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AMAZONITIC K-FELDSPAR IN GRANODIORITE AT PORTMAN LAKE, NORTHWEST TERRITORIES: INDICATIONS OF LOW $f(O_2)$, LOW $f(S_2)$, AND RAPID UPLIFT

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ABSTRACT

Amazonitic K-feldspar is locally important at the margin of a granodiorite – granite batholith in the Portman Lake area, 8 km north of the Saskatchewan – Northwest Territories border. The "amazonite"-bearing rocks are not evolved members of the suite, contrary to the usual case in occurrences of lead-bearing K-feldspar. The suite is peraluminous; the presence of sillimanite, garnet, amazonitic orthoclase and intermediate microcline, gahnite, ilmenite, epidote (inferred to be primary) and pyrrhotite suggests that galena- and sphalerite-bearing metasedimentary material was desulfurized and assimilated by normal granodioritic magma. The fugacities of oxygen and sulfur were buffered at relatively low values. Rapid uplift of the Archean batholith prevented the completion of the conversion of the magmatic K-feldspar to low microcline. The area has not been significantly reheated in the 2.6 Ga since intrusion.

Keywords: amazonitic K-feldspar, lead, granodiorite, granite, peraluminous, low $f(O_2)$, low $f(S_2)$, orthoclase, intermediate microcline, assimilation, uplift, Archean, Saskatchewan – Northwest Territories area.

SOMMAIRE

La présence du feldspath potassique à caractère amazonitique caractérise localement la bordure d'un batholite granodioritique à granitique dans la région du lac Portman, à 8 km au nord de la frontière entre Saskatchewan et les Territoires du Nord-Ouest. Les roches à feldspath amazonitique ne sont pas évoluées, comme on s'attendrait en général des hôtes de ce feldspath potassique enrichi en plomb. La suite est hyperalumineuse; la présence de sillimanite, grenat, orthose et microcline intermédiaire amazonitiques, gahnite, ilménite, épidote (que l'on considère primaire) et pyrrhotine fait penser que des roches métasédimentaires porteuses de galène et de sphalérite ont été désulfurisées et assimilées par un magma granodioritique normal. Les fugacités d'oxygène et de soufre ont été maintenues à des valeurs relativement faibles. Un soulèvement rapide du batholite archéen a entravé la mise en ordre complète du feldspath potassique, de sorte que le microcline ordonné est absent. Aucun réchauffement important n'a eu lieu dans la région au cours des 2.6 milliards d'années depuis l'intrusion.

Mots-clés: feldspath potassique amazonitique, plomb, granodiorite, granite, hyperalumineux, faibles fugacités d'oxygène et de soufre, orthose, microcline intermédiaire, assimilation, soulèvement, archéen, région de la frontière Saskatchewan – Territoires du Nord-Ouest.

INTRODUCTION

Strikingly green (amazonitic) K-feldspar occurs as an important rock-forming mineral in the border facies of a granodiorite – granite batholith in the Portman Lake area, 8 km north of the Saskatchewan – Northwest Territories border. Contrary to the usual setting for amazonitic K-feldspar, in granitic pegmatites, the Portman Lake material occurs in medium- to coarse-grained plutonic rocks that are not geochemically evolved. In common with some pegmatitic occurrences, however, gahnite and hydrothermally deposited sulfides are closely associated with the amazonitic K-feldspar. This paper focuses on the petrography, mineralogy and geochemistry of whole-rock samples from the Portman Lake suite, and expands on the preliminary report of Stevenson (1985a).

The crystallization of lead-bearing K-feldspar from anatectically derived granitic melts near the Geco (Ontario) and Broken Hill (Australia) base metal deposits was interpreted to reflect a desulfurization reaction in the assemblage (presumed to be metasedimentary) during anatexis (Stevenson & Martin 1986). Many petrographic and geochemical features of "amazonite"-bearing pegmatites are present in the more mafic Portman Lake granitic suite, indicating that sulfide–silicate equilibria may have controlled the formation of amazonitic K-feldspar there as well.

GEOLOGICAL SETTING

The granodiorite and granite at Portman Lake (Fig. 1) represent the continuation of a granodiorite – diorite complex (the so-called Northeastern Basement Complex: Koster 1962) exposed south of the Saskatchewan border. Koster & Baadsgaard (1970) described the complex as a massive synkinematic to late kinematic composite batholith that displays nebulitic structures consistent with an origin by anatexis. They obtained a date of 2370 ± 40 Ma for the suite by the K/Ar method. Banks (1980) reported a K/Ar age of 2280 Ma on biotite from the Portman Lake region. He described the area as an Archean inlier that largely escaped the effects of the Hudsonian orogeny through uplift. Stevenson *et al.* (1987) determined an age of 2589 ± 4 Ma (Pb-Pb

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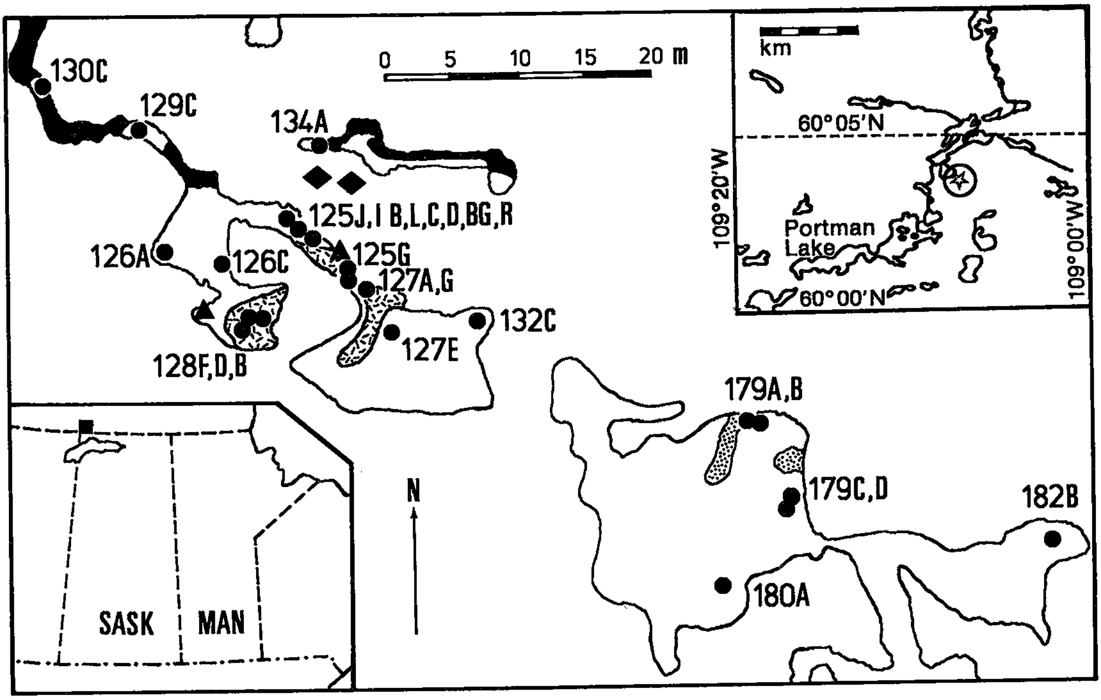

FIG. 1. Map showing the pattern of outcrops at the Portman Lake amazonitic K-feldspar locality, Northwest Territories. Lower left inset shows the location of the project area in reference to the Saskatchewan – Northwest Territories border. Inset at upper right shows the relationship of the amazonitic K-feldspar occurrence (encircled star) to Portman Lake. Sampling sites mentioned in the text are shown on the outcrop map. Map-units shown are: aplite (black), pegmatite (dot pattern), "amazonite"-bearing granodiorite and granite (stippled), and normal granodiorite and granite (unpatterned). The rest of the area (also left unpatterned) is devoid of exposures. Samples 124 and PGRAB are taken from piles of talus (indicated by two diamonds) in the "amazonite"-bearing zone. Triangles: occurrences of sulfides (not sampled for this study).

method) for the granodiorite samples from the Portman Lake area; zircon separates gave 2589^{+31}_{-20} Ma, whereas galena and amazonite gave 2610 ± 10 Ma (Pb/Pb model age).

