GS2024-7

Precise U-Pb zircon age and geochemical constraints on the geodynamic settings of the Falcon Lake intrusive complex and S-type Caddy Lake granite intrusion in the western Superior province, southeastern Manitoba (parts of NTS 52E11, 14)

by X.M. Yang

In Brief:

- The 2695.7 ±1.0 Ma Falcon Lake igneous complex consists of calcalkaline and alkaline rocks
- The calcalkaline quartz monzonite was emplaced post-amalgamation of the Wabigoon and Winnipeg River domains, while the alkaline diorite was likely emplaced in an extensional regime
- The Caddy Lake S-type granite is genetically linked to rare-metal pegmatites, emplaced in a terrane boundary zone

Citation:

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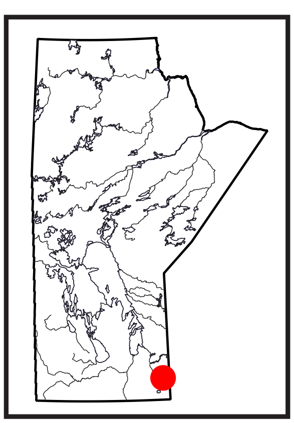

Summary

Precise timing and geochemical characterization of granitoid intrusions are key to exploring intrusion-related mineral deposits, including gold and rare metals, and/or critical minerals (e.g., lithium, tantalum, cesium, rare-earth elements, zirconium). Previous investigations revealed that these types of mineralization are either hosted in, or related to, a variety of intrusions in the Wabigoon domain and its boundary zone with the Winnipeg River domain of the western Superior province in southeastern Manitoba. However, little is known about their timing and the specific geodynamic processes that led to the diverse intrusion-related mineralization in the region. The new precise U-Pb zircon age of 2695.7 ±1.0 Ma provided here for the Falcon Lake intrusive complex is accompanied by geochemical data allowing a better understanding of the geodynamic settings and associated mineral potential that developed during the assembly of the western Superior province in southeastern Manitoba. The Falcon Lake intrusive complex is a unique, compositionally zoned and layered composite intrusion formed by two distinct magma series: calcalkaline and alkaline. These magmas likely originated within different geodynamic environments and exhibit distinct mineral potential. The calcalkaline magma, which displays Neoarchean sanukitoid characteristics, is hypothesized to have formed from partial melting of a depleted mantle previously metasomatized by slab-related melts and/or fluids. This process was likely triggered by the upwelling of hot asthenospheric mantle caused by slab break-off. The calcalkaline rocks dominate the Falcon Lake intrusive complex and are associated with significant gold mineralization. In contrast, the alkaline magma is thought to have been generated through the partial melting of residues left by the earlier extraction of tonalite-trondhjemite-granodiorite suites during intra-arc extension due to slab rollback. This magma, characterized by high zirconium (330 ppm) and elevated total rare-earth-element concentrations (>462 ppm), together with the calcalkaline magma, contributed to continental crust growth in the western Superior province (craton).

Approximately 4.5 km north of the Falcon Lake complex lies the ca. 2687 ±7 Ma Caddy Lake muscovite-biotite (two-mica) granite, which is an S-type intrusion emplaced in response to crustal thickening from the collision of the Wabigoon and Winnipeg River domains of the western Superior province. Given the established genetic linkage between S-type granites and critical-metal–bearing pegmatites—such as those containing lithium, tantalum and cesium—exploration of the Caddy Lake granite could reveal significant potential for critical-mineral mineralization in the region.

Introduction

The Manitoba Geological Survey's ongoing multiyear program 'Granitoids in Manitoba: petrogenesis and metallogeny' focused in 2024 on the timing and geodynamic evolution of granitoid rocks in the Falcon Lake intrusive complex (FLIC) and the Caddy Lake granite intrusion in the western Superior province, southeastern Manitoba. The FLIC, which is one of few well-preserved Archean layered intrusions in Manitoba characterized by intact primary magmatic fabrics (e.g., compositional layering, magma-flow foliation and lineation), hosts, and/or is associated with, significant gold mineralization (Fingler, 1991; Tirschmann, 1992). It provides an excellent opportunity for investigating the timing, petrogenesis, metallogeny and geodynamic settings of such layered igneous complexes of Archean age. The FLIC was dated previously by Halden et al. (2007) using laser-ablation microprobe, inductively coupled plasma–mass spectrometry (LAM-ICP-MS) techniques, yielding U-Pb zircon ages ranging from 2733 ±33 Ma to 2723 ±9 Ma, with large uncertainties. The dates suggest that a more precise timing of the phases and processes that influenced the FLIC is required when studying its petrogenesis and geodynamic setting(s) because: 1) magmatism lasting for >10 m.y. seems to conflict with the view that the FLIC formed by fractionation of a mantle-derived magma (e.g., Mandziuk et al., 1989a, b;

Tirschmann, 1992); and 2) the dates themselves are inconsistent with temporal and spatial associations of various magmatic rocks produced during the central Superior orogeny (or locally termed Kenoran orogeny; see Percival et al., 2006, 2012), including collision-related granitic rocks such as S-type granites that are the source for rare-metal (e.g., lithium, tantalum, cesium) pegmatites in the region and elsewhere (e.g., Černý et al., 1981; Černý and Ercit, 2005; Yang, 2014, 2023; Yang et al., 2019; Macdonald, 2024).

The ca. 2687 ±7 Ma Caddy Lake two-mica granite intrusion is an S-type granite located approximately 4.5 km north of the FLIC (Figure GS2024-7-1). This granite can be termed leucogranite as it contains less than 5% ferromagnesian minerals (Yang, 2014, 2023; Yang et al., 2019). Based on Halden et al. (2007), the intrusion is 36 m.y. younger than the youngest phase quartz monzonite (2723 ±9 Ma) of the FLIC, which raises the aforementioned problem of inconsistent dates. However, the fundamental question of 'what geodynamic processes link the origin of the FLIC to the Caddy Lake S-type granite intrusion?' remains to be answered.

Examination of the new, precise U-Pb zircon date for the FLIC presented in this study, when considered along with the geochemistry of the complex and the occurrence of the Caddy Lake S-type granite in terms of their distinct geodynamic settings and mineral potential, assists in better understanding geodynamic evolution and related mineralization during the assembly of the Wabigoon and Winnipeg River domains, which constitute part of the western Superior province. In addition to addressing the aforementioned problems, the major findings from this study provide insights into the tectonic evolution of the western Superior Province in southeastern Manitoba, as well as the mineral potential of the region during various stages of geodynamic processes, as recorded by the FLIC and the Caddy Lake granite intrusion.

Geological setting

The FLIC is situated in southeastern Manitoba, near the Ontario border, approximately 112 km east of Winnipeg along Trans-Canada Highway 1 (Figure GS2024-7-1). It occurs as a stock with an exposed area of approximately 10 km^2. It is emplaced into the northwestern portion of the Wabigoon domain that consists of Archean supracrustal sequences of basaltic–andesitic metavolcanic to metavolcaniclastic rocks uncomformably overlain by subordinate metasedimentary rocks including conglomerate, greywacke, arkosic sandstone and mudstone (Blackburn et al., 1991; Tirschmann, 1992; Ayer, 1998a). The emplacement of the FLIC appears to have been controlled by deep transcrustal faults. The generally east-northeast regional structural trend of the greenstone belt, manifested by subvertical folding, is characterized by major foliation dipping steeply to the north and metamorphic mineral assemblages of upper-greenschist to middle-amphibolite facies (Tirschmann, 1992; Ayer, 1998a).

The FLIC is a concentric, compositionally zoned and layered composite intrusion of sigmoidal shape displaying outer, lens-shaped bodies of gabbro units and dioritic gabbro tails (units A to D; see Figure GS2024-7-2; Mandziuk et al., 1989a, b). The main part of the complex consists of an old outer zone of diorite to granodiorite (unit E) and a younger inner zone of quartz monzonite (unit F), according to earlier detailed bedrock geology mapping at 1:5000 scale (Mandziuk, 1989; Figure GS2024-7-2). Primary rhythmic layering and fabrics of mineral lineation and foliation are well preserved in the FLIC, suggestive of its post-kinematic features formed during magma emplacement rather than tectonic deformation (Mandziuk et al., 1989a, b). Xenoliths of country rocks and cognate inclusions are common, particularly in the central part (units E and F) of the complex. Detailed petrographic descriptions of each lithological unit of the FLIC, presented in Tirschmann (1992), indicate that myrmekitic textures are evident in all units of the FLIC, together with perthitic textures in units E and F. This strongly suggests that their parental magmas are water saturated (cf. Candela, 1997; Yang and Lentz, 2005; Winter, 2014).

The presence in the core of the FLIC of two major breccia pipes (Figure GS2024-7-2) hosted by the quartz monzonite to minor monzogranite intrusive phases of unit F is worth noting (Figure GS2024-7-3a). The breccia pipes appear to comprise in situ quartz monzonite fragments in very fine grained silicified and sericitized monzonitic matrix. The fragments are angular to irregular in shape and range from block to lapilli in size. These breccias likely formed via implosion of an internal boiling process during late-stage magmatic hydrothermal evolution of the FLIC (Gibbins, 1971; Halwas, 1984), resulting in disseminated sulphide (quartz-carbonate) mineralization and/or veinlets consisting of pyrite, pyrrhotite, sphalerite, galena, and chalcopyrite and locally gold (Mandziuk et al., 1989a; Fingler, 1991; Tirschmann, 1992).

