New Age Controls on Rock Units in the Chéticamp Area, Western Cape Breton Island, Nova Scotia, Canada

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Introduction

The Chéticamp area of Cape Breton Island is located in the western part of the Aspy terrane, which is generally considered to be part of the microcontinent of Ganderia (Fig. 1). This area has been an economic mineral exploration target since the 1890s with the discovery of Zn, Cu and Pb in rocks now known as the Jumping Brook Metamorphic Suite (JBMS), as well as Cu and Ba mineralization in the associated plutonic units and Fisset Brook Formation (e.g. Sangster *et al*., 1990 and references therein).

Pre-Carboniferous rocks in the Chéticamp area include varied metasedimentary rocks, mafic and felsic metavolcanic rocks, amphibolite, and varied gneissic and plutonic rocks; ages range from Late Neoproterozoic to Devonian, and inter-relationships are complex and uncertain (e.g. Lin *et al*., 2007). The area is dominated by the Late Neoproterozoic "Chéticamp Pluton" (Barr *et al*., 1986; Jamieson *et al*., 1986) and hence is not typical of the rest of the Aspy terrane, which is made up mainly of Ordovician(?)-Devonian metavolcanic, metasedimentary and plutonic rocks. However, contacts of the pluton are mainly faults, and hence its relationship with the adjacent JBMS has been uncertain (e.g. Barr *et al*., 1986, 1992; Jamieson *et al*., 1989, 1990; Lin *et al*., 2007; Tucker, 2011; Slaman, 2015).

It has been suggested that these rocks and others in western Cape Breton Island may correlate with those in parts of Ganderia in central Newfoundland and New Brunswick (Fig. 1; inset), which host important economic mineral deposits (e.g. Barr *et al*., 1998; van Staal, 2007; van Staal *et al*., 2009; Tucker, 2011). In order to resolve the uncertainties caused by conflicting field relations and ages, and to further investigate the possible regional correlations, more detailed studies of field relations, rock types, geochemistry, ages and tectonic setting have been undertaken in the Chéticamp area; preliminary results of U-Pb dating are reported here.

Geological Summary

Details of the mapping program and previous geological investigations were summarized by White *et al*. (2014). Preliminary results of the 2014 and 2015 field season were presented by Slaman *et al*. (2014) and White *et al*. (2015a, b, 2016) and are summarized here together with previous work in the area.

Pre-Devonian rocks in the Chéticamp area are mainly metamorphic and plutonic (Fig. 1). The metamorphic rocks were assigned to the Jumping Brook Metamorphic Suite (JBMS) by Jamieson *et al*. (1989, 1990) and later modified by Barr *et al*. (1992), Tucker (2011), Slaman *et al*. (2014) and White *et al*. (2015b, 2016). The suite consists of the Faribault Brook, Barren Brook, Dauphinee Brook, Corney Brook, and Fishing Cove River formations, as well as the Rocky Brook conglomerate and George Brook amphibolite. Mapping in 2014 defined a previously unnamed metamorphic unit to the south, which was named the Stewart Brook Formation and included in the JBMS (Slaman *et al*., 2014; White *et al*., 2015b). Additional mapping in 2015 showed that the metasedimentary Stewart Brook formation in the

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White, C. E., Barr, S. M., van Rooyen, D., McCarron, T., Slaman, L. R. and Shute, J. M. 2016: *in* Geoscience and Mines Branch, Report of Activities 2015; Nova Scotia Department of Natural Resources, Report ME 2016-001, p. 131-142.

