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Geochemistry of metavolcanic rocks from the Ranyah area, Kingdom of Saudi Arabia

by

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GEOCHEMISTRY OF METAVOLCANIC ROCKS FROM

THE RANYAH AREA, KINGDOM OF SAUDI ARABIA

by

Robert C. Greene[1]/

ABSTRACT

Major-element analyses of 26 samples from seven map units of metavolcanic rocks from the Ranyah area are compared with analyses in the literature of rocks from known tectonic settings. The evidence suggests that most of the layered rocks of the Ranyah area originated in immature island arcs. The Khaniq formation originated in a continental margin setting during cratonization. The Arfan and Juqjuq formations are related to a later subduction event.

INTRODUCTION

Much recent work on the geochemistry of volcanic rocks has focused on the distinctive chemical characteristics of samples from known tectonic settings. Chemical parameters have been further utilized to deduce the probable depth, temperature, and partial-melting history required to produce lavas of known composition. Tectonic setting is well established, however, only for rocks in relatively youthful settings, because as rocks become more tectonized with increasing age, their original tectonic setting becomes less certain.

The metavolcanic rocks in western Saudi Arabia are of late Proterozoic age, and those in the Ranyah area probably between 785 and 745 Ma old. (Greene, in press, 1982a). They have undergone several periods of orogenesis and have been intruded by plutonic rocks, and their original tectonic setting is obscure. In this report, I will compare the major-element and some minor-element compositions of metavolcanic rocks from the Ranyah area to those of modern or youthful volcanic rocks of known tectonic settings. In this way, limited deductions can be made about the original tectonic setting and petrologic affinity of the Ranyah Precambrian rocks.

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Twenty-six major-element and two rare-earth-element analyses of metavolcanic rocks from the Ranyah area are presented and discussed in this paper (tables 1, 4). The analyzed rocks were collected from seven principal map units (fig. 2). Variation diagrams (figs. 5 to 12) illustrate the chemical characteristics of a suite of rocks from each unit and compare them with the chemistry of selected volcanic rocks from known tectonic settings (table 3).

Previous work on geochemistry of volcanic rocks versus tectonic setting in the Arabian Shield

Roobol and others (1983) have examined the chemistry of representative volcanic rocks from 11 volcano-sedimentary belts in the central Arabian Shield. They divide the belts into three groups based on presumed age. The oldest rocks (sequence C) are characterized by low contents of K_2O, rubidium, strontium, and TiO_2, and less distinctly, other lithophile elements. These rocks also have very high Na/K ratios. Sequence-B rocks have similar characteristics, but the range of values for the lithophile elements extends somewhat higher and Na/K ratios also extend to intermediate values. The youngest volcanic rocks (sequence A) have lithophile element contents ranging from low through inermediate to high, and similarly, a wide range of Na/K ratios. Roobol and others (1983) conclude that the "construction of the central Arabian Shield was a multi-stage evolutionary process involving the emplacement of progressively more mature lavas in a changing volcanic arc setting". By comparison with reference fields from various modern tectonic settings, they believe that sequence-C volcanic rocks were formed in immature island arcs, sequence B in more mature island arcs, and sequence A in volcanic arcs transitional to continental margins.

Roobol and others (1983) conclusions are generally similar, though different in detail, from those of the present author. The chief difficulties with their work lie in the facts that the volcano-sedimentary belts belonging to sequences A, B, and C are intermingled, not geographically separated; and, the radiometric dating upon which the sequences are based is scanty, particularly in the area south of latitude 20°30', which includes the Ranyah area.

Schmidt and Brown (in press) discuss some aspects of the chemistry of both volcanic and plutonic rocks from 13 areas scattered widely throughout the Arabian shield. They divide the rocks into a primary, andesitic assemblage of volcanic rocks intruded by a dioritic suite of plutonic rocks and a secondary, cratonization suite of rhyolitic volcanic rocks intruded by a granitic-gabbroic suite of plutonic rocks. Using the terminology of Schmidt and others (1979), the andesitic assemblage includes the Baish, Bahah, Jiddah, and Halaban groups, and the cratonization assemblage includes the Ablah, Murdama, Shammar, and Jubaylah groups. The andesitic assemblage rocks are believed to range in age from 900 to 700 Ma and the cratonization assemblage from 775 to 560 Ma. Rocks of the Samran group in the Jiddah-Rabigh area are included in the Jiddah group, and those of the Hulayfah group in the Nuqrah area (Delfour, 1977, 1980-81) are included in the Halaban group.

Na_2O-CaO-K_2O (NCK) diagrams show the compositional range of the analyzed volcanic rocks (Schmidt and Brown, in press). Baish, Bahah, and Jiddah metavolcanic rocks are very low in K_2O and range from basalt high in CaO to dacite high in Na_2O. Halaban rocks are similar but some contain more K_2O. Volcanic rocks of the cratonization assemblage show a trend (not in chronological order) from low K_2O andesite to high K_2O rhyolite. (Na_2O+K_2O) - FeO* - MgO (AFM) diagrams show that the andesitic assemblage rocks are mostly calc-alkaline and resemble in composition ones from the Aleutian Islands and the Cascade Mountains; however, some basalts are tholeiitic. Cratonization assemblage rocks are also mostly calc-alkaline.

Plots of total alkalis (Na_2O + K_2O) vs. SiO_2 for the Baish, Bahah, and Jiddah group rocks show that the dacite and rhyolite fall in the tholeiitic field of Kuno (1966) and basalt and andesite in tholeiitic, high-alumina, and alkalic fields (Schmidt and Brown, in press). Halaban group rocks are scattered throughout all fields. Cratonization assemblage rocks are also scattered, with Murdama, silicic Shammar, and Jubaylah rocks ranging to distinctly alkalic.

Schmidt and Brown (in press) conclude that the andesitic rocks originated in intra-oceanic volcanic-magmati arcs. As the crust thickened, successively younger rocks became more mature in composition. Cratonization occurred during a major collisional or culminant orogeny after about 660 Ma and the cratonization assemblage rocks were formed. These rocks are both volcanic and plutonic and range from calc-alkaline to alkalic.

Dodge and others (1979) discuss the geochemistry of 39 samples of lavas and pyroclastic rocks of the Arfan and Juqjuq formations (Halaban group of Schmidt and others, 1979) in the Bir Juqjuq quadrangle, which lies directly east of the study area of this report. The rocks range in composition from basalt with 50 percent SiO_2 to rhyolite with 75 percent; however, the majority are basaltic andesite and andesite containing 52 to 63 percent SiO_2. Silica variation diagrams show smooth trends for MgO, FeO*, and CaO, but considerable scatter for Al_2O_3, Na_2O, K_2O, and TiO_2. Likewise, the analyses show considerable scatter of the total alkalis (Na_2O+K_2O) versus silica diagram, but the majority fall in the alkali and high-alumina fields of Kuno (1966).

Rare-earth-element patterns show considerable fractionation, and are similar to those of calc-alkaline and alkaline rocks of island arcs. Dodge and others (1979) conclude that the trends on the major-element variation diagrams and particularly on the AFM diagram resemble those of alkaline island arc rocks and that of the Cascade Mountains.

Location and geologic mapping

The term "Ranyah area", as used in this report, refers to the Ranyah and Jabal Dalfa 30-minute quadrangles, lat 21° to 21°30' N., long 42°30' to 43°30' E. (figs. 1, 2). These quadrangles have been geologically mapped by the author (Greene, in press, 1982a). Adjacent quadrangles to the east, west, and south have been mapped by the author and other geologists of the U.S. Geological Survey. Those to the north have been mapped by geologists of the Saudi Arabian Directorate General of Mineral Resources.

Geology of the Ranyah area and units sampled

The geology of the Ranyah area is shown in a generalized geologic map (fig. 2). The oldest rocks consist of hornblende and plagioclase gneisses (map unit gn) which outcrop in the northeast and east-central parts of the area. These are followed by the principal units of layered rocks, the Dighan, Rawdah, Jabal Silli, Jabal Dalfa, Shithr, and Umm Shat formations, which consist of a wide variety of metavolcanic and metasedimentary rocks, but with metabasalt and meta-andesite most abundant (fig. 2). From the Rawdah formation, a metabasalt, a meta-andesite, and a metadacite were analyzed for this report. From the Jabal Silli formation, three metabasalts and a rhyolite were analyzed. From the Jabal Dalfa formation came two metabasalts and from the Shithr formation two metabasalts, two metabasaltic andesites, and one rhyolite. Lastly from this group, a metabasalt, a metabasaltic andesite, and a rhyolite from the Umm Shat formation were analyzed.

A major episode of gneiss intrusion and doming represented by the Shaib Hadhaq gneiss followed eruption and deposition of the layered rocks. The older plutonic rocks of the Jabal Dalfa quadrangle were also intruded at abut this time. The Urayyiq member of the Shaib Hadhaq gneiss contains abundant residual blocks of metabasalt, and two samples of this rock type were analyzed for this report. The gneiss-doming event, representing the culminative orogeny in this area (Schmidt and others, 1978; Schmidt and Brown, in press, was followed by intrusion of the Al Jizah granite in the Ranyah quadrangle, the younger granitic rocks of the Jabal Dalfa

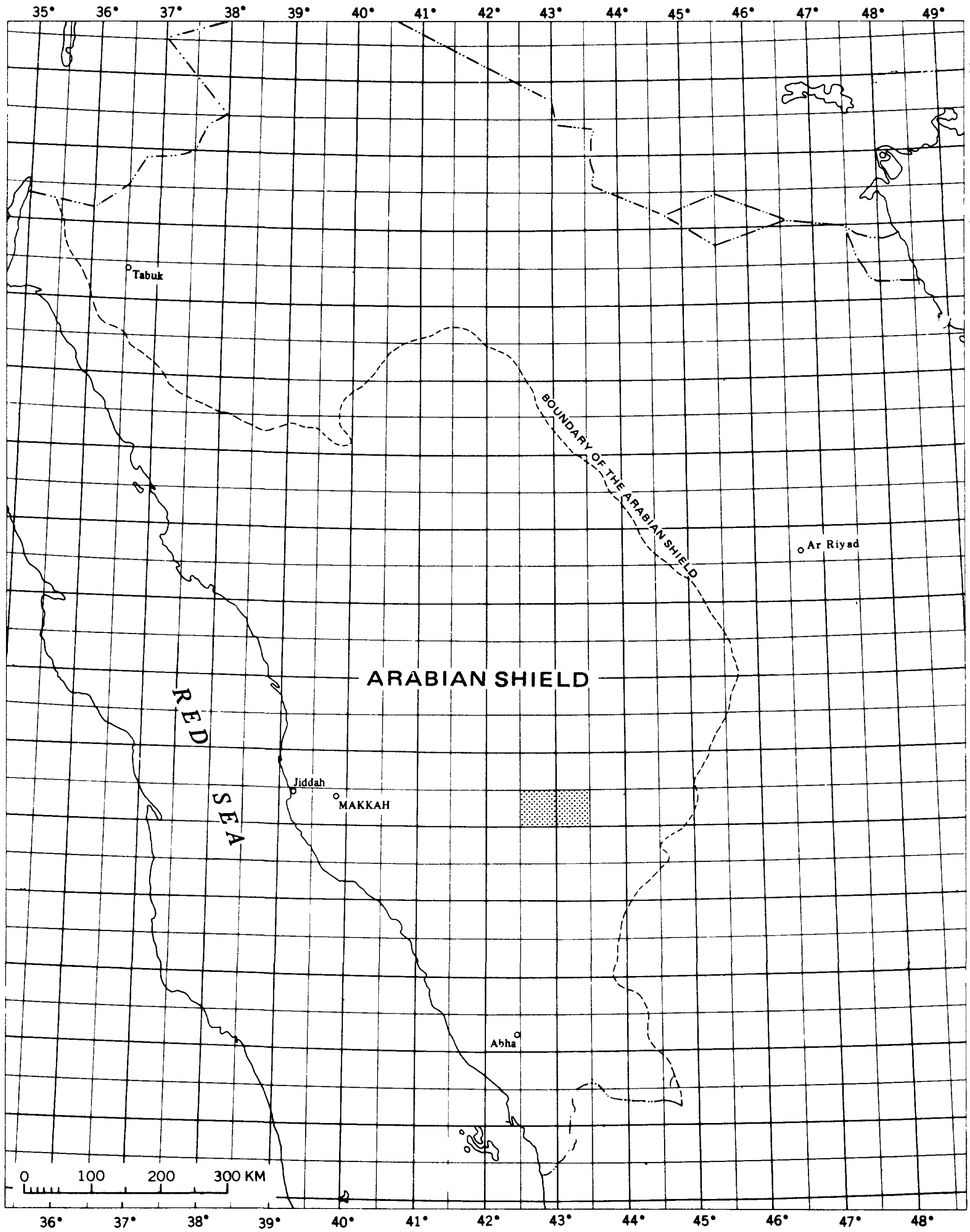

Figure 1.--Index map of western Saudi Arabia showing the location of the Ranyah and Jabal Dalfa quadrangles.

EXPLANATION

QTb

Basalt flows

Plutonic and hypabyssal intrusive rocks

bgr	sp

bgr, Kwar Barahah granite, includes porphyritic member and Ar Ruzayzah granite
sp, serpentinite, locally includes other ultramafic rocks

sgr

Jabal Suily granite, includes fine-grained member

gab

Gabbro

jgr	ygr

jgr, Al Jizah granite. ygr, younger granitic rock units of Jabal Dalfa quadrangle

hgn	hu	ogd

hgn, Shaib Hadhaq gneiss, includes biotite tonalite
hu, Shaib Hadhaq gneiss, Urayyiq member
ogd, older plutonic rocks of Jabal Dalfa quadrangle

gn

Gneiss

Metavolcanic and metasedimentary rocks

msg	
kv	ar

msg, Murdama formation-siltstone and gneiss
kv, Khaniq formation-rhyolite and minor mafic volcanic rocks
ar, Arfan formation-metavolcanic and metasedimentary rocks

ds	rmb	sm	sc	db	sb	usv	smb

ds, Dighan formation-metasiltstone, granulite, schist
rmb, Rawdah formation-metabasalt and meta-andesite, includes chert member
sm, Jabal Silli formation-metabasalt
sc, Jabal Silli formation-metabasalt and carbonate member
db, Jabal Dalfa formation-metabasalt includes sedimentary member
sb, Shithr formation-metabasalt and meta-andesite, includes amphibolite and conglomerate members
usv, Umm Shat formation-metabasalt and meta-andesite, includes rhyolite member
smb, Umm Shat formation-marble and metabasalt member