The major lithologies near Portman Lake are coarse-grained granodiorite and granite; there are also scattered lenses of fine-grained granodiorite. Ten meters north of the amazonitic K-feldspar locality, the pluton is cut by a dyke of pink to red microcline-bearing aplite (Fig. 1). Such cross-cutting aplitic veins and dykes are common in the area.

DESCRIPTION OF THE ROCKS

The granodioritic and granitic rocks contain variable proportions of grey plagioclase (An_{30-50}), K-feldspar, quartz, biotite, garnet, hornblende and epidote, with accessory apatite, zircon, ilmenite ($Ilm_{99}Hem_1$), gahnite, sphalerite, pyrite and pyrrhotite. The plagioclase and K-feldspar grains attain 2 cm across; the texture is seriate. The K-feldspar is typically white except in an area 15 m square, where its color grades to light green, then medium green (Fig. 2).

The finer-grained lenses (up to 3 m in longest dimension) seem to grade into the coarser rocks. The presence of clots of coarse-grained granodiorite up to 1 cm across in the lenses suggests that the lenses may have formed by a pressure-quench mechanism after the bulk of the magma had crystallized. Some of these lenses contain interstitial and vein sphalerite, pyrrhotite, pyrite, chalcopyrite and galena. One of the mineralized lenses is in the "amazonite"-bearing zone, and another lies immediately to the west (Fig. 1). Galena, pyrite and pyrrhotite also occur in a vein 3 mm wide that cuts the coarse-grained granodiorite near the edge of the "amazonite"-bearing zone. In the mineralized lenses, the plagioclase is sericitized, and gahnite is a common constituent. One lens consists of quartz, muscovite, altered feldspar, and garnet that poikilitically encloses sillimanite, quartz and muscovite.

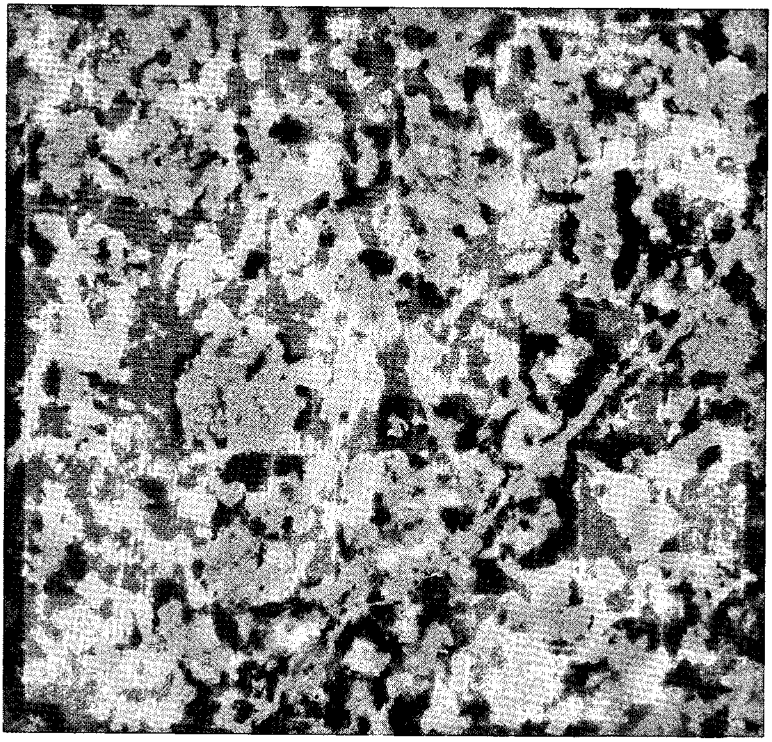

FIG. 2. Representative sample of "amazonite"-bearing granodiorite from the Portman Lake locality. Note the diagonal veinlet of pink K-feldspar that cuts the sample; the plagioclase becomes white near the vein, but the amazonitic K-feldspar does not seem affected. Scale bar: 1 cm.

TABLE 1. CHEMICAL COMPOSITION OF PORTMAN LAKE ROCKS

	124A	126A	128B	127G	PGRAB	125G	127A	128F	129C	132C	134A	180A	179D	182B	126C	179B	125J	179C	130C
SiO_2 wt.%	61.56	68.66	62.64	63.13	70.68	62.86	64.03	67.12	68.72	69.39	68.85	64.44	63.07	65.49	70.54	71.26	67.67	67.60	73.62
TiO_2	0.20	0.44	0.96	0.83	0.83	0.76	1.08	0.46	0.55	0.68	0.68	1.06	0.76	0.78	0.57	0.05	0.47	0.47	0.01
Al_2O_3	11.26	13.42	14.98	15.36	13.85	16.44	14.31	16.31	14.52	13.27	13.99	13.64	15.65	14.78	14.27	17.84	16.40	16.03	14.85
Fe_2O_3	11.05	8.89	9.20	8.60	5.87	8.61	9.60	4.24	6.52	6.46	5.52	9.40	8.58	7.06	4.95	2.87	4.11	4.22	0.77
MnO	0.10	0.07	0.14	0.15	0.46	0.14	0.15	0.06	0.12	0.11	0.11	0.14	0.13	0.13	0.20	0.10	0.06	0.07	0.03
MgO	0.26	0.29	0.89	0.78	0.31	0.81	0.82	0.65	0.48	0.58	0.81	0.86	1.11	0.77	0.45	0.34	0.77	0.56	0.18
CaO	0.16	0.25	3.20	3.25	2.86	2.93	3.22	2.78	2.47	2.49	0.81	3.80	3.34	2.98	2.45	0.32	3.37	3.03	0.11
Na_2O	1.62	1.65	2.40	2.57	2.99	2.80	2.69	2.74	3.48	2.49	2.93	2.94	2.65	2.66	2.50	0.31	2.80	2.97	3.73
K_2O	2.66	2.97	4.56	4.52	1.29	4.20	3.33	5.39	3.21	3.68	5.64	3.31	3.49	4.05	3.75	5.03	4.36	4.30	7.20
P_2O_5	0.04	0.03	0.59	0.48	0.06	0.17	0.30	0.13	0.23	0.17	0.13	0.30	0.26	0.23	0.08	0.02	0.11	0.12	0.01
BaO	0.04	0.06	0.16	0.20	0.04	0.18	0.20	0.19	0.13	0.16	0.23	0.17	0.15	0.23	0.21	0.04	0.14	0.22	0.02
SrO	0.01	0.01	0.04	0.04	0.02	0.04	0.04	0.05	0.03	0.03	0.02	0.04	0.05	0.05	0.03	0.00	0.05	0.05	0.00
LOI	4.82	3.14	0.48	0.49	0.15	0.72	0.83	0.41	0.42	0.53	1.20	0.56	1.56	0.92	0.40	2.39	0.27	1.12	0.31
total	93.78	99.88	100.24	100.40	99.41	100.66	100.60	100.53	100.88	100.04	100.92	100.66	100.80	100.13	100.40	100.57	100.58	100.76	100.84
A/CNK	1.93	2.10	1.02	1.02	1.20	1.20	1.03	1.06	1.06	1.05	1.13	0.89	1.10	1.04	1.13	2.73	1.06	1.07	1.05
Mg'	9.3	12.9	38.3	35.9	20.9	37.3	33.8	60.7	29.2	35.6	58.1	36.2	51.2	43.2	36.0	46.9	74.2	52.6	92.6
Nb ppm	-	14	17	8	4	6	19	9	50	16	36	32	20	18	9	14	9	25	2
Zr	97	191	217	177	214	240	290	184	219	304	231	368	320	240	249	113	174	202	62
Y	-	-	3	12	97	11	17	16	26	24	30	28	30	36	24	17	17	15	22
Sr	13	46	300	341	175	336	350	403	218	292	157	360	382	380	279	32	390	421	37
Rb	61	68	138	143	52	148	140	135	170	137	162	110	95	116	102	178	107	118	168
Th	35	12	8	11	32	13	-	16	11	13	5	7	5	3	20	14	15	10	2
Pb	3662	751	811	911	1962	967	269	249	38	54	79	33	53	32	192	16	52	54	92
Zn	7.5%	5100	549	438	182	806	326	160	612	401	200	173	462	208	385	62	103	163	43