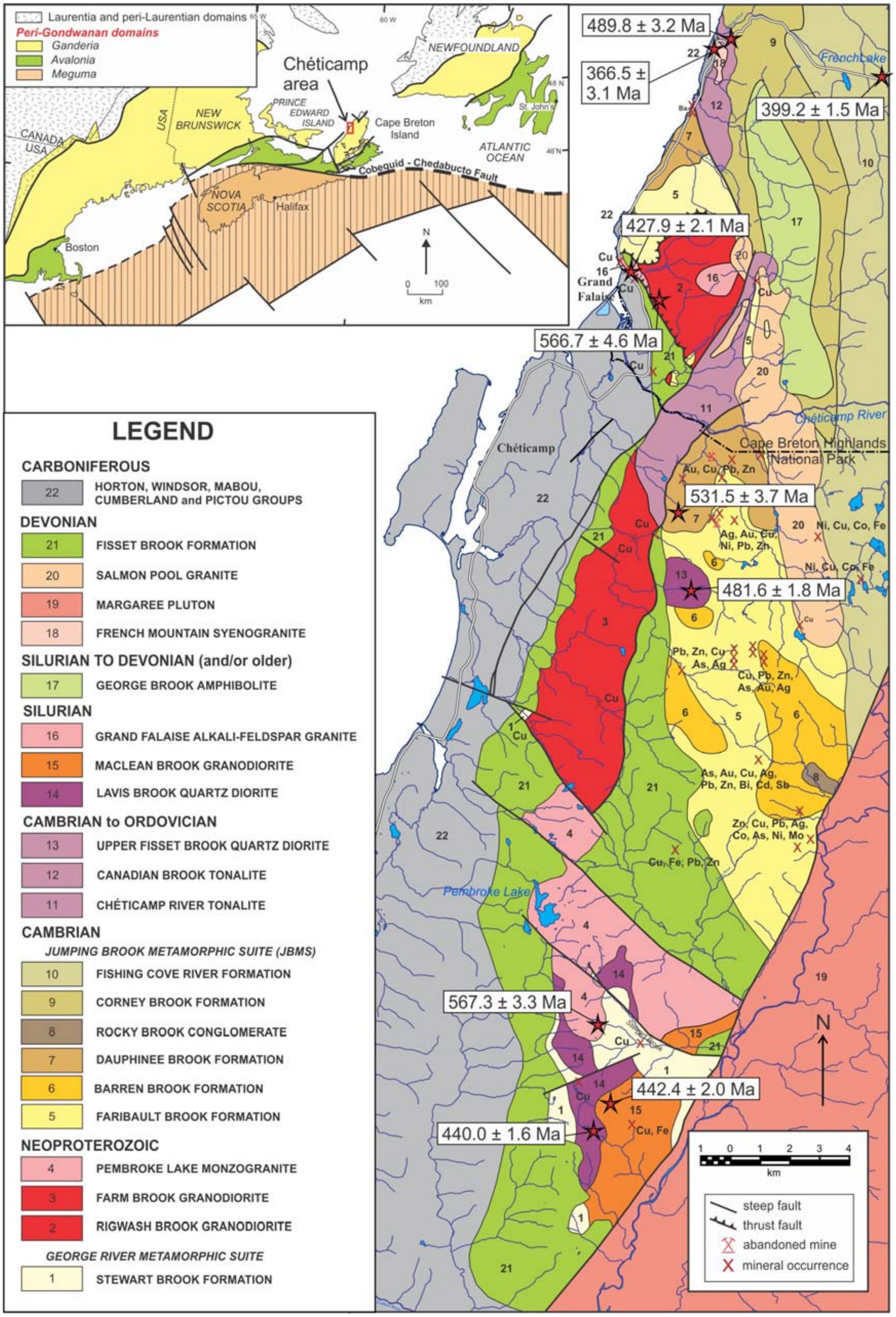

Figure 1. Simplified geology map of the Chéticamp area modified from White *et al*. (2015b). Stars with dates are samples from this study. Inset map of the northern Appalachian orogeny after Hibbard *et al*. (2006) showing the location of the study area (red box) in Ganderia of western Cape Breton Island, Nova Scotia.

southern part of the map area is lithologically similar to parts of the George River metamorphic suite exposed farther to the east in the Bras d'Or terrane (White *et al*., 2015a, 2016).

Previously included in the JBMS (e.g. Jamieson *et al*., 1989, 1990) was the George Brook Amphibolite, which, based on its igneous protolith, is herein considered younger and hence removed from the metamorphic suite. All these units have been deformed and regionally metamorphosed to varying degrees, generally ranging from greenschist facies (chloritoid-biotite grade) in the eastern and southern parts of the area to amphibolite facies (kyanite grade) in the northeastern part (e.g. McCarron *et al*., 2016). The eastern part of the JBMS is flanked by the Belle Cote Road orthogneiss and on the northeast by the Pleasant Bay complex (Jamieson *et al*., 1986; Barr *et al*., 1992; Horne *et al*., 2003).

These metamorphic units have been intruded by, or are in faulted contact with, varied Neoproterozoic to Silurian dioritic to syenogranitic plutons (most of which were previously assigned to the Chéticamp Pluton) and the Devonian Margaree and Salmon Pool plutons (e.g. Barr *et al*., 1992; Slaman, 2015). New U-Pb (zircon) dating presented in this report shows that plutonic units of five different ages occur in the area: (1) ca. 567 Ma (Pembroke Lake monzogranite, Farm Brook granodiorite and Rigwash Brook granodiorite); (2) ca. 485-480 Ma (Chéticamp River tonalite, Canadian Brook tonalite and Upper Fisset Brook quartz diorite); (3) ca. 440 Ma (MacLean Brook granodiorite and Lavis Brook quartz diorite); (4) ca. 429 Ma (Grand Falaise alkali-feldspar granite); and (5) ca. 370 Ma (French Mountain syenogranite and the previously dated Salmon Pool granite). The Neoproterozoic, Cambrian and Silurian-Devonian plutons have petrographic and chemical characteristics consistent with calc-alkaline affinity and emplacement in a volcanic-arc tectonic setting, indicating a long history of subduction-related magmatism in the area.

Along the eastern and southern flanks of the highlands the older units are overlain or in faulted contact with volcanic and sedimentary rocks of the Middle to Late Devonian Fisset Brook Formation and the Carboniferous Horton, Windsor, Mabou, Cumberland and Pictou groups (Giles *et al*., 1997a, b).

