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Baddeleyite (ZrO_2) in Gabbroic Rocks from Axel Heiberg Island, Canadian Arctic Archipelago

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Abstract

Baddeleyite (ZrO_2) is an unusual accessory mineral in two gabbros from Axel Heiberg Island, Canadian Arctic Archipelago. One of the rocks also contains zircon ($ZrSiO_4$). Origin of baddeleyite by impact heating and breakdown of zircon or, alternatively, of breakdown of metamict zircon trapped in the gabbroic melt from the sandstone country rocks, is rejected. In analogy to its occurrence as a late stage differentiation product in lunar basaltic rocks, baddeleyite in gabbroic rocks from Axel Heiberg is also interpreted as a primary late stage magmatic differentiate of the gabbroic melt.

Introduction

During a study of mafic igneous rocks from the northern part of the Canadian Arctic Archipelago, baddeleyite (ZrO_2) was found in two gabbros. Both samples were collected from the western part of Axel Heiberg Island at latitude 79°27′15″, longitude 90°42′W (rock no. A 394), and latitude 79°29′50″, longitude 90°47′10″ (rock no. A 845). The present study is concerned with a description and interpretation of this unusual occurrence of baddeleyite, and its host rocks.

Occurrence

The baddeleyite-bearing mafic rocks from Axel Heiberg Island belong to the suite of Cretaceous igneous rocks that intruded all Mesozoic sedimentary units below the lutaceous Upper Cretaceous Kanguk Formation (Fricker, 1963; Tozer, 1963). Specimen A 394 is from a 45 m thick dike of gabbro emplaced into the Upper Jurassic Awingak Formation. The country rock, essentially quartz arenite with some intercalations of dark gray shale, is exposed at the east side of the dike. The contact zone consists of about 3 m of fine-grained quartzite and a few layers of spotted slate. The sample was collected from the upper part of the dike some 4 m below the contact. Gabbro A 845 is from a dike at least 15 m thick in the Upper Triassic and lowermost Jurassic Heiberg Formation. The contact aureole on the northern side is characterized by a whitish zone of about 1 m thickness. Of this, the first 0.1 m to 0.2 m adjacent to the intrusive body is composed of quartzite. Two samples (nos. A 845a and 845b) were collected about 3 m away from the contact.

Both dikes are rather massive and uniform; they consist of a dark gray to dusky green gabbro that weathers dark yellowish with shades of brown. The average grain size ranges from about 0.2 to 2 mm. Plagioclase phenocrysts are locally recognizable.

Mineralogical and Chemical Composition

Under the microscope, rock A 394 and rocks 845a and b display a subhedral-granular to subophitic texture. Although A 394 exhibits a higher degree of alteration than 845a and b, the mineralogical composition of the three specimens is similar. Slightly zoned plagioclase crystals (An_{54-58}, optically determined; average $An_{50.1}$ in A 845, microprobe analysis) are locally altered to white mica and epidote. Zoning is slight, with CaO ranging from 9.5–11.2 wt percent (Table 1). Some plagioclase

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grains show lath development and form a subophitic intergrowth with pyroxene. Rare albite was observed with the microprobe in a section of A 394. Electron microprobe analyses and optical data indicate that augite ranges from 6.7 to 15.6 wt percent MgO and from 13.5 to 16.3 wt percent CaO (Table 1). Some larger augite grains contain uralite. Biotite flakes represent an additional alteration product. Quartz occurs in irregular interstitial patches and in micropegmatite. A few small discrete grains of olivine are found in section A 845b. The opaques consist of equant-to-elongate titaniferous magnetite and tabular and skeleton crystals of ilmenite. Chalcopyrite is present but is scarce. Crystals of sphene and apatite are well developed. Several small crystals of zircon occur in section A 394. The mode was determined by point count of rocks A 394 and A 845 (Table 2). Because the rocks are not foliated or lineated, limited sampling of only one thin section is considered statistically adequate.

