Canadian Mineralogist
Vol. 19, pp. 147-161 (1981)

ANATECTIC PERALUMINOUS GRANITES FROM THE CARMANVILLE AREA, NORTHEASTERN NEWFOUNDLAND

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Abstract

In the Carmanville region granitic plutons emplaced within mafic hornblendic rocks are relatively mafic and contain hornblende. Those emplaced within pelitic rocks are peraluminous and contain muscovite, locally with garnet and andalusite. Those emplaced in quartzofeldspathic gneisses are metaluminous and contain biotite with little or no muscovite. Pelitic rocks around the peraluminous plutons exhibit a sequence of metamorphic and metasomatic changes leading to the development of peraluminous granitoid rocks. Relations between deformation and metamorphism, together with distribution of the assemblage quartz–muscovite–andalusite–K-feldspar, show that the peak temperatures in the pelitic rocks reached minimum melting conditions for quartzofeldspathic compositions. Major-element geochemistry shows that the plutons could be derived by advanced partial melting of the country rocks. There is no evidence for derivation from a more mafic parent. The composition of the granitoid segregations in the country rocks not only is consistent with the local metamorphic grade, but approaches that of the plutons, although the segregations are more peraluminous. The plutons were probably generated by radiogenic heat in a tectonically thickened sedimentary pile. The melt compositions, originally slightly peraluminous owing to their derivation from peraluminous sediments, were modified by the addition and subsequent escape of strongly peraluminous aqueous solutions derived from the country rocks. The plutons represent not only products of anatectic melting and subsequent differentiation, but also the interaction of melt, host rock and aqueous solution.

Keywords: peraluminous granites, crustal melting, anatexis, northeastern Newfoundland. Davidsville Group.

Sommaire

Dans la région de Carmanville (Terre-Neuve), les massifs granitiques intrusifs dans les roches mafiques à hornblende sont relativement mafiques et contiennent eux aussi de la hornblende. Ceux qui sont intrusifs dans des roches pélitiques sont hyperalumineux; ils contiennent de la muscovite accompagnée localement de grenat et d'andalousite. Ceux qui se trouvent dans les gneiss quartzo-feldspathiques sont méta-alumineux et contiennent de la biotite, mais peu ou pas de muscovite. Les roches pélitiques autour des massifs hyperalumineux montrent une suite de transformations métamorphiques et métasomatiques qui mènent au développement de roches granitoïdes hyperalumineuses. Les relations entre déformation et métamorphisme, ainsi que la distribution de l'assemblage quartz–muscovite–andalousite–feldspath potassique, montrent que la température des roches pélitiques a atteint le point de fusion minimum des compositions quartzo-feldspathiques. D'après la géochimie des éléments majeurs, les massifs pourraient résulter d'une fusion partielle des roches encaissantes. Aucune indication génétique ne les relie à un magma plus mafique. La composition des ségrégations granitoïdes dans les roches encaissantes n'est pas seulement compatible avec le stade de métamorphisme régional; elle est proche de celle des massifs, quoique plus alumineuse. Les massifs ont probablement été formés par accumulation de chaleur radiogénique dans une succession de dépôts sédimentaires tectoniquement épaissie. Les compositions magmatiques, déjà alumineuses de par leur formation à partir de sédiments hyperalumineux, ont été modifiées par la circulation de solutions aqueuses fortement hyperalumineuses provenant des roches encaissantes. Les massifs résultent non seulement d'une fusion anatectique suivie de différenciation, mais aussi d'une interaction du magma avec la roche encaissante et les solutions aqueuses.

(Traduit par la Rédaction)

Mots-clés: granite hyperalumineux, fusion de la croûte, anatexie, groupe Davidsville, Nord-Est de Terre-Neuve.

Introduction

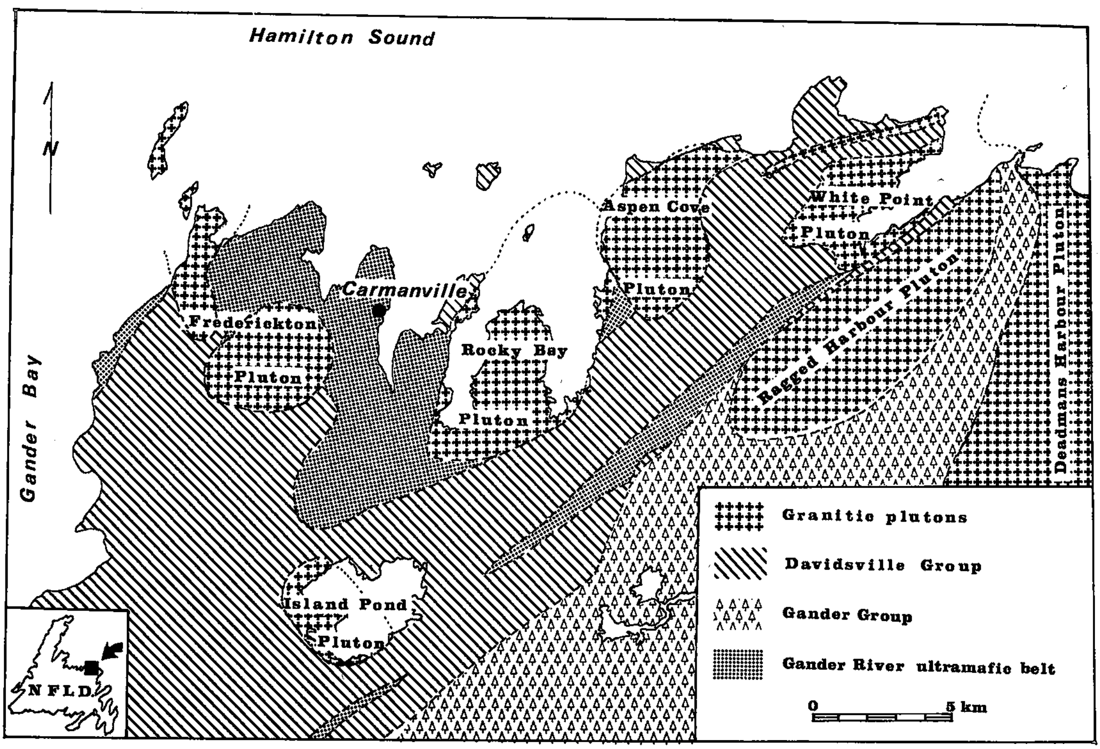
Granitoid plutons in the Carmanville region of northeastern Newfoundland exhibit striking similarities to their host rocks. Plutons emplaced within mafic hornblendic rocks are relatively mafic and contain hornblende; those emplaced in pelitic rocks are peraluminous and contain muscovite, with local garnet and andalusite; those emplaced within quartzofeldspathic gneisses are metaluminous and contain biotite with little or no muscovite. Metamorphosed pelitic rocks around the peraluminous plutons exhibit a sequence of metamorphic and metasomatic changes leading to the development of peraluminous granitoid rocks. This paper considers the relations between the peraluminous plutons and their surrounding country rocks, and the origin and evolution of their peraluminous character.