The Caddy Lake two-mica leucogranite intrusion, which displays an arcuate shape, is situated about 4.5 km north of the FLIC (Figure GS2024-7-1). It has a U-Pb zircon age of 2687 ±7 Ma dated by Halden et al. (2007) using LAM-ICP-MS techniques. This granite contains accessory garnet, epidote, zircon, apatite and allanite (Duncan, 1989), and is an S-type granite that is part of the Rennie River plutonic suite (Yang, 2014, 2023; Yang et al., 2019). The Caddy Lake intrusion was emplaced across the terrane boundary between the Winnipeg River and Wabigoon domains of the western Superior province. It cut the gneissic tonalite-trondhjemite-granodiorite (TTG) suites of the Winnipeg River domain and intruded into metasedimentary rocks that unconformably overlie metavolcanic to metavolcaniclastic rocks of the Wabigoon domain (Figure GS2024-7-1). More importantly, critical metals (e.g., Li, Ta, Cs) hosted in pegmatites (e.g., Lucy and Artdon pegmatite dikes; see Davies et al., 1962; Bannatyne, 1985) are thought to be associated genetically with S-type granites in the region and elsewhere (Černý and Meintzer, 1988; Černý and Ercit, 2005; Yang, 2014, 2023; Yang et al., 2019).

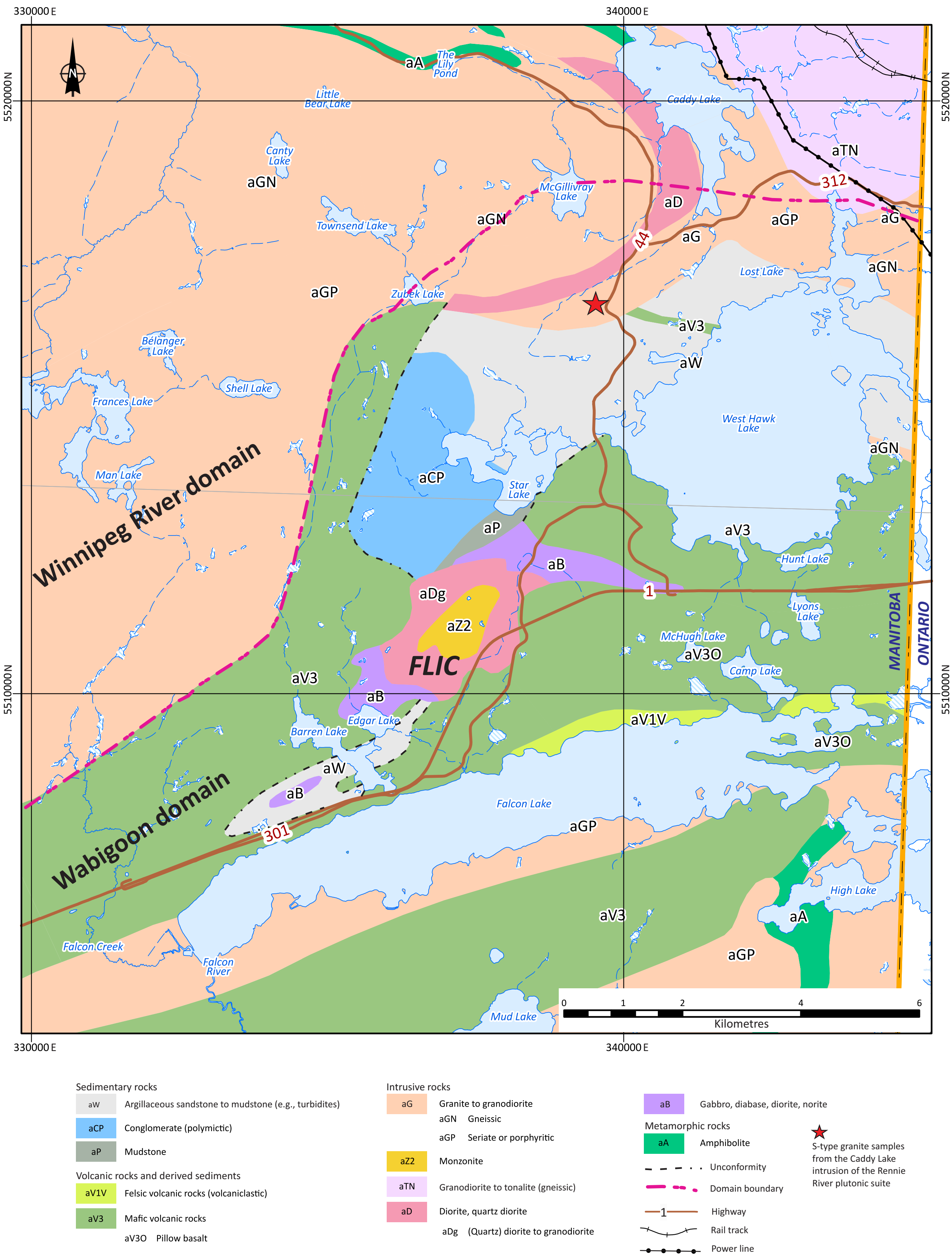

Figure GS2024-7-1: *Regional geology of the Falcon Lake area, showing that the Falcon Lake intrusive complex (FLIC) occurs in metavolcanic to metavolcaniclastic and metasedimentary rock units of the Archean Wabigoon domain that is flanked by gneissic granitoids of tonalite-trondhjemite-granodiorite suites within the southern margin of the Winnipeg River domain (modified from Manitoba Energy and Mines, 1987). Pink dashed line represents the terrane boundary between the Wabigoon and Winnipeg River domains. Location of samples from the S-type Caddy Lake leucogranite intrusion of the Rennie River plutonic suite (Yang, 2014; Yang et al., 2019) is indicated by the red star. All co-ordinates are in UTM Zone 15, NAD83.*

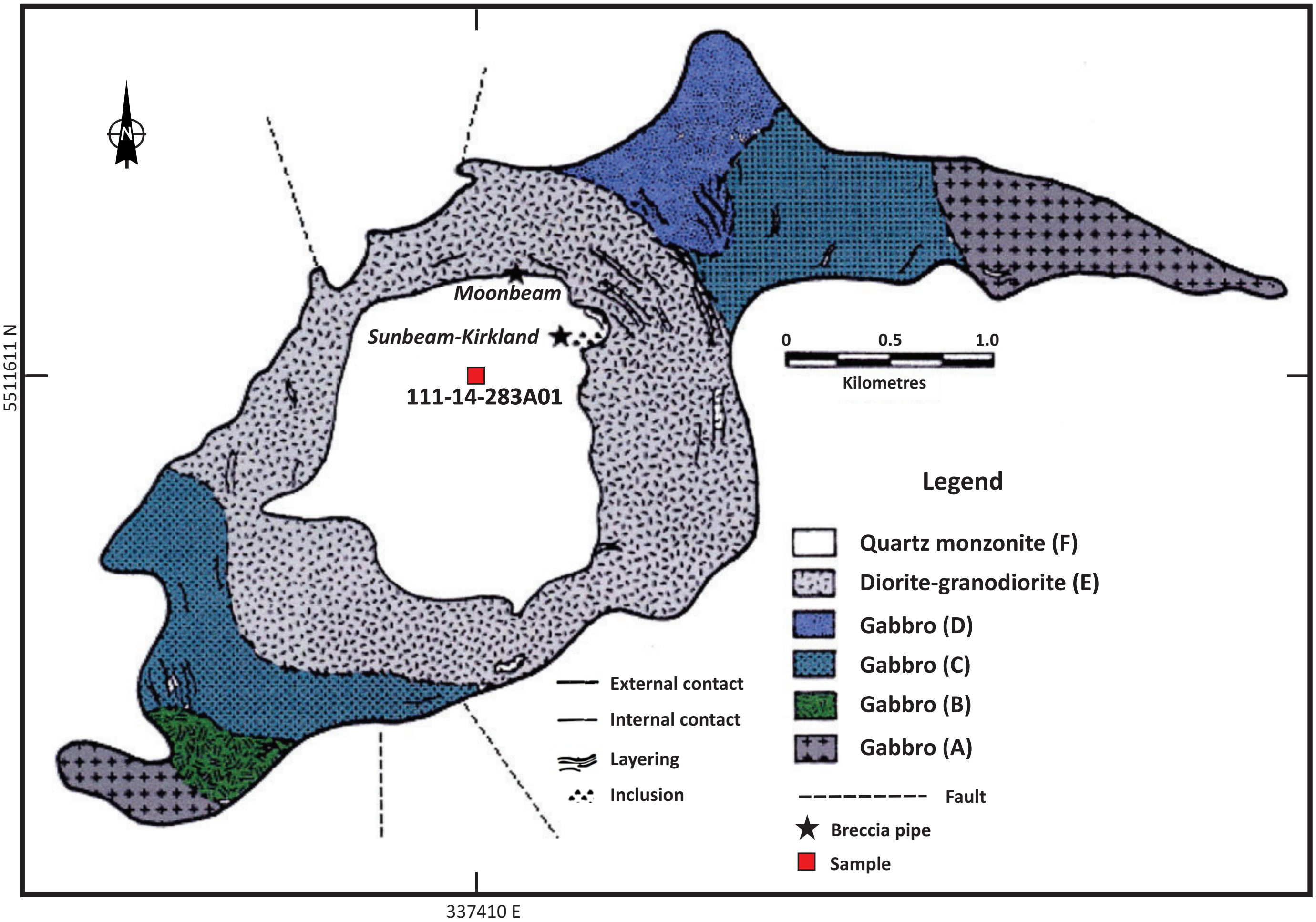

Figure GS2024-7-2: *Simplified geology map of the Falcon Lake intrusive complex (FLIC) that consists of four older gabbroic units (A to D) in the outer zones, and two younger, main internal units (E and F) of quartz diorite to granodiorite and quartz monzonite (modified after Mandziuk et al., 1989a, b). Also shown are the locations of two breccia pipes and the geochronological sample collected for this study. All co-ordinates are in UTM Zone 15, NAD83.*

