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Geology of the Mahd Adh Dhahab District, Kingdom of Saudi Arabia

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ABSTRACT

Approximately 200 km^2 around the Mahd adh Dhahab mine were mapped at 1:18,000 scale, with emphasis on establishing the volcanic stratigraphy. The Mahd Group, which rests over a basement of metamorphosed tonalite, is divided into the Lahuf formation and Tuwal formation, which are separated by an unconformity. The Lahuf is divided into a lower felsic pyroclastic member, a middle felsic tuff member, and an upper mafic member. The overlying Tuwal formation is divided into the Mine member, which consists predominantly of subaqueous felsic pyroclastic rocks with minor dolostone and chert, and the Ghuwayshat member, which consists predominantly of subaerial ignimbrites. The Mahd Group also contains numerous basaltic and rhyolitic subvolcanic intrusions, some of which were extruded as lava flows. The Mahd Group was folded, intruded by rocks of the Ramram cauldron, and eroded prior to deposition of the overlying Ghamr group. Remnants of the latter consist of fanglomerate, volcaniclastic sediments, and dacitic lava flows. Burial of the region under rocks of the Ghamr group probably accounts for prehnite-pumpelleyite facies metamorphism. Vein mineralization at Mahd adh Dhahab and other occurrences is probably unrelated to the magmatism that produced the Mahd and Ghamr groups. The Wadi Sayilah-Wadi Ghadayrah fault system was active during deposition of the Mahd and Ghamr groups and accounts for about 2.6 km of cumulate uplift of the basement block relative to the Mahd basin.

Major-element data show that the Mahd Group was produced from separate basaltic and dacitic-rhyolitic magmas that overlapped without mixing. The alkalis and alkaline-earth elements were particularly mobile during metamorphism (which caused widespread albitization of feldspars) and also during hydrothermal alteration (which added secondary microcline). This mobility adversely affected rubidium-strontium whole-rock systematics, which makes whole-rock isochron dates obtained from these rocks questionable. The new geological data presented here are combined with the geochronologic data of Calvez and Kemp (1982) to re-interpret the geologic history of this area.

INTRODUCTION

Mahd Adh Dhahab is the largest of the ancient gold mines of the Arabian Shield and is currently in production. The discovery in the mid-1970's of new ore bodies in the southern mineralized zone (Worl, 1978a) underscored the need for a geologic map of the surrounding district. The apparent association of the known mineralization with rhyolite (Luce and others, 1979) and(or) "agglomerate" beds (Worl, 1978b) further justified looking for similar controls elsewhere.

This report presents the results of geologic mapping of approximately 200 km^2 surrounding the mine and is a part of the research at Mahd Adh Dhahab initiated by the U.S. Geological Survey in 1981. Companion studies include dating of mineralization (Afifi and others, in prep. C), a mineralogical study of the veins (Afifi and others, in prep. B), fluid-inclusion and stable isotopic studies (Afifi and others, in prep. D), a petrologic study of the area (Afifi and others, in prep. A), a study of geology and hydrothermal alteration (Doebrich and LeAnderson, 1984), mapping of Mine Hill and the underground workings (Hilpert and others, 1984), and lithogeochemical exploration (Worl and others, 1986).

SUMMARY OF PREVIOUS WORK

Geologic studies in the Mahd Adh Dhahab district commenced in 1932 with the rediscovery of the ancient Mahd Adh Dhahab mine. An account of the history of exploration and mine development is presented by Hilpert and others (1984).

The district was initially mapped at 1:50,000 scale by Goldsmith and Kouther (1971). They recognized an older basement of "granite gneiss", which is nonconformably overlain by several thousand meters of Precambrian volcanic and sedimentary rocks that they called the Mahd Adh Dhahab Series. They also recognized an angular unconformity within the Series that was used to divide it into a lower and an upper sequence (fig. 1).

The district was included in 1:100,000-scale maps by LeFevre (1969), Agguttes and Duhamel (1971), Dottin (1975), and Hopwood (1979). However, these maps do not add substantial detail to the earlier work of Goldsmith and Kouther (1971).

Kemp and others (1982) compiled the regional geology at a scale of 1:250,000 and introduced a new stratigraphic nomenclature (fig. 1). The basement "granite gneiss" of Goldsmith and Kouther (1971) was recognized as a batholith and renamed the Dhukhur tonalite. The lower and upper sequences of the Mahd Adh Dhahab Series were renamed the Mahd Group and Ghamr group, respectively.

A geochronologic study by Calvez and Kemp (1982) clarified the significance of these three divisions. A Uranium-Lead date on zircons indicates that the Dhukhur batholith was intruded at 816 ± 3 Ma. Zircons from the Ramram granophyre and the Hufayriyah tonalite batholith, both of which intrude the Mahd Group, were dated at 769 ± 5 and 760 ± 10 Ma. Deposition of the Mahd Group was, therefore, bracketed between 816 ± 3 and 769 ± 5 Ma. They also obtained a single rubidium-strontium whole-rock date of 748 ± 22 Ma on rhyolite of the Ghamr group. However, the rubidium-strontium dates obtained on volcanic rocks by Calvez and Kemp (1982) and Huckerby (1984) are considered unreliable due to the mobility of both elements during metamorphism and hydrothermal alteration (discussed later in this report).

Goldsmith and Kouther, (1971)	Kemp and others, (1982)	This study
MAHD ADH DHAHAB SERIES		
Upper sequence	GHAMR GP.	GHAMR GP.
Unconformity	Unconformity	Unconformity
Lower sequence	MAHD GP.	MAHD GP.
	Tulaymisah fm.	
	Haf fm.	
	- Juraysiyah mb.	
	- Zur mb.	
		Tuwal fm.
		- Ghuwayshat mb.
		- Mine mb.
		Unconformity
		Lahuf fm.
		- Upper mb.
		- Middle mb.
		- Lower mb.
	- Za'anah mb.	
Unconformity	Unconformity	Unconformity
Granite gneiss	Dhukhur tonalite	Dhukhur batholith

Figure 1.–Proposed stratigraphic divisions for the Mahd Adh Dhahab district and correspondence to previous schemes.

Afifi and others (in prep. C) obtained a rubidium-strontium isochron of 649 ± 35 Ma from vein minerals at Mahd Adh Dhahab, which is in agreement with common Pb ages on galena obtained by Stacey and others (1980) and Rye and others (1982). This indicates that mineralization is unrelated to volcanism, being about 120 m.y. younger than the Mahd Group.

The area in the immediate vicinity of the mine, known as Jabal Mahd Adh Dhahab, was mapped in detail by Luce and others (1975), Worl (1978a), Huckerby and others (1983), and Doebrich and LeAnderson (1984). The underground workings were mapped by Dirom (in Hilpert and others, 1984), and by Gold Fields Mahd Adh Dhahab Ltd. (unpublished maps). The local stratigraphic sequence established by Luce and others (1975) consists of andesite, followed by lower agglomerate, lower tuff, upper agglomerate, and upper tuff. These rocks are intruded by a small plug of porphyritic-aphanitic rhyodacite known as the Mine Hill Rhyolite, which was described in detail by Hilpert and others (1984).

REGIONAL SETTING

The map area is located astride the eastern margin of a large Precambrian basin (henceforth called the Mahd basin) that contains a thick accumulation (>10 km?) of mafic-felsic volcanic and volcaniclastic rocks of the Mahd and Ghamr groups (fig. 2; Kemp and others, 1982). The rocks of the Mahd Group were deformed, intruded by the Ramram complex, and eroded prior to deposition of the Ghamr group, which resulted in a regionally distinct angular unconformity (Kemp and others, 1982). The Ghamr group, which locally has a preserved thickness of about 1.5 km, is similar in lithology to the Mahd Group, but is less deformed. It probably covered most of this region, but is only preserved as outliers within synclines and grabens.

PRESENT WORK

The present work has focused on the Mahd Group, which hosts all known mineralization in the district. Mapping at a scale of 1:18,000 on enlarged aerial photographs from available coverage was undertaken during 1981 and 1982. Topographic control over most of the area is poor and so the map was compiled on a photographic base in order to facilitate reference to ground features. This report is primarily a description of the district's geology, whereas results from related studies are to be presented elsewhere (Afifi and others, in prep. A, B, C, and D).

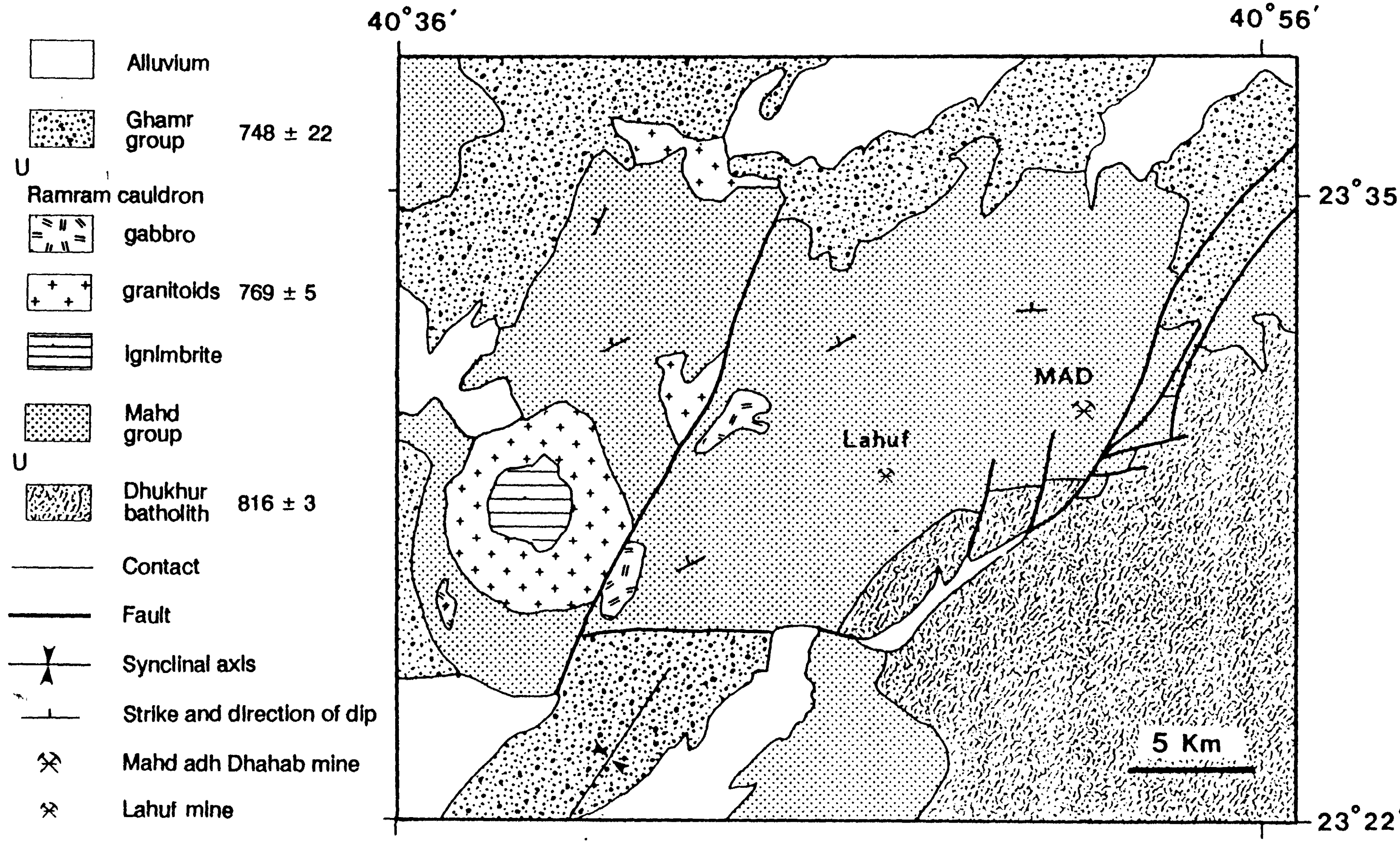

Figure 2.–Summary map of the regional geology, modified from Kemp and others (1982).

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PHYSIOGRAPHY

The terrain of the district consists of low hills (< 200 m of relief) dissected by a dendritic pattern of wadis. An east-west-trending topographic divide passes immediately north of Jabal Mahd Adh Dhahab, separating the Wadi Sayilah drainage to the south from the Wadi Al-Arj drainage to the north. This divide locally follows a line of hills known as Al Tuwal (the Tall Hills), which are underlain by resistant felsic porphyry of the Mahd Group. The highest elevation within the map area is the peak of Jabal Mahd Adh Dhahab (1,238 m), located directly south of the divide (pl. 1). The topographic prominence of Jabal Mahd Adh Dhahab is due to the presence of a large number of resistant quartz veins and silicified wall rocks. In this regard, it is worth noting that post-vein (and, therefore, not silicified) mafic dikes have been eroded as deep trenches on the Jabal, but appear to be more resistant to erosion elsewhere.

PETROLOGIC TERMINOLOGY

The volcanic rocks of the district have generally retained their original textures, despite having been subjected to devitrification, metamorphism, metasomatism, and hydrothermal alteration. For this reason, terms such as "vitric tuff" will be used instead of the more accurate (but cumbersome) term "meta-devitrified vitric tuff."

The word "metamorphic" will be applied to the indistinguishable effects of devitrification, hydration, diagenesis, and burial. The term "metamorphic alteration" will be used to designate chemical changes that are thought to have resulted from metamorphism, while the term "hydrothermal alteration" will be restricted to changes caused by reaction of metamorphosed or unmetamorphosed rock with mineralizing (hydrothermal) fluids.

There is some confusion in previous work in the Mahd Adh Dhahab district regarding the nomenclature of volcaniclastic rocks. Terms such as "agglomerate" or "volcanic conglomerate", for example, were inaccurately used to describe matrix supported tuff-breccia (which originated as debris flows). The nomenclature of volcaniclastic rocks in this report follows the usage of Fisher (1966) and Fisher and Schmincke (1984), which is preferable to that of Schmid (1981).

LATE PROTEROZOIC PLUTONIC ROCKS

DHUKHUR BATHOLITH

Layered rocks of the Mahd and Ghamr groups were deposited over a basement of metamorphosed granitoids initially described as granite gneiss by Goldsmith and Kouther (1971), and collectively assigned to the Dhukhur tonalite (dt) by Kemp and others (1982). The wall rocks of this batholith are not exposed within the district, but Kemp and others (1982) inferred that they belong to the Arj Group, a poorly defined unit that has not yet been dated. Huckerby (1984) described a small exposure of tightly folded phyllites and quartzofeldspathic gneiss (located outside the map area), which appears to be a screen of the Arj Group. He attempted to date these rocks by the rubidium-strontium whole-rock method, but the large scatter of data points failed to produce an isochron.

The basement rocks crop out on the up-thrown block east of the Wadi Sayilah fault system, but are for the most part concealed beneath rocks of the Mahd Group to the west of the fault (pl. 1); therefore, a deeper level of erosion is exposed on the up-thrown block east of Wadi Sayilah.

The Dhukhur batholith is poorly exposed, partly because of its poor resistance to erosion and partly because it has been extensively intruded by dike swarms and plutons (described separately). The principal rock type is light-gray, equigranular, medium-grained granodiorite-tonalite consisting of subhedral zoned oligoclase-andesine, anhedral perthite, and quartz, with minor magnetite, zircon, and monazite. Former mafic minerals, probably amphibole and biotite, have been replaced by retrograde chlorite, muscovite, epidote, and ± hematite. The tonalite has a weak to moderate penetrative foliation (flaser or cataclastic fabric) that is metamorphic in origin. Quartz grains, for example, have been flattened and subsequently annealed, while feldspar and mafic-mineral grains have been aligned subparallel to the foliation. This texture is evidently not due to magma flow, as proposed by Kemp and others (1982).

Pebbles of the Dhukhur tonalite are present in the basal conglomerate of the Mahd Group, which lacks penetrative foliation, indicating that the batholith was metamorphosed and subsequently unroofed prior to deposition of the overlying volcanic rocks.

The age of the Dhukhur batholith (816 ± 3 Ma) is similar to that of other diorite-tonalite batholiths that invaded the older arc assemblage of the Asir terrain (Stoeser and Camp, 1985). The metamorphosed and eroded batholith, along with remnants of its wall rocks, effectively formed a basement over which younger supracrustal rocks of the Mahd Group were deposited.