— — — CONTACT

——— FAULT

X LOCATION OF ANALYZED SAMPLE

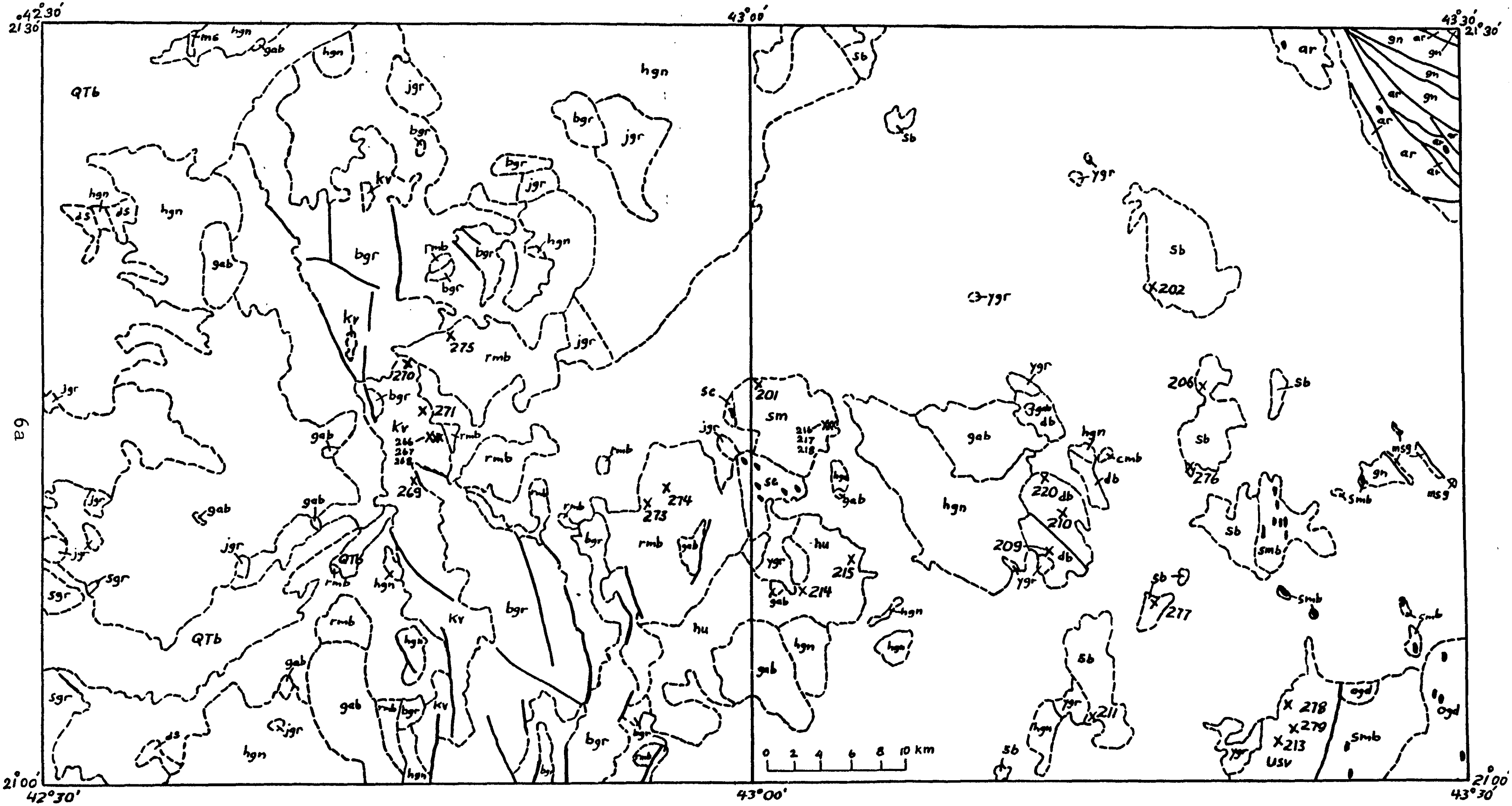

Figure 2.--Generalized geologic map of the Ranyah and Jabal Dalfa quadrangles.

Table 1.--**Major element analyses of 26 metavolcanic rocks from the Ranyah area**

[Samples 138266-279 analyzed by X-ray Assay Laboratories, Limited, Don Mills, Ontario; FeO measured by wet-chemical analysis; all other elements including total iron as Fe_2O_3 by X-ray fluorescence. Samples 138201-220 analyzed by Directorate General of Mineral Resources-U.S. Geological Survey laboratory, Jiddah; analyses by colorimetric, atomic absorption, and volumetric methods. Original data are shown in this table; they have been recalculated to 100 percent water-free before plotting in variation diagrams]

	Khaniq formation						Rawdah formation		
Sample number	138266	138267	138268	138269	138270	138271	138273	138274	138275
SiO_2	49.30	73.50	74.60	53.40	69.20	75.30	62.60	56.70	48.70
Al_2O_3	16.50	13.10	12.10	17.40	14.30	12.30	14.70	16.50	18.00
Fe_2O_3	3.78	1.00	1.05	2.62	1.30	1.27	2.58	1.81	4.96
FeO	4.10	0.40	0.90	4.80	1.50	0.50	4.50	5.80	5.40
MgO	5.96	.27	.26	3.56	0.44	.12	1.68	1.78	4.98
CaO	8.62	1.12	.38	7.60	1.64	.27	6.78	8.29	12.30
Na_2O	3.41	4.27	3.93	3.61	4.36	4.28	2.84	2.57	1.21
K_2O	1.38	3.22	4.41	1.14	3.24	3.61	1.35	1.62	0.23
H_2O	3.54	1.23	.47	2.08	1.85	.47	1.23	2.62	2.69
TiO_2	1.08	.07	.12	1.25	.21	.09	0.89	0.86	.66
P_2O_5	0.32	.01	.01	0.28	.04		.15	.15	.14
MnO	.13	.05	.03	.11	.08	.02	.16	.14	.18
Total (-O)	98.12	98.24	98.26	97.85	98.16	98.23	99.46	98.84	99.45

	Shithr formation					Jabal Silli formation			
Sample number	138276	138277	138202	138206	138211	138201	138216	138217	138218
SiO_2	70.10	51.80	48.20	49.80	53.40	49.70	73.00	48.40	50.30
Al_2O_3	13.00	17.20	20.80	19.30	14.20	14.80	13.10	19.40	15.20
Fe_2O_3	1.82	3.84	5.11	3.78	4.59	6.20	1.86	3.03	5.39
FeO	3.00	7.60	5.04	4.88	7.84	7.50	1.39	4.74	7.30
MgO	0.56	4.28	3.95	3.92	4.32	5.78	0.49	3.85	4.71
CaO	3.35	8.60	14.04	13.88	7.95	10.30	1.32	16.50	7.80
Na_2O	4.44	3.22	0.45	1.07	3.50	3.37	5.20	1.75	3.69
K_2O	.73	0.59	.24	0.17	0.34	0.21	1.92	0.16	0.66
H_2O	.77	.77	1.09	1.57	1.03	1.30	1.02	1.17	1.66
TiO_2	.35	1.24	.80	.91	2.51	1.02	.19	.47	2.75
P_2O_5	.08	.31	.05	.06	.15	.05	.01	.01	.21
MnO	.12	.19	.18	.16	.19	.19	.06	.16	.17
Total	98.32	99.64	99.95	99.50	100.02	100.42	99.56	99.64	99.84

Table 1.--Major element analyses of 26 metavolcanic rocks from the Ranyah area-Continued

	Umm Shat formation			Jabal Dalfa formation			Urayyiq member of Shaib Hadhaq gneiss	
Sample number	138278	138279	138213	138209	138210	138220	138214	138215
SiO_2	76.00	52.80	49.90	44.70	48.30	44.60	48.00	47.70
Al_2O_3	11.40	15.90	17.80	19.20	17.90	17.90	18.50	17.90
Fe_2O_3	1.84	4.06	4.33	3.61	3.24	5.29	5.51	8.06
FeO	0.40	7.40	5.46	7.62	4.46	6.40	4.29	5.07
MgO	.20	6.29	4.95	6.26	5.28	4.65	4.81	4.51
CaO	.48	7.32	12.16	15.30	18.11	16.23	15.30	12.60
Na_2O	4.72	2.52	1.87	1.36	0.98	1.42	1.67	2.04
K_2O	1.87	0.25	0.21	0.12	.13	0.18	0.31	0.14
H_2O	1.23	3.62	1.64	.85	.80	2.06	1.12	.95
TiO_2	.16	.36	1.08	.48	.23	.69	.45	1.01
P_2O_5	.03	.04	.05	.01	.01	.02	.01	.08
MnO	.03	.13	.16	.15	.12	.17	.11	.18
Total	98.36	100.69	99.61	99.66	99.56	99.61	100.08	100.24

quadrangle, and gabbro.

The next principal event was the eruption of the volcanic rocks of the Khaniq formation, which consists of rhyolite with minor mafic volcanic rocks. Six samples --four rhyolites, a meta-andesite and a metabasaltic andesite --were analyzed for this report. Metavolcanic and metasedimentary rocks of the Arfan formation (northeast corner of the area and adjacent Juqjuq quadrangle) have recently been shown to be almost contemporaneous with the Khaniq formation (Darbyshire and others, 1983). A small amount of siltstone and cataclastic gneiss of the Murdama formation form the youngest layered rocks in the area.

Post-tectonic granites include the Jabal Suily and Kwar Barahah granites, the latter co-magmatic with the volcanic rocks of the Khaniq formation. Serpentinite has been intruded in the Nabitah fault zone (southeast part of the area), and along Najd faults (northeast and central parts).

Rock nomenclature

Rock names for metavolcanic rocks are difficult to assign, and several classifications have been considered for this report. The mineral compositions of the metavolcanic rocks (table 2) studied for this report only in part resemble those of the volcanic rocks from which they were derived. The rocks have been metamorphosed, mostly to greenschist facies, so that the rock nomenclature scheme used is based on the chemistry of the rocks where analyses are available. The Rittmann nomenclature scheme for analyzed rocks (Rittmann, 1952, p. 93-102) gives usable names for many rocks, but Rittmann's rock names such as rhyodacite and quartz latite which are based on K_2O, Na_2O, and Al_2O_3 contents, are meaningful only if the parameters defining them are fully explained. Moreover, rock names involving minerals, such as andesine basalt and olivine andesite are used in the Rittmann nomenclature, and these may not reflect the actual mineralogy, especially in metamorphosed rocks. Therefore, the Rittmann nomenclature was rejected.

The Irvine and Barrager (1971) scheme has become popular, in part because it classifies volcanic rocks into series that have some genetic meaning. However, applying this scheme to rocks from the Ranyah area did not work well, and was rejected because rocks containing 52 to as much as 59 percent SiO_2 are classified thereby as basalt, apparently owing to relatively low Na_2O content.

The author has settled for the simple classification shown in Carmichael, Turner, and Verhoogen (1974, p. 557), which is as follows: less than 52 percent SiO_2, basalt; 52 to 55 percent SiO_2, basaltic andesite; 55 to 63 percent

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks

[Leader indicate not present; tr, trace; p, phenocrysts; g, ground mass; x, present]

	Quartz	K-feldspar	Plagio-clase	Actin-olite	Chlorite	Clino-pyroxene	Epidote	Calcite	Opaque minerals	Micro-felsite	Location and description
					Khaniq formation						
Sample number: 138266 Field number: RD 96-12 Rock type: Metabasaltic andesite	-	-	80	-	3	15	-	tr	2	-	Section, 1 km NW of Harf. Dark greenish gray, slightly mottled, medium, even grain, intergranular texture
Sample number: 138267 Field number: RD 96-13 Rock type: Rhyolite	-	-	p-tr	-	-	-	-	tr	-	100	Olive gray, irregular lighter mottle, micrograined, irregular, recrystallized(?) texture, local alinement
Sample number: 138268 Field number: RD 96-14 Rock type: Rhyolite	p-tr g-25	p-tr g-75	-	1	-	-	-	tr	tr	-	Brownish gray, even, aphanitic groundmass with pink micro-phenocrysts
Sample number: 138269 Field number: RD 280A Rock type: Meta-andesite	-	-	p-20 g-50	30	-	-	-	-	-	-	Al Khaniq water gap. Dark greenish gray, even aphanitic groundmass with plagioclase phenocrysts to 3 mm, intergranular with some flow alinement
Sample number: 138270 Field number: RD 585A Rock type: Rhyolite	28	-	70	2	-	-	-	tr	tr	-	7 km NW of Harf. Brownish gray, even, micrograined, euhedral plagioclase microlites
Sample number: 138271 Field number: RD 588A Rock type: Rhyolite	p-1	-	p-1	-	-	-	tr	-	tr	98	

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks-Continued

	Quartz	Plagio-clase	Horn-blende	Clino-pyroxene	Ortho-pyroxene	Opaque minerals	Location and description
				Urayyiq member of Shaib Hadhaq gneiss			
Sample number: 138214 Field number: RD-818 Rock type: Metabasalt	-	40	60	-	-	tr	Flats south of Jabal ash Shayal. Dark gray, fine grained, irregular foliation
Sample number: 138215 Field number: RD-829-2 Rock type: Metabasalt	1	70	tr	20	5	3	Flats east of Jabal ash Shayal. Dark gray, micrograined, uniform

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks-Continued

	Quartz	Plagio-clase	Actin-olite	Biotite	Epidote	Calcite	Opaque minerals	Microcrys-talline groundmass	Location and description
					Rawdah formation				
Sample number: 138273 Field number: RD-106A Rock type: Metadacite	-	p-tr	-	-	-	tr	tr	100	10 km SE of Rawdah. Mottled dark gray to black, aphanitic, texture fragmental- replacement
Sample number: 138274 Field number: RD-109A Rock type: Meta-andesite	p-1	p-15	x	x	-	tr	-	85	10 km SE of Rawdah, 2 km NE of 106. Medium dark gray, micrograined, even, micro-texture fragmental
Sample number: 138275 Field number: RD-600A Rock type: metabasalt	-	x	x	-	x	-	x	100	8 km NW of Rawdah. Dark greenish gray, mottled with slightly lighter and darker colors, medium grained, texture fragmental - replacement

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks-Continued

	Quartz	K-feldspar	Plagio-clase	Horn-blende	Clorite	Biotite	Clino-pyroxene	Sphene	Opaque Minerals	Location and description
					Jabal Silli formation					
Sample number: 138201 Field number: RD-625-2 Rock type: Metabasalt	-	-	40	60	-	-	-	-	tr	Northern edge of Jabal Silli. Dark gray with lighter speckle and streak, medium grained, irregular texture
Sample number: 138216 Field number: RD-839-3 Rock type: Rhyolite	33	33	33	-	tr	tr	-	-	tr	Eastern edge of Jabal Silli. Medium gray, slightly yellowish, slight mottle, micro-grained
Sample number: 138217 Field number: RD-939-4 Rock type: Metabasalt	-	-	50	50	-	-	1	tr	tr	Irregular grayish black and medium gray, micrograined and fine grained, irregular foliation
Sample number: 138218 Field number: RD-839-5 Rock type: Metabasalt	-	-	70	30	-	tr	-	-	1	Dark gray, micrograined, lighter near veins

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks-Continued

	Plagio-clase	Actin-olite	Horn-blende	Clino-pyroxene	Allanite	Opaque minerals	Location and description
					Jabal Dalfa formation		
Sample number: 138209 Field number: RD-723-1 Rock type: Metabasalt	35	-	65	-	-	tr	Flats at the western flank of Jabal Dalfa. Grayish black, micro-grained, uniform rock with prominant lineation formed by amphibole needles
Sample number: 138210 Field number: RD-734-4 Rock type: Metabasalt	35	65	-	tr	-	-	Northern part of Jabal Dalfa. Dark greenish gray with white splotch, medium grained, irregular lineation and foliation
Sample number: 138220 Field number: RD-943-1 Rock type: Metabasalt	30	-	30	40	-	-	2 km northwest of northern end of Jabal Dalfa. Grayish black, medium grained, irregular lineation