Sample descriptions

To update the age and geochemistry of the FLIC, a whole-rock sample (111-14-283A01) was collected from unit F quartz monzonite in the core of the FLIC for precise U-Pb zircon dating and geochemical analysis (Figure GS2024-7-2). This quartz monzonite is massive, medium grained and equigranular to seriate, but locally contains a few euhedral K-feldspar phenocrysts (up to 2.2 cm in length). It consists of 30–40% plagioclase, 30–35% hornblende, 20–25% K-feldspar, 5–10% quartz and minor biotite (Figure GS2024-7-3b, c). As determined by electron probe micro-analyzer (Tirschmann, 1992), plagioclase comprises 24.9–30.3% anorthite belonging to oligoclase. Thus, in the petrological sense, this rock should be termed 'granitic rock' (s.l.), as constrained by the anorthite content of the plagioclase and bulk-rock composition (this study). Myrmekitic texture in some parts of the plagioclase margin and the perthitic microcline are evident, suggestive of the water-saturated magma from which these minerals crystallized (Candela, 1997; Yang and Lentz, 2005; Winter, 2014). Accessory minerals are magnetite, zircon, titanite, apatite and allanite. Tirschmann (1992) pointed out the presence of ilmenite rims on some magnetite crystals, indicative of a reaction with late-magmatic hydrothermal fluids. The quartz monzonite has a moderately high magnetic susceptibility (MS) value of 11.7 × 10^{-3} SI, indicative of its oxidized state and consistent with the presence of magnetite and titanite. These features are typical of normal I-type and magnetite-series granites (Yang 2014, 2023), as outlined in Chappell and White (1974, 2001), and Ishihara (1977, 1981, 2004).

The Caddy Lake leucogranite is massive, equigranular and medium-grained, and undeformed. It consists of 40–45% K-feldspar, 30–35% quartz, 20–25% plagioclase, up to 5% biotite, minor muscovite, and up to 1% garnet (Figure GS2024-7-3d). This granite has a very low MS value of 0.045 × 10^{-3} SI, similar to that of reduced S-type and ilmenite-series granites (Yang 2014, 2023) according to Chappell and White (1974, 2001), and Ishihara (1977, 1981, 2004).

Geochemical characteristics

Elemental-analysis results for the FLIC rocks, including partial rare-earth elements (REEs), were reported by Tirschmann

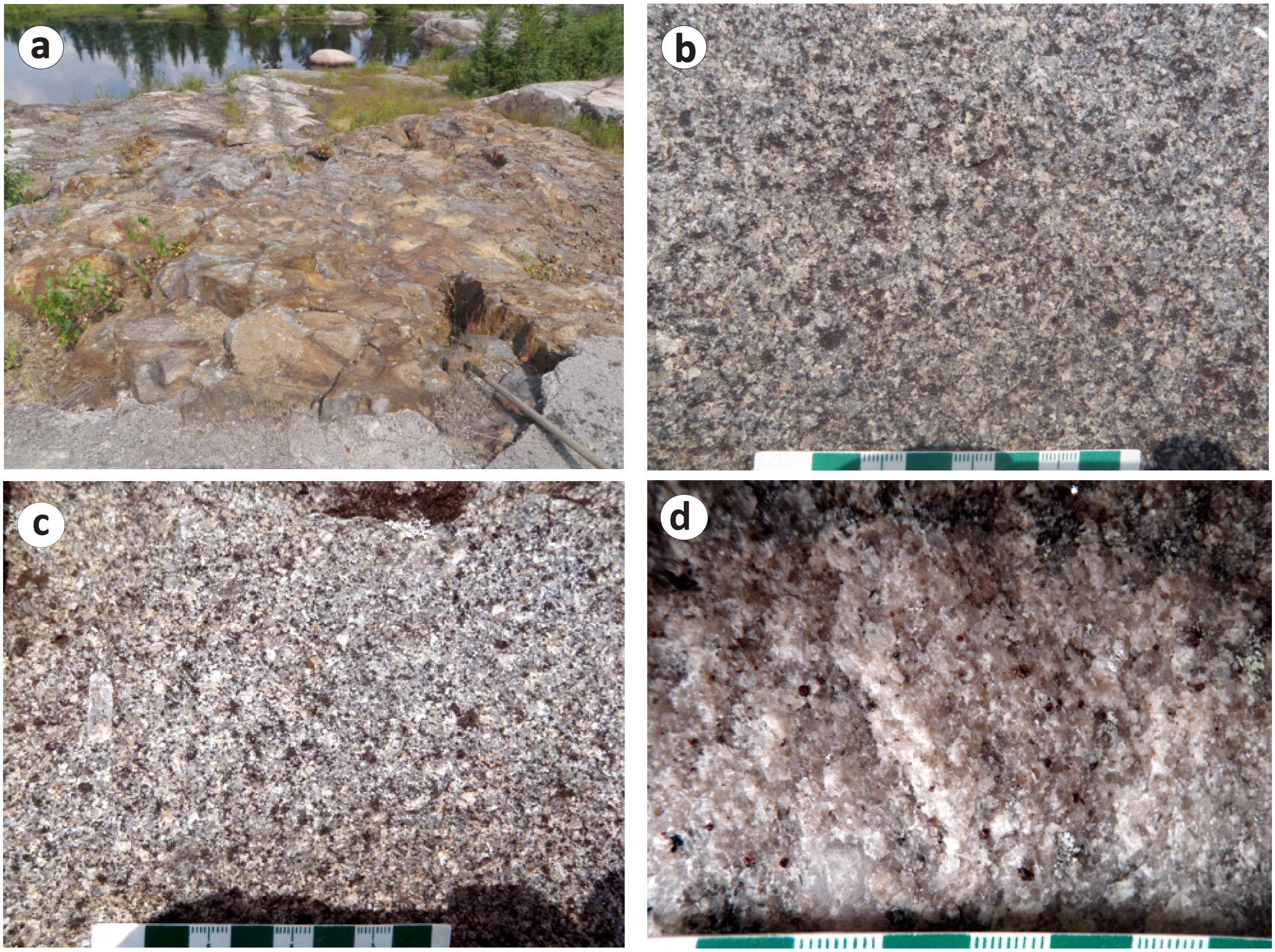

Figure GS2024-7-3: *Field photographs of outcrops of the Falcon Lake intrusive complex (FLIC):* ***a)*** *sulphide-bearing breccia pipe (337473E, 5511650N) in the core of the FLIC (sledgehammer handle at right for scale);* ***b)*** *medium-grained quartz monzonite (337410E, 5511611N);* ***c)*** *quartz monzonite from the same outcrop as in (b), showing a few euhedral to subhedral K-feldspar phenocrysts;* ***d)*** *massive, medium-grained, undeformed, garnet-bearing two-mica leucogranite from the Caddy Lake intrusion (339676E, 5516634N). All co-ordinates are in UTM Zone 15, NAD83.*

(1992). The analytical data are summarized and tabulated in Table GS2024-7-1, alongside the complete elemental-analysis results (including full REE data) from three bulk-rock samples acquired during this study. As a first step, the main geochemical characteristics of the FLIC and Caddy Lake granite are presented in a set of geochemical diagrams showing sample alkalinity, alumina and silica saturation state, as well as Fe*{= FeO^{total}/(FeO^{total}+MgO)} ratios. Then, Nd-Sr-O isotopic data published in the relevant literature are briefly reviewed to investigate the nature of the source rocks.

Major and trace elements

Heterogeneity in geochemical compositions is apparent, as shown in the mineralogical classification diagrams of CIPW (Cross, Iddings, Pirsson and Washington) normative Q' versus ANOR, as well as of K_2O versus SiO_2, for the whole-rock samples from the FLIC compared with those from the Caddy Lake leucogranite intrusion (Table GS2024-7-1; Figure GS2024-7-4a, b). The FLIC bulk-rock samples range in lithology from quartz monzonite, quartz monzodiorite, monzonite, monzogabbro to gabbro. Only one sample of unit F falls in the field of monzogranite. Most of the samples plot along the alkalic-calcic trend defined by Frost et al. (2001; see Whalen and Frost, 2013), although some from units A, B and E deviate from this pattern. According to the classification of Peccerillo and Taylor (1976), most of the samples from unit E are shoshonitic and samples from unit F are high-K calcalkaline, indicative of their enrichment in K_2O (Figure GS2024-7-4b), in contrast to sodic TTGs. Results from samples of units A to D are more scattered, displaying various magmatic affinities ranging from arc tholeiitic, calcalkaline, to high-K calcalkaline and shoshonitic series. Such a large variation in K_2O and SiO_2 contents is hardly generated by common magmatic fractionation, as thought previously, but can be readily explained by hydrothermal

Table GS2024-7-1: Major (wt. %) and trace (ppm) elements data of whole-rock samples from the Falcon Lake intrusive complex (FLIC) and Caddy Lake intrusion (CLI).