Previous Dating

Interpretations of the tectonic evolution of the Chéticamp area have been hampered by the lack of reliable radiometric ages. Interpretations relied on only a few whole-rock and mineral Rb-Sr and K-Ar ages on plutonic units and broad geological correlations with similarly dated units elsewhere in Cape Breton Island (e.g. Currie, 1987). Many of these earlier ages were considered unreliable due to the effects of alteration and uncertain sample selections and locations (e.g. Barr *et al*., 1982, 1985; Jamieson and Craw, 1983). To address some of these issues, U-Pb zircon and $^{40}Ar/^{39}Ar$ amphibole, biotite and muscovite dating techniques were used that are less susceptible to resetting and alteration than previously used methods (Table 1) (Currie *et al*., 1982; Jamieson *et al*., 1986; Reynold *et al*., 1989; Lin *et al*., 2007).

The earliest U-Pb zircon ages from the study area (Table 1) were conducted by Currie *et al*. (1982) on what was described as a felsic dyke cutting the rock cliffs at Grand Falaise. These zircon grains yielded a crystallization age of 439 ± 7 Ma, considerably older than the K-Ar biotite age of 363 ± 9 Ma from the same sample (e.g. Wanless *et al*., 1979). A sample collected from the muscovite- and biotite-bearing unit of the former Chéticamp Pluton (Pembroke Lake monzogranite of this study; Fig. 1) yielded a U-Pb zircon crystallization age of 550 ± 8 Ma (Jamieson *et al*., 1986). Although within the upper limits of the error, this age is older than the combined Rb-Sr whole-rock/muscovite isochron age of 526 ± 74 Ma (recalculated using Ludwig, 2003) cited by Cormier (1972) for the Chéticamp Pluton (Chéticamp River tonalite of this study; Fig. 1) or the whole-rock Rb-Sr isochron age of 513 ± 38 Ma (recalculated using Ludwig, 2003) obtained by Barr *et al*. (1986) for the Chéticamp Pluton (Pembroke Lake and Farm Brook plutons of this study). The Salmon Pool granite (Fig. 1) yielded a U-Pb zircon crystallization age of 365 +10/-5 Ma (Jamieson *et al*., 1986).

A sample from what was described as a felsic metatuffaceous bed in the JBMS (Dauphinee Brook formation in this study) was dated by Lin *et al*.

Table 1. Summary of previous radiometric ages (Ma) for the Chéticamp-Margaree area. Rb-Sr ages recalculated using Ludwig (2003).

	K/At		Rb-Sr				Ar/Ar			U-Pg		
Unit	bt	musc	bt	musc	wr-bt	wr-musc	amph	bt	musc	zircon	monazite	Reference
Pleasant Bay complex (MacKenzie River granite)			368±18	415±21								1
Pleasant Bay complex (MacKenzie River granite)	354±16	356±16										2
Chéticamp River tonalite (Chéticamp Pluton)						526±74						3
Pleasant Bay complex (MacKenzie River granite)					368±14							3
Grand Falaise syenogranite (Corney Brook complex)	363±9											4
Grand Falaise syenogranite (Jumping Brook rhyolite)										439±7		5
Chéticamp River, Farm Brook, and Pembroke Lake plutons (Chéticamp Pluton)						513±38						6
Pembroke Lake monzogranite										550±8		7
Salmon Pool granite										365 +10/-5		7
Belle Côte orthogneiss										433 +20/-10		7
Pleasant Bay complex				384±4								7
Pleasant Bay complex				369±12								7
Pleasant Bay complex				381±4								7
George Brook amphibolite							383±3					8
George Brook amphibolite							384±3					8
George Brook amphibolite							390±3					8
Corney Brook formation								383±3				8
Pembroke Lake monzogranite									545±4 high-T			8
Pembroke Lake monzogranite									493±4 low-T			8
Belle Côte orthogneiss										442±3		9
Dauphinee Brook formation										<546±2		10
Dauphinee Brook formation										<551±0.9		10
Dauphinee Brook formation										<420±7		10
Pembroke Lake monzogranite										567.5±3.6		11
Rigwash Brook granodiorite										567.3±4.3		11
Chéticamp River tonalite										484.5±2.5		11
Upper Fisset Brook quartz diorite										480.1±1.8		11
Lavis Brook quartz diorite										440.3±1.7		11
MacLean Brook granodiorite										440.5±1.4		11
Grand Falaise alkali-feldspar granite										428.7±2.2		11
French Mountain syenogranite										366.6±3.1		11
Dauphinee Brook formation										531.5±3.7		11
Fishing Cove River formation											399.2±1.5	11

Notes: Units in brackets are previous names. Abbreviations: musc = muscovite; amph = amphibole; bt = biotite; wr = whole rock. References: 1 = Fairbairn *et al*., 1960; 2 = Wanless *et al*., 1968; 3 = Cormier 1972; 4 = Wanless *et al*., 1979; 5 = Currie *et al*., 1982; 6 = Barr *et al*., 1986; 7 = Jamieson *et al*., 1986; 8 = Reynolds *et al*., 1989; 9 = Horne *et al*., 2003; 10 = Lin *et al*., 2007; and 11 = this study.