Geological Setting

During Cambro-Ordovician time, the Carmanville region formed part of the southeastern margin of the Lower Paleozoic Iapetus Ocean, which underwent a complex series of sedimentational and deformational processes leading to the collapse of the continental rise prism, obduction of oceanic crust and eventual cratonization (Currie *et al.* 1980). For the present purpose, the host rocks of the granites may be divided into an older psammitic to semipelitic unit (Gander Group), deposited as part of the continental rise prism, and a younger flyschoid semipelitic to pelitic unit (Davidsville Group), formed in an extensive submarine fan environment by turbidity currents, olistostromes and other mechanisms (Pajari *et al.* 1979). Allochthonous relics of oceanic crust (Gander River ultramafic belt) commonly separate the two units and occur as retransported rafts within the Davidsville Group. Assembly of this package was essentially complete by Caradocian time; stratigraphic evidence demonstrates that deformation and intrusion of the assembled complex commenced in pre-Llandovery (probably Ashgillian) time (Currie *et al.* 1980).

Field Relations

The plutons discussed in this report form part of a roughly east–west chain of plutons extending some 50 km across the generally northeast-trending tectonic "grain" of the surrounding sedimentary and volcanic rocks (Fig. 1). The Frederickton and Rocky Bay plutons, emplaced in mafic volcanic rocks, consist largely of hornblende tonalite with minor granodiorite. [Terminology for the granitoid rocks follows the recommendations of Streckeisen (1976).] The Ragged Harbour and Deadmans Bay plutons



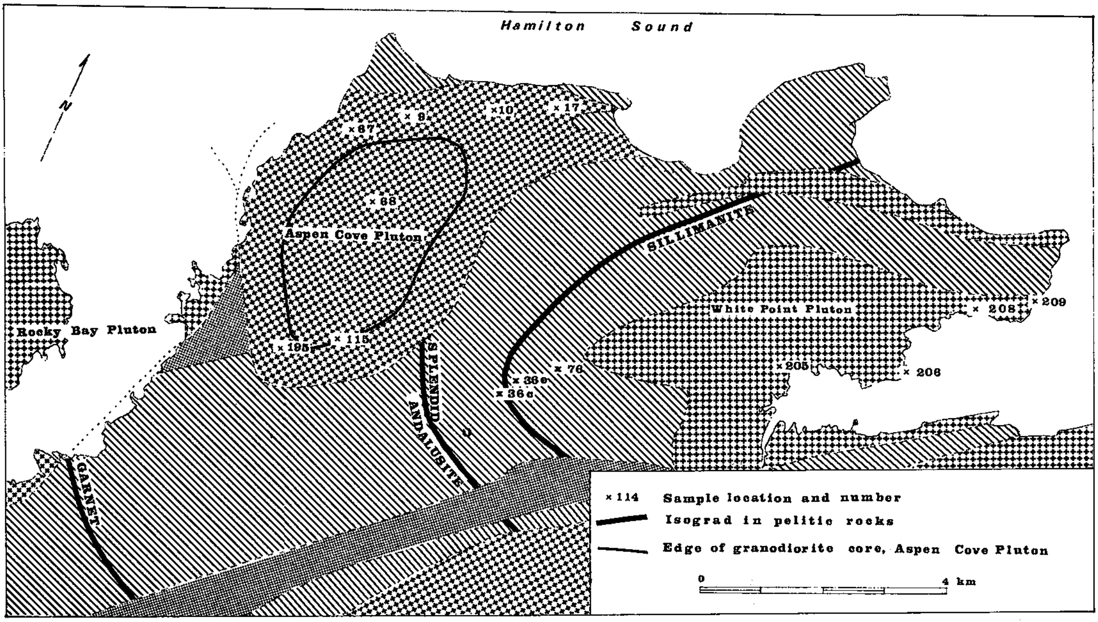


FIG. 1. (a) Geological sketch of the Carmanville area, northeastern Newfoundland; (b) localities and relation to isograds for samples listed in Tables 1 and 2.

consist mainly of biotite granite with porphyritic to megacrystic K-feldspar. The eastern part of the Deadmans Bay pluton, one of the largest in Newfoundland, was studied by Jayasinghe & Berger (1976). The present report concerns the White Point, Aspen Cove and Island Pond plutons, as well as minor granitoid rocks within the surrounding Davidsville Group.

Davidsville Group

Over most of its outcrop area the Davidsville Group, although complexly deformed, is metamorphosed only to chlorite + muscovite grade. East of Carmanville the metamorphic grade rises rapidly, as indicated by the sequence of isograds shown in Figure 1b. The isograds curve strongly around the migmatitic White Point pluton. Porphyroblasts within the Davidsville Group exhibit intricate relations with successive periods of deformation (Pickerill *et al.* 1978), but the isograds appear unaffected by later deformation.

Irregular veins and segregations of quartz occur throughout the Davidsville Group. With increasing grade of metamorphism, these segregations become lenticular in shape and tend to lie at a fixed, usually low, angle to the foliation. Between the andalusite and sillimanite isograds, quartz is joined by pink andalusite crystals, typically surrounded by a thin selvedge of muscovite, and by minor K-feldspar. We did not observe the quartz–albite assemblages so characteristic of rocks of similar metamorphic grade elsewhere (Currie 1968). The appearance of pink andalusite is sufficiently striking and regular that we mapped it as a "splendid andalusite" isograd (Fig. 1). With increasing metamorphic grade, over a distance of about 2 km, andalusite and muscovite increase in relative abundance within the quartz-rich segregations, locally composing as much as 25% of the volume. Potassium feldspar is a minor but ubiquitous component of the segregations.

Near the sillimanite isograd, traces of plagioclase, biotite and tourmaline appear in the segregations, which here form 2–5% of the rock. These lenticular masses lie at a high angle, but not perpendicular, to the prominent foliation (Fig. 2) and are associated with marked "necking" of the surrounding rocks. Despite boudin-like features, the host rock exhibits no obvious competency contrasts, and the segregations are reasonably evenly distributed along and across the foliation (Figs. 2, 3).

With increasing metamorphic grade, the composition of the segregations changes rather abruptly over an interval of about 100 m. Plagioclase and biotite increase in abundance at the expense of quartz and muscovite, although

FIG. 2. Discoid granitic segregations in the Davidsville Group, site 36C. The segregations lie at a high angle, but not perpendicular, to the gneissosity. Note necking in the surrounding homogeneous rocks. Arrow indicates a compositionally distinct layer.

