Geochemical Reconnaissance of Late Proterozoic Volcanic and Mafic Plutonic Rocks of the Al ʻAwshaziyah Quadrangle and Related Rocks in the Qufar Quadrangle, Northern Arabian Shield

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By GERHARD W. LEO

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Geochemical Reconnaissance of Late Proterozoic Volcanic and Mafic Plutonic Rocks of the Al 'Awshaziyah Quadrangle and Related Rocks in the Qufar Quadrangle, Northern Arabian Shield

By Gerhard W. Leo

Abstract

The Al 'Awshaziyah quadrangle and adjacent Qufar quadrangle in the northern part of the Arabian Shield are underlain by two distinct volcanic sequences and a variety of intrusive rocks ranging from gabbro to peralkaline granite. The older, layered sequence (Nuf and Aqab formations) is tentatively correlated with the Halaban formation (now Hulayfah Group) in the north-central and southeastern part of the shield; its age is estimated at 738 Ma.

The Nuf and Aqab formations consist of a basal sequence of andesite, basalt, and graywacke intruded by plugs of gabbro locally grading to pyroxenite and are overlain by intermediate to rhyolitic flows and tuffs (upper Nuf and upper Aqab formations). The basal Nuf contains pillow basalts and interbedded marbles, whereas the Aqab apparently lacks these but contains sandstone and locally thick conglomerate, especially in its upper part. The entire sequence is deformed and is metamorphosed at greenschist to lower amphibolite facies grade. A mostly felsic, relatively undeformed and unmetamorphosed volcanic-volcaniclastic sequence (Hadn formation, approximately 650–600 Ma old) unconformably overlies the Nuf and Aqab formations. The Hadn has been correlated with the Shammar group, and it could also be equivalent to the upper rhyolite of the Arfan formation (upper Halaban). Two source calderas for the Hadn have been identified.

The mafic basal part of the Nuf and Aqab shows some tholeiitic characteristics, but overall trace-element abundances, and plots based on Th, Ta, Hf, and La suggest a calc-alkaline trend. No clearcut oceanic (mid-ocean ridge basalt) affinity is apparent for these rocks, an observation somewhat at odds with lead-isotope data in the northern shield and geochemical interpretation on the Halaban. The mafic to intermediate volcanics are compatible with an origin in a maturing island arc. The Hadn, and possibly also the felsic upper part of the Aqab, may have been derived from a continental crustal source. According to current plate-tectonic models, the Hadn, in particular, has been related to magmatic activity accompanying Pan-African cratonization of the Arabian Shield.

INTRODUCTION

A growing body of published data on the petrology, geochemistry, and geochronology of the Arabian Shield has been accumulating over the past decade (Jackaman, 1972; Dodge and others, 1979; Fleck and others, 1980; Duyverman and others, 1982; Roobol and others, 1983; Darbyshire and others, 1983; Stacey and Stoeser, 1983; Stoeser and others, 1984; Stuckless and others, 1982 and in press). Most of the data and related interpretations are from the southern and central part of the shield, whereas relatively little detailed petrologic and geochemical work has been done thus far on Proterozoic volcanic rocks of the northeastern shield. As a result, the stratigraphy and correlation of the latter rocks with better-studied rocks to the south remain conjectural and their chemistry largely unknown. The present report growing out of reconnaissance mapping of the Al 'Awshaziyah quadrangle in 1982 and 1983 (Leo, 1984, see fig. 1) presents and interprets major- and trace-element data on two late Proterozoic volcanic suites widely exposed in the Al 'Awshaziyah quadrangle and the Qufar quadrangle to the north (Kellogg, 1983; Leo and Kellogg, 1984). To some extent the chemical data serve to support but also to constrain the increasingly elaborate and detailed plate-tectonic models for the shield as a whole (see Stoeser and Camp, 1985, and references cited therein). Nevertheless, it is recognized that, owing to the relatively small data base of this report, conclusions and interpretations herein must be recognized as being preliminary and reconnaissance in nature.

The Al 'Awshaziyah quadrangle is located in the northern part of the Arabian Shield (fig. 1). The quadrangle was mapped at 1:100,000 scale as part of the cooperative program between the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. Nearby quadrangles mapped at 1:100,000 include the Qufar (Kellogg, 1983), Harrat Hutaymah (Pallister, unpub. data, 1983), Ghazzalah (Quick, 1983), Rak (Kellogg, 1984), and Hā' il (Kellogg and Stoeser, 1983) quadrangles (fig. 1). The area between 26° and 27°N. and 40°30′ and 42°E., which includes the Al 'Awshaziyah quadrangle, has recently been compiled at 1:250,000 as the Wadi Ash Shu'bah quadrangle (Quick and Doebrich, 1986; see fig. 1). The entire region was earlier mapped in reconnaissance at 1:500,000 scale (Brown and others, 1963). Chevremont (1982) made a reconnaissance study of the mafic and ultramafic plutonic rocks of the Hā' il region, with observations on volcanic and volcaniclastic rocks.

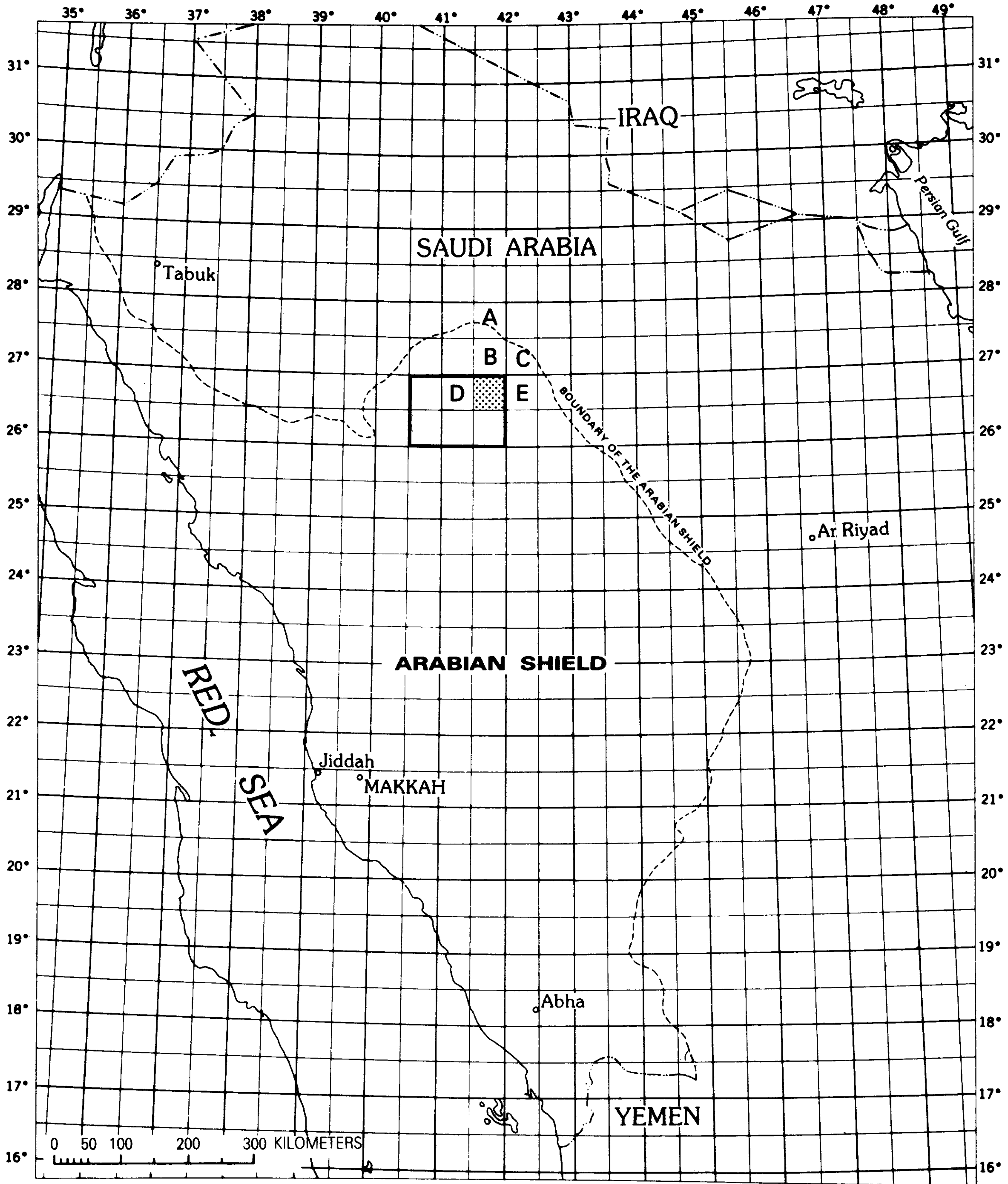


Figure 1. Index map of the Arabian Shield showing the location of the 1:100,000-scale Al 'Awshaziyah quadrangle (shaded) and other quadrangles cited in this report: A, Hā il (Kellogg and Stoeser, 1983); B, Qufar, (Kellogg, 1983); C, Rak (Kellogg, 1984); D, Ghazzalah (Quick, 1983); E, Harrat Hutaymah (Pallister, unpub. data, 1983); heavy outline, Wadi Ash Shu'bah 1:250,000 quadrangle (Quick and Doebrich, 1986).

GEOLOGIC SETTING

A generalized geologic map of the Al 'Awshaziyah quadrangle is shown in figure 2. The lithology is dominated by (1) large and abundant syntectonic and posttectonic plutons with radiometric ages ranging from about 740 to 580 Ma and (2) a variety of late Proterozoic volcanic rocks with associated volcanogenic sediments and mafic plutons. The granites were not included in this study for several reasons, including their great extent and local compositional variations; difficulty of obtaining fresh material; and already available data on several large posttectonic plutons in the region (Stuckless and others, 1982 and in press).