MAHD PLUTONIC ROCKS

The Dhukhur batholith (dt) and the north-trending dike swarms are intruded by younger stocks of hornblende quartz diorite (di) (trondhjemite of Huckerby, 1984), biotite hornblende granodiorite (gd), and granite and aplite (gr) that crop out in the uplifted basement block east of Wadi Sayilah (pl. 1). These plutons were named the "Mahd Intrusive Complex" by Huckerby (1984), but will be named the Mahd Plutonic Complex in this report in order to distinguish them from subvolcanic intrusives of the Mahd Group. Unlike the Dhukhur batholith, these plutons lack metamorphic foliation and appear to have been emplaced at relatively shallow (epizonal) depth. A small plug of chloritized quartz diorite also intrudes the contact between the Lahuf and Tuwal formations northeast of the tailings pond (pl. 1).

The rubidium-strontium whole-rock dating of the Mahd Plutonic Complex by Huckerby (1984) provided essentially identical ages of 772 ± 36 and 776 ± 41 Ma. These ages closely overlap the zircon ages of the Hufayriyah tonalite batholith (760 ± 10 Ma) and the Ramram granophyre (769 ± 5 Ma), both of which intrude rocks of the Mahd Group (Calvez and Kemp, 1982; Kemp and others, 1982). The Ramram granophyre (fig. 2) is the innermost of several ring intrusions that encircle an isolated caldera-fill sequence of rhyolitic ignimbrites (Afifi, 1983), indicating that these plutons locally vented on top of the Mahd Group. The plutonic rocks are regarded as the terminal event in the Mahd magmatic cycle, having ascended into their volcanic predecessors.

LATE PROTEROZOIC LAYERED AND SUBVOLCANIC ROCKS

MAHD GROUP

The Mahd Group is a thick (>5,000 m) accumulation of layered mafic-felsic volcanic rocks and their subvolcanic complements. Subdivision into smaller units was made difficult by vertical repetition of rock types and lateral facies changes. Kemp and others (1982) mapped the regional distribution of the rocks of the Mahd Group and divided them into two possibly correlative formations, one of which has three members (fig. 1). These divisions proved inadequate for the following reasons: (1) they included all Mahd Group rocks from the district in the Zur member of the Haf formation, which encumbers further subdivision; (2) their various members are difficult to distinguish because each contains similar rock types; and (3) specific correlation of the sequence present in the district with that at Jabal Al Zur (located 45 km southwest of Mahd Adh Dhahab) is doubtful because of facies changes.

Several new lithostratigraphic divisions are recognized in this study, distinguished primarily by differences in composition. The correspondence of the new divisions to previous nomenclature is shown in figure 1. The volcanic units are distinguished as mafic, intermediate, or felsic because more specific distinctions (for example, rhyodacite, rhyolite) cannot be consistently applied in the field due to the widespread albitization and (or) hydrothermal alteration that has affected the region. The layered rocks may locally be subdivided, as at Jabal Mahd Adh Dhahab, on the basis of their bedding and textural characteristics. The entire section is extensively invaded by subvolcanic intrusives, which are near-surface extensions of the dense dike swarms in the basement and are regarded as integral parts of the sequence. However, it should be noted that not all intrusive rocks are related to the Mahd Group volcanics, some being likely equivalents to dacite flows in the overlying Ghamr group.

The Mahd Group is composed primarily of felsic volcanic rocks (tuff, lapilli tuff, and tuff-breccia) and (locally) lava flows and domes. Mafic volcanic rocks occur as lava flows with marginal tuffs, lapillistone, and agglomerate. Intermediate-composition rocks, such as andesite and dacite, are uncommon as primary lavas.

The Mahd Group is divided into the older Lahuf formation and the younger Tuwal formation; these are separated by an unconformity. These two units contain a wide variety of rock types that, when proven sufficiently continuous along strike, are designated as members. Additional divisions of formational and lower rank will undoubtedly be added as more of the region is mapped.

Lahuf Formation

The Lahuf formation is divided into three members designated as lower, middle, and upper. The lower Lahuf consists predominantly of felsic pyroclastic rocks; the middle member consists of thinly bedded and laminated tuffaceous sandstone and siltstone; and the upper member consists predominantly of subaerial mafic volcanics. A complete section of the Lahuf is exposed in the southwestern part of the map area (pl. 1) near the ancient Lahuf Mine. From this area, the lower and middle members appear to terminate abruptly toward Jabal Mahd Adh Dhahab, where the upper member rests directly on the basement. The lateral termination of these units probably reflects deposition near the eastern margin of the Mahd basin.

Lower Member--The lower member (lt) of the Lahuf consists mainly of very thickly bedded felsic lapilli tuff. Lithic fragments are mostly accidental, comprising several varieties of felsic-intermediate lava, as well as rip-up clasts of laminated tuff and chert. Some lapilli, which resemble long-tube pumice in shape, are composed primarily of fine-grained chlorite. Phenocryst fragments consist of twinned plagioclase (usually albitized), potassic feldspar, and (locally) quartz. Minor or rare fragments of magnetite, chloritized amphibole, apatite, and zircon are locally present (appendix 1). The matrix consists of microcrystalline quartz, chlorite ± phengite ± epidote ± carbonates ± hematite, which are thought to have replaced vitric ash. Secondary chlorite and hematite appear to be mutually exclusive, which imparts a mottled green and purple coloration. These rocks occur in structureless beds that are several meters thick and appear to have been deposited by subaqueous mass flows that reworked unconsolidated pyroclastic debris (described later in this report). They are interbedded with thin beds and laminae of felsic tuff, which are similar in composition to (but better sorted than) the lapilli tuffs. The aggregate thickness of these rocks is about 600 m.

A 1-5-m-thick basal conglomerate is present at the foot of the hills located immediately southwest of Jabal Mahd Adh Dhahab, but appears to be absent elsewhere. Pebbles consist of vein quartz, basalt, felsic vitrophyre, and foliated granitoids; this last was evidently eroded from the underlying basement, indicating that the base of the Lahuf is a nonconformity. The clasts are supported by a matrix of arkosic sandstone largely derived by disaggregation of basement tonalite. The sandstone contains secondary chlorite, calcite, and epidote. In the southwestern part of the district, the felsic tuffs are underlain by a discontinuous layer of mafic lapilli tuff (lta) (pl. 1) consisting of vesicular trap fragments in a hematite-epidote-rich matrix.

Middle member--The middle member (ls) of the Lahuf formation consists of light-green plane and ripple laminated tuffaceous sandstone and siltstone (or current-sorted crystal-vitric tuff), with subordinate thin beds of felsic crystal-lithic tuff and lapilli tuff. The laminated tuffs contain accidental volcanic blocks with impact and drape structures. The base of this member is defined by a transition from massive lapilli tuff below into laminated beds above. The middle member of the Lahuf is discontinuous along strike and was probably deposited in a shallow subaqueous environment during a lull in volcanic activity (pl. 1).

Upper member--The upper member of the Lahuf formation ("andesite" of previous workers) consists mainly of mafic lava flows (la) with marginal flow breccia, agglomerate, and lapilli stones. The lava flows were erupted on land, as indicated by vesicular or brecciated tops and the absence of pillow structures. They were intruded by a large number of basalt/diabase dikes that cannot, for the most part, be distinguished from the flows due to development of a thick desert varnish. Most of these intrusions terminate beneath the pre-Mahd unconformity, indicating that they are roughly contemporaneous with the lavas. In addition to the mafic lavas, there are minor accumulations of fragmented felsic rocks (las). The latter occur as welded ash-flow tuff (ignimbrite) in the western part of the district and as well bedded tuffaceous sandstone/siltstone toward the east.

Typical mafic lava has a pilotaxitic texture, with phenocrysts and microlites of albitized plagioclase in a devitrified groundmass of chlorite, epidote, hematite, albite, and quartz (appendix 1). Mafic phenocrysts (probably pyroxene and olivine) have been completely replaced by secondary minerals, chiefly chlorite. Vesicles are filled with epidote ± chlorite ± quartz ± calcite ± prehnite. The vesicular and fragmental mafic rocks contain a larger proportion of metamorphic minerals (chlorite, albite, epidote, and calcite) than adjacent mafic dikes and sills. This difference is attributed to greater permeability of the volcanic rocks by metamorphic fluids. Chemical and petrographic data indicate that this unit is composed primarily of basalt and basaltic andesite.

Layered Rocks of the Tuwal Formation

The base of the Tuwal formation is defined by a sharp contact between mafic volcanic rocks of the upper member of the Lahuf formation and felsic rocks above. This contact appears to be an unconformity for the following reasons: 1) on the south side of Jabal Mahd Adh Dhahab, bedding in the upper Lahuf member dips steeply northeast, while bedding in the overlying Mine member of the Tuwal formation dips moderately northward; despite faulting along the contact, it nevertheless appears to be an angular unconformity (a detailed description is found in Huckerby, 1984); 2) an arkosic conglomerate containing angular pebbles and boulders of the upper member of the Lahuf is locally present above the contact; 3) the top of the upper member of the Lahuf is locally friable and stained by oxides, probably due to pre-Tuwal weathering; 4) mafic flows of the upper member of the Lahuf were erupted subaerially, while beds above the contact appear to have been deposited in a submarine environment; and 5) many cross faults that offset the Lahuf formation appear to terminate at the contact (pl. 1).

In the eastern part of the district, the Tuwal formation consists primarily of water-lain felsic fragmental rocks that are named the Mine member, whose thickness exceeds 1,500 m. The Mine member becomes much thinner to the west, where it is overlain by subaerial felsic ignimbrite of the Ghuwayshat member (pl. 1).

Mine member--The Mine member (mt) is mapped primarily as a single unit consisting of lapilli tuff and tuff-breccia interbedded with current-sorted tuffs. Locally, three other lithologic units, chert (mct) dolomite (mm), and mixed-clast lapilli tuff (mat) can be distinguished within the primary unit and are mapped separately. The primary tuffaceous unit (mt) is felsic in composition and the two lithologic end members (the lapilli tuff and tuff-breccia and the current-sorted tuffs) are interbedded on various scales, reflecting a common environment of deposition.

Each are described as follows:

<u>Lapilli tuff and tuff-breccia lithology</u>--Consists of lithic lapilli and blocks of a wide variety of volcanic and sedimentary clasts. These clasts vary greatly in both shape and size (<1mm - >2m). Cognate fragments are felsic vitrophyre and former pumice. Accidental fragments consist of laminated tuff, mafic lava, chert, and (or) dolostone. Pumice is usually chloritized and (or) silicified, and is recognized by virtue of its wispy outlines. The pumice lapilli do not display evidence of collapse by welding, but their longest dimensions are frequently aligned parallel to bedding as a result of sedimentation and compaction. The lithic fragments range in color from reddish brown (due to replacement by hematite) to green (chlorite), but such coloration usually varies within a single specimen. Whole and broken phenocrysts of sodic plagioclase + potassic feldspar ± quartz ± magnetite are common. Most of the phenocryst fragments have not been extensively rounded or broken by transport. The lithic and crystal fragments are supported by a matrix of microcrystalline quartz, feldspar, phengite, and chlorite ± hematite. Outlines of unwelded shards are sometimes preserved, indicating a pyroclastic origin. In most rocks, however, the origin of the very fine-grained siliceous matrix is not clear, but fine vitric ash or volcanic mud are the most likely precursors.

These rocks occur in beds that range in thickness from about 0.2 m to >10 m. There is a distinct positive correlation in each bed between the maximum size of included fragments and bed thickness; therefore, the degree of sorting is inversely proportional to bed thickness. The following attributes indicate that these beds were deposited by mass flow of water-tephra slurries in a submarine environment: 1) the compositional variety of lithic and crystal fragments within individual beds; 2) interbedding of lapilli tuff and tuff-breccia with beds of chert, carbonate, and current-sorted tuffs; 3) the incorporation of rip-up fragments of chert and carbonate in the lapilli tuffs; and 4) the lack of welding of former vitric components. These rocks resemble submarine pyroclastic flows described by Fiske and Matsuda (1964) and Tasse and others (1978). Using the criteria of Middleton and Hampton (1976), most of the felsic lapilli-tuff and tuff-breccia beds may be classified as either a) debris-flow or b) turbidity-current deposits whose individual characteristics are described as follows: A) Debris-flow deposits---The ore-hosting upper and lower "agglomerate" on Jabal Mahd Adh Dhahab contain very thick structureless beds (2 - >10 m thick) of lapilli tuff and tuff-breccia. Lithic fragments include a variety of felsic and mafic lava, tuff, granophyre, chert, and dolostone, but definite pyroclasts, such as pumice, are uncommon. Some fragments of laminated tuff occur as contorted ribbons, indicating a lack of excess turbulence during transport. Crystal fragments of fine-grained feldspar and quartz are sparse. Both lithic and crystal fragments are entirely supported by a matrix composed of microcrystalline quartz, feldspar, chlorite, and illite/smectite. Although some lithic fragments exceed 0.5 m in diameter, there is no sorting or grading over several tens of meters of stratigraphic thickness. These rocks most closely resemble laharic breccia and are thought to be deposits of submarine debris flows. Regardless of their origin, these rocks are neither "agglomerate", as originally described by Luce and others, (1975), nor are they "volcanic conglomerate", as proposed by Huckerby and others (1983). B) Turbidity-flow deposits---These typically occur as thick beds of graded lapilli tuff separated by very thin beds and laminae of well-sorted coarse and fine tuff. In the thicker beds (>0.5 m), normal grading is distinguished by the concentration of dense lithic fragments (such as vitrophyre, chert, and rip-up clasts) toward the base. Smaller and less dense fragments (such as chloritized pumice and crystal fragments) are usually randomly distributed throughout the bed. Basal scours are uncommon, but lithic fragments at the base of the graded interval sometimes protrude into the underlying laminated tuff as a result of compaction. The graded interval corresponds to the A division of the Bouma sequence (Middleton and Hampton, 1976) and is usually overlain by a B division of thinly bedded or laminated tuffs. The latter is composed of better sorted and finer equivalents of the lithic, crystal, and matrix components present in the A division. The planar lamination is occasionally convoluted, but ripple lamination is rare. It should be emphasized that graded bedding is not always obvious, particularly in thin (<10 cm) beds of lapilli-poor tuffs. The continuous-distribution grading characteristic of sedimentary turbidites is virtually absent in these rocks because of the large difference in the sizes of lithic, crystal, and matrix components.

Current-sorted tuffs---The lower tuff on Jabal Mahd Adh Dhahab, which is about 230 m thick, is a succession of thin planar beds and laminae of tuffaceous sandstone and siltstone. The sandstone beds consist of the same lithic and crystal fragments present in the mass-flow deposits, whereas the siltstone laminae are similar in composition to the siliceous (vitric?) matrix of the lapilli-tuff and tuff-breccia beds. Laminated siltstones (or vitric tuff) typically alternate with very thin-to-thick-bedded volcanic sandstone (or crystal-lithic tuff). Mudstone and shale layers are rare, reflecting the small amount of detrital clay in the Mahd Group. Slump folds, load structures, scours, and ripple laminae are occasionally present. While most sandstone beds are relatively well sorted, some display normal-distribution grading. Occasional exotic blocks of vitrophyre or lapilli tuff as much as 2 m across are present. These blocks are underlain by impact structures and overlain by mantle bedding, indicating that they fell or rolled into place.

The aggregate composition of the sandstone-siltstone successions (in terms of lithic, crystal, and matrix (silt) components) is similar to lapilli-tuff and tuff-breccia beds with which they are interbedded. This indicates that the current-sorted tuffs are an integral part of a turbidite sequence, being distal or channel-margin equivalents of the debris- and turbidity-flow deposits.

Chert (mct)---Several discontinuous layers of gray-green chert and purple jasper within the Mine member extend from Jabal Mahd Adh Dhahab to Lahuf (pl. 1). These beds are 0.1-5 m thick and typically contain planar lamination indicative of sedimentary origin; siltstone laminae may also be present. The bedded chert consists mostly of microcrystalline quartz with subordinate chlorite, hematite, or pyrite.

The bedded cherts are frequently underlain by massive zones of cherty tuff. Although these rocks consist predominantly of microcrystalline quartz, outlines of former phenocryst fragments, lapilli, and glass shards betray their volcanic origin. Feldspar and lithic fragments in these rocks are partly or completely replaced by quartz aggregates. The cherty-tuff zones are commonly brecciated and invaded by stockworks of gray pyritic chert. Examples of cherty-tuff zones occurring directly underneath bedded chert and jasper are found on the north slopes of the hills located immediately west of Jabal Mahd Adh Dhahab.

