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Geology and regional setting of the Al Masane ancient mine area, Southeastern Arabian Shield, Kingdom of Saudi Arabia

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ U.S. Geological Survey, Flagstaff, Arizona

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GEOLOGY AND REGIONAL SETTING OF THE AL MASANE ANCIENT MINE AREA, SOUTHEASTERN ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

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ABSTRACT

Stratiform zinc-copper massive-sulfide deposits at Al Masane occur in thin dolomitic interbeds within Proterozoic felsic crystal tuff and mafic flows and volcaniclastics. These strata dip steeply westward and are underlain by shale and shaly graywacke to the east and overlain by lapilli crystal tuff to the west. This section is part of the Habawnah fold or mineral belt that extends from the Wadi Wassat area southward into Yemen. Western parts of the Habawnah fold belt, including the Al Masane area, are characterized by a bimodal assemblage of of phenocryst-poor basalts and sodic rhyolite crystal tuff, and by zinc-copper mineral deposits. Strata in the eastern part of the belt, mostly east of the Ashara fault zone, contain abundant phenocryst-rich mafic volcanic rocks, little felsic crystal tuff, and barren or locally nickeliferous massive pyrite deposits.

Stratified rocks and gabbro sills of the Al Masane area were isoclinally folded and metamorphosed to the greenschist facies. Structural analysis indicates that foliation, lineation, joints, major and minor folds, and one of three sets of faults formed during a single east-west compressional deformational episode. Axial-plane foliation dips steeply westward and is usually coincident with bedding. Lineation plunges steeply to the northwest throughout the map area and is parallel to the intersection of joints of two major sets and to the intersection of these joints with foliation. Major folds have north-trending, gently plunging axes to which the axis of a minor fold set is essentially parallel. A second minor fold-set has a steeply plunging axis parallel to lineation. The Saadah massive-sulfide body is elongated by a fold of this system.

Unmetamorphosed Proterozoic felsic sills, quartz monzonite and gabbro plutons, porphyritic diorite dikes, mafic dikes, and basalt dikes, in that apparent order, have

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intruded the stratified section. Basalt dikes are offset by southwestward-dipping reverse faults and by faults parallel to bedding.

Malachite and metal-oxide-bearing gossans in the Al Masane area were mined in ancient times. Radiocarbon dating of charcoal in slag indicates that the ores were smelted about 1,200 years ago. Gossans are depleted in copper, silver, and zinc, relative to underlying sulfide, by factors of about 0.33, 0.2, and 0.08, respectively. Evaluation of numerous analyses of gossans, carbonates, and silicate rocks indicates that exploration for zinc-copper massive-sulfide deposits in the region should center on detailed geochemical studies of dolomitic beds.

Dolomitization of host siliceous shales and tuffs and the formation of the massive-sulfide bodies at Al Masane probably caused by submarine fumarolic hydrothermal activity during periods of relative volcanic quiescence. Further work in the Al Masane region should include a study of the dolomitized areas and a search for other potential alteration "pipe" products (e.g. chlorite) as a guide to location of proximal deposits.

Zinc-copper deposits at Al Masane and in the Dhahar-Al Hajrah and Kutam-Farah Garan areas have characteristics in common and are associated with felsic volcanic centers in the western bimodal part of the Habawnah mineral belt. They probably have parallel origins related to sea-floor volcanism. Deposits at Al Masane and Dhahar-Al Hajrah are possibly in the same general stratigraphic interval. Characteristics and distribution of altered rocks at Kutam suggest that the observed structural control of mineralization may represent remobilization.

Chemical characteristics of volcanic rocks at Al Masane and elsewhere, along with features such as zinc-copper-iron sulfide mineralization, rhyolite-basalt bimodality, and the quartz phenocryst-rich nature of the felsic rocks, are compatible with an unusually primitive tholeiitic island-arc origin for the strata and mineral deposits of the Habawnah mineral belt.

INTRODUCTION

The Al Masane area, in the southeastern Arabian Shield (fig. 1), lies in rugged plateau country deeply incised by drainages emptying into Wadi Thar, which runs eastward into the Rub Al Khali. Elevations range from 1,500 to 2,000 m. The area is sparsely vegetated except locally in drainages

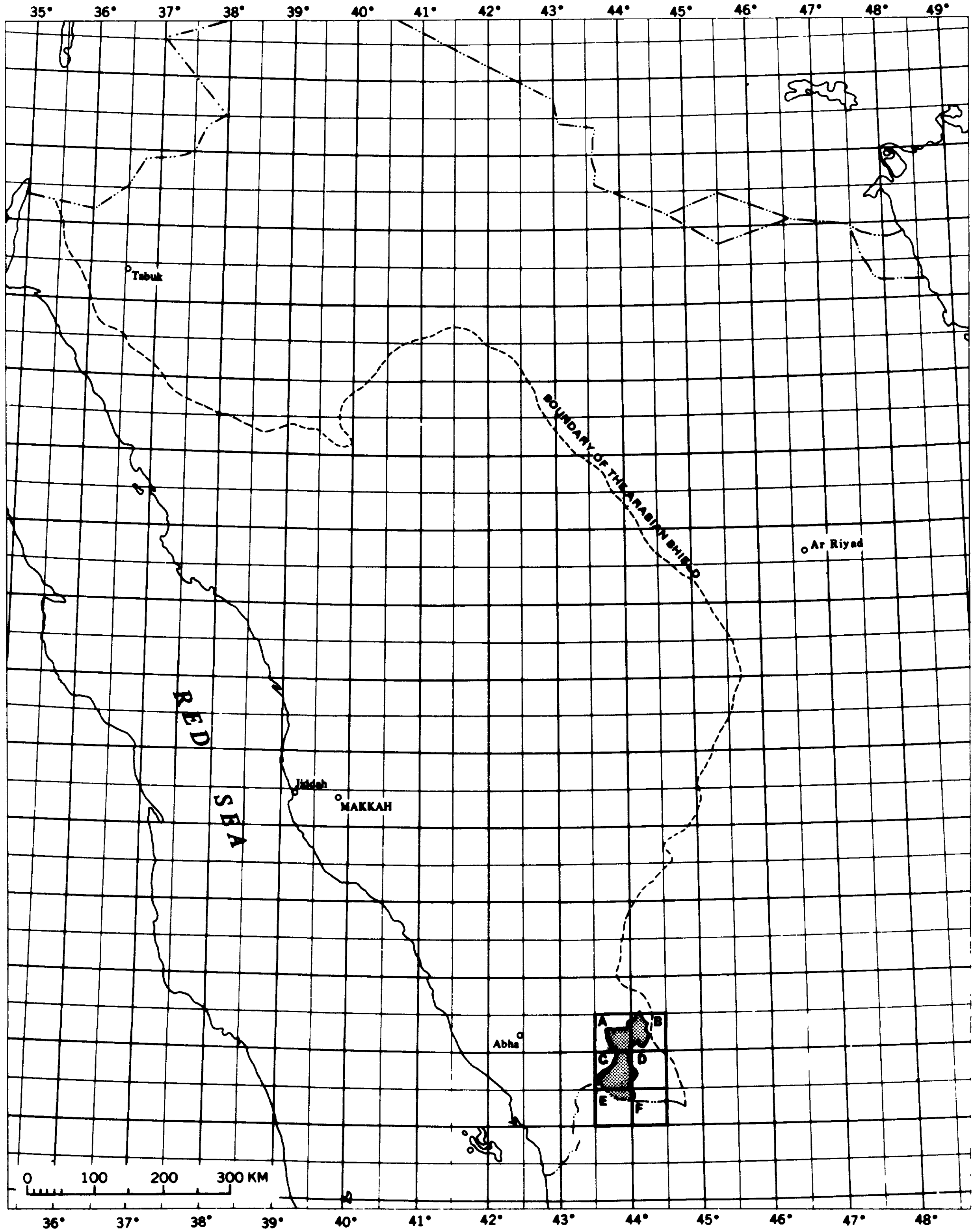


Figure 1. Index map showing location of the Al Masane area (solid rectangle) and the Habawnah fold belt (shaded). Thirty-minute quadrangles are: A, Wadi Malahah; B, Wadi Wassat; C, Mayza; D, Wadi Habawnah; E, Wadi Amadin Al Husn; F, Najran.

where acacia trees are abundant. Soil cover is light and bedrock exposure is excellent. The Arabian Shield Development Company has recently completed 96 km of new road westward from Al Masane to Ash Sharayi on the paved highway between Khamis Mushayt and Najran. The area is also reached by dirt road from Najran, 90 km to the south-southwest.

There are a number of ancient mine excavations in gossans of the Al Masane area, and several ancient smelter sites. The gossans and ancient workings first received the attention of modern exploration and geological investigation when they were shown to Hatem El-Khalidi, Arabian Shield Development Company (ASDC), by local Bedouins in the late 1960's. Since 1971, the area has been under concession and exploration by a joint venture of the ASDC and the National Mining Company (NMC). Following extensive exploratory diamond drilling in the mid-1970's, ASDC and NMC retained Watts, Griffis, and McOuat, Ltd. (WGM) in 1979 to conduct a feasibility study and then to drive a decline and a drift parallel to the sulfide body. Underground exploration mining and drilling are currently in an advanced stage. This work has been followed with considerable interest by the private sector, because the Al Masane could become the first producing-massive sulfide mine in Saudi Arabia in modern times. Reports of the venture in nongeologic literature include those in Saudi Business, September 14, 1979, in Aramco World Magazine, July-August 1981, and in Canadian Air Comments, May 1982.

At the commencement of my work at Al Masane in 1976 the only geologic studies of the area were those of Meaton and Assiri (1970), Greenwood (1980a; field work 1974), unpublished reports by ASDC, and preliminary results of some USGS sampling included in Roberts and others (1975). Meaton and Assiri (1970), from a few days reconnaissance, attempted to develop a structural outline of the Sheb Al Houra-Wadi Shann area and suggested certain structural controls for ore deposition. Greenwood (1980a), in mapping the Wadi Malahah quadrangle, was able to make only brief investigations of the mineralized areas. He concluded that the mineral deposits of the Al Masane area were developed in faulted and sheared metasedimentary rock.

While working at Al Masane in late 1977, I had profitable exchanges with field parties of the Riofinex Geological Mission and learned that Riofinex was also conducting a study of the mineral belt between Wadi Wassat and the Yemen border and that they, too, would work in the Al Masane area. Riofinex (1978) carried out a geochemical drainage sediment study in the larger Al Masane area which followed up on a pilot drainage geochemical study by Cheeseman and Thekair (1977) that included work at Al Masane. The Riofinex geochemistry successfully registered anomalies reflecting all known mineralization, and also anomalies not related to known mineralization in the ASDC concession area. Riofinex concluded that this exploration method is readily applicable to the region and discussed refinements in the methodology.

Riofinex conducted no other topical studies at Al Masane, but suggested from regional stratigraphic and structural synthesis that the stratigraphic section at Al Masane is high in the regional stratigraphic succession and approximately at a position of transition from very thick strata of a lower mafic-felsic cycle into overlying mafic volcanic rocks of a new cycle. Riofinex concludes (1978, p. 92) that such a stratigraphic position, based on the currently popular model that volcanogenic mineralization is favored during waning stages of felsic volcanism at the close of a "volcanic cycle", gives Al Masane and similar transitions into upper mafic volcanic rocks elsewhere in the district considerable potential for base-metal mineralization. They consider (p. 40) that "the Al Masane deposit is the most significant known mineralization in the district."

In March 1977, I guided R. O. Rye and R. J. Roberts on a trip to Al Masane, and later selected sulfide samples from the core of ASDC drill hole no. 7 beneath the Saadah gossan for Rye's Arabian massive-sulfide isotope study. Rye and others (in press) found the sulfur isotopes in Al Masane pyrite and sphalerite to have a narrow $\delta^{34}S$ range between 5.3 and 7.3 per mil, except for one sample at 1.2 per mil. They conclude that seawater sulfate must have been involved in the formation of the deposit and that the isotope values are consistent with a volcanogenic-submarine origin.

In two unpublished reports for the Directorate General of Mineral Resources, J. F. Daniels (1977, 1978) provided extensive petrographic descriptions of gossans and of fresh sulfide ore from drill cores of the Al Masane area. He found palimpsest textures in the gossan indicative of primary and supergene base-metal-bearing sulfides, and, from chemical data, estimated the degree of leaching or enrichment for given metals during gossan formation.

H. Sabir (1982) made a petrographic study of sulfides from mine and drill-core samples of both the Saadah and Houra bodies. He found a systematic mineral zoning with sphalerite being enriched over chalcopyrite at "the top" of the south Al Houra lens. He fails to define top or to give the orientation of his diagrammatic section (Sabir, 1982, fig. 1), but the drill hole shown on this figure was drilled upwards to the west (Fernette, written commun., 1984), however the sphalerite-rich portion is on the east. Sabir also notes that there are three ore types: (1) submassive to banded, (2) disseminated, and (3) brecciated or "conglomeratic". He suggests that the brecciation was a product of sedimentary transport prior to consolidation of the ore, but does not give its spatial relation to other ore types.

In April of 1982, P. Elsass and G. Pouit spent 11 field days mapping a 4 x 1 km area between Wadi Saadah and Wadi Wazagh. In an unpublished preliminary report (Elsass and Pouitt, 1982), they distinguish five major lithologic units and suggest that the Saadah and Houra ore bodies are in the same horizon on opposing sides of a syncline. They present a simplified map modified after my geologic map of the area. An unpublished appendix to their report is a petrographic study of 30 thin sections by A. M. Hottin.

In a comprehensive study of gossan development in the Arabian Shield, Ryall and Taylor (1981) include a section on the gossans at Al Masane. Their work complements that of Daniels (1977, 1978), and they present analytical data for both sulfides and gossan showing depletions or enhancements of numerous metals in the gossan.

During the underground phase of exploration at Al Masane, Greg Fernette and Edward Neckzcar of Watts, Griffis, and McOuat, Ltd., conducted extensive surface and subsurface geologic studies and submitted unpublished reports to ASDC. They are preparing a report for publication describing the ore bodies and associated wall rocks, documenting the volcanogenic character of the ores. A draft of this report was made available to me in May 1983.

In early 1976, I joined the USGS mission in Saudi Arabia for the purpose of conducting a study of the mineral belt between the Wadi Wassat district and the Yemen border (Project 5.1 in the Second Development Plan of the Directorate General for Mineral Resources, 1396-1401). In conducting reconnaissance of the mineral belt in late 1976, I recognized that an understanding of the mineralization in the well-preserved and well-exposed section at Al Masane might be critical to developing a picture of the geologic evolution and metallogeny of the region and, accordingly, I successfully sought permission to make a detailed study of the area an integral part of my project. Some aspects of the mineral belt study have been completed (Conway, 1981; Roberts and others, 1981) and others (regional gossan study, regional geologic and metallogenic synthesis) are in progress.

Field work for the Al Masane study was accomplished during 43 days in early and late 1977 and in early 1978. In the summer of 1978 I returned unexpectedly to domestic projects in the U. S. and have not returned to the Al Masane area. Map compilation, petrography, and writing have proceeded sporadically in the interim. Preliminary versions of the map and manuscript were sent, in 1981 and early 1982 respectively, to the USGS and ASDC. In these, the basic geologic information was assembled, without the expanded introduction, acknowledgements, and bibliography, and the expanded sections on interpretation and regional implications of the present version.

At Al Masane an attempt was made to conduct a broad-based study. Fundamental information on stratigraphy, structure, petrography, geochemistry, and mineralization are presented in this paper and are of importance in regional interpretations. All analytical data and locations of analyzed samples are given in the report. Petrographic descriptions are based on examination of 65 thin sections.

The quality of mapping (plate 1) is variable. The central part of the area was mapped in more detail. Fringe areas, especially to the west and north, were examined only in reconnaissance. Many contacts in these areas are photo-interpretive.

ACKNOWLEDGEMENTS

I acknowledge the considerable commitment of U.S. Geological Survey resources to the Al Masane project. At my request a topographic map of the Al Masane area was made by F. J. Fuller and D. J. Faulkender. In early 1978 they flew the aerial photography and surveyed the area; later that year Fuller constructed the topographic map by photogrammetric methods. Their cooperation and the excellent topographic base map are much appreciated. Both the map and the photographs have been utilized by projects of other missions. I am grateful to K. J. Curry, under whose direction the DMMR analytical laboratory analyzed hundreds of samples from Masane and elsewhere in the mineral belt under specified quality control and by total-solution methods.

C. W. Smith, who concurrently worked at Dhahar, and with whom I enjoyed a few field days at Kutam, Dhahar, and Al Masane, helped in many ways, personally and professionally. I am indebted to R. J. Roberts, chief of the USGS economic geology section at the time of my work, for his approval of my approach and his continual encouragement. To my outstanding USGS field crew, Mohammed Said Albarazi, Ibrahim Mahmud Abdullah, and Mohammed Abdulla Maliha Al Ghatani, I express my sincere appreciation.

It was by the consent of Hatem El-Khalidi, inasmuch as ASDC holds an exploration license at Al Masane, that I had the opportunity to work at Al Masane. To Hatem and his wife, Ingrid, I express a special thanks for kindness and assistance as I carried out my field work. I was impressed and motivated by the indomitable optimism that marks El-Khalidi's character.

I feel a special gratitude to Greg Fernette for his objective and enormously helpful review of an earlier version of this paper, for his generous loan of personal copies of literature on the Al Masane area which I had been unable to obtain or of which I was unaware, and for his permission to refer to unpublished chemical data. Discussions of Al Masane geology with him have been extremely helpful, particularly in bringing me up to date on recent WGM exploration and geologic investigation. I hold him in esteem for his unselfish assistance.

This work was done in accordance with the work agreement between the Ministry of Petroleum and Mineral Resources of the Kingdom of Saudi Arabia and the U.S. Geological Survey.

GEOLOGIC SETTING

Habawnah fold belt

I propose the name Habawnah fold belt taken from Wadi Habawnah, a major drainage that heads in the Mayza quadrangle and drains eastward into the Wadi Habawnah quadrangle, for the belt of deformed Proterozoic stratified rocks extending southward about 100 km from the Wadi Wassat area into Yemen (fig. 1). In reference to the numerous mineral deposits in these stratified rocks, this belt can also be called the Habawnah mineral belt.

Extensive masses of foliated plutonic rocks of the Wadi Tarib batholith flank the fold belt on the west (Greenwood, 1980a, 1980b; Anderson, 1979) and possibly on the southeast (Conway, 1981). Younger plutons, largely unfoliated, intrude within the fold belt and extensively on its eastern margin (Sable, 1992, unpub. data) According to Greenwood (1980a, 1980b) and Anderson (1979) the stratified rocks and most of the Wadi Tarib batholith were deformed and metamorphosed in the Aqiq orogeny. Greenwood suggests (1980a, 1980b) that minor late syntectonic rocks of the Wadi Tarib batholith were subsequently emplaced, then deformed in the Ranyah orogeny. Posttectonic granites of the region are attributed by Greenwood to the later Yafikh and Bishah orogenies.

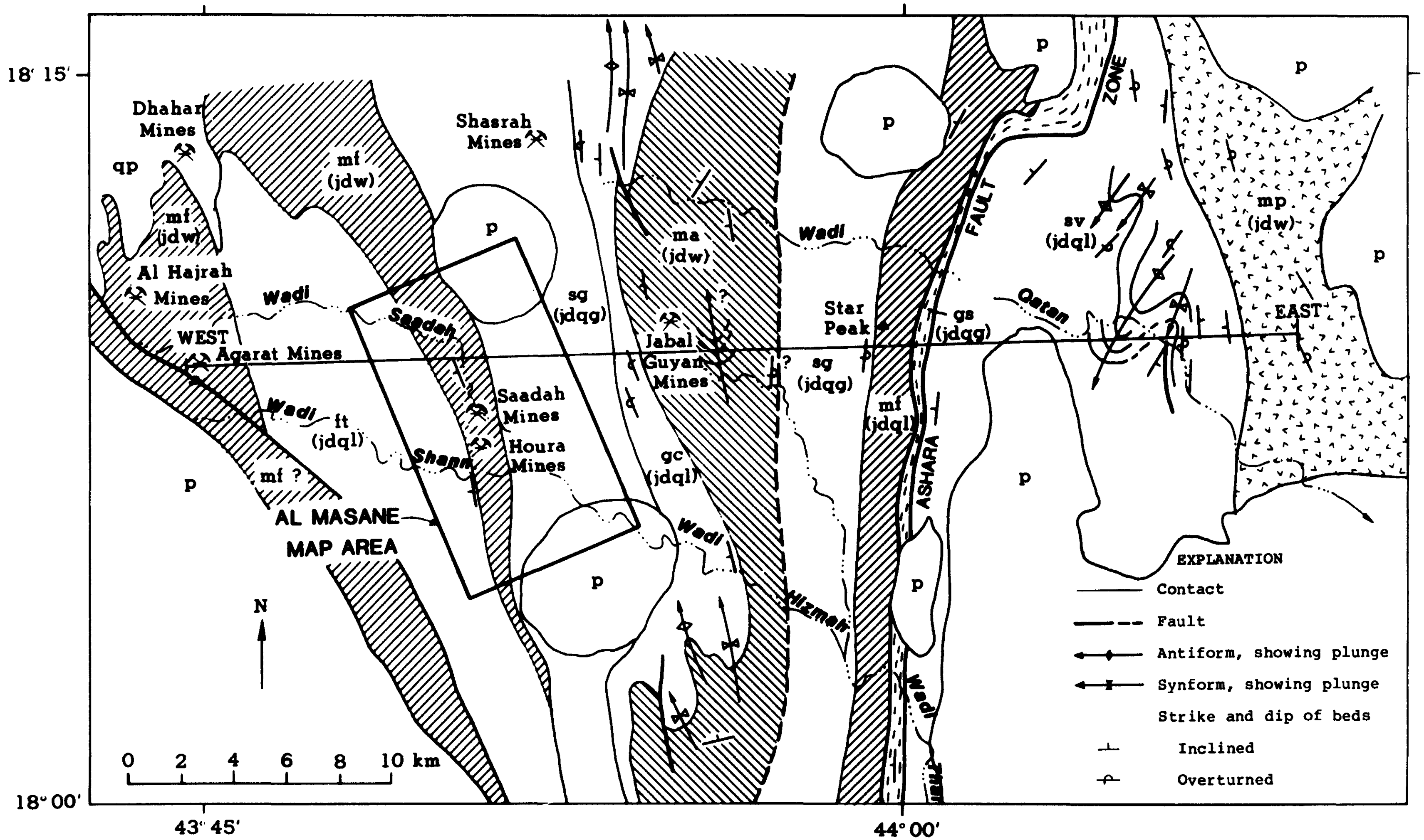
A Riofinex Geological Mission team compiled a map of the Habawnah fold belt from their reconnaissance mapping and from USGS quadrangle maps. Riofinex refers to the region as the Wadi Wassat-Kutam district, southeast Asir. Smith (1981) considers that the stratified rocks of the fold belt may be correlative with strata to the north in the Tathlith region.

From my work in the region and from a study of the above-cited works and other pertinent literature, I conclude that a distinctive suite of Proterozoic stratified rocks constituting the western part of the Habawnah fold belt, and including the Al Masane area, is continuous from the central Wadi Malahah quadrangle south to the Yemen border. This western belt contains a distinctive suite of Zn-Cu massive-sulfide deposits found repeatedly associated with a bimodal submarine suite of felsic crystal tuffs and mostly aphyric mafic volcanic rocks. In contrast, the stratified rocks of the northeastern part of the fold belt, in the Wadi Qatan and Wadi Wassat areas, are characterized by sparsity of felsic crystal tuffs, by pyroxene phenocryst-rich mafic flows, and by great "barren" pyritic massive-sulfide bodies (a minor amount of nickel is present in some). These strata appear to be in contact with the western bimodal belt along the Ashara fault zone in the Wadi Wassat quadrangle, and they may extend southward.

The greatest width of continuous exposure across the strike of the Habawnah fold belt is about 40 km, from the Wadi Qatan area in the Wadi Wassat quadrangle westward to the Dhahar area in the Wadi Malahah quadrangle. A generalized map of the Dhahar-Qatan portion of the Habawnah fold belt, which includes the Al Masane area, is shown in figure 2A. The geologic framework is largely from Greenwood (1980a, 1980b) but is modified to account for the results of my study (four weeks in March and April 1978) of the stratified rocks between Dhahar and Wadi Qatan.

Proterozoic stratigraphy and structure

This work concentrates on the lithology and sequence of the stratified Proterozoic rocks of the Al Masane region. Accordingly, the geologic map is a lithostratigraphic map and, except for the Ordovician-Cambrian Wajid Sandstone, the map units are named only by lithologic type. The rocks are described in the report under headings corresponding to the



A

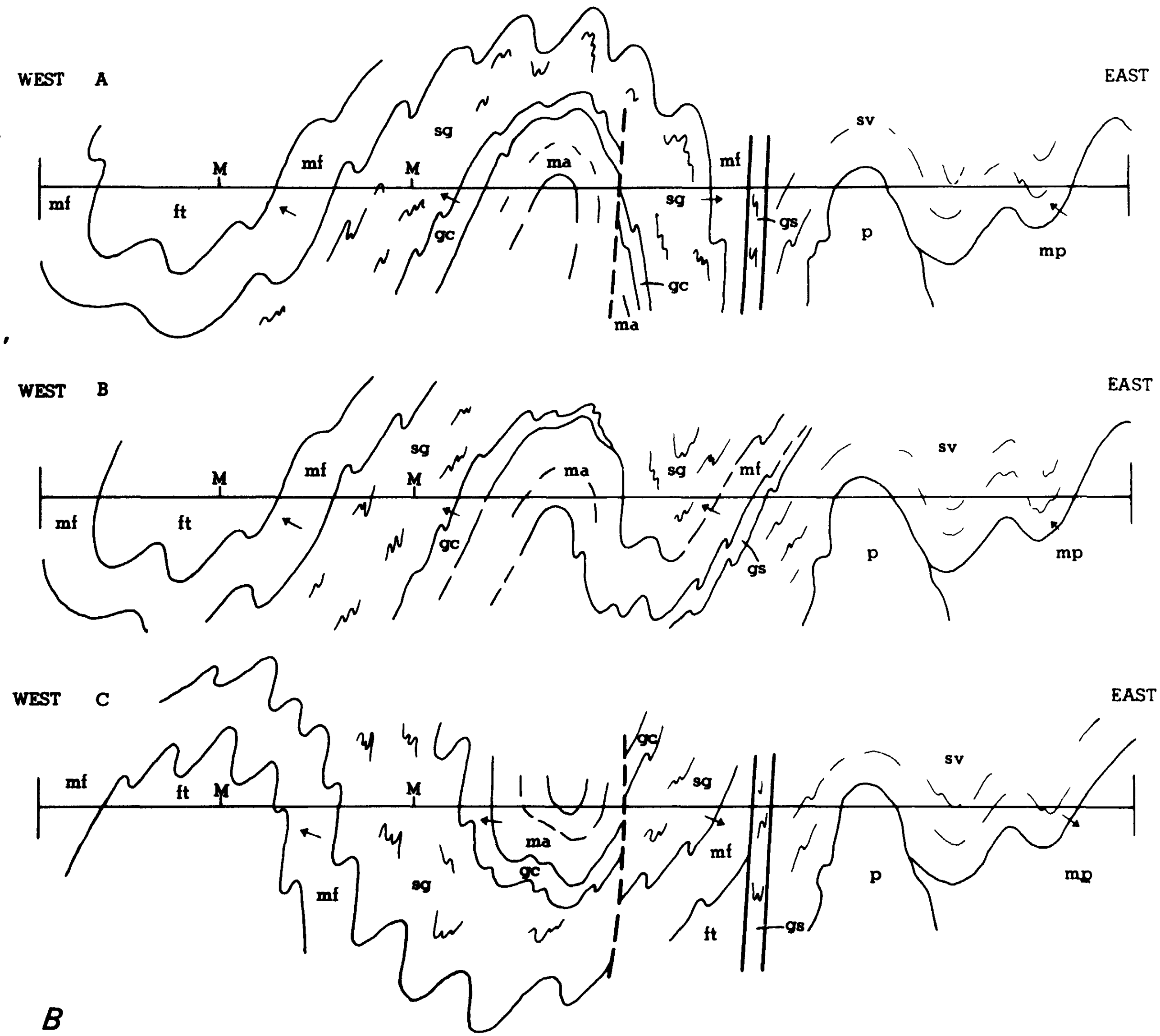
Figure 2. Simplified geologic framework and hypothetical structure sections of the region between Dhahar and Wadi Qatan. A, Geologic map showing location of the Al Masane map area in relation to major lithologic belts, structures, and mines. B, Alternative hypothetical structure sections with Al Masane map boundaries marked M. Arrows point in the directions of stratigraphic tops.

