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Geochemical and petrographic studies of Ta mineralization in the Nuweibi albite granite complex, Eastern Desert, Egypt

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Abstract The Nuweibi albite granite is one of 14 known Sn-Ta-Nb bearing granitoids in the Eastern Desert region of Egypt. The granite is a highly leucocratic, albite-rich rock with accessory columbite-tantalite, cassiterite, microlite and ixiolite as well as topaz, garnet and white mica. Ages of 450–600 Ma were obtained from zircons by the $^{207}Pb/^{206}Pb$ evaporation method. Great uncertainty is caused by the small size and poor quality of the grains, but the precision is sufficient to indicate that the granite is late- or postorogenic with respect to the Panafrican orogeny. The Nuweibi granite is divided into a western and an eastern part by a regional fault. Both parts of the granite are compositionally similar but there are important differences and a clear compositional gap between them, so they are considered separate facies of an intrusive complex. The eastern part of the granite is more highly mineralized, has higher modal albite contents and higher Ta/Nb ratios, both in the whole rock and in the ore minerals. It is suggested that the two parts of the granite evolved from a common source and were emplaced sequentially, the eastern part representing a later, more fractionated magma. Textural evidence strongly suggests that the granite has a magmatic origin overall, but disturbance of geochemical trends at the whole-rock scale and at the scale of zoning profiles in individual grains of columbite-tantalite indicate post-magmatic overprinting. By analogy with other Ta-bearing albite granites, the sodic bulk composition of the Nuweibi granite can be explained by fluorine enrichment in the magma. Fluorine contents in the magma were high enough to stabilize topaz, and muscovites contain 2–4 wt.%. F. However, whole-rock F contents are low. We speculate that the low Ca, Al and P contents of the magma prevented abundant F-bearing minerals to form and led to loss of fluorine to now-eroded roof rocks.

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Introduction

The main sources of Nb-Ta ores are granitic pegmatites, carbonatites and peralkaline granites (Möller et al. 1989). A less common type of Nb-Ta mineralization takes the form of disseminated ore minerals in fine-grained leucocratic granites of meta- to peraluminous composition. These leucogranites typically form small stocks or cupolas associated with larger intrusions and are not only important economically as low-grade, high-tonnage ore deposits, but they also provide a testing ground for understanding the processes leading to extreme chemical fractionation of granitic magma. Compositionally, these rocks can be seen as plutonic equivalents of rare-metal pegmatites and they share much of the highly specialized mineralogy of the latter (Li-phosphates and micas, complex Nb-Ta oxides).

The Nuweibi granite is one of 14 known Ta-Nb enriched albite granitoids in eastern Egypt which were first described in some detail by Sabet and Tsogoev (1973), Hussein (1973) and others. According to Sabet et al. (1976), the Nuweibi granite contains Ta-Nb ore reserves of 30 million tons at 0.02% Ta_2O_5 and 0.01% Nb_2O_5.

Rare-metal granites: nomenclature and genetic controversy

Pioneering work on rare-metal granitoids by Soviet geologists (Beus et al. 1962; Beus 1968) considered them to be high-level granitic rocks formed by metasomatic fluid overprinting of a "normal granite", and they were therefore named "apogranite". The term apogranite has specific genetic implications and therefore a non-genetic nomenclature, which describes the rocks according to modal mineralogy and texture, is preferred, i.e., alkali-feldspar- or albite granite, modified by a textural and mineral prefix as appropriate (porphyritic topaz-albite granite, etc.).

The compositional similarity of albite granites and rare-metal pegmatites has been mentioned before. It follows, perhaps, that the same controversy rages over the origin of mineralization in both rock associations. The early work on albite granites emphasized metasomatic features and concluded that the rare-metal enrichment and other compositional peculiarities were post-magmatic (the "apogranite" hypothesis). Likewise, the Ta-Nb-Li mineralization in granitic pegmatites tends to occur in albite-rich units, which were also considered to be metasomatic by many workers (see Cerny 1992). These viewpoints have been challenged by the discovery of volcanic and subvolcanic equivalents of apogranites such as the Macusani obsidian in Peru (Barnes et al. 1970), the Transbaikalian ongonites (Kovalenko et al. 1971) the Richemont rhyolite, Massif Central (Cuney and Raimbault, 1991; Cuney et al. 1992), and to some extent the topaz rhyolites of SW North America (Christiansen et al. 1986). The studies of these rocks, along with experimental results on the granitic system with added fluorine, boron and lithium (e.g., Pichavant and Manning 1984; London 1987) have led many recent workers to consider the unusual compositional features of albite granites and rare-metal pegmatites to be magmatic (see discussions in Kovalenko and Kovalenko 1984; Cerny 1992).

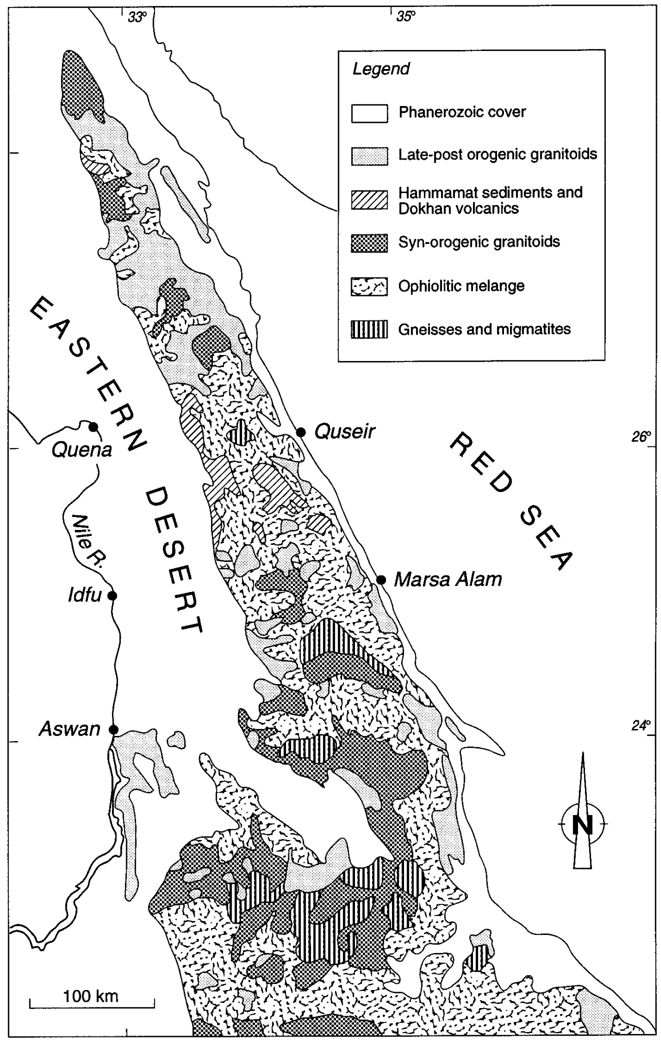

Fig. 1 Regional geologic map of the basement rocks in the Eastern Desert, Egypt

Geologic setting

The basement rocks of the Central Eastern Desert in Egypt were classified by Reis et al. (1983) into four litho-tectonic units: (1) Meatiq unit of gneisses and migmatites (crystalline rocks of the Nubian Shield), (2) Eastern Desert ophiolites melange unit (a subduction complex consisting of serpentinites, metagabbros, metavolcanics and metasediments), (3) Dokhan volcanic unit (calc-alkaline arc-volcanics); and (4) Hammamat unit of molasse-type clastic sedimentary rocks.

The Meatiq unit includes rocks of pre-Panafrican age of the Nubian Shield. The other three units form part of the Panafrican orogenic assemblage, which began with the closing of a marginal sea and formation of the Eastern Desert ophiolitic melange. The end of compressive, subduction-style tectonics was marked by a great unconformity which appears to have developed in the region at about 600 Ma (Rogers and Greenberg 1983), and is represented by the Dokhan volcanics and Hammamat molasse sediments.

The basement rocks described are intruded by a series of granitic intrusions which make up about 13% of the exposed area (Fig. 1). These range in composition from quartz diorite to alkali feldspar granite. Recent classifications of the granites by Hussein et al. (1982) and El-Gaby et al. (1990) can be summarized as follows:

1. G1 (or Ga) granites: older, gray, "synorogenic" calc-alkaline tonalite-granodiorite series of subduction character. The gray granites grade into granitic gneisses and migmatites and occur in the form of autochthonous and parautochthonous intrusions parallel to the structural grain of the country rocks.
2. G2 (Gb) granites: younger, pink, "syn-to postorogenic" calc-alkaline granites of collisional character. These are considered the plutonic equivalents of the Dokkan volcanics.
3. G3 (Gc) granites: anorogenic "A-type" subalkaline to peralkaline granites believed to have intruded intermittently in the period from the end of the Panafrican orogeny into the Tertiary.

The distribution of 14 rare-metal-enriched albite granitoids is shown in Fig. 2. They belong to the third granitic series outlined above, and share the following general features: (a) small size (< 1 to 3 km^2 in outcrop), often part of larger granitic massifs; (b) characteristic forms: domal (Nuweibi, Muelha, Zabara), lensoid (Humr Waggat, Ineigi, Um Naggat) or stock-like (Igla, Abu Dabbab); (c) close spatial relationship to major faults or fault zones; (d) wallrocks consisting of older gray granites, metasediments or metadiorites.

The age of the albite granites in Egypt is not well known. Sabet et al. (1976) suggested a late Proterozoic age for the rocks based on field relations, whereas El Gaby et al. (1990) suggested that the albite granites of Egypt might be related to Mesozoic magmatism. We present new single-zircon Pb-Pb ages later which show that the Nuweibi granite is of late- to post-Panafrican age.

