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Paleomagnetic investigations at Mahd adh Dhahab, Kingdom of Saudi Arabia

by

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

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ABSTRACT

Paleomagnetic studies of 25 oriented bedrock specimens from Jabal Mahd adh Dhahab, located 160 km southeast of Al Madinah, Kingdom of Saudi Arabia, have yielded important structural information relating to the geologic history of this base and precious metal deposit. Samples were collected along one traverse away from the mineralized zones, across the northeast-plunging antiform that constitutes the dominant regional structure of the area, and along another traverse down the axis of the mineralized zones. Lithologies range from andesite flows through andesitic to rhyodacitic tuffs, lapilli tuffs, and volcaniclastic sediments. Measurements of remanent magnetization direction and intensity before and after stepwise alternating-field demagnetization ranging from 25 Oersted (Oe) to 1000 Oe were carried out on all samples. Three classes of demagnetization behavior were observed: A very stable class with little change in direction and intensity of magnetization; a class in which rapid changes were observed at first but which then settled on a high coercivity stable component of magnetization; and a class in which the magnetization was composed of a spectrum of low coervicity components, and continuous variation of direction and intensity of magnetization occurred.

A structural correction restoring the bedding to horizontal resulted in a significant reduction in dispersion of magnetization directions, and implies that the magnetization was acquired before the northeast-trending deformation. At least one geomagnetic reversal is recorded and, together with drillhole electric logs, suggests structural repetition of some parts of the area.

The determined paleopole location, after correction for Tertiary rotation of Arabia from Africa, falls on the apparent polar wander path for Gondwanaland at an age of 600-590 Ma, which is younger than the mineralization age of about 680 Ma and the age of the Mahd group of rocks (772 Ma) determined from geochronologic studies, and implies that the rocks have been remagnetized during the middle Pan African times.

The results of this work suggest that more extensive paleomagnetic investigations of the felsic volcanic and volcanic-derived rocks of the northern Arabian shield should provide greater insight into the structural evolution of the shield, and these investigations are recommended.

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INTRODUCTION

A suite of 26 oriented bedrock specimens were collected from the Jabal Mahd adh Dhahab area, Kingdom of Saudi Arabia, during the course of geophysical investigations of the base and precious metal deposits in the district. The primary purpose of this part of the work was to define the natural remanent and induced rock magnetizations of the various lithologies of the district, to be used in the interpretation of a detailed magnetic map of the area (Gettings, 1981). The results of the natural remanent magnetization (NRM) measurements were so interesting as to merit consideration of paleomagnetism in the samples collected; however, the sampling program was not designed for a paleomagnetic study, and the data examined is not optimum for paleomagnetic and structural analyses. The present report is principally an initial justification for further paleomagnetic research on the volcaniclastic layered rocks of the region.

Previous work

Numerous studies of the Mahdb adh Dhahab area have been published or open-filed, most of which focus on the precious and base metal deposits. Regional geologic relationships are reported in Brown and others (1963), Goldsmith and Kouther (1965, 1966, 1971), and Kemp and others (1982). Geologic studies of the Mahd adh Dhahab district and deposits are given in Shaw (1936), Dirom (1946, 1975, unpub. data). Playter (1953), Bhutta (1960), Theobold (1965), Bagdady and others (1974, 1978), Luce and others (1976, 1975, 1979), Sabir and Roberts (1977a,b), Hakim (1978a,b, 1980, 1982), Worl (1978a,b,c, 1979), and Huckerby and others (1982). Results of relevant geochemical, geochronologic, and isotopic studies are given in Roberts and others (1978a, b, unpub. data). Rye and others (1979, in press, 1982), Stacey and others (1980), and Calvez and Kemp (1982). Geophysical investigations are described in Davis and others (1965), Arabian Geophysical and Surveying Company (ARGAS) (1975), Flanagan and Pitkin (1979), and Gettings (1981).

Acknowledgments

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GENERAL GEOLOGY

The area studied is about 3 km^2 in extent, approximately centered on Jabal Mahd adh Dhahab, and will be referred in this report as Mahd adh Dhahab. The area is composed of a steeply north-dipping series of pyroclastic and clastic rocks of andesitic to rhyodacitic composition. These layered rocks are part of the Zur member of the Haf formation in the Mahd group (Kemp and others, 1982), and are probably part of a caldera complex (Luce and others, 1979; Kemp and others, 1982). The entire series was deposited unconformably on the Dhukhr tonalite dated at 816 $\pm$ 4 Ma (Kemp and others, 1982), and subsequently deformed by several tectonic episodes (Worl, 1978a; Luce and others, 1979; Kemp and others, 1982). The Mahd group is dated at 772 $\pm$ 28 Ma (Rb/Sr isochron), supported by an age of 760 $\pm$ 10 Ma (U/Pb on zircon) for the Hufayriyah tonalite that cuts the Mahd group rocks northeast of Mahd adh Dhahab (Calvez and Kemp, 1982).

A generalized geologic map of the area (fig. 1.), drawn from Luce and others (1979), shows the major stratigraphic and structural features of the Mahd adh Dhahab area. The lowest stratigraphic unit exposed is composed of andesite flows and breccias in fault blocks in the southwest of the area surveyed. These rocks are overlain by a sequence of subaerial and subaqueous volcanic and volcaniclastic sediments, tuffs, and agglomerates. Stratigraphically up-section (southwest to northeast), that sequence is divided into the lower agglomerate, lower tuff, upper agglomerate, and upper tuff (Luce and others 1975). The lower agglomerate, upper agglomerate, and upper tuff are further subdivided on the basis of detailed surface and underground mapping, and drill core logging (Worl, 1978a). The stratigraphy is summarized in table 1. The clastic rocks contain fragments of andesitic to rhyodacitic volcanic rocks, silicic tuff, chert, feldspar grains, diorite, and pumice. The common minerals are chlorite, plagioclase, potassium feldspar, quartz, epidote, and minor amphibolite. The presence of lapilli and bombs of various sizes indicate that the rocks are at least in part from a near-vent facies. Considerable potassium and iron alteration occurs, hydrothermal in origin (Worl, 1978a; Hakim, 1980; Gettings, 1981). However, regionally these rocks are little altered and have only been slightly metamorphosed in the low greenschist facies (Kemp and others, 1982).

