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Contents/Contenu   Page 1 report/Début de l'article

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Contents/Contenu
Page 1 report/Début de l'article

Age and extent of the Frontenac plutonic suite in the Central metasedimentary belt, Grenville Province, southeastern Ontario

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Abstract: Eight U-Pb zircon age determinations extend the geographic range of the A-type Frontenac plutonic suite (1.18–1.15 Ga) for a limited distance across the boundary between Frontenac and Elzevir terranes, stitching two fundamentally different blocks of the Central metasedimentary belt that were juxtaposed by ca. 1.2 Ga. Frontenac plutons in the boundary shear zone are deformed and recrystallized, whereas those in the Elzevir footwall and in the overriding Frontenac block are not. This study supports the interpretation that deformation and recrystallization of the plutonic rocks in the bounding shear zone occurred during or very soon after emplacement rather than being the result of later Grenvillian tectonism, the implication in this case being that the A-type plutonism was not anorogenic.

Résumé : Huit datations U-Pb sur zircon ont comme résultat d'élargir l'aire géographique de la suite plutonique de Frontenac de type A (1,18–1,15 Ga) sur une distance limitée au-delà de limite entre les terranes de Frontenac et d'Elzevir, réunissant deux blocs fondamentalement différents de la ceinture métasédimentaire centrale dont la juxtaposition remonte à 1,2 Ga environ. Les plutons de Frontenac dans la zone de cisaillement limite sont déformés et recristallisés tandis que ceux du mur d'Elzevir et du bloc chevauchant de Frontenac ne le sont pas. Cette étude appuie l'interprétation selon laquelle la déformation et la recristallisation des roches plutoniques dans la zone de cisaillement limite ont eu lieu pendant ou juste après leur mise en place. Elles n'auraient pas été causées par un tectonisme grenvillien plus tardif. Dans ce cas, le plutonisme de type A n'était donc pas anorogénique.

Contents/Contenu
Page 1 report/Début de l'article

INTRODUCTION

The granitoid plutonic rocks in the Frontenac Axis of the Grenville Province, southeastern Ontario, are distinctive enough that Wynne-Edwards (1965) referred to them as 'Frontenac type'. This categorization was based on his many years of experience mapping in this region (Wynne-Edwards, 1962, 1963, 1965, 1967) and on the recognition that they differ petrologically from plutonic rocks elsewhere in the Central metasedimentary belt: they comprise a suite of monzonite, quartz syenite, and granite that contrasts with tonalite, granodiorite, and leucogranite that form the bulk of the plutonic rocks farther west. Both suites have associated gabbroic phases.

Modern geochronology has shown that these two suites differ in age by at least 45 Ma, the youngest of the tonalite suite so far dated being ~1225 Ma (Corfu and Easton, 1995) and the oldest of the monzonite suite, ~1180 Ma (van Breemen and Davidson, 1988; Marcantonio et al., 1990; Wasteneys, 1994). It has also revealed that the younger, Frontenac-type suite contains plutons of two distinct ages, 1180–1150 Ma and 1090–1065 Ma, information not available to Wynne-Edwards. The plutonic rocks of these three age groups are referred to here, from oldest to youngest, as the 'Elzevir', 'Frontenac', and 'Skootamatta' suites (the last name coined by Easton (1992)). The currently known distribution of the three suites in Ontario and the lithotectonic subdivisions of the Central metasedimentary belt within which they occur are shown in Figure 1. A similar age division is recognized in neighbouring Quebec (tonalite dated at 1285 and ~1240 Ma, monzonitic rocks of the Chevreuil suite, ~1165 Ma, and potassic syenite of the Kensington suite, ~1080 Ma (Machado et al., 1991; Corriveau et al., 1998)).

Following the lead of Wynne-Edwards (1972), Moore (1982) proposed division of the Central metasedimentary belt in Ontario into four 'terrains' [sic]. Brock and Moore (1983) subsequently amalgamated two of these divisions, leaving three principal lithotectonic blocks, from northwest to southeast: Bancroft, Elzevir, and Frontenac (Davidson, 1986), as outlined in Figure 1. More recently, the Elzevir terrane has been divided into smaller terranes and domains and elevated to 'superterrane' status (Easton, 1992). All of these smaller divisions, however, have elements in common, notably the presence of tholeiitic to calc-alkaline volcanic rocks within a predominantly carbonate sedimentary succession, lack of a coarse, clastic, sedimentary component in this succession,

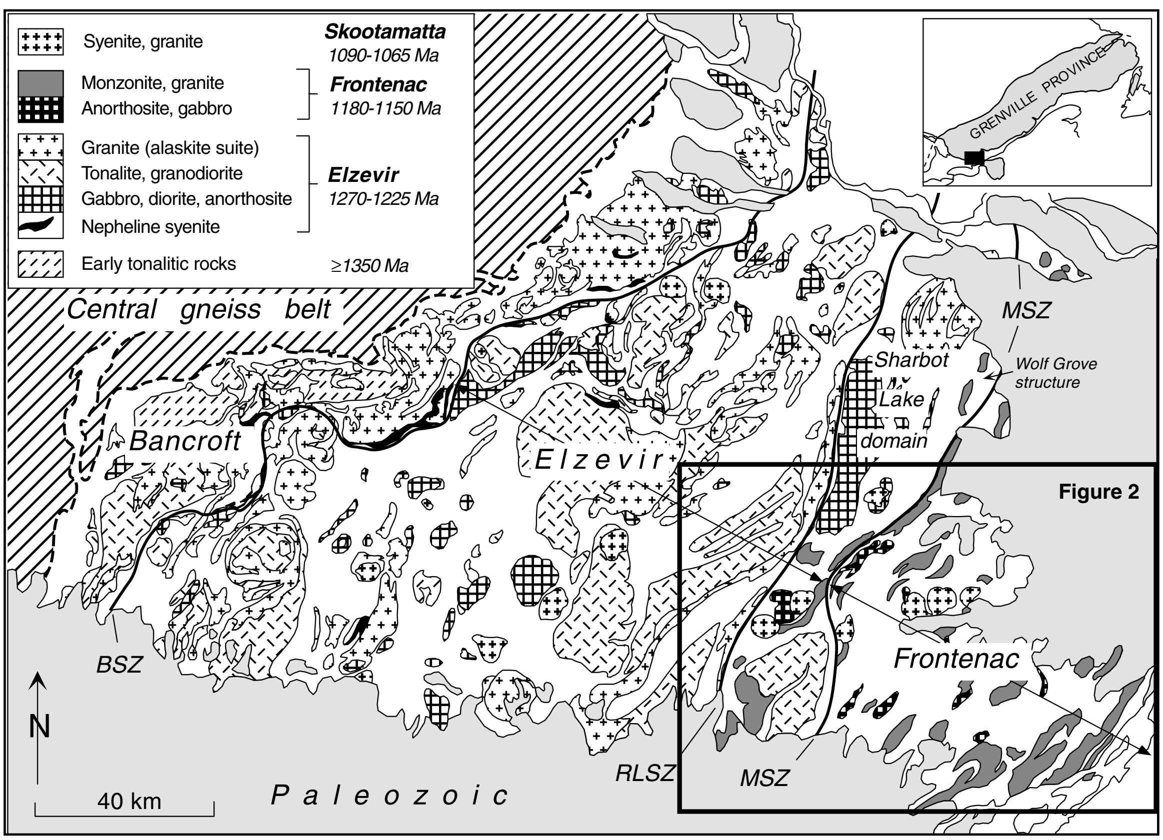

*Figure 1. Distribution of plutonic rocks in the Central metasedimentary belt, Ontario (*modified from *Lumbers et al., 1990). Note that the Frontenac suite is restricted to southeast of the Robertson Lake shear zone, and Elzevir suite to northeast of the Maberly shear zone. BSZ = Bancroft shear zone; RLSZ = Robertson Lake shear zone; MSZ = Maberly shear zone*

and prevalence of the Elzevir plutonic suite, itself calc-alkaline; all of these rocks are older than 1225 Ma. The supracrustal rocks of the Frontenac terrane, in contrast to those of the Elzevir, contain quartzofeldspathic and pelitic gneiss and quartzite in addition to marble, and lack recognizable volcanic protoliths. Plutonic rocks with the aspect of the calc-alkaline Elzevir suite are also absent, and all plutonic rocks so far dated belong to either the Frontenac or Skootamatta suite.

