# Topaz-bearing rocks from Mount Gibson, North Queensland, Australia

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## Abstract

Dikes, sills, and irregular pods of topaz-bearing aplite, lithium fluorine granite, and topazite represent F-rich extreme differentiates of a suite of mineralized alkali feldspar granites near Mount Garnet, northeastern Australia. Topaz is a magmatic phase in two aplites and the topazite and a hydrothermal mineral in the third aplite, lithium fluorine granite, and the alkali feldspar granite. The granites plot close to the 100 MPa (1 kbar) $H_2O$-saturated ternary minimum in the haplogranite system (consistent with their history of extended fractionation), but the aplites are significantly displaced from that minimum, suggesting either vapor phase losses of quartz and feldspar components (into pegmatites) or crystallization from hydrous fluid.

Trace elements (e.g., Rb, Ga, Nb) retained in feldspars, micas, and opaque minerals are enriched in the granites and aplites but not in the topazite. Other trace elements are strongly depleted, having been partitioned into halogen-rich hydrous fluids and lost into the country rocks. The strong enrichment of Ba, Sr, and Eu in the highly fractionated topaz aplites is unusual and is thought to indicate crystallization from or reequilibration with hydrous fluids rather than silicate melts.

Topaz aplites of this area are chemically similar to ongonites of central Asia and central Arizona, U.S.A., and small differences in major element chemistry reflect the differing F content of the provinces. Topazites are similar to those reported from the U.S.A., and the granites are chemically similar to topaz rhyolites of the western U.S.A.

## Introduction

The topaz-bearing rocks of the Mount Gibson area, 12 km east-northeast of Mount Garnet, North Queensland, form part of the Coolgarra Batholith, a mineralized composite body of Carboniferous age (Richards, 1980; Johnston and Black, 1986). The topaz-bearing rocks are associated with alkali feldspar granites and microgranites. Chemical analyses of the rocks, which include topaz aplites, lithium fluorine granite, and topazite, are discussed in this paper and compared with similar rocks reported from the western U.S.A. and Mongolia.

## Regional geology and tectonic setting

The North Queensland region comprises two major structural elements: (1) the Precambrian shield comprising multiply deformed metasedimentary rocks and (2) to the east, mid-Paleozoic sediments of the Hodgkinson Basin, possibly underlain at depth by Precambrian basement (De Keyser and Lucas, 1968). These two structural elements are separated by the Palmerville Fault (De Keyser, 1963). This major crustal discontinuity, which is thought to have developed mainly during the Devonian period, has been the locus for Permo-Carboniferous volcanism and plutonism including the Coolgarra Batholith (Oversby et al., 1980).

The tectonic development of the region has been discussed by Arnold and Fawckner (1980). They consider that before the late Silurian an active magmatic arc occupied the eastern margin of the Precambrian craton. During the late Silurian, the Hodgkinson Basin formed by rifting and crustal extension as subduction gave way to upwelling of hot, low-density material from the mantle. Sedimentation within the basin began during the late Silurian and continued until the late Devonian. Continental margin subduction recommenced between late Devonian and the early Carboniferous, causing the basin to be uplifted, tectonized, and cratonized.

Isotopic studies by Black and McCulloch (1990) suggest that the voluminous felsic magmas of Permo-Carboniferous age (including the Coolgarra Batholith) were derived from mantle material by a two-stage partial melting process. New crustal material was successively added from below by underplating or emplacement into the lower crust. Remelting of the underplates and fractional crystallization of the resultant magmas produced the observed felsic volcanics and intrusives.

## Geology of the Mount Gibson area

The topaz-bearing rocks intrude and brecciate tightly folded quartzo-feldspathic sediments of the Hodgkinson Formation, a thick sequence of Siluro-Devonian flysch.
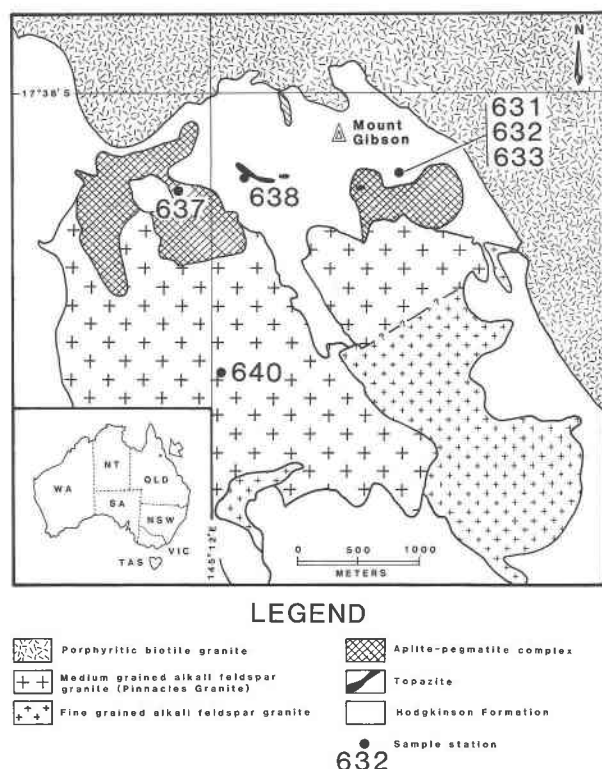
LEGEND

Porphyritic biotile granite

Medium grained alkali feldspar granite (Pinnacles Granite)

Fine grained alkali feldspar granite

Aplite-pegmatite complex

Topazite

Hodgkinson Formation

Sample station

632

Fig. 1. Location diagram and interpretative geological map of the Mount Gibson area.

