

Article

U-Pb, Ar-Ar, and Re-Os Geochronological Constraints on Multiple Magmatic–Hydrothermal Episodes at the Lake George Mine, Central New Brunswick

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Abstract: The Lake George antimony mine was at one time North America's largest producer of antimony. Despite being widely known for the antimony mineralization, the deposit also hosts a range of styles of mineralization such as multiple generations of W-Mo bearing quartz veins as well as a system of As-Au bearing quartz–carbonate veins. In situ U-Pb zircon geochronology, using LA ICP-MS, of the Lake George granodiorite yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.6 ± 3.0 Ma. Step heating of phlogopite separated from the lamprophyre dykes produced a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau segment date of 419.4 ± 1.4 Ma. Single molybdenite crystal analysis for Re-Os geochronology was conducted on two W-Mo-bearing quartz veins, which cross-cut altered granodiorite and altered metasedimentary rocks and yielded two dates of 415.7 ± 1.7 Ma and 416.1 ± 1.7 Ma respectively. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of muscovite from alteration associated with Au-bearing quartz–carbonate veins yielded one representative plateau segment date of 414.1 ± 1.3 Ma. The dates produced in this study revealed that the different magmatic–hydrothermal events at the Lake George mine occurred over approximately a 10-million-year period at the end of the Silurian and the start of the Devonian following the termination of the Acadian orogeny.

Keywords: U-Pb geochronology; Ar-Ar geochronology; Re-Os geochronology; intrusion-related; W-Mo; gold; antimony mine; New Brunswick

1. Introduction

The Lake George antimony mine, located approximately 30 km west of Fredericton in west-central New Brunswick (Figure 1), was once North America's largest producer of antimony. In addition to antimony, the area surrounding the Lake George mine contains W, Mo, and Au mineralization; however, these commodities were never the focus of exploration or development.

Antimony was first discovered in the Lake George area during road construction in 1863; since then, the area has seen sporadic exploration and mining activity [1]. The Lake George Mining and Smelting company was formed in 1876 to operate the Hibbard mine. In 1869, the first shaft was sunk on the property followed by the construction of a mill and smelter by the Hibbard Antimony Company in 1880. Between 1863 and 1969, three shafts were sunk on the Hibbard, Adams, and Lawrence showings. Between 1972 and 1981, 34,417 tonnes of concentrate grading 65–66% Sb was produced at the Lake George Mine [1]. Prior to 1984, approximately 0.85 Mt of ore grading approximately 4.15% antimony was mined from several occurrences.

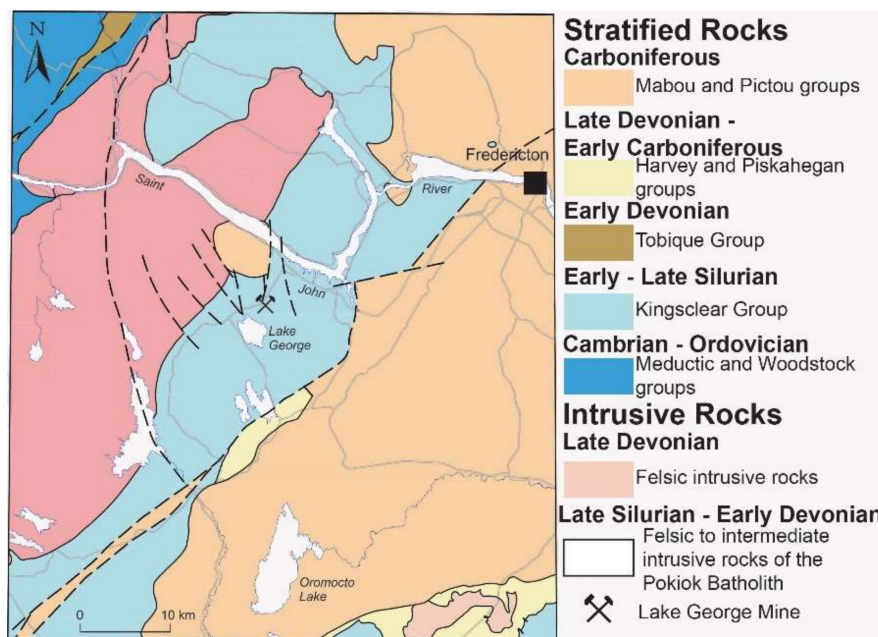


Figure 1. Geological map of the Lake George area and surrounding region in central New Brunswick.

In 1990, Apocan Inc. acquired the property and reopened the mine in 1994 in response to a drastic increase in the price of antimony. Production resumed in 1996 but came to an end in December of that year with closure of the mine due to mechanical issues and falling antimony prices. Approximately 1 Mt of ore grading 4% Sb was extracted from the No. 1 and No. 2 orebodies between 1985 and 1990 [1]. As of 1997, the proven, probable, and possible ore reserves totaled 262,000 tonnes at 3.45% Sb [2]. A recent NI 43-101 report quoted an indicated mineral resource of 153,147 tonnes grading 3.73% Sb and inferred mineral resource of 718,046 tonnes grading 2.61% Sb at a cut-off grade of 1.5% Sb [3].

Previous investigations have distinguished the relative timing of magmatic and hydrothermal events within the Lake George contact-metasomatic aureole based on cross-cutting relationships [4–6]; however, the absolute timing of these events has not been thoroughly investigated owing to the limitations of geochronological methods and techniques previously employed. For example, previous K-Ar dating studies did not have the precision necessary to resolve the absolute timing of the various geologic events [5–7]. More recently, geochronological constraints were placed on the quartz–feldspar porphyry dyke (QFP) [8] and the Lake George granodiorite [9] with U-Pb zircon geochronology using thermal ionization mass spectrometry (TIMS). Despite applying a common lead correction, all analyses exhibited variable degrees of discordancy. U-Pb zircon TIMS geochronology is limited by the high cost per sample analyzed, which is why newer methods with much lower costs per analysis such as laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS) have largely replaced TIMS for broad scale or reconnaissance studies. Another advantage of LA ICP-MS U-Pb geochronology over TIMS is the ability to date minerals in situ, allowing the user to selectively analyze specific domains within the zircon crystals. Modern U-Pb, Re-Os and Ar-Ar geochronological methods provide the opportunity to garner information on the absolute timing of events and quantify the duration of this multi-generational magmatic hydrothermal system.

The objective of this study is to establish the absolute timing of the various magmatic and hydrothermal events in the Lake George polymetallic system to help constrain the genesis of the multiple mineralizing events.

2. Regional Geology

In the Fredericton area, Silurian rocks of the Kingsclear Group form an approximately 80 km wide belt known as the Fredericton Trough, which lies between the Miramichi Highlands to the northwest

and the St. Croix Highlands to the southeast [10]. The most recent interpretations suggest that the Fredericton trough was either an arc-trench gap or a fore-deep basin in what remained of the Iapetus Ocean. Erosion of the Miramichi Highlands occurred into this basin, while the arc was accreted onto the North American continental margin and subsequently uplifted [11].

The Early Silurian Kingsclear Group comprises the Hayes Brook, Cross Creek, Burtts Corner, and Taxis River formations, which lie to the northwest of the Fredericton Fault and the Digdeguash, Sand Brook, and Flume Ridge formations to the southeast of the Fredericton Fault. Within the Kingsclear Group, detritus was identified that originated from the adjacent Ordovician units [12,13]. The contacts between the Kingsclear Group and the Cambro-Ordovician rocks they overlie are often faulted however the contacts in some areas are unconformable depending on their location within the Fredericton Trough [14–16]. A large portion of the eastern part of the Fredericton Trough is overlain unconformably by Carboniferous age sedimentary rocks.

Mineralization at the Lake George mine is hosted in Silurian Kingsclear Group metasedimentary rocks of the Burtts Corner Formation. The Kingsclear Group metasedimentary rocks in the area surrounding the mine consist of graywacke, sandstone, siltstone, and black, non-graphitic shale with variable amounts of carbonate (up to 40%). These sedimentary rocks preserve both complete and partial Bouma sequences, indicative of a turbiditic origin [4]. Graptolite fossils from the Burtts Corner Formation indicate deposition sometime between the Wenlock and the Ludlow periods [17]. The sedimentary rocks have undergone lower greenschist facies regional metamorphism resulting from the D₁ phase of the Acadian Orogeny [18]. This D₁ phase is a penetrative deformation and produced tight folding with northeast-trending axial planar cleavages in the Lake George area [19].

Granitic phases, along the northeastern margin of the Pokiok Batholith (Figure 1), have been dated through U-Pb geochronology of various accessory minerals. Ages reported include the oldest phase of the Pokiok Batholith, the Hartfield Tonalite [20], which yielded a date of 415 ± 1 Ma (U-Pb titanite). The dates obtained for the other granitoids of the Pokiok Batholith include the Hawkshaw Granite at 411 ± 2 Ma (U-Pb titanite), followed by the Skiff Lake Granite at 409 ± 2 Ma (U-Pb zircon), and the younger Allandale Granite at 402 ± 1 Ma (U-Pb monazite; $^{207}\text{Pb}/^{235}\text{U}$ age) [20]. The U-Pb zircon TIMS age of 400.5 ± 1.2 Ma for the Zealand Be-W pegmatite-aplite dyke is indistinguishable from the age of Allandale Granite [21].

3. Mine Geology

At the Lake George mine, which lies on the southeast margin of the Pokiok Batholith, a granodiorite stock (informally referred to as the Lake George granodiorite intrudes tightly folded Early to Late Silurian turbiditic sedimentary rocks of the Burtts Corner Formation (Figures 1 and 2). Within these Silurian sedimentary sequences, deformation associated with the Acadian Orogeny produced upright, open to tight roughly north–south trending folds and accompanying northeast-trending, 20° south-dipping axial planar cleavage within the Kingsclear Group [19]. The apex of the granodiorite stock lies approximately 500 m north of the Hibbard shaft and approximately 350 m below surface (Figure 2). Intrusion of the granodiorite stock into the Kingsclear Group resulted in a distal biotite-grade contact metamorphic aureole that extends up to 1 km from the intrusion contact and a narrow (200–300 m from the stock) proximal cordierite–andalusite grade contact metamorphic aureole. The contact metamorphic corundum + potassium feldspar assemblage was observed [5] within the stability field of andalusite, placing an upper pressure limit on contact metamorphism at 1.75 kbar (175 MPa).