STRATIFIED ROCKS FROM WEST TO EAST

mf	Aphyric mafic volcanic rocks and felsic crystal tuff
ft	Felsic tuff, conglomerate, shale, graywacke
sg	Shale, graywacke
gc	Graywacke, conglomerate
ma	Aphyric mafic volcanic rocks, minor(?) felsic crystal tuff
gs	Graphitic shale
sv	Sedimentary and volcaniclastic rocks
mp	Porphyritic mafic volcanic rocks

INTRUSIVE ROCKS

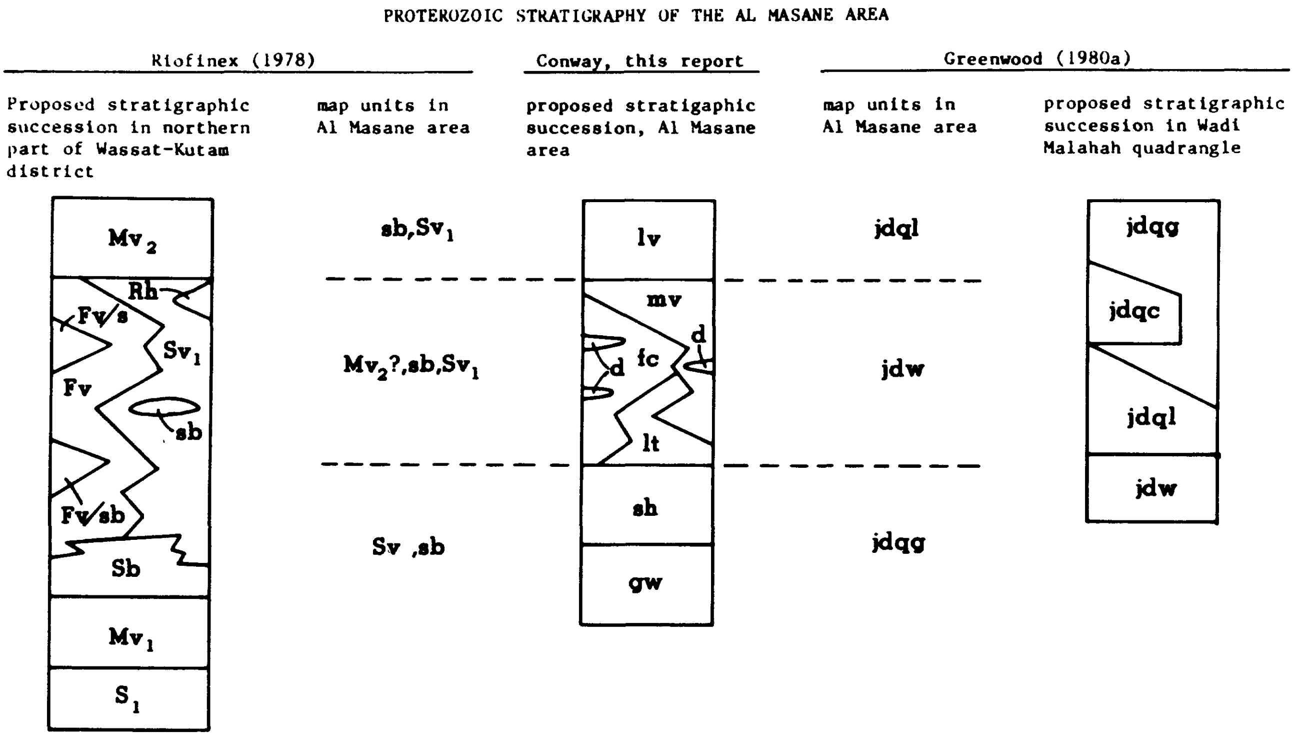
qp	Quartz porphyry
p	Plutonic rocks



map units, in my proposed oldest to youngest sequence. A comparison between my geologic sequence and those of Riofinex (1978) and Greenwood (1980a) for the Al Masane area ia shown in figure 3. G. Fernette and E. Neckzcar (unpub. data) have further subdivided my units mv and fc in a 1:2,000-scale map of a 6-km^2 area near the Saadah and Houra ore bodies.

I consider it premature at this time to propose formal geologic names. In our (the collective geologic community) study of the stratified rocks of this region we are still at a pioneering stage. Greenwood (1980a, 1980b) has proposed a regional stratigraphic framework, Riofinex (1978) has proposed one quite different, Smith (1981) has suggested modifications to Greenwood's column, and I discuss constraints and alternatives (fig. 2B and discussion below) that will be expanded and further evaluated as more work is done. These are all but working hypotheses, and as such, remain to be tested. The adoption of formal geologic names (North American Commission on Stratigraphic Nomenclature, 1983; Hedberg, 1976) is based in part upon a knowledge of the nature of upper and lower contacts, in other words of knowing what lies stratigraphically above and beneath a named unit. We do not completely understand the stratigraphic succession in the Habawnah fold belt or even in the Al Masane area.

Riofinex (1978) has taken an approach to portrayal of the geologic units similar to mine (this report and Conway, 1981) by using only lithostratigraphic terms. However, in lithologic subdivision, that is, choice of map units, I am more in agreement with Greenwood (see figs. 2A and 3). I consider that Greenwood's identification and description of rock types is superior, his choice of map units more logical, and his placement of contacts more accurate. As an example, Riofinex shows the Saadah gossan zone at Al Masane as being in a geologic unit (sb) characterized by black shale (with associated felsic tuff, breccia, chert, argillite and marble), and they fail to map the pronounced contact between the resistant, high-standing felsic crystal tuff (fc, on my map), which is the host unit for the massive-sulfide deposits, and the shale sequence (sh) exposed in the broad valley to the east. Greenwood, on the other hand, does map this contact. He considers it to be a fault between his Wassat formation (jdw) on the west (including crystal-lithic tuffs) and his graphitic sedimentary unit (jdqg) of the Qatan formation on the east (including the shale).



<u>Riofinex units:</u>

Mv_2 - basalt to andesite flows, breccias, and tuffs, with volcaniclastic sandstone and argillite
Rh - rhyolite
Fv - schist derived from felsic volcanic rock; with chlorite schist, Fv/s; with marble and shale, Fv/sb
Sv_1 - andesitic to rhyolitic bedded tuff, conglomerate, graywacke, siliceous shale, marble, and local mafic to felsic flows and breccias
Sb, sb -black, locally graphitic, pyritic to hematitic shale, felsic bedded tuff, tuffaceous chert, volcaniclastic breccias
Mv_1 - basalt to andesite flows, breccias, and tuffs with volcaniclastic conglomerate, sandstone, argillite, black shale, chert and marble
S_1 - volcaniclastic sandstone, argillite, conglomerate, shale and marble with minor mafic to felsic flows and tuffs

<u>Conway units:</u>

lv - lapilli tuff and volcanic breccia
mv - mafic volcanic rocks
d - dolomite - shaly, tuffaceous, calcareous
fc - felsic crystal tuff
lt - lapilli tuff
sh - shale, minor limestone and graywacke
gw - graywacke

<u>Greenwood units:</u>

JIDDAH Group
Qatan Formation
jdqg - graphitic fine-grained sandstone to phyllite with minor conglomerate and marble; clasts include felsic volcanic rocks
jdqc - pebble to cobble conglomerate
jdql - conglomerate to to phyllite with minor marble and mafic volcanic rocks; clasts include felsic volcsnic rocks
Wassat Formation
jdw - basaltic to dacitic flow rocks, breccia, and tuff; massive to poorly bedded crystal and crystallithic tuff; minor conglomerate, phyllite, chert and marble

Figure 3. Comparison of the Al Masane stratigraphy as proposed in this study with regional stratigraphic successions proposed by Riofinex (1978) and by Greenwood (1980a).

I differ with Greenwood on some major points. For example, I conclude that there has been no significant faulting on the contact discussed above. This is true also for some other contacts he maps as faults, notably those of the gabbro sills. I recognize much faulting parallel or nearly parallel to bedding but found no evidence in most cases that movement was great enough to disrupt in the least the normal stratigraphic succession. Fernette and Neckzcar (unpub. data) reached a similar conclusion. Were I to show these faults, my map would have numerous strike-parallel faults. As portrayed by Greenwood on maps and structure sections, some of the strike-parallel faults in the region, especially at lithologic contacts, have offsets measured in kilometers. The differences in our stratigraphic interpretations derive largely from our differing analysis of faulting. Greenwood, by the huge offsets on his faults, has numerous repetitions of units across the Wadi Wássat and Wadi Malahah quadrangles. Note the four belts of the Wassat formation, jdw, in figure 2A. In structure sections on his maps Greenwood shows no fold connections between the corresponding units of the different fault blocks.

I disagree with Greenwood, on lithologic grounds alone, in his correlation of the four belts of mafic volcanic rocks (jdw) at Dhahar, Al Masane, Jabal Guyan, and Wadi Qatan. The mafic flow rocks and much of the mafic volcaniclastic material at Wadi Wassat and Wadi Qatan are commonly porphyritic, containing augite and plagioclase phenocrysts (probably basaltic rocks) or plagioclase phenocrysts (probably andesitic rocks). Associated with these mafic flows and epiclastic rocks are minor graywacke, sandstone, rhyodacitic and calcareous tuff, and limestone. Graded beds are present in the sedimentary rocks. Pillows are sparse to absent in the volcanic rocks. These are my observations coupled with descriptions from Roberts and others (1981), Greenwood (1980b), and Jackaman (1972). This assemblage contrasts strongly with the mafic volcanic belts (Al Hajrah, Al Masane, and Jabal Guyan) mapped as Wassat formation (jdw) westward in the Wadi Malahah quadrangle (fig. 2A). In these belts the mafic rocks are mostly nonporphyritic or weakly porphyritic (aphyric). Sparse small phenocrysts in some flows are plagioclase; I saw no pyroxene phenocrysts, and Greenwood (1980a) reports none. Pillow structures are common in these rocks. Felsic crystal tuffs are found with these mafic rocks in all three belts, though they are less abundant in the easternmost belt (Jabal Guyan). Quartz crystals are usually conspicuous in the felsic crystal tuff; inconspicuous plagioclase (probably universally albite) is present in most. The felsic crystal tuffs and mafic rocks are locally complexly interbedded or chaotically intermixed.

Greenwood (1980a) describes the felsic rocks, recognizing their bedded tuffaceous character, and refers to them as dacite. Chemical analyses of these rocks (Fernette and Neckzcar, unpub. data) indicate that they are sodic rhyolite. They are petrographically and compositionally similar, though less rich in SiO_2 and Na_2O to felsic crystal tuff (unpublished analyses) widespread in the Wadi Amadin Al Husn quadrangle (Conway, 1981).

A fourth belt of rocks, along the boundary between the Wadi Wassat and Wadi Malahah quadrangles in the vicinity of Star Peak (fig. 2A), may also consist largely of aphyric mafic flows and felsic crystal tuff. Greenwood (1980a, 1980b) has mapped these rocks as the green to gray metasedimentary unit of the Qatan formation (jdql). Mafic flows and felsic crystal tuffs in the western three-fourths of this belt just south of Star Peak are especially similar to those at Al Masane. This belt and those at Al Masane and Dhahar are designated as a bimodal mafic-felsic unit (mf) in figure 2A. I am somewhat hesitant to disagree with Greenwood in my characterization of this unit because I have examined it in few places and because Greenwood's mapping seems generally to be of excellent quality. However, even if most of this belt is composed of other rock types, the predominance in one part of the belt of aphyric mafic flows and felsic crystal tuffs is sufficient for the stratigraphic and structural possibilities presented in this paper. Relatively rapid facies changes are the rule in such volcanic sections.

The Jabal Guyan belt (fig. 2A) is labeled ma (mafic volcanic rocks) rather than mf only because it seems to have a considerably higher ratio of mafic rocks to felsic tuff. The lithologies are similar to those of the other three belts. Felsic crystal tuff is abundant in this belt along the margin of the body near the Jabal Guyan mines.

By labeling three of the four belts as mf I do not mean to imply that they are necessarily stratigraphically equivalent, nor do I mean to imply that one or more could not be equivalent to ma. Note the various possible correlations in the three interpretive cross sections of figure 2B. In section B, ma is shown as being equivalent to the mf belt at Star Peak.

A discussion of the comparative characteristics of the other regional stratified units (ft, sg, gc, gs, and sv) of figure 2A and ensuing constraints on regional stratigraphy are not essential to this paper.

Important constraints on the regional stratigraphy arise from stratigraphic facings (or tops) as indicated by sedimentary or volcanic structures. Evidence is presented in this paper that the steeply westward-dipping section within the Al Masane map area is upright - that is, the strata are westward facing. In contradiction, Fernette and Neckzcar (unpub. data) find evidence near the sulfide bodies in the new underground workings for eastward-facing beds. Possible reconciliation of this contradiction is discussed in the structure section of this paper. Another important control on the facing direction of the strata in the region is in the western part of the Jabal Guyan mafic belt (ma) and adjoining graywacke and conglomerate unit (gc). I found numerous west-facing graded beds in the graywacke of unit gc west of Jabal Guyan and several near the western boundary of this unit east of the Shasrah mines. North of Jabal Guyan, I also found pillow structures at several places that show that the beds are westward facing. These data are consistent with several of Greenwood's (1980a) attitudes within the ma and gc units of figure 2A.

I therefore consider that the strata from Jabal Guyan to the western boundary of the Al Masane map are westward facing. This interpretation is shown in all three structural profiles of figure 2B. Smith (1981) believes, on the basis of an east to west gradation of "non-layered pyroclastic breccias to crudely layered breccias and tuffs and then to finely-laminated water-laid tuffs", that strata at Dhahar are westward facing. If this conclusion is correct for the overall Dhahar-Al Hajrah section, none of the three interpretive cross sections of figure 2B can be correct at the west end where they imply eastward-facing strata at Dhahar-Al Hajrah.

A key relation for Greenwood's (1980b) stratigraphy is that the Wassat formation is stratigraphically overlain by the light-colored dacitic unit of the Qatan formation in the Wadi Qatan area (mp and sv, respectively, in fig. 2A). Though I would not dispute it too strongly, I am not convinced of this relationship. The numerous attitudes (only those attitudes with facing criteria are shown) in these two units near their boundary (see fig. 2A) are conflicting. Some of the apparent discrepancy is no doubt due to minor folding, which is not always recognized in the field. Nevertheless, at a number of places in both units near the contact I found consistent tops (graded beds) to the east. Similarly, in the east limb of the easternmost synform (in unit sv) I found graded beds facing eastward. These data imply that the contact is overturned and that the major folds are upside down (section C, fig. 2B).

PROTEROZOIC STRATIFIED ROCKS

Graywacke

Observations from one traverse and at a few scattered localities indicate that the graywacke unit (gw) in the eastern map area is characterized by a predominance of graywacke over shale and by the presence of conglomerate graywacke. Graywacke is coarsest east of the east limb of the folded gabbro sill; it ranges there from medium sand to pebble conglomerate. Plagioclase grains are abundant and quartz grains are locally conspicuous, constituting several percent of the rock. Clasts are felsic volcanic material. A few resistant beds are lithic and feldspathic arenites. The thin- to thick-bedded rocks are drab brown and olive in color and locally have fairly well developed to poorly developed graded beds.

Westward, shale and wacke are interbedded and gradational. Some shale beds are calcareous and contain sparse altered disseminated pyrite(?). Resistant beds of dark-green siliceous siltstone were observed near the west margin of the unit. These are possibly felsic tuffaceous rocks. The central and northern parts of the unit sustain a tableland that which stands a few hundred meters higher than the shale unit just to the west. In southern exposures, shaly rocks are more abundant, and the unit is more deeply eroded. These exposures include carbonaceous shale and graywacke (plate 3) that was identified as a conducting mass in a regional airborne electromagnetic (INPUT) survey (Wynn and Blank, 1979).

Shale

The shale unit (sh) occupies a broad strike valley in the eastern part of the map area. It is gradational eastward into the graywacke unit described above, and the map contact is approximate. Its eastern boundary is defined as the easternmost exposures of the sparse brown limestone lenses that characterize this unit. Aluminous shale is the most abundant rock. Siliceous shale and graywacke are interbedded locally throughout the sequence. The brown limestone lenses, a few centimeters by a few meters in dimension, are sporadically mixed with the other rock types. On the west margin of the unit, some finer grained beds are slightly dolomitic. Some graywacke beds are somewhat tuffaceous, containing small (few millimeters) white pumice(?) platelets. The unit seems to be relatively homogeneous along strike in the map area.

All the lithologic variants in this unit are shaly. They are incompetent and have low resistance to weathering and erosion. They are intricately folded isoclinally and possess a slaty cleavage throughout. A micaceous sheen and crenulation are common. Most variants are locally calcareous, with calcite constituting as much as 30 percent of the matrix.

Aluminous shale occurs in beds a few meters to a few tens of meters thick and is more deeply eroded than the graywacke and siliceous shale interbeds. It is gray blue or gray brown and weathers to light olives and tans. The shale consists largely of the metamorphic sheet silicates--sericite and minor biotite or chlorite--and quartz; feldspar is absent or sparse. It is locally gradational into siliceous shale or sandy shale but has relatively sharp boundaries with the discrete interbeds of medium- to coarse-grained graywacke.

The siliceous shale is thinly laminated and dark green or gray to black. Beds are 0.2-3 m thick. It is much more resistant than the aluminous shale and appears to be somewhat cherty. It is referred to as shale, because its lamination and fine grain size are similar to those of the aluminous shale. However, quartz is more abundant than sheet silicates. Some interbeds might also be called siltstone. Similarity to aphyric tuffaceous interbeds of the felsic crystal tuff unit suggests that the siliceous shale might be volcanic ash.

Graywacke interbeds constitute perhaps 10-20 percent of the shale unit. The graywacke is fine to coarse grained and gray to brown in color. It weathers to light brown. It is gradational into shale by decrease in overall grain size or less frequently by increase of the shale matrix. Fine-grained graywacke is relatively abundant and commonly grades into shale. Medium- to coarse-grained graywacke is uncommon. It occurs as discrete 0.5- to 3-m-thick beds with sharp nongradational boundaries. The graywacke is poorly sorted; graded bedding is scarce and often indistinct. Grains in the graywacke are largely plagioclase and felsic lithic fragments (fig. 4). Feldspathic graywacke predominates over lithic graywacke. Some beds contain a few percent quartz grains. Plagioclase grains are twinned, unzoned albite. A small proportion of the albite is euhedral, but most crystals are broken, and, in the more foliated rocks, it is cataclastically degraded. Lithic fragments are a fine mosaic of quartz and feldspar with epidote, chlorite, and sericite. Some aggregates of epidote, chlorite, biotite, or actinolite may be pseudomorphic after mafic phenocrysts.

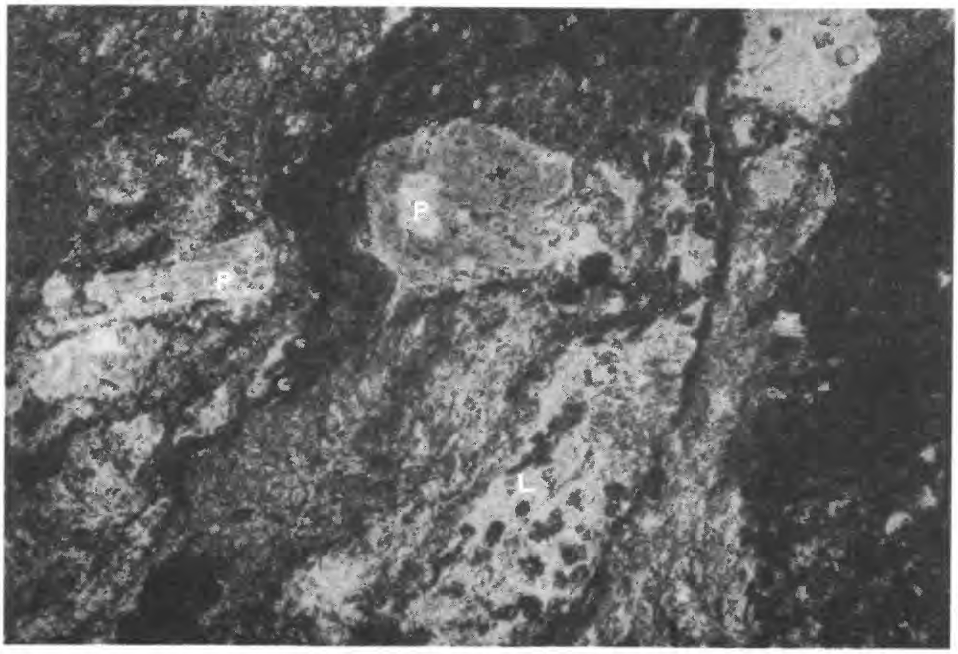


Figure 4. Photomicrograph of graywacke from the shale map unit. Lithic fragments (L) and plagioclase crystals (P). Field of view approximately 2 x 3 mm. Plane-polarized light.

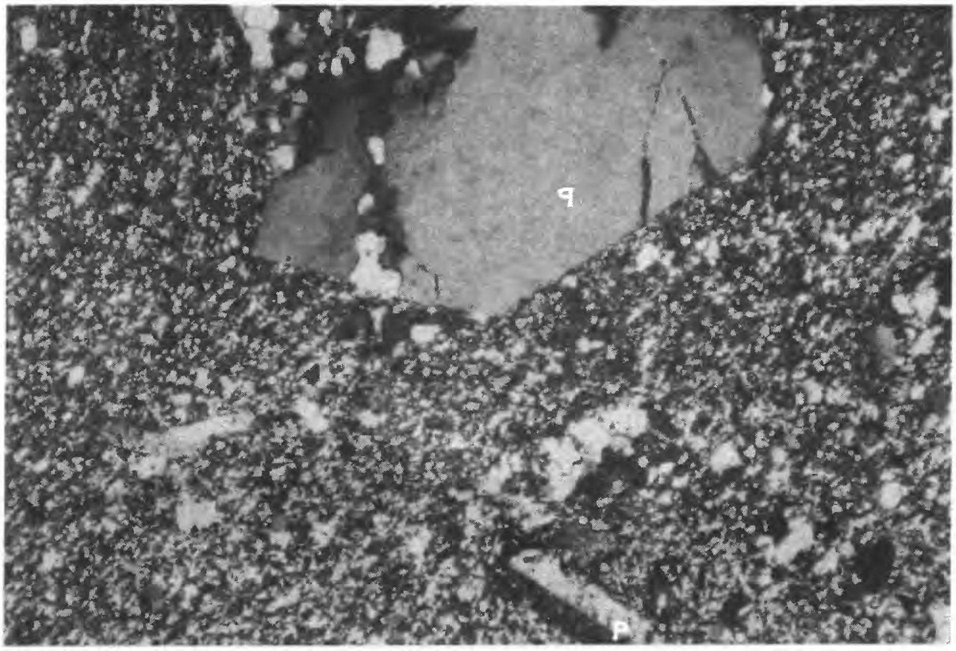


Figure 5. Photomicrograph of felsic crystal tuff from the felsic crystal tuff map unit. Euhedral quartz (q) and plagioclase (p) phenocrysts in a fine-grained felsic matrix. Field of view approximately 2 x 3 mm. Cross-polarized light.

Matrix minerals are quartz, plagioclase, sericite, epidote, chlorite, calcite, and, less commonly, biotite and actinolite. Small white platelets (<1 cm), apparently pumice clasts, occur in a small proportion of the coarse graywacke beds. They are composed almost entirely of very fine quartz and feldspar. The brown limestone lenses are thinly laminated and fine grained. They contain 70-80 percent calcite, plus quartz, sericite, and disseminated and clustered iron oxide (hematite and limonite?).

The shale unit was deposited in a quiet-water environment above the calcium-carbonate compensation depth (about 4-5 km). Largely fine grained volcanic detritus and possibly volcanic ash were sporadically carried into a basin in which clay (possibly also of volcanic origin) was being continuously deposited. Paucity of graded bedding indicates that turbidity currents were not the primary medium of transport for the graywacke. Local interbeds of black shale indicate recurring euxinic conditions.

Some euhedral plagioclase and bipyramidal quartz grains in the graywacke and rarely in the shale are evidence of a volcanic origin. Sparse aggregates of epidote, chlorite, biotite, or actinolite may be metamorphically reconstituted mafic phenocrysts. Overall felsic composition of the graywacke and a paucity of quartz and virtual absence of potassium feldspar indicate that the volcanic material is approximately of dacitic composition.

Felsic crystal tuff

Felsic crystal tuff (fc) is interbedded with mafic volcanic rocks (mv), lapilli tuff (lt), and dolomite (d) in the central part of the map area. Most of the relatively thin dolomitic beds in the map area are within the felsic crystal tuff, where they have weathered to form small strike valleys. The felsic crystal tuff and closely associated mafic rock flows are among the most resistant rocks in the area and sustain hills and ridges higher than the areas underlain by shale to the east and lapilli tuff and volcanic breccia (lv) to the west.

The felsic crystal tuff is light to dark green to grayish green and of massive character, though foliation is always present. Lineation, defined by mineral streaking, is often a salient feature. Foliation is more pronounced in fine-grained calcareous or shaly variants or where the tuff is intermixed with mafic detritus.

At first inspection, the thick massive beds of the felsic crystal tuff appear to be porphyritic flows or sills. They are often remarkably homogeneous. However, a number of features, some subtle, demonstrate the bedded and tuffaceous character of these rocks. The tuff contains within it interbeds of carbonate, shale, pillow flows, and mafic volcanic detritus. Ordinary felsic crystal tuff is locally gradational into each of these types of interbeds. Moreover, variations in the tuff itself indicate deposition of beds of different character. The most obvious variations are in quartz-phenocryst content and in size of quartz crystals. Plagioclase phenocrysts are not so easily seen in hand specimen but also vary in size and abundance. Changes in phenocryst character are generally gradational and subtle but are occasionally abrupt. Beds, as defined by homogeneity of phenocryst character, are fractions of a meter to tens of meters thick. Quartz-phenocryst-rich beds are the most abundant, but many variations in proportion of plagioclase to quartz are present. Uncommonly beds are plagioclase-phenocryst-rich or aphyric. Plagioclase and quartz phenocrysts commonly occur in shaly or dolomitic interbeds within the felsic crystal tuff.