TABLE 1. Modes

| Sample no. Rock type | 631 | 632 | 633 | 637 | 638 | 640 |
|---|---|---|---|---|---|---|
| | Aplite | Potassium aplite | Soda aplite | Lithium fluorine granite | Topazite | Alkali feldspar granite |
| **Modal minerals** | | | | | | |
| Quartz | 40.9 | 23.3 | 39.0 | 29.1 | 76.5 | 36.5 |
| Microcline | 24.1 | 44.1 | 14.9 | 33.7 | 0.0 | 46.4 |
| Plagioclase | 30.4 | 25.9 | 39.6 | 32.5 | 0.0 | 12.5 |
| Biotite | 1.0 | 4.3 | 3.0 | 4.3 | 0.0 | 4.6 |
| Sericite | 0.1 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 |
| Fluorite | 0.0 | 0.0 | 0.3 | 0.1 | 0.0 | 0.0 |
| Topaz | 3.5 | 2.1 | 2.6 | 0.3 | 14.5 | 0.0 |
| Vugs | 0.0 | 0.0 | 0.0 | 0.0 | 9.0 | 0.0 |
| Accessories | <0.1 | >0.2 | <0.1 | <0.1 | <0.1 | <0.1 |

accessories include ilmenite, a bastnäsite group mineral, columbite, thorite, zircon, and sulfides.

In thin section (Fig. 2a) this granite shows considerable deuteric alteration, viz., sericitization of plagioclase feldspar, kaolinization (?) of potassium feldspar, chloritization of micas, replacement of micas by fluorite, development of swapped albite rims (Smith, 1974; van de Pijpekamp, 1982), and replacement of potassium feldspar by hydrothermal topaz. Relatively euhedral potassium feldspar is characterized by extreme development of perthitic albite; clearly its original composition was sodic. The lithium iron mica present is protolithionite (brown, orange-brown, pale yellow, $Z \geq Y > X$, respectively), which is commonly interstitial and invariably partly chloritized.

## APLITES, LITHIUM FLUORINE GRANITE, AND TOPAZITE

These highly evolved rocks are volumetrically very minor components of the Coolgarra Batholith. For example, the aplite (sample 631) occurs as a thin sill (≤200 mm) with a pegmatitic selvage 30–40 mm wide on its lower edge. This fine-grained white rock consisting of quartz + topaz + potassium feldspar + albite + zinnwaldite is porphyritic in both topaz and quartz, with the latter occurring as distinctive small (1-mm), round grains. Its texture is saccharoidal due, in part, to the abundant groundmass plagioclase.

The aplite rich in potassium feldspar (sample 632) was collected from a thicker sill (750 mm) and is generally fine grained with some large (5-mm) grains of quartz and topaz. Modal layering is defined by varying concentrations of zinnwaldite (black) and potassium feldspar, quartz, and topaz (white), presumably resulting from flowsorting processes during intrusion. Small pegmatitic schlieren may be present at the contacts of the aplite and country rocks.

The soda aplite (sample 633) is a more heterogeneous rock than samples 631 or 632. It occurs as a pale, fawncolored, irregular mass closely associated spatially with sample 632. The texture is granular, with average grain size 1 mm. Occasional quartz phenocrysts and aggregates up to 20 mm and phenocrysts of topaz (10 mm), albite

This is the youngest formation within the Hodgkinson Basin (Fig. 1). These sedimentary rocks occur as a pendant within the roof zone of a composite granitic batholith that, in this area, comprises a medium-grained alkali feldspar granite (the Pinnacles Granite) and smaller bodies of alkali feldspar microgranite, mixed pegmatites, and aplites. These rocks display a close spatial association with the topaz-bearing rocks, and studies by Johnston (1984) suggest that the latter are extreme differentiates of the Pinnacles Granite or related phases. Dating by Johnston and Black (1986) has shown that the age of the Pinnacles Granite (311 ± 5 Ma) is indistinguishable from that of aplite 632 (312 ± 4 Ma), which is consistent with that relationship. Similarly the initial $^{87}Sr/^{86}Sr$ ratios are identical (0.74 ± 0.04). Contact metamorphism is well developed within the roof pendant (Blake, 1972), and biotite- and monazite-rich selvages occur immediately adjacent to the topaz-bearing intrusions. The area is strongly mineralized, and many of the creeks in the area have been worked for alluvial cassiterite.

## PINNACLES GRANITE

The Pinnacles Granite is a medium-grained alkali feldspar granite that outcrops over some 12 km² in the Mount Gibson area. Principal constituents are quartz and beige potassium feldspar, with accessory albitic plagioclase and protolithionite (sample 640, Table 1). Traces of hydrothermal fluorite, topaz, and sericite are present. Other
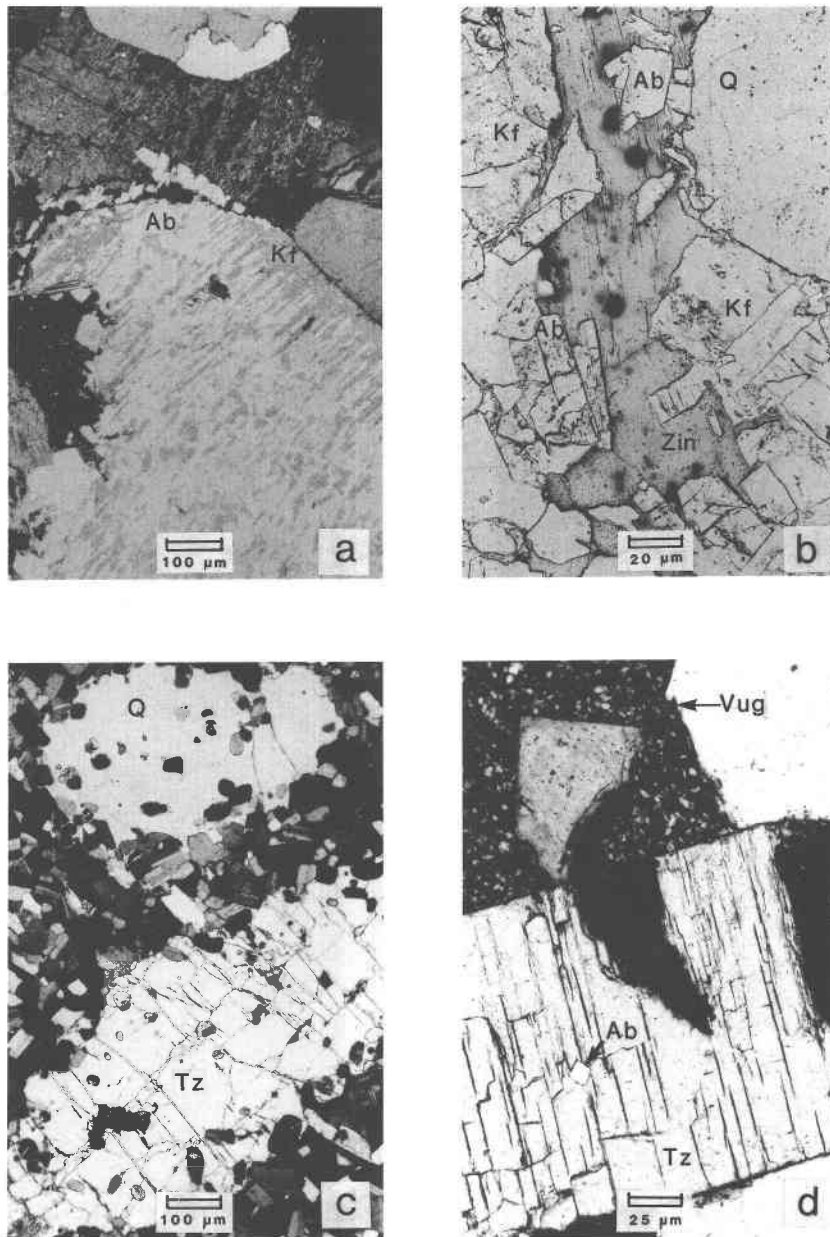
Fig. 2. Photomicrographs. (a) Alkali feldspar granite sample 640; strong development of exsolution and grain boundary albite clearly shown. (b) Lithium fluorine granite sample 637; euhedral plagioclase (Ab$_{98}$) is surrounded by interstitial zinnwaldite and perthite-free potassium feldspar (Kf). (c) Aplite sample 631; "porphyroblasts" of quartz and topaz ?resorb early formed feldspars. Note unaltered appearance. (d) Topazite sample 638; euhedral topaz, anhedral quartz, single lath of albite and kaolin-filled vugs clearly shown.

