minor amount of mechnical abrasion on particles near the deposit. The sample site 150 m south of station A appears anomalously low in tungsten because most of the wolframite is larger than 10 mesh at this location, and thus was excluded from the analyzed sample. Scheelite is abundant in about half of the -30+80 mesh (fine) fractions, but does not correlate with high tungsten, implying that it is not a major carrier of this element. Because scheelite is principally a minor surface coating on wolframite grains, it weathers to produce fine-grained and volumetrically minor detritus.

Tin exceeds the analytical limit (1000 ppm) in both size fractions for all sample sites near the granite and veined zones. Farther away, tin content is higher in the coarse fraction than in the fine fraction, which suggests that cassiterite in the deposit is mostly coarser than 30 mesh (0.6 mm) and that grains have not been significantly broken or abraded during transport. Tin content decreases rapidly away from the deposit, with the effect that a tin anomaly might not have been detected much more than a kilometer from the source.

Tungsten also decreases regularly and rapidly away from the deposit but, because of the abundance of coarse-grained wolframite, the wadi-sediment anomaly zone is somewhat larger

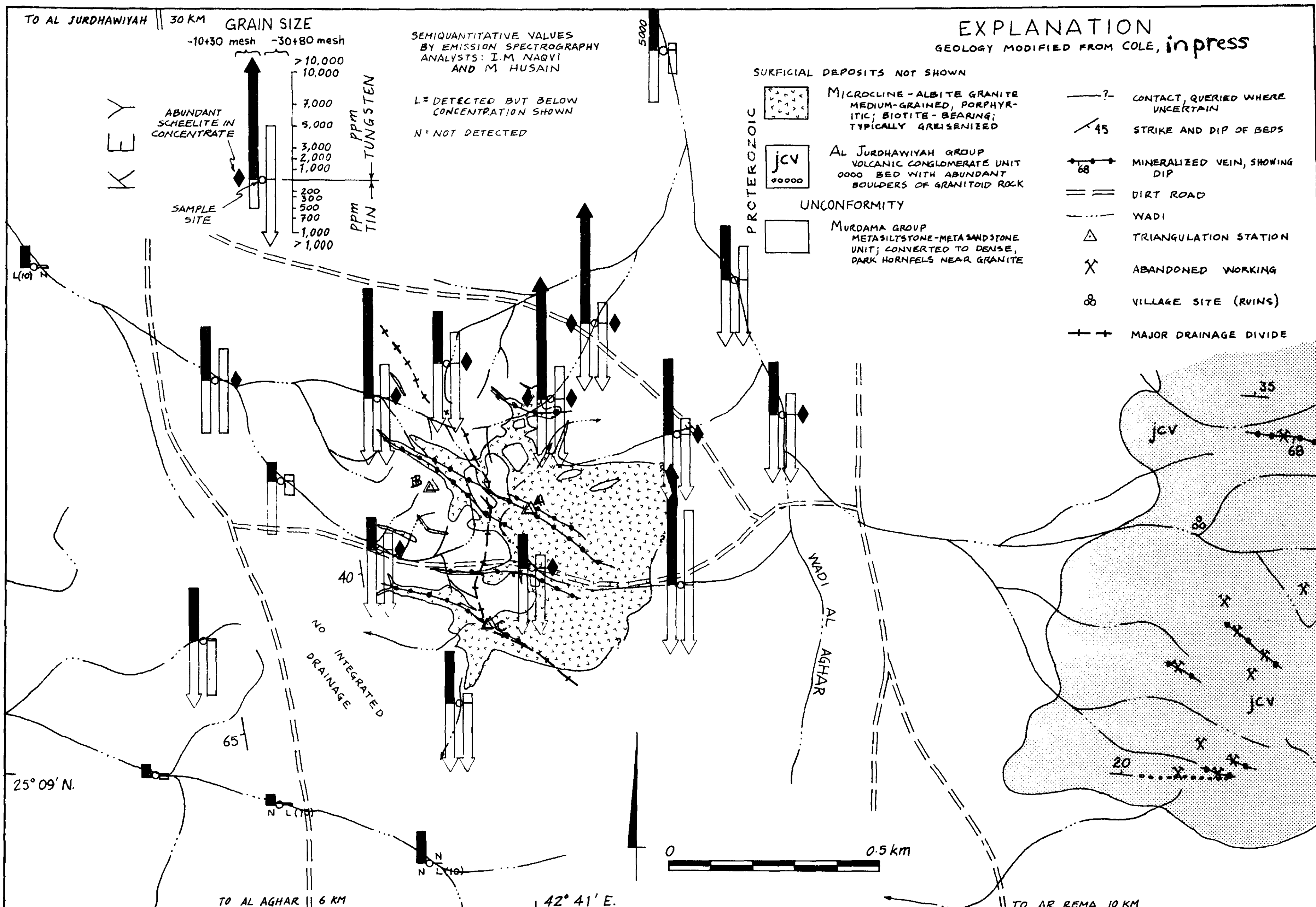


Figure 6.–Regional geologic map of the Baid al Jimalah district, showing values of tungsten and tin in magnetite-free panned concentrates of wadi sediment.

than that for tin. Nevertheless, tungsten would probably be below the limit of detection (50 ppm) in panned concentrates collected from sites more than 1.5 km from the mineralized outcrop, particularly in the -30+80 mesh fraction, and especially if the ferrimagnetic fraction of the sample has not been removed. The dilution of the sample by magnetite is significant at this deposit, as illustrated by comparing these results to those from the regional geochemical survey. Samater collected one sample from Wadi al Aghar (fig. 6) northeast of station A and analyzed the bulk panned concentrate of the -30+80 mesh fraction. The value for tungsten in that sample is 1500 ppm (R. Samater, oral commun. 1980), compared with 3000 ppm in the magnetite-free -30+80 mesh panned concentrate of a sample from this study, collected about 100 m further downstream.