Wynne-Edwards (1965) recognized Frontenac-type plutonic rocks in what is now defined as the Sharbot Lake domain, the southeasternmost division of the Elzevir terrane (Fig. 1). That some of these are coeval with the Frontenac suite is borne out by the present study. Frontenac suite intrusions have yet to be identified west of the Robertson Lake shear zone, the western boundary of the Sharbot Lake domain. Skootamatta suite intrusions, on the other hand, are more widespread, occurring throughout the Frontenac and Elzevir terranes (Fig. 1).

The boundary between the Frontenac terrane and the Sharbot Lake domain of the Elzevir terrane is a major ductile shear zone in which mylonitic foliation dips moderately to steeply southeast (Davidson and Ketchum, 1993). This zone ranges from 4 km to as much as 12 km across at the surface. At its widest, internal zones of more intensely mylonitized gneiss part around map-scale lenses of less deformed rock, generally cored by plutonic rocks. The northwestern limit of this shear zone is sharply defined between the villages of Sharbot Lake and Lanark (Fig. 2), and is well exposed at Maberly, whence it gets its name. Its location is less well documented south of Sharbot Lake, where splays of mylonitic rocks diverge southwestward within supracrustal rocks of the Sharbot Lake domain, dying out along the northern side of the Hinchinbrooke tonalite pluton, dated at ~1255 Ma (Wallach, 1974). The boundary between the different supracrustal assemblages typical respectively of the Sharbot Lake domain and the Frontenac terrane, however, passes along the east side of the Hinchinbrooke tonalite, and likely lies within marble tectonite. Northeast of Lanark, the Maberly shear zone passes

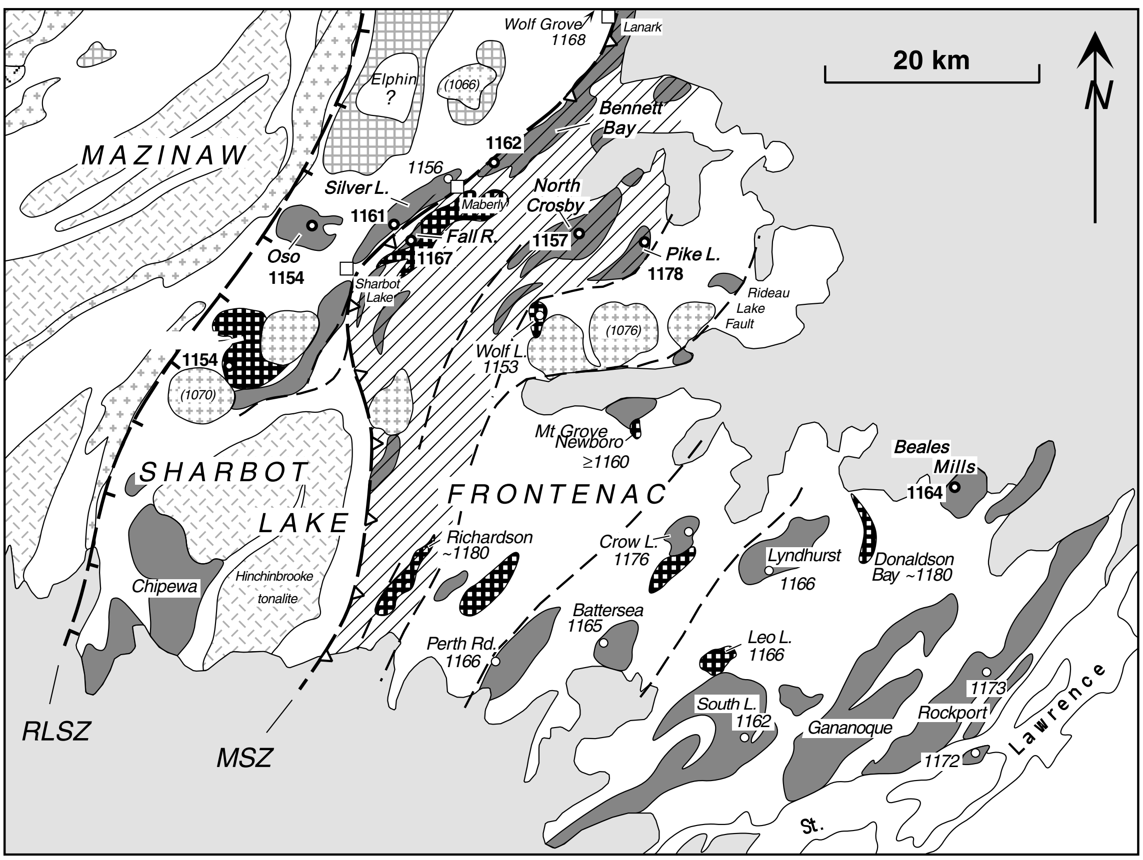

Figure 2. Distribution of plutons of the Frontenac suite in the Sharbot Lake domain and Frontenac terrane. Plutons of the Elzevir and Skootamatta suites are shown in subdued patterns; see *Figure 1 for legend. Name and ages of plutons dated in this study are bolded. Other ages shown are from Davidson and van Breemen (1980: South Lake and Rockport (1173 Ma)), Marcantonio et al. (1990: Perth Road, Battersea, Crow Lake, Lyndhurst), Wasteneys (1994: Richardson, Wolf Lake, Newboro, Leo Lake, Donaldson), Wasteneys et al. (1996: Rockport (Wellesley Island, 1172 Ma), and Corfu and Easton (1997: Silver Lake ('Maberly stock', 1156 Ma) and Wolf Grove). Undated plutons assigned to the Frontenac suite are correlated on the basis of rock type and chemistry.*

southeast of the Wolf Grove structure (Fig. 1; Corfu and Easton, 1997). The change in metamorphic grade across the Maberly shear zone varies along its length; whereas all of the Frontenac hanging wall is characterized by metasedimentary gneiss in granulite facies, grade in the footwall decreases southwestward from upper amphibolite facies in the Wolf Grove structure to upper greenschist facies near Lanark, and then increases gradually to mid-amphibolite facies at Sharbot Lake, continuing to rise southward to lower granulite facies.

Lumbers et al. (1990) referred to the Frontenac and Skootamatta suites as the 'syenite-monzonite' and 'monzonite-diorite' suites respectively, and classified them both as 'A-type'; they stated (p. 266) that the earlier "...syenite-monzonite suite is known only south of the Rideau Lake Fault in the Frontenac Axis region...". Wasteneys (1994) subsequently reported U-Pb zircon and baddeleyite ages between 1180 and 1153 Ma for gabbroic rocks in the Frontenac terrane, including one north of the Rideau Lake Fault (Wolf Lake gabbro; Fig. 2). More significantly, Corfu and Easton (1997) obtained ages of 1168 Ma for foliated granite in the Wolf Grove structure and 1156 Ma for undeformed monzodiorite just north of Maberly, both of these lying in the proximal Sharbot Lake domain footwall of the Maberly shear zone. Thus the Frontenac suite extends beyond the Frontenac terrane into the southeastern Elzevir terrane, confirming the earlier assignation of Wynne-Edwards (1965).

Plutonic rocks of Wynne-Edwards' Frontenac type are not deformed in the central and southeastern parts of the Frontenac terrane. In contrast, plutonic rocks are severely deformed along the leading edge of the Maberly shear zone and variably deformed where they lie between the related mylonite zones higher in the Frontenac hanging wall. To determine whether or not these plutonic rocks belong to the Frontenac suite and, if possible, to determine the age of their deformation, variously deformed plutonic rocks from five localities were chosen for U-Pb zircon study. In addition, undeformed, Frontenac-type monzodiorite from two plutons in the Sharbot Lake domain several kilometres from the Maberly shear zone, and monzonite in the interior of the Frontenac terrane, were also dated. The eight locations are shown in Figure 2.

***Figure 3. A)** Syenite dykes (light grey) cut commingled diorite and gabbro; Oso pluton, road cut on Highway 509. **B)** Commingled dyke with contact-parallel internal fabric cuts similar commingled rock with no foliation. North Crosby pluton, road cut on county road 8.*

ANALYTICAL TECHNIQUES

All zircon fractions were strongly abraded until the crystals assumed a well rounded shape (Krogh, 1982), to minimize the effects of peripheral lead loss and/or to remove metamorphic rims. Analytical techniques for measuring U-Pb isotopes in zircon at the Geological Survey of Canada (GSC) are summarized in Parrish et al. (1987). Mass spectrometry, data reduction, and method of propagation of analytical uncertainties of the relevant components in the calculation of isotopic ratios and ages followed the numerical procedure of Roddick et al. (1987). A modified form of York's (1969) method for linear regression analysis was used (*see* Parrish et al., 1987). The isotopic data are presented in Table 1. All age uncertainties are given at the 95% confidence level. Many of the data sets plot in discordant clusters.

