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Geology of the Silsilah ring complex, and associated tin mineralization, Kingdom of Saudi Arabia—a synopsis

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Abstract

A significant tin deposit has been identified in the northeast part of the Late Proterozoic Arabian Shield. Cassiterite–topaz–quartz greisens are distributed over 16 km^2 in flat-topped cupolas of a highly evolved, zinnwaldite-bearing alkali-feldspar granite which composes part of the Silsilah ring complex (lat 26°06′N, long 42°40′E). The 587 m.y. old alkali-feldspar granite is overlain by a carapace of aplite and pegmatite. The carapace acted as an impermeable boundary, beneath which fluids accumulated and caused greisenization of the alkali-feldspar granite and deposition of disseminated cassiterite. Subsequently emplaced quartz-wolframite veins cut the alkali-feldspar granite and the aplite-pegmatite carapace.

The rest of the Silsilah ring complex is composed of peralkaline granite, its hypabyssal equivalent, and alkaline dacite. The occurrence of alkaline dacite, peralkaline granite, and alkali-feldspar granite (oldest to youngest) in a single ring fracture suggests that these rocks form a single differentiation series. Major, trace, and rare-earth element data support this hypothesis. The alkaline dacite evolved to the peralkaline granite by fractionation of sodic plagioclase and Fe–Ti oxides. The peralkaline granite continued differentiation by fractionation of anorthoclase, Na-pyriboles, and zircon. This process yielded the peraluminous composition, incompatible trace element enrichment, and flat REE patterns with large negative europium anomalies that are characteristic of the alkali-feldspar granite. This unusual differentiation trend may be typical of other, highly evolved intrusive suites and associated, yet undiscovered, tin-tungsten deposits in the Arabian Shield.

Introduction

Deposits of tin, tungsten, and other rare metals are associated with a group of petrologically similar granitoid rocks known variously as S-type (Chappell and White, 1974), ilmenite series (Ishihara, 1977), and metallogenically specialized (Tischendorf, 1977). These rocks are characterized by highly evolved major element compositions, incompatible trace element enrichment, are peraluminous, and often contain an aluminum-rich silicate such as muscovite. Mineral exploration programs have demonstrated that rocks of this type also occur within the Precambrian Arabian Shield (Elliott, 1980; Stoeser and Elliott, 1980; du Bray and others, 1982; du Bray, 1983a) and that the potential for discovery of deposits of tin, tungsten, and other rare metals associated with these highy evolved granitoid rocks is significant.

Results of a systematic geochemical survey in the northeast Arabian Shield (Allen et al., 1983) indicate that wadis that drain the Silsilah ring complex (Fig. 1) contain highly anomalous concentrations of Be, Nb, Pb, and Sn. Du Bray (1983b) identified the Fawwarah alkali-granite, a component of the complex, as a metallogenically specialized granite and subsequently identified two intensely mineralized, cassiterite-bearing greisens. A large body of milky white quartz, numerous weakly mineralized greisen pods, quartz veins in greisen envelopes, and quartz-wolframite veins, all found in the southwest part of the complex indicate that an extensive hydrothermal system was once active here. Percussion drill samples of the cassiterite-bearing greisens contain an average tin content of less than 1000 ppm, although some 1 m intervals contain as much as several percent tin. The economic viability of the deposit could be predicated by the location of a very large tonnage of low-grade ore.

General characteristics of the Silsilah ring complex

The Silsilah ring complex is an igneous suite, mostly composed of highly evolved rocks (du Bray, 1983b), that crops out in a ring fracture centered at lat 26°07′ N. and long 42°42′ E. (Fig. 1). A U–Pb zircon age for the Fawwarah alkali-feldspar granite, the youngest component of the ring complex, is 587±8 m.y. (J. S. Stacey, written comm., 1984). Rocks of the ring complex intrude graywacke of the Murdama group. The sandstone, locally known as the Maraghan lithic graywacke, crops out within the ring complex and occurs in a very large area outside the ring. The rocks exposed in the ring complex form a prominent toroidal topographic feature, hereafter referred to as the ring, 12 km in diameter that rises between 10 and 300 m above the surrounding pediment surface; the average relief along the ring is about 100 m. The cross-

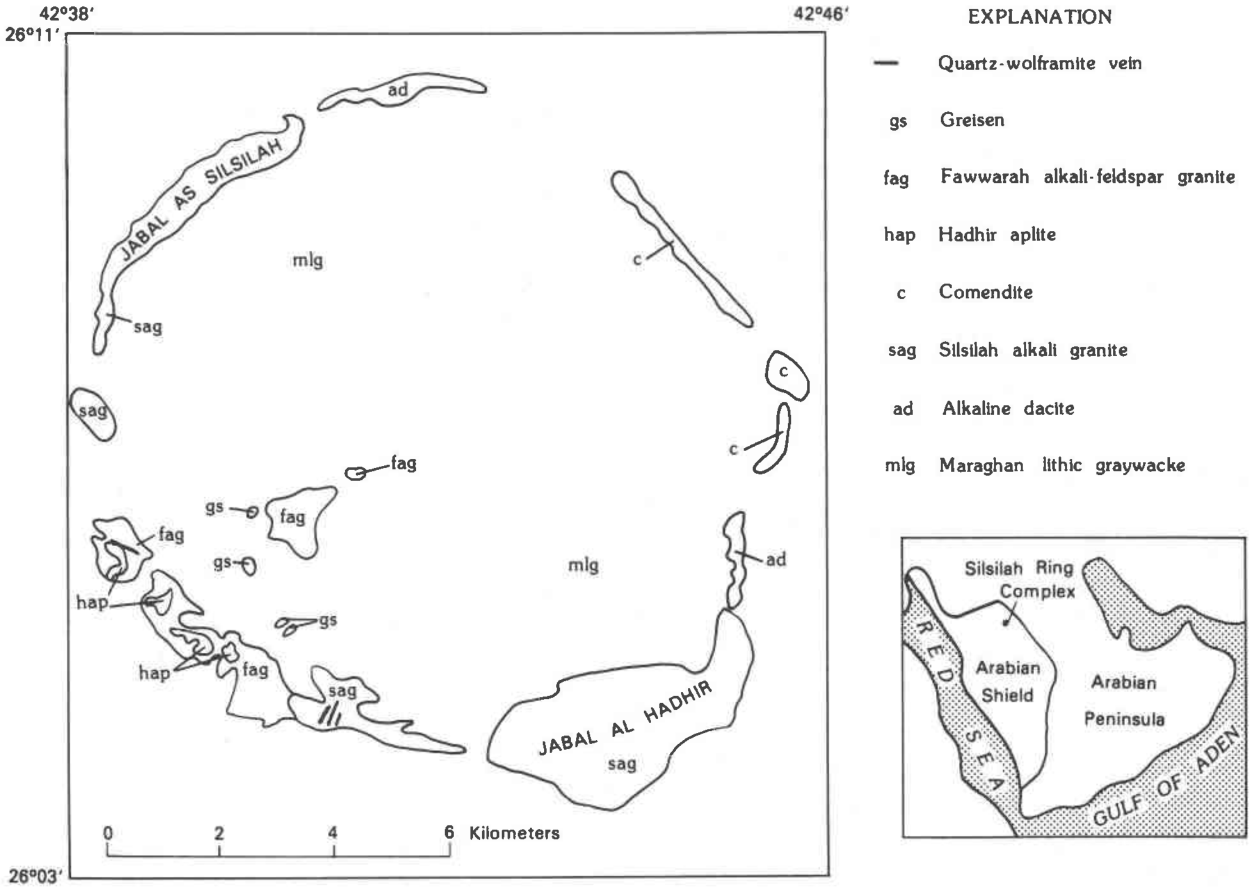

Fig. 1. Geologic sketch map of the Silsilah ring complex.

sectional dimension of the toroidal feature is between 30 m in the northeast and about 3 km in the southeast.

