U-Pb tantalite, Re-Os molybdenite, and $^{40}Ar/^{39}Ar$ muscovite dating of the Brazil Lake pegmatite, Nova Scotia: a possible shear-zone related origin for an LCT-type pegmatite

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ABSTRACT

The Brazil Lake pegmatite of southwestern Nova Scotia is a rare example of Li-Cs-Ta (LCT) -type pegmatite in the Meguma terrane of Nova Scotia. This spodumene-rich pegmatite is hosted by metasedimentary and metavolcanic rocks of the Silurian White Rock Formation, which records both Acadian and Alleghanian deformation. In order to constrain the petrogenesis and thermal history of the pegmatite, samples of tantalite, molybdenite, and muscovite were collected for U-Pb, Re-Os, and $^{40}Ar/^{39}Ar$ dating, respectively. A single, large, euhedral tantalite crystal from an albite-quartz-spodumene assemblage yielded concordant U-Pb ages between 365 and 395 Ma (all ± 1–2 Ma). In contrast, molybdenite from quartzite adjacent to the pegmatite gave a Re-Os age of 353 ± 2.5 Ma. Finally, a coarse muscovite grain from a quartz-feldspar-muscovite intergrowth surrounding a blocky K-feldspar megacryst was dated with the $^{40}Ar/^{39}Ar$ spot laser technique and yielded a maximum age of 347.6 Ma for a core analysis and minimum age of 318.4 Ma for a rim analysis. These data are interpreted to indicate that the time of pegmatite crystallization occurred at 395 Ma with the younger U-Pb tantalite ages (i.e., youngest ~ 365 Ma), the 353 Ma Re-Os molybdenite age, and the oldest $^{40}Ar/^{39}Ar$ age (i.e., 347 Ma) recording hydrothermal activity related to later magmatic events in this part of the Meguma terrane (e.g., 357 Ma Wedgeport Pluton). The muscovite ages record resetting and cooling related to the ca. 357 Ma magmatic event and later overprinting by Alleghanian deformation at ca. 320 Ma in this area. The older age for the pegmatite does not correlate with any known magmatic event in the area and therefore, its origin may have been related to Acadian metamorphism.

RÉSUMÉ

La pegmatite du lac Brazil dans le Sud-Ouest de la Nouvelle-Écosse constitue la seule pegmatite de type Li-Cs-Ta (LCT) reconnue dans le terrane de Meguma en Nouvelle-Écosse. Cette pegmatite riche en spodumène est incluse dans des roches métasédimentaires et métavolcaniques de la Formation silurienne de White Rock, marquée à la fois par les déformations acadienne et alléghanienne. Pour limiter la pétrogenèse et le passé thermique de la pegmatite, on a prélevé des échantillons de tantalite, de molybdénite et de muscovite en vue de datations U-Pb, Re-Os et $^{40}Ar/^{39}Ar$, respectivement. Un simple gros cristal automorphe de tantalite provenant d'un assemblage d'albite-quartz-spodumène a présenté des âges U-Pb concordants se situant entre 365 et 395 Ma (tous ± 1-2 Ma). En revanche, la molybdénite du quartzite adjacent à la pegmatite a accusé un âge Re-Os de 353 ± 2,5 Ma. On a finalement daté un gros grain du muscovite provenant d'une intercroissance de quartz-feldspath-muscovite entourant un phénocristal en bloc de K-feldspath au moyen de la technique laser du spot de détection $^{40}Ar/^{39}Ar$, et on a obtenu un âge maximal de 347,6 Ma d'une analyse de carotte et un âge minimal de 318,4 Ma d'une analyse de bordure. Ces données sont interprétées comme une indication que la cristallisation de la pegmatite est survenue vers 395 Ma; la datation U-Pb de la tantalite plus récente (la plus récente étant d'environ 365 Ma), la datation Re-Os de la molybdénite de 353 Ma et la datation $^{40}Ar/^{39}Ar$ la plus ancienne (c.-à-d. 347 Ma) témoignent d'une activité hydrothermale apparentée à des phénomènes magmatiques ultérieurs dans cette partie du terrane de Meguma (p. ex. pluton de 357 Ma de Wedgeport). Les datations de la muscovite signalent une remise en place et un refroidissement reliés au magmatisme d'environ 357 Ma et une surimpression ultérieure par la déformation alléghanienne dans ce secteur vers 320 Ma. L'âge plus ancien de la pegmatite ne correspond à aucun phénomène magmatique connu dans ce secteur; son origine pourrait par conséquent être apparentée au métamorphisme acadien.

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INTRODUCTION

The Brazil Lake pegmatite (BLP), southwestern Nova Scotia, is a Li-Cs-Ta (LCT)-type (erný 1991a, b) as manifested by the presence of abundant, coarse (i.e., m-scale) spodumene, rubidium-rich K-feldspar and mica, and Nb-Ta oxide mineralization (Hutchinson 1982; Corey 1993, 1995; Hughes 1995; Kontak 2004). Although the pegmatite was first discovered in 1960 (Taylor 1967) and has since been the focus of exploration and petrological studies (Corey 1993, 1995; Hughes 1995), the age of emplacement is constrained only to less than that of the host rocks (i.e., ca. 440 Ma White Rock Formation; MacDonald *et al.* 2002), with possible genetic links to magmatic or metamorphic events. For example, the BLP may have a magmatic association, with either the 440 Ma Brenton Pluton (Keppie & Krogh 2000) or 380 Ma South Mountain Batholith (Kontak *et al.* 2003) as progenitors, or a metamorphic origin relating to the ca. 400–410 Ma Acadian Orogeny. The ambiguous genetic affiliation of LCT-type pegmatite has been noted and discussed by erný (1991a) and continues to be a subject of debate (e.g., London 1992, 1996). Given that the age of the BLP will strongly influence any genetic interpretation and by inference have clear implications for the petrogenesis of the BLP and, more importantly, the metallogenetic potential of the southwest Nova Scotia Sn-base metal domain (Chatterjee 1983), a project was initiated to resolve the time of pegmatite formation and subsequent thermal history. A multi-disciplinary geochronological approach was used that involved U-Pb dating of tantalite, Re-Os dating of molybdenite, and $^{40}Ar/^{39}Ar$ dating of muscovite. The results of these analyses are presented and discussed below.