Pillow flows and mafic detrital rocks occur locally within the felsic crystal tuff, usually in beds or flows too small to map separately or in a complex fragmental intermixing. Some of these localities are shown by stippling on the geologic map (plate 1). Many others no doubt exist. Much of the material in these areas is a detrital mixture of the felsic crystal tuff and mafic debris. The mafic fragments range in size from pillows or larger blocks down to sand-size fragments. The mixture is chaotic and immature. There has been little or no sedimentary transport. It would appear that the mixing is largely or wholly due to extrusion of pillow flows essentially contemporaneously with deposition of crystal tuff. The distribution of these mixed rocks appears irregular; they do not often occur in simple layers or lenses. They are not distributed evenly in the felsic crystal tuff, and most of the tuff is completely free of mafic flows or debris.

Clastic texture is seldom seen in the felsic crystal tuff. Lithic lapilli fragments are nearly absent, in contrast to their relative abundance in graywacke and lapilli tuff of other units in the map area. The groundmass of the tuff is remarkably homogeneous even at the microscopic scale. The material deposited was apparently simply ash and crystal. No sedimentary structures and no graded bedding were observed. Coarse clastic material (breccia or conglomerate) was seen only in the section immediately west of the

Wadi Saadah gossan. The clasts in this breccia are probably all felsic volcanic clasts, largely of felsic crystal tuff.

At several localities, notably a few hundred meters west of the Saadah gossan (locality 1, plate 2), where felsic crystal tuff contacts the west sides of mapped pillow flow units, a few meters of the tuff contains clasts of mafic volcanic rock. This is evidence for tops to the west in agreement with facings in pillow flows.

Quartz phenocrysts in the tuff are euhedral to subhedral, commonly bipyramidal and from 0.3 to 1.5 mm in size (fig. 5). Plagioclase phenocrysts are euhedral to anhedral, unzoned, twinned, low-An albite, usually a little smaller than the quartz phenocrysts. The quartz phenocrysts have been little modified by metamorphism, being recrystallized and (or) slightly comminuted in some rocks. Clusters of epidote with euhedral boundaries in one sample are apparently pseudomorphs after pyroxene or amphibole phenocrysts.

The groundmass minerals sericite (~20 percent), chlorite (~10 percent), epidote (~20 percent), albite (~25 percent), quartz (~20 percent), and calcite (~5 percent) are all present in most samples. The best preserved (least metamorphically equilibrated) sample contains larger amounts of quartz and feldspar with only a trace of sericite, a few percent calcite, and no epidote. Groundmass minerals are generally very fine grained, though small euhedral porphyroblasts of epidote are sometimes present. Because of the fine grain size, quartz and feldspar are not easily distinguished in most thin sections. Potassium feldspar was not recognized but could be present in small amounts in the groundmass. Tuff containing albite phenocrysts but no quartz phenocrysts was recognized only in northern parts of the unit, where it is rare.

Quartz phenocrysts are more abundant in the central part of the exposed strike length and probably more abundant in central to upper (tops to west) parts of the stratigraphic succession. There is a gradational decrease in size and abundance of phenocrysts southward and possibly northward from the general area where Wadi Saadah crosses the unit. In the light-colored southernmost exposures, sparse quartz and feldspar phenocrysts are small. In northern exposures near the southeastern margin of the granite pluton, the unit contains massive dark tuffs nearly free of quartz phenocrysts. Tuff containing only albite phenocrysts is found in this area. Low in the section in this area are clastic rocks (grit-pebble wacke or lapilli tuff) not found to the south.

It seems from the size distribution of crystals that one source area for the tuff was approximately near the central part of the map area. Larger crystals and a high proportion of crystal to fine ash would have been deposited near the source, whereas smaller crystals and a higher proportion of fine ash were transported farther from the source. The tuff apparently intertongues to the south with lapilli tuff (lt) and possibly intertongues to the north with plagioclase crystal tuff and coarse graywacke or lapilli tuff (not shown as a separate map unit). The presence of the breccia and massive-sulfide lenses in the upper and central crystal-rich portion of the tuff also indicates proximity to a volcanic source. It is now widely recognized that massive-sulfide deposits commonly form as a result of submarine hydrothermal activity at volcanic centers. Coarse breccias, possibly formed by hydrothermal explosions (Henley and Thornley, 1979), are characteristically associated with massive sulfide deposits (Sangster, 1972).

Fernette and Neckzcar (unpub. data) interpret the felsic crystal tuff as being a composite of felsic flows, tuffs, and domes that they have subdivided into five map units. They postulate the existence of several eruptive centers, possibly spatially associated with the Saadah and Houra sulfide bodies. These ideas, resulting from very detailed surface and underground mapping, are generally compatible with my findings and represent logical extensions. My felsic crystal tuff unit can certainly be subdivided for mapping purposes, and I would not be surprised if it contains flows, although I tried unsuccessfully to apply criteria (flow foliation, sharp contacts, homogeneity of a lenticular unit, and massive texture) for their identification.

Lapilli-crystal tuff

Lapilli-crystal tuff (lt) occurs in the south-central part of the map area in conformable contact with the east margin of the felsic crystal tuff (fc) and on strike with felsic crystal tuff to the south. Its stratigraphic relation with the felsic crystal tuff to the south is obscured by the gabbro sills, especially the large U-shaped sill. The U-shape of this sill appears not to be a result of folding, and I would argue that the felsic crystal tuff intertongues with lapilli-crystal tuff and wedges out southward in the area of the bend in the sill. I did not examine the strata precisely at the keel of the sill where some felsic crystal tuff could be present. The lapilli crystal tuff is dark brown to grayish and weathers to a lighter dirty brown. White or light-colored pumice platelets up to about a centimeter in diameter are visible in most outcrops. Locally these fragments are as large as 5 cm. The unit also contains sand- to granule-size felsic lithic clasts. Coarse (grit to pebble size) volcanic breccia was found locally in the southernmost exposures examined. Phenocrysts are albite (~10 percent), quartz (~5 percent), and rare potassium feldspar. In addition to quartz and feldspar, sericite, chlorite, and epidote (zoisite or clinozoisite) are the most abundant groundmass minerals. A little biotite in some samples has replaced chlorite; epidote also replaces some chlorite.

Dolomite

Impure dolomite layers interbedded with felsic crystal tuff and mafic volcanic rocks are less than a meter to about 20 m thick. Only the larger beds (d) are shown on the map. Small dolomitic lenses or partings and carbonate-rich zones are abundant, especially in the felsic crystal tuff (fc). Contacts with volcanic rocks, especially the tuff, are gradational, sometimes over several meters. These field relations and mixing of carbonate and volcanic materials, as observed in hand specimen, clearly indicate that carbonate sedimentation and volcanism were contemporaneous.

Dolomite is a somewhat arbitrary name for these carbonate-rich layers, but it is used because dolomite seems to be more abundant than calcite. These rocks show weak to strong reactions with dilute HCl, and thus they contain some calcite. In thin section one sees two distinct carbonate minerals, a blocky form that has a good rhombic cleavage and a form which occurs as stringers with sericite in foliation planes. The stringer carbonate is apparently calcite and dissects and replaces the blocky forms. The blocky form is or probably was dolomite. These crystals are partly to totally clouded with fine iron oxide (limonite?). These two carbonate phases constitute about 50 percent of the rock. The remainder is sericite, chlorite, albite(?), and quartz. Sericite flakes are visible in some hand specimens.

Dolomite is medium to light rusty brown and is weakly to moderately foliated. Limonite pseudomorphs after pyrite are common and, with an increase in alteration products of sulfide minerals, the dolomite grades locally into gossan. The major gossans in the map area are found closely associated with the dolomite layers; they appear to be essentially lateral equivalents. In the Saadah gossan, gossan and carbonate are intimately associated.

Mafic volcanic rocks

Mafic volcanic rocks (mv) occur interbedded within and stratigraphically above the felsic crystal tuff in the central to northern parts of the area. The mafic volcanic rocks constitute a wedge that thickens to the north map boundary and lenses out near the south edge of the area. Finer grained mafic detrital (tuffaceous?) material and shaly rocks become proportionally more abundant in the southernmost exposures.

Pillow flows are the predominant mafic rock type in the thinner eastern segment (within felsic crystal tuff), where they are locally spectacularly displayed (figs. 6, 7) in relatively fresh water-worn exposures in the steep canyon walls of Wadi Saadah. They may be subordinate to mafic tuff and agglomerate in the thicker western exposure (G. Fernette, written comm., 1983), but are difficult to discern in the deeply weathered surfaces of low relief.

Draped pillow forms at several places (localities 2 and 3, plate 2; figs. 6 and 7, and 8) indicate that the eastern lens is stratigraphically up to the west. In most exposures throughout unit mv, intense foliation makes it difficult to distinguish pillow structure and therefore impossible to determine tops. Nevertheless, after observing pillows in all stages of degradation, one can usually distinguish between pillow structures and clastic or agglomerate structures. Whether nonpillowed flows exist, I am not certain. Most of the nonpillowed mafic rocks are chaotic clastics. Most appear to be immature, locally derived material, perhaps largely derived from eroded pillow flows. Some is silt- to coarse-sand-size tuff or volcanic sand. Small light-colored felsic clasts are present in some of these finer grained rocks. Locally, felsic crystal tuff is intermixed in a manner somewhat analogous to that described for mafic rocks in the felsic crystal tuff unit (fc). Some of these areas of mixing are indicated on the map with a stippled pattern. There is great variation in mixing characteristics. In some areas there are beds of typical felsic crystal tuff, whereas in certain apparently mafic dark-green rocks, euhedral quartz crystals are the only indication that felsic detritus was mixed with mafic material.

The mafic material in all volcanic structural types is consistently aphyric or nearly so. In a few specimens skeletal opaque oxides seem to be pseudomorphic after mafic phenocrysts. Amygdules of quartz or quartz and epidote or chlorite are common but never abundant. Amygdules are crudely spherical to moderately elongate. The groundmass

Figure 6. Pillows in the small steep drainage immediately west of the Saadah gossan (locality 2, plate 2). Lower cusp of large elongate pillow near center of picture suggests flowage over two pillows below, indicating tops to the west. View westward.

Figure 7. Pillows in upper Wadi Saadah (locality 3, plate 2). Draping, especially apparent as infilling by pillow at top center, indicates that the outcrop is stratigraphically up to the west. View westward.

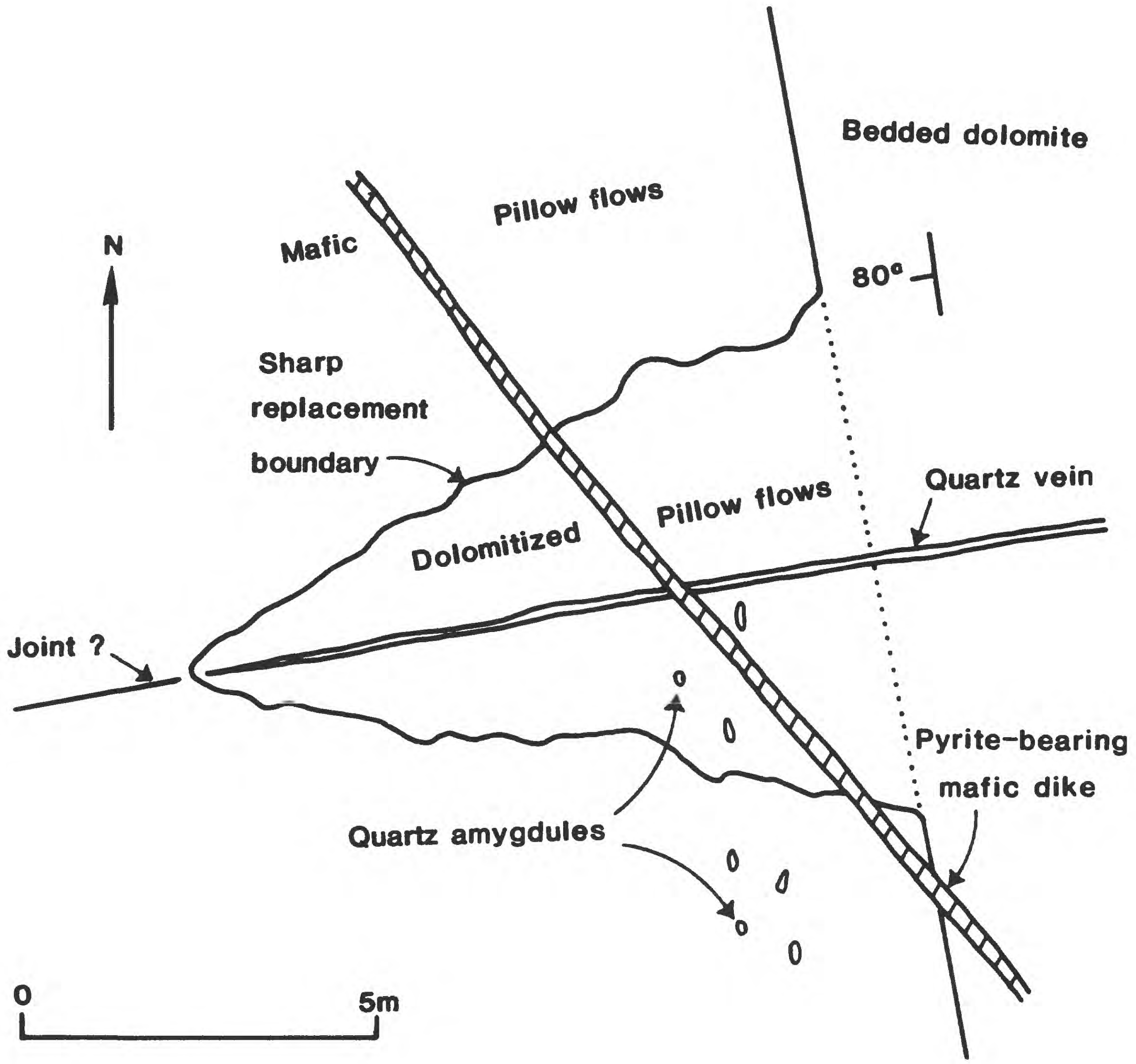


Figure 8. Sketch map showing pillow flows dolomitized along an apparent joint. The dolomite that has replaced the mafic rocks is continuous with bedded dolomite that is conformable along strike with the mafic unit. This occurrence is 1 km south of the Saadah gossan (see fig. 18) and is at the contact of the same dolomite layer in which the Saadah gossan occurs.

has been extensively recrystallized to form minerals of the greenschist facies, but a primary texture of felted plagioclase laths is commonly preserved. Chlorite, epidote, and albite constitute the bulk of the groundmass. Most samples contain 5-20 percent calcite and some quartz. A little sericite is present in some samples. Metamorphism seems more advanced in specimens from the mafic layer just west of the Saadah ancient mine; these contain 5-10 percent fine actinolite-tremolite blades and bursts of needles.

The mafic rocks are probably basaltic in composition for the most part, but some may be andesite. Some pillow flows with an unusually high quartz content are probably silicified.

Dolomitic and shaly beds occur within the mafic volcanic rocks but are not as common as within felsic crystal tuff (fc). Only the larger dolomite beds are shown on the map.

Dolomitization of mafic rocks is common in the area and locally is pervasive. It is commonly associated with quartz veins or pods and is more extensive near dolomite beds. Dolomitized mafic rocks have essentially the same mineralogy and overall character as dolomite of the dolomite beds. Figure 8 shows an observed relation in which a 10-cm-wide quartz vein crosses the contact between a dolomite bed and pillow flows. Dolomitization of the pillow flows is systematically related to the quartz vein and apparently progressed from the dolomite bed into the pillow flow rock. The boundary between the unaltered and dolomitized pillows is sharp. Quartz amygdules are preserved in the dolomitized portion.

Helaby and Dodge (1976) report carbonate alteration associated with gold-bearing quartz veins in mafic rocks at Jabal Guyan. The Jabal Guyan ancient gold mines occur in an area of mafic volcanic rocks and felsic crystal tuffs (unit ma, fig. 2A) similar to units mv and fc in the Al Masane area.

Lapilli tuff and volcanic breccia

The lapilli tuff and volcanic breccia unit (lv), which underlies a large western part of the map area, was examined in several traverses to the south and at few helicopter stops to the north. It is characterized by felsic volcaniclastic rocks that are probably of rhyodacitic to rhyolitic composition. Lapilli tuff is perhaps the most abundant textural type, but tuff and volcanic breccia are common.

Reworked volcanic material--volcanic sandstone and conglomerate--are rare. Graded bedding is indistinct and rare. Shale interbeds up to tens of meters thick are also present. This unit is in conformable contact with the mafic volcanic unit (mv) and, by my interpretation, rests upon it.

Lapilli tuff is most abundant in the eastern part of the unit. It is typically medium to dark gray blue on fresh surface and weathers light gray to brown. Quartz crystals and white or light-colored pumice plates (up to several centimeters) are conspicuous, especially in the coarser rocks. Non-lapilli felsic fragments are also abundant. Both sand-size tuff, sometimes containing inconspicuous lapilli platelets, and grit to pebble-size volcanic breccia intervals are common in the western part of the unit. The coarse beds and those with equidimensional fragments tend to be massive and have only a weak foliation. Rare altered areas in breccias contain several percent disseminated sulfides. The alteration in one place is characterized by a mottling of fine-grained white quartz and dark-green zoisite-clinozoisite.

Light-brown-weathering interbeds of shale are most abundant in the central part of the unit, and very fine grained light- to dark-brown tuffaceous rocks (laminated and siliceous, similar to siliceous shale of the eastern shale unit) are most abundant in the western part. Coarse pyroclastics and lapilli tuff are also present in the west. Some dark resistant tuffaceous beds in the central and western parts of unit resemble the gabbro sills in overall exposure appearance. Dark-gray-blue to black calcite ovoids (a few millimeters to 15 cm in long dimension) elongated by a factor of 2 to 4 constitute up to a percent or two of lapilli tuff or tuff in the western third of the unit in the southern part of the area. They are coarse-grained (3 mm) marble, unlike the fine-grained dolomite or calcite beds found in other units of the map area, and their origin is uncertain. They are "rounded" as if transported, but occur in first-order volcanic sediments with angular clasts.

Mineralogy of the tuff, lapilli tuff, and volcanic breccia is similar to that of the lapilli tuff unit. Most samples contain both quartz and plagioclase phenocrysts. Plagioclase is twinned, unzoned, and metamorphically altered to albite. Epidote, chlorite, and sericite are present in most of specimens examined. Calcite seems less abundant (up to 5 percent) than in the felsic crystal tuff and lapilli tuff to the east. It was found in less than half the thin sections examined. The epidote mineral in most samples has blue-to-yellow or blue-to-brown interference colors and is probably zoisite or clinozoisite. Actinolite-tremolite needles were found in one specimen.

Relatively few folds were observed in the less competent rocks of this unit in comparison with the ubiquitous folds in the shale map unit (sh). Some of the deformation observed is probably attributable to intrusion of the numerous large gabbro sills rather than to regional tectonism. A few small-scale graded beds and a general westward decrease in grain size in sequences tens of meters thick, plus vesicles at the west sides of a few gabbro sills (see below), suggest that this unit is stratigraphically up to the west.

The lapilli tuff and volcanic breccia map unit (lv) is separated from the lapilli tuff map unit (lt) only by a narrow interval of shale and pillow flows of the mafic volcanic unit (mv) in the southern part of the map area. These tuff units have similar lithologies and might be products of the same cycle of volcanism. They probably constitute a continuous section south of the map area.

PROTEROZOIC INTRUSIVE ROCKS

Gabbro sills

Gabbro sills (gs), a few meters to several hundred meters thick, intrude all stratified units but are more abundant in the western part of the area. These correspond to Greenwood's (1980a) metadiabase sills. Some of the large masses in the west actually consist of multiple intrusive sheets. The gabbro is mostly fine grained, but the interiors of some larger sills are coarse grained. Margins are commonly chilled and basaltic in texture. Some larger sills are columnar jointed. The joint intersections plunge eastward in sills that dip westward.

Vesicles were found in the outer half meter or less of the western margins of three or four sills in the lapilli tuff and volcanic breccia unit (fig. 9; locality 4, plate 2). Their presence is interpreted as resulting from gravitational accumulation of exsolved gas at the tops of sills. Thus, the sills probably were intruded in a near-horizontal position and have since been tilted westward. The sills have been folded with the strata they intrude and have been metamorphosed to greenschist facies. Foliation is strong to imperceptible, depending largely on the distance from the sill margin. It is more intense at the margins.

Figure 9. The vesicular western margin of a gabbro sill that intrudes the lapilli tuff and volcanic breccia map unit near Wadi Shann about 1.7 km from the west side of the map area (locality 4, plate 2). On the basis of the assumption that the vesicles were produced by exsolved gases that rose upward in the magma to the roof of the sill, which was intruded prior to folding, the intruded section is considered to be stratigraphically up to the west.

Dolomitization of sill rocks, particularly small sills in the shale or mafic volcanic rock units, is common, though not nearly so widespread as in the mafic volcanic rocks. It is often associated with quartz veins.

The sills are considered to be gabbroic on the basis of color index. Saussuritized plagioclase constitutes about 35 percent of the gabbro, actinolitic amphibole 40 percent, and epidote and chlorite most of the balance. Clots of leucoxene(?), presumably after ilmenite, make up several percent, and trace amounts of pyrite and calcite are commonly present. The amphibole is pleochroic from colorless to pale green. Both large, euhedral crystals and smaller, metamorphically crystallized, ragged, crosscutting crystals are of the same composition. Presumably the euhedral actinolite crystals are pseudomorphic after hornblende, which in a few rocks is phenocrystic. No evidence for precursory pyroxene was found. Chlorite is most common as patches in actinolite.

Most sills are apparently quartz free, but a few contain 10-15 percent primary quartz. The quartz gabbro has a mineralogy similar to the gabbro. Quartz occurs as anhedral crystals sometimes intergrown symplectically with plagioclase. The plagioclase is albite ($N_{plag} < N_{qtz}$).

Slightly porphyritic felsic sills (f) of approximately dacitic composition exist in some of the gabbro sills. These have been metamorphosed to greenschist facies along with the host mafic sills. Perhaps they were differentiated in place from the basaltic sill magma. These sills are distinct from the felsic sills (fs) of the following section.

Plutonic rocks

The plutonic contacts were mapped largely by photo interpretation and the lithologic descriptions of plutonic rocks on plate 1 are taken from Greenwood (1980a). These rocks were examined only in reconnaissance in this study.

Felsic sills

Small felsic sillss (fs) have intruded, mostly concordantly, into the stratified rocks. They are seldom thicker than a few meters, and most are about a meter thick. The sills contain quartz and plagioclase phenocrysts and are mostly leucocratic. Those in the shale map unit (sh) have a few percent small phenocrysts and a fine-grained aplitic groundmass. A few sills examined in the felsic crystal tuff (fc) have 15-20 percent phenocrysts and are not leucocratic. They contain blocky zoned plagioclase (andesine?) phenocrysts, resorbed quartz phenocrysts, and biotite book phenocrysts partly altered to chlorite. Clusters of chlorite and calcite appear to be pseudomorphic after pyroxene? phenocrysts. This sill type is apparently rhyodacite. The finer grained sills are probably more siliceous.

The felsic sills were not metamorphosed with the strata they intruded. They cross-cut foliation and contain primary minerals. Alteration (sericitization of feldspar and chloritization of biotite) occurred during a later, milder event (intrusion of plutons?).

Some of the sills, particularly those in the northern part of the shale unit where they are more abundant, may be genetically related to the quartz monzonite plutons. No field examinations in and near the plutons were made with this question in mind.

Porphyritic diorite dikes

Unmetamorphosed diorite dikes (pd) as much as 20 m in width dip northeastward and transect folded metamorphosed strata and the gabbro sills (gs). They were identified only in the southwestern part of the area.

The diorite is 60 percent plagioclase (including 15 percent secondary sericite), 30 percent pyroxene, and 10 percent hornblende and magnetite, with trace amounts of chlorite, biotite, calcite, serpentine (after olivine?), and quartz. Euhedral plagioclase is zoned from An_{53} to An_{40}, and its size range (0.5-8 mm) defines a seriate porphyritic texture. Euhedral to subhedral clinopyroxene crystals are mostly augite ($2V(-) \sim 40^\circ - 50^\circ$) but occasionally have aegirine-augite ($2V(-) \sim 15^\circ$) cores. The augite is partly altered to hornblende that zones from pale green out to dark green. Small euhedral dark-green hornblende crystals are disseminated in the groundmass. Quartz occurs in ovoidal areas micrographically intergrown with potassium feldspar?.

Mafic dikes

Mafic dikes (m), in the northern part of the map area, trend mostly northwestward. Very few of these were examined. Trends are similar to those for porphyritic dikes (pd), but lithologies are more akin to basalt dikes (b).

Basalt dikes

East-west basalt dikes (b) a few meters wide occur throughout the map area. They are unfoliated and intrude all other Proterozoic rock types. The dikes intrude a prominent east-west joint set and commonly are weathered several meters deeper than the intruded stratified rocks (fig. 10). All the prominent linear features of this system are shown on the geologic map as dikes. Dikes were identified in most of these linear features but are not necessarily present in all. Many of them are obscured by talus.

The basalt dikes are black, aphanitic, and sometimes contain plagioclase phenocrysts. Gabbroic texture was seen in one dike. Pyrite is usually present in trace amounts. Calcite, apparently as amygdules, dissolves out to leave small (0.5-1 m) weathering pits. The dikes are basaltic or andesitic. At one locality a basalt dike is dolomitized where it intrudes dolomitized pillow flows. No petrographic work was done on these rocks.

The basalt dikes of the Al Masane area are part of a Proterozoic map unit of the Wadi Malahah quadrangle (Greenwood, 1980a), which consists of felsic to mafic, metamorphosed to nonmetamorphosed dikes. I have therefore shown them as Proterozoic on my map. I have no evidence to the contrary, having seen them in neither intrusive nor unconformable relation to the Wajid Sandstone.

Figure 10. View eastward along the course of a basalt dike 0.3 km north of the Saadah gossan. The weathering of the dike has formed chutes dropping steeply into Wadi Saadah and rising up the opposite canyon wall.

Figure 11. Looking north along the axis of a large antiform in the northwestern part of the broad strike valley underlain by the shale map unit.

PROTEROZOIC QUARTZ VEINS

Many quartz veins (q) in the area trend north-south, and some occupy north-south fault zones that offset the basalt dikes (b). Others tend to follow lithologic contacts. Some of the larger quartz veins (1-3 m wide) are shown on the geologic map (plate 1). The most important is in the south-central part of the map area in the mafic volcanic unit (mv). It contains several ancient mine workings. Carbonate alteration is not commonly associated with these veins, as it is with small cross cutting quartz veins (discussed in mafic volcanic rocks section).

ORDOVICIAN-CAMBRIAN WAJID SANDSTONE

The Ordovician-Cambrian Wajid Sandstone (OꞒw) caps a few small buttes in the northern part of the area, where it unconformably overlies quartz monzonite. There are extensive exposures immediately to the southwest of the map area. It is described by Greenwood (1980a) in his report on the geology of the Wadi Malahah quadrangle.