Samples 124A and 126A contain 177 and 110 ppm Cu, respectively. * Total iron is expressed as Fe_2O_3. Samples 124A and 126A are sulfide-bearing; 128B, 127G, PGRAB and 125G are amazonite-bearing; 130C is a pink aplite, and the rest are various granites and granodiorites. Samples 124A, 126A, 179B, 125J and 130C are fine grained. LOI: loss on ignition. Mg': atomic ratio 100Mg/(Mg + Fe). A/CNK: atomic ratio Al/(Ca+Na+K).

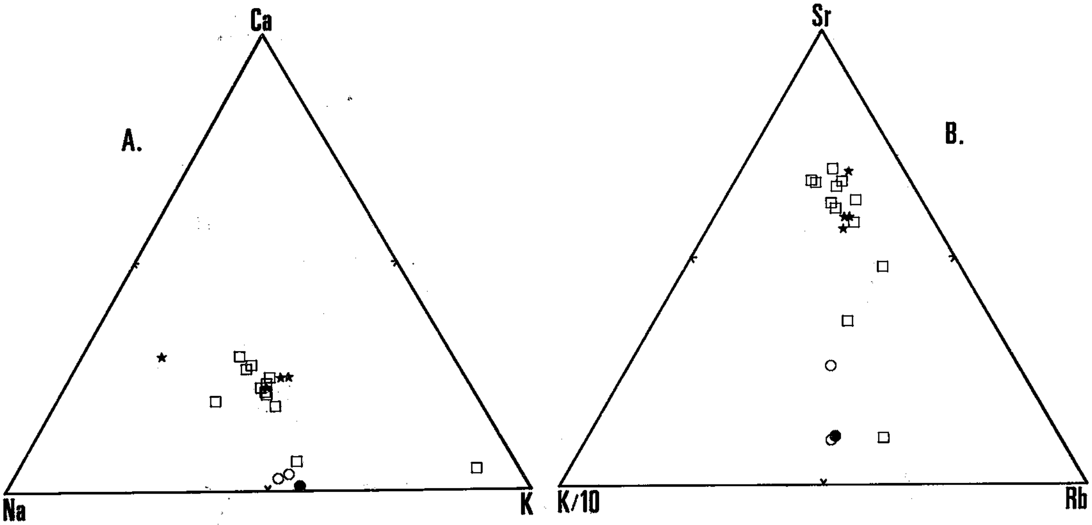

FIG. 3. Bulk compositions of rocks from the Portman Lake amazonitic K-feldspar locality. "Amazonite"-free granodiorite and granite: open squares; "amazonite"-bearing granodiorite and granite: stars; fine-grained, sulfide-bearing granite: open circles; aplite: filled circle. Compositions (atomic basis) are expressed in terms of Ca, Na and K (A), and Sr, K/10 and Rb (B).

ANALYTICAL TECHNIQUES

Major- and trace-element data were determined by X-ray fluorescence (XRF) using a Philips PW 1400 spectrometer. Analytical precision for major elements is 1% absolute; for trace elements, it is 5% absolute. Electron-microprobe data were obtained with a Cameca Microbeam MB-1 instrument using wavelength dispersion. The accelerating voltage was 15 kV, the beam current was 10 nA, and counting times on samples and standards were 10 seconds for all elements except Ba (50 s) and Pb (150 s). The following standards were used: orthoclase (Si, Al, K), andradite (Fe, Ca), MgO (Mg), $MnTiO_3$ (Mn, Ti), albite (Na), $BaSO_4$ (Ba) and vanadinite (Pb). Average levels of detection for Ba and Pb were about 900 and 400 ppm, respectively.

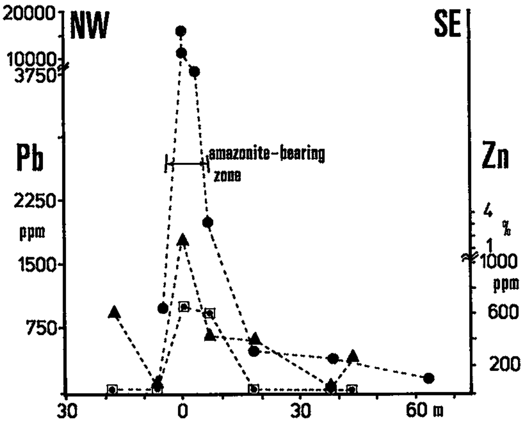

FIG. 4. Profile of Pb concentration in K-feldspar (circles) and whole-rock samples (squares), and of Zn concentration in whole-rock samples (triangles) along a NW-SE section (Fig. 1) across the "amazonite"-bearing zone.

Splits of the amazonitic K-feldspar separates prepared for the Pb-isotope study (Stevenson *et al.* 1987) were X-rayed using a Guinier–Hägg focusing camera ($CuK\alpha_1$ radiation; synthetic $MgAl_2O_4$ internal standard, *a* 8.0833 Å at room temperature). The diffraction maxima were indexed and used as input for the calculation of the cell parameters (program of Appleman & Evans 1973).