(5 mm), and potassium feldspar (15 mm) are also present. This aplite is plagioclase and quartz rich (Table 1).

The lithium fluorine granite (sample 637) occurs as a sill (>2 m), its upper surface studded with large (50–100-mm) euhedral potassium feldspar crystals. This white, speckled, fine-grained granular intrusive contains approximately equal proportions of quartz, potassium feldspar, and plagioclase but little topaz (Table 1). The most distinctive features in hand specimens are the presence of

small (1-mm), rounded quartz phenocrysts and a weak alignment of mica crystals.

The topazite (sample 638) was collected from an irregular, podlike body (<3 m in thickness), plunging northeast at 30°. The material sampled fills the voids between giant quartz and topaz crystals radiating inward from the floor and ceiling of what must have been a large cavity. It is a pinkish white, fine-grained, equigranular, friable vuggy rock comprising quartz, accessory topaz, rare albite

**TABLE 2.** Mineral chemistry

| Sample no. | 631 | 632 | 637 | 631 | 632 | 637 | 631 | 632 | 637 |
| Mineral | Mica | Mica | Mica | Kf | Kf | Kf | Plag | Plag | Plag |
| Analyses | 4 | 3 | 5 | 3 | 1 | 8 | 1 | 2 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 39.8 | 39.1 | 41.7 | 64.7 | 64.1 | 65.1 | 66.5 | 68.3 | 68.1 |
| TiO$_2$ | 1.1 | 1.1 | 0.4 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Al$_2$O$_3$ | 20.0 | 19.6 | 21.4 | 18.2 | 17.9 | 18.0 | 19.5 | 19.8 | 19.4 |
| FeO | 18.0 | 19.8 | 18.8 | 0.1 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 |
| MnO | 0.5 | 0.5 | 0.5 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| MgO | 4.4 | 2.9 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| CaO | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.5 | 0.2 |
| Na$_2$O | 0.4 | 0.3 | 0.4 | 1.2 | 0.3 | 1.1 | 10.5 | 11.2 | 11.4 |
| K$_2$O | 9.2 | 9.4 | 9.7 | 15.0 | 15.7 | 15.3 | 0.1 | 0.2 | 0.1 |
| Cl | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Rb$_2$O | 0.8 | — | 0.9 | — | — | — | — | — | — |
| Li$_2$O | 0.6 | — | 4.3 | — | — | — | — | — | — |
| Total | 95.0 | 92.8 | 98.4 | 99.4 | 98.2 | 99.6 | 97.4 | 100.1 | 99.2 |
| | | | | **Formula proportions** | | | | | |
| Si | 6.6 | 6.6 | 6.9 | 12.0 | 12.0 | 12.0 | 11.9 | 11.9 | 12.0 |
| Ti | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Al | — | — | — | 4.0 | 4.0 | 3.9 | 4.1 | 4.1 | 4.0 |
| [4]Al | 1.4 | 1.4 | 1.1 | — | — | — | — | — | — |
| [6]Al | 2.5 | 2.5 | 3.1 | — | — | — | — | — | — |
| Fe | 2.5 | 2.8 | 2.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mn | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mg | 1.1 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Ca | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 |
| Na | 0.1 | 0.1 | 0.1 | 0.4 | 0.1 | 0.4 | 3.7 | 3.8 | 3.9 |
| K | 2.0 | 2.0 | 2.0 | 3.6 | 3.8 | 3.6 | 0.0 | 0.1 | 0.0 |
| Cl | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Rb | 0.1 | — | 0.1 | — | — | — | — | — | — |
| Li | 0.4 | — | 2.9 | — | — | — | — | — | — |
| O | 24.0 | 24.0 | 24.0 | 32.0 | 32.0 | 32.0 | 32.0 | 32.0 | 32.0 |
| Al + Si | 10.5 | 10.5 | 11.1 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 |
| Ti + Fe + Mn + Mg | 3.8 | 3.7 | 2.8 | — | — | — | — | — | — |
| Ca + Na + K | 2.1 | 2.1 | 2.2 | — | — | — | — | — | — |
| Fe/(Fe + Mg) | 0.7 | 0.8 | 1.0 | — | — | — | — | — | — |
| An | — | — | — | 0.9 | 0.7 | 0.4 | 3.7 | 3.3 | 1.3 |
| Ab | — | — | — | 10.7 | 2.7 | 9.7 | 95.7 | 95.6 | 97.9 |
| Or | — | — | — | 88.5 | 96.6 | 89.9 | 0.6 | 1.1 | 0.8 |
| Total cations | — | — | — | 4.0 | 3.9 | 4.0 | 3.8 | 4.0 | 3.9 |

*Note:* Mica = zinnwaldite, Kf = potassium feldspar, Plag = albite, dash = not measured or not quoted. Li and Rb measured by AAS on mineral separates.

laths, muscovite shreds, and accessory cassiterite (Table 1). Pockets of gem topaz are not uncommon. Some banded coarse-grained variants are also present. The F content of topaz from this unit is very high at 19.1% (Johnston, 1984). This implies a magmatic rather than hydrothermal origin for the rock (Burnham and Ohmoto, 1980). We therefore do not consider it to be a greisen.