Intrusion	**CLI**		**FLIC**										
Lithology	Granite	Granite	Quartz monzonite	Gabbro		Gabbro	Gabbro	Gabbro		Diorite		Quartz monzonite	
Unit			F	A		B	C	D		E		F	
Sample	14-258A01	14-259A01*	14-283A01	AVE	STDV	AVE	AVE	AVE	STDV	AVE	STDV	AVE	STDV
	n = 1	n = 1	n = 1	n = 4		n = 2	n = 2	n = 4		n = 12		n = 5	
Data source	Yang, 2023			Tirschmann, 1992									
SiO_2	76.03	74.74	66.1	52.85	2.84	47.44	55.90	52.83	2.33	57.13	3.36	67.23	1.08
TiO2	0.049	0.009	0.323	1.00	0.18	0.30	0.90	1.08	0.18	0.80	0.20	0.27	0.06
Al_2O_3	13.51	14.01	15.22	17.15	0.57	16.79	20.20	18.64	1.38	16.91	0.87	16.17	0.23
$Fe_2O_3^{T}$[1]	1.27	0.77	3.61										
Fe_2O_3				3.02	0.33	3.21	2.55	3.30	0.99	3.49	1.31	1.72	0.30
FeO				7.18	0.94	6.92	3.89	5.06	0.70	3.98	1.71	1.46	0.27
MnO	0.035	0.008	0.058	0.14	0.01	0.17	0.10	0.11	0.02	0.10	0.03	0.05	0.02
MgO	0.1	0.02	1.27	4.92	1.42	10.02	1.86	3.15	0.69	3.10	0.96	0.98	0.21
CaO	1.1	0.89	2.99	7.92	1.77	12.93	6.79	7.52	1.13	5.37	1.15	2.77	0.15
Na_2O	3.42	3.39	4.28	3.28	0.29	1.84	4.21	3.48	0.18	3.72	0.34	3.99	0.27
K_2O	4.95	5.28	4.05	1.81	1.34	0.24	3.13	2.95	0.51	3.94	0.72	4.47	0.14
P_2O_5	<0.01	0.04	0.19	0.44	0.39	0.21	0.40	0.89	0.30	0.43	0.19	0.03	0.02
LOI	0.31	0.19	1.24	0.59	0.19	1.10	0.55	0.53	0.16	0.66	0.27	0.52	0.18
Total	100.8	99.35	99.33	100.30		101.15	100.77	99.54		99.63		99.65	
σ[2]	2.1	2.4	3.0	2.7	0.9	1.0	4.2	4.3	0.8	4.3	1.0	3.0	0.2
τ[3]	205.9	1180.0	33.9	14.3	3.4	51.4	18.3	14.4	3.2	17.1	3.5	45.8	7.9
Sc	1	<1	5										
V	<5	<5	41										
Cr	30	<20	50										
Co	2	<1	8										
Ni	<20	<20	<20										
Cu	<10	<10	20										
Zn	60	<30	50										
Ga	18	20	19										
As	<5	<5	77										
Rb	232	238	146	65	54	8	95	101	3	150	36	160	21
Sr	74	52	668	666	116	756	1170	1159	161	857	109	703	50
Y	13.9	25.6	9.7	22	8	13	20	20	6	19	5	4	5
Zr	61	24	172	168	128	42	221	271	146	330	63	171	33
Nb	5.1	1.9	11.6	7	9	1	12	10	6	18	4	9	3
Sn	2	3	2										
Cs	3.4	5.3	6.1										
Ba	308	121	1022										
				N = 2		N = 2	N = 1	N = 2		N = 3		N = 2	
La	15.6	4.37	67.4	65.8		11.18	123	113.3		117.7		58.2	
Ce	28.3	7.32	121	128.5		22.45	243	223.5		234.3		103.5	

[1] $Fe_2O_3^T$ denotes total Fe_2O_3.

[2] The Rittmann Serial Index $\sigma = (Na_2O+K_2O)^2/(SiO_2-43)$, units in wt. % (Rittmann, 1962).

[3] The Gottini index $\tau = (Al_2O_3-Na_2O)/TiO_2$, units in wt. % (Grasso, 1968).

Abbreviations: AVE, average; CLI, Caddy Lake intrusion; FLIC, Falcon Lake intrusive complex; LOI, loss-on-ignition; STDV, standard deviation; n, number of samples analyzed; N, number of samples analyzed for rare-earth elements using instrumental neutron activation analysis (Tirschmann, 1992).

Table GS2024-7-1 (continued): Major (wt. %) and trace (ppm) elements data of whole-rock samples from the Falcon Lake intrusive complex (FLIC) and Caddy Lake intrusion (CLI).

Intrusion	**CLI**		**FLIC**										
Lithology	Granite	Granite	Quartz monzonite	Gabbro		Gabbro	Gabbro	Gabbro		Diorite		Quartz monzonite	
Unit			F	A		B	C	D		E		F	
Sample	14-258A01	14-259A01*	14-283A01	AVE	STDV	AVE	AVE	AVE	STDV	AVE	STDV	AVE	STDV
	n = 1	n = 1	n = 1	n = 4		n = 2	n = 2	n = 4		n = 12		n = 5	
Data source	Yang, 2023			Tirschmann, 1992									
Pr	3.21	0.75	13										
Nd	11.4	2.85	42.6	53.45		16.2	92.4	93.75		91.4		32.9	
Sm	2.42	0.83	5.73	7.765		2.845	12.9	13.15		13.3		4.8	
Eu	0.342	0.214	1.32	1.49		1.025	2.49	2.92		2.7		1.1	
Gd	2.21	1.87	3.47										
Tb	0.37	0.45	0.42	0.93		0.59	0.84	0.75		0.8		0.4	
Dy	2.22	3.33	2.01										
Ho	0.46	0.73	0.37										
Er	1.44	2.13	1.11										
Tm	0.231	0.325	0.158										
Yb	1.56	2.13	0.95	1.765		0.69	1.79	1.615		1.9		1.0	
Lu	0.249	0.312	0.141	0.24		0.085	0.25	0.195		0.3		0.2	
Hf	1.8	1.1	4.1										
Ta	0.63	0.55	1.13										
W	1.5	<0.5	2.3										
Tl	1.19	1.33	0.71										
Pb	53	34	23										
Th	27.8	5.85	25.6										
U	9.03	8.86	8.39										
ΣREE	70	28	260	260		55	477	449		462		202	
Sr/Y	5.3	2.0	68.9	35.5	19.0	58.1	64.0	63.0	23.8	48.8	18.5	294.7	137.8
La/Yb	10.0	2.1	70.9	37.3		18.6	68.7	68.9		60.6	4.0	56.9	
Nb/Y	0.4	0.1	1.2	0.2	0.3	0.0	0.6	0.5	0.3	1.1	0.5	3.4	1.7

[1] $Fe_2O_3^T$ denotes total Fe_2O_3.
[2] The Rittmann Serial Index $\sigma = (Na_2O+K_2O)^2/(SiO_2-43)$, units in wt. % (Rittmann, 1962).
[3] The Gottini index $\tau = (Al_2O_3-Na_2O)/TiO_2$, units in wt. % (Grasso, 1968).
Abbreviations: AVE, average; CLI, Caddy Lake intrusion; FLIC, Falcon Lake intrusive complex; LOI, loss-on-ignition; STDV, standard deviation; n, number of samples analyzed; N, number of samples analyzed for rare-earth elements using instrumental neutron activation analysis (Tirschmann, 1992).

alteration or crustal contamination in open systems (cf. Winter, 2014; Rollinson and Pease, 2021). More recently, source potash enrichment induced by recycling of sediments has been used to explain high-K calcalkaline to shoshonitic magmatism (Wang et al., 2024), but this mechanism is not likely to have produced such a chaotic relationship as that shown in Figure GS2024-7-4b. Collectively, the FLIC samples are much less evolved than the leucogranite samples from the Caddy Lake intrusion, which plot in the syenogranite field and are attributed to the calcalkaline series, in terms of their Rittmann Serial Index ($\sigma = \{(Na_2O + K_2O)^2/(SiO_2 - 43)\}$, units in wt. %; Rittmann, 1962) values of 2.1 to 2.4 (Table GS2024-7-1), based on Yang (2007), and to the high-K calcalkaline series, based on their magmatic affinity (Figure GS2024-7-4b).