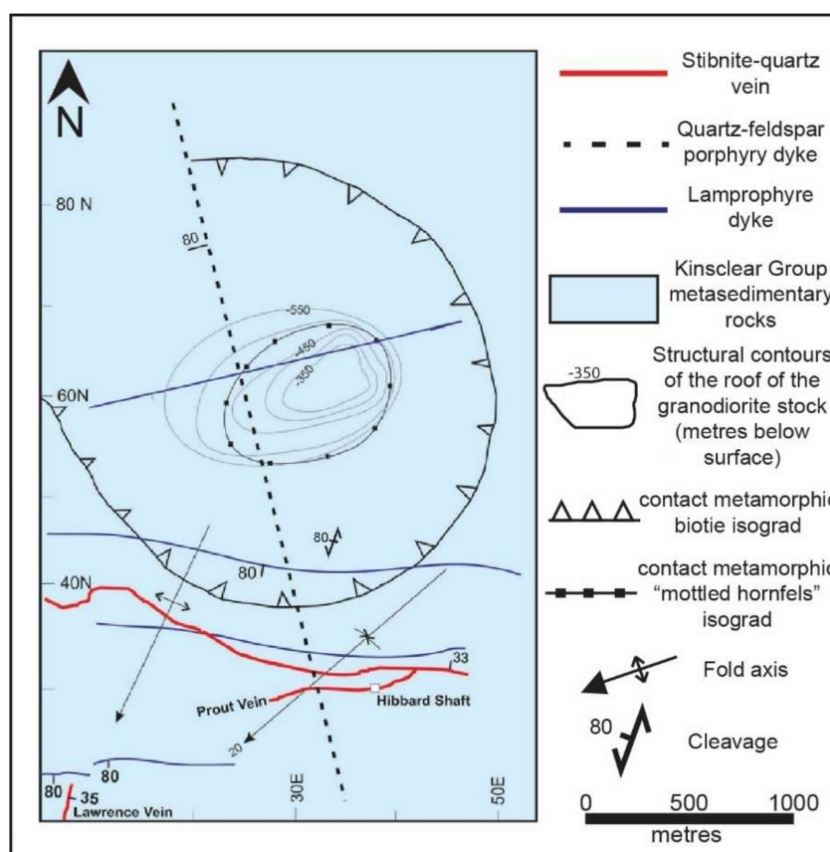


Figure 2. Geological map of the Lake George mine, illustrating the granodiorite stock contoured at depth, the quartz–feldspar porphyry dyke, the lamprophyre dykes, and vein systems in the area (modified from [6]).

The cross-cutting relationships of the various magmatic and hydrothermal events at the Lake George mine have been described in detail [5]. A total of three intrusive events and five generations of veins are described below (Figure 3). Emplacement of the granodiorite stock is the oldest intrusive event (I-1) followed by the formation of the first generation of W-Mo bearing quartz veins (Type I). These veins have zoned calc-silicate alteration envelopes (garnet–clinopyroxene–wollastonite) and were not observed directly cross-cutting the granodiorite; however, they do cross-cut the contact metamorphic aureole [5]. Following the formation of the Type I veins, a series of subvertical roughly east-striking lamprophyre dykes (I-2) were emplaced into the sedimentary rocks. Subsequently, a northwest-striking quartz–feldspar porphyry (QFP) dyke (I-3), which cross-cuts the lamprophyre dykes, was emplaced. The second generation of quartz veining (Type II W-Mo), postdates the QFP dyke, and the Mo-bearing prehnite-quartz veinlets (Type III) cross-cut Type II veins and represent the latest W-Mo mineralizing event at the Lake George mine. The first episode of Au-Sb mineralization at the Lake George mine is a network of quartz–carbonate veins and veinlets with corresponding sericitic alteration envelopes (Type IV) containing gold-bearing pyrite and arsenopyrite, followed by the Sb-quartz veins, which contain stibnite and quartz with minor pyrite, pyrrhotite, native antimony, and arsenopyrite (Type V). The Type V veins include the Hibbard, Adams, Lawrence, and Prout veins (Figure 2), and were the sites of previous antimony mining.

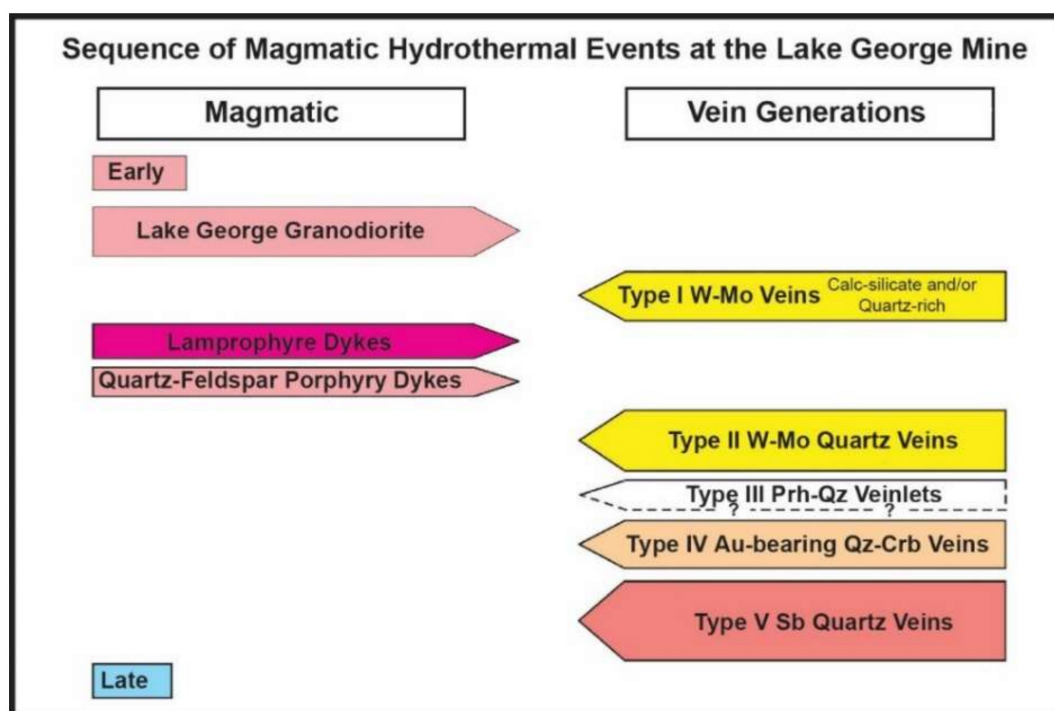


Figure 3. Schematic representation of the relative sequence of the magmatic hydrothermal events present in the area surrounding the Lake George antimony mine (modified from [6]).

3.1. Lake George Granodiorite

The Lake George granodiorite is a fine- to medium-grained and seriate to porphyritic stock that straddles the plagioclase–biotite tie line on the ACF diagram [5,22]. Petrochemical characteristics of the stock are transitional between I- and S-type granites [5]. The granodiorite cupola is not exposed at surface but has been intersected in underground drilling. The contact metamorphic aureole associated with the emplacement of the granodiorite stock predates all hydrothermal activity (i.e., Type I through Type V veins) [6].

The Hawkshaw Granite crops out 4.5 km northwest of the Lake George mine and is the nearest phase of the Pokiok Batholith (Figure 1, [23]). The Hawkshaw Granite consists primarily of pink, equigranular to seriate biotite granite and granodiorite [24]. Both the Hawkshaw Granite and the Lake George granodiorite exhibit low ferric iron ratios indicative of ilmenite series granitic rocks. Similarities in major- and trace-elements has led some authors to suggest that the Hawkshaw Granite and Lake George granodiorite are petrogenetically linked through fractional crystallization [23]. These geochemical characteristics suggests the magma that formed the Lake George granodiorite was derived from the partial melting of arc-like lower continental crust in a volcanic arc to late orogenic environment, near the time of emplacement of the Pokiok Batholith [23].

Geochronology of the Lake George granodiorite was first undertaken using K-Ar analysis of biotite which yielded a date of 390 ± 7 Ma [7]. Previous U-Pb zircon geochronology of the Lake George granodiorite yielded an upper $^{207}\text{Pb}/^{206}\text{Pb}$ Concordia intercept date of 414 ± 2 Ma [9].

3.2. Lamprophyre Dykes

A series of east-striking, steeply south-dipping lamprophyre dykes at the Lake George mine were emplaced into the Kingsclear Group metasedimentary rocks. These fine- to medium-grained hornblende-phyric dykes are basaltic trachyandesitic in composition and have ultra-potassic geochemical characteristics [25]. The geochemistry and mineralogy of these dykes are characteristic of shoshonitic lamprophyres of calc-alkaline affinity. K-Ar geochronology of actinolitic hornblende from

the dyke yielded a date of 382 ± 7 Ma [6]. The same method applied to phlogopite from these dykes yielded a date of 415 ± 8 Ma [6].

3.3. QFP Dyke

A quartz–feldspar porphyry (QFP) dyke at the Lake George mine strikes north-northwest and dips steeply to the west, is approximately 3–5 m thick and contains quartz and two feldspars as phenocrysts within an aphanitic groundmass. Normative mineralogy calculations from whole-rock analysis suggests that the dyke plots at the boundary between the granite and granodiorite on a QAP diagram [26]. On trace element geotectonic discrimination diagrams their composition plots in the volcanic arc granitoid field [27]. The size and texture of the phenocrysts and groundmass in the QFP dyke are relatively consistent from depth to the surface, with the exception of more brecciated margins near surface. The groundmass is recrystallized and variably hydrothermally altered which was interpreted to reflect auto-metasomatic alteration by exsolved deuteritic fluids [8].

Uranium–lead zircon geochronology conducted through isotope dilution–thermal ionization mass spectrometry (ID-TIMS) on the QFP dyke yielded an upper intercept date of $420.8 \pm 5.9/-4.0$ Ma [8]. Five single and double zircon fractions were analyzed and corrected for common Pb. The four zircon analyses used to produce the age were 94.0–99.4% concordant and the MSWD of this age was 2.9.

4. Sampling

Samples were collected with the aims of understanding the origins of the gold mineralization as well as the temporal relations between as many magmatic–hydrothermal events as possible using more modern and robust analytical methods. The samples used in this study were collected from drill core that is housed on the mine site or were part of a catalogue of historic samples housed at the University of New Brunswick (UNB) in Fredericton. Samples of the Lake George granodiorite were taken from drill core which was least altered in appearance (Figure 4). The samples of lamprophyre dyke came from the preexisting sample catalogue as well as from least altered samples of drill core (Figure 5).

Type II W–Mo-bearing quartz veins were sampled from drill core and were submitted for molybdenite extraction and analysis. Molybdenite which was sampled and separated from these veins was done with special attention to choosing molybdenite that was not in contact with any other sulphides. Sample KT-11-03 (Figure 6a) was collected from a scheelite- and molybdenite-bearing quartz vein in drill hole 81-27 from a depth of 2438.8 to 2424.4 feet (743.4–739.0 m) that cut across altered Lake George granodiorite. The sample consists of sericitized coarse-grained granodiorite that contains molybdenite associated with quartz. The irregular shape of the 3 cm long molybdenite mass suggests that it may have been remobilized. The second sample (KT-11-04; Figure 6b) was collected from drill hole 80-15 between 693 and 693.5 feet (211.2–211.4 m) where molybdenite was contained within a 0.5 cm wide quartz vein that cut greywacke.