STRUCTURE

Major folds and bearing on the stratigraphic succession

Major folds have amplitudes on the order of tens to perhaps a few hundred meters, and their axes plunge at shallow angles (<30) in either direction along the regional strike of the beds (fig. 11). These folds are isoclinal, and most axial planes dip steeply to the west. Approximately 40 such folds are visible across the width of the shale (sh) unit. Many of these are shown on the geologic map (plate 1) where traverses were made. Most of these folds are overturned to the east, but the overturn symbol is omitted because these data were not always noted on field mapping sheets and because of the density of fold axes. Possibly the largest fold of this system in the field area is a synform delineated by the folded gabbro sill in the graywacke (gw) at the east margin of the map. No folds of this system were identified within the felsic crystal tuff (fc) or mafic volcanic rocks (mv), where they would likely be visible as folded interbeds (shale, dolomite, etc.). Fernette and Neckzcar (unpub. data) were also unable to identify major folds in this part of the section. The explanation for the contrast apparently lies in the differing competencies of the shale and the more massive volcanic rocks.

Evidence from pillow flows and sills shows that stratigraphic tops are to the west in the felsic crystal tuff (fc), mafic volcanic rocks (mv), and eastern part of the lapilli tuff and volcanic breccia (lv). Grading of beds suggests that the central and western parts of the latter unit dip mostly to the west. A few graded beds were found in the shale unit, but because of multiple folding, they are not useful for determining overall stratigraphic tops for this unit. However, if there is no major folding in the felsic crystal tuff east of the internal lens of mv, the shale unit must be stratigraphically beneath the felsic crystal tuff. This conclusion is supported by the occurrence of several antiform-synform couples in the shale in which a distinctive bed appears in the east limb of the synform and the common limb of the doublet, then disappears in the west limb of the antiform (fig. 12). The most important instance is near the center of cross section B-B', where a lapilli tuff bed in the westernmost fold recognized in the shale (sh) apparently dips beneath a mafic pillow flow at the base of the felsic crystal tuff (fc).

In contrast to the foregoing, Fernette and Neckzcar (unpub. data) conclude that, at least in the vicinity of the Saadah and Houra sulfide bodies, the strata are overturned and face east. Their opinion is based on a number of observations, made mostly underground, including the following: pillow facings in the layers just west of the Saadah gossan are dominantly to the east (in contradiction to my observations); at several contacts, clasts of one rock type are found within an adjoining lithology to the east; metal zonation (zinc/copper ratio increasing eastward) indicates, from comparison with other massive-sulfide bodies, that the top is to the east.

Possibly the resolution to our opposing conclusions lies in the existence of one or more unrecognized folds in the section of mafic and felsic volcanic rocks in the central part of the map area. Elsass and Pouit (1982) postulate an anticline within the mafic volcanic section that separates the Saadah and Houra gossans. According to this, the Saadah and Houra sulfide bodies are in the same horizon but on opposing limbs of this anticline. Fernette (written commun., 1983) disagrees with this, partly because he believes that the data at both Houra and Saadah show tops to the east, and partly, of course, because there is no structural evidence for the fold. This possibility of folding needs to be further evaluated.

The involvement of the gabbro sills (gs) in folding is germane to the problem under discussion. As discussed

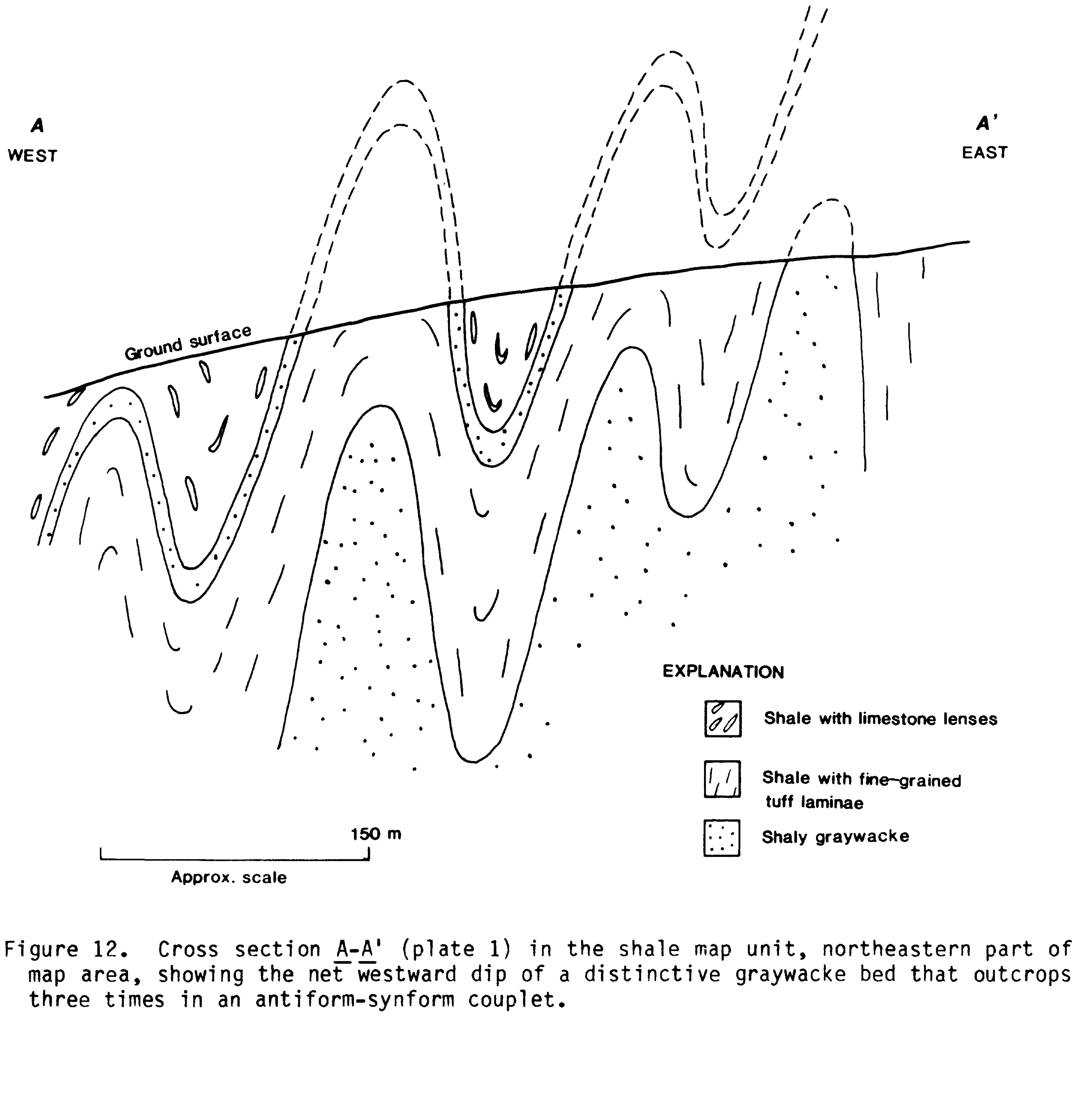


Figure 12. Cross section A-A' (plate 1) in the shale map unit, northeastern part of map area, showing the net westward dip of a distinctive graywacke bed that outcrops three times in an antiform-synform couplet.

earlier, it is hypothesized that the gabbro sills predate folding and regional metamorphism, and that vesicles concentrated on the western margins of some sills indicate stratigraphic tops to the west for the intruded strata. It was also stated earlier in the report, however, that the "U" shape of the large sill at the southern termination of the felsic crystal tuff (fc), may be a primary intrusive form. U shapes and other irregular forms encountered in gabbro sills in underground mining and drilling are considered by Fernette and Neckzcar (unpub. data) to predate folding.

It appears that some bends in sills are primary and that others are a result of folding. One small sill that is unquestionably folded occurs in a major antiform in the western part of the shale (sh) just north of cross section line B-B' (plate 1). The large sill in the graywacke (gw) is thought to be folded. The large U-shaped sill at the southern termination of the felsic crystal tuff should perhaps be examined again to see whether or not it has been folded. A fold axis in this bend would extend northward within the felsic crystal tuff.

Minor folds and crenulations

Folds with amplitudes on the order of few meters were found throughout the area, primarily in shaly and carbonate-rich beds (plate 2). They belong to two distinct groups, one with moderate to steep plunges to the northwest and one with shallow to moderate plunges to the south (fig. 13). Most of the folds are antiform-synform couplets, or "drag folds." Crenulation is a common, though often subtle, feature in the shaly rocks. Most crenulations have plunges similar to those of the two minor fold groups.

Most of the northwest-plunging folds have a dextral sense, indicating a component of bedding translation in which western beds moved northward and upward at about 30° - 40° relative to eastern beds. A contact of the Wadi Saadah gossan is folded in this sense. The south-plunging folds are smaller and considerably more abundant. The average plunge of the 21 south-plunging folds is 31°, exactly perpendicular to the average of 57 lineations (61°) (fig. 14) and nearly perpendicular to the average of the northwest sinistral folds (50°). Dextral folds predominate over sinistral folds by a factor of 2 in this group, but the presence of both indicates that there was both up and down movement, parallel to the lineation, of western beds relative to eastern beds. The distribution of crenulations is less systematic (fig. 13), and the sense of movement shows a negative correlation with the sense of movement on folds of similar plunge.

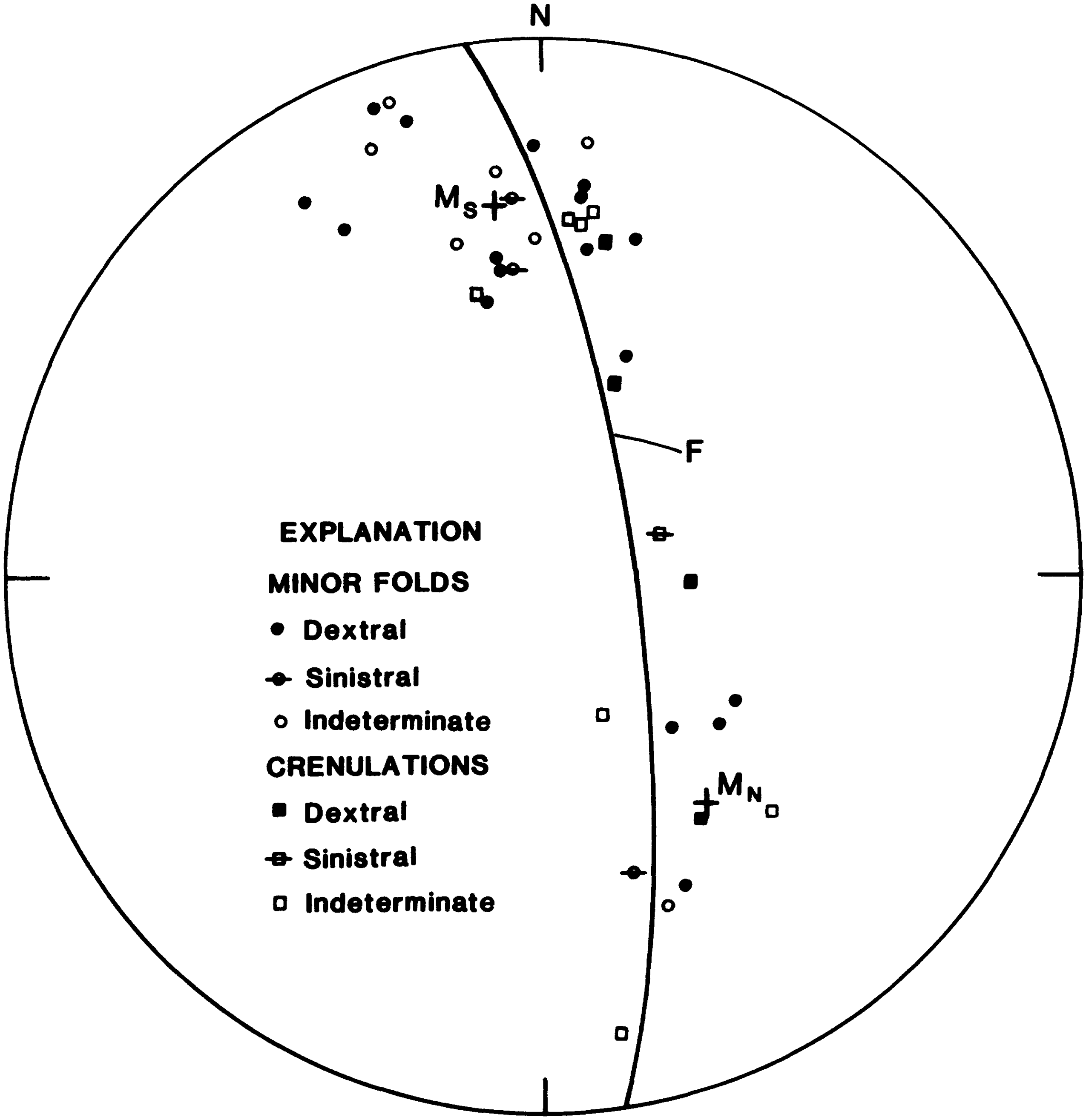


Figure 13. Axes and senses of deformation of minor folds and crenulations in reference to average plane of foliation (great circle F; see fig. 14). The cross M_S is the average of the cluster of gently southward-plunging folds; the cross M_N is the average of the cluster of steeply northwestward-plunging folds. In this and following equal-area stereograms, projections are onto the upper hemisphere.

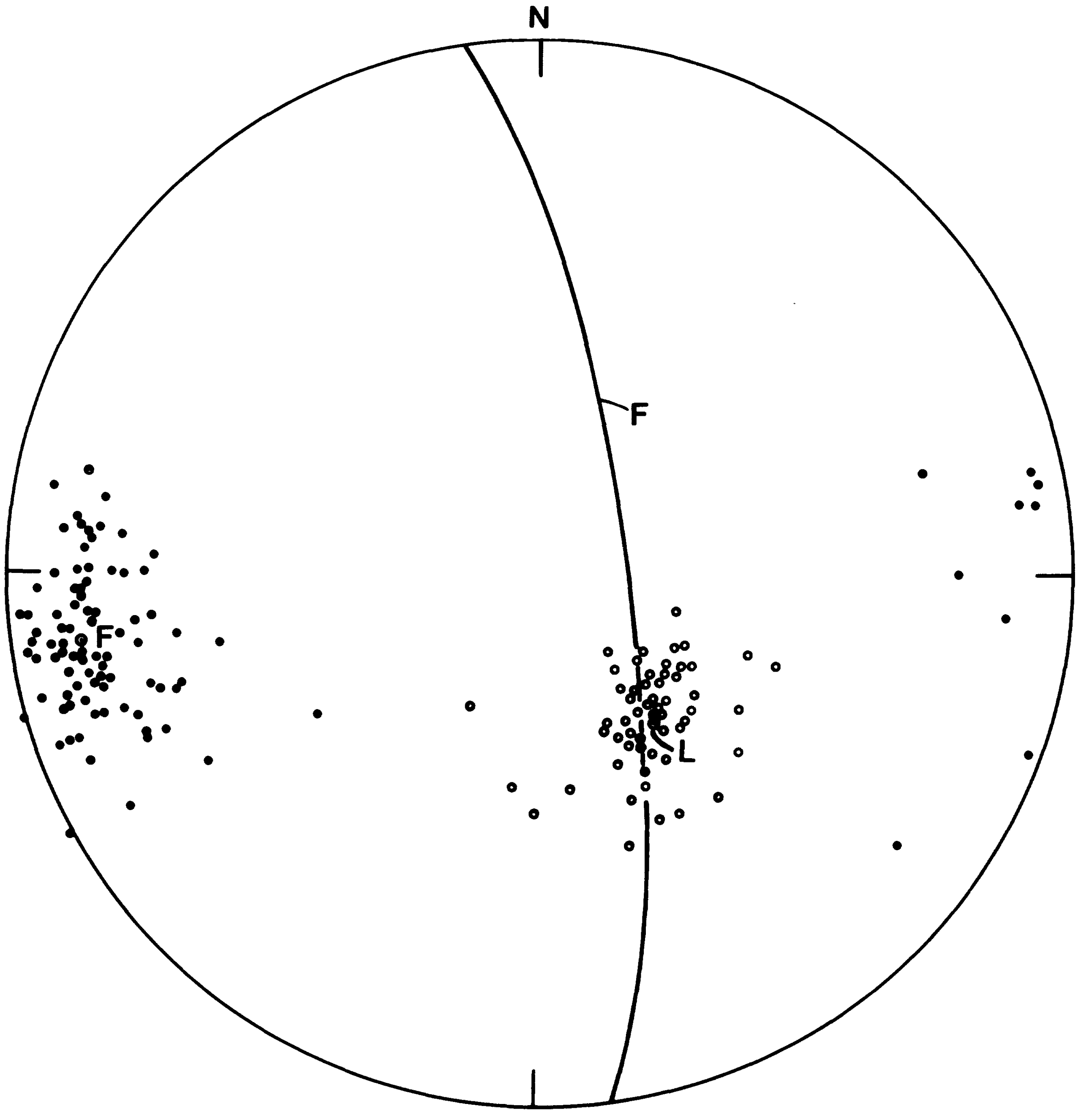


Figure 14. Lineations (circles) and poles to foliation (dots). Circled dots L and F are the average lineation and pole to foliation, respectively. The great circle F is the projection of the intersection of the average foliation plane with the upper hemisphere.

Foliations and lineations

The tight clustering of foliation and lineation data in figure 14 reflects the structural homogeneity of the study area. The average foliation (F, fig. 14) strikes N. 8° W. and dips 76° W. The average lineation (L, fig. 14) plunges 61° at an azimuth of N. 38° W. and lies only 1-2° off the great circle representing the average foliation. Thus the average measurements for the area closely represent actuality, which is that lineations lie in the foliation plane.

Foliation throughout the area is considered to be axial-plane foliation and nearly everywhere coincides with bedding. Thus the folding is isoclinal. Foliation is generally pronounced and strongly defined by parallel orientation of sheet minerals and by rock parting.

The lineations are streaks formed by elongation or disaggregation and smearing of minerals or clasts and by movement "tracks" of resistant objects such as quartz phenocrysts made during bedding-plane or foliation-plane slippage. These lineations are visible on most good exposures of foliation surfaces and are often conspicuous. Larger elements that are parallel or near parallel to the mineral streaks and tracks are tectonically elongated (elongation factors of 1.5 to 3) volcanic and sedimentary clasts and mafic flow pillows.

Joints

Poles to 75 joints in the Al Masane area are shown in figure 15. Though not so tightly clustered as the lineation and foliation data, they clearly show three major sets. At many localities (plate 2) measurements were made on all three sets. Joint sets A and B are conspicuous throughout the area where there are bold outcrops of massive rocks. Joints of set C, though less obvious, are also common throughout the area. At a few structure stations (plate 2), four joints were measured in single outcrop. Locally even more could have been measured. But joints outside the three main sets seem to show no systematic arrangement. These are represented by a few scattered measurements in figure 15. Joints of both set A and set B are nearly perpendicular to the joints of set C.

A minority of the basalt (b) dikes, some of those that trend west-northwest to northwest, and also the porpyritic diorite (pd) dikes may intrude joint set A. The group of short west-northwest-trending faults mapped in the southern part of the felsic crystal tuff (fc, plate 1) may actually

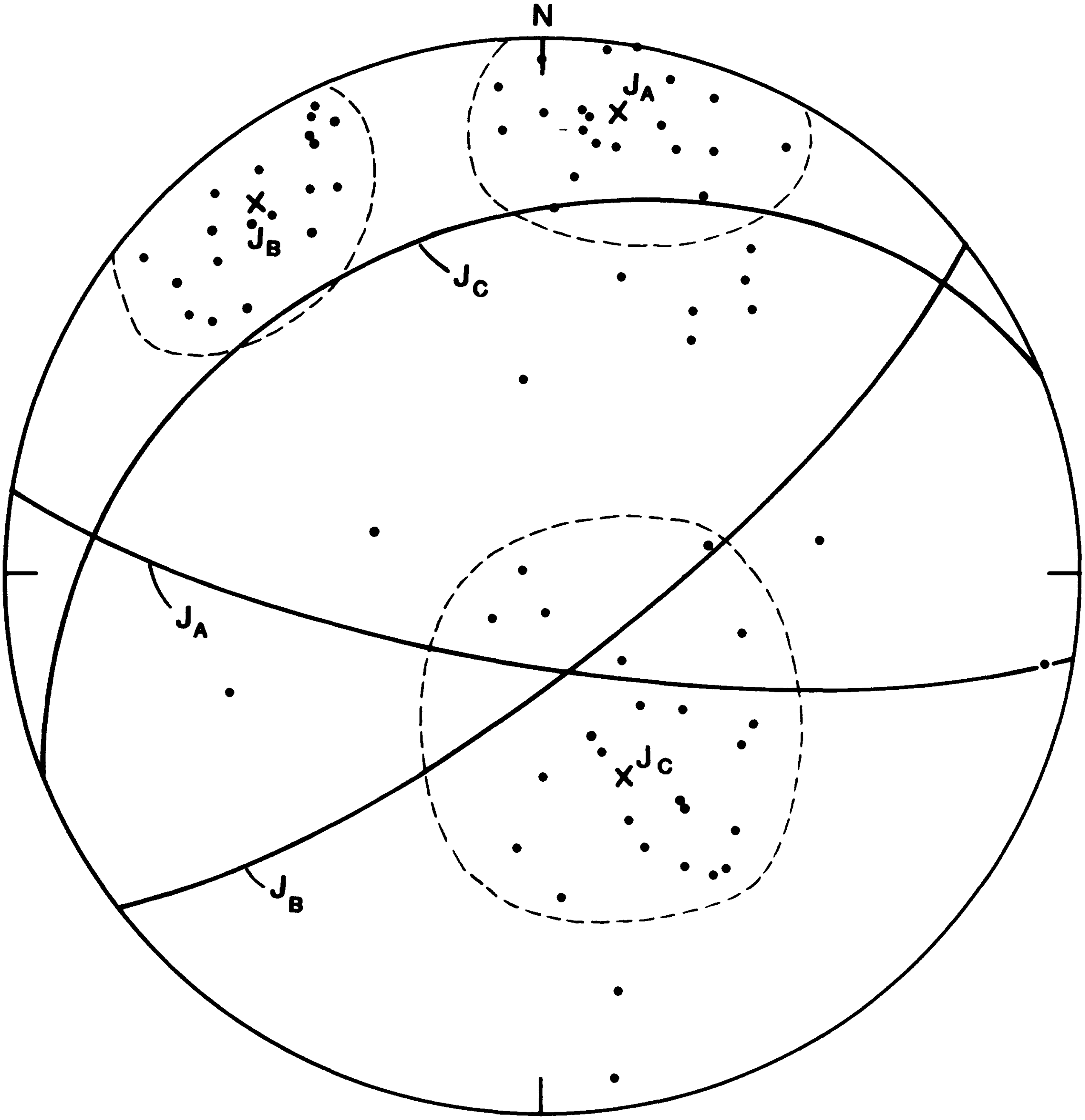


Figure 15. Poles to joints. Dashed lines enclose poles and average poles (X), J_A, J_B, and J_C of joint sets A, B, and C. Great circles (J_A, J_B, and J_C) are the projections of the intersections of the average joints with the upper hemisphere.

be joints of set A. Two northeast-trending faults, considered to be the oldest faults in the area (see section on faulting), are possibly genetically related to joint set B.

A fourth set of joints, not considered above and probably totally unrelated to these three sets, is the pronounced set of essentially vertical east-west joints along which the basalt (b) dikes were intruded. Joints of sets A, B, and C are considered to be products of regional orogenic (compressional) deformation, whereas the openings along which the dikes intruded are considered to be tensional gashes of a later tectonic episode.

Faults

There are three main fault systems in the map area, none of which contain faults with more than tens to perhaps a few hundred meters of offset. Not included in this discussion of faults are the group of short west-northwest-trending faults mapped in the felsic crystal tuff, which are likely pronounced joints of set A and which have little or no offset.

The oldest set consists of two short northeast-trending faults. One offsets a gabbro sill along the central part of Wadi Shann and the other is on the north side of Wadi Lahayfah 500 m from its intersection with Wadi Hizmah. Apparent movements on these faults are left lateral and right lateral, respectively.

A second set consists of northwest- to north-northwest-trending reverse faults that dip at moderate to steep angles to the southwest or west-southwest. Faults of this system are the most abundant and apparently have the most offset. These occur in the central and western parts of the area. Apparent offsets on these faults are measured in tens of meters, but actual offset could be considerably more.

Faults of the third set are essentially bedding-plane faults and strike parallel to foliation. Quartz veins up to a few meters in width are common in these faults; this relation was recognized where quartz veins occur on lines along which basalt dikes are offset in an apparent right-lateral sense. The best example is in the west-central strike valley of the shale (sh) 200 m east of the antiformally folded thin gabbro sill. Few, if any, of these faults are mapped for their full length. They are difficult to recognize except where there are quartz veins or offset dikes. There is little conspicuous fault gouge or cataclastic material in these zones. Some large quartz veins of this trend were not shown to occupy fault zones, but nevertheless may do so. The best example is the large vein which was mined anciently at several localities in the south-central part of the area. There was probably a continuum between demonstrated apparent right-lateral faulting and penetrative bedding-plane slippage, providing variable sites favorable to quartz deposition.

The latter two sets of faults both offset basalt dikes, but their relative ages were not determined. The following argument suggests that the set of two short northeasterly faults predates the intrusion of the basalt dikes.

The northeasterly fault on Wadi Shann intersects a north-northwesterly fault, but because the intersection is beneath drainage alluvium, relative ages cannot be determined with certainty. However, considering the amount of offset on the westward-dipping gabbro sill on the northeasterly fault and the shallower westward dip of the north-northwesterly fault, I would expect to see a discontinuity in the trend of the latter if it were offset by the northeasterly fault. By a similar argument, one might also expect to see a discontinuity in the trend of the porphyritic diorite dike (pd) at that locality. It appears therefore that both the north-northwesterly fault and the diorite dike are younger than the northeasterly fault. Because the diorite dike is intruded to the northwest by basalt (b), the northeasterly faults must predate the basalt dikes.

In the Wadi Malahah quadrangle, Greenwood (1980a) shows many extensive faults parallel or subparallel to the strike of strata and often bounding the various map units. Some of these faults pass through the Al Masane area and would be at several boundaries between stratified units of my map (plate 1) and at almost all gabbro sill (gs) boundaries. Though I find no evidence for many of these faults and consider offsets on others to be of a much smaller magnitude than Greenwood illustrates, I nevertheless agree with Greenwood regarding the existence of some of the faults he mapped. These belong to my second and third fault systems, most probably to the third system of strike-parallel faults. A reverse fault in the west-central part of the Al Masane area lies close to the east margin of a cluster of sills and may be one of the faults Greenwood mapped.

Tectonic implications

A complete structural analysis of the Al Masane area is beyond the scope of this work. The Al Masane structural data will at some point be integrated with data from my regional study between Dhahar and Wadi Qatan in an effort to evaluate the regional structure and stratigraphy. A preliminary analysis is given below.

Figures 16 and 17 illustrate systematic relations between folding, foliation, lineation, and jointing that link most of the structures developed in the Al Masane area to a single orogenic event. Actual field relations between foliation, lineation, and joints of sets A and B are sketched in the block diagram of figure 16. The intersections of joints of both sets with the foliation plane are invariably seen to be parallel to lineation. This relation is seen statistically in figure 17 in the near coincidence of the average lineation (L) with the intersections of the great circles representing the average joints (J_B and J_A) and the average foliation (F). It is also seen in figure 17 that the average pole to joint set C (J_C) and the average axis (M_N) for northwestward-plunging minor folds are very close to L and the intersections of the great circles; and that the average gently southward-plunging minor fold axis (M_S) is nearly perpendicular to these intersections. In other words, the lineations, the intersections of joint sets A and B and their intersections with foliations, the axes of one set of minor folds, and a line perpendicular to joint set C are all essentially parallel. Moreover, the axes of the other set of minor folds, which probably approximates the major fold axes of the region, are perpendicular to this composite of linear elements.