(2007) and yielded a zircon age of 551 ± 0.9 Ma (Table 1). Lin *et al*. (2007) also reported detrital zircon ages for a psammitic sample from the JBMS in the same area, the youngest of which is 546 ± 2 Ma (Table 1). In contrast, a unit described as quartz porphyry in the JBMS yielded an age of 420 ± 7 Ma (Lin *et al*., 2007). Based on this age, Lin *et al*. (2007) interpreted the rhyolite to intrude the JBMS, although some other workers have considered the unit to be extrusive (e.g. Lynch and Mengel, 1995). However, this sample contains excessive common Pb and the age should be used with caution (White *et al*., 2015a).

Reynolds *et al*. (1989) conducted an $^{40}Ar/^{39}Ar$ study on amphibole, biotite and muscovite from the plutonic units and JBMS. Amphibolite and biotite from mafic units associated with the George Brook amphibolite yielded plateau and total gas ages that range from ca. 383 to 390 Ma (Table 1), similar to Rb-Sr and K-Ar muscovite, biotite and whole rock ages from granite and pegmatite samples in the Pleasant Bay complex (Table 1) exposed to the north (Fairbairn *et al*., 1960; Wanless *et al*., 1968; Cormier, 1972; Jamieson *et al*., 1986).

East of the current study area on the higher metamorphic-grade flanks of the JBMS, the Belle Côte Road orthogneiss yielded U-Pb zircon crystallization ages of 433 +20/-10 Ma and 442 ± 3 Ma (Jamieson *et al*., 1986 and Horne *et al*., 2003, respectively).

Methods

In order to better constrain the ages and evolution of units in the Chéticamp area, eight plutonic units were sampled for U-Pb zircon dating (Fig. 1). In addition, three metavolcanic/metasedimentary and one foliated granitic sill from the JBMS were sampled for zircon and monazite dating. However, due to poor zircon recovery and high common Pb in zircon grains that were recovered, only two of the country rock samples produced interpretable data.

All samples were sent to Overburden Drilling Management (ODM) in Ottawa, Ontario, for electro-pulse disaggregation and zircon separation. Zircon grains were then picked, mounted in an epoxy-covered thin section, polished to expose the core of the zircon grains and imaged using cold cathodoluminescence to identify internal zoning and inclusions. These images were used to select ablation points (30 µm diameter), avoiding any visible inclusions, cracks or other imperfections. If internal zoning was present and the zircon grain was big enough to allow multiple analyses, two ablation points were chosen: one near the margin of the grain and one near the core of the grain. U and Pb isotopic compositions were measured by LA-ICP-MS in the Department of Earth Sciences at the University of New Brunswick following the procedure outlined by McFarlane and Luo (2012) and Archibald *et al*. (2013). Concordia ages were calculated for clusters of three or more near-concordant points using Isoplot v3.75 (Ludwig, 2003). Data were organized by sample and rock type, then sorted by percent discordance. In the figures, tables and results, $^{206}Pb/^{238}U$ ages are used for zircons younger than 1.0 Ga, whereas $^{207}Pb/^{206}Pb$ ages are used for older grains. The results posted in this paper are considered preliminary and are likely to be revised slightly in later publications.

Results

Sample LS14-029

Sample LS14-029 is a coarse-grained to megacrystic biotite-muscovite monzogranite from the Pembroke Lake monzogranite in the southern part of the map area (Fig. 1). The analyzed zircon grains are mostly euhedral to subhedral and 75 to >100 µm in length with length to width ratios of ca. 1:1 to 3:1. Most grains are cloudy, inclusion-free and optically zoned. Twenty-two analyses of 22 zircon grains show uranium contents from 49 to 960 ppm and Th/U ratios of ca. 0.345 to 0.985. Many of the zircon analyses are discordant but eight analyses (eight grains) have concordant U–Pb ages within analytical errors, yielding a concordia age of 567.3 ± 3.3 Ma (Fig. 2a). This age is interpreted as the crystallization age of the sample.