PLUTONS IN THE SHARBOT LAKE DOMAIN

Oso pluton

The Oso pluton (Ijewliw, 1999) is centred approximately 4 km northwest of Sharbot Lake village (Fig. 2). Elongate east-west, 6 km long by 3 km wide, it intrudes a succession of thinly layered, micaceous, quartzofeldspathic schist, metarhyolite, amphibole schist, and rusty weathering pyrite-magnetite-tourmaline-quartz rock (SEDEX protolith) along its south side, and layered marble elsewhere. The plutonic rocks are massive and cut across folds, foliation, and easterly plunging lineation in the country rocks. Two main phases constitute this composite stock, 1) medium- to coarse-grained rocks grading from dark grey pyroxene-hornblende±biotite gabbro through lilac-grey hornblende±biotite diorite to biotite-hornblende monzodiorite, and 2) medium- to fine-grained, grey-pink hornblende monzonite to bright rose-pink hornblende- and/or augite±biotite monzosyenite and quartz-perthite syenite. Dykes related to this phase cut the coarser grained, more mafic suite (Fig. 3A). Both phases were apparently emplaced as multiple sets of crudely crescentic sheets, concave to the east, grossly conforming to a major east-plunging synform in the country rocks, yet with apophyses cutting across this structure. Narrow septa of marble, internally preserving small folds, commonly separate sheets of the different intrusive phases or pulses of the same phase. Small marginal satellites, particularly in the concave marble core of the coalescent crescents, are fine grained and commonly exhibit commingling between mafic and felsic components; in places the mafic component is very fine-grained gabbro carrying plagioclase phenocrysts. The northwest margin of the pluton lies in the immediate hanging wall of the Roberston Lake shear zone; there the plutonic rocks show effects of low-temperature alteration and are cut by narrow mylonite zones. Southeast-dipping marble mylonite exposed locally near this contact, as well as along the strike of the shear zone, carries extensional shear-sense indicators.

The dated sample is coarse-grained monzodiorite from the earlier plutonic phase, collected from blasted outcrop on the Bell Line Road 800 m west of Highway 509. The zircon crystals extracted for analysis were clear, well formed, pale pink, doubly terminated or broken prisms and tablets as large as 600 µm long and 200 µm wide (Fig. 4A). They showed no obvious cores, little fracturing, and no evidence of overgrowth. Four fractions of the cleanest grains were picked on the basis of variation in shape. Zircon U concentrations were low (40 to 68 ppm). The five zircon fractions are concordant or nearly so (Fig. 5). The weighted mean $^{207}Pb/^{206}Pb$ age of all five data points is 1154 ± 2 Ma (mean square of weighted deviates (MSWD) = 2.4).

Mountain Grove pluton

Named after the village of Mountain Grove, which lies astride the Robertson Lake shear zone about 1 km from its northwest margin, this pluton intrudes layered amphibolite derived from basalt flows along its northern contact, and marble along its western and southern sides. To the east it is intruded by massive leucogranite of the Leggat Lake pluton, an undated intrusion whose rocks are identical in appearance and composition to those of the McLean granite pluton centred some 10 km to the west and dated at 1070 Ma (Davidson and van Breemen, 2000). The Mountain Grove pluton, roughly 7 km in diameter with an incursion of marble on its west side, is composed of two distinct phases, 1) massive, medium- to very coarse-grained noritic gabbro and anorthosite in the north, and 2) relatively fine-grained, generally massive, hornblende gabbro and diorite in the south, associated in places with small amounts of monzodiorite, monzonite, and syenite near its outer contact. Straight-walled commingled dykes composed of fine-grained, plagioclase-phyric mafic 'pillows' in a subordinate felsic matrix cut the northern unit and are likely related to the southern one. Although mapped separately by Wynne-Edwards (1965) and Wolff (1982), foliated quartz syenite south of the diorite unit is probably related to the Mountain Grove gabbroic rocks (Davidson, 2000). Like the Oso pluton, the Mountain Grove gabbro cuts across earlier folds and foliation in its country rocks.

The dated sample is mafic monzodiorite collected near the southwest contact with marble in which an extensive wollastonite skarn is developed. The extracted zircon was composed mainly of irregular grains full of dark inclusions and elongate 'negative-crystal' bubbles along which many of the grains have broken. Among these were larger elongate grains with clear, well formed, pyramidal terminations at one end and irregular, concave terminations at the other; prism faces also show concave depressions (Fig. 4B). This morphology suggests that zircon grew in interstices within the partly crystallized rock, moulding earlier formed grains of other minerals. Zirconium was thus a conserved element (Nicholls, 1988), and zircon was on the liquidus late in the rock's crystallization history.

Two fractions are near concordia; a third is discordant at 1.1% (Fig. 5). Concordant and nearly concordant fractions B and A yield $^{207}Pb/^{206}Pb$ ages that agree within experimental error. On the basis of these data points, an age and uncertainty of 1154 ± 3 Ma is assigned to the crystallization of this pluton. Regression analysis through the three points and the origin yields an upper intercept age of 1154.9 ± 2.4 Ma. Although

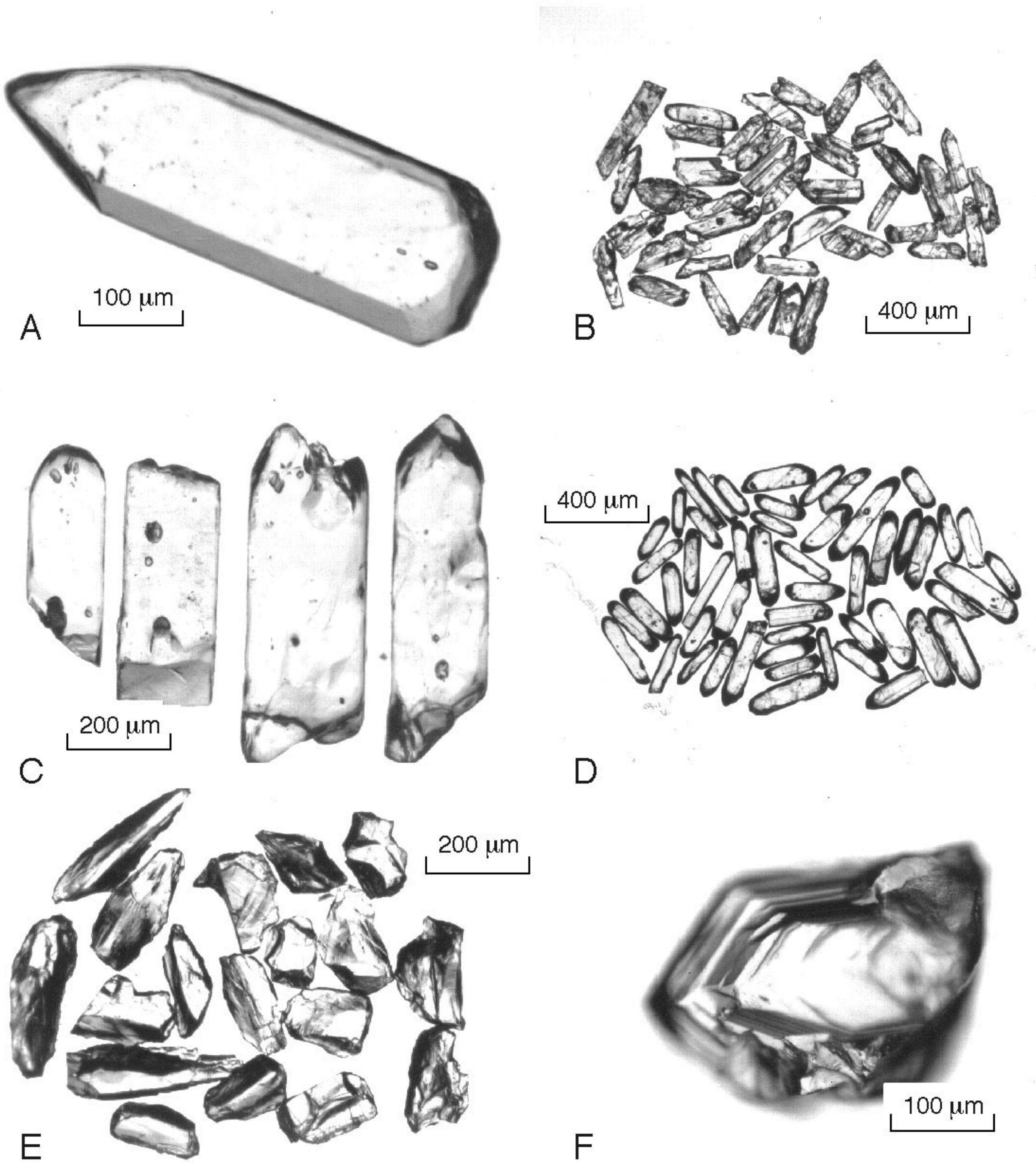

Figure 4. *Characteristics of zircon grains extracted for determining the age of Frontenac suite plutonic rocks.* ***A)*** *One of five large, clear, doubly terminated crystals of fraction E, Oso pluton.* ***B)*** *Fraction A, Mountain Grove pluton, some grains exhibiting single terminations and irregular prism faces indicating moulding on earlier formed mineral grains.* ***C)*** *Fraction C, Bennett Bay pluton, showing crystals of a size and clarity similar to those of zircon from the Oso pluton (A), but with pitted surfaces and rounded terminations.* ***D)*** *Fraction A, Fall River mangeritic gneiss, showing somewhat rounded terminations on zircon grains with igneous morphology.* ***E)*** *Fraction E, North Crosby pluton; shard-like grains derived from colourless, late-stage growth on large, pink cores, and flange-like projections between other rock-forming minerals.* ***F)*** *North Crosby pluton, step-faceted, late-stage zircon growth.*

