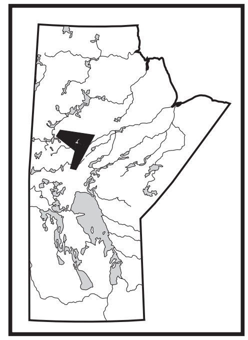
# GS-6 Geochemistry of an alkaline, ca. 1885 Ma K-feldspar–porphyritic, monzonitic to syenogranitic suite, northeastern Kisseynew Domain, Manitoba (parts of NTS 63O)

by J.B. Whalen[1], H.V. Zwanzig, J.A. Percival[1] and N. Rayner[1]



Whalen, J.B., Zwanzig, H.V., Percival, J.A. and Rayner, N. 2008: Geochemistry of an alkaline, ca. 1885 Ma K-feldspar–porphyritic, monzonitic to syenogranitic suite, northeastern Kisseynew Domain, Manitoba (parts of NTS 63O); *in* Report of Activities 2008, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 66–78.

## Summary

Recent work in the northeastern Kisseynew Domain has provided evidence that this area is underlain by or intercalated with Superior Province basement that is exposed in structural culminations. Where examined, this basement is mantled by Ospwagan-like paragneiss that may be an exploration target for Thompson-type Ni deposits. Closely associated with the basement culminations is the ca. 1885 Ma K-feldspar–porphyritic Footprint Lake plutonic suite (FLPS), which ranges in composition from syenite–monzonite to syenogranite–monzogranite. It represents a rare alkalic to alkali-calcic suite, low-silica end members of which are thought to represent low-degree partial melts of subduction-modified subcontinental lithospheric mantle (SCLM). Felsic end members are thought to reflect mixing between SCLM-derived magma and crustal melt. Archean Nd-model ages obtained from low-silica FLPS samples are interpreted as reflecting their mantle sources, not crustal contamination, and as such support the presence of Archean SCLM beneath this area at ca. 1885 Ma. The unusual and distinctive geochemical and isotopic characteristics of the FLPS make it a potential 'marker unit' for identifying the presence of Superior Province basement elsewhere in the Kisseynew Domain of Manitoba and Saskatchewan.

## Introduction

Recent work in the northeastern Kisseynew Domain of the Trans-Hudson Orogen has been carried out as part of the Flin Flon project of the Targeted Geoscience Initiative Program, which is aimed at identifying new base-metal exploration targets in northern Manitoba and Saskatchewan. This work has suggested the widespread presence of Superior Province crust and an overlying supracrustal sequence resembling the Ospwagan Group, host to Thompson Ni deposits, beneath migmatitic supracrustal rocks of the Burntwood Group (Growden et al., 2006; Percival et al., 2006, 2007; Rayner et al., 2006; Zwanzig et al., 2006a, b). Mapped Archean basement inliers formed by structural culminations include heterogeneous, granulite-grade orthogneiss associated with paragneiss and distinctive K-feldspar–porphyritic plutons. Uranium-lead zircon and Nd isotopic work on these plutons yielded 1879 ±13 and 1882 ±10 Ma crystallization ages and Archean (2.85–2.79 Ga) Nd model ages (Percival et al., 2006, 2007). This report summarizes the distinctive geochemical and Nd isotopic characteristics of these Kisseynew Domain K-feldspar–porphyritic plutons, herein named the Footprint Lake plutonic suite (FLPS), and also the K-feldspar–porphyritic Clarke Lake pluton of similar age (Percival et al., 2005) within the Superior Boundary Zone (Figure GS-6-1). Some relatively modern analogues are provided along with a preliminary discussion of possible petrogenetic and tectonic implications of the FLPS. A major goal of this report is to facilitate the identification of other plutons belonging to this suite within the central to western Kisseynew Domain of Manitoba and Saskatchewan, because they may represent a 'marker unit' for Archean basement inliers with unconformable early Paleoproterozoic supracrustal sequences that could host Ni deposits. For this reason, only the most relevant information concerning the FLPS is reviewed below, and the relationship between the FLPS and the broadly coeval equigranular to gneissic granodiorite on the west side of the Superior Boundary Zone (Zwanzig et al., 2003), as well as coeval mafic–ultramafic intrusions (Zwanzig, 2005), is not fully assessed.