Analytical results for other elements of interest in the panned concentrates are shown in scatter diagrams in figure 7. The figure emphasizes the fact that all elements shown, with the exception of zinc and zirconium, are much more abundant in the -10+30 mesh fraction than in the -30+80 mesh fraction. The scatter patterns for beryllium, bismuth, and molybdenum do not show such a strong bias toward the coarse fraction at low values, although the bias seems significant for samples with higher elemental concentrations. The scatter pattern for tin is not interpretable because so many values exceed the upper analytical limit of determination (1000 ppm). Further analysis of these data indicates a moderate to strong positive correlation between the concentration of tungsten and the concentration of other elements in the coarse sediment fraction.

To understand these observations, it is necessary to examine the mineralogy of the panned concentrates. The coarse fraction contains many multimineral grains (rock fragments) and is not suitable for detailed mineral separation. However, we can visually identify most of the dark grains as wolframite, cassiterite, oxidized (gossanous) lumps of metallic minerals, and lesser magnetite and epidote. The light-colored minerals appear to be mostly fluorite, scheelite, carbonate, muscovite, and quartz-feldspar fragments with heavy mineral inclusions. I.M. Naqvi (USGS, Jiddah) attempted more comprehensive mineral identifications for the -30+80 mesh fraction of one sample (collected 250 m northwest of station B), by using heavy liquids and the isodynamic separator to concentrate individual minerals, and by analyzing these separates with X-ray diffractometer and emission spectrograph. His work identified major amounts of hematite, zircon, fluorite, cassiterite, scheelite, epidote, and sphene; moderate amounts of wolframite, sphalerite, and ilmenorutile (an iron-bearing titanate-niobate-tantalate with rutile structure); and minor amounts of pyrrhotite(?) and wurtzite(?; hexagonal ZnS).