REGIONAL AND LOCAL GEOLOGICAL SETTING

The study area occurs in the southwestern part of the Meguma terrane of the Canadian Appalachian Orogen and is dominated by Lower Paleozoic metasedimentary and metavolcanic rocks and Devonian granitic intrusions (Fig. 1a). The area of interest is located just past the western edge of the 380 Ma (Reynolds *et al.* 2004; Kontak *et al.* 2003), peraluminous South Mountain Batholith and some 40 km from the past producing (1985–1992) East Kemptville tin deposit (Fig. 1b). Importantly, many other lithophile-element mineralized centres occur in this region, informally referred to as the southwest Nova Scotia tin-base metal domain (Chatterjee 1983) and discussed in detail by Kontak *et al.* (1989). The Brazil Lake area is underlain by a mixed package of metasedimentary and metavolcanic rocks that are cut by small pegmatite bodies and the Brenton Pluton, the latter of which is also transected by pegmatite (Fig. 2a).

The oldest rocks surrounding the study area (Fig. 1b) are the Cambrian-Ordovician Meguma Group that consists of an older, sandstone-dominant Goldenville Formation and younger overlying siltstone- and shale-dominant rocks of the Halifax Formation. Overlying the Meguma Group are mixed metasedimentary and metavolcanic rocks of the Silurian White Rock Formation. The metasedimentary rocks are dominated by massive quartzite with minor pelitic beds, whereas the metavolcanic rocks are basaltic, although southwest of the study area around Yarmouth minor felsic rocks also occur (White *et al.* 2001; MacDonald *et al.* 2002). A U-Pb zircon age of 438 ± 3 Ma was obtained for the felsic rocks (MacDonald *et al.* 2002). The Brenton pluton, a probable subvolcanic intrusion related to the White Rock Formation based on its chemistry (MacDonald *et al.* 2002), has a U-Pb zircon age of 439 ± 4 Ma (Keppie & Krogh 2000), and is in fault contact with both the White Rock and Halifax formations (Fig. 1b). The Brenton pluton consists of biotite-muscovite syenogranite to monzogranite and is highly deformed with a penetrative Acadian fabric. Within the intrusion are two mica-bearing, garnet-tourmaline pegmatite bodies (Fig. 2a) that commonly cut and retrograde the fabric of the granite (Fig. 2b).

Acadian deformation in the area produced northeast-trending, upright folds with a shallow southwest plunge and a related penetrative fabric; regional scale shear zones are present throughout the study area (Fig. 1b). An overprinting fabric of Alleghanian age (Culshaw & Liesa 1997; Culshaw & Reynolds 1997; Moynihan 2003) has crenulated the S_1 fabric with the orientations of related fabrics and lineations depending on geographic location (Culshaw & Liesa 1997; White *et al.* 2001; Moynihan 2003). Metamorphic grade varies from greenschist- to amphibolite-facies, with the higher grade rocks localized to the contact areas between the White Rock and Goldenville formations on the margins of the Yarmouth syncline (MacDonald, 2000; MacDonald *et al.* 2002). Peak metamorphic conditions were estimated at 4 kbars and 550–600°C by Moynihan (2003). This change in metamorphic grade also coincides with a boundary between two distinct trends of vertical gradient magnetic anomalies, which OReilly *et al.* (1992) termed the Deerfield Shear Zone and which White *et al.* (2001) later mapped in as the Chebogue Point Shear Zone, following the terminology of Culshaw & Liesa (1997). These two zones merge (CP-DSZ in Fig. 1b), but a formal name has yet to be used for the laterally extensive shear zone (C. White, personal communication 2004).

The BLP outcrops on the eastern side of the Yarmouth syncline within rocks of the White Rock Formation (Fig. 1b). Rock types in the area include fine- to coarse-grained amphibolite, minor mafic tuff, dark green-black pelite, psammite, and adjacent to the pegmatite lenses, fine-grained tourmaline-bearing, silica-rich rock. The pelitic unit may contain staurolite, garnet, and andalusite, whereas tourmaline and rare holmquistite (Hutchinson 1982) occur in the amphibolite adjacent to the pegmatite lenses. The quartzite adjacent to the pegmatite lenses is mainly buff, but locally the buff color gives way to white which may in part be an exomorphic alteration (i.e., silicification) related to pegmatite emplacement (D. Black, personal communication 2003). In addition, thin (cm-scale) white seams of very pure quartzite (perhaps representing recrystallized quartz veins?) cut the buff quartzite.