Previous work

The Nuweibi granite and others of its kind were discovered in a UNDP airborne radiometric survey of Egypt and examined during a joint Egypt-Soviet geologic program in the 1970s (Sabet and Tsogoev 1973; Sabet et al. 1976). This early work considered the rocks to be "apogranites" derived by metasomatic enrichment in rare metals and sodium from leaching of underlying,

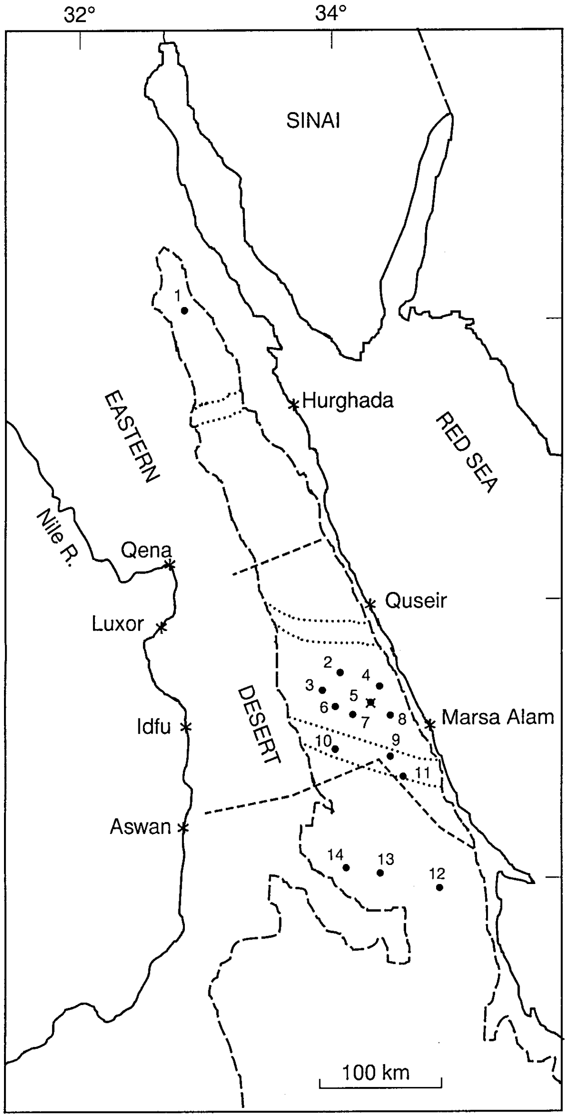

Fig. 2 Distribution of the most important rare metal-bearing granitic intrusions in Egypt: *1*, Hawashia; *2*, Umm Naggat; *3*, Umm Samra; *4*, Abu Dabbab; *5*, Nuweibi; *6*, Ineiga; *7*, Humr Waggat; *8*, Igla; *9*, Zabara; *10*, Muweilha; *11*, Nugrus; *12*, El Gharabiya; *13*, Nikeiba; *14*, Humr Akarem

larger bodies of biotite granites. However, a visible connection with the supposed parental biotite granites could be demonstrated only in the case of Humr Waggat (Sabet and Tsogoev 1973).

A number of detailed studies of individual "apogranites" of Egypt have challenged the metasomatic model or suggested that metasomatism merely strengthens an already-advanced magmatic rare-metal enrichment (El Tabal 1979; Riad 1979; Asran 1985; Jahn et al. 1993). Recent studies of individual rare-metal granites are given by Mohamed (1994) for the Abu Dabab granite and Morsey and Mohamed (1992) for the Muelha granite. Emphasis on the structural aspects of rare-metal granite emplacement and mineralization was made by Abu and Mussa (1984) and Matheis (1992).

Field relations

Figure 3 shows a geologic map of the Nuweibi granite. A prominent feature of the granite is its division into eastern and western parts by a fault along the Wadi Nuweibi. The eastern part of the granite has outcrop dimensions of about 950 m N-S and 400 m on average E-W. The highest elevation is about 300 m above sea level. The granite has intruded a metasedimentary sequence (mica schists and hornblende schists) alternating with metavolcanics and serpentinites. The contacts with the metamorphic rocks at the eastern part of the granite are shallow-dipping (15–20°), suggesting that the present exposure level is close to the granite roof. Albite granite dikes and apophyses are common in the metasediments. Marginal pegmatite zones ("stockscheider"), quartz segregations ("quartz cap" described by Renno et al. 1993) and quartz-amazonite veins occur near the contact as well and these are locally associated with minor greisenization of the metasediments.

The western part of the Nuweibi granite has a triangular shape in outcrop, with overall dimensions of 1.2 km EW and 1 km NW. The elevation is slightly higher than the eastern part, at 450 m. The western part is surrounded mostly by older gray granites (G1 series) and the contacts with these are nearly vertical, indicating perhaps a deeper level of exposure despite the higher topographic position. Apophyses and small dikes of the Nuweibi granite intrude the country rocks, and greisenization and pegmatitic border zones are less abundant than in the eastern part.

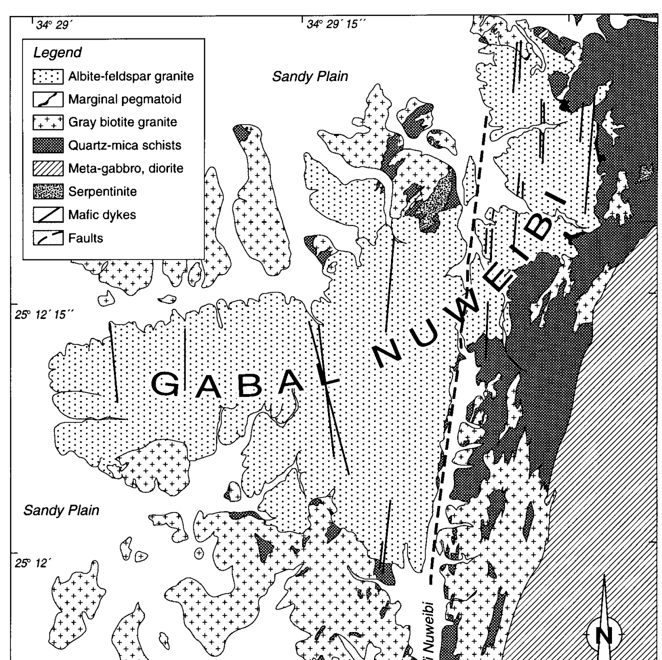

Fig. 3 Geologic map of the Nuweibi albite granite

Both parts of the granite are leucocratic, with a fine to medium-grained texture. The eastern part tends to be more porphyritic whereas the western part is seriate to equigranular. Both parts of the granites show locally prominent brown to black staining due to manganese-iron impregnations. These can take several forms: rounded patches 1–10 cm across, dendrites of the same overall dimension, and fillings along joint planes.

Three structural trends are prominent in the Nuweibi granite. The dominant direction of joints is NNE, parallel to the Wadi Nuweibi fault. This trend is also taken by mafic and intermediate dikes in the granite and by quartz-amazonite veins. Bakhit (1972) considers the NNE trend as the youngest structural trend in the region, but in the Nuweibi area a NE-SW trend of joints cuts the NNE-set of joints and dikes and is therefore younger. A third trend is E-W. It is shown by joints and is particularly well expressed by E-W drainage patterns in the granite. There are also some E-W trending felsic dikes in the western part of the granite. The E-W trend was considered the oldest regional structural trend by Bakhit (1972).

Investigative methods

The Nuweibi granite was sampled on a series of E-W profiles. Eighty samples were collected from outcrop in the eastern part along nine profiles 125 m apart with a sampling interval of 50 m. Forty samples were collected from outcrop in the western part along four profiles spaced 250 m apart, with a sampling interval of 100 m. More than 90 thin sections and 20 polished sections were examined. Nb-Ta ore minerals were studied with a JEOL JSM-35C scanning electron microscope fitted with an Ortec EDS spectrometer. Electron microprobe analyses were performed at the University of Kiel using a Cameca Camebax microprobe. Conditions of analyses were 15 kV accelerating voltage and beam current of 14 nA. Natural and artificial standards were used and data reduction followed Pouchou and Pichoir (1984).

Eighty-six samples of the granite were analyzed for major and selected trace elements by X-ray fluorescence (Siemens SRS303, Rh-tube, 45 kV 35 mA). The powdered samples were fused at 1120 °C after mixing 1 : 3 with lithium tetraborate. The rare-earth elements, Ta, Hf, Th, U and Cs were measured in a subset of 14 samples by INAA. Powdered samples (ca. 100 mg) were enclosed in silica glass ampules and irradiated for 16 h at a thermal neutron flux of about 1×10^{13} n/cm^2/s in the research reactor of the Technische Universität, München. Because of its high concentration in the Nuweibi rocks, Ta could also be measured by XRF, and the data shown in the tables and diagrams were derived by this method. For those samples analyzed by both methods, the Ta values agree within 10%.

Many of the REE are below detection limit of standard INAA. Therefore, REE analyses of 10 samples were repeated by ICP-AES at the GeoForschungsZentrum Potsdam, using the method described by Zuleger and Erzinger (1988). Finally, 32 samples from the granite and 6 samples from its country rocks were analyzed for fluorine by ion-selective electrode, and for Li using flame photometry by XRAL laboratories, Toronto.

Oxygen isotope measurements were performed on 27 whole-rock samples at the Technische Universität, München, following separation by conventional fluorination techniques.

Single zircon dating was performed using the evaporation method of Kober (1987) at the Lehrstuhl für Geochemie, Universität Tübingen.