Figure 4. Photograph of drill core showing the Lake George granodiorite (sample LG-80-33-2017). The diameter of the drill core is approximately 5 cm.

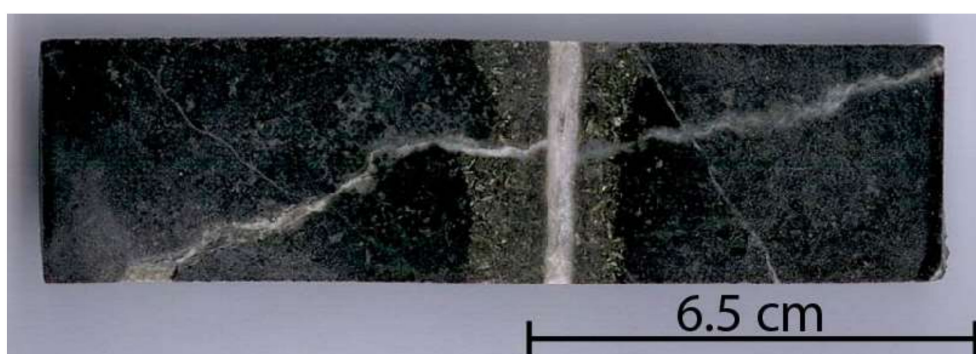


Figure 5. Photograph of drill core slab displaying a lamprophyre dyke cross-cut by a quartz vein and its associated alteration envelope (sample 80-12).



Figure 6. (a) Photograph displaying a W-Mo-bearing quartz vein cross-cutting altered granodiorite. (b) Photograph displaying a W-Mo-bearing quartz vein (approximately 0.5 cm wide) cross-cutting an altered metasedimentary rock (greywacke). The diameter of the drill core is approximately 5 cm.

The samples of gold-bearing quartz–carbonate veins were taken from drill core with historic gold assays [28,29], from large bulk sample piles brought to surface during mining, as well as historic samples originating from the gold room [1]. Samples of gold-bearing quartz–carbonate veins were taken and muscovite from the green sericitic alteration was separated and analyzed using step heating $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. Gold in these samples is refractory and is hosted within sulphides (arsenopyrite and arsenian pyrite) found within the green sericitic alteration envelopes surrounding the veins. Sample LG-80-33-1848 (Figure 7) was taken from drill core housed at the mine site and contains a quartz–carbonate vein with associated sericitic alteration surrounding the vein from which coarse-grained (up to 1 mm diameter) muscovite was separated. Sample 03-LG-1 (Figure 8) was a grab sample taken from a rock pile at surface that was extracted for bulk rock assay from the gold zone underground at the 850 level [29]. Muscovite from sample 03-LG-1 was too small to be picked by hand and therefore was analyzed as whole-rock chips (180–250 μm diameter) which contained >95% muscovite and quartz with the remainder being made up of chlorite, ankerite, and sulphides. Sample LG-78-4-143.5 (Figure 9) was taken from drill core and contains muscovite from the sericitic alteration surrounding the gold-bearing quartz–carbonate vein hosted within altered sedimentary rocks. Sample LG-85-3 (Figure 10) was part of the catalogue at UNB, which was originally taken underground from

the gold zone in the 1150 level on the west side. Muscovite from sample LG-85-3 and LG-78-28-143.5 ft were also separated, but the crystals from these samples were relatively small ($>50\text{ }\mu\text{m}$).



Figure 7. Photograph displaying a quartz vein (approximately 0.5 cm wide) cross-cutting an altered granodiorite (LG-80-33-1848). The diameter of the drill core is approximately 5 cm.



Figure 8. Photograph displaying a quartz–carbonate vein, roughly 0.7 cm in width, which is cross-cutting contact-metamorphosed (biotite-grade), altered sedimentary rocks (sample 03-LG-1).



Figure 9. Photograph displaying a quartz–carbonate vein, roughly 0.2 cm in width, which is cross-cutting contact-metamorphosed (biotite-grade), and sericitically altered sedimentary rock. The diameter of the drill core is approximately 5 cm. Sample LG-48-4-143.5 was taken from Diamond Drill Hole (DDH) 78-4 at a depth of 143.5 feet (43.7 m).



Figure 10. Photograph displaying sericitic alteration associated with gold mineralization in sample LG-85-3. This sample was taken from underground at the Lake George mine from the gold zone in the 1150 level on the west end.

5. Analytical Methods

Samples of Lake George granodiorite and lamprophyre dyke were collected for in situ laser ablation inductively coupled plasma-mass spectrometry (LA ICP-MS) U-Pb geochronology in order to establish absolute timing of these magmatic events. To determine the age of emplacement of Type II W-Mo veins, the veins were sampled and molybdenite separates prepared for Re-Os geochronology. Whole rock samples of lamprophyre dyke and gold-bearing quartz-carbonate veins were submitted for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis using step heating.

5.1. LA ICP-MS U-Pb Methodology

All U-Pb geochronology was conducted at the University of New Brunswick isotope geochemistry lab using in situ LA ICP-MS. The system in use at UNB is comprised of a Resonetics M-50 193 nm ArF excimer laser coupled with an Agilent 7700x quadrupole ICP-MS. The LA ICP-MS system at UNB is equipped with a variety of features that enhance their ability to date minerals with common lead, most of which are focused upon improving the sensitivity of the ICP-MS. These features include mixing of N_2 downstream from the ablation cell which enters through a Laurin Technic PTY PEEK Y-connector and squid smoothing device before reaching the ICP-MS, mercury traps which are in line with all gas lines entering the ablation cell (keeps $^{204}\text{Hg} < 150$ cps), along with a secondary external rotary pump [30]. The primary standard used for external calibration of the data from these analyses was the NIST 610 doped glass standard. The matrix matched consistency standard used when ablating zircon was the Temora 1 standard [31]. Zircon was ablated using a fluence of 4.5 J/cm^2 , a frequency of 4.5 Hz and a spot size of $36 \text{ }\mu\text{m}$. When titanite was ablated, the matrix-matched consistency standard was the Khan Mine standard [32]. Titanite was ablated using a fluence of 6 J/cm^2 , a frequency of 4.5 Hz and a spot size of $45 \text{ }\mu\text{m}$. Data reduction was performed using IOLITE [33] and plotted using Isoplot [34].

5.2. Re-Os Methodology

To establish an absolute age for the timing of the W-Mo stockwork veins, two molybdenite-bearing samples were collected for Re-Os geochronological analysis. Drill core samples containing molybdenite were submitted to the University of Alberta Radiogenic Isotope Facility. Each sample was subjected to metal-free crushing after which the molybdenite was extracted by gravity and magnetic concentration methods. Methods used to analyze the molybdenite are described in detail by other authors [35,36]. The ^{187}Re and ^{187}Os concentrations in the molybdenite were determined by isotope dilution mass spectrometry using Carius-tube digestion, solvent extraction, anion exchange chromatography, and negative thermal ionization mass spectrometry techniques. A mixed double spike containing known amounts of isotopically enriched ^{187}Re , ^{190}Os , and ^{188}Os analysis was used. Isotopic analysis was performed using a ThermoScientific Triton mass spectrometer with Faraday collectors. Total procedural blanks for Re and Os are less than 3 picograms and 2 picograms, respectively, which are insignificant for the Re and Os concentrations in molybdenite. The Chinese molybdenite powder HLP-5 [37] is routinely analyzed as a Re-Os age standard. For this sample over a period of two years, an average Re-Os date of 221.5 ± 0.4 Ma (1 SD uncertainty, $n = 8$) is obtained. This Re-Os age date is indistinguishable from the established age of 221.0 ± 1.0 Ma [37].

5.3. $^{40}\text{Ar}/^{39}\text{Ar}$ Methodology

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology was conducted at the Queen's University Ar-Ar geochronology lab. The samples were first crushed, sieved, and then washed. Mineral separates were purified by hand picking. For fine-grained rocks, whole rock fragments in the 180–250 μm diameter range were used. After preparation, the sample along with a flux monitor was placed in an irradiation capsule and irradiated with fast neutrons at the McMaster Nuclear Reactor in Hamilton Ontario. The samples were irradiated at the McMaster reactor in position 5C or 8D without Cd shielding. Hb3Gr hornblende GA1550 biotite (1081.0 Ma and 99.738 Ma, respectively; referenced to FC at 28.294 Ma, [38]) were used as flux monitors. After irradiation, the samples were step heated using a 30W New Wave Research MIR 10-30 CO_2 laser in a stainless-steel chamber attached to an ultrahigh-vacuum purification system. Argon isotope analysis was done using an MAP-216 mass spectrometer [39]. The $^{40}\text{Ar}/^{39}\text{Ar}$ dates calculated for these samples use the ^{40}K decay constant and flux monitor ages [38] and all errors are quoted at 2-sigma. Age spectra were generated using ISOPLOT 3.71 [34]. Because the samples are very radiogenic, no meaningful inverse isochron dates or initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratios could be defined.

6. Results

6.1. LA ICP-MS U-Pb Geochronology

6.1.1. Lake George Granodiorite

A total of 14 spot analyses were conducted on six zircon grains (Figure 11) from the medium-grained granodiorite sample (sample LG-80-33-2017). The Temora 1 zircon standard has an accepted age of 417 Ma and the analyses produced a concordant age of 419.5 ± 2.9 Ma (Figure 12). Of the 14 analyses from six zircons, 11 yielded near-concordant results (Table 1). From those 11 near-concordant analyses, five formed a roughly concordant population without requiring a common lead correction (see bold analyses, Table 1) which yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 419.6 ± 3.0 Ma (Figure 13).



Figure 11. Transmitted light photomicrograph taken using the 10× objective lens showing a zircon grain from the Lake George granodiorite. The dark holes in the zircon grain are ablation pits (sample LG-80-33-2017).