In thin section, the aplites, lithium fluorine granite, and topazite display a number of distinctive features. In contrast to the Pinnacles Granite, they display only minor deuteric alteration. Principal rock-forming minerals include euhedral, randomly oriented, twinned albite (Ab$_{96}$, grain size 0.2–1.0 mm) and interstitial potassium feldspar (Or$_{88-90}$) with prominent microcline twinning (Tables 1 and 2). Interstitial zinnwaldite (red-brown, orange, very pale yellow with $Z \geq Y \gg X$) occurs in variable concentrations and contains small grains of zircon, monazite, and thorite surrounded by pleochroic halos (Fig. 2b); rare film perthite is only present in the lithium fluorine granite, and the lack of perthitic albite exsolutions in the potassium feldspars of the aplites indicates crystallization

under subsolvus conditions, with almost pure end-members (Ab, Or) crystallizing (see Table 2). Aplite samples 631 and 632 contain abundant subhedra of quartz and topaz with rounded resorbed inclusions of albite and potassium feldspar (Fig. 2c). These are thought to have grown toward the end of crystallization in response to rising concentrations of F. The vuggy nature of the topazite is shown in Figure 2d.

The appearance of topaz as a possible magmatic phase in aplite samples 631 and 632 indicates a higher F content during crystallization for those aplites than for the Pinnacles Granite. Measurements by Congdon and Nash (1988) on a topaz-bearing vitrophyre from west-central Utah, U.S.A., indicate that an F content between 2 and 3% may be required before topaz will crystallize. Also, experimental work by Webster et al. (1987) has shown that H$_2$O saturation and high F contents in residual melts will stabilize topaz near the solidus. In contrast, sample 633 has small amounts of clear, anhedral hydrothermal topaz that replaces potassium feldspar and sometimes albite.

## SAMPLE PREPARATION AND ANALYTICAL TECHNIQUES

Material was collected by drilling and blasting. Sample weights ranged from 5.0 kg for medium-grained samples to 2.5 kg for fine-grained material. Each sample was crushed and milled using tungsten carbide faced equipment.

Major elements (except $Na_2O$, $Fe^{2+}$, and F) were measured by wavelength dispersive X-ray fluorescence spectrometry on fused glass discs using the method of Norrish and Chappell (1977). $Na_2O$ and $Li_2O$ were determined using flame photometry, and $Fe^{2+}$ was determined by titration against a standard solution of potassium dichromate (Peck, 1964). F was determined colorimetrically by autoanalyzer using the method of Fuge (1976). Measurement of volatile constituents ($CO_2$ and $H_2O$) was done using the method of Riley (1958).

Trace elements (except for REE, Cr, Cs, Hf, Sb, Sc, Ta) were measured in duplicate by X-ray fluorescence spectrometry on pressed powder pellets using the method of Norrish and Chappell (1977). REE, Cr, Cs, Hf, Sb, Sc, Ta were measured (also in duplicate) by instrumental neutron activation analysis using the method of Chappell and Hergt (1989). Corrections were applied to Ta measurements to compensate for Ta contamination from the tungsten carbide mill.

For major elements, values quoted are the mean of three determinations (except for F, which was measured twice, and $H_2O$ and $CO_2$, which were measured once). Trace element values quoted are the mean of two measurements. If close agreement was not achieved between duplicates, the sample was reanalyzed.

All measurements (except $Li_2O$ and F) were carried out at the Australian National University in Canberra. $Li_2O$ content of the samples was measured in the Geology Department laboratories of James Cook University of North Queensland, and F determinations were made at the Davies Laboratories of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Townsville.

Electron microprobe analyses of minerals (Table 2) were carried out at James Cook University of North Queensland using a Siemans Etec Autoscan scanning electron microscope fitted with a Link 290 Si(Li) spectrometer. Estimates of precision and relative accuracy for this unit have been prepared by Dunham and Wilkinson (1978).

## MAJOR AND TRACE ELEMENT COMPOSITIONS

### Pinnacles Granite and lithium fluorine granite

Analytical data for these rocks are presented in Table 3. The lithium fluorine granite is slightly more aluminous than the Pinnacles Granite, possibly as a consequence of its higher F content. In terms of normative quartz, albite, and orthoclase (Table 3), both rocks plot close to the $H_2O$-saturated ternary minimum at 100 MPa (1 kbar) (see Fig. 3).

Abundances of $TiO_2$, FeO, $Fe_2O_3$, MnO, MgO, S, $P_2O_5$, and CaO are very low relative to the low-Ca granite of