Based on the Shand's index diagram (Figure GS2024-7-5a; Maniar and Piccoli, 1989), the FLIC samples are exclusively metaluminous (except for one quartz monzonite sample from unit F that is peraluminous), whereas leucogranite samples from the Caddy Lake intrusion are moderately peraluminous. It should be noted that the FLIC samples are characterized by the presence of a CIPW normative association of quartz+hypersthene+diopside, suggestive of a dominantly calcalkaline affinity (Yoder and Tilley, 1962; Yang, 2007). The Caddy Lake leucogranite samples contain 0.58–1.33 wt. % normative corundum, consistent with their peraluminous signature. On the Fe* ratios versus SiO_2 plot (not shown), based on Frost et al. (2001), the FLIC rocks are exclusively magnesian, which suggests that they were formed by relatively oxidized magmas, whereas the ferroan nature of the Caddy

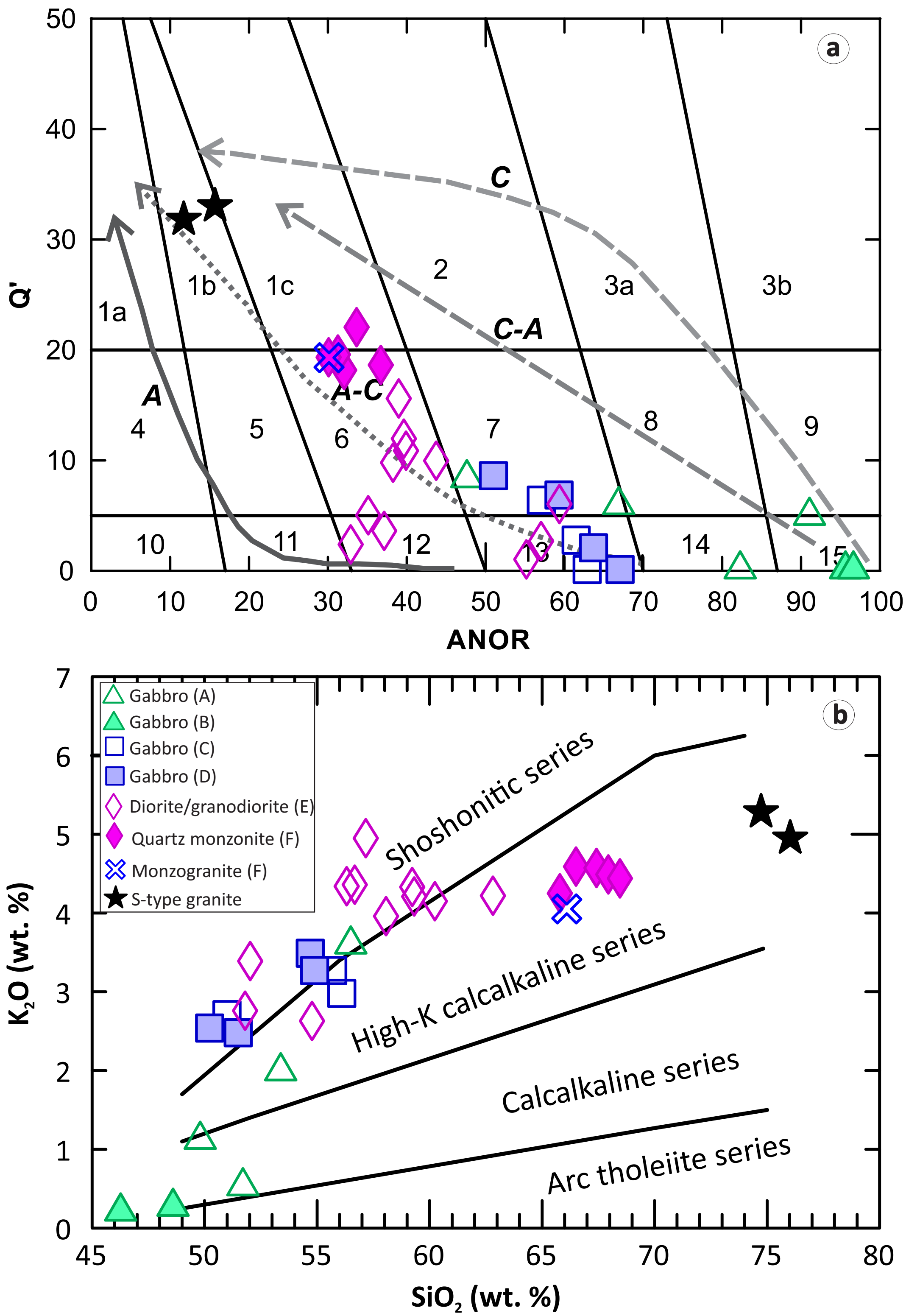

Figure GS2024-7-4: *Geochemical classification of whole-rock samples from the Falcon Lake intrusive complex and the Caddy Lake S-type granite intrusion of the Rennie River plutonic suite:* ***a)*** *the CIPW (Cross, Iddings, Pirsson and Washington) normative Q' versus ANOR diagram (after Streckeisen and Le Maitre, 1979); where Q' = 100 x Qz/(Qz + Or + Ab + An) and ANOR = 100 x An/(An + Or), identifies the rock types as alkali-feldspar granite (1a), syenogranite (1b), monzogranite (1c), granodiorite (2), tonalite (3a), calcic tonalite (3b), alkali-feldspar quartz syenite (4), quartz syenite (5), quartz monzonite (6), quartz monzodiorite (7), quartz diorite (8), quartz gabbro (9), alkali-feldspar syenite (10), syenite (11), monzonite (12), monzogabbro (13), diorite (14), gabbro (15), and the coarse dashed and solid lines with arrows indicate differentiation trends of different magmatic suites (after Whalen and Frost, 2013), including calcic (C), calcalkalic (C-A), alkali-calcic (A-C), alkalic (A), based on the modified alkali-lime index (Frost et al., 2001). Abbreviations: Ab, albite; An, anorthite; Or, orthoclase; Qz, quartz;* ***b)*** *K_2O (wt. %) versus SiO_2 (wt. %) magmatic-series discrimination diagram (after Peccerillo and Taylor, 1976). Data from Tirschmann (1992) and Yang (2023).*

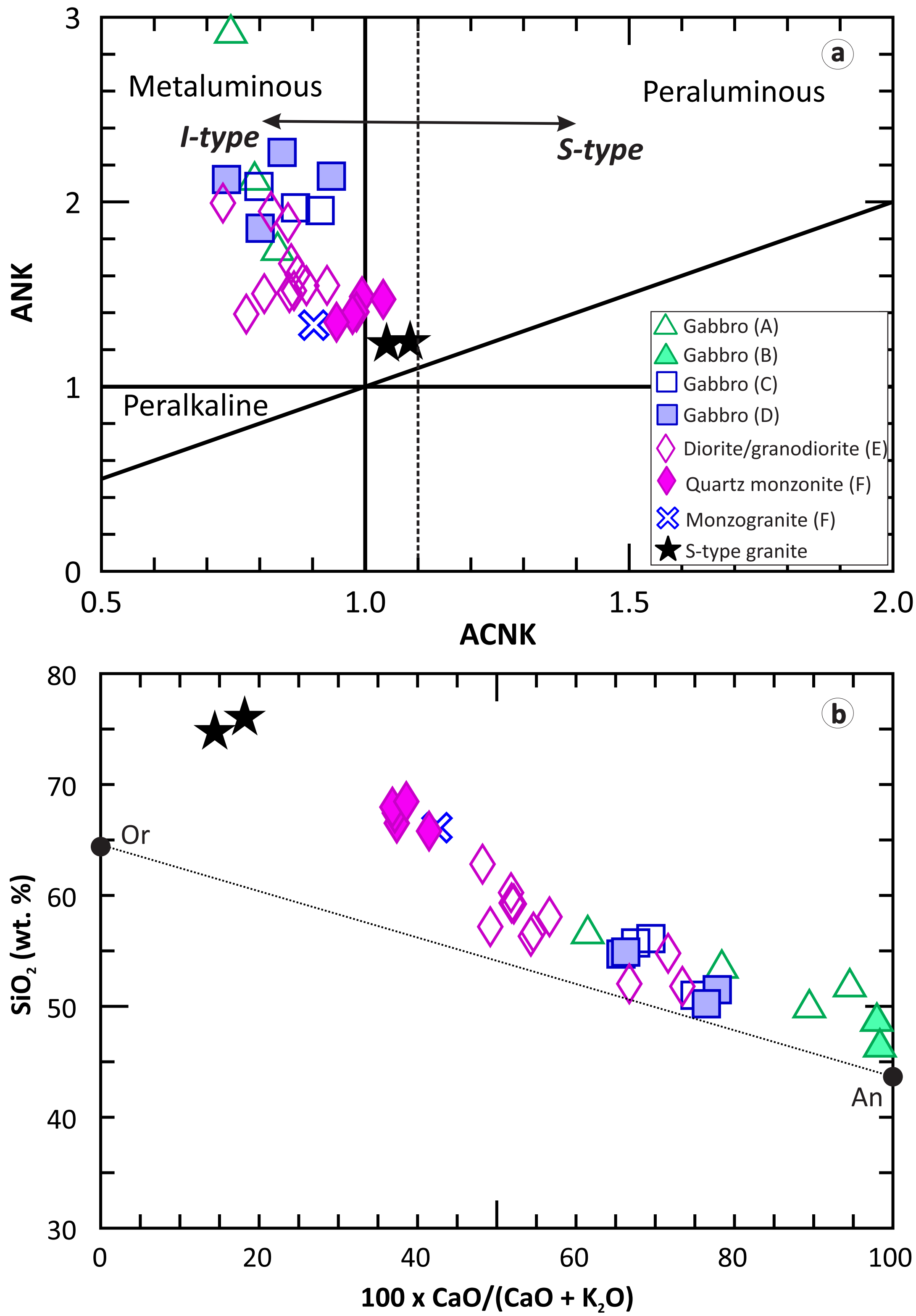

Figure GS2024-7-5: *Discrimination diagrams of the alumina- and silica-saturation state of whole-rock samples from the Falcon Lake intrusive complex and the Caddy Lake S-type granite intrusion of the Rennie River plutonic suite:* ***a)*** *Shand's index plot (A/CNK = {Al_2O_3/(CaO + Na_2O + K_2O)}, A/NK = {Al_2O_3/(Na_2O + K_2O)}), in which the vertical dashed line (A/CNK = 1.1) separates strongly peraluminous S- from I-type granites (after Chappell and White, 1974, 2001; fields from Maniar and Piccoli, 1989);* ***b)*** *SiO_2 (wt. %) versus CaO/(CaO + K_2O) diagram identifying the silica-saturation state of the samples, where the dashed line (silica-saturation line) expressed by the equation: $SiO_2 = –21.6 \times \{CaO/(CaO + K_2O)\} + 64.8$, units in wt. %) intercepting the y-axis at SiO_2 contents of 64.8 wt. % and 43.2 wt. % as defined by orthoclase (Or) and anorthite (An), respectively (modified from Enrique and Esteve, 2019), separates the rocks that are silica undersaturated (below the line) from those that are silica oversaturated (above the line). Data from Tirschmann (1992) and Yang (2023).*

Lake leucogranites indicates that they formed through reduced magmatic differentiation.