This set of systematic relations can only mean that the structures involved formed essentially simultaneously in the same stress regime. They can be related to a single deformational episode in which the principal axis of compressional stress was oriented approximately perpendicular to the foliation. This axis is also approximately a bisectrix to the small angle between joint sets A and B. This configuration corresponds to the predicted arrangement for fractures forming in response to such a stress (Hubbert, 1951; Hobbs and others, 1976, p. 326). Joint set C would be perpendicular to the near-vertical least-principal-stress axis and might be related to thrusting or erosional unloading at higher levels. The observed major isoclinal folds with near-horizontal axes formed in response to the east-west compression. Lineations plunging 60° to the northwest and minor folds and crenulations plunging 30° to the south-southeast imply that these major folds, on average, plunge gently southward. The lineations would have formed as a result of penetrative bedding-plane slippage perpendicular to the fold axes, and the minor folds and crenulations would be drag features formed also in response to bedding-plane (usually foliation-plane) slippage in limbs of larger folds.

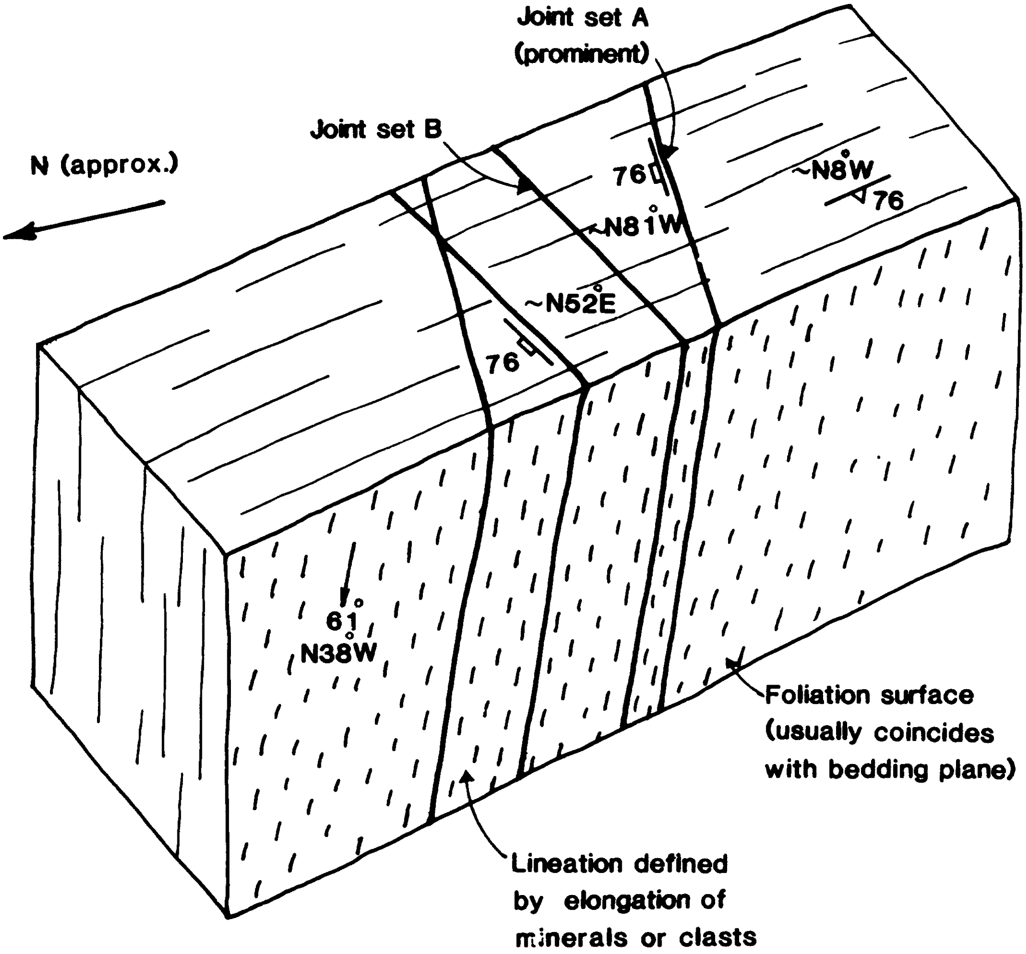


Figure 16. Block diagram illustrating the colinearity of lineation (mineral elongation) and intersections of joint sets A and B in the plane of foliation.

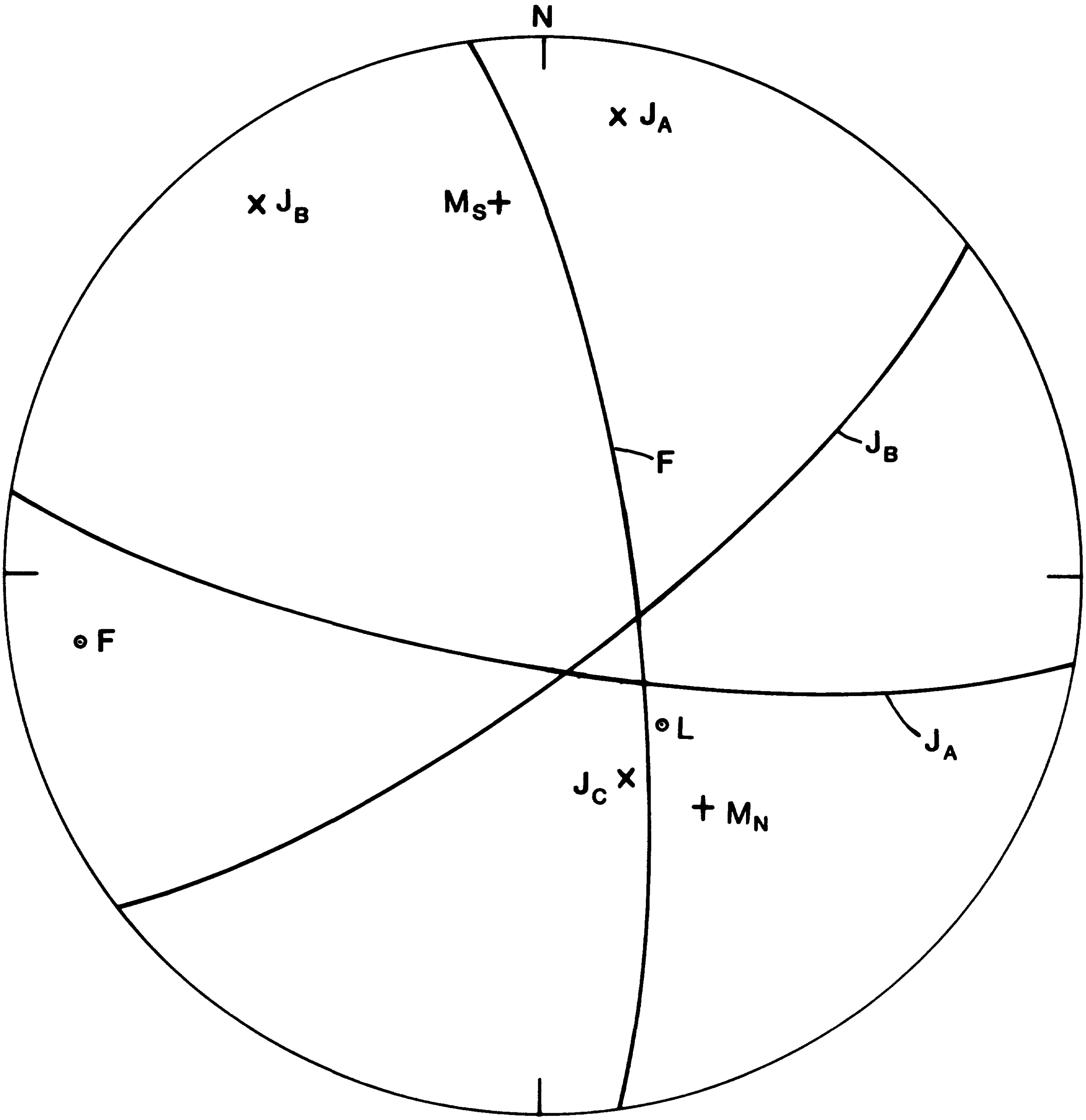


Figure 17. Comparison of average lineation, average minor fold axes, average foliation, average pole to foliation, average joints, and average poles to joints (symbols as in figs. 13, 14, and 15). Note the near coincidence of the average lineation, average northwest-plunging minor folds, and the average pole to joint set C with the intersections of foliation and average joints of sets A and B.

The minor folds of the set plunging gently southward are probably parasitic (second or third order) to the major (first or second order) folds in the area. Their fold axes are approximately parallel to the largest folds observed in the area, and their average plunge may hint at a gentle southward plunge of the first-order folds in the area. I suspect that the first-order folds are not the largest folds ("major folds") seen in the Al Masane area but are on the order of those hypothesized in figure 2A. They are not yet defined. The presence of both sinistral and dextral (looking southward, down axis) folds in this minor fold set is most simply interpreted to mean that some (sinistral) occur in the western limbs of major antiforms and others (dextral) occur in eastern limbs of major antiforms. In a classical view, which has genetic implications to which I ascribe, these are drag folds. A further analysis of these structures (including many more field measurements) might result in definition of major folds yet unseen and could aid in resolution of the problem of stratigraphic facing, discussed earlier. The greater proportion (~ 2:1) of dextral folds (implying western beds moving down with respect to eastern beds) may indicate a position for Al Masane, in the perspective of hypothetical (first-order) regional folds, in the eastern limb of an overturned "antiformorium."

If this interpretation is correct, and if stratigraphic tops are to the west, as argued elsewhere in this paper, the antiformorium would in fact be an antiformal (upside down) synclinorium. This arrangement would accord with hypothetical structure section C (fig. 2B). I made one field observation in the Al Masane area to support downward-facing folding. At locality 5, northeastern quadrant of plate 2, graded beds in the west limb of a synform in the shale unit (sh) seem to imply that the fold is a synformal anticline.

I raised the question earlier in the report about the possibility of folds facing downward at Wadi Qatan. I consider the suggestive evidence for downward-facing folds at Al Masane and Wadi Qatan to constitute a nonpreferred working hypothesis. This hypothesis of a regionally upside down section (refolded overturned limb of a huge recumbent fold(s)) should be considered along with other models for the stratigraphy and structure. The simplicity of the structure, as outlined above, argues against such a complicated structural framework.

The small set of northwest-plunging minor folds, which has axes parallel to lineation, is considered to have formed during and possibly late in major orogenic deformation. There is no evidence from my relatively small data set of a continuum between the two sets of minor folds. I conclude that they were generated independently, that is, one has no parentage in the other. For example, the northward-plunging folds are not locally rotated (refolded) members of the gently southward plunging set. This mode origin is similar to that proposed by Hopwood (1978) for "intrafolial folds." observed in isoclinally folded parts of many fold belts.

These mostly sinistral folds can be related to no larger folds. Their formation is best explained in terms of drag, with westerly beds moving northward and slightly upward relative to easterly beds. They could not logically form strictly contemporaneously with the set of minor folds to which they are perpendicular. Perhaps they formed late in the compressional episode as a result of a slight rotation of stress axes. These folds are rare, and, as in the case of the folded Saadah gossan (figs. 18, 19, and 20), developed in relatively ductile material. The Saadah gossan was probably elongated parallel to lineation prior to its folding and simply "rolled" a little to form the fold. Similar elongation and folding of ore bodies parallel to mineral lineation has been documented in other mineralized fold belts (Hopwood, 1978).

Little faulting occurred during the compressional deformation that resulted in the structures discussed above. The two northeasterly faults, considered to be the oldest in the area, are essentially parallel to joint set B and probably represent local movement on these joints during their formation. Some strike-parallel faulting may have occurred late in this deformational episode, possibly in response to a slight change in the stress field as suggested for the northwest-plunging minor folds.

Subsequent to the major orogenic deformation, only relatively minor jostlings occurred. The two plutons intruded the section and imposed local deformational structures on strata within a few hundred meters of the plutons. This event was apparently followed by a north-south tensional episode that opened joints along which the basaltic dikes intruded. Afterward. a northeast-southwest compression caused shortening on the southwest-dipping reverse faults and possibly also the apparent right-lateral offset on the bedding-plane faults. Alternatively, the bedding-plane faults resulted from a separate event.

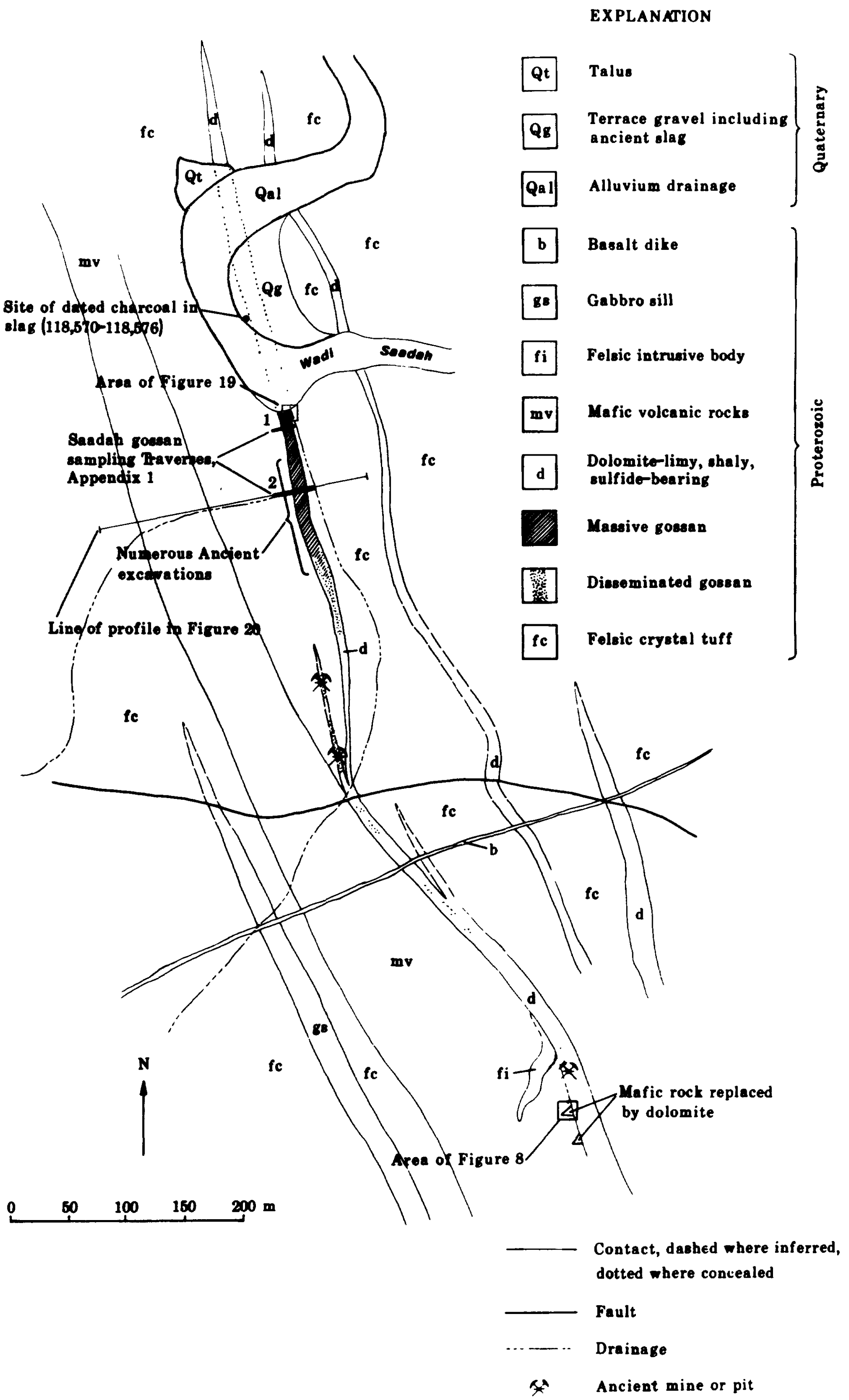


Figure 18. Geologic map of the Saadah gossan area, showing location of massive and disseminated gossans, the Saadah gossan sampling traverses, ancient mines, dated charcoal site, and figures 8, 19, and 20.

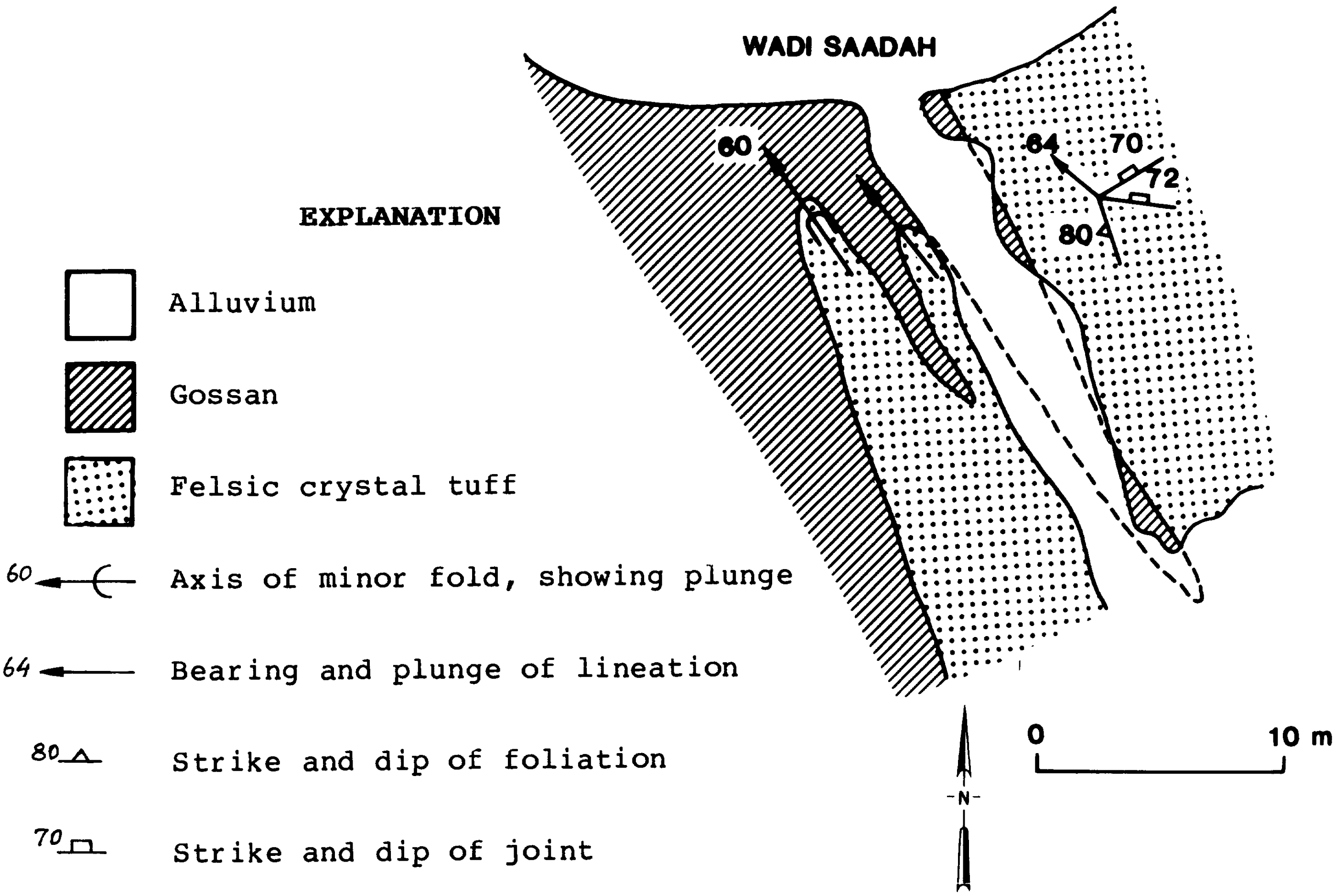


Figure 19. Sketch map of the folded contact of the Saadah gossan and felsic crystal tuff showing geometric relations between fold axes, lineation, joints and foliation.

METAMORPHISM

Some greenschist-facies minerals are oriented within foliation planes and(or) in lineation directions. They likely formed during the regional orogenic deformation discussed above. The mineral suites are all characteristic of the greenschist facies but show variable degrees of disequilibrium. Metamorphic amphibole (actinolite-tremolite) indicates highest greenschist-facies conditions locally. There is no correlation between grade of metamorphism and nearness to the plutons; several of the actinolite-tremolite-bearing pillow flows are in the center of the area. All mineral assemblages appear to be prograde. The only higher temperature minerals being altered to greenschist-facies minerals are the magmatic minerals of the gabbro sills.

Following the regional metamorphic event, felsic sills, diorite dikes, plutons, and the basaltic sills were intruded. None of these rocks are foliated, and primary magmatic minerals are largely preserved. However, the presence of some chlorite and epidote in the dikes and sills suggests that these rocks might have undergone incipient low-grade greenschist metamorphism in a nontectonic environment.

DOLOMITIZATION

Formation of carbonate-rich rocks occurred at several stages in the evolution of the Proterozoic rocks. Dolomite (with addition of Mg?) may have formed in these beds at a later time. Dolomite, usually associated with quartz veins, locally has replaced other rocks, primarily mafic volcanic rocks.

Sedimentary carbonate (mostly calcite) was an important minor rock type deposited contemporaneously with the felsic crystal tuff (fc) and mafic volcanic rocks (mv). Both carbonate and closely associated sulfide may have been chemically precipitated as a result of the cooling and mixing with sea water of oversaturated mineral-rich waters from hydrothermal systems on the ocean floor. Whatever the source of carbonate, the systematic bedded character of the dolomite (d) beds clearly indicates a sedimentary origin. These beds were not necessarily originally dolomite or even very carbonate rich. Their common close association with dolomitized rocks (for example, dolomitized pillow flows, fig. 8) and the petrographic similarity of carbonate in both the beds and the replaced volcanic rock suggest the possibility that the beds were also enriched in total carbonate in the dolomitization process.

Dolomitization of mafic volcanic rocks (mv) is described in an earlier section, and an example is illustrated in figure 8. Areas up to many tens of square meters are largely replaced by dolomite. The metasomatic replacement is usually irregular, as opposed to the systematic example of figure 8, and is nearly always associated with quartz veining. Replacement of other rock types by dolomite is far less common, but it was observed in gabbro sills and rarely in felsic crystal tuff. Greg Fernette (written commun., 1983) raised the possibility that the dolomitization of mafic volcanic rocks occurred as part of the hydrothermal activity that also resulted in formation of the massive-sulfide deposits. This is an attractive hypothesis, particularly since the sulfide lenses and the carbonate beds are clearly contemporaneous. There seems to be no systematic spatial relation between sulfide lenses and dolomitized areas, as would be expected if they are genetically related (for example, a footwall stockwork of dolomitized rocks and quartz veins beneath a sulfide lens). However, evidence for sedimentary transport of the sulfides (Fernette and Neckzcar, unpub. data) reduces the expectation of this spatial association.

Alternatively, the dolomitization could have been a diagenetic process or have occurred even later. Scarce dolomitization in the gabbro sills is evidence that it was still occurring (or recurred) after the sills were intruded. Even this, however, does not necessarily imply a great lapse of time between dolomitization and active volcanism. The sills could be hypabyssal products of the same volcanic cycle. Comparative chemical studies of the sills and extrusive mafic volcanic rocks might profitably be made with this in mind.

ORE DEPOSITS, MINERALIZATION, AND GEOCHEMISTRY

Ancient mines and slags

The major ancient workings of the area are in the gossans at the first horseshoe bend in Wadi Saadah (Saadah gossan) upstream from its intersection with Wadi Shann and in Sheb Al Houra (Houra gossan), a small northern tributary to Wadi Shann (plate 3 and fig. 18). Workings in the Saadah gossan consist of about a dozen pits or trenches ranging in size from a meter to 7 m in length and up to a few meters deep. Workings in the poorly exposed Houra gossan are similar but less extensive. Excavations in these gossans are in zones richest in malachite. There are other minor excavations, mostly in small gossans, elsewhere in the area (see plate 3). A trench several meters wide and 10 m long was made by the ancients in a large quartz vein in the south-central part of the area (plate 3). A few small pits in quartz veins were found elsewhere in the area.

There are two ancient smelter sites in the map area. It is from these heaps of slag and clay smelter fragments that Al Masane takes its name--Masane meaning "workings" or "factories."

One site is at the inside bend of Wadi Saadah only a few hundred meters north of the ancient workings of the Saadah gossan (fig. 18 and plate 3). Seven samples of loose charcoal fragments were collected from a 130-cm-high stream cut bank in the western part of this slag pile. The lower (0-20 cm) and upper (110-130 cm) composite charcoal samples were dated by Meyer Rubin at the USGS Radiocarbon Laboratory, Reston, Virginia. The dates are indistinguishable at 1,230±200 and 1,240±200 years before present, respectively.

Slag and clay smelter fragments are present a few hundred meters downstream from the intersection of Wadi Saadah and Wadi Shann on the south bank of Wadi Hizmah. The slag here is poorly exposed and scattered. Much of the slag area is under cultivation. Slag may be present further to the west than shown in plate 3. This site was probably used for processing of ore from the Wadi Houra ancient workings, because no slag is found closer to Wadi Houra. However, the volume of slag, based on surface distribution, may be considerably greater than at Wadi Saadah. This suggests, since the Saadah workings are more extensive than the Houra workings, that the ancient smelter site in Wadi Hizmah may have processed ore from more than just the Houra mine area.

Gossans and sulfide bodies

The distribution of gossans in the Al Masane area is shown in plate 3. The gossans examined are, with two exceptions, stratiform and associated with thin dolomitic and/or shaly layers interbedded with felsic crystal tuff and mafic volcanic rocks. The two exceptions are small east-west veins only a few centimeters wide.

The Saadah gossan is the largest and best exposed gossan. It is nearly 200 m in exposure length, and a northern extension is buried beneath alluvium of Wadi Saadah. At the sites of sample traverses 1 and 2 (analyses in appendix 1, locations shown in fig. 18 and plate 3), the gossan widths are 9.2 m and nearly 20_o m, respectively. The gossan dips with the strata about 75 to the west. Its greater width at the location of traverse 1 is probably due to folding, as illustrated in figure 19. This northwest-plunging fold is one of the set of minor folds whose plunges are consistently parallel to lineations and to elongations of coarser elements (for example, pillows). There is no indication of similar folding elsewhere in the gossan. Both tectonic elongation and the folding should have the effect of elongating the sulfide body along an axis plunging approximately 60 to the northwest. The proportion of gossan in the dolomite layer gradually diminishes southward (fig. 18). For about 400 m south of the gossan, the dolomite locally contains malachite veinlets and small gossan lenses.

A cross section of the strata in the immediate vicinity of the Saadah gossan is shown in figure 20. Descriptions in the caption of figure 20 come from a traverse in the steep drainage on the west wall of the larger north-south drainage that the gossan parallels. Gossan sampling traverse 2 was made at the base of this traverse. The conglomerate (possibly volcanic breccia) layer immediately above the gossan is limited in length to about 500 m. The conglomerate and overlying crystal tuff wedge out just south of the gossan, and the conglomerate is not found to the north across the alluvium in the bend of Wadi Saadah.

The Houra gossan lies in the floor of a straight stretch of Sheb Al Houra. This gossan is poorly exposed because of thin talus deposits along the drainage bottom. Ancient excavations were made in the few good exposures of gossan.