Petrography and mineral chemistry

In both the eastern and western parts of the Nuweibi granite, the rocks are leucocratic and medium to fine-grained in hand specimen. The two parts differ, however, in texture, modal mineralogy and geochemistry (discussed later). It is important to note that the petrographic contact between the two parts occurs some tens of meters east of the Wadi Nuweibi (Fig. 4). In the field there are no macroscopic features to indicate the nature of the contact between the two parts. Samples located just east of the fault have textures intermediate between the eastern and the western part of the granite and they are termed “transitional” in this study. In fact, however, the geochemical evidence (below) shows a compositional gap, and not a transition, between the eastern and western part of the granite.

The contrast in mineral composition between eastern and western parts of the intrusion is shown by the modal analyses in Fig. 4. Albite and accessory minerals are more abundant in the eastern part than in the western part whereas K-feldspar, quartz and white mica show the opposite behavior. All samples plot within the alkali feldspar granite field of Streckeisen (1976).

The texture in samples from the eastern part of the granite tends to be porphyritic, with medium-grained quartz and K-feldspar phenocrysts embedded in a fine-grained, randomly oriented, albite-rich groundmass (Fig. 5a). The granite in the western part of the intrusion has a seriate to equigranular texture (Fig. 5b). As mentioned already, the samples just east of the fault zone have a “transitional”, seriate texture. The contact zones, particularly at the eastern edge of the intrusion, locally develop pegmatite segregations with comb-structure or “stockscheider” growth of feldspar and beryl perpendicular to the contact.

The mineral constituents of the albite granite are mainly quartz and alkali feldspars (albite, orthoclase and lesser microcline) with minor micas (muscovite and very rare relict biotite) and accessory zircon, garnet, topaz, iron oxides, apatite, thorite, beryl and Nb-Ta-Sn ore minerals. The ore minerals, identified by SEM-EDS, include columbite-tantalite, microlite, ixiolite, stibiotantalite and cassiterite. They are discussed separately in a later section. Many samples show prominent dendrites

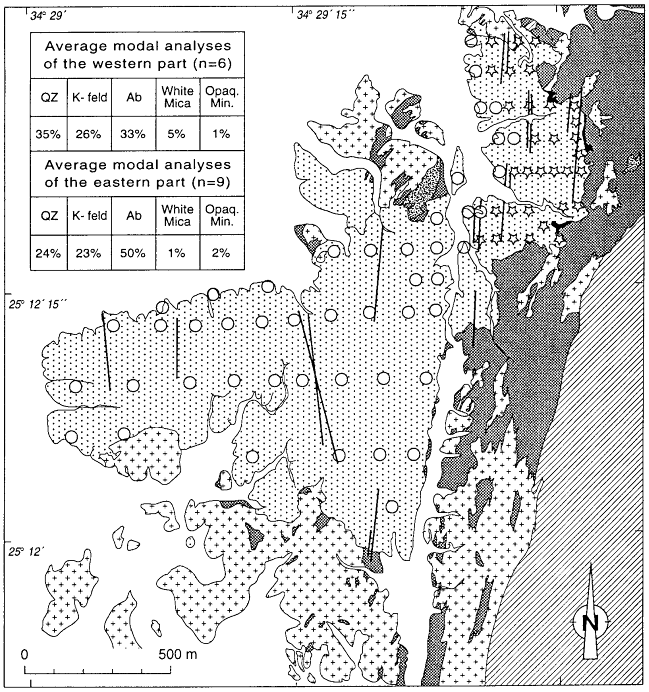

Fig. 4 Outline of the Nuweibi granite from Fig. 3, with sample locations and petrographic information. Symbols, *circles* - equigranular to seriate texture; *stars*, porphyritic texture. Modal analyses based on point-counting thin section, 1000 points per sample

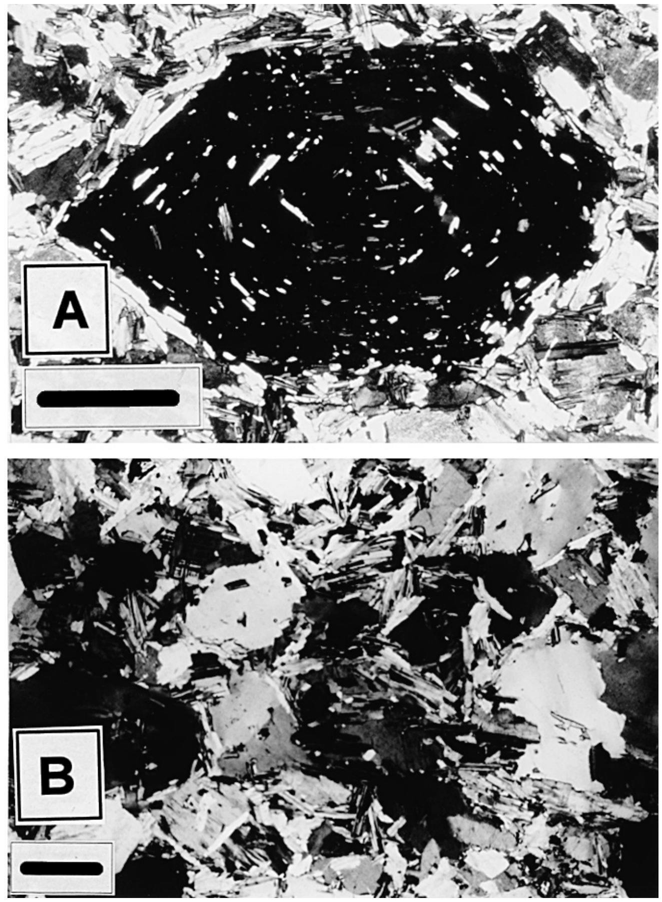

Fig. 5A,B Photomicrographs of textural varieties of the Nuweibi granite. Scale bar in both photos is 0.3 mm. **A** Porphyritic texture typical of the eastern part of the granite. The euhedral quartz phenocryst shows "snowball" texture of concentrically-aligned albite laths. **B** Seriate texture typical of the western part of the granite, with equant quartz and K-feldspar grains and interstitial albite laths

and impregnations of manganese and iron oxides (0.5 to 5 cm in diameter) along joint planes as well as in the body of the rock. Local enrichments of amazonite near quartz-amazonite veins give the granite a greenish tint.

Because of its importance to the debate of metasomatic versus magmatic origin of the albite-rich mineralized granite, the petrography is described in some detail below. The following descriptions refer to both parts of the granite except where otherwise stated.

Quartz occurs in three forms, (1) euhedral to anhedral phenocrysts from 1 to 5 mm in diameter, (2) anhedral interstitial grains in the groundmass; and (3) secondary quartz veinlets. Undulose extinction of the quartz is common, particularly in the western part of the intrusion. Many quartz phenocrysts include minute albite laths which are arranged concentrically about the grain center along growth planes (Fig. 5a). This striking texture has been described as "snowball" quartz from other albite granites (e.g. Beus 1982; Pollard 1989; Schwartz 1992; Zhu and Liu 1992). "Snowball" quartz is characteristic of the eastern part of the Nuweibi granite although it also occurs in some samples from the western part. Beus (1982) argued that the "snowball quartz" grew metasomatically, but we follow Pollard (1989) and Schwartz (1992) in concluding that this texture is magmatic and indicates early crystallization of albite from the melt. Key observations supporting this interpretation are that (1) the "snowball" quartz is subhedral to euhedral and the size of quartz grains is quite uniform, both features being typical for phenocrysts and atypical for quartz blasts, and (2) the near-perfect alignment of albite along growth zones in the quartz is only possible if growth was not impinged by other grains (i.e., in the magmatic state). Vance (1969) concluded, too, that textures showing aligned plagioclase laths in quartz and K-feldspar phenocrysts like those of the Nuweibi granite formed in the magmatic state. Rare inclusions of white mica, K-feldspar, biotite, garnet and columbite-tantalite were also observed within the quartz phenocrysts.

K-feldspar occurs in the Nuweibi granite as phenocrysts with euhedral to subhedral tabular form. Small amounts of fine-grained, interstitial K-feldspar also occur in the groundmass. Generally, the K-feldspar crystals are clouded by fine sericite. Replacements of albite and topaz occur locally. The K-feldspar phenocrysts in the eastern part of the intrusion, like quartz, commonly contain abundant, regulary-aligned inclusions of albite laths. This texture is less common in the western part. Two types of perthites occur. Vein- or string

Table 1 Representative average compositions of feldspar from the Nuweibi albite granite

	Albite			K-Feldspar		
Location	East part	East part	West part	East part	East part	West part
type	inclusions	groundmass	groundmass	inclusions	groundmass	groundmass
n	8	16	9	11	7	4
SiO_2	70.57	69.48	69.32	65.79	65.47	64.88
Al_2O_3	19.58	18.56	19.28	18.31	18.09	18.27
FeO	0.00	0.01	0.12	0.01	0.03	0.02
MnO	0.00	0.00	0.01	0.02	0.02	0.02
CaO	0.08	0.06	0.02	0.02	0.04	0.00
Na_2O	10.77	10.20	10.57	0.27	0.22	0.24
K_2O	0.12	0.10	0.15	16.95	16.89	16.98
BaO	0.05	0.05	0.05	0.09	0.03	0.09
Total	101.27	98.68	99.84	101.45	100.77	100.50
Si	3.03	3.03	3.03	3.007	3.012	2.998
Al	0.99	0.99	0.99	0.984	0.978	0.992
Ca	0.00	0.00	0.00	0.001	0.002	0
Na	0.90	0.90	0.89	0.024	0.019	0.021
K	0.00	0.00	0.00	0.989	0.992	1.002
Ba	0.00	0.00	0.00	0.002	0	0.002
Ab	98.87	99.05	98.95	2.34	1.92	2.09
Or	0.72	0.61	0.93	97.57	97.9	97.91
An	0.41	0.34	0.13	0.09	0.18	0

Analyses by electron microprobe. Number of cations based on 8 oxygens

perthite is well developed in the western part, and probably reflects normal unmixing during cooling. A second variety of heterogeneous, patchy perthite is more common among the eastern part samples, and is interpreted as a result of the reaction between the K-feldspar and late magmatic fluids (see Shelley 1993). Microcline twinning is much more common in the western part than in the east, and is more common in the groundmass grains than in the phenocrysts. Microprobe analyses of K-feldspar from the eastern and western parts of the Nuweibi albite granite revealed a typical composition of Or_{98} with no difference between the eastern and western parts (Table 1).

