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QUARTZ–TOURMALINE ORBICULES IN THE SEAGULL BATHOLITH, YUKON TERRITORY[1]

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ABSTRACT

Quartz–tourmaline orbicules occur in leucocratic granite of the Seagull batholith, south-central Yukon Territory. The orbicules are spherical to ovoid masses, typically 6 to 8 cm in diameter, that are composed mainly of tourmaline (schorl) and quartz, with microcline and albite. Many orbicules are internally zoned. Within a dark outer zone that consists mainly of tourmaline and quartz, tourmaline has replaced or partly replaced perthitic microcline, albite and quartz. A more leucocratic inner zone consists of quartz, tourmaline, microcline and albite in which no replacement textures are evident. Some orbicules have a central miarolitic cavity that is lined with crystals of quartz and tourmaline. A halo of biotite-free granite surrounds each orbicule. The orbicules appear to be the product of a hydrous, B-, F- and Fe-bearing fluid that was trapped in a crystallizing granitic melt. Anomalous concentrations of Sn (12–90 ppm) in the orbicules suggest that this fluid may have been related to the hydrothermal fluids that formed Sn-bearing veins and skarns associated with the Seagull batholith.

Keywords: tourmaline, schorl, orbicules, tin, granite, Seagull batholith, Yukon Territory.

SOMMAIRE

Des orbicules à quartz + tourmaline ont été observées dans le granite leucocrate du batholite de Seagull, dans la partie centre-sud du Territoire du Yukon. Ce sont des masses sphériques à ovoïdes, typiquement de 6 à 8 cm de diamètre, composées principalement de tourmaline (schorl) et de quartz, avec du microcline et de l'albite. Plusieurs orbicules présentent une zonation. Dans une zone externe foncée, composée surtout de tourmaline et de quartz, la tourmaline a remplacé, en tout ou en partie, le microcline perthitique, l'albite et le quartz. Une zone interne plus pâle, dans laquelle aucune texture de replacement n'a été observée, se compose de quartz, tourmaline, microcline et albite. Certaines orbicules presentent une cavité miarolitique centrale, tapissée de cristaux de quartz et de tourmaline. Chaque orbicule est entourée d'une auréole de leucogranite, sans biotite. Les orbicules seraient le produit d'un fluide aqueux contenant B, F et Fe, et piégé dans le magna granitique. Les concentrations anomales de Sn (12–90 ppm) dans les orbicules font penser que ce fluide était peut-être relié aux fluides hydrothermaux responsables de la formation des veines et skarns stannifères associés avec le batholite de Seagull.

Mots-clés: tourmaline, schorl, orbicules, étain, granite, batholite de Seagull, Territoire du Yukon.

INTRODUCTION

Tourmaline-bearing orbicules are a distinctive feature of the Seagull batholith in south-central Yukon Territory. They were recognized first by Gower (1952), who considered them to be miarolitic cavities formed by fluids evolved during the crystallization of the Seagull granite. Poole (1956) observed that tourmaline in the orbicules appeared to have formed by replacement of feldspar and by open-space crystallization in a central cavity. He attributed these features to B-rich fluids concentrated in "local centers" during the last stages of crystallization of the granitic magma. On the other hand, Dick (1979, 1980) considered the orbicules to be features of postmagmatic replacement related to fractures in the granite. Mato *et al.* (1983) referred to the orbicules as miarolitic cavities, in many cases "filled", and noted that they occur in the upper portions of the batholith.

During the course of a regional study of granitic rocks and related mineral deposits, Sinclair (1986) recognized the anomalous Sn content of the orbicules and suggested that a relationship may exist between the orbicules and Sn-bearing veins and skarns associated with the Seagull batholith. In this paper, we document the textural, mineralogical and chemical characteristics of the orbicules and consider aspects of their origin and relationship to Sn deposits.

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THE SEAGULL BATHOLITH

The Seagull batholith is a partly unroofed, leucocratic granitic intrusive body exposed over about 300 km^2 in the Cassiar Mountains in southeastern Yukon Territory (Fig. 1). The area has high relief, with elevations ranging from 1200 to more than 2000 m above sea level, and is characterized by U-shaped glacial valleys with drift-covered valley floors. Rock exposures are best developed along ridge crests and valley walls.

The batholith was emplaced approximately 100 Ma ago, based on K–Ar and Rb–Sr isotopic age determinations (Wanless *et al.* 1972, Dick 1980, Mato *et al.* 1983). The batholith has intruded the Yukon Cataclastic Complex, a tectonic *mélange* of sedimentary, volcanic and intrusive rocks deformed during the Early Mesozoic collision between the ancient North American craton and an allochthonous island arc terrane (Tempelman-Kluit 1979, Abbott 1981). The Seagull granite has a high initial $^{87}Sr/^{86}Sr$ value of 0.712 (Mato *et al.* 1983) and likely crystallized from a magma derived by partial melting of sialic crustal rocks related to the Early Mesozoic collision.

Contacts between the Seagull batholith and country rocks are sharp, and dip steeply on the southwestern side and moderately on the northeastern side. The upper contact of the batholith, as outlined by large roof-pendants, is subhorizontal and plunges gently to the northwest. The sharp contacts with country rocks, the presence of miarolitic cavities, and the porphyritic texture of the granite near its margin suggest that the batholith was emplaced at a relatively shallow level.