Table 2.—**Estimated modes and hand specimen descriptions of analyzed rocks-Continued**

	Quartz	Plagio-clase	Actino-lite	Horn-blende	Biotite	Epidote	Opaque minerals	Location and description
				Shithr formation				
Sample number: 138202 Field number: RD-639 Rock type: Metabasalt	-	35	65	-	-	-	2	Center of quadrangle, 2.5 km north of Wadi Ranyah. Dark gray, aphanitic, replacement texture
Sample number: 138206 Field number: RD-662 Rock type: Metabasalt	-	30	65	-	-	5	1	Center of quadrangle, 3 km south of Wadi Ranyah. Medium dark gray, even, aphanitic, replacement texture
Sample number: 138211 Field number: RD-741 Rock type: Metabasaltic andesite	10	35	-	50	tr	-	3	South-central part of quadrangle, 9 km west of Jabal Haddad. Dark gray, micrograined, even, texture lepidoblastic
Sample number: 138276 Field number: RD-695A Rock type: Rhyolite	15	73	-	-	2	10	tr	Center of quadrangle, 8.5 km south of Wadi Ranyah. Irregular mottle medium dark to dark gray, micrograined, and fine grained, texture intergranular to seriate
Sample number: 138277 Field number: RD-719A Rock type: Metabasaltic andesite	30	p-tr	-	65	2	2	1	South-central part of quadrangle, 5 km southeast of Jabal Dalfa. Dark gray, micrograined, slight planar streaking, replacement texture

Table 2.--Estimated modes and hand specimen descriptions of analyzed rocks-Continued

	Quartz	Plagio-clase	Actin-olite	Horn-blende	Chlorite	Biotite	Epidote	Calcite	Opaque minerals	Micro-felsite	Location and description
					Umm Shat formation						
Sample number: 138278 Field number: RD-753-1 Rock type: Rhyolite	p-tr	p-1	-	-	-	-	-	tr	tr	99	Umm Shat, northern part. Medium gray, aphanitic with microphenocrysts plagioclae, even groundmass
Sample number: 138213 Field number: RD-755 Rock type: Metabasalt	-	30	70	-	-	tr	-	-	1	-	Umm Shat, western part. Medium dark gray, faint mottle, micrograined, replacement and poikilitic textures
Sample number: 138279 Field number: RD754A Rock type: Metabasaltic andesite	x	x	-	x	x	-	x	x	x	-	Umm Shat, west-central part. Medium dark gray, micrograined with darker porphyroblasts hornblende, texture fragmental, replacement

SiO_2, andesite; 63 to 68 percent SiO_2, dacite; more than 68 percent SiO_2, rhyolite. These names so defined are used in the discussion that follows.

COMPOSITION OF METAVOLCANIC ROCKS VERSUS COMPOSITION OF PARENT LAVAS AND TUFFS

Since the analyses of the metavolcanic rocks will be considered in the following sections as if they were unaltered rock compositions, it is important to consider to what extent this assumption is true.

From an examination of the analyses, table 1, the first consideration is water content. If the water content is large, the analysis should be regarded with suspicion, as a gain of water may signify mobilization of certain elements. Some analyses having more than 3 percent water were discarded, whereas two (138266 and 138279, Al Khaniq and Umm Shat, respectively) were retained. One analysis from Al Khaniq (138269) and two from Rawdah (138274 and 138275) have more than 2 percent water. However, all others contain less than 2 percent water. Hence the water contents of most of the rocks are not suggestive of compositional change during metamorphism.

Coish (1977) makes plots of major and minor elements versus water as an independent variable for the Betts Cove ophiolite, Newfoundland. He reasoned that if an element shows an increasing or decreasing trend with increase in water content, that element has moved in or out of the rock, respectively. Conversely, if it shows no relationship, it has been stable. Plots of major elements versus water as independent variable (figs. 3, 4) were made for the four units with four or more samples: Jabal Silli, Shithr, Al Khaniq and Rawdah (including one sample not in table 1 containing 4.9 percent water). Jabal Silli and Shithr rocks pass this test well, as no relationship is shown. Rawdah rocks show trends, particularly in SiO_2, total iron, and Al_2O_3, if the water-rich sample is included. Without it, they do not. Apparently, discarding the water-rich sample was correct. The Al Khaniq rocks do show distinct trends, suggesting that SiO_2, Na_2O, and K_2O have been lost in the more water-rich rocks and MgO, total iron, Al_2O_3, and CaO gained.

Coish (1977) also suggests plotting major and minor elements versus a known immobile element such as zirconium which varies systematically with igneous processes. Systematic trends suggest that the element plotted has remained immobile, while erratic trends suggest that it has been mobilized. Zirconium analyses are available for the Rawdah and Al Khaniq rocks. The trends (not illustrated) are smooth for all samples except 138267, a rhyolite from Al Khaniq. However, the composition of this sample is so

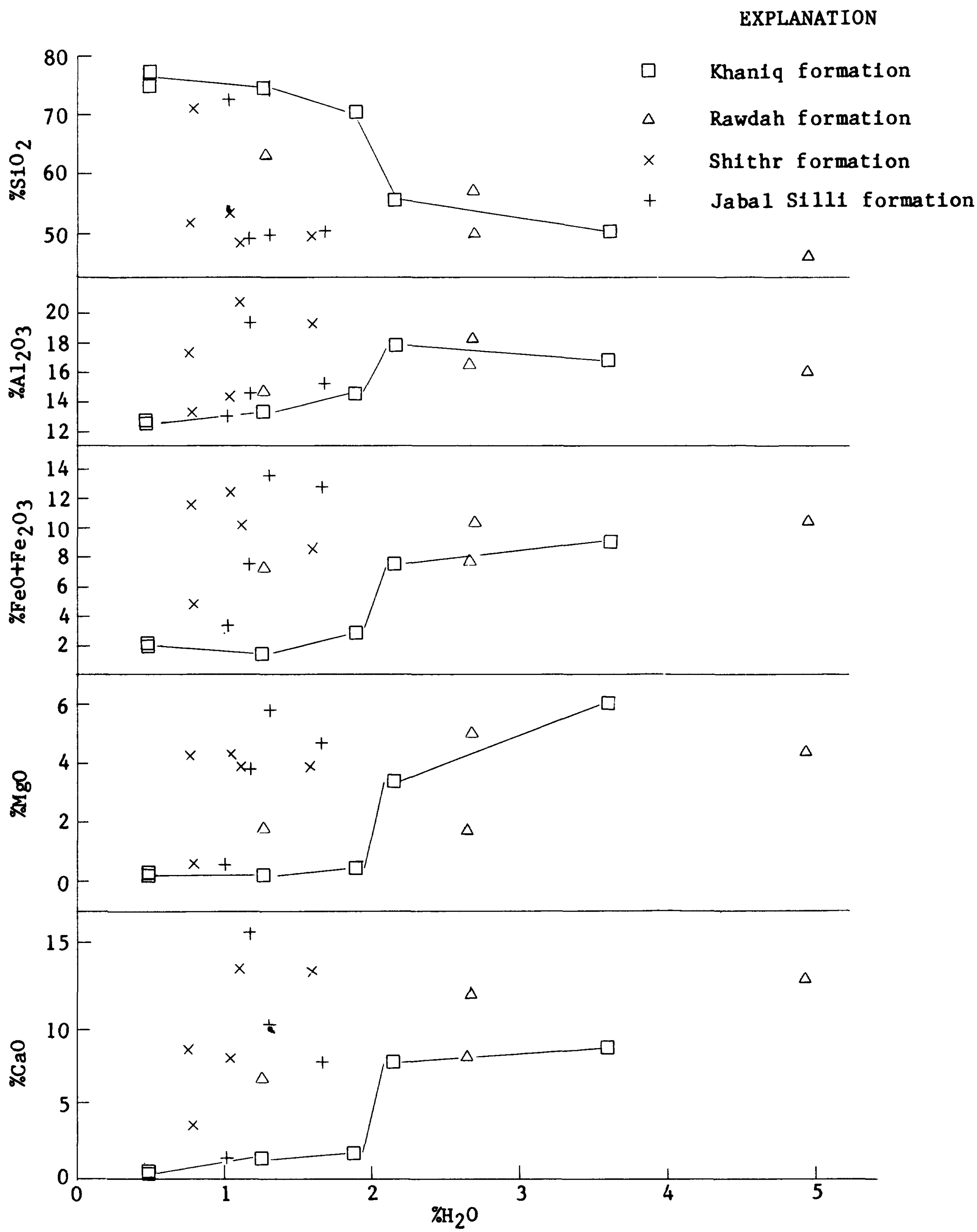

Figure 3.--Variation diagrams: Si_2, Al_2O_3, FeO + Fe_2O_3, MgO, and CaO versus H_2O for four volcanic rock suites from the Ranyah area.

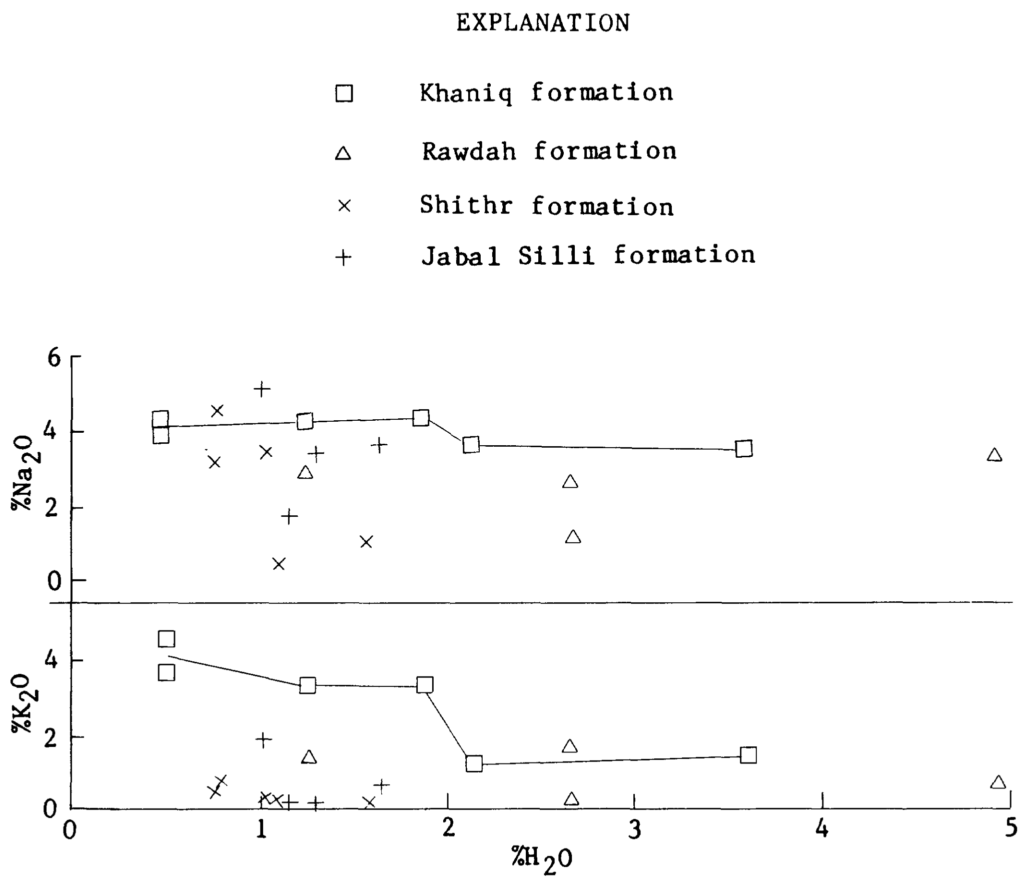

Figure 4.--Variation diagrams: Na_2O and K_2O versus H_2O for four volcanic rock suites from the Ranyah area. Symbols as in figure 3.

similar to that of two others (138268 and 271) that no problem seems to exist and the analysis was retained.

Another criterion for testing whether the analyses represent original lava compositions is the mineral content of the rocks (table 2). It is reasonable to assume that the presence of original olivine and pyroxene show that there has been little change in composition of the rock. The next best minerals are hornblende, actinolite and biotite. Epidote and chlorite, and especially calcite are much more suggestive of open-system behavior. The modes of the analyzed rocks show that the Jabal Dalfa and Urayyiq samples all look very reliable, as their mafic mineral content is all pyroxenes and amphiboles. The Jabal Silli samples look similaly good, except that the rhyolite sample contains some chlorite. Two out of the three Umm Shat samples rate poorly, as one contains calcite and the other calcite, chlorite, and epidote. Two of the five Shithr samples rate highly, but three contain epidote and thus rate poorly. The three Rawdah samples likewise rate poorly, each containing calcite or epidote. The Al Khaniq samples mostly rate poorly, containing calcite or epidote.

In summary, the evidence for stability is favorable for some units and equivocal for others. Jabal Dalfa, Urayyiq, and Jabal Silli rocks seem clearly reliable. The Shithr samples rate well on the major elements versus water plots, but less well on mineralogy. Umm Shat rocks (2 of 3) rate poorly on mineralogy and no other criteria are available. The three Rawdah samples considered in the sections which follow rate well on the major elements versus water plots but poorly on mineralogy. They rate well on the plots of major elements versus zirconium. The Al Khaniq samples must be regarded as the most suspect, as they rate poorly on both mineralogy and the major elements versus water plots. However, they also rate well on the plots of major elements versus zirconium.

VARIATION DIAGRAMS

Variation diagrams are very useful for determining the petrologic affinity of rock suites. They are commonly constructed plotting major elements versus SiO_2 or MgO as the independent variable. SiO_2 is most satisfactory for these rocks; accordingly, Na_2O, K_2O, Al_2O_3, CaO, FeO + Fe_2O_3, MgO, TiO_2, and Na_2O + K_2O are plotted versus SiO_2 in the diagrams which follow (figs. 5 to 12). All analyses are recalculated to 100 percent, water free, before plotting, and the figures cited in the discussions of the diagrams reflect this recalculation. The rocks of each unit are treated as a suite in the diagrams, and are shown by a distinctive symbol, though large compositional gaps exist within some units.

Analyses of volcanic rocks from known tectonic settings are also plotted on the variation diagrams. These analyses, in part averages and in part individual analyses, also are recalculated to 100 percent, water free, and are listed in table 3. The analyses are numbered on the diagrams and keyed to table 3.

Na_2O versus silica

The Khaniq volcanic rocks show a small rise in Na_2O contents from 3.6 percent for basaltic andesite to 4.0 to 4.5 percent for rhyolite (fig. 5). The Shithr basalts have very low values (0.5 to 1.1 percent), basaltic andesites have much higher values (3.3 to 3.5 percent) and the upper part of the trend is similar to that for Al Khaniq. The trend for Jabal Silli rocks is similar but at a higher level -- basalts and rhyolite contain more Na_2O. The trends for Umm Shat and Rawdah are at a lower level -- basaltic andesite and andesite are relatively low in Na_2O and basalts are intermediate. Jabal Dalfa and Urayyiq basalts have low to intermediate Na_2O contents (1.0 to 2.0 percent).