The BLP consists of two separate pegmatite lens, each with

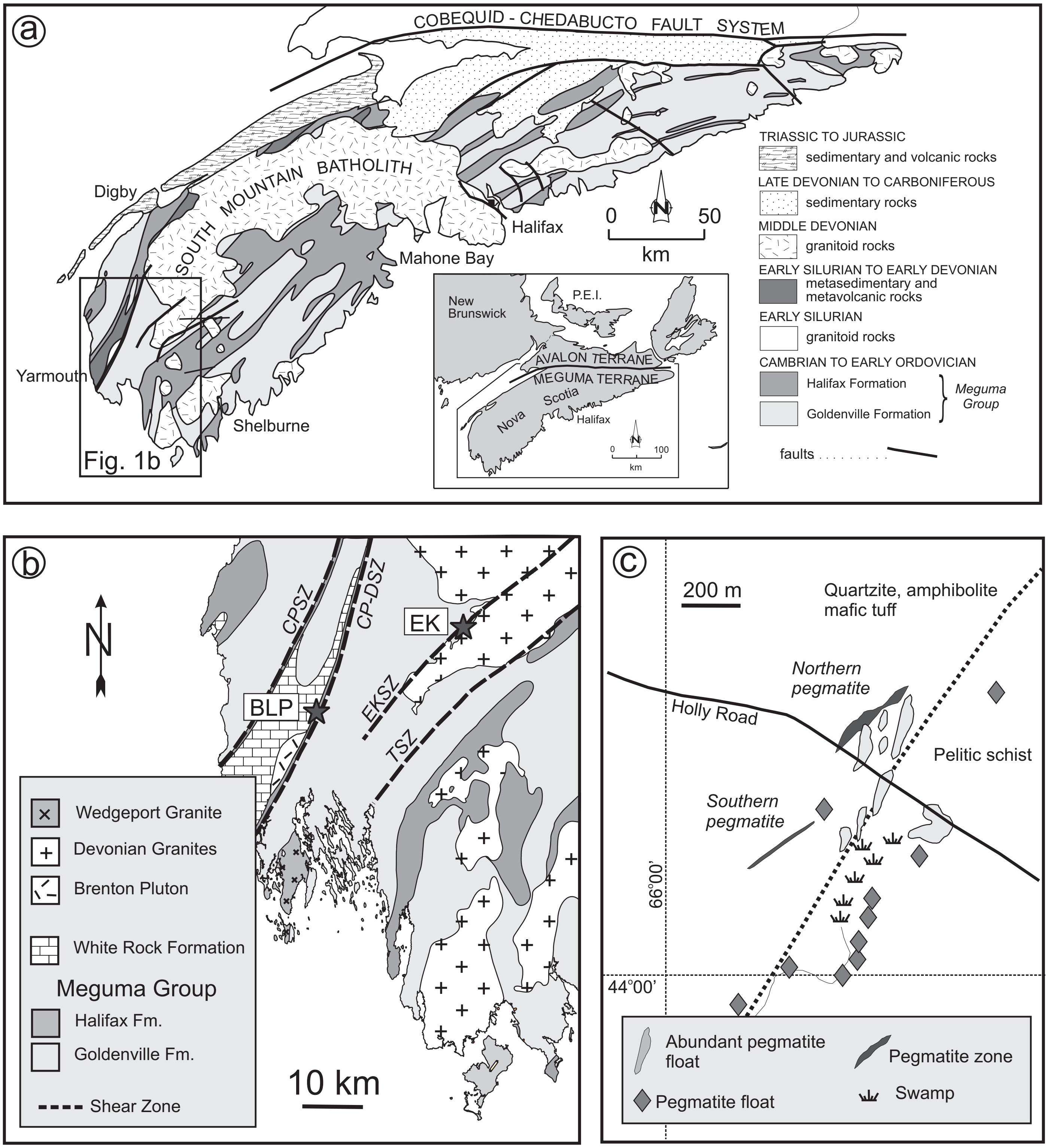
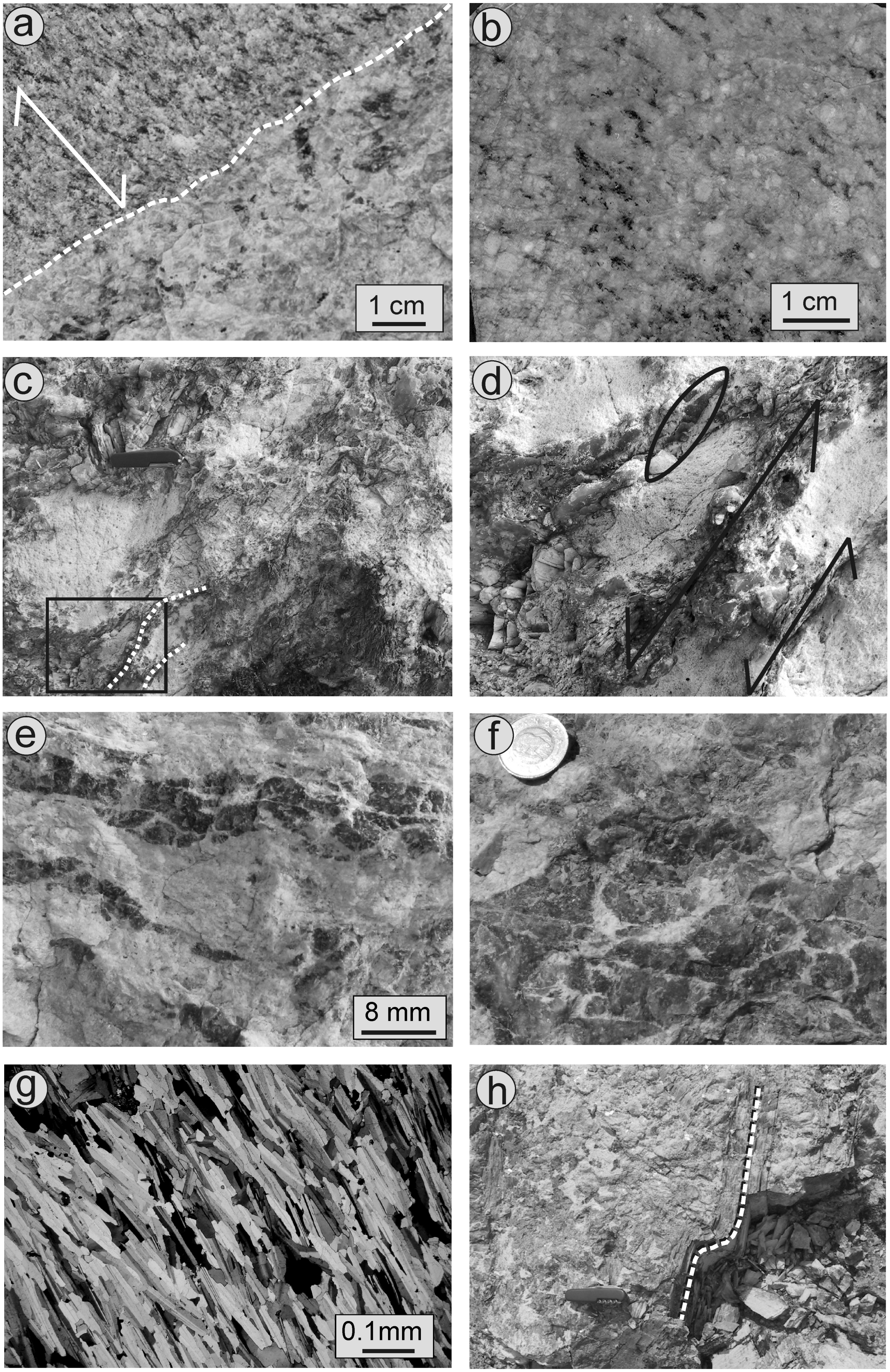


Fig. 1 (a) Regional setting and geology of the Meguma terrane in the Appalachian Orogen. (b) Regional geological map of southwestern Nova Scotia (modified after White *et al.* 2001) showing the location of the Brazil Lake pegmatite (BLP), location of the former producing East Kemptville tin - base metal deposit, and extent of regional shear zones in this area (TSZ – Tobeatic Shear Zone, EKSZ – East Kemptville Shear Zone, CP-DSZ – Chebogue Point-Deerfield Shear Zone, CPSZ – Cranberry Point Shear Zone). (c) Map outlining extent of the Brazil Lake pegmatite field. Note that the extent of the northern pegmatite lens is based on diamond drill holes. The samples used in this study come from the southern pegmatite outcrop. Figure modified after map provided by D. Black (personal communication 2004).


a
b
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1 cm
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a subcrop extent of a few hundred m length and ≤20–25 m width, that strike northeasterly with near vertical to steeply southeast dips (Fig. 1c). The pegmatite lenses have complex internal zonation and are dominated by areas of megacrystic (i.e., 1–2 m) blocky K-feldspar and spodumene with an intergranular matrix with variable proportions of quartz-feldspar-spodumene-muscovite. Formation of secondary albite after K-feldspar is manifest as either fine-grained sacchroidal albite or euhedral platy cleavelandite. These zones of secondary albite, previously been referred to as albitic aplite (Hutchinson 1982; Hughes 1995), are locally pervasive and such areas are preferentially enriched in Ta-Nb and phosphate minerals (Kontak 2004).