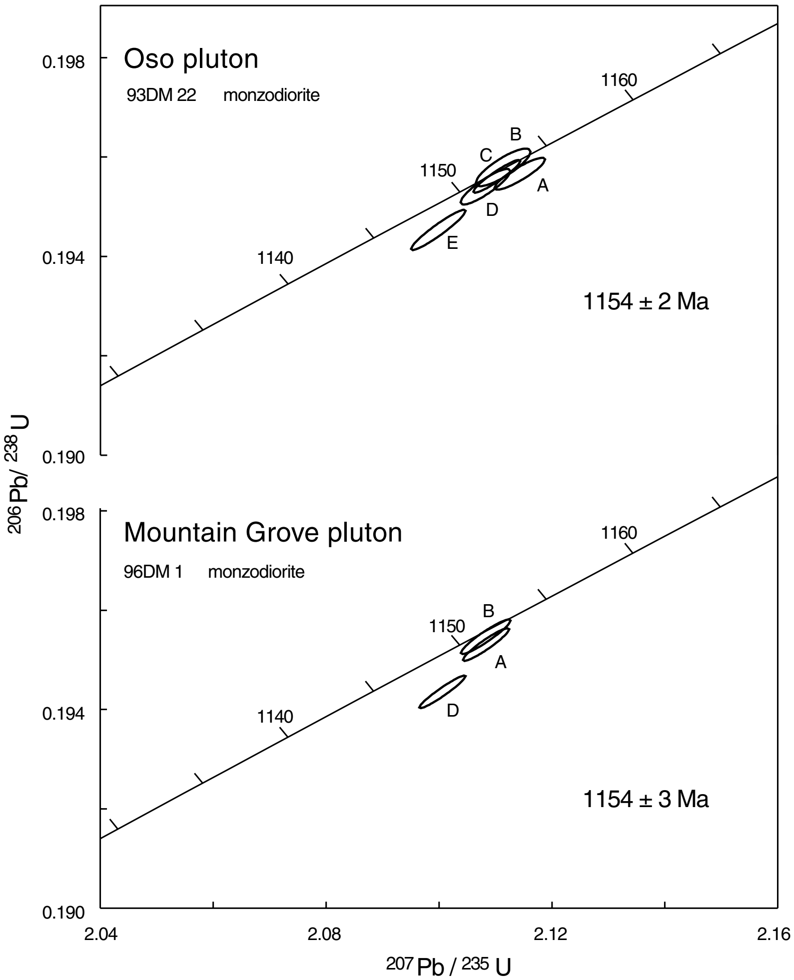

Figure 5.

Uranium-lead concordia diagrams for the Oso and Mountain Grove plutons, Sharbot Lake domain.

the interstitial zircon morphology does not indicate inheritance, a MSWD of 9.7 indicates significant scatter of the data points beyond analytical uncertainty.

PLUTONS SPATIALLY ASSOCIATED WITH THE MABERLY SHEAR ZONE

Silver Lake pluton

The elongate Silver Lake pluton, generally less than 1.5 km wide, extends from Maberly 10 km southwest towards Sharbot Lake. It lies in the immediate footwall of the Maberly shear zone. This composite pluton was emplaced at a shallow angle across contacts between layered amphibolite, rusty schist, and marble, the same assemblage that forms the country rocks of the Oso pluton some 7 km to the west. Most of the Silver Lake pluton is composed of massive, pink, medium-grained monzonite and syenite, but at the northeast end, monzonite grades abruptly into hornblende monzodiorite and hornblende-augite gabbro, previously dated at 1156 ± 2 Ma (Corfu and Easton, 1997). Towards its tapering southwest end, a unit of pink, medium-grained biotite granite lies along the southern contact, separated in part from syenite by a narrow screen of schist and marble. Closest to the Maberly shear zone this granite carries a poorly developed biotite foliation, but its quartz grains are neither elongated nor recrystallized and are only weakly strained. Thus the foliation does not represent a mylonitic fabric.

The sample was collected from a rock cut along an abandoned railway right-of-way south of Highway 7, 200 m west of the Fall River Road. Zircon separates were composed of clear, pale pink, well formed, doubly terminated crystals with sharply defined faces, ranging from stubby prisms and tablets to elongate needles with aspect ratios as great as 10:1. These simply zoned crystals had no evidence of cores or overgrowths. The analyzed fractions were separated on the basis of morphology.

Three data points yield a regression line with a lower intercept close to zero and an upper intercept age of 1161.1 +2.4/-1.6 Ma (Fig. 6). The igneous age is assigned at 1161 +3/-2 Ma.

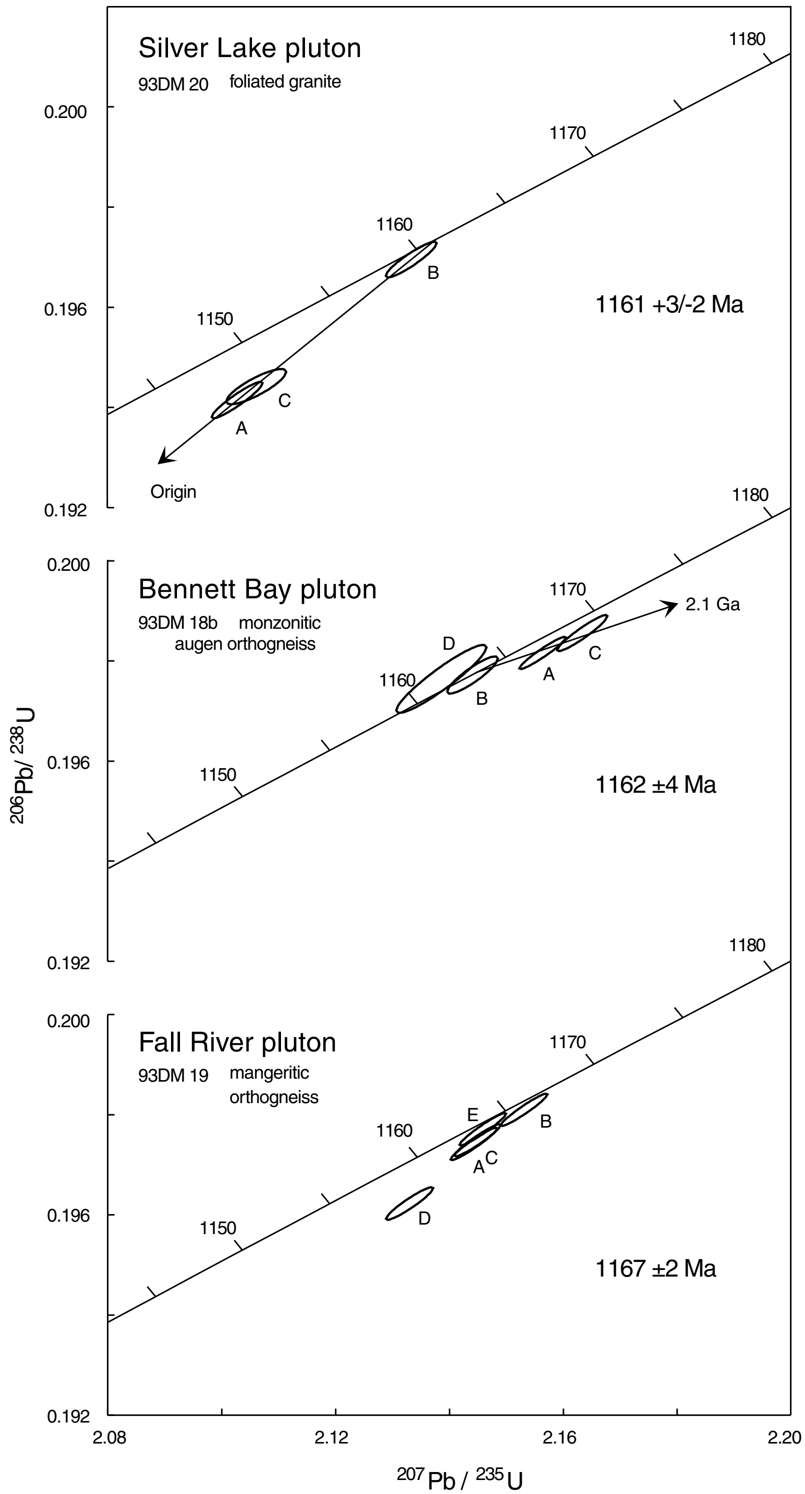

Figure 6.