## Geological setting

The geological context of the area covered by this report has been recently much revised and described in detail in a number of Manitoba Geological Survey Reports of Activities (e.g., Percival et al., 2006, 2007; Rayner et al., 2006; Zwanzig et al., 2006a) and preliminary maps (Zwanzig et al., 2006b). The distinct heterogeneous assemblage including Archean gneiss and the FLPS may represent structural or basement inliers among the younger Paleoproterozoic metasedimentary and leucogranitoid rocks that dominate the Kisseynew Domain. Geological, geochemical and Nd isotopic results have provided a basis for correlations that have been made between ortho- and paragneiss units within the inliers and rock types within the Superior Boundary Zone units, including the Ospwagan Group in the Thompson Nickel Belt (Zwanzig et al., 2006a).

Six bodies of K-feldspar–porphyritic intrusive rock, herein grouped into the Footprint Lake plutonic suite (FLPS), were examined within the northeastern Kisseynew Domain. They occur at Atik Lake, Wapisu

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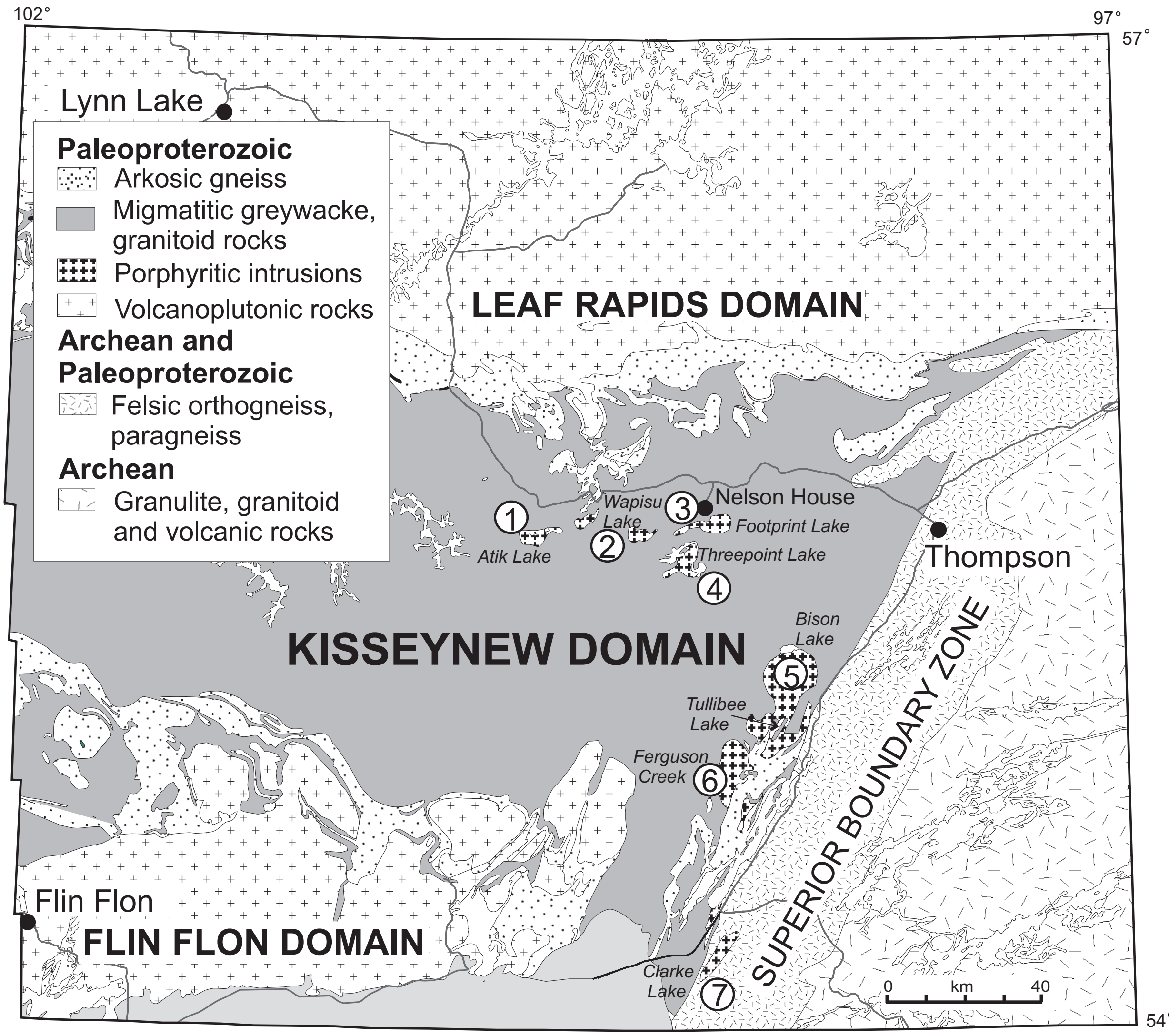