Sample LS14-006

Sample LS14-006 is a medium-grained, equigranular granodiorite from Rigwash Brook

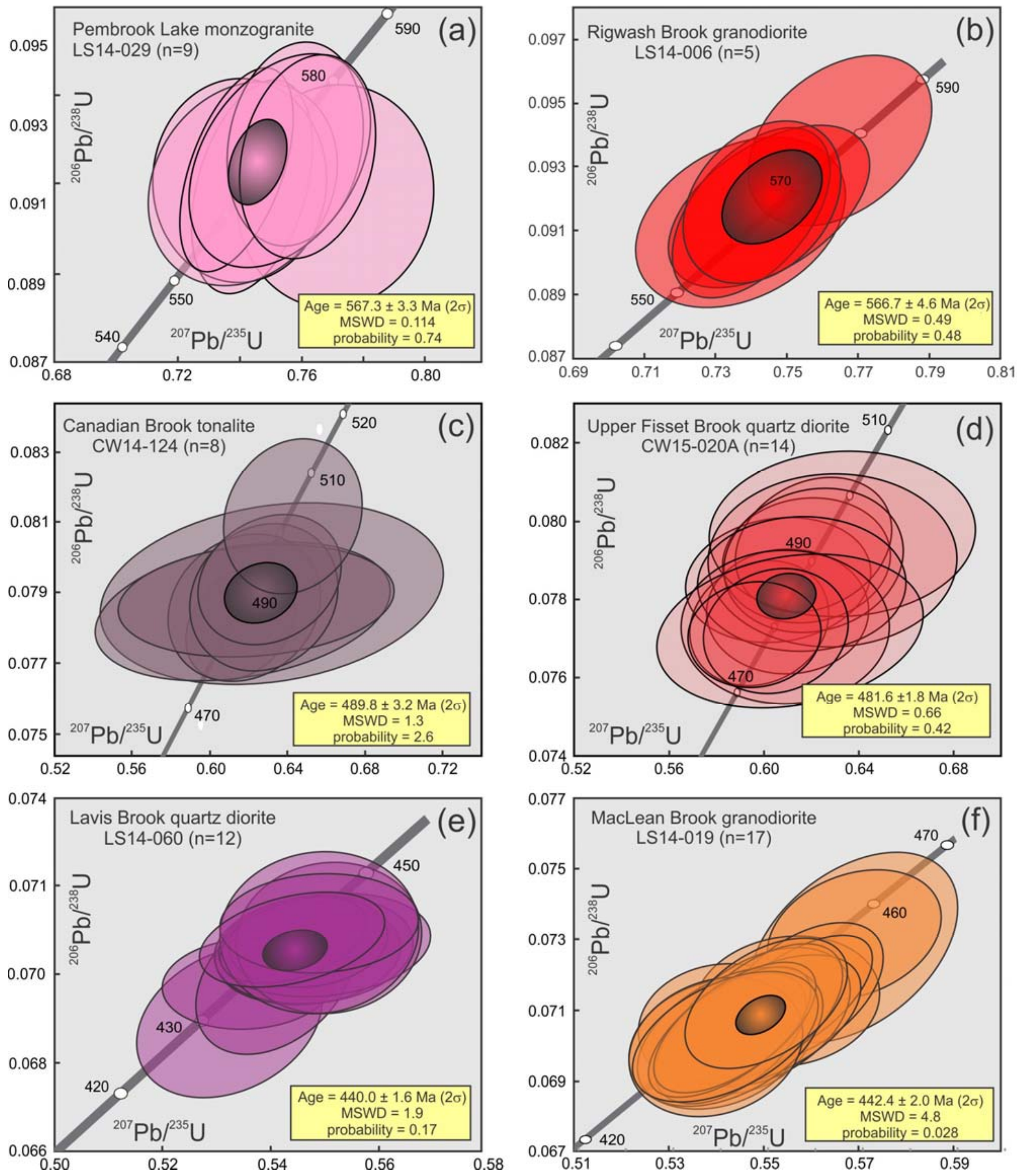

Figure 2. U-Pb concordia diagrams for older plutonic units. (a) Pembroke Lake monzogranite. (b) Rigwash Brook granodiorite. (c) Canadian Brook tonalite. (d) Upper Fisset Brook quartz diorite. (e) Lavis Brook quartz diorite. (f) MacLean Brook granodiorite.

granodiorite south of Grand Falaise (Fig. 1). Zircons analyzed from this sample are euhedral with bipyramidal termination and up to ~150 μm in length. Oscillatory zoning is visible in some grains. Fifty-four analyses were completed on 38 zircon grains (17 were core-rim pairs). Uranium contents and Th/U ratios vary from 81 to 1429 ppm and 0.426 to 1.378, respectively, with many of the cores having higher Th/U ratios. Only five zircon core analyses fall on or near concordia (≤ 10% discordant) and have concordant U–Pb ages that overlap within analytical error, yielding an age of 566.7 ± 4.6 Ma (Fig. 2b). This age is interpreted as the crystallization age of the granodiorite. Several discordant older inherited zircon grains were also found in this sample.

Sample CW14-124

The dated sample of Canadian Brook tonalite (CW14-124) is from the northernmost body collected along the Cabot Trail (Fig. 1). The sample is medium-grained equigranular tonalite. Most zircon grains are clear with minor inclusions; they are multifaceted almond-shaped and some have dipyramidal terminations. One hundred and thirty-three analyses were obtained on 92 zircon grains including 41 core-rim analyses. Uranium contents vary from 17 to 431 ppm with no significant difference between core and rim values. The U/Th varies from 0.140 to 1.393. Using eight overlapping near-concordant grains (≤ 10% discordant) produces a concordia age of 489.8 ± 3.2 Ma (Fig 2c), which is interpreted as the crystallization age of the sample.