FIG. 3. Section in the plane of the granitic segregations (about 90 m east of site 36C). The segregations do not form a continuous network in this plane. Segregations here form about 5% of the rock volume, but tend to be concentrated on planes such as that shown.

quartz-rich cores persist for a further 200–300 m. With increasing plagioclase and biotite contents, the relative volume of the segregations increases, reaching 12–20% of the volume, sufficient that the segregations define a new planar structure in the rock (Fig. 4). Along the margins of the White Point complex, the quartzofeldspathic (granitoid) layers are up to 10 cm thick, and the intervening biotite gneiss screens are intensely and tightly folded (Fig. 5). Successive granitoid layers differ substantially from one another in plagioclase/K-feldspar ratio and biotite content. Some contain minor garnet. All fall within the composition of granite as defined by Streckeisen (1976). The range in composition and texture observed in these segregations spans or exceeds that observed in the major plutons. The segregations exhibit little or no internal foliation, although they are well aligned with one another.

White Point pluton

The White Point pluton (Fig. 1) differs from the surrounding migmatitic rocks only in scale, consisting of granitic screens and pods from 0.5 to 200 m across that cut intensely small-folded migmatitic, generally semipelitic, gneiss. The granitoid sheets differ substantially from one another in composition, ranging from fine grained muscovite–biotite granite through coarse grained leucocratic muscovite granite occasionally containing traces of andalusite, to aplitic muscovite–garnet granite. Cross-cutting relations, although uncommon, suggest that the varieties have no consistent age relations; that is, each cuts the others. With the exception of the cores of some pods, all the granitoid rocks exhibit a pronounced foliation parallel to the northeast-trending tectonic grain.

On the northern edge of the White Point

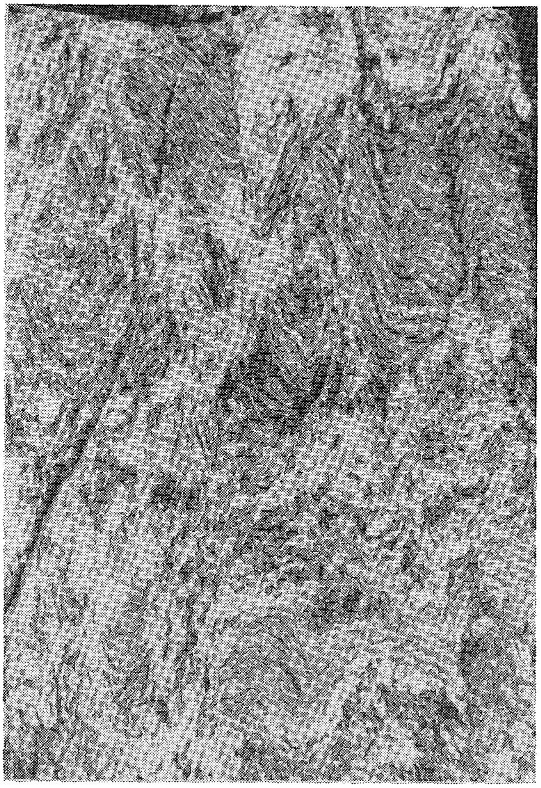


FIG. 4. Granitic segregations 380 m east of site 36C. The segregations are strongly elongate, forming a foliation parallel to the plane of the segregations. Note increase in volume of segregations relative to Figure 2.

FIG. 5. Migmatite, western part of the White Point pluton, about 2000 m east of site 36C. East of this point, the leucosome forms discrete screens.

pluton, a screen of muscovite–biotite granite some 200 m in width curves westerly toward the Aspen Cove pluton. The intersection of this screen with the Aspen Cove pluton was not observed owing to lack of outcrop, but it probably connects the two plutons.

Aspen Cove pluton

The Aspen Cove pluton forms a kidney-shaped body that transects its host rocks in the southwestern quadrant, but that is generally conformable elsewhere. A poorly exposed contact-aureole occurs southwest of the pluton, but on its eastern side the pluton passes gradationally into a thin zone of granitic screens. On its northern margin the pluton is intensely sheared. Both granite and host exhibit thin schistose foliation, and granitic dykes are isoclinally folded.

The Aspen Cove pluton exhibits a concentric zonation from near-massive medium grained pink to buff biotite granodiorite in the core, through biotite–muscovite granite to muscovite–garnet leucogranite on the margins. The associated dyke suite consists mainly of muscovite–garnet leucogranite. Compositional changes are gradual and progressive. The core contains no primary muscovite, but over a distance of about 1 km the rock grades to biotite–muscovite granite. A marginal zone 50–200 m wide contains no biotite, but rather muscovite + garnet. Nowhere did we observe stable biotite + muscovite + garnet. Xenoliths are extremely rare in the Aspen Cove pluton, although a few occur in dykes associated with the pluton.

Island Pond pluton

The Island Pond pluton forms an equant body some 5 km across emplaced in muscovite–chlorite-grade pelitic rocks of the Davidsville Group. A cordierite–andalusite-grade hornfels aureole, extending some 500 m from the contact, is anomalously and intensely small-folded, suggesting that emplacement of the pluton produced structural disturbance in its surroundings. The marginal parts of the pluton consist of reddened alkali feldspar porphyries (grain size 1–2 mm). Lithologically similar porphyry dykes occur sparingly in the contact aureole. Most of the pluton consists of monotonous coarse grained, leucocratic biotite–muscovite granite. Although most of the pluton is massive, a septum of foliated material crosses the central part. Small dykes of aplitic muscovite–garnet granite, similar to parts of the White Point and Aspen Cove plutons, cut the Island Pond pluton.

Timing and Conditions of Emplacement of the Granitoid Rocks

Field and petrographic examinations show that, with increasing metamorphic grade, segregations within the pelitic Davidsville Group gradually approach the mineralogy and texture of granitoid rocks cutting the Group. Conversely, granitic rocks in this region are peraluminous only where they are enclosed by pelitic rocks. These observations suggest that the origin of the segregations and the peraluminous character of the granitoid rocks may be connected. Additional evidence of such a connection can be deduced from the timing and conditions of emplacement of the granitoid rocks.

The main fabric of the Davidsville Group resulted from two nearly coplanar deformations (D1 and D2) separated by a period of porphyroblastesis, as can be seen in many thin sections where schistosity or slaty cleavage sweeps around porphyroblasts containing straight inclusion trails inclined to the external fabric (Pickerill *et al.* 1978). A third period of deformation (D3) kinks or crenulates (or both) the main foliation. A D3 foliation or crenulation overprints parts of all plutons except the Deadmans Bay pluton.