The region is structurally characterized by north-trending faults and broad, northeast-plunging open folds. The Mahd adh Dhahab area is located a few km southwest of a major northwest-trending system of Najd faults, and is bounded to the east by a northeast-trending right lateral fault that lies beneath the alluvium (Goldsmith and Kouther, 1971; Worl, 1978b; Kemp and others, 1982). Mahd adh Dhahab itself is located on the axis of a large northeast-plunging antiform (Kemp and others, 1982) that is well defined by the aeromagnetic data of the area (Gettings, 1981). At least two periods of folding deformation are recognised

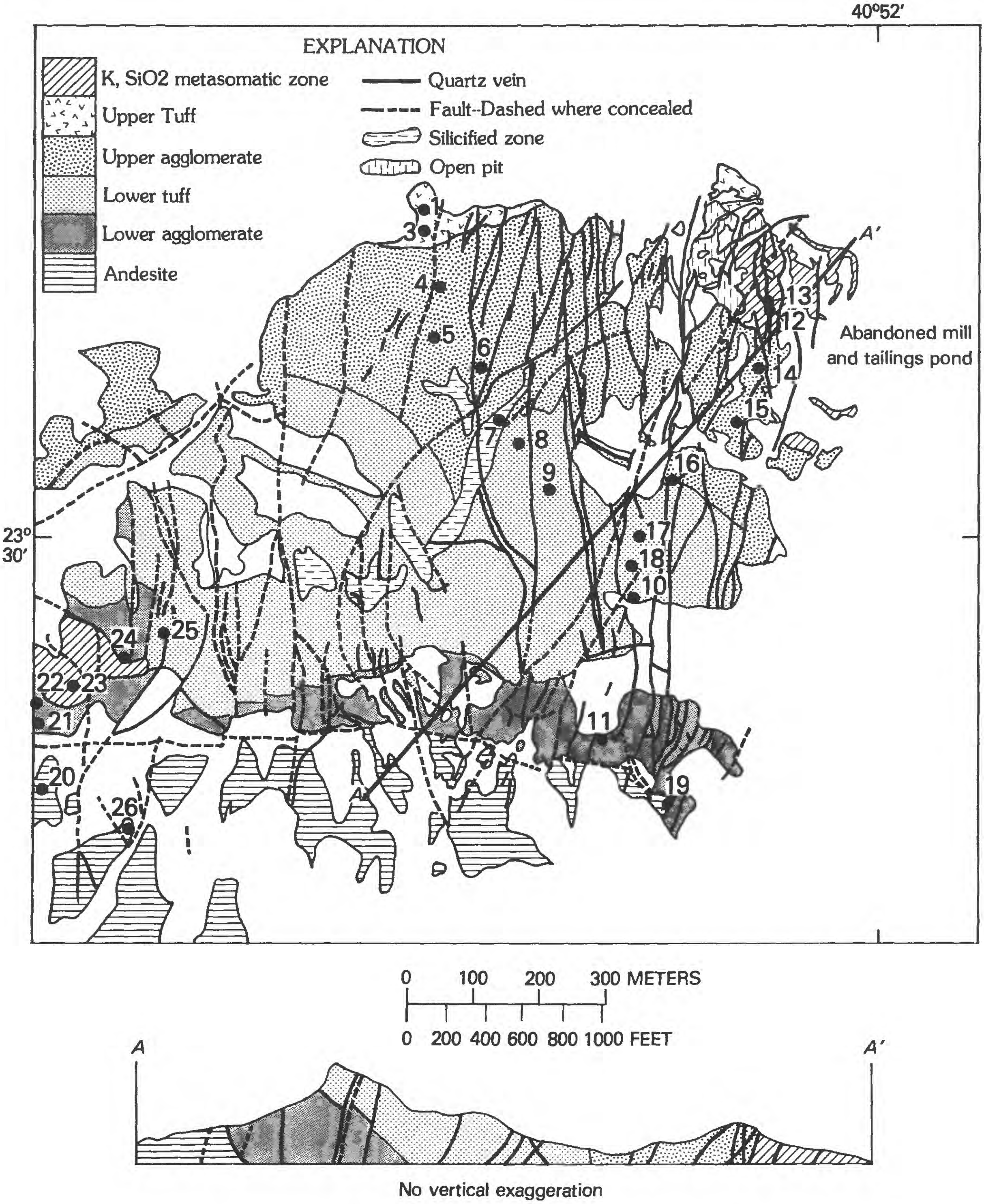


Figure 1.—Generalized geology of the Mahd adh Dhahab area and localities of samples 1-26 (black dots), described in tables 1-4. Adapted from Luce and others (1979).

Table 1.—Stratigraphic column for the Mahd adh Dhahab area, Kingdom of Saudi Arabia, showing approximate positions of samples.

Unit and subunit stratigraphic designations are from Luce and others (1975) and Worl (1978b). Table adapted from Worl (1978b)

MAGNETIC POLARITY	SAMPLE	UNIT	SUBUNIT	LITHOLOGY
NORMAL		UPPER TUFF	uta	AGGLOMERATE-CONGLOMERATE—Red to pale-green, characterized by abundance of pale-green dacite fragments; white, gray, and red tuff; red chert; fragmental plagioclase; locally abundant fragmental quartz. Coarse layering. Intercalated waterlain tuff and argillite
NORMAL	1 3	UPPER TUFF	utt	ARGILLITE-CALCAREOUS TUFF—Fine-bedded gray argillite intercalated with calcareous and talcose, brown, massive to fine-bedded tuff and minor volcanic wacke. Local zones of massive talc
				——————Unconformity or fault——————
REVERSED	4 5	UPPER AGGLOMERATE	uaa	GRAY AGGLOMERATE—Subrounded fragments of white, red, and gray chert, siliceous tuff, pyrite-rich tuff, andesite to rhoydacite volcanic rock, and chlorite- and epidote-rich clots set in a gray, siliceous and pyritiferous groundmass. Local pink potassium feldspar scattered randomly through groundmass and fragments
				——————Local unconformity——————
REVERSED / NORMAL	6 14 7 15 16	UPPER AGGLOMERATE	uat	CRYSTAL-LITHIC TUFF TO AGGLOMERATE—Pale- to dark-green, with gray chert, brown to gray tuff, wispy chlorite, gray siliceous lapilli, locally abundant fragmental plagioclase, and andesite to rhoydacite volcanic rock set in gray, siliceous graoundmass. Generally bedded and locally graded. Intercalated fine-grained massive green tuff. Pink potassium feldspar is locally abundant as a partial to total replacement of the fragmental plagioclase and to a lesser extent as scattered crystals through groundmass-and all fragments
NORMAL	8 9 17 18 25	LOWER TUFF	lt	TUFF AND SEDIMENTARY ROCKS—Fine-grained massive to finely bedded tuff, lapilli tuff, volcanic wacke, and sandstone. Highly potassium-feldspathized in the vicinity of the SAMS mine
NORMAL	23 22 21	LOWER AGGLOMERATE	lau	UPPER UNIT—Mafic agglomerate, mostly andesitic and chloritic fragments set in gray, siliceous groundmass, and mafic lapilli tuff, plagioclase crystal tuff, and massive cherty tuff. Local fragments of massive sulfide(?) and pyrite-rich tuff
REVERSED	11 19	LOWER AGGLOMERATE	lam	MIDDLE UNIT—Mafic agglomerate; agglomerate with andesite; chloritic, red, gray, and black massive tuff; and dioritic fragments in chlorite and epidote groundmass. Intercalated dense massive green to brown chert
NORMAL		LOWER AGGLOMERATE	lal	LOWER UNIT—Massive to slightly bedded andesite tuff and lapilli tuff with minor intercalted mafic agglomerate
				——————Unconformity——————
NORMAL	20 26	ANDESITE		ANDESITE—Mostly dense to fine-grained; some crystalline units may be dioritic sills; few intercalated pyroclastic layers. Generally propylitically altered; in fault contact with lower agglomerate