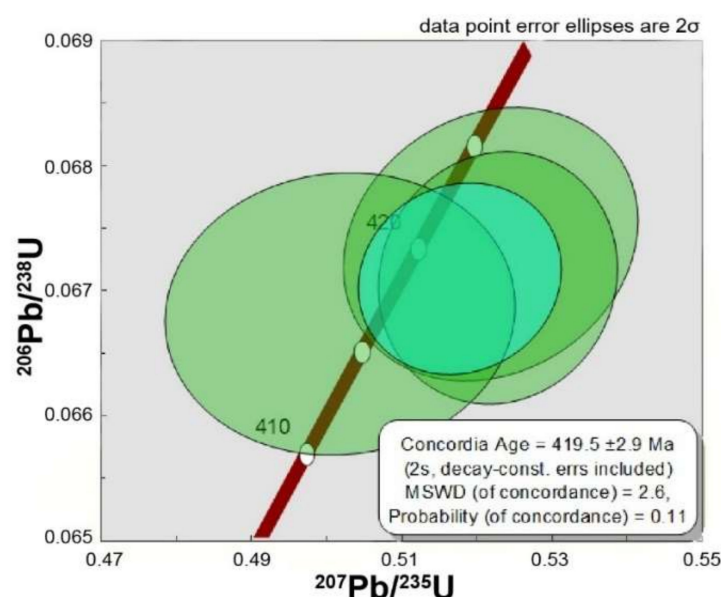


Figure 12. U-Pb concordia diagram for four analyses of the Temora 1 zircon standard. Data point error ellipses are reported at 2σ.

Table 1. U-Pb zircon geochronological data from Lake George Granodiorite (sample LG-80-33-2017). Pb* represents the percentage of radiogenic lead present in the analyses.

Sample	Duration (s)	%Pb*	%Disc	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	Err. Corr.	U (ppm)	Th (ppm)
z6.1	7.8	95.9	70.7	0.639	0.014	0.0574	0.0012	0.8261	3950	3400
z1.1	15.9	99.3	39.8	0.461	0.009	0.0561	0.0007	0.4627	2513	1009
z6.3	4.6	97.8	52.9	0.572	0.012	0.0631	0.0010	0.6654	4518	3122
z5.2	10.1	97.2	56.3	0.678	0.012	0.0685	0.0010	0.3340	3299	808
z1.4	10.7	98.9	38.5	0.587	0.023	0.0679	0.0013	0.8395	2020	858
z2.2c	17.2	96.7	61.3	0.734	0.016	0.0693	0.0010	0.7430	1364	586
z2.1r	13.4	98.9	42.3	0.602	0.019	0.0682	0.0010	0.7799	2170	1285
z1.3	11.5	99.3	34.8	0.578	0.013	0.0683	0.0013	0.6965	1469	833
z3.1	7.8	95.1	68.9	0.901	0.020	0.0727	0.0011	0.0715	1238	300
z2.3r	16.1	98.5	42.4	0.703	0.012	0.0767	0.0011	0.1882	1100	511
z1.2	20.2	99.1	31.8	0.700	0.015	0.0802	0.0012	0.5105	755	497

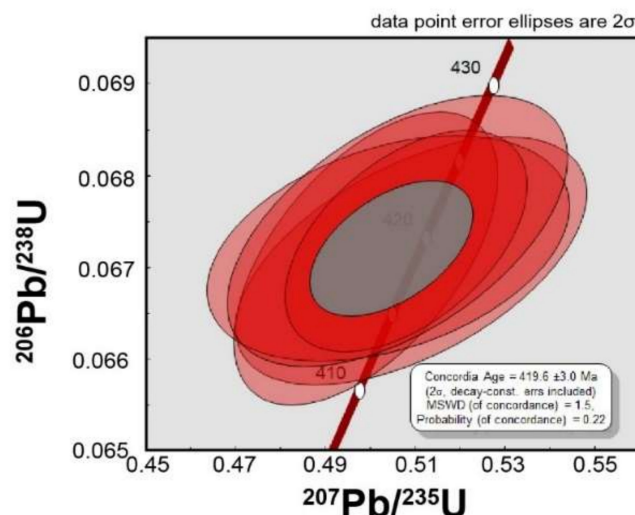


Figure 13. U-Pb concordia diagram for a population of 5 near-concordant zircon analyses (sample LG-80-33-2017), from the Lake George granodiorite plotted on concordia (bold analyses in Table 1). Data point error ellipses are reported at 2σ .

6.1.2. Lamprophyre Dykes

In situ LA ICP-MS U-Pb geochronology was conducted on titanite crystals (Figure 14) from two samples (78-21 and 80-12, see Figure 5). The results of the analyses plot as three populations. In order to produce dates for each of these populations, a ^{204}Pb correction was applied. The oldest population has five data points and yielded a ^{204}Pb corrected concordia date of 476 ± 11 Ma (Table 2, Figure 15). The next younger population, comprised of 18 analyses, yielded a ^{204}Pb corrected weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 435 ± 6 Ma (Table 3, Figure 16). The youngest population consisted of four analyses and yielded a ^{204}Pb corrected concordia date of 412 ± 9 Ma (Table 4, Figure 17). The titanite data was standardized using the Khan Mine titanite, which has an accepted age of 520 ± 2 Ma [40,41].

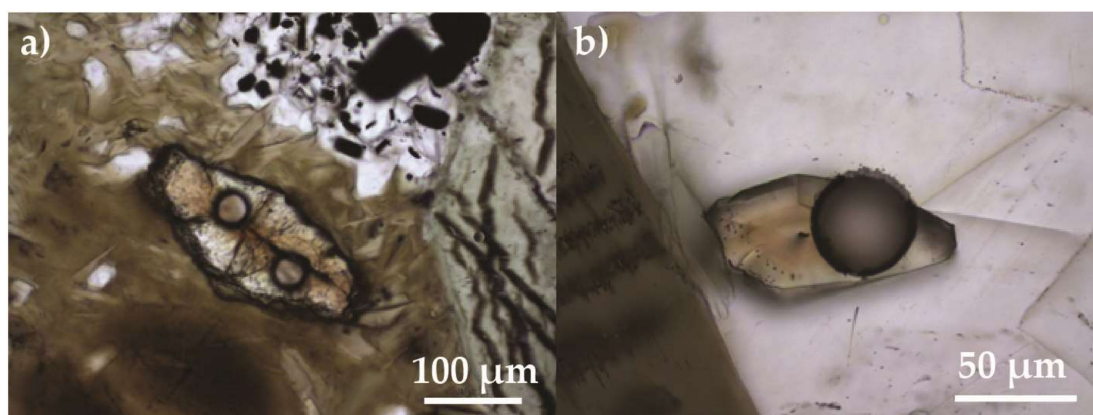
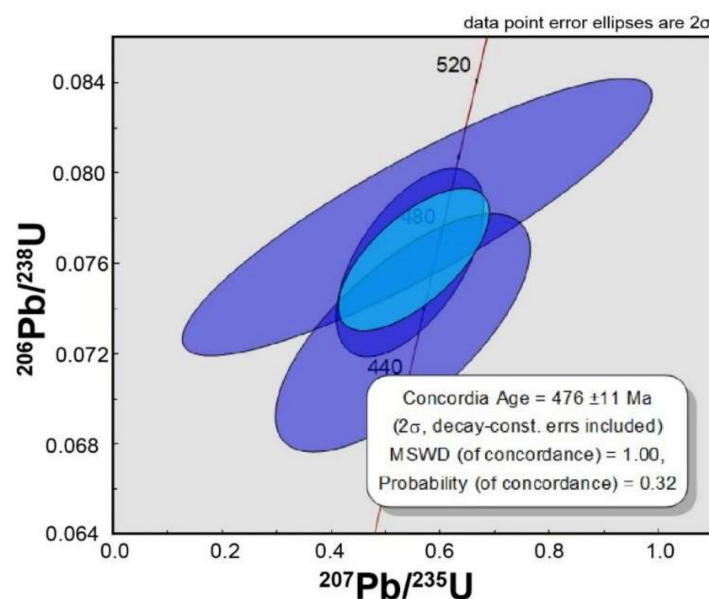


Figure 14. (a) Plane polarized light photomicrograph of lamprophyre sample displaying a titanite crystal within a chloritized biotite lath. The circular features in the center of the titanite crystals are ablation pits (sample 80-12). (b) Plane polarized light photomicrograph of lamprophyre sample displaying a titanite crystal within a carbonate grain. The circular feature is the ablation pit (sample 78-21).

Table 2. U-Pb titanite geochronological data from oldest population in the lamprophyre dyke (samples 78-21 and 80-12).

Sample	Duration(s)	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	Err. Corr.	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	2σ
78-21-9.3	29.6	0.55	0.11	0.0760	0.003	0.58	472	21
78-21-1.1	28.0	0.46	0.16	0.0734	0.004	0.56	457	22
80-12-3.1	28.6	0.56	0.35	0.0780	0.005	0.88	484	30
80-12-16.1	29.8	0.23	0.22	0.0722	0.005	0.78	449	30
80-12-20.2	12.4	0.53	0.19	0.0729	0.004	0.70	454	26

**Figure 15.** Oldest population of five ^{204}Pb corrected titanite analyses from a lamprophyre dyke plotted on the concordia diagram. The date listed above is a ^{204}Pb corrected concordant ^{206}Pb - ^{238}U age (data shown in Table 2). Data point error ellipses are reported at 2σ .**Table 3.** U-Pb titanite geochronological data from the intermediate population in the lamprophyre dyke (samples 78-21 and 80-12).

Sample	Duration(s)	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	Err. Corr.	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	2σ
78-21-3.1	20.8	0.50	0.10	0.0710	0.003	0.38	442	19
78-21-9.1	29.1	0.49	0.07	0.0690	0.003	0.57	430	18
80-12-10.1	13.5	0.46	0.08	0.0666	0.003	0.32	416	17
80-12-12.1	28.4	0.51	0.19	0.0706	0.004	0.74	440	26
80-12-19.1	29.5	0.32	0.31	0.0700	0.006	0.89	436	34
78-21-4.1	7.6	0.48	0.36	0.0706	0.006	0.81	440	35
80-12-12.2	29.6	0.57	0.21	0.0722	0.005	0.78	449	29
80-12-13.1	27.0	0.51	0.18	0.0707	0.004	0.72	441	22
80-12-18.1	29.5	0.39	0.19	0.0707	0.004	0.74	440	25
80-12-ep1.2	25.7	0.44	0.22	0.0667	0.005	0.79	416	28
80-12-17.1	23.5	0.55	0.27	0.0701	0.006	0.85	437	36
80-12-ep1.1	20.7	0.38	0.27	0.0682	0.005	0.74	425	29
80-12-1.2	16.0	0.44	0.22	0.0706	0.004	0.69	440	22
80-12-11.1	28.9	0.55	0.19	0.0704	0.004	0.69	439	23
80-12-4.1	29.2	0.44	0.20	0.0695	0.005	0.62	433	30
80-12-16.2	29.5	0.36	0.35	0.0703	0.006	0.84	438	37
80-12-20.1	10.5	0.54	0.18	0.0719	0.005	0.54	448	27
80-12-1.1	25.8	0.34	0.33	0.0717	0.006	0.84	446	36

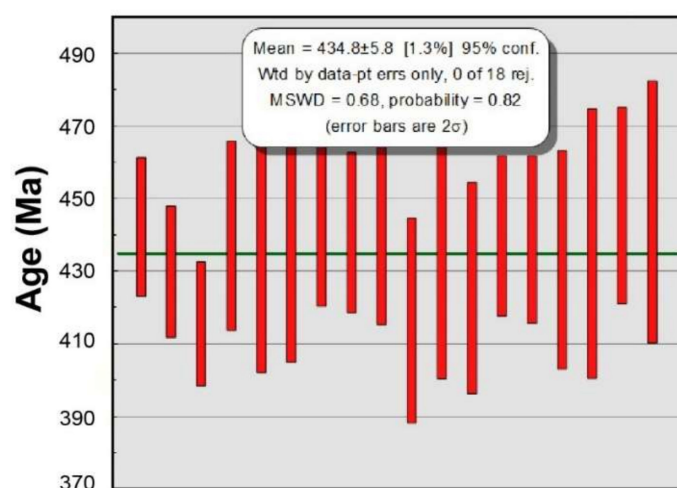


Figure 16. This population of eighteen analyses from a lamprophyre dyke is the second oldest U-Pb date produced using titanite from a lamprophyre dyke. The date listed above is a ^{204}Pb corrected weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date (data shown in Table 3). Error bars are to 2σ .