On the west side of Gander Bay, fossiliferous strata of Llandoverian age contain D1, D2 and D3 (Currie *et al.* 1980). Porphyroblastesis therefore began in post-Llandovery time. Some pluton emplacement postdated D2 but preceded D3. The Frederickton and Rocky Bay plutons yield K/Ar ages of 405 $\pm$15 *Ma* (Wanless *et al.* 1965, unpubl. data). Since the central core of these plutons is massive, their emplacement probably overlapped D3, the minimum age of which is thus fixed at about 405 *Ma*. According to van Eysinga (1975), the upper limit of Llandovery time lies at 423 *Ma*. Hence the maximum period available for metamorphism and intrusion is about 20 *Ma*. Granitoid segregations in the Davidsville Group, whose aluminosilicate mineralogy is congruent with that in the surrounding metamorphic rocks, show little internal foliation, but themselves define a new D3 foliation (Fig. 4). Formation of these segregations, emplacement of the plutons, the peak of metamorphism in the country rocks, and D3 deformation must have been almost contemporaneous. Rare granitic dykes cutting the segregations suggest that granite emplacement may have outlasted the other phenomena.

The evidence suggests that metamorphism commenced in Middle to Late Silurian time, with the peak of metamorphism and emplacement of plutons occurring near the end of the Silurian. Middle Devonian (360 $\pm$14 *Ma*) K/Ar ages obtained from the White Point pluton suggest that the rocks remained hot for a long period. The post-tectonic Deadmans Bay pluton gives K/Ar ages of 345 $\pm$15 *Ma* (Wanless *et al.* 1965, 1972).

Pressure–temperature conditions under which the various granitoid rocks were emplaced can be deduced from mineral assemblages. Color alteration of conodonts (Epstein *et al.* 1977) indicates that temperatures in the little-metamorphosed Davidsville Group south of Carmanville reached 300°C or more. Just below the andalusite isograd, staurolite occurs with quartz. Richardson (1968) deduced a minimum pressure of about 1.5 kbar for this assemblage with pure iron staurolite. The addition of magnesium would raise this pressure, since the alternative assemblage cordierite + andalusite + quartz is stabilized by the addition of magnesium. Above the "splendid andalusite" isograd, the segregations contain the assemblage andalusite–K-feldspar–muscovite–quartz. For pure phases, this assemblage is stable only along a univariant curve in P–T space in the presence of excess water. Quartz-rich segregations indicate the presence of a hydrous phase (Fyfe *et al.* 1978, Vidale 1974), and thus the assumption of excess water appears reasonable. For pure phases, and with the pressure of 1.5 kbar previously noted, the temperature of these initial segregations would be roughly 600°C, according to the data of Kerrick (1972).

However, this approximately univariant assemblage appears, not in one place only, but over a belt about 2 km wide in which the grade of the surrounding rocks rises, as indicated by the appearance of sillimanite. If the segregations were in equilibrium with their host, P–T conditions must have changed approximately along the univariant muscovite-breakdown curve. This curve is not strictly univariant, because of possi-

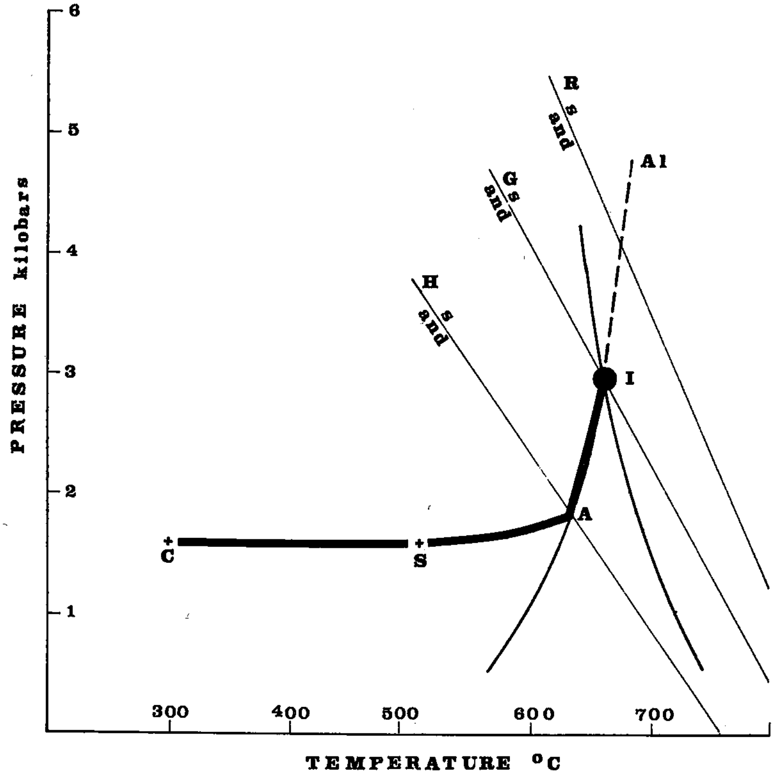


FIG. 6. Pressure–temperature conditions of metamorphism and granite emplacement. Point C gives probable temperature reached in the little-metamorphosed Davidsville Group; S indicates minimum conditions for staurolite+quartz stability; A gives the conditions deduced for the appearance of quartz+muscovite+K-feldspar+andalusite. Higher-grade occurrences of this assemblage fall on curve A–I, whose width indicates schematically the P–T variation possibly due to solid solution in K-feldspar and muscovite. At I melt appears. Andalusite granites crystallize on curve A–I in the andalusite stability field. Three estimates of andalusite–sillimanite equilibria are shown: H (Holdaway 1971), R (Richardson *et al.* 1969) and G (Greenwood 1976).

ble variations in composition of muscovite and K-feldspar, but is rather a narrow band, shown schematically in Figure 6. This band terminates at an invariant point near 650°C, 3 kbar, where melt appears (Thompson & Algor 1977). Petrographic evidence in the segregations suggests that P–T conditions attained this invariant point. At the sillimanite isograd, andalusite essentially disappears from the segregations, albite and biotite appear, and the proportion of quartz drops dramatically. At almost the same point the host rocks surrounding the segregations become migmatitic. These observations suggest melting of muscovite + quartz in the segregations and of quartz + albite + K-feldspar in the host rocks, forming a melt relatively rich in the albite component. The persistence of the quartz–andalusite–K-feldspar–muscovite assemblage indicates that originally hotter and deeper rocks are exposed toward the White Point pluton. The disappearance of this assemblage in favor of granitoid material suggests the intervention of melting, probably with conditions near 650°C, 3 kbar.