Some island arc tholeiites from the Kermadecs and Japan (nos. 17 to 20) have similar values to the basalts of Jabal Dalfa and Urayyiq and a similar trend to the Rawdah and Umm Shat rocks. Mid-ocean ridge and continental tholiites (nos. 1 to 3, 12, 14) and continental high-alumina basalt (nos. 15, 16) all have higher N_2O contents (2.5 to 3.0 percent). The trend for the Talasea, New Britain island arc tholeiite series (nos. 8 to 11) is similar to that for Shithr and Al Khaniq basaltic andesite and rhyolite. The declining trend of the Andes-Cascades (nos. 23 to 26) continental margin calc-alkaline rocks does not match any of the Ranyah area suites.

K_2O versus silica

Basalts from all units have very low K_2O contents (.1 to .3 percent, one at .7 percent) (fig. 6). The Al Khaniq rocks have relatively high K_2O contents, ranging from 1.1 for andesite to 4.5 for the most potassic rhyolite. Trends for the other units terminate in rhyolite of low $K2^O$ content (.8 to 2.0 percent). Rawdah andesite and dacite have intermediate values (1.7 and 1.4).

Basalts from a variety of tectonic environments also have low K_2O contents and little differentiation is possible, although unlike the Ranyah area rocks, most have more than .3 percent K_2O. Basalt from the island arc tholeiite series (nos. 18 and 20) of Japan have similar values to rocks from Shithr. Both the Talasea, New Britain, island arc tholeiite (nos. 8 to 11) and the Andes-Cascades continental margin calc-alkaline series follow closely the trend of the Al Khaniq rocks. Two continental tholeiites (nos.

Table 3.—Some representative individual and average analyses of volcanic rocks from known tectonic settings, recalculated to 100 percent, water-free

	Mid-Atlantic ridge basalt (1)	Indian Ocean basalt (2)	East Pacific rise basalt (3)	East Pacific rise, andesite glass (4)	Island arc tholeiites (5)	Lau basin basalt (6)	New Britain basalt (8)	New Britain andesite (9)
SiO_2	49.8	49.7	50.4	60.2	50.7	49.0	51.7	58.7
TiO_2	1.4	2.8	1.8	1.8	0.8	1.0	0.8	0.9
Al_2O_3	15.9	13.5	15.1	12.9	19.2	16.2	15.9	15.4
Fe_2O_3	2.2	6.3	11.1	12.3	5.5	1.6	2.7	2.2
FeO	7.3	8.1			5.0	7.2	7.0	6.7
MnO	0.16	-	0.2	-	.2	0.2	.17	.18
MgO	8.6	6.5	7.2	1.7	5.3	9.3	6.7	3.2
CaO	11.2	8.8	11.5	5.7	9.4	12.8	11.7	7.0
Na_2O	2.7	2.6	2.7	4.4	3.1	2.2	2.4	3.8
K_2O	.26	0.87	.19	0.65	.58	.12	.44	1.5

1. Average of 33 basalts (Melson and Thompson, 1961).
2. Ninety-east ridge, DSDP site 216, average of 7 basalts (Thompson and others, 1975).
3. Average of 3 basalts: 1)Engle and others, 1965, table 1, analysis PDV-3, 2) Engle and Engle, 1961, p. 1799, analysis 1, 3), 3) Kay and others, 1970, p. 1593, analysis V2023.
4. Kay and others, 1970.
5. Average of 7 (Ewart and Bryan, 1972; Jakes and Gill, 1970).
6. Average of 6 least altered, least fractionated (Hawkins, 1976).
8. Talasea, island arc tholeiitic series, (Lowder and Carmichael, 1970, number 311).
9. Talasea, island arc tholeiitic series, (Lowder and Carmichael, 1970, number 114).

Table 3.--Some representative individual and average analyses of volcanic rocks from known tectonic settings, recalculated to 100 percent, water-free-Continued

	New Britain dacite (10)	New Britain rhyolite (11)	Picture Gorge basalt (12)	Yakima basalt (13)	Late Yakima-Ellensburg basalt (14)	Catnip Creek basalt (15)	Modoc basalt (16)	Kermadec arc lavas (17)	Northeast Japan Lava (18)
SiO_2	66.5	75.3	50.1	54.5	50.5	48.7	49.3	49.7	51.4
TiO_2	0.7	0.3	1.6	2.0	3.2	1.05	1.2	0.9	0.8
Al_2O_3	14.6	12.6	15.9	14.0	13.6	17.6	19.0	17.4	17.9
Fe_2O_3	1.6	1.6	3.6	2.6	1.9	2.7	2.2	2.6	3.2
FeO	3.8	.9	8.0	9.4	12.6	7.5	7.1	7.1	7.3
MnO	.14	.07	0.2	0.2	0.25	0.15	0.09	.2	.14
MgO	1.5	.24	6.6	4.2	4.4	8.2	7.4	7.2	6.2
CaO	4.0	1.3	10.5	8.0	8.4	11.0	10.1	12.7	10.7
Na_2O	4.5	4.0	2.8	3.0	2.9	2.5	3.0	1.6	1.8
K_2O	2.1	3.8	.5	1.5	1.4	.42	.4	.4	.32
P_2O_5	.21	.02	.3	.4	.7	.21	.14	.1	.09

10. Talasea, island arc tholeiitic series, (Lowder and Carmichael, 1970, number 306).
11. Talasea, rhyolite obsidian, island arc tholeiitic series, (Lowder and Carmichael, 1970, number 343).
12. Columbia River plateau, "average" (Waters, 1961, p. 592, analysis A).
13. Columbia River plateau, "average" (Waters, 1961, p. 593, analysis B).
14. Columbia River plateau, "average" (Waters, 1961, p. 594, analysis A).
15. Sheldon Antelop range, northwestern Nevada, continental margin high-alumina series, average of 6 unpublished analyses.
16. Medicine Lake highlands, northeastern California continental margin high-alumina series (Anderson, 1941, p. 387, table 1, number 2).
17. Island arc tholeiitic series, average of 10 lavas with FeO*/MgO 1 to 2, (Miyashiro, 1974, p. 332, table 3).
18. Outer volcanic zone, island arc tholeiitic series, average of 10 lavas with FeO*/MgO 1 to 2 (Miyashiro, 1974, p. 332, table 3).

Table 3.--Some representative individual and average analyses of volcanic rocks from known tectonic settings, recalculated to 100 percent, water-free-Continued

	Northeast Japan lava (19)	Izu peninsula olivine basalt (20)	Amagi olivine basalt (21)	Augite-olivine andesite (22)	Cascade Range calc-alkaline series (23)	Central Andes lava (24)	Central Andes lava (25)	Central Andes lava (26)	Hawaiian Islands basalt (27)
SiO_2	54.5	48.1	49.9	53.7	62.5	57.8	67.5	73.6	49.9
TiO_2	0.9	0.5	0.6	1.6	0.6	1.1	0.5	0.3	2.5
Al_2O_3	18.7	16.5	18.4	18.8	17.2	16.7	15.8	13.9	14.0
Fe_2O_3	3.2	3.4	2.9	1.1	1.5	2.6	2.3	1.7	3.0
FeO	6.2	8.7	7.7	7.5	3.3	4.0	1.2	.2	8.6
MnO	.14	.13	.28	0.14	.09	0.1	.1	.04	0.16
MgO	3.9	8.3	7.1	4.3	2.8	4.2	1.4	.5	8.5
CaO	9.3	12.5	9.9	7.8	5.3	6.7	3.7	1.8	10.4
Na_2O	2.3	1.4	2.5	4.0	4.2	4.4	3.9	3.5	2.1
K_2O	.66	.14	.48	.70	2.0	2.0	3.0	4.0	.38
P_2O_5	.14	.15	.17	.29	.3	.3	.2	.1	.26

19. Outer volcanic zone, island arc tholeiitic series, average of 10 lavas with FeO*/MgO 2 to 3 (Miyashiro, 1974, p. 332, table 3).
20. Japan, island arc tholeiite (Kuno, 1960, p. 125, table 1, number 1).
21. Japan, island arc high alumina series (Kuno, 1960, p. 125, table 1, number 4).
22. Sidara basin, Japan, island arc high alumina series (Kuno, 1960, p. 125, table, number 7).
23. Western North America, inner volcanic zone, continental margin calc-alkaline series, average of 6 (Miyashiro, 1974, p. 333, table 3).
24. South America, continental margin calc-alkaline series, average of 10 lavas with FeO*/MgO 1 to 2 (Miyashiro, 1974, p. 333, table 3).
25. South America, continental margin calc-alkaline series, average of 8 lavas with FeO*/MgO 2 to 3 (Miyashiro, 1974, p. 333, table 3).
26. South America, continental margin calc-alkaline series, average of 5 lavas with FeO*/MgO 3 to 4 (Miyashiro, 1974, p. 333, table 3).
27. Oceanic island tholeiitic series, average of 181 tholeiitic basalts from all islands (MacDonald and Katsura, 1964, p. 124, table 9, number 8).

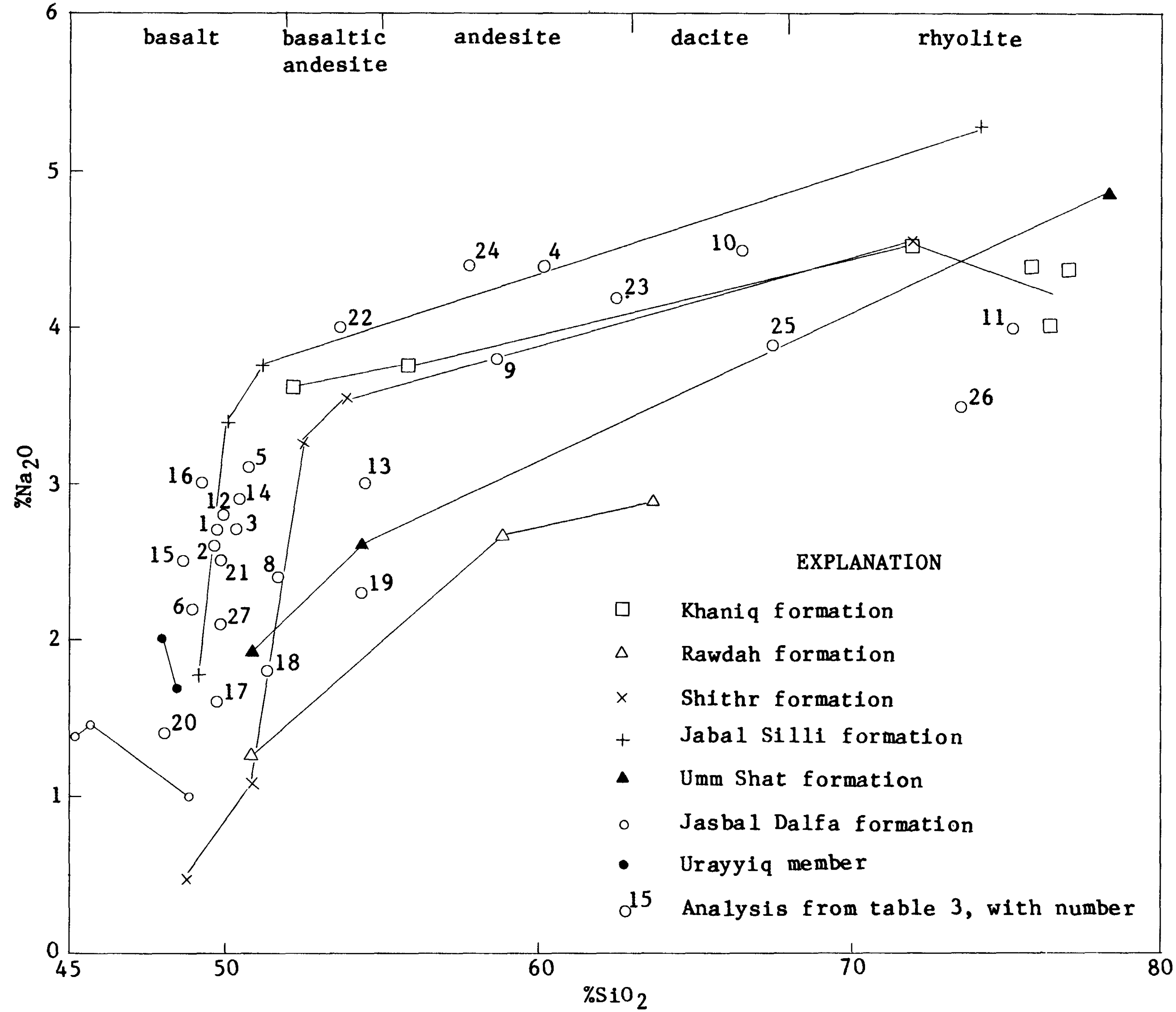

Figure 5.--Variation diagram, Na_2O versus Si_2O, for volcanic rock suites from the Ranyah area.

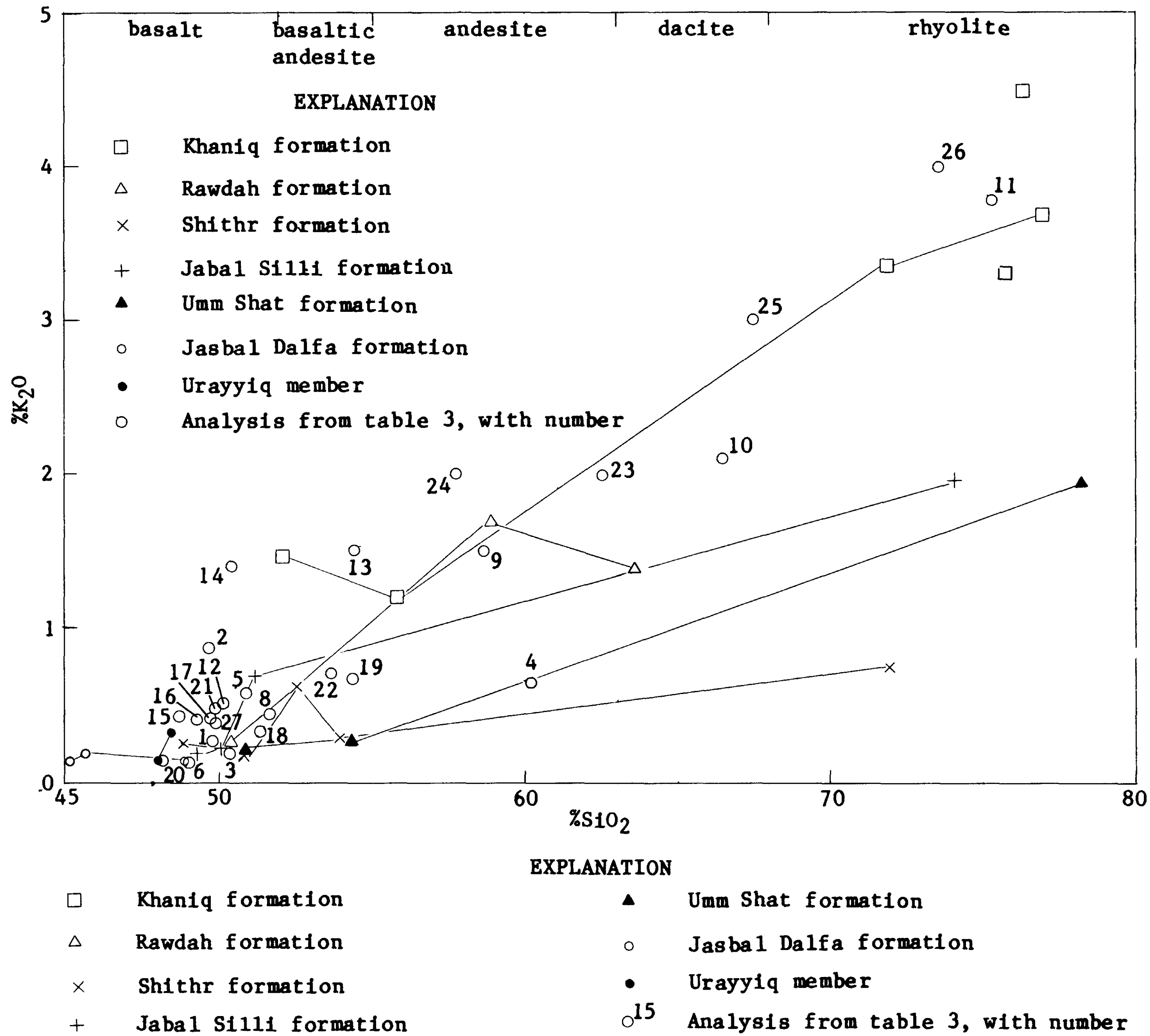

Figure 6.--Variation diagram, K_2O versus SiO_2, for volcanic rock suites from the Ranyah area.