Brown and others (1963) defined three layered sequences in the northeastern shield. From oldest to youngest, these are (1) the dominantly andesitic Halaban group,[1] (2) the overlying, shallow-marine Murdama group, and (3) the posttectonic Shammar group comprising felsic flows, ashflow tuffs, and associated sediments. Owing to the very broad and largely unconfirmed shieldwide correlations inherent in this terminology (e.g., rocks correlated with the Halaban group are widely distributed in the northeast, east-central, and southeast parts of the shield; see Schmidt and Brown, 1984, fig. 1), these names have not been used in the course of recent mapping of the northern shield. Nevertheless the general volcanic lithology of units correlated with the Halaban resembles that of Brown and others (1963). The Halaban has also been correlated with the Hulayfah group in the north-central shield (see Delfour, 1977), a usage recently extended to the newly named Wadi Ash Shu'bah 1:250,000 quadrangle (Quick and Doebrich, 1986).

AQAB AND NUF FORMATIONS

The older, more mafic volcanic sequence (currently Hulayfah group) formerly correlated with the Halaban by Brown and others (1963) was named Aqab formation in the Al 'Awshaziyah quadrangle (Leo, 1984) and Nuf formation to the north (Chevremont, 1982; Kellogg, 1983; Nuf not shown in fig. 2). The names Nuf and Aqab are retained in this report for purposes of comparison with their original descriptions. The Nuf, and by extension the Aqab, are indirectly dated by the K-Ar method at approximately 740 Ma (Delfour, 1977). A more direct U-Pb zircon date of 738 Ma has recently been obtained on a granodiorite that cuts Hulayfah rocks but is overlain by the Hadn (C.E. Hedge, pers. commun., cited by Quick and Doebrich, 1986). This must be regarded as a minimum age for the Hulayfah group.

[1] The Halaban and Murdama were referred to as formations and the Shammar as "Shammar rhyolite" by Brown and others (1963), but owing to their subsequent elevation to group status (see Schmidt and others, 1973), the term group is used throughout this paper to designate these units.

The Aqab formation is moderately to strongly deformed and is metamorphosed at greenschist facies grade, whereas the Nuf locally reflects amphibolite facies metamorphism (Kellogg, 1983). The Aqab and Nuf show lithologic similarities, especially in the lower parts of their section, where both consist dominantly of mafic metavolcanic rocks; however they show some consistent distinctions suggesting somewhat different depositional environments (Leo, 1984, table 1). In particular, the upper part of the Aqab contains extensive conglomerate consisting of cobbles in a matrix of highly indurated graywacke. This association suggests a significant erosional hiatus within the Aqab volcanic episode and further suggests a depositional environment ranging from subaerial to nearshore (compare Greenwood and others, 1976, p. 16). The Nuf, by contrast, contains no conglomerate but has local marble lenses as well as local pillow basalts (Kellogg, 1983). Thus the Nuf appears to reflect a marine environment of deposition. This paper is concerned in part with geochemical differences in the two formations that would reflect their distinct depositional environments.

The Aqab formation has a maximum thickness of 6,000 m in the Al 'Awshaziyah quadrangle and is divided into three members (Leo, 1984). From bottom to top they are the basalt-andesite member, the dacite-rhyolite member, and the conglomerate member, which is not considered further here. The basalt-andesite member consists of dark-gray to greenish-black, aphanitic to fine-grained, locally amygdaloidal, typically nonporphyritic lava (see appendix for more detailed descriptions of analyzed samples). These rocks show a well-preserved primary texture generally consisting of felted plagioclase laths in a largely amorphous dark matrix. Plagioclase phenocrysts are faintly cloudy to moderately saussuritized; extensive breakdown of plagioclase is uncommon. Mafic constituents are represented by patches of chlorite+epidote, ±amphibole (actinolite?). Amygdules are filled by crystalline epidote and (or) quartz. Disseminated magnetite constitutes 3 to 5 percent.

The dacite-rhyolite member is much more abundant and widely distributed than the basalt-andesite member. It includes purple to brown dacitic ash-flow tuffs that commonly show eutaxitic texture and have small white to pink phenocrysts, and greenish-gray, poorly sorted lithic tuffs and tuffaceous sandstones.

The dacitic tuffs have silicic, devitrified matrices that are slightly to moderately altered. Crystal tuffs contain subidiomorphic, cloudy to saussuritized plagioclase phenocrysts, subordinate quartz, and volcanic rock fragments. More mafic rocks transitional to andesite contain green hornblende, which apparently replaces primary pyroxene.

GABBRO AND PYROXENITE

Numerous masses of gabbro are distributed through the region and constitute three general types. Black, distinc-

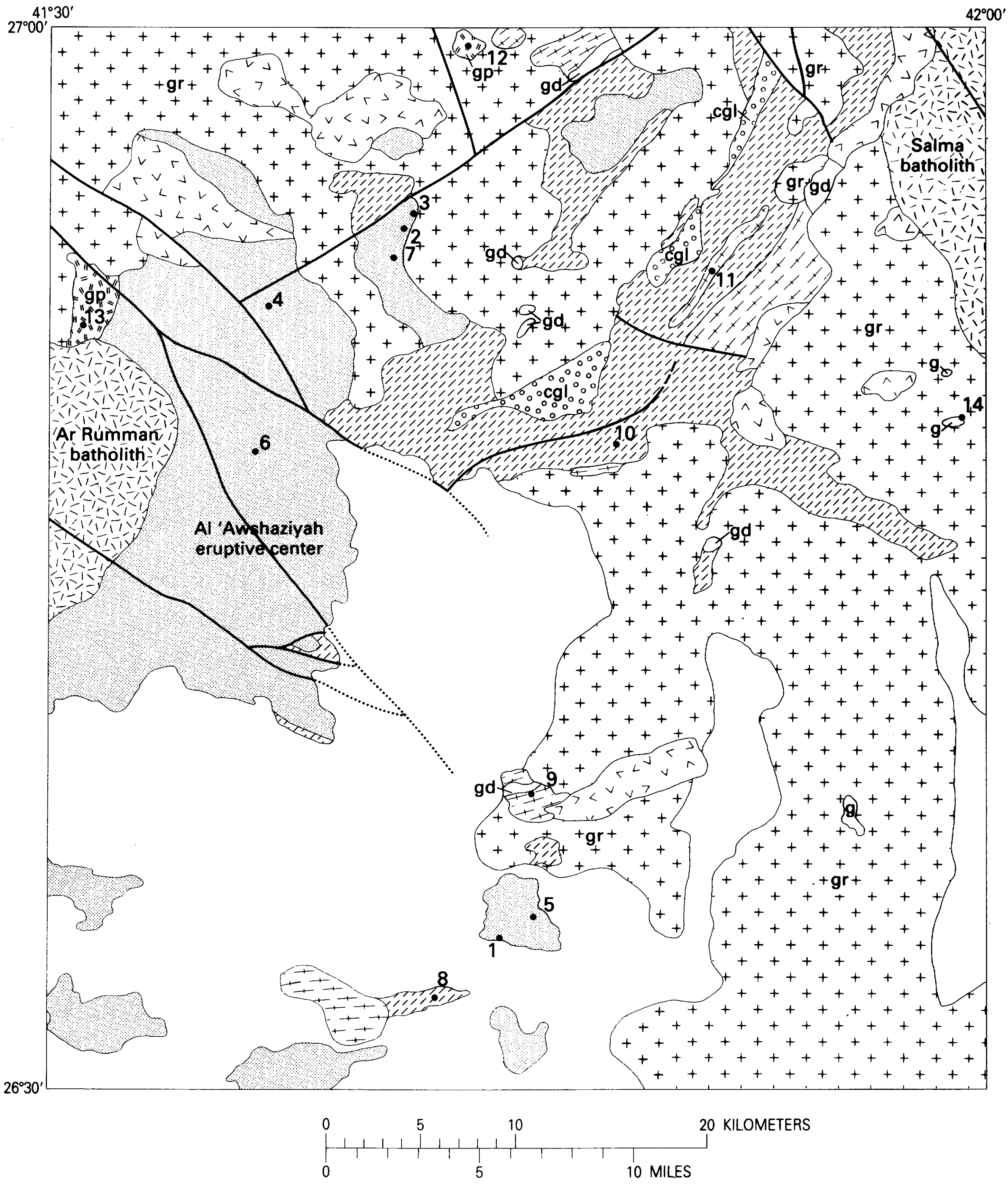
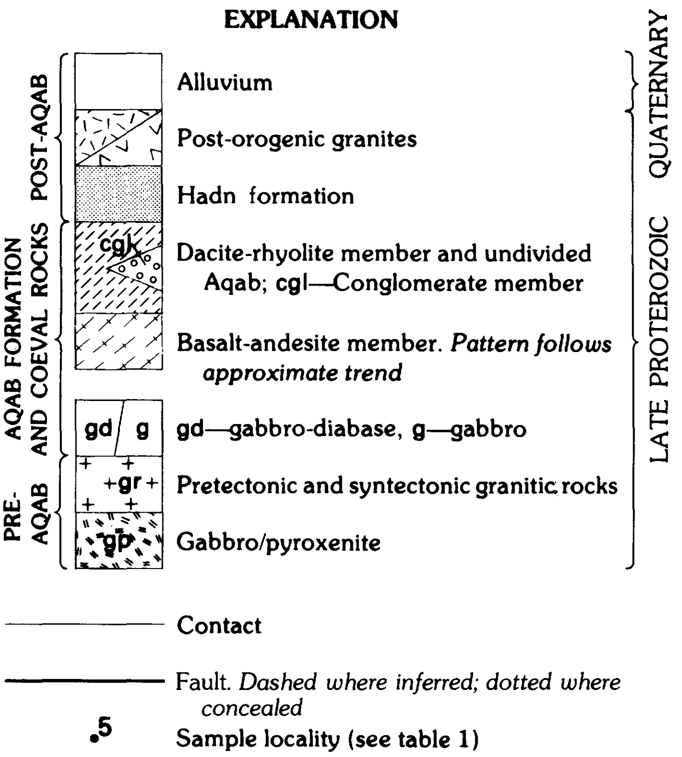


Figure 2. Generalized geologic map of the Al 'Awshaziyah quadrangle, Kingdom of Saudi Arabia (modified from Leo, 1984).



tive gabbro-pyroxenite with rhythmic banding on the scale of a few millimeters to several meters forms two bodies in the northern part of the Al 'Awshaziyah quadrangle (gp on fig. 2). This rock consists of diopsidic clinopyroxene partly replaced by tremolitic amphibole, 0 to 50 percent plagioclase (An_{37-65}), and rare grains of serpentinized olivine. The gabbro-pyroxenite is intruded by the oldest granite in the region (gr on fig. 2) and possibly can be correlated with Hā' il mafic-ultramafic suite (Chevremont, 1982).