The FLIC samples all plot above the silica-saturation line (Figure GS2024-7-5b) as defined by Enrique and Esteve (2019), which suggests that their parental magmas are exclusively silica oversaturated. This is consistent with petrographic observations that the rocks in units A to F of the FLIC contain quartz, despite the fact that they show an enormous difference in modal quartz contents (Tirschmann, 1992). Although there appears to be a high correlation between the SiO_2 contents of the FLIC rocks and their $CaO/(CaO+K_2O)$ ratios, compositional gaps are evident between units F and E, between units E and D, as well as between units D and A, and B. Such gaps were noted by Gibbins (1971), whose observations were dismissed by Tirschmann (1992) as simply a function of sampling bias transposed onto the Harker diagrams. As previously mentioned, the compositional variation (Figure GS2024-7-4b) cannot be explained by fractional crystallization along the liquid line of descent of the same parental melt in a closed system. Compared with the FLIC, the Caddy Lake leucogranites are much more evolved in composition as indicated by their very low $CaO/(CaO + K_2O)$ ratios (<20), high τ[1] (Gottini index; see Grasso, 1968) values of 206–1180 and high silica contents of 74.74–76.03 wt. % (Table GS2024-7-1; Figure GS2024-7-5b).

Since alkalis and silica are readily affected by hydrothermal alteration (Figure GS2024-7-4a, b), it is necessary to adopt an immobile geochemical proxy, such as the Nb/Y ratio of high-field-strength elements (Pearce, 1996; Lentz, 1998; Rollinson and Pease, 2021), to assess the alkalinity of igneous rocks. This can be done by calculating the predicted σ^* value with the analyzed Nb/Y ratio of a sample in question (Yang and Lawley, 2024). A comparison of the σ^* with the measured σ value of the sample would then provide information about both alkali and silica mobility as well as alkalinity of the sample. Gabbro samples in units A to D have low Nb/Y ratios of 0.0–0.71 (Figure GS2024-7-6a), returning σ^* values of 0.8–3.3 that suggest they must be calcic to calcalkaline. The σ^* values are mostly comparable to measured σ values, although some are a little lower than the measured values (3.8–5.4) that exhibit a large range (Figure GS2024-7-6a), indicating addition of alkalis, particularly of K_2O, due to hydrothermal alteration (Yang and Lawley, 2024). Quartz monzonite samples from unit F have Nb/Y ratios >0.8 but σ values between 1.2 and 3.5, which suggests they contain notable Fe-Ti oxide-mineral (e.g., magnetite, ilmenite) cumulates that crystallized from a calcalkaline parental magma. Unit E diorite samples show varied Nb/Y and σ values, and mostly fall in the alkaline-series field (Figure GS2024-7-6a); they contain remarkably high Zr (average 330 $\pm$63 ppm; Table GS2024-7-1) and ΣREE values (>462 ppm; Table GS2024-7-1), although some plot outside of the field. These outliers may have been caused either by hydrothermal alteration, or by cumulous Fe-Ti–oxide minerals, which hypothesis is supported by petrographic investigations (Mandziuk, 1989; Mandziuk et al., 1989b; Tirschmann, 1992).

All samples from the FLIC have (Nb/Y) concentrations less than 60 ppm (Table GS2024-7-1) and thus cannot be postkinematic A-type granites (Whalen et al., 1987; Eby, 1990, 1992; Whalen and Hildebrand, 2019). Except for unit B gabbro, the FLIC rocks mostly display high La/Yb (>20) and Sr/Y (>40) ratios (Figure GS2024-7-6b) as well as very high Sr contents (Table GS2024-7-1), suggesting that their source region may have lacked plagioclase but contained a significant amount of garnet because of high pressure (Rapp and Watson, 1995; Rapp et al., 2003). These rocks exhibit enriched light-REE patterns without notable Eu anomalies (not shown), indicative of rocks formed from a parental magma characterized by high oxygen fugacity. Geochemically, the FLIC rocks are indistinguishable from Neoarchean sanukitoids and/or adakitic granitoids elsewhere (Shirey and Hanson, 1984; Stern and Hanson, 1991; Martin et al., 2005, 2009; Richards and Kerrich, 2007; Sun et al., 2010; Yang and Lawley, 2024; Yousefi and Lentz, 2024). They more closely resemble post-arc slab-failure granitoids given the degree of differentiation manifested by their silica contents (Hildebrand et al., 2018; Whalen and Hildebrand, 2019; Hildebrand and Whalen, 2021; Zwanzig, 2024). Hence, the occurrence of the FLIC sanukitoids could be used as a geological marker for geodynamic processes including slab failure and/or slab break-off caused by terrane collision.

Nd-Sr-O isotopes

Trace Nd-isotope analysis reveals that the quartz monzonite sample (111-14-283A01) from unit F of the FLIC has an initial ε_{Nd}^{t} (where ε is the degree on neodymium [Nd] enrichment relative to depleted mantle and *t* the time of formation of the rock) value of +1.1, a depleted-mantle Nd-model–age T_{DM} (where T is the age in Ga and $_{DM}$ means ‘depleted mantle’) of 2.89 Ga and a two-stage depleted-mantle Nd-model age of 2.79 Ga (Yang, 2023). This suggests that its parental magma may have been derived from a depleted-mantle source that had separated from primitive mantle at ca. 2.89 Ga and likely resided in the source region for about 100 m.y. During this period, the depleted mantle may have been metasomatized by melts and/or fluids derived from subduction as evidenced by a moderately low initial $(^{87}Sr/^{86}Sr)_i$ of 0.7027 (Halden et al., 2007) and a geochemical signature characterized by elevated light-REE concentrations (Table GS2024-7-1). In contrast, the Caddy Lake granite intrusion may have been derived from partial melting of immature crustal materials, as suggested by its $\delta^{18}O$ values of +8 to +9‰ (Duncan, 1989) and initial $(^{87}Sr/^{86}Sr)_i$ of 0.7087 (n = 7; see Farquharson and Clark, 1971) as well as geochemical fingerprinting in terms of high-field-strength elements (e.g., of high Zr and Nb contents; Figure GS2024-6).

[1] $\tau = (Al_2O_3 - Na_2O)/TiO_2$, units in wt. %; τ was proposed by Grasso (1968) and is referred to as the ‘Gottini index’ that can readily be used to describe the degree of magmatic differentiation (Yang, 2007), where a higher τ value signifies a greater level of differentiation.