on a regional scale (Kemp and others, 1982): An early event yielding northerly-trending fold axes; and a later event trending northeast. As many as six periods of faulting can be recognised at Mahd adh Dhahab (Luce and others, 1979): A north-northwest set (pre-mineralization); northeast, north, and northwest sets (syn-mineralization); a (post-mineralization) northeast set, many of which contain andesite dikes; and a latest set trending north-west. Locally within the mineral deposit, low-angle faults are present and are related to deformation at the time of mineralization (Worl, 1978a). Structural analyses by Worl (1978a) revealed that the area could be divided into structurally homogeneous blocks, each folded to varying degrees and in different orientations.

Paleomagnetically, the structure so defined for each block is the aggregate of all previous deformational events. The paleo-magnetic data indicate that the northeast-trending deformation that formed the regional antiform and produced the steep north-easterly dips of the layered rocks in the map area occurred much later than the mineralization; this is discussed later.

PALEOMAGNETIC DATA

Twenty-six oriented rock specimens from localities shown in figure 1 were selected for paleomagnetic measurements. The sample locations form two traverses, one across the northeast-trending antiform away from the mineralized zones, and the other down the axis of the zone of mineralization. Samples 2, from an andesite dike (between localities 1 and 3), was so weathered that it could not be cored for measurements. In the field, block samples of approximately 1 kg mass were oriented using a Brunton compass and spirit level. The area has no magnetic anomalies of sufficient intensity to produce significant orientation errors by this method (Gettings, 1981). Cores 2.5 cm long and 2.54 cm in diameter were cut from the least weathered parts of each specimen using a drill press and a water-cooled diamond coring bit in the laboratory. Coring, magnetic cleaning, and magnetization direction measurements were carried out at the USGS rock physical properties laboratory in Jiddah, using a 5 Hz spinner magneto-meter and a single-axis alternating field demagnetizer. (Refer to McElhinny, 1973, for a discussion on the use of these instruments).

Sample collection was performed by the author in May, 1975; laboratory measurements were completed by the author and A. Showail in January, 1978; and data reduction was carried out by the author in April, 1978.

The remanent magnetism for each specimen was measured before magnetic cleaning, and after 18 levels of successively more intense alternating field demagnetization, ranging from 25 Oersted (Oe) to 1000 Oe. Most specimens were only cleaned to the 800 Oe level. No thermal demagnetization was attempted, although for those rocks containing hematite such treatment is appropriate and should be undertaken in future studies.

Two procedures for treatment of the data are possible. In the first, the magnetization results for each sample or lithology at a site are analysed by a suitable criteria to determine the optimum cleaning level for that sample or site, and thus the chosen direction of magnetism. The results of these individual analyses then form the set of magnetization directions for paleomagnetic interpretation. In the second procedure, results from all samples from a site or lithology are averaged using Fisher's (1953) statistics for dispersion on a sphere for each level of magnetic cleaning. The level that gives the tightest grouping (minimum dispersion) is chosen as optimum, and the specimen magnetization directions at that level are selected for paleomagnetic interpretation.

The first procedure was followed in this work because of the lack of multiple specimens from each site, and the wide variation of lithologies and degrees of alteration at the several sites sampled. This procedure was appropriate for the existing sampling program, although the second technique has been the most widely used in paleomagnetic studies in Saudi Arabia to date (Kellogg and Reynolds, 1980; Kellogg and Beckman, 1982; Kellogg and Blank, 1982). The remanent magnetization data for each specimen was treated in the following manner:

The path of the remanent vector for all demagnetization steps for each specimen was plotted on an equal-area stereonet (fig. 2A).

A stability index, which considers the change in direction of magnetization between successive cleaning levels, and accounts for changes in the magnitude of the magnetization vector (fig. 2B), was computed and plotted for each specimen, as was a standard plot of the common logarithm of the ratio of the measured magnetization intensity (J) at a given cleaning level to the uncleaned (NRM) intensity (J_0) (fig. 2C).

The three plots for each specimen (direction, stability index, and log J/J_0) were studied to determine the stable direction. In all but three cases the chosen direction was that which maximized the stability index. In the cases of samples 12 and 19, the maximum of the stability index occurred as a statistically insignificant peak on a plateau of the curve defining the maximum, and a direction from a lower cleaning level at the beginning of the plateau was used. For specimen 22, a relatively "hard" component of the magnetization was not removed until the cleaning levels of 500 Oe and greater were attained, and the stability index was still increasing to a relative maximum at the last cleaning level performed (800 Oe); the direction at the 800 Oe level was chosen.

Table 2 presents the chosen magnetization directions, together with other pertinent data for the 25 specimens; and lithologic descriptions of the samples are given in table 3.