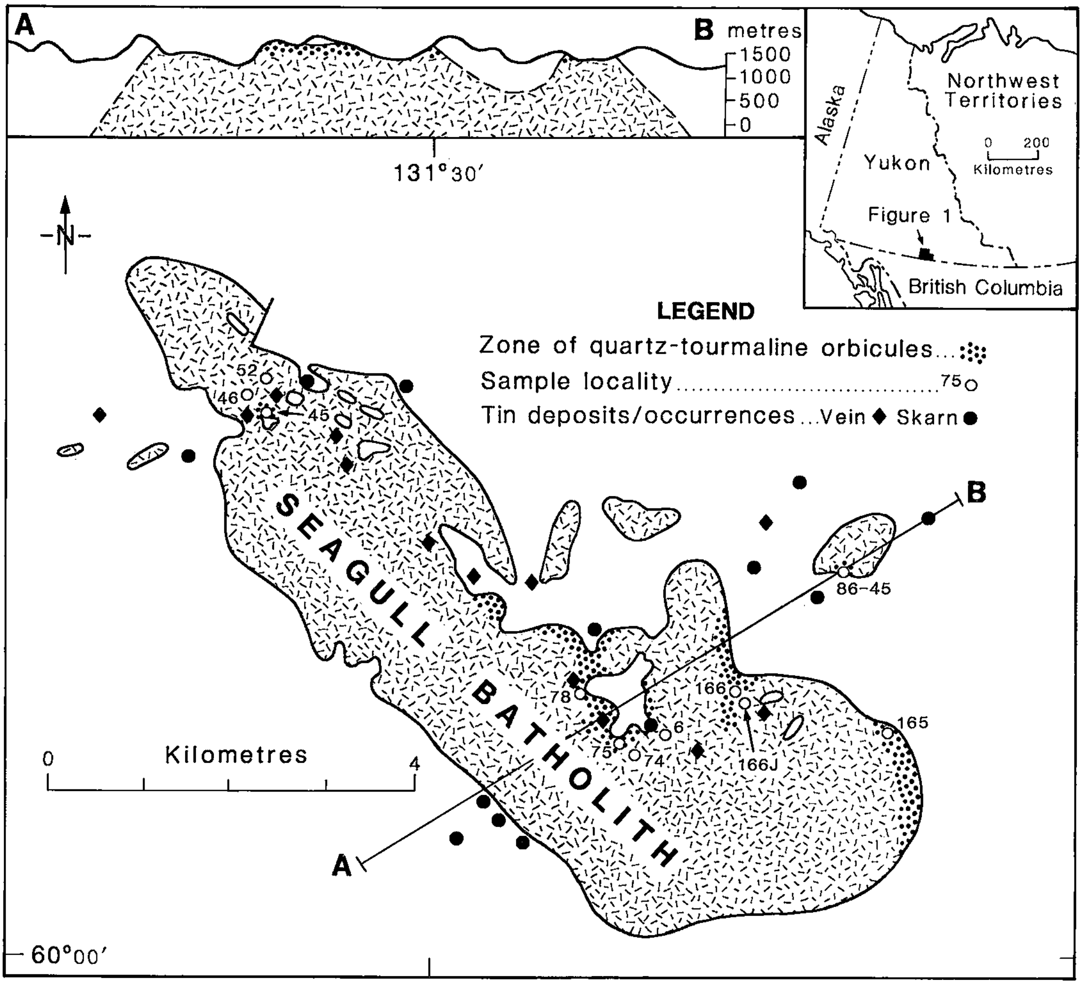


FIG. 1. Map of the Seagull batholith, showing the distribution of quartz–tourmaline orbicules (modified from Gower 1952, Abbott 1981, Mato *et al.* 1983).

Lithologies

The batholith consists entirely of leucocratic granite, which is composed mainly of two distinct textural varieties. Medium- to coarse-grained seriate granite forms approximately 90% of the exposures, and fine-grained, commonly porphyritic granite, about 10%, although intermediate textural variations exist (Poole 1956, Mato *et al.* 1983). The two varieties of Seagull granite typically have irregular, gradational contacts; no consistent age relationships are evident. In general, the coarser-grained seriate granite occurs mainly in the central part of the batholith, whereas the finer-grained porphyritic granite is more common near the margin.

The two varieties of granite are similar mineralogically and average 38% quartz, 33% K-feldspar, 25% plagioclase and 4% biotite, based on 22 modal analyses of thin sections, including data from Poole (1956). In the seriate granite, plagioclase is mainly indistinctly twinned oligoclase (An_{10-15}) that is locally replaced by white mica and rimmed by secondary albite. Minor albite (An_{0-5}) also occurs as albite-twinned, interstitial grains that apppear to be primary. The K-feldspar is characterized by cross-hatched twinning and perthitic intergrowths of albite (10–30% by volume).

In the porphyritic granite, phenocrysts consist mainly of perthitic microcline and quartz; plagioclase phenocrysts are minor. Albite accounts for 3–10% (by volume) of the perthite phenocrysts. Albite also occurs as discrete anhedral grains that are partly altered to white mica and locally overgrown by secondary albite.

In both varieties of granite, quartz forms irregular to subspherical grains that contain minute (0.05 mm) inclusions of muscovite, biotite, albite and tourmaline. Quartz also forms granophyric intergrowths with K-feldspar in the groundmass of the porphyritic granite. Subhedral interstitial biotite flakes contain inclusions of zircon, thorite and apatite. Primary muscovite is rare. Fluorite (0.5–1% by volume) occurs as primary anhedral interstitial grains and as secondary grains within plagioclase. Trace amounts of ilmenite, rutile, monazite and topaz occur as disseminated grains.

Chemical composition

The chemical composition and CIPW normative mineralogy typical of the Seagull granite show little variation (Table 1). The major-element data show that both types of Seagull granite are siliceous (74–77% SiO_2), alkali-rich (8–9% K_2O+Na_2O) and low in TiO_2, Fe_2O_3, FeO, CaO and MgO. F contents range from 0.15 to 0.65%, significantly higher than those of most other granitic rocks (*cf.* Bailey 1977). The seriate granite is slightly metaluminous, whereas the porphyritic variety is peraluminous. All the samples analyzed are characterized by normative corundum.

The Seagull granite has relatively high contents of lithophile elements such as Li, Be, Nb, Y, Rb and Ga, but only minor Ba and Sr compared to average granitic rocks, such as the low-Ca granite of Turekian & Wedepohl (1961). The levels of concentration of these elements and the low TiO_2, Fe_2O_3, FeO, CaO and MgO abundances are typical of highly differentiated, F-rich silicic rocks such as topaz rhyolites (*cf.* Christiansen *et al.* 1986), "specialized" (Sn-related) granites (*cf.* Tis-

TABLE 1. CHEMICAL COMPOSITION OF SEAGULL GRANITE

	Coarse-grained granite		Fine-grained, porphyritic granite		
	74	6	46	52	166J
Major elements (wt%)					
SiO_2	75.7	75.8	75.4	76.9	74.3
TiO_2	0.13	0.12	0.14	0.12	0.09
Al_2O_3	12.6	12.0	13.3	12.3	12.8
Fe_2O_3	0.1	0.1	0.4	0.2	0.1
FeO	0.9	1.2	0.6	0.9	1.0
MnO	0.01	0.02	0.01	0.02	0.01
MgO	0.04	0.09	0.18	0.00	0.04
CaO	0.66	0.71	0.63	0.39	0.68
Na_2O	3.2	3.5	2.5	2.9	3.2
K_2O	5.74	4.90	5.58	5.05	5.18
H_2O_T	0.4	0.3	0.8	0.6	0.3
CO_{2T}	0.2	0.0	0.3	0.1	0.3
P_2O_5	0.01	0.03	0.04	0.00	0.00
S_T	0.01	0.01	0.06	0.02	0.00
F	0.34	0.31	0.31	0.15	0.65
Cl	0.03	0.02	0.01	0.01	0.00
$-O{=}F_2+S_T$	0.15	0.14	0.16	0.07	0.27
Total	99.9	99.0	100.1	99.6	98.4
CIPW Norm					
quartz	34.81	35.79	39.44	40.49	35.90
corundum	1.17	0.58	3.19	2.02	1.98
orthoclase	34.12	29.34	33.27	30.15	31.34
albite	27.01	29.86	21.27	24.71	27.72
anorthite	0.00	1.09	0.00	0.21	0.00
hypersthene	1.44	2.19	0.89	1.30	1.76
magnetite	0.15	0.15	0.59	0.29	0.15
ilmenite	0.25	0.23	0.27	0.23	0.18
apatite	0.02	0.07	0.10	0.00	0.00
pyrite	0.02	0.02	0.11	0.04	0.00
fluorite	0.70	0.64	0.64	0.31	0.97
calcite	0.26	0.00	0.23	0.23	0.00
D.I.*	97.11	95.57	97.17	97.37	96.94
A.S.**	0.99	0.97	1.18	1.12	1.06
Trace elements (ppm)					
Ba	124	80	80	68	30
Rb	489	630	510	326	668
Sr	28	9	9	11	10
B	11	148	6	10	6
Be	6.1	13	-	14	7.6
Li	95	100	36	111	176
As	-	11	1	24	28
Nb	59	67	75	57	77
Y	106	120	140	87	220
Zr	216	180	170	220	182
Cu	16	2	4	14	10
Pb	16	26	13	32	34
Zn	18	26	-	17	19
Sn	10	<3	<3	<3	5
Ga	23.3	24.9	24.0	24.7	27.4