TABLE 1. Electron Microprobe Analyses of Plagioclase (Labradorite) and Augite from Gabbro No. A 845 (in wt percent)*

	Labradorite	Augite		Numbers of ions on the basis of 32 oxygens	6 oxygens
SiO_2	55.4(54.1-56.3)	49.6(47.5-51.1)	Si	10.102	1.941
Al_2O_3	27.1(25.7-28.3)	1.8(1.6-2.2)	Al	5.824	0.059
Fe_2O_3**	0.11	n.d.†	Al	--	0.024
TiO_2	0.07(0.05-0.09)	0.83(0.56-1.6)	Fe^{3+}	0.015	--
FeO	0.33	15.9(13.4-20.6)	Ti	0.010	0.024
MnO	<0.02	0.37(0.23-0.52)	Mg	0.014	0.747
MgO	0.05(<0.02-0.08)	12.8(6.7-15.6)	Fe^{2+}	0.050	0.520
CaO	10.1(9.5-11.2)	15.6(13.5-16.3)	Mn	--	0.012
Na_2O	5.3(5.0-5.6)	0.27(0.22-0.31)	Na	1.874	0.021
K_2O	0.38(0.31-0.40)	<0.02	Ca	1.973	0.654
Total	98.84††	97.14††	K	0.088	--
			Z	15.95	2.00
			X	4.00	4.00
			Ab	47.6	Mg 38.9
			An	50.1	Fe 27.1
			Or	2.3	Ca 34.0

*Numbers are averages of 10 analyses each of 20 different and randomly selected grains. Observed ranges in composition are given in parentheses.

**Contents of Fe^{2+} and Fe^{3+} were estimated from neutral iron measured with the electron microprobe by calculating total X cations (i.e., Fe^{2+}, Mg, Na, Ca, K) to be as close as possible or equal to 4.00.

†Not determined.

††Low totals are probably the result of insufficient sampling (twenty different and randomly selected grains for every two or three elements) of the strongly zoned minerals.

TABLE 2. Modal Compositions (in Volume Percent) Determined by Point-counting of Sections A 394 (over 1000 Points) and A 845a (over 1500 Points)

	A394	A845a		A394	A845a
Pyroxene	23	23.6	Opaques	7.5	8.3
Amphibole	6.5	3.7	Apatite	Traces	0.9
Biotite	5	3.7	Zircon	Traces	n.f.*
Plagioclase	54.6	57.6	Sphene	n.f.*	0.7
Quartz	3.4	1.5	Carbonate	n.f.*	Traces

*not found in sections studied

In Table 3, bulk rock analyses and norms of A 394 and A 845a are compared with another analysis of a gabbro from Axel Heiberg Island (Fricker, 1963) and with the average analysis of eight other similar rocks from the northern part of the Canadian Arctic Archipelago (Blackadar, 1964). It is apparent that the baddeleyite-bearing gabbros are similar in composition to other gabbros from this area. The mineralogical and chemical compositions together with the field evidence indicate that the baddeleyite-bearing tholeiitic gabbros belong to the Cretaceous mafic igneous rocks that are widely distributed in the Canadian high Arctic.

Description of Baddeleyite

Baddeleyite occurs irregularly dispersed throughout A 394 and A 845. It can easily be recognized in sections, even in case of very small ($\leq 10\mu$) grains, by its characteristic blue-green luminescent color under electron bombardment in the electron microprobe. Zircon, on the other hand, emits a blue luminescence. Baddeleyite occurs interstitially as well as embedded in augite and is often associated with apatite. A total of fourteen grains were found in a polished thin section of rock A 845, and five grains in a section of A 394. Electron microprobe analysis (average of 35 spot analyses) of the grain shown in Figure 1 showed that chemically the baddeleyite is nearly pure ZrO_2 (97.8 wt percent), with minor amounts of HfO_2 (0.93 wt percent), SiO_2 (0.08 wt percent), FeO (1.3 wt percent), and TiO_2 (0.56 wt percent); (total, 100.67 wt percent). No other elements in amounts >0.2 percent were detected.

In addition to baddeleyite, section A 394 contains at least seven grains of zircon ($ZrSiO_4$), which were identified with the electron microprobe by their major element contents. Both baddeleyite and zircon grains are exceedingly small in the sections studied, most grains having longest dimensions of $\leq 15\mu$. However, the few larger grains studied (~ 25–50μ in longest dimensions) have rather straight, sharp outlines and show no evidence of mechanical rounding (Fig. 1). One zircon grain in rock no. A 394 is intergrown with a euhedral pseudohexagonally-shaped apatite crystal, where the zircon has grown around the apatite. Baddeleyite is also sometimes associated with apatite. However, baddeleyite and free SiO_2, and baddeleyite and zircon, were not observed in contact with each other.