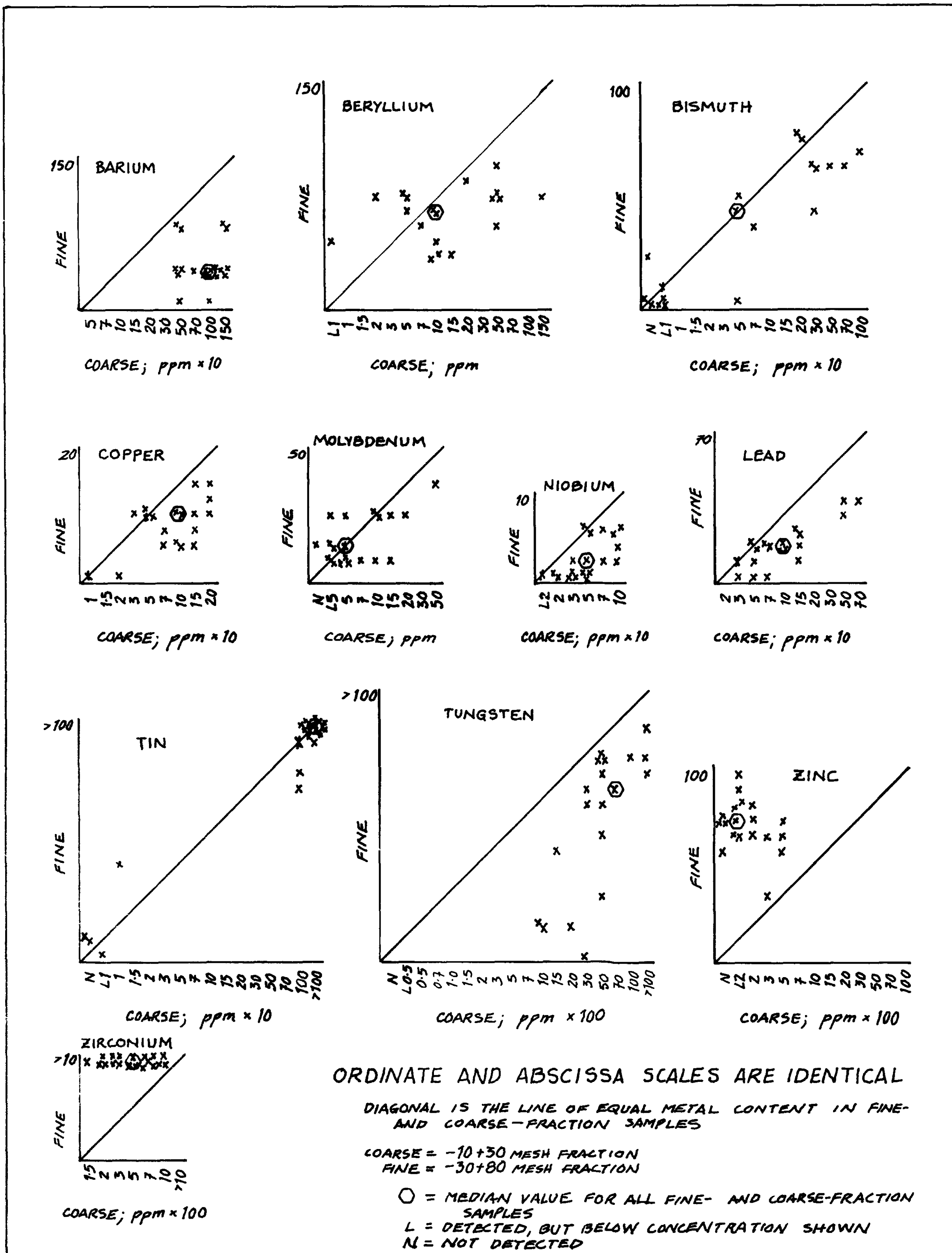


Figure 7.–Plots of minor-element content in fine- versus coarse-fraction samples of magnetite-free panned concentrates of wadi sediment. Semiquantitative values determined by emission spectrography (I. M. Naqvi and M. Husain, analysts).