The data can be divided into three classes, each with a characteristic set of plots of magnetization direction path, stability index, and log J/J_0. The data for a representative specimen from each class is shown in figure 2. Class 1 specimens, represented by specimen 3, are characterized by a small dispersion throughout magnetization; that is, the path of magnetization directions during demagnetization forms a cluster of relatively small dispersion. The stability index plot is relatively flat and near the maximum theoretical value of 1.0, and the magnetization intensity plot log J/J_0 is nearly flat or slowly decreasing. Most of the samples of this class are fine-grained, well-laminated tuffs containing hematite; these would be much more effectively demagnetized by thermal demagnetization. Class II specimens, represented by sample 14, have magnetization direction paths that first wander and then cluster. The stability index plot varies extensively at first and then plateaus at a value near 1.0, and the plot of log J/J_0 first decreases rapidly and then levels off. These rocks are very fine grained crystal, lithic, or lapilli tuffs, or very fine grained basalt. Class III specimens, represented by sample 25, magnetization direction paths that wander continuously, sometimes clustering until a particular component of the magnetization is removed, then wandering again at higher demagnetization levels. These samples, mostly very fine grained crystal or lithic tuffs, have many soft components of magnetization, and no dominant hard component was found. Stability index plots for this class vary erratically, and log J/J_0 generally decreases, but many have superimposed shoulders or local relative maxima.

Table 2.--Summary of paleomagnetic results for 25 bedrock specimens from the Mahd adh Dhahab area, Kingdom of Saudi Arabia

[Column heading abbreviations: K, measured volume susceptibility in the cgs system (dimensionless); demag level, demagnetizaation level of the chosen remanent direction, in oersteds; J, intensity of chosen remanent magnetization, in electromagnetic units per cubic centimeter; J/J^0, ratio of J to intensity of remanent magnetization before demagnetization; Q, Konigsberger ratio of remanent intensity at chosen demagnetization level to induced magnetization; Dec., declination of remanent magnetization direction clockwise from north in degrees; Inc., inclination of remanent magnetization direction in degrees, positive downwards; Strike, strike of plane of bedding, in degrees clockwise form north; Class, class of demagnetization behavior (see text and fig. 2)]

Sample	k	Demag. level (Oe)	Remanent magnetization: J (emu-cm^{-3})	J/J^0	Q	Deg. (deg.)	Inc. (deg.)	Structural correction: Strike (deg.)	Dip (deg.)	Corrected direction: Deg. (deg.)	Inc. (deg.)	Class
1	43	675	0.32	0.98	0.526	358.8	27.7	105	69 N.	354	-41	I
3	36	200	0.41	1.12	.027	353.5	23.7	104	76 N.	349	-46	I
4	45	475	1.14	.98	.061	159.6	-50.0	105	70 N.	172	13	I
5	54	650	.51	.08	.023	172.7	-47.8	105	70 N.	179	19	II
6	38	275	223.70	.93	14.290	168.8	-32.5	105	60 N.	173	22	I
7	28	275	.23	.25	.020	347.6	35.2	113	56 N.	354	-13	III
8	36	375	.87	.85	.060	357.0	-10.5	105	52 N.	349	-48	I
9	36	200	.10	.30	.007	358.5	15.1	111	55 N.	353	-37	III
10	69	400	.11	.12	.004	26.5	-30.3	129	50 N.	351	-76	II
11	44	625	.54	1.95	.030	174.1	-56.6	130	80 N. 50 N.	194	±14	II
12	38	600	1.98	0.21	.126	356.2	28.5	90	15 N.	356	13	II
13	64	700	.91	.08	.035	214.4	-50.0	90	15 N.	206	-35	II
14	2	425	3.48	.91	4.447	184.7	-34.1	135	30 N.	191	-9	I
15	36	200	.05	.25	.003	333.8	15.3	060	40 N.	335	-21	III
16	29	175	1.86	1.15	.157	357.2	37.1	127	77 N.	2	-28	I
17	36	450	.50	.38	.031	4.2	-13.4	106	70 N.	321	-77	I
18	29	475	1.12	.91	.094	8.2	-25.3	110	55 N.	329	-75	I
19	56	450	.58	.01	.025	192.0	3.2	130	50 N.	180	45	III
20	3,790	600	69.79	.10	.045	34.12	17.6	86	40 N.	340	-23	II
21	78	700	3.30	.31	.102	357.0	17.6	86	40 N.	357	-24	I
22	126	800	2.45	.26	.047	347.0	-60	86	40 N.	343	-46	III
23	34	25	115.20	1.02	8.179	270.4	-10.1	86	40 N.	262	-10	I
24	34	700	1.12	.08	.081	357.2	2.0	105	40 N.	353	-38	II
25	38	375	.03	.04	.002	356.6	-52.2	95	30 N.	331	-81	III
26	4,950	800	51.88	.01	.025	351.5	-5.2	86	40 N.	350	-42	II