CHEMICAL COMPOSITION OF THE WHOLE ROCKS

Nineteen samples taken from the map-area (Fig. 1) were analyzed by XRF spectrometry (Table 1). Of these, four are "amazonite"-bearing, two are fine grained and sulfide-bearing, one is aplitic, and twelve consist of "amazonite"-free granite and granodiorite. The compositional diversity among these samples is illustrated in terms of Ca, Na and K (Fig. 3A). Most of the points in Figure 3A define an expected linear path of progressive depletion in Ca and subtle progressive enrichment in K. The sulfide-bearing fine-grained rocks plot on the same trend, very close to the aplite, suggesting that the fine-grained rocks are genetically related to the more calcic members of the suite. The proportion of Na and K does not seem to have been modified by the hydrothermal activity that led to sulfide mineralization. One of the evolved bulk-compositions is highly enriched in K, but is not "amazonite"-bearing. The four "amazonite"-bearing samples are relatively calcic members of the suite; three plot close to the samples of normal granodiorite, whereas a fourth is relatively depleted in potassium.

The same samples are plotted in terms of Sr, K/10 and Rb in Figure 3B, wherein all the rocks conform to a single evolutionary trend. The "amazonite"-bearing samples again plot among the geochemically least evolved members of the suite (*i.e.*, those richest in Sr).

In general, there is no discernible distinction in major-element concentrations between "amazonite"-bearing and "normal" granitic rocks. The granitic rocks are mildly to strongly aluminous, and all have Al/(Ca + Na + K) greater than 1. This feature reflects the presence of garnet and other aluminous phases. The rocks contain up to 7% normative corundum (Stevenson 1985b). The amazonitic samples resemble normal granodiorite and granite in all respects except their Pb content. Galena-free "amazonite"-bearing samples contain between 800 and 2000 ppm Pb, whereas most "amazonite"-free samples contain less than 100 ppm. This level of concentration is closer to the 6 to 56 ppm Pb in the average granite and granodiorite (Wedepohl 1978). Zn concentration is more erratic, but also shows an increase as the "amazonite"-bearing and mineralized zone is approached (Fig. 4). Zn values range from 62 to more than 500 ppm in the granodiorite. Wedepohl (1978) estimated that a typical calc-alkaline granite contains between 35 and 105 ppm Zn.

The fine-grained sulfide-mineralized samples follow the general trend in variation diagrams (Figs. 3A, B) and are depleted in Mg, Ca, P, Ti, Ba and Sr. Geochemically, these samples closely resemble the aplite, and like it, they may represent small domains of pressure-quenched residual magma.

THE COMPOSITION OF THE ROCK-FORMING MINERALS

K-feldspar

The perthitic K-feldspar varies from white to medium green over a short distance. Color appears to be homogeneous within individual grains (Fig. 2). Both the white and amazonitic K-feldspar commonly exhibits a grid pattern of albite- and pericline-twinned domains, indicative of microcline formed by inversion from a monoclinic parent. However, not all the K-feldspar is triclinic, and none of it is low microcline (see below). The K-feldspar ranges from micro- to mesoperthitic, and inclusions of quartz, plagioclase, biotite and apatite are common. There is no textural difference between white and green K-feldspar in this suite. Some samples show a subtle rapakivi texture.

Grains of K-feldspar were analyzed using an electron microprobe (Table 2). The K-feldspar ranges from Or_{88} to Or_{94}; major-element concentrations in amazonitic and white K-feldspar do not differ. The data illustrate that at a nearly constant Or content Pb concentration covaries with color. The white K-feldspar contains less than 300 ppm Pb as a rule, whereas the amazonitic K-feldspar may exceed 14,800 ppm Pb. The higher the Pb content, the more intense the green color (*cf.* Foord & Martin 1979). There are, however, exceptions: the white K-feldspar from the fine-grained mineralized lens adjacent to the amazonite-bearing zone contains the greatest amount of Pb, approximately 1.60%. The Pb content of individual grains of K-feldspar is homogeneous. Reflected-light microscopy, X-ray diffraction,

TABLE 2. CHEMICAL COMPOSITION OF K-FELDSPAR FROM PORTMAN LAKE, N.W.T.

	179A	180A	182B	132C	125I	127A	128D	128F	128B	127G	124D	124E	125G	125D	125L	125C	125R	125BG	124A
SiO_2 wt.%	63.76	65.16	64.56	63.88	63.91	62.15	63.84	64.70	64.52	64.39	63.80	62.81	63.93	64.12	63.01	64.78	64.10	63.43	63.10
Al_2O_3	19.01	19.02	18.81	18.93	19.06	18.80	19.01	18.76	18.73	19.02	19.30	19.26	19.27	18.87	19.35	19.07	19.34	19.24	19.29
FeO*	0.02	-	0.01	0.05	-	-	0.02	0.03	0.03	0.02	-	-	0.03	0.03	0.11	trace	0.02	0.01	0.03
MgO	-	0.11	0.02	-	-	-	0.01	0.01	0.02	0.01	-	-	-	0.01	0.02	0.01	0.01	-	-
CaO	0.03	0.02	0.02	0.02	0.01	trace	0.01	0.02	0.01	0.02	0.03	-	0.01	0.02	0.07	0.02	0.04	0.15	0.03
Na_2O	0.92	0.92	0.58	0.87	0.95	0.86	0.81	0.83	0.86	0.98	1.14	0.87	0.76	1.18	1.24	0.76	0.68	0.95	0.84
K_2O	15.78	15.05	14.79	15.91	15.96	15.83	15.18	15.02	15.98	15.24	14.16	14.32	15.26	14.33	15.03	13.85	13.55	14.74	15.63
BaO	0.81	0.70	1.00	1.01	0.68	1.51	0.99	0.82	0.65	1.04	1.01	0.80	0.92	0.82	0.74	0.45	0.60	0.15	0.26
PbO	0.05	0.02	0.02	0.05	0.11	0.04	0.25	0.37	0.24	0.21	0.73	1.59	0.40	0.57	0.43	1.26	1.07	1.72	1.36
total	100.38	101.00	99.81	100.72	100.68	99.19	100.12	100.56	101.04	100.93	100.17	99.65	100.58	99.95	100.00	100.20	99.41	100.39	100.54
Pb ppm	420	215	175	465	1005	365	2365	3460	2235	2005	6800	14800	3700	5280	3980	11655	9975	15950	12645
Ab mole %	8.1	8.5	5.6	7.6	8.3	7.6	7.5	7.7	7.5	8.9	10.9	8.4	7.0	11.1	11.0	7.7	7.1	8.8	7.5
Or	91.6	91.3	94.2	92.2	91.6	92.4	92.4	92.1	92.4	90.9	88.8	91.6	92.9	88.7	88.3	92.1	92.5	89.7	92.2
An	0.3	0.2	0.2	0.2	0.1	0	0.1	0.2	0.1	0.2	0.3	0	0.1	0.2	0.7	0.2	0.4	1.5	0.3

Average composition of K-feldspar determined by electron microprobe. Details concerning operating conditions and standards are recorded by Stevenson (1985b). * Total iron is expressed as FeO. Samples 125BG and 124A are taken from the mineralized zone. Color of the samples: 179A, 180A, 182B, 132C, 125I, 127A, 125BG and 124A are white, 128D, 128B, 127G are light green, and 128F, 124D, 124E, 125G, 125D, 125L, 125C and 125R are medium grey-green.