We believe the differences in chemistry between the coarse and fine sediment fractions are related to the different proportions of minerals in the two size classes. High zinc in the fine fraction reflects the dominance of fine-grained sphalerite and wurtzite(?), and the high zirconium implies that most zircon crystals are smaller than 30 mesh (0.06 mm). The high proportion of zircon in the fine fraction may also be responsible for diluting the concentrations of elements carried by other minerals, thereby lowering those concentrations relative to the coarse fraction. In the coarse fraction, the correlation of high tungsten (and tin) values with high values for other metals suggests that the major minerals wolframite and cassiterite may contain minute inclusions of other minerals; for example, native bismuth or bismuthinite, galena, arsenopyrite, and the like. These mineral associations and intergrowths have been reported in other tungsten deposits of similar character (Kelly and Rye, 1979; Kelly and Turneaure, 1970).

In summary, analysis of the wadi sediments shows that the Baid al Jimalah deposit is essentially a point source for the dispersion of tungsten and tin. The rapid decrease in concentration of these elements toward the south and west implies that the geochemical anomaly zone around this deposit could be less than a few kilometers in diameter. Additional work is in progress to define the limits of the anomaly, especially in the major Wadi al Aghar to the northeast, where the most distant sample contains high values of tin, tungsten, and zinc. This program will also assess the contribution to wadi sediments from the ancient lead-zinc-silver district to the east (see fig. 6 and description in next section).

Our present study implies that certain modifications of the technique might improve the usefulness of wadi-sediment sampling in locating similar deposits. Removal of magnetite from panned concentrates would increase the overall concentrations of elements other than iron, manganese, and titanium, and could raise the concentration of many important trace elements above the spectrographic limit of determination. With regard to grain size of the panned concentrate, this particular type of deposit would be more easily detected with a coarse sand fraction for two reasons: the major ore-bearing minerals wolframite and cassiterite are coarse grained, and the major diluent, zircon, is fine grained. In general, we feel that better definition of geochemical anomalies could be attained in certain geologic environments if the suitable range of grain sizes could be found that excluded most zircon from the analyzed concentrate. It may not always be possible, as it was in this case, to make that separation simply by sieving, without also losing information from other minerals with the same size distribution as the zircon.

PERIPHERAL LEAD-ZINC-SILVER DEPOSIT

There is an ancient mine and village site about 2 km east of the tungsten-bearing granite. Certain aspects of the mineralization there raise the possibility of a genetic link between the two deposits. The following description summarizes and expands upon the reports of Fakhry (1941), Mytton (1970), and Muller (1975).

The ancient mine district consists of more than 30 elongate excavations within an area of about 5 km^2, the largest trench being almost 200 m long, 2 to 3 m wide, and several meters deep. Central to the area of excavations are the ruins of stone foundations for a number of buildings. Grindstones are not present. There are hundreds of small slag dumps at the village site, and they dot the surrounding hills adjacent to small excavations. Thus, the physical evidence indicates a large mining community that lasted for a significant period of time. Undoubtedly, ancient miners visited the tungsten deposit to the west and examined the quartz veins, although the only signs of activity are a few stone cairns and one possible small, shallow pit. Interest in the tungsten deposit probably ended because of the lack of commodities in use at that time, particularly gold, silver, and copper.

The mineralized veins dominantly trend N.70°W. to N.80°W. and are either vertical or dip steeply to the south. They cut the basal volcanic-clast conglomerate unit of the Al Jurdhawiyah group a short distance above the flat-lying unconformity at the top of the highly folded Murdama group. The veins consist of hematite- and limonite-stained, weakly sheared, vuggy to massive quartz, with varying amounts of galena, arsenopyrite, chalcopyrite, pyrite, sphalerite, and brownish carbonate. Minor calcite-chlorite alteration of the wall rock and local patches of high-grade disseminated sulfides are present. It appears that brecciation of vein quartz preceded the deposition of sulfides.