Major elements, Ba by XRF analysis; FeO by wet chemical analysis; H_2O_T, CO_{2T}, S_T by infrared spectrometric analysis; F by selective ion electrode analysis; Cl by colorimetric analysis; Rb, Sr, As, Nb, Y, Zr, Pb by energy dispersive XRF analysis; Li, Cu by atomic absorption spectrometric analysis; B, Be, Zn, Ga by ICP emission spectrometric analysis; Analytical Chemistry Section, Geological Survey of Canada, Ottawa.

Sn analyses by emission spectrometric method; X-Ray Assay Laboratories, Don Mills.

* Differentiation Index (Thornton & Tuttle 1960).
** Degree of Alumina Saturation (mol% $Al_2O_3/(CaO+Na_2O+K_2O)$).

chendorf 1977), and rare-metal Li- and F-rich granites (*cf.* Kovalenko 1978). Elevated contents of the lithophile elements are probably the consequence of a high degree of chemical evolution in the Seagull granite; however, part of the lithophile element content may have been derived from sialic crustal rocks that were the source of the Seagull granitic magma.

Quartz–tourmaline orbicules

The Seagull granite contains between 6 and 11 ppm B, except for one anomalous sample that contains 148 ppm (Table 1); tourmaline generally occurs only in trace amounts. The roof zone of the batholith, however, contains quartz–tourmaline orbicules that consist of as much as 40% tourmaline. The orbicules are spherical to ovoid in shape although, in places, two or more orbicules may be joined to form larger, more irregular bodies. Spherical orbicules are typically 6 to 8 cm in diameter, but range from 2 to 10 cm or more. Locally, the orbicules and host granite are cut by tourmaline-bearing fractures or quartz–tourmaline veins, but most orbicules are spatially unrelated to such features. We have examined numerous sections through different orbicules, and have not observed the fracture-controlled, polygonal ("pseudohexagonal") shapes described by Dick (1979, 1980).

The orbicules are concentrated mainly in the porphyritic granite at the top of the batholith, where they constitute 10 to 15% (by volume) of the rock (Fig. 2). They extend to several hundred meters below the upper contact and gradually decrease in abundance with depth. Orbicules at depth have lower tourmaline contents and lack miarolitic cavities that occur in many orbicules near the top of the batholith.

The orbicules are most abundant in the southeastern exposures of the batholith, particularly along the eastern and northeastern margins and beneath roof pendants (Fig. 1). Some orbicules occur in the seriate granite, but most are hosted by porphyritic granite. Various clastic and carbonate sedimentary rocks and mafic to felsic intrusive rocks are in contact with orbicule-bearing phases of granite; however, no relationship between the occurrence of orbicules and a particular type of country rock is evident.

Mineralogy of the Orbicules

The quartz–tourmaline orbicules consist of several concentric zones that are defined by various proportions of the constituent minerals (Fig. 3). From host granite inward, these zones consist of 1) a leucocratic halo of biotite-free granite 1 to 2 cm wide that surrounds each orbicule, 2) a dark outer zone 1 to 5 cm wide that consists mainly of quartz and tourmaline, and 3) a more leucocratic inner zone with a radius of 1 to 2 cm that consists of quartz, microcline, albite and tourmaline. In many cases, the dark outer zone extends to the center of the orbicule, and the more leucocratic inner zone is absent. In some orbicules, the dark outer zone surrounds a central miarolitic cavity lined with crystals of quartz, tourmaline and, in a few places, topaz.

The leucocratic halo that surrounds each orbicule is similar in both mineralogy and texture to the adjacent granite except for the absence of biotite. This similarity, and the lack of textural evidence indicative of alteration, such as pseudomorphs of white mica or chlorite aggregates after biotite, suggest that the leucocratic haloes crystallized as biotite-free granite.

The transition from the leucocratic halo to the dark

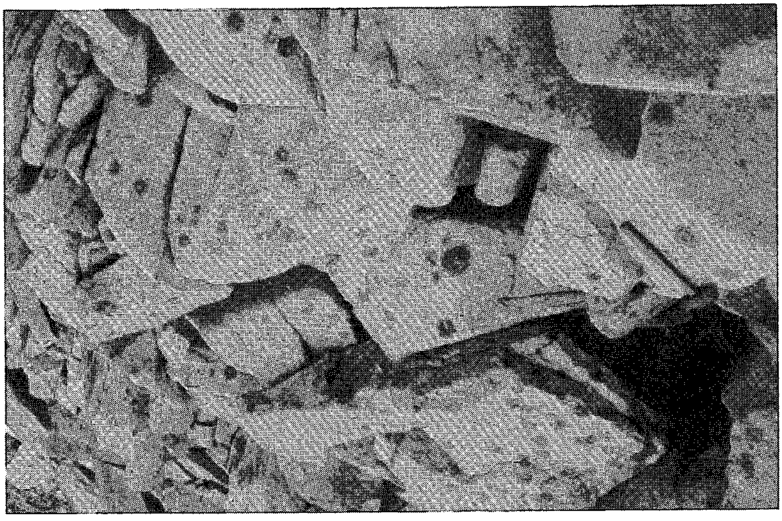


FIG. 2. Quartz–tourmaline orbicules in the Seagull granite. GSC 203425–V.

