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PERALKALINE AND PERALUMINOUS GRANITES AND RELATED MINERAL DEPOSITS OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

by

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PERALKALINE AND PERALUMINOUS GRANITES AND RELATED MINERAL DEPOSITS OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

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ABSTRACT

In the Precambrian Arabian Shield granitoid plutonic rocks are widespread and range in age from 800 to 550 Ma old; but the mineral-resource potential associated with these plutonic rocks is restricted mainly to the younger, postorogenic granites. Two granite types of current economic interest are zirconium-niobium-enriched peralkaline granites and tin-tungsten-enriched peraluminous granites. Both types are highly evolved, are enriched in lithium, rubidium, and fluorine, and have distinctive mineralogy, textures, and chemistry. The zirconium-niobium-enriched granites are related to medium- to large-sized plutons and complexes of peralkaline granite, and the tin-tungsten-enriched granites are related to medium-sized plutons of biotite or biotite-muscovite granite.

Existing geochemical and geologic data for many parts of the Arabian Shield were compiled as a basis for evaluating the resource potential of the granites of the Shield. Commodities associated with granites that have potential for economic mineral deposits include tin, tungsten, molybdenum, beryllium, niobium, tantalum, zirconium, uranium, thorium, rare-earth elements, and fluorite. Prospecting methods useful in discriminating those granites having significant economic potential include reconnaissance geologic mapping, petrographic and mineralogic studies, geochemical sampling of rock and wadi sediment, and radiometric surveying.

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INTRODUCTION

Plutonic rocks of granitic composition are widespread and abundant in the Precambrian shield in Saudi Arabia and include granodiorite, monzogranite, syenogranite, and alkali-feldspar granite that are peralkaline, metaluminous, and peraluminous in terms of alumina saturation. Although in other parts of the world economic deposits of many metals are found associated with such granites, no economic deposits have yet been found in Saudi Arabia associated with similar granites. However, many mineral occurrences and geochemical anomalies and a few significant mineral prospects are associated with granites in the Arabian Shield. Until recently, the granites were not considered prime exploration targets, but information gathered during the last few years suggests some of the Arabian granites have high potential for associated mineral deposits (Lalande, 1977; Elliott, in press; Cole and others, 1981; du Bray and others, 1982).

Peraluminous and peralkaline granites, enriched in niobium, tin, and other trace elements and similar to specialized granites as defined by Tischendorf (1977), have been identified in the northern, eastern, and southeastern Arabian Shield (Elliott, in press; du Bray and others, 1982). Elsewhere in the world, specialized granites are associated with deposits of tin, niobium, tantalum, tungsten, lithium, beryllium, uranium, and rare-earth elements. In Saudi Arabia discoveries of mineral deposits associated with granites include the Ghurayyah niobium-zirconium deposit (Lalande, 1977) and the Baid al Jimalah West tungsten deposit (Cole and others, 1981); granites associated with both of these deposits are chemically similar to specialized granites.

The method of plutonic rock classification used in this report is the IUGS system (Streckeisen, 1976). In addition, the following modifying terms for granites are used: peralkaline, metaluminous, peraluminous, calc-alkaline, granitic, and granitoid. A peralkaline granite is one in which molecular Al_2O_3 is less than (Na_2O + K_2O) and which contains normative acmite (Carmichael and others, 1974). A metaluminous granite is one in which molecular Al_2O_3 is less than (CaO + Na_2O + K_2O) but Al_2O_3 is greater than (Na_2O + K_2O)(Carmichael and others, 1974). In peraluminous granites, molecular Al_2O_3 is greater than (CaO + Na_2O + K_2O), and normative corundum is present (Carmichael and others, 1974). Calc-alkaline granites are those that belong to an igneous rock series in which the weight percentage of SiO_2 is between 56 and 61 when the weight percentage of CaO is equal to (K_2O + Na_2O) (Peacock, 1931). Granitic is used as a general compositional modifer to describe all granites plus granodiorites. Granitoid refers to plutonic rocks having "granitoid" textures and includes all granites plus granodiorites and tonalites (Streckeisen, 1976).

This report is the result of work completed between 1977 and 1979 as part of subproject 3.12, Prospecting in felsic plutonic rocks, and performed in accordance with a work agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey (USGS). This report results from field and laboratory studies conducted by the author combined with previous and current work by others.

DATA STORAGE

This is a summary report, and therefore no Data File was established and no entries or updates were made to the Mineral Occurrence Documentation System (MODS) data bank.

MINERAL DEPOSITS ASSOCIATED WITH GRANITOID ROCKS

A great variety of mineral commodities are found worldwide in various deposit types that are spatially and commonly genetically associated with granitoid rocks. The commodities of greatest interest because of their high economic value include tin, tungsten, molybdenum, copper, gold, silver, and uranium. Other commodities of lesser economic value but known to be associated with granitoid rocks include tantalum, niobum, rare-earth elements, fluorine, lithium, beryllium, and thorium. Both of these groups are considered to be potential exploration targets in the Arabian Shield. Other commodities commonly associated with granitoid rocks, including bismuth, antimony, arsenic, lead, and zinc, are not considered in this report because of their low economic value and large supplies from other types of deposits unrelated to granitoid rocks.

The commodities considered here are found in many deposit types worldwide either within intrusive rocks or nearby in the rocks hosting the intrusions. The most common deposit types include stockwork or porphyry, contact metasomatic, vein, replacement, and placer deposits. A review of the geochemistry and deposit types common to each commodity is summarized from various chapters of Brobst and Pratt (1973).

Beryllium

Beryllium has a crustal abundance of 2 to 3.5 parts per million (ppm) and is found principally in common rock-forming minerals, especially in plagioclase where it substitutes for tetravalent silicon. In igneous rocks, the beryllium content increases as the silica and alkali contents increase. During differentiation of a granitic magma, beryllium is enriched in late-magmatic fluids. With increasing enrichment, separate beryllium minerals such as beryl may form. Because beryllium minerals, including beryl, chrysoberyl, phenakite, and euclase, are resistant to weathering, secondary sedimentary deposits may form during weathering of primary beryllium deposits. Elemental beryllium is relatively immobile, and therefore the beryllium content changes very little with metamorphism.

Beryllium deposits include pegmatitic and hydrothermal types. In pegmatites, beryllium minerals are found with feldspar and quartz and commonly in association with spodumene and muscovite. Hydrothermal beryllium deposits can be hypothermal, mesothermal, or epithermal. In hypothermal beryllium deposits, such as veins, greisen zones, or disseminations in granite, tungsten and tin minerals are commonly associated with beryllium minerals. In mesothermal deposits, beryllium minerals may occur as replacement bodies in limestone, commonly with fluorite and diaspore. An example of an epithermal deposit is beryllium-bearing mantos with fluorite (Griffitts, 1973).

Copper

The average abundance of copper in granitic rocks is about 15 ppm. It is strongly concentrated in late- to post-magmatic fluids and is strongly chalcophile in that it forms sulfides and sulfosalts in deposits associated with iron, lead, zinc, and silver. Primary copper minerals oxidize and dissolve during weathering, and the presence of copper in weathered zones is commonly indicated by secondary minerals such as malachite, azurite, or chrysocolla. In the plutonic environment, copper deposits are porphyry, vein, and contact metasomatic types. Most porphyry copper deposits occur in hypabyssal or porphyritic rocks that have broad alteration zones. Pyrite is typically abundant, and the deposits may be structurally complex and contain breccia zones or pipes and crackle zones. Molybdenum, gold, and silver commonly are present in minor amounts and are produced as byproducts from porphyry deposits. Vein copper deposits have alteration assemblages similar to those of porphyry copper deposits, but alteration is restricted to vein envelopes (Cox and others, 1973). In contact zones of granitoid plutons and carbonate rocks, copper-bearing skarns may form. These skarns are zones of complex mineralogy generally including garnet, pyroxene, epidote, and other calc-silicate minerals and iron-bearing minerals such as magnetite, pyrite, or pyrrhotite. Skarn deposits may also contain economic amounts of gold or tungsten associated with copper.

Fluorine

The average fluorine content in granites and granodiorites is 870 ppm, but in alkalic rocks it is higher, about 1,000 ppm. Fluorine is a major component of magmatic volatile phases and may reach high concentrations in highly differentiated intrusive rocks such as alkalic and silicic granites or carbonatites. The most important fluorine mineral is fluorite, but much of the fluorine in granites is contained in hydroxyl-bearing minerals such as mica and topaz. The presence of fluorite and (or) topaz in granitic rocks is a good indicator of fluorine enrichment.

In plutonic igneous rocks, fluorine deposits are commonly associated with pegmatites and carbonatites and are in contact aureoles. The dominant source of fluorine, however, is from hydrothermal deposits including veins, mantos, pipes, and stockworks, many of which have little or no association with known plutonic rocks (Worl and others, 1973).

Gold

Gold is one of the rarer elements in the Earth's crust, and data on its abundance are meager. A reasonable estimate of the average crustal abundance of gold is 0.003 to 0.004 ppm. Gold occurs in all types of rock, although gold deposits are found more commonly with felsic or intermediate than with mafic igneous rocks. The types of gold deposits associated with intrusive rocks vary considerably and include vein, contact metasomatic, stockwork, and replacement deposits. Porphyry copper deposits commonly produce byproduct gold (Simons and Prinz, 1973).