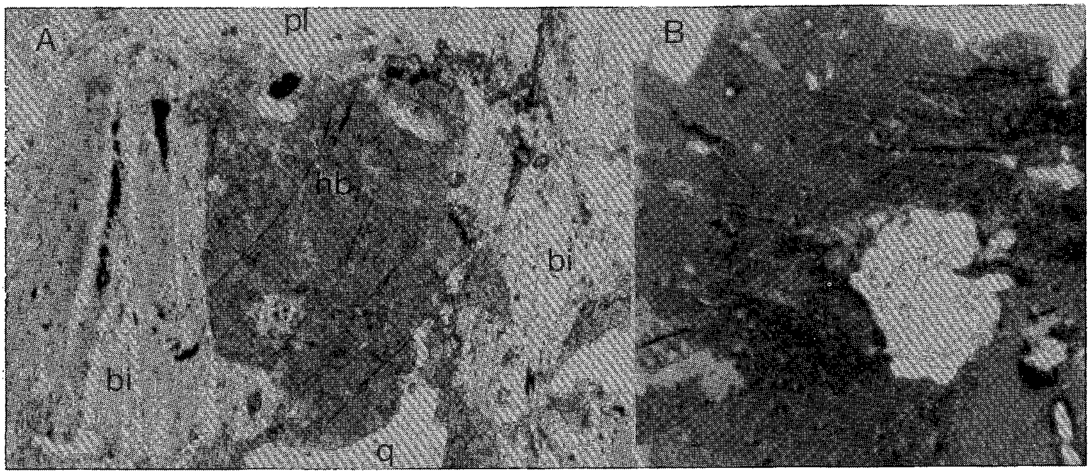

FIG. 5. A. Textural relationship among biotite (bi), hornblende (hb, 0.4 mm across), quartz (q) and plagioclase (pl). Epidote grains are enclosed in biotite, at or near the interface with hornblende. Sample 182B, plane light. B. Composite "grain" of quartz (core), apatite (prismatic crystal that abuts against the quartz core), partly mantled by allanite, then by epidote. The aggregate, which measures 0.3 mm across, is enclosed in biotite (dark). Sample 127E, plane light.

and electron-microprobe studies show that galena is not present in the amazonitic K-feldspar.

The K-feldspar in the Portman Lake suite contains large amounts of barium (up to 1.2% BaO: Table 2). Ba concentration may be as high in amazonitic as in white K-feldspar.

TABLE 3. BIOTITE AND AMPHIBOLE COMPOSITIONS, SAMPLE 182B, PORTMAN LAKE, N.W.T.

	1	2	3
SiO_2 wt.%	33.66	38.80	40.36
TiO_2	2.55	-	0.92
Al_2O_3	15.69	15.77	12.90
FeO*	30.66	27.55	27.23
MnO	0.53	0.71	0.68
MgO	4.44	1.76	2.84
CaO	0.13	10.87	11.37
Na_2O	0.17	1.32	1.22
K_2O	7.89	1.46	1.43
Total	95.72	98.24	98.95
Si †	5.408	6.129	6.323
^{IV}Al	2.592	1.871	1.677
^{VI}Al	0.379	1.065	0.704
Ti	0.308	0.0	0.109
Mg	1.063	0.415	0.662
Fe^{2+}	4.120	3.639	3.567
Mn	0.072	0.095	0.091
K	1.617	0.295	0.285
Na	0.052	0.405	0.371
Ca	0.022	1.839	1.909
Total	15.633	15.753	15.698

† Cation assignments based on 22 oxygen atoms for the biotite, 23 for amphibole. * Total iron expressed as FeO. Column 1: biotite; columns 2 and 3: amphibole grain, core and rim, respectively. More data are provided by Stevenson (1985b).

Plagioclase

Like the K-feldspar, the plagioclase is seriate, unzoned, and subhedral to anhedral. It also occurs in myrmekitic intergrowths adjacent to K-feldspar grains. Andesine compositions are typical for the coarse-grained rocks. The plagioclase contains little or no Fe, Mg or Ba, but Pb content ranges from 0 to 6000 ppm and seems to follow the same trend as in the K-feldspar; the plagioclase in the amazonitic K-feldspar zone may contain thousands of ppm Pb, whereas normal granodiorite or granite contains little or no Pb. The high-Pb plagioclase is not anomalously colored. The Pb contents were found to be inconsistent; in particular, the albite lamellae in amazonitic perthite may or may not contain appreciable concentrations of Pb.

Ferromagnesian minerals

Biotite ($Annite_{57-82}$) is the predominant ferromagnesian mineral. It encloses *hornblende* (ferrotschermakite) in the coarse-grained rocks (Fig. 5A). The biotite ranges from less than 1 mm across in the fine-grained lenses to 15 mm in the coarser varieties. Hornblende in the granodiorite rarely exceeds 5 mm across; it abuts against quartz, is anhedral, and may show epidote at its interface with enclosing biotite (Fig. 5A). Hornblende is absent in the amazonitic K-feldspar zone. Zircon, apatite and ilmenite are commonly included in both biotite and hornblende, whereas epidote (± allanite), pyrite, pyrrhotite and gahnite are less common. The chemical compositions of biotite and hornblende in specimen 182B are reported in Table 3. The total Al content of the hornblende in the rim of the zoned grain analyzed suggests a confining pressure of 8 kbars, according to the empirical geobarometer of Hammarstrom & Zen (1986).

Garnet occurs as reddish subhedral grains up to 3 mm across. Some are poikilitic, fractured, or skeletal. Commonly included are ilmenite, biotite, quartz and apatite; less common are pyrite, pyrrhotite, sphalerite, gahnite, sillimanite and muscovite. These inclusions are found in samples transitional between the coarse- and fine-grained zones. Garnet rarely comprises more than 3% of the rock, and is absent from the mineralized zone. The compositional range observed is 70–87% Alm, 5–22% Sp, 2–12% Py and 0–4% Gr (Stevenson 1985b). Garnet grains typically have an Fe-rich core and a Mn-rich rim.

Epidote

Three types of occurrence are found in this suite. Epidote is common in alteration assemblages along with muscovite in some of the more altered rocks in the suite; epidote also occurs in rare late calc-silicate veins, and in several samples of unaltered, coarse-grained biotite and biotite–hornblende granodiorite, where it is included in biotite, hornblende, and locally in plagioclase. The included epidote grains are between 1 to 2 mm across and subhedral to euhedral. A rolling extinction suggests compositional zoning. An overgrowth of epidote on allanite (Fig. 5B) is common. Epidote preferentially appears in biotite at its contact with anhedral hornblende (Fig. 5A). Epidote is subhedral to anhedral in contact with plagioclase, and some appears intergrown with it.

In third type of occurrence, epidote is found in unaltered samples that show no evidence of veining. It resembles the examples of primary epidote of Zen & Hammarstrom (1984). This occurrence obeys the criteria of Zen & Hammarstrom (1988) for a primary origin. Naney (1983) determined that epidote has a field of stability above the solidus of one granodioritic bulk-composition at $P(\mathrm{H_2O}) = P_{\mathrm{total}} = 8$ kbars, but not at 4 kbars.

Spinel and sulfides

Fe- and Zn-bearing spinel (*i.e.*, hercynite–gahnite solid solution) is found in the mineralized lenses and in the transition zone between these lenses and the coarse-grained host rock. The grains typically are green, less than 1 mm across, subhedral and subrounded. Common associations in the transition zone are biotite–ilmenite–spinel, garnet–ilmenite–spinel, and spinel–quartz. In the mineralized lenses, where there is much muscovite and sericite, the spinel may be associated with muscovite, sphalerite, pyrite, pyrrhotite and quartz. The sulfides typically enclose the spinel, indicating that it is an earlier phase. The spinel is ferroan gahnite that ranges from $\mathrm{Hc_{40.4}Gh_{52.3}Spl_{7.3}}$ to $\mathrm{Hc_{64.1}Gh_{30.3}Spl_{5.6}}$ (Hc hercynite, Gh gahnite, Spl spinel *sensu stricto;* Stevenson 1985a,b).