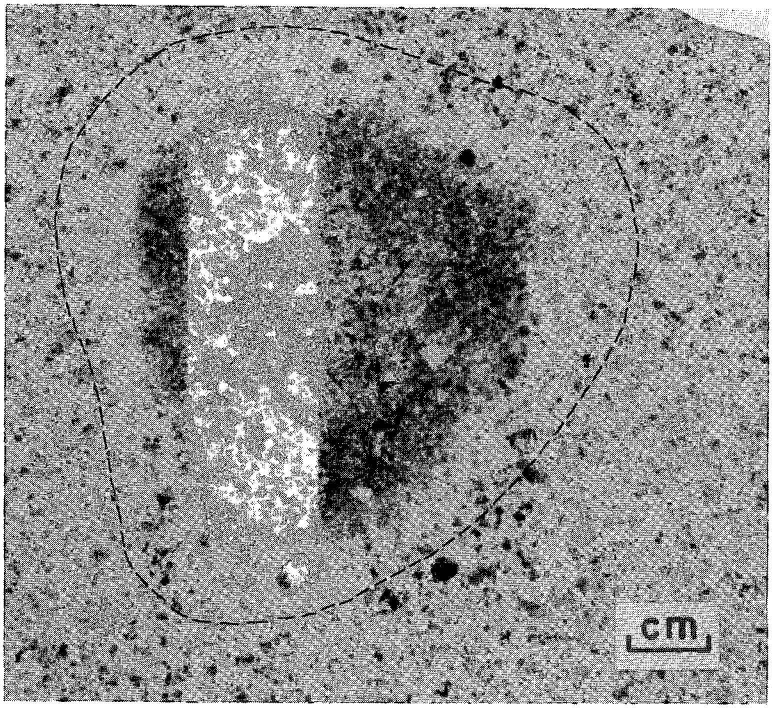


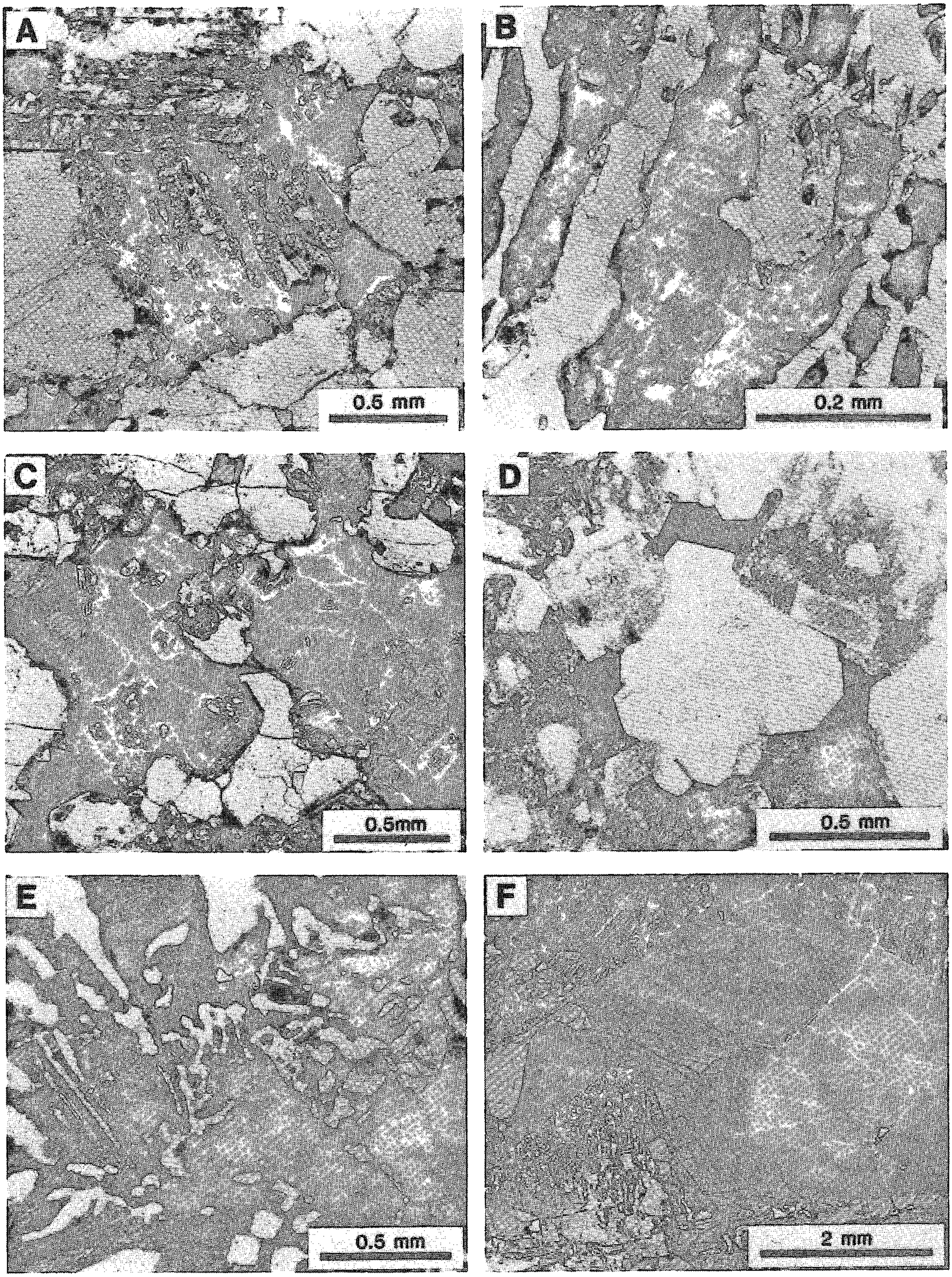
FIG. 3. Zoned quartz–tourmaline orbicule in fine-grained porphyritic granite. The dark outer zone of the orbicule, which consists mainly of quartz and tourmaline, is surrounded by a leucocratic halo of biotite-free granite (the outer limit of the leucocratic halo is indicated by the dashed line). The leucocratic inner zone consists mainly of quartz, tourmaline, microcline and albite. GSC 204152–K.

outer zone is characterized by the abrupt appearance of tourmaline. The outer zone consists of dark brown to black tourmaline (25–40% by volume), quartz (35–50%), discrete albite (10–30%), perthitic microcline (0–15%), and minor amounts of fluorite (0–1%) and muscovite (0–0.5%). Trace amounts of rutile, zircon, thorite, ilmenite, pyrite, arsenopyrite, wolframite, monazite and topaz also are present. In hand specimen, the outer zone is similar in texture to the host granite.

Textural relationships indicate that the tourmaline in the outer zone has replaced microcline, albite and quartz to varying degrees. Early stages of tourmalinization are characterized by stringers and irregular networks of tourmaline replacing perthitic microcline (Fig. 4A). The tourmaline stringers appear to have replaced mainly microcline, as opposed to albite intergrowths; tourmaline stringers commonly cross-cut microcline with unreplaced albite intergrowths (Fig. 4B), and remnants of unreplaced albite intergrowths are present at advanced stages of tourmalinization. Albite in discrete grains also is unreplaced in the early stages of tourmalinization (Fig. 4A). In the more advanced stages, tourmaline has completely or nearly completely replaced microcline and associated albite intergrowths, partly replaced discrete albite grains, and replaced quartz along grain boundaries. In the advanced stages, tourmaline commonly forms poikilitic grains that contain inclusions of quartz and remnants of microcline and albite (Fig. 4C). Rutile, zircon, thorite and monazite also occur as inclusions in tourmaline. In some orbicules, minor amounts of muscovite are associated with tourmaline.

The more leucocratic inner zone of the orbicules consists of fine-grained quartz (30–40% by volume), tourmaline (20–40%), microcline (20–25%), albite (15–20%) and fluorite (0.5–1%). Within the inner zone, tourmaline typically occurs as discrete, anhedral, interstitial grains (Fig. 4D) and, less commonly, as irregular grains within granophyric intergrowths of quartz and K-feldspar (Fig. 4E). No replacement of microcline or albite by tourmaline was observed within the inner zone.