Table 4. U-Pb titanite geochronological data from youngest population in the lamprophyre dyke (samples 78-21 and 80-12).

Sample	Duration(s)	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	Err. Corr.	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	2σ
80-12-14.1	30.8	0.54	0.15	0.0669	0.004	0.61	417	26
80-12-13.2	29.5	0.54	0.11	0.0683	0.003	0.70	426	18
78-21-5.1	23.3	0.49	0.08	0.0644	0.003	0.37	403	15
78-21-6.1	4.8	0.47	0.16	0.0648	0.004	0.67	405	24

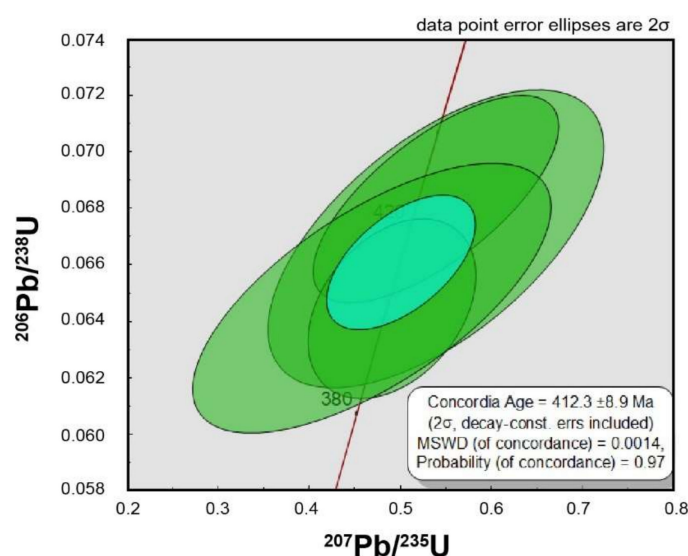


Figure 17. U-Pb concordia diagram displaying the youngest ^{204}Pb corrected concordant $^{206}\text{Pb}/^{238}\text{U}$ date produced using titanite from a lamprophyre dyke. The date listed above is a ^{204}Pb corrected concordant $^{206}\text{Pb}/^{238}\text{U}$ date (data shown in Table 4).

6.2. Re-Os Molybdenite (W-Mo Veins)

Single molybdenite crystal Re-Os isotopic analysis of sample KT-11-03 (Figure 6a) yielded a date of 415.7 ± 1.7 Ma. Analysis of molybdenite from sample KT-11-04 (Figure 6b) yielded a date of 416.1 ± 1.7 Ma. The isotopic data and model ages are listed below in Table 5.

Table 5. Isotope dilution thermal ionization mass spectrometry (ID TIMS) analyses of ^{187}Re and ^{187}Os in molybdenite from sample KT-11-03 and KT-11-04, KT-11-03: Model Age = 415 ± 1.7 Ma (2σ), KT-11-04: Model Age = 416.1 ± 1.7 Ma (2σ).

Sample	Location	Re (ppm)	$\pm 2\sigma$	^{187}Re (ppb)	$\pm 2\sigma$	^{187}Os (ppb)	$\pm 2\sigma$	Model Age (Ma)	$\pm 2\sigma$
KT-11-03	DDH 81-27	41.29	0.11	25951	67	180.3	0.1	415.7	1.7
KT-11-04	DDH 80-15	41.37	0.11	26002	66	180.9	0.1	416.1	1.7

6.3. $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

6.3.1. Lamprophyre Dyke (Phlogopite)

The analytical data for phlogopite from sample 80-12 is listed in Table 6 and the age spectrum is plotted in Figure 18. The $^{40}\text{Ar}/^{39}\text{Ar}$ data did not yield a reliable plateau date but the last step yielded a high temperature plateau segment date of 419.4 ± 1.4 Ma (34.1% of the ^{39}Ar released).

Table 6. Argon step heating data of phlogopite separate from sample 80-12, J value = 0.007576 ± 0.000017 (1σ), Plateau Segment Date = 419.4 ± 1.4 Ma (2σ) (34.10% ^{39}Ar).

Step No.	Power (%)	$^{40}\text{Ar}/^{39}\text{Ar}$	$\pm 1\sigma$	$^{40}\text{Ar}^*/^{39}\text{Ar}(\text{K})$	$\pm 1\sigma$	$^{40}\text{Ar}^*$ (%)	Cumulative ^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$	Ca/K	$\pm 1\sigma$
1	0.8	28.656	0.687	27.061	4.765	94.4	0.07	337.21	54.17	0.41	0.18
2	1.5	34.104	0.105	33.813	0.214	99.1	1.86	412.38	2.34	0.70	0.03
3	2.3	34.637	0.065	34.350	0.082	99.2	10.58	418.23	0.89	0.18	0.01
4	2.6	35.107	0.076	34.983	0.090	99.6	17.91	425.09	0.97	0.05	0.00
5	2.8	35.365	0.065	35.272	0.092	99.7	23.10	428.22	0.99	0.06	0.00
6	3.0	35.418	0.080	35.381	0.102	99.9	28.34	429.40	1.11	0.08	0.00
7	3.2	35.747	0.060	35.667	0.074	99.8	37.92	432.48	0.79	0.22	0.01
8	3.5	35.495	0.067	35.390	0.083	99.7	47.04	429.49	0.89	0.19	0.01
9	3.8	34.907	0.055	34.815	0.074	99.7	57.41	423.27	0.80	0.22	0.01
10	4.0	34.643	0.063	34.525	0.080	99.7	65.90	420.12	0.87	0.23	0.01
11	4.3	34.484	0.050	34.454	0.063	99.9	100.00	419.36	0.68	0.49	0.02

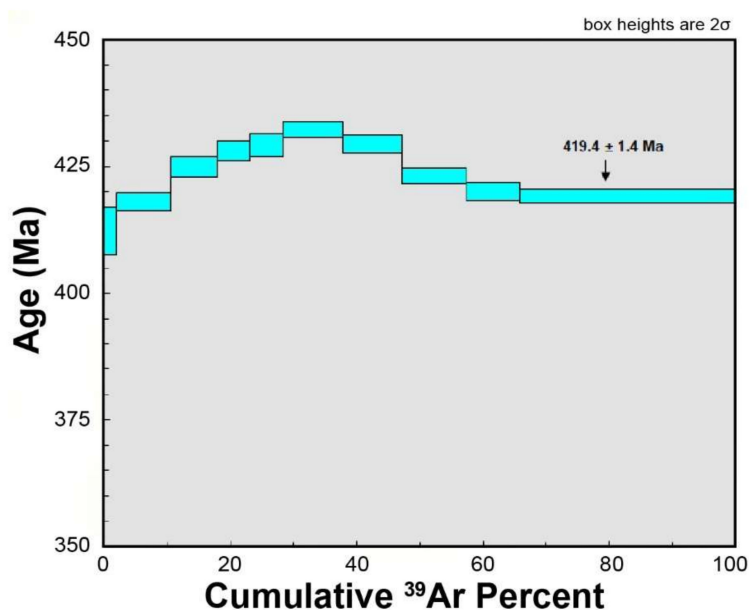


Figure 18. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum for phlogopite separate from lamprophyre dyke (sample 80-12).

6.3.2. Au-Bearing Veins (Muscovite)

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology was conducted on very fine- to coarse-grained hydrothermal muscovite from the alteration envelopes that mantle gold-bearing quartz–carbonate veins (Type IV). The $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic data from the analyses of gold-bearing samples LG-80-33-1848 ft, 03-LG-1, LG-78-4-143.5 ft, and LG-85-3 are reported in Tables 7–10, respectively, and the age spectra are shown in Figures 19–22. Plots of the cumulative percentage of ^{39}Ar released versus the Ca/K ratios were also generated (Figure 23a–d) to assess purity. The fine grain size of muscovite in some samples (as small as 1–10 μm) may have increased the potential for recoil loss of ^{39}Ar during irradiation to have occurred [42]. This would have the effect of increasing the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio resulting in erroneously old dates. A summary of the up to date geochronology of all magmatic–hydrothermal events at the Lake George Mine is presented in Figure 24.

Table 7. Argon step heating data of muscovite from sample LG-80-33-1848, J value = 0.005696 $\pm$ 0.000037 (1 σ), Plateau Date = 410.3 $\pm$ 1.1 Ma (2 σ) (MSWD = 1.4, 100% ^{39}Ar).

Step No.	Power (%)	$^{40}\text{Ar}/^{39}\text{Ar}$	$\pm 1\sigma$	$^{40}\text{Ar}^*/^{39}\text{Ar}(\text{K})$	$\pm 1\sigma$	$^{40}\text{Ar}^*$ (%)	Cumulative ^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$	Ca/K	$\pm 1\sigma$
1	3.0	63.513	1.870	39.952	2.824	62.9	0.24	370.13	23.65	0.32	0.41
2	4.0	45.229	0.531	42.931	0.672	94.9	1.50	394.91	5.55	0.15	0.07
3	5.0	45.928	0.394	44.671	0.451	97.3	4.11	409.23	3.70	0.02	0.04
4	6.0	45.472	0.234	44.863	0.244	98.7	12.44	410.80	2.00	0.01	0.01
5	6.7	44.817	0.213	44.394	0.219	99.1	25.27	406.96	1.79	0.00	0.01
6	7.3	45.004	0.214	44.645	0.226	99.2	34.20	409.02	1.85	0.00	0.01
7	7.9	45.045	0.218	44.613	0.228	99.0	45.09	408.76	1.87	0.01	0.01
8	8.5	44.961	0.243	44.739	0.251	99.5	56.09	409.79	2.06	0.00	0.01
9	9.1	45.087	0.217	44.932	0.227	99.7	63.31	411.36	1.86	0.00	0.01
10	10.0	44.808	0.193	44.595	0.201	99.5	73.52	408.61	1.64	0.00	0.01
11	11.0	45.074	0.226	44.917	0.236	99.7	80.24	411.25	1.94	0.00	0.01
12	12.5	44.871	0.205	44.676	0.217	99.6	87.49	409.27	1.78	0.00	0.02
13	45.0	45.173	0.195	45.030	0.203	99.7	100.00	412.17	1.66	0.04	0.01

Table 8. Argon step heating data of whole-rock muscovite from sample 03-LG-1, J value = 0.005703 $\pm$ 0.000017 (1 σ), Plateau Date = 418.3 $\pm$ 1.6 Ma (2 σ) (MSWD = 1.1, 85.9% ^{39}Ar), Plateau Segment Date = 415.9 $\pm$ 2.9 Ma (2 σ) (MSWD = 0.33, 27.33% ^{39}Ar).