Sample CW15-020A

This sample from the Upper Fisset Brook quartz diorite (Fig. 1) is coarse-grained, equigranular, quartz diorite. The analyzed zircon grains are similar in morphology to those in the Canadian Brook tonalite. All 60 zircon grains have uranium contents between 36 and 115 ppm and Th/U ratios between 0.667 and 1.790. All the zircon analyses are less than 10% discordant, and 21 analyses overlap within analytical errors, yielding a concordia age of 481.6 ± 1.8 Ma (Fig. 2d). This age is interpreted as the crystallization age of the sample.

Sample LS14-060

Sample LS14-060 consist of medium-grained, sub-porphyritic quartz diorite from the Lavis Brook quartz diorite, which occurs in the southernmost part of the study area (Fig. 1). Zircons analyzed from this sample are large (>250 µm in length) euhedral grains with bipyramidal terminations. Forty-six analyses were completed on 40 zircon grains (three were core-rim pairs). Uranium contents and Th/U ratios vary from 112 to 624 ppm and 0.504 to 1.118, respectively, with no significant difference between core and rim analyses. Twelve analyses have concordant U–Pb ages that overlap within analytical error, yielding an age of 440.0 ± 1.6 Ma (Fig. 2e). This age is interpreted as the crystallization age of the quartz diorite. No older inherited zircons were encountered in this sample.

Sample LS14-019

This sample is medium-grained, sub-porphyritic granodiorite with subhedral plagioclase from the MacLean Brook granodiorite (Fig. 1). The analyzed zircon grains are mostly euhedral with bipyramidal terminations and are >150 µm in length. Most grains are clear and have oscillatory zoning. A minor population of small (<30 µm in length), stubby, faceted grains is also present. Seventy-six analyses were obtained on 43 zircon grains including 33 core-rim analyses. Uranium contents vary from 122 to 604 ppm with no significant difference between core and rim values. The U/Th varies from 0.373 to 1.121. Seventeen analyses (17 zircon grains) have concordant U–Pb ages that overlap within analytical errors, yielding an age of 442.4 ± 2.0 Ma (Fig. 2f), which is interpreted as the crystallization age of the sample. No older inherited zircons were encountered in this sample.

Sample CW15-014A

Sample CW15-014A is coarse-grained, equigranular alkali-feldspar granite from the cliff section above the talus slope at Grand Falaise and is part of the Grand Falaise alkali-feldspar granite. Uranium contents vary from 35 to 660 ppm with no significant differences between core and rim values. U/Th varies from 0.50 to 1.12. This sample has mostly small (<20 um) zircons; there were enough larger ones to pick about 60 grains. Most had euhedral crystal shapes, with bipyramidal terminations. Grains are mostly brown to yellow or cloudy, with some clear ones. Dark grains with abundant inclusions were not picked. Using 11 near-concordant grains produces a concordia age of 427.9 ±2.1 Ma (Fig. 3a), which is interpreted as the crystallization age of the sample.

Sample CW14-121

This sample is fine- to medium-grained, equigranular syenogranite collected from the French Mountain syenogranite along the Cabot Trail (Fig. 1). The analyzed zircon grains are small (<50 µm in length), mostly elongate, have no terminations, and are broken. A few rounded, faceted grains are present. Most grains are dark brown to red. Nineteen analyses were obtained on 19 zircon grains. All were discordant. Uranium contents vary from 1750 to 11362 ppm and U/Th ration varies from 0.086 to 0.491. Common Pb is an issue with this sample. However, after a common Pb-correction is applied to the data (see McFarlane and Luo, 2012) all the zircon analyses fall on or near concordia (≤ 10% discordant). Of the 16 analyses, 5 have concordant U–Pb ages that overlap within analytical errors, yielding an age of 366.5 ± 3.1 Ma (Fig. 3b), which is interpreted as the crystallization age of the sample.

Sample CW14-117A

This sample is coarse-grained metasandstone to metaconglomerate from the Dauphinee Brook formation of the JBMS (Fig. 1). The analyzed zircons varied in shape and size and had variable degrees of clearness and inclusions. One hundred and fifteen analyses were obtained on 100 zircon grains including 15 core-rim analyses. Ninety-eight of the zircon analyses fall on or near concordia (≤ 10% discordant) and define two groups separated in frequency and age (Figs. 4a, b). The oldest peak has nine concordant U–Pb core ages that overlap within analytical errors, yielding an age of 602.7 ± 2.7 Ma, which is similar to three overlapping concordant U–Pb rim ages of 608.8 ± 2.5 Ma. The youngest peak has four concordant U–Pb ages that overlap within analytical errors, yielding an age of 531.5 ± 3.7 Ma, which is interpreted as the maximum depositional age for the sample.