Combining analytical results from Mytton (1970) and Muller (1975) with those of samples collected by the authors, the best ore samples contain up to 3.4 percent lead, 2.5 percent zinc, and notable although sporadic amounts of arsenic and tin. Silver is present in anomalous amounts in virtually every type of sample (vein, dump, slag), with 12 of 15 values between 5 ppm and 500 ppm (by atomic absorption or emission spectrography), and may have been the principal commodity of interest during the period of mining activity. Muller reported a high value of 880 ppm silver by an unknown assay method for material gleaned from dump piles. Gold is present in slightly anomalous concentrations, with a high value of 3.4 ppm (fire assay) for vein material reported by Mytton.

The mineralization at both the ancient mining district and at the tungsten deposit may be the result of a single hydrothermal event. Both deposits consist chiefly of ore deposited in near-vertical quartz veins that trend in a west-northwesterly direction. The southernmost veins at the lead-zinc-silver district are essentially on strike with the heavily veined zones at the tungsten deposit. Both sets of veins cut the Murdama group rocks, but only the lead-zinc-silver veins undeniably cut the Al Jurdhawiyah group rocks as well. However, the ancient mines are located in a small group of hills, approximately 20 m above the subhorizontal basal unconformity of the Al Jurdhawiyah group, and as little as 10 m topographically above the highest outcrops of granite across Wadi al Aghar (fig. 2). In light of the fact that no rocks of the Al Jurdhawiyah group crop out near the tungsten deposit and, lacking any indication of faulting between the two areas, one may conclude that the area of the tungsten deposit was topographically high when Al Jurdhawiyah deposition began. Although this topographic high could have existed because of silicification around the (pre-Al Jurdhawiyah) tungsten deposit, we do not feel this evidence is compelling for the age of this mineralization. Cole's regional mapping shows that the basal Al Jurdhawiyah unconformity locally has considerable relief, and thus the paleo-high at Baid al Jimalah may be coincidental. We believe that the tungsten mineralization post-dates the Al Jurdhawiyah group, noting also the absence of clasts of Baid al Jimalah granite porphyry or of vein quartz in the basal conglomerates of the group.

Although one deposit is dominated by tungstates and oxides and the other by sulfides, both bear anomalous amounts of the same metals. Lead and zinc are the major ore elements at the ancient mine sites but, as shown by the wadi sediments, also occur at the tungsten deposit. Tin in cassiterite is common at the tungsten deposit and is present in anomalous amounts in ore samples from the ancient mine site (as much as 500 ppm). Arsenic, silver, and molybdenum are locally present in anomalous amounts at both deposits.

In summary, information regarding the trends and character of mineralization, its age, and the chemistry of the ore suggest a genetic link between the two deposits. Further work in geochronology, geophysics, and fluid inclusions is planned to test the hypothesis of such a link. It is possible that additional cupolas of granite lie beneath the surface in the Baid al Jimalah district and that the related hydrothermal activity has produced other mineralized areas.

IMPLICATIONS AND RECOMMENDATIONS

The mineralized granite and veins of the Baid al Jimalah tungsten deposit share many common structural, mineralogical, and chemical characteristics with economic deposits of tungsten and tin in the plutonic environment worldwide (Hosking, 1973, p. 22ff). In particular, the deposit is genetically related to the uppermost part of a small body of greisenized leucocratic microcline-albite granite porphyry; the wall rocks were brittle, impermeable, and weakly contact metamorphosed; and the ore is chiefly stockwork quartz veins with wolframite and cassiterite.