13, 14) from the Columbia plateau have K_2O contents in the range of the Al Khaniq basaltic andesite and andesite.

Al_2O_3 versus silica

The alumina contents distinguish the various rock suites from the Ranyah area possibly better than any other element (fig. 7). Alumina contents of basalt and basaltic andesite are high (mostly over 17 percent) and suggest that they would belong to a "high alumina" series if Al_2O_3 content were the criteria for such an assignment.

The silica-poor basalts of Jabal Dalfa and Urayyiq have high alumina contents (18 to 19.4 percent). The Al Khaniq trend shows the highest alumina values for andesite and two rhyolites, although the two most silicic rhyolites contain less than 13 percent. The Rawdah and Umm Shat suites have smooth descending trends lying below that for Al Khaniq. Some of the Shithr and Jabal Silli basalts and basaltic andesites have very high alumina contents (17.3 to 21.0 percent), others are more moderate (14.4 to 15.5 percent). Rhyolites in these series have moderately high values.

Alumina contents are clearly different in samples from the different tectonic environments. Values from mid-ocean ridges (nos. 1 to 4), continental tholeiites (Columbia plateau, nos. 12 to 14) and oceanic islands (Hawaiian Islands, no. 27) are lower than nearly all of the Ranyah area rocks of similar silica content. Three of the four points on the Andes-Cascades calc-alkaline trend (nos. 23 to 26) are close to the Al Khaniq trend. Island arc tholeiites (nos. 5, 17, 18) and high-alumina basalt (no. 21) and continental high-alumina basalt from Nevada and California (nos. 15, 16) have similar alumina contents to those of basalt and some basaltic andesite from all the Ranyah area suites. The Talasea-New Britain trend (nos. 8 to 11) approximates that of basaltic andesite and rhyolit from Umm Shat, Jabal Silli, and Shithr.

CaO versus silica

Basalts from all units have high CaO contents, most range from 12.5 to 18.3 percent, whereas two from Jabal Silli are 7.9 and 10.4 percent (fig. 8). CaO contents of basaltic andesite range from 7.5 to 9.1 percent. Andesites, dacite, and rhyolites continue smooth descending trends. Rawdah rocks have distinctly higher CaO contents, whereas the trends for Al Khaniq, Umm Shat, Shithr, and Jabal Silli are intermingled.

Plots of silica versus CaO for rocks from elsewhere show little definition by tectonic setting. Values for basalts from all environments are intermingled; however, the highest values, 12.5 to 13 percent are all from island arcs. Island

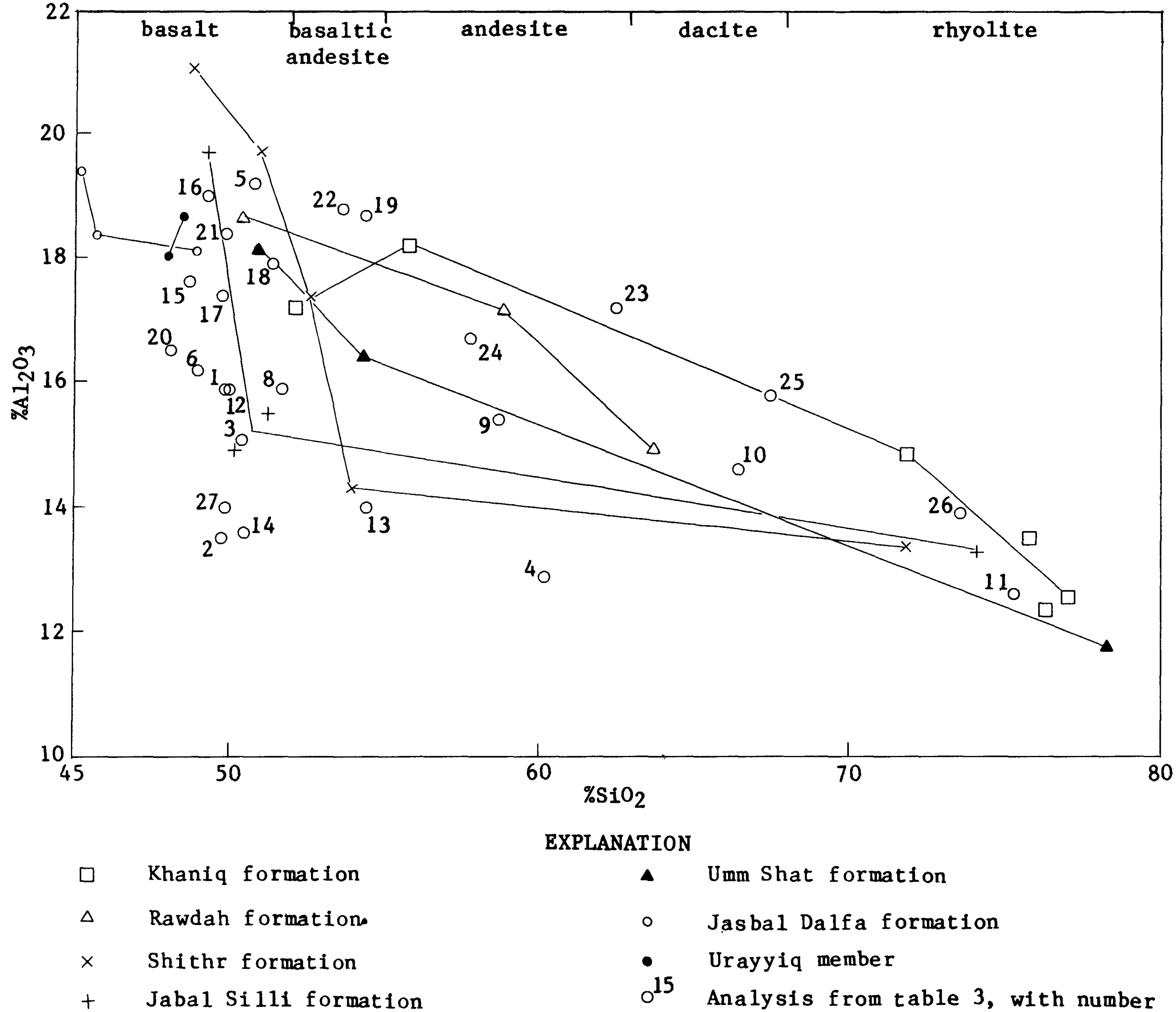

Figure 7.--Variation diagram, Al_2O_3 versus SiO_2, for volcanic rock suites from the Ranyah area.

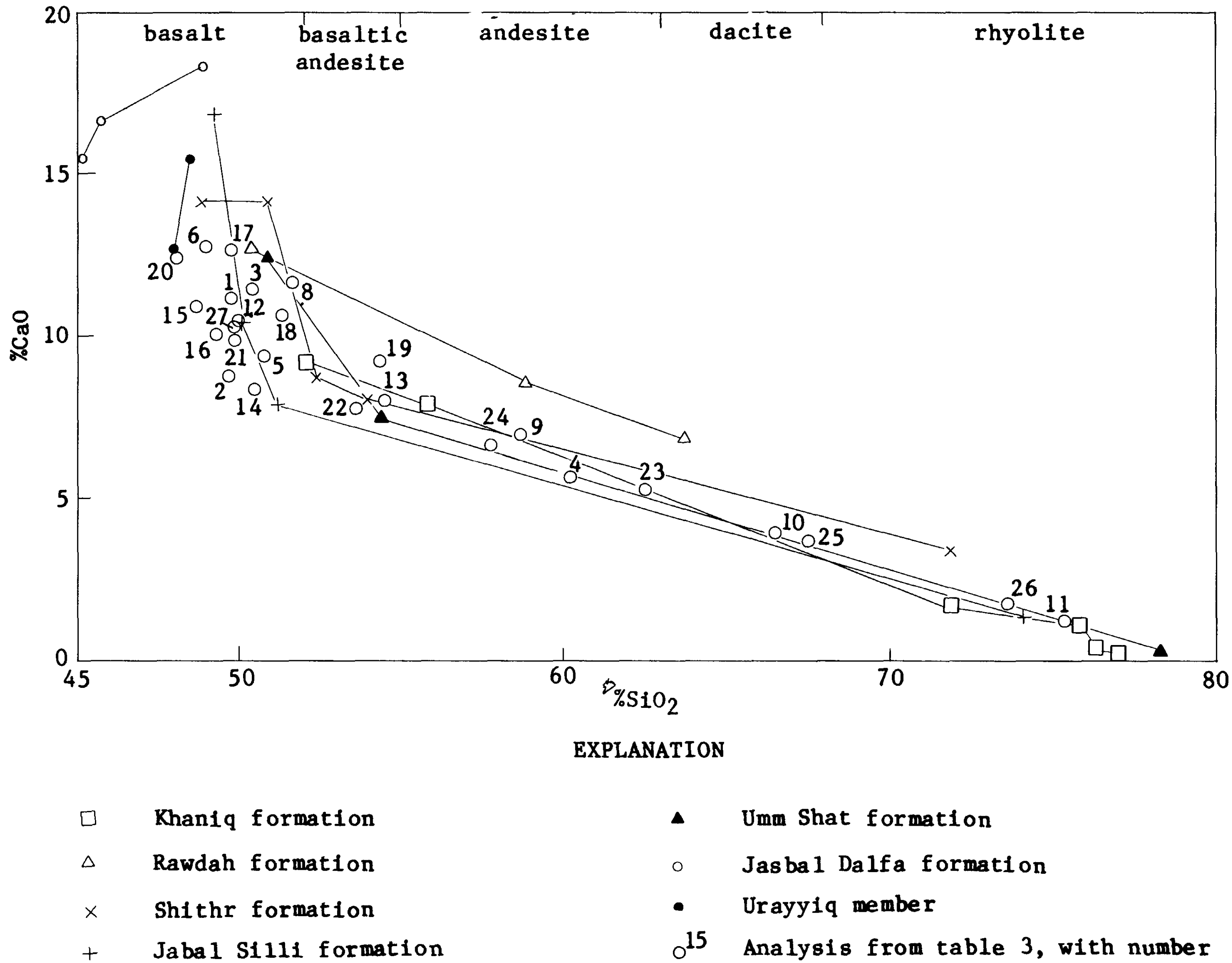

Figure 8.--Variation diagram, CaO versus SiO_2, for volcanic rock suites from the Ranyah area.

arc (Talasea-New Britain, nos. 8 to 11) and continental margin (Andes-Cascade, nos. 23 to 26) trends both follow closely that shown by rocks from Al Khaniq, Umm Shat, Shithr, and Jabal Silli.

The Jabal Dalfa basalts, plus one each from Urayyiq and Jabal Silli have unusual compositions in that they contain more than 15 percent CaO, less than 50 percent SiO_2, and less than 7 percent MgO. However, neither their normative compositions (not tabulated) nor their modal mineralogy (table 2, nos. 138209, 210, 220, 214, and 217) show features incompatible with a volcanic origin. The normative compositions suggest that bytownite and diopside-rich pyroxene were cumulus phases in a magma chamber whose contents were erupted to sufficient depth to include the magma rich in the cumulus minerals.

FeO + Fe_2O_3 versus silica

Total iron contents of basalts and basaltic andesites from the Ranyah area vary irregularly from low (7.8 percent) to high (13.8 percent) (fig. 9). Andesite and rhyolite of Al Khaniq form a trend with a relatively low iron to silica ratio, and andesite and dacite of Rawdah a somewhat higher trend. Rhyolites of Jabal Silli and Shithr have rather high iron contents.

Iron contents of rocks from various tectonic environments are also widely scattered. However, certain features emerge. Most of the values over 11 percent are mid-ocean ridge (nos. 2 to 4), oceanic island (no. 27), or continental (nos. 13, 14) tholeiites. Island arc tholeiites and high alumina basalt from the Kermadecs and Japan (nos. 17 to 21) and continental high-alumina basalt (nos. 15, 16) have iron contents similar to the middle range of iron contents of Ranyah area basalt and basaltic andesite. The Andes-Cascade calc-alkaline trend (nos. 23 to 26) corresponds closely to the trend for Al Khaniq andesite and rhyolite. The Talasea-New Britain trend (nos. 8 to 11) of island arc tholeiites shows distinctly high iron-silica ratios and corresponds in part to the trends shown of Rawdah, Shithr, and Umm Shat rocks.

MgO versus silica

MgO contents of basalt and basaltic andesite from the Ranyah area range from 3.9 to 6.5 percent (fig. 10). These values are low, especially for basalts with less than 50 percent SiO_2. It is evident that despite the low silica content of the Jabal Dalfa and Urayyiq rocks, they are not the products of the eruption of magma low in a magma chamber in which olivine or pyroxene crystals have accumulated.