All the granite plutons contain muscovite with accessory amounts of andalusite. This assemblage (muscovite–albite–K-feldspar–andalusite–quartz), which petrographic evidence suggests as stable and primary, can coexist with melt only along a vapor-absent univariant curve extending from the invariant point I of Figure 6 (*cf.*, Thompson & Algor 1977). The position of this invariant point, together with data on the stability of andalusite, require that the tempera-

TABLE 1. CHEMICAL COMPOSITION OF GRANITIC SEGREGATIONS AND ADJACENT COUNTRY ROCKS

	Site 36C							Site 36 E							NP 76
	Granitic segregations					Country rock		Granitic segregations					Country rock		Segregation
SiO_2	76.26	76.30	74.74	74.98	74.26	51.58	50.52	77.31	76.47	80.07	79.33	75.88	50.65	52.70	74.73
TiO_2	0.06	0.07	0.07	0.07	0.06	1.08	1.07	0.12	0.08	0.08	0.10	0.10	1.14	1.06	0.15
Al_2O_3	13.37	13.70	13.82	13.83	14.13	23.23	23.15	14.24	14.58	12.38	12.93	15.40	23.68	23.72	14.11
Fe_2O_3	0.01	0.07	0.17	0.16	0.06	4.51	4.46	0.21	0.38	0.28	0.20	0.42	3.43	3.00	0.28
FeO	0.50	0.49	0.64	0.46	0.52	9.29	9.57	0.93	0.47	0.47	0.69	0.70	9.33	8.73	1.52
MnO	0.01	0.02	0.04	0.02	0.01	2.28	2.40	0.05	0.01	0.03	0.04	0.06	1.70	1.61	0.07
MgO	0.01	0.01	0.01	0.01	0.01	2.33	2.25	0.46	0.25	0.27	0.31	0.37	2.36	2.13	0.45
CaO	0.32	0.47	0.49	0.31	0.29	0.67	0.76	0.91	0.89	0.78	0.78	1.02	0.75	0.62	1.40
Na_2O	2.13	2.05	2.21	1.91	1.87	0.53	0.75	2.55	2.58	2.06	2.26	2.29	0.89	0.68	3.80
K_2O	6.63	5.74	6.72	7.33	7.77	2.87	2.68	1.74	2.96	2.58	2.42	2.49	3.40	3.23	3.08
P_2O_5	0.14	0.21	0.26	0.19	0.17	0.21	0.20	0.18	0.19	0.16	0.13	0.22	0.16	0.15	0.01
H_2O	0.86	0.93	0.86	-	0.77	1.56	-	-	1.26	1.15	-	1.42	2.70	-	0.68
Total	100.30	100.06	100.02	99.26	99.90	100.13	98.11	98.70	100.12	100.30	99.17	100.37	100.17	97.62	100.28
CO	2.1	3.3	2.0	2.2	2.1	18.8	18.5	6.6	5.6	4.8	7.2	5.2	18.0	18.8	2.0

CO gives the amount of normative corundum in the analysis in weight percent. - no data

tures and pressures of such melts lie very close to I. Other mechanisms producing magmatic andalusite can be invoked (Clarke *et al.* 1976), but all give similar P–T estimates. The aluminosilicate triple point of Holdaway (1971) does not allow the coexistence of andalusite and melt, although andalusite granites are not uncommon in the Canadian Appalachians (Clarke *et al.* 1976). The triple point of Richardson *et al.* (1969) would allow coexistence of melt and andalusite from the invariant point of Figure 6 to about 4.5 kbar. Field evidence suggests that the andalusite–sillimanite transition lies close to the invariant point, which would be compatible with an intermediate aluminosilicate triple point, such as that suggested by Greenwood (1976). Regardless of the triple point chosen, the temperatures and pressures recorded by the andalusite-bearing phases of the plutons lie close to those reached by the surrounding country rocks.

Mineral-assemblage data suggest regional temperatures of about 300°C. The succession of isograds indicates temperature increases to about 500°C, > 1.5 kbar, near the andalusite isograd. Hotter, deeper rocks near the White Point pluton crystallized near 650°C, 3 kbar, as did parts of the granite plutons.

Major Element Geochemistry of the Granitoid Rocks

Field observations indicate a continuous transition from relatively large masses of granitic rocks (plutons, dykes, screens) through small masses of granitic rocks (segregations, leucosome of migmatite) to segregations rich in quartz with accessory amounts of feldspar, muscovite and andalusite. We have chemically analyzed the granitic rocks and estimated the composition of the quartz-rich segregations. Below the "splendid andalusite" isograd, the segregations contain more than 95 vol. % quartz. Just below the sillimanite isograd, the segregations contain about 70% quartz, 15% andalusite, 10% muscovite and 5% K-feldspar, equivalent to roughly 83 wt. % SiO_2, 14% Al_2O_3 and 3% (K_2O+Na_2O). This composition is equivalent to about 12 wt. % normative corundum.

We analyzed granitic segregations from three localities shown in Figure 1 and projected the results onto the plane quartz–albite–orthoclase (Fig. 7), an appropriate representation since normative quartz+albite+orthoclase exceeds 90% for all analyses. Segregations from site 36C, lying in pelitic rocks, plot remote from both the minimum-melt composition at 3 kbar and the solute in equilibrium with quartz+albite+K-feldspar at 650°C, 3 kbar. The solubility of quartz–muscovite mixtures is unknown, but the data of Burnham (1967) on solubility of quartz–albite–K-feldspar–muscovite suggest that the K/Na ratio of the solutions would be slightly higher than that of the starting materials. The solubility of muscovite near its stability limit increases sharply relative to K-feldspar+andalusite (*cf.*, Fyfe *et al.* 1978). The compo-

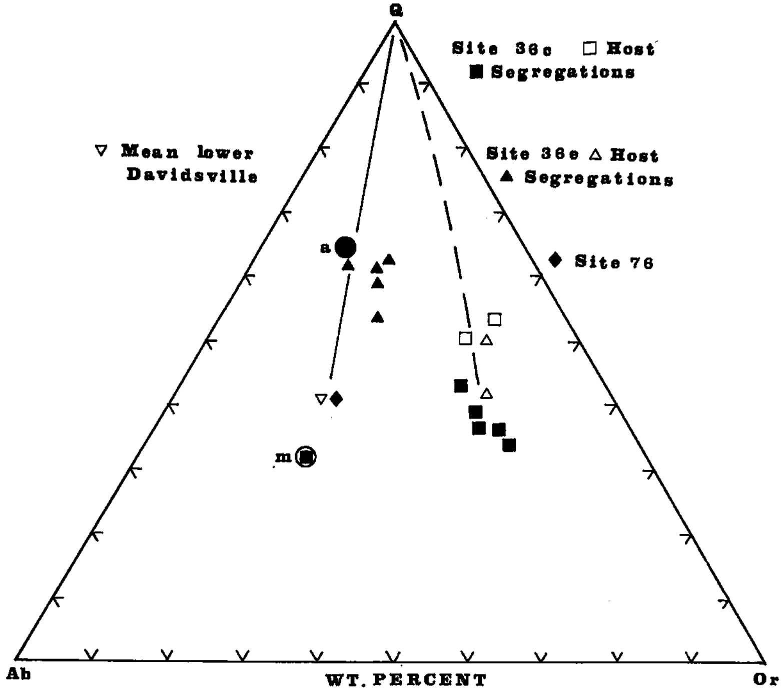


FIG. 7. Projection of analyses of segregations onto the plane Q–Ab–Or. Dashed line near Q–Or sideline indicates compositions in equilibrium with pelitic hosts, the solid line, those in equilibrium with quartzofeldspathic hosts; "m" indicates minimum-melt composition at 3 kbar (after Tuttle and Bowen 1958), "a" the aqueous-solute composition in equilibrium with granite at 650°C, 3 kbar (after Burnham 1967).

sitions of 36C are compatible with expected solute compositions in equilibrium with quartz–muscovite mixtures not containing albite, *i.e.*, with the pelitic rocks surrounding the segregations.