Two varieties of tourmaline are evident in the outer zone of the orbicules. One is pale orange to orange-brown pleochroic, and the other is pale blue to medium blue pleochroic. Distribution of the two varieties is irregular, both within and between tourmaline grains, and no correlation between color and nature of primary mineral replaced is apparent. Subtle variations in color reflecting zones of crystal growth are present only in


A
0.5 mm
B
0.2 mm
C
0.5mm
D
0.5 mm
E
0.5 mm
F
2 mm

tourmaline crystals lining miarolitic cavities (Fig. 4F). Tourmaline in the inner zone consists entirely of the orange pleochroic variety.

CHEMISTRY OF THE ORBICULES

The average chemical composition of 15 quartz–tourmaline orbicules from four sites in the Seagull batholith is given in Table 2, along with the average composition of five samples of the host granite. The outer zones and inner zones were combined in the orbicule samples. Leucocratic haloes were excluded from both the orbicule and granite material analyzed.

Variations in the composition of the orbicules are shown in Figure 5. Total Fe content ($Fe_2O_3 + FeO$) varies directly as a function of B_2O_3 (Fig. 5A), and reflects the abundance of tourmaline. The high FeO content relative to that of Fe_2O_3 indicates that the Fe in the tourmaline (the principal Fe-bearing mineral in the orbicules) is predominantly Fe^{2+}. Reasonably good negative correlation between K_2O and B_2O_3 (Fig. 5B) and poor negative correlation between Na_2O and B_2O_3 (Fig. 5C) reflect the greater tendency of tourmaline to replace microcline relative to albite.

On average, the orbicules contain much more Fe and B, and slightly more F than the host granite. They are relatively depleted in K, Rb and Li, and have slightly lower contents of SiO_2 and Na. Tin content of the orbicules ranges from 12 to 90 ppm Sn. In comparison, the Seagull granite samples typically contain <3 to 10 ppm Sn (Table 1), and granite adjacent to the orbicules contains between 5 and 21 ppm Sn (Table 2). Sn in the orbicules is concentrated primarily in rutile, which occurs as inclusions in tourmaline. Electron-microprobe analyses of nine grains of rutile in a Sn-rich orbicule yielded between 0.12 and 1.3% Sn (average 0.63%). Despite a careful search, no cassiterite, stannite, or other Sn-bearing minerals was identified in the orbicules.

TABLE 2. CHEMICAL COMPOSITION OF QUARTZ-TOURMALINE ORBICULES AND HOST GRANITE

	Orbicules			Host Granite		
	$\bar{x}$ (15)	s	range	$\bar{x}$ (5)	s	range
Major elements (wt %)						
SiO_2	71.3	1.8	66.0-73.1	74.8	0.7	73.6-75.4
TiO_2	0.16	0.04	0.10-0.26	0.10	0.01	0.09-0.10
B_2O_3	3.05	0.62	2.35-4.51	-	-	-
Al_2O_3	13.94	0.61	12.9-15.4	13.2	0.4	12.8-13.6
Fe_2O_3	1.2	0.9	0.0-3.2	0.4	0.2	0.1-0.7
FeO	4.9	1.5	2.4-7.6	0.8	0.2	0.5-1.1
MnO	0.03	0.01	0.02-0.04	0.01	0.01	0.01-0.02
MgO	0.10	0.05	0.01-0.19	0.14	0.12	0.01-0.30
CaO	0.45	0.39	0.08-1.62	0.43	0.26	0.15-0.67
Na_2O	1.9	0.7	0.4-2.7	3.2	0.4	2.6-3.5
K_2O	1.02	0.68	0.04-2.13	5.25	0.29	4.84-5.60
H_2O_T	1.2	0.3	0.8-1.8	0.7	0.5	0.3-1.3
CO_{2T}	0.4	0.3	0.1-1.0	0.5	0.6	0.1-1.4
P_2O_5	0.02	0.01	0.01-0.04	0.03	0.01	0.01-0.03
S_T	0.06	0.03	0.01-0.10	0.04	0.03	0.01-0.07
F	0.82	0.47	0.28-2.10	0.34	0.24	0.08-0.68
Cl	0.02	0.01	0.01-0.06	0.01	0.00	0.01-0.02
$-O=F_2+S_T$	0.37	0.19	0.17-0.89	0.16	0.09	0.07-0.30
Total	100.2	1.0	99.2-102.5	99.7	1.0	98.4-100.9
Trace elements (ppm)						
Ba	21	5	15-31	37	11	31-52
Rb	115	74	6-224	546	57	491-632
Sr	7	2	5-14	9	1	7-11
B	-	-	-	37	29	7-78
Be	6.8	2.0	4.9-13	6.1	1.5	4.5-7.9
Li	32	16	17-71	174	19	144-192
Nb	61	14	27-79	86	5	78-91
Y	121	73	27-250	131	73	43-200
Zr	167	41	42-200	174	85	180-230
As	12	13	1-49	44	36	11-84
Cu	17	42	3-170	8	1	7-8
Pb	9	5	2-22	20	8	11-32
Sn	28	23	12-90	11	7	5-21
Ga*	22.1	3.7	17.1-26.2	23.0	1.5	21.2-24.5

$\bar{x}$=mean; s=standard deviation.

Major elements, Ba by wavelength dispersive XRF analysis on fused disks; FeO by modified Seil method (Bouvier et al., 1972); H_2O_T, CO_{2T}, S_T by infrared spectrometric analysis; F by selective ion electrode analysis; Cl by colorimetric analysis; Rb, Sr, As, Nb, Y, Zr, Pb by energy dispersive XRF analysis; Li, Cu by atomic absorption spectrometric analysis; B, Be, Ga by ICP emission spectrometric analysis; Analytical Chemistry Section, Geological Survey of Canada, Ottawa.

Sn analyses by emission spectrometric method; X-Ray Assay Laboratories, Don Mills.

*6 samples of the orbicules were analyzed for Ga.

COMPOSITION OF THE TOURMALINE

Analytical methods

The chemical composition of approximately 140 tourmaline grains in 17 orbicules was determined by wavelength-dispersion electron-microprobe analysis using a CAMEBAX instrument. Accelerating voltage was 15 kV, beam current was 30 nA, and beam size was

FIG. 4. Photomicrographs showing textural features of the quartz–tourmaline orbicules. (A) Microcline grain partly replaced by irregular stringers of tourmaline (grey) in the outer zone of an orbicule; albite (upper left) and quartz grains are relatively unaffected. GSC 204747–1AA. (B) Unreplaced microcline (dark, turbid) and albite (grey, albite-twinned) in perthitic microcline partly replaced by tourmaline (white). GSC 204747–2AA. (C) Remnant grains of microcline, albite and quartz in tourmaline that has nearly completely replaced microcline. Two varieties of tourmaline are present, an orange-pleochroic variety (dark grey) and a blue-pleochroic variety (light grey). GSC 1991–195–R. (D) Tourmaline grains (grey) interstitial to quartz, microcline and albite in the leucocratic inner zone of an orbicule. GSC 204747–20A. (E) Granophyric intergrowth of quartz, K-feldspar and tourmaline in the leucocratic inner zone of an orbicule. GSC 204747–12A. (F) Zoned tourmaline filling a miarolitic cavity lined by highly tourmalinized K-feldspar crystals; the darker zones are orange-pleochroic, the lighter zones are pale blue-pleochroic. GSC 1991–195–E.