Albite is the most abundant mineral in the eastern part of the intrusion, where it reaches up to 61% by volume (average 50%). The western part contains only about 33 vol.% albite on average. Albite occurs in three forms: (1) minute, euhedral laths (not more than 0.15 mm in length) included in quartz and K-feldspar phenocrysts; (2) larger (0.2–1 mm), subhedral to euhedral lath-shaped grains in the groundmass, commonly exhibiting cataclastic effects; and (3) minor, late albite replacing K-feldspar along grain boundaries. An important texture, developed locally at the granite contact, is the alignment of albite laths parallel to the contact. Flow-aligned albite is found in both the groundmass and in quartz phenocrysts, and is strong evidence for the magmatic origin of the albite. Electron microprobe analyses of albite revealed a typical composition of Ab_{98-99}, with no zoning and no difference between the early generation of albite included in quartz and the later groundmass albite (Table 1).

White micas are more abundant in the western part of the granite than in the east. They occur in four settings: (1) as colorless to pale green, weakly pleochroic inclusions in quartz phenocrysts, interpreted as primary; (2) as irregularly distributed, subhedral to anhedral flakes of equivocal origin in the groundmass; (3) as medium-grained flakes of clearly secondary origin in K-feldspar grains; and (4) as medium-grained subhedral crystals, commonly with abundant iron oxides and zircon inclusions, which are believed to be pseudomorphs after biotite (Fig. 6a). Although biotite is generally lacking in the Nuweibi granite, minute biotite inclusions were noted very rarely in quartz phenocrysts. Electron microprobe analyses of white micas showed that they can be classified as dioctahedral Fe-muscovites (Table 2). The first generation muscovite (inclusions in quartz) has higher SiO_2 and Al_2O_3, and lower MnO, FeO and F contents than the groundmass mica. The groundmass muscovite (second generation) from the eastern part has higher contents of Al_2O_3 and SiO_2 and lower contents of FeO, MnO and F than its equivalent from the western part. The average fluorine contents of muscovite are 1.3% and 3.8% for the eastern and the western parts, respectively.

Zircon is commonly enclosed in muscovite as subhedral prismatic crystals. The SEM/EDS study of zircon from eastern and western part samples revealed extremely high Hf contents, with an average Zr/Hf ratio of 4. Prismatic zircon crystals were also observed intergrown with or included in columbite-tantalite.

Garnet was found only in the eastern part of the intrusion, where it occurs in two forms: (1) as euhedral, fresh, inclusions (tens to one hundred microns in size) in quartz phenocrysts (Fig. 6b); and (2) as larger (up to 1 mm), subhedral, commonly fractured grains in the groundmass. Microprobe analyses of the two garnet types (Table 3) show compositions of $Sp_{81-63}Alm_{18-36}$. The groundmass garnets are zoned, with increasing Fe

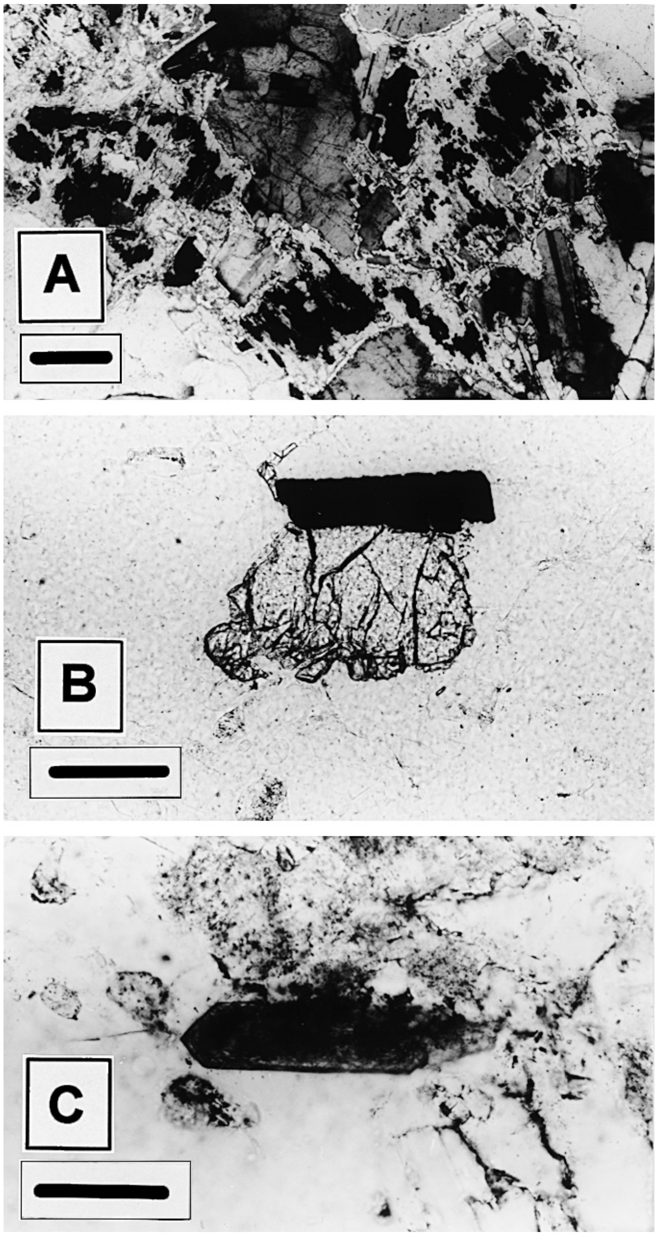

Fig. 6A–C Photomicrographs of selected minerals in the Nuweibi granite. **A** Relict biotite patches (dark) overgrown by muscovite rims. Scale bar is 0.1 mm. **B** Columbite-tantalite grain (black) and garnet (gray, high relief) included in quartz phenocryst.Scale bar is 0.02 mm. **C** Prismatic zircon with cloudy, partly metamict core. Scale bar is 0.02 mm

and decreasing Mn from core to rim. The garnet included in quartz is unzoned.

Topaz is found in both the eastern and the western parts of the granite. It occurs in two main generations: (1) as rare interstitial anhedral crystals (up to 0.4 mm in diameter) with sharp boundaries against the surrounding minerals and believed to be of a primary magmatic origin; and (2) as anhedral crystals, some replacing K-feldspar, associated with beryl at the granite contact. Inclusions of albite and columbite-tantalite were occasionally observed in topaz. Alteration of topaz to sericite is not uncommon. Representative electron microprobe analyses of the primary topaz (Table 4) show average fluorine contents of 10.5 wt.%. Fluorine contents increase from core to rim.

Table 2 Representative compositions of white mica from the Nuweibi albite granite

Sample location	5–4 East part mean (n = 5)	Standard deviation.	W3-2 West part mean (n = 4)	Standard deviation
SiO_2	47.24	0.78	41.89	1.48
TiO_2	0.01	0.01	0.02	0.01
Al_2O_3	27.44	2.10	20.76	0.74
FeO	8.87	2.30	11.47	0.98
MnO	1.29	0.30	3.29	0.26
MgO	0.13	0.18	0.04	0.03
CaO	0.00	0.00	0.00	0.00
Na_2O	0.23	0.24	0.19	0.06
K_2O	9.58	0.80	10.23	0.17
F	1.32	0.40	3.77	0.57
O = F	−0.56	0.17	−1.59	0.24
Total	96.12	1.56	92.37	1.97
Si	6.57	0.13	6.58	0.17
Al^{iv}	1.43	0.13	1.43	0.17
Ti	0.08	0.02	0.22	0.02
Al^{vi}	3.07	0.19	2.42	0.04
Fe	1.56	0.27	1.51	0.12
Mn	0.15	0.04	0.44	0.03
Mg	0.03	0.04	0.00	0.00
Ca	0.00	0.00	0.00	0.00
Na	0.06	0.07	0.06	0.01
K	1.70	0.14	2.05	0.03
F	0.58	0.18	1.87	0.27

Analyses by electron microprobe, all Fe as FeO
Cations based on 22 oxygens

Table 3 Chemical composition of garnets from the Nuweibi albite granite

Sample	5–4	East part		3–3	East part	
	Rim	Core	Core	Core	Rim	Rim
SiO_2	36.22	35.64	35.38	34.91	36.38	36.25
TiO_2	0.00	0.00	0.03	0.01	0.00	0.01
Al_2O_3	20.18	20.53	20.29	20.28	20.27	20.17
Cr_2O_3	0.00	0.09	0.01	0.00	0.00	0.03
FeO	15.53	9.75	9.81	9.05	14.26	14.66
MnO	26.93	32.80	32.11	32.92	27.78	26.59
MgO	0.00	0.01	0.01	0.01	0.00	0.00
CaO	0.41	0.25	0.24	0.32	0.27	0.51
Total	99.27	99.07	97.88	97.50	98.96	98.22
Si	6.02	5.94	5.96	5.92	6.05	6.06
Al	3.95	3.98	3.99	3.98	3.97	3.97
Ti	0.00	0.00	0.00	1.28	0.00	0.00
Cr	0.00	0.01	0.00	0.00	0.00	0.00
Fe	2.16	1.36	1.38	1.28	1.98	2.05
Mn	3.79	4.63	4.59	4.73	3.91	3.77
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.07	0.04	0.04	0.06	0.05	0.09
Almandine	35.88	22.55	22.96	21.09	33.33	34.69
Spessartine	62.96	76.78	76.37	77.92	65.82	63.79
Grossular	1.16	0.66	0.67	0.99	0.84	1.52