The oxygen-isotopic compositions of bedded chert (+12.6 percent relative to SMOW) and the sulfur-isotopic compositions of pyrite in the chert (-1.5 to +4.2 percent, relative to CDT) indicate a hydrothermal origin (Afifi and others, in prep. D). The bedded chert was probably deposited by venting of hydrothermal fluid onto the sea floor and the cherty-tuff zones resulted from silicification beneath the point(s) of discharge. Because chert beds are cut by quartz veins at Mahd Adh Dhahab, it is important to distinguish two hydrothermal events, the former related to volcanism at about 780 Ma, and the latter related to mineralization at about 650 Ma (Afifi and others, in prep. D).

Dolostone (mm)---Rare dolostone lenses occur within the Mine member. They consist of brown-weathering, white crystalline dolomite and calcite with minor amounts of chlorite, quartz, chert, hematite, and (or) pyrite. These beds are usually thin and discontinuous, but locally attain a thickness of about 5 m. Thin planar bedding is sometimes preserved (but is usually obliterated) by dolomitization. The presence of dolomite fragments in the felsic-lapilli tuffs indicates that the carbonate layers underwent submarine erosion. The carbon-isotopic composition of the dolostones (+3.5 to +4.8 percent, relative to PDB) indicates a marine origin, while the oxygen-isotopic composition (+15.0 to +20.1 percent, relative to SMOW) reflects diagenetic and metamorphic effects (Afifi and others, in prep. D). A bed of pure white dolostone immediately north of the old town of Al-Mahd was quarried, probably for use as flux in ancient smelting operations.

Mixed-clast lapilli tuff (mat)---These beds are similar to the felsic lapilli tuffs and tuff-breccias, but contain in addition abundant clasts of augite and mafic lava. Their intermediate composition is due to admixture of reworked mafic and felsic tephra.

Mafic Volcanic Rocks--The Mafic volcanic rocks (mb) of the Tuwal formation are present as a discontinuous unit of lava flows, breccias, agglomerates, and lapilli tuffs (pl. 1). These rocks are severely altered, and in outcrop they are usually colored green due to abundant secondary chlorite. The lava flows are distinguished by their massive nature, scoriaceous borders, and the presence of marginal breccia and agglomerate. Thin sheets (<0.5 m) of massive trap rocks locally present beneath this unit appear to be sills. The fragmental rocks occur above and lateral to lava flows, and consist of poorly sorted monolithic trap and scoria fragments, and accidental fragments of feldspar porphyry. Although these rocks locally overlie dolostone beds and resemble hyaloclastites in texture, no pillow structures or pillow fragments were found.

The trap rocks contain some microphenocrysts of albitized plagioclase, but they are otherwise aphyric. The original mafic glass has been replaced by microcrystalline chlorite, smectite, quartz, and hematite. Vesicles have been filled by chlorite, carbonates, epidote, prehnite, and (or) quartz. In some areas, the mafic tuff is invaded by discordant zones of dolomite-hematite alteration that appear to be rooted in the underlying dolostone beds.

Ghuwayshat Member--The Ghuwayshat member (mwt) of the Tuwal formation, named after Shi'ban Al Ghuwayshat in the northwest part of the district (pl. 1), is composed of subaerial felsic pyroclastic rocks, chiefly ignimbrites. Although their regional extent is unknown, the ignimbrites have a minimal thickness of about 300 m within the mapped area. They are massive and generally lack distinct primary or welding stratification. Lithic fragments consist of essential trachytic vitrophyre and chloritized pumice. The pumice fragments display various degrees of collapse by welding, producing a eutaxitic texture. Phenocryst fragments consist of potassium feldspar + albite ± quartz ± magnetite. The lithic and crystal fragments are supported by a microcrystalline matrix composed of quartz, feldspar, chlorite, and (or) hematite, which locally preserves the outlines of former shards. Unwelded tuffs are light green in color, while their welded equivalents are dark purplish gray due to a greater proportion of hematite/chlorite. The contact between the Mine member and the Ghuwayshat member is locally marked by the presence of a thick breccia/conglomerate layer with clasts of both mafic and felsic vitrophyre. The ignimbrites are regarded as subaerial equivalents of subaqueous pyroclastic rocks of the Mine member. Some workers (for example, Francis and Howells, 1973; Sparks and others, 1979) have argued that welding may occur under water; however, such an origin for these ignimbrites is unlikely.

Subvolcanic Rocks of the Tuwal Formation

Undifferentiated felsic and mafic dikes--The volcanic and subvolcanic rocks of the Mahd Group were fed by extensive swarms of dikes that dissect the basement (Dhukhur batholith, dt). The relative abundance of these dikes decreases sharply at the base of the Mahd Group and progressively up-section within the latter (pl. 1). The dikes consist of basalt, diabase, feldspar porphyry, and quartz-feldspar porphyry whose lithologies are identical to lavas and sills of the Mahd Group.

The dikes are north trending throughout the Dhukhur batholith, but locally fan out in other directions, apparently following pre-existing foliation trends in the batholith. Conjugate sets of northeast- and northwest-trending dikes are present, indicating predominantly east-west extension. At least thirty percent of the area shown as the Dhukhur batholith is actually underlain by numerous unmapped dikes and, in many locations, sheeted dikes occur to the exclusion of intervening wall-rock screens. These observations indicate that the magmatism that produced the Mahd Group was accompanied by major east-west extension.

Mafic subvolcanic intrusions--A large number of basalt-diabase dikes and sills intrude the rocks of the Mahd Group. Although quite similar in appearance, field relations indicate that several generations of mafic intrusions are present. For example, the dike swarms in the upper member of the Lahuf formation that were truncated by the pre-Tuwal unconformity are evidently older than similar-looking dikes that intrude the Tuwal formation, which are probably older than post-vein mafic dikes at Jabal Mahd Adh Dhahab.

The Lahuf formation contains a number of distinctive diabase sills, the largest of which, the Lahuf diabase, intruded along the Mahd Group-basement contact in the western part of the area (pl. 1). Typical diabase is medium grained and consists of subhedral zoned labradorite (0.64-0.40 anorthite) and interstitial augite. Minor magnetite (with exsolved ilmenite) and apatite are also present. Plagioclase is partly replaced by sericite, chlorite, and epidote, but augite has remained fresh. Other metamorphic minerals include hematite, calcite, and prehnite. In the vicinity of quartz veins at the Mahd and Lahuf mines, the diabase is further altered to an assemblage of orange microcline, chlorite, and pyrite ± hematite.

Mafic dikes and sills in the Tuwal formation are clustered near the old village of Al-Mahd (pl. 1) and are proximal to a central plug that consists of at least six concentric ring dikes. A sill that emanated from the central plug contains well-developed columnar joints. Most of these intrusions contain the same mineral assemblage as the Lahuf diabase, but are porphyritic to aphanitic in texture. The mafic intrusions described thus far are regarded as predictable subvolcanic equivalents of mafic volcanic rocks of the Mahd Group. Both groups are plagioclase-phyric and similar in composition. The apparent absence of pyroxene from the mafic volcanic rocks is probably due to their greater permeability, which facilitated replacement of pyroxene by metamorphic chlorite. The Lahuf diabase is definitely older than the mineralization because it has been cut and altered by quartz veins. On the other hand, a distinct generation of friable mafic dikes cut all generations of quartz veins at Jabal Mahd Adh Dhahab. These dikes have been partly replaced by chlorite, smectite, and iron oxides; vesicles and joints have been filled with calcite and chlorite. Another characteristic of the post-vein mafic dikes is their highly variable rubidium-strontium ratios (reported by Huckerby, 1984), which probably are due to assimilation of potassic alteration from their mineralized wall rocks.

Felsic lava domes and subvolcanic intrusions--Felsic lava flows, sills, and plugs are present throughout the Tuwal formation. These rocks are usually porphyritic-aphanitic, with medium- to fine-grained phenocrysts of plagioclase and potassium feldspar (± quartz). Plagioclase, frequently albitized, is usually indistinguishable from alkali feldspar in a hand specimen, except when the latter is dusted by hematite. The subvolcanic intrusive rocks occur as sills, stocks, and endogenous domes. These bodies generally are massive or flow banded, and have sharp discordant contacts. Forceful injection locally domed their wall rocks, resulting in semiconformable contacts. Intrusive breccia and breccia dikes are locally present at their margins and are attributed to phreatic activity attending intrusion.

Extruded lavas are usually difficult to distinguish from sills, but occur at a particular stratigraphic level, supporting a series of conical hills known as Al Tuwal (pl. 1). The lava flows and domes are recognized by the presence of monolithic autoclastic and flow-front breccias located around their margins. The flow-front breccias contain chaotic blocks (as large as 3 m across) that appear to have slid from the advancing lava flow. The sills usually have columnar joints, while the lavas usually display contorted flow banding and spherulitic devitrification.

Based on phenocryst populations, four varieties of felsic lavas and intrusives were distinguished throughout the district: (1) feldspar porphyry (dp), which contains 1-6 mm phenocrysts of sodic plagioclase ± alkali feldspar ± magnetite and 0-2 percent chlorite or pumpelleyite pseudomorphs after amphibole(?) or biotite(?), and is dacitic to rhyolitic in composition; (2) quartz-feldspar porphyry (rp), distinguished by the additional presence of 1-5 mm quartz phenocrysts, and is rhyolitic in composition; (3) felsite (f), which is the aphyric equivalent of (1) and (2); and (4) dacite porphyry (hp), distinguished by the presence of about 10 percent chlorite pseudomorphs after prismatic amphibole(?) phenocrysts, as well as sodic plagioclase in a holocrystalline groundmass; it occurs as sills in the northwest part of the district (pl. 1).

Alkali-feldspar phenocrysts are untwinned or simply twinned, and consist of almost pure orthoclase (<0.1 albite component). Plagioclase phenocrysts are polysynthetically twinned, but are usually albitized (0.95-0.99 albite, <0.01 orthoclase). Quartz phenocrysts range in shape from euhedral bipyramids to anhedral resorbed crystals. Other phenocrysts include fine-grained titaniferous magnetite (replaced by hematite-ilmenite), apatite, and rare zircon. Original mafic silicates, if any, have been replaced by chlorite. Textures in the lava flow suggest that the groundmass was initially glassy, but now consists of microcrystalline quartz, feldspar, chlorite, smectite, and hematite. The groundmass color ranges from dark gray (abundant microcrystalline quartz) to brown (hematite), green (chlorite), and tan (illite-smectite).

The Mine Hill Rhyolite on Jabal Mahd Adh Dhahab has received a good deal of attention because of the apparent spatial association of ore with the rhyolite, which has led most previous workers (for example, Luce and others, 1979; Huckerby and others, 1983; Hilpert and others, 1984; Doebrich, 1984) to infer that mineralization was caused by intrusion of the rhyolite. This intrusion was mapped as feldspar porphyry (pl. 1) because it lacks identifiable quartz phenocrysts. Samples that display the least amount of hydrothermal alteration contain phenocrysts of albitized plagioclase with only minor potassium feldspar, suggesting that "rhyodacite" is a more appropriate name (Hilpert and others, 1984). Chemical data (discussed later) also indicate that the Mine Hill Rhyolite is by no means the most felsic intrusion in the district. The albitized plagiolase was locally replaced by hydrothermal microcline, chlorite, and quartz, which indicates that albitization preceded hydrothermal alteration. Afifi and others (in prep. C) present geological and strontium-isotopic evidence indicating that intrusion of the Mine Hill Rhyolite preceded mineralization by about 120 m.y., and is, therefore, unrelated to mineralization.

GHAMR GROUP

Rocks of the Ghamr group crop out at Jabal Al-Maogiah and also in a small graben southeast of the jabal (pl. 1). The average dip of these rocks is 10° N., whereas attitudes in the underlying Mahd Group are variable and generally steeper (about 40°). A boulder conglomerate at the base of the Ghamr includes cobbles of Mahd Group rocks, indicating that the contact between the Mahd and the Ghamr is an angular unconformity. The nature of this contact was recognized by Goldsmith and Kouther (1971), who used it to separate the lower from the upper part of the Mahd Adh Dhahab Series.

Basal Conglomerate

A 10-15-m-thick brown cobble conglomerate (gc) is present at the base of the Ghamr, but only within the paleograben southeast of Jabal Al-Maogiah. This unit consists of crudely bedded, friable, polymictic cobbly sandstone and conglomerate. The subrounded cobbles and pebbles represent rock types in the basement and Mahd Group, and are supported by a matrix of poorly sorted arkosic lithic sandstone. This conglomerate represents immature detritus eroded from uplifted blocks of the basement and rocks of the Mahd Group that were subsequently deposited in an alluvial-fan environment.

The presence in the Ghamr conglomerate of quartz-vein cobbles is of particular interest because these cobbles are similar in appearance to veins that occur in situ at Mahd Adh Dhahab. Other similarities in fluid-inclusion and isotopic characteristics were observed (Afifi and others, in prep. D). This suggests that mineralized veins may have been eroded prior to the deposition of the Ghamr group. For this reason, the matrix of the Ghamr conglomerate was tested for the presence of placer gold (table 2, Ghamr group), but none was detected.

Volcanic Sandstone

This sequence (gt) consists of white, purple, and green thin-to-medium-bedded units of volcanic sandstone with occasional thick beds of purple conglomerate. The sandstone contains abundant lithic fragments of both intraformational and volcanic origin, as well as fragments of quartz and feldspar phenocrysts. Pebbles and boulders in the conglomerate consist mainly of felsic porphyry, apparently eroded from the more resistant rocks in the Mahd Group. Both lithic and crystal components of the sandstone appear to be derived largely from eroded volcanic rocks of the Mahd Group. These rocks are distinctly more friable than fragmental rocks of the Mahd Group and contain intergranular chlorite, smectite, and calcite. Prehnite and pumpelleyite are locally present, indicating that burial metamorphism followed the deposition of the Ghamr group.

Porphyritic Dacite

Lava flows of porphyritic dacite (ga) occur on top of Jabal Al Maogiah and at two stratigraphic levels within the adjacent graben (pl. 1). It is likely that these flows represent several eruptions rather than a single flow that cascaded from Al Maogiah into the adjacent graben. An extrusive origin is indicated by the presence of scoriaceous and oxidized flow tops, sandstone-filled joints, and local channeling in flow tops. The dacite contains phenocrysts of hornblende and plagioclase in an aphanitic groundmass replaced by smectite and chlorite. Stretched vesicles are filled with chlorite ± calcite.

QUATERNARY DEPOSITS

Quaternary deposits consist of older pediment and fan gravel (Qpf) and recent wadi sand (Qal). The pediments are covered by a lag deposit of wind-faceted cobbles and boulders whose upper surfaces are coated by a thick layer of desert varnish. The wadi alluvium was described by Bagdady and others (1978).

STRUCTURE

The geological history of the area is dominated by repeated episodes of block faulting that initially affected thickness and facies variations in the rocks of both the Mahd and Ghamr groups, and subsequently juxtaposed them against the basement. The presence of the major faults had to be inferred from stratigraphic detail because they generally lie hidden beneath wadis. Most faults cannot reliably be traced into the basement due to the lithologic homogeneity of the Dhukhur batholith.

GROWTH FAULTS

The earliest structures are growth faults that actively controlled the deposition of the Mahd Group. These lie hidden beneath tributary drainages west of Jabal Mahd Adh Dhahab and fan out perpendicular to the strike of bedding from north to northwest (pl. 1). Their presence is revealed by abrupt changes in thickness and facies, and by offsets or rotation of the layered rocks, particularly in the Lahuf formation. The growth faults lose stratigraphic throw upsection and most cannot be traced above the Lahuf-Tuwal unconformity (pl. 1). Some are listric, as implied by rotation of the basement-upper Lahuf block located immediately south of Jabal Mahd Adh Dhahab. Growth faults account for the eastward termination of the lower and middle members of the Lahuf, which thicken westward toward the axis of the Mahd basin (fig. 2). Block faulting during deposition of the Mahd Group was probably a consequence of regional east-west extension indicated by the sheeted dike swarms in the basement. Despite this, the basement remained buried throughout the deposition of the Mahd Group, as indicated by the lack of basement detritus in the latter. Units of the Mahd Group thin eastward across the district, partly due to thinning or lateral termination of some units over inferred basin-margin faults (for example, lower and middle members of the Lahuf formation), and partly due to pre-Ghamr erosion, which removed a substantial section of the Tuwal formation east of Jabal Mahd Adh Dhahab (fig. 3).