In the mineralized lenses, pyrite–pyrrhotite–sphalerite assemblages are commonly set in swirls of fine-grained white mica (Stevenson 1985a, Fig. 4.3). Small amounts of galena and chalcopyrite are also present. Pyrite cubes locally are mantled by pyrrhotite and sphalerite. In areas transitional between the coarse-grained rock and a mineralized lens, assemblages of sphalerite–garnet and pyrrhotite–garnet are present.

TABLE 4. CELL PARAMETERS AND INDICATORS OF COMPOSITION AND DEGREE OF Al-Si ORDER, K-FELDSPAR FROM PORTMAN LAKE, N.W.T.

	a	*b*	*c*	α	β	γ	*V*	*a**	*b**	*c**	α*	β*	γ*	$t_1$0	Or	Pb	
132C	8.5751	12.9563	7.2157	90.471	115.926	88.350	720.68	0.129717	0.077215	0.154098	90.277	64.076	91.605	0.839	98.1	465	IM
	0.0015	0.0031	0.0013	0.027	0.015	0.033	0.20	0.000027	0.000019	0.000025	0.024	0.015	0.031		93.7		
132C	8.6089	12.9553	7.2075	90	115.896	90	723.15	0.129124	0.077188	0.154230	90	64.104	90	0.458	96.7	465	OR
	0.0041	0.0038	0.0025		0.032		0.31	0.000056	0.000022	0.000038		0.032			100.7		
127A	8.5764	12.9605	7.2128	90.617	115.927	88.146	720.66	0.129710	0.077198	0.154159	90.216	64.078	91.762	0.868	97.6	363	IM
	0.0028	0.0047	0.0028	0.058	0.032	0.048	0.35	0.000044	0.000028	0.000055	0.053	0.032	0.041		93.7		
127G	8.5788	12.9646	7.2131	90.051	116.047	89.722	720.75	0.129746	0.077134	0.154310	90.078	63.953	90.284	0.524	97.5	1510	IM
	0.0009	0.0017	0.0007	0.015	0.008	0.012	0.11	0.000011	0.000010	0.000012	0.014	0.008	0.012		93.9		
PLB	8.5832	12.9735	7.2106	90	116.014	90	721.58	0.129642	0.077080	0.154320	90	63.986	90	0.449	96.0	7000	OR
	0.0017	0.0027	0.0013		0.015		0.19	0.000025	0.000016	0.000025		0.015			96.2		
128B	8.5673	12.9607	7.2174	90.588	115.964	88.411	720.24	0.129870	0.077186	0.154109	90.120	64.041	91.481	0.827	99.1	2544	IM
	0.0020	0.0034	0.0018	0.031	0.023	0.029	0.26	0.000036	0.000020	0.000045	0.032	0.023	0.031		92.5		
124D	8.5678	12.9655	7.2118	90.246	115.964	89.172	720.19	0.129832	0.077136	0.154229	90.130	64.037	90.801	0.637	99.0	6800	IM
	0.0006	0.0010	0.0006	0.013	0.006	0.010	0.08	0.000011	0.000006	0.000013	0.013	0.006	0.010		92.4		
P-GRAB	8.5716	12.9733	7.2102	90	116.046	90	720.35	0.129853	0.077081	0.154371	90	63.954	90	0.443	98.6	8000	OR
	0.0007	0.0016	0.0007		0.007		0.11	0.000011	0.000010	0.000013		0.007			92.9		
125R2	8.5699	12.9647	7.2148	90.387	115.945	88.619	720.59	0.129803	0.077156	0.154141	90.242	64.056	91.347	0.767	99.8	9974	IM
	0.0013	0.0016	0.0011	0.016	0.014	0.020	0.14	0.000022	0.000009	0.000020	0.016	0.014	0.020		91.9		
125B	8.5741	12.9564	7.2128	90.455	115.971	88.256	720.01	0.129790	0.077219	0.154217	90.343	64.031	91.718	0.849	95.7	15950	IM
	0.0017	0.0022	0.0014	0.025	0.018	0.026	0.21	0.000026	0.000013	0.000033	0.023	0.018	0.025		91.9		
125B	8.5931	12.9739	7.2126	90	116.116	90	722.01	0.129605	0.077078	0.154410	90	63.884	90	0.451	98.0	15950	OR
	0.0016	0.0023	0.0009		0.015		0.17	0.000031	0.000014	0.000021		0.015			97.5		

Specimens 132C, 127A, 125R2 and 125B consist of white K-feldspar; the others are amazonitic. OR orthoclase, IM intermediate microcline. Lead concentration quoted in ppm. Units: *a*, *b*, *c* in Å, *V* in Å³, *a**, *b**, *c** in $Å^{-1}$, α, β, γ, α*, β*, γ* in degrees Or in %. Or quoted on first line is Or(*b***c**), calculated using the expression of Blasi (1977). Or content quoted on second line is Or(*V*), calculated using the expression of Kroll & Ribbe (1983) for intermediate degrees of Al-Si order. The proportion of Al in the $T_1$0 position is given by $t_1$0, which has a value of 1 in low microcline and 0.25 in high sanidine. Sample PLB was provided by Dr. H.H. Bostock, Geological Survey of Canada.