The Saadah gossan lies on the east margin and the Houra gossan on the west margin of a mafic pillow layer interbedded with felsic crystal tuff. They are not along a single shear zone as suggested by Meaton and Assiri (1967, 1970).

Gossans in the Badwah area at the north-central map border are approximately on strike with the Saadah and Houra gossans. No detailed mapping was done in this area, but a few samples were collected for analysis during a short helicopter stop. Much of the nonresistant shaly and(or) dolomitic rock in the Badwah area is weakly mineralized. Massive gossan is uncommon at Badwah. Probable conglomerate was noted about 30-40 m northeast of sample station 725 (plate 3). Dark-brown gossanous layers a few centimeters thick are interlayered with fine-grained sedimentary rocks in the eastern mineralized zone at Badwah. Both gossan and host rock contain disseminated malachite that is commonly seen only on a freshly broken surface.

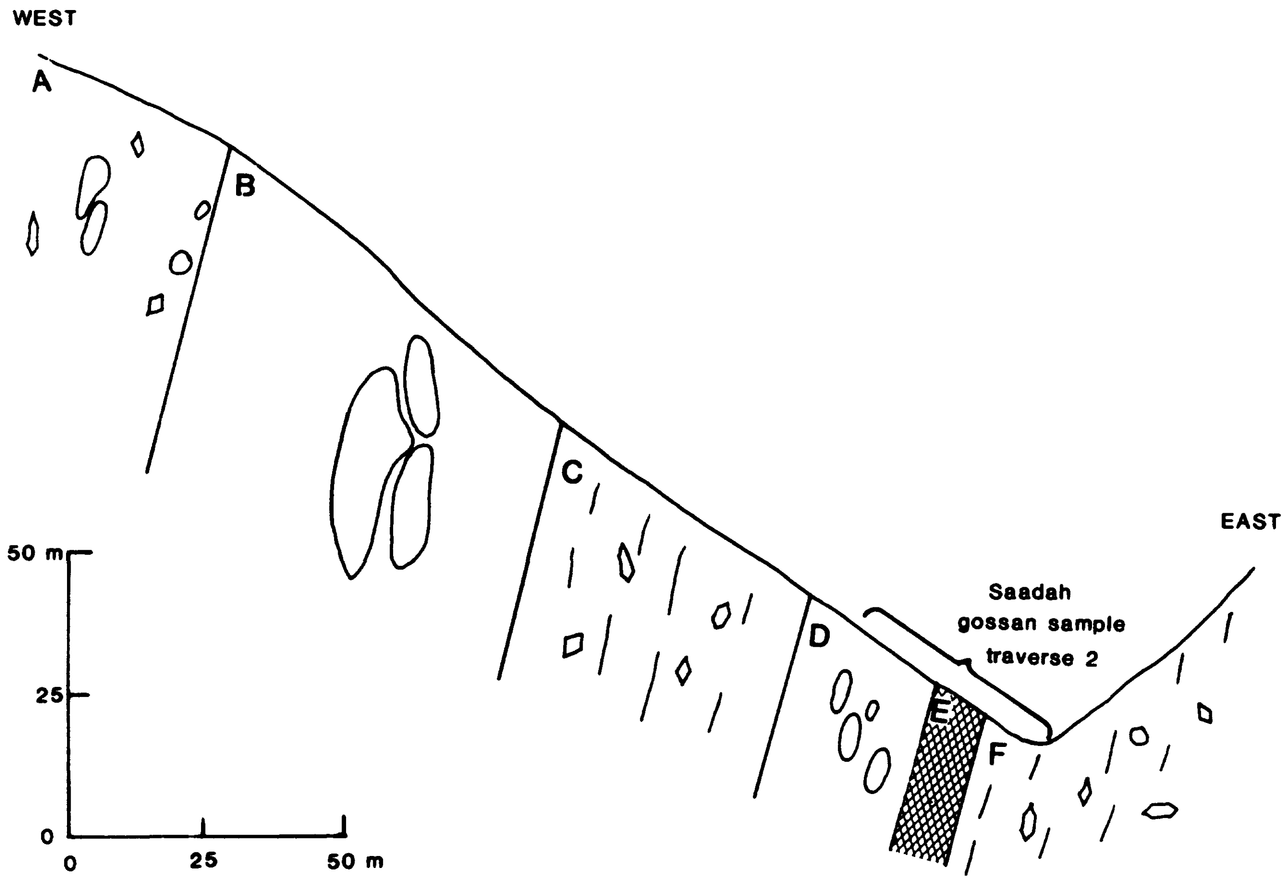


Figure 20. Cross section (see fig. 18 for location) of strata bounding the Saadah gossan. A. Mostly felsic crystal tuff with interbeds of pillow flows. Crystal tuff in contact with unit B contains mafic clasts in basal meter suggesting tops to west (locality 1, plate 2). B. Mafic pillow flows. Pillows are flattened in plane of foliation and elongated parallel to regional mineral lineation; they are 0.2 to 1 m in horizontal section and are smaller near unit A. Pillow draping indicates stratigraphic tops to the west (locality 2, plate 2). C. Felsic tuff. Quartz phenocrysts are present in most of this sequence but absent locally; rocks are fine grained and grade from light gray and tan at the base to dark gray green at the top. D. Conglomerate or volcanic breccia. Clasts are highly flattened in the plane of foliation; clasts are felsic volcanic rock, a large proportion of which contain quartz phenocrysts. E. Gossan. Mostly massive red and orange iron oxide with local black powdery material and talc or pyrophyllite. Dolomitic matrix and layers. Local veins of malachite. F. Felsic crystal tuff. Quite homogeneous, but subtly bedded with scarce thin beds of green shale. Contains quartz and plagioclase phenocrysts.

Mineralized portions of dolomitic or shaly beds in the central to southern parts of the map are similar in character to weakly mineralized parts of the Saadah and Houra gossans. Mineralizations are clearly stratabound and confined to the minor layers rich in fine-grained sedimentary material and poor in first-order volcanic material. Massive gossan is not common and usually occurs as little lenses gradational into disseminated gossan.

Only two crosscutting gossan veins were found in the study area. They are 2- to 3-cm-wide veins of massive gossan in a gabbro sill in the southern part of the area and in the northern part of the shale map unit.

Chemistry of gossans, mineralized rocks, and carbonate rocks

Analyses of gossans and mineralized rocks are given in appendices 1 and 2. Included in appendix 1 are analyses of composite samples from two traverses across the Saadah gossan, and of felsic crystal tuff and conglomerate within a few meters of the gossan. The silicate rocks, with no visible mineralization except for minor iron-oxide staining, contain silver, copper, lead, and zinc at levels much higher than in common felsic crystal tuff (see appendix 3). Zinc content is high (to 2,500 ppm) both east and west of the gossan, whereas lead and copper values are notably high (to 1,500 and 1,850 ppm, respectively) only in the conglomerate west of the gossan.

The 20 Saadah gossan analyses average 5.3 ppm (0.17 oz/ton) silver, 4,726 ppm (0.47 percent) copper, 3,387 ppm (0.34 percent) lead, and 3,454 ppm (0.34 percent) zinc. The extremely high lead (8.0 percent) and zinc (8.7 percent) values of sample 118312 and the zinc (7.6 percent) value of sample 118313 are excluded from these averages because these samples consist partially of black powdery materials (probably lead and zinc oxide) that are not common in the gossan.

In early drilling beneath the Saadah gossan, massive to disseminated sulfide in intercepts up to several tens of meters was found to average about 4.5 percent zinc, 1.5 percent copper, 31 ppm (1 oz/ton) silver and 5.3 ppm (0.03 oz/ton) gold (Hatem El-Khalidi, oral commun., 1977; and written commun. to Ralph Roberts, 1974; ASDC, 1974). Comparing these contents to the average metal contents of the gossan, it appears that the copper, silver and zinc are depleted in the gossan by factors of 0.33, 0.2, and 0.08, respectively (table 1). Daniels (1977) analyzed both gossans and fresh sulfide samples from Saadah. From his gossan and sulfide averages depletion factors of 0.36 and 0.08 for

Table 1.--Average base- and precious-metal contents of the Wadi Saadah gossan and underlying massive sulfide

	Percent			Parts per million		
	Zn	Cu	Pb	Ag	Au	Sc
This report						
Gossan	0.34	0.47	0.34	53	-	-
Sulfide	4.5	1.5	-	31	.94	-
Gossan/sulfide[1]	.08	.31	-	17	-	-
Daniels (1977)						
Gossan	0.56	0.70	0.092	-	-	242
Sulfide	6.8	2.0	0.88	-	-	156
Gossan/sulfide[1]	.08	.36	1.04	-	-	155

[1]Ratio.

copper and zinc and an enrichment factor of 1.04 for lead are derived (table 1).

The remarkably good agreement between my depletion factors and those of Daniels for zinc and copper may be partly fortuitous. Daniels' sulfide values are higher than mine because he analyzed selected drill-core samples rich in sulfides. Why his gossan values should also be systematically higher than mine, so as to result in the calculation of comparable depletion factors, is puzzling. Analytical bias may be involved. In spite of these uncertainties, the close agreement suggests that these factors can be used as a rough guide to ore content beneath gossans in the region. For strict comparison of AAS analyses, however, complete dissolution of the sample is necessary, as was done for this study.

Several gossan and gossany dolomite samples in the southward extension of the dolomite layer containing the Saadah gossan have high metal contents (samples 118728, 118729, 118132, 118131, 118126, 118129, appendix 2).

The Houra gossan (appendix 2) also has high contents of silver, copper, and zinc, and one of the four analyses is high in lead. Sample 118156 contains 11 percent zinc.

Badwah gossan analyses show only weak silver and lead enrichments over background but show strong copper and zinc enrichments, especially in the eastern zone. The copper to zinc proportion is much higher in this eastern Badwah zone (5 to 1, or 20 to 1 if the very high zinc value of sample 118720 is excluded) than in the Saadah and Houra gossans (about 1.5 to 1).

A small gossan in the south-central part of the map area (samples 118236 and 118237, appendix 2 and plate 3) is notable for its high silver and lead contents. Sample 118237 contains 1.3 percent lead and 74 ppm (2.4 oz/ton) silver. This gossan is small in outcrop and unimpressive in appearance, but these values indicate that it might be worth further investigation.

It is clear that sulfide-mineral deposits in the Masane area are related to the dolomite layers. Metal values in the dolomite samples (appendix 3) are considerably higher than associated felsic crystal tuff and higher than limestone in the area. (Silver is an exception, being higher in the limestone lenses, appendix 3.) In the Al Masane area there are gradations from dolomite through gossany dolomite to gossan. Similarly, distal geochemical gradients that might give "direction" to buried deposits may exist in dolomite. Detailed, systematic analytical study of the dolomite layers combined with detailed ground geophysical exploration at sites of geochemical anomalies is warranted for the Al Masane area and elsewhere in the region where dolomite layers are associated with subaqueously deposited volcanic rocks.

Quartz veins

The major quartz veins in the area trend approximately north-south, and many or all occupy faults. The longest quartz vein is in a pillow-flow layer in the south-central part of the area (see plate 3). It contains a half dozen ancient excavations, the largest of which is several meters deep and 10-15 m long. The quartz vein is a few meters wide. The quartz is gray to milky bull quartz and was apparently mined for gold. No gold was visibly detected, and no appreciable gold was found in two analyzed quartz vein samples (samples 118339 and 118340, appendix 2).

Chemistry of silicate rocks

Analyses of silicate rocks are arranged in appendix 4 according to map unit. The numerous silicate samples were analyzed to provide a background geochemistry against which to compare and contrast the gossans and carbonates and to look for anomalous metal values in the silicate rocks themselves. The chemistries of the units are quite homogeneous, including samples close to ore deposits (for example, sample 118113, felsic crystal tuff about 40 m from the Saadah gossan). The phenomenon of high metal content in silicate rocks adjacent to gossans, as discussed above, is probably limited to a few tens of meters from the gossan. Therefore, sites of a few silicate-rock samples with anomalously high metal values should be investigated. For example, sample 118645 contains high values of lead and zinc and comes from a site in the central part of the area near the dolomite layer that northward contains the Saadah gossan and lies near some ancient excavations in a quartz vein. It is concluded that silicate-rock chemistry is not as useful as dolomite chemistry in mineral exploration in the particular geologic environment of the Al Masane mineral deposits.

Average values for selected elements from the mafic volcanic unit and the felsic crystal tuff unit at Al Masane are compared in table 2 with Wassat formation and Qatan formation averages (Greenwood, 1980a, 1980b) from both the Wadi Malahah and Wadi Wassat quadrangles. These comparisons have implications for regional lithologic correlations and mineralization.

Table 2.--Averages of trace-element contents of Al Masane silicate rocks compared with regional averages of the Wassat and Qatan formations

[Underscored values are by atomic-absorption analysis; all other values are by semiquantitative spectrographic analysis except that for a few elements from the Wassat and Qatan formations some atomic absorption values are included in the averages; * indicates colorimetric analysis]

	Parts per million													Percent
	Ag	Cu	Zn	Pb	Ni	Cr	Co	V	Sr	Ba	Sc	Y	Zr	Ti
Wassat formation, Wadi Wassat quadrangle[1]	1.26	52	36	10	69	297	40	105	198	218	5	10	58	0.2
Wassat formation, Wadi Malahah quadrangle[2]	.95	66	68	10	28	279	40	218	146	72	29	13	16	.24
Mafic volcanic rocks, Al Masane[3]	1.3	103			63	560	54	503	238	20	48	19	33	.37
		83	85	25	56	302	48							
Felsic crystal tuff, Al Masane[3]	.6	18			7	176	13	38	257	312	21	41	72	.36
		12	75	12	12	125	17							
Qatan formation[4], Wadi Malahah quadrangle[2]	.62	41	74	10	22	107	34	142	142	133	21	13	28	.2
Qatan formation[5], Wadi Wassat quadrangle[1]	1.07	41	52	16	77	266	67	80	166	214	10	24	81	.15

[1] Average of data[6] from Greenwood (1980b, table 3).

[2] Average of data[6] from Greenwood (1980a, table 1).

[3] Average of data[6] from Appendix 4.

[4] Green to gray metasedimentary rocks.

[5] Light-colored dacitic unit.

[6] Values of samples obviously or possibly altered were not included in the averages. Random values considered to be extraordinarily high were also deleted. Values of lower sensitivity limits were used in the infrequent instances where the element was not found or was found to be present below the lower sensitivity limit.

At Al Masane and throughout the Wadi Malahah quadrangle, the Wassat formation contains both mafic and felsic volcanic rocks. Because Greenwood (1980a, table 3) does not identify the samples lithologically, I assume that analyses of both felsic and mafic rocks are present in the list of analyzed samples from the Wassat formation. If this is so, no direct comparison can be made between my averages for Al Masane and those of Greenwood for the two quadrangles; the average Wassat Formation values for the Wadi Malahah quadrangle may be equivalent to some combination of average mafic volcanic rocks and average felsic crystal tuff for Al Masane. Indeed, for 8 of the 14 elements in table 2, the Wassat formation values lie between the mafic volcanic rocks and felsic crystal tuff values, with from 30 percent to 87 percent mafic volcanic component required for appropriate end-member mixing. Considering the close approach to the lower detection limit for some of the remaining 6 elements, the scatter of data for some elements within units, and the inaccuracies of the analytical method, neither the wide range of required mixing proportions nor the theoretically impossible mixing for 6 elements would preclude a combination of felsic rocks and mafic rocks constituting the Wassat formation average. On the other hand, comparison of individual analyses for several elements, notably nickel, reveals an argument against mixing. There is relatively little scatter for nickel values in felsic crystal tuff and in mafic volcanic rock, yet nickel values for Wassat formation rocks in table 3 of Greenwood (1980a) tend to be intermediate, rather than being at the distinctly higher and lower levels expected if they represented felsic and mafic end members.

Thus I assume, without confirmation, that both mafic and felsic rocks are represented in Greenwood's Wassat formation in the Wadi Malahah quadrangle. In any case, I can make no direct comparison between the Al Masane rocks and similar lithologies in this quadrangle. It cannot be determined at present whether the "background" levels of the Al Masane rocks are anomalous in the region.

While it is possible that the mafic volcanic rocks of Al Masane are geochemically similar to mafic volcanic rocks of the Wassat formation elsewhere in the Wadi Malahah quadrangle, it is seen from table 2 that the mafic volcanic rocks of the Al Masane area are distinct in several ways from the mafic volcanic rocks (Wassat formation) of the Wadi Wassat quadrangle. Because the Wassat formation in the Wadi Wassat quadrangle is composed almost entirely of basalt, an average of Greenwood's (1980b) analyses should be representative of the basalt of this unit. The differences in

Table 3.--Average trace-element contents of volcanic rocks of the Habawnah fold belt and Mesozoic and Cenozoic oceanic rocks

	Parts per million											Percent	
	Cu	Ni	Cr	Co	V	Rb	Sr	Ba	Sc	Y	Zr	TiO_2	K_2O
MAFIC ROCKS													
Al Masane[1]	83	56	302	48	503	-	238	20	48	19	33	0.37	0.19
Wadi Amadin Al Husn quadrangle[2]	-	-	-	-	-	20	300	<100	-	-	-	1.3	.07
Wassat formation, Wadi Wassat quadrangle[1]	52	69	297	40	105	-	198	218	5	10	58	.2	-
Water Island spilites, NE Caribbean[3]	70	37	68	34	244	10	176	113	38	14	34	-	.81
Early island arc[4]	-	50	50	-	-	5	200	100	-	-	50	.8	.5
Island-arc tholeiitic basalt[5]	-	30	50	-	270	5	200	75	-	-	70	.8	.44
Island-arc tholeiitic andesite[5]	-	20	15	-	175	6	220	100	-	-	70	1.25	.43
Island-arc calc-alkaline basalt[5]	-	25	40	-	255	10	330	115	-	20	100	1.05	1.07
Island-arc calc-alkaline andesite[5]	-	18	25	-	175	30	385	270	-	21	110	.76	2.04
Abyssal tholeiitic basalt[6]	77	97	297	-	292	-	130	14	-	43	95	-	.15
MORB (midocean ridge basalt)[4]	-	100	300	-	-	2	100	15	-	-	100	1.5	-
FELSIC ROCKS													
Al Masane[1]	12	12	125	17	38	-	257	312	21	41	72	0.36	0.86
Wadi Amadin Al Husn quadrangle[2]	-	-	-	-	-	60	130	100	-	-	-	.28	.97
Water Island keratophyre (intrusive) - NE Car.[3]	10	4	3	4	12	23	87	401	9	-	108	-	2.8
Water Island keratophyre (extrusive) - NE Car.[3]	19	9	20	7	36	7	109	126	16	-	107	-	.37
Island-arc tholeiitic dacite[5]	-	1	4	-	19	15	90	175	-	-	125	.23	1.58
Island-arc calc-alkaline dacite[5]	-	5	13	-	68	45	460	520	-	-	100	.23	1.92

[1]Data from table 2; K_2O from G. Fernette and E. Neckzcar, unpub. data.
[2]C. M. Conway, unpub. data; averages are of 3 basalts and 3 rhyolites.
[3]Donnelly and Rogers (1980, table 1).
[4]Rogers (1982, tables 1, 3).
[5]Jakes and White (1972, tables 2A, 2B).
[6]Melson and Thompson (1970).

barium, scandium, and vanadium values are remarkably large and must be real. The Al Masane rocks contain 10 times as much scandium and 5 times as much vanadium, but only 1/10 as much barium as do the Wadi Wassat quadrangle mafic volcanics. Less disparate, but probably also real, zinc and zirconium are about twice as abundant in the Al Masane rocks as in the Wadi Wassat rocks. Copper may also be more concentrated in the Al Masane rocks. Nickel, chromium, and cobalt seem to be at comparable levels. The differences support independent arguments presented earlier for the nonequivalence of "Wassat formation" in the Wadi Malahah and Wadi Wassat quadrangles.

Although the felsic crystal tuff of Al Masane is not considered to be stratigraphically equivalent to the green to gray metasedimentary rocks of the Qatan formation in the Wadi Malahah quadrangle, they are, nevertheless, probably both products of felsic volcanism and are closely associated stratigraphically. The Qatan formation includes a lapilli tuff and volcanic breccia unit in the western part of the Al Masane area that is similar to felsic crystal tuff. Zinc, nickel, chromium, silver, and scandium contents are similar in the felsic crystal tuff and Qatan formation of the Wadi Malahah quadrangle and different from the Qatan formation of the Wadi Wassat quadrangle (table 2). Only in zirconium content are the Al Masane felsic rocks and the Qatan formation of the Wadi Wassat quadrangle similar and distinct from the Qatan formation of the Wadi Malahah quadrangle. The Qatan formation in the two quadrangles is similar and possibly distinct from the Al Masane felsic crystal tuff in titanium, strontium, and copper. Thus the geochemistry may weakly reflect an affinity between felsic crystal tuff and the Qatan rocks of the Wadi Malahah quadrangle. However, proportional elemental abundances between the "felsic rocks" of the Al Masane and the Wadi Wassat areas bears little similarity to the corresponding proportional abundances between "mafic rocks" of the two areas.

Greenwood (1980a, p. 32) noted that the median nickel value in the Wassat formation in the Wadi Wassat quadrangle is twice as large, but zinc and copper median values half as large, as respective values in the Wassat Formation of the Wadi Malahah quadrangle. He observed that the stratified nickel deposits of the Wadi Qatan area were thus "in a belt of nickel-rich and zinc-poor rocks, whereas stratiform zinc and copper deposits (of the Al Masane area) appear to be in a belt of nickel-poor and zinc-rich rocks." Ignoring the Wassat formation of the Wadi Malahah quadrangle, which may be a mixture of mafic and felsic rocks, and comparing only mafic volcanic rocks of the Al Masane area with Wassat formation mafic volcanic rocks of the Wadi Wassat quadrangle, we see (table 2) that the relationship suggested by Greenwood holds for zinc and copper, but not for nickel. The average nickel content for the Al Masane rocks is only slightly lower than in the Wassat formation of the Wadi Wassat quadrangle. Chromium and cobalt, which have geochemical affinity to nickel, are at slightly higher levels in the Al Masane mafic rocks.

In an attempt to make similar comparisons for the felsic rocks of both areas we see that the felsic crystal tuff is somewhat richer in zinc than the Qatan formation of the Wadi Wassat quadrangle, but contains only about half as much copper. Average nickel, chromium, and cobalt contents are much greater in the Qatan formation of the Wadi Wassat quadrangle than at Al Masane. Averages of the Qatan formation of the Wadi Malahah quadrangle tend to be intermediate but usually closer to values of felsic crystal tuff.

The correlations noted by Greenwood imply that strata of the Wadi Wassat quadrangle have better potential for nickel deposits than strata of the Malahah quadrangle and that the reverse is true for zinc-copper deposits. This assertion is probably valid; it is consistent with my arguments that there are several fundamental differences between the strata of the two areas. Nevertheless, this generalization must be applied with caution. Two facts--the nickel, chromium, and cobalt contents of the mafic volcanic rocks at Al Masane are virtually the same as those of the mafic rocks of the Wadi Wassat quadrangle, and that no nickel occurrences have been found in an association with the mafic rocks of the Wadi Malahah quadrangle--suggest that there is not necessarily a corrrelation between nickel level in the mafic rocks and rickel level in asociated massive-sulfide bodies.

GENESIS OF MASSIVE SULFIDES

The conclusion that the Al Masane massive-sulfide deposits are of volcanogenic origin is reasonable because of their association with volcanic rocks and because of their strata-bound character and consistent occurrence with the dolomite layers. I observed talc associated with the gossans, and Fernette and Neckzcar (unpub. data) found talc, chlorite, and chert lenses with the sulfides in drill core and in exploratory drifts. Fernette and Neckzcar (unpub. data) consider that the chert, talc, and chlorite, as well as the dolomite and sulfide, are of sedimentary origin. As noted by Fernette and Neckzcar, talc with similar characteristics and association at the Mattagami deposit (Roberts and Reardon, 1978) is considered to be of sedimentary origin.

My observations are insufficient to allow construction of a specific model for the evolution of the Al Masane deposit. Fernette and Neckzcar (unpub data), with more detailed mapping and underground data in the immediate vicinities of the sulfide bodies, have developed a model in which the sulfides are genetically related to hypothetical felsic eruptive sites to the west. In their model, the stratigraphic section is overturned and faces eastward. Felsic breccias and small semiconformable areas of silicification in rhyolite on the western margins of sulfide lenses are considered to be original footwall materials. The chert, chlorite, and talc lenses in close association with sulfides are considered to be products of exhalation of thermal fluids from the hot footwall area. An eastward increase in the Zn/Cu ratio in the Saddah gossan supports this model because an upward and outward increase in the Zn/Cu ratio has been demonstrated in numerous volcanogenic sulfide bodies (Franklin and others, 1981).

Because I found evidence for tops to the west in the pillow-flow unit between the Saadah and Houra horizons, because no footwall alteration pipes have been recognized, and because of the implications for folding (see discussion in structure section), I am not prepared to accept this model in its entirety. Brecciated sulfides and breccia composed of chlorite and chert (Fernette and Neckzcar, unpub. data) indicate sedimentary transport of ores and associated sediments. There is a strong possibility, particularly considering the complicated interlayering of sulfides and associated talc, chlorite, chert, and dolomite (Fernette and Neckzcar, unpub. data) that the sulfide bodies are distal. All the sulfide material, possibly including both mechanically transported and locally chemically precipitated material (from pools of brine), may be considerably removed from the source vent.

Increasing thickness of the felsic crystal tuff northward and a northward increase in both the amount and size of crystals in this unit suggest that its source is in the northern part of the map area or north of the map area. Hydrothermal systems north toward the source of the tuff (a possible caldera, as discussed earlier) may have been the source of the sulfides. This notion is attractive because of increasing evidence that hydrothermal systems are structurally localized and that the most favorable structures are faults related to submarine caldera formation (Ohmoto, 1978; Kouda and Koide, 1978; Hodgson and Lydon, 1977). A magma body beneath the caldera would be the heat source for the geothermal system.

Such a caldera source for the rhyolite is speculative; there may have been multiple geothermal systems throughout the area. In any case, the dolomite interbeds within both the felsic and the mafic volcanic rocks represent periods of relative volcanic quiescence when geothermal systems had sufficient time to produce sulfide and other chemical sediments at the sea water-rock interface. Consequently there could be well-developed alteration pipes and clearly proximal deposits in the Al Masane area. It is from such sites that the dolomite and associated sediments (including the sulfides) might have been derived. The dolomite lenses are impure. They contain both calcite, dolomite, sericite, quartz, and, near the sulfide bodies, chlorite and talc. They may be shaly or tuffaceous. These lenses are properly viewed as products of both distal or subdued volcanic (tuff, shale) and geothermal (sulfide, chert, talc, chlorite, carbonate) activity. Parry and Hutchinson (1981) found that at Four Corners in the Noranda District, Quebec, the base-metal sulfides are laterally equivalent to "exhalative tuffs" that accumulated during volcanic quiescence. This relationship is analogous to that at Al Masane, where the "exhalative tuffs" are the dolomite beds.

Carbonate materials in both the dolomite lenses and in dolomitized volcanic rock in the Al Masane area are similar. Locally, carbonate of the dolomite beds is continuous, with little or no distinction, into dolomitized mafic flows (see fig. 8). Carbonate that has replaced large areas of silicate rock is metasomatic in origin; the replacement process was possibly driven by a geothermal system. As already argued, the carbonate beds are of a distal, effusive geothermal origin. There is therefore a strong possibility that the "sedimentary" and the "metasomatic" dolomite are of related origin.