Uranium-lead concordia diagrams for the Silver Lake, Bennett Bay, and Fall River plutons, north-western Maberly shear zone.

Bennett Bay pluton

The Bennett Bay is an elongate sheet of monzonite in the immediate hanging wall of the Maberly shear zone, generally less than 1 km wide and extending for more than 25 km from Maberly northeast beyond Lanark. It is spatially associated with lenticular, map-scale masses of gabbro and anorthosite. The plutonic rocks are variably foliated and recrystallized, although parts of the gabbro lenses retain little-deformed primary igneous texture. In the most intensely deformed parts, the rocks have been reduced to fine-grained, layered orthogneiss and mylonitic gneiss with feldspar augen, in places containing disaggregated boudins of anorthositic gabbro (Fig. 7A). Foliation dips moderately to steeply southeast and carries an oblique, undulating though generally east-plunging lineation. Shear-sense indicators such as C-and-S fabric and shear-band foliation (Fig. 7B) imply relative displacement of the hanging wall side to the west-northwest. Late pegmatite dykes within the pluton cut this fabric, but are themselves deformed in the same sense.

The dated sample is foliated monzonite with large perthite augen, collected from the top of the ridge north of McGowan Lake, 2.5 km east of Maberly on Highway 7. This site is structurally just above a narrow unit of mylonitized gabbro with anorthositic boudins that mark the base of this part of the Maberly shear zone. Extracted zircon grains ranged from stubby prisms to elongate blades of similar in form to those of the Oso monzodiorite. Many of the larger crystals exhibited pitted surfaces and partly rounded terminations as if partly resorbed (Fig. 4C), but were otherwise clear and free of inclusions; again, no obvious cores or overgrowths were observed, and fractions were chosen on the basis of differing morphology.

Four data points are reversely aligned. The $^{207}Pb/^{206}Pb$ age of concordant fraction B (Table 1) is somewhat younger than the two discordant data points, A and C, but older that the youngest, reversely discordant fraction, D, which was composed of 250 μm long igneous prisms. Regression of the data yields an upper intercept of 2.1 +0.8/-0.7 Ga and a lower intercept of 1163.3 +1.9/-5.7 Ma (MSWD = 0.6) (Fig. 6). The weighted mean $^{207}Pb/^{206}Pb$ age of concordant fractions B and D is 1162 ± 4 Ma and this age is assigned to the time of igneous crystallization. The early Proterozoic upper intercept age suggests a small component of inherited zircon, in spite of the lack of optical evidence for cores. All considered, despite the deformed and recrystallized nature of the Bennett Bay monzonite at the sample locality, the zircon analyses provide no evidence for metamorphism younger than the range of ages derived from the plutons of the Frontenac suite.

Fall River mangeritic augen gneiss

A lens of brown-weathering, greenish-grey augen orthogneiss extends from the north shore of the east part of Sharbot Lake northeastward towards Maberly. It is flanked to the northwest, in order from the pluton margin, by narrow units of coarsely crystalline marble, flaggy, quartzofeldspathic metasedimentary rocks at granulite facies, variably foliated gabbro, mylonitic syenite, heterogeneous quartzofeldspathic straight gneiss, and marble tectonite, this last being at the base of the Maberly shear zone adjacent to the southwestern part of

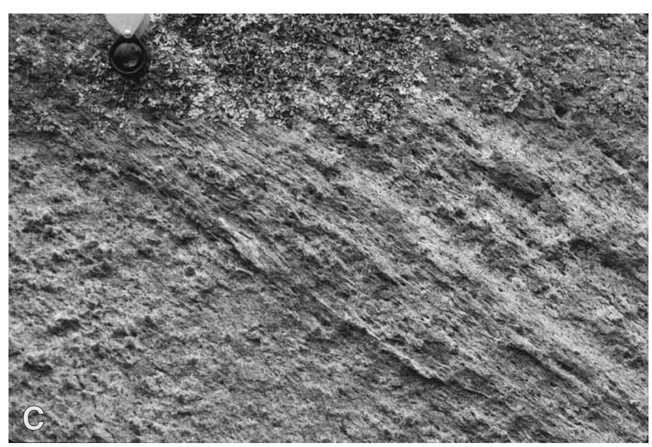

Figure 7. *Strained Frontenac suite plutonic rocks associated with the Maberly shear zone.* ***A)*** *Elongate boudins of gabbroic anorthosite within mylonite at Maberly.* ***B)*** *Protomylonite developed from gabbro with shear band foliation indicating thrust sense to the left (west-northwest); Highway 7, 2 km east of Maberly.* ***C)*** *Mylonitic fabric in monzonite, North Crosby pluton, near its northern contact with marble.*

the Silver Lake pluton. The deformed gabbro and mylonite may represent the attenuated southwest continuation of the Bennett Bay pluton, which may thus lie a little lower in the structural section of the Maberly shear zone than the Fall River mangeritic augen gneiss. On its southeast side the Fall River pluton is separated by a narrow marble unit from recrystallized, corundum-bearing anorthosite and gabbro. A similar augen gneiss extends for several kilometres south of Sharbot Lake (Easton and Davidson, 1994).

The dated sample was obtained from a newly blasted roadcut on the Fall River Road, 3.1 km south of Highway 7. The rock is a uniform, strongly foliated augen gneiss with the composition of quartz-poor monzonite. Its groundmass is a fine mosaic of recrystallized feldspars, ortho- and clinopyroxene, hornblende, traces of garnet, and minor quartz in the form of multigrained lenticles. The augen are single grains of perthite with bent exsolution lamellae enveloped by finely recrystallized orthoclase.

The zircon grains extracted for analysis were well formed, zoned prisms without inherited cores. Their terminations were somewhat rounded (Fig. 4D) and they showed no sign of metamorphic overgrowth. Small, equant, multifaceted crystals typical of metamorphic zircon were not observed. Five fractions were picked on the basis of morphology and size. Of five data points, three are clustered and slightly discordant and one is discordant at 1.2% (Fig. 6). The weighted average of all $^{207}Pb/^{206}Pb$ ages is 1167 ± 2 Ma (MSWD = 4.1), which is assigned to the time of igneous crystallization. The $^{207}Pb/^{206}Pb$ age of fraction D, composed of broken-off tips of zircon prisms, is no younger than the other four analyzed fractions; as in the case of the Bennett Bay pluton, the U-Pb data show no evidence for metamorphism of significantly younger age. The metamorphic texture and assemblage of this rock appear to have developed at or very shortly after the time of igneous crystallization.

Table 1. U-Pb analytical data.