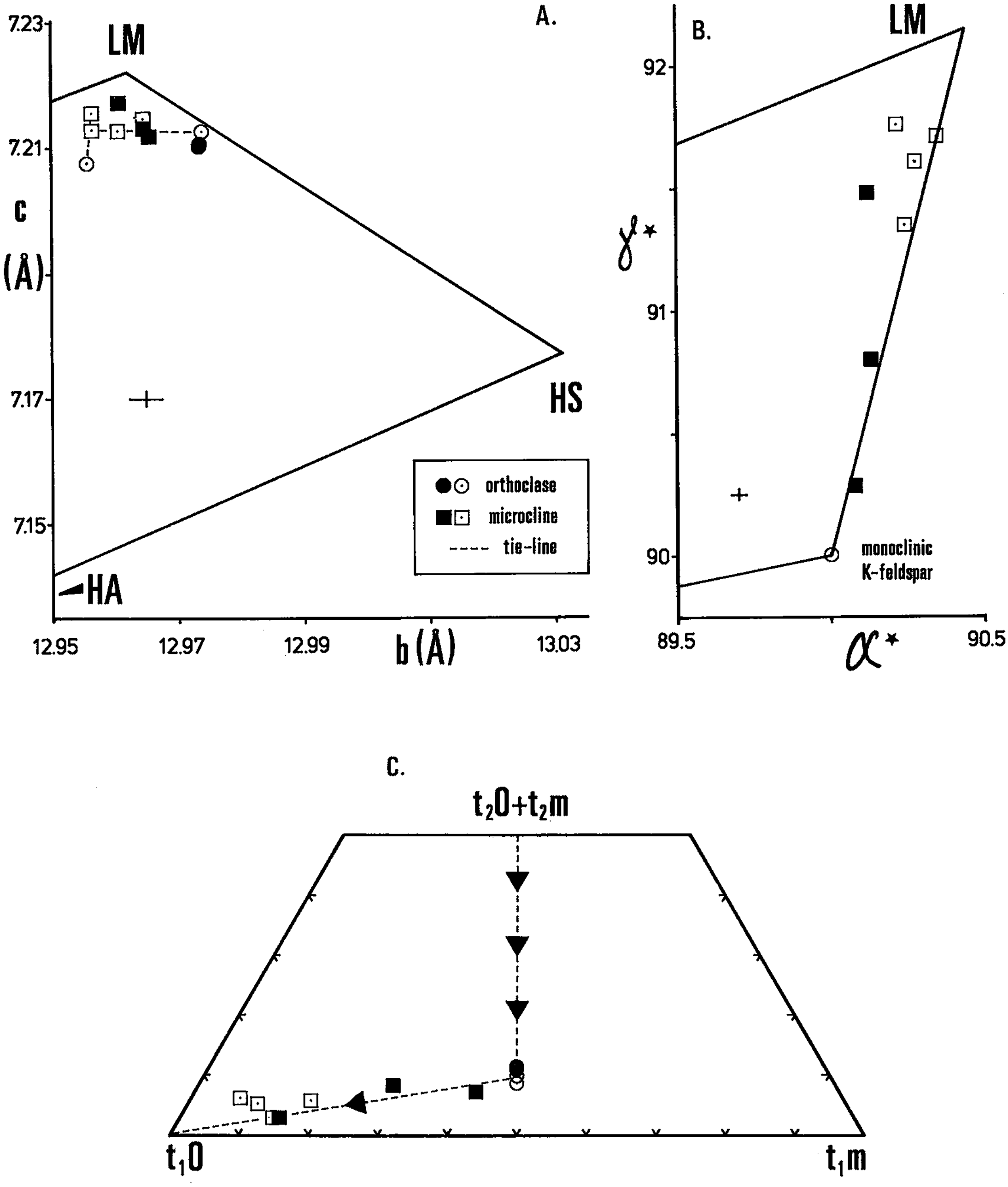

FIG. 6. A. A portion of the b - c quadrilateral showing the distribution of the orthoclase and microcline data-points. Symbols: LM low microcline, HS high sanidine, HA high albite. The error bars in b and c represent an average standard error for all the samples plotted. The standard errors are provided by the program of Appleman & Evans (1973). Open symbols: white K-feldspar; black symbols: amazonitic K-feldspar. Tie lines join coexisting orthoclase and intermediate microcline in the same 1-mm^3 sample selected for analysis. B. A portion of the α^* - γ^* plot showing the location of the microcline data-points with respect to the LM corner. The error bars in α^* and γ^* represent an average standard error for all the samples plotted. The standard errors are provided by the program of Appleman & Evans (1973). C. Part of the triangular plot t_1O - t_1m - (t_2O + t_2m), showing the distribution of data points along a two-step path of ordering (dashed line with arrows). In all three diagrams, note the absence of low microcline, which is expected in mesozonal felsic plutonic rocks, especially in those of Archean age.

X-RAY-DIFFRACTION STUDY

Nine K-feldspar concentrates were chosen for an X-ray-diffraction study: six are amazonitic, two are white, low-lead K-feldspar, and one is a lead-rich white K-feldspar from a mineralized zone. Cell parameters calculated using the least-squares program of Appleman & Evans (1973), indicators of degree of Al–Si order, and Pb contents are listed in Table 4.

Of the nine samples, two contain orthoclase only, two contain both orthoclase and structurally intermediate microcline, and five contain intermediate microcline only. The structural conversion to low microcline, expected below 400°C, has not occurred in the Portman Lake suite.

Plots of b *versus* c, α^* *versus* γ^* and $t_1O - t_1m - (t_2O + t_2m)$ (Figs. 6A, B, C) reveal that not all the intermediate microcline samples possess the same degree of Al–Si order. The range is from nearly fully ordered (near low microcline) to unusually disordered intermediate microcline (near orthoclase). The orthoclase also shows a range in degree of Al–Si order. The samples seem to have been quenched at various points along a two-step path of ordering (Fig. 6C). Pb concentrations are not correlated with Or (mol. %) calculated from the b^* and c^* values, indicating negligible modification of the structure due to the incorporation of lead.

There are very few documented occurrences of coexisting intermediate microcline and orthoclase; Mergoil-Daniel & Chevalier (1984), Akizuki (1981), Martin & Bowden (1981) and Hibbard (1979) are relevant references. The quality of the cell refinements reported here precludes the possibility that the intermediate microcline is simply a mechanical mixture of low microcline and orthoclase. Equally unlikely is the possibility that orthoclase and intermediate microcline coexist as separate grains in a single hand-specimen. Where the conversion from the monoclinic state to the triclinic state has begun, all the grains of feldspar in a given sample are likely to be at the same stage, *i.e.*, equally affected by the fluid phase that was present to catalyze the conversion. Although the core and rim of feldspar grains were not sampled separately in this study, a zonation in degree of Al-Si order (orthoclase predominant in the core, intermediate microcline in the rim), as found by Hibbard (1979), is possible, but is considered unlikely in view of the absence of visible differences between core and rim.

The amazonitic K-feldspar at Portman Lake exhibits as much variability in degree of Al-Si order as does the rest of the K-feldspar population. Both amazonitic orthoclase and amazonitic intermediate microcline are found in the suite; each undoubtedly contains inactive lead, as well as active lead, which is associated with a defect and molecular water, and is responsible for the color (Hofmeister & Rossman 1985). Thus the intensity of the color is not a function of total lead content. What about the relationship between degree of Al-Si order and lead content? The amazonitic K-feldspar may be as ordered as the most ordered white intermediate microcline, regardless of total lead concentration. The lead content thus does not seem to exert a control on the degree of Al-Si order attained by the K-feldspar; the degree of order apparently reflects instead cooling history of the suite and availability of an aqueous medium (see below). Hofmeister & Rossman (1985) proposed the opposite point of view, but this was based on a comparison of lead-rich orthoclase and lead-poor microcline from very different geological contexts.

DISCUSSION

The presence of ilmenite, gahnite and garnet with sillimanite inclusions, the development of nebulitic structures reported by Koster & Baadsgaard (1970), and the metaluminous to peraluminous character of the bulk compositions, as reflected by normative corundum, all suggest that the Portman Lake suite could have been derived by the ultrametamorphism of a metasedimentary precursor (White & Chappell 1977). There are no obvious metasedimentary parental rocks exposed in the area.

The suite also has points in common with ilmenite-series granites (Ishihara 1981). There is a complete lack of magnetite; the accessory minerals include pyrrhotite, garnet and hornblende. Ilmenite-series suites typically are associated with sulfide-free Sn and W mineralization, with only minor galena and sphalerite. The scarcity of galena and sphalerite and the presence of Pb-bearing K-feldspar are consistent with Ishihara's generalizations. However, concentrations of Sn or W are not known in the area.