The most common alteration products in pipes beneath proximal massive sulfide deposits are chlorite and sericite (Franklin and others, 1981, p. 542-555). Carbonate alteration in pipes is uncommon. Carbonate occurs in pipes beneath massive-sulfide deposits at Madenkoy, Turkey, and in the Sturgeon Lake area of Ontario. In both areas the host volcanic and sedimentary strata are unusually rich in carbonate material. At Madenkoy, a copper-zinc massive-sulfide deposit occurs in an unmetamorphosed Cretaceous sequence of mafic volcanic rocks and porphyritic dacite tuffs and flows (Cagatay and Boyle, 1980). The massive sulfide is hosted by the dacitic rocks and is immediately overlain by "a unit of carbonate-rich, locally sulfide impregnated, pumiceous tuff that is overlain by spilitized mafic flows" (Franklin and others, 1981, p. 523). The footwall alteration assemblage consists of illite or sericite, kaolinite, montmorillonite, dolomite, siderite, and pyrite. The Madenkoy deposit also has a hanging-wall alteration of montmorillonite, calcite, kaolinite, and illite.

According to Franklin and others (1977) the 8,000-m-thick volcanic pile in which the ore deposits of the Sturgeon Lake area occur are unusually rich in carbonate when compared with the average Archean rocks of Goodwin (1972). The bimodal volcanic rocks, including a thick sequence of epiclastic rock with felsic clasts in a mafic matrix, all have a carbonate-rich (largely dolomite) matrix. Alteration pipes beneath the sulfide bodies contain large amounts of siderite, with chloritoid, andalusite, and minor chlorite (Franklin and others, 1975). Quartz and sericite are concentrated in the uppermost parts of the pipes. A large, semiconformable alteration zone beneath the pipes is characterized by a lack of feldspar and the presence of accessory ferruginous dolomite, chlorite, and andalusite. As at Madenkoy, siderite is a dominant mineral in the alteration pipe. Siderite is considered to have formed from dolomite by the substitution of iron derived from rising hydrothermal brine (Franklin and others, 1975).

The overall volcanogenic framework (basic physical characteristics of the volcanic suite and the products of hydrothermal alteration) of the Al Masane area is similar to the volcanogenic frameworks of Madenkoy and Sturgeon Lake. All three areas are characterized by bimodal suites of mafic pillows and flows and felsic pyroclastic rocks. Primary petrologic characteristics of the volcanic rocks are not well enough known to permit comparison. Carbonate interbeds or an unusually high content of groundmass carbonate in the volcanic rocks, or both, characterize all three areas. Minor black carbonaceous (graphitic) shales are present at both Sturgeon Lake and Al Masane. Black shale is present in the shale map unit at Al Masane and was also found underground intimately associated with the sulfide bodies (Fernette and Neckzcar, unpub. data). Massive-sulfide bodies in all three areas are similar, with zinc being considerably more abundant than copper. Finally, carbonate metasomatism occurred in all areas, producing dolomite and siderite in alteration pipes beneath ore bodies at Madenkoy and Sturgeon Lake, and causing dolomitization of silicate rocks (mostly mafic volcanic rocks) at Al Masane. These similarities suggest that carbonate-bearing pipes, possibly with siderite-rich cores proximal to sulfide bodies, might exist at Al Masane.

Implications for exploration

At the time my field work was done at Al Masane, I was not cognizant of the potential significance of the dolomitization. Regrettably, I failed to map the dolomitized areas I observed. In further studies at Al Masane and in the greater Al Masane region, dolomitized areas should be searched for and carefully mapped. In particular a search should be made for siderite, which might exist only in pipes beneath ore deposits. Variations in carbonate composition should be studied for systematic changes that might indicate directions to mineralized centers.

Other types of alteration should also be searched for in the region. Any silicified or sericitized areas should be examined for possible relation to alteration pipes. Chlorite-rich pipes could be present. In retrospect, I wonder if some of the felsic tuff I observed as being contaminated with mafic materials (some of the larger areas indicated by stippling in unit fc on plate 1) was actually chlorite altered. In particular, I recommend an examination of the area within 300 m directly east of the Houra deposits where stippling on plate 1 indicates intimate mixing of felsic and mafic detritus.

The dolomite beds in the area are marker horizons that, in my view, are direct indicators of periods of volcanic quiescence and, most importantly, of venting of hydrothermal fluids. These beds no doubt contain laterally extensive geochemical gradients that may define haloes around ore deposits. Major- and trace-element studies of these beds potentially constitute the single most powerful exploration tool in the region. Existence and systematics of trace-element haloes (K, Zn, Pb, Au, and Ag) are documented for Fe-rich dolomites and tuffs contemporaneous with lead-zinc ore at McArthur, Australia (Lambert and Scott, 1973). Similar haloes in sedimentary rocks laterally contemporaneous with ore deposits are described by Rose and others (1979, p. 120).

REGIONAL METALLOGENIC SETTING

The Al Masane deposits have characteristics in common with zinc-copper occurrences in the Dhahar and Kutam areas in the Wadi Malahah and Mayza quadrangles west of the Ashara-Wadi Mau fault zone. (The Wadi Mau fault zone in the Wadi Amadin Al Husn quadrangle is continuous northward with the Ashara fault zone in the westernmost Wadi Wassat quadrangle.) East of this fault zone, massive sulfides are pyrite rich and a few are nickeliferous; no zinc-copper occurrences are known. In contrast, west of this fault zone numerous zinc-copper occurrences have been found, many of which were mined anciently. To my knowledge only one nickeliferous occurrence, the Yassan gossan in the southeastern Wadi Malahah quadrangle, has been found west of the Ashara-Wadi Mau fault zone.

West of the Ashara-Wadi Mau fault zone the regional stratified section is largely volcanic and volcaniclastic and includes major intervals of shaly rock that is commonly graphitic. The volcanic rocks are largely mafic and felsic with little intermediate rock. From chemical analysis of felsic rocks in the Wadi Amadin Al Husn quadrangle (Conway, unpub. data) and at Al Masane (Fernette and Neckzcar, unpub. data) and from petrgraphic and field comparisons (including localities in the Mayza quadrangle), I tentatively conclude that the voluminous felsic crystal tuffs (quartz and plagioclase phenocrysts) of the region are largely rhyolite and not dacite as referred to by previous workers (Greenwood, 1980a; Anderson, 1979). I also tentatively suggest that basalt is more abundant than andesite in the mafic belts of the region.

The zinc-copper occurrences in this volcanic bimodal western part of the Habawnah mineral belt are closely associated with large masses of felsic rock; mafic volcanic rocks are also present. In some cases, much of the felsic porphyritic rock may be intrusive. As at Al Masane, the sulfide lenses sometimes occur in thin interbeds of fine-grained clastic or chemical sedimentary to volcanic rocks (chert, limestone, shale, tuff).

This broad setting applies to the three major zinc-copper districts, Al Masane, Dhahar-Al Hajrah (Smith, 1980); and Kutam-Farah Garan (Smith and others, 1977; Smith, 1979), and to most of the minor prospects of the region. Most of the sulfide bodies of the region contain appreciable quantities of silver and gold and most of the gold and silver occurrences (mostly quartz veins, many anciently mined) in the region (Smith and others, 1977; Smith, 1979; Riofinex, 1978; this report) are closely associated with zinc-copper sulfides. The Jabal Guyan ancient gold mine (Helaby and Dodge, 1976), the major gold occurrence in the Habawnah mineral belt, is not associated with a massive-sulfide deposit but is hosted in a complex of felsic and mafic volcanic rocks similar to those at Al Masane and Dhahar (fig. 2). I suggest that Jabal Guyan is a good place to explore for zinc-copper massive sulfides.

In agreement with Riofinex (1978), I suggest that the zinc-copper sulfide deposits at Al Masane, Dhahar-Al Hajrah, and Kutam-Farah Garan are all fundamentally volcanogenic. They are all closely associated with felsic volcanic centers, and their similar characteristics are due to formation from similar volcanic-hydrothermal systems. I further suggest that some of the differences between these occurrences are due to metamorphic modification that has caused mobilization and recrystallization of the sulfides and possibly differentiation of the metals. The closely associated gold veins may be an example of metamorphic differentiation.

The zinc-copper deposits in the Dhahar-Al Hajrah region (Smith, 1981) are remarkably similar to those at Al Masane except that there are broad areas of disseminated mineralization in chloritized rocks at Al Hajrah. Smith (1981) proposed a volcanogenic origin for the Dhahar-Al Hajrah deposits. It is important to note that whereas Greenwood (1980a) considered all the quartz phenocryst-bearing rocks at Dhahar to be intrusive, Smith (1981) found evidence that a large proportion is actually extrusive. At Dhahar aphyric mafic flows with pillows are closely associated with subtly layered felsic crystal tuffs. Dolomitic lenses occur within the felsic crystal tuff. Gossans are similar in appearance and composition, and sulfides from drill core have a high zinc to copper ratio. As at Al Masane, talc and carbonate material are closely associated with the sulfides.

Smith (1981) concludes that the disseminated mineralization at Al Hajrah is a stockwork-type mineralization spatially related and probably genetically related to quartz porphyry dikes. Almost certainly the disseminated mineralization in chloritized rocks represents footwall alteration in a volcanogenic hydrothermal system; it implies the nearby presence of a proximal massive-sulfide lens that would have formed above the alteration "pipe" at the rock-sea water interface.

The Al Masane and Dhahar-Al Hajrah deposits possibly occur in approximately the same regional geologic unit (fig. 2). In further developing a specific genetic model for exploration in this section, characteristics of the deposits of both areas should be considered together. The extensive alteration (pyritization, chloritization, and epidotization) documented by Smith at Al Hajrah has not been recognized at Al Masane but could nevertheless exist in the area. On the other hand, perhaps only carbonate footwall alteration characterizes the Al Masane deposits.

Smith and others (1978) consider that the Kutam deposit and similar smaller deposits at Farah Garan and Hemair in the southwestern part of the Mayza quadrangle are epigenetic. However, Smith's statement (Smith, 1979, p. 41) that the origin of the quartz porphyry (in the Kutam region) "is important in respect to the genesis of the sulfide deposits...." clearly indicates that he was thinking in terms of a genesis related ultimately to felsic igneous activity. From my observations at Kutam and Farah Garan and from a careful review of the published descriptions of these occurrences, I suggest that these deposits are mobilized and recrystallized volcanogenic deposits. A specific model for the origin and modification of the Kutam deposit is outlined in the following paragraphs.

The mineralization at Kutam (Smith and others, 1978; Anderson, 1979) occurs in quartz porphyry near a contact with a body of mafic volcanic rocks. Anderson (1979, and in Smith and others, 1978) considers apophyses of the porphyry in the mafic rocks and inclusions of the mafic rocks in porphyry to be the evidence of an intrusive origin for the quartz porphyry. Anderson (1979) includes the porphyry in a large plutonic mass of porphyritic diorite and quartz diorite. Smith (in Smith and others, 1978), questioning the intrusive nature of the quartz porphyry, says there is no direct evidence of intrusive features, and he describes possible bedded variations in the quartz porphyry and apparent interlayering or conformity with other rock types (chert, graphitic schist, and mafic volcanic rocks). Thus both intrusive and extrusive rhyolite are possibly present in the bimodal host suite at Kutam.

Mineralization at Kutam is largely structurally controlled (Smith and others, 1978). Concentrations of sulfides (pyrrhotite, pyrite, chalcopyrite, and sphalerite) occur primarily along faults and shear zones trending N. 20° W. to N. 60° W. The southwestward-dipping shear zones are essentially parallel to penetrative foliation and were initially controlled by foliation. However, later movement on the faults, notably that on the major Kutam fault, postdates formation of schistosity. This fault forms the southwest boundary of the mineralized area and is itself mineralized.

The footwall block consists mostly of quartz porphyry but also contains mafic volcanic rocks. In and near the 20-m-wide Kutam fault zone are jasperoid, marble, talc, actinolite schist, and sericite schist. The hanging wall contains mostly quartz porphyry and mafic volcanic rocks. Chlorite alteration is widespread in upper parts of the hanging wall, and silica alteration occurs beneath this. Sphalerite is most abundant in the Kutam fault and nearby in the hanging wall. Chalcopyrite is most abundant in the chloritized rocks, where it partially replaces chlorite. From analysis of drill core, Smith and others (1978) documented a consistent zonation throughout the mineralized area of zinc enrichment in the uppermost hanging wall and footwall.

The evidence for fault-controlled, postmetamorphic crystallization of sulfide minerals at Kutam does not preclude a premetamorphic volcanogenic origin. The nature of the host rocks, the types and distributions of alteration, and the metal zonation are all consistent with formation of a massive-sulfide deposit above a magmatically driven hydrothermal system on the sea floor (see for example, Franklin and others, 1981; Henley and Thornley, 1979; Large, 1977; Sangster, 1972; Klau and Large, 1980).

A common, well-documented habitat for volcanogenic massive sulfide deposits is a felsic volcanic center, quiescent with regard to volcanism, but active hydrothermally. At Kutam both extrusive and hypabyssal porphyritic rocks are apparently present as evidence of proximity to an effusive site. The chlorite, sericite, and silica alteration in the footwall at Kutam are similar in character and distribution to alteration pipes beneath many volcanogenic massive-sulfide deposits (for example, Gibson and others, 1983; Riverin and Hodgson, 1980; Connelly and Conway, 1983).

In recent years, studies of alteration associated with massive-sulfide deposits have shown that in addition to the alteration "pipes" immediately beneath volcanogenic massive-sulfide deposits there is often a much larger semiconformable alteration zone from which the "pipes" arise or upon which the "pipes" may be superimposed (Franklin and others, 1981, p. 542; Gibson and others, 1983; MacGeehan, 1978; Franklin and others, 1977; Walford and Franklin, 1982). Silicification may form an impermeable cap approximately at the top of this lower conformable alteration. At Noranda (Gibson and others, 1983), such a silicified cap rock is considered to have been breached along synvolcanic faults to allow discharge of thermal metal-bearing brine onto the sea floor. Massive-sulfide bodies and subjacent chlorite and sericite pipes were formed from interaction of this brine with sea water and wall rock. Similar siliceous cap rocks and pipes have been observed at Bagdad, Arizona (Connelly and Conway, 1983; Conway and Connelly, unpub. data).

Such a model may be applied to the Kutam deposit, where sulfides occur above and within a footwall chlorite-sericite alteration area that is above a silicified zone. The silicified zone at Kutam may have been an impermeable cap to a broad semiconformable alteration area, and the structurally overlying chlorite- and sericite-rich rocks may represent the alteration pipe at a site where the cap was ruptured. Massive sulfides within and above the chlorite-sericite zone and jasperoid and marble above the chlorite would all be materials formed by precipitation from cooling brines being diluted at the rock-sea water interface. Thus stratigraphic tops would be to the southwest at Kutam; the present hanging wall would be the original hanging wall. The metal zonation is consistent with this hypothesis. In subsequent deformation, relatively incompetent zones of sulfide, chlorite, and sericite localized faulting, notably the Kutam fault. Other reconstructions are possible as well, particularly given the great variation in footwall alterations of studied volcanic massive-sulfide deposits (Franklin and others, 1981).

Remobilization of massive-sulfide deposits in orogenic belts is now widely recognized (Kinkel, 1962; Kalliokoski, 1965) and was a deterrent to the evolution of the theory of volcanogenic origin of massive-sulfide deposits. Superimposed shearing on the footwall rocks of the Flin-Flon deposit (Sangster, 1972; Franklin and others, 1981) has remobilized the sulfides and obscured the original alteration patterns. Nevertheless, from numerous similiarities to well-preserved volcanogenic massive sulfides elsewhere, it is concluded that the Flin-Flon deposit is also volcanogenic. The arguments for the volcanogenic origin of the Kutam deposit are similar to those for Flin-Flon.

TECTONOMAGMATIC SETTING

In 1974, at a symposium on metallogeny and plate tectonics, Garson and Shalaby (1976) proposed that stratified rocks of the Proterozoic Arabian-Nubian Shield formed in a primitive marginal basin (Red Sea geosyncline) similar to that of the modern southwest Pacific. They envisaged a plate tectonic model with a westward-dipping subduction zone at an African Archean craton-ocean basin boundary at the present position of the Zagros. Repeated rifting of the craton resulted in formation of additional subduction zones and marginal basins in which new oceanic crust and island-arc volcanic rocks of the Shield formed. These basins were closed during successive orogenic events with sutures marked in both Arabian and Nubian Shields by belts of ultramafic rocks interpreted to be ophiolites. Mineral deposits of the region were genetically related to stages of the plate-tectonic evolution; Cu-Ni, Cu-Ni-Co, and Cr mineralization in ultramafic rocks to ocean-ridge volcanic processes, Cu-Mo, Cu-Au, and Cu-Zn mineralization in mafic and felsic volcanic rocks to island-arc volcanism, and Sn-Mo-Ta-Be and Sn-Mo mineralization in late granites of the shield to volatile streaming in the continental crust (segmented Archean crustal blocks). The metallogenesis of the region was considered to be analogous to that of the modern circum-Pacific region.

It is difficult to understand why Garson and Shalaby invoked an Archean craton in their model, inasmuch as no Archean rocks were known in the shield area and, in fact, no basement was recognized beneath the oldest volcanic rocks dated at about 1 b.y. There is yet no conclusive evidence for a pre-existing continental crust beneath the middle to late Proterozoic rocks of the shield, though other authors have also postulated such a crust, and some specific terranes, many since discounted, have been cited as candidates. Recently, the Kashebib Group in the Red Hills of Sudan has been suggested as a candidate for continental basement (Pohl, 1981). Lead (Stacey and Stoeser, 1983) from rocks and ores of the Al Amar region of the Arabian Shield has an apparent continental contribution, and single samples from Najran, Saudi Arabia, and Aswan, Egypt are of similar character. In total, the evidence of recent years is compelling that no continental crust existed beneath the oceanic volcanic rocks of most of the shield (Gass, 1981; Stacey and Stoeser, 1983).

Aside from the Archean basement problem, the tectonomagmatic settings proposed by Garson and Shalaby for the ore deposits of the shield have been largely supported by subsequent studies. Most of these studies have not dealt with mineral deposits, but only with magmatic and tectonic evolution. In studies of regional metallogenesis, Al-Shanti and others (1978) assigned a tripartite classification similar to that of Garson and Shalaby and suggested that mineral and lithologic belts might be correlated across the Red Sea, and Delfour (1980) proposed an integrated geologic, tectonic, and metallogenic scenario for mineral deposits of the northern Arabian Shield. Other reviews of the massive sulfide deposits of the Arabian Shield (Routhier and Delfour, 1975; Roberts, 1976; Rye and others, (in press) have dealt primarily with local settings and evidence for epigenetic or syngenetic origin.

Jackaman (1972) suggested, on the basis of chemical similarity to modern island-arc rocks, that volcanic rocks in the Wadi Bidah and Wadi Wassat areas might have formed in an ancient island-arc environment. Greenwood and others (1976), emphasizing extensive regional mapping and also utilizing limited chemical data (mostly from Jackaman, 1972), proposed that the southern Arabian Shield was cratonized in late Proterozoic time from volcanic and plutonic rocks that "evolved in an intra-oceanic, island-arc environment."

Numerous publications of recent years (for example, Neary and others, 1976; Al-Shanti and others, 1978; Schmidt and others, 1978; Fleck and others, 1980; Engel and others, 1980; Greenwood and others, 1980; Gass, 1981; Kroner, 1981; Greenwood and others, 1982; Roobol and others, 1983) generally support the island arc-subduction model, but with wide variations in details of the models. Thus there is little doubt concerning the general tectonomagmatic setting of the submarine massive sulfides of the Arabian-Nubian Shield, though many questions remain regarding important regional and local details of metallogenesis. Variations in the plate-tectonic mechanism, boundaries and sequence of formation of the individual arcs, possible sites and degree of continental-margin involvement, intra-arc structure and magmatic evolution, all of which will be essential for developing actualistic models of metallogenesis that will have practical application in exploration, are largely issues of the future. A key avenue of research in addressing these problems is the petrochemistry of the igneous rocks.

It has long been known that distinct rock series exist in Neogene volcanic arcs (Kuno, 1960, 1966). Jakes and Gill (1970) showed that an island-arc tholeiitic suite (essentially the same as Kuno's tholeiitic or pigeonitic series), generally early and near the trench, is clearly distinguished in trace-element content from an island-arc calc-alkaline suite (Kuno's calc-alkaline or hypersthenic series), generally later and further from the trench, and from the abyssal tholeiitic series. Subsequent work (Mackenzie and Chappel, 1972; Miyashiro, 1974; Garcia, 1978; Donnelly and Rogers, 1980; Ewart and LeMaitre, 1980; Ewart, 1982; Rogers, 1982; and Dixon and Stern, 1983) has provided further documentation of a continuum of differences between volcanic rocks formed at mid-ocean ridges, in oceanic islands, in primitive island arcs, in mature island arcs, and in continental margin arcs. It appears possible that geochemical subdivisions of these classes may by made in certain instances. Detailed work (e.g. Mariana arc, Dixon and Stern, 1983) indicates considerable comnplexity and overlap in the generation of "primitive-like" and "mature-like" volcanics.

This recognition of geochemically defining characteristics, in connection with other criteria of definition of volcanic rock suites, has led to studies of volcanic rocks hosting polymetallic sulfide deposits in an effort to better understand the settings and evolutions of mineral deposits. MacGeehan and MacLean (1980a, 1980b) consider that the mineralized Archean volcanic belt at Matagami, Quebec, which along with virtually all greenstone belts in the Canadian sheild has been called calc-alkaline, is actually an extensively altered (basically regionally spilitized) bimodal tholeiitic complex composed of basalt and rhyolite. The alteration has led to artificial "calc-alkaline" trends. By means of distinct differences in content and ratios of least mobile trace elements (Ti, Zr, Y, Nb, Cr, and rare-earth elements) in modern volcanic rocks of the ocean floor, oceanic islands, and island arcs, Pearce and Gale (1977) have attempted to identify depositional environments of ancient volcanic rocks and associated massive sulfide deposits. Fox (1979) applied standard petrochemical diagrams and discriminant analysis (based on Cenozoic island-arc tholeiitic and calc-alkaline suites from numerous sites) to classify felsic volcanic rocks in 22 massive-sulfide districts, virtually all previously considered to be calc-alkaline, as being tholeiitic or calc-alkaline. Fox found 11 districts to be tholeiitic and 11 to be calc-alkaline. He further found a remarkably strong correlation between suite type and hosted-ore-deposit type. Zinc-Cu deposits occurred almost exclusively with tholeiitic rocks, and Pb-Zn-Cu deposits almost exclusively with calc-alkaline rocks. This association confirmed a prediction by Hutchinson (1973) that volcanogenic massive-sulfide type might be a function of host-rock type. This correlation should directly affect exploration philosophy in the Archean greenstones of Canada, and no doubt presages further efforts in the field of dual metallogenesis-petrogenesis studies.

This review points to a potentially fruitful approach to metallogenesis in the Habawnah mineral belt and throughout the Arabian Shield. Appropriate data are scanty at this point. My evaluation of available semiquantitative trace-element data (Greenwood, 1980a, 1980b; this study) and major-oxide data (Conway, unpub. data; Fernette and Neckzcar, unpub. data), along with the regional geologic character of the Habawnah mineral belt, supports Greenwood's (1980a, 1980b) characterization of the volcanic rocks of the Wadi Wassat and Wadi Malahah quadrangles as belonging to the island-arc tholeiitic series and suggests that the same is true for the Wadi Amadin Al Husn volcanic rocks. However, the trace-element indicators (table 3) are mixed.

A few values in table 3 are calc-alkaline in character (Rb in Wadi Amadin Al Husn mafic and felsic rocks, Sr in Al Masane felsic rocks, Ba in Wassat formation mafic rocks, and TiO_2 in Wadi Amadin Al Husn mafic rocks), but most are indicative of either an island-arc tholeiitic or abyssal tholeiitic origin. Nickel, chromium, vanadium, and possibly cobalt are moderately to unusually high in the Habawnah belt (except for V in mafic rocks of the Wassat formation) in comparison with modern island arc tholeiites. They are similar to and in some cases exceed abyssal tholeiite concentrations. The Habawnah belt rocks are also like abyssal tholeiites in low K_2O content, and the Al Masane and Wassat formation mafic rocks are like abyssal tholeiites in low TiO_2. Other TiO_2 values and most strontium, yttrium, and zirconium values suggest an island-arc tholeiitic origin. This island-arc tholeiitic to abyssal thoeiitic geochemical character is shown graphically in figure 21.

I suggest, but cautiously and tentatively because of the limited and mostly semiquantitative data, that the volcanic rocks of the Habawnah belt are unusually primitive island-arc tholeiitic rocks. Obviously, the large quantity of felsic material precludes abyssal tholeiitic affinity. In recent studies of the Mariana arc, Dixon and Stern (1983) have found a wide range in trace-element compositions That give, as in the Habawnah rocks, mixed indications of calc-alkaline, arc tholeiitic, and abyssal tholeiitic compositions. Dixon and Stern found that the most iron-enriched (tholeiitic) rocks tended to be associated with well-developed calderas, suggesting a possible relation with edifice maturity. Some Mariana samples (Dixon and Stern, 1983, 57-A2 and 57-C, table 4) are similar to the Al Masane and Wassat formation mafic rocks in having nickel and vanadium contents (chromium and cobalt not reported) similar to abyssal tholeiites. Bloomer (1983) suggests that the high nickel content in some Mariana basalts may be due to close association with ophiolitic rocks, for which there is some evidence from dredging. Jakes and Gill (1970) had earlier predicted that ophiolites may form in tholeiitic early parts of island arcs above subduction centers as well as in mid-ocean spreading centers. The discovery of small amounts of ultramafic material near the nickel-bearing Hadbah deposit (Riofinex, 1978) in the Wadi Wassat quadrangle and its nearness to the major Ashara fault zone, which strikes northward toward the Hamdah ultramafic complex, suggest that the high contents of the ferro-alloy elements in the Habawnah belt may reflect earliest stages of island-arc development and close association with tholeiitic oceanic crust.