Discussion

Three modes of origin of the baddeleyite in gabbroic rocks from Axel Heiberg Island were considered, but two (1 and 2) were rejected.

(1) Baddeleyite has been described as a high temperature (≥1676°C) decomposition product of zircon in impact glasses, where it usually forms whitish, strongly reflecting clouds around zircon cores (El Goresy, 1965; Clark and Wosinsky, 1967; Kleinmann, 1969). However, because the rocks studied here show no evidence of shock, and because the occurrence of baddeleyite is unlike that observed in impact glasses, this mode of origin is rejected.

(2) Baddeleyite may be the decomposition product of zircon or metamict zircon trapped in the gabbro from the country rock. The country rock in the vicinity of both gabbro dikes is mainly composed of fine-grained quartz arenite with an average quartz and chert content of more than 95 percent. This rock type is characteristic for the Heiberg and Awingak Formations (Fricker, 1963), and fresh, angular to slightly rounded zircon grains occur in the Awingak sandstone (Fricker, 1963). A heavy-mineral fraction was prepared from a quartz arenite sample which was collected from the contact zone in the Heiberg formation and in the vicinity of gabbro A 845. The detrital fraction consists mainly of zircon and lesser amounts of rutile, pyrite, and a few fragments of tourmaline. The generally hypidiomorphic to slightly abraded zircon grains with an average grain size of <0.2 mm are fresh, and only a few contain traces of metamict zircon. Baddeleyite was not detected.

Although baddeleyite can originate by heating of metamict zircon (Ueda, 1957; Lima de Faria, 1964), its very low abundance in the quartz arenite makes this origin unlikely for the baddeleyite in the gabbroic rocks. Furthermore, non-metamict zircon breaks down at 1676°C to baddeleyite and cristobalite (Butterman and Foster, 1967), but this mode of origin of baddeleyite from trapped zircon can also be ruled out, because this temperature is well above the liquidus of basalt (Cohen, Ito, and Kennedy, 1967).

TABLE 3. Chemical Analyses and Norms of Baddeleyite-bearing Gabbro and of Similar Rocks from the Canadian Arctic Archipelago

	1	2	3	4
SiO_2	49.9	48.9	48.5	48.1
Al_2O_3	13.3	13.4	12.7	13.4
Fe_2O_3	2.55	2.9	1.3	3.6
FeO	12.1	13.5	13.2	10.6
MgO	4.2	3.5	4.9	4.7
CaO	8.4	8.1	9.8	8.5
Na_2O	3.75	3.0	2.9	2.7
K_2O	1.05	1.25	0.8	0.94
H_2O^+ H_2O^-	1.5	1.0	2.4	1.7
TiO_2	2.8	3.2	2.6	3.1
P_2O_5	0.35	0.34	0.43	0.41
MnO	0.23	0.27	0.23	0.21
CO_2	--	--	--	1.8
Total	100.1	99.4	99.8	99.8

CIPW MOLECULAR NORM

q		--	1.01	--	5.50
or	pl	6.44	7.79	4.98	5.80
ab		34.92	28.40	27.44	25.33
an		17.00	20.47	20.32	22.65
wo	di	9.75	7.82	11.12	2.69
en		4.43	3.08	5.08	1.52
fs		5.13	4.74	6.11	1.17
en	hy	4.96	7.10	6.38	12.03
fs		5.75	10.92	7.68	9.20
fo	ol	1.98	--	2.10	--
fa		2.29	--	2.53	--
mt		2.77	3.20	1.43	3.93
il		4.05	4.70	3.82	4.51
ap		0.76	0.75	0.95	0.90
cc		--	--	--	4.76

1 Baddeleyite-bearing gabbro, western Axel Heiberg Island (A 394). Analyst M. Weibel (Swiss Federal Technical Institute, Zurich).