Trend with increasing silica content distinguish only

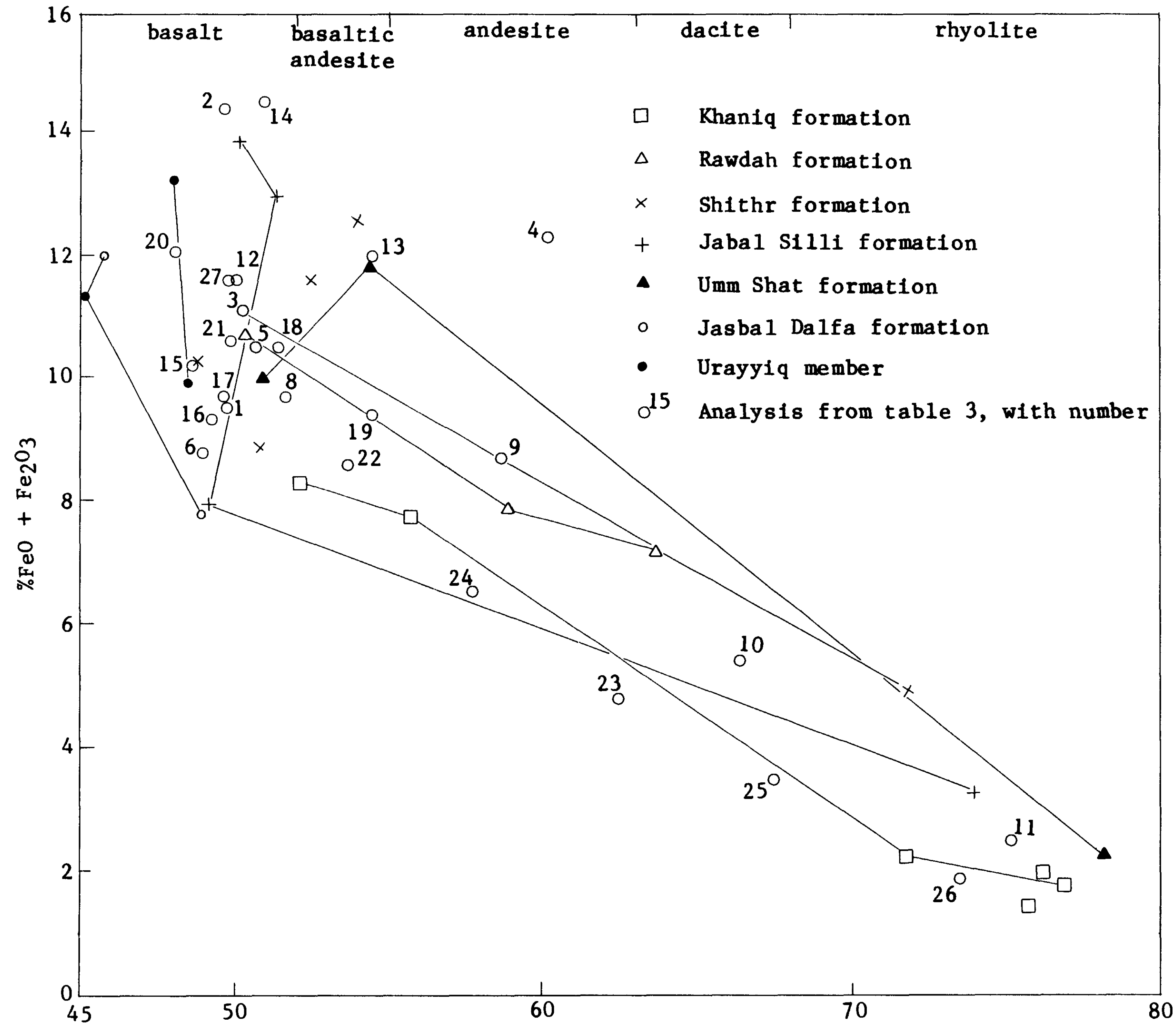

Figure 9.--Variation diagram, $FeO + Fe_2O_3$ versus SiO_2, variation diagram for volcanic rock suites from the Ranyah area.

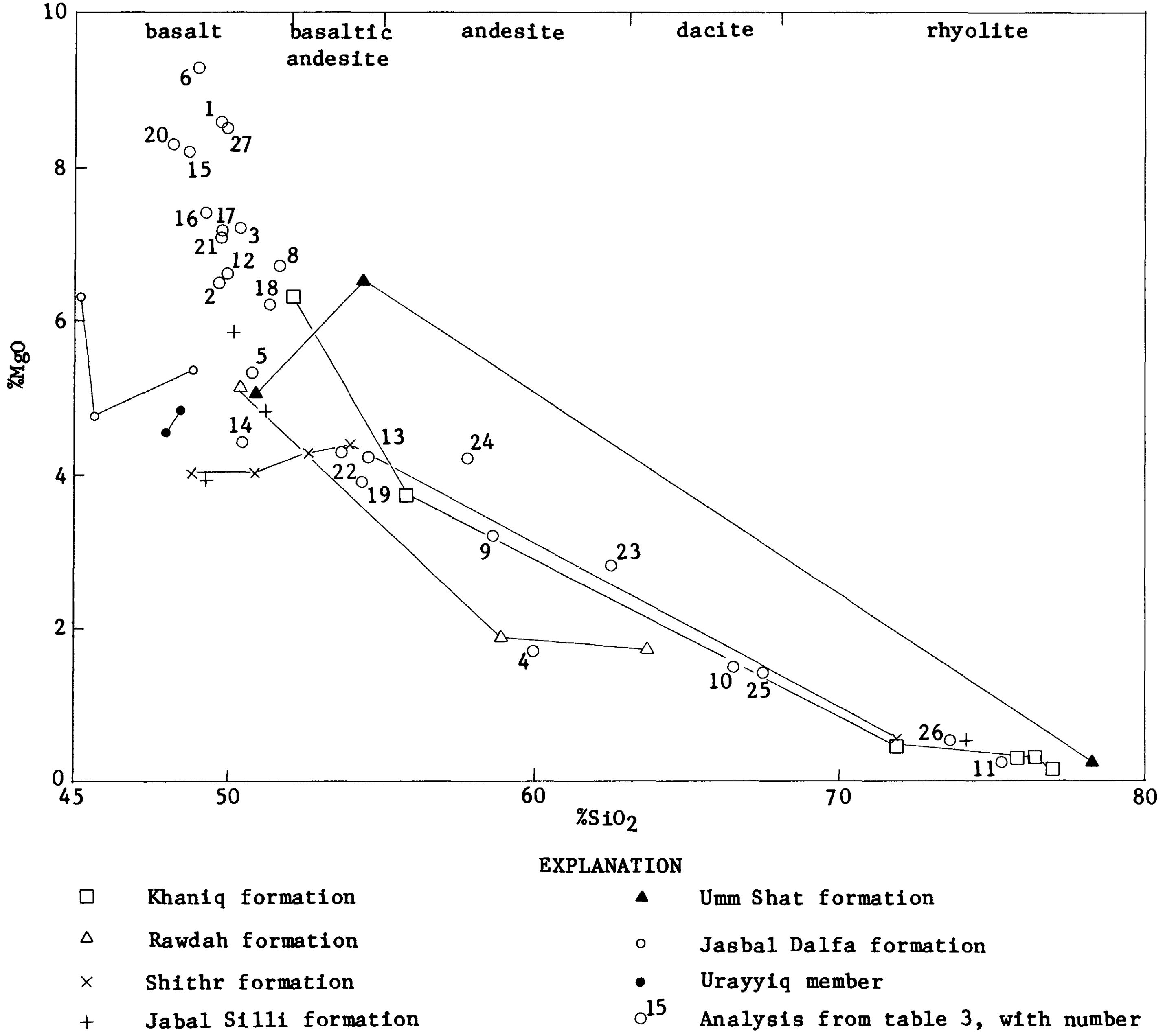

Figure 10.--Variation diagram, MgO versus SiO_2, for volcanic rock suites from the Ranyah area.

slightly the different Ranyah area suites. Basaltic andesites from Al Khaniq and Umm Shat are relatively high in MgO (6.4, 6.5 percent); rhyolites from these units as well as from Shithr and Jabal Silli are all low in MgO (.1 to 6 percent). Rawdah andesite and dacite have low MgO/silica ratios.

MgO contents of the plotted rocks from elsewhere provide remarkably little differentiation by tectonic environment. Examples of basalts from all tectonic environments have MgO contents (6.5 to 9.3 percent) higher than any of the Ranyah area rocks. Those in the same range as Ranyah area rocks include examples of island arc tholeiite (nos. 5, 18, 19), island arc high-alumina basalt (no. 22), and continental tholeiites (nos. 13, 14). The Talasea-New Britain (nos. 8 to 11) and Cascade-Andes (nos. 23 to 26) trends are distinct for andesite but merge for dacite and rhyolite. Al Khaniq and Shithr trends lie close to both but lack intermediate members.

TiO_2 versus silica

Basalt and basaltic andesite from the Ranyah area have low TiO_2 contents (.2 to 1.25 percent) (fig. 11), with two notable exceptions, one basalt from Jabal Silli (2.8 percent) and one basaltic andesite from Shithr (2.5 percent). Andesite and dacite from Rawdah have intermediate values (.9 percent), and rhyolite low values (.07 to .36 percent).

Differing tectonic settings are clearly characterized by different TiO_2 contents. Mid-ocean ridge basalts (nos. 1 to 4), continental tholeiites (nos. 12 to 14), and oceanic island tholeiites (Hawaiian Islands, no. 27) have high TiO_2 contents (1.6 to 3.2 percent). Basalts, both tholeiitic and high-alumina, from island-arc settings (nos. 5, 17, 18, 20, 21) and continental margin high-alumina basalts (nos. 15, 16) have low values similar to the Ranyah area rocks. For dacites and rhyolites, the island arc Talasea-New Britain (nos. 9 to 11) and continental margin Cascade-Andes (nos. 23 to 26) trends are not clearly separated. However, there is a suggestion that the continental margin trend (nos. 23 to 26) lies at relatively low TiO_2 values close to the Al Khaniq trend.

$K_2O + Na_2O$ versus silica

The plot of silica versus total alkalies (fig. 12) shows substantial differences between several of the rock suites from the Ranyah area. Basalts are mostly low in total alkalis (.9 to 2.2 percent), but two samples from Jabal Silli contain more alkalis (3.6, 4.4 percent). The Al Khaniq suite is highest in alkalis and the Jabal Silli suite is next highest. However, both trends lie well below the

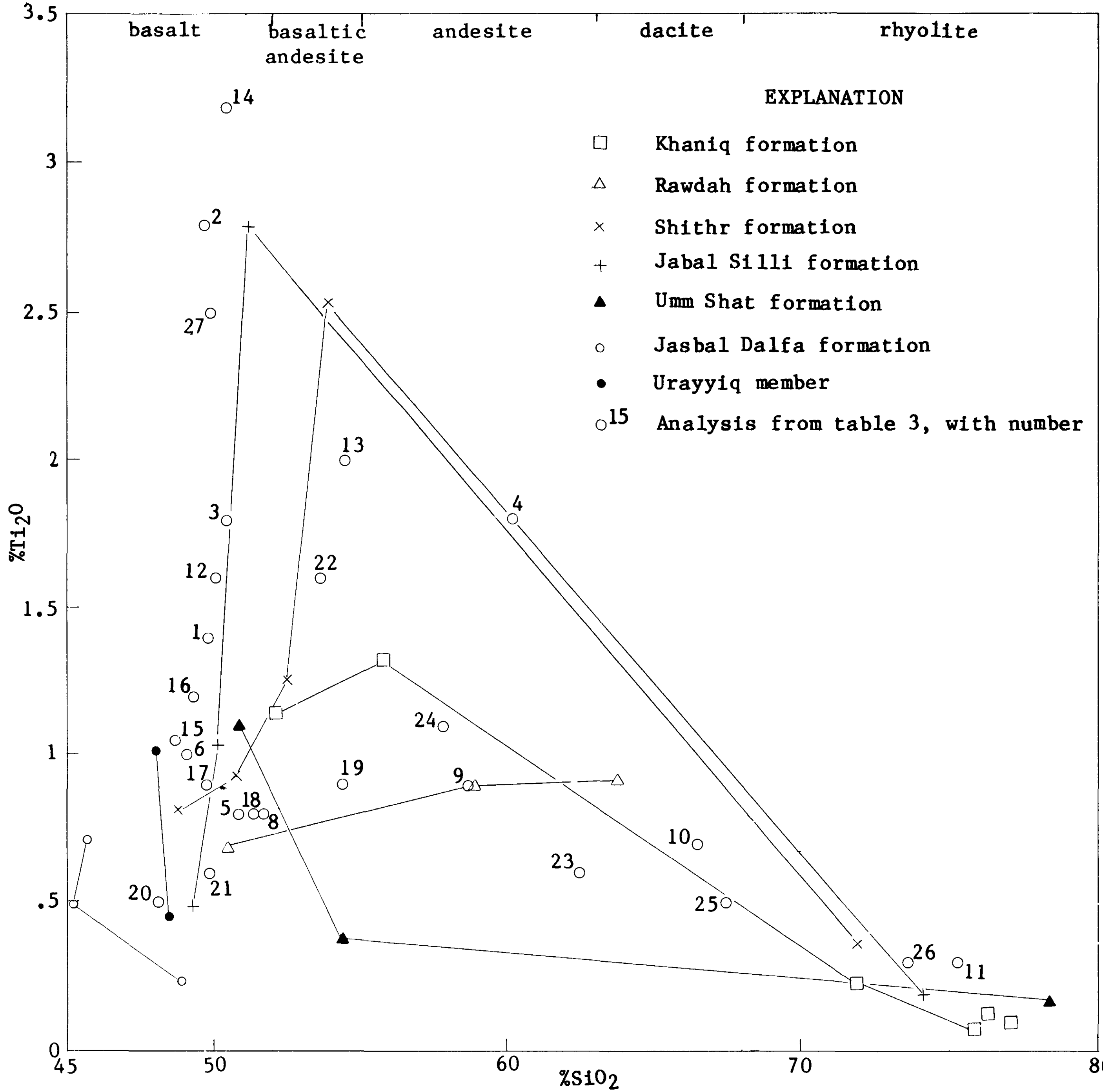

Figure 11.--Variation diagram, TiO_2 versus SiO_2, for volcanic rock suites from the Ranyah area.

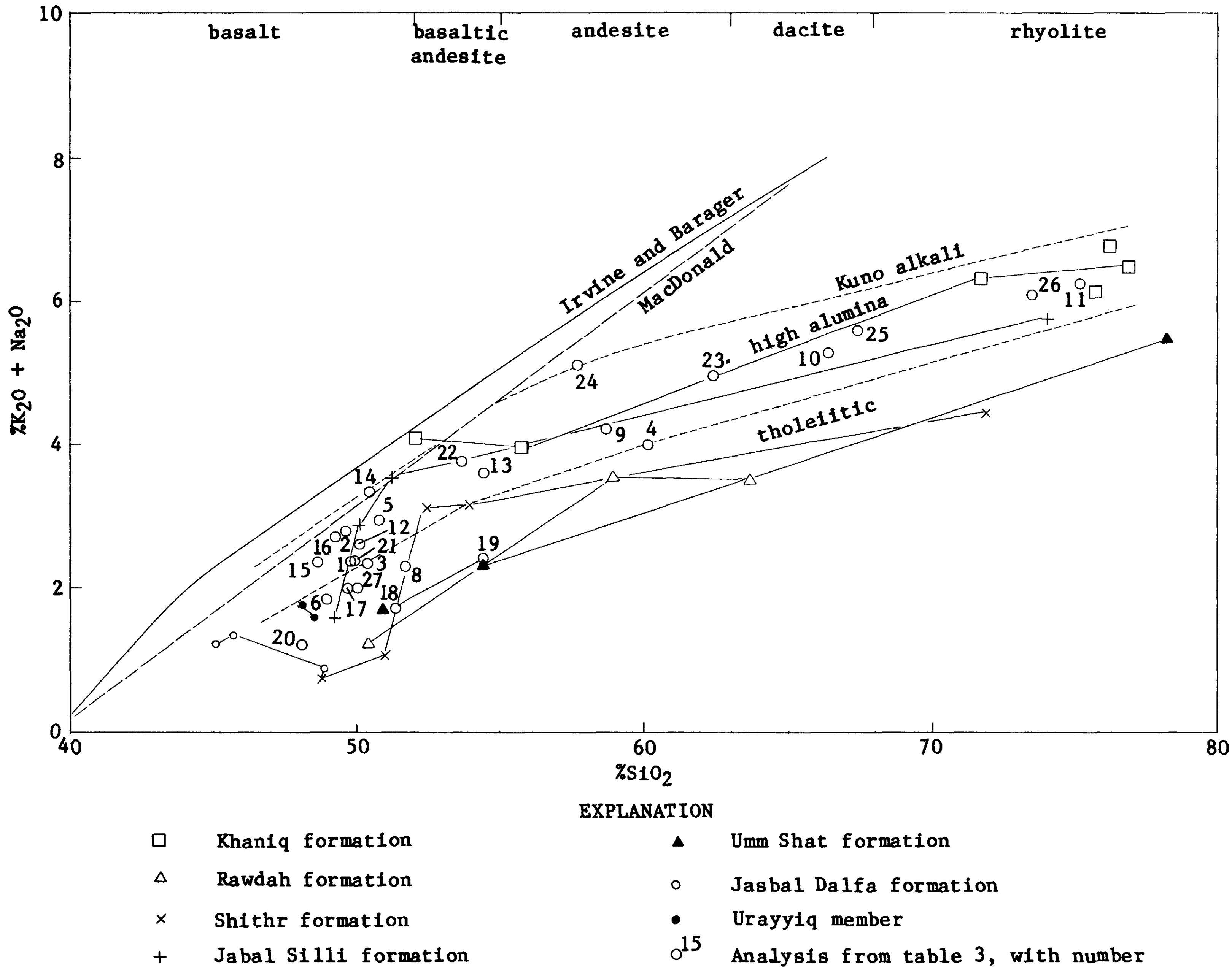

Figure 12.--Variation diagram, K_2O versus SiO_2, for volcanic rock suites from the Ranyah area.

boundary line separating alkali and sub-alkali fields of Irvine and Barrager (1971) and the alkali series-tholeiite series boundary of MacDonald (1968). Both the Al Khaniq and Jabal Silli trends lie largely in the high-alumina field of Kuno (1966). The Umm Shat and Rawdah rocks contain less alkalis and are clearly in the tholeiitic field. The Shithr basalt and rhyolite are similar but the basaltic andesites are higher in alkalis.