Fraction[a]	Wt.[b] (mg)	U (ppm)	Pb[c] (ppm)	$^{206}Pb^d/^{204}Pb$	Pb[e] (pg)	$^{208}Pb^f/^{206}Pb$	^{207}Pb ±1SE[f] / ^{235}U	^{206}Pb ±1SE[f] / ^{238}U	^{207}Pb ±1SE[f] / ^{206}Pb	$^{207}Pb/^{206}Pb$ Age (Ma)	Discord[h] (%)
Oso pluton				**93DM 22**	**Z3971**		**UTM 364325E, 4962500N (18)**				
A, 200, N 0	84	62	12	2771	23	0.113	2.114 ± 0.11	0.1957 ± 0.08	0.07837 ± 0.05	1156 ± 2	0.40
B, 250, N 0	81	33	7	3371	10	0.169	2.111 ± 0.12	0.1958 ± 0.10	0.07821 ± 0.06	1152 ± 3	-0.05
C, 350, N 0	135	56	12	6641	14	0.176	2.110 ± 0.10	0.1956 ± 0.08	0.07824 ± 0.04	1153 ± 1	0.12
D, 200, N 0	80	40	8	6662	6	0.117	2.108 ± 0.10	0.1954 ± 0.09	0.07825 ± 0.05	1153 ± 2	0.25
E, 300, N 0	70	68	14	7814	7	0.163	2.100 ± 0.12	0.1945 ± 0.10	0.07829 ± 0.04	1154 ± 2	0.78
Mountain Grove pluton				**96DM 1**	**Z4179**		**UTM 356100E, 54949700N (18)**				
A, 200, N 5	23	249	52	10139	7	0.171	2.108 ± 0.10	0.1953 ± 0.09	0.07829 ± 0.03	1154 ± 1	0.40
B, 200, N 5	28	233	49	5148	16	0.162	2.108 ± 0.10	0.1955 ± 0.09	0.07823 ± 0.04	1153 ± 2	0.16
D, 200, N 5	123	202	41	14462	21	0.143	2.101± 0.10	0.1944 ± 0.09	0.07839 ± 0.03	1157 ± 1	1.11
Silver Lake pluton				**93DM 20**	**Z3977**		**UTM 369500E, 4961725N (18)**				
A, 150, N 0.5	11	330	65	7962	2	0.104	2.103 ± 0.11	0.1941 ± 0.09	0.07855 ± 0.04	1161 ± 2	1.6
B, 150, N 0.5	14	224	45	5688	7	0.100	2.133 ± 0.11	0.1970 ± 0.09	0.07856 ± 0.04	1161 ± 2	0.2
C, 200, N 0.5	15	216	43	1912	20	0.098	2.106 ± 0.13	0.1944 ± 0.09	0.07857 ± 0.07	1161 ± 3	1.51
Bennett Bay pluton				**93DM 18b**	**Z3976**		**UTM 381700E, 4966650N (18)**				
A, 150, N 0	40	201	41	15691	6	0.109	2.156 ± 0.10	0.1982 ± 0.08	0.07892 ± 0.03	1170 ± 1	0.45
B, 100, N 0, t	41	168	34	9615	9	0.102	2.144 ± 0.10	0.1977 ± 0.09	0.07865 ± 0.05	1163 ± 2	0.02
C, 400, N 0	78	93	19	13048	7	0.124	2.163 ± 0.10	0.1986 ± 0.09	0.07902 ± 0.04	1173 ± 1	0.48
D, 250, N 0	49	161	33	4697	21	0.121	2.139 ± 0.19	0.1976 ± 0.17	0.07848 ± 0.07	1159 ± 3	-0.34
Fall River mangerite				**93DM 19**	**Z4312**		**UTM 370950E, 4960400N (18)**				
A, 200, N 2	72	196	40	15255	11	0.112	2.144 ± 0.10	0.1974 ± 0.08	0.07878 ± 0.03	1167 ± 1	0.48
B, 100, N 2	80	193	39	14360	13	0.107	2.153 ± 0.10	0.1981 ± 0.08	0.07883 ± 0.03	1168 ± 1	0.26
C, 100, N 2	43	186	37	12582	8	0.101	2.145 ± 0.10	0.1975 ± 0.08	0.07877 ± 0.03	1166 ± 1	0.43
D, 100, N 2, t	25	191	38	7659	8	0.100	2.133 ± 0.10	0.1962 ± 0.08	0.07884 ± 0.04	1168 ± 1	1.22
E, 200, N 2	77	195	39	17684	11	0.112	2.146 ± 0.10	0.1977 ± 0.08	0.07872 ± 0.03	1165 ± 1	0.19
North Crosby pluton				**91DM 131a**	**Z3975**		**UTM 387525E, 4959300N (18)**				
A, 300, N 0	81	119	26	17866	6	0.241	2.105 ± 0.10	0.1946 ± 0.08	0.07846 ± 0.03	1159 ± 1	1.15
B, 200, N 0	24	155	32	10016	5	0.144	2.107 ± 0.10	0.1950 ± 0.09	0.07837 ± 0.03	1156 ± 1	0.74
C, 150, N 0	25	134	29	8233	5	0.209	2.105 ± 0.10	0.1948 ± 0.09	0.07836 ± 0.04	1156 ± 1	0.82
D, 200, N 0. r	123	85	19	23446	2	0.240	2.115 ± 0.10	0.1956 ± 0.09	0.07841 ± 0.04	1157 ± 1	0.51
E, 250, N 0, r	73	52	12	3763	12	0.259	2.122 ± 0.12	0.1964 ± 0.10	0.07836 ± 0.06	1156 ± 2	0.02
Pike Lake pluton				**91DM 14b**	**Z3267**		**UTM 396625E, 4959500N (18)**				
A, 150	31	110	24	3784	11	0.173	2.169 ± 0.11	0.1991 ± 0.09	0.07901 ± 0.06	1172 ± 2	0.18
B, 70	34	120	26	4518	11	0.179	2.188 ± 0.11	0.2003 ± 0.09	0.07925 ± 0.05	1178 ± 2	0.16
C, 100	53	96	20	3810	9	0.156	2.184 ± 0.11	0.1999 ± 0.09	0.07925 ± 0.06	1178 ± 3	0.35
Beales Mills pluton				**94DM 53**	**Z3970**		**UTM 423025E, 4936225N (18)**				
A, 150, N 0	31	154	32	7919	7	0.162	2.139 ± 0.11	0.1970 ± 0.09	0.07872 ± 0.04	1165 ± 2	0.53
B, 100, N 0	22	124	26	4082	8	0.171	2.115 ± 0.11	0.1949 ± 0.09	0.07871 ± 0.05	1165 ± 2	1.59
C, 200, N 0	39	110	23	2899	18	0.169	2.137 ± 0.12	0.1973 ± 0.11	0.07854 ± 0.07	1161 ± 3	-0.04
D, 150, N 0	26	151	31	1988	24	0.151	2.120 ± 0.14	0.1955 ± 0.10	0.07866 ± 0.09	1164 ± 4	1.18

[a] Approximate average sizes in µm before abrasion; M and N refer to magnetic and nonmagnetic fractions at side slope indicated in degrees; t = tips, r = rims. [b] Error on weight = ± 1µg. [c] Radiogenic Pb. [d] Measured ratio corrected for spike and Pb fractionation of 0.09 ± 0.03%/AM. [e] Total common Pb on analysis corrected for fractionation and spike. [f] Corrected for blank and common Pb, fractionation, and spike. [g] Age error quoted is 2 SE in Ma. [h] Discordance along a discordia to origin.

PLUTONS IN THE NORTHWEST SHEARED PART OF THE FRONTENAC TERRANE

North Crosby pluton

The North Crosby pluton is relatively large, composite, and straddles the northern boundary of North Crosby Township, extending for at least 20 km from the north end of Bobs Lake northeastward towards Perth. Its northeastern part is overlain by Paleozoic sedimentary rocks. Massive rocks occupy the core of its 4 km wide central part and also of its tapering southwest end. These rocks become increasingly foliated outward, particularly towards the pluton's northwest contact with marble where they progress through protomylonite to mylonite (Fig. 7C). In places along the southeast contact, layering and foliation in metasedimentary gneiss containing cordierite, garnet, and elongate sillimanite-spinel faserkiesel are truncated at a high angle by monzonite with a well developed, contact-parallel foliation. Metre-scale septa of marble tectonite are traceable for several kilometres within the southeastern part of the pluton, reminiscent of the marble septa in the Oso pluton. Most of the pluton is composed of feldspathic rocks ranging from violet-grey monzodiorite and monzonite to pink syenite and quartz syenite, which in their massive parts are very similar in appearance to rocks of equivalent composition in the Oso pluton. Hornblende diorite and gabbro occur as discrete lenses in the southwest part of the pluton. In some places blocks of relatively massive gabbro are included within foliated monzonite or syenite whose foliation wraps the blocks. Commingled dykes are common locally; some are foliated parallel to their contacts, whereas others are not deformed, regardless of the structural state of their host rocks. An instructive exposure on County Road 6 displays an internally deformed, commingled dyke cutting undeformed, commingled rock (Fig. 3B), implying that deformation occurred within the dyke as it cooled after emplacement in its already crystallized host. In general, the structural relationships exhibited by this pluton are better explained by appealing to synemplacement deformation rather than to an altogether younger event of regional deformation.