Three principal and several minor rock types comprise the ring complex (Fig. 1). The northwest and southeast quadrants of the complex are composed of Silsilah alkali granite, the southwest quadrant of Fawwarah alkali-feldspar granite, and the Hadhir aplite forms a sill-like mass that crops out on top of the alkali-feldspar granite. These rocks account for about 40, 20, and 10 percent of the ring complex, respectively. Two other lithologies crop out in the northeast and southeast quadrants of the complex and together account for about 30 percent of its area. One is very fine grained alkaline rock composed of mugearite, benmoreite, trachyte, and tristanite (Irvine and Baragar, 1971). These are the alkaline analogs of dacite in the system of subalkaline volcanic rocks, and are called alkaline dacites hereafter for simplicity. The other is composed of fine-grained, porphyritic comendite (Noble, 1968). Quartz-potassium feldspar pegmatite crops out between the Fawwarah alkali-feldspar granite and the Hadhir aplite. Quartz veins penetrate each of the plutonic units, and a pegmatitic plug is located 1 km inside the southwest margin of the ring. Two strongly mineralized greisens are located near the plug. Weakly mineralized greisen pods occur at several places inside the southwest part of the ring and several more occur within the Fawwarah alkali-feldspar granite.

The Maraghan lithic graywacke is intruded by, and therefore is older than, rocks of the Silsilah ring complex. These layered rocks occur everywhere at the outer periphery of the ring complex and in a circular area of about 40 km^2 within the ring. It is a massively bedded immature sandstone with minor interbedded siltstone. Stoping does not seem to have been operative during emplacement of the ring complex rocks because blocks of the host metasedimentary rocks found within the intrusive units are rare and of limited size. The Maraghan lithic graywacke was regionally metamorphosed in lower greenschist facies conditions. Locally, the grade was very slightly enhanced by emplacement of the ring complex.

The alkaline dacite is locally tuffaceous and vesicular, suggesting that some of the magma vented and that the remainder solidified at a shallow depth. Intrusive relations indicate that the alkaline dacite magma was emplaced prior to the other components of the complex. This grayish-black to blackish-red rock weathers recessively and forms dike-like outcrops.

The comendite is characterized by petrographic attributes similar to those of the Silsilah alkali granite, which suggests that it represents part of the alkali granite magma that was quenched at a shallow level in the ring fracture. This unit intrudes, and therefore is younger than, the alkaline dacite. This pale-reddish brown comendite forms prominent dike-like outcrops.

The Silsilah alkali granite is the volumetrically predominant component of the ring complex. Intrusive relations at the southeastern edge of the ring complex indicate that the Silsilah alkali granite intrudes and therefore is younger than the alkaline dacite and the comendite.

The Hadhir aplite is a volumetrically minor component of the complex. It crops out in a flat-lying sheet less than 50 m thick on top of the Fawwarah alkali-feldspar granite in the southwest part of the complex. The aplite also crops out as recessive-weathering slabs located inside the southwestern limit of the ring complex where again it appears to rest on top of the Fawwarah alkali-feldspar granite. About 4 km west of Jabal al Hadhir at the southern limit of the complex a sill-like mass of aplite approximately 15 m thick underlies the Silsilah alkali granite and indicates that the aplite intrudes and therefore is younger than the alkali granite.

Coarse grained quartz and potassium feldspar in graphic intergrowth form a flat-lying pegmatite sheet that pinches and swells along strike between the Hadhir aplite and the underlying Fawwarah alkali-feldspar granite. It consists of a series of coalescing pegmatite pockets and layered aplite. It is between 0.1 and about 10 m thick, and locally contains large, bladed interstitial crystals of oxidized fayalite. Contacts between the pegmatite and both the alkali-feldspar granite and the aplite are gradational.

The Fawwarah alkali-feldspar granite crops out prominently throughout the southwestern quadrant. Intrusive relations between the Hadhir aplite and the alkali-feldspar granite indicate that the latter is younger. It crystallized below the structurally coherent, impermeable, aplitic carapace.

The large size and circular shape of the Silsilah ring complex and the fine grain size characteristic of much of the rock that composes it suggest that it represents magma that was emplaced in the near surface part of a major, closely-spaced ring fracture system. Elliptical pegmatitic pockets found throughout the Hadhir aplite and the Fawwarah alkali-feldspar granite and the compositional similarity between the intrusives and experimentally determined low pressure minimum melt compositions indicate that they crystallized at very shallow depths.

Evidence in favor of piston-like subsidence of a central core, like that demonstrated for large calderas (Smith and Bailey, 1968), is scarce. The concentric fault patterns that are found in areas where caldera core subsidence has occurred are not apparent. A shallow trench excavated radially inward from the alkali-feldspar granite-alluvial interface demonstrates that the host lithic graywacke is not in fault contact with the rocks of the complex. The presence and structural coherence of the Maraghan lithic graywacke inside the ring also argues against a major episode of cauldron subsidence. These rocks would, in most cases, be significantly more disrupted and dismembered, had they experienced significant piston-like subsidence. There is little evidence of copious dike injection that would have occurred in a structurally dismembered, foundered block located above an active magma chamber.

Several lines of evidence indicate that rock, presumably the central pluton from which the currently exposed rocks of the ring complex evolved, is present at a shallow depth below the graywacke. Audiomagnetotelluric profiles across the ring indicate that the depth to intrusive rock at the center of the ring, that is the thickness of the graywacke, does not exceed several hundred meters (Flanigan and Zablocki, 1983). The presence of the two cupola-like bodies of Fawwarah alkali-feldspar granite inside the ring (Fig. 1), of aplite dikes that penetrate the graywacke, and of hydrothermally altered rock throughout the southwestern quadrant of the complex also suggest that intrusive rock is present close to the surface. At the present level of exposure, all extrusive products that may have been part of the system have been removed by erosion.

Petrography

Host rock

The Maraghan lithic graywacke is principally composed of brownish-green to olive-gray fine sandstone and siltstone. The matrix is a silt-size intergrowth of turbid, fine-grained clay minerals. Volcanic lithic clasts (50%) outnumber monocrystalline quartz clasts (30%), which in turn are more abundant than subangular clasts of plagioclase (20%). The lithic fragments are felsite, turbid grains of argillite, and distinctive, fine-grained volcanic clasts that contain small phenocrysts of plagioclase.

Intrusive rocks

The alkaline dacite is hypidiomorphic inequigranular and is composed of an intergranular to weakly trachytic intergrowth of sodic plagioclase and iron-titanium oxides. Most samples are composed of between 50 and 80% unzoned, subhedral plagioclase laths 0.2 mm long. Anhedral to subhedral grains of iron-titanium oxides 0.05 mm in diameter compose from 20 to 30% of the rock. Apatite, which occurs in subhedral grains as much as 0.01 mm long, is the only accessory mineral.