The metasedimentary and mafic metavolcanic (amphibolite) rocks of the area are strongly deformed and contain a penetrative fabric oriented northeast with near-vertical dip. Within the amphibolite, small (≤1 cm), elongate lenses of plagioclase have a vertical plunge. Although the pegmatite is generally isotropic and the megacrysts of K-feldspar and spodumene in fact have the long axes of crystals oriented perpendicular to the wall rock fabric, the pegmatite locally contains a fabric, as manifest by : (1) small shears through muscovite-rich zones (Fig. 2c, d); (2) flattened quartz megacrysts with 10–20:1 aspect ratios (Fig. 2e, f); (3) a penetrative micro-fabric in the albitic aplite zones (Fig. 2g); and (4) rare cases of kinked spodumene crystals in the intergranular areas adjacent to large megacrysts (Fig. 2h). In these cases microfolds have subvertical fold axes, thus similar in orientation to the plunge of plagioclase lenses in the amphibolite unit. In addition, we note that the boundary between the pegmatite and wall rock is not sheared, thus no preferential partitioning of strain occurred along this horizon.

The mineral assemblages in the metamorphic rocks in the area of the BLP were used by Moynihan (2003) to estimate peak metamorphic conditions at near 550–600°C and 4 kbars. Interestingly, these conditions are close to or exceed the solidus of a Li-rich felsic melt at such pressures (London 1992).

Fig. 2 (Facing Page) (a) Outcrop of the Brenton Pluton showing pegmatite cutting deformed granite (contact marked by dashed white line) with a penetrative fabric (indicated with cleavage symbol). (b) Slabbed sample of deformed granite from Brenton Pluton adjacent to a pegmatite showing that the biotite-rich fabric of the granite is retrograded. Black minerals are remnant biotite grains in a leucocractic matrix. (c) Albitic aplite zone in BLP with muscovite-rich zones (highlighted with dashed white lines) preferentially aligned in northeast direction. Box indicates area enlarged in Fig. 2d. Knife for scale is ca. 8 cm long. (d) Close-up of albitic aplite zone showing preferential alignment of muscovite-rich area (fabric symbol). A detached grain of quartz that is stretched parallel to the flattening direction is circled. (e) Flattened and dismembered dark quartz megacryst in albitic aplite area between K-feldspar megacrysts. Note the extreme attenuation of the quartz grain. (f) Quartz megacryst with autobreccia texture and intergranular fill of albite. Note two-dollar coin for scale. (g) Thin section (under crossed nicols) of aplitic albite showing the preferred alignment of albite laths (i.e., steep northeast-trending fabric). (h) Kinked spodumene crystal with fold outlined by the dashed line. Picture was taken looking straight down on the outcrop. Knife for scale is ca. 8 cm long.

RELEVANT GEOCHRONOLOGY AND FIELD RELATIONSHIPS

The timing of magmatic and tectono-metamorphic events in the East Kemptville-Yarmouth area of southwestern Nova Scotia is constrained by U-Pb zircon and monazite, Rb-Sr whole rock, Re-Os molybdenite, and $^{40}Ar/^{39}Ar$ whole rock and mineral ages. Relevant to this study are the following: (1) 439 ± 4 Ma mafic-felsic volcanic rocks of the White Rock Formation and the co-magmatic Brenton Pluton (U-Pb zircon; Keppie & Krogh 2000; MacDonald *et al.* 2002); (2) intrusion at 375 Ma of the Davis Lake Pluton and related mineralization at East Kemptville (Rb-Sr whole rock and Re-Os molybdenite, respectively; Dostal & Chatterjee 1995; Kontak *et al.* 2003); (3) regional Acadian deformation and metamorphism at ca. 400 Ma ($^{40}Ar/^{39}Ar$; Muecke *et al.* 1988) and overprinting Alleghanian deformation at 320–300 Ma (Rb-Sr and $^{40}Ar/^{39}Ar$ dating: Kontak & Cormier 1991; Kontak *et al.* 1995; Culshaw & Reynolds 1997); and (4) emplacement of the Wedgeport Pluton at 357 Ma (U-Pb zircon; MacLean *et al.* 2003).

The time of emplacement of the Brazil Lake pegmatite is constrained by the following field relationships. As noted above, deformation of the pegmatite is manifested by thin shear bands within muscovite-rich zones, flattened quartz megacrysts, a penetrative fabric within albitic pegmatite, and kinked spodumene crystals. In addition, the fabric in the wall rock records peak metamorphic conditions of ca. 4 kbars and 600°C (Moynihan 2003) and adjacent to the pegmatite the mineral assemblages in the amphibolite are not retrograded. Collectively, these observations suggest the pegmatite may have been emplaced before or during the time of regional deformation. Important additional observations are boulder trains of pegmatite that have been traced from the Brazil Lake area to the Brenton Pluton (Figs. 1b, c) where, in places, undeformed pegmatite is observed to cross cut and retrograde the penetrative biotite fabric in the granite (Figs. 2a, b). Thus, locally some pegmatite post-dated the formation of the biotite fabric, which is presumably of Acadian age.

The most recent and relevant geochronological study in this part of the Meguma Terrane is that of Moynihan (2003) who used the spot laser $^{40}Ar/^{39}Ar$ technique to date amphibole and mica. Included in this study were muscovite and amphibole from the BLP and wall rock. Maximum ages obtained were ca. 350 Ma, but younger ages to ca. 325 Ma were also obtained for muscovite. These data are discussed in more detail below in the context of this work.

ANALYTICAL TECHNIQUES

Three samples of material were selected for dating in the present study: muscovite and tantalite from within the pegmatite and molybdenite from quartzite adjacent to the pegmatite (i.e., <1 m away). The three samples are from the southern pegmatite lens of the BLP (Fig. 1c), and are from within a few metres of each other.