A more widely distributed gabbro type (gd on fig. 2) consists of green-brown hornblende and prismatic, strongly zoned plagioclase (An_{32-75}). Texturally this gabbro is gradational to diabase and is locally associated with Aqab basalt. Hence it is tentatively correlated with the Aqab formation.

A third type of gabbro, forming relatively small and steep-sided plugs (g on fig. 2), is cut by synorogenic granite and therefore may also be of Aqab age. This gabbro is medium grained, dark gray, and consists dominantly of calcic plagioclase (An_{70-82}) and diopsidic pyroxene, locally accompanied by serpentinized olivine, deep red-brown amphibole (kaersutite?), red biotite, and accessory apatite.

HADN FORMATION

The Hadn formation (the term is used here to include the Al 'Awshaziyah formation of Leo, 1984) overlies both the Aqab and Nuf formations. The age of the Hadn has been indirectly determined at approximately 650 to 600 Ma (C.E. Hedge, pers. commun., 1985). The contact with the Aqab is locally exposed along an angular unconformity in the Al 'Awshaziyah quadrangle. In the Qufar quadrangle (Kellogg, 1983) no contacts between Hadn and Nuf have been found. The upper parts of both the Aqab and Nuf contain dacitic and rhyodacitic flows and tuffs. Thus, these two older volcanic sequences overlap the compositional range of the Hadn. This compositional overlap, which is particularly well exposed in the upper part of the Aqab formation (Leo, 1984, fig. 2 and pl. 1), makes the contact with lithologically similar Hadn hard to locate. The similarity between the upper Aqab and the Hadn notwithstanding, eruption of the two units is separated by a hiatus of more than 100 Ma.

The Hadn formation comprises a sequence of rhyolitic to dacitic flows, ash-flow tuffs, tuffaceous sandstones, and local conglomerate layers (much less massive than the Aqab conglomerate). The unit is regionally correlated with the more widely distributed Shammar group (Kellogg, 1983). A major source area for the Hadn is a caldera in the west-central part of the Al 'Awshaziyah quadrangle (Al 'Awshaziyah eruptive center, Leo, 1984). Broad exposures of Hadn formation in the western part of the Al 'Awshaziyah quadrangle are flat-lying to gently dipping. The Hadn formation in the southeastern and northeastern parts of the Qufar quadrangle is highly folded and locally overturned (Kellogg, 1983). This indicates that the crust in the eastern and northeastern part of the study area was tectonically more active throughout the late Proterozoic than in the west and southwest, where tectonism has been virtually negligible at least since the Hadn volcanism.

The welded tuffs typically have a devitrified groundmass and 5 to 25 percent phenocrysts including elongated, well-twinned plagioclase prisms, quartz, and sanidine (the latter in a minority of samples). Accessory constituents include magnetite±biotite. Alteration in most samples ranges from very slight to moderate. Fragmental rocks are generally more altered than welded tuffs and lava flows, and rocks of more mafic composition are more altered than the siliceous rocks. The overall extent of alteration of these rocks is less than that of the Aqab and Nuf formations.

Although the investigated area is relatively small, correlation of the major underlying units with more broadly distributed volcanic suites makes it likely that the assemblage of the Al 'Awshaziyah quadrangle is representative of a significantly larger area.

CHEMISTRY

Analytical Methods

Eleven samples of volcanic rocks and three samples of mafic plutonic rocks from the Al 'Awshaziyah quadrangle were analyzed for major-element chemistry by standard rapid-rock procedures in the U.S. Geological Survey laboratories at Reston, Va. The samples selected for analysis ranged from virtually unaltered to moderately altered, consistent with partial recrystallization at greenschist facies grade (especially Aqab samples, see appendix), but showed a minimum of fractures and (or) obviously introduced material. Rb, Sr, Ba, Nb, Zr, and Y were determined by X-ray fluorescence, and 26 trace elements including rare-earth elements (REE) were determined by instrumental neutron activation (INA). Results are tabulated in table 1. Norms were calculated by the GNAP program (Stuckless and VanTrump, 1979; T.L. Wright, unpub. data) on a water-free basis (adjusted oxides not shown in table 1). Fe_2O_3 was adjusted where necessary according to the principle of Irvine and Baragar (1971) that limits the amount of Fe_2O_3 to the weight percent $TiO_2+1.5$, the remaining Fe_2O_3 being converted to FeO and combined with the FeO value. Analytical data obtained by Karl S. Kellogg, U.S. Geological Survey, from X-Ray Assay Laboratories, Ltd., Don Mills, Ontario, on 17 samples of related rocks that include Nuf, intermediate to felsic Aqab, and Hadn from the Qufar quadrangle (Kellogg, 1984 and unpub. data) are used here by permission. These data are shown in several plots and are also utilized in table 2.

Precision for the various analytical procedures on Al 'Awshaziyah samples is as follows. Rapid-rock analysis (concentration range and relative precision, both in percent): >10, 1–2; 1–10, 2–10; 0.1–1, 10–20; and 0.1, 50–100. X-ray fluorescence spectrometry: >20 ppm, 5 percent relative; <20 ppm, ±2 ppm absolute. Instrumental neutron activation analysis: variable, but nearly all values accurate to <10 percent, most <5 percent. Among rare-earth elements (REE) Gd has an error limit of <10 percent and Tm <20 percent, but these elements are mostly omitted from REE plots (fig. 8). Precision reported by X-Ray Assay Laboratories, Ltd. is ±2 percent for major oxides and ±10 percent for trace elements including REE (oral commun., 1986).

Analytical Results

Major Elements

Major-element Harker plots of the volcanic-rock data (fig. 3) reflect the continuum of compositions evident from megascopic and microscopic characteristics. Nuf and mafic Aqab samples generally span the compositional range from basalt (47–52 percent SiO_2) through basaltic andesite and andesite (52–62 percent SiO_2). Hadn samples, combined with felsic Aqab, define the general range dacite through rhyolite. A slight compositional gap apparent in the range of SiO_2=59–64 percent (fig. 3) could be an artifact of sampling.

Data points for Nuf, mafic Aqab, and gabbro show considerable scatter, which in some cases can be resolved into mutually distinct, more or less linear trends (e.g., FeO*,[2] MgO, CaO, Na_2O, TiO_2, and P_2O_5). The following observations can be made:

1. The Aqab points show a tholeiitic trend over the SiO_2 range of 48 to 54 percent, notably in the enrichment of FeO*, Na_2O, and P_2O_5, with accompanying depletion in MgO and CaO. Continuation of this trend is not particularly apparent in the felsic Aqab.
2. The greater scatter of Nuf points relative to mafic Aqab for Al_2O_3, FeO*, and CaO, together with the distinctly different fields of Nuf and mafic Aqab for nearly all the oxides, suggests one or more of several possibilities: (a) the Nuf and Aqab may not be comagmatic; (b) some of the Nuf samples, e.g., the basalt containing 49 percent SiO_2, 8.2 percent Al_2O_3, 10 percent MgO, and 19.2 percent CaO, are not primary liquids but rather represent cumulates (the aforementioned sample is not far from an augite composition with excess Al_2O_3 that could be contained in 25 percent plagioclase); (c) some of the differences between the Al 'Awshaziyah and Qufar samples could be related to analytical procedures in two different laboratories (see section on trace elements). In this connection it may be noted, however, that the data points for felsic rocks, representing analyses by both laboratories, show less scatter (figs. 3, 6). Because of the writer's lack of familiarity with the analyzed Qufar samples and lack of knowledge concerning point 2c (above), the above possibilities cannot be fully evaluated. It seems safe to assume that 2b is a factor, especially inasmuch as gabbro-pyroxenite (anal. 12–13, table 1) show somewhat similar compositions as some of the Nuf "basalt." Finally, the alteration of most of the analyzed samples probably contributes to the observed scatter.

On an AFM plot (fig. 4) most of the mafic samples fall into the tholeiite field as defined by Irvine and Baragar (1971), whereas most of the felsic samples, both Hadn and Aqab, fall in the calc-alkaline field. Most, but not all of the same mafic samples also plot as tholeiites in figure 5. In paleotectonic diagrams (figs. 9–11) the tholeiitic and calc-alkaline categories are somewhat mixed. Aqab samples plot well in the calc-alkaline field in figure 9, plot (along with Nuf samples) in the orogenic andesite field (fig. 10), and skirt the mid-ocean ridge basalt–orogenic andesite boundary in figure 11 (data for Nuf not available). Thus, none of the mafic volcanics for which data exist has clear-cut oceanic affinities. The three gabbro samples, by contrast, partially plot in mid-ocean ridge basalt fields (see esp. figs. 9, 11).

Trace Elements Other Than Rare Earths

Trace elements are listed in table 1, and several plots of elements obtained for both sets of samples are shown in

[2]Total iron as FeO.