The comendite is allotriomorphic to hypidiomorphic granular and distinctly porphyritic. Quartz forms rounded to bipyramidal, anhedral to subhedral phenocrysts as much as 4 mm in diameter that compose about 5% of the rock. Anorthoclase forms subhedral to euhedral laths as much 4 mm long that compose as much as 60% of the rock. Ragged interstitial iron-titanium oxide grains are 0.2 to 4 mm in diameter and compose about 1%. Spindle shaped laths of arfvedsonite as much as 0.5 mm long compose another 2 to 3%. Anhedral, interstitial albite forms as much as 10%. The matrix is characterized by irregularly-shaped, interstitial patches of quartz and feldspar in micrographic intergrowth and by spherulitic overgrowths of alkali feldspar on quartz and anorthoclase phenocrysts.

The grayish-red Silsilah alkali granite is hypidiomorphic granular and is locally characterized by a micrographic groundmass. The felsic constituents are plagioclase, quartz, and anorthoclase (Fig. 2). Average contents of these minerals are 10, 21, and 63%, respectively; the color index is 6. Phenocrysts of quartz and anor-

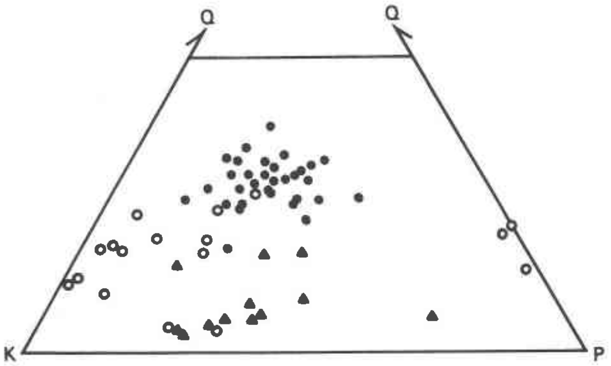

Fig. 2. Quartz-potassium feldspar–plagioclase (QKP) ternary diagram showing the modal composition of the Silsilah ring complex components. Each plotted point represents a modal analysis (between 400 and 700 points counted on a stained slab measuring at least 50 cm^2) for a single sample. Albite is counted as plagioclase so that the ratio of albite to potassium feldspar is discernible. Properly plotted for modal classification (Streckeisen, 1976) these points plot on the quartz–alkali feldspar sideline of the ternary at the indicated modal quartz content. Plot symbols: open circles—Silsilah alkali granite, triangles—Hadhir aplite, solid circles—Fawwarah alkali-feldspar granite.

thoclase give the rock a distinctly porphyritic character. Anhedral, rounded quartz phenocrysts are as much as 2.5 mm in diameter. Blocky laths of perthitic anorthoclase form subhedral to euhedral phenocrysts as much as 4 mm long that are Carlsbad-twinned. Albite forms subhedral phenocrysts as much as 1 cm long in a few samples but is principally found in the groundmass. Soda pyriboles such as katophorite, minor arfvedsonite, and aegirine-augite are the mafic silicates in the alkali granite. Fayalite was identified in one sample. Abundant zircon, iron-titanium oxides, and allanite are the accessory minerals. The groundmass is a fine-grained, allotriomorphic granular intergrowth composed of quartz and perthitic alkali feldspar.

The Hadhir aplite is fine grained and allotriomorphic inequigranular. The felsic constituents are albite, quartz, and potassium feldspar (Fig. 2). Average contents of these minerals are 33, 9, and 56%, respectively; the color index is 2. The apparently low quartz content of this rock may be spurious and could result from the difficulties encountered in performing modal analyses of fine-grained rocks such as this. Quartz, albite, and potassium feldspar form scarce, anhedral phenocrysts as much as 2 mm in diameter. Potassium feldspar phenocrysts are perthitic and partly altered to clay minerals. Biotite and white mica form scarce anhedral to subhedral crystals as much as 1 mm long. The white mica is weakly pleochroic from colorless to very light brown and is probably zinnwaldite. Fluorite is the principal accessory mineral and forms anhedral grains as much as 0.8 mm in diameter. The groundmass is an allotriomorphic, locally micrographic, intergrowth composed of quartz and alkali feldspar. Irregularly shaped, quartz-filled miarolitic cavities as much as 2 mm in diameter are present.

The Fawwarah alkali-feldspar granite is very light gray, medium grained, and allotriomorphic equigranular. The felsic constituents are albite, quartz, and microcline (Fig. 2). Average contents of these minerals are 25, 33, and 38%, respectively; the color index is 4. Quartz forms subround anhedral grains 2 to 3 mm in diameter. Microcline is perthitic and forms anhedral to subhedral grains that are 2 to 3 mm long. Some grains poikilitically enclose grains of albite and quartz. The plagioclase is unzoned albite that forms anhedral to subhedral laths as much as 3 mm long, interstitial to quartz and microcline. White mica and rare biotite are present. The white mica is zinnwaldite and forms subhedral interstitial grains 0.5 to 1.5 mm long that are pleochroic from nearly colorless to either very light brown or very pale bluish green. A trace amount of zircon is present as very small subhedral crystals in the groundmass. Other accessory minerals present include fluorite and topaz. As much as 1 modal% fluorite forms subhedral, purple-tinged grains as much as 1 mm in diameter and wormy, interstitial grains that are commonly associated with the micas. As much as 0.5 modal% topaz forms colorless wormy crystals in the groundmass although it too forms scarce subhedral grains as much as 2 mm in diameter.

Geochemistry of the igneous rocks

Analytical methods are described and individual analyses from which the averages of Table 1 were computed are in du Bray (1984).

Major elements

The major element chemistry of the ring complex components displays systematic variation as a function of age. The alkaline dacite is characterized by low contents of silica and low differentiation indices whereas the younger components, especially the Fawwarah alkali-feldspar granite, are characterized by high silica contents and high differentiation indices (Table 1). Total iron, Al_2O_3, MgO, CaO, TiO_2, P_2O_5, and MnO contents decrease from the older to the younger rocks, that is, from the low silica to the high silica rocks. Na_2O contents are nearly constant. K_2O contents increase with increasing silica contents, reach a maximum in samples of the alkali granite, and then decrease slightly with increasing silica. Fluorine contents increase with increasing silica contents. The Na_2O/K_2O ratio in samples of the complex varies discontinuously.

The alkaline dacite and comendite were treated as volcanic rocks and classified on the basis of their chemistry. Samples of the alkaline dacite are metaluminous and follow an iron-enrichment trend (Fig. 3) similar to that displayed by the rocks of the Skaergaard intrusion (Wager and Deer, 1939). The alkaline dacite is characterized by high alkali element content, high total iron content, and low silica content. Samples of this rock type are alkaline, as defined by Irvine and Baragar (1971); members of both the sodic and potassic suites of alkaline rocks are represented in the complex. The composition of the alkaline dacite ranges from benmoreite and mugearite to tristanite and trachyte. The tristanite and trachyte are compositionally transitional to samples of comendite. The chemistry of comendite samples (Figs. 3–5) support the petrographic inferrence that these rocks are quenched equivalents of the Silsilah alkali granite. The samples are peralkaline and acmite normative.