The tantalite sample for U-Pb geochronology (Fig. 3a) consisted of coarse radiating tantalite crystals from albite-rich intergranular material within a spodumene-rich part of the pegmatite. Although not used routinely for dating, tantalite is ideally suited for dating of rare-element (e.g., LCT-type) pegmatite and has been successfully applied in, for example, Archean terranes of Canada (Smith *et al.* 2000) and Australia (Kinny 2000), the Proterozoic of northern Sweden (Romer & Wright 1992) and younger, Cretaceous pegmatite of the Northwest Territories (Mauthner *et al.* 1995). At Brazil Lake, the tantalite crystals are up to 1–2 cm long and 2–5 mm thick and are dark brown with a tabular habit (Fig. 3a). The occurrence of tantalite associated with secondary albite, in part of cleavelandite habit, is typical of Ta-Nb mineralization within the pegmatite. A single large (<~1 cm), tantalite crystal was extracted from whole rock pegmatite using metal tweezers. Five fragments from this single tantalite crystal were analyzed at the University of Alberta Radiogenic Isotope Facility, Edmonton, Alberta. The five fragments weighing between 16 and 495 micrograms were dissolved in Teflon TFE digestion vessels housed in monel jackets using a 48%HF:7N HNO_3 acid mixture at 220°C for 72 hours. A measured amount of $^{205}Pb/^{235}U$ tracer solution was added to the acid mixture in each vessel prior to digestion. Purification of Pb and U from the dissolved tantalite fragments was accomplished using anion exchange chromatography with an HBr/HCl procedure similar to that reported for Fe-bearing minerals such as titanite or rutile (e.g., Heaman *et al.* 2002). The purified uranium and lead aliquots were loaded together onto out-gassed Re filaments in a mixture of phosphoric acid and silica gel. Their isotopic compositions were determined on a VG354 thermal ionisation mass spectrometer using both Faraday and Daly photomultiplier (analogue) detectors in single detector peak-hopping mode. The Pb and U isotopic data were corrected for mass discrimination (0.12 and 0.14%/amu, respectively), blank (2 and 0.5 pg, respectively), and spike addition. The isotopic composition of common Pb present in the tantalite analyses above that estimated to be blank contribution was calculated using the two-stage model of Stacey & Kramers (1975). The uranium decay constants used in this study ($^{238}U = 1.55125 \times 10^{-10}$ yr^{-1} and $^{235}U = 9.8485 \times 10^{-10}$ yr^{-1}) and the isotopic composition of present day uranium of 137.88 are the values recommended by Jaffey *et al.* (1971).

The molybdenite-bearing sample is quartz-rich material adjacent the BLP (Fig. 3b). The clear, white color of the molybdenite-bearing, mineralized sample contrasts with the buff color of the White Rock Formation quartzite in the area, thereby suggesting that it may be a deformed and recrystallized quartz vein. However, field relationships are equivocal and, hence, preclude absolute certainty regarding its classification as either White Rock Formation quartzite or deformed quartz vein material. Similar multi-cm wide zones of white quartzite oriented at high angles to transposed bedding, which may also represent recrystallized quartz vein material, occur in other parts of the White Rock Formation. In the sample of interest, one large (1 × 1 cm) grain of molybdenite (BRZ-2002-1) was removed and the material homogenized by use of a diamond-tipped dental drill. A trial analyses established the Re abundance of the molybdenite concentrate, followed by two full Re-Os analyses (BRZ-2002-1a, 1b; Table 2). Duplicate analysis

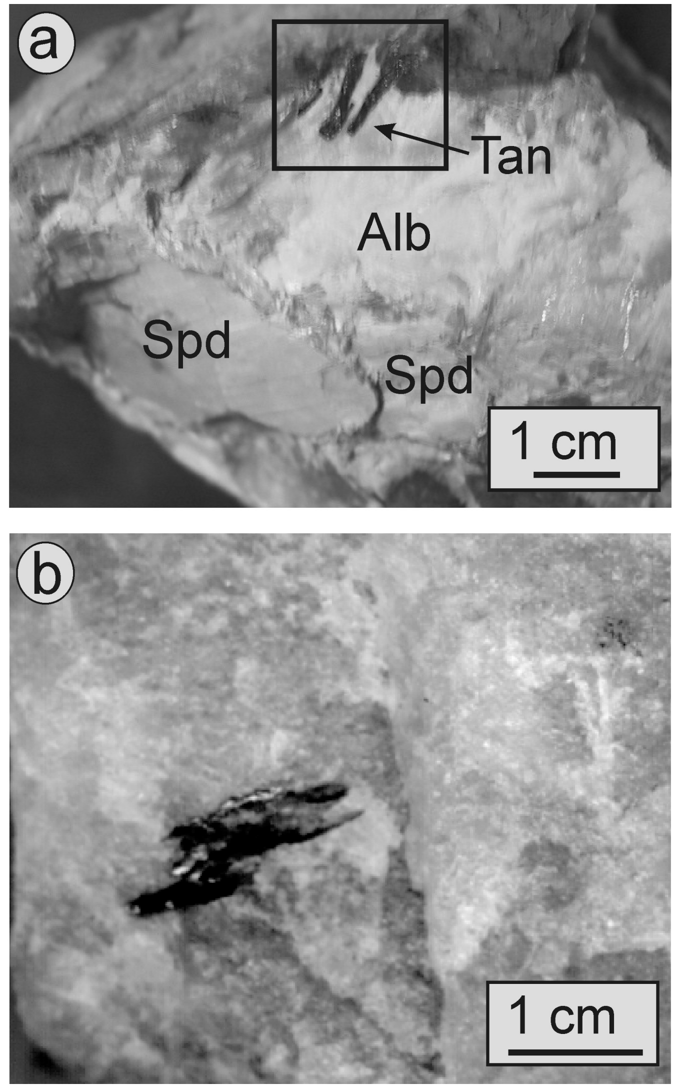

Fig. 3 (a) Sample of coarse-grained, intergranular spodumene (Spd)-albite (Alb)-muscovite (at the contact of Spd-Alb) material with euhedral blades of tantalite (Tan; within the box area). (b) Photograph of molybdenite flake (sample BRZ-2002-1 of Table 2) of ca. 1 cm size in quartzite from adjacent to Brazil Lake pegmatite. Finer grained molybdenite grains (sample BRZ-2002-2 of Table 2) were liberated from this sample upon crushing. Note the purity of the sample is (i.e., silica-rich) and its fine-grained, saccharoidal texture.

of this material was done because of the problematic nature of dating coarse molybdenite grains due to internal decoupling of Re and Os (Selby & Creaser 2004). This effect was monitored by the analysis of two sample aliquots with vastly different weights (94 and 256 mg), i.e., if sample homogenization has not been achieved the two different aliquots will return different ages. In addition, the remaining quartz material was pulverized and all remaining molybdenite extracted to comprise another analysis (BRZ-2002-2; Table 2). Re and Os concentrations in the molybdenite were determined using isotope dilution mass spectrometry at the University of Alberta Radiogenic Isotope Facility, Edmonton, Alberta using Carius tube, solvent extraction, and chromatographic techniques. Complete analytical procedures and error calculations are given in Selby *et al.* (2003).

A single sample of coarse mica of ca. 2 cm width, part of a book of muscovite 1 cm thick, was collected from an intergranular mixture of quartz-feldspar-mica between spodumene - K-feldspar megacrysts of ca. 1 m size. This muscovite book was separated parallel to its cleavage into thin sheets and a single, cylindrical-shaped grain prepared for irradiation. Core versus rim analysis of the single muscovite sample by laser fusion was done at the Geochronology Laboratory, Queen's University, Kingston, Ontario, following the procedures outlined in Kontak *et al.* (1999). Dates and errors (Table 3) are calculated using formulae of Dalrymple *et al.* (1981), and the constants recommended by Steiger & Jäger (1977). Errors calculated represent analytical precision at 2σ, assuming that the errors in the ages of the flux monitors are zero. This technique is suitable for comparing within-spectrum variation and determining which steps form a plateau (McDougall & Harrison 1988, p. 89). A conservative estimate of this error in the J-value is 0.5 % and can be added for inter-sample comparison.