Lithium

Lithium has a crustal abundance of 10 to 20 ppm, and in igneous rocks, it is significantly enriched in granites, especially highly differentiated silicic and alkalic types. The principal source of lithium is pegmatites, including homogenous or zoned types. Spodumene is the most common lithium mineral; others are lepidolite, petalite, amblygonite, and eucryptite (Norton, 1973).

Molybdenum

With an average crustal abundance of about 1 to 1.5 ppm, molybdenum is one of the rarer metals and is found in deposits principally associated with granitic rocks as the sulfide mineral molybdenite. The common types of deposits are stockworks and breccia pipes in hypabyssal granitic intrusions that have characteristic alteration zones or halos. Molybdenite is commonly associated with pyrite and fluorite and minor amounts of tungsten, tin, and (or) copper minerals. Molybdenum is also found in contact metasomatic deposits at granite-carbonate contacts, where it may be associated with scheelite, bismuthinite, and (or) chalcopyrite, and in quartz veins and pegmatites (King and others, 1973).

Niobium and tantalum

Because of their similar chemical properties and behavior, niobium and tantalum are found together in most rocks and minerals in which they occur. The crustal abundance of niobium is about 20 ppm and that of tantalum, which is rarer and also in much higher demand, is about 2 ppm. Most niobium and tantalum deposits are closely associated with granitoid rocks, but there are some differences in their associations. The greatest concentrations of niobium are in alkalic granite, nepheline syenite, and related rocks, whereas the greatest concentrations of tantalum are in albitized granite and pegmatite that are late-stage differentiates of granitic batholiths. Many niobium deposits in carbonatites have very low contents of tantalum. The principal ore mineral is columbite-tantalite; other important ore minerals are euxenite, pyrochlore, and loparite. Small amounts of niobium and tantalum are present in ordinary magmatic rocks as trace and minor elements in iron and iron-titanium-bearing minerals. Niobium and tantalum can substitute for titanium, tin, tungsten, and zirconium. Niobium-tantalum deposits are found as pegmatitic and albitized zones in nepheline syenites or in carbonatites. In silicic and alkalic granites, niobium-tantalum ores are produced from placers formed by weathering of these enriched granites and nepheline syenites (Parker and Adams, 1973).

Rare-earth elements

The rare-earth elements (REE) include yttrium (atomic number 39) and lanthanum through lutetium (atomic numbers 57-71). The crustal abundance of the combined group of REE has been estimated at less than 200 ppm. The most abundant REE and their average abundances are lanthanum (30 ppm), yttrium (30 ppm), cerium (60 ppm), and neodymium (28 ppm) (Levinson, 1974). In igneous rocks, the greatest concentrations of REE are found in silicic granites. Deposits of REE occur as veins, pegmatites, or skarns or in carbonatites (Adams and Staatz, 1973).

Silver

Silver is a chalcophile element, and, because it is similar to monovalent copper in ionic size and valence, it may substitute for it in various minerals. Deposits are more commonly associated with igneous rocks of intermediate composition than with felsic granites; the crustal abundance of silver is about 0.07 ppm, in felsic granite it is about 0.05 ppm. Porphyry copper and copper-zinc-lead replacement and vein deposits associated with granitoid rocks commonly produce silver as a byproduct, and approximately 75 percent of the world's silver is produced as a byproduct or coproduct of base-metal ores. However, silver is produced as the principal product from many mesothermal and epithermal vein and replacement deposits associated with granitoid rocks (Heyl and others, 1973).

Thorium

The crustal abundance of thorium ranges between 6 and 13 ppm. During magmatic differentiation thorium is concentrated in the residual melt and fluids and thus is more abundant in granitic and alkalic rocks. Thorium deposits include veins, carbonatites, pegmatites, disseminations in certain alkalic rocks, and placers where the thorium is commonly associated with REE, niobium, titanium, and (or) zirconium (Staatz and Olson, 1973).

Tin

Tin has a crustal abundance of 2 to 3 ppm but the average is about 3.5 ppm in silicic igneous rocks. Cassiterite is the principal ore mineral of tin, but in igneous rocks tin may be dispersed in iron-, titanium-, or calcium-bearing minerals such as biotite, rutile, and garnet. In granitoid rocks, tin is enriched in biotite-muscovite granite.

Tin deposits take various forms but commonly show a clear-cut association with silicic and felsic igneous rocks. Deposit types include hydrothermal vein, disseminated, pegmatite, contact metasomatic, fumarole, and placer. Lithium, boron, and bismuth are good indicator elements in geochemical prospecting for tin (Sainsbury and Reed, 1973). Tin-bearing granites are also commonly enriched in rubidium, tungsten, molybdenum, beryllium, and fluorine (Beus, 1969; Tischendorf, 1977), all of which are useful indicator elements.

Tungsten

The tungsten content of granitic rock is about 1.5 ppm. Tungsten is spatially and genetically associated with granites and is concentrated in residual magmatic solutions. Contact metasomatic deposits, quartz veins, and stockwork or disseminated deposits are most typical. In economic deposits, tungsten is commonly associated with tin and less commonly with molybdenum (Hobbs and Elliott, 1973).

Uranium

The uranium content of granitic rocks is about 4 ppm. During magmatic differentiation, uranium is concentrated in the late-magmatic residuum and forms uranium minerals in veins and pegmatites. Most uranium deposits in granites form veins, commonly as fissure fillings along faults, joints, or fracture zones, with associated sericitic, argillic, chloritic and (or) hematitic alteration (Finch and others, 1973).

SPECIALIZED GRANITES

In many regions of the world such as southwestern England, Malaysia, Nigeria, and Bolivia (Hosking, 1965), tin and other commodities are associated with granites. Similarities between many of these granites have been noted, and the term "tin granite" has been applied to them (Edwards and Gaskin, 1949).

Data for granites associated with tin and other minor elements were reviewed by Tischendorf (1977), who named these granitoid rocks "specialized granites", a term essentially synonomous with "tin granite"; that is, a granite that is genetically associated with tin deposits. Although the association of tin deposits with granitoid rocks is emphasized, the term "specialized granites" also includes granites associated with one or more of a group of elements that includes tungsten, molybdenum, beryllium, lithium, niobium, and tantalum (Tischendorf, 1977). These elements are associated with tin in deposits or form their own deposits that contain little or no tin.

Tischendorf (1977) concluded that specialized granites occur in special geotectonic positions and have common geologic settings and features, common geochemical signatures, and common petrographic and mineralogic features. Tin mineralization in elongated zones or belts associated with post-tectonic granites (the last products of the magmatic activity of an intrusive cycle) exemplifies the criterion of a special geotectonic position (Tischendorf, 1977).

Specialized granites seem to represent high-level rather than deep-seated intrusions. They have complicated internal structures, and commonly have several textural and grain-size phases, such as porphyritic and aplitic. These polyphase intrusions may be the result of extreme differentiation, which is a necessary condition for the formation of specialized granites and associated mineral deposits. Within an intrusive complex the geochemically and mineralogically specialized granites occur predominantly in the apical level of larger plutons as stocks or ridges.

Tischendorf (1977) compared the analyses of 962 specialized granites with those of 2,327 normal granites and concluded that specialized granites contain significantly more SiO_2 and less CaO, TiO_2, and MgO than normal granites. Specialized granites are also significantly enriched in tin, lithium, rubidium, tungsten, molybdenum, beryllium, and fluorine and have a lower K/Rb ratio than normal granites. Similarly, Beus (1969) cited high lithium, tin, tungsten, and rubidium contents and low Mg/Li and Zr/Sn ratios as means to discriminate parent granites of lithium, beryllium, tin, tungsten, tantalum, and niobium deposits. The suggested values for specialized granites (Tischendorf, 1977) and the geochemical criteria of Beus (1969) are compared to values for average granite (Levinson, 1974) (table 1).

The specialized granites are typically syenogranite and alkali-feldspar granite (Tischendorf, 1977) and are genetically associated with larger bodies of biotite or biotite-muscovite granite. According to Tischendorf (1977), specialized granites can be distinguished by modal composition, by accessory mineralogy, and by characteristic textural features and metasomatic alteration. The proposed average modal composition (in percent) is: quartz, 35 ± 3; alkali feldspar, 33 ± 6; plagioclase (An_5), 25 ± 3; dark mica, 3 ± 1; light mica, 3 ± 1; accessory minerals, 1.

Accessory minerals common in specialized granites include topaz, fluorite, tourmaline, cassiterite, columbite-tantalite, and beryl. Certain minerals, including magnetite, ilmenite, rutile, and epidote, are atypical of specialized granites.

In specialized granites the usual crystallization sequence is commonly reversed in that quartz crystallizes before dark mica. This abnormal sequence of crystallization may result mostly from the presence of abundant volatile constituents, such as chlorine and fluorine (Tischendorf, 1977).

Metasomatic alteration, commonly of two types, also is typical of specialized granites. One type is a late-magmatic process, commonly referred to as autometasomatism, which involves the addition of alkalis; it typically results in the blastic growth of new microcline, mica, and albite and may include additions of quartz, topaz, and tourmaline. A later postmagmatic metasomatism (greisenization) that is controlled by tectonic factors may lead to the formation of rare-earth element deposits (Tischendorf, 1977).