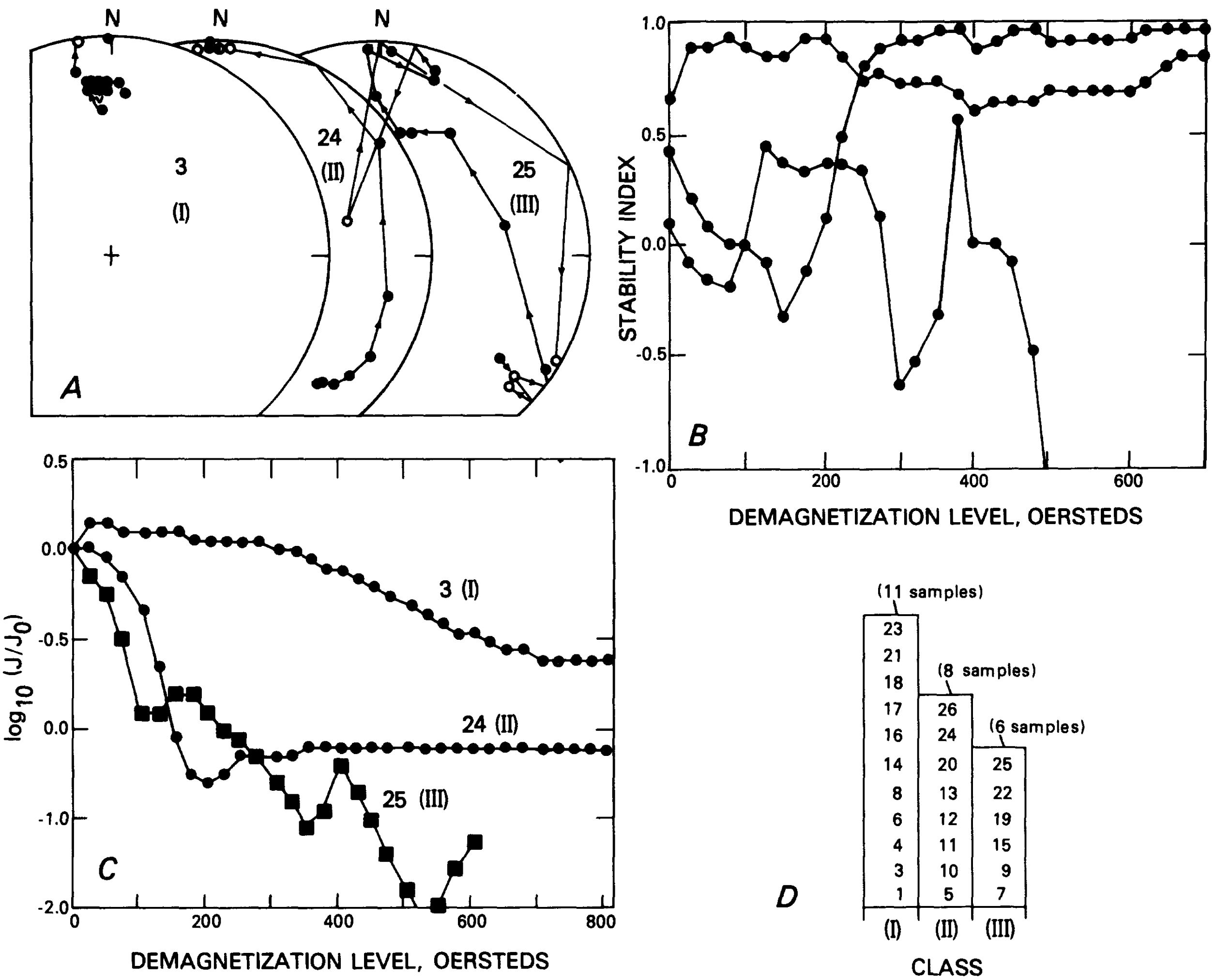


Figure 2.--Representative plots of path of remanent magnetization direction (A), stability index (B), and remanent magnetization intensity (C) for the three observed classes of demagnetization behavior. Samples of class I are represented by sample, class II by sample 24, and class III by samples 25. In A, an equal-area projection is used; solid dots are in the lower hemisphere, open circles are in the upper hemisphere. The distribution of numbered samples into the three classes is shown in (D). Refer to the text for a detailed discussion of classes I, II, and III.

A histogram of demagnetization behaviour of the samples by class is shown in figure 2(D). Examination of this distribution with regard to sample lithologies and rock units does not reveal any obvious correlation between either lithology or stratigraphic unit, and magnetization class, it appears more likely that the classes are reflecting variations of type and content of magnetic minerals, and the degree of hematite alteration of the samples and the contained magnetic minerals.

The treatment of the data discussed above yields a set of chosen magnetization directions considered to be optimum for this dataset, subject to the caveats of insufficient samples and lack of thermal demagnetization studies. The chosen magnetization directions (table 2) are plotted on an equal-area projection in figure 3.

INTERPRETATION OF RESULTS

Examination of the distribution of "cleaned" remanent magnetization directions (fig. 3.) shows that the directions cluster in three groups: A group with a mean direction of about 355^0 declination and inclination of about 30^0 down; a group with mean declination of 355^0 and inclination of about 10^0 up; and a group with reverse polarity of declination 190^0 and inclination of about 40^0up. The reverse polarized cluster is composed of samples 4, 5, 6, and 14 (fig. 1) that are in or near to the lower contact of the upper member of the upper conglomerate (gray agglomerate of Worl, 1978a), samples 11 and 19 that are in the middle unit of the lower conglomerate (Worl, 1978a), and sample 13 from the rhyolite porphyry of Luce and others (1975), that is the metamorphosed lower tuff of Worl (1978a). The downdip extensions of the units sampled by specimens 4, 5, and 6, and 11 and 19, are the parts of the section penetrated by drill holes MD-9 and MD-8 respectively. Apparent resistivity and self-potential electric logs of these holes correlate (Gettings, 1981), and suggest that the rocks penetrated in these portions of the two holes are the same unit. This interpretation is in conflict with the surface mapping, but samples 11 and 19 are from blocks that are completely fault-bounded (Worl, 1978a), and late-stage northeast-trending faults are present just to the east of the bottom of MD-9, and are intersected in drill hole MD-5 (Worl, 1978a). These observations suggest that relationships are sufficiently ambiguous that fault repetitions may have occurred.

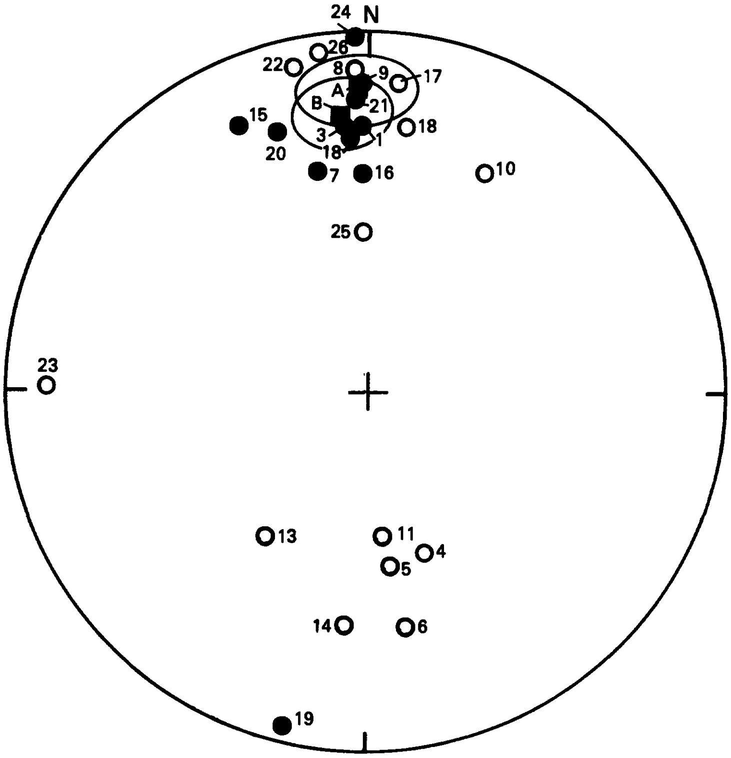
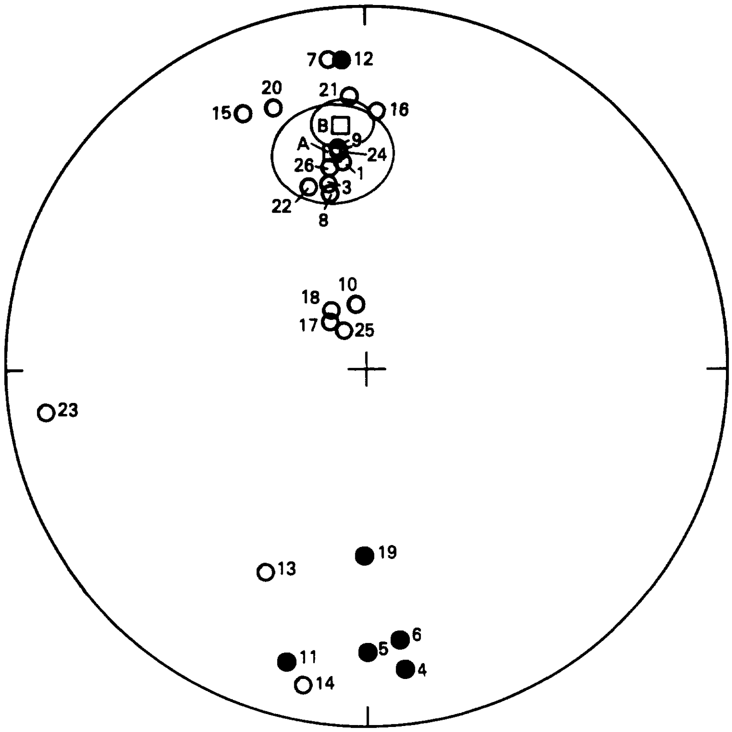