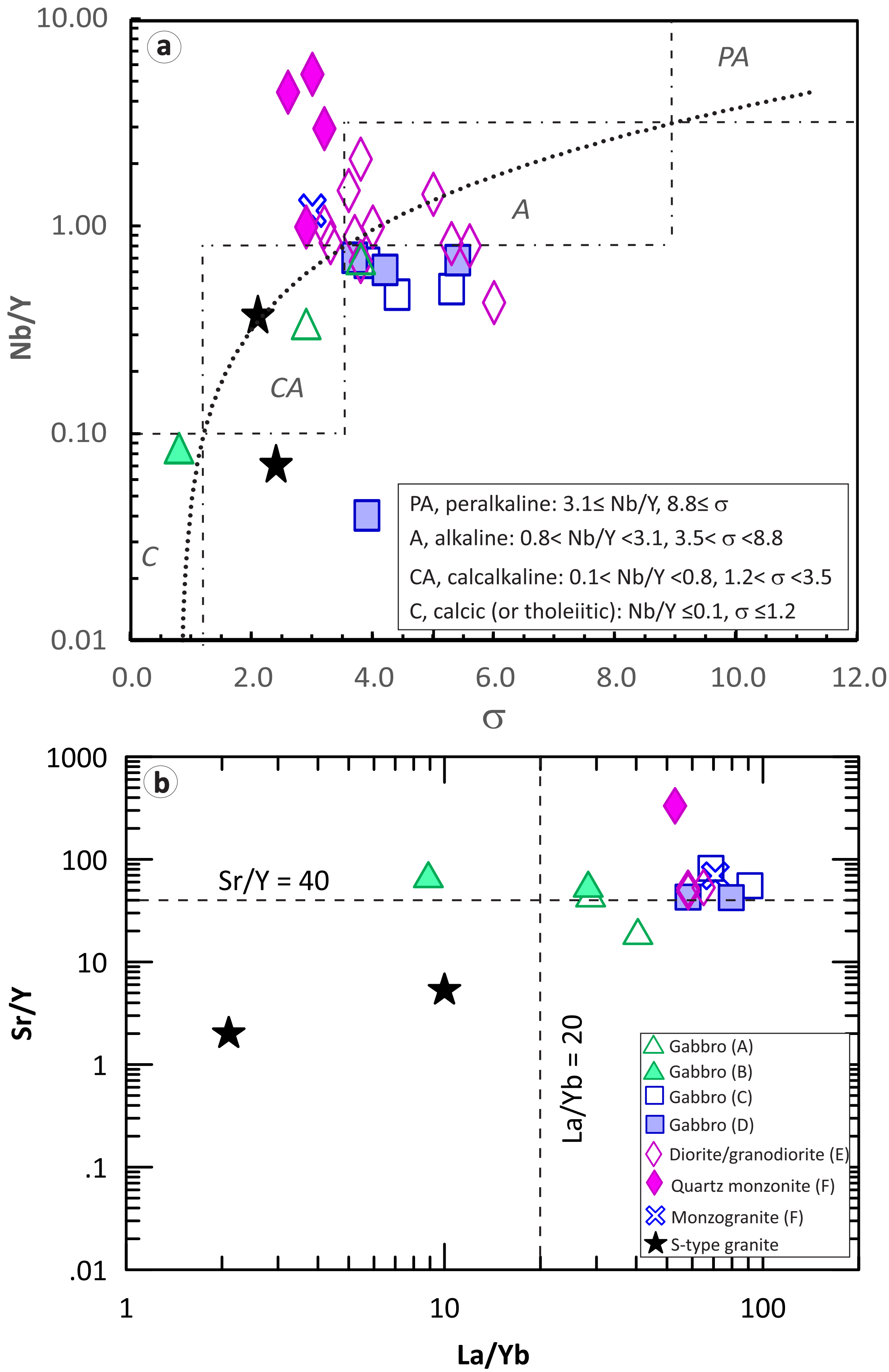

Figure GS2024-7-6: *Geochemical discrimination diagrams for whole-rock samples from the Falcon Lake intrusive complex and the Caddy Lake S-type granite intrusion of the Rennie River plutonic suite:* ***a)*** *Nb/Y versus σ plot (after Yang and Lawley, 2024), where* $\sigma = (Na_2O + K_2O)^2/(SiO_2 - 43)$*, units in wt. % (Rittmann Serial Index; Rittmann, 1962);* ***b)*** *Sr/Y versus La/Yb plot (after Richards and Kerrich, 2007). Data from Tirschmann (1992) and Yang (2023).*

U-Pb zircon dating

A new U-Pb zircon date for the FLIC is presented and compared with previously published geochronological data, including the age of the Caddy Lake granite, since determining precise timing is essential to a better understanding of the geodynamic evolution of the complex within the context of accretionary tectonics in the western Superior craton.

Methods

Uranium-lead zircon geochronological analysis was performed at the Jack Satterly Geochronology Laboratory at the University of Toronto (Toronto, Ontario) using high-precision chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) dating techniques (Hamilton, 2022). A detailed methodology can be found in Yang (2024).

Results

The zircon population from the dated quartz monzonite sample (111-14-283A01) comprises a range of grain sizes and a mixture of relatively pristine to variably turbid or cloudy grains locally charged with inclusions and cracks. These features are commonly observed in magmatic zircons (Corfu et al., 2003). In the case of some of the zircon crystals (inset a, Figure GS2024-7-7), even chemical abrasion did not much improve the precision of the analyses. Three best-quality prismatic zircon grains (Z1, Z2 and Z3 in inset b, Figure GS2024-7-7) were annealed, etched, and analyzed for U-Pb chemical and isotope compositions. These grains have Th/U ratios of 0.76–0.85, typical of magmatic zircons (Rubatto, 2017). The U-Pb isotopic data (Table GS2024-7-2) are variably discordant but are quite colinear, with an anchored (0 Ma) regression yielding an upper intercept age of 2695.7 ±1.0 Ma (mean square of weighted deviates or MSWD = 0.99, probability or *P* = 0.37), as shown in Figure GS2024-7-7. This age agrees well with the $^{207}Pb/^{206}Pb$ age of the concordant analytical result for Z3 at 2695.6 ±1.8 Ma (see Table GS2024-7-2). This age of 2695.7 ±1.0 Ma is interpreted as the emplacement and/or crystallization age of the quartz monzonite phase in unit F of the FLIC.

Discussion

The precise age of 2695.7 ±1.0 Ma reported here correlates well with late- or post-tectonic granitoids, including components of the Neoarchean sanukitoid suites found elsewhere in the Wabigoon domain of the western Superior province (e.g., ca. 2698–2690 Ma; Stern and Hanson, 1991; Ayer, 1998b; Stevenson et al., 1999; Lin and Beakhouse, 2013). However, this new date differs from three U-Pb zircon ages reported previously by Halden et al. (2007) using LAM-ICP-MS techniques: 2723 ±9 Ma on unit F quartz monzonite, 2724 ±10 Ma on unit E diorite and 2733 ±15 Ma on unit C gabbro in the FLIC. Although the Halden et al. (2007) ages are indistinguishable within uncertainties, they do not match the $^{206}Pb/^{238}U$ age of 2695.7 ±1.0 Ma obtained in this study. The discrepancy between the dating results of Halden et al. (2007) and this study may be due to an inaccurate correction for common Pb. However, the limited data provided in the table of Halden et al. (2007) do not allow for a thorough assessment of such a possibility. Alternatively, combining the precise date of this study with the dates from Halden et al. (2007) suggests that the FLIC may have a protracted history of 37 m.y. That explanation does not seem to be very probably for such a small composite stock as the FLIC. Given the techniques used in Halden et al. (2007) and in this current study, the CA-ID-TIMS U-Pb zircon age of 2695.7 ±1.0 Ma reported herein should be adopted as crystallization (and/or emplacement) age for the FLIC.

The Caddy Lake S-type granite was dated at 2687.2 ±6.7 Ma by Halden et al. (2007) also using LAM-ICP-MS U-Pb zircon techniques, which age is generally consistent with its emplacement into a thickened crust setting due to terrane collision between the Wabigoon and Winnipeg River domains. If that assumption is correct, the Caddy Lake granite must have occurred just after the emplacement of the FLIC at 2695.7 ±1.0 Ma. Thus, the FLIC and Caddy Lake intrusions must have been postorogenic or postcollisional granitoid intrusions that stitched and welded the merged domains (see Percival et al., 2006, 2012; Yang et al., 2019). In addition to the previously described undeformed fabrics evident in the FLIC (Mandziuk et al., 1989a, 1989b; Tirschmann,1992) and Caddy Lake granite, this conclusion is based largely on the interpretations outlined below:

- The FLIC is geochemically comparable to Archean sanukitoids, which likely formed by partial melting of a depleted mantle metasomatized previously by slab-related melts and/or fluids. Such melting took place only after terrane collision, triggered by upwelling of hot asthenospheric mantle because of slab break-off or failure (Martin et al., 2005; Hildebrand et al., 2018; Whalen and Hildebrand, 2019; Hildebrand and Whalen, 2021).
- The precise timing of FLIC crystallization (or emplacement) at 2695.7 ±1.0 Ma indicates that it was emplaced during a postorogenic stage after the Wabigoon domain was docked at the southern margin of the Winnipeg River domain ca. 2700 Ma (see Percival et al., 2006, 2012), but before emplacement of the ca. 2687±7 Ma Caddy Lake S-type granite intrusion into thickened crust resulting from terrane collision (Yang et al., 2019).

The main findings

Listed below are several major findings from this report, which has addressed the problems thus far identified with, and advanced the understanding of, geodynamic evolution and related mineralization associated with the formation of the western Superior province.

- Geodynamic evolution of the western Superior province was recorded in the FLIC, which was emplaced after docking of the Wabigoon domain on the southern margin (present