Step No.	Power (%)	$^{40}\text{Ar}/^{39}\text{Ar}$	$\pm 1\sigma$	$^{40}\text{Ar}^*/^{39}\text{Ar}(\text{K})$	$\pm 1\sigma$	$^{40}\text{Ar}^*$ (%)	Cumulative ^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$	Ca/K	$\pm 1\sigma$
1	3.0	54.417	0.967	46.786	1.295	85.9	1.43	424.75	10.47	1.00	0.18
2	4.0	45.834	0.185	44.379	0.223	96.7	14.13	405.17	1.82	2.36	0.12
3	4.7	46.083	0.230	45.390	0.256	98.4	26.26	413.43	2.08	2.06	0.11
4	5.4	46.242	0.211	45.815	0.234	99.0	40.55	416.88	1.90	1.23	0.07
5	6.1	46.368	0.215	45.946	0.233	99.1	52.39	417.94	1.89	0.43	0.04
6	6.7	46.096	0.256	45.644	0.274	99.0	64.09	415.49	2.23	0.18	0.02
7	7.3	45.797	0.284	45.317	0.305	98.9	74.36	412.83	2.49	0.10	0.02
8	7.9	45.828	0.270	45.163	0.313	98.5	81.26	411.57	2.55	0.12	0.04
9	8.5	46.262	0.318	45.645	0.373	98.7	86.84	415.50	3.03	0.09	0.04
10	9.5	46.385	0.387	45.359	0.442	97.8	91.41	413.17	3.60	0.10	0.06
11	11.5	47.157	0.586	45.967	0.672	97.5	94.37	418.11	5.46	0.16	0.08
12	45.0	47.991	0.335	46.262	0.390	96.4	100.00	420.51	3.16	0.57	0.07

Table 9. Argon step heating data of muscovite from sample LG-78-4-143.5, J value = 0.005702 ± 0.000017 (1σ), Plateau Date = 422.4 ± 1.7 Ma (2σ) (MSWD = 1.3, 67.8% ^{39}Ar), Plateau Segment Date = 418.4 ± 2.6 Ma (2σ) (MSWD = 0.2, 26.00% ^{39}Ar).

Step No.	Power (%)	$^{40}\text{Ar}/^{39}\text{Ar}$	$\pm 1\sigma$	$^{40}\text{Ar}^*/^{39}\text{Ar}(\text{K})$	$\pm 1\sigma$	$^{40}\text{Ar}^*$ (%)	Cumulative ^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$	Ca/K	$\pm 1\sigma$
1	3.0	55.925	0.712	41.033	0.843	73.4	1.95	378.26	7.01	0.01	0.08
2	4.0	48.148	0.271	46.378	0.286	96.3	10.71	422.17	2.32	0.01	0.02
3	5.0	46.726	0.236	46.285	0.248	99.1	28.43	421.42	2.02	0.01	0.02
4	5.6	46.701	0.229	46.420	0.237	99.4	41.29	422.51	1.92	0.01	0.02
5	6.2	46.402	0.194	46.135	0.203	99.4	55.57	420.20	1.65	0.01	0.01
6	6.8	46.061	0.183	45.819	0.194	99.5	69.74	417.63	1.58	0.01	0.01
7	7.4	45.984	0.221	45.665	0.233	99.3	79.49	416.38	1.90	0.02	0.02
8	8.0	46.071	0.289	45.644	0.307	99.1	87.07	416.21	2.50	0.01	0.02
9	8.8	45.964	0.305	45.475	0.331	98.9	92.84	414.83	2.70	0.03	0.03
10	9.6	46.483	0.515	46.022	0.589	99.0	95.75	419.28	4.79	0.04	0.06
11	11.5	45.804	0.552	44.994	0.685	98.2	97.56	410.91	5.59	0.22	0.10
12	45.0	43.689	0.441	42.214	0.558	96.6	100.00	388.06	4.62	0.80	0.10

Table 10. Argon step heating data of muscovite separate from sample LG-85-3, J value = 0.007563 ± 0.000018 (1σ), Plateau Segment Date = 414.1 ± 1.2 Ma (2σ) (MSWD = 1.8, 67.33% ^{39}Ar).

Step No.	Power (%)	$^{40}\text{Ar}/^{39}\text{Ar}$	$\pm 1\sigma$	$^{40}\text{Ar}^*/^{39}\text{Ar}(\text{K})$	$\pm 1\sigma$	$^{40}\text{Ar}^*$ (%)	Cumulative ^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$	Ca/K	$\pm 1\sigma$
1	0.8	29.968	0.067	28.531	0.095	95.2	11.74	353.29	1.07	0.80	0.33
2	1.5	30.363	0.086	28.989	0.248	95.4	14.56	358.43	2.79	2.14	0.91
3	2.0	32.630	0.093	31.989	0.256	97.9	17.21	391.77	2.82	2.27	0.96
4	2.8	32.742	0.080	32.304	0.147	98.6	22.48	395.24	1.61	1.45	0.61
5	3.2	33.443	0.091	33.285	0.212	99.5	25.64	405.98	2.31	0.55	0.26
6	3.8	32.985	0.077	32.565	0.120	98.7	32.68	398.10	1.32	1.19	0.50
7	4.0	34.253	0.074	34.133	0.080	99.6	51.79	415.22	0.87	0.26	0.11
8	4.3	34.282	0.071	33.987	0.073	99.1	100.00	413.64	0.79	0.23	0.10

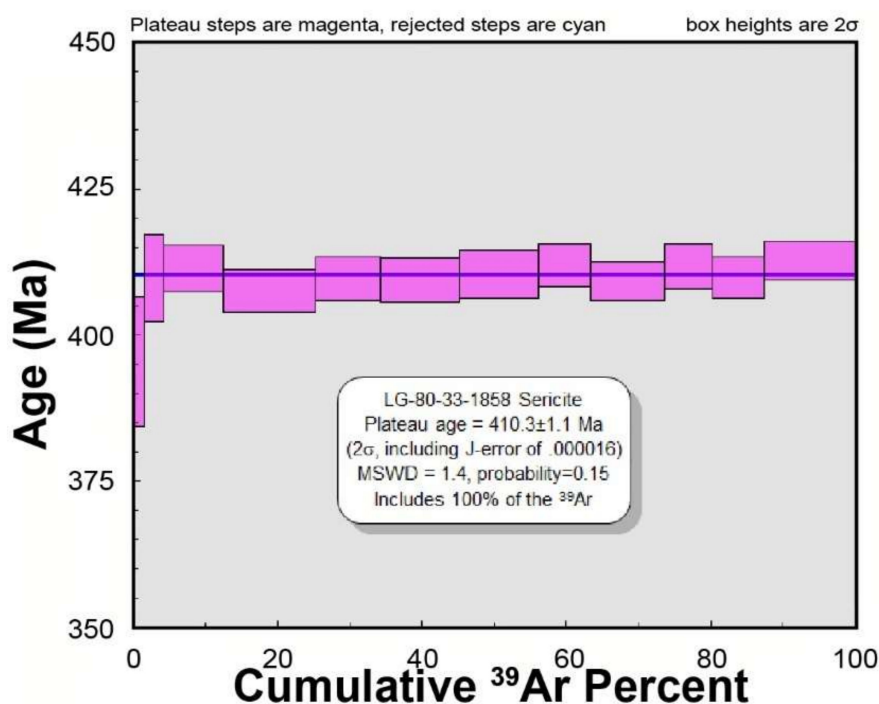


Figure 19. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of muscovite separate from the sericitic alteration surrounding the gold-bearing quartz-carbonate vein from drill core sample LG-80-33-1848 (563.3 m).

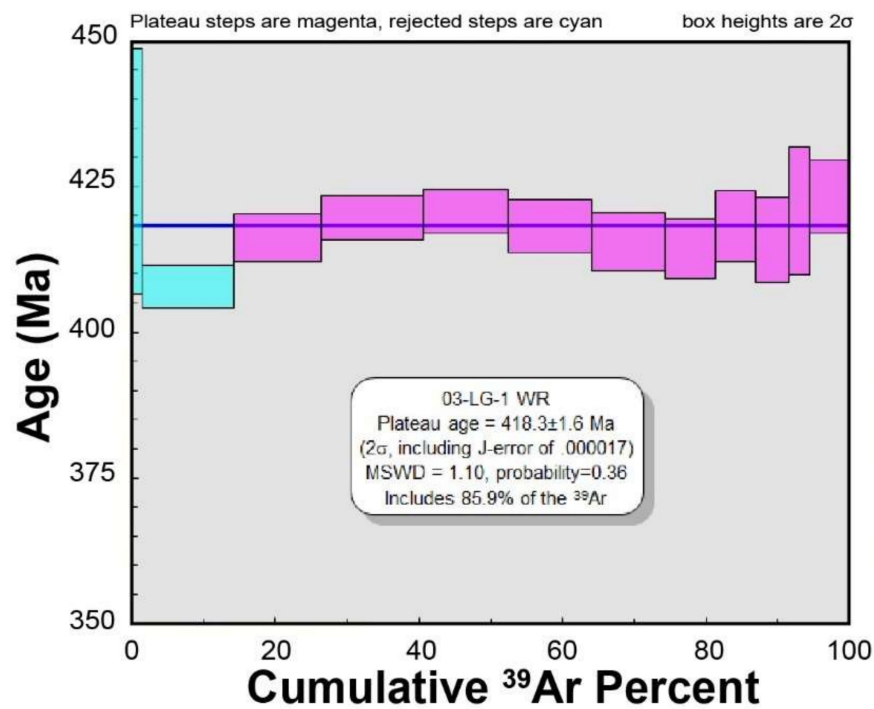


Figure 20. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of whole-rock chips dominated by muscovite from the sericitic alteration surrounding gold-bearing quartz–carbonate veins from sample 03-LG-1.