Analyses by electron microprobe, total Fe as FeO
Cations based on 24 oxygens

Table 4 Chemical composition of topaz from the Nuweibi albite granite

Sample	5–4, grain 1 (East part)			5–4, grain 2	
	Core	Core	Rim	Rim	Core
SiO_2	32.81	32.94	32.98	32.97	33.36
Al_2O_3	55.78	55.69	55.47	55.91	55.86
FeO	0.03	0.01	0.05	0.00	0.02
MnO	0.00	0.04	0.02	0.01	0.01
K_2O	0.00	0.01	0.02	0.00	0.01
F	8.37	8.95	11.02	11.13	8.08
Total	97.02	97.64	99.75	100.02	97.41
Si	2.40	2.40	2.41	2.40	2.42
Al	4.80	4.79	4.78	4.80	4.77
Fe	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00
F	1.93	2.07	2.55	2.56	1.85

Analyses by electron micoprobe, total Fe as FeO
Cations based on 24 (O, OH, F)

Beryl is restricted to some granite samples at the eastern contact with metasediments. The beryl crystals are medium to coarse-grained with prismatic shape, elongated perpendicular to the contact surface. Columbite-tantalite, zircon and albite laths were observed as inclusions within beryl.

Manganese-iron oxide impregnations occur as dendritic clusters and films along grain boundaries. The X-ray diffraction patterns suggest that much of the material is cryptocrystalline. Diffuse peaks of manganite could be identified with difficulty. No enrichments in Nb or Ta were found in analyses of this material.

Nb-Ta minerals

Columbite-tantalite is the main ore mineral in the Nuweibi granite. Other Ta-Nb-Sn bearing minerals identified in SEM-EDS analyses include ixiolite with up to 11 wt.% SnO_2 (semiquantitative EDS data), stibiotantalite with Sb_2O_3 up to 6 wt.% (EDS data), microlite, and cassiterite. However, these phases are so rare that no detailed textural or chemical description can be given, and the following section concentrates on the main ore mineral, columbite-tantalite.

Columbite-tantalite occurs as bladed, euhedral to subhedral, fine-grained crystals (0.05 to 0.2 mm in size) in two main generations: (1) as inclusions in muscovite (commonly associated with iron oxides and zircon) in quartz phenocrysts (Fig. 6b), and in topaz and beryl crystals (in near-contact samples from the eastern part); (2) as dispersed grains among the groundmass constituents in both eastern and western parts. Zircon (Hf-, Th-, U-rich) was commonly observed included in and intergrown with columbite-tantalite, especially in the crystals included in micas from both the eastern and western parts.

Under the scanning electron microscope, columbite-tantalite crystals from both the eastern and western parts commonly exhibit zoning textures, symmetric to asymmetric in the western part samples and irregular to patchy in the eastern part samples (Fig. 7). The rims are consistently higher in Ta than the cores (Ta-rich rims appear brighter in the SEM images). The irregularity of zoning is higher and the Ta-rich rims are wider in columbite-tantalite crystals from the eastern samples relative to the western samples. It is also important that the Ta / Nb ratio in general is higher in the eastern than in the western group samples. Figure 8 shows the compositions of the columbite-tantalite minerals from the Nuweibi albite granite plotted in the Nb-Ta-Fe-Mn quadrilateral. The trend of increasing Mn / Mn+Fe with increasing Ta / Ta+Nb, which is commonly reported and interpreted as a primary fractionation trend (e.g., Cerny et al. 1986; Spilde and Shearer 1992), is true in the Nuweibi samples only for the core analyses. The strong positive correlation between Mn / Mn + Fe and Ta / Ta + Nb ratios in the cores of the columbite-tantalite crystals is consistent with continuous growth in normal magmatic conditions. In contrast, the discontinuous and irregular relation between these ratios in the rims of the crystals and the embayment of cores is typical of crystals from the eastern part of the granite, and indicates the later action of processes other than crystal-melt equilibrium.

Whole-rock geochemistry

Because the Nb-Ta mineralization is nearly all confined to the eastern part of the granite, previous geochemical studies have tended to neglect the western part. Our sampling profiles across the whole granite allow us to

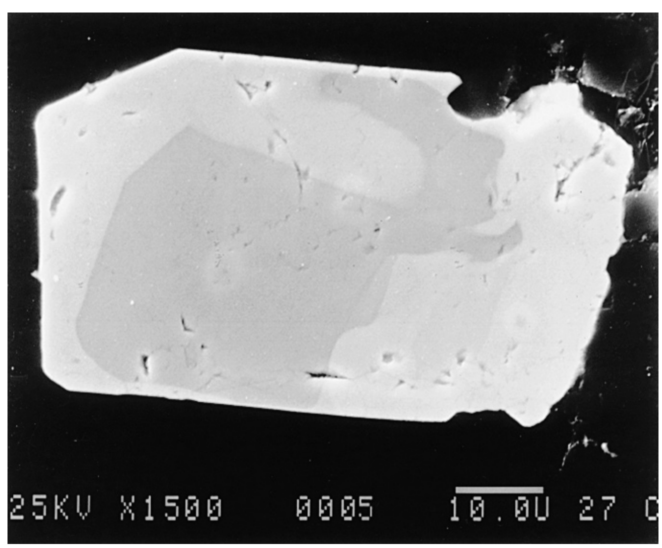

Fig. 7 SEM-photomicrograph of a discontinuously zoned columbite-tantalite grain from the eastern part of the Nuweibi granite. Note the resorbed dark core (Ta-poor) and overgrowth of brighter, Ta-rich material

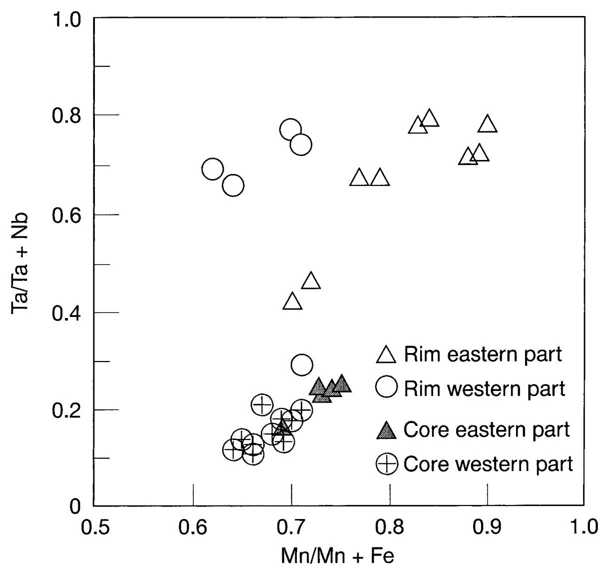

Fig. 8 Diagram of the Ta-Nb-Fe-Mn variations in zoned columbite-tantalite grains from the Nuweibi granite. Note the correlation of Ta/Nb and Mn/Fe in the cores and lack of correlation in the rims

compare the compositions of both parts and attempt to define their relationship to each other.

Table 5 gives the average and range of composition from 86 samples of the Nuweibi granite. In keeping with its leucocratic nature, the granite, in both parts, has very low Ca, Mg, Fe and Ti contents. Both parts are metaluminous or very slightly peraluminous (A/CNK ratios of 1.05 and 1.07 from east and west, respectively). This peraluminosity is expressed in trace amounts of garnet, topaz and muscovite. There are important differences in composition between the eastern and western parts to be discussed later, but both are relatively enriched in the lithophile elements Rb, Sn, Ta, Nb and depleted in Sr, Ba and Zr relative to average low-Ca granite.

Major element variations

The most striking major-element differences are the higher Na_2O and Al_2O_3, and lower SiO_2 of the eastern part compared to the western part samples. This difference can be explained by the modal mineralogy (Fig. 4) and it shows up well in a plot of SiO_2 against Na_2O in Fig. 9 and in the mesonorm Qz-Ab-Or triangle of Fig. 18 (discussion section). A very important feature to note from these and most subsequent diagrams is the compositional gap between the two groups of samples. Note, too, that the "transitional" samples, i.e., those which occur just east of the Wadi Nuweibi fault, do not fill this compositional gap. They are texturally transitional and occur in an intermediate position geographically, but in terms of chemical composition there is a gap between the western or eastern groups of samples.