**TABLE 3.** Chemical analyses

| Sample no. Rock type | 631 Aplite | 632 Potassium aplite | 633 Soda aplite | 637 Lithium fluorine granite | 638 Topazite | 640 Alkali feldspar granite |
|---|---|---|---|---|---|---|
| $SiO_2$ | 74.54 | 68.60 | 76.19 | 76.14 | 89.52 | 76.48 |
| $TiO_2$ | <0.01 | 0.04 | 0.04 | <0.01 | <0.01 | 0.03 |
| $Al_2O_3$ | 14.89 | 17.65 | 13.26 | 13.23 | 7.36 | 12.04 |
| $Fe_2O_3$ | <0.01 | 0.06 | 0.15 | 0.07 | 0.01 | 0.24 |
| FeO | 0.09 | 0.60 | 0.58 | 0.78 | 0.03 | 0.83 |
| MnO | <0.01 | 0.01 | 0.01 | 0.01 | <0.01 | 0.01 |
| MgO | <0.03 | 0.08 | <0.03 | <0.03 | <0.03 | <0.03 |
| CaO | 0.26 | 0.26 | 0.43 | 0.31 | <0.01 | 0.51 |
| $Na_2O$ | 4.29 | 4.06 | 4.87 | 3.91 | 0.02 | 3.80 |
| $K_2O$ | 4.51 | 6.64 | 3.06 | 4.55 | 0.07 | 4.54 |
| $P_2O_5$ | 0.01 | 0.01 | 0.01 | <0.01 | <0.01 | <0.01 |
| S | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| $H_2O^+$ | 0.31 | 0.35 | 0.47 | 0.39 | 0.39 | 0.39 |
| $H_2O^-$ | 0.06 | 0.08 | 0.14 | 0.07 | 0.05 | 0.15 |
| $CO_2$ | 0.24 | 0.43 | 0.27 | 0.50 | 1.43 | 0.66 |
| F | 0.60 | 1.02 | 0.55 | 0.60 | 2.26 | 0.46 |
| Rest | 0.17 | 0.33 | 0.26 | 0.33 | 0.03 | 0.26 |
| O ≡ F | 0.25 | 0.43 | 0.23 | 0.25 | 0.95 | 0.19 |
| Total | 99.72 | 99.79 | 100.06 | 100.64 | 100.22 | 100.21 |
| **Trace elements** | | | | | | |
| Li | 27 | 260 | 171 | 548 | 12 | 165 |
| Ba | 250 | 220 | 55 | 10 | <5 | <5 |
| Rb | 959 | 1771 | 865 | 1322 | 12 | 754 |
| Sr | 83.0 | 50.0 | 27.5 | 5.5 | 2.5 | 8.0 |
| Pb | 22 | 38 | 15 | 43 | 5 | 31 |
| Th | 12 | 21 | 58 | 36 | 14 | 83 |
| U | 2.0 | 3.0 | 8.2 | 13.0 | 5.4 | 20.5 |
| Zr | 49 | 58 | 97 | 61 | 24 | 162 |
| Nb | 12.0 | 82.0 | 71.0 | 46.5 | 9.5 | 55.0 |
| Ta | 2 | 15 | 13 | 5 | <1 | 4 |
| Y | 2 | 7 | 101 | 15 | <1 | 186 |
| Cu | <1 | <1 | <1 | 1 | 5 | 2 |
| Zn | 3 | 32 | 20 | 22 | 3 | 59 |
| Ga | 40.0 | 43.0 | 36.8 | 32.6 | 1.2 | 31.4 |
| Cr | 1 | 2 | 1 | <1 | <1 | 1 |
| Sb | <0.1 | <0.1 | <0.1 | 0.25 | 1.6 | <0.1 |
| Cs | 7.2 | 12.0 | 12.2 | 24.5 | 0.4 | 15.4 |
| Hf | 3.6 | 4.2 | 6.4 | 4.5 | 3.0 | 10.6 |
| Sc | 0.9 | 2.6 | 2.8 | 3.3 | 0.3 | 2.3 |
| Sn | 10 | 9 | 4 | 6 | 5 | 20 |
| **Rare earth elements** | | | | | | |
| La | 4.8 | 5.9 | 48.0 | 23.5 | 17.0 | 45.5 |
| Ce | 10.8 | 14.2 | 115 | 46.0 | 48.0 | 92 |
| Nd | 3.5 | 5.1 | 39.5 | 12.0 | 10.4 | 39.5 |
| Sm | 0.67 | 1.28 | 10.00 | 2.80 | 2.10 | 11.40 |
| Eu | 0.27 | 0.22 | 0.10 | 0.03 | 0.02 | 0.04 |
| Gd | — | 1.2 | 9.7 | 2.1 | 0.7 | 12.6 |
| Tb | — | 0.30 | 2.05 | 0.65 | 0.16 | 2.70 |
| Ho | — | 0.4 | 4.5 | 1.2 | — | 5.0 |
| Yb | 1.34 | 3.45 | 21.8 | 8.5 | 0.51 | 19.4 |
| Lu | 0.22 | 0.53 | 3.35 | 1.34 | 0.08 | 2.90 |
| **Ratios** | | | | | | |
| K/Rb | 39.0 | 31.1 | 29.1 | 28.6 | 48.4 | 50.0 |
| FE | 0 | 8 | 19 | 8 | 23 | 21 |
| **Normative minerals** | | | | | | |
| Q | 32.11 | 18.95 | 35.42 | 35.40 | 89.15 | 36.62 |
| C | 2.90 | 3.69 | 1.75 | 1.79 | 7.26 | 0.84 |
| Or | 20.02 | 39.92 | 18.41 | 27.45 | 0.42 | 27.12 |
| Ab | 36.26 | 34.34 | 41.17 | 33.05 | 0.14 | 32.12 |
| An | 0.00 | 0.00 | 0.38 | 0.00 | 0.00 | 0.00 |

*Note:* FE = $[Fe^{3+}/(Fe^{2+} + Fe^{3+})] \times 100$. Major elements expressed in percent, trace elements in ppm. Dash = not measured. Normative minerals (expressed as percentages) were calculated on an F-free basis using FeO/$Fe_2O_3$ as measured.

Turekian and Wedepohl (1961) for which complete analytical data are published. Similarly the ratio $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ is very low (Table 3). F abundances, ranging from 0.46 to 0.60%, are relatively high, with F resident in dark

Fig. 3. Normative compositions of samples 631, 632, 633, 637, 638, and 640 plotted in the system Q-Ab-Or. Ternary minima for $H_2O$-saturated melts at 100 MPa (1 kbar) containing 0% and 1% F also shown (from Manning, 1981a).



Fig. 4. REE patterns normalized against chondritic values of Hanson (1978). General concave-upward pattern results from fractionation of monazite, limiting enrichment of LREE, while HREE are largely unbuffered.

micas and hydrothermal fluorite. Other volatiles account for ≤1% of the totals (see Table 3).