A sample of grey, coarse-grained monzodiorite was collected for dating from the massive core of the pluton. The copious zircon separate contained large, clear, pink, terminated prisms and prism fragments up to 700 µm long by 200 µm wide (fractions A and C), smaller equant and tabular crystals (fraction B), and a population of clear, colourless, shard-like fragments (fractions D and E), some of them partly faceted (Fig. 4E, F). A few grains showed that the colourless

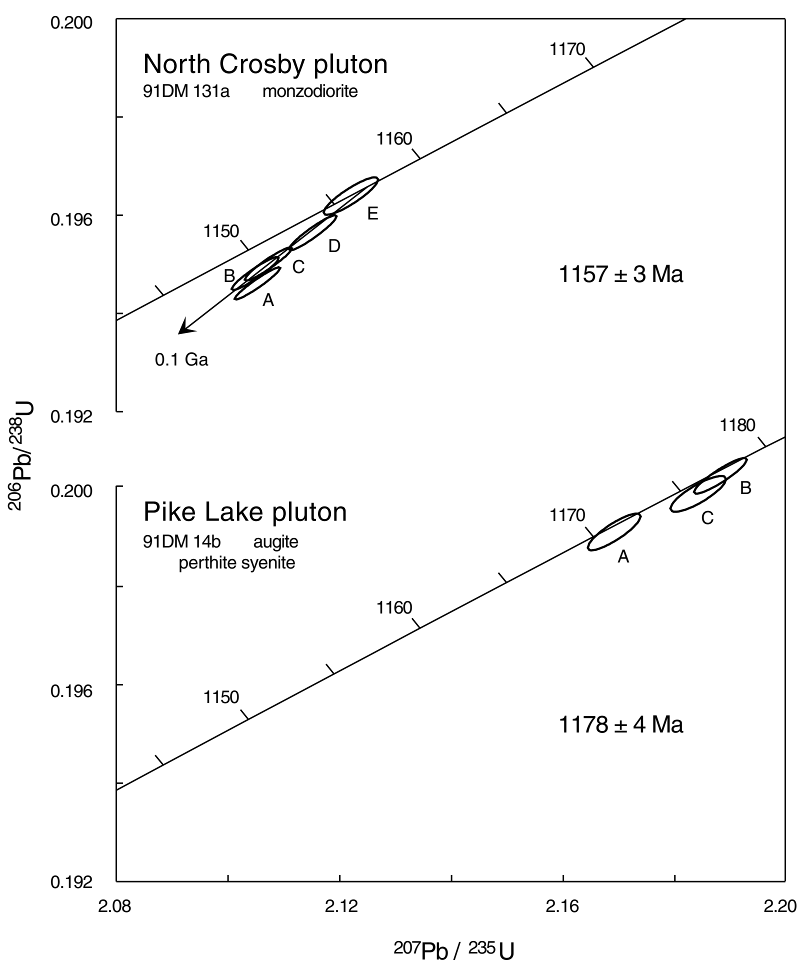

Figure 8.

Uranium-lead concordia diagrams for the North Crosby and Pike Lake plutons, in the sheared northwestern part of the Frontenac terrane.

zircon fragments were derived from the outer, step-faceted rims of large pink crystals (Fig. 4F), suggestive of overgrowths.

Five data points are concordant to 1.1% discordant, are aligned, and yield a regression line with intercepts at 1157 +3.5/-1.5 Ma and ca. 0.1 Ga (Fig. 8). The only concordant data point, E, corresponds to a $^{207}Pb/^{206}Pb$ model age of 1156 ± 2 Ma. The age and uncertainty of igneous crystallization is therefore assigned at 1157 ± 3 Ma. Fractions D and E (Fig. 4E) were composed of the shard-like grains described above; they have the lowest U contents and are the least discordant of the five fractions. The concordant $^{207}Pb/^{206}Pb$ age of data point E indicates that the clear outer rims were formed during igneous crystallization and were not due to subsequent metamorphic overgrowth.

Pike Lake pluton

This elongate pluton lies between Pike and Black lakes, 15 km southwest of Perth. It is separated from the adjacent North Crosby pluton to the northwest by a band of metasedimentary gneiss and marble tectonite. It is composed largely of syenite similar to the syenitic phases of the North Crosby pluton, but in much of the pluton this is represented by thoroughly recrystallized, pink, buff, or greenish-yellow orthogneiss. The dated sample was collected on the road south of Stanleyville from a small outcrop of relatively massive, medium-grained, greenish augite-perthite syenite.

The clear, colourless zircon population was divided into three fractions. The grains in fraction A were slightly elongate (2:1) and somewhat rounded, with minor internal fractures and inclusions. They ranged in length from 100 to 250 µm. Many had broken ends. Fractions B and C consisted of more elongate grains, with an average length of approximately 200 µm. The zircon grains were subhedral, with rounded terminations. Some were fractured and/or contained minor fluid inclusions.

The three data points are concordant to nearly concordant. Points B and C correspond to $^{207}Pb/^{206}Pb$ ages of 1178 Ma, and point A has a $^{207}Pb/^{206}Pb$ age of 1172 Ma (Fig. 8). As there is no analytical overlap between these ages, either the older is correct and the younger represents metamorphically disturbed zircon, or the younger is correct and the older fractions contain a component of inherited zircon. The first interpretation is preferred because prismatic fraction B and C have the same age, and because the younger fraction has a more rounded morphology. An age and uncertainty of 1178 ± 3 Ma is assigned to the crystallization of this pluton. This age is significantly older than the other ages obtained for Frontenac suite plutons reported here, but is similar to ages obtained for the Crow Lake (1176 Ma; Marcantonio et al., 1990) and Rockport plutons (1173 Ma; van Breemen and Davidson, 1988) in the interior of the Frontenac terrane to the south (Fig. 2). The fact that the Pike Lake pluton is both older and more recrystallized than the younger plutons near the Maberly shear zone accords with the concept that the Frontenac suite was introduced during the active life of the shear zone.

INTERIOR OF THE FRONTENAC TERRANE

Beales Mills pluton

Exposed on the northeast shore of Charleston Lake and largely buried beneath Paleozoic sedimentary rocks to the north and east (Fig. 2), the Beales Mills pluton intrudes marble and metasedimentary granulite along its exposed southern contact, truncating north-trending layering and lithological contacts in these rocks (Wynne-Edwards, 1963). Contact skarn is developed in marble at Charleston Lake (Wynne-Edwards, 1967). The predominant plutonic rock is massive, medium-grained, pink to buff biotite-hornblende monzonite. In several places the monzonite is heavily charged with angular to subrounded xenoliths of country rock gneiss. Unlike the plutonic rocks in the northwestern Frontenac terrane, foliation is absent.

According to a tectonic model for this region advanced by Hildebrand and Easton (1995), Frontenac suite plutons and the siliceous metasedimentary rocks they intrude belong to a "...hot, pluton-saturated arc basement..." that was tectonically emplaced "...on top of cool platformal carbonates." (Hildebrand and Easton, 1995, p. 917). The implication of this statement is that the contacts between Frontenac suite plutons and marble are tectonic rather than intrusive. Accepting Wynne-Edwards' evidence that the Beales Mills pluton (then undated) intrudes marble, these authors assigned this pluton to the younger "1080 to 1060" Ma group of intrusions (Skootamatta suite) that has been identified elsewhere in the Central metasedimentary belt (*see* Davidson and van Breemen, 2000). To test this assignation and the hypothesis in general, a sample of massive, xenolith-free monzonite was collected for dating from a roadcut just south of Beales Mills village.

The zircon population contained doubly terminated grains varying from stubby tablets or equant prisms to elongate prisms with aspect ratios as great as 5:1. Four fractions of different aspect were picked for analysis. Most grains were clear, colourless to pale pink, and lacked obvious cores. Some of the larger crystals contained bubbles aligned with the prismatic axis. Grains in the fraction of elongate prisms (fraction D) were slightly fractured and tended to break during abrasion.

The four data points range from concordant to 1.6% discordant (Fig. 9). No distinction can be made between the euhedral tabular zircon morphologies among the fractions. A regression of all four data points yields upper and lower intercept ages of 1163.4 +6.7/-2.3 Ma and -0.2 Ga respectively, with a MSWD of 4.2 that is consistent with the slight scatter of data points. In view of the concordance to moderate discordance of the data points and a lower intercept near the origin, the weighted mean $^{207}Pb/^{206}Pb$ age for all four fractions, 1164 ± 2 Ma, is assigned to the time of igneous crystallization. This age is indistinguishable from the ages obtained for several other Frontenac plutons to the south and southwest (*see* Fig. 2), in particular the nearby Lyndhurst pluton (1166 ± 3 Ma; Marcantonio et al., 1990), which Hildebrand and Easton (1995), on the basis of their hypothesis, singled out as a klippe of "hot upper plate" on footwall marble. The age of the Beales Mills pluton corroborates the arguments of Davidson and Carmichael (1996) that this hypothesis is untenable.