The composition of segregations at site 36E, lying 90 m upgrade from the sillimanite isograd in mixed pelitic and semipelitic rocks, lies very close to the composition of an aqueous solution in equilibrium with quartz–albite–K-feldspar–muscovite mixtures at 650°C, 3 kbar (Burnham 1967, p. 50), *i.e.*, with the compositions of the surrounding quartzofeldspathic gneiss.

The composition of a segregation at site NP76 plots, in Figure 7, on a line joining the minimum-melt composition at 3 kbar to the aqueous solute composition at 650°C, 3 kbar for quartz–albite–K-feldspar–muscovite mixtures. This composition could therefore be the result of the mixing of minimum melt with an aqueous solution derived from the surrounding rocks, both in equilibrium with the surrounding rocks.

Small-scale quartz-rich segregations with mineral assemblages compatible with metamorphic assemblages in the surrounding rocks can be ascribed to the action of a hydrous phase (Fyfe *et al.* 1978, Vidale 1974), whether the phase serves as a medium for bulk transport or diffusion. The composition of the segregations in the Carmanville region can be explained by this model. The composition at site 36E seems indicative of a high-temperature aqueous solution process, whereas that at 36C could be the result of such a process, but the experimental data to demonstrate that this composition is in equilibrium with surrounding albite-free pelitic rocks are lacking. If so, the range of equilibration must be relatively short, since albite-bearing strata occur within a few tens of metres. Site NP76 suggests that aqueous solutes make a contribution to the composition of the segregations even after the onset of melting, although with increasing degrees of partial melting this contribution presumably declines.

The major element geochemistry of the larger plutons is summarized in Table 2 and shown graphically in Figures 8 and 9. Normative quartz+albite+orthoclase total to more than

TABLE 2. CHEMICAL COMPOSITION OF THE WHITE POINT, ASPEN COVE AND ISLAND POND PLUTONS

	White Pond Pluton						Aspen Cove Pluton					Island Pond
Type	2	2	3	3	1	1	2	2	2	3	3	3
	NP 205	NP 206	NP 208	NP 209	NP 68	NP 115	NP 195	NP 67	NP 9	NP 17	NP 10	KC 9
SiO_2	70.27	73.76	75.42	75.46	64.05	67.12	72.99	73.93	74.94	74.89	75.57	74.91
TiO_2	0.47	0.15	0.08	0.05	0.50	0.41	0.23	0.11	0.11	0.03	0.03	0.08
Al_2O_3	15.32	14.80	15.13	15.09	17.78	16.28	15.11	14.82	14.03	14.32	13.84	14.21
Fe_2O_3	0.37	0.02	0.01	0.01	2.22	0.44	0.34	0.05	0.25	0.33	0.32	0.43
FeO	2.39	1.09	0.77	0.81	3.84	2.96	1.03	1.41	1.19	0.56	0.65	0.92
MnO	0.04	0.02	0.01	0.10	0.95	0.13	0.04	0.04	0.06	0.15	0.11	0.06
MgO	0.89	0.18	0.15	0.21	1.34	1.78	0.37	0.12	0.23	0.07	0.07	0.31
CaO	1.91	0.86	0.80	0.77	1.96	3.67	1.10	1.39	1.10	0.40	0.37	1.02
Na_2O	4.14	4.17	4.88	4.58	3.58	4.03	3.58	4.13	3.96	3.95	4.13	3.64
K_2O	3.13	4.49	3.37	2.56	2.76	1.61	4.45	3.55	3.77	5.12	4.70	3.33
P_2O_5	0.18	0.06	0.04	0.03	0.12	0.12	0.17	0.02	0.02	0.01	0.01	0.03
H_2O	1.16	0.81	0.85	0.56	0.95	1.54	0.81	0.9	0.47	0.53	0.39	0.59
Total	100.27	100.40	100.51	100.24	100.05	100.09	100.22	100.15	100.13	100.35	100.17	99.53
CO	1.7	2.7	2.0	3.4	5.7	1.6	2.8	1.7	1.5	1.6	1.3	3.0

CO gives the amount of normative corundum in the analysis in weight percent. Analysis KC 9 is of a composite sample of the Island Pond pluton believed to represent an average. The rock types are 1 biotite granodiorite, 2 biotite-muscovite granite, 3 muscovite or muscovite-garnet leucogranite, pegmatite and aplite.

90% for all the analyses, so that the plane quartz–albite–orthoclase (Fig. 8) is an appropriate representation. Figure 9, a projection onto the plane Al_2O_3–(K_2O+Na_2O)–(FeO+MgO+MnO) through anorthite, is a convenient method of displaying both the mafic mineralogy and the peraluminous character of the rock. The composition of the Island Pond pluton and the leucocratic parts of the Aspen Cove and White Point plutons lie very close to and trend toward the composition of NP76, that is, the highest-grade segregations in the country rocks. The White Point and Aspen Cove plutons display well-defined trends that tend toward this point or to the minimum-melt composition. In a general way, the mafic ends of the trend tend towards the composition of the Davidsville Group. This trend is particularly clear in Figure 9, where the Aspen Cove pluton tends directly towards the projection of the pelitic part of the Davidsville Group, whereas the mafic part of the White Point pluton overlaps the composition of the semipelitic part of the Davidsville Group.

The geometrical analysis of partial fusion (Presnall 1969) suggests that the Aspen Cove and White Point plutons could have arisen by advanced partial fusion of the pelitic and semipelitic parts of the Davidsville Group, respectively. In the projection of Figure 8, the initial melt would lie near the minimum-melt composition at the appropriate pressure (not necessarily the pressure of the host rocks in this instance). After exhaustion of one of the solid phases (presumably albite in this instance), the developing partial melt would migrate up the quartz–orthoclase cotectic line toward the bulk composition of the solid, eventually leaving the cotectic line and reaching the original solid composition upon total melting. An advanced partial melt derived from the Davidsville Group would therefore be expected to project near the quartz–orthoclase cotectic in Figure 8, and with differentiation compositions should travel down the cotectic line toward the minimum-melt composition. If the melt is generated at higher pressure than is appropriate for the level of emplacement, this differentiation trend will appear to migrate from the orthoclase field toward the "ternary" minimum, since the orthoclase–quartz cotectic migrates toward higher quartz content with decreasing pressure, as shown in Figure 10. The polybaric–polythermal evolutionary curve of Figure 10, derived from the data of Tuttle & Bowen (1958), is virtually identical to that ex-