ANALYTICAL RESULTS

The isotopic results obtained for tantalite, molybdenite, and muscovite are given in Tables 1, 2 and 3, respectively, and we discuss the data starting with the oldest ages. The U-Pb results for five fragments from one tantalite crystal are presented in Table 1 and displayed on a concordia diagram in Fig. 4. All three fragments display moderate uranium contents (214–567 ppm), low model thorium contents (1.4–3.2 ppm) and correspondingly low Th/U ratios (0.004–0.009). The Brazil Lake tantalite contains a modest amount of common lead (9–22%), which is reflected in the relatively low $^{206}Pb/^{204}Pb$ ratios (265–737) reported in Table 1, and this component contributes significantly to the overall uncertainty in the analyses. All five tantalite fractions yield nearly concordant U-Pb ages with $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages that vary between 366.1 and 394.6 Ma (Table 1).

The results for the three Re-Os molybdenite analyses are identical within error at 352–354 Ma. Most importantly, the two ages for the coarse molybdenite grain (BRZ-2002-1a, 1b) are identical for the two weight fractions (i.e., 94 and 236 mg) which are identical to the finer grain fraction (BRZ-2002-2), thus indicating that decoupling of Re and Os is not a problem for this material. Incorporating the error in the decay constant of 0.31% (Smoliar *et al.* 1996) and propagating it with the analytical uncertainly gives errors of 2.5 Ma, we thus interpret the Re-Os molybdenite age for this sample to be 353.0 ± 2.5 Ma.

The muscovite grain was analyzed along the margin area (5 analyses) and the core (4 analyses). For the margin, ages range from 318 to 342 Ma, but three fall in the narrower range of 332.2 to 334.3 Ma. For the core area, ages range from 328 to 347 Ma. The integrated age for the sample is 333.7 ± 1.5 Ma.

DISCUSSION AND CONCLUSIONS

The results using three different geochronometers to date the BLP have resulted in ages spanning some 77 Ma, ranging from 395 Ma for U-Pb tantalite ($^{206}Pb/^{238}U$ age for fraction 3) to 318 Ma for laser $^{40}Ar/^{39}Ar$ spot analysis on a single grain of coarse muscovite. In order to assign an age to pegmatite formation and unravel its subsequent thermal history, it is important to assess the nature of the data for each of these chronometers in the context of the method and their reliability and then to interpret the data in the context of the geological history of the region.

U-Pb tantalite dating

Tantalo-niobates such as tantalite and columbite are ideally suited for U-Pb dating because of the potential to incorporate U (200–1000 ppm; Romer & Wright 1992; Kinny 2000) and, therefore, contain a significant radiogenic lead content. Romer & Wright (1992) investigated one columbite sample in the contact aureole of a Paleoproterozoic granite that was subjected to a Caledonian upper greenschist to lower amphibolite facies regional metamorphic overprint and this columbite displayed

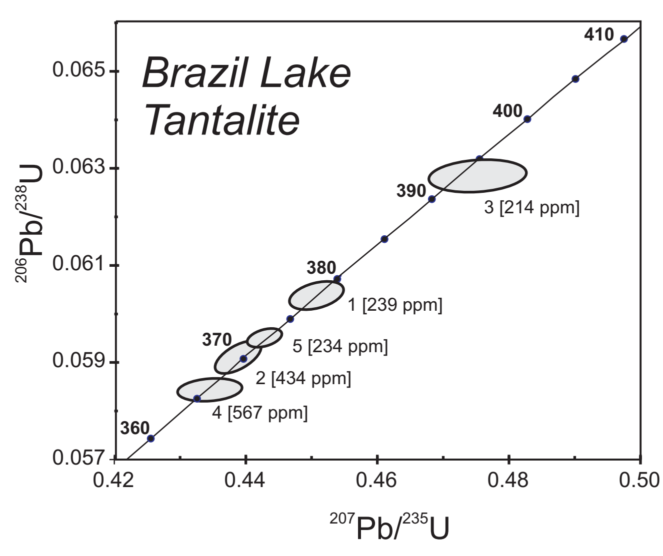

Fig. 4 Conventional concordia plot displaying U-Pb analyses for tantalite grains from Brazil Lake pegmatite (Fig. 3a).

Table 1. U-Pb Tantalite Results from Brazil Lake, Nova Scotia

Description[1]	Weight (mg)	U (ppm)	Th (ppm)	Pb (ppm)	Th/U[2,3]	TCPb[4] (pg)	Percent[5] Common	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Model Ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	% Disc[6]
1, dk brn blocky fragment (1)	247	238.9	1.6	15.1	0.007	492	13.2	473	0.06038 ± 11	0.4507 ± 16	0.05413 ± 18	377.9 ± 0.7	377.8 ± 1.1	376.5 ± 7.5	-0.4
2, dk brn blocky fragment (1)	453	433.9	1.8	25.9	0.004	1174	10.0	638	0.05912 ± 13	0.4389 ± 14	0.05384 ± 14	370.3 ± 0.8	369.5 ± 1.0	364.6 ± 5.7	-1.6
3, dk brn blocky fragment (1)	495	213.9	2.0	15.6	0.009	1683	21.8	265	0.06284 ± 13	0.4749 ± 29	0.05482 ± 34	392.9 ± 0.8	394.6 ± 2.0	404.7 ± 13.6	3.0
4, dk brn blocky fragment (1)	16	566.6	3.2	36.1	0.006	96	16.8	357	0.05843 ± 9	0.4345 ± 19	0.05393 ± 24	366.1 ± 0.6	366.4 ± 1.4	368.2 ± 10.0	0.6
5, dk brn blocky fragment (1)	125	234.1	1.4	13.9	0.006	152	8.8	737	0.05849 ± 7	0.4428 ± 10	0.05398 ± 11	372.5 ± 0.4	372.2 ± 0.7	370.3 ± 4.6	-0.6

Notes: **1.** Abbreviations - dk = dark, lt = light, brn = brown, euh = euhedral. 20NM: Non-magnetic split at full field (1.8A) and 20 degree side tilt using a Frantz Isodynamic Separator. Numbers in parentheses correspond to the number of tantalite fragments analysed. **2.** Atomic ratios corrected for blank (2pg Pb; 0.5pg U), fractionation and initial common Pb (Stacey & Kramers 1975). **3.** Th concentration estimated from the amount of ^{208}Pb present in the analysis and the $^{207}Pb/^{206}Pb$ age. **4.** TCPb refers to the total amount of common lead present in the analyses in picograms. **5.** Percent Common refers to the percentage of common lead presenet in the analysis. **6.** % Disc refers to the amount of discordance along a reference line to zero age.
All errors in this table are reported at 1 sigma (0.09402±2 means 0.09402±0.00002).