Trace element abundances show strong enrichments of the lithophile elements, viz., Li, Rb, Cs, Th, U, Nb, (Y), Ga, and Hf (Table 3), whereas Ba and Sr are strongly depleted. REE data are presented in Table 3 and chondrite normalized patterns in Figure 4.

### Aplites

Aplite samples 631 and 632 are significantly enriched in $Al_2O_3$ (Table 3) relative to the other samples. $TiO_2$, $Fe_2O_3$, FeO, MnO, CaO, MgO, and $P_2O_5$ levels are all very low, as is the $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratio (cf. Exley and Stone, 1964; Hall, 1971). F contents of the aplites range from 0.55 to 1.02% and are similar to those of lithium fluorine granites in other provinces (Bailey, 1977).

These rocks can be satisfactorily represented in terms of normative quartz, albite, and orthoclase (Fig. 3). All samples are displaced from the ternary minimum composition (see Fig. 3), with sample 632 being more potassic and sample 633 being more sodic than the minimum.

Trace element chemistry of the aplites is also presented in Table 3. Selected REE patterns are shown in Figure 4 and Rb, Sr, and Ba trends in Figure 5. Although the data base is limited, it appears that Ba, Sr, and Eu are enriched in the aplites relative to the Pinnacles Granite, whereas REE, Th, U, Y, Zr, Cu, Zn, Hf, Sn are significantly depleted. Other elements (Rb, Ga, Nb, Ta, ±Li) are enriched.

Aplite sample 631 has lower Pb, Th, U, Zr, Nb, Ta, Y, Cu, Zn, Cs, Li, Hf, and Sc than potassium aplite sample 632, which in turn has generally lower trace element abundances than soda aplite sample 633. The latter is grouped with the aplites because it shows similar (but

weak) Ba and Sr enrichment and because it does not have a ternary minimum composition. In other respects, its composition is more like the Pinnacles Granite, especially its REE abundances, which are virtually identical to those of the Pinnacles Granite.

### Topazite

Major element composition of sample 638 (topazite) is unusual in that it includes principally $SiO_2$, $Al_2O_3$, and F. $H_2O$ and $CO_2$ are the other major constituents. All trace elements are strongly depleted.

### Discussion

#### Pinnacles Granite and lithium fluorine granite

The major element compositions of both rocks are consistent with protracted fractional crystallization. For example, highly fractionated rocks should, in a closed system, approach ternary minimum compositions (Tuttle and Bowen, 1958). The position of such minima will depend on the type and amount of the various volatile constituents in the respective melts (Manning, 1981a; Burnham and Nekvasil, 1986). Samples 637 and 640 display such behavior (Fig. 3) and probably represent ternary minima at varying F levels. Taken at face value, their positions in Figure 3 suggest that these melts contained less than 1% F. This is unlikely to have been the case for sample 637 (containing topaz) but may be accurate for sample 640. Note also that the experimental results, derived under $H_2O$-saturated conditions, may not be directly applicable to natural systems (Manning, 1981a).

Trace element abundances (e.g., elevated Li and Rb

and low Ba and Sr) are also consistent with protracted fractional crystallization (Neuman et al., 1954). Also, the REE patterns (concave upward) appear to be fractionation generated. LREEs in the Pinnacles Granite (sample 640) were buffered at around 100–200 times chondritic values (see Fig. 4) by fractionation of monazite as shown by kinking of the patterns between Nd and Sm, as modeled by Yurimoto et al. (1990). HREEs, whose solubilities in the melt were possibly enhanced by high F content (Collins et al., 1982; London, 1987), remained unbuffered during fractionation, giving rise to the observed concave-upward patterns. Deep Eu anomalies are consistent with protracted fractionation of plagioclase feldspars (Hanson, 1980).

Systematically higher abundances of the rare alkalis in the lithium fluorine granite (sample 637) and a lower K/Rb ratio are consistent with it being more evolved than the Pinnacles Granite (sample 640). However, the depletion of Pb, Zn, Cu, Th, U, Zr, Nb, Y, Hf, Sn, and all REE relative to sample 640 is not consistent with this hypothesis. This, we believe, reflects the divergent crystallization history of the two rocks. The chemistry of sample 640 is consistent with fractional crystallization of a silicate melt, with a modest component of postsolidification hydrothermal alteration that has slightly dispersed trace element chemistry (Johnston and Black, 1986). In contrast, sample 637 has also crystallized from a silicate melt but, we speculate, evolved hydrous fluid toward the end of crystallization. Thus, dominantly magmatic trace element abundances have been overprinted by melt/fluid and crystal/fluid equilibria. Hence the lower abundances of REE and Nb would be consistent with partitioning of such elements from the remaining melt to the hydrous fluid (Kilinc and Burnham, 1972; Holland, 1972; Pichavant and Manning, 1984; Webster et al., 1989), which we infer to have been very chloride rich (Witt, 1988). Additionally, dissolution of early formed monazite by the exsolved hydrous fluids would also reduce REE, Th, and $P_2O_5$ values in sample 637. This fluid would ultimately be lost into the aureole (cf. Mitropoulos, 1981). Abundant monazite in hornfelsed contacts with host rocks is clear evidence that this occurred. The location of lost HREE is less certain, but they may have partitioned into abundant hydrothermal fluorite. Similarly, partitioning of Zr, Hf, and U into the exsolving hydrous fluid and possible dissolution of primary zircon by that fluid are suggested by the common occurrence of zircon as a daughter mineral in fluid inclusions of related granites and of mineralization (Witt, 1987, 1988). Also, losses of Pb and Zn are consistent with results of Urabe (1985, 1987), who found that at low pressures (160 MPa, 1.6 kbar) Pb and Zn partitioned in favor of a Cl-rich fluid.