Major element analyses for the three principal constituents of the ring complex indicate that these are highly evolved rocks (Table 1). The Silsilah alkali granite is weakly peralkaline and acmite normative. Differentiation indices indicate that the Silsilah alkali granite is slightly more evolved than the low-calcium granite (Table 1). In particular, the alkali granite is characterized by greater contents of Na_2O, K_2O, CaO, TiO_2 and total iron and lower contents of Al_2O_3, MgO, and P_2O_5. The Hadhir aplite is metaluminous whereas the Fawwarah alkali-feldspar granite is weakly peraluminous and corundum normative. The differentiation indices for samples of these two plutons are greater than that of the low-calcium granite; the aplite is a little less evolved than the alkali-feldspar granite. These two plutons are characterized by very high contents of SiO_2; high contents of Na_2O, K_2O, and F; and very low contents of total iron, MgO, CaO, TiO_2, P_2O_5, and MnO.

Certain similarities exist between the major element

Table 1. Average composition of Silsilah ring complex components. N, indicates not detected at the indicated value; L, indicates less than the indicated value; hyphen indicates not present; ND, indicates not determined.

Unit Number samples	Alkaline dacite (4)	Silsilah alkali granite (5)	Hadhir aplite (2)	Fawwarah alkali-feldspar granite (5)	low Ca granite* (2327)
	Major element analyses, in weight percent				
SiO_2	53.2	73.0	74.7	75.0	74.2
Al_2O_3	14.0	12.7	12.5	13.2	13.6
Fe_2O_3	10.6	1.71	0.14	0.23	0.81
FeO	1.28	0.82	.20	.45	1.10
MgO	1.50	.12	.09	.05	.27
CaO	4.19	.74	1.23	.38	.71
Na_2O	4.64	4.40	3.90	4.50	3.48
K_2O**	2.65	5.19	5.14	4.51	5.06
H_2O	3.90	.45	.75	.48	ND
TiO_2	1.89	.25	.07	.03	.20
P_2O_5	0.65	.03	.02	.02	.14
MnO	.15	.06	.01	.02	.05
F	.10	.07	.37	.31	.09
Total(-O)	98.75	99.84	98.96	99.34	99.67
	CIPW norms, in weight percent				
Q	8.4	27.2	31.7	31.5	32.9
C	-	-	-	0.9	1.7
or	15.9	31.0	30.9	26.9	30.0
ab	39.8	38.0	33.6	38.4	29.5
an	9.7	-	1.4	-	2.1
ac	-	0.7	-	-	-
wo	2.4	1.3	0.8	-	-
en	3.8	.3	.2	.1	0.8
fs	-	-	.2	.6	1.0
mt	-	2.1	.2	.3	1.2
hm	10.7	-	-	-	-
il	3.1	.5	.1	.1	.4
ap	1.6	.1	-	-	.3
fr	0.1	.1	.8	.5	.2
D.I.†	64.0	94.9	96.2	96.9	92.4
	Trace elements, in parts per million††				
Li	28	22	123	513	40
F	1014	641	2667	3617	850
Rb	63	108	297	669	170
Sr	415	35	17	20	100
Y	37	46	71	105	40
Zr	330	515	124	116	175
Nb	35	47	30	50	21
Ba	848	127	35	17L	840
Sn	5N	10L	22	80	3
U	2.1	4.3	6.9	11.9	3
Th	5.7	12	22	33	17
	Rare-earth elements, in parts per million††				
La	50	114	22	18	55
Ce	107	219	53	58	92
Nd	55	101	33	30	37
Sm	12	18	9.8	11	10
Eu	3.61	0.84	0.2	0.13	1.6
Tb	1.72	2.04	2.3	2.4	1.6
Dy	9.4	12.6	15	18	7.2
Yb	4.3	8.02	8.9	16	4
Lu	0.64	.91	1.30	2.33	1.2

* Turekian and Wedepohl (1961)
** Includes 2.63 percent CO_2
† Differentiation index = Q + or + ab
†† Trace element averages for the four units are based on 9, 43, 15, and 53 samples, respectively. Averages for U and Th are based on the number of samples indicated at the top of the table

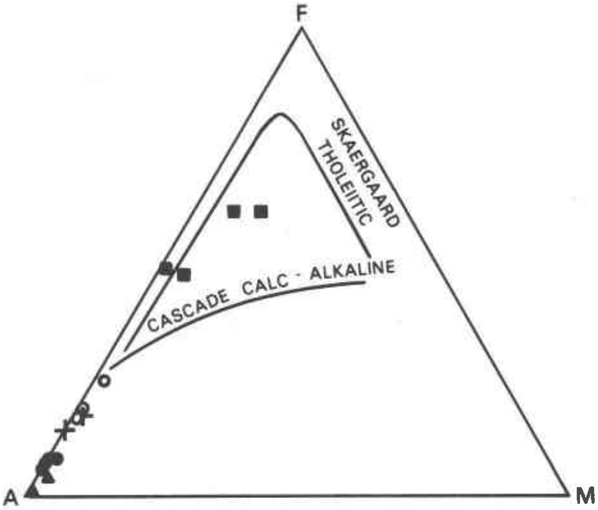

Fig. 3. Alkali–iron–magnesium (AFM) ternary diagram, in weight percent, for samples of the Silsilah ring complex. A = $(Na_2O + K_2O)$, F = $(FeO + 0.8998 \times Fe_2O_3)$, M = MgO. Trend lines from Irvine and Baragar (1971). Plot symbols: squares—alkaline dacite, plusses—comendite, open circles—Silsilah alkali granite, triangles—Hadhir aplite, solid circles—Fawwarah alkali-feldspar granite.

composition of some components of the Silsilah ring complex and highly evolved igneous rocks identified elsewhere in the World. The aplite and especially the alkali-feldspar granite have compositions similar to those presented by Tischendorf (1977) for metallogenically specialized granites. Similarities also exist between the composition of the alkali-feldspar granite and the aplite and S-type granites (White and Chappell, 1977), ilmenite-series granites (Ishihara, 1977), and topaz rhyolites (Burt et al., 1982). Each of these highly evolved rock types, like the metallogenically specialized granites, is associated with deposits of tin, tungsten, and other rare metals. In contrast, the composition of the Silsilah alkali granite is not as evolved as compositions of these highly evolved rock types.