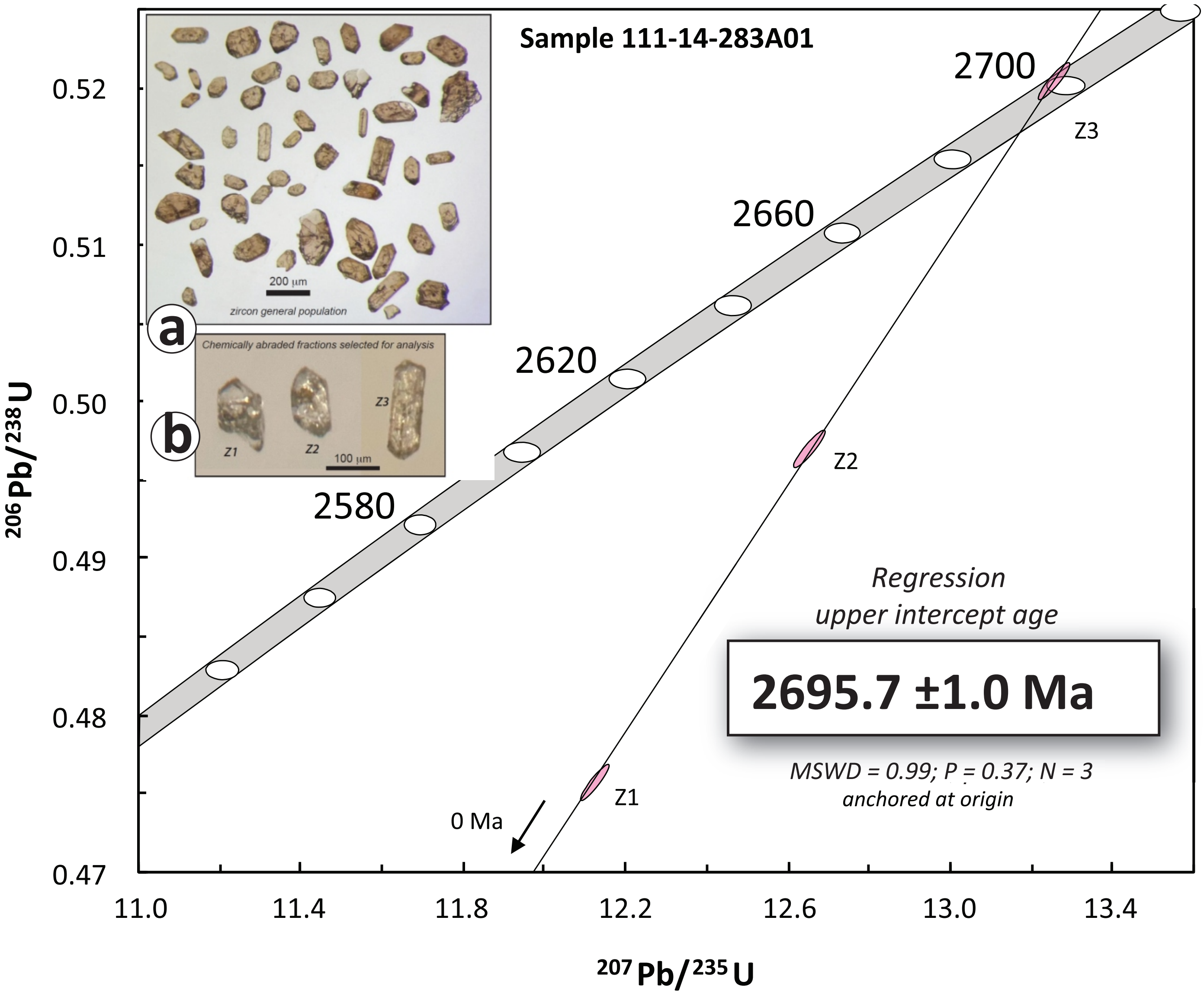

Figure GS2024-7-7: *Concordia diagram of chemical abrasion-isotope dilution-thermal ionization mass spectrometry U-Pb zircon age data for the quartz monzonite sample from the Falcon Lake intrusive complex in the Wabigoon domain of the western Superior craton, where Z1, Z2 and Z3 represent the three best-quality prismatic zircon grains analyzed. Abbreviations: MSWD, mean square of weighted deviates; N, number of analyses; P, probability.*

coordinates) of the Winnipeg River domain dominated by gneissic TTGs.

- The FLIC displays the geochemical signature of sanukitoids that may have been derived from partial melting of depleted mantle metasomatized by prior slab melts and/or fluids, indicating the termination of net growth of continental crust in the western Superior craton.
- The slightly younger Caddy Lake S-type leucogranite was emplaced across the terrane boundary zone between the Wabigoon and Winnipeg River domains, which may have host-rock potential for critical-element mineralization within pegmatites that are genetically related to the S-type granites. However, the crust-derived S-type granites did not contribute to net growth of continental crust in the western Superior province.
- The FLIC and Caddy Lake S-type granite formed during distinct tectonic stages of the geodynamic evolution involved in the assembly of the western Superior province. Firstly, terrane collision led to slab break-off (or failure), which triggered partial melting of the metasomatized, depleted mantle due to upwelling of hot asthenospheric mantle, resulting in the formation of the FLIC. Subsequently, heat from this mantle process induced partial melting of the thickened crust, which led to the formation of the S-type granite.

Economic considerations

The 2695.7 ±1.0 Ma Falcon Lake intrusive complex is a concentric, layered, composite intrusion, comprising two distinct parental magmas: the units A to D and F are calcalkaline, and unit E belongs to the alkaline series. The calcalkaline magmas

Table GS2024-7-2: Uranium-lead isotopic data for zircon in the quartz monzonite sample from the Falcon Lake intrusive complex in the Wabigoon domain of the western Superior craton obtained using chemical abrasion-isotope dilution-thermal ionization mass spectrometry.

Sample/ fraction	Description	U (ppm)	Th/U	Pb^T (pg)	Pb_C (pg)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	± 2σ	$^{206}Pb/^{238}U$	± 2σ	Corr. Coeff. (rho)	$^{207}Pb/^{206}Pb$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	Disc. (%)
Quartz monzonite sample from the Falcon Lake intrusive complex: 111-14-283A01 (location: UTM Zone 15 NAD83: 337410E, 5511611N)																				
Z1	1 brkn, cls, shrp tip	340	0.853	314	2.38	6953	12.12315	0.02906	0.475757	0.000931	0.9273	0.184812	0.000173	2614.0	2.2	2508.8	4.1	2696.5	1.5	8.4
Z2	1 cls, dt, shrt pr	257	0.763	226	2.73	4444	12.65210	0.03150	0.496996	0.000979	0.9168	0.184633	0.000192	2654.1	2.3	2600.9	4.2	2694.9	1.7	4.2
Z3	1 cls-grey, c-e, dt, flat 3:1 pr	204	0.806	191	2.48	4114	13.25546	0.03232	0.520500	0.000974	0.9118	0.184703	0.000196	2698.0	2.3	2701.3	4.1	2695.6	1.8	-0.3

All analyzed zircon fractions represent best optical quality (crack-, inclusion-, core-free), freshest (least altered) available grains. All zircons were chemically abraded.

Pb^T is total amount (in picograms) of Pb.

Pb_C is total measured common Pb (in picograms) assuming the isotopic composition of laboratory blank: 206/204 - 18.49 ±0.4%; 207/204 - 15.59 ±0.4%; 208/204 - 39.36 ±0.4%.

Pb/U atomic ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; $^{206}Pb/^{204}Pb$ is corrected for spike and fractionation.

Th/U is model value calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age, assuming concordance.

Disc. (%) indicates percent discordance for the given $^{207}Pb/^{206}Pb$ age.

Uranium decay constants are from Jaffey et al. (1971).

Abbreviations: brkn, broken; c-e, cloudy-etched; Coeff., coefficient; cls, colourless; dt, doubly-terminated; pr, prismatic; shrp, sharp; shrt, short; Z, zircon.

with sanukitoid signature may have formed as a result of partial melting of a depleted mantle previously metasomatized by slab-related melts and/or fluid; upwelling of hot asthenospheric mantle likely triggered the partial melting of the depleted lithospheric mantle due to slab break-off. Large to giant Au and/or porphyry Cu-Au ore deposits are notably thought to be closely linked to sanukitoid (and/or adakitic) intrusions (Richards and Kerrich, 2007; Sun et al., 2010; Lin and Beakhouse; 2013; Whalen and Hildebrand, 2019; Yang and Lawley, 2024; Yousefi and Lentz, 2024). The alkaline magma was generated by the partial melting of residues left behind by earlier extraction of voluminous I-type granitoids (i.e., TTGs), due to intra-arc extension caused by slab rollback. This process, together with formation of the FLIC, contributed to the net growth of the continental crust in the western Superior craton and produced high Zr (330 ppm) and total REE contents (>462 ppm) in the magma/rock (i.e., unit E diorite; Table GS2024-7-1).

Additionally, sulphide minerals (e.g., pyrite, pyrrhotite, chalcopyrite, arsenopyrite, sphalerite and molybdenite) and gold mineralization are present in the breccia pipes interpreted to have formed by implosion from a late volatile-rich magma (water saturated) within the core of the FLIC (i.e., unit F; Mandziuk et al., 1989a, b). Up to 6.5 g/t gold was reported in grab samples from the Moonbeam breccia pipe as well as in the contact zones between the country rocks to the northwest of the FLIC (Fingler, 1991). This type of mineralization resembles porphyry Cu-Au systems to some extent, as reported by Fingler (1991), consistent with quartz-biotite-sericite-pyrite (±carbonate) alteration present in fractured breccia, likely at the exposed root of the porphyry system.

Furthermore, spodumene, lepidolite and beryl are present in some granitic pegmatite dikes (e.g., Lucy and Artdon pegmatites) that occur in the Falcon Lake area (Davies et al., 1962; Bannatyne, 1985), and they may have been sourced from the Caddy Lake S-type granite intrusion that is part of the Rennie River plutonic suite. This is consistent with the fact that S-type granites are closely linked to critical-metal mineralization (Li, Ta, Cs, Be) hosted in granitic pegmatites. More recently, Grid Metals Corp. has reported drilling intercepts of high-grade rare-metal pegmatites (e.g., 12.2 m grading 2.2% Li_2O and 3.3 m grading 10.3% Cs_2O) at its Falcon West lithium property (Grid Metals Corp., 2024). The promising mineral exploration results confirm high prospectivity for rare metals hosted in pegmatite dikes that are associated genetically with S-type granite intrusions emplaced into the terrane boundary (or collision) zone between the Wabigoon and Winnipeg River domains of the western Superior province, southwestern Manitoba.

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