Table 2. Re/Os data for sample BRZ-2002-1 from Brazil Lake pegmatite, Nova Scotia.

Sample ID	Weight (gms)	Re (ppm)	^{187}Re (ppm)	^{187}Os (ppm)	Age (Ma) (±2σ)
BRZ-2002-1a	94	4.997	3.14	18.45	351.7 (1.3)
BRZ-2002-1b	236	5.26	3.306	19.44	351.9 (1.3)
BRZ-2002-2	36	7.125	4.478	26.51	354.2 (1.4)

Table 3. Ar-Ar datea for Brazil Lake pegmatite muscovite, southern Nova Scotia.

	$^{36}Ar/^{40}Ar$ (± 2σ)	$^{39}Ar/^{40}Ar$ (± 2σ)	Ca/K	$\%^{40}Ar$ Atm.	$\%^{39}Ar$ of total	$^{40}Ar^*/^{39}Ar$ (± 2σ)	Age (Ma) (± 2σ)
Sample BRZ-2002-4, coarse muscovite flake, J value = 0.007525 ± 0.000030							
Rim	0.001233 ± 0.000030	0.023655 ± 0.000135	0.28	36.41	2.48	26.9 ± 0.4	332.2 ± 4.7
Rim	0.000185 ± 0.000091	0.036858 ± 0.000409	0.019	5.46	0.48	25.6 ± 0.8	318.4 ± 8.9
Rim	0.000514 ± 0.000023	0.031346 ± 0.000191	0.005	15.18	2.2	27.1 ± 0.3	334.3 ± 3.1
Rim	0.000152 ± 0.000026	0.035510 ± 0.000220	0	4.48	1.7	26.9 ± 0.3	332.5 ± 3.1
Rim	0.000114 ± 0.000010	0.034823 ± 0.000157	0.002	3.36	19.41	27.7 ± 0.2	342.1 ± 1.7
Core	0.000965 ± 0.000063	0.025318 ± 0.000239	0	28.49	0.61	28.2 ± 0.8	347.6 ± 8.7
Core	0.000081 ± 0.000007	0.036438 ± 0.000165	0.002	2.38	28.76	26.8 ± 0.1	331.3 ± 1.5
Core	0.000159 ± 0.000010	0.035893 ± 0.000161	0.004	4.7	29.53	265 ± 0.1	328.6 ± 1.7
Core	0.000133 ± 0.000010	0.035095 ± 0.000152	0.002	3.92	14.84	27.4 ± 0.1	337.9 ± 1.7

only partial resetting during Caledonian metamorphism. From this example, these minerals are considered relatively robust with an indication from U-Pb systematics for a moderately high closure temperature to Pb diffusion (e.g., Romer & Wright 1992). Although sulphide inclusions in tantalite may be an inherent problem for TIMS analysis because of multiple sources of common lead (e.g., Romer & Wright 1992), imaging of the tantalite from the BLP (D. Kontak, unpublished data) indicates that no such inclusions exist in the samples analyzed. Although the BLP is locally deformed (Kontak 2004), the tantalite-bearing sample used for dating records no evidence of post-crystallization deformation and, instead, the tantalite grains formed a cluster of radiating euhedral crystals in a host of coarse albite (Fig. 2c). Thus, given the nature of the tantalite analyzed, the absence of a later, much younger, high-temperature (i.e., >500–600°C) thermal overprinting event, and the quality of the tantalite analyses, the ~27 m.y. range of $^{206}Pb/^{238}U$ ages obtained is surprising. The five U-Pb tantalite analyses lie on a possible short mixing line with end member ages at ca. 395 and 365 Ma and it is likely that these ages are geologically significant. Additional support for a mixing line is the inverse correlation between uranium content and age (Table 1 and Fig. 3). The tantalite fraction with the oldest age of ~395 Ma (#3) has the lowest uranium content (214 ppm) and the fraction with the lowest age of ~365 Ma (#4) has the highest uranium content (567 ppm). No correlation exists between age and proportion of common lead in the analyses (Table 1). Two possible interpretations for these tantalite U-Pb results are (1) the tantalite in the Brazil Lake pegmatite formed at ~395 Ma (or possibly slightly older) and experienced post-crystallization disturbance at ~365 Ma or later, causing partial lead loss, or (2) the tantalite formed during pegmatite emplacement at ~365 Ma and inherited some older ~395 Ma tantalite from crustal contamination. We consider the first interpretation to be the best explanation for the Brazil Lake tantalite U-Pb results because tantalite is generally quite rare in crustal rocks and it seems remote that there would be tantalite xenocrysts originally present in the Brazil Lake magma. In addition, the correlation between uranium content and decreasing age is most consistent with higher uranium portions of the crystal losing a higher proportion of radiogenic lead during a post-crystallization thermal or hydrothermal disturbance. Given the aforementioned features of tantalite, we interpret that initial pegmatite formation is recorded by the older age of ~395 Ma and a second event is recorded at ~365 Ma, or slightly later.

The ~395 Ma U-Pb tantalite age approximates the ca. 400 Ma age for Acadian deformation in this area (Muecke *et al.* 1988; Muir 2000) and falls between the known ages for recognized magmatism of ca. 440 and 380 Ma for the White Rock Formation and associated subvolcanic magmatism (i.e., Brenton pluton) and the South Mountain Batholith, respectively (see above). Thus, it is important to emphasize that there is at present no known magmatic affiliation for the BLP in the area. Hence, we again note that the pegmatite is located within amphibolite-facies rocks along the southern contact of the White Rock Formation with the Meguma Group that coincides regionally with a major shear zone, the Chebogue Point Shear Zone (White *et al.* 2001). The conditions of formation of this shear zone and associated high-grade metamorphism have not been resolved; however, the spatial association with the Acadian-age structure and the apparent Acadian deformation age for the pegmatite suggest a possible relationship, which we expand on below.

Regarding the younger tantalite ages, we note the following relevant information: (1) the emplacement of the Wedgeport pluton at 357 Ma (MacLean *et al.* 2003); (2) concordant ages for molybdenite (Re-Os) and greisen muscovite ($^{40}Ar/^{39}Ar$) of ca. 362 Ma (D. Kontak, unpublished data) for a mineralized leucomonzogranite body, the Clayton Hill pluton (Horne *et al.* 2000), located 7–8 west of the South Mountain Batholith; and (3) the ca. 350 Ma $^{40}Ar/^{39}Ar$ muscovite ages at Brazil Lake obtained in this study and by Moynihan (2003). Thus, the younger U-Pb tantalite ages may reflect widespread hydrothermal activity previously undetected in this part of the Meguma terrane that relates to a widespread thermal and/or magmatic event.