Some Rb and Li would also have been partitioned from the remaining melt into the hydrous fluid (Webster et al., 1989), but the Rb already frozen in potassium feldspars would account for the observed abundances since fluid/crystal partition coefficients for Rb (and Cs) into feldspars are close to unity (Carron and Lagache, 1980).
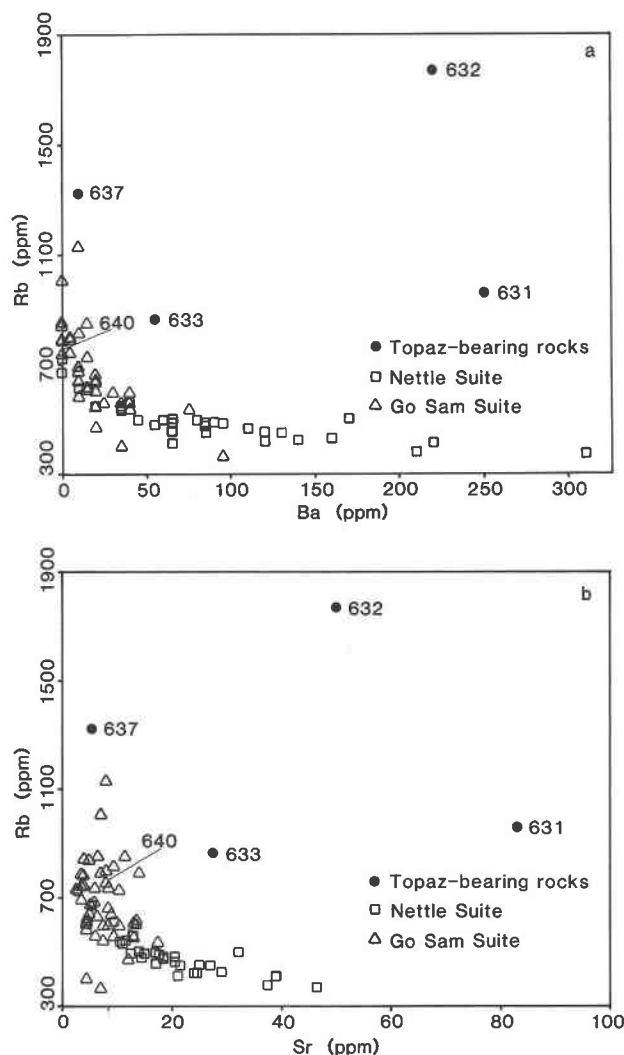


Fig. 5. (a) Plot of Ba vs. Rb for granites and topaz-bearing differentiates of the Coolgarra Batholith. Additional data for the Nettle and Go Sam suites from Johnston (1984). Samples 631, 632, and 633 are significantly displaced from the fractionation trends displayed by the batholith as a whole, which suggests these abundances are not magmatic. (b) Plot of Sr vs. Rb for granites and topaz-bearing differentiates of the Coolgarra Batholith. Sr displays similar trends to Ba, but its enrichment is significantly less. Sample 638 (topazite) with only 12 ppm Rb does not appear on these plots.

## Aplites

We suggest that samples 631 and 632 did not crystallize from a silicate melt but more likely from a dense, alkali- and aluminosilicate-rich hydrous fluid (cf. London, 1986a). The source of this fluid may have been the Pinnacles Granite or other small pluton of the same suite. The reasons for this view are as follows:

1. The aplites show a marked departure from the loci of $H_2O$-saturated ternary minima at various pressures and F contents. Nonminimum compositions are readily ex-

plained by transfer of alkalis and silica through the hydrous fluid to crystallize as either microcline or albite elsewhere in the system (Burnham and Nekvasil, 1986; Stern et al., 1986). The observed pegmatitic selvages may have been produced in this way.

2. It is surprising that samples 631, 632, and 633, which, on the basis of their K/Rb ratios, are more fractionated than the Pinnacles Granite, have much higher Ba and Sr abundances than the Pinnacles Granite (Figs. 5a and 5b). High Ba, Sr, and Eu abundances (relative to the Pinnacles Granite) cannot be generated in the aplites by melt/crystal equilibria involving the fractionation of feldspars if the partition coefficients of Arth (1976) are applicable to this system.

3. High Ba, Sr, and Eu values could be generated by fluid/crystal equilibria involving feldspars if partition coefficients of Carron and Lagache (1980) are applicable to this system, even though Ba, Sr, and Eu levels in the fluid may be very low (Nabelek, 1986).

4. The Nb/Ta and Th/U ratios in the aplites are quite different from those observed in the Pinnacles Granite.

5. Depleted REE abundances set samples 631 and 632 apart from sample 640 (the Pinnacles Granite) and aplite sample 633. Although REE would partition strongly from a silicate melt into an exsolving chloride-rich fluid (Webster et al., 1989), partition coefficients for crystals and fluid calculated for the REE by Nabelek (1986) from the data of Flynne and Burnham (1978) and Hanson (1980) show that the REE would not have partitioned from the fluid into coexisting feldspars. If the REE were not precipitated in monazite or zircon, they would ultimately be lost into the country rocks (cf. Mitropoulos, 1981).

6. The compositions of the micas in samples 631 and 632 are quite different from those in the lithium fluorine granite (Table 2), with significantly lower [6]Al and much higher $Mg^{2+}$ than sample 637 for the same $Fe_{tot}$ abundances. Similarly, the $Li_2O$ content of zinnwaldite in aplite sample 631 is only 0.60%, whereas in the same mineral from the lithium fluorine granite (sample 637) it is 4.34% (Table 2). Micas of the Pinnacles Granite are similar to those of the lithium fluorine granite but less evolved (Johnston, 1984).

7. No evidence for hydrothermal alteration is apparent in samples 631 and 632. Hence subsolidus addition of Ba and Sr and removal of other elements are unlikely.

8. No clear evidence is available to suggest that any of the aplites is a cumulate, nor can it be shown that they are unrelated to the granitic hosts with which they are associated (Johnston, 1984).

Sample 633 is somewhat different from samples 631 and 632 in that its trace element abundances are almost all higher than those of the two latter rocks; this is especially so for the REE. A possible explanation is that, rather like sample 637, sample 633 crystallized predominantly from a silicate melt that evolved a fluid at quite a late stage. However, the system may have remained relatively closed, and thus high abundances of lithophile elements (particularly the REE) were preserved.