In the petrogenetic models of White & Chappell (1977) and Ishihara (1981), the process of crystal fractionation is not attributed an important role. Rather, the bulk compositions of the magma are considered to have been generated by anatectic reactions, and largely to reflect the subtleties of the bulk composition of the parent material. Whole-rock compositions indicate that Pb and Zn are enriched across the suite, which would imply that the metasedimentary material that underwent partial melting most likely contained galena and sphalerite. A net loss of sulfur is expected upon anatexis, as argued by Stevenson & Martin (1986), leading to the incorporation of Pb and Zn in the melt phase. If this melt becomes saturated in water, it is also possible that Pb and Zn can partition strongly into the aqueous phase and lead to local anomalous concentrations in cupolas, where bubbles could accumulate. In addition, some Pb and Zn could originate by local contamination of the magma by the incorporation of wallrock.

However, careful mapping in the area did not reveal any appropriate wallrock, let alone wallrock that contains base-metal sulfides. Nor do the lead isotope data (Stevenson *et al.* 1987) support this proposal.

The concentration of Pb and Zn in a silicate and an oxide mineral, respectively, suggest unusual values of some of the intensive parameters *P, T*, $f(O_2)$ and $f(S_2)$. A low fugacity of oxygen seems required to account for an ilmenite-series granite (Ishihara 1981), possibly a reflection of the presence of carbon in the metasedimentary rocks inferred to have been subjected to anatexis. The same process would ensure that whatever sulfur is in the melt would remain as HS^-. Lead-isotope ratios (Stevenson *et al.* 1987) indicate that the Pb in the sulfide and silicate phases in the Portman Lake suite shares the same origin.

The temperature of the system can be evaluated by biotite–garnet geothermometry (Ferry & Spear 1978). Stevenson (1985b) determined *T* to be in the range 559°C (1 kbar) to 623°C (10 kbar). From the presence of primary epidote, a lower limit of pressure close to 8 kbars seems to be indicated (Zen & Hammarstrom 1984, Naney 1983); the experimental data-base in the interval of pressure between 5 and 8 kbars should be explored to evaluate the threshold pressure at $P(H_2O) = P_{total}$ at which epidote could crystallize from a magma. A confining pressure of 8 kbars, also consistent with the hornblende geobarometer of Hammarstrom & Zen (1986), would indicate a temperature of 613°C for the biotite - garnet assemblage, in agreement with the water-saturated solidus derived for similar Fe- and Mg-bearing granodiorite compositions (Naney 1983).

The formation of the fine-grained lenses at Portman Lake may indicate that bubble-bearing, evolved pockets of magma underwent rapid decompression, leading to escape of a volatile phase, forced nucleation and, hence, a fine-grained rock. The mechanism is that advocated for the formation of aplite in pegmatitic systems by Jahns & Tuttle (1963). The local reduction in pressure would have promoted the release in sulfur from the remaining melt to the fluid phase. We appeal to this release to explain the appearance of disseminated sulfides coexisting with silicate and oxide phases in the transition zone to the mineralized lenses. Gahnite appears with garnet and biotite, pyrrhotite has increased, and pyrite (early) is mantled by pyrrhotite and sphalerite. Sphalerite–garnet and pyrrhotite–garnet assemblages are also developed. The occurrence of pyrrhotite and sphalerite without pyrite indicates a fugacity of sulfur below that of the pyrite–pyrrhotite boundary. Spry & Scott (1986) showed that the assemblage sphalerite–garnet is restricted to low $f(S_2)$ and low $f(O_2)$ conditions (also indicated by the persistence of ilmenite in this zone).

The transition zone preserves a record of low $f(S_2)$ conditions. As fluid flow continued, the $f(H_2S)$ and $f(S_2)$ eventually increased as the system sealed itself. This led to the deposition of sphalerite, pyrite, pyrrhotite, galena and chalcopyrite, either disseminated as interstitial grains or in veinlets, in the mineralized lenses. Lower-temperature deposition of galena in a late vein in the granodiorite is likely due to the slightly greater solubility of Pb over Zn expected in hydrothermal fluids (Barnes 1975).

Once the $f(S_2)$ increased, the aqueous fluids probably began scavenging Pb from the feldspars. The magmatic K-feldspar may have lost some of its Pb during the ordering reaction (Stevenson & Martin 1986). Note that not all of the structurally bound Pb in the K-feldspar is equally mobile: the so-called "inactive" Pb can be expected to be present in a plagioclase-type substitution, and another part, called "active", is associated with molecular water lodged in a defect generated by the scheme of substitution $Pb^{2+} + \square (H_2O) = 2K^+$, the scheme that is required for the absorption of light that gives the characteristic greenish color of the amazonitic K-feldspar (Hofmeister & Rossman 1985). The Pb that is electrostatically balanced by the substitution of Al for Si is likely to be less easily removed by a circulating fluid phase. The Pb-bearing white K-feldspar may thus contain a fraction of the Pb that it once contained as amazonitic K-feldspar.

The plagioclase can contain significant amounts of Pb (except in the mineralized zone, where the Pb was probably released into the fluid medium as a result of thorough recrystallization during the sericitic alteration). The slightly more radiogenic Pb of the galena with respect to the amazonitic K-feldspar (Stevenson *et al.* 1987) presumably is a consequence of this scavenging process, in which Pb was leached from various hosts and mixed in solution.

The above interpretation is consistent with the regional context. The area sits near the center of an Archean inlier (Banks 1980) within the Churchill Province, which was largely reworked during the Hudsonian Orogeny (1800–1900 Ma). The inlier preserved its Archean age through a major uplift that carried the pluton to a shallower crustal level. The tectonic uplift conceivably may have occurred before final crystallization of the magma, and may have caused the fracturing that led to the formation of the fine-grained facies.

The inferred tectonic uplift is also held responsible for the interruption in the ordering reaction in the K-feldspar. The metastable persistence of orthoclase and intermediate microcline is very unusual in an Archean terrane, and indicates (i) that the rate of regional cooling to a temperature below the 400°C isotherm (at which low microcline should have nucleated) was rapid, and (ii) the area was not subjected to important reheating since then. Experiments designed to leach Pb isotopes from one whole-rock sample (132C) revealed evidence for a remobilization of the isotopes at 2475 ± 13 Ma (Stevenson *et al.* 1987). This sample contains a mixture of orthoclase and intermediate microcline, both metastable intermediate states in the transformation of a magmatic K-rich feldspar (sanidine solid-solution) to low microcline; thus we contend that the 2475 Ma event, which may be correlated with the intrusion of leucogranitic material that led to the aplitic dykes, was brief and did not lead to important reheating of the crust in the region. The lack of re-equilibration in the feldspar assemblage accounts for the unusual reliability of the K-Ar system to date these Archean rocks.

Our proposal, involving crustal rocks of sedimentary origin, their participation in anatectic reactions at an approximate depth of 25 km, followed by rapid uplift of the plutonic mass, possibly even before its final crystallization, without ensuing regional reheating of any significance, is not unique as a scenario for emplacement of a granodioritic body. However, the fact that the scenario pertains to rocks roughly 2.6 Ga old implies that the overall thermal and compositional structure of the crust in Archean times may have closely ressembled what it is now. Furthermore, if the sequence of events proposed were to occur on a broad scale, "fertile" detritus containing Pb-rich, relatively disordered K-feldspar and sodic plagioclase can be expected. Metasedimentary rocks that bear such detritus could release Pb at low temperatures as a result of the ordering of Al and Si in the K-feldspar, and albitization and Al-Si ordering in the sodic plagioclase. We consider such reactions to be potentially important in the source beds related to Mississippi-Valley-type deposits.

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