Table 5 Summary of the whole-rock chemical composition of the Nuweibi albite granite

	East part Mean	Standard Deviation	West part Mean	Standard Deviation
SiO_2	72.64	1.44	74.89	1.46
TiO_2	0.01	0.03	0.00	0.00
Al_2O_3	15.33	0.89	13.67	0.64
Fe as Fe_2O_3	0.31	0.26	0.53	0.08
MnO	0.10	0.05	0.08	0.03
MgO	0.06	0.07	0.08	0.02
CaO	0.21	0.28	0.14	0.06
Na_2O	6.21	0.90	4.91	0.41
K_2O	3.77	0.95	4.10	0.45
P_2O_5	< 0.02	–	< 0.02	–
LOI	0.33	0.22	0.36	0.11
Total	99.16	–	99.12	–
Pb	59	12	63	11
Zn	27	35	230	92
Rb	397	118	496	101
Sr	18	28	7	4
Ba	40	37	31	13
Sn	20	19	65	33
Ta	155	44	63	34
Nb	61	20	87	34
Y[a]	3	3	6	2
Zr	47	21	98	21
Hf	27	3	22	2
Ga	76	11	57	5
Th	19	9	26	12
F	456	606	1520	755
Li	24	18	166	92
La[a]	2.1	1.7	7.0	4.8
Ce[a]	7.5	2.2	20.5	5.8
Nd[a]	4.3	2.8	9.1	4.8
Sm[a]	1.4	0.7	1.7	1.4
Eu[a]	0.02	0.01	0.04	0.05
Gd[a]	0.74	0.44	1.40	0.54
Tb[a]	0.44	0.12	0.45	0.15
Dy[a]	2.50	0.66	3.70	1.10
Ho[a]	0.47	0.14	0.83	0.15
Er[a]	2.00	0.73	4.30	0.56
Tm[a]	0.59	0.20	1.30	0.08
Yb[a]	6.30	2.30	14.80	0.50
Lu[a]	0.99	0.42	2.40	0.10

Major elements (in wt.%) and trace elements (in ppm) analysed by XRF on 51 samples (easten part) and 35 samples (western part)
[a]Y and REE by ICP-AES on 6 samples (eastern part) and 4 samples (western part)
Li by AES and F by ion-sensitive electrodes on 16 samples (eastern part) and 16 samples (western part)

Fractionation indicators

In discussing trace elements or element ratios in terms of fractional crystallization of granite it is useful to divide those elements controlled by accessory minerals (Zr, REE and the ore elements Ta, Nb, Sn) from those which occur in the rock-forming feldspars (Rb, Sr, Ba, Ga).

Figure 10 shows the variation of Al and Ga, whose concentrations are controlled by feldspar fractionation. Here, the compositional gap is very clear and the transitional samples do not fill the gap but plot on either side. Figure 11 combines the Al/Ga and K/Rb variables and shows that, whereas a clear separation of the

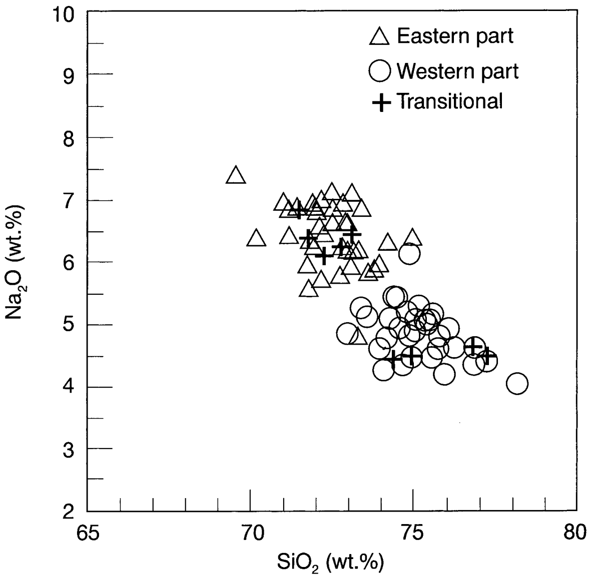

Fig. 9 Variation diagram of SiO_2 and Na_2O in whole-rock samples of the Nuweibi granite. Explanation of symbols: *triangles,* eastern samples; *circles*, western samples; *crosses*, transitional samples

eastern and western groups prevails in terms of Al / Ga, this is not the case for K/Rb. The two variables are fairly well-correlated, and the two groups have different fractionation trends. Because of the very low concentrations of Sr and Ba in most samples, their variation is difficult to interpret and no diagrams are shown. The volatile elements Li and F, whose influence on the granite system is very important (see discussion), are shown in Fig. 12. Both parts of the granite have low Li and F compared with many other rare-metal granites in the literature. The western samples show a positive correlation between the two elements whereas the eastern samples have lower F and Li, and show a poor correlation. This difference reflects the fact that there is more muscovite in the western than in the eastern part of the granite.

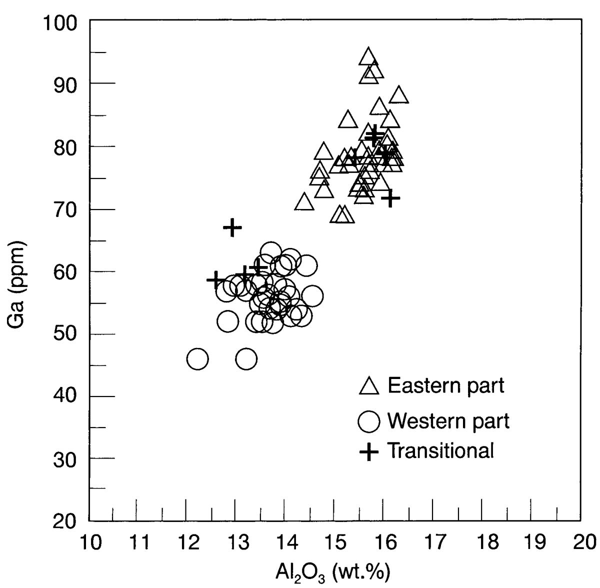

Fig. 10 Variation diagram of Al_2O_3 and Ga in whole-rock samples of the Nuweibi granite. Explanation of symbols: *triangles*, eastern samples; *circles*, western samples; *crosses*, transitional samples

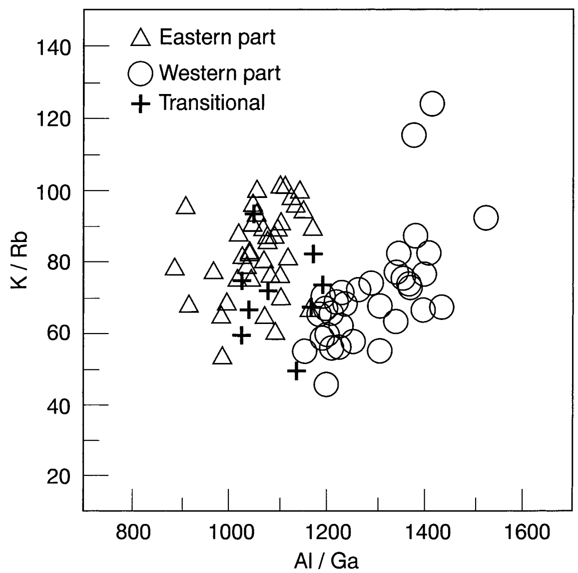

Fig. 11 Variation diagram of K / Rb and Al / Ga in whole-rock samples of the Nuweibi granite. Explanation of symbols: *triangles*, eastern samples; *circles*, western samples; *crosses*, transitional samples

Ore elements

The ore elements in the Nuweibi granite are Sn, Ta and Nb. Their relative variations in the granite are shown in a triangular plot on Fig. 13. This plot shows the com-

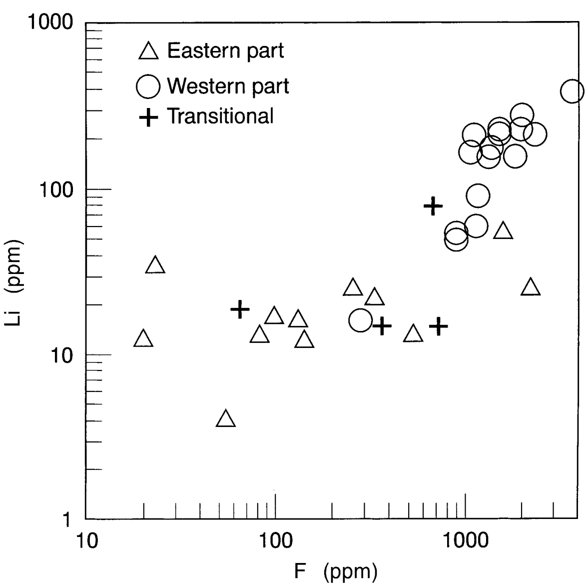

Fig. 12 Variation diagram of F and Li in whole-rock samples of the Nuweibi granite. Symbols as in Fig. 11

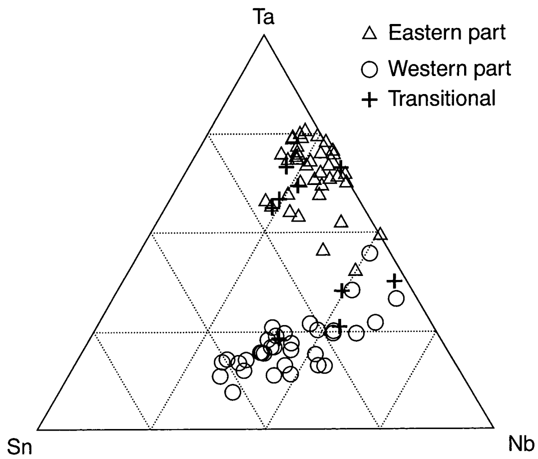

Fig. 13 Triangular diagram showing the relative contents of Sn, Nb and Ta in whole-rock samples of the Nuweibi granite. Symbols as in Fig. 11

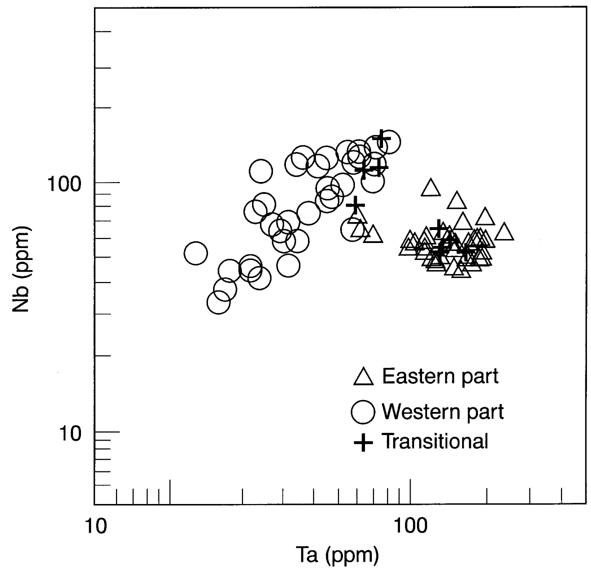

Fig. 14 Variation diagram of Ta and Nb in whole-rock samples of the Nuweibi granite. Symbols as in Fig. 11

positional gap between eastern and western samples and the fact that transitional samples straddle, but do not fill, this gap.