Table 1.--Geochemical criteria for specialized or ore-related granites

[All element concentrations in ppm; leader (-) indicates no data available]

Element	Specialized (Tischendorf, 1977)	Ore-related (Beus, 1979)	Barren (Beus, 1979)	Average granite (Levinson, 1974)
Tin	30±15	15±4	5±1	3
Lithium	220±100	80±20	37±6	30
Rubidium	550±200	300±15	200±30	150
Tungsten	7±3	5±1	2±0.3	2
Beryllium	13±6	-	-	5
Fluorine	3,700±1500	-	-	735
K/Rb	<100	-	-	-
Mg/Li	-	75±30	280±80	-
Zr/Sn	-	30±10	76±20	-

Specialized granites can be classified into three subtypes based on their chemical characteristics and mineralization (Ginzburg, 1972).

1. Muscovite-rare element-bearing granites (normal evolution)

   Typical minerals: biotite, muscovite

   Mineralization: tungsten, beryllium, molybdenum

   Youngest members of the normal evolution series: apogranites of the calc-alkaline series

2. Lithium mica-rare element-bearing granites (plumasitic evolution)

   Typical minerals: lithium biotite, protolithionite, zinnwaldite, lepidolite

   Mineralization: tin, tantalum, tungsten, lithium, beryllium

   Youngest members of the plumasitic evolution series: apogranites of the subalkaline series

3. Riebeckite-arfvedsonite-aegirine-rare-earth element-bearing granites (agpaitic evolution)

   Typical minerals: biotite, riebeckite, arfvedsonite, aegirine, astrophyllite

   Mineralization: Niobium, tantalum, zirconium, rare-earth elements, beryllium

   Youngest members of the agpaitic evolution series: apogranites of the alkaline series

GRANITES OF THE ARABIAN SHIELD

The Arabian Shield, an area of approximately 770,000 km^2, consists mainly of diorite to trondhjemite batholiths and granodiorite to granite plutons (Greenwood and Brown, 1973) that range in age from 900 to 550 Ma (Stoeser and Elliott, 1980). Nearly all known mineral occurrences and prospects are associated with the younger (less than 700 Ma old) granitoid rocks of the Shield; therefore, economic deposits are also more likely to be associated with them. The search for such deposits in the Arabian Shield can be logically restricted to these postorogenic granitoid rocks. These bodies include peraluminous, metaluminous, and peralkaline types, which have the modal composition (Streckeisen, 1976) of granodiorite, monzogranite, syenogranite, or alkali-feldspar granite.

Greenwood and Brown (1973) indicated that granite and granodiorite are three times more abundant in the northeastern region of the Shield than in the southwestern region. The greater distibution of postorogenic granites to the north and east in the Shield is shown in figure 1. Greenwood and Brown (1973) proposed two major series of plutonic rocks: an older calcic series ranging in composition from diorite to trondhjemite and a younger (postorogenic) calc-alkalic series of granodiorite and granite. Stoeser and Elliott (1980) subdivided these postorogenic granites into calc-alkaline and peralkaline granites.

The calc-alkaline granites are mostly pink to gray granodiorites and monzogranites containing primary subsolvus feldspars. They are generally medium grained and equigranular to porphyritic. Their content of mafic minerals, mostly biotite and commonly hornblende, ranges from 1 to 8 percent. These granitoid rocks crop out as oval to irregularly shaped plutons and rarely as ring dikes (Stoeser and Elliott, 1980).

The peralkaline granites are mostly gray, pink, or red, medium- to coarse-grained alkali granites containing primary hypersolvus feldspars. They consist of perthite, quartz, and sodic-mafic silicates including aegirine, aegirine-augite, arfvedsonite, and, less commonly, aenigmatite. In the northeastern part of the Shield, the alkali granites are commonly associated with pink to red granophyric granite and rhyolitic volcanic rocks in intrusive-extrusive complexes (Stoeser and Elliott, 1980). Many of the peralkaline granites were emplaced in ring complexes, which are distinctive on Landsat images and small-scale photomosaics.

A third group of granites, not previously defined, is alkali-feldspar granites. Granites in this group, mostly peraluminous and perhaps genetically related to the peralkaline granites, are biotite or biotite-muscovite alkali-feldspar granites containing microcline and albite. The composition of the albite ranges from 0 to 5 percent anorthite; thus, the plagioclase content is counted as alkali feldspar rather than as plagioclase in the Streckeisen (1976) modal classification scheme. If the anorthite content were greater than 5 percent, then many of these granites would be named syenogranite or monzogranite. Some of the peraluminous granites that occur as small plutons are enriched in tin and other elements and are chemically and petrographically similar to specialized granites (Tischendorf, 1977). Others are similar to Tischendorf's (1977) precursor granites, which have chemical, mineralogic, and petrographic features intermediate between normal and specialized granites and which commonly show a spatial association with specialized granites. They may represent the parent magma of specialized

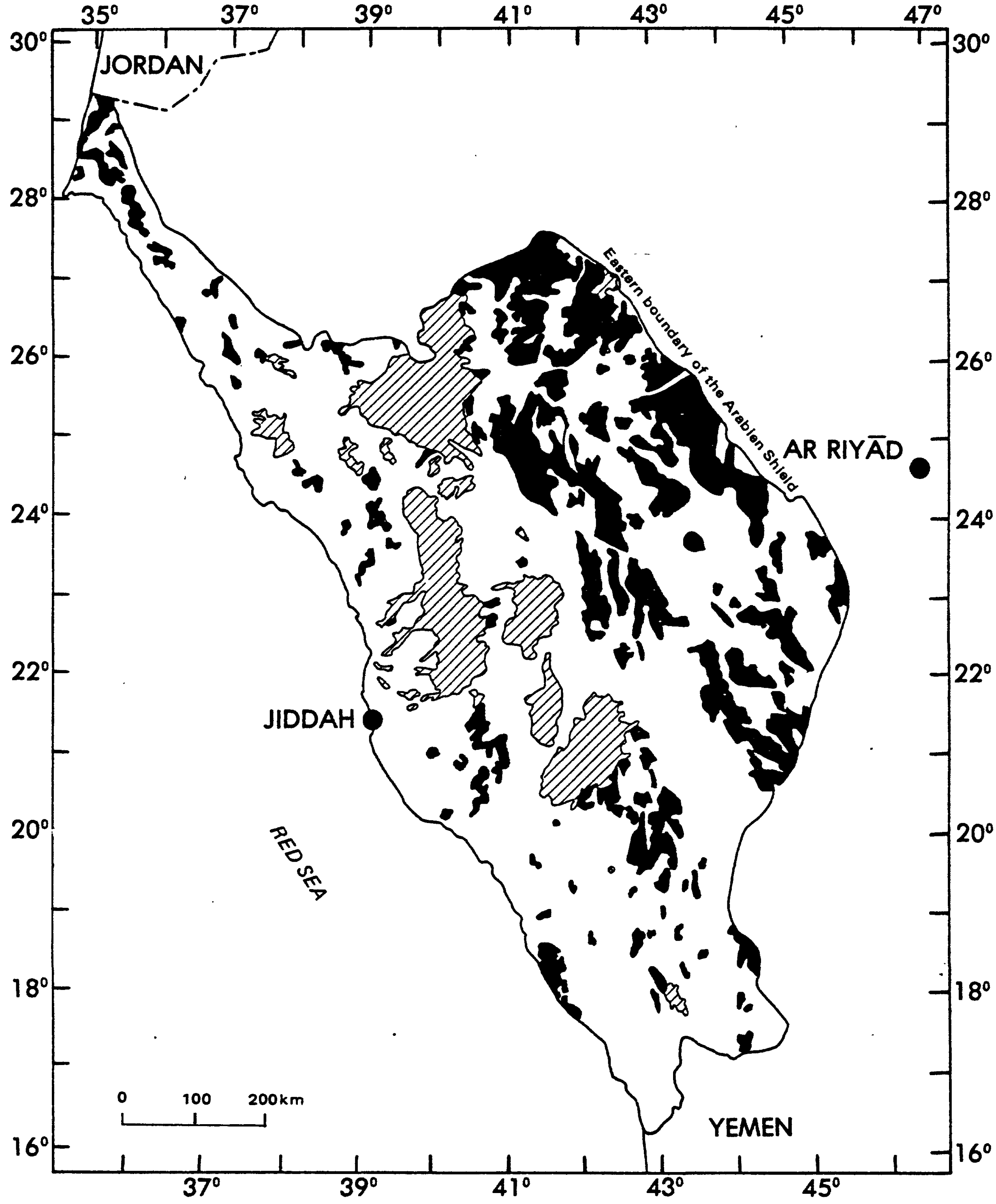


Figure 1.--Map showing the distribution of postorogenic granites (solid pattern) in the Arabian Shield; Cenozoic basalt fields are shown as ruled pattern. Modified from Stoeser and Elliott (1980).