Trend lines for Al Khaniq, Jabal Silli, Shithr, and Umm Shat suites would cross trend lines for CaO content if plotted on the same axes. However, it would not be meaningful to assign a Peacoc index to these suites on this basis, because none contain rocks with SiO_2 contents near the crossing points.

All of the points plotted as examples of tectonic environments fall in the sub-alkali field. Tholeiitic series rocks from the Kermadecs and Japan (nos. 17 to 20) have low alkali contents similar to most of the Ranyah area basalts. Mid-ocean ridge and continental tholeiites (nos. 1 to 4, 12 to 14), island arc high-alumina basalt, (nos. 21, 22) and continental high-alumina basalt (nos. 15,16) have a small range of values and all plot in the high-alumina field of Kuno (1966). They provide little help in assigning a tectonic setting to Ranyah area rocks. The Talasea-New Britain (nos. 9 to 11) and Andes-Cascade (nos. 23 to 26) trends converge in the dacite field and both parallel closely the trend for Al Khaniq rocks.

TRIANGULAR DIAGRAMS

AFM diagram

The AFM diagram (total iron-MgO-total alkalis, fig. 13) shows remarkably smooth trends for each of the rock series plotted. The Al Khaniq rocks lie in the calc-alkaline field (Irvine and Barager, 1971), Umm Shat is doubtful, and the others are in the tholeiitic field. Al Khaniq, Umm Shat, Rawdah, Shithr, and Jabal Silli rocks all show a normal alkali enrichment trend with minor initial iron enrichment for Al Khaniq and Jabal Silli. Samples from Jabal Dalfa and Urayyiq, however, have an iron enrichment trend parallel to the initial leg of the Skaergaard trend (Wager and Deer, 1939).

Q-An-Or+Ab diagram

The normative quartz-anorthite-albite plus orthoclase diagram (fig. 14) shows distinctive features for some of the rock suites. Jabal Dalfa and Urayyiq rocks have small to no normative quartz but the latter are richer in normative Na+K feldspar. Al Khaniq and Jabal Silli rocks are with one exception richer in normative Na+K feldspar than the others, even at low to nil normative quartz contents.

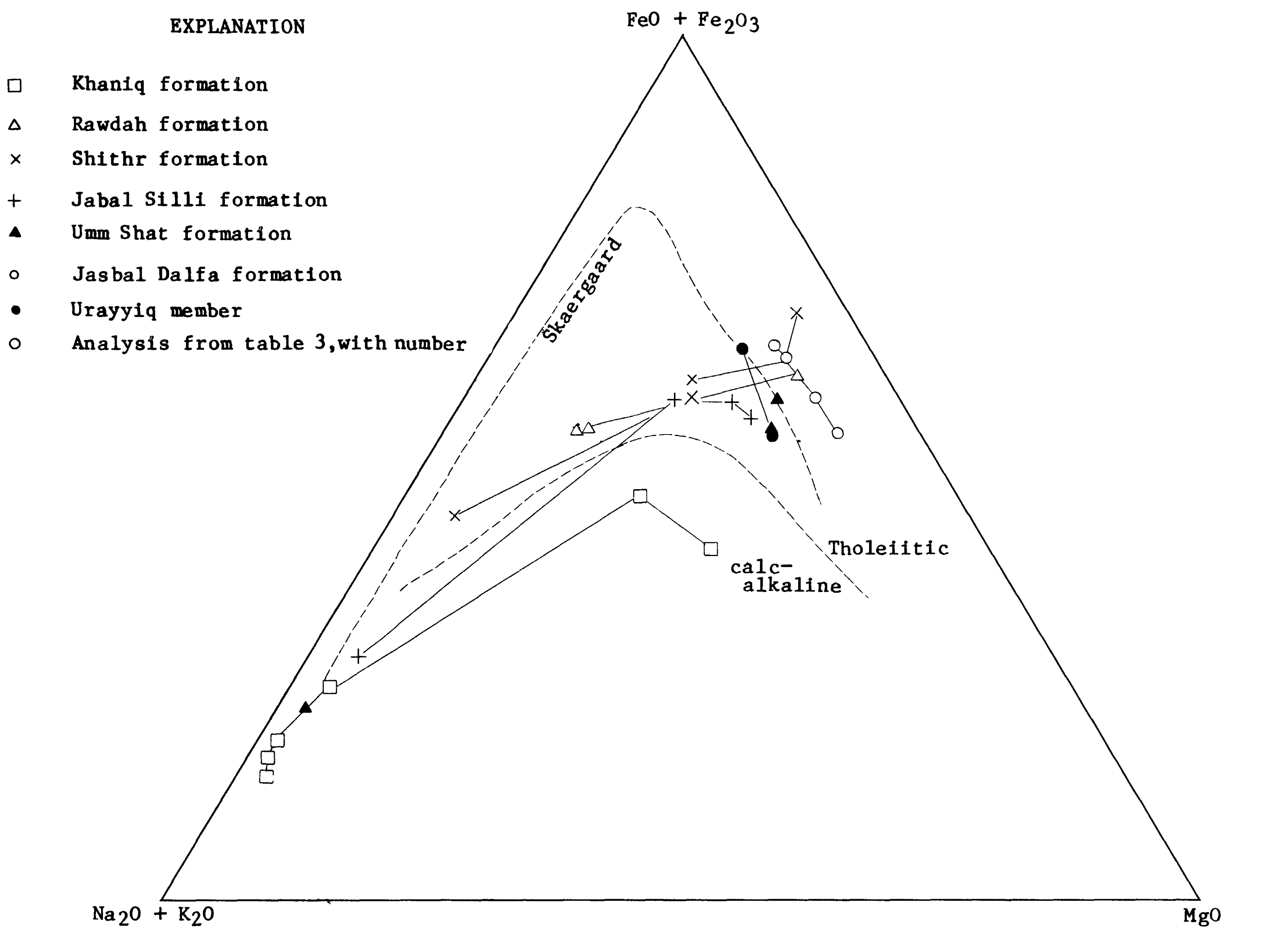

Figure 13.--AFM diagram for volcanic rock suites from the Ranyah area. Symbols as in figures 5 to 12. Tholeiitic-calc-alkaline field boundary from Irvine and Barager, 1971, Skaergaard trend from Wager and Deer, 1939.

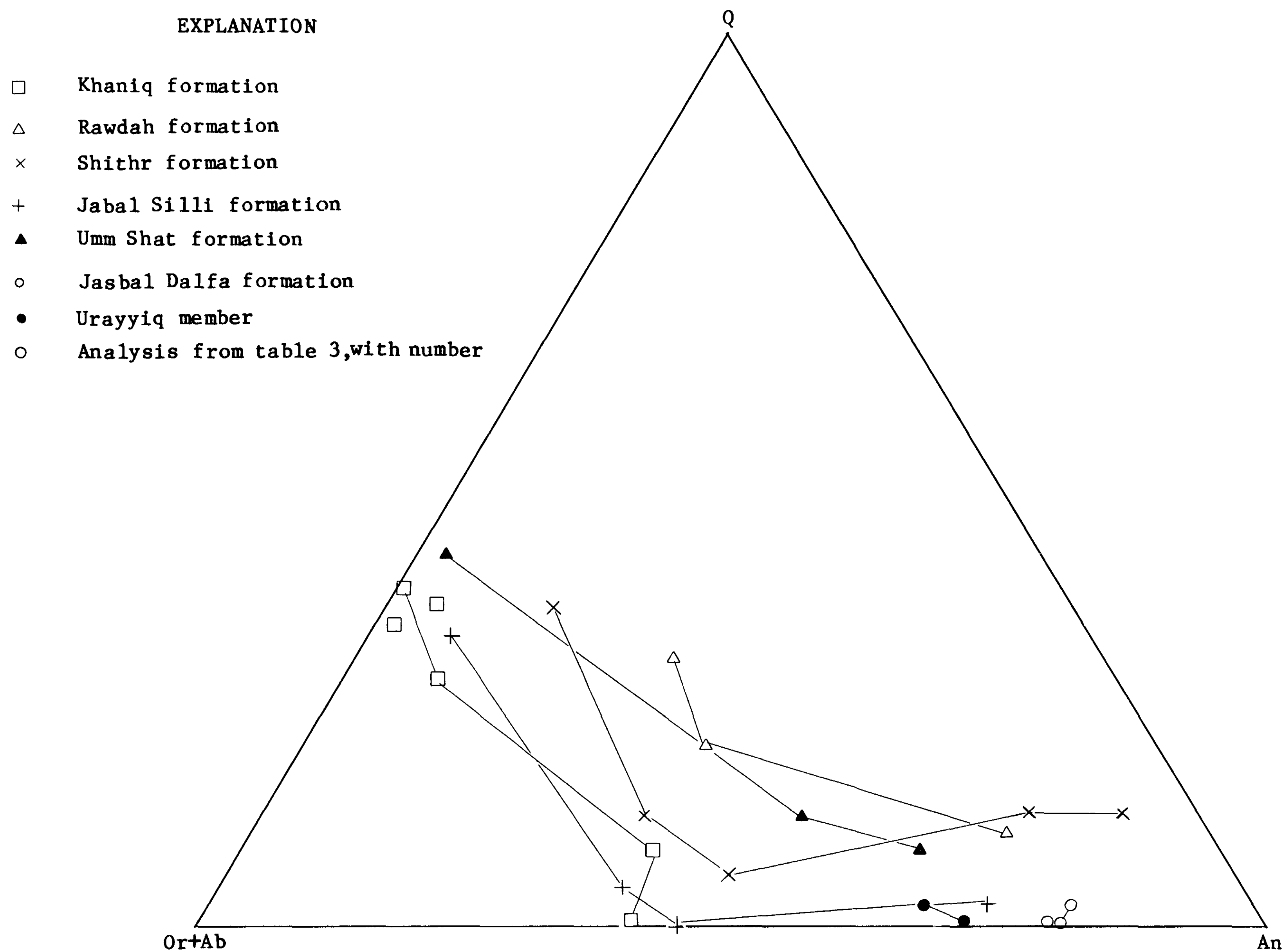

Figure 14.--Q-OR+Ab-An diagram for volcanic rock suites from the Ranyah area. Symbols as in figures 5 to 12.

MINOR-ELEMENT DISCRIMINATION DIAGRAMS

Pearce and Cann (1973) propose several discrimination diagrams utilizing selected trace and minor elements to distinguish ocean-floor (mid-ocean ridge) basalts, low-potassium (island-arc) tholeiites, calc-alkali (island-arc) basalts, and ocean island or continental basalts. Two of these diagrams involve titanium, zirconium, and strontium; analyses for these elements are available for the Al Khaniq, Rawdah, and two of the Shithr rocks. The results of these plots (fig. 15) are not as satisfactory as those for the major elements considered heretofore. All samples are low enough in titanium to plot below or near the bottom of the ocean floor field, but a wide range of zirconium contents spread them indiscriminantly over the tholeiite and calc-alkali fields.

Sun and Nesbitt (1978) have drawn diagrams plotting CaO/TiO_2 and Al_2O_3/TiO_2 ratios versus TiO_2. These diagrams (not illustrated) show, as do the average TiO_2 contents plotted in figure 11, that mid-ocean ridge basalts are characterized by higher TiO_2 than basalts of island arcs. However, there is considerably more overlap, as the mid-ocean ridge basalt field plotted by Sun and Nesbitt extends as low as .6 percent TiO_2, and island arc values as high as 15 percent are shown. Sun and Nesbitt propose that low-titanium basalts originate by partial melting of a depleted source that had experienced a previous episode of extraction of high-titanium magma.

RARE-EARTH ELEMENTS

Analyses for nine rare-earth elements (REE) (table 4) were obtained on two rocks from the Rawdah formation, a basalt with 50.3 percent SiO_2 and a dacite with 63.7 percent SiO_2. Rare-earth elements from the basalt sample (fig. 16) show a slightly fractionated pattern with mild enrichment in light REE. It is similar to many basalts in that REE values range from 5 to 20 times condrite amounts. There is no europium anomaly. Terbium was below detection limit (1.0 ppm) and is not plotted. The pattern is similar to that of several basalts from Rabaul and Talasea, New Britain (Arth, 1981) and is almost identical to sample 8014, a porphyritic basalt from Rabual caldera. The pattern bears no resemblance to ocean-floor basalt such as that from the mid-Atlantic ridge (Frey, 1974) or Samail ophiolite sheeted dikes (Pallister and Knight, 1981) both of which are depleted in light REE. Further, the pattern does not resemble continental basalt such as that from Cat Hills, New Mexico, (Baldridge and others, 1982) which is more highly enriched in light REE.