Figure 14 shows the variation of Ta against Nb. Note the good positive correlation of these elements in the western samples, the compositional gap, and the lack of Nb-Ta correlation in the eastern samples. The Ta-Nb trend in the western part of the granite is the expected result of igneous fractionation (i.e., crystal-melt partitioning), and the lack of correlation in the eastern part suggests that other factors controlled or overprinted the Nb and Ta concentration (e.g., fluid interactions, see below). Finally, Fig. 15 shows the variation of the Ta / Nb ratio with Na_2O. This variation is important since some workers suggest that the rare metals in "apogranites" are correlated with albitization. The diagram shows a tight grouping of the western group and transitional samples at relatively low values of Na_2O and Ta / Nb and a very scattered distribution for the eastern group samples to higher values (Ta / Nb ratios reaching up to nearly 4). As a group, the eastern samples in Fig. 15 are enriched in Na_2O relative to the western samples (higher modal albite) and they have higher Ta / Nb ratios. However, within the eastern group samples, the wide range in Ta / Nb ratio shows no correlation with Na_2O, and this suggests that, at least within the eastern part of the granite, Ta-enrichment occurred without albitization.

Rare-earth elements

Both parts of the Nuweibi granite show similar rare-earth element distribution patterns on a chondrite-normalized diagram (Fig. 16), and this is good evidence for a common origin. The eastern group of samples has slightly lower total REE contents than the western group, which is consistent with other indicators that the degree of fractionation is higher in the eastern part. The shape of the REE patterns is characterized by a large negative Eu anomaly and an enrichment of HREE relative to LREE. Patterns such as these are common for highly-fractionated granites, aplites and pegmatites, the HREE enrichment being attributed to preferential crystallization of LREE-bearing phases like monazite (Mittlefehldt and Miller 1983), and they are also typical for the low-P series of rare-metal granites according to Raimbault et al. (1991). Close examination of Fig. 16 shows a convex-upward segment of the normalized HREE pattern from Er to Lu. This curvature may be a weak expression of the tetrad effect described by Irber et al. (1994). The effect is due to minor differences in solubility of individual lanthanide elements in presence

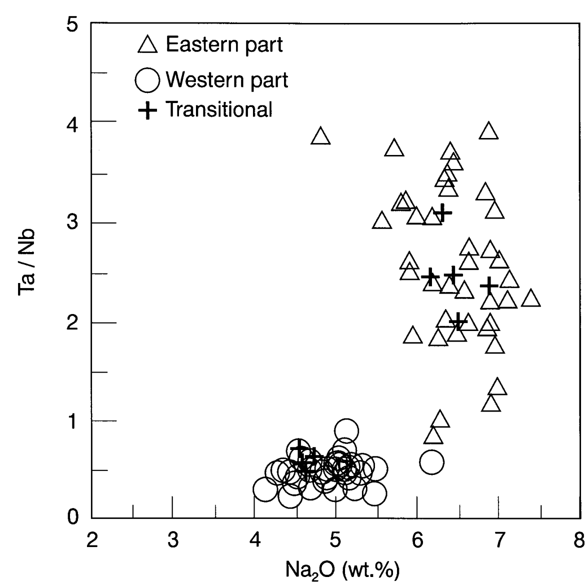

Fig. 15 Variation diagram of Ta/Nb and Na_2O in whole-rock samples of the Nuweibi granite. Symbols as in Fig. 11

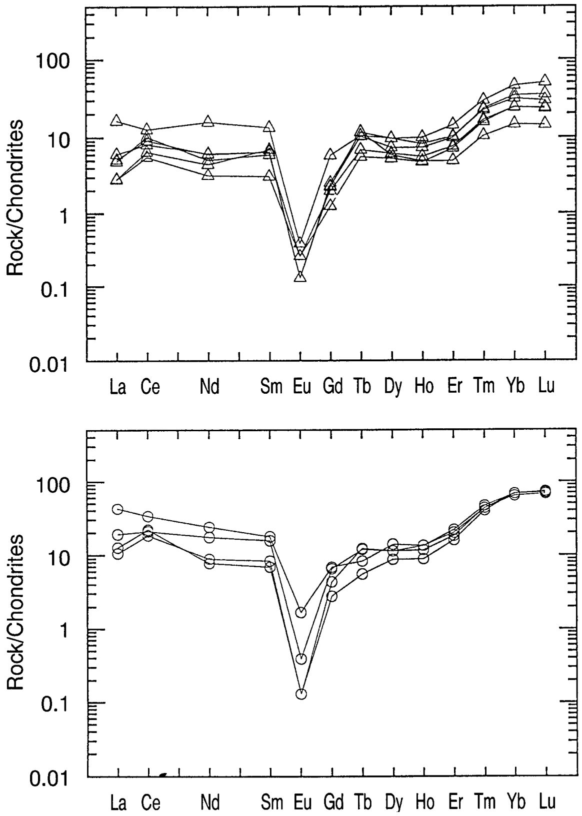

Fig. 16 Chondrite-normalized REE contents in the Nuweibi granite eastern part (*triangles*) and western part (*circles*)

of complexing agents (e.g., F) in aqueous fluid, and it indicates post-magmatic fluid interaction with the samples. Note, however, that the tetrad effect is present in both parts of the granite and so fluid interaction must be postulated for both parts.

Oxygen isotope composition

The oxygen isotopic composition of 27 whole-rock samples of the Nuweibi granite (12 samples from western part, 15 samples from the east) was determined with the hope of detecting evidence for fluid interaction, and the results are presented in Table 6. The overall range of $\delta^{18}O$ values is from 8.2 to 12.9 permil, but all but two values fall between 8.4 and 10.9 permil. The variation of $\delta^{18}O$ values is slightly higher in the western part than in the east (standard deviations 1.28 and 0.6, respectively) but their average values are very similar at 9.6 (east) and 9.7 (west), and are not distinguishable statistically. These $\delta^{18}O$ values can be interpreted as magmatic values corresponding to the "normal" to "high" ^{18}O granites in the sense of Taylor (1988), and this conclusion is consistent with the leucocratic, peraluminous composition of the Nuweibi granite.

The similarity of $\delta^{18}O$ values in the western and eastern parts has important implications to the interpretation of the genesis of these two parts of the granite.

Table 6 Oxygen isotopic composition (whole-rock) of the Nuweibi albite granite

East part	$\delta^{18}O$	West part	$\delta^{18}O$
(1)-3	10.0	1–2w	8.5
(2)-1	8.4	2–3w	9.3
(2)-4	9.0	2–8w	12.9
(3)-2	10.1	3–1w	8.9
(3)-5	10.2	3–3w	10.2
(4)-1	9.4	3–4w	8.2
(4)-2	9.4	3–5w	10.0
(4)-7	10.0	3–9w	10.3
(5)-4	9.2	3–10w	10.9
(5)-5	9.8	4–1w	8.8
(5)-10	9.7	zw4	9.6
(5)-11	8.5	8–3w	9.2
(6)-4	10.1		
(9)-3	9.3		
(9)-6	10.3		
Mean	9.6	Mean	9.7
Standard deviation	0.6	Standard deviation	1.3

Isotopic composition relative to SMOW (permil)
Analytical precision is better than 0.1 permil

Either both units have not been extensively altered or, if they have been altered, then at the same temperature, to the same degree, and by fluids of the same composition. Therefore, it is difficult to call on a higher degree of alteration in the eastern part of the Nuweibi granite to explain the albitic nature and the concentration of Ta.

Zircon age determinations

As mentioned in a previous section, the age of the rare-metal albite granitoids in the Central Desert of Egypt is not well established, and there is even the extreme possibility that they might be as young as Mesozoic (El-Gaby et al. 1990). This question is important if the granites are to be understood in relation to the geologic evolution of the region. In particular, if the albite granites have Panafrican ages they would represent postorogenic magmatism closely following plate convergence and formation of the pink granites (G2). If their age is Mesozoic, however, the granites would have a wholly anorogenic setting. Because previous studies suggested that the Nuweibi albite granite may have experienced severe metasomatic effects, particularly in the more albite-rich, mineralized, eastern part of the intrusion, we chose to use zircon dating. Unfortunately, the minute amount of zircons in the rocks is such that conventional U-Pb dating was impossible and resort was made to the single-crystal evaporation method of Kober (1987). Table 7 gives the results of analyses of 10 grains. It turns out that the zircons in the Nuweibi granite are very small, irregular and partly metamict (see Fig. 6c), so the precision of analyses is very poor and the common Pb correction is unusually high. Nevertheless the dating results permit the conclusion that the Nuweibi granite formed in a Panafrican and not a Mesozoic time frame, and the granite therefore has a postorogenic

Table 7 Summary of lead isotopic age dating of zircons (evaporation method) from the Nuweibi albite granite

Sample	Description	T ºC	Scans	Age (Ma)	1 Standard deviation
2–7W	Brown, microcracks	1308	4	495	68
3–6 W, grain 1	Brown, elongate, broken	1343	1	696	–
" "		1377	10	527	49
" "		1408	7	523	16
grain 2	Brown, long	1343	16	610	34
" "		1377	14	564	54
3–2E, grain 1	Brown, very small	1308	1	428	–
" "		1343	9	496	14
3–2E, grain 2	Brown, very small	1308	24	450	20
" "		1377	23	425	24

position in the geologic evolution of the region. This is in keeping with other peraluminous, rare-metal granites reviewed by Cerny and Meintzer (1988) and Pollard (1989).