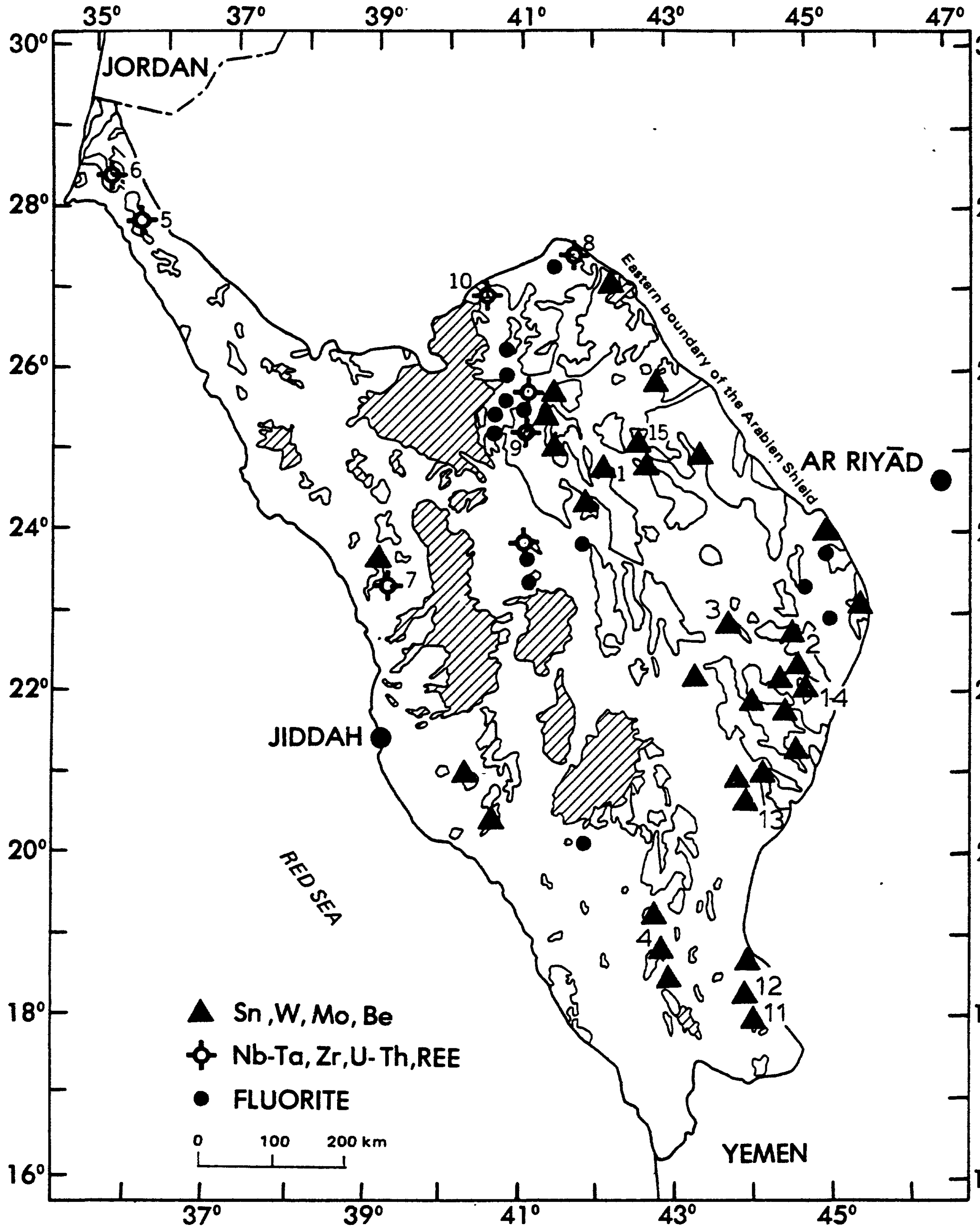
granites and are less affected by late- and post-magmatic alteration. In at least two cases in the east-central and southeastern parts of the Shield, strong spatial, temporal, chemical, and petrographic evidence suggests that the tin-bearing and precursor granites are genetically related.

In a study of postorogenic granites of the northeastern Shield, Stuckless and others (unpub. data) found that the degree of alumina saturation varies from strongly peralkaline to weakly peralkaline to metaluminous and to weakly peraluminous both within and between single intrusive complexes. They suggest that all of the postorogenic granites, regardless of degree of alumina saturation, are genetically related.

Although many mineral occurrences and prospects are spatially associated with granitoid rocks in the Arabian Shield, no economic deposits have yet been found directly associated with them. However, some of the epithermal gold deposits that have been mined, including those along the Jabal Ishmas fault zone and the Mahd adh Dhahab deposit, may be related to felsic plutonic sources (Worl, 1979; 1980; Rye and others, 1982, 1983). The economic potential of the tungsten deposit discovered at Baid al Jimalah West (MODS02661) in the northeastern part of the Shield (Cole and others, 1981), which is associated with a specialized granite, has been evaluated by the Riofinex Geological Mission (Lofts, 1982).

The numerous occurrences of tin, tungsten, molybdenum, beryllium, niobium-tantalum, zirconium, uranium-thorium, rare-earth elements, and fluorite are discussed below in the same order they are numbered on figure 2. Nearly all of these are associated with postorogenic granites of the Shield and predominantly with the peraluminous to metaluminous and peralkaline types; however, a few occurrences are associated with calc-alkaline granitoid rocks including the tungsten at El Koom (number 1, fig. 2), tungsten and molybdenum at the Uyaijah ring structure (number 2), molybdenum at Jabal Kirsh (number 3), and beryllium at Bir Karath (number 4). Occurrences of tin and tungsten tend to be associated with peraluminous granites. Occurrences of niobium-tantalum, zirconium, uranium, thorium, REE, and, to some extent, fluorite show a consistent association with peralkaline granites and complexes. These two types of granite, the zirconium-niobium-enriched peralkaline and the tin-tungsten-enriched peraluminous, are of considerable interest because of their economic potential.

The best studied zirconium-niobium-enriched granite is the Ghurayyah prospect (Lalande, 1977; Drysdall, 1979) (number 5, fig. 2; MODS00765). This deposit consists of a small porphyritic plug, about 900 m in diameter, of leucocratic riebeckite-aegirine alkali microgranite. It is located



EXPLANATION

1. El Koom
2. Uyaijah ring structure
3. Jabal Kirsh
4. Bir Karath
5. Ghurayyah granite plug (MODS00765)
6. Jabal Tawlah
7. Umm al Birak
8. Jabal Aja batholith
9. Jabal at Tuwalah complex
10. Bayda Nathil peralkaline complex
11. Jabal al Gaharra microcline-albite granite
12. Jabal Bani Bwana granite porphyry
13. Jabal Tarban alkali-feldspar granite
14. Jabal as Sitarah alkali-feldspar granite
15. Baid al Jimalah West tungsten prospect (MODS02661)

Figure 2.--Map showing mineral occurrences and prospects associated with postorogenic granites (solid pattern on fig. 1, uncolored here for clarity) in the Arabian Shield; Cenozoic basalt fields are shown as ruled pattern. Numbered localities are discussed in text. Modified from Stoeser and Elliott (1980).

about 3 km east of, and is probably genetically related to, a large peralkaline complex consisting of an alkali granite rim and granodiorite core (Harris and Marriner, 1980).

Harris and Marriner (1980) concluded that the alkali granite rim crystallized from a volatile-rich, highly fractionated magma derived by partial melting in the lower crust. During the last stages of fractionation, the highly fractionated magma combined with a coexisting alkaline volatile phase to produce the Ghurayyah plug. The last phase of magmatic activity was the emplacement of the circular graniodiorite core.

Resources of zirconium, niobium-tantalum, uranium, and other metals in irregularly distributed accessory minerals including zircon, columbite-tantalite, uraninite, and monazite have been identified. Possible reserves of about 400 million metric tons having an average grade of 0.75 percent zirconium, 0.25 percent niobium-tantalum, 0.25 percent REE, 0.02 percent tin, and 0.01 percent uranium have been estimated (Lalande, 1977).

Similar zirconium-niobium-enriched granites are found at Jabal Tawlah (number 6, fig. 2) and Umm al Birak (number 7) (Irvine, 1979). These two granites and the Ghurayyah stock have the following features in common: association with peralkaline granites; anomalous radioactivity; and location along east- and north-northwest-trending structures as inferred from regional magnetic patterns.

Several peralkaline complexes in the northeastern part of the Shield potentially contain niobium-zirconium-enriched granites; examples include Jabal Aja (number 8, fig. 2), Jabal at Tuwalah (number 9), and Bayda Nathil (number 10). These complexes are anomalously radioactive relative to their host rocks and are associated with zirconium and (or) niobium anomalies.

Jabal Aja (number 8, fig. 2) is a composite batholith, approximately 80 km long and as much as 30 km wide, located at the extreme northeastern edge of the Arabian Shield. Some of its more interesting features are: an outer ring of peralkaline alkali granite; a complex core of granophyric granite; a xenolith, 5 km long, of comenditic rhyolite and granite porphyry; and capping rhyolites. Associated mineral occurrences are a fluorite vein, a radioactive quartz vein and pegmatite, and a small enriched cupola near the northeastern corner of the complex. Analyses of rock samples from these occurrences indicate from less than 100 to more than 1,000 ppm zirconium, from 100 to 2,000 ppm niobium, from 20 to 150 ppm tin, from 50 to more than 2,000 ppm yttrium, and from 50 to more than 1,000 ppm lanthanum.

The Jabal at Tuwalah complex (number 9, fig. 2) is exposed over an area 30 km wide by 50 km long and consists of several plutons of peralkaline granite associated with granophyric granite, rhyolite, and volcaniclastic rocks (Delfour, 1977). Zircon-bearing pegmatites are common.

Another peralkaline complex at Bayda Nathil (number 10, fig. 2) near the northern edge of the Shield is poorly exposed and little studied. It is interesting, however, because it locally contains about 1 percent elpidite, a hydrous sodium-zirconium silicate mineral, in a medium- to coarse-grained peralkaline granite composed of perthite, quartz, arvfedsonite, and aegirine-augite.