Trace elements

Each of the three principal ring complex components can be distinguished on the basis of trace element composition. Relative to the average low-calcium granite (Turekian and Wedepohl, 1961) the Silsilah alkali granite is depleted in Li, F, Rb, Sr, Ba, and Th and is enriched in Y, Zr, Nb, Sn, U, and Be; its Rb/Sr ratio is 3.1 and is slightly greater than that of the low-calcium granite. The trace element chemistry of the comendite is similar to that of the Silsilah alkali granite (Fig. 5), which confirms that it is the quenched equivalent of the alkali granite. The Hadhir aplite is enriched in Li, F, Rb, Y, Nb, Sn, Th, U, and Be and depleted in Sr, Zr, Ba, and Cu; its Rb/Sr ratio is 17.5 and is much greater than that of the low-calcium granite. The Fawwarah alkali-feldspar granite is enriched in Li, F,

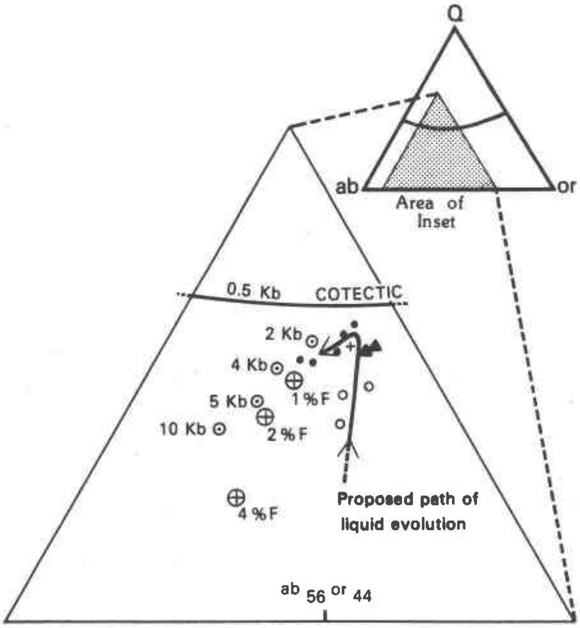

Fig. 4. Ternary diagram showing the normative quartz, albite, and orthoclase contents (Q–ab–or) of components of the Silsilah ring complex. Circled points from top right to bottom left, represent the minimum melting compositions in the experimental system SiO_2–$KAlSi_3O_8$–$NaAlSi_3O_8$–H_2O for $P(H_2O) = P(Total) = 2, 4, 5, 10$ kbar (Winkler and others, 1975). Circled pluses indicate minimum melting compositions at 1 kbar with excess H_2O and 1, 2, and 4% fluorine (Manning, 1981); other plot symbols as in Fig. 3.

Rb, Y, Nb, Sn, Th, U, and Be and depleted in Sr, Zr, Ba, and Cu; its Rb/Sr is 28.1 and is about fifteen times that of the low-calcium granite. Trace element enrichments and depletions identified in the Hadhir aplite are better developed in the Fawwarah alkali-feldspar granite. The degree to which the latter is enriched in some elements and depleted in others is extreme.

The degree of incompatible trace element enrichment observed in each of these rocks demonstrates that the Hadhir aplite and the Fawwarah alkali-feldspar granite are significantly more evolved than the Silsilah alkali granite (Table 1). Tischendorf (1977) indicates that incompatible element enrichment, including combinations of F, Rb, Li, Sn, Be, W, and Mo and high Rb/Sr ratios are diagnostic characteristics of metallogenically specialized granites. Topaz rhyolites described by Burt et al. (1982) and S-type granites described by Chappell and White (1974) are similarly enriched in these same elements.

The trace element composition of the alkaline dacite is distinct. In particular, these rocks are not enriched, but are depleted instead, in most incompatible trace elements and they contain significantly more barium than the Silsilah alkali granite. The high zirconium content of these rocks is significant in light of the zirconium content of the Silsilah alkali granite.

Rare-earth elements

The REE chondrite-normalized patterns (Table 1, Fig. 6) for the alkaline dacites have a gentle and negative slope and lack a europium anomaly. The comendites have REE patterns identical to those of the Silsilah alkali granite. The total REE content increases from almost 200 ppm in the alkaline dacites to about 450 ppm in the comendites. The total REE content and chondrite-normalized REE patterns for samples of the Silsilah alkali granite are similar to those determined for other peralkaline rocks in the northeastern Arabian Shield (Stuckless et al., 1982). Of the rocks that compose the Silsilah ring complex, the Silsilah alkali granite has the highest average REE content, 469 ppm. The REE patterns are negatively sloping, parallel to the average pattern for the alkaline dacites and are characterized by a moderate, negative europium anomaly. The average total REE content in the Hadhir aplite is about 145 ppm, less than a third of that in the alkali granite. Chondrite-normalized REE patterns for samples of the Hadhir aplite are nearly flat but slightly negatively sloping and are characterized by a negative europium anomaly slightly greater than that observed in the alkali granite. The average total REE content of the Fawwarah alkali-feldspar granite is about 164 ppm, whereas the low-calcium granite contains about 210 ppm of the same nine REE (Turekian and Wedepohl, 1961). Chondrite-normalized REE patterns for the Fawwarah alkali-feldspar granite are nearly flat and characterized by a large negative europium anomaly. Flat REE patterns and large negative europium anomalies are characteristic of highly evolved granitoid rocks (Miller and Mittlefehldt, 1982).

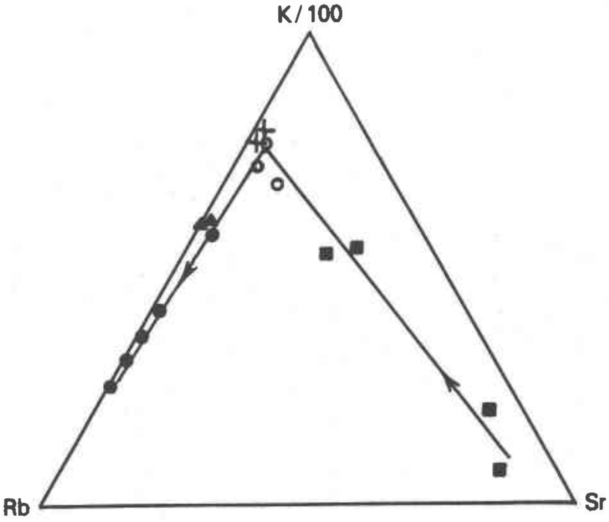

Fig. 5. Trace element variation diagram showing the relative proportions of strontium, potassium, and rubidium in components of the Silsilah ring complex. Plot symbols as in Fig. 3.

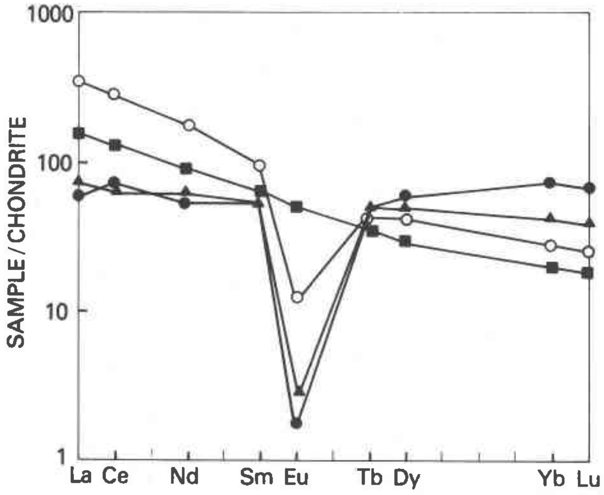

Fig. 6. Average chondrite-normalized rare-earth element patterns for components of the Silsilah ring complex. Silsilah alkali granite average includes data for two comendite samples. Plot symbols as in Fig. 3.

Economic geology

Greisens

Two types of greisenized rock, which represent complete and incomplete greisenization of the Fawwarah alkali-feldspar granite, are associated with rocks of the ring complex. These greisen lithologies are spatially unrelated to quartz veins. Primary igneous textures characteristic of the Fawwarah alkali-feldspar granite are distinctly preserved in the incompletely greisenized rock and in rock associated with the completely greisenized rock that has undergone argillic alteration. Primary igneous textures have been tentatively identified in the completely greisenized rock.