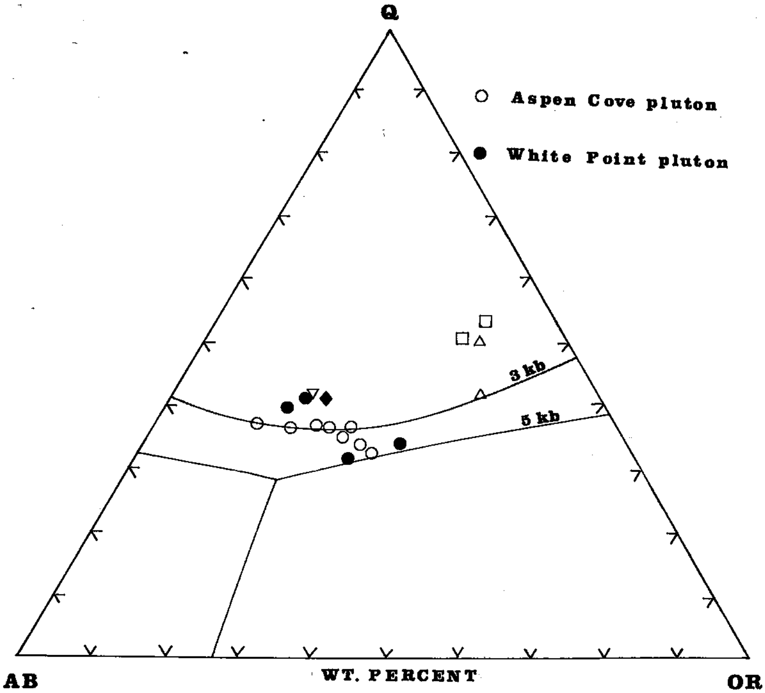


FIG. 8. Projection of analyses of granitic rocks from the Aspen Cove and White Point plutons into Q–Ab–Or. Cotectic lines for melting in the system Q–Ab–Or at 3 and 5 kbar (after Tuttle & Bowen 1958). Symbols same as Figure 7, except as noted.

hibited by the Aspen Cove pluton. The paths of partial fusion and fractional crystallization in Figure 9 cannot be predicted exactly, but from general principles, advanced degrees of partial melting will give rise to liquids that gradually approach the bulk composition of the protolith. Conversely, fractional crystallization will give rise to paths trending away from a more mafic protolith towards minimum-melting compositions, which in this projection will lie near the centre of the alkali–alumina join. In fact, the trends defined by the chemical analyses point with striking directness to the composition of the pelitic Davidsville Group for the Aspen Cove pluton and the semipelitic Davidsville Group for the White Point pluton. In both cases, the observed variation in ferromagnesian composition can be explained by fractionation of varying amounts of muscovite and biotite, in accordance with the observed mineralogy.

Petrogenetic Interpretation

The peraluminous plutons of the Carmanville region form part of a chain of granitoid plutons more than 50 km in length. Thermal aureoles, structural disturbance and the low grade of the country rocks around the Fredericton, Rocky Bay and Island Pond plutons strongly suggest that they were emplaced as hot, discrete masses derived elsewhere, and not generated close to their present site. East of Carmanville, distribution of the assemblage quartz–muscovite–K-feldspar–andalusite indicates that relatively large volumes of the pelitic Davidsville Group reached temperatures sufficient to partially melt the quartzofeldspathic assemblages within the Group. The nature of segregations within the metamorphosed rocks suggests that compositions due to equilibrium with aqueous fluids in lower-grade rocks pass continuously into melt compositions in high-grade rocks. The originally deepest and hottest parts of the Davidsville Group outcrop around the White Point pluton.

The composition of the Aspen Cove pluton can be explained by assuming extensive partial melting of the Davidsville Group at pressures of about 5 kbar, followed by crystallization at pressures decreasing to 3 kbar. The composition

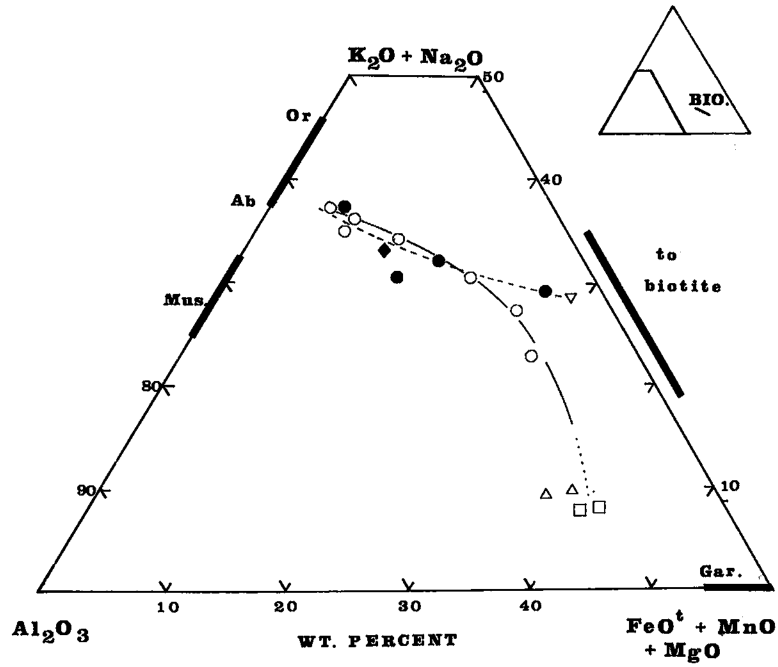


FIG. 9. Chemical compositions of granitic rocks projected through anorthite onto (K_2O+Na_2O)–Al_2O_3–$(FeO^t+MnO+MgO)$. Trends for the Aspen Cove and White Point plutons drawn in by eye. Symbols same as Figures 7 and 8.

of the White Point pluton can be explained by extensive partial melting of semipelitic parts of the Davidsville Group at pressures of 3–4 kbar. The Island Pond pluton as a whole and the composition of leucocratic parts of the White Point and Aspen Cove plutons tend towards the compositions of the highest-grade segregations within the Davidsville Group. We will now comment on the convergence in composition between the segregations and the granitoid plutons and on the role of the segregations in the generation of anatectic melts.