***Figure GS-6-1:*** *Geology of the eastern Kisseynew and bounding domains, showing locations of the Footprint Lake plutonic suite (FLPS) and the Clarke Lake pluton, central Manitoba. Geochemical data were collected from the following ca. 1885 Ma plutons, identified by number: 1, Atik Lake; 2, Wapisu Lake; 3, Footprint Lake; 4, Threepoint Lake; 5, Bison–Tullibee lakes; 6, Ferguson Creek; and 7, Clarke Lake.*

Lake, Footprint Lake, Threepoint Lake; Tullibee–Bison lakes and Ferguson Creek (Figure GS-6-1, plutons 1–6). Of these, plutons 2 and 3 were mapped and sampled most extensively. All plutons are fairly homogeneous, contain hornblende+biotite±pyroxene and have K-feldspar phenocrysts up to 4 cm in diameter. In the northern plutons (plutons 1–4), deformation states vary from moderately to strongly foliated, to augen gneiss (Figure GS-6-2a, -2b). Due to the state of strain, the low quartz and plagioclase content of many FLPS exposures in this area may have remained unrecognized in the field; hence, the unit was incorrectly identified as quartz monzonite (at the time including monzogranite) to monzonite (Baldwin et al., 1979), rather than a syenite–monzonite to syenogranite–monzogranite suite (see below). Where southern FLPS plutons 5 and 6 were sampled, the deformation state was lower and abundant quartz is obvious (Figure GS-6-2c), confirming their syenogranite and monzogranite compositions. Moreover, the lack of known contact relationships due to poor exposure and the inability to perform meaningful isotopic dating led to the assumption that the FLPS intruded the (younger) widespread greywacke migmatite (Burntwood Group). The FLPS, particularly its northern plutons, is variably intruded by granitic and pegmatitic dikes and veins. Mafic dikes up to 4 m wide (*see* Figure GS-7-3b *in* Percival et al., 2006) occur within all of the plutons, and diffuse enclaves of diorite to gabbro are present in the Atik Lake body. Contacts with surrounding rocks are generally obscured by dikes of pegmatite and/or are strongly sheared. Most frequently, the nearest well-exposed and readily identifiable rock type is either garnet-rich metasedimentary migmatite, equated with the regionally ubiquitous Burntwood Group, or late pink pegmatitic leucogranite. At southwest Wapisu Lake,