Figure 3.--Equal-area plot of the chosen directions of magnetization for samples 1-26. Upper hemisphere points shown by open circles; lower hemisphere points shown by solid dots. The solid square (lower hemisphere) labeled A is the mean direction for all samples except 23; the solid square labeled B is the mean direction for the 16- sample subgroup listed in table 4. Ovals surrounding these squares show the projection of the cone of 95 percent confidence for the means.

Figure 4.--Equal-area plot of the chosen directions of magnetization of samples 1-26 after rotation of data points to correct for reported dip of beds. (See text.) Symbols are as defined in figure 3.



An attempt was made to bring the two normally polarized clusters (fig. 3) together through the use of a structural correction to each of the magnetization directions. The correction applied was a rotation that would bring the bedding attitudes determined from the available mapping (Luce and others, 1975; Worl, 1978a) to horizontal. For the group of samples 1, 3, 4, 5, 6, 7, 8, 9, 11, 19, 20, 22, 23, 24, 25, and 26, this constitutes the paleomagnetic fold test (McElhinny, 1973) for the northeast-plunging regional antiform. The results of this correlation (fig. 4) show that the clusters have less dispersion than before rotation, and the two northern clusters have merged into one; however, a new cluster, samples 10, 17, 18, and 25 has appeared, with near-vertical inclinations.

Mean directions and paleopole positions for the data of figures 3 and 4, and subgroups of these data, were computed using the statistical methods of Fisher (1953) implemented in the program of Donzeau and Kellogg (1982). The groupings used were: All data except sample 23 (in a rhyolite porphyry or highly metasomatized zone where a structural correction could not be defined, figure 1), before and after application of the structural correction; and a subgroup composed of samples 1, 3, through 9, 11, 16, 19, 20, 21, 22, 24, and 26, both before and after structural correction. The subgroup is appropriate for the fold test (McElhinny, 1973) because subgroup sample localities cross the nose of the northeast-plunging antiform. Table 4 shows the results of the four mean directions and paleopole calculations. The samples that are not part of the subgroup are all associated with the mineralized zones or areas of intense quartz veining (table 3). In these areas, the structural correlation is a combination of deformation due to the regional events and the mineralization. The age of magnetization probably is post-mineralization, thus a correction defined by attitudes in these zone will not in general bring the measured directions of magnetization into the cluster. The structural correction for samples 11 and 19 is poorly controlled due to a paucity of measured attitudes in the area; however, the corrections applied do bring them into a cluster of smaller dispersion, suggesting that the correction applied approximately correct. The antipodes of the reversed magnetization directions were used to make all the data be of one polarity, as is customary for calculations of mean directions. Omitting the Class III samples (nos. 7, 9, 19, and 22) from the averaging can be seen to improve the groupings for the structurally corrected subgroup (fig. 4); however, the mean direction is not substantially changed, and in view of the uncertainties in the structural corrections, it was judged best to calculate the mean of the subgroup.

Table 3.--Lithologic descriptions of oriented bedrock samples from the Mahd adh Dhahab area, Kingdom of Saudi Arabia.

1. Pink, finely laminated, fine-grained silicic tuff, probably water lain. Contains rock fragments and some fine quartz veinlets. Potassium alteration present.

3. Whitish-pink crystal-lithic tuff containing rock fragments and crystals to 5 mm in size. Matrix silicic; rock fragments predominate over crystals; fragments are chert and hematized mafic(?) rock. Bedding not apparent; potassium alteration apparent.

4. Purplish silicic lithic lapilli tuff with rock fragments to 10 mm, predominantly chert. Some rock fragments are themselves brecciated. Mafic fragments hematized; potassium alteration present; bedding not apparent.

5. Purplish, silicic crystal-lithic lapilli tuff. Rock fragments to 10 mm predominate and are mostly chert; some fragments brecciated. Feldspar grains potassium altered; mafic fragments hematized.

6. Pinkish-purple, silicic, lithic lapilli tuff; rock fragments to 20 mm, mostly chert. Some chloritic fragments present, many of which are hematized. A few potassium altered feldspar grains are present. Poorly bedded.

7. White quartz vein with some stringers of chloritic material and hematized patches. Sample is brecciated and rehealed with quartz; some malachite present.

8. Greenish-brown, fine-grained, well-bedded silicic tuff. Slight iron and potassium alteration present; some plagio- clase crystals present. Well laminated with beds alternating between fine- and very fine-grained.

9. Pinkish-brown, very fine-grained, well-bedded silicic tuff. Finely laminated into beds as thin as 2 mm. Some hematiza- tion present and some small plagioclase crystals are visible.

10. Greenish, very fine-grained silicic tuff showing some hematization.

11. Brownish-green, silicic, lithic lapilli tuff; fragments predominantly chert and very irregular in outline. Iron and potassium alteration present.

12. Greenish-pink silicic lithic lapilli tuff; contains pyrite and potassium-altered feldspar. Hematized fractures; fragments difficult to see except on weathered surfaces; matrix and fragments seem to be same material (auto- brecciated?). Pervasive potassium alteration.