Major and minor element data and selected ratios for samples of several plutons in the northern Shield (table 2, analyses 1-5) show that these rocks are peralkaline as indicated by the agpaitic ratio (molecular $(Na_2O+K_2O)/Al_2O_3$) of greater than one. These granites also have higher than normal SiO_2, Na_2O, and K_2O and lower Al_2O_3, MgO, and CaO. They show significant enrichment in zirconium, fluorine, lithium, rubidium, niobium, lanthanum and yttrium and notable depletion in strontium. The Mg/Li ratios are low, the K/Rb ratios are intermediate, and the Rb/Sr ratios are high relative to normal granites (table 4). These peralkaline granites are probably parents or precursors to small niobium-zirconium-enriched plutons.

Tin-tungsten-enriched alkali granites are principally, as presently known, in a belt in the eastern part of the Shield from about lat 18° to 26° N. The identification and possible economic significance of this class of postorogenic granites have been pointed out by Elliott (in press), Cole and others (1981), and du Bray and others (1982). Previous work has also identified anomalous tin and (or) tungsten associated with a number of young granites. Geological and geochemical reconnaissance of part of the eastern Shield by Whitlow (1966a,b, 1968a,b,c) identified geochemical anomalies of tin, tungsten, and other elements associated with several young granite plutons. Anomalous tin associated with several young granites in the southern Shield was reported by Greenwood (1980a,b); and numerous reports of the occurrence of tungsten in granites include those by Ankary (unpub. data), Whitlow (1965), Goldsmith (1971), and Overstreet and others (1972).

Between 1977 and 1979 additional geologic and geochemical studies were conducted by the author on the granites identified by Greenwood (1980a,b) and in areas recommended by Whitlow (1966b). As a result, several tin-bearing granites similar to specialized granites as defined by Tischendorf (1977) and several plutons similar to Tischendorf's class of precursors to tin-mineralized granites were recognized.

Table 2.--Geochemistry of peralkaline, precursor, and tin-bearing granites of the Arabian Shield

[Leader (-), not determined; N, not detected at limit of determination; sample descriptions and analytical techniques at end of table]

	Peralkaline granites					Precursor granites					Tin-bearing granites				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Major elements (weight percent)															
SiO_2	77.2	74.7	74.9	74.9	76.4	75.00	74.20	75.90	75.90	72.10	72.90	75.00	77.80	75.00	77.60
TiO_2	0.42	0.27	0.33	0.26	0.31	0.26	0.13	0.08	0.06	0.25	0.09	<0.01	0.10	0.01	0.02
Al_2O_3	9.4	11.0	9.3	11.1	11.0	12.10	13.00	12.40	12.80	13.60	12.70	13.90	11.90	13.90	12.50
Fe_2O_3	2.4	1.8	4.1	1.4	1.6	.04	.35	.44	.45	.67	.99	.37	.20	.25	.15
FeO	1.4	.86	.94	1.0	1.2	1.10	1.09	.86	.61	1.73	1.40	.37	.47	.30	.50
MnO	-	-	-	-	-	-	.03	.04	.02	.05	-	.05	-	.08	.06
MgO	.03	.08	.05	.11	.03	.04	.14	.07	.08	.28	.04	.03	.05	.03	.04
CaO	.35	.35	.64	.35	.27	.60	.90	.55	.55	1.05	.31	.29	.25	.21	.13
Na_2O	4.4	4.4	3.8	4.7	4.2	4.00	3.60	3.90	3.75	4.10	5.30	4.87	4.70	5.07	4.13
K_2O	4.5	4.1	4.3	4.4	4.6	4.8	5.10	4.90	4.75	4.95	3.90	4.35	4.20	4.32	4.05
P_2O_5	<.02	<.02	<.02	<.02	<.02	<.02	.04	<.02	.02	.01	<.02	<.02	<.02	<.02	<.02
CO_2	-	-	-	-	-	-	.15	.05	.05	.20	-	.05	-	.05	.05
F	.17	.28	.16	.46	.12	.37	.22	.30	.23	.29	.19	.28	.22	.13	.30
H_2O	-	-	-	-	-	-	.77	.38	.48	.76	-	.32	-	.31	.28
L.O.I.[1]	<.1	.32	.54	<.1	<.1	.23	-	-	-	-	.21	-	.28	-	-
Total	100.27	98.16	99.06	98.68	99.73	98.54	99.72	99.87	99.75	100.04	98.03	99.88	100.17	99.66	99.81
Minor elements (parts per million)															
Li	90	180	110	80	60	88	60	92	91	171	216	325	148	162	437
Rb	200	337	355	182	155	466	240	270	230	440	660	660	564	940	920
Sr	34	17	34	34	34	42	46	16	26	17	17	5	17	3	4
Sn[2]	N	N	N	N	-	10	4	8	<4	<4	150	55	50	36	60
Ta	-	-	-	-	-	-	10	15	<10	<10	-	20	-	45	15
Pb	-	-	-	-	-	30	28	44	42	50	70	70	150	100	65
U	-	-	-	-	-	-	8	6	<4	12	-	<4	-	4	12
Th	-	-	-	-	-	-	30	30	20	48	-	20	-	26	34
Nb	100	20	70	<20	-	20	42	60	50	70	30	65	30	90	120
Y	100	150	100	50	-	150	70	120	80	190	70	44	70	16	44
Zr	>1,000	300	1,000	200	-	100	200	180	130	140	70	55	70	44	80
Ce	-	-	-	-	-	-	110	100	70	50	-	40	-	40	30
La	200	20	100	70	-	30	30	20	50	50	30	<20	<20	<20	20
Data ratios															
Mg/Li	2.0	2.7	2.7	8	0	2.7	14.0	4.6	5.3	9.9	1.1	0.6	2.0	1.1	0.6
K/Rb	187	101	101	200	246	85	176	150	171	93	49	55	62	38	36
Agpaitic[3]	1.29	1.06	1.17	1.13	1.09	0.973	.880	.945	.884	.890	1.019	.915	1.032	.936	.894
Rb/Sr	5.9	19.8	10.4	5.4	4.6	11.1	5.2	16.9	8.8	25.9	38.8	132.0	33.2	313.3	230.0
Zr/Sn	-	-	-	-	-	10	50	23	>32	>35	0.5	1.0	1.4	1.2	1.3

1/ Loss-on-ignition (L.O.I.) values are equal to originally reported L.O.I. values minus fluorine values.
2/ Limit of determination for tin, 10 ppm.
3/ Agpaitic ratio = molecular $(Na_2O + K_2O)/Al_2O_3$

EXPLANATION

Except as noted, minor elements determined semiquantitatively at DGMR-USGS laboratory, Jiddah, by emission spectrography. Analyses 1-5, 6, 11, and 13 by Skyline Labs, Colorado; SiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, and Li by atomic absorption; TiO_2 and P_2O_5 by colorimetry; Sr and Rb by flame-emission spectrography; F by specific-ion electrode. Analyses 7-10, 12, 14, and 15 by Amdel, Adelaide, Australia; major element oxides and H_2O and CO_2 by wet-chemical methods or by combined X-ray fluorescence and wet methods; Li by atomic absorption; F by specific-ion electrode; Rb, Sr, Sn, Ta, Pb, U, Th, Nb, Y, Zr, Ce, and La by X-ray fluorescence.

SAMPLE DESCRIPTIONS

1. Sample 112991; Jabal Aja alkali granite; lat 27°20.8' N., long 41°26.1' E.; data from Stoeser and Elliott (1980); locality 8, fig. 2.
2. Sample 112837; Jabal at Tuwalah alkali granite; lat 25°33.4' N., long 41°02.1' E.; locality 9, fig. 2.
3. Sample 112896; Jabal Awja alkali granite; lat 25°49.0' N., long 40°58.0' E.
4. Sample 112918; Jabal Qunnawat alkali granite; lat 26°09.8' N., long 41°21.5' E.
5. Sample 124017; Jabal Dibbagh alkali granite; lat 27°54.9' N., long 35°44.6' E.

6. Sample 112946; Jabal Qutn alkali-feldspar granite; lat 26°00.1' N., long 42°17.8' E.
7. Sample 124069; Wadi Ghemm albite-microcline granite; lat 17°56.0' N., long 44°00.1' E.
8. Sample 124273; Jabal Sahah albite-microcline granite; lat 22°11.3' N., long 44°48.3' E.
9. Sample 124275; Jabal Sahah albite-microcline granite; lat 22°10.0' N., long 44°48.8' E.
10. Sample 124287; Jabal Sabhah albite-microcline granite; lat 23°17.8' N., long 44°36.3' E.

11. Sample 124056; Jabal al Gaharra albite-microcline granite; lat 18°05.5' N., long 44°00.4' E.; locality 11, fig. 2.
12. Sample 124183; Jabal al Gaharra albite-microcline granite; lat 18°05.4' N., long 44°00.5' E.; locality 11, fig. 2.
13. Sample 124083; Jabal Bani Bwana albite-microcline granite; lat 18°29.0' N., long 43°54.2' E.; locality 12, fig. 2.
14. Sample 124254; E. of Jabal Tarban albite-microcline granite; lat 21°13.7' N., long 44°02.1' E.; locality 13, fig. 2.
15. Sample 124264; Jabal as Sitarah albite-microcline granite; lat 22°06.0' N., long 44°42.6' E.; locality 14, fig. 2.