## Topazite

Sample 638 (topazite), plotting at the Q apex of the Q-Ab-Or triangle (Fig. 4), clearly cannot have crystallized directly from a silicate melt. This and other topazites of the Coolgarra Batholith have many characteristics of pegmatites. They appear to be cavity-fill material with earliest formed minerals comprising giant quartz and topaz crystals (up to 600 mm). The large crystals probably crystallized from a low-viscosity, supercritical aqueous fluid (Jahns and Burnham, 1969; Stern et al., 1986) with high F content (Glyuk and Anfilogov, 1973). Fine-grained, banded, porous (9% vugs) aggregates of quartz and topaz (with a trace of albite) have crystallized around and between the giant crystals. These may have crystallized from a dense halogen- and alkali-rich aqueous fluid, possibly in contact with a fluid-saturated silicate melt (London, 1986a, 1986b). Quartz and topaz (± albite, depending on F content of the system) would precipitate from this fluid and growth of these minerals would continue as Al, Si, and F were transferred through the supercritical fluid from the remaining melt to the sites of deposition. High F content would inhibit the crystallization of potassium feldspar and micas (Kovalenko and Kovalenko, 1976). Thus topazites are essentially hydrothermal (Manning, 1981b; Birch, 1984), being formed from an aqueous phase that accompanies a silicate melt. However, F content must have been high—possibly up to 3%—if Glyuk and Anfilogov's (1973) experimental work is applicable to natural systems.

The mineralogy of the topazite is such that there are virtually no hosts for any trace elements. Relatively high abundances of LREE, Zr, and Nb suggest the presence of monazite, zircon, and columbite, respectively.

## COMPARISON WITH OTHER PROVINCES

### Ongonites

The Mount Gibson aplites (samples 631 and 632) appear closely similar to ongonites (topaz-bearing quartz keratophyres) first described from Mongolia by Kovalenko et al. (1971) and more recently by Kortemeier and Burt (1988) from central Arizona, U.S.A. Ongonites, the subvolcanic analogues of lithium fluorine granites, are thought to have crystallized from highly fractionated melts containing up to 3.5% F (Bailey, 1977).

The Mount Gibson aplites generally have lower F contents (0.55–1.02%) than the Mongolian ongonites (0.8–3.2%) (Kovalenko, 1973), although their ranges overlap. For this reason (Manning, 1981a), the Mount Gibson aplites contain more $SiO_2$ and $K_2O$ and less $Al_2O_3$ and $Na_2O$ than the "type" ongonites. Both suites of rocks, being highly fractionated, have very low abundances of $TiO_2$, FeO, $Fe_2O_3$, MgO, MnO, CaO, and $P_2O_5$. They are both peraluminous and highly reduced. Compared to the ongonitic Dysart dike of Kortemeier and Burt (1988), the Mount Gibson rocks are lower in $SiO_2$ and $Al_2O_3$ and much lower in F. $Fe_{tot}$ is similar, but the Dysart dike is much more oxidized than the Mount Gibson rocks. $Na_2O$

values are similar in both suites, but sample 632 contains an order of magnitude more $K_2O$ than the Dysart ongonite.

With some exceptions, trace element abundances are similar in both the Mount Gibson and Mongolian rocks. Comparisons with data compiled by Christiansen et al. (1983) indicate that sample 631 has abundances of Li, Zr, Nb, Zn, Cs, Hf, Sn that fall below the range of the Mongolian ongonites, whereas sample 632 displays lower Cs, Hf, Sn, and Zr but higher Li than the Mongolian ongonites. Comparison with the Dysart dike of Kortemeier and Burt (1988) indicates that the Mount Gibson rocks have lower Li, Ba, Sr, Nb, Hf, and Sn and higher Rb, Th, Zr, Ta, and Y, whereas U is similar in both suites. The behavior of REE in Mongolian ongonites and the Mount Gibson aplites appears to be closely similar, but no data are available for the Dysart dike.

## Topazites

Topazites are closely related to ongonites (Kortemeier and Burt, 1988). These authors noted the transition from topazite to ongonite in the Breadpan and Dysart dikes and suggested that such changes may have reflected changes in HF concentrations and timing and degree of loss of volatiles to the country rock. This transition has not been observed at Mount Gibson. However, topazite outcrops in close proximity to samples 631 and 632. The Mount Gibson topazite has significantly higher $SiO_2$ (and possibly F) and lower $Al_2O_3$ than any of the Breadpan samples. The trace element levels in sample 638 are significantly lower than the Breadpan samples (except Ba and Y). This suggests a more complete loss of virtually all elements into a vapor phase than occurred during crystallization of the Breadpan samples.

There are several other occurrences of these rock types recorded in the literature (e.g., Eadington and Nashar, 1978; Manning, 1981a; Birch, 1984; Kleeman, 1985), and they are generally similar to the Mount Gibson rocks, although they vary in detail.

## Topaz rhyolites

Soda aplite (sample 633), lithium fluorine granite (sample 637), and the Pinnacles Granite (sample 640) show similarities in chemistry with the topaz rhyolites of the western U.S.A. (Burt et al., 1982; Christiansen et al., 1983). Thus, although ongonites and topaz rhyolites have overlapping major and trace element abundance ranges and appear to be regarded by Christiansen et al. (1983) as identical, we treat them separately here to emphasize our view that ongonites are generally more evolved than topaz rhyolites.

The major and trace element compositions of samples 633, 637, and 640 are similar but not identical to the "average topaz rhyolite" of Christiansen et al. (1983). For example, $SiO_2$, $Al_2O_3$, and F abundances for these samples often lie above the range of the average, whereas most other major elements lie below it. Also, trace element values mostly lie within the range of the "average

topaz rhyolite," but some (e.g., Li, Rb) are higher and others (e.g., Sn) are lower. REE patterns for topaz rhyolites, e.g., from Spor Mountain and Thomas Range, Utah, U.S.A. (Christiansen et al., 1984), are similar to that of sample 640 (see Fig. 4).

Other examples of topaz rhyolites have been more recently reported by Rubin et al. (1987) and Congdon and Nash (1988). Once again, since they are enriched in many incompatible elements, these rhyolites show similarities with the Mount Gibson rocks. However, the observed trace element abundances are the end result of several processes including partial melting of a variety of source rocks, fractionation, fluid loss, and postemplacement alteration. These in turn are controlled by other factors including temperature, pressure, partition coefficients, and abundance of volatiles such as $H_2O$, $CO_2$, Cl, and F. It is therefore not surprising that the ranges of trace elements are quite wide.

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