13. Pink, fine-grained crystal tuff. Potassium-altered feldspars and pyrite pseudomorphs present; small rock fragments in fine-grained silicic matrix. Laminated on millimeter scale; rock is pervasively potassium- feldspathized.

14. Extensively hematized silicic lapilli tuff; chert fragments to 20 mm and pyrite pseudomorphs to 5 mm. Poorly bedded.

15. Gray-green, crystal-lithic tuff with approximately equal proportions of pink feldspar crystals and chlorite fragments to 5 mm. Well-bedded with fine-grained silicic matrix.

Table 3.--Lithologic descriptions of oriented bedrock samples from the Mahd adh Dhahab area, Kingdom of Saudi Arabia, continued.

16. Greenish, lithic lapilli tuff with chert fragments in a fine-grained cherty matrix. Hematized with minor potassium alteration; small chloritic fragments and small feldspar crystals present.

17. Brownish-green, very fine-grained silicic tuff bedded in millimeter- to centimeter-thick layers. Some iron and potassium alteration on fractures; contains veinlets of quartz.

18. Very fine-grained, gray silicic tuff. Small plagioclase(?) crystals present. Hematized on fractures and contains quartz veinlets.

19. Gray-green, lithic lapilli tuff containing chert and chloritic fragments to 10 mm. Chloritic areas often hematized; pyrite pseudomorphs and pink feldspar crystals present.

20. Gray-black, fine-grained aphanitic andesite/basalt; no phenocrysts observed.

21. Pinkish-gray, hematized and potassium-feldspathized, lithic lapilli tuff. Lithic fragments are chert and chloritic material to 10 mm in a fine-grained silicic matrix. Numerous pink feldspars present.

22. Pinkish-gray, crystal-lithic tuff containing chlorite and chert fragments and pink feldspar crystals of about the same size as the rock fragments. Matrix is fine-grained silicic material; potassium-feldspathization and some hematization observed.

23. Pink-gray, crystal-lithic lapilli tuff with fragments to 10 mm. Chloritic fragments extensively hematized; feldspar crystals are all pink. Minor chert fragments; crystals and fragments bedded; matrix fine-grained. Chloritic material often wispy. Abundant feldspar crystals.

24. Brownish-green, fine-grained silicic crystal tuff bedded on a millimeter scale. Pink feldspar crystals present; hematized on fractures.

25. Gray-green, very fine-grained silicic tuff. Hematized on fractures; finely bedded. Specimen (not core) contains fragment of another bed of crystal-lithic tuff.

26. Purplish, fine-grained, aphanitic andesite/basalt; fractured and epidotized so that brown and black splotches appear under hand lens. No phenocrysts observed.

Table 4.--Comparison of mean paleomagnetic directions before and after correction for dip of beds

[Dec., declination of mean remanent magnetization direction in degrees clockwise from true north; Inc., inclination of the mean remanent direction, positive downwards; R, sum of the unit vectors for the n samples in the group; K, Fisher's (1953) best estimate of precision; α_{95}, semiangle of the cone of 95 percent confidence, in degrees; dp and dm are the semiminor and semimajor axes, respectively, of the oval of 95 percent confidence about the paleomagnetic pole]

Group	Mean direction Dec. (deg.)	Inc. (deg.)	R	k	α_{95} (deg.)	Paleomagnetic pole Lat (deg.)	Long (deg.)	dp (deg.)	dm (deg.)
All samples except number 23 (n = 24)									
Original..............	357.1	15.3	20.9	7.4	11.7	74.0 N.	128.6 W.	6.2	12.0
Corrected.............	351.6	-37.8	20.5	6.5	12.6	44.6 N.	128.2 W.	8.8	14.9
1, 3, 4, 5, 6, 7, 8, 9, 11, 16, 19, 20, 21, 22, 24, 26 (n = 16)									
Original..............	353.7	21.3	14.9	13.1	10.6	76.2 N.	112.5 W.	5.9	11.1
Corrected.............	354.2	-31.4	15.5	30.7	6.8	49.1 N.	130.7 W.	4.2	7.6

The values of dispersion, k (best estimate of precision, Fisher, 1953) and of $_{95}$ (the semiangle of the cone of 95% confidence) for the subgroup mean directions listed in table 4 show that the dispersion of the mean direction is reduced significantly by the structural correction (k = 30.7; $_{95}$ = 6.8^0 after structural correction as compared to k = 13.1; $_{95}$ = 10.6^0 before) and thus the paleomagnetic fold test is satisfied, and magnetization predates the formation of the northeast-plunging antiform. For the dataset including all samples except 23, the dispersion is slightly increased by the structural correction (k = 7.4); $_{95}$ = 11.7^0 before correction: k = 6.5; $_{95}$ = 12.6^0 after correction), suggesting that the structural correction for samples not in the subgroup is either the result of a combination of pre- and post-magnetization deformations, or is the result of complex chemical remagnetization. The results suggest that further paleomagnetic studies in the area may be useful in sorting out the deformational history of the area,

The paleopole position for the subgroup after structural correction (table 4), and after correction for the Tertiary rotation of the Arabian plate away from Africa (9.9^0 about a pole at lat 31.2^0 N. and long 25.4^0 E.), falls at lat 51^0 N. and long 146^0 W., near the 600-590 Ma portion of the apparent polar wander path for west Gondwanaland (Hagstrum and others, 1980), and thus suggests that the age of magnetization is about 600 Ma. This is substantially younger than either the age of the Mahd group of rocks, or the age of mineralization (as discussed above). The age of magnetization inferred for the Mahd adh Dhahab rocks is essentially the same as that obtained by Kellogg and Beckmann (in press) for seven sites in the eastern Arabian shield, where remanent magnetization observed is interpreted to have been acquired during cooling through the blocking temperatures of the magnetic minerals following a regional thermal pulse.

The direction of magnetization of many of the samples is noted to be surprisingly similar to those for Tertiary rocks in Saudi Arabia. Although Tertiary remagnetization cannot be ruled out, similar directions have been obtained for rocks of the same age as Mahd adh Dhahab elsewhere in Saudi Arabia and African (Kellogg and Beckmann, in press), and it appears that the pole position during the late Precambrian-early Cambrian times was near to that of the Tertiary times. The fact that the fold test is satisfied would also seem to require an earlier magnetization age than Tertiary.