Tectonic significance of the Frontenac suite

As outlined above, only those plutons of the Frontenac suite near the Maberly shear zone and subsidiary shear zones in the northwest Frontenac terrane are deformed and recrystallized; those in the Sharbot Lake domain and in the core of the Frontenac terrane are not, save for the development of minor or localized foliation that can be attributed to emplacement mechanisms. At first glance, therefore, it would seem that the severe deformation in the Frontenac–Elzevir boundary zone may represent post-plutonic tectonism restricted to the boundary region that, given the presence of thrust-sense shear indicators in this zone (Fig. 7, B), would imply compressive closure between these terranes at some time after ~1150 Ma.

Several lines of evidence, however, suggest that this interpretation is incorrect and that the tectonic history of this region is more complex. The main one is the finding of Mezger et al. (1993) and Corfu and Easton (1997) that titanite from metamorphic rocks throughout the region southeast of the Robertson Lake shear zone, including within the Maberly shear zone, records U-Pb ages in the same range as or only slightly younger than the age range of the Frontenac suite itself. As the closure temperature of titanite (≤600°C) is below estimates of metamorphic temperature for the granulite-facies metamorphism in the Frontenac terrane (e.g. Lonker, 1980) and the amphibolite-facies metamorphism in the Wolf Grove structure of the Sharbot Lake domain (Buckley et al., 1997), it would appear that peak regional metamorphism preceded emplacement of Frontenac suite intrusions. This is supported by the field evidence that older metamorphic mineral assemblages are overprinted in the aureoles of plutons. In addition, ages of metamorphic zircon in Frontenac terrane metasedimentary gneiss (Wasteneys, 1994), and of both zircon and monazite in similar rocks in the equivalent region of southwestern Quebec (Corriveau and van Breemen, 1994), suggest regional metamorphism at ca. 1190–1180 Ma, slightly earlier than the oldest members of the Frontenac suite.

Second, zircon crystals extracted from deformed Frontenac suite plutons near the terrane boundary show no evidence for secondary zircon growth: fractions of clear tips from both Bennett Bay and Fall River augen orthogneiss, and of apparent overgrowths in monzonite from the North Crosby pluton, are no different in age than fractions of abraded zircon cores from the same rocks. There is thus no evidence for post-plutonic growth of zircon in these deformed rocks, even though they have recrystallized to varied degrees.

Third, recrystallized Frontenac-suite plutonic rocks in the immediate hanging wall of the Maberly shear zone locally exhibit granulite-facies mineral assemblages (e.g. Fall River pluton), yet the ages of titanite from their country rocks, as outlined above, does not support the co-existence of regional granulite-facies metamorphic conditions following plutonism.

Fourth, mylonitic fabric indicating northwestward thrust-sense displacement is preferentially developed in the plutonic rocks at the margins of some plutons in the hanging wall of the Maberly shear zone (e.g. North Crosby pluton). Its orientation is parallel to outer contacts where these cut across layering in siliceous country rock gneiss, and it is equally strongly developed against marble.

A reasonable interpretation of these facts is that the northwestern part (leading edge) of the Frontenac terrane was undergoing active compression (ductile thrusting over the Sharbot Lake domain) at the time that Frontenac magma was introduced, and that deformation continued as the magma crystallized and cooled. If the plutonic rocks were in a deforming environment when only a little below their crystallization temperature, granulite-facies assemblages would

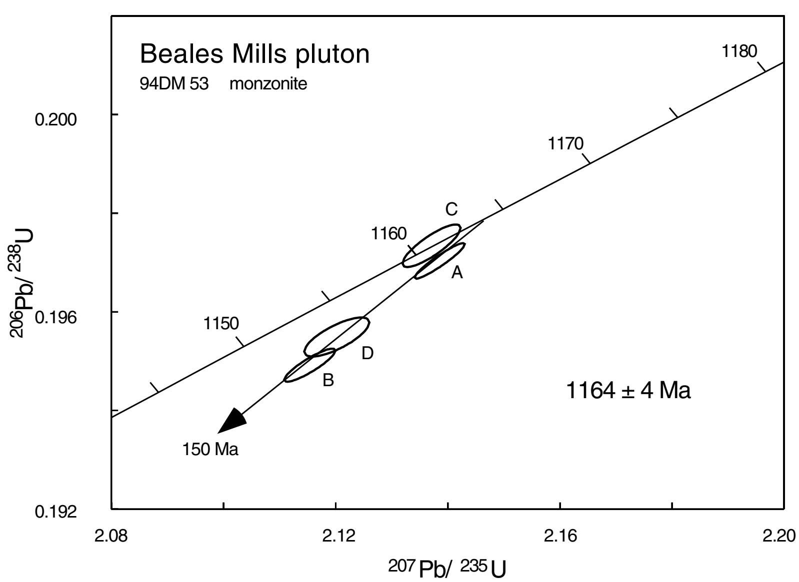

Figure 9.

Uranium-lead concordia diagram for the Beales Mills pluton, interior of the Frontenac terrane.

form during high-temperature recrystallization, particularly if the rocks remained relatively dry. Granulite-facies assemblages in such rocks therefore need not be an indicator of regional metamorphic conditions. The same reasoning can explain the presence of augen gneiss, protomylonite, and mylonite with contact-parallel fabric at discordant contacts.

On the other hand, the type of plutonism represented by the Frontenac suite is more reminiscent of magmatism in an environment of crustal extension, and it is possible that a period of extension occurred immediately following compressive closure between the Frontenac and Elzevir blocks. Closure may have occurred as early as ca. 1.22 Ga, shutting down magmatism in the Elzevir terrane (youngest plutonism ca. 1225 Ma; Corfu and Easton, 1997). This would be enough time (ca. 30 Ma) for thermal relaxation to allow high-grade metamorphism (ca. 1190 Ma) in the thickened Frontenac block, and the development of A-type magma beneath it (earliest Frontenac suite plutonism ca. 1180 Ma). Renewed and perhaps intermittent compression during or shortly after intrusion of the Frontenac suite, however, is necessary to explain the findings presented above. The Frontenac suite can thus be considered post-collisional with respect to the Elzevirian orogeny, but syntectonic with respect to the continuing development of the Grenville Orogen as a whole.

SUMMARY

The age determinations reported above corroborate those of Corfu and Easton (1997) and confirm that plutons of the Frontenac suite occur throughout the Frontenac terrane and Sharbot Lake domain (an across-strike distance of approximately 100 km), much farther northwest than suggested by Lumbers et al. (1990). Similar ages obtained for the Chevreuil suite in neighbouring Quebec (Corriveau et al., 1998) attest to the even greater along-strike distribution of this type of plutonism within the Central metasedimentary belt.

The magmas responsible for the Frontenac suite were probably generated in the upper mantle (gabbro and anorthosite) and overlying crust (granitoids). Following the collision that terminated the Elzevirian orogeny at ca. 1.2 Ga, these magmas rose through the thickened crust, perhaps during a period of post-collisional extension, to form 1) composite plutons that crystallized and remained undeformed where they ponded beneath the Maberly shear zone (Sharbot Lake domain), 2) elongate plutons of deformed and recrystallized rock where they penetrated this zone during or shortly before it was tectonically reactivated, and 3) undeformed plutons where they passed through this zone and crystallized at a higher structural level (Frontenac terrane). In high-grade metasedimentary gneiss, the preservation of U-Pb titanite ages in the same range as that of the Frontenac suite (1180–1150 Ma) and of ^{40}Ar/^{39}Ar hornblende ages of ca. 1125 Ma attests to relatively slow regional cooling immediately following post-collisional plutonism. Apart from the introduction of small plutons of the Skootamatta suite some 100 Ma later, very little appears to have happened in the Frontenac–Sharbot Lake block after ca. 1150 Ma, in strong contrast to its neighbouring terranes (for a summary *see* Davidson, 1998). Adirondack Highlands terranes to the southeast and Morin terrane and regions farther east underwent deformation, high-grade metamorphism, and continued plutonism between 1100 and 1030 Ma; similarly, the northwestern part of the Central metasedimentary belt and the region of older gneissic rocks beyond it underwent severe ductile deformation at high metamorphic grade during this time. Subsequent to its initial cooling following emplacement of the Frontenac suite, the Frontenac–Sharbot Lake block is therefore envisaged as riding high in the tectonic pile that constituted the Grenville Orogen during its post-collisional history.

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