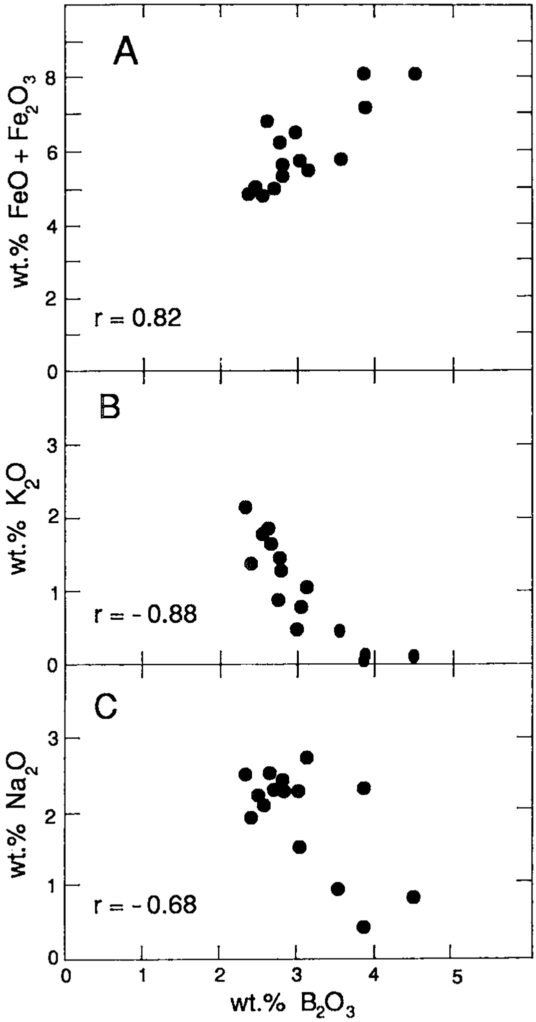


FIG. 5. Plots of FeO + Fe_2O_3(A), K_2O(B) and Na_2O(C) *versus* B_2O_3 for the orbicules.

5 µm. Natural minerals, synthetic equivalents and pure metals were used as standards. Data reduction was conducted according to the methods of Pouchou & Pichoir (1984). The total Fe content is reported as FeO, based on a high Fe^{2+} content of the tourmaline determined from analyses of tourmaline separates by the modified Seil method (Bouvier *et al.* 1972) and Mössbauer spectroscopy.

Structural formulae for tourmaline were calculated on the basis of 29 oxygen atoms and the assumption that B is stoichiometric. Formulae containing Si in excess of 6 atoms per formula unit were normalized to 6 atoms. The amounts of excess Si are generally small (<0.04 atoms per formula unit), but are difficult to account for in terms of the structure of tourmaline (*cf.* Fortier & Donnay 1975, Jolliff *et al.* 1986).

Results

Compositions of typical tourmaline grains are given in Table 3. Overall, the tourmaline grains have a relatively restricted range of compositions, characterized by high contents of FeO (15.00–19.49 wt.%) and low contents of MgO (0–0.81 wt.%). On a triangular Fe–Al–Mg plot (Fig. 6), compositions of orange and blue pleochroic tourmalines both fall close to the composition of end-member schorl. The low Mg contents reflect a negligible dravite component, and low Li contents (62–82 ppm, based on analysis of six tourmaline separates by atomic absorption techniques) indicate a negligible elbaite component. The cation formulae (Table 3) suggest that vacancies are present in the *X* and *Y* sites. However, structural determinations on schorl in general indicate a lack of *Y*-site vacancies (Foit & Rosenberg 1977, Rosenberg & Foit 1979); the *Y* site is therefore assumed to be full, with charge balance maintained by substitution of O^{2-} for OH^- and F^-, and proton deficiency in the *X* site.

Compositional variations exist both within and between tourmaline grains. Al_Y substitutes extensively for Fe and other elements (Mg, Mn, Ti) in the Y site, in both the orange- and blue-pleochroic varieties of tourmaline (Fig. 7A). Content of Al_Y is highest in the blue pleochroic tourmaline, but can be either higher or lower than in adjacent grains of the orange-pleochroic variety (Fig. 7B). Variations in composition of zoned grains of tourmaline (Fig. 8) show no consistent trends.

The pleochroism of the tourmaline appears to correlate most closely with contents of Ti and Mg (Fig. 9). Blue-pleochroic tourmaline has low contents of Ti (≤0.03 atoms per formula unit) and Mg (≤0.06 atoms per formula unit) compared to orange-pleochroic tourmaline. The pleochroism is unrelated to major elements such as Fe and Al. Slack & Coad (1989) similarly attributed blue pleochroism in tourmaline from the Kidd Creek massive sulfide deposit to lower Ti contents. The exact causes of the color variation, however, could include other factors, such as charge-transfer processes (Faye *et al.* 1974), the presence of other trace elements, and structural imperfections.

DISCUSSION

Genesis of the orbicules

Quartz–tourmaline orbicules, commonly referred to as "nodules", "clots", "spots", or "knots", occur in granitic rocks in other parts of the world, including England (Brammall & Harwood 1925, Ghosh 1934), France (Maitrallet 1976), Germany (Schust *et al.* 1970), Czechoslovakia (Němec 1975), South Africa (Scholz