Strongly mineralized, completely greisenized alkali-feldspar granite is present immediately beneath the Hadhir aplite and pegmatitic rock found at the base of the aplite. The aplite itself crops out subhorizontally beneath the Maraghan lithic graywacke. The intensity of greisenization decreases downward and within a few meters incompletely greisenized alkali-feldspar granite is present. Incompletely greisenized rock grades downward into progressively less altered Fawwarah alkali-feldspar granite. Completely greisenized rock is resistant in the weathering environment, and forms low hills, whereas incompletely greisenized rock has been more readily eroded, and crops out peripherally on the flanks of hills formed by completely greisenized rock. Greisen is emergent beneath aplite throughout the southwest part of the complex. These geologic relations suggest that additional sheet-form or cupola-like bodies of greisenized rock may exist beneath thin veneers of aplite and in as yet unexposed positions below the Maraghan lithic graywacke.

The completely greisenized rock contains quartz, topaz, and cassiterite, and trace amounts of iron-titanium oxides and white mica. This lithology has been identified in two small hills located less than 1 km inside the southwestern part of the ring (Fig. 1). Completely greisenized rock has an irregular outcrop pattern and grades into reddened, argillically altered alkali-feldspar granite and to incompletely greisenized rock. Disseminated grains of cassiterite occur in structureless quartz-topaz greisen that constitute from 0 to about 10% of the rock. Cassiterite also occurs in elliptical pods 0.05 to 5 m in diameter that are 50 to 90% cassiterite in a matrix of quartz and topaz. Contacts between almost barren quartz-topaz rock and the cassiterite pods are extremely sharp.

Incompletely greisenized rock contains quartz, white mica, topaz, and trace amounts of albite and cassiterite. This lithology is not as abundant as completely greisenized rock. Within the complex incompletely greisenized alkali-feldspar granite is encountered in several different settings. In addition to occurrences peripheral to completely greisenized rock, it occurs as pods within the Fawwarah alkali-feldspar granite. Several of these pods were identified in isolated positions within the southeastern part of the alkali-feldspar granite pluton. Isolated pods are also associated with the two small masses of alkali-feldspar granite located inside the ring. These pods of greisenized alkali-feldspar granite are surrounded by Maraghan lithic graywacke. The pods are approximately elliptical in shape and are between 10 and 200 m in diameter.

The mean and standard deviation of concentration for each element in a set of 64 samples of the two strongly mineralized greisens is given in Table 2. Each sample is

Table 2. Compositions of samples collected from the two intensely mineralized greisens in the southwest part of the Silsilah ring complex. Samples composited from rock chips collected in 10 m intervals. All values in parts per million, except iron, magnesium, calcium, and titanium which are in percent.

Element	Mean	Standard deviation	Number samples*
Fe	2.76	1.15	68
Mg	0.04	0.03	68
Ca	.84	.61	68
Ti	.01	.03	43
Mn	429	524	68
Ag	9	5	63
B	13	4	22
Ba	61	33	68
Be	2	2	24
Bi	53	54	66
Cr	296	93	68
Cu	106	68	68
Mo	12	8	57
Nb	64	19	68
Ni	7	2	59
Pb	661	477	68
Sc	6	2	7
Sr	130	42	23
V	16	5	54
Y	12	3	22
Zn	324	137	21
Zr	83	20	68
As	1367	1913	64
Sn	9527	21347	64
W	175	241	64
Rb	361	393	64
F	1489	1328	64

* Number of samples with unqualified data

composited from rock chips collected semicontinuously within 10 m intervals. Of particular interest are the mean concentrations of Ag, B, Bi, Mo, Nb, Pb, Zn, As, Sn, W, and F which are present in anomalous to highly anomalous concentrations relative to the low-calcium granite of Turekian and Wedepohl (1961). The elements Sn, W, As, Bi, Pb, and Zn are all present in highly anomalous concentrations and have wide ranges of abundances. However, only tin and tungsten occur at economically interesting grades. Few samples contain less than 1000 ppm tin (du Bray, 1983c).

Quartz veins

Samples of quartz veins that cut the Fawwarah alkali-feldspar granite contain interesting concentrations of some trace elements. As much as 300 ppm silver was determined and most contain 0.5 ppm. As much as 500 ppm bismuth was determined and many samples contain 10 ppm. Several samples contain 700 ppm molybdenum and most contain 10 ppm. Most of the quartz vein samples contain 100 to 1000 ppm lead and a few contain as much as one percent. The tin content of the vein samples ranges between about 50 and 100 ppm. Tungsten was not detected in most of the vein samples but the large quartz vein near the northwest end of the Fawwarah alkali-feldspar granite contains very high but variable concentrations of tungsten.

Most of the quartz veins that cut the Silsilah alkali granite don't contain anomalous concentrations of the trace metals. A quartz vein system at the south end of the ring complex 5 km west of Jabal al Hadhir contains very high though erratic concentrations of tungsten. Samples from these veins contain as much as 50 ppm silver, 300 to 2000 ppm As, 15 to 300 ppm bismuth, 10 to 700 ppm molybdenum, 15 to 7000 ppm lead, 200 to 1000 ppm tin, up to 900 ppm lithium, and as much as 5000 ppm fluorine.

Petrogenesis of the igneous rocks

The allotriomorphic and micrographic textures that characterize the Hadhir aplite and the Fawwarah alkali-feldspar granite suggest that the melts represented by these rocks solidified by cotectic crystallization. The normative compositions of the complex components are compared to minimum melting compositions in the experimental system SiO_2–$KAlSi_3O_8$–$NaAlSi_3O_8$–H_2O (Fig. 4). Normative compositions for samples of the Silsilah alkali granite plot well below the minima trend; they contain more of the *ab* and *or* components and less of the *Q* component than experimentally determined minimum melt compositions. These samples are characterized by a nearly constant *ab*/*or* ratio while *Q* displays significant variation. The Hadhir composition plots slightly below the 1 kilobar (kbar) minimum composition. The Fawwarah alkali-feldspar granite shows considerable compositional variation parallel to and displaced slightly below the minima trend, towards slightly *or*-enriched, *Q*-depleted compositions that are appropriate to crystallization in the $P(H_2O)$ range between about 0.5 and 4 kbar. By interpolation, the average composition of the Fawwarah alkali-feldspar samples plots slightly below the minimum melting composition that corresponds to $P(\text{total}) = P(H_2O) =$ about 1.5 kbar which is equal to 4 km of overburden.

The effect of varying amounts of fluorine on the minimum melting composition is also displayed because the aplite and the alkali-feldspar granite contain large amounts of fluorine. Fluorine dramatically affects the phase equilibria in the granite system. It shifts the minimum melt compositions towards *ab*-enriched compositions (Manning, 1981). Samples of the alkali-feldspar granite whose compositions suggest the greatest crystallization depths generally contain the highest fluorine concentrations. The average normative composition of the alkali-feldspar granite is coincident with the minimum melt composition that would be obtained for about 0.25% fluorine and $P(\text{Total}) = 1$ kbar or about 3 km of overburden. This is a maximum depth estimate because the fluorine-dominated greisenization indicates that some fluorine initially contained in the alkali-feldspar granite melt exsolved and was lost during late magmatic processes. The fluorine content of samples is therefore a minimum value for the melt.