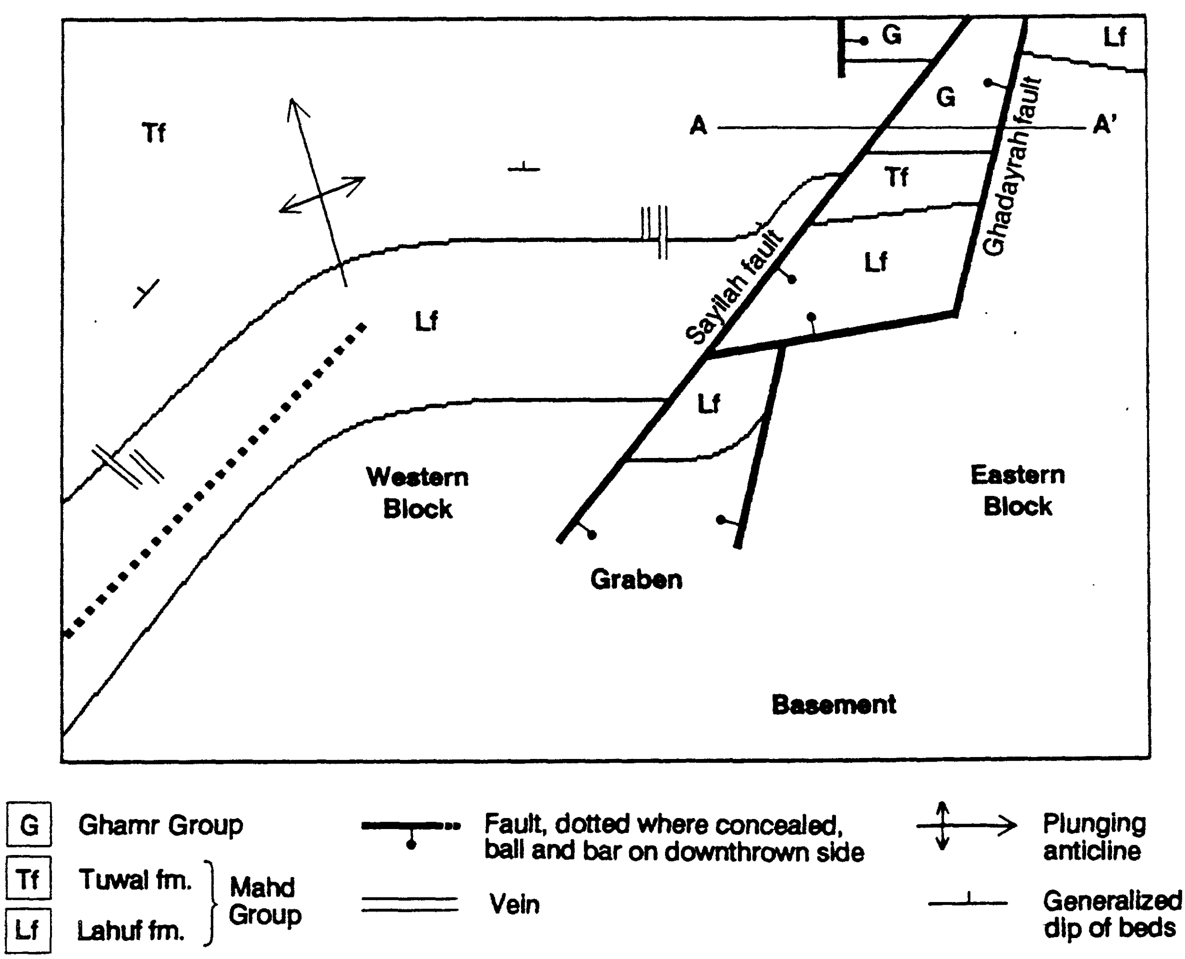


Figure 3.--Structural sketch map of the Mahd Adh Dhahab district. A-A': line of cross section shown in figure 4.

LOCAL STRUCTURES

Bedding attitudes in the Mahd Group are locally variable due to disruption by numerous subvolcanic intrusions and faults. Disharmonic mesofolds in the Mahd Group were generally the result of soft-sediment deformation rather than tectonic deformation. Intrusion-cored anticlines and domes, as well as a variety of "trap-door" faults, formed in order to accommodate the large volumes of subvolcanic intrusions, particularly around the old village of Al-Mahd (pl. 1). Some faults appear to have been localized by mechanical contrasts between the solidified intrusives and their wall rocks, examples of which were described by Hilpert and others (1984) around the Mine Hill Rhyolite. Structures associated with faults include normal and reverse drag folds, particularly along the Sayilah fault (pl. 1). Homoclinal folds, such as the progressive northward steepening of dip 40° - 80° on Jabal Mahd Adh Dhahab, are due either to drape folding over a buried fault or forceful intrusion of rhyolite.

DRAPE FOLDS

The Mahd Group and Ghamr group accumulated in a large arcuate basin (Mahd basin) that partly encircles the basement (fig. 2; Kemp and others, 1982). The Mahd Adh Dhahab district straddles the eastern margin of this basin. Subsidence of the Mahd basin most likely occurred along a series of basin-margin faults that terminate upward as drape folds in the overlying volcanic cover. Apart from local variations, the Mahd Group strikes east-west in the eastern part of the district, but swings to the southwest in the western part. This defines a northwest-plunging anticline (also manifested by the outward-fanning trends of dikes and faults that generally strike perpendicular to bedding) (pl. 1). This structure, and the basinward dips of the Mahd Group, is most likely due to drape folding over buried blocks of the rigid basement (fig. 3). The draping may be due to differential compaction around a basin-margin fault and (or) renewed fault movement. A flexure of similar geometry is apparent along the Lahuf-Tuwal unconformity northeast of the tailings pond (pl. 1), implying the presence of a buried fault (oriented approximately north-south) in the underlying basement (fig. 3).

POST-MAHD TECTONISM

The present outcrop pattern was established largely through movement along the Sayilah and Ghadayrah faults, which are connected (and offset?) by an east-northeast-trending cross fault (pl. 1). These faults divide the rocks of the Mahd Adh Dhahab district into three principal blocks: 1) an eastern block, in which the tonalitic basement is extensively exposed; 2) a western block, in which the basement remains largely concealed beneath the Mahd Group; and 3) a wedge-shaped central graben, in which the Ghamr group was deposited and subsequently preserved from erosion (fig. 3). The evolution of the central graben is illustrated schematically in figure 4. The Ghamr group was initially deposited within the graben over tilted and eroded beds of the Mahd Group. Abundant cobbles of basement and Mahd-Group lithologies in the basal fanglomerate of the Ghamr indicates the presence of active faults.

The horizontal separation of the base of the Mahd Group (pl. 1) allows some crude estimates of the relative vertical movement of the principal fault blocks. The base of the Mahd Group is separated horizontally by about 6 km across the Ghadayrah and east-northeast-trending cross fault, which (assuming an average dip of 30°) amounts to uplift of the eastern block by about 3.2 km relative to the central graben. The western block was apparently uplifted by about 0.6 km relative to the central graben. The net relative uplift of the eastern block with respect to the western block is therefore about 2.6 km. This uplift accounts for the extensive exposure of the basement and rocks of the Mahd Plutonic Complex on the eastern block.

Huckerby (1984) attributed the outward-directed dips of the Mahd Group to plastic upwelling of the basement, analogous to a gneiss-cored complex. This hypothesis is implausible in light of the following evidence: 1) the contact between the basement and the Mahd Group is either depositional or a discordant fault; 2) there are no indications of plastic deformation in the basement during and after deposition of the Mahd Group; on the contrary, all available evidence indicates widespread brittle extension; 3) there are no indications of a steep metamorphic gradient between the basement and the Mahd Group; and 4) metamorphic foliation in the basement was acquired prior to deposition of the Mahd Group and is discordant with the basement-Mahd Group contact.

METAMORPHISM

The earliest metamorphic event only affected the Dhukhur batholith and its wall rock (Arj Group?). It attained conditions of the amphibolite facies, as indicated by the presence of amphibolites and quartzo-feldspathic gneiss in the older rocks and the well-developed penetrative foliation in the tonalite. Metamorphism of the basement rocks must have proceeded immediately after intrusion of the Dhukhur batholith, dated at 816 ± 3 Ma (Calvez and Kemp, 1982), and certainly before deposition of the Mahd Group, which ended about 770 Ma (the age of the Mahd Plutonic Complex, the Ramram Complex, and the Hufayriyah batholith).

BURIAL METAMORPHISM

Following deposition, the volcanic rocks were subjected to various diagenetic effects, such as devitrification, cementation, and hydration. These effects cannot be

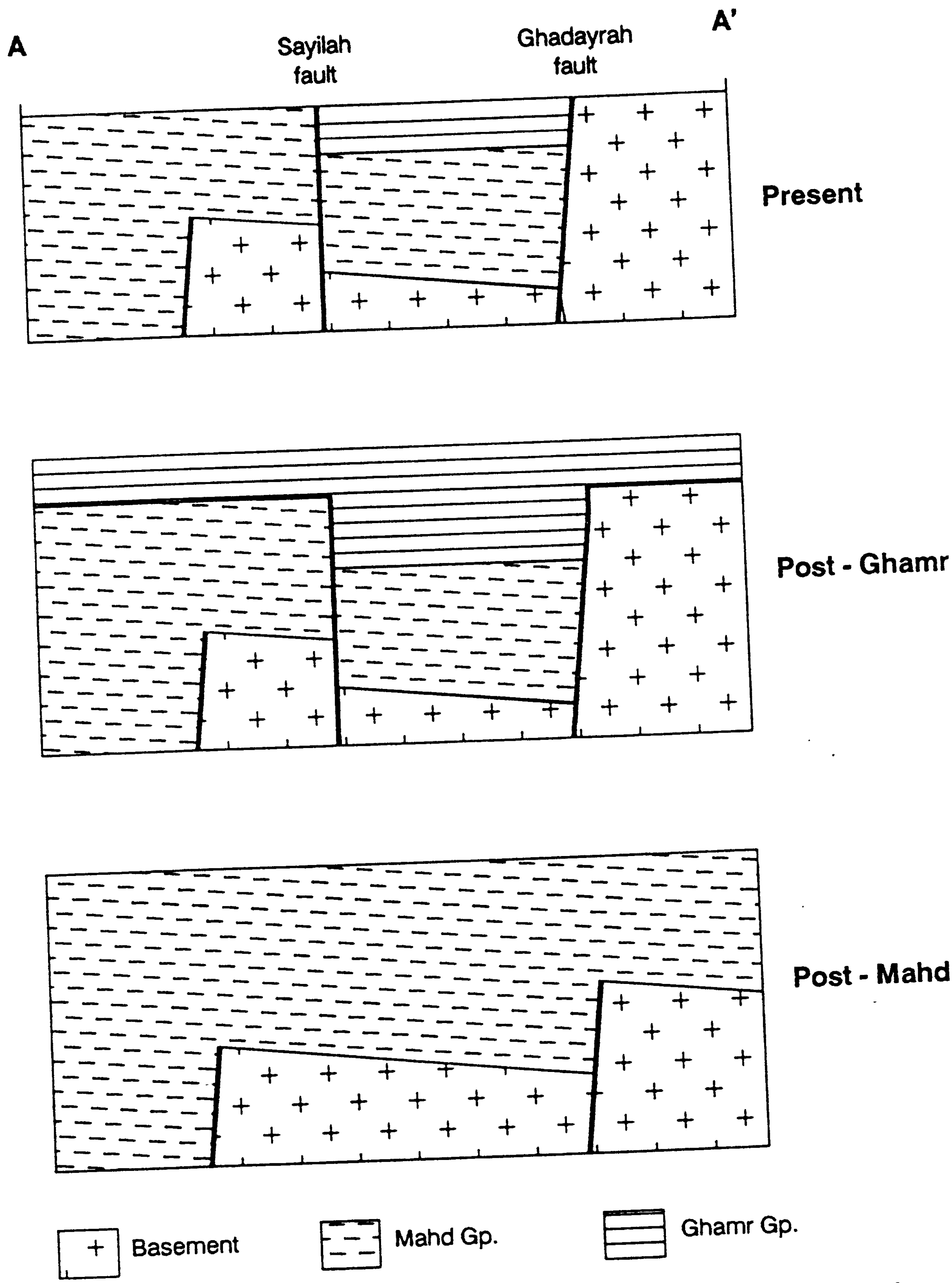


Figure 4.–Schematic cross sections along A-A' (fig. 3) illustrating the evolution of the central graben.

adequately distinguished from the subsequent effects of burial metamorphism. Vitric components in the volcanic rocks have been replaced by metamorphic minerals, including chlorite, quartz, albite, microcline, phengite, epidote, and hematite. The only glass that remained is found as tiny melt inclusions ($<10\mu$ across) preserved in quartz phenocryst due to their isolation from water.

Aside from local development of fracture cleavage, no penetrative foliation is present in rocks of the Mahd and Ghamr groups. Most rocks include metamorphic chlorite ± albite ± epidote ± phengite ± calcite ± dolomite or ankerite ± hematite± sphene.

The feldspar phenocrysts retained little of their initial composition and structural state. Alkali feldspars (initially sanidine) have been replaced by almost pure orthoclase. Plagioclase, which coexists with alkali feldspar, is usually replaced by pure albite (An 0-6). Labradorite is frequently preserved in thick diabase sheets, but it is albitized in the mafic volcanic rocks. The metamorphic chlorites are widely variable in composition, and some chlorites contain interlayers of smectite and (or) vermiculite (Afifi and others, in prep. A). Phengite is also variable in composition between muscovite, celadonite, and smectite, probably due to interlayering of these components. Prehnite [$Ca_2Al_2Si_3O_{10}(OH)_2$] (with as much as 0.39 Fe^{+3} substitution) or epidote (0.25-0.33 pistachite) are commonly present in the mafic and intermediate rocks, but appear to be mutually exclusive. Hematite-ilmenite partly replace magnetite-ulvospinel phenocrysts. Metamorphic sphene (with 0.15-0.24 Al^{+3}) is commonly present in felsic tuffs. Pumpelleyite is occasionally present in vesicles and as replacement of former hornblende(?). Mafic rocks contain a mixture of relic igneous minerals (such as augite and labradorite) and metamorphic minerals, indicating incomplete re-equilibration at lower temperature. A greater abundance of metamorphic minerals, corresponding to a closer approach to equilibrium, is found in permeable rocks, such as vesicular lava flows and tuffs, rather than in massive subvolcanic intrusions. No zeolites, laumontite, lawsonite, zoisite-clinozoisite, or tremolite were found, despite being carefully sought. Calculated equilibria between metamorphic minerals (Afifi and others, in prep. A) indicate peak conditions corresponding to those of the prehnite-pumpelleyite facies.

CONTACT METAMORPHISM

Contact metamorphic effects are sometimes observed next to subvolcanic intrusions, particularly in the densely intruded area north of Jabal Mahd Adh Dhahab. This is manifested by baking and formation of chlorite-spotted hornfels around the contacts. Other effects include formation of a pseudo-eutaxitic (almost gneissic) fabric in felsic lapilli tuffs underneath a large mafic sill, attributed to compaction while being heated by the sill.

HYDROTHERMAL ALTERATION

In addition to the metamorphic effects described thus far, scattered areas of the Mahd Adh Dhahab district, including areas of known mineralization, have undergone various degrees of hydrothermal alteration. Felsic rocks at Mahd Adh Dhahab have undergone silicification, replacement of feldspars (including metamorphic albite) by orange microcline or sericite, and introduction of various amounts of hydrothermal chlorite, microcline, pyrite, hematite, and (or) carbonates. Mafic rocks at Mahd Adh Dhahab and Lahuf were altered to microcline + chlorite + epidote ± pyrite ± hematite. Dolomite beds near veins were replaced by talc + dolomite + calcite ± pyrite ± anhydrite. Talc + dolomite ± calcite ± quartz is also found along faults. The presence of pink-orange microcline, which appears cloudy due to dusting by micron-sized hematite and illite, is particularly widespread. When such microcline occurs in veins, it displays the characteristic rhombic shape of former adularia.

CHEMICAL COMPOSITION OF THE VOLCANIC ROCKS

A substantial number of major-element rock analyses from the district have accumulated over the past decade through the efforts of several workers. Although most analyses are of altered rocks from Jabal Mahd Adh Dhahab, Afifi and others (in prep. A) added a significant number of analyses of "unaltered" rocks collected a good distance from the nearest mineralization. The available data were compiled specifically to seek causes of variation among volcanic rocks in terms of magmatic, metamorphic, and hydrothermal processes.