CONCLUSIONS AND RECOMMENDATIONS

Paleomagnetic data from 25 specimens in two traverses at Jabal Mahd adh Dhahab have shown that many of the rocks of the stratigraphic sequence have components with stable remanent magnetization, implying that further paleomagnetic analysis of the layered volcanic and volcaniclastic rocks of the northern Arabian shield, particularly the felsic rocks, will help delineate the structural history there. At least one geomagnetic reversal is recorded in the sequence, so that it may be possible to construct a limited geomagnetic timescale for part of the late Proterozoic. In the Mahd adh Dhahab area, the combined evidence from downhole electric logs and paleomagnetic studies suggest possible structural repetition of parts of the sequence of layered rocks, a result in conflict with the present geologic mapping, but not definitely disproven.

The paleomagnetic data for the traverse across the northeast-plunging anticline satisfy the fold test of McElhinny (1973), and imply that the remanent magnetization directions were acquired previous to the northeastern- trending deformation. The paleopole position for this area suggests an age of magnetization of about 600 Ma for these rocks which is interpreted to be the age at which regional remagnetization occurred in much of the Arabian shield following a heating episode during the Pan-African event. The separation in time of the northeast- and north-trending deformations is in agreement with regional scale geologic mapping (Kemp and others, 1982), and recent syntheses of the geologic history of the Arabian shield (Stoeser and others, 1984), and the present interpretation indicates that a timespan of about 200 Ma during the late Proterozoic and early Cambrian is represented by the rocks in Mahd adh Dhahab area.

From the data considered in this report, it is possible to postulate a synoptic picture of the geologic history of the area, as depicted in figure 5. The rocks of the Mahd adh Dhahab area were erupted and deposited in part subaerially and in part subaqueously at about 770 Ma, and subsequently deformed by folding and faulting along north- to northeast-trending axes in the late stages of the Hijaz orogenic cycle of Stoeser and others (1984). Magnetization directions presently observed in the rocks were acquired following the thermal pulse in the early part of the Najd orogeny of Stoeser and others (1984) at about 600 Ma. The final stage of this orogeny imposed the northeast-trending folding, faulting, and andesite dike emplacement, and the northwest-trending post-mineralization faulting. The Nabitah and Najd orogenies together form the Pan-African event for the Arabian shield (Stoeser and others, 1984), and thus the mineralization and magnetization of the Mahd adh Dhahab rocks appear to have taken place in early and middle Pan-African times, respectively.

Considering the promising results obtained from the limited sampling of this study, further paleomagnetic work in the area is recommended. Future programs should include sampling of other layered rocks in the northern shield, as well as the Mahd group, in areas where the structure is relatively simple or well understood. Further sampling at Jabal Mahd adh Dhahab, including the underground decline, is merited in order to help refine the structural interpretation.

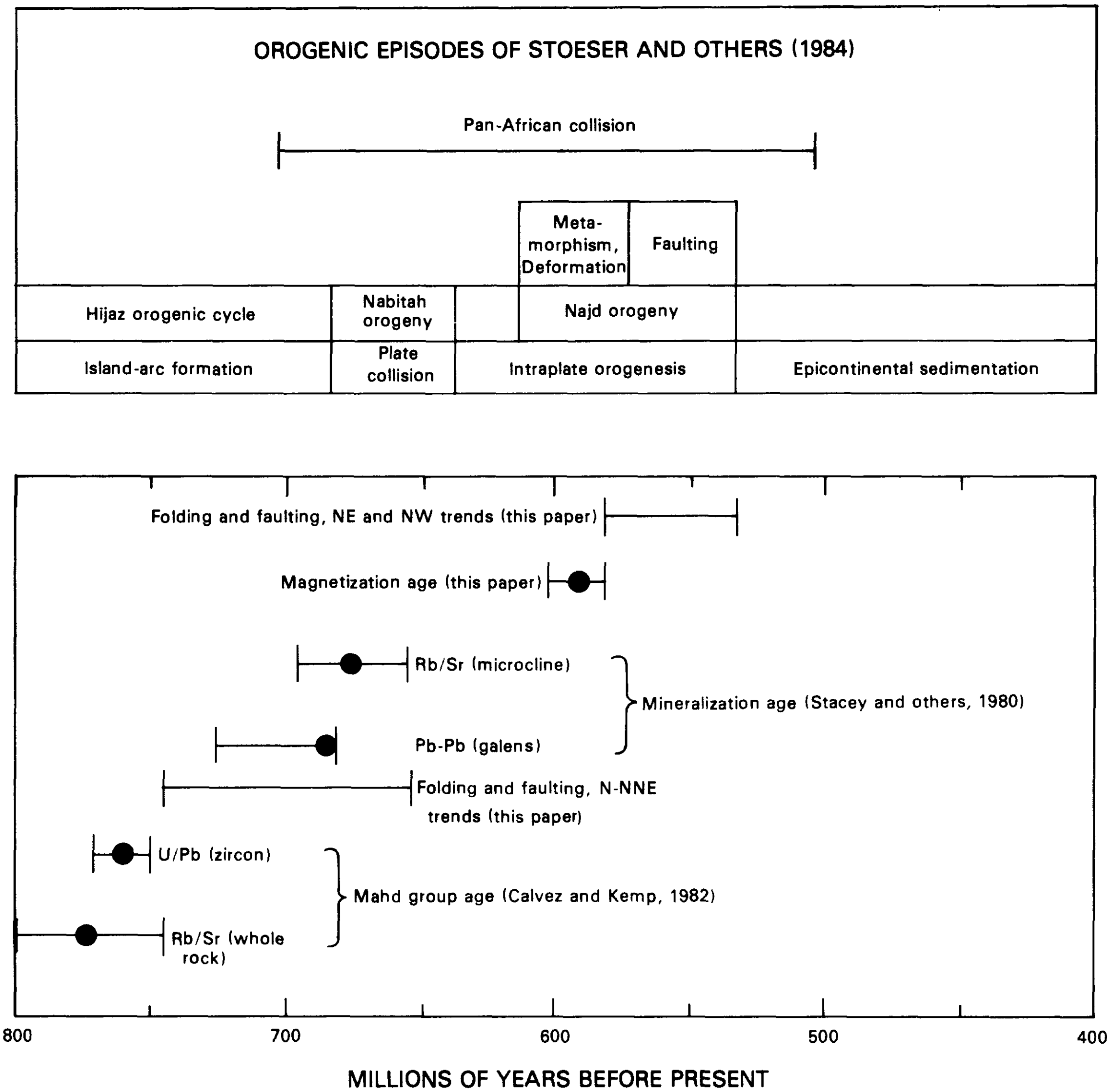


Figure 5.--Inferred structural history for the Mahd adh Dhahab area.

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