Table 1. Major- and trace-element chemistry of 14 samples from the Hadn (Al 'Awshaziyah formation of Leo, 1984) and Aqab formations and mafic intrusive rocks in the Al 'Awshaziyah quadrangle

[ND, not determined; --, nil or unreliable value; sample locations shown in figure 2; descriptions are in the appendix]

	Hadn formation							Aqab formation				Gabbro and pyroxenite		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Major Oxides (in percent)														
SiO_2	70.7	76.1	69.9	70.7	68.2	73.3	70.9	69.0	50.9	48.1	53.9	54.7	53.9	49.9
Al_2O_3	13.8	13.2	15.4	14.7	14.4	13.8	13.6	14.4	18.9	20.3	14.7	9.5	10.9	20.9
Fe_2O_3	1.8	0.92	1.7	1.8	2.14	1.8	1.8	1.9	2.7	2.5	3.2	1.8	1.9	1.8
FeO	1.2	0.62	1.9	1.2	2.78	1.9	2.0	1.2	6.5	7.3	8.7	6.5	7.6	5.3
MgO	0.3	0.25	1.6	0.22	1.3	0.22	0.5	0.98	4.5	4.9	3.2	10.3	9.9	7.8
CaO	1.3	1.0	3.0	0.62	2.5	0.28	1.3	1.9	8.9	10.6	5.3	13.2	10.9	8.5
Na_2O	5.2	3.5	2.7	6.7	4.9	5.2	5.3	5.3	3.4	2.2	4.2	1.7	1.9	3.3
K_2O	3.3	4.5	2.2	2.3	2.2	3.1	3.3	2.0	1.1	0.58	0.90	0.28	0.34	0.46
H_2O	0.94	1.1	1.63	0.74	1.3	0.58	1.0	1.2	1.26	1.33	2.44	0.96	1.44	2.11
TiO_2	0.31	0.08	0.39	0.25	0.64	0.25	0.31	0.39	1.2	1.0	1.7	0.29	0.39	0.31
P_2O_5	0.02	0.03	0.12	0.05	0.07	0.08	0.07	0.16	0.35	0.22	0.46	0.12	0.13	0.13
MnO	0.09	0.04	0.05	0.12	0.16	0.08	0.16	0.06	0.15	0.21	0.2	0.17	0.18	0.11
CO_2	0.16	0.02	0.27	0.04	0.03	0.05	0.26	0.91	0.1	0.05	0.64	0.15	0.08	0.02
Total	99.	101.	101.	99.	101.	101.	101.	99.	100.	99.	100.	100.	100.	101.
Normative Minerals—H_2O free (in percent)														
Q	25.54	36.22	37.63	21.56	23.46	29.82	24.21	28.39	0.52	0.77	8.36	6.24	5.65	—
C	—	0.87	4.07	0.28	—	1.69	—	2.60	—	—	—	—	—	—
Or	19.86	26.65	13.10	13.77	13.09	18.31	19.60	12.04	6.59	3.50	5.48	1.68	2.05	2.76
Ab	44.82	29.68	23.02	57.44	41.75	43.98	45.07	45.67	29.15	19.00	36.60	14.57	16.39	28.34
An	4.65	4.65	12.49	2.53	10.87	0.55	3.59	2.68	33.50	44.71	19.15	17.69	20.60	41.47
Ac	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Wo	0.32	—	—	—	0.40	—	0.33	—	3.46	3.00	0.28	19.58	13.83	0.14
En	0.76	0.62	4.02	0.56	3.26	0.55	1.25	2.48	11.35	12.46	8.21	25.99	25.13	9.32
Fs	0.38	—	1.55	0.53	2.60	1.74	1.98	0.10	8.11	10.29	11.22	10.42	12.31	3.81
Fo	—	—	—	—	—	—	—	—	—	—	—	—	—	7.28
Fa	—	—	—	—	—	—	—	—	—	—	—	—	—	3.28
Mt	2.66	0.42	2.48	2.64	3.12	2.61	2.62	2.81	3.97	3.70	4.78	2.64	2.81	2.65
Hm	—	0.64	—	—	—	—	—	—	—	—	—	—	—	—
Il	0.60	0.15	0.75	0.48	1.22	0.48	0.59	0.75	2.31	1.94	3.33	0.56	0.70	0.60
Ap	0.05	0.07	0.29	0.12	0.17	0.19	0.17	0.39	0.84	0.53	1.12	0.29	0.31	0.31
Cc	0.37	0.05	0.62	0.09	0.07	0.11	0.59	2.11	0.23	0.12	1.50	0.35	0.19	0.05
Total	100.00	100.00	100.01	100.00	100.01	100.01	100.01	100.01	100.02	100.01	100.03	100.01	100.01	100.01
Salic	94.87	98.06	90.31	95.58	89.17	94.34	92.47	91.37	69.75	67.98	69.60	40.18	44.68	72.56
Femic	5.13	1.94	9.70	4.43	10.84	5.67	7.53	8.64	30.27	32.03	30.43	59.82	55.33	27.44
Di	0.61	—	—	—	0.79	—	0.66	—	6.78	5.90	0.55	37.74	26.81	0.28
Hy	0.84	0.62	5.56	1.09	5.47	2.28	2.90	2.59	16.14	19.84	19.15	18.24	24.46	13.00
Ol	—	—	—	—	—	—	—	—	—	—	—	—	—	10.56
DI[1]	90.22	92.54	73.76	92.77	78.29	92.10	88.88	86.09	36.26	23.27	50.44	22.49	24.08	31.10
Trace Elements (in ppm)														
Rb	62	131	77	34	48	45	38	54	28	28	23	13	13	40
Sr	70	106	640	84	397	111	149	215	709	664	493	328	253	1248
Ba	717	842	1505	723	1170	827	1061	722	523	265	573	59	119	249
Th	5.4	11.2	8.23	4.85	7.74	5.29	5.32	3.7	1.87	1.41	3.18	0.4	0.7	0.4
Zr	267	130	242	387	246	404	379	147	129	76	170	48	56	64
Hf	6.8	3.82	5.3	9.12	6.17	9.51	9.35	3.47	2.7	1.2	4.14	0.7	0.9	0.71
Nb	10	8	<5	10	7	13	11	8	6	<5	11	6	8	<5
Ta	0.51	0.79	0.5	0.86	0.5	0.9	0.89	0.3	0.3	0.2	0.4	<0.3	<0.3	0.2
Y	49	24	24	43	30	45	45	22	24	18	36	15	14	10
Co	1.	1.	5.55	0.4	7.1	1.2	0.5	5.0	30.3	30.	28.1	37.	43.6	51.2
Cu	ND	ND	ND	ND	ND	ND	ND	ND	32	22	50	63	88	82
Ni	ND	ND	ND	ND	ND	ND	ND	ND	37	21	22	98	62	137
Zn	73	30	56	108	68	108	117	46	82	78	123	61	84	61
Cr	4.	4.	19.4	1.	38.3	4.	<2	18.2	140	36.2	16	726	483	350
Sc	3.09	1.87	6.7	8.97	10.3	7.44	9.63	7.15	25.5	30.5	32.6	49.2	50.4	3.5
U	2.2	3.5	2.6	2.02	2.3	2.05	2.11	1.54	0.65	0.34	1.11	<0.5	<0.5	<0.3
La	27.5	26.6	27.9	38.3	25.5	38.	39.6	15.8	13.8	9.5	20.9	3.5	5.9	5.8
Ce	54.4	47.6	48.1	79.8	47.4	80.	84.3	30.5	29.3	19.1	43.6	9.6	13.4	11.4
Nd	28.	17.	22.	43.	25.	43.	46.	17.	18.3	12.	28.	7.	10.	7.4
Sm	6.85	3.39	4.39	9.29	5.5	9.24	9.8	3.53	4.42	3.04	6.72	1.85	2.12	1.3
Eu	1.01	0.438	1.01	1.79	1.16	1.02	2.01	0.865	1.27	1.01	1.76	0.51	0.58	0.781
Gd	6.40	3.50	4.	8.	4.	9.	9.	4.	4.	3.	6.	2.	—	—
Tb	1.13	0.405	0.43	1.21	0.63	1.21	1.24	0.42	0.62	0.42	1.01	0.21	0.20	0.12
Tm	0.72	0.22	0.3	0.6	0.4	0.62	0.7	0.21	0.2	0.2	0.5	0.1	0.1	0.1
Yb	5.23	1.8	2.08	4.33	2.54	4.13	4.26	1.68	2.2	1.53	3.55	0.87	0.79	0.34
Lu	0.799	0.277	0.330	0.615	0.376	0.579	0.680	0.246	0.325	0.250	0.529	0.149	0.157	0.05
K/Rb	450	286	347	570	384	572	725.00	314	329	175	336	185	249	97.5
Rb/Sr	0.89	1.24	0.12	0.4	0.12	0.4	0.25	0.25	0.4	.04	0.05	0.04	0.05	0.03

[1]Differentiation index.

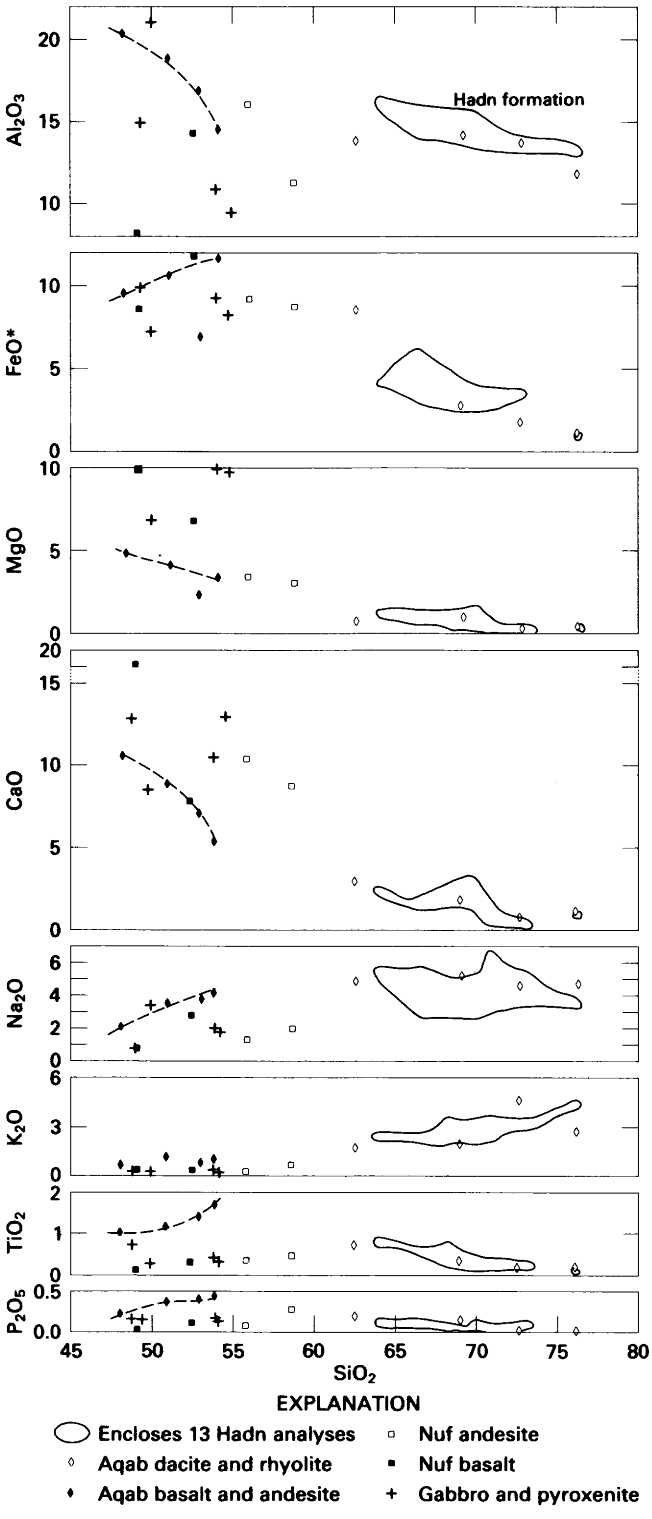


Figure 3. Harker diagrams of late Proterozoic volcanics and mafic intrusives in the Al 'Awshaziyah and Qufar quadrangles. Data from table 1 and K.S. Kellogg (unpub. data, 1984). FeO*, total iron as FeO. Dashed lines show tholeiitic trend for part of Aqab (see text). Values are in percent.