Table 1 includes 26 major-oxide analyses of volcanic and subvolcanic rocks taken from Afifi and others (in prep. A). These were augmented with 6 partial analyses from Hakim (1978), 37 partial analyses from Huckerby (1984), and 5 complete analyses from Hilpert and others (1984). The analyses of Hakim (1978) and Huckerby (1984) lack volatile and trace-element determinations, and also lack adequate descriptions. For this reason, approximately half of their analyses, particularly those that totaled less than 95 weight percent, were excluded. Analyses were selected to be representative of "unaltered" lavas and subvolcanic rocks from the district as a whole, but a few altered rocks from the mineralized areas were included for comparison. Except for a single dacite of the Ghamr group (sample 172179), all of the selected analyses are from the Mahd Group.

For the purpose of comparison, a separate compilation of about 300 analyses representative of unaltered Cenozoic subalkalic volcanic rocks was generated. These data were obtained from various sources, such as Carmichael and others (1974), Ewart (1979), Ewart (1982), Bacon and others (1981), and Gill (1981).

Table 1.–Major-oxide analyses of rocks from the Mahd Adh Dhahab district. All values are in weight percent.

Sample:	172179c	172180a	172205m	172239	172301	172318	172341a	172344a	172360
SiO_2	66.28	76.44	74.76	76.28	68.66	75.91	52.64	76.83	65.63
TiO_2	1.23	0.19	0.19	0.18	0.66	0.28	1.06	0.24	0.97
Al_2O_3	14.33	11.46	12.63	12.10	13.54	12.57	17.01	12.04	12.89
FeO*	5.34	1.51	2.69	1.46	4.39	2.26	8.75	1.60	7.26
MnO	0.11	0.04	0.07	0.03	0.12	0.04	0.16	0.05	0.15
MgO	0.62	0.49	0.98	2.87	0.83	0.39	4.57	0.42	2.20
CaO	2.08	0.88	0.17	0.43	1.94	0.64	8.25	1.71	3.62
Na_2O	4.30	4.21	2.42	4.64	5.83	5.83	2.87	6.35	4.36
K_2O	3.73	1.91	4.26	0.71	0.90	1.66	0.34	0.20	0.13
P_2O_5	0.39	0.03	0.03	0.03	0.11	0.07	0.16	0.04	0.23
LOI	1.53	1.89	1.72	2.22	2.11	0.86	2.52	1.75	2.06
H_2O-	0.38	0.05	0	0.37	0.26	0.20	0.11	0.14	0.18
Total	100.32	99.11	99.93	101.31	99.34	100.72	98.43	101.37	99.68

Sample:	172367	172405b	172415	172452	172453d	172467	172490	172595b	172600
SiO_2	76.08	49.40	68.83	78.11	76.25	52.86	63.87	61.85	53.11
TiO_2	0.12	0.87	0.65	0.17	0.17	0.69	0.86	0.54	0.81
Al_2O_3	9.96	18.81	13.57	11.94	11.31	15.69	13.82	17.37	16.33
FeO*	1.59	8.05	4.44	1.69	1.95	8.39	5.65	4.18	7.61
MnO	0.10	0.16	0.13	0.05	0.02	0.53	0.12	0.07	0.13
MgO	2.27	4.30	2.10	0.29	0	8.14	1.82	2.19	4.70
CaO	0.14	9.52	1.82	1.01	1.49	1.71	3.80	4.61	8.17
Na_2O	0.64	1.81	2.56	5.28	4.55	1.67	5.71	4.08	2.60
K_2O	5.71	2.62	3.87	0.71	1.52	3.50	0.41	1.21	0.37
P_2O_5	0.02	0.14	0.15	0.03	0.03	0.07	0.28	0.12	0.18
LOI	1.56	3.09	1.84	1.56	1.76	4.67	3.26	3.16	4.06
H_2O-	0.21	0.08	0.18	0	0.35	0.59	0.36	0.19	0.32
Total	98.41	98.85	100.14	100.84	99.39	98.50	99.99	99.56	98.40

Sample:	172693	172699	172745	172760	172842	172848	172851b	91-112
SiO_2	49.77	48.72	76.98	75.51	77.79	48.81	72.52	54.52
TiO_2	0.73	1.03	0.24	0.22	0.24	0.87	0.18	0.85
Al_2O_3	19.64	16.60	10.60	11.76	10.87	19.01	12.99	14.79
FeO*	7.24	9.82	3.35	3.14	1.99	8.49	3.38	9.00
MnO	0.14	0.18	0.05	0.12	0.05	0.18	0.15	0.40
MgO	5.02	5.99	0.47	0.62	0.13	5.08	0.66	4.31
CaO	7.98	8.38	1.34	0.29	1.29	8.16	0.35	4.18
Na_2O	3.84	1.89	3.57	5.89	5.69	2.92	2.15	0.17
K_2O	1.19	2.23	1.11	0.43	0.17	1.58	6.58	5.72
P_2O_5	0.09	0.22	0.04	0.06	0.05	0.11	0.03	0.12
LOI	2.61	2.82	1.19	1.18	1.15	2.98	1.60	4.53
H_2O-	0.30	0.44	0.19	0.04	0.20	0.28	0	0
Total	98.55	98.30	99.12	99.26	99.62	98.47	100.60	98.57

[+] Analyzed by A.M. Afifi, University of Michigan, by X-ray fluorescence on fused powders, following the method of Norrish and Hutton (1969).

* Total iron as FeO.

Table 1.—Major-oxide analyses of rocks from the Mahd Adh Dhahab district—(Continued)

Description of Samples

172179c:	Brown vesicular dacite, plagioclase phenocrysts, Ghamr Group.
172180a:	Quartz feldspar porphyry dike, Lahuf formation.
172205m:	Altered Mine Hill rhyolite.
172239:	Light green felsic lapilli tuff, Tuwal formation.
172301:	Rhyodcaite crystal vitric tuff, Tuwal formation.
172318:	Flow layered feldspar porphyry, Tuwal formation.
172341a:	Basalt sill, Tuwal formation.
172344a:	Rhyolitic lapilli tuff, feldspar + quartz phenocrysts, Tuwal formation.
172360:	Andesite lapilli tuff, upper member, Lahuf formation.
172367:	Laminated silicified rhyolite, Tuwal formation.
172405b:	Diabase dike, upper member, Lahuf formation.
172415:	Andesite lapilli tuff, upper member, Lahuf formation.
172453d:	Dark gray quartz feldspar porphyry, Tuwal formation.
172452:	Feldspar-porphyry dike, Tuwal formation.
172467:	Microcline-altered andesite, upper member, Lahuf formation.
172490:	Sill of dark gray dacite, quartz phenocrysts, Tuwal formation.
172595b:	Dacite porphyry (hp), Tuwal formation.
172600:	Basalt dike, Tuwal formation, south of J. Al Maogiah.
172693:	Lahuf diabase, Lahuf fomation, SE of lahuf mine.
172699:	Plagiolase-phyric trap, upper member, Lahuf formation, Lahuf mine
172745:	Welded tuff, Ghuwyashat member, Tuwal formation.
172760:	Least-altered Mine hill rhyolite.
172842:	Welded tuff, upper member of Lahuf formation.
172848:	Lahuf diabase, Lahuf formation.
172851b:	Altered Mine Hill rhyolite, Mahd Mine.
91-112:	Altered rhyolite, southern mineralized zone, Mahd Mine.

Variation Of Major Oxides

Due to the porphyritic nature of most rocks, their composition cannot strictly be regarded as that of the magmas from which they formed. Moreover, all rocks contain a substantial proportion of secondary minerals that were added as a result of devitrification, metamorphism, and(or) hydrothermal alteration. For these reasons, the whole-rock data were plotted along with compositions of phenocrysts (pyroxene, hornblende, alkali feldspar, plagioclase, and (or) quartz) and metamorphic-hydrothermal minerals (chlorite, phengite, prehnite, epidote, sphene, pumpelleyite, albite, microcline, and carbonates) on Harker diagrams (fig. 5). Except for quartz and iron oxides, mineral compositions were obtained by microprobe analysis (Afifi and others, in prep. A). The rock analyses were divided into three categories: (1) lava flows and intrusions, denoted by solid symbols; (2) fragmental rocks, denoted by open symbols; and (3) equivalents of (1) or (2) that are known to be hydrothermally altered, denoted by the "X" symbols. This breakdown is not exact, because analyses obtained from other sources may have been from altered areas, and ideally would have been included in the third category. It should be noted that analyses were not normalized to 100 percent on an anhydrous basis prior to plotting because such practice is unjustifiable for hydrated and carbonated rocks.

Most of the major and minor oxides, including Al_2O_3, FeO* (total iron), MgO, TiO_2, and P_2O_5, display regular variation with SiO_2. This variation is similar to trends observed in unmodified igneous rocks, indicating that these elements were not substantially mobilized by metamorphism and (or) hydrothermal alteration. The oxides CaO, MnO, K_2O, and Na_2O, on the other hand, display substantial scatter, attributed to their mobility during metamorphism and (or) hydrothermal alteration.

The inclusion of mineral compositions on the harker diagrams provides a graphic means to assess the results of addition or removal of specific minerals. The effect of mineral addition, whether by accumulation of phenocrysts or nucleation of a secondary mineral, is to shift the whole-rock composition along a vector toward the added mineral. Removal of a mineral, whether by fractional crystallization or leaching, shifts the bulk composition along a vector away from that mineral. Filling of vugs with secondary chlorite, for example, will shift the bulk composition toward chlorite; SiO_2, CaO, Na_2O, and K_2O will decrease, and FeO* and MgO will increase; Al_2O_3 will remain unchanged in mafic rocks but will increase in felsic rocks. The length of each mineral addition/removal vector, corresponding to the degree of departure from the initial composition, depends both on the amount of mineral added or removed, and the difference in composition between the mineral and the rock. When one or more minerals replace another, the bulk composition of the rock will shift along the sum of all mineral-addition or removal vectors. Thus, for a given rock to maintain its magmatic composition, all secondary-mineral vectors must equal zero.

EXPLANATION OF FIGURE SYMBOLS AND ABBREVIATIONS--FIGURE 5

SYMBOLS

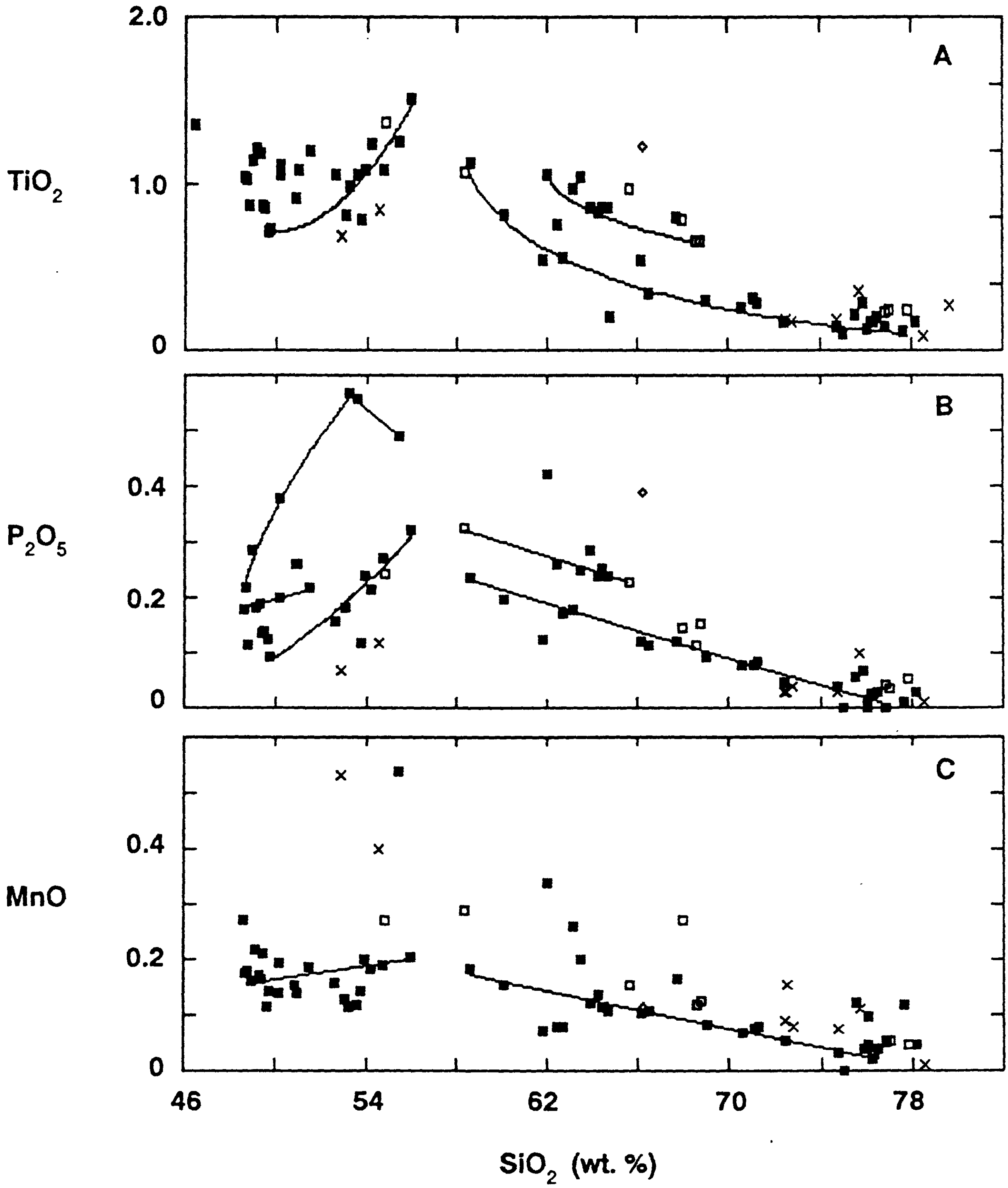
◇ Dacite, Ghamr group

Mahd Group:
- ■ Lavas and intrusions
- □ Fragmental rocks
- × Hydrothermally altered rocks

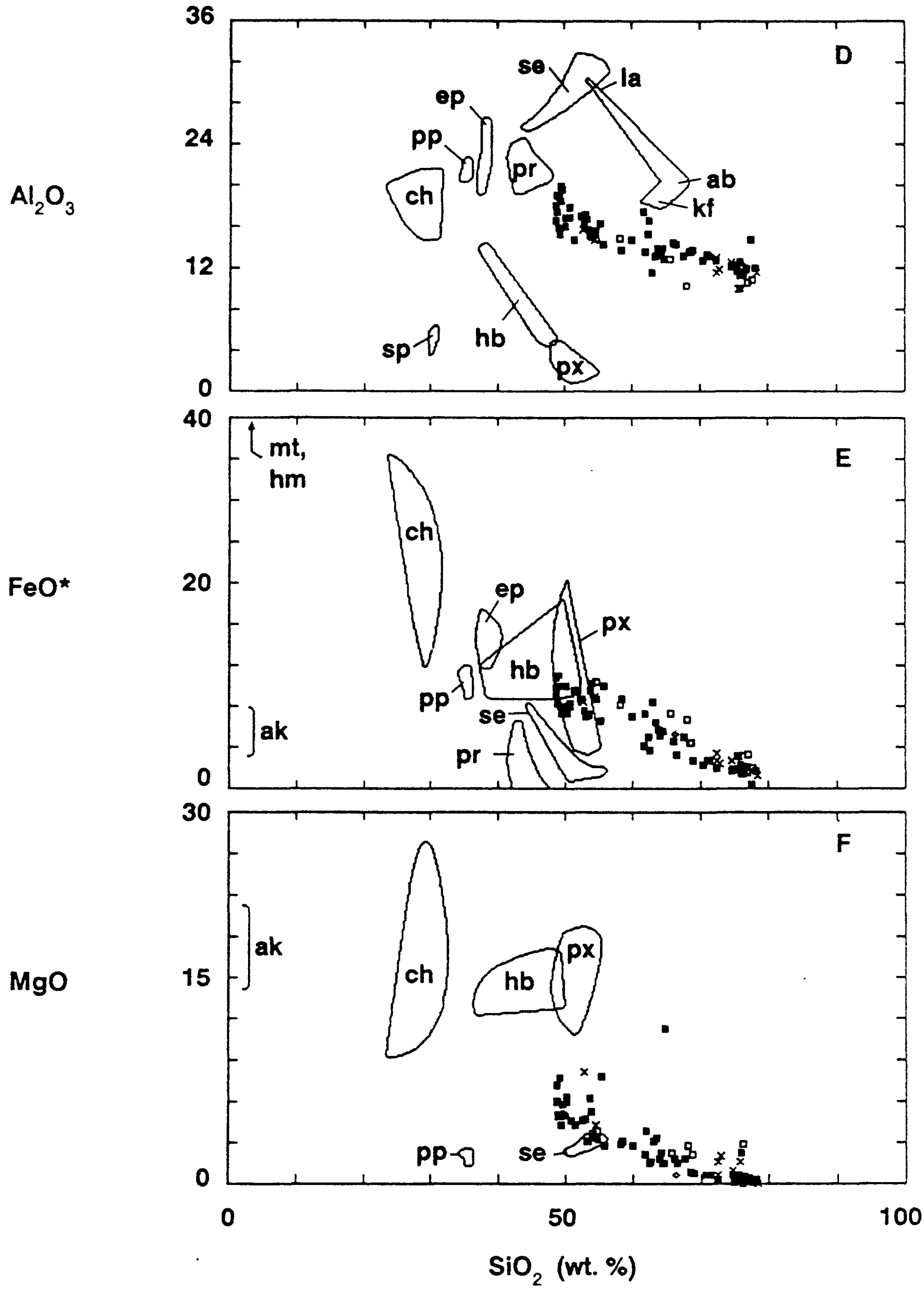
ABBREVIATIONS

ak = ankerite
ch = chlorite
hb = hornblende
px = augite
ep = epidote
se = sericite
pp = pumpelleyite
Kf = K-feldspar
pr = prehnite
la = labradorite
ab = albite
mt = magnetite
hm = hematite