The presence of the white mica zinnwaldite does not require that the alkali-feldspar granite crystallized at high pressure, that is, at great depth. Experimental work (Miller et al., 1981) has demonstrated the stability of non-ideal white micas extends to the much lower pressures than that proposed for muscovite (Yoder and Eugster, 1954).

The Hadhir aplite is considered to be the quenched equivalent of the Fawwarah alkali-feldspar granite because of the similarity of their chemical compositions and because of their close spatial association. The texture characteristic of the Hadhir aplite may be a function of its having experienced pressure quenching. Soon after the magma represented by these two lithologies was emplaced in the ring fracture, it may have begun to exsolve a fluid phase. The volume expansion and increased pressure created by the exsolved fluid could have caused extensive fracturing of the wallrock which in turn would have led to dramatic reduction of confining pressure. With confining pressure greatly reduced, the conditions necessary for exsolution of a fluid phase would have been enhanced and rapid fluid loss would greatly increase the magma's liquidus and solidus temperatures. Rapid solidus depression would have resulted in rapid, disorderly crystallization of the magma (Tuttle and Bowen, 1958). The process would have occurred rapidly and the fractures would have been sealed by aplite dikes. Once resealed, more orderly solidification of the remaining magma, represented by the alkali-feldspar granite, which was located below some finite thickness of pressure-quench aplite, could proceed. Small chemical differences between the aplite and the alkali-feldspar granite indicate that some differentiation continued following the quenching event.

The Silsilah alkali granite is slightly porphyritic and so its solidification history involves at least some crystallization under noncotectic conditions. The trend of increasing *Q* displayed by samples of the alkali granite (Fig. 4) may indicate that noncotectic crystallization of anorthoclase is responsible for the compositional variation displayed by this pluton. Crystallization and removal of anorthoclase with a composition like that of the perthite in the alkali granite, namely $ab_{56}or_{44}$, would have the effect of changing the composition of the remaining liquid along a trend coincident with that depicted by samples of the alkali granite and comendite (Fig. 4) and toward the composition of the Hadhir aplite. The most *Q*-enriched sample of comendite can be considered to approximate the cotectic composition towards which the liquid represented by the alkali granite was evolving. Consequently, the alkali granite must also have crystallized less than 4 km below the surface.

Since feldspar contains more molar Al_2O_3 than molar Na_2O plus K_2O its crystallization and removal from the magma represented by the alkaline dacite caused the composition of the remaining liquid to become enriched in Na_2O and K_2O relative to Al_2O_3 and the liquid evolved to a peralkaline composition. Peralkalinity was achieved and permitted crystallization of soda pyriboles including aegirine-augite, katophorite, and arfvedsonite. The comendite is the most peralkaline component, a fact which is emphasized by the presence of arfvedsonite, end-member soda amphibole. The amphiboles are less sodic in the less peralkaline Silsilah alkali granite. The crystallization and removal of the soda pyriboles, with agpaitic ratios much greater than 1, caused the composition of the remaining melt to evolve toward a peraluminous composition such as that characteristic of the Hadhir aplite and the Fawwarah alkali-feldspar granite.

Igneous processes that yield a peralkaline liquid favor partitioning of zirconium into the liquid phase because alkali-zircono-silicate complexes are stabilized (Watson, 1979). Zirconium is concentrated in peralkaline magmas during the differentiation process but is buffered at 100 to 200 ppm in nonperalkaline magmas by crystallization of zircon. The extreme enrichment of zirconium in the Silsilah alkali granite is a function of this complexing phenomenon and is characteristic of the peralkaline granites of the northeastern Arabian Shield (Stuckless et al., 1982). The high zirconium content of the alkaline dacite may also result from this process.

The dramatic reduction in zirconium content between the alkali granite and both the aplite and alkali-feldspar granite is probably related to fractionation of zircon which occurred in response to soda amphibole fractionation. Amphibole fractionation can cause a peralkaline magma to evolve to one with a peraluminous composition and in so doing will greatly reduce the ability of the magma to stabilize zircono-alkali-silicate complexes (Watson, 1979). With the destabilization of these complexes, the magma became zirconium-saturated and zircon began to crystallize, as indicated by the abundance of accessory zircon in the Silsilah alkali granite, causing dramatic depletion of zirconium in the remaining magma. In high-silica liquids amphiboles themselves have mineral-melt distribution coefficients for zirconium that are greater than one. Thus, fractionation of soda amphibole may cause additional reduction of the magma's zirconium content.

The observation that the chemical evolution of the ring complex is time dependent and systematic is confirmed by the fact that the alkaline dacite, the oldest component of the complex, is strontium-enriched, the Silsilah alkali granite, of intermediate age, is potassium-enriched, and the Hadhir aplite and the Fawwarah alkali-feldspar granite, the youngest components of the complex, are rubidium-enriched (Fig. 5). The contents of these elements are controlled by their mineral-melt distribution coefficients and the prevailing phase equilibria. Primitive, basaltic magmas are characterized by high concentrations of strontium relative to potassium (Turekian and Wedepohl, 1961). Compositions such as this become increasingly potassium enriched as plagioclase crystallizes and removes strontium from the liquid (Hanson, 1978). Rubidium, which acts incompatibly, remains in the melt so that rocks of intermediate composition contain little more rubidium than the primitive magma from which they are derived. When potassium feldspar nucleates, late in magmatic evolution, potassium begins to be effectively removed from the liquid (Hanson, 1978) and the relative concentration of rubidium begins to increase. If this trend continues, a small volume of highly evolved magma with a very high rubidium content may result. Rubidium is finally and effectively removed from the liquid by crystallization of micas (Hanson, 1978). This differentiation process is depicted by a smooth variation curve on a ternary strontium-potassium-rubidium diagram that begins near the strontium apex, trends toward the potassium apex, and then turns dramatically toward the rubidium apex. Geochemical data for the components of the Silsilah ring complex follow this trend and suggest that the components are cogenetic and evolved by processes of igneous differentiation.

The barium content of the complex's components further substantiates the proposed cogenesis of the complex's components and suggests that the alkali-feldspar granite and the aplite represent a small part of the primitive, parental magma. The high barium content of the alkaline dacite and the affinity of biotite and potassium feldspar for barium (Hanson, 1978) suggest that one or both of these minerals was part of the partial melt assemblage. The dramatic and monotonic decrease of barium, from the oldest component to the youngest, demonstrates the evolution of the magma toward barium-depleted compositions by crystallization and removal of potassium-bearing sodic plagioclase from the alkaline dacite magma, by crystallization and removal of anorthoclase from the peralkaline magma, and finally by crystallization and removal of mica and potassium feldspar from the peraluminous magma. The extremely low barium content of the complex's youngest components, relative to its content in the oldest component, indicates that the former represent a small proportion of the latter.