Tin-bearing granites have been identified at four locations in the southeastern and eastern Shield. These are the Jabal al Gaharra microcline-albite granite (lat 18°05' N., long 44°00' E., number 11, fig. 2), the Jabal Bani Bwana granite porphyry (lat 18°29' N., long 43°55' E.; number 12), an alkali-feldspar granite near Jabal Tarban (lat 21°13' N., long 44°02' E.; number 13), and the Jabal as Sitarah alkali-feldspar granite (lat 22°06' N., long 44°42' E.; number 14).

The Jabal al Gaharra microcline-albite granite (number 11, fig. 2) was the first to be recognized as a tin-bearing granite. Greenwood (1980b) reported a tin value of 100 ppm for a sample of this granite. The results from a later study (Elliott, in press) indicate that this granite is anomalous in tin and other elements and that it has distinctive textures and mineralogy. Jabal al Gaharra is an elongate pluton (4.5 km by 1.5 km) composed of microcline-albite granite emplaced late in the Precambrian along a fault zone cutting Precambrian metasedimentary and metavolcanic rocks. This leucocratic granite has an average mode of quartz, 32.3 percent; albite, 34.6 percent; microcline, 28.3 percent; and mica, 4.8 percent. Medium-grained poikilitic quartz and microcline with interstitial and included albite laths form a distinctive texture. Pale brown mica with rims of colorless muscovite is interstitial. Diagnostic accessory minerals include abundant fluorite and topaz and rare cassiterite. The quartz contains abundant fluid inclusions, many of which consist of three phases: vapor, water-rich liquid, and liquid carbon dioxide. This type of fluid inclusion may be diagnostic of this type of granite. The Jabal al Gaharra granite is high in SiO_2 and alkalis and low in TiO_2, MgO, and CaO (analyses 11, 12, table 2). It contains higher than normal amounts of fluorine, rubidium, lithium, and tin and lower amounts of strontium. In addition, geochemical rock sampling (table 3) suggests local anomalous beryllium, bismuth, niobium, and lead contents. Analysis of heavy-mineral concentrates and wadi sediments in the Jabal al Gaharra area (table 3) shows strong and consistent anomalies in tin and niobium and smaller, less consistent anomalies in beryllium, lead, and zinc. The chemistry, petrography, and mineralogy of the Jabal al Gaharra granite closely resemble those of specialized granites as defined by Tischendorf (1977).

A granite porphyry at Jabal Bani Bwana (number 12, fig. 2) in the northeastern part of the Wadi Malahah quadrangle, is chemically similar to the Jabal al Gaharra granite although it is texturally different. In March 1979, fieldwork in areas suggested by Whitlow (1966b) resulted in the recognition of tin-bearing granites near Jabal Tarban (number 13, fig. 2) and at Jabal as Sitarah (number 14). These granites are similar in geologic setting, chemistry, petrography, and mineralogy to the granite at Jabal al Gaharra and are

Table 3.--Results from geochemical rock and sediment sampling of tin-bearing granites

[All results in parts per million; leader (-), not determined. For rock samples molybdenum, niobium, lead, yttrium, zinc, rubidium, and strontium determined by X-ray fluorescence; lithium determined by atomic absorption; fluorine by specific-ion electrode methods. All elements for heavy-mineral concentrates and beryllium, bismuth, lanthanum, tin, and tungsten for rock samples determined by semiquantitative spectrography]

	Rock samples				Heavy-mineral concentrates of sediment			
Sample*	1 (44)	2 (3)	3 (3)	4 (2)	1 (36)	2 (6)	3 (2)	4 (5)
Beryllium	2-15	3-7	2-15	5,7	<1-50	2-7	2	1-2
Bismuth	<10-30	<10	<10	<10	<10	<10	50	<10-50
Lanthanum	<20-50	<20	<20-70	<20,20	<20-300	<20-150	70	30
Molybdenum	<5	<5	<5	<5	<5-20	<5	<5	<5-10
Niobium	30-75	25-75	15-60	50,110	<20->2000	<20-70	70	<20,20
Lead	<35-65	65-120	15-90	35,50	10-300	10-30	50	10-50
Tin	<10-200	<10-50	<10-300	30,30	<10->1000	<10-150	>1000	>1000
Tungsten	<50	<50	<50	<50	<50-70	<50	<50	<50
Yttrium	10-410	25-140	30-45	55,105	30-300	30-100	200	70-100
Zinc	<50-125	140-160	<50-65	<50,55	<200-2000	<200-300	<200	<200
Zirconium	10-100	45-100	25-145	80,95	50->1000	50-700	>1000	>1000
Lithium	20-540	130-210	5-165	50,440	-	-	-	-
Fluorine	1120-5200	920-2240	1200-6120	2560,3000	-	-	-	-
Rubidium	120-760	345-615	160-835	357,832	-	-	-	-
Strontium	<10-30	<10	<10-87	<10,28	-	-	-	-

*Sample type and location (number in parentheses is number of samples analyzed):

1. Granite, Jabal al Gaharra.
2. Granite porphyry, Jabal Bani Bwana.
3. Granite east of Jabal Tarban.
4. Granite, Jabal as Sitarah.

classified as specialized granites. Results from geochemical sampling (table 3) show that both the suite and levels of concentration of anomalous elements are comparable to those from the Jabal al Gaharra area.

These tin-bearing granites may be similar to granites in the Eastern Desert of Egypt associated with small deposits of tin, tungsten, tin-tungsten, tin-tantalum, and tantalum (El Ramly and others, 1970). Descriptions of tin-tantalum-bearing granites by Sabet (1974a, b) suggest many similarites with the tin-bearing granites of Saudi Arabia including high SiO_2 and lithium contents, low titanium, magnesium, and calcium contents, and low K/Rb ratios. Mineralogic similarities include an abundance of albite and the presence of muscovite, topaz, and fluorite.

Major and minor element data and selected ratios of the tin-bearing granites of Saudi Arabia (table 2, analyses 11-15) and results from geochemical sampling (table 3) show that these leucogranites have high concentrations of SiO_2 and Na_2O, and low concentrations of TiO_2, Fe_2O_3, FeO, MgO, and CaO. In terms of alumina saturation, these rocks are weakly peralkaline or weakly peraluminous, but the accessory minerals, for example, muscovite and topaz, are characteristic of peraluminous granites. Most, if not all, of these granites have undergone late-magmatic changes or autometasomatism, possibly including alkali metasomatism; therefore, these analyses may not be representative of the parent magma. These granites show strong enrichment in lithium, rubidium, tin, tantalum, and niobium; significant enrichment in fluorine, lead, and possibly uranium and thorium; and depletion of strontium and zirconium relative to normal or average granite (tables 2, 4; Brobst and Pratt, 1973).

Rock-chip sampling defines local anomalous values of silver, beryllium, bismuth, lead, yttrium, and zinc and strong and consistently anomalous values of niobium, tin, lithium, fluorine, and rubidium. The results of analyses of heavy-mineral concentrates of wadi sediment also indicate local anomalous values of beryllium, bismuth, lead, yttrium, and zinc and sporadically distributed anomalous values of lanthanum, molybdenum, and tungsten (table 3). Niobium and tin values are commonly highly anomalous in heavy-mineral concentrates.

Granites chemically equivalent to Tischendorf's (1977) precursors of specialized granites were found at Wadi Ghezm (lat 17°56' N., long 44°00' E.), at Jabal Sahah (lat 22°10' N., long 44°48' E.), at Jabal Sabhah (lat 23°18' N., long 44°36' E.), and in the northeastern Shield at Jabal Qutn (lat 26°00' N., long 42°18' E.). Major and minor element values for these precursor granites (table 2, analyses 6-10) show that these granites have high SiO_2, slightly high Na_2O and K_2O, and low TiO_2, Fe_2O_3, FeO, MgO, and CaO compared to normal granites (table 4; Tischendorf, 1977). The mineralogy, which includes muscovite and biotite, is characteristic of peraluminous granites. Minor and trace element geochemistry shows strong enrichment in fluorine and strong depletion in strontium (table 4). These granites also are significantly enriched in lithium, rubidium, tin, tantalum, lead, uranium, thorium, niobium, yttrium, and cerium (tables 2, 4; Brobst and Pratt, 1973). The Mg/Li ratios are low, the Rb/Sr ratios are high, and the K/Rb and Zr/Sn ratios are intermediate (table 2).

A tentative list of criteria for recognizing tin-bearing granites in the Arabian Shield has been developed based on the study of such granites recognized thus far.

1. The tin-bearing granites are leucocratic alkali-feldspar granites that occur as small plutons of less than about 10 km^2, probably as satellites of larger plutons.

2. They occur in a north-trending belt in the eastern Shield.

3. They have distinctive poikilitic textures and are commonly subporphyritic.

4. The only mafic mineral is a light-brown mica that is interstitial to quartz and feldspar.

5. Distinctive accessory minerals include abundant fluorite and topaz and rare cassiterite.

6. Fluid inclusions are abundant in quartz and commonly contain liquid carbon dioxide.

7. They have low TiO_2, MgO, CaO, and strontium contents and high fluorine, rubidium, lithium, and tin contents. The Mg/Li, K/Rb, and Zr/Sn ratios are low, and the Rb/Sr ratio is high.