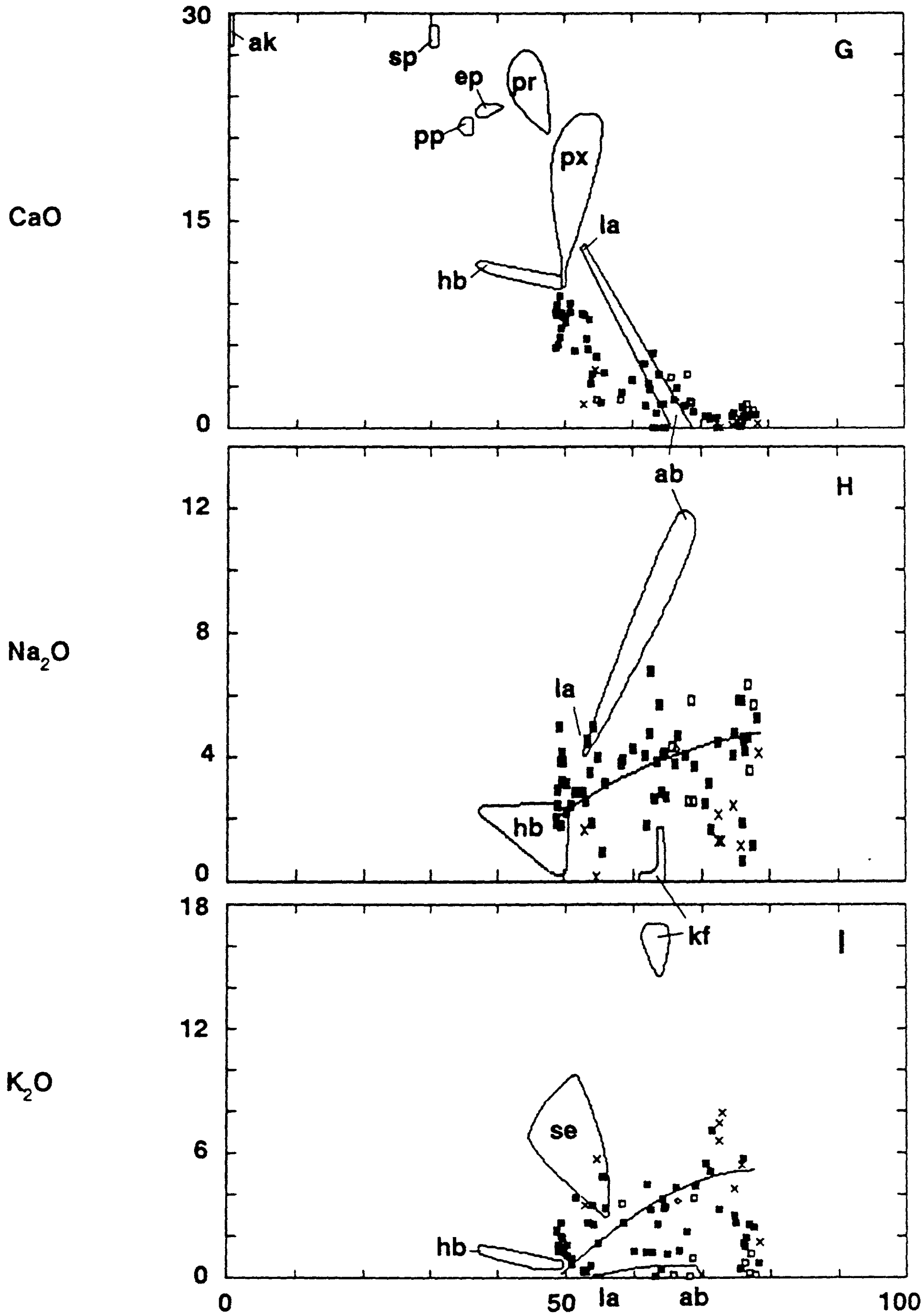
Figure 5.--Harker diagrams for racks and minerals of the Mahd Group.



Figures 5A through 5C.–Harker diagrams for rocks and minerals of the Mahd Group plotting TiO_2, P_2O_5, and MnO versus SiO_2; all values in weight percent. Lines denote inferred magmatic trends.



Figures 5D through 5F.--Harker diagrams for rocks and minerals of the Mahd Group plotting Al_2O_3, FeO*, and MgO versus SiO_2; all values in weight percent. Fields enclose mineral compositions determined by Afifi and others (in prep. A-D).



Figures 5G through 5I.–Harker diagrams for rocks and minerals of the Mahd plotting CaO, Na_2O, and K_2O versus SiO_2. All values in weight percent. Fields enclose mineral compositions determined by Afifi and others (in prep. A-D).

Silica Variation

The distribution of silica in the Mahd Group (fig. 6) is trimodal, with only 5 percent of the samples in the typical andesite range (56-62 weight percent SiO_2). The three modes correspond to (1) basalt-basaltic andesite, including mafic volcanic rocks of the upper Lahuf member, mafic flows and tuffs of the Tuwal formation, and mafic subvolcanic intrusions, (2) dacite, represented by the feldspar porphyritic lava flows and intrusions, and (3) rhyolite, represented by feldspar and quartz-feldspar porphyritic lavas and intrusives. The sample population is biased due to poor representation of felsic rocks that constitute the bulk of the Mahd Group. It is likely that the mafic and felsic rocks are not related by differentiation, being products of separate and independent magmas that overlapped in space and time.

Due to mobility of silica in the metamorphic and hydrothermal environments, SiO_2 variation can only serve as a crude indicator of initial composition. Some lava flows contain as much as 78 weight percent silica, attributed to accumulation of quartz phenocrysts and (or) addition of secondary quartz. In general, however, it appears that most samples do not deviate from their initial SiO_2 content by more than 5 weight percent, as indicated by the magnitude of scatter on harker diagrams of the less mobile elements such as in TiO_2 and P_2O_5 (figs. 5A and 5B).

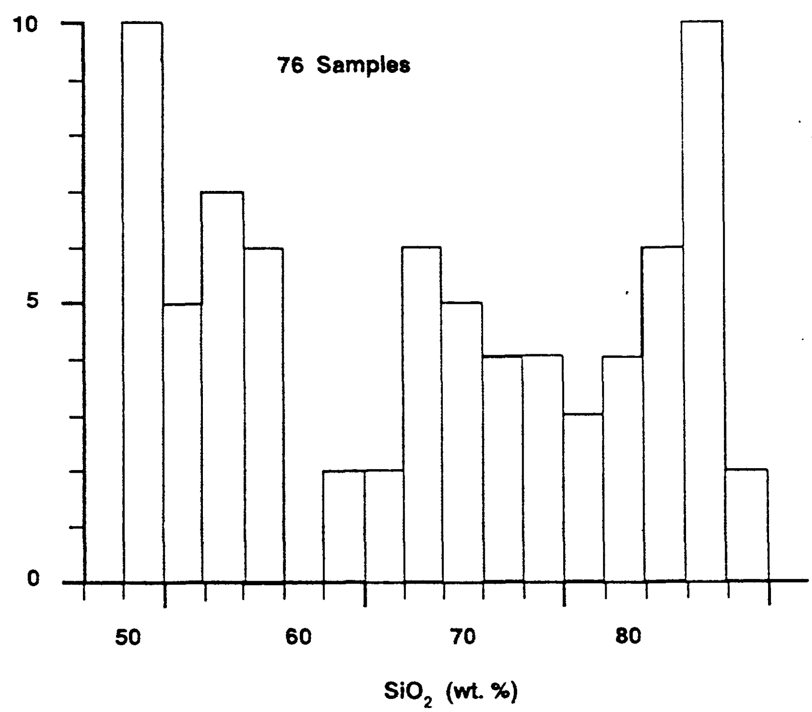


Figure 6.--Histogram of SiO_2 concentrations in volcanic and subvolcanic rocks of the Mahd Group.

Magmatic Variation

The curvilinear trends in the Harker diagrams of Al_2O_3, TiO_2, FeO, MnO, and MgO (fig. 5) are due to introduction and differentiation of several batches of basaltic, rhyolitic, and dacitic magmas. Several individual subtrends (approximated by solid lines) are inferred on the harker diagram for TiO_2 and P_2O_5, which are regarded as relatively immobile (figs. 5A and 5B). The inferred magmatic trends are also mirrored by smooth trends on variation diagrams for the less mobile trace elements, such as zirconium, niobium, and yttrium (Afifi and others, in prep. A).

The evident mobility of calcium, sodium, and potassium renders classification using common schemes, such as those of Irvine and Baragar (1971) and Miyashiro (1974), unreliable. Nevertheless, most analyses fall in the subalkaline region on the alkali-silica plot (Miyashiro, 1974), but substantial scatter indicates that the total alkali content has changed. The phenocryst compositions and low zirconium contents also indicate that these rocks are subalkalic. The mafic rocks do not display iron enrichment on the AFM plot, suggesting a calc-alkaline affinity. Due to the abundance of phenocrysts, fractional crystallization is a likely mechanism for explaining some of the variation on Harker diagrams, particularly for the less-mobile elements. Both TiO_2 and P_2O_5 initially increase with SiO_2 from basalt to basaltic andesite, and progressively decrease from dacite to rhyolite (figs. 5A and 5B). These subtrends are probably due to saturation and removal of titaniferous magnetite and apatite, respectively. The inflections in the harker diagrams for TiO_2 and P_2O_5 also rule out mixing of basaltic and rhyolitic magmas as a potential mechanism to account for the intermediate compositions. The basalts display significant variation in Al_2O_3, CaO, MgO, and FeO at constant SiO_2, which is probably due to fractionation of pyroxene and plagioclase.

Secondary Processes

Rocks from the Mahd Adh Dhahab district are systematically depleted in CaO by comparison with unaltered Cenozoic subalkalic volcanic rocks throughout the world (fig. 7). The exceptions are the silicified rhyolites, which are slightly enriched in CaO. The CaO-depleted rocks have been enriched in Na_2O (fig. 5H) due to widespread albitization of plagioclase. Moreover, samples collected from mineralized areas ("X" symbols, fig. 5I) are enriched in K_2O at the expense of both CaO and Na_2O, reflecting the replacement of all feldspars (including albite) by hydrothermal microcline and phengite.

In mafic and intermediate rocks, some calcium liberated from the decomposition of plagioclase, pyroxene, and amphibole phenocrysts was contained by calcium-rich secondary minerals, such as carbonates, epidote, prehnite, or sphene (fig. 5G); the remainder (which accounts for wholesale calcium depletion) appears to have been lost to metamorphic and (or) hydrothermal fluids. The calcium-rich rhyolites appear to have gained calcium from metamorphic fluids. This calcium was incorporated in secondary epidote or carbonate. The net effect was a district-wide transfer of calcium from mafic and intermediate-composition rocks to the rhyolites.

The initial variation in Na_2O and K_2O has been approximated by solid lines based on the average variation of these oxides in Cenozoic subalkalic volcanic rocks. In rocks of the district, K_2O is negatively correlated with Na_2O, which contrasts with the positive correlation between these oxides in unaltered suites of volcanic rocks (fig. 8). In general, most rocks (particularly the tuffs) are enriched in Na_2O and depleted in K_2O due to metamorphic albitization, whereas rocks that are known to be hydrothermally altered ("X"-symbols, fig. 8) are depleted in Na_2O and enriched in K_2O due to replacement of albite and any relict plagioclase by hydrothermal microcline. Textural relations indicate that hydrothermal microcline replaced albitized plagioclase, and hence metamorphic albitization preceded hydrothermal alteration. Geochronologic and isotopic studies also indicate that metamorphic albitization and hydrothermal alteration were discrete events (Afifi and others, in prep. c), ruling out hydrothermal and metamorphic fluids being mutually interrelated. The hydrothermally altered rocks are also variably enriched in MnO, and MgO with respect to their metamorphosed equivalents (figs. 5C and 5F), most likely due to the addition of chlorite, which contains as much as 2 weight percent MnO.

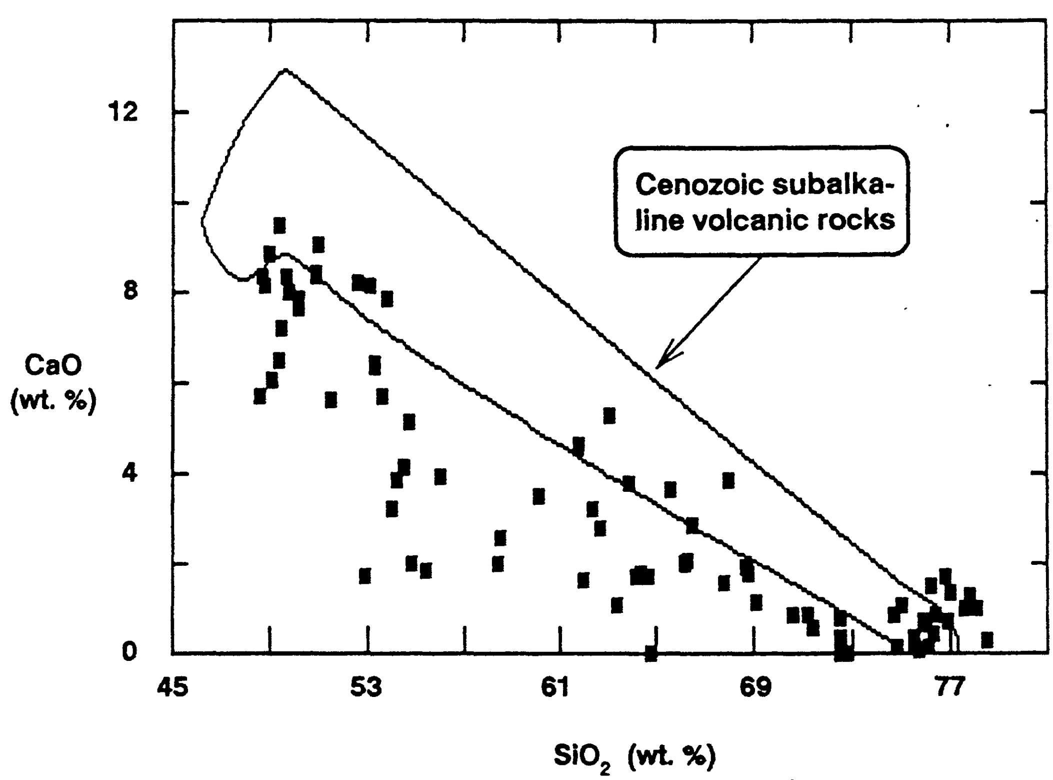


Figure 7.–Relative depletion/enrichment of CaO in rocks of the Mahd Group with respect to unaltered Cenozoic subalkaline volcanic rocks.