Discussion: magmatic evolution and fluid overprinting

We emphasize here two main questions which arise from the geologic, petrographic and geochemical data presented above. First, are the two parts of the Nuweibi granite comagmatic and if so, why is there such a contrast in composition with no smooth transition? Second, is the Ta-Nb mineralization and albite-rich composition of the Nuweibi granite the result of magmatic crystallization, or metasomatic overprinting by fluids derived from leaching deeper levels?

Relationship of the western and eastern parts

Although this study has emphasized the differences between the eastern and western group of samples it must be emphasized that both parts of the Nuweibi intrusive complex are highly evolved leucogranites with the same unusual suite of accessory minerals (cassiterite, columbite-tantalite, topaz) and nearly identical REE and oxygen isotopic compositions. These facts, combined with their very close association in the field, makes it certain that they are cogenetic.

In detail, however, there is a compositional gap between them, with differences in composition and texture between samples spaced only 50 m apart. The compositional gap can be explained either by a tectonic offset of a once-continuous, zoned body (the eastern part representing a higher, more fractionated level) or by the intrusive juxtaposition of two batches of differently-evolved magmas (see Fig. 17). The first explanation seems more likely since a prominent large-scale fault occurs along Wadi Nuweibi between the eastern and western parts. On the other hand, the main fault trace in Wadi Nuweibi does not coincide with the position of the geochemical gap between western and eastern parts, thus the alternative hypothesis of two sequential intrusions cannot be ruled out.

Origin of mineralization

To some extent, the debate of metasomatic versus magmatic origin for the mineralization of the Nuweibi granite and others of its kind centers around the development of the extreme albite-rich bulk composition (61% modal albite vs. 33% from eastern and western samples, respectively). The following observations argue strongly for a magmatic origin of the albite-rich rocks:

1. Intrusive contacts with the country rocks are sharp and there is no albitization of the wall rocks.
2. Flow-alignment of groundmass albite laths can be observed at some contact zones in the eastern part of the intrusion.
3. Euhedral albite laths aligned along growth planes of quartz and K-feldspar phenocrysts indicate that albite was an early-magmatic phase.

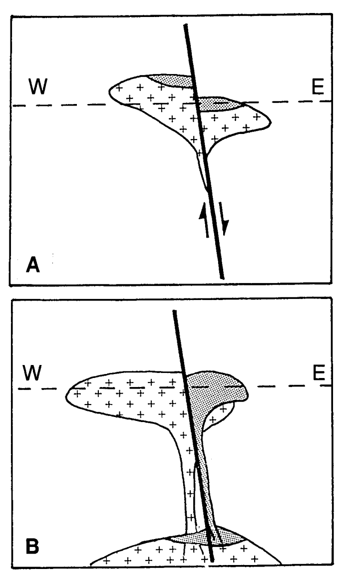

Fig. 17A,B Schematic diagrams showing two alternatives for the development of eastern and western parts of the Nuweibi granite (*dashed line* represents present erosion level). **A** The eastern part is the down-faulted roof of a once continuous pluton. **B** The eastern part is a separate intrusion derived from a more evolved portion of a common parental magma

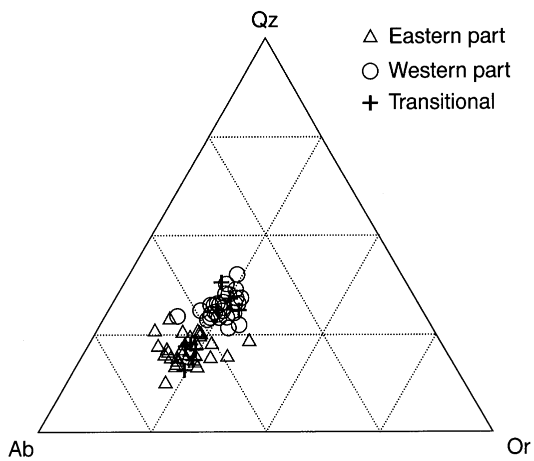

Fig. 18 Normative Qz-Ab-Or contents of whole-rock samples from the Nuweibi granite. Explanation of symbols: *triangles*, eastern samples; *circles*, western samples; *crosses*, transitional samples

4. The alternative explanation requires replacement phenomena. Groundmass albite occurs as discrete, lath-shaped grains distributed uniformly throughout the rock with no relict textures. Indeed, replacement textures of albite after K-feldspar (patchy perthite, albite rims) do occur. These can be easily recognized in thin section and they are very minor in extent.

Accepting the evidence for a magmatic nature of both parts of the Nuweibi granite, a magmatic model must explain the position of the samples on the normative Qz-Ab-Or diagram (Fig. 18). The western-group samples plot in a "normal" haplogranite minimum position whereas the eastern group plots separately, across the compositional gap, at a position richer in Ab and poorer in Qz than the western group. Based on our current understanding of the phase relations in the granite system, there are only two explanations for the different positions of the eastern and western sample groups on this diagram. First, the eastern group magma was generated under much higher pressure than the western group. According to Luth et al. (1964) a pressure of about 10 kbar would be consistent with the albite-rich composition. Alternatively, the eastern group formed from a melt enriched in fluorine relative to the western group. According to Manning (1981) a F content of 4 wt% at 1 kbar pressure would be consistent with the eastern group compositions.

The "high-pressure" hypothesis is thought to be unlikely because a pressure difference of 7–9 kbar between the eastern and western parts implies that they were separated, prior to emplacement, by more than 20 km vertically. Also, the 10 kbar pressure pertains to water-saturated granite but such a magma could not rise 20 km through the crust without encountering the solidus. If the magma were originally water-undersaturated, an even greater pressure than 10 kbar would be required to produce the albite-rich composition.

The second hypothesis suggests that both parts of the granite were generated from a common magma but evolved to different degrees. An increase in fluorine concentration during fractionation caused the bulk composition of the residual melt to shift toward albite. The only problem with this explanation is that present whole-rock contents of F are not high in the Nuweibi granite (average 500 and 1500 ppm for east and west samples, respectively). However, these values reflect the modal mineralogy and may not represent the composition of the magma; the higher F contents in the western part simply reflects the higher modal abundance of mica. Elevated magmatic fluorine contents are suggested by the occurrence of accessory topaz and of muscovite with high fluorine contents (up to 4 wt.% F). Low concentrations of Ca, Al and P in the melt prevented fixation of fluorine in crystalline phases and F was ultimately lost to the roof rocks.

We suggest that the eastern part of the granite formed from a F-rich residual melt of the same magma from which the western part crystallized. This model is speculative and cannot be fully tested because the roof of the intrusion has been eroded off (note: rocks on the flanks of the Nuweibi granite were analyzed and are not enriched in F). Despite lack of confirmation, the idea that fluorine first built up in the magma and was finally lost during crystallization succeeds in explaining many features of the Nuweibi granite complex, not just the albitic nature of the eastern part. For example, the fluorine buildup allowed the magma temperatures and crystallization interval to extend below the F-free solidus. This permitted the eastern part to reach extreme levels of fractionation. Subsequent loss of fluorine from the low-temperature residual magma, would cause a "compositional quench", and this effect could explain the porphyritic texture of the eastern-group samples. The buildup of fluorine can also explain the high Ta/Nb ratios of the eastern group samples relative to the western group and the zoning of columbite-tantalite. Keppler (1993) showed that addition of F to the haplogranite system strongly increases the solubility of Nb and Ta in the melt, whereby Ta is more soluble than Nb. Thus, a buildup of F in the residual melt would raise the Ta/Nb ratio in the melt by preventing crystallization of early, Nb-rich columbite-tantalite, and the solubility increase could also cause resorption of earlier-formed crystals (corroded cores, see Fig. 7). Final crystallization, perhaps following loss of F, would then cause overgrowths of columbite-tantalite with high Ta/Nb ratios.

Conclusions

Geologic field relations, rock textures and whole-rock geochemical compositions of the eastern and western parts of the Nuweibi albite granite indicate that the two parts are genetically related and essentially igneous in origin. New zircon dating by the evaporation method indicates that the Nuweibi granite formed in the late Panafrican event (600–450 Ma).

The eastern part of the Nuweibi granite is significantly richer in albite than the western part, and has a higher abundance of Ta as well as higher Ta / Nb ratios both in whole-rock and in tantalite-columbite minerals. Although initial workers have evoked Na-metasomatism to produce the albite and to enrich the granite in ore elements, textural evidence indicates that the albite in the eastern part of the granite is largely magmatic in origin. The oxygen isotopic ratios of whole-rock samples indicate that fluid overprinting, if present at all, is developed to the same degree in the eastern and western parts of the granite, and cannot, therefore, explain the special nature of the eastern part.

The geochemical and mineralogical features of the Nuweibi granite complex can be explained using a magmatic model by invoking high F contents in the melt. Although whole-rock fluorine contents are low, the presence of accessory topaz and F-rich muscovite indicate that the magma was enriched in F. It is suggested that much of the magmatic fluorine was lost upon crystallization because the low Ca, P and Al contents of the melt precluded fixation of F in crystalline phases. The roof rocks have been eroded and therefore this hypothesis cannot be directly tested unless, perhaps, a study of melt inclusions were undertaken.

Although the albite granite is magmatic in origin and the columbite-tantalite crystals crystallized from a melt (textures, coherent geochemical trends in grain cores) we do note disturbance of whole-rock geochemical trends with respect to the ore elements Sn, Nb and Ta, and zoning profiles in individual columbite-tantalite grains which suggest non-magmatic (fluid-controlled) redistributions of these elements after crystallization.

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