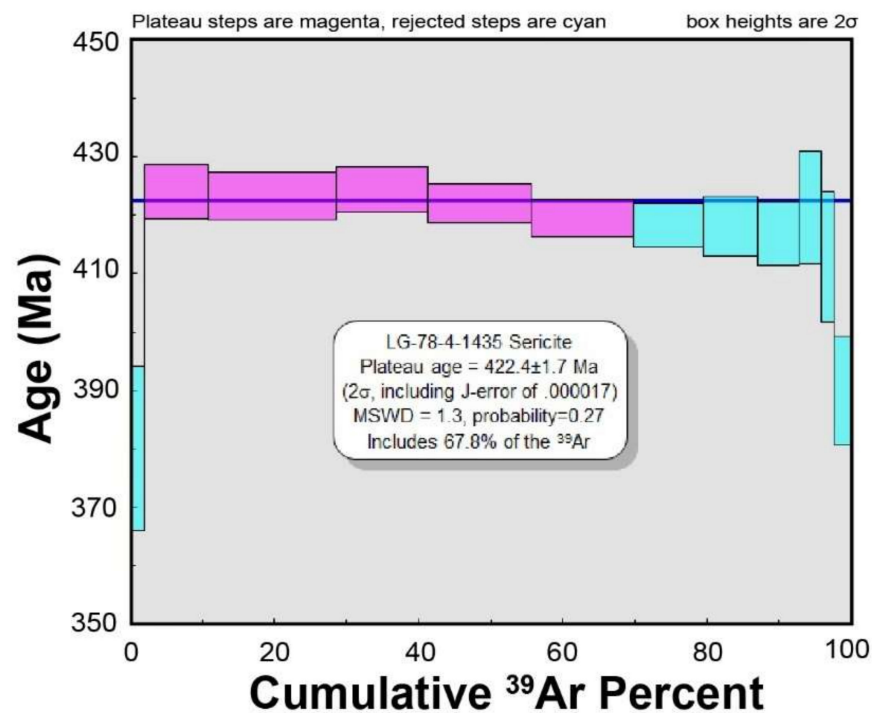


Figure 21. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of muscovite from the sericitic alteration surrounding gold-bearing quartz–carbonate veins from drill core sample LG-78-4-143.5.

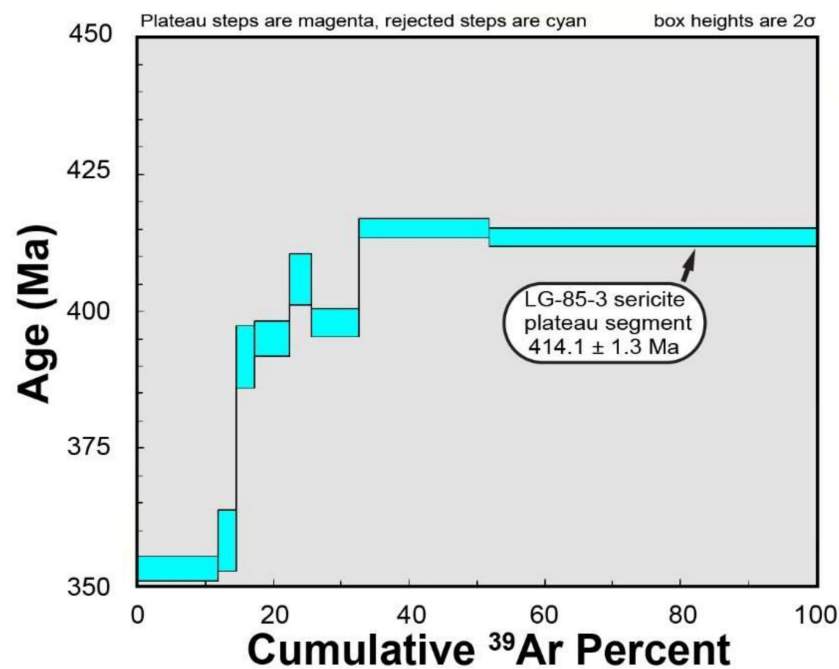


Figure 22. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of hydrothermal muscovite separate from the sericitic alteration envelope surrounding the gold-bearing quartz-carbonate veins from sample LG-85-3.

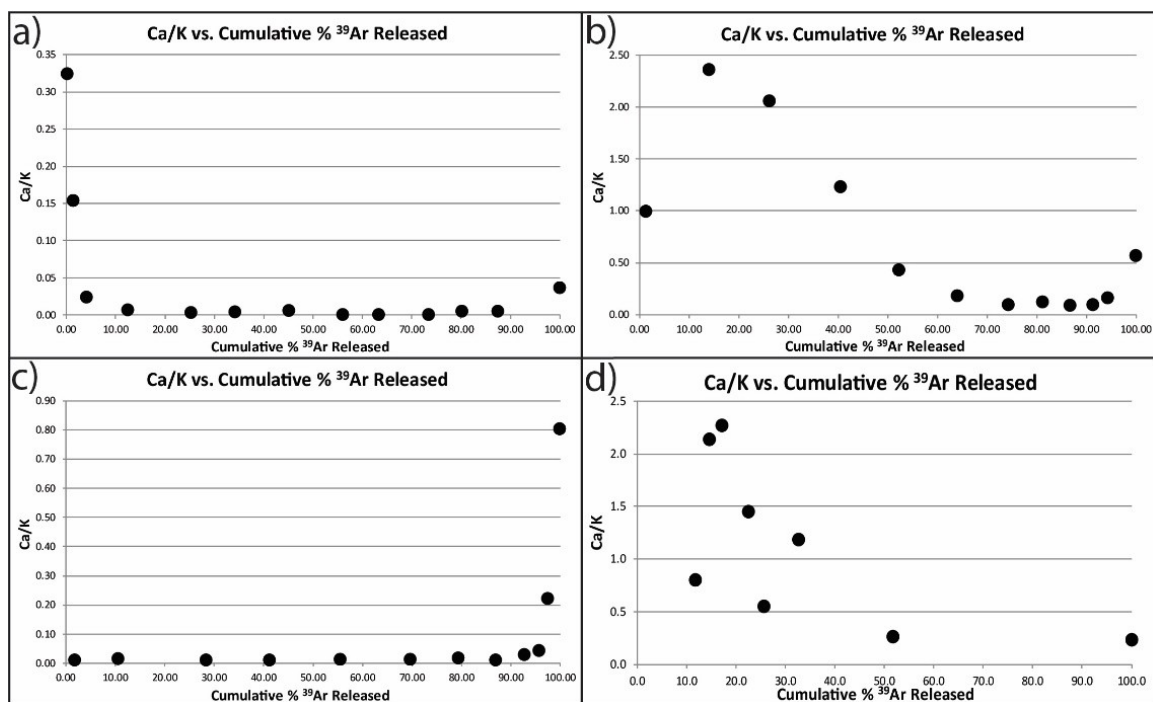


Figure 23. Graphs of Ca/K ratios versus the cumulative percentage of ^{39}Ar released in each step the of samples of muscovite from the sericitic alteration surrounding the gold-bearing quartz-carbonate vein from samples (a) LG-80-33-1848; (b) 03-LG-1; (c) LG-78-4-143.5 and (d) LG-85-3.

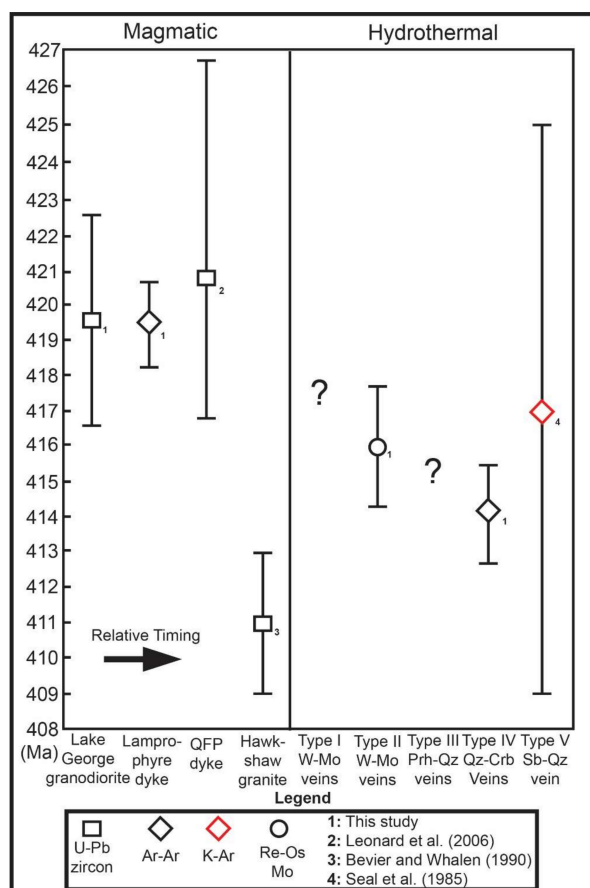


Figure 24. Schematic representation comparing the dates obtained from this study and others of the various magmatic–hydrothermal events at the Lake George mine. The events are ordered from left to right by previously identified cross-cutting relationships and labeled with the age of the most recent geochronological methods used to date them. The errors associated with the dates reported are all 2σ .

Analysis of the muscovite separate from sample LG-80-33-1848 produced a 13 step (out of 13) $^{40}\text{Ar}/^{39}\text{Ar}$ plateau date of 410.3 ± 1.1 (2σ) Ma (100% of the ^{39}Ar) in Isoplot (Figure 19). On the graph of cumulative percentage of ^{39}Ar released versus the Ca/K ratio (Figure 23a), all of the calculated Ca/K values are <0.05 , except the first step confirming sample purity.

Using analyses from sample 03-LG-1, an age spectrum plot was created (Figure 20) and a plateau date (steps from 2 to 12) of 418.3 ± 1.6 (2σ) Ma (MSWD of 1.1, 85.9% of the ^{39}Ar released; Figure 20) was calculated. The graph of Ca/K versus cumulative percentage of ^{39}Ar released (Figure 23b) shows that this plateau date was created using steps with Ca/K ratios as high as 2.06. A plateau segment date (steps from 6 to 10) of 415.9 ± 2.9 Ma (2σ , MSWD of 0.3 and 27.3% of the ^{39}Ar) was also calculated. The Ca/K ratios for the steps used to calculate this plateau segment date range from 0.09 to 0.18 (Figure 23b).