figures 6 and 7. The following observations can be made:

1. The relatively stable elements Th and Hf show reasonably linear increases when plotted against SiO_2 (fig. 6). Similar linearity might be expected for Zr, but in fact the Zr-SiO_2 plot shows considerable scatter, and the compositional fields of mafic and felsic rocks are more sharply separated than for Th and Hf. The four unusually low Zr values (0–20 ppm) for some Nuf samples may reflect analytical error. However, they also have very low Hf contents (<1 ppm) and no detectable Rb (fig. 7).
2. Rb and Sr both show significant scatter (table 1; fig. 7), so that a correlation between Sr content and depth to a seismic zone (Hart and others, 1970) cannot be applied on the basis of these data.
3. Th, Hf, and Rb data points for Hadn and felsic Aqab show some overlap in figures 6 and 7, adding to the impression that these units are petrologically similar despite their apparent structural and temporal separation.
4. A subtle but consistent distinction, shown by dashed lines in figures 6 and 7, is apparent between the mafic Aqab and most of the Nuf, in that the latter shows generally lower values of the plotted elements than the former; this is true of Th and Hf as well as Zr and Rb (Zr values also are consistently lower in felsic Aqab than in Hadn). These data are summarized in table 2. Taken together (and assuming the low Zr and Rb values of the Nuf samples to be essentially accurate) these differences in abundances constitute a basis of distinguishing between Nuf and Aqab in accord with the more oceanic environment of the Nuf. Trace-element abundances for the Nuf basalts and associated gabbro-pyroxenite are within the general range of island-arc tholeiites (Jakeš and White, 1971; Jakeš and Gill, 1970). They are consistently lower than abundances of the same elements in the mafic Aqab, which has abundances more in the range of calc-alkaline rocks.

Rare-Earth Elements

Rare-earth element (REE) patterns are shown in figure 8. Except for one gabbro pattern (anal. 14, table 1) (fig. 8*A*), they are slightly to moderately fractionated with enriched light REE's, depleted heavy REE's, and negligible to moderate Eu anomalies, and overall abundances that increase more or less systematically with increasingly felsic compositions.

The weakly fractionated patterns of Nuf samples (fig. 8*A*; K.S. Kellogg, unpub. data) are similar to those of calc-alkaline suites (Jakeš and Gill, 1970; Arth, 1981). Thus, the REE's do not appear to reflect the tholeiitic character suggested in the AFM diagram. The reason for this not clear. The Nuf patterns, nevertheless, are less fractionated than basaltic Halaban samples of Dodge and others (1979). Two gabbro-pyroxenite patterns (fig. 8*A*) show generally similar REE abundances to those of the Nuf basalts. The negative Eu anomaly suggests a plagioclase residue,

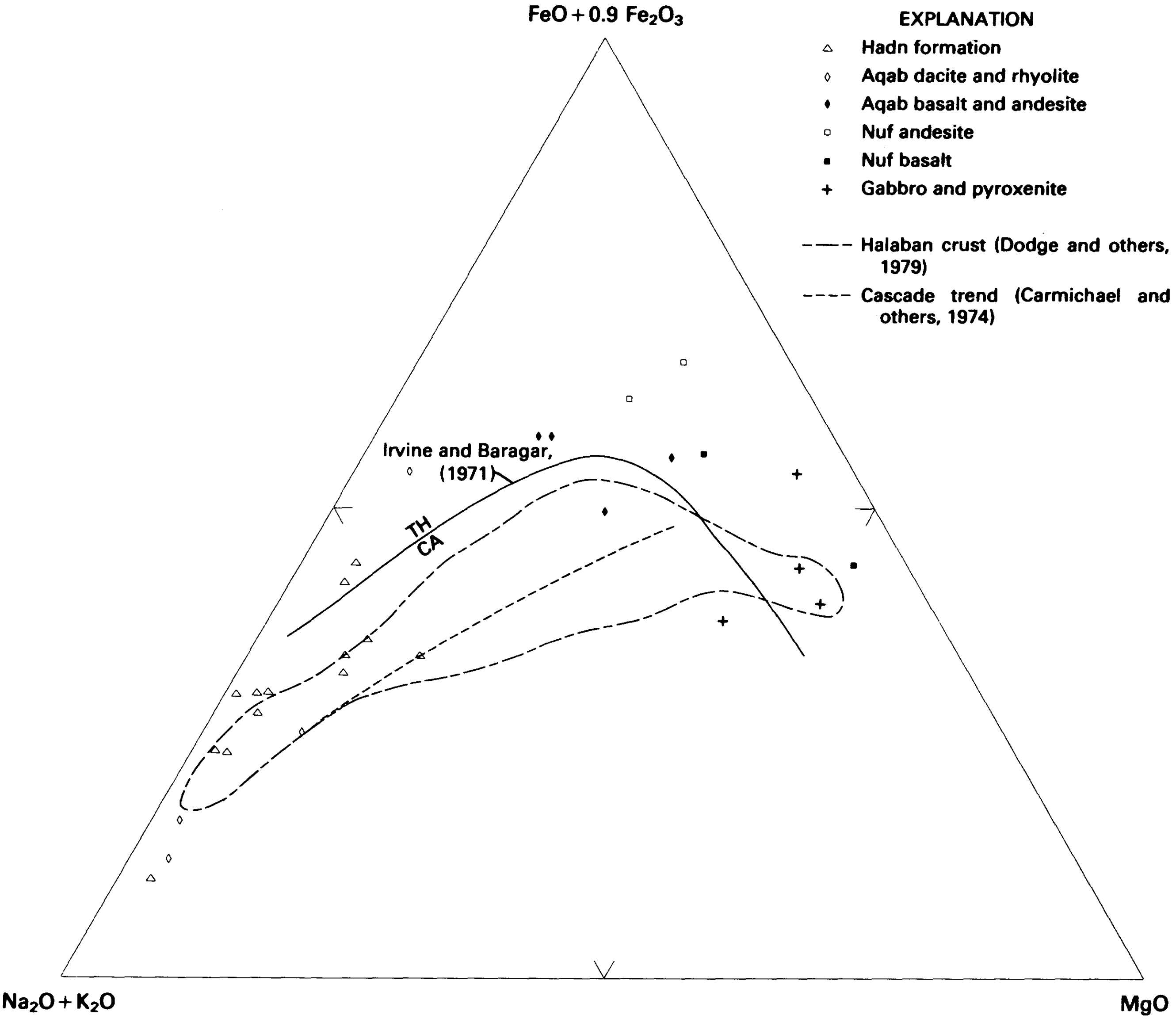


Figure 4. AFM diagram of Nuf, Aqab, and Hadn formations, and mafic intrusives. TH, tholeiitic field; CA, calc-alkaline field.

whereas the moderate fractionation of heavy REE's is compatible with a residue of hornblende (Hanson, 1978, fig. 5). The very distinctive remaining pattern (fig. 8*A*, no. 14), a gabbro containing olivine, biotite, augite, and (primary?) hornblende as mafic phases, suggests a plagioclase cumulate and a residue containing garnet.

Aqab patterns of mafic flow rocks (nos. 9–11, fig. 8*B*) are very uniform, moderately fractionated, and show negligible to small negative Eu anomalies. The pattern for sample no. 8, a dacitic tuff, shows somewhat greater fractionation of light REE's and a more conspicuous negative Eu anomaly, both consistent with its relatively more silicic and alkalic character, although the overall REE abundances are comparable with those of the mafic samples.

The Hadn patterns (fig. 8*C*) show an overall greater degree of enrichment and related fractionation than the Aqab samples; they are generally comparable with the upper, rhyolitic to dacitic part of the Halaban group (Arfan Formation) (Hadley, 1976; Dodge and others, 1979, fig. 5).

DISCUSSION

Since the inception of modern studies of the Arabian Shield, it has been interpreted in progressively complex and detailed models as the product of accretion of a sequence of late Proterozoic island arcs, culminating in a collision with the African plate during the Pan African orogeny (approx. 550–650 Ma B.P.) (Greenwood and others, 1976; Schmidt and others, 1979; Greenwood and others, 1980; Fleck and others, 1980; Greenwood and others, 1982; Duyverman and others, 1982; Stoeser and others, 1984; Camp, 1984). The

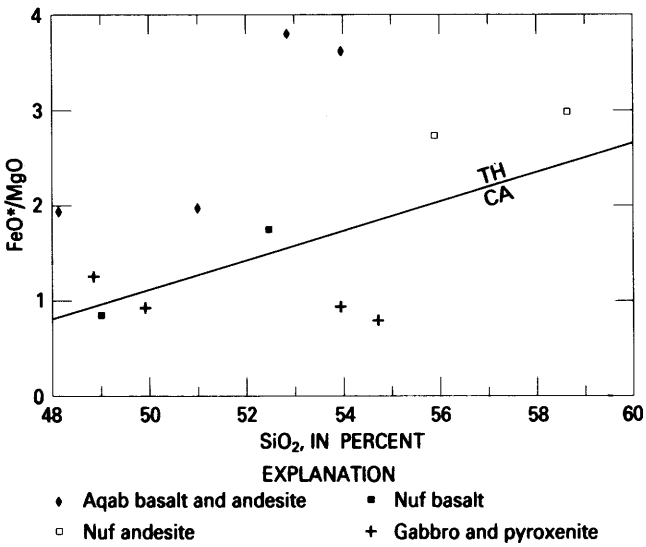


Figure 5. FeO^*/MgO-SiO_2 plot of mafic rocks only (after Miyashiro, 1974). FeO^*, total iron as FeO; TH, tholeiitic field; CA, calc-alkaline field.