8. Geochemical sampling yields anomalies in some or all of the elements: lithium, fluorine, tin, niobium, lead, bismuth, and beryllium.

9. They are specialized granites as defined by Tischendorf (1977).

The granites classed as precursors to specialized granites have the following characteristics:

1. They crop out as medium-sized plutons (50-200 km^2) in a north-trending belt in the eastern Shield commonly in proximity to tin-bearing granites.

2. They are alkali-feldspar granites that contain biotite or biotite and muscovite.

3. They are chemically similar to the tin-bearing granites but have lower lithium, rubidium, and tin contents and higher TiO_2, MgO, CaO, and strontium contents. The Mg/Li, K/Rb, and Zr/Sn ratios are higher and the Rb/Sr ratio is lower than in tin-bearing granites, but, in general, the ratios are closer to those of specialized granites than to those of normal granites of Tischendorf (1977). Most are weakly peraluminous.

4. Geochemical sampling yields a suite of anomalous elements similar to that of the tin-bearing granites but with lower concentrations.

In two cases, those of Jabal al Gaharra and Jabal Sahah, precursor and tin-bearing granites in close proximity are probably genetically related. The tin-bearing granite is probably a more highly evolved and possibly a later differentiate of the same parent magma.

Average major oxide contents, minor element contents, and selected ratios for peralkaline, precursor, and tin-bearing granites were compared with those for normal and specialized granites of Tischendorf (1977) (table 4). The peralkaline, precursor, and tin-bearing granites are more silicic, somewhat higher in alkali content, and lower in TiO_2, Al_2O_3, FeO, MgO, and CaO contents than normal granites (Tischendorf, 1977) and are notably enriched in fluorine, lithium, rubidium, niobium, and possibly yttrium. The precursor and tin-bearing granites have very similar major oxide contents but show some differences in minor element geochemistry; the tin-bearing granites are notably enriched in lithium, rubidium, and tin and depleted in strontium, zirconium, lanthanum, and yttrium relative to precursor granites. Peralkaline granites contain less Al_2O_3 and more Fe_2O_3, zirconium and lanthanum than precursor and tin-bearing granites.

The Mg/Li ratios (table 4) of the peralkaline, precursor, and tin-bearing granites are closer to those of specialized than to those of normal granites; these granites also have much higher Rb/Sr ratios than normal granites. The K/Rb

Table 4.--Comparison of peralkaline (PERALK), precursor (PRE-SN), and tin-bearing (SN) granites with normal and specialized (SPECIAL) granites of Tischendorf (1977)

[Results SiO_2-fluorine in percent, lithium-yttrium in ppm. Leader (-) indicates no data available. Number in parentheses below sample type is number of samples analyzed]

	PERALK (5)	PRE-SN (5)	SN (5)	NORMAL (2327)	SPECIAL (962)
SiO_2	75.62	74.60	75.66	70.84	73.38
TiO_2	0.32	0.16	0.05	0.34	0.16
Al_2O_3	10.36	12.78	12.98	14.33	13.97
Fe_2O_3	2.26	.39	.39	1.31	.80
FeO	1.08	1.08	.61	1.78	1.10
MgO	.06	.12	.04	.81	.47
CaO	.39	.73	.24	1.89	.75
Na_2O	4.30	3.87	4.81	3.44	3.20
K_2O	4.38	4.90	4.16	4.34	4.69
F	.24	.28	.22	.085	.318
Lithium	104	100	258	30	274
Rubidium	246	329	749	150	550
Strontium	31	29	9	285	-
Niobium	50	48	67	20	-
Zirconium	750	150	64	180	-
Tin	-	5	70	3	10-50
Lanthanum	98	36	16	25	-
Yttrium	93	122	49	40	-
Mg/Li	3.5	7.2	0.9	163	10
K/Rb	148	135	48	>100	<100
Rb/Sr	7.9	13.6	149	.53	-
Agpaitic*	1.14	0.91	.96	.957	.999

*Agpaitic ratio = molecular $(Na_2O + K_2O)/Al_2O_3$

ratios (table 4) for samples of the tin-bearing granites are similar to those of specialized granites, whereas those of peralkaline and precursor granites are similar to those of normal granites. Both precursor and tin-bearing granites in Arabia are very similar to Tischendorf's class of specialized granites.

Compared to specialized granites, peralkaline granites show differences relative to Al_2O_3 and Fe_2O_3 contents but are more similar with respect to SiO_2, CaO, and MgO contents than to normal granites (table 4). Both the peralkaline and specialized granites are enriched in fluorine, lithium, and rubidium relative to normal granites.

A significant tungsten deposit associated with a specialized granite has been reported in the northeastern Shield by Cole and others (1981; also, Lofts, 1982). The Baid al Jimalah West tungsten deposit (number 15, fig. 2; MODS02661) is both within and marginal to a small, irregular dike complex of late Proterozoic porphyritic microcline-albite granite. This granite is highly enriched in lithium, fluorine, beryllium, tungsten, and tin and is strongly veined and greisenized. The mineralized zone crops out over an area 700 m wide by 800 m long and consists of intense quartz veining in the granite and in the hornfels marginal to the granite. Swarms, networks, and stockworks of closely spaced quartz veins containing wolframite, fluorite, scheelite, and muscovite and minor amounts of cassiterite, pyrite, arsenopyrite, and feldspar, were deposited immediately after emplacement of sheets and dikes of porphyritic microcline-albite granite in fine-grained metasedimentary rocks. The discovery of this deposit indicates that specialized granites should be given high priority as exploration targets because of the potential for discovery of associated mineral deposits.

Although peraluminous and peralkaline granites are widespread in the Arabian Shield, certain areas of the Shield appear to be more promising than others for the occurrence of the niobium-zirconium- and tin-tungsten-enriched granites. The niobium-zirconium-enriched granites found thus far occur in the northwestern Shield along a north-northwesterly trend and are associated with peralkaline granites. Many peralkaline granite plutons and complexes are found elsewhere in the northern and eastern Shield (Stoeser and Elliott, 1980), particularly along a north-trending belt in the northern Shield from about lat 23°30' N., long 43°00' E., north to the edge of the Shield at about lat 27°45' N. Many mineral deposits are along this belt, and the potential for the discovery of niobium-zirconium-enriched granites associated with these peralkaline complexes is high.

The tin-tungsten-enriched and precursor granites found thus far occur in a north-trending belt in the eastern Shield from about lat 18°00' N., long 44°00' E., to about lat 26°00' N., long 42°20' E. This belt is 900 km long and includes large areas in which the geology and mineral resources are poorly known. The discovery of the Baid al Jimalah West tungsten deposit near the northern end of the belt is an indication of the undiscovered mineral potential of this belt and of the need for more geologic, geochemical, and geophysical studies in the eastern Shield.

PROSPECTING METHODS

Prospecting methods used by the author to detect and locate specialized granites included geologic, geochemical, and geophysical methods. Geologic methods included reconnaissance mapping and sampling for petrographic, chemical, and mineralogic studies. Geochemical methods included rock-chip and wadi-sediment sampling. The most useful geophysical technique was radiometric surveys; magnetic surveys were also helpful.

Geologic reconnaissance was planned by examination of geologic maps, aerial photographs, and Landsat images. Small-scale geologic maps (1:500,000, 1:250,000) fairly accurately indicated the distribution and location of most moderate to large granitoid plutons and generally permitted discrimination between calc-alkaline and peralkaline types. Larger scale maps (1:100,000) provided more information, especially for smaller plutons and intrusive complexes. Granitic plutons were usually obvious on aerial photographs, photomosaics, and Landsat images and could commonly be discriminated by type according to the shape and style of the intrusion. For example, many of the peralkaline granites occur as ring-shaped complexes and are distinctive on Landsat images or photomosaics. Various enhanced Landsat images were employed to discriminate between granitoid types and, in the most favorable cases, to locate peralkaline and peraluminous granites (D. B. Stoeser, unpublished data).

Geologic reconnaissance methods were used in areas of poorly known geology to locate and map granitoid rocks and their contacts with adjacent units, to look for features suggestive of mineralization such as alteration and the occurrence of veins or stockwork zones, and to collect rock samples for petrographic, chemical, and mineralogic studies. Petrographic studies included modal analysis of stained rock slabs and examination of thin sections for textures and mineralogy. Major element contents were determined using standard methods on selected samples, and normative contents were computed for classification and comparison by chemistry. The mineralogy was determined by optical methods and augmented by X-ray techniques when necessary.

Certain accessory minerals in granitoid rocks and derived sediments may indicate the favorability or presence of ore deposits, but accessory mineral suites have received little attention in previous work in the Arabian Shield. Studies of accessory minerals in granitoid rocks associated with porphyry- or stockwork-type ore bodies suggest that these rocks are characterized by distinct assemblages of accessory minerals and (or) accessory mineral chemistry (W. N. Sharp, written commun., 1980). In addition, in some granitoid rocks the accessory minerals themselves, for example, columbite-tantalite, are an economic source of rare or critical metals.

Accessory minerals were studied in thin section, in sediments derived from granitoid rocks, and in heavy-mineral concentrates derived from representative samples of unaltered rocks. Because many of the accessory minerals are resistant to weathering and have specific gravities greater than those of most common rock-forming minerals, they tend to be preferentially concentrated in the sediments derived from the granites. These minerals were identified by use of a stereo microscope after heavy-mineral concentration.