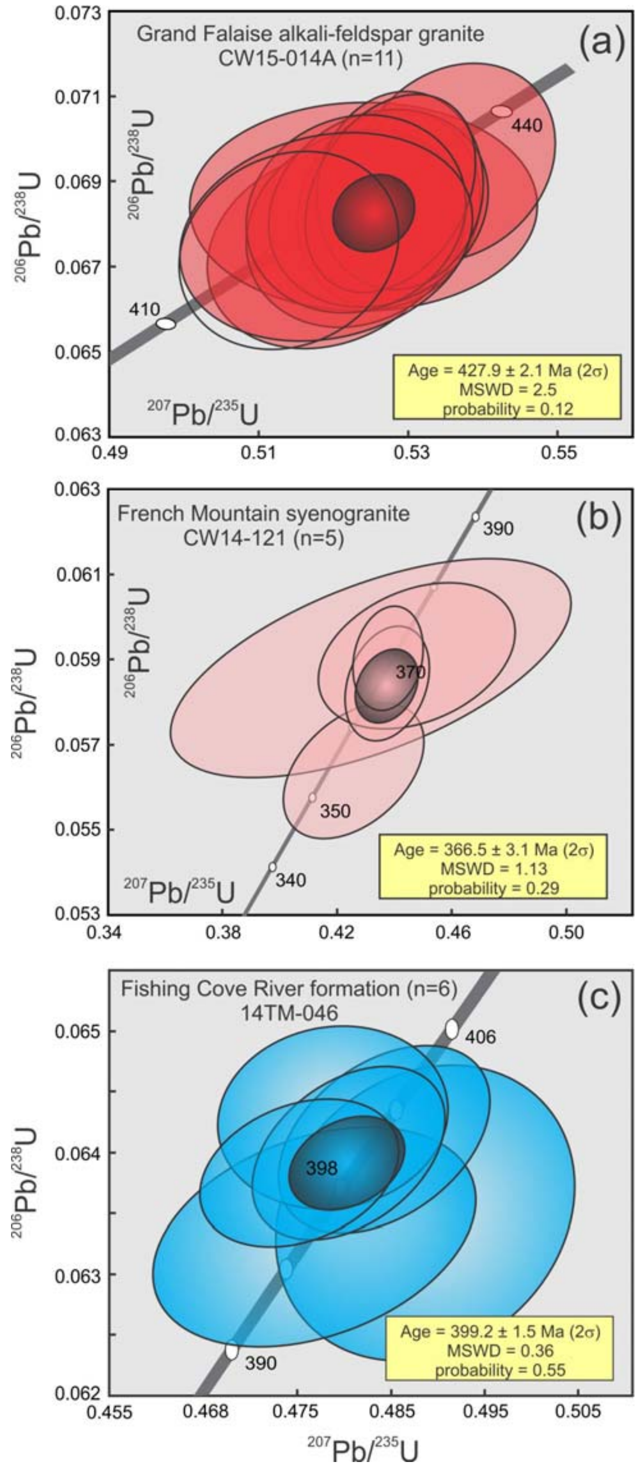

Figure 3. U-Pb concordia diagrams for younger plutonic units and garnet schist. (a) Grand Falaise alkali-feldspar granite. (b) French Mountain syenogranite. (c) Garnet schist from Fishing Cove River formation.

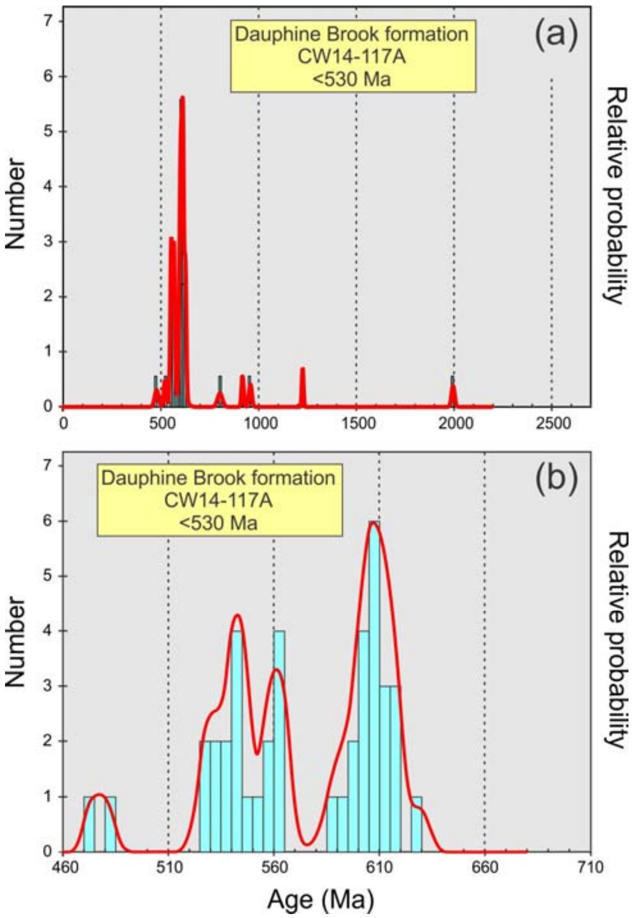

Figure 4. Relative probability plots for zircons from a coarse-grained metasandstone to metaconglomerate from the Dauphinee Brook formation of the JBMS. (a) All zircon analyses. (b) Younger zircon analyses.