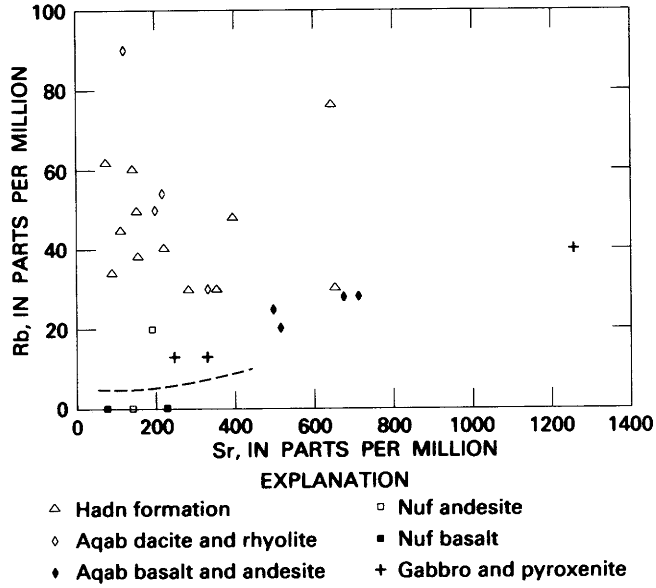


Figure 7. Plot of Rb against Sr. Dashed line separates Nuf and Aqab samples.

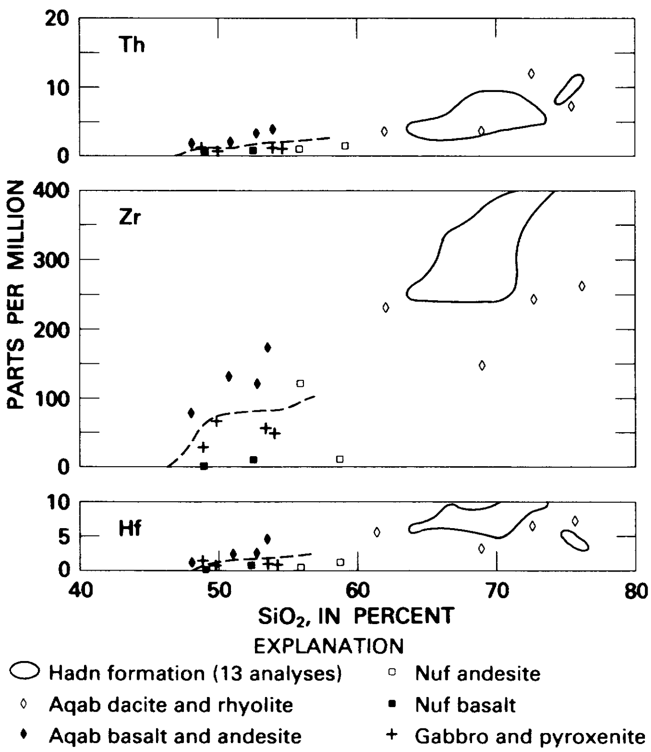
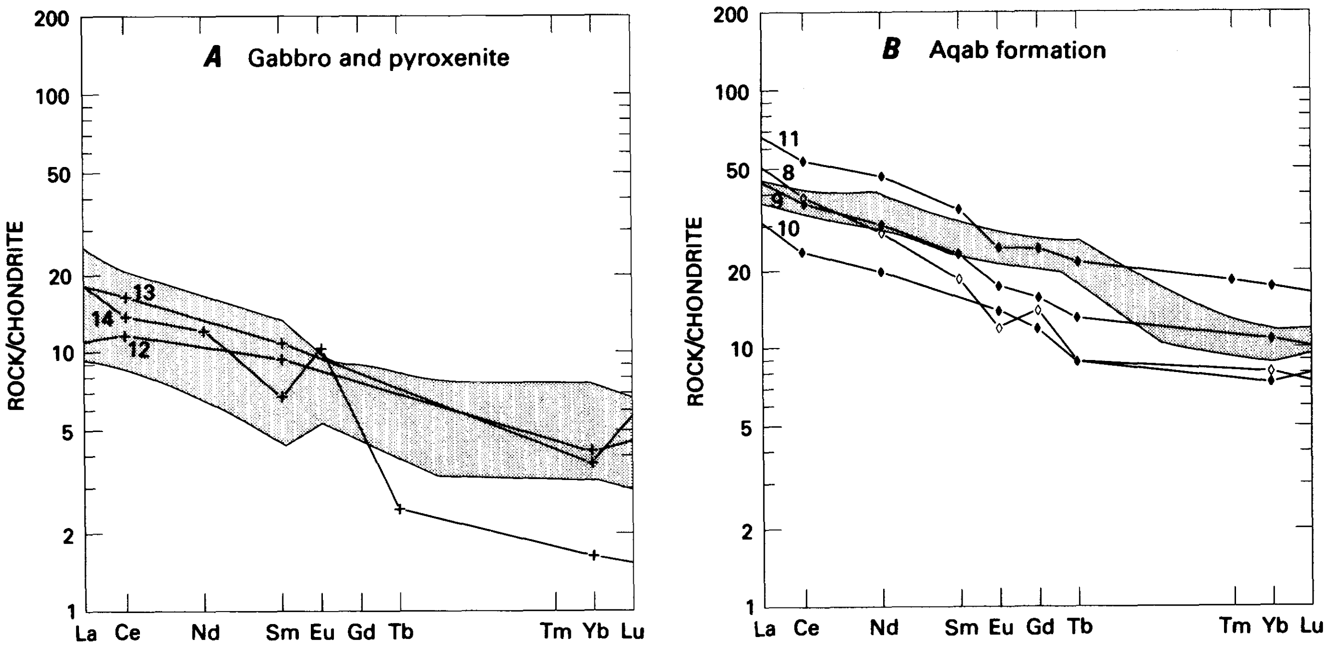


Figure 6. Plot of Th, Zr, and Hf against SiO_2. Dashed lines separate most Nuf from Aqab samples (see text).

most recent formulation (Stoeser and Camp, 1985) postulates the accretion of several microplates, three of ensimatic island-arc affinity and two of continental affinity. The region under discussion falls within the so-called Nabitah orogenic belt, which separates sialic basement to the east from ensimatic island-arc terranes to the west. A different interpretation of the evolution of the shield postulates alternating rifting and compression without subduction (Kemp and others, 1982).

Recent lead-isotope studies (Stacey and Stoeser, 1983) confirm that most of the western shield, correlated with island-arc terranes of Halaban and older age and including the present study area, is derived from oceanic crust and mantle. An oceanic-crustal source was independently postulated by Dodge and others (1979) for rocks of the Halaban group (Juqjuq and Arfan formations) in the Bi'r Juqjuq quadrangle (Hadley, 1976) in the southeastern part of the shield on the basis of geochemical and Sr-isotope data. As indicated earlier, the Halaban (now regarded as equivalent to Hulayfah) is here provisionally correlated with the Aqab and Nuf formations on the basis of lithology and stratigraphic position, although a spatial separation of about 700 km between the Bi'r Juqjuq area and the present study area, as well as discrepancies in reported radiometric ages[3], makes such a correlation rather tentative. Comparison of the

[3]Stoeser and others (1984) cite an Rb-Sr whole-rock isochron age range of 680–800 Ma for the Halaban, but Darbyshire and others (1983) determined an Rb-Sr isochron age of 612 ± 22 Ma for the Juqjuq formation and 608 ± 9 Ma for the Arfan formation. These disparities are discussed by Darbyshire and others (1983). The younger ages more nearly correspond to the Hadn age range than to the heretofore accepted Halaban age.



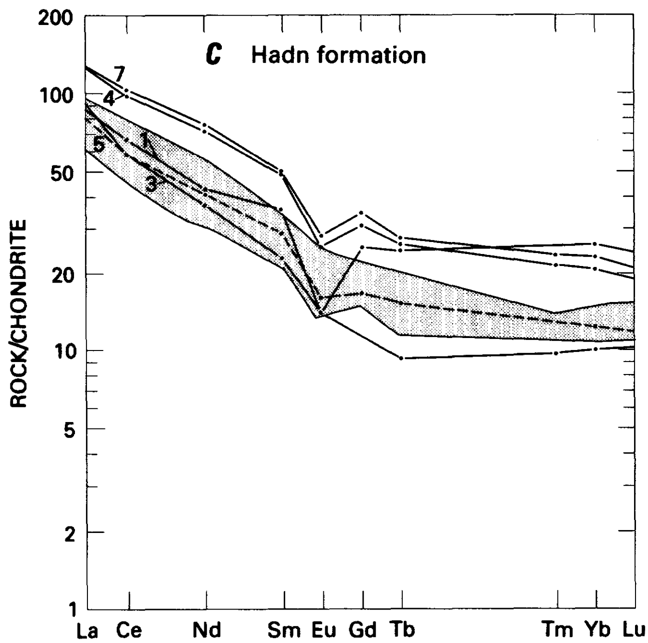


Figure 8. Rare-earth element (REE) plots for Aqab and Hadn formations and mafic plutons in the Al 'Awshaziyah quadrangle. Numbers correspond to analyses in table 1; symbols as in figure 7. *A*, Gabbro and pyroxenite; shaded field is mafic Nuf from Qufar quadrangle (K.S. Kellogg, unpub. data). *B*, Felsic and mafic Aqab; shaded field for mafic Halaban from Dodge and others, 1979. *C*, Hadn formation, with shaded Halaban field for tuffaceous rocks (Dodge and others, 1979). Patterns for analyses 2 and 6 omitted to reduce clutter.

geochemical character of the two groups of rocks is nevertheless instructive.

To the extent that data are available, the Halaban studied by Dodge and others (1979) is generally similar to the Nuf and Aqab except that basaltic rocks of the former are somewhat more alkalic than Nuf-Aqab basalts, have greater REE concentrations and somewhat more fractionated REE trends (fig. 8), and the Halaban suite as a whole shows a somewhat more pronounced calc-alkaline trend than the Nuf and Aqab (fig. 4). The geochemistry is compatible with that of a relatively evolved island-arc assemblage. An oceanic crustal source for the Halaban is postulated mainly on the basis of relatively low ^{87}Sr initial ratios (0.7018 for andesite and 0.7028 for alkali basalt) (Dodge and others, 1979). Sr-isotope data have not been determined for the Nuf and Aqab.