TABLE 3. COMPOSITION OF REPRESENTATIVE TOURMALINE GRAINS IN QUARTZ-TOURMALINE ORBICULES FROM THE SEAGULL BATHOLITH

	Outer Zone						Inner Zone		Zoned Crystals			
	78A-C		166E-B		86-45C-C		166A-37	166A-40	78B		86-45	
	orange	blue	orange	blue	orange	blue	orange	orange	core	rim	core	rim
SiO_2	35.19	35.37	34.93	35.16	35.58	35.93	34.72	34.80	35.25	35.09	34.77	35.07
TiO_2	0.55	0.00	0.79	0.07	0.41	0.00	0.93	1.26	0.46	0.55	0.61	0.08
Al_2O_3	30.47	30.08	30.95	31.98	31.28	34.05	30.30	29.79	30.08	30.13	30.17	31.69
FeO*	18.21	19.57	18.11	17.76	17.34	16.40	18.53	18.06	19.15	19.49	18.31	18.19
MnO	0.09	0.12	0.09	0.13	0.08	0.14	0.08	0.03	0.08	0.07	0.11	0.05
MgO	0.34	0.16	0.21	0.04	0.74	0.04	0.38	0.53	0.28	0.28	0.57	0.17
CaO	0.04	0.04	0.04	0.04	0.06	0.00	0.05	0.05	0.04	0.05	0.02	0.02
Na_2O	2.91	2.92	2.62	2.66	2.81	1.99	2.65	2.66	2.79	2.51	2.71	2.36
K_2O	0.05	0.09	0.07	0.05	0.06	0.03	0.05	0.06	0.07	0.06	0.07	0.07
F	1.46	0.89	1.27	1.48	1.29	0.86	1.75	1.71	1.89	1.73	1.79	1.62
$-O=F_2$	0.61	0.37	0.53	0.62	0.54	0.36	0.74	0.72	0.79	0.73	0.75	0.68
Total	88.70	88.87	88.55	88.75	89.11	89.08	88.70	88.23	89.30	89.23	88.38	88.64
	Structural Formulae Based on 29 Oxygen Atoms											
B**	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Si	5.995	6.000	5.946	5.955	5.989	5.952	5.941	5.970	6.000	5.988	5.968	5.960
Al_T	0.005	0.000	0.054	0.045	0.011	0.048	0.059	0.030	0.000	0.012	0.032	0.040
Al_Z	6.000	6.000	6.000	6.000	6.000	6.000	6.000	5.994	6.000	6.000	6.000	6.000
Al_Y	0.115	0.014	0.156	0.340	0.194	0.599	0.051	0.000	0.033	0.049	0.071	0.308
Ti	0.071	0.000	0.101	0.009	0.052	0.000	0.120	0.163	0.059	0.070	0.079	0.011
Fe^{2+}	2.595	2.777	2.578	2.516	2.441	2.272	2.652	2.592	2.725	2.781	2.628	2.586
Mn	0.013	0.017	0.013	0.019	0.011	0.020	0.011	0.005	0.012	0.010	0.017	0.007
Mg	0.087	0.042	0.053	0.010	0.184	0.009	0.096	0.135	0.071	0.071	0.146	0.043
Y total	2.881	2.850	2.901	2.894	2.882	2.900	2.930	2.895	2.900	2.981	2.941	2.955
Ca	0.008	0.006	0.008	0.007	0.010	0.000	0.008	0.010	0.007	0.009	0.004	0.003
Na	0.962	0.960	0.865	0.823	0.915	0.640	0.880	0.883	0.919	0.831	0.900	0.779
K	0.010	0.020	0.015	0.012	0.012	0.007	0.011	0.014	0.015	0.013	0.016	0.015
X total	0.980	0.986	0.888	0.842	0.937	0.647	0.899	0.907	0.941	0.853	0.920	0.797
F	0.788	0.479	0.685	0.794	0.689	0.452	0.947	0.930	1.018	0.933	0.970	0.871

* Total Fe calculated as FeO.
**B assumed to be stoichiometric.

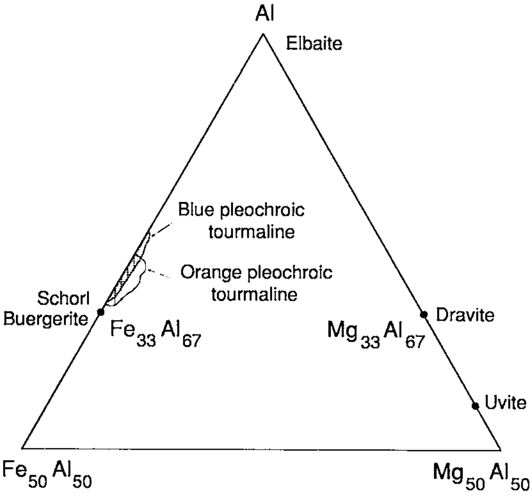


FIG. 6. Composition of the tourmaline in the quartz–tourmaline orbicules, in terms of Fe, Al and Mg.

1946), Malaysia (Hutchison & Leow 1963) and Australia (Waterhouse 1916, Tilley 1919). These occurrences have many features in common with orbicules in the Seagull batholith, such as size, shape, composition and distribution in the upper part of leucocratic, commonly peraluminous, granitic plutons. In general, two hypotheses have been proposed for the origin of quartz–tourmaline orbicules. One is that the orbicules are features of postmagmatic replacement related to hydrothermal alteration of previously crystallized granite (*e.g.*, Brammall & Harwood 1925, Schust *et al.* 1970, Němec 1975, Maitrallet 1976, Dick 1979, 1980). The other is that they are magmatic–hydrothermal features related to the separation and entrapment of aqueous, B-rich fluids within coexisting granitic magma (Waterhouse 1916, Tilley 1919, Taylor 1979).

Various aspects of the orbicules in the Seagull batholith support the magmatic–hydrothermal hypothesis. The orbicules are concentrated within granite at the top of the batholith, irrespective of the type of country rock, and decrease in abundance and tourmaline content

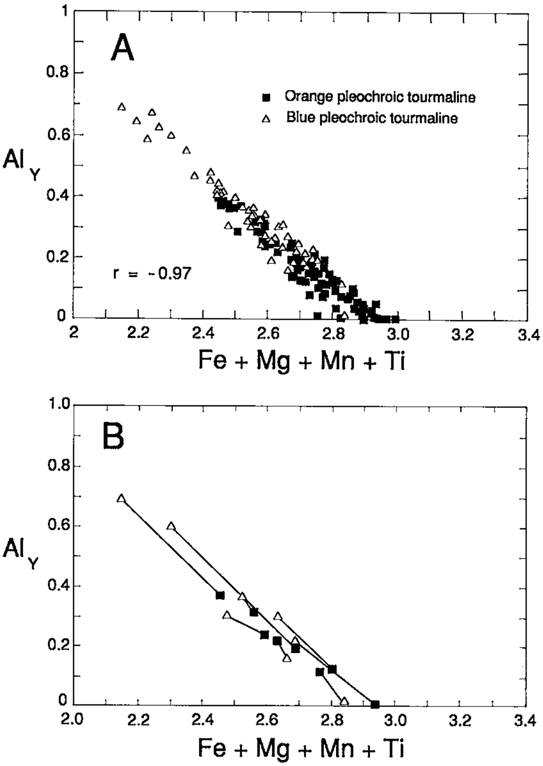


FIG. 7. Plots of Al_Y *versus* Fe + Mg + Mn + Ti for tourmaline in the quartz–tourmaline orbicules. In B, compositions of adjacent grains of orange-pleochroic and blue-pleochroic tourmaline are joined by lines.

with depth. The distribution of the orbicules, their typically spherical shape, and the absence of structural features related to their form or distribution are consistent with the separation and entrapment of aqueous, B-rich fluid in the roof zone of a crystallizing magma.

The textural features within the orbicules are probably due to the interaction of crystal-bearing melt and aqueous, B-, F- and Fe-rich fluid that was trapped as the surrounding melt solidified. Primary fluid inclusions in quartz, tourmaline and fluorite in the orbicules have salinities ranging from 8 to 42 equiv. wt.% NaCl + $CaCl_2$ (Samson & Sinclair 1992), indicating that the fluids are also Cl-rich. Initially, the melt and fluid trapped in the orbicules may have been in equilibrium, but as they cooled, disequilibrium ensued. Reaction between the aqueous fluid and minerals already crystallized within the orbicules resulted in the extensive replacement of feldspar by tourmaline in the outer zone. In some orbicules, this replacement essentially reached completion, and excess B in the fluid precipitated as crystals of tourmaline in miarolitic cavities in the center of the orbicules. In orbicules in which replacement was less extensive, an inner zone formed in which tourmaline