The dacite sample has a more highly fractionated pattern with light REE close to 30 times chondrite amounts and heavy

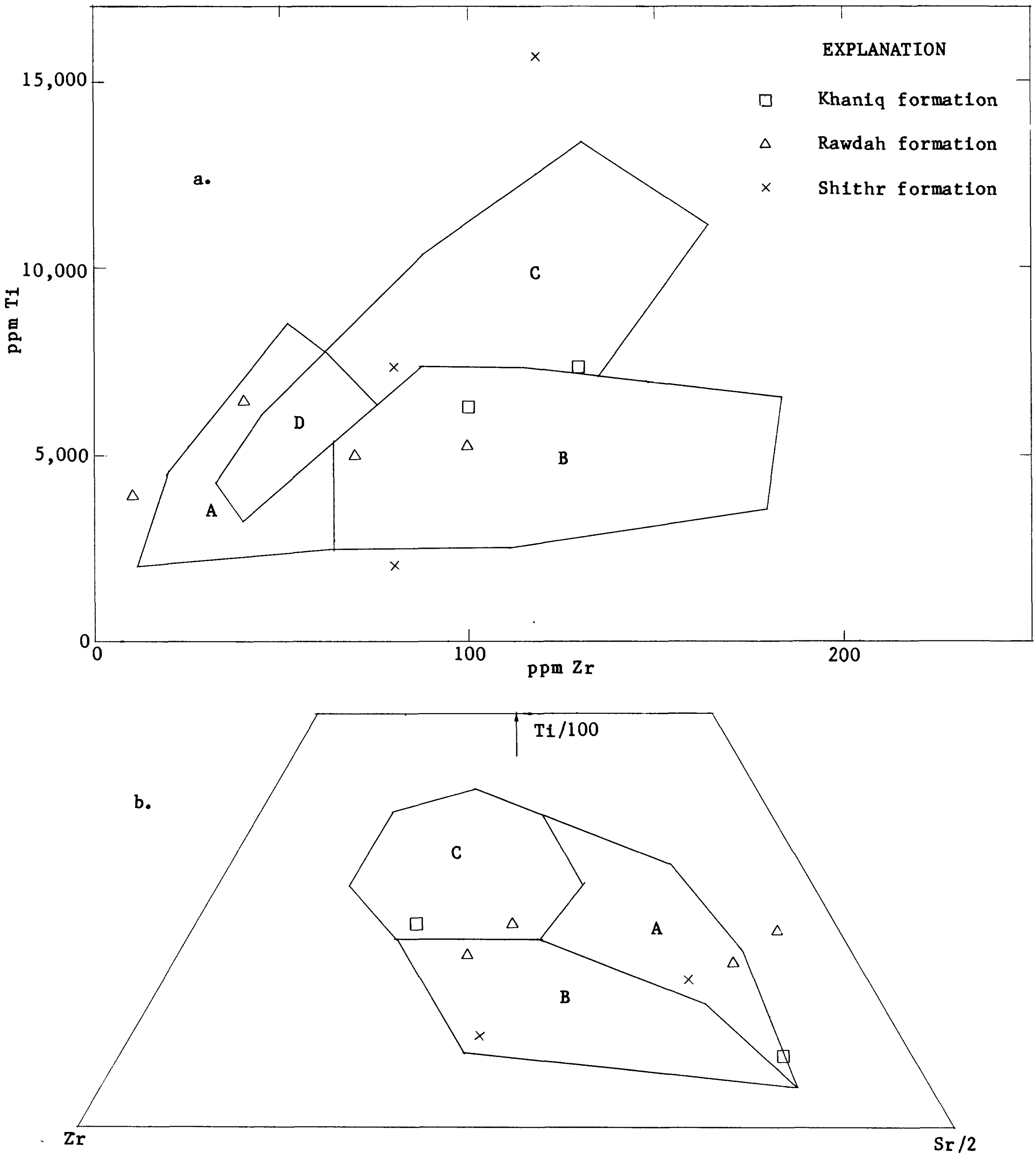

Figure 15—Discrimination diagrams, after Pearce and Cann, 1973.
a. Ti versus Zr; b, Ti/100 versus Sr/2 versus Zr. Field A, low potassium (island arc) tholeiites; Field B, calc-alkali basalts; Field C, ocean floor (mid-ocean ridge) basalts; Field D, field containing all types.

Table 4.--**Rare-earth element analyses for two samples from the Rawdah formation**

[Analysis by Instrumental neutron activation at X-ray Assay Laboratories, Don Mills, Ontario. Results in parts per million]

	Sample number Rock type	138275 Basalt	138273 Dacite
Lanthanum		3.6	10.0
Cerium		10	25
Neodymium		7	18
Samarium		2.2	5.4
Euorpium		0.8	1.4
Terbium		1.0	1.1
Dysprosium		2.4	6.2
Ytterbium		1.5	3.9
Lutetium		.22	0.61

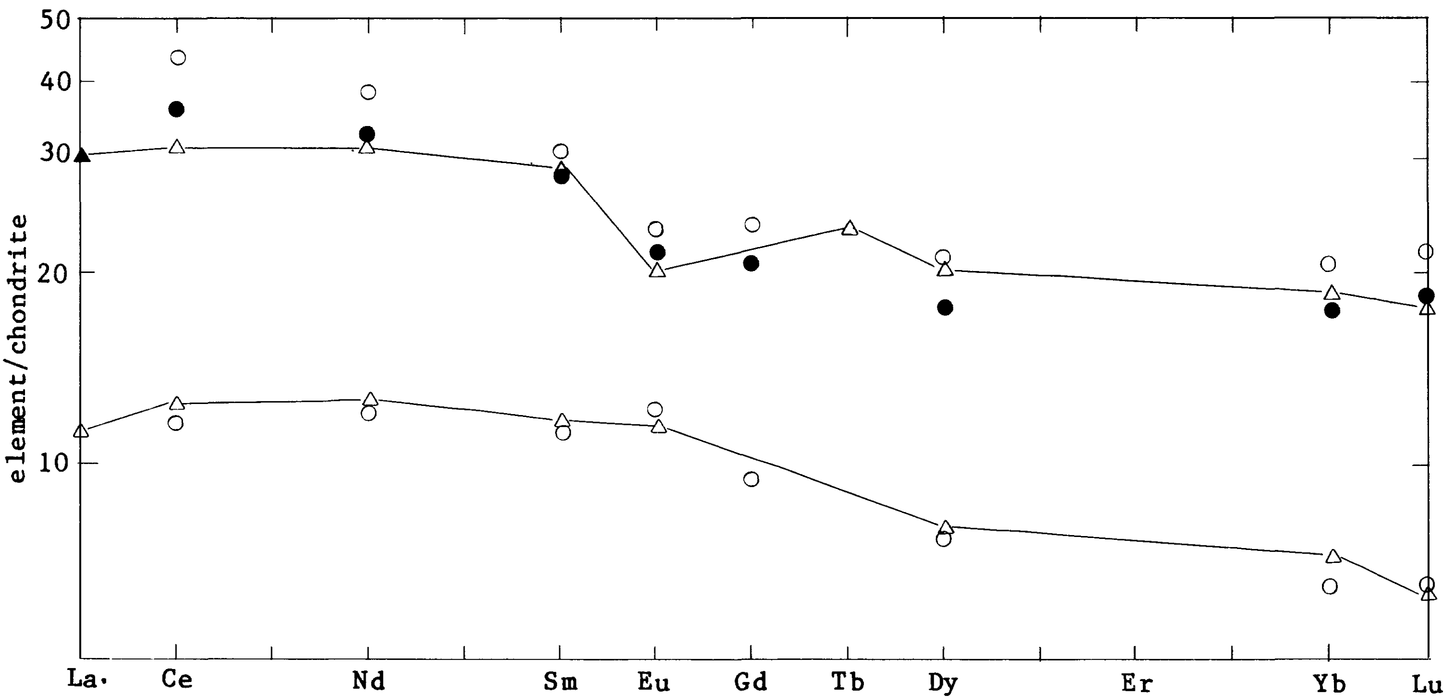

Figure 16.--Chondrite-normalized rare-earth plots for two samples from the Rawdah formation. Triangles, lower line, basalt sample 138275; triangles, upper line, dacite sample 138273; circles, samples from Rabaul caldera, New Britain: small, open circles; porphyritic basalt 8014; small, filled circles, andesite 8015; larger, open circles, dacite 8042.

REE about 18 (fig. 16). There is a negative europium anomaly and terbium is a little above detection limit. The pattern is nearly identical to that for andesite and dacite samples 8015, and 8042 from the Rabaul caldera, New Britain (Arth, 1981). Arth concludes that the REE patterns show that the lavas of New Britain were produced by total equilibrium fractional crystallization from a basalt or basaltic andesite liquid, and are a distinct sequence for each volcanic center. The rare-earth-element data are highly suggestive that the Rawdah suite of rocks originated in an island arc setting similar to that at the Rabual caldera.

SUMMARY AND DISCUSSION

The chemistry of the seven volcanic rock suites from the Ranyah area has been compared with that of volcanic rocks with known tectonic settings and petrologic affinities. Some of the Ranyah area rocks have unusual compositions, low in silica, low in MgO, and high in CaO, but most are readily comparable with the suites taken from the literature.

Basalt and basaltic andesite from each of the Ranyah area units are most nearly similar to rocks from island arc tholeiitic series, but are also comparable to those of island arc high-alumina and continental margin high-alumina series. This is most clearly shown by their contents of Al_2O_3, TiO_2, and total iron.

Mid-ocean-ridge basalts, oceanic-island tholeiites, and continental tholeiites are clearly not present in the Ranyah area; they have too little Al_2O_3, too much TiO_2, and most have too much iron.

The Talasea-New Britain island-arc tholeiitic trend and the Andes-Cascades continental-margin calc-alkaline trend are similar for total alkalis, MgO, CaO, and TiO_2, but are distinct for Al_2O_3 and total iron. These trends generally follow the trends of the Ranyah rea suites that contain rhyolite - Al Khaniq, Shithr, Jabal Silli and Umm Shat. Trends for Al_2O_3 and total iron suggest that the Al Khaniq series is more closely comparable to the Andes-Cascades continental margin trend.

Kuno (1960) originally described high alumina basalt from the Huzi Volcanic zone in central Honsyu and the Izu Islands. It is a type intermediate in alkali content between tholeiite and alkali basalt. High-alumina basalt from this area has a higher Al_2O_3 content, generally 17 to 20 percent, than the other basalt types. Later, Kuno (1966) extended high-alumina basalt into a high-alumina rock series including andesite, dacite and rhyolite. This series is defined strictly on the basis of total alkalis versus silica content, as is shown by the field boundaries on figure 12, and has nothing to do with alumina content. The high-alumina rock series used for comparison in this paper (nos. 15, 16, 21, 22) plot in Kuno's high-alumina field (fig. 12); however, some of the tholeiitic series rocks (nos. 5, 9 to 11) also plot there, whereas others (nos. 6, 8, 18 to 20) plot in the tholeiitic field.

Ti-Zr and Ti-Zr-Sr diagrams (fig. 15, Pearce and Cann, 1973) give additional, though marginal, evidence for an island arc origin for the Rawdah, Shithr and Al Khaniq rocks and the rare-earth-element data strongly suggests that the Rawdah rocks originated in an island arc tholeiite series. Hence, the bulk of the major and trace element data lead to the assignment of the Rawdah, Shithr, and Umm Shat rocks to tholeiitic series originating in island arcs. Jabal Silli rocks are somewhat richer in alkalis and Al Khaniq rocks are still more so, the latter lying in Kuno's high-alumina field. The Jabal Dalfa and Urayyiq rocks are unusually low-silica, island-arc tholeiites with low MgO and high CaO contents and distinct iron enrichment.

The major element geochemical data has shown that most of the volcanic rock units from the Ranyah area belong to island-arc tholeiitic series and resemble rock suites from modern primative, or immature island-arc settings. The rare-earth-element data for the Rawdah formation is also very primative.

Roobol and others (1983; Introduction to this report) find that only sequence C, the oldest rocks, bear the geochemical signature of immature arcs. The age evidence for the Ranyah area rocks is not unequivocal, but the presumed age range of 785 to 745 Ma falls in Roobol and others sequence B; therefore this study does not confirm their general scheme.

Schmidt and Brown's (in press) total alkalis versus silica and AFM diagrams include such a wealth of data that the analyses in this report could be added without extending the ranges of plotted points. Also, several suites of rocks, notably those from the Halaban group and several groups from the cratonization suite, extend to much more alkalic compositions than any represented in the Ranyah area. The Khaniq formation rocks fit in the cratonization suite on the total alkalis versus silica diagram.

The AFM diagram, however, for the Ranyah area rocks shows most of the units to be tholeiitic, while those reported by Schmidt and Brown are calc-alkaline with scattered analyses plotting in the tholeiitic field. The Ranyah area study shows that a local study of one or a few units can reveal information that is lost when a quantity of data are plotted together.

During late Proterozoic time, the Ranyah area evidently evolved from an island arc to a continental setting. Previous authors (Schmidt and others, 1979, Greenwood and others, 1980, 1982) have proposed an island arc origin for much of the southern Arabian Shield, and that interpretation is confirmed by the geochemistry of the Rawdah, Jabal Dalfa, Jabal Silli, Sithr, and Umm Shat formations and the metabasalt in the Urayyiq member. Geologic evidence shows that the region later became continental, as vast quantities of tonalitic to granitic gneiss (fig. 2, unit hgn) were intruded and domed upward in the western two-thirds of the Ranyah area (Greene, in press, 1982b), and areas to the north (Greene, unpublished data) and south (Schmidt, in press, in press, in press). The gneiss doming is part of the culminant orogeny discussed by Schmidt and others (1979) and Schmidt and Brown (in press).

Volcanic rocks of the Khaniq formations were extruded during the culminant orogeny, but their geochemistry has been shown to be consistent with a continental margin setting. The magma from which they originated evolved into a somewhat more alkalic composition, as is shown by the composition of the Kawr Barahah granite which intruded the volcanic pile (fig. 2, Greene, in press). Since the Khaniq formation is substantially younger than the other units studied for this report, it is not possible to establish the position of a dipping subduction zone by the change in chemistry, as suggested by Kuno (1966).

The Nabitah fault zone, with its accompanying belt of serpentinite intrusions, is present in the southeast part of the area and extends about 220 km to the south to near Hamdah (Schmidt and others, 1979). Schmidt and others believe that the Nabitah fault represents a suture. However, similar types of rocks are found on each side of the fault in the Jabal Dalfa quadrangle (fig. 2; Greene, 1982a). Najd faults, however, outcrop in the northeast and east-central parts of the area (fig. 2) and underlie much of the intervening gravel plain, as suggested by the aeromagnetic map of the Jabal Dalfa quadrangle (Greene, 1982a) and by projection from the adjacent Bir Juqjuq quadrangle (Hadley, 1976). The Najd faults separate a geologic province distinct from the one including the rest of the area, one underlain by gneiss (fig. 2, unit gn), the Arfan and Murdama formations, and in the Bir Juqjuq quadrangle, the Juqjuq formation and granite.

Dodge and others (1979) made a geochemical study of volcanic rocks from the Arfan and Juqjuq formations, which are, according to the latest information (Darbyshire and others, 1983), of an age similar to the Khaniq formation. The total alkalis versus silica plot for the Arfan and Juqjuq shows that these rocks belong to alkali or high-alumina series and the AFM diagram shows a calc-alkaline trend. The rare-earth-element data support an origin in a calc-alkaline or alkaline island-arc series.

Dodge and others believe that that the original setting of these rocks resembles the Cascade mountains of the north-western United States, a continental margin setting.

Sice the metavolcanic rocks of the Arfan and Juqjuq formations lie in a different geologic province and have a different geochemical signature than most of the Ranyah area rocks, and have now been shown to be considerably younger, they must be related to an entirely different subduction system.

DATA STORAGE

Field data and other supporting documents related to this report have been archived in data file USGS-DR-04-19 (Greene, 1984). No new Mineral Occurrence Documentation System (MODS) localities were established.

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