Tungsten-bearing veins at Baid al Jimalah seem to indicate the simple paragenetic sequence of muscovite (possibly with cassiterite), quartz, and wolframite followed by scheelite, fluorite, and carbonate, which is similar to the general sequences observed in England, Burma, Tasmania (Hosking, 1973), Portugal (Kelly and Rye, 1979), Bolivia (Kelly and Turneaure, 1970), Australia (Taylor and Steveson, 1972), and Egypt (El-Ramly and others, 1959). Sulfide minerals have not been discovered in large amounts and have not been sufficiently studied at the deposit to determine their position in the paragenetic sequence. The mineralogy of sulfides is also poorly known, but the presence of sphalerite and pyrrhotite(?) in wadi sediments (plus hematite after pyrite), and the overall enrichment in lead, zinc, arsenic, molybdenum, bismuth, and silver in outcrop samples, suggest the mineralogy may be similar to that found in other deposits.

Detailed studies by Kelly and Turneaure (1970) and by Kelly and Rye (1979) demonstrate that the sulfide minerals in tin-tungsten lodes form later and at lower temperatures than wolframite and cassiterite, leading in many cases to a zonal mineral-distribution pattern. The oxide phases are present nearer the intrusive granite, and the sulfide phases become prominent farther away, as is also established in the work of Taylor and Steveson (1972) and Sillitoe and others (1975). A similar zonal arrangement may be present in the Baid al Jimalah district, represented by the tungsten-tin deposit and the lead-zinc-silver deposit 2 km to the east.

The granite porphyry of Baid al Jimalah belongs to the class of specialized, tungsten- and tin-mineralized granites as defined by Tischendorf (1977). It is a high-silica granite, enriched in lithium, fluorine, beryllium, rubidium, niobium, tin, and tungsten, and depleted in calcium, magnesium, strontium, and barium. Baid al Jimalah is similar in chemistry and petrography to the tin-bearing granite of Jabal al Gaharra in the southeastern Arabian Shield (Elliott, in press), but is more highly enriched in granitophile elements, and exhibits strong greisenization and veining which are not present at the exposed level of the Jabal al Gaharra pluton.

The significance of Baid al Jimalah and Jabal al Gaharra is that they indicate that the crust of the Arabian Shield had evolved in late Proterozoic time to a stage suitable for the production of specialized granites. Further evidence is given by the report of wolframite-bearing quartz veins in weakly greisenized, postorogenic biotite granite at El Koom 125 km south of Baid al Jimalah (Hummel and Ankary, 1972; J.E. Elliott, oral commun. 1980), and by the report of late tin- and tungsten-bearing granites in the Nubian Shield of Egypt (El-Ramly and others, 1959). It is likely that other specialized granites exist in the Kingdom, some of which may contain economic deposits.

The typical small size of these granite bodies and the general lack of ancient excavation in tin- and tungsten-bearing veins requires that the best modern methods of exploration be found and developed to aid in the search for these mineral resources. A program is in progress to examine additional methods for treating wadi-sediment samples to enhance the sensitivity of the technique for targeting anomalous zones. Work is also underway to see if Landsat images of Baid al Jimalah display a distinctive spectral signature that is related to the mineralization.

This preliminary investigation of the deposit demonstrates that Baid al Jimalah is an encouraging prospect, with the appropriate parameters of size, degree of alteration and mineralization, and apparent grade to warrant further study and evaluation. The second phase of work is in progress, including detailed surface mapping at 1:1000 scale to refine the shape, extent, and structure of the granite porphyry and the veined zones. Work is also underway to evaluate the feasibility of various geophysical methods for detecting granite or mineralized ground at depth.

Additional sampling is required to evaluate the surface grade at the deposit. It should be possible to excavate trenches in the Murdama rocks, in the fractured granite, and in at least parts of the densely veined zones. This procedure would permit continuous-channel sampling of the various mineralized rocks, and would lead to a determination of grade (and variability of grade) at the surface. Upon receipt of favorable analytical data, or positive indications from geophysical work, plans should be formulated for core-drilling, with the goal of investigating the continuity and grade of the deposit at depth.

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