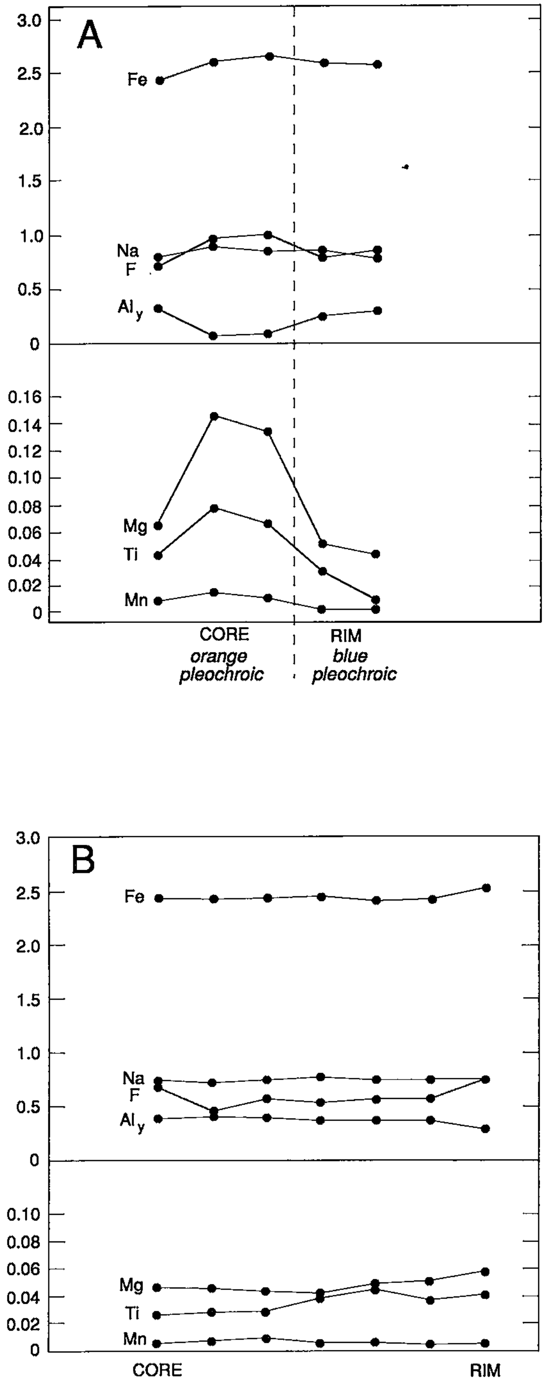


FIG. 8. Plots showing compositional variation of zoned grains of tourmaline in quartz–tourmaline orbicules. Numerical values are atoms per formula unit. In A, zones alternate between pale blue- and pale orange-pleochroic from core to rim. In B, a core consisting of orange-pleochroic zones is surrounded by dominantly pale blue-pleochroic zones.

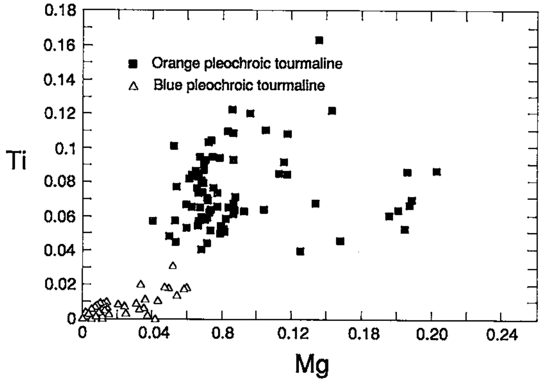


FIG. 9. Plot of Ti *versus* Mg for tourmaline in the quartz–tourmaline orbicules.

occurs as discrete grains associated with quartz, microcline and albite, and within granophyric intergrowths of quartz and K-feldspar.

The leucocratic halo that surrounds each orbicule is distinguished from the adjacent granite solely by the absence of biotite. No indication of pre-existing biotite is evident; the absence of biotite in the halo is probably due to a deficiency of Fe in the melt that crystallized around the orbicule-forming fluid. The deficiency of Fe may have been related, at least in part, to partitioning of Fe from the melt into the orbicule-forming fluid.

Relationship of the orbicules to tin mineralization

Sn occurrences associated with the Seagull batholith have been described by Gower (1952), Dick (1979, 1980), Maser (1981), Brenchley (1982), Mato *et al.* (1983), and Layne & Spooner (1986, 1988, 1991). Sn-bearing quartz veins contain cassiterite, fluorite, tourmaline, base-metal sulfide minerals, arsenopyrite, hematite, muscovite–illite, chlorite and calcite. The veins occur in fine-grained porphyritic granite near the upper contact of the batholith or in country rock immediately above the contact. Sn-bearing skarns occur in carbonate-rich rocks around the periphery of the batholith and in roof pendants. In addition to cassiterite and stannite, Sn-bearing minerals in the skarns include malayaite and nordenskiöldine (Dick 1980). Anomalous amounts of Sn also occur in garnet, epidote and amphibole (Dick 1980, Layne & Spooner 1991).

Studies of the Sn occurrences (Dick 1980, Dick & Hodgson 1983, Layne & Spooner 1986, 1988, 1991) indicate that the mineralizing fluids contained abundant B, F, Cl and Fe. The fluid associated with the formation of the quartz–tourmaline orbicules had a similar chemistry; thus a genetic relationship with the mineralizing fluids seems likely.

The association of Sn deposits with granitic rocks containing similar quartz–tourmaline orbicules occurs elsewhere in the world, for example, Cornwall (Brammall & Harwood 1925), Tasmania (Waterhouse 1916, Klominsky 1972, Taylor 1979) and Malaysia (Richardson 1939, Hutchison & Leow 1963). Furthermore, orbicules in the Heemskirk Granite in Tasmania contain cassiterite (Waterhouse 1916). The presence of quartz–tourmaline orbicules in granitic plutons elsewhere thus may indicate potential for Sn deposits, particularly if the orbicules contain anomalous concentrations of Sn.

CONCLUSIONS

Quartz–tourmaline orbicules in the Seagull batholith formed from aqueous fluid that contained abundant B, F, Cl and Fe. This fluid separated from a shallowly emplaced, crystal-rich felsic magma and was trapped in small segregations or pockets within the magma beneath the subhorizontal upper contact of the magma chamber. As the crystal-rich magma containing these pockets cooled and crystallized, the fluid reacted with the crystals. Close to the upper contact, the fluid content of the pockets was high, and microcline and albite were extensively replaced by tourmaline. In some cases, miarolitic cavities lined with crystals of quartz and tourmaline formed in the center of the orbicule. With increasing depth below the upper contact, less fluid was trapped in the crystallizing magma, and fewer orbicules formed. Furthermore, in these orbicules, replacement of microcline and albite by tourmaline was less extensive, and miarolitic cavities are absent.

The formation of quartz–tourmaline orbicules likely represents the final stage of fluid separation from the magma. Sn-rich fluids probably evolved earlier and escaped into surrounding rocks to form Sn-bearing veins and skarns; only the last of this fluid to evolve was trapped in the crystallizing magma and formed the orbicules. The anomalous Sn content of the orbicules reflects the earlier generation of Sn-rich fluids by magmatic crystallization and indicates favorable potential for associated Sn deposits.

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