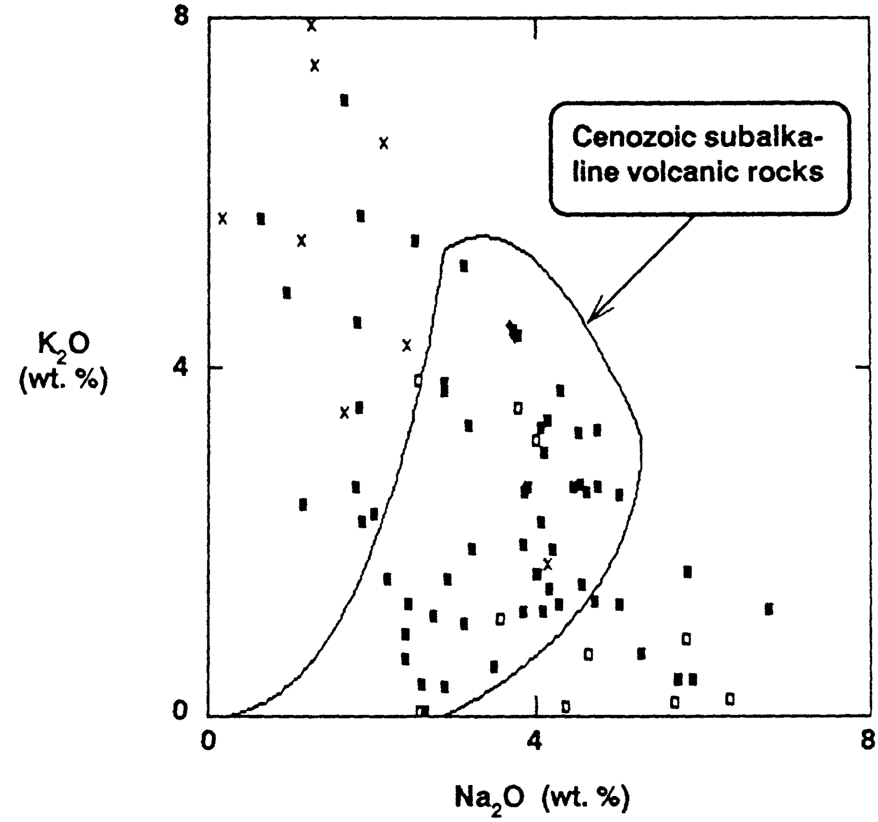


Figure 8.–Negative correlation between K_2O and Na_2O in rocks of the Mahd Group in contrast to unaltered Cenozoic subalkaline volcanic rocks. Symbols same as figure 5.

MOBILITY OF RUBIDIUM AND STRONTIUM: IMPLICATIONS FOR DATING

Calvez and Kemp (1982) noted that the rubidium-strontium whole-rock date that they obtained from 9 samples of Mahd Group rhyolite (737 ± 28 Ma), while statistically valid, was in disagreement with the age of the Ramram granite (769 ± 5 Ma), which intrudes the Mahd Group. They attributed this discrepancy to the mobility of rubidium and strontium during diagenesis and (or) metamorphism, and applied a filtering technique to reject samples that apparently had lost rubidium and gained radiogenic strontium in order to obtain a date of 772 ± 28 Ma.

Huckerby (1984) obtained a number of rubidium-strontium whole-rock isochron and errorchron dates on rocks of the district, which ranged from 786 ± 33 Ma for the upper member of the Lahuf formation to 709 ± 16 Ma for mafic dikes in the Mahd Group; without addressing diagenetic/metamorphic effects, he interpreted these dates as ages of magmatism. The behavior of rubidium and strontium in the metamorphic/hydrothermal environment is critical to obtaining useful rubidium-strontium whole-rock isochron dates. The compiled concentrations of these two elements were generated from analyses by Huckerby (1984), Hilpert and others (1984), and Afifi and others (in prep. D). Harker plots of rubidium and strontium mimic the scatter in those of K_2O and CaO, as illustrated by a 0.91 linear correlation coefficient between rubidium and potassium (fig. 9), and a 0.81 coefficient between strontium and calcium (fig. 10). The previous discussion shows that rocks from the district lost rubidium (with potassium) to metamorphic fluids, and gained rubidium (in microcline) from hydrothermal fluids. Likewise, strontium was leached (with calcium) from albitized mafic and intermediate-composition rocks and added to felsic rocks (in epidote and calcite) during metamorphism. The hydrothermally altered rhyolite ("X" symbols, fig. 10) lost more strontium than their metamorphosed (but unaltered) equivalents. Therefore, the $^{87}Sr/^{86}Sr$ composition of volcanic rocks of the district has been contaminated by diagenetic, metamorphic, and (or) hydrothermal fluids. The rubidium-strontium ratios of these rocks changed substantially from their initial (magmatic) values, rendering insignificant any rubidium-strontium whole-rock dates obtained on volcanic rocks from this area, even though some of the dates are based on valid isochrons. Rubidium and strontium are less susceptible to secondary mobilization in massive bodies of plutonic rocks, partly because such bodies are less permeable to metamorphic fluids, and because the rocks are holocrystalline. The rubidium-strontium whole-rock dates obtained by Huckerby (1984) on the Mahd Plutonic complex are acceptable because they are in reasonable agreement with geological constraints and the zircon age of the Ramram granite.

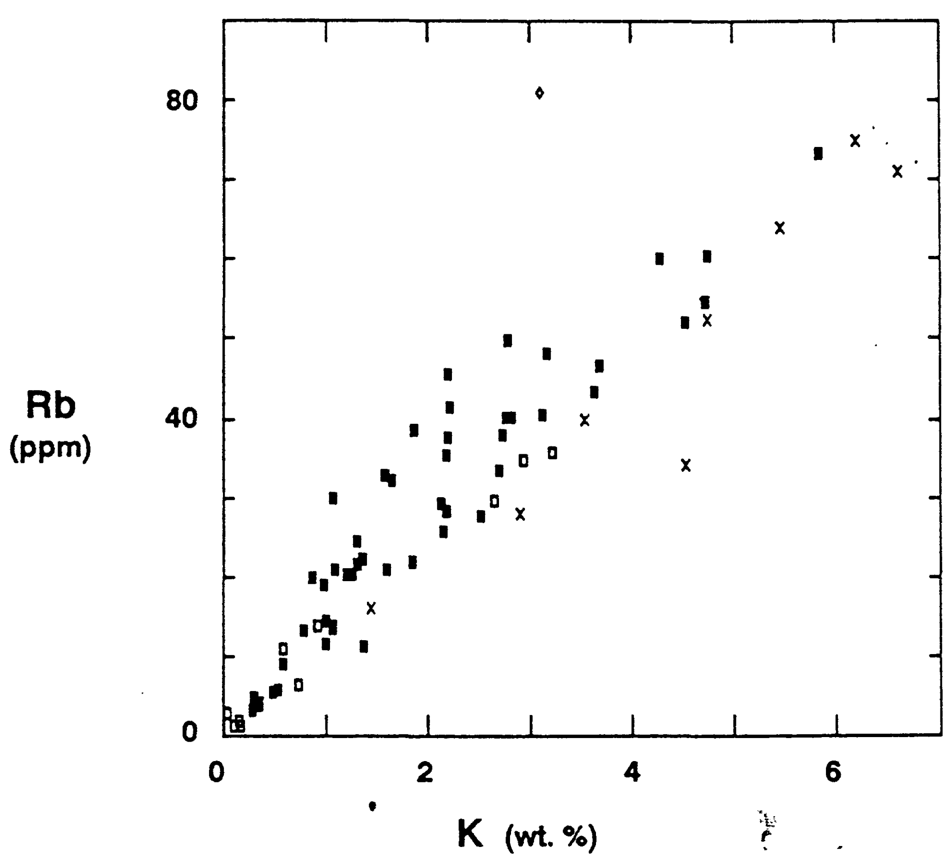


Figure 9.–Correlation of rubidium with potassium. Symbols same as figure 5.

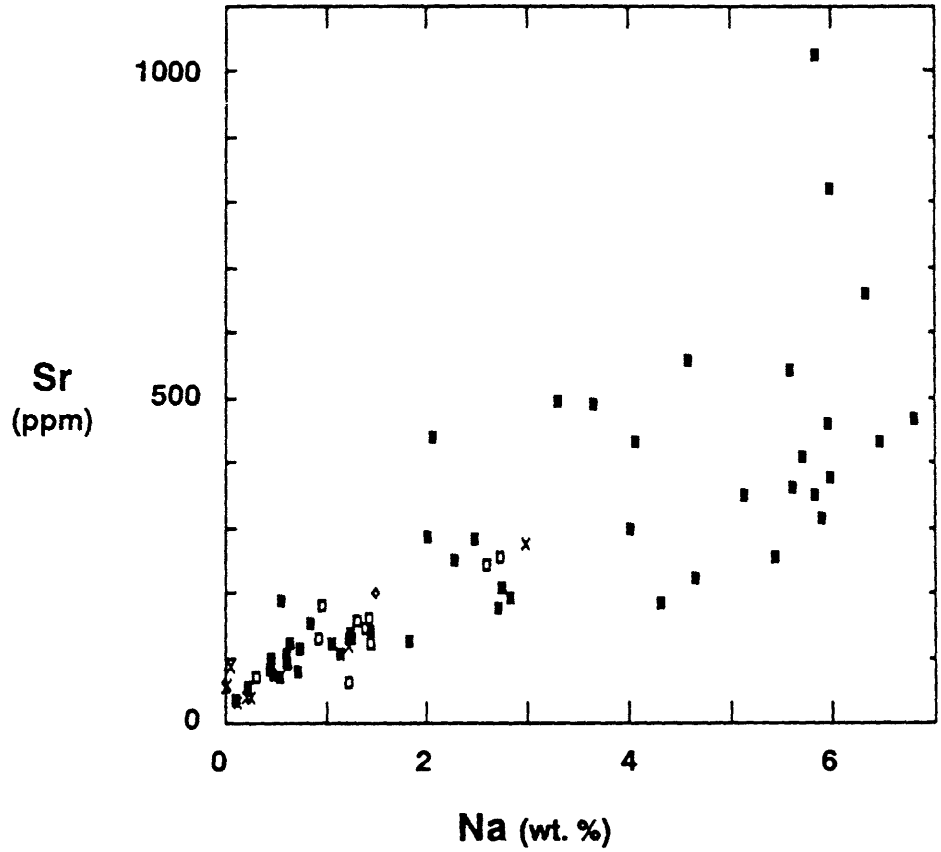


Figure 10.—Correlation of strontium with calcium. Symbols same as figure 5

MINERALIZATION

SYNGENETIC/DIAGENETIC SULFIDES

Trace amounts of pyrite, chalcopyrite, copper sulfides, and rarely pyrrhotite are disseminated throughout rocks of the district. The majority of these sulfides occur in hydrothermally altered rocks and have sulfur-isotopic compositions similar to vein sulfides, indicating a hydrothermal origin. A few, notably disseminated pyrrhotite + pyrite in felsic lapilli tuff, are depleted in ^{34}S (-11.5 permil), indicating a diagenetic origin (Afifi and others, in prep. D).

METAMORPHIC(?) VEINS

A few small quartz + calcite ± prehnite ± talc veinlets occur along faults and fractures, and are not enveloped by any hydrothermal alteration. Such veinlets are distinctive in their appearance and oxygen-isotopic composition (Afifi and others, in prep. d) from mineralized veins, but none are large enough to be shown on plate 1.

Hydrothermal Veins

The Mahd adh Dhahab mine contains substantial gold-silver-copper-zinc-lead ore in quartz veins and has been mined since antiquity. New discoveries at the southern mineralized zone contain reserves of 1.1 million tons of 27 g/t gold and 73 g/t silver (Worl, 1978a), which were in the process of being mined in 1988. The ancient Lahuf mine and the northwest extensions of the Lahuf vein contain mineralization similar to the Mahd Adh Dhahab mine, but on a much smaller scale. In addition, a number of smaller vein clusters (called "regional" veins) are present in the district. In order to facilitate discussion, the regional vein clusters are designated, from east to west, by numbers 1-13 on plate 1. Most of these localities contain shallow pits and other indications of ancient prospecting. The regional veins are similar in appearance, stable isotopic compositions, and fluid-inclusion characteristics to barren and mineralized veins at Jabal Mahd Adh Dhahab (Afifi and others, in prep. D). Most consist of milky and comb quartz with carbonate-filled vugs, while mineralized segments may contain disseminated sulfides (pyrite, chalcopyrite, and sphalerite), chlorite, hematite, microcline, and microscopic gold and tellurides. However, the number and volume of quartz veins at Jabal Mahd Adh Dhahab far exceeds all other occurrences combined, indicating that it was the principal focus of fluid discharge.

The 13 vein clusters, including the Mahd Adh Dhahab and Lahuf mines, occur along a curved belt that follows the broad anticlinal flexure in the Mahd Group, with most veins astride the unconformable contact between the Lahuf and Tuwal formations. Most veins strike perpendicular to this contact, fanning out from northern trends at Mahd Adh Dhahab to northwestern trends at Lahuf. Therefore, it is likely that the veins fill radial extension fractures and faults that formed when the Mahd Group was flexed, probably in response to drape-folding over a buried basement block (fig. 3). The Mahd Adh Dhahab and Lahuf mines are located on opposite limbs of a fold. The recognition of these controls is important both to exploration and understanding the origin of mineralization. The possibility that the veins formed prior to flexure (which implies that the veins at Lahuf were rotated with respect to those at the Mahd Adh Dhahab mine) is considered unlikely.

A limited number of samples were assayed from potentially mineralized veins outside Jabal Mahd Adh Dhahab. The results (table 2) display large variation, particularly for the base metals. The highest concentrations (0.18 g/t gold and 70 g/t silver) were obtained from a quartz vein located immediately west of Jabal Mahd Adh Dhahab. These values are significantly anomalous in comparison to previous results from the jabal (for example, Worl, 1978a; Worl and others, 1986) and follow-up sampling of this vein is recommended. Anomalous concentrations of silver were also detected near Lahuf at localities 5 and 11 (pl. 1).

Experience gained at Mahd Adh Dhahab has shown that ore bodies are high in grade, small in volume, and have little surface expression. The probability for the presence of more blind ores at the Mahd Adh Dhahab mine remains high.

The spatial association of ore bodies at Mahd Adh Dhahab to the Mine Hill Rhyolite had led most previous workers (Hakim, 1978; Luce and others, 1979; Doebrich, 1984; Huckerby and others, 1983, and Hilpert and others, 1984) to argue that mineralization is associated spatially and genetically with the Mine Hill Rhyolite. This conclusion was disputed by Afifi and others (in prep. D), who concluded that mineralization occurred about 120 m.y. after intrusion of the Mine Hill and other rhyolites in the district, probably in response to intrusion of an evolved granitoid at depth.

Table 2.--Elemental content of samples collected from the mineralized areas in the Mahd Adh Dhahab district. All values in parts per million.

Sample	Au	Ag	Cu	Pb	Zn	Description
172377	0.18	70.0	8000	1500	1900	Quartz vein, locality 3.
172328	-	1.8	10000	27000	3250	Quartz stringers, locality 4.
172356	-	0.8	700	1050	500	,,
172347	-	-	30	-	15	Quartz vein, locality 6.
172348	-	-	25	45	85	,,
172349	0.06	9.2	30000	700	1200	,,
172350	-	-	30	25	45	,,
172352	0.05	1.6	4000	185	1250	Quartz vein, locality 5..
172355	0.3	-	60	35	300	Quartz vein, locality 5.
172358	-	-	70	80	80	Quartz vein, locality 5.
172354	-	0.8	20	20	115	Pyritic rhyodacite, near 5.
172381	0.08	0.7	35000	95	1200	Quartz vein, locality 7.
172443	-	1.6	1000	15	200	Quartz vein, locality 7.
172398	-	0.9	5000	1100	8000	Quartz vein, locality 8.
172902	-	0.7	5000	950	650	,,
172463	-	1.1	600	160	450	Quartz vein, SE of 3
172466	-	0.9	4500	40	550	,,
172714	0.06	10.3	20000	6850	300	Quartz vein, locality 11.
172715	0.06	1.9	50000	2450	950	,,
172357	-	0.9	70	15	100	Boulder conglomerate, base of Ghamr.
172674	0.08	5.4	40	20	20	Pyritic rhyolite, E of J. Ramram
172905	.06	.5	30	25	90	Jasper, W side of Jabal Mahd Adh Dhahab
172906	-	-	270	20	40	,,

- below detection limit.

SUMMARY

The Dhukhur batholith was intruded (816 Ma) into older volcanic and sedimentary rocks of the Arj Group. Both the Dhukhur batholith and the Arj Group are regarded as part of the Asir volcanic-arc terrane (Stoeser and Camp, 1985). The Dhukhur batholith and Arj Group were buried, metamorphosed to the amphibolite facies, and subsequently unroofed by erosion. This unnamed orogeny, which probably occurred around 800 Ma, effectively formed a primitive continental basement, over which supracrustal rocks of the Mahd and Ghamr groups were subsequently deposited. The virtual absence of terrigenous clastic sediments from the district indicates that detritus produced by unroofing of the Dhukhur batholith was transported to a distant basin.