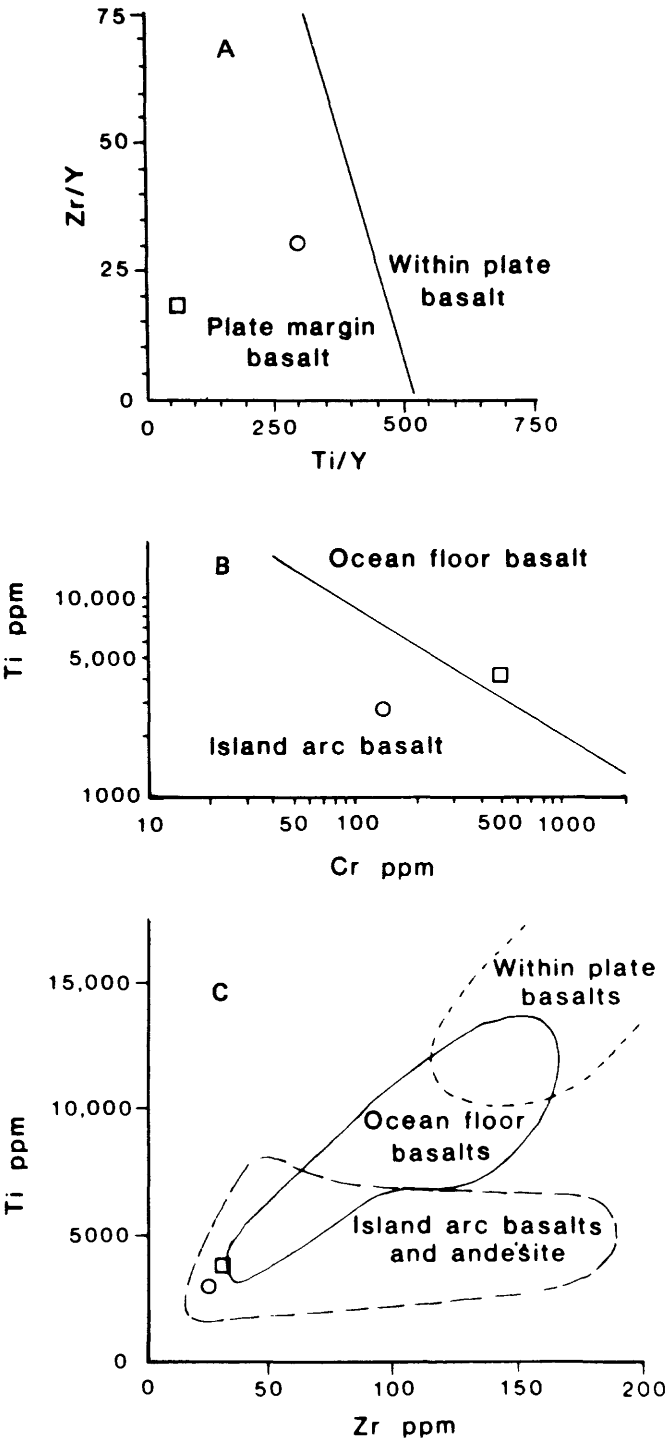


Figure 21. Discrimination diagrams utilizing the relatively immobile elements Zr, Y, Ti, and Cr, with fields for intraplate basalt, 'plate-margin' basalt, island-arc basalt, and ocean-floor basalt defined from Cenozoic basalts (from Pearce and Gale, 1977). Squares, average mafic rocks from Al Masane; circles, average mafic rocks from the Wassat Formation of the Wadi Wassat quadrangle (from table 3). Neither Al Masane nor Wassat Formation averages are characteristic of intraplate basalt (A C). They are of island-arc to ocean-floor affinity (B, C) with the Al Masane average apparently being more geochemically primitive than Wassat average (B).

Aside from trace elements, certain general features of the volcanic rocks ofthe Habawnah fold belt point to a tholeiitic island arc origin. The bimodal character is similar to Archean tholeiitic belts in Canada (MacGeehan and MacLean, 1980a, 1980b; Fox, 1979), to early Proterozoic rocks at Bagdad, Arizona (Connelly and Conway, 1983; Conway and Connelly, unpub. data), to Paleozoic rocks of West Shasta, California (Barker and others, 1979), to late Jurassic to early Cretaceous volcanics ofthe northeast Caribbean (Donnelly and Rogers, 1980), and to late Cenozoic rocks of the west Pacific (Mariana arc, Dixon and Stern, 1983; Tongan islands, Bryan, 1979), and finally to other Proterozoic belts in the western to central parts of the Arabian Shield (Roobol and others, 1983). In most of these cases the felsic rocks are rhyodacite to rhyolite; the Cenozoic Pacific rocks are called dacite, but some are high-silica rocks that by some classifications would be called rhyolite. The felsic rocks in all cases tend to be sodic and are commonly keratophyric. The role of spilitization and keratophyrization is important in these rocks, but is beyond the scope scope of this study; such secondary effects on composition cannot produce or significantly change the property of bimodality of the suite.

Fox (1979) suggests that quartz-phenocryst abundance tends to be characteristic of felsic tholeiitic rocks. It is known that calc-alkaline felsic rocks associated with some ore deposits (for example, the Kuroko deposits of Japan) are quartz-phenocryst poor. If this is correct, the abundance of quartz phenocrysts in the felsic crystal tuffs of the Habawnah belt argues for a tholeiitic origin. Quartz crystals are also ubiquitous in the tholeiitic island-arc rocks associated with massive-sulfide deposits at West Shasta, California and Bagdad, Arizona (C .M. Conway, unpub. data). The great abundance of felsic rocks in the Habawnah belt contradicts Fox's (1979) suggestion, however, that calc-alkaline but not tholeiitic suites are characterized by voluminous felsic material. The high volume of rhyolite (keratophyre) in the primitive island-arc rocks of the Antilles (Donnelly and Rogers, 1980) is further evidence of extensive silicic magmatism in the island-arc tholeiitic environment.

Fox (1979) also suggests that massive-sulfide deposits tend to be more iron rich in tholeiitic rocks than in calc-alkaline rocks. This may be related to the fact that tholeiitic rocks contain more iron than calc-alkaline rocks of corresponding silica content. The enormous pyrite deposits of the Wadi Wassat quadrangle (Roberts and others, 1981) and the relatively pyrite-rich zinc-copper deposits of the western part of the Habawnah mineral belt are compatible with this general correlation. The lack of appreciable lead in sulfides of the region is also compatible with Fox's finding that ores in tholeiitic terranes are lead poor.

In a study along an east-west transect of the central Arabian Shield Roobol and others (1983) found chemical characteristics of all volcanic belts to be those of island-arc tholeiitic to calc-alkaline rocks with a suggestion that the youngest, generally easterly belts (sequence A) are transitional between island arcs and continental-margin volcanic arcs. Intermediate-age and oldest belts (sequences B and C), generally in the central and western parts of the Shield, composed of low-K tholeiite and sodic dacite/rhyolite, seemed to be the most primitive. The Habawnah belt has characteristics in common with sequences B and C: presence of low-K tholeiite and sodic felsic rocks, bimodality, association with trondhjemites, and depletion in lithophile elements.

Roobol and others (1983) suggest that bimodality may be a common feature of early Arabian Shield arcs but that modern island arcs generally have a single mode in the andesite range. As noted above, however, arc tholeiitic rocks of many ages, including some Cenozoic Pacific arcs are bimodal. The late Jurassic to early Cretaceous rocks of the Antilles region of the Caribbean (Donnelly and Rogers, 1980) has close analogies in bimodality and other features to the Arabian arc tholeiitic series.

Students of ancient arcs are well advised to keep in mind the diversity of crustal environments and differing degrees of maturity in modern arcs. According to Dixon and Stern (1983), these two variables make it "difficult to unambiguously characterize island arc magmas and understand their origin." Stern and Ito (1983) further recommend that because of "the potential interdependence of many dynamic process among arcs....the study of each arc should be based on the evidence from that arc alone instead of attempting to apply conclusions reached from studies of other arcs." This recalls the recommendation to petrologists by Turner (1970) that seeking for differences between rock suites may be more fruitful than seeking for similarities. A caution to students of modern arcs, these statements serve as encouragement to students of Arabian-Nubian ancient arcs in suggesting that through detailed mapping, petrography, and chemical studies we can characterize individual deformed arcs and distinguish them from others of the regional orogenic complex. Characterizing and contrasting the massive-sulfide deposits is a part of this task. It may come back full circle to tell us more about what kinds of ore deposits may exist in a terrane of certain character and how they might be searched for.

I concur with Roobol and others (1983) that it is premature to attempt detailed construction of plate-tectonic models for the shield. What is needed first is detailed reconstruction of the individual arcs, flanking sedimentary basins, and ultramafic complexes and development of means to distinguish between arcs, basins, and potential ophiolite complexes. This necessarily entails the long process of mapping, wherein geologic units are defined and correlated, which is advancing rapidly in the Shield. However, the nature of the geosynclinal rocks of the shield, with rapid facies changes and major tectonic boundaries, dictates that "long-range correlations are hazardous and radiometric data on magmatic events cannot be given regional connotation" (Gass, 1981, p. 389).

DATA STORAGE

No entries were made to the Mineral Occurrence Documentation System in connection with this report. Geochemical data related to the project are archived in data file USGS-DF-04-18 (Conway, 1984).

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Appendix 1.--Chemical analyses, Saadah gossan sampling traverses

[Analyses by DGMR-USGS chemistry laboratory. Dissolution by HF and $HClO_4$ for AAS analyses. D, duplicate; N, not detected; L, less than; C, covered interval]

Sample number	Comments sample type	AAS Parts per million							Colorimetric (ppm)		Quant. spec. (ppm)			Composite sample		Interval between samples (m)
		Ag	Cu	Pb	Zn	Ni	Co	Mn	Cr	Mo	As	Be	Cd	Number of chips	Interval of sample (m)	
E to W	Traverse number 1 (see plate 3 and figure 18 for location)[1]															
118286	Felsic crystal tuff	0.5	65	35	155	20	20	455	175	N(5)	-	-	-	-	-	3
118287	...do	1.0	40	25	190	15	20	520	225	N(5)	-	-	-	-	-	1
118288	Gossan	2.0	1,550	100	700	10	15	140	225	20	-	-	-	-	-	1
118290	Limonitic gossan	N	1,850	85	1,750	15	10	585	150	60	-	15	-	-	-	1
118291	Malachite-bearing limonitic gossan	0.5	950	65	325	50	15	675	325	20	-	-	-	6	1.5	0
118292	Limonitic and hematitic gossan	11.0	8,250	950	2,750	15	45	3,200	225	50	L(200)	10	-	7	2	4 C
118293	Hematitic and limonitic gossan	6.0	6,050	1,550	4,500	20	35	820	250	30	300	50	-	8	1.8	3 C
118294	Gossan	4.0	2,300	1,600	4,500	20	20	320	225	20	300	30	-	3	0.5	3
118295	Hematitic gossan, pyrite casts	13.0	3,500	5.750	5,000	15	25	1,300	175	70	300	30	-	5	1.2	2
118297	Sericite schist, with or without	4.0	850	240	1,150	10	10	480	125	N95)	-	-	-	4	2.5	-
1182980	quartz phenocrysts;	3.0	1,050	210	2,150	10	25	885	185	10	-	-	-	-	-	-
	white- or red-stained minor	-	-	-	-	-	-	-	-	-	-	-	-	5	3.5	0
118298	gossany stringers	3.0	1,100	240	2,150	10	25	780	175	10	-	-	-	-	-	-
118299	118299, Malachite-	3.0	4,750	2,300	1,650	15	20	1,300	400	20	-	15	-	6	4	0
118300	and black-oxide-bearing	2.0	800	450	950	10	15	160	250	N(5)	-	-	-	6	5	0
118301	Sericitic crystal tuff	2.0	25	30	145	15	25	365	200	N(5)	-	-	-	6	5	-
E to W	Traverse number 2 (see plate 3 and figure 18 for location[2]															
118302	Fresh felsic crystal tuff; one	N	180	30	2,500	15	15	480	225	N(5)	-	-	-	7	3	0
118302D	mineralized chip	N	180	30	2,500	15	15	550	325	N(5)	-	-	-	6	3	0
118303	Felsic crystal tuff	0.5	50	10	1.750	15	20	410	350	N(5)	-	-	-	6	3	0
118304	...do	0.5	30	20	750	15	20	665	250	N(5)	-	-	-	6	3	0
118305	...do	5.0	115	50	1,000	15	20	690	250	N(5)	-	-	-	6	3	0
118307	Felsic crystal tuff with trace															
	mineralization	2.0	275	30	3,000	25	25	570	250	N(5)	-	-	-	4	0.4	0.5
118308	Massive gossan, mostly limonitic	1.0	6,250	1,000	5,750	20	30	370	250	60	-	30	-	4	1	0
118309	...do	4.0	6,000	3,200	8,250	25	30	325	300	90	700	30	-	4	1	0
118310	...do	14.0	8,750	11,000	5,500	20	40	6,760	300	90	700	30	-	6	1.5	0
118311	...do	14.0	11,250	13,000	7,250	25	35	13,350	200	90	1,500	30	-	6	1.5	0
118312	Carbonatiferous gossan with	10.0	7,000	80,000	87,000	930	20	6,000	250	10	-	-	70	6	1.1	0
118313	black powdery oxide	5.0	15,000	20,000	76,000	45	35	9,250	325	10	700	-	150	5	1.0	0
118314	Gossan with talc?	6.0	5.750	700	7,250	25	30	1,900	325	20	-	-	-	5	0.8	0
118315	Sericitic rock with iron-oxide	3.0	2,550	850	1,250	25	20	750	250	10	-	-	-	6	1.4	0
118317	streaks. 118317, trace malachite	2.0	1.850	1.750	1.500	20	25	410	275	N(5)	300	-	-	6	1.6	0
118318	Highly foliated conglomerate with	3.0	1,850	1,500	1,330	20	10	430	275	N(5)	300	-	-	7	3	0
118319	felsic clasts; some clasts	3.0	750	145	1,250	15	10	435	150	N(5)	-	-	-	6	3	0
118320	with quartz phenocrysts	3.0	1,450	1,000	1,900	15	20	240	150	N(5)	-	-	-	-	-	-
118320D	Slight Fe stain. No gossan	3.0	1,450	1,000	1,900	15	20	240	150	N(5)	-	-	-	7	3	0
118321		3.0	1,200	1,000	2,400	20	25	240	150	N(5)	-	10	-	6	3	-

[1]Distances estimated.
[2]Distances taped.

Appendix 2.--Chemical analyses of gossan and mineralized rocks
[Analyses by DGMR-USGS chemistry laboratory. Dissolution by HF and $HClO_4$ for AAs analyses.
D, duplicate; N, not detected; L, less than]

Sample number S to N	Comments	AAS (ppm)								Colorimetric (ppm)		Quant.spec. (ppm)				
		Au	Ag	Cu	Pb	Zn	Ni	Co	Mn	Cr	Mo	Sr	As	Sb	Bi	Cd
118587	Gossan, east-west vein............	-	2	550	30	55	30	55	650	65	20	100	-	-	-	-
118586	Shaly mineralized beds	-	2	85	40	105	80	105	650	415	7	70	-	-	-	-
118585	(composite samples)............	-	1.7	45	45	35	15	35	125	100	10	-	-	-	-	-
118240	Shaly mineralized zone............	-	1.2	60	20	30	15	20	140	95	N(5)	-	-	-	-	-
118236	Massive gossan....................	-	4	450	2,700	1,200	35	45	400	30	N(5)	100	5,000	1,000	-	-
118237	...do.............................	-	74	750	13,000	650	25	40	300	45	N(5)	100	5,000	1,000	-	-
118235[1]	Gossan............................	-	.5	180	35	90	50	55	920	250	10	-	-	-	-	-
118232[1]	...do.............................	-	1.0	15	10	50	25	25	110	200	10	-	-	-	-	-
118233[1]	...do.............................	-	.5	55	50	180	20	25	90	250	10	-	-	-	-	-
118339	Quartz vein.......................	.06	1.5	10	25	75	-	-	-	-	-	-	-	-	-	-
118340	...do.............................	L(.05)	0.7	60	35	55	-	-	-	-	-	-	-	-	-	-
118341[1,2]	Mineralized dolomitic zone........	-	N	10	15	70	20	10	690	550	N(5)	-	-	-	-	-
118342[1]	Gossan with white powdery oxide...	-	3.0	165	220	430	110	55	810	625	N(5)	-	-	-	-	-
118345[1]	East to west across gossan:	-	2.0	370	45	3,500	45	25	8,000	525	N(5)	-	-	-	-	-
118344[1]	each sample is a 5- to 7-	-	3.0	120	25	500	155	55	750	625	N(5)	-	-	-	-	-
118345[1]	chip composite over 1 to	-	2.0	100	10	385	30	20	440	250	N(5)	-	-	-	-	-
118346[1]	1.5 m.............................	-	2.0	190	25	1,750	75	50	2,500	500	N(5)	-	-	-	-	-
118734	Gossan	-	1.6	75	40	800	100	40	4,500	990	N(5)	-	-	L(100)	-	-
118156[1]	...do	-	4.0	2,100	85	110,000	25	45	8,000	250	20	-	-	-	-	300
118157[1]	...do Wadi........	-	9.0	12,000	5,500	12,000	30	30	90	150	60	-	500	-	70	70
118159[1]	...do Houra.......	-	5.0	235	75	1,000	20	30	400	175	30	-	-	-	-	-
118159D[1]	...do Gossan......	-	14.0	240	80	1,000	20	30	405	150	30	-	-	-	-	-
118161[1]	...do	-	1.0	1,500	90	6,400	20	35	530	325	30	-	-	-	-	-
118284	Quartz vein.......................	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
118728	Dolomitic gossan..................	-	1.2	4,500	480	70,000	25	35	1,750	90	N(5)	-	-	-	-	-
118729	...do.............................	-	2.8	500	60	5,500	95	65	1,900	630	N(5)	-	-	-	-	-
118132	Gossan............................	-	3.7	1,250	250	1,300	50	30	1,300	215	L(5)	-	-	-	-	-
118131	Malachite-bearing gossan..........	-	40	100,000	12,000	9,000	30	40	8,850	110	140	-	-	-	-	-
118126	Brown dolomitic gossan............	-	10	175	240	2,000	15	25	2,450	50	N(5)	-	-	-	-	-
118127	Gossan............................	-	7.5	750	185	4,000	15	55	50	40	15	-	-	-	-	-
118128	...do.............................	-	8	900	50	3,000	15	35	750	95	L(5)	-	-	-	-	-
118129	Gray gossan with powders	-	4	300	185	3,000	40	20	900	135	5	-	-	-	-	-
118129D	white oxide.......................	-	3	355	160	2,950	45	10	950	110	N(5)	-	-	-	-	-
118610	Gossan, east-west vein............	-	1.9	170	30	120	45	60	1,000	90	N(5)	-	-	-	-	
118610D	...do.............................	-	1.5	185	20	135	35	40	1,050	65	N(5)	-	-	-	-	-
118720	Red to gray-brown	-	1.5	6,500	35	8,000	15	50	4,000	15	N(5)	-	-	-	-	-
118721	gossan with	-	1.4	23,500	25	500	10	40	2,200	200	N(5)	-	-	-	-	-
118722	malachite	-	1.4	1,900	35	550	400	65	2,450	1,955	N(5)	-	-	500	-	-
118722D	veinlets.	-	1.0	2,150	20	490	380	55	2,500	1,880	N(5)	-	-	-	-	-
118723	Badwah......	-	1.5	3,500	45	550	140	70	2,600	960	N(5)	-	-	L(100)	-	-
118724	gossan......	-	1.5	15,500	65	650	50	70	3,500	165	N(5)	-	-	-	-	
118725	Gossan, float	-	1.7	165	45	600	30	65	2,300	95	L(5)	-	-	-	-	-
118726	Weakly mineralized	-	1.3	550	40	4,500	60	50	1,700	110	7	-	-	-	-	-
118727	beds.	-	1.2	70	30	450	30	40	2,100	170	N(5)	-	-	-	-	

[1]Values are from June 12, 1977, report of DGMR lab Job 550. The same values are given in an Oct. 29, 1978, report of Job 550, except the Cr values are 1/2 to 1/25 of those in the 1977 report, and Ag is 58.0 and 54.0 in samples 118159 and 118159D, respectively.
[2]Values are unreasonably low. Sample numbers for this sample and for 118146 (felsic crystal tuff, Appendix 4) were possible exchanges.

Appendix 3. Chemical analyses of carbonate rocks

[Analyses by DGMR-USGS chemistry laboratory. Dissoultion by HF and $HClO_4$ for AAS analyses. D, duiplicate, N, not detected.]

Sample number	Comments	AAS (ppm)							Colorimetric (ppm)		Quant. spec. percent		Quant. spec. (ppm)
		Ag	Cu	Pb	Zn	Ni	Co	Mn	Cr	Mo	Mg	Ca	Sb
S to N	Limestone lenses in shale unit												
118600	....	4	30	55	45	25	30	5,000	20	N(5)	1	20	-
118624	....	3.3	35	35	40	20	35	1,350	50	N(5)	.2	20	-
118618	....	3.6	35	50	45	30	35	3,500	45	N(5)	1	20	-
118395	....	2	25	45	50	20	25	2,050	15	N(5)	1	20	-
S to N	Limestone in lapilli tuff and volcanic breccia unit												
118335	Interbed.........................	4	20	45	85	35	25	5,000	20	N(5)	.5	20	-
118389	Marble nodule plus tuff matrix...	.2	20	15	80	N(10)	15	800	60	N(5)	.7	2	-
S to N	Dolomite beds and dolomitized mafic rocks												
118220	In shale unit....................	1	130	35	120	30	20	900	24	N(5)	.7	2	-
118220D	....	.5	115	25	100	25	15	820	20	N(5)	.7	2	-
118638	....	1.8	165	30	120	130	60	1,250	935	N(5)	1	10	150
118046	....	1.8	85	35	130	55	55	2,500	395	N(5)	1.5	10	-
118135	Dolomitized pillow flow..........	1.4	35	30	120	50	45	800	165	(N5)	.7	10	-
118151	....	2	125	45	85	145	60	1,400	285	N(5)	2	5	-
118218	Dolomitized pillow flow..........	1.5	65	40	70	50	45	1,050	1,190	N(5)	3	5	260
118628	In shale unit....................	1.2	55	15	75	20	30	1,350	110	N(5)	.2	7	-

Appendix 4. Chemical analyses of silicate rocks

[Analyses by DGMR-USGS chemistry laboratory. Dissolution by HF and $HClO_4$ for AAs analyses D, duplicate; N, not detected]

Sample number	Comments	AAS (ppm) Ag	Cu	Pb	Zn	Ni	Co	Mn	Colorimetric (ppm) Cr
S to N				Shale unit					
118604	Black silicic shale.......	N(0.2)	30	15	30	N(10)	N(10)	265	225
118398	....	.6	20	15	90	N(10)	10	75	40
118222	Graywacke................	.6	30	15	60	20	30	850	155
118648	Cg graywacke.............	.8	50	25	110	25	20	800	115
118634	Cherty shale.............	.4	10	25	90	N(10)	20	1,100	110
118635	Aluminous shale...........	.4	30	15	70	N(10)	10	500	95
118625	...do....................	.2	20	15	20	N(10)	N(10)	50	95
118622	Quartz-crystal lapilli tuff	1.0	80	10	110	50	40	900	145
118620	Dark silicic shale........	.2	20	15	50	N(10)	10	900	160
118619	Aluminous shale...........	.2	30	20	90	30	10	1,100	40
118143	Black silicic shale.......	.8	15	10	35	25	15	500	145
118616	Graywacke................	.4	40	20	50	15	20	600	120
118369	Black silicic shale.......	N(.2)	30	15	30	40	20	95	370
118373	...do....................	N(.2)	10	10	80	10	20	345	50
118373D	...do....................	.2	10	15	80	N(10)	10	290	60
118629	Dark silicic shale........	.2	20	10	60	N(10)	10	320	150
118631	Spotted aluminous shale...	.4	60	20	60	35	20	120	135
118615	Quartz-crystal lapilli tuff	.4	20	15	70	15	10	700	95
118612	Graywacke................	1.6	50	30	80	25	30	3,000	110
				Shale in central to western parts of area					
118590	Aluminous shale (composite)	.8	50	25	65	25	20	185	185
118589	...do....................	.6	50	20	65	25	20	90	200
118565	Dark-gray aluminous shale	.4	50	20	40	N(10)	10	500	75
118566	Weathered shale...........	.2	30	10	60	15	N(10)	45	110
118354	Weakly mineralized,	.6	55	95	60	10	15	250	135
118355	iron oxide-stained	.8	60	20	145	10	10	250	70
118356	shale (composite	.8	90	30	350	15	10	160	60
118357	samples)................	.8	45	25	200	15	15	450	50
				Felsic crystal tuff					
118580	Aphyric..................	.2	10	10	50	N(10)	10	1,100	145
118582	...do....................	.6	10	10	100	N(10)	10	300	100
118639	Aphyric, fresh............	.1	10	10	40	30	N(10)	210	135
118645	....	.4	30	105	300	30	20	250	210
118142	Fresh....................	.8	N(5)	10	10	N(10)	15	350	155
118146[1]	....	1.4	210	1,500	260	20	30	1,100	95
118147	....	1.0	N(5)	10	70	10	20	850	110
118148	Aphyric..................	1.2	10	15	80	10	20	600	110
118133	....	.6	N(5)	10	80	10	10	700	150
118149	....	1.4	10	25	149	10	30	500	100
118112	....	.8	10	15	90	10	20	1,500	90
118112D	....	.2	10	15	80	N(10)	30	1,300	110
118121	....	.2	10	10	50	25	20	600	135
118119	....	.6	10	10	50	10	10	400	84
118113	....	.6	50	10	90	10	15	350	105
118114	....	.6	10	10	80	15	20	300	145
118216	Fresh....................	.6	50	15	250	20	10	750	190
118377	Aphyric..................	.4	10	10	80	N(10)	10	850	125
118383	Quartz-poor..............	.2	10	15	80	N(10)	10	650	110
118379	Black....................	.4	10	10	100	M(10)	20	750	135

Appendix 4. Chemical analyses of silicate rocks-Continued

Sample number	Comments	AAS (ppm)							Colorimetric (ppm)
		Ag	Cu	Pb	Zn	Ni	Co	Mn	Cr
S to N		Lapilli tuff							
118595	Tuff breccia.............	0.6	390	10	50	N(10)	20	800	100
118595D	....	.4	370	20	50	N(10)	30	600	85
118592	Lapilli tuff.............	.6	20	15	100	10	20	1,100	65
118226	Quartz-crystal lapilli tuff	.6	180	10	60	20	20	700	210[1]
118212	Lapilli tuff.............	.8	50	15	280	20	20	650	70
118145	Base of felsic crystal	2.0	25	15	50	15	30	950	15
118145D	tuff unit..............	1.6	30	10	35	30	40	900	110
S to N		Lapilli tuff and volcanic breccia							
118567	....	.6	10	20	110	N(10)	15	1,100	90
118351	....	.2	20	15	200	20	25	1,150	215
118172	....	.6	30	15	90	10	15	900	110
118169	....	.6	30	15	90	10	20	800	95
118384	....	.2	40	15	50	N(10)	20	550	95
118391	....	.4	20	15	70	N(10)	20	800	90
		Mafic volcanic rocks							
118583	....	.6	30	20	70	N(10)	10	750	40
118348	....	1.4	90	20	90	30	60	1,050	60
118153	....	1.8	40	20	153	90	50	700	880
118155	....	2.2	80	25	70	80	60	800	790
118643	....	1.4	60	40	70	70	50	1,050	270
118643D	....	1.2	60	40	80	50	40	900	275
118163	....	1.0	100	10	60	50	50	600	285
118141	....	1.6	50	30	70	90	45	800	775
118360	....	1.4	130	15	80	30	40	1,500	65
118135	Dolomitized Same zone	1.4	35	30	120	30	40	1,500	65
118138	Fresh	1.2	50	30	45	60	35	700	225
118123	Graywacke(?)............	1.2	90	30	110	30	50	1,500	135
118111	....	1.0	110	15	60	100	50	500	1,130
118122	....	1.8	240	15	60	100	50	1,250	35
118213	....	.8	100	15	70	160	80	800	2,100
118214	....	1.2	30	20	110	45	60	1,600	155
118214D	....	.8	40	25	120	30	60	1,600	175
118218	Dolomitized..............	1.0	130	35	120	30	20	900	35
118382	....	1.0	110	30	70	40	50	1,050	750
S to N		Gabbro sills							
118229	....	.6	240	15	120	50	70	1,300	300
118352	Quartz-bearing gabbro.....	.4	30	15	100	35	50	1,200	160
118167	....	.8	120	10	110	45	60	1,600	165
118124	....	1.6	120	30	90	35	40	1,250	90

[1]Values are unreasonably high. Sample numbers for this sample and for 118341 (gossan, Appendix 2) were possibly exchanged.