Sample 14TM-046

This sample of schist was collected from the Fishing Cove River formation (JBMS) exposed at a roadside outcrop along the Cabot Trail directly west of French Lake on top of French Mountain (Fig. 1). The sample contains subidiomorphic garnet porphyroblasts ranging up to 1 mm in diameter set in a fine-grained matrix consisting of muscovite, biotite, feldspar, quartz and rutile. Monazite grains occur throughout the rock matrix and as inclusions in garnet, suggesting that monazite either pre-dated or was synchronous with garnet growth. Six monazite analyses have concordant U–Pb ages that overlap within analytical errors, yielding an age of 399.2 ± 1.5 Ma (Fig. 3c), which is interpreted to represent monazite growth during prograde metamorphism.

Discussion and Summary

New mapping has identified more plutonic units than previously recognized in the 'Chéticamp Pluton' and adjacent areas (Slaman *et al*., 2014; Slaman, 2015; White *et al*., 2015a, b; 2016). U-Pb zircon dating shows that they have a wide range in ages including Neoproterozoic, Late Cambrian-Early Ordovician, Silurian and Devonian. As a result, the name Chéticamp Pluton has been abandoned in favour of individual names for each separate plutonic unit. Geochronology also confirms that at least the western part of the JBMS is younger than ca. 530 Ma, which is consistent with the results from Lin *et al*. (2007) and explains previous conflicting interpretations of both an intrusive and faulted contact between the Chéticamp Pluton and the JBMS (see Tucker (2011) and Slaman (2015) for discussions). In addition, the monazite age of ca. 399 Ma confirms an Early Devonian age for high-grade metamorphism in the eastern part of the JBMS and by inference the lower grade metamorphism in the western parts.

The new ages also aid in interpretation of some of the previous geochronological data. The muscovite age for the Pembroke Lake monzogranite displays a classic age-gradient spectrum with the high-temperature steps up to ca. 545 Ma, which was considered cooling following the crystallization age of the pluton (Reynolds *et al*., 1989). However, the lower step (ca. 493 Ma) was considered to be related to overprinting by Silurian metamorphism and related deformation (Reynolds *et al*., 1989), but it is instead likely related to overprinting by the younger plutonic events in the area. The ca. 439 Ma U-Pb zircon age interpreted to date felsic dykes feeding the JBMS at Grand Falaise (e.g. Currie *et al*., 1982) is similar (within error) to the age of the Grand Falaise alkali-feldspar granite and is likely related to this pluton. The ca. 399 Ma metamorphic monazite age suggests that the younger (ca. 355-390 Ma) K-Ar, Rb-Sr, and Ar-Ar mineral and whole-rock ages from the JBMS and Pleasant Bay complex record cooling following Early Devonian high-grade Barrovian-style metamorphism in these areas (e.g. McCarron *et al*., 2016).

The recognition of distinct Neoproterozoic and Cambrian-Ordovician arc-related magmatic events in the Chéticamp area together with the <530 Ma age for the MORB-like JBMS help constrain the tectonic model along the leading edge of Ganderia and strengthen its correlation with Newfoundland's Exploits Subzone and related mineral deposits. The data from the Chéticamp area suggest that the JBMS and its related VHMS deposits may have developed on top of older crust, which may have played an important role in their enrichment in metals in the Exploits Subzone of Gandaria (Rogers *et al*., 2006; Galley *et al*,. 2007; van Staal, 2007; McNicoll *et al*., 2010).

Acknowledgments

Previous work on the Chéticamp Pluton and current work on the mafic units in JBMS are parts of M.Sc. thesis projects supervised by Drs. Sandra M. Barr (Acadia University) and Chris E. White (Nova Scotia Department of Natural Resources-NSDNR). Funding is provided by NSERC Discovery Grants to S.M.B. and operating funds provided to C.E.W from NSDNR. Special thanks are directed to Dr. Geoff Baldwin (NSDNR) for his exceptional help on the economic aspects in the field. Travis McCarron (University of New Brunswick) is also thanked for including data collected as part of his Ph.D. thesis project on the metamorphism of the Jumping Brook Metamorphic Suite. Additional insights into the economic geology of the Chéticamp area were provided by Garth DeMont (NSDNR). James Bridgland (Cape Breton Highlands National Park) is thanked for his help in securing a sample collection permit for work in the park. Janelle Brenton and Tracy Lenfesty are greatly thanked for the help in the Departmental Library. Edits by Geoff Baldwin on an earlier version of this paper greatly improved its quality.

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