Following erosion, east-west extension, accompanied by high heat flow, generated basaltic magmas in the mantle and a large volume of dacitic-rhyolitic magma in the lower crust. The crustal extension was accommodated in the brittle upper crust by intrusion of the north-trending dike swarms that fed the volcanic eruptions that produced the Mahd Group. The Mahd Group accumulated in a large arcuate basin that was bounded to the east by faults, probably including the ancestral Sayilah-Ghadayrah fault system (fig. 2).

The intermingling of subaerial lava flows and ignimbrites with submarine carbonates, chert, and water-lain tuffs in the Mahd Group reflects deposition on both sides of the shoreline along the margin of an active volcanotectonic basin. Pyroclastic eruptions provided a large volume of unsorted felsic tephra, which was transported or reworked by mass flow into the Mahd basin. Subaqueous debris and turbidity flows further redeposited tephra in the deeper parts of the basin. Intervals of quiescence were marked by local carbonate and chert deposition. The volcanic pile was invaded by subvolcanic intrusions of basaltic, dacitic, and rhyolitic composition, which were locally extruded as lava flows and tephra throughout the Mahd Adh Dhahab district. Subsidence along the axis of the Mahd basin and drape folding over buried basin-margin faults account for the regional basinward tilting of the Mahd Group. Local folds in the Mahd Group were also generated by intrusion and compaction of layered rocks around intrusions, among other causes.

Deposition of the Mahd Group was essentially complete by about 770 Ma, when plutonic rocks of the Mahd plutonic complex, the Ramram cauldron, and the Hufayriyah tonalite batholith were emplaced. The Ramram cauldron consists of concentric ring intrusions ranging in composition from gabbro to granophyre; these intrusions encircle a >300-m-thick caldera-fill sequence of ponded rhyolitic ash-flow tuffs (Afifi, 1983; Afifi and others, in prep. A). It is likely that these plutons are the terminal phase of the Mahd magmatic cycle and that they represent magmas that ascended into their volcanic complements. The Mahd Group and associated plutons may be part of what was tentatively identified as the northeast-trending "Jiddah arc" by Stoeser and others (1985), which forms the southern border to the Bir Umq suture zone.

At about 748 ± 22 Ma (Calvez and Kemp, 1982), renewed uplift along the Sayilah-Ghadayrah fault system exposed portions of the basement and Mahd Group to erosion. Fanglomerates and tuffaceous sediments were locally deposited over tilted and eroded rocks of the Mahd Group, and possibly covered the entire region (fig. 2). Metamorphic assemblages at the base of the Ghamr group indicate that prehnite-pumpelleyite facies metamorphism peaked after burial beneath the Ghamr. Diagensis and metamorphism substantially altered the major-element composition of the volcanic rocks. Most volcanic rocks, which now resemble the spilite-keratophyre association, were depleted in calcium and strontium, and enriched in sodium due to interaction with diagenetic and metamorphic fluids.

Mineralization at the Mahd Adh Dhahab and Lahuf mines occurred at 649 Ma and is probably related to a post-orogenic granite at depth (Afifi and others, in prep. C). Veins were localized near the contact between the Lahuf formation and the Mine member, fanning out around the axial plane of a northwest-plunging anticlinal flexure. This pattern suggests that most veins occupy fractures that formed in response to local folding of the Mahd Group.

DATA STORAGE

All field and laboratory data for this report, including petrographic descriptions, sample sites, thin sections, fieldnotes, and results of geochemical analyses, are stored in Data File USGS-DF-04-23 in the Jeddah office of the U.S. Geological Survey Saudi Arabian Mission.

No updated information was added to the Mineral Occurrence Documentation System (MODS) data bank and no new files were established.

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Appendix 1.--Summary of petrographic observations of samples collected from the Mahd Adh Dhahab district.

Sample	qz	pl	or	px	mt	ch	mu	ep	hm	carb	other	Remarks	Unit
Dhukhur batholith:													
172160b	x	x	x			x	x	x				foliated granodiorite	dt
172410	x	x	x		x	x					zi	foliated granodiorite	dt
Lower member of the Lahuf formation:													
172277b	x	x	x		-	x			x	c/d	zi,ap	felsic lapilli tuff	lt
172278e	x	x	x			x		x	x		-hb?	Intermediate lapilli tuff	lt
172404a		x				x		x				intermediate crystal lithic vitric tuff	lt
172404b		x	x			x		x	x			intermediate crystal lithic vitric tuff	lt
172427		x				x		x		c/d		intermediate welded tuff	lt
172434	x	x				x		x	x			intermediate lapillistone	lt
Upper member of the Lahuf formation:													
172150a		x				x		x		c/d		mafic flow	la
172150b		x	x			x	x	x				felsic crystal vitricl tuff	las
172150c		x	x		-	x		x	+	A		felsic crystal lithic tuff	las
172157		x				x		x		c/d		andesite	la
172158		x				x		x	x			felsic crystal vitric tuff	la
172159a		-	-			x	x				py,ap	felsic crystal lithic vitric tuff	las
172159b			-			x	x				py,ba	felsic crystal lithic vitric tuff	las
172159e		x				x	x				clay	felsic crystal lithic vitric tuff	las
172277a	x	x	x			x					sp	laminated felsic crystal tuff	las
172361		x				x		x	+	c/d	py	amygduloydal andesite	la
172374	x		x			x	x			c/d		felsic crystal lithic vitric tuff	las
172401		x				x		x	x	c/d		intermediate lapillistone	la
172405						x		x		c/d		mafic lapillistone	la
Mine member of the Tuwal formation:													
Felsic and mixed fragmental rocks:													
172155a		x				x				c/d	ap	felsic crystal vitric tuff	mt
172192a	x		x			x						felsic crystal vitric tuff (pumice)	mt
172192b	x		x			x						felsic crystal vitric tuff (pumice)	mt
172194a			x			x	x		x		py	felsic crystal vitric tuff (pumice)	mt
172195						x	x	x		c/d	py	felsic lithic vitric tuff	mt
172196		x				x	x				py	felsic crystal lithic vitric tuff	mt
172197	x	x	x			x	x				py	felsic crystal lithic vitric tuff	mt
172199	x		x			x	x					felsic crystal lithic vitric tuff	mt
172222	x		x		x	x	x		x			felsic crystal lithic vitric tuff	mt
172223		-	x			x	x				py	felsic lithic vitric tuff	mt
172227	x		x			x						felsite	mt
172229a			x				x				py	felsic crystal vitric tuff	mt
172229b			x				x				py	felsic crystal vitric tuff	mt
172233b	x	x	x		-	x		x			pu	felsic crystal vitric tuff	mt
172236						x	x				sp	Baked tuff	mt

Appendix 1.–Summary of petrographic observations–Continued.

Sample	qz	pl	or	px	mt	ch	mu	ep	hm	carb	other	Remarks	Unit
172238	x	x	-		x	x	+	x		c/d	sp	felsic crystal lithic tuff	mt
172238c	x		x			x				A		felsic crystal vitric tuff	mt
172239b	x	ab	x		x		x		x			felsic crystal vitric tuff	mt
172239b	x	x				x	x	x		c/d	pr,sp,cp	felsic crystal lithic lapilli tuff	mt
172241		x	x		x	x	x	x		c/d	sp	felsic crystal lithic vitric lapilli tuff	mt
172242a		x	x		-	x				c/d	pr,pu	felsic crystal lithic tuff	mt
172242b	x	x	x			x						felsic tuff	mt
172247	x	x	x	x		x		x		c/d	cp,po,py,sp	felsic crystal lithic vitric tuff	mt
172249a		x	x		-	x	x	x				felsic crystal vitric tuff	mt
172256a		x				x	x		x	c/d	pr,cp	carbonated mafic tuff	mt
172256b		x	x		-						py,sp?	felsic crystal vitric tuff	mt
172270		x	x			x		x	x		pr,sp	felsic crystal lithic tuff	mt
172275	x	x	x		-	x	x			c/d		crystal lithic tuff	mt
172288		x	x			x	x		x	A	sp	felsic crystal vitric tuff	mt
172294		x	x	x		x		x		c/d	pr,hb?,sp,ap	mixed clast tuff	mt
172301	x	x	x		x	x		x		c/d		felsic crystal vitric tuff	mt
172310a	x	x	x			x				A		felsic crystal vitric tuff	mt
172315b		x							x	c/d		carbonated felsic porphyry	mt
172315c	x	x	x		-				+	c/d		felsic crystal vitric tuff	mt
172323b			x		-		+		+		sp	siltstone	mt
172330	x	x	x		-	x	x		x	c/d		volcanic sandstone	mt
172344a	x	x	x		-	x			+	c/d	sp	felsic crystal lithic vitric tuff	mt
172345	x	-	-			x	x		x	c/d	sp	felsic crystal vitric tuff	mt
172348	x	x	x		-	x	x			A	ap	felsic crystal lithic tuff	mt
172349a	x	x	x		-	x	x				ap	felsic crystal vitric tuff	mt
172349b	x	x	x			x			x		py	felsic crystal vitric tuff	mt
172440	x	x	x		-	x		x	+	c/d		felsic crystal vitric tuff	mt
172475		x				x	x		x			hornfelsed welded? tuff	mt
172489a			x			x				c/d		hornfelsed felsic crystal vitric tuff	mt
172502		x		x	x	x					ap	mixed clast tuff	mt
172532b		x			x	x	x			c/d	pr?	mafic lapillistone	mt
172560	x	x	x			x		x		c/d		felsic crystal lithic tuff	mt
172572		x	x			x	x			c/d		felsic crystal vitric tuff	mt
172576		x	x			x	x		x			felsic crystal tuff	mt
172588a		x	x						x	c/d		heterolitihic breccia	mat
172714a												laminated siltstone	mt
172722b	x		x			x	x				clay	lithic crystal vitric tuff	mt
172723	x		x			x				A		tuffaceous sandstone	mt
172751			x			x	x		x	c/d		crystal lithic tuff	mt
Carbonate beds in the mine member:													
172232						x				c/d		limestone	mm
172234	x					x			x	c/d		limestone	mm
172263						x				c/d		dolostone	mm
172310b									x	c/d		dolostone	mm
172315a						x			x	c/d		dolostone	mm
172336	x				-	x	x		x	c/d	pr	dolostone	mm
172455										c/d		dolostone	mm

Appendix 1.--Summary of petrographic observations--Continued.

Sample	qz	pl	or	px	mt	ch	mu	ep	hm	carb	other	Remarks	Unit
Mafic volcanic rocks in the mine member:													
172265		-				x	x		+	c/d		carbonated trap	mb
172532a		x				x		x	x	c/d		mafic lapillistone	mb
172535		-				x			+			chloritized trap	mb
172542		-				x		x	?	c/d		mafic lapilli tuff	mb
172549a		x				x		x	?	c/d	pr	mafic lapillistone	mb
172549b		-				x	?	x	x	c/d	pr?	mafic lapillistone	mb
172550b						x			x	c/d		mafic lapillistone	mb
172571a		-				x				c/d	pr?	mafic lapillistone	mb
172588b		x				x		x		c/d		mafic lapillistone	mb
Ghuwayshat member of the Tuwal formation:													
172744	x	x	x			x			x	c/d	sp?	unwelded crystal lithic vitric tuff	mwt
172749	x	x							x	c/d		unnwelded crystal vitric tuff	mwt
Feldspar porphyrys:													
172155b			x			x				c/d		felsic porphyry dike	dp
172160a		x			x	x		x	x			felsic porphyry dike	dp
172160c		x	x		-	x				c/d		felsic porphyry dike	dp
172258		x				x						felsic porphyry	dp
172286b		x	x		x	x		x		c/d	pu,-hb	dacite porphyry	dp
172295		x	x		x	x				c/d	ap	felsic porphyry	dp
172318		x	x		-	x	x	x	+		ap	felsic porphyry	dp
172353		x				x		x	x		ap	felsic porphyry	dp
172392		x	x			x	x				py	silicified felsic porphyry	
172445		x				x		x		c/d	ap	felsic porphyry	dp
172711	x		x						x			felsic porphyry (Lahuf)	dp
172716b			x			x					clay	felsic porphyry (Lahuf)	dp
172717			x		-	x			+			felsic porphyry (Lahuf)	dp
172719c		x	x						x			felsic pophyry (flow)	dp
172766			x								clay	Mine Hill Rhyolite	dp
172767			x								clay	Mine Hill Rhyolite	dp
Quartz-feldspar porphyrys:													
172156a	x	x			x							felsic porphyry	rp
172156b	x	x			x	x				c/d	zi	felsic porphyry	rp
172180a	x	x					x			c/d		felsic porphyry	rp
172255	x	x	x		x	x		x		c/d	sp?,ap	felsic porphyry	rp
172278c	x	x	x		x	x		x		c/d		felsic porphyry	rp
172279b	x	x	x		x	x	x			c/d	ap	felsic porphyry dike	rp
172279c	x	x	x		x	x	x	x		c/d		felsic porphyry dike	rp
172286a	x	x	x			x				c/d	sp,zi	felsic porphyry	rp
172259	x	x	x		-	x		x	+		sp	felsic porphyry	rp
172316b	x	x	x		-				+	A	sp	felsic porphyry	rp
172343a	x	x			-	x			+	c/d		felsic porphyry	rp
172354	x	x	x	-	x	+		x		c/d	sp,ap	intermediate porphyry	rp
172354b	x	x			x	x		x	+	c/d		felsic porphyry	rp
172354	x	x	x	-	x	+		x		c/d	sp,ap	intermediate porphyry	rp
172354b	x	x			x	x		x	+	c/d		felsic porphyry	rp

Appendix 1.–Summary of petrographic observations–Continued.

Sample	qz	pl	or	px	mt	ch	mu	ep	hm	carb	other	Remarks	Unit
172442		x	x					x	x			felsic porphyry	rp
172453d	x	x	x		-				+	A		felsic porphyry	rp
172529b	x	x	x				x	x		c/d	mi	felsic porphyry	rp
Felsites:													
172276		x	x				x		x	c/d		felsic porphyry	f
172366	x		x			x					rutile	silicified rhyolite	f
172541			x			x			x	c/d		felsite (flow)	f
172702						x					py	aphyric felsite	f
172750									x	c/d		aphyric felsite (flow)	f
Intermediate intrusions:													
172168a		x		-	-	x		x	+			altered quartz diorite(?)	di
172168b		x				x	x	x			-hb	altered quartz diorite(?)	di
172595b			-		-	x		x	+	c/d	-hb	altered dacite	hp
Mafic intrusions in the Lahuf formation (Lahuf diabase):													
172278d		x		x	x	x	x	x		c/d	ap	gabbro	ld
182278f		x		x	x	x		x		c/d		diabase dike	ld
172280c		x		x	x	x		x	+	A	pr?	gabbro	ld
172281		-		x	x	x	+		+		pr	gabbro	ld
172422		x		x	x	x	x	x	+	c/d	hb?,pr	subophitic gabbro	ld
172428		x			x	x	x	x		c/d		mafic dike	ld
172467		-		-		x	x		+		mi	altered diabase	la
Mafic intrusions in the Tuwal formation:													
172233a		-			-	x	x		+	c/d	py	carbonate-altered trap	ma
172235				x		x	x					mafic sill	ma
172241b		-		x	x	x	x			c/d	pr,pu,cv	mafic sill	ma
172254		x		x		x	x			c/d	pr,cv	mafic dike	ma
172279a		x		x	x	x		x		c/d	mi	trap dike	ma
172341a		x		x	x	x		?		c/d	cp	mafic dike	ma
172341b		A	x	x	x	x				c/d	pr	mafic dike	ma
172461		x		x	-	x		x	+	c/d	pr,pu,ap	porphyritic basalt	ma
Ghamr Group:													
172179b	x	x				x		x			pr,pu	volcanic sandstone	gt
172179c		x				x					hb	hornblende andesite	ga

Abbreviations:
(A) ankerite, (ap) apatite, (ba) barite, (carb) carbonate minerals, (c/d) calcite/dolomite, (ch) chlorite, (cp) chalcopyrite, (cv) covellite, (ep) epidote (pistachite-rich), (hb) hornblende, (hm) hematite, (mt) magnetite, (mi) secondary microcline, (mu) phengitic muscovite/sericite, (or) orthoclase/microcline, (pl) plagioclase (mostly albite), (po) pyrrhotite, (pr) prehnite, (pu) pumpelleyite, (px) augite, (py) pyrite, (qz) quartz, (sp) sphene, usually grothitic, (zi) zircon.

Symbols:
(x) present, (+) added during metamorphism or hydrothermal alteration; (-) completely replaced by secondary minerals.