Relative REE content and chondrite-normalized patterns also provide some insight into the genesis of the ring complex components. The lack of a europium anomaly in samples of the alkaline dacite suggests that these rocks represent primary liquids which have undergone little, if any, differentiation. Plagioclase and iron-titanium oxides are major constituents of the alkaline dacites but are almost absent in the other components. Their near absence indicates that they were removed from the melt, perhaps by filter pressing or crystal settling. Except for europium in plagioclase, the REE have mineral-melt distribution coefficients that are less than 1 in both plagioclase and iron-titanium oxides (Hanson, 1978). Consequently, crystallization and removal of iron-titanium oxides and plagioclase from the alkaline dacite liquid did not cause REE fractionation, but their removal led to the overall REE enrichment observed in the alkali granite. The removal of plagioclase did cause development of a negative europium anomaly.

Derivation of the chondrite-normalized REE patterns that typify the alkali-feldspar granite and the aplite from that characteristic of the peralkaline rocks was also achieved by crystal fractionation. As indicated by the total REE content of these rocks (Table 1), the tendency for the REE to act incompatibly and to be enriched in residual melt was more than balanced by their removal in the minerals crystallizing from the magma represented by the alkali granite. Relative to the alkali granite, REE patterns for the aplite and alkali-feldspar granite are flattened and characterized by much larger negative europium anomalies.

The REE distribution coefficients in anorthoclase (Hanson, 1978), such as that which is the major mineral phase in the weakly peralkaline Silsilah alkali granite, are such that its crystallization and removal caused the magnitude of the negative europium anomaly to increase and caused the overall REE content of the remaining liquid to increase. However, the tendency for REE abundances to increase was counteracted by crystallization of zircon and allanite from the alkali granite magma. The REE distribution coefficient patterns for these two minerals are complimentary. Their simultaneous crystallization in equal amounts leads to overall reduction of the magma's REE content and to slightly greater light REE (LREE) depletion than heavy REE (HREE) depletion because distribution coefficients for LREE in allanite are greater than distribution coefficients for HREE in zircon (Mahood and Hildreth, 1983).

Absolute enrichment of the HREE as well as enrichment relative to the LREE was achieved by several processes. Some flattening of the REE patterns and absolute enrichment of the HREE may have been achieved by anorthoclase fractionation. Distribution coefficients for the LREE in anorthoclase are greater than for the HREE, and since abundant anorthoclase crystallized and was removed from the magma represented by the alkali granite the HREE became enriched in the melt relative to the LREE. Mahood and Hildreth (1983) have demonstrated that in high silica magmas mineral-melt distribution coefficients for REE in iron-titanium oxides are greater than one and are significantly greater for LREE than HREE. Crystallization and fractionation of iron-titanium oxides, abundant in the alkali granite and extremely scarce in the aplite and alkali-feldspar granite, may have caused further LREE depletion. Finally, Candela (1984) has demonstrated that LREE are more strongly partitioned into halogen-enriched hydrothermal fluids than HREE. Thus, magmas that evolve a halogen-enriched fluid phase, such as the fluorine-rich fluids that escaped from both the aplite and alkali-feldspar granite, will be depleted of LREE relative to the HREE.

The temporal, spatial, and tectonic association of the Silsilah ring complex components suggest that these rocks are cogenetic. The components of the complex may represent samples that depict the successive chemical evolution of a large magma. The chemical variation portrayed by the components depicts a discontinuous process that involved magma evolution via separation of melt from earlier formed crystals, and emplacement of batches of magma whose compositions represent stages of the parent magma's evolution. Petrographic observations and chemical data suggest that the early chemical evolution of primitive magma represented by the alkaline dacite to a composition like that of the alkali granite was controlled by the fractionation of iron-titanium oxides and sodic plagioclase. Chemical evolution by crystallization and removal of anorthoclase, soda pyriboles, zircon, and iron-titanium oxides and evolution of a LREE-enriched fluorine-rich hydrothermal fluid caused the composition of the remaining magma to become like those of the aplite and the alkali-feldspar granite.

Petrogenesis of the mineralized rocks

The genesis of the mineralized rocks, in particular, the quartz-cassiterite-topaz greisens and the wolframite-bearing quartz veins are only partly understood. The nearly complete separation of high-grade accumulations of cassiterite in greisens from high-grade but erratic accumulations of wolframite in quartz veins suggests that a large, strongly zoned hydrothermal system once existed in the southwest part of the ring complex.

The Fawwarah alkali-feldspar granite contains a highly anomalous quantity of tin (Table 1) so that it, and not the graywacke, is the likely source of the tin. Tin acted as an incompatible element during crystallization and its concentration in the melt increased progressively. Tin was ultimately partitioned into a fluorine-rich fluid phase (Bailey, 1977) that exsolved as the Fawwarah alkali-feldspar granite crystallized, although a small proportion of tin was partitioned into zinnwaldite. This fluid phase seems to have been trapped below the previously crystallized, competent and impermeable Hadhir aplite and caused recrystallization of the alkali-feldspar granite in its roof zone. Mineralization may have been localized by faults or in fractures that developed as the alkali-feldspar granite cooled and contracted. Similarly, weakly mineralized greisen patches within the alkali-feldspar may be structurally controlled.

The results of experiments in the granite–NaF–SnO_2 system (Stemprok, 1982) indicate that two immiscible liquids, one silicate-dominated and the other fluoride-dominated, evolve under conditions appropriate to magmatic and hydrothermal processes. Tin is almost exclusively partitioned into the silicate liquid. The pod-like accumulations of cassiterite in the greisens may represent the immiscible unmixing of silicate and fluoride liquids during the greisenization process, and the concommitant partitioning of tin into the former.

Summary

A tin greisen deposit is associated with an alkali-feldspar granite that forms part of a ring complex at Jabal as Silsilah. The petrologic and geochemical characteristics of the Fawwarah alkali-feldspar granite are like those of granites located elsewhere in the World that also are associated with deposits of tin, tungsten, and rare metals. The alkali-feldspar granite is peraluminous, incompatible trace element-enriched, and is characterized by a flat chondrite-normalized REE pattern that includes a very large, negative europium anomaly. The mineralogy of the alkali-feldspar granite is also distinctive because it includes zinnwaldite and topaz.

Differentiation and mineral fractionation controlled magma evolution as components of the ring complex were sequentially emplaced. The Fawwarah alkali-feldspar granite and its quenched equivalent, the Hadhir aplite, were derived from the Silsilah alkali granite, which in turn was derived from liquid represented by alkaline dacite. Separation of iron-titanium oxides and plagioclase from the geochemically primitive alkaline dacite magma caused the remaining magma to evolve toward a composition represented by the Silsilah alkali granite and its quenched comenditic equivalent. The crystallization and separation of soda pyriboles, anorthoclase, and zircon then caused the remaining magma to evolve to a composition represented by the Fawwarah alkali-feldspar granite and the Hadhir aplite.

Evolution of the ring complex and its associated tin deposit concluded with local, intense alteration of the Fawwarah alkali-feldspar granite to a cassiterite-bearing greisen. The alteration was achieved by a late-stage, hydrothermal fluid that was probably fluorine dominated. The fluid was locally trapped in cupolas beneath the impermeable carapace formed by the Hadhir aplite. The effect of the fluid was to convert the alkali-feldspar granite to an assemblage of quartz, topaz, and cassiterite. Elliptically shaped, high-grade accumulations of cassiterite may owe their existence to the evolution of a second, immiscible fluid phase. Samples of greisens suggest that the locus of economically viable deposits of tin is not restricted to the two known, strongly mineralized greisens.

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