The upper, rhyolitic part of the Arfan formation yielded an $^{87}Sr_0$ of 0.7045 to Dodge and others (1979), and was assumed by them to reflect a distinct, probably continental-crustal source. Such an interpretation also appears most reasonable, albeit speculative, for the Hadn as well as for the ash flows in the upper part of the Aqab and Nuf. Other considerations that must be taken into account in any evaluation of the Nuf, Aqab, and Hadn include the differences in depositional environments of the Nuf (marine) and Aqab (nearshore to subaerial); the lower incompatible-element abundances, lower K/Rb, and higher Na_2O/K_2O in the Nuf relative to the Aqab and Hadn (table 2) that may reflect these distinct environments; dominantly calc-alkaline trends for all the volcanics but particularly for the Aqab and Hadn as indicated by REE plots and a discrimination plot utilizing Th, Ta, and Hf (fig. 9); and the orogenic character of the mafic volcanic rocks (figs. 10–11). The latter two plots indicate a possibly significant distinction between the volcanic and the gabbroic rocks, suggesting enriched type mid-ocean ridge basalt (E-MORB) affinity of the latter. In the absence of more

Table 2. Summary of trace-element abundances in the Hadn, Aqab, and Nuf formations and in mafic intrusives of the Al 'Awshaziyah quadrangle compared to island-arc abundances
[( ), doubtful value; --, not available; elements except potassium are in parts per million]

Element/ratio	Hadn (Average of 13)	Aqab		Nuf	Gabbro and pyroxenite (Average of 4)	Basalt	
		Felsic (Average of 4)	Mafic (Average of 4)	Mafic (Average of 4)		Island-arc tholeiites	Calc-alkaline[1]
K_2O (percent)	2.80	2.72	0.92	0.44	0.33	0.4	1
Na_2O/K_2O	1.84	2.05	3.92	4.59	6.71	4–6	2–3
Rb	52	56	32	(5)	9	5	10
Sr	257	216	471	158	544	200	340
Ba	978	722	454	--	89	75	115
K/Rb	518	420	414	(363)	177	1000	340
Rb/Sr	.20	.26	.07	(.05)	.02	.02	.03
Th	6.2	6.5	2.4	.7	.6	.5	1.1
Zr	292	147	124	(10)	50	70	100
Hf	7.2	5.7	2.8	.8	.7	1.0	2.6
Zr/Hf	40	26	44	(12)	71	70	39
Ta	.7	.3	.3	--	.3	--	--
Y	37	22	26	--	13	--	20
Sc	6.9	7.2	29.5	--	(50)	--	--
U	2.2	1.9	.2	.3	.5	.15	.2
La	32	28	16	4.8	6.7	1.1	9.6
Yb	5.9	3.6	3.3	1.1	1.2	1.4	2.7
La/Yb	5.4	7.8	4.8	4.4	5.6	1.0	3.5

[1]Jakeš and White, 1971.

data, possible differences in paleotectonic setting cannot be evaluated. However, inasmuch as these gabbros very likely represent cumulate and not primary magmas, trace-element differences such as low La (fig. 11) relative to more feldspathic rocks are to be expected. Moreover, the source of the gabbro may have been different from that of the mafic volcanics.

Regarding the volcanic rocks, the following tentative conclusions may be drawn from the available data. The Nuf and Aqab represent an island-arc assemblage generated from oceanic or transitional crust. The Nuf reflects a marine environment, and its source was somewhat depleted in large-ion lithophile elements while the Aqab was erupted from relatively more enriched crust in a nearshore to emergent part of the same arc. The felsic upper parts of the Aqab and Nuf formations could reflect a sialic continental source, based on their chemistry, although the origin of such crust 740 Ma B.P. is uncertain. The Hadn formation more probably reflects a continental crustal source. Sr- and Pb-isotope data could help to clarify this point.

Eruption of the Hadn-equivalent Shammar group has been generally attributed to renewed igneous activity, beginning about 650 Ma B.P., and related to collision between the Arabian and African cratons (Schmidt and others, 1979; Greenwood and others, 1980); or, in the most recent interpretation, collision between the continental Afif terrane with western arc terranes along the Nabitah mobile belt after about 680 Ma B.P. (Stoeser and Camp, 1985). The data presented here do not seem to contradict such a model. In summary, field relations and geochemistry of late Proterozoic volcanics in the northernmost Arabian Shield appear to reflect on a local scale the sequence of island-arc accretion culminating in Pan-African continental collision envisaged for the shield as a whole.

APPENDIX: PETROGRAPHIC DESCRIPTIONS OF ANALYZED SAMPLES

Numbers keyed to table 1.

1. Field number 185234;[1] south edge of prominent plateau representing distal part of Hadn formation. Gray-brown porphyritic rhyolite[2] consisting of 15 percent tabular, cloudy and slightly sericitized 1 to 2 mm plagioclase (An_5)[3] phenocrysts, locally in glomeroporphyritic aggregates with deep green, partly chloritized hornblende. Groundmass consists of equigranular aggregate of quartz, slightly cloudy plagioclase, sanidine, and scattered (3 percent) opaque material.

[1]All field data for this report, including a sample location map, are stored in data file USGS–DF–04–03 in the Jiddah office of the U.S. Geological Survey Saudi Arabian mission. A sample location map is also available from the author by request.

[2]Samples 1 through 7 have compositions generally ranging from rhyolite to rhyodacite.

[3]Based on extinction angles measured on the flat stage, where possible in the zone ⊥(010) and (100).

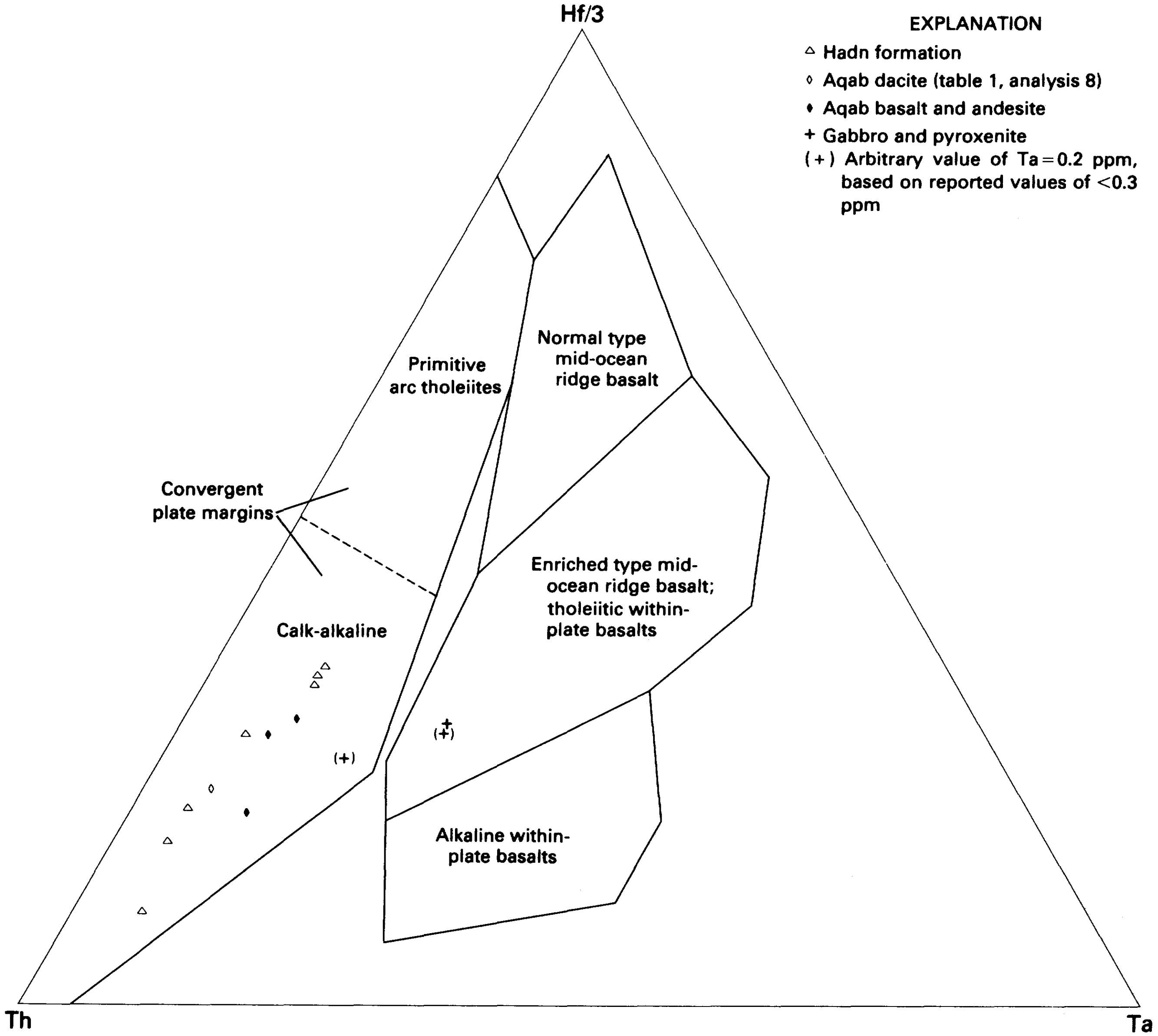


Figure 9. Th-Ta-Hf/3 paleotectonic discrimination diagram (Wood, 1980) of volcanic rocks and mafic intrusives from the Al Awshaziyah quadrangle. Data for samples from Qufar quadrangle not available.