According to Dimitriadis (1978), partial melts generated from pelitic rocks do not contain more than 2% normative corundum, and commonly less than 1.5%. Comparison with Tables 1 and 2 shows that virtually all the granitoid rocks in the Carmanville region have higher contents of normative corundum, and that the amount tends to increase in the leucocratic products that plot in Figure 7 near the minimum-melt composition. Clearly, some factor must operate in the natural case that was not considered in the experiments. The segregations are particularly rich in normative corundum, in excess of 6% in some granitoid segregations, and up to 12% in some lower-grade material. We conclude that this composition is due to equilibration between the pelitic wall-rocks and aqueous solutions. Hence, incorporation of aqueous solutions from the country rocks will increase the normative-corundum content of a developing magma. Only magmas undersaturated in water tend to rise and be intruded (Presnall & Bateman 1973, Burnham 1967). Such magmas will tend to absorb water from their surroundings, setting up chemical potential gradients leading to inward diffusion of water. Further, since such magmas have a certain amount of "superheat", they can assimilate material from the surroundings, including peraluminous segregations originally developed at lower grade. The increase in peraluminous character is enhanced if water later escapes from the magma, since the data of Burnham (1967) show that solutions in equilibrium with granitic magma contain normative sodium silicate. Assuming the solutions taken in resemble 36E in composition, the composition of the magma will also be displaced from minimum-melt composition toward the quartz corner in the projection of Figure 8. Again the effect is enhanced by

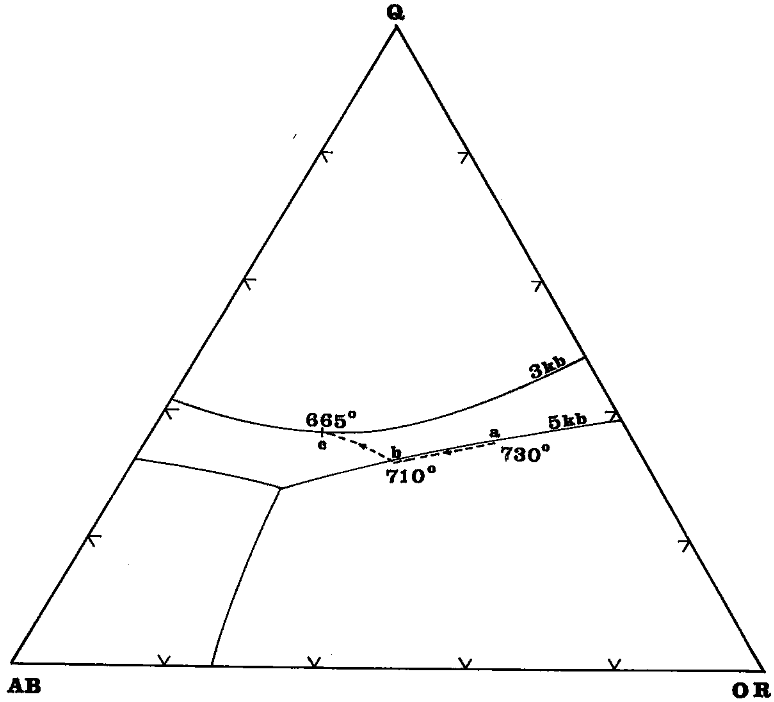


FIG. 10. Polybaric–polythermal composition variation of a melt in the system Q–Ab–Or. The melt is assumed to start on the Q–Or cotectic at 730°C, 5 kbar (point a), a composition appropriate to advanced partial melting of pelitic compositions such as those shown in Figure 8. The melt remains at 5 kbar until the temperature falls to 710°C (point b), at which point the temperature and pressure simultaneously decrease to reach 665°C, 3 kbar (point c). This curve should be compared with the trend of the Aspen Cove pluton in Figure 8.

subsequent escape of water, since Burnham's data show that in an isothermal system solutions in equilibrium with granite at low pressures contain more albite+orthoclase relative to quartz than those at high pressures. These considerations explain why the leucocratic parts of the plutons converge towards the composition of the segregations. Both represent minimum melts in a system open to aqueous solutions; the incoming solutions equilibrated with pelitic material, and the outgoing solutions, with granitic magma. The leucocratic parts of the plutons contain roughly 3% normative corundum. We assume that the incoming solute contains 6% normative corundum, and that the solute constitutes 3% by weight (Burnham 1967, p. 50). Assuming that the initial melt contains 1.5% normative corundum (Dimitriadis 1978), then if all normative corundum in the aqueous solution remains in the melt, as suggested by the sodium-silicate-normative character of aqueous solutions in equilibrium with granitic magma, a weight of aqueous solution about 8.5 times the weight of magma would have to pass through the developing magma in order to raise its normative corundum content to 3 wt. %. At first sight this value seems preposterously high, raising questions about the significance of material exchange by aqueous solution transport. However, the data of Taylor (1977) indicate that a very large-scale exchange of water between magma and wall rocks is possible.

If the local anatexis model, which we here propose, is incorrect, then the material in the plutons must have originated at greater depth in the crust, or in the mantle. Several qualitative considerations militate against deep-seated sources. Gravity traverses (H. Miller, pers. comm. 1978) indicate no sign of a dense "root" to the plutons, and the geochemistry does not suggest the presence of a more mafic precursor. Indeed, the geochemistry suggests that a significant part of the plutons must be of local derivation, regardless of the presence or absence of a deep-seated component. The pattern of K/Ar ages of the plutons, decreasing from west to east from Late Silurian to Carboniferous, can be explained only by *ad hoc* assumptions if they result from invasion of deep-seated material. This pattern receives a natural explanation if the plutons result from self-heating of a K-rich Davidsville Group (*cf.*, Table 1) thickened in Late Ordovician time into a west-dipping slab, as suggested by regional structural considerations (Pickerill *et al.* 1978, Currie *et al.* 1980). Assuming that the overlying rocks lack heat sources, high temperatures are reached first in the deep, western part of the slab, which could lead to early intrusion of magma rising buoyantly into relatively cold country rocks (Frederickton and Rocky Bay plutons). High temperatures are reached later and last longer in shallower and more eastern parts of the slab (Aspen Cove and White Point plutons). Indeed, high temperatures persist for an extended period even after melting temperatures are reached, which possibly explains the young K/Ar ages recorded from the Deadmans Bay pluton. Preliminary computer simulation of the temperature regime (Pajari, Cherry & Currie, in prep.) suggests that the observed pattern of ages could result from self-heating beginning in the Late Ordovician.

Summary and Conclusions

The mineralogy of granitoid rocks in the Carmanville region varies with the character of the host rocks. Peraluminous granites appear only in peraluminous host rocks, and the character of segregations in the host rocks progressively approaches that of the plutons as the metamorphic grade rises. Structural considerations show that granite emplacement, the peak of metamorphism and formation of the segregations essentially coincided. The bulk-rock geochemistry of the plutons could have resulted from partial melting of the surrounding rocks at temperatures and pressures close to those indicated by metamorphic mineral assemblages in the surrounding rocks. The anomalously quartz- and normative-corundum-rich character of the plutons could result from large-scale circulation through the magma of aqueous solutions derived from the surrounding country rocks.

We conclude that the peraluminous plutons originated by self-heating of K-rich pelitic rocks tectonically thickened into a west-dipping slab. The three plutons observed represent, respectively, material that has remained essentially at its site of generation (White Point pluton), material that has risen and partially differentiated (Aspen Cove pluton), and strongly differentiated leucocratic material that has risen to a relatively high level (Island Pond pluton).

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Received August 1980, revised manuscript accepted December 1980.