The age spectrum plot from sample LG-78-4-143.5 shows a progressive decrease in age for each step from low temperature to high temperature (Figure 21). A $^{40}\text{Ar}/^{39}\text{Ar}$ plateau segment date (steps from 2 to 6) of 422.4 ± 1.7 (2σ) Ma (MSWD of 1.3 and 67.8% of the ^{39}Ar) was also calculated. On the graph of cumulative percentage of ^{39}Ar released versus the Ca/K ratio (Figure 23c), the steps used to calculate the plateau segment date had Ca/K ratios of 0.01. The high temperature plateau segment defined by steps from 7 to 10 has a date of 418.4 ± 2.6 Ma (MSWD of 0.23 and 26.0% of the ^{39}Ar). The steps used to calculate the high temperature plateau segment date had Ca/K ratios ranging from 0.01 to 0.04.

From the step heating data for sample LG-85-3, an age spectrum plot was generated (Figure 22, Table 10) and a $^{40}\text{Ar}/^{39}\text{Ar}$ high-temperature plateau segment date (steps from 7 to 8) of 414.1 ± 1.3

(2σ) Ma (MSWD of 1.8, 67.3% of the ^{39}Ar released) was calculated. The age spectrum plot shows a large range in ages through the low- to mid-temperatures steps, which correspond to steps with high calculated Ca/K ratios (from 0.55 to 2.27; Figure 23d).

7. Discussion

7.1. Lake George Granodiorite

The results of the in situ LA ICP-MS U-Pb zircon geochronology of the Lake George granodiorite (Figure 6) produced a Late Silurian date of 419.6 ± 3.0 Ma (Figure 13). This suggests that the Lake George granodiorite is not genetically related to the Hawkshaw Granite as previously hypothesized [23] and is the oldest intrusive phase dated in the Pokiok Batholith. Previous U-Pb TIMS zircon geochronology on this intrusion yielded an upper intercept ($^{206}\text{Pb}/^{207}\text{Pb}$) date of 414 ± 2 Ma [9], calculated using three zircons to which a common lead correction was applied with each zircon exhibiting varying degrees of discordancy. The date produced from the current study is a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date from 5 near-concordant analyses, none of which required a common lead correction. This updated date is in agreement with the geochronology conducted in this and other studies and is corroborated by the relative timing determined by the cross-cutting relationships documented by previous authors [5]. For these reasons, this newly calculated date (419.6 ± 3.0 Ma) is believed to be a more accurate estimate of the true age of emplacement of the Lake George granodiorite.

7.2. Lamprophyre Dyke

Understanding the absolute timing of lamprophyre dyke emplacement is critical as lamprophyres have been implicated in enriching melts in large ion lithophile elements (LILE), light rare earth elements (LREE) as well as gold [43,44]. The results of in situ analysis of titanite using LA ICP-MS U-Pb geochronology of a lamprophyre dyke produced three populations (Figures 15–17). The date produced from the youngest of the three populations of titanite (412 ± 9 Ma, Figure 17) is the only U-Pb titanite date produced, which would not be xenocrystic as the two other populations yielded dates that are too old when compared to cross-cutting relationships established underground [6]. Titanite from both populations also underwent variable degrees of lead loss. Although this date (412 ± 9 Ma) is within error of many of the other dates produced in this study, the known cross cutting relationships [6] place emplacement of this dyke shortly after that of the Lake George granodiorite, which make this date too young to be representative of the age of lamprophyre dyke emplacement. This date also lacks the precision necessary to resolve the absolute timing between the various magmatic phases.

The $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of phlogopite from the lamprophyre dyke (sample 80-12), specifically the high temperature plateau segment date (419.4 ± 1.4 Ma), is most likely the best estimate of the age of emplacement of the lamprophyre dyke. Partial chloritization of the phlogopite is evident based upon the hump from low-moderate temperature steps and significant amount of ^{39}Ar released at low temperature, both of which are evidence that recoil loss and/or redistribution of ^{39}Ar during irradiation occurred [45]. Several authors have documented the capacity of chloritization in biotite to enhance the recoil redistribution and loss of ^{39}Ar in irradiated samples [45,46]. In metamorphic terranes, the effects of very minor chloritization in biotite are even more effective at resetting the Ar-clock than temperature [47]. Auto-metasomatism is common in lamprophyric dyke systems [48], consequently there is considerable potential for primary phlogopite to be altered to chlorite during and directly following dyke emplacement. For these reasons, the 419.4 ± 1.4 Ma date should be considered a maximum age for emplacement of the lamprophyre dyke and is the most representative of the true age of dyke emplacement produced from this study.

7.3. Au-Bearing Veins

7.3.1. LG-80-33-1848

Sample LG-80-33-1848 produced a plateau segment date of 410.3 ± 1.1 Ma, which is the youngest of all the dates produced from the Type IV gold-bearing quartz–carbonate veins. The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum (Figure 19) displays a progressive increase in the dates, ranging from 370 to 412 Ma with increasing step temperature suggestive of a diffusion-loss profile, which is often seen in larger crystals [43]. The plateau segment date of sample LG-80-33-1848 overlaps well with the age of the Hawkshaw Granite obtained from U–Pb of titanite (411.2 ± 2.0 , [20]). The interpretation of this date is that it represents the age this sample reached the closure temperature for argon retention in muscovite ($\sim 400 \pm 50$ °C, [49]) meaning it is a cooling age, possibly due to the larger muscovite crystals or because it was the only sample crossing cutting the Lake George granodiorite.

7.3.2. 03-LG-1

The plateau segment date of 418.3 ± 1.6 Ma calculated for sample 03-LG-1 was calculated using steps with Ca/K values as high as 2.06 which are much greater than the Ca/K ratios predicted for muscovite. The high temperature plateau segment date (415.9 ± 2.9 Ma) was produced from steps with minimum Ca/K values (steps from 7 to 10) and therefore is considered to be the best estimate of the age of muscovite formation in this sample. The age spectrum diagram has a low-moderate temperature hump and a large portion of the ^{39}Ar released at low temperature, an indication that recoil loss of ^{39}Ar occurred during irradiation. The recoil loss of ^{39}Ar is likely due to the very small grain size of the muscovite as well as being analyzed as whole-rock chips. If recoil loss of ^{39}Ar occurred, then the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio would increase, which would ultimately produce an erroneously old date. For these reasons the dates produced from this sample are not likely the most representative for the age of the Type IV gold-bearing quartz–carbonate veins.

7.3.3. LG-78-4-143.5

The oldest date obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Type IV veins was from sample LG-78-4-143.5 (422.4 ± 1.7 Ma). The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau diagram displays a progressive decrease in the age with each step (see Figure 21). This progressive decrease in age along with a large percentage of the ^{39}Ar released at low temperatures, suggests recoil loss of ^{39}Ar has occurred. The fine grain size of this muscovite results in an increased chance of recoil loss of ^{39}Ar , thus increasing the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio, which would ultimately result in an erroneously old age. The high temperature plateau segment date from this sample (418.4 ± 2.6 Ma) is also problematic as the Ca/K ratios for the steps used to produce that date are much higher (>0.2) than those expected from muscovite and therefore the date would not be representative of the muscovite associated with the Type IV gold-bearing quartz–carbonate veins.

7.3.4. LG-85-3

Sample LG-85-3 produced a high temperature plateau segment date of 414.1 ± 1.3 Ma, which is within error of the high temperature plateau segment date from sample 03-LG-1. These two dates overlap within error of each other, despite sample 03-LG-1 being analyzed as whole-rock chips and sample LG-85-3 as a muscovite separate. A potential explanation for the slightly older age from sample 03-LG-1 would be the much finer grain size of muscovite in that sample resulted in some recoil loss of ^{39}Ar during irradiation. This recoil loss of ^{39}Ar would have the effect of increasing the $^{40}\text{Ar}/^{39}\text{Ar}$ of the sample and thus produce a slightly older age. The fine-grained nature of both samples and the presence of other unidentified potassium-bearing phases complicated the interpretations of the age spectrums.

Based upon cross-cutting relationships documented by previous research [6], the age of the Type IV gold-bearing veinlets must be younger than all other magmatic–hydrothermal events at the Lake George Mine, other than antimony-bearing quartz veins for which the deposit was previously

mined. The dates obtained from the Type II quartz veins using single crystal Re-Os of molybdenite (approximately 416.1 ± 1.7 Ma) should be slightly older than the age of the Type IV gold-bearing quartz–carbonate veinlets. The high temperature plateau segment date produced from sample LG-85-3 is likely the best estimate of the age of emplacement of the Type IV gold-bearing quartz–carbonate veins.

8. Conclusions

Although the relative timing of the various magmatic–hydrothermal events at the Lake George mine was previously documented, the absolute timing of these events using geochronology conducted in the current study gives insight into the duration of this multi-episodic magmatic–hydrothermal to later overprinting hydrothermal systems and provides a framework for the exploration of similar mineralization along the eastern margin of the Pokiok Batholith.

1. LA ICP-MS analyses of zircon from the Lake George granodiorite produced a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 419.6 ± 3.0 Ma from 6 near-concordant zircon analyses. This age suggests that the Lake George Granodiorite is one of the oldest intrusions in the Pokiok Batholith and cannot be related to the nearby Hawkshaw Granite as previously proposed [23]. The Hartfield tonalite (415 ± 1 Ma, [20]) is the intrusion closest in age to the Lake George granodiorite. More recent work on the Hartfield tonalite suggests its age does overlap with the Lake George granodiorite (417 ± 2 Ma from zircon, [50]).
2. LA ICP-MS analyses of titanite from the lamprophyre dyke produced an age that lacks the precision necessary to establish the absolute timing of its emplacement. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of phlogopite from the lamprophyre dyke produced a high temperature plateau segment date of 419.4 ± 1.4 Ma. This date is in agreement with the observed cross-cutting relationships and is a reasonable preliminary age, likely representative of the true timing of emplacement of these calc-alkaline lamprophyre dykes.
3. Analysis of two single molybdenite crystals using Re-Os geochronology from the Type II W-Mo veins yielded dates of 415.7 ± 1.7 Ma and 416.1 ± 1.7 Ma. These dates are in agreement with previously established cross-cutting relationships [6] and the geochronology of other magmatic hydrothermal events and are likely representative of the true age of emplacement of the Type II W-Mo veins.
4. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of hydrothermal muscovite from the sericitic alteration envelopes that surround the Type IV gold-bearing quartz–carbonate veins was severely complicated by the very fine grain sizes of the muscovite analyzed as well as the contribution of ^{39}Ar from mineral phases other than muscovite. The sample that generated a date most representative of the age of formation of the Type IV gold-bearing quartz–carbonate veins is sample LG-85-3, which yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau segment date of 414.1 ± 1.3 Ma. This date is in agreement with the known cross-cutting relationships [6] as well as the other geochronology produced in this study.
5. We conclude that all mineralization occurred during a period between approximately 417 and 413 Ma, which followed the emplacement of the Lake George granodiorite, the lamprophyre dykes, and the QFP dykes (see Figure 24). To this point, this is the oldest mineralization identified, which is associated with the emplacement of the Pokiok Batholith.

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