2. Field number 185376; Hadn formation, top of 265 m (vertical) exposure of nearly continuous ash-flow tuffs. Dark-gray, aphanitic felsic ash-flow tuff consisting dominantly of a cryptocrystalline, moderately devitrified groundmass showing weakly developed eutaxitic texture. Small angular quartz and feldspar crystals, mostly filling vesicles, and sparse felsic rock fragments constitute 5 percent. Dusty disseminated opaque material is the only mafic constituent.
3. Field number 185380; Hadn formation, estimated 200 m stratigraphically below preceding sample. Red-brown, moderately sorted (fragments <3 mm) ash-flow tuff consisting of angular fragments of quartz plagioclase and various felsic volcanic rocks in a matrix of more or less devitrified shards and nearly unaltered glass that define a well-developed eutaxitic texture. The clastic constituents range from unaltered to moderately altered. The deep red color is probably due to disseminated hematite.
4. Field number 185417; Hadn formation, northern part of Al 'Awshaziyah eruptive center. Red-brown ash-flow tuff, strongly eutaxitic texture. Consists of cryptocrystalline, barely devitrified groundmass (coarser crystallization along flow planes) and 20 percent fresh to slightly altered plagioclase (An_{0-10}) and subordinate sanidine. Mafic silicates are absent. Sparse dusty disseminated hematite and scattered clumps of magnetite. Visible alteration is minimal.
5. Field number 185076-2; top of prominent plateau of no. 1, distal part of Hadn formation. Moderately sorted tuffaceous sandstone in a sequence of tuffs, ignimbrites, and volcanic

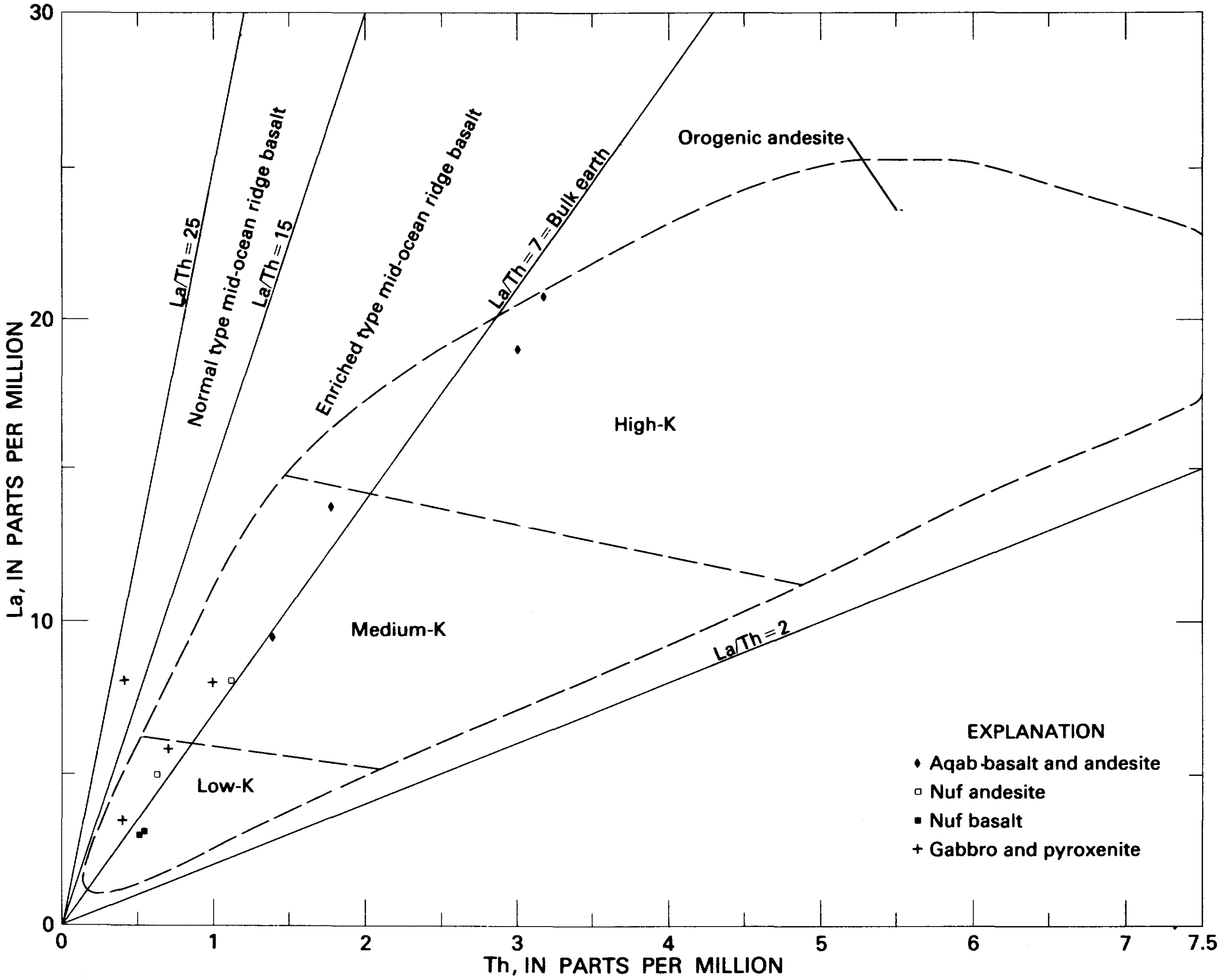


Figure 10. La/Th diagram for mafic volcanics and intrusives (Gill, 1981).

sediments. Consists of angular to rounded volcanic-rock fragments, fresh to moderately altered plagioclase, quartz, and subordinate sanidine. Estimated 3 percent secondary chlorite and epidote, and 1 percent disseminated magnetite.

6. Field number 185130; Hadn formation, near center of Al 'Awshaziyah eruptive center. Red-brown, little altered ash-flow tuff with well-developed eutaxitic texture. Consists of barely devitrified glass, more sparsely devitrified along flow planes and cross fractures. Contains 5 percent subrounded rock fragments, plagioclase (An_3), and quartz. Strong red reflection from disseminated hematite(?).

7. Field number 185391; Hadn formation, ridge east of eruptive center. Orange-brown flow or tuff with a holocrystalline matrix consisting mostly of plagioclase laths (little alkali feldspar identified) and 7 percent moderately sericitized plagioclase (An_5) phenocrysts, interstitial chlorite-epidote aggregates, disseminated amorphous and (or) opaque material, and <1 percent secondary carbonate.

8. Field number 185055; Aqab formation, dacite-rhyolite member. Well-sorted, tuffaceous sandstone in sequence of tuffs and flows. Consists of plagioclase (An_{0-5}), quartz, and subordinate sanidine, and rock fragments in a cryptocrystalline, partly amorphous matrix. Matrix and rock fragments are moderately to strongly sericitized and chloritized. The plagioclase clasts are slightly to moderately altered. About 2 percent disseminated opaques.

9. Field number 185254; Aqab formation, basalt-andesite member. Dark lava (basalt) with aphanitic groundmass and 20 percent tabular plagioclase phenocrysts. Groundmass is felted intergrowth of plagioclase laths and green metamorphic hornblende, with subordinate (<3 percent) pale brown metamorphic biotite, evenly disseminated granular opaque mineral (magnetite?), scattered rounded quartz aggregates representing vesicle fillings, and carbonate filling narrow fractures. Relict plagioclase phenocrysts are slightly to moderately saussuritized and exhibit albite twinning and relict zoning (An_{13-30}). Rock reflects upper greenschist facies.

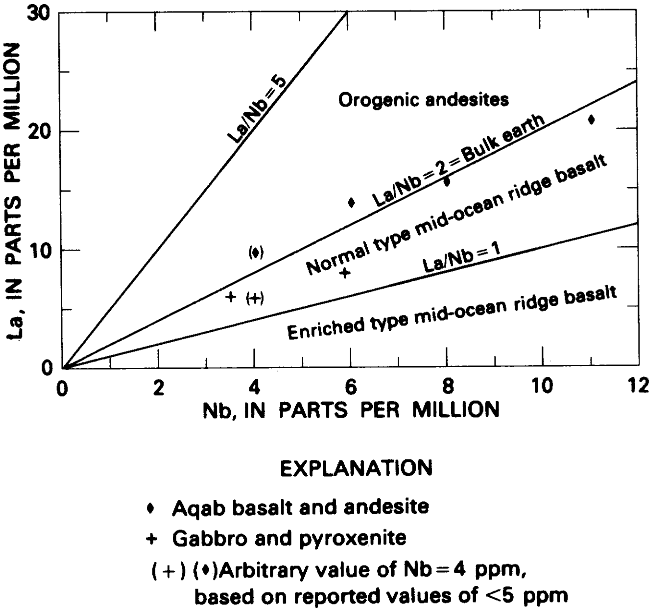


Figure 11. La/Nb diagram for mafic Aqab volcanics and intrusives (Gill, 1981). Data for Nuf samples not available.

10. Field number 185273; Aqab formation, basalt-andesite member. Dark-gray, porphyritic lava (basalt) consisting of intergranular groundmass of felted acicular plagioclase with interstitial magnetite, epidote and chlorite, and 25 percent tabular, slightly to moderately altered, calcic plagioclase phenocrysts (relict zoning An_{58-75}) and <2 percent aggregates of granular epidote and biotite. Rock reflects low greenschist facies.
11. Field number 185610; Aqab formation, basalt-andesite member. Dark-gray aphanitic nonporphyritic flow (basaltic andesite) consisting of intersertal groundmass (intergrown felted plagioclase, magnetite, chlorite and epidote) and crosscutting quartz-carbonate-epidote veins. Relict plagioclase is normally zoned An_{22-30}. Rock reflects low greenschist facies.
12. Field number 185029; rhythmically layered gabbro-pyroxenite intrusion at northern boundary of quadrangle. Greenish-black rock with aphanitic groundmass and 40 percent euhedral clinopyroxene megacrysts as much as 5 mm in diameter, fringed by actinolitic amphibole. Cryptocrystalline groundmass consists of amphibole and plagioclase(?). The abundance of pyroxene and lack of other megacrysts suggests incipient cumulate development, but clinopyroxene crystals are not in mutual contact.
13. Field number 185154; larger gabbro-pyroxenite intrusion on west side of quadrangle, similar to preceding sample. Rock is generally similar to preceding sample both texturally and compositionally, except that there is more evident plagioclase in the matrix, and replacement of clinopyroxene by actinolitic amphibole is somewhat farther advanced.
14. Field number 185540; isolated gabbro plug. Light-gray, medium-grained gabbro consisting of primary plagioclase (An_{50}), olivine, red-brown hornblende (kaersutite?), and red-brown biotite. Secondary minerals include reaction rims of bowlingite(?) and fibrous actinolitic amphibole around olivine, and pale green chlorite and magnetite replacing biotite.

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