Re-Os molybdenite age

Recent studies of molybdenite from a variety of geological environments have shown that it is a reliable geochronometer with a high blocking temperature (i.e., 600–700°C) and robust nature such that it has the ability to retain primary ages despite the influence of tectono-thermal activity (e.g., Stein *et al.* 1998; Raith & Stein 2000). Problems occur related to decoupling of Re and Os in molybdenite (e.g., Stein *et al.* 1998, 2000; Košler *et al.* 2003; Selby & Creaser 2004), but they can be avoided with careful sample selection and preparation, as indicated by concordance of Re-Os ages with other geochronometric results (e.g., Selby *et al.* 2003). In the present study, concordant results for different weight fractions of a homogenized sample of a single large molybdenite grain and a homogenized sampling of smaller grains from the same hand sample indicate that elemental decoupling is not a problem. Thus, the 353.0 ± 2.5 Ma age for the molybdenite is considered a reliable estimate of the time of formation of this mineral. In addition, the high blocking temperature for the Re-Os system likely precludes resetting of this chronometer.

That the timing of molybdenite mineralization is significantly different than the age of pegmatite formation is not unexpected, given that molybdenite has not been found in the BLP and the dated sample is the only known occurrence of this mineral in the area. In light of this observation, it is relevant to note that the Wedgeport pluton (Fig. 1), located south of the BLP, was re-dated recently using U-Pb zircon and yielded an age of 357 Ma (MacLean *et al.* 2003). This pluton has A-type chemical affinities and, most importantly, has spatially-related pegmatite and chalcophile-lithophile element mineralization. Although this pluton is too distal to the molybdenite mineralization at Brazil Lake to suggest a direct genetic relationship, its presence nevertheless suggests that a similar but unexposed intrusion of the appropriate age may occur in the study area.

Thus, the 353 Ma Re-Os molybdenite age is interpreted to reflect the presence in the area of a magmatic-thermal event of appropriate age which is in places also manifested by vein formation.

$^{40}Ar/^{39}Ar$ muscovite ages

The laser $^{40}Ar/^{39}Ar$ ages provide detailed geochronological information on a small aliquot of material from a much larger domain and, as such, provide the ability to resolve potential age gradients in material. Such a scenario may occur where a thermal overprint affected an area and consequently promoted elemental diffusion within a host mineral, in this case argon diffusion in muscovite. In order to investigate this possible scenario and determine the time of muscovite crystallization, core and rim analysis of a single muscovite grain were made. As noted previously, although the ages ranged from a low of 318 Ma to a maximum of 347 Ma, with the former from the rim and the latter from the core, data from the two domains overlap considerably. As the maximum age of pegmatite formation is ca. 395 Ma and the analysed muscovite is consistent with a magmatic origin based on its texture and chemistry (D. Kontak, unpublished data), the 347 to 318 Ma ages are interpreted to reflect the effect of one or more overprinting thermal events which caused degassing of the samples. Although the simplest scenario would be to have a single thermal event at ~318 Ma with variable resetting, for which there is supporting evidence in this area (Kontak & Cormier 1991; Kontak *et al.* 1995; Culshaw & Reynolds 1997; Keppie & Dallmeyer 1995), we cannot rule out complete out-gassing at ca. 350 Ma during the same event that resulted in molybdenite formation. Thus, the maximum $^{40}Ar/^{39}Ar$ age of 347 Ma may approximate one post-crystallization event in the BLP (also recorded by the Re-Os molybdenite chronometer), whereas the younger age of 318 Ma may relate to the younger Alleghanian event. The intervening ages may represent either sampling of mixed age domains in the grain or partial resetting of the same areas.

The conclusions for the $^{40}Ar/^{39}Ar$ dating of muscovite from the BLP are similar to those of Moynihan (2003) based on a more comprehensive $^{40}Ar/^{39}Ar$ study of wall-rock amphibole and pegmatitic muscovite (northern pegmatite) from this same area. Moynihan (2003) obtained maximum ages of ca. 350 Ma and minimum ages of ca. 320 Ma and, whereas he considered the older age to represent the time of post-Acadian cooling to below 350°C, the younger age was considered to represent a reheating event related to the Alleghanian orogeny. The present data base is consistent with these interpretations.

Implications of the U-Pb tantalite age for the origin and metallogeny of the Brazil Lake pegmatite and surrounding area

As reviewed by erný (1991a), the most likely model for rare-element pegmatite origin is derivation from fertile granite rather than localized, *in situ* melt generation via anatectic processes accompanying regional metamorphism. However, the overall setting of the BLP clearly shows a strong structural and metamorphic affiliation and, therefore, suggests a relationship. Thus, we note that it is not uncommon for pegmatite to be located in structural zones, as noted for example by Longstaffe *et al.* (1980) for pegmatite of the Winnipeg River district. Also relevant is that evolved or specialized granites are associated with fault or shear zone environments, such as the leucogranite of southern Brittany, France. In this latter case, Strong & Hanmer (1980) argued for an origin involving faulting, frictional heating, fluid flux, and fractional melting. A similar model has been suggested for the Himalayan leucogranite (Le Fort 1981), which also show a strong association with regional structures (e.g., Le Fort *et al.*1987; Harrison *et al.* 1997). Thus, for the BLP we suggest that the location of the pegmatite in a zone of high-grade metamorphism is not coincidental and reflects generation at depth of a crust-derived melt incorporating the components of the models alluded to above. We suggest that the elevated geothermal gradient in these zones, estimated at 45°C/km by Moynihan (2003), resulted in partial melting commencing at 5–6 kbars pressure for the most favourable conditions (e.g., Burnham 1979; Johannes & Holtz 1996); slightly deeper crustal levels are also accommodated by the model. The presence of high Li in the BLP indicates that a source enriched in muscovite is likely (London, in press) and that a highly fractionated melt must have been generated via crystal fractionation to produce such an end-product, a Li-rich melt carrying several wt. % Li_2O (London 1992). Thus, we suggest generation of a melt at depth followed by fractional crystallization during ascent to a shallower crustal level and finally extraction at a late stage of a volatile-rich melt. Given that Li-rich melts inherently have a low viscosity which enables them to migrate considerable distances (e.g., several km) from their source (Baker 1998), the prospective area for pegmatite occurrence can be found along the strike continuation of the Chebogue Point Shear Zone. Similarly, given that similar metamorphic and structural conditions existed on the parallel shear zone on the west side of the Yarmouth syncline, this area is also considered prospective for similar pegmatite.

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