2 Baddeleyite-bearing gabbro, western central Axel Heiberg Island (A 845). Analyst M. Weibel.

3 Gabbro, western central Axel Heiberg Island (A 20). Analyst M. Weibel.

4 Average of eight gabbros, Queeen Elizabeth Island, Northern Canadian Arctic Archipelago (from Blackadar, 1964).

(3) Baddeleyite has apparently not previously been described from terrestrial basaltic rocks, where zircon appears to be the major Zr-bearing phase. There, zircon is a late crystallization product (Poldervaart, 1956). However, the mineral is a relatively common accessory phase in lunar basalts, where it usually occurs interstitially as a late-stage phase, commonly associated with silica, silica-rich glass, K-feldspar, apatite, whitlockite, *etc* (*e.g.,* Apollo 11: Ramdohr and El Goresy, 1970; Agrell *et al,* 1970. Apollo 12: El Goresy, Ramdohr, and Taylor, 1971; Brown *et al,* 1971; Keil, Prinz, and Bunch, 1971; Simpson and Bowie, 1971. Apollo 14: Brown *et al,* 1972; El Goresy, Taylor, and

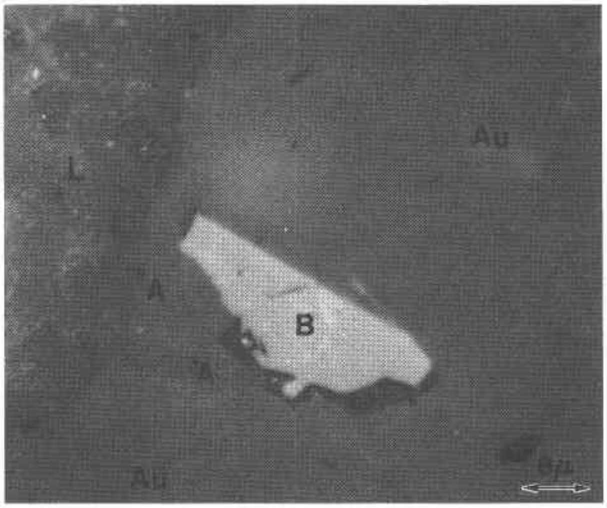

FIG. 1. Largest baddeleyite grain observed in the sections studied of rock A 845. Baddeleyite (B) is surrounded by augite (Au) and closely associated with apatite (A) and labradorite (L).

Ramdohr, 1972; Lovering *et al,* 1972. Apollo 15: Dowty *et al,* 1973). The similarity in occurrence and association of the baddeleyite in the gabbroic rocks from Axel Heiberg (*e.g.,* associated with quartz, apatite; late stage) to lunar rocks suggests that the terrestrial occurrence also is an indigeneous, late stage, magmatic differentiate. This proposition is also supported by the occurrence of baddeleyite in other late stage terrestrial assemblages such as granitic pegmatites (Tröger, 1967).

Although not observed in contact with each other, the occurrence of zircon, baddeleyite, and free SiO_2 in the same rock is noteworthy. The work of Butterman and Foster (1967) indicates that zircon breaks down at 1676°C into baddeleyite and cristobalite ($ZrSiO_4 \overset{1676°C}{\rightleftarrows} ZrO_2 + SiO_2$), and the probability of having all three phases in an equilibrum situation is remote. It appears, therefore, that during the late-stage crystallization of the gabbroic magma, when these phases formed and when much of the magma had already crystallized, equilibration and chemical exchange even over short distances within the rock was limited, and variations in very localized physicochemical conditions were apparently responsible for the formation of zircon, baddeleyite, and free silica.

Note Added in Proof

The common occurrence of baddeleyite in lunar basalts, combined with its small grain size in both lunar and the two terrestrial basaltic rocks from Axel Heiberg, suggested to us that baddelyite may, in fact, not be as rare in terrestrial rocks as appears to be implied by its apparently sole occurrence in Axel Heiberg gabbros. A search was therefore undertaken in approximately 20 basaltic rocks from Oahu and Molokai, Hawaii, six of which (all rocks belonging to the alkalic suite) were found to contain baddeleyite. It is therefore suggested that baddeleyite is probably a relatively common trace mineral in terrestrial basaltic rocks and is associated with late stage interstitial material but, because of its small grain size, has apparently been overlooked in the past.

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