Both essential and accessory mineralogy are important for the discrimination of specialized granites. The distinctive mineralogy of peralkaline granites includes hypersolvus feldspar, and sodium-rich pyriboles including arfvedsonite, riebeckite, and aegirine-augite. Zircon is commonly abundant, fluorite is commonly present, and elpidite ($Na_2ZrSi_6O_{15} \cdot H_2O$) has been found in several samples of peralkaline plutons of the northeastern Shield. Other common accessory minerals are sphene, magnetite, apatite, allanite, ilmenite, and monazite. In the case of the niobium-zirconium-enriched Ghurayyah granite plug, which shows extreme enrichment in niobium, zirconium, and other elements, the accessory mineral suite includes pyrochlore, hematite, goethite, eudialyte, monazite, columbite-tantalite, thorite, cassiterite, xenotime, betafite, and uraninite (Lalande, 1977).

The tin-tungsten-enriched granites are two-feldspar subsolvus granites composed of microcline, albite, quartz, and muscovite as essential minerals. The precursor granites are commonly two-mica granites with muscovite and biotite. The tin-tungsten-enriched granites contain fluorite, topaz, zircon, apatite, cassiterite, and iron oxide minerals as accessory minerals. The accessory mineral suite is the same in the precursor granites except that topaz and cassiterite have not been identified.

Geochemical methods used in the study of granites of the Arabian Shield included rock-chip and wadi-sediment sampling. Granitic plutons were systematically sampled by collection of rock chips at several locations. These samples were analyzed by semiquantitative emission spectrography for 30 elements and by wet chemical methods for lithium, fluorine, and tungsten. The results were checked for anomalous concentrations of elements of interest and (or) suites of characteristic elements to select areas for further, more detailed work.

A system of standardized data collection during rock sampling was developed that used preprinted forms, which were later utilized for development of computer-based data files. The information collected at each locality included a description of lithology, mineralogy (including color index, quartz content, and potassium feldspar/plagioclase ratio), color of the sample, structure, presence of alteration and (or) ore minerals, location, and scintillometer reading. Most of this information was entered in coded form so that keypunching could be done directly from the field form.

Wadi-sediment samples were also collected from interior and peripheral drainages of all granitic plutons and analyzed by semiquantitative emission spectrography. The results were used to characterize the type of granite and (or) indicate the presence of previously undetected mineralized rock. As in the case of rock samples, procedures for data collection and the collection and treatment of the sediment samples were standardized, and a preprinted form was used. The data were keypunched directly from this form and included information on location, dominant grain size, drainage area size, bedrock source, and sediment color.

Careful consideration was given to the selection of the wadi-sediment sample sites: The drainage pattern was examined on aerial photographs to select drainages that would give as complete coverage as possible of the pluton and its contact zone. The number of samples collected did not need to be large because only the geochemical affinity of a pluton was being tested; in many cases, fewer than 10 were adequate for this purpose. Areas and drainages with abundant windblown sand were avoided because sediment samples from these areas would be diluted and might contain exotic materials. A natural dropout point, where heavy minerals would tend to concentrate in the drainage, was the preferred sample site.

At each site, 3 to 4 kg of -10 mesh material were collected using a 10-mesh screen and pan and put into a canvas bag. At base camp, half of the original sample was panned to prepare a heavy-mineral concentrate, which was dried and submitted for analysis. One-fourth of the sample was seived and the resulting -30+80 mesh fraction was labeled and submitted for analysis. One-fourth of the original sample was archived for further work.

Early in the study, geochemical data obtained for the -30+80 mesh and the -10+30 mesh fractions of wadi sediment were compared. Although results were much the same, the data suggested that in the same drainage the -30+80 fraction provided wider areal coverage than the -10+30 fraction. The -80 mesh fraction, commonly used in more temperate climates, was judged inferior to both the -10+30 and -30+80 fractions because of dilution by windblown material. These conclusions compare favorably to those of Theobald and Thompson (unpub. data).

Radiometric surveying was the geophysical technique most applicable to the detection of specialized granites in the Arabian Shield. During the reconnaissance fieldwork, total-count scintillometer readings were routinely made at all localities. Calc-alkaline granites were consistently less radioactive than either the peralkaline or peraluminous granites. The peralkaline granites generally were the most radioactive, commonly two to three times more radioactive than calc-alkaline granites. Scintillometer readings of five to six times background level were found at sites where peralkaline granites intrude rocks of low radioactivity such as sedimentary sequences or intermediate to mafic igneous rocks. Radioactive granites such as the Ghurayyah granite plug also have a well-defined radiometric signature on airborne scintillometer survey maps (Irvine, 1979).

Magnetic surveys were also useful in the discrimination of some specialized granites. Irvine (1979) found that radioactive granites of the northwestern Shield are associated with structures having prominent magnetic signatures and strong magnetic features interpreted as mafic intrusions.

SUMMARY

Mineral commodities in wide variety are associated with granitoid rocks in many parts of the world and occur in porphyry (or stockwork), vein, contact metasomatic, pegmatite, and other types of deposits. The commodities of greatest economic importance are tin, tungsten, molybdenum, copper, gold, silver, and uranium. Other elements of lesser economic value include tantalum, niobium, rare-earth elements, fluorine, lithium, beryllium, and thorium.

Granites from many parts of the world associated with tin and other commodities have striking similarities. These "specialized" granites are distinct from "normal granites" in terms of geologic setting, chemistry, mineralogy, petrography, and alteration.

Granitoid rocks are widespread in the Arabian Shield, and compilation of existing data and additional geologic and geochemical reconnaissance in the Shield indicate that many of these granites are similar to "specialized" granites and have some resource potential. The granites with the greatest resource potential are the younger or postorogenic granites that are abundant in the northern, eastern, and southeastern parts of the Shield. The younger granites may be subdivided into two major types, calc-alkaline and peraluminous to peralkaline.

Throughout the Shield many mineral occurrences and prospects are associated with granites; nearly all of these are associated with the younger granites and, within this group, predominantly with the peraluminous to peralkaline granites. The commodities associated with granites include tin, tungsten, molybdenum, beryllium, niobium, tantalum, zirconium, uranium, thorium, rare-earth elements, and fluorite. Some gold deposits may also be associated with granites. In the Shield, other important commodities, including copper and silver, have little or no known association with granites in the Shield.

Two types of specialized granites in Saudi Arabia are of considerable interest because of their economic potential: the zirconium-niobium-enriched peralkaline granites and the tin-tungsten-enriched peraluminous granites. An example of the former is the Ghurayyah granite plug, which has possible reserves of zirconium and niobium-tantalum as well as of rare-earth elements, tin, and uranium. These zirconium-niobium-enriched granites are associated with plutons and complexes of peralkaline granite, which are numerous in the northern half of the Shield. Known zirconium-niobium prospects include Ghurayyah, Jabal Tawlah, and Umm al Birak (fig. 2). Peralkaline complexes in the northeastern Shield that have potential for zirconium-niobium prospects include Jabal Aja, Jabal at Tawlah, and Bayda Nathil (fig. 2).

Tin-tungsten-enriched granites occur in a north-trending belt in the eastern Shield, and tin-bearing granites have been identified at four localities. Precursors of specialized granites are also present along this belt and are spatially associated with these specialized granites in two cases. The tin granites have distinctive mineralogy, textures, and chemistry and are particularly enriched in fluorine, rubidium, lithium, and tin. They are leucogranites and have high SiO_2, Na_2O, and K_2O contents and low TiO_2, Fe_2O_3, FeO, and CaO contents compared to normal granites, and their accessory minerals, such as muscovite and topaz, are characteristic of peraluminous granites. Although no economic deposits have yet been found associated with the four tin-bearing granites, the recent discovery of a significant tungsten-tin deposit associated with a similar specialized granite in the northeastern Shield indicates a potential for this type of specialized granite.

Both the zirconim-niobium- and tin-tungsten-enriched granites are specialized granites and represent the end products of magmatic differentiation. The zirconium-niobium-enriched peralkaline granites are the youngest members of an agpaitic evolution series, whereas the tin-tungsten-enriched granites are probably the youngest members of a plumasitic evolution series. Both represent the last granitic melts of igneous rock series that were emplaced in an intracontinental crustal environment from magmas that were probably generated from either the mantle or basal parts of a continental crust.

This study suggests that the most useful prospecting methods for identifying specialized granites in the Arabian Shield are reconnaissance geologic and geochemical surveys because these granites have distinctive mineralogy, textures, and chemistry. Sodium-rich pyriboles, zircon, and fluorite are distinctive minerals in zirconium-niobium-enriched granites, and muscovite, topaz, and fluorite are distinctive minerals in tin-tungsten-enriched granites. Rock samples from zirconium-niobium-enriched granites commonly have anomalously high concentrations of fluorine, rubidium, lithium, and rare-earth elements in addition to elevated concentrations of zirconium and niobium; sediments from these granites may also have anomalously high concentrations of tin and beryllium. Samples of tin-tungsten-enriched granites are enriched in lithium, fluorine, rubidium, niobium, lead, bismuth, and beryllium, as well as tin and (or) tungsten. The arsenic content may also be anomalous, as is the case at the Baid al Jimalah West tungsten prospect (Lofts, 1982).

This study also suggests that the most useful geophysical technique is radiometric surveying. Peralkaline granites are the most radioactive, but peraluminous granites are also anomalously radioactive relative to calc-alkaline granites and other rocks in the Arabian Shield.

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