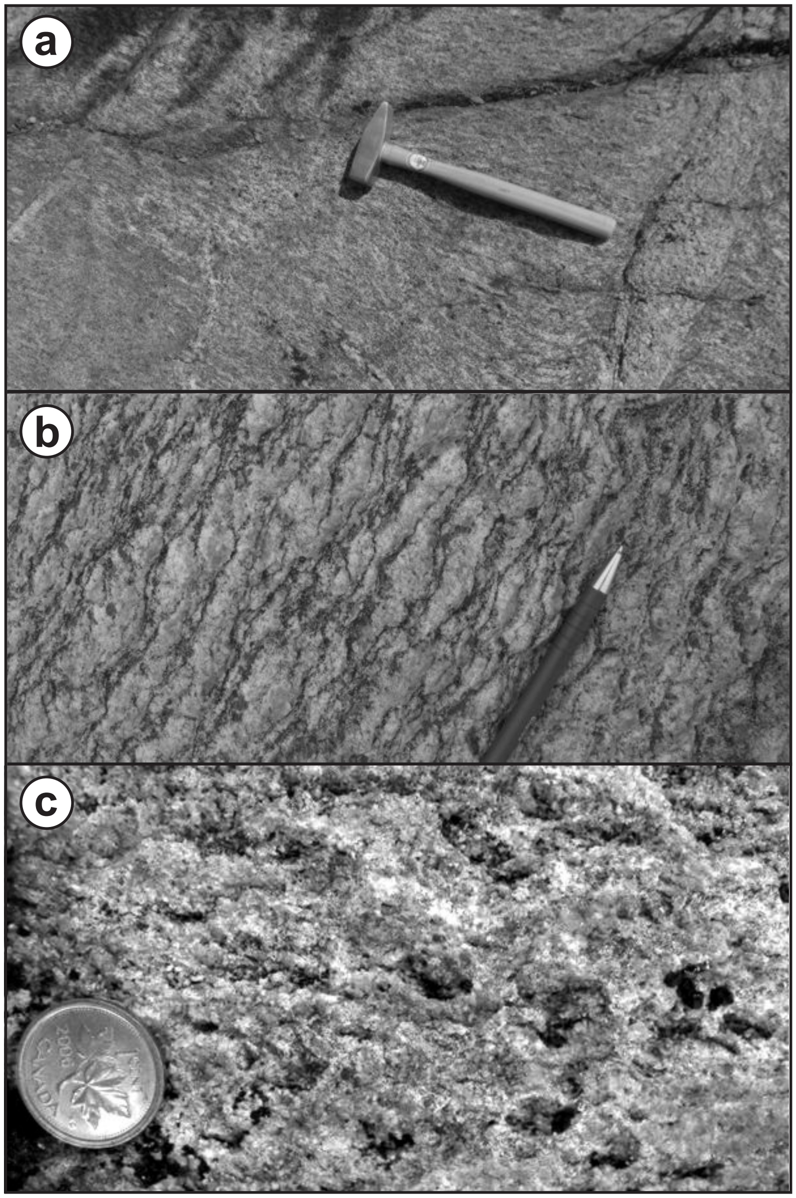


***Figure GS-6-2:*** *Field photographs of Footprint Lake plutonic suite:* ***a)*** *gneissic monzonite ($SiO_2$ = 54 wt. %) exposure on Atik Lake (33 cm long hammer for scale);* ***b)*** *moderately to strongly foliated monzogranite ($SiO_2$ = 66 wt. %) exposure on Footprint Lake (7 cm of a pencil for scale);* ***c)*** *slightly foliated syenogranite ($SiO_2$ = 73 wt. %) exposure near Ferguson Creek (1.8 cm penny for scale).*

diverse quartz-rich clastic rocks are exposed that are interpreted as pre-Burntwood and may lie unconformably upon the Wapisu Lake pluton. At another locality on southeast Footprint Lake, compositionally well-banded biotite tonalite gneiss is exposed close to the much less deformed FLPS, suggesting the former could represent an Archean hostrock.

The Clarke Lake pluton (Figure GS-6-1, pluton 7) occurs in the Thompson Nickel Belt and intrudes the Ospwagan Group on the west and Superior Province–type basement on the east. The body is at least 8 km wide and 15 km long, but its southern extent is unknown. Previously mapped as Archean granite, this medium- to coarse-grained, homogeneous, foliated biotite-hornblende granodiorite carries a single foliation, unlike the adjacent polydeformed Archean gneiss, and lacks deformed mafic dikes. Its field characteristics resemble those of exposed Paleoproterozoic intrusions in the Superior Boundary Zone (Zwanzig et al., 2003). For these reasons, a Clarke Lake pluton sample was dated in 2005 by sensitive high-resolution ion microprobe (SHRIMP) U-Pb geochronology. It yielded a weighted-mean $^{207}Pb/^{206}Pb$ age of 1885 ±5 Ma, interpreted as the crystallization age, and an εNd value of –3.3 and $T_{CHUR}$ age of 2.5 Ga (Percival et al., 2005). Based on their temporal and lithological similarities, plutons of the FLPS were initially (but incorrectly; *see* below) interpreted as being cogenetic with the Clarke Lake pluton.

## Geochemistry

### *Major elements*

The Footprint Lake plutonic suite (FLPS) is shown in Figure GS-6-3 on the cation Q-P and normative Q′-ANOR major-element–based granitoid rock classification diagrams of Debon and Le Fort (1983) and Streckeisen and LeMaitre (1979), respectively. To facilitate description and characterization, FLPS samples were subdivided into four silica-based groups, each of which is plotted with a distinct symbol, as is the average composition for each group. Based on these diagrams, this suite ranges from syenite and monzonite, through quartz syenite and quartz monzonite, to syenogranite and monzogranite, following an alkaline oversaturated trend (labelled ALKOS in Figure GS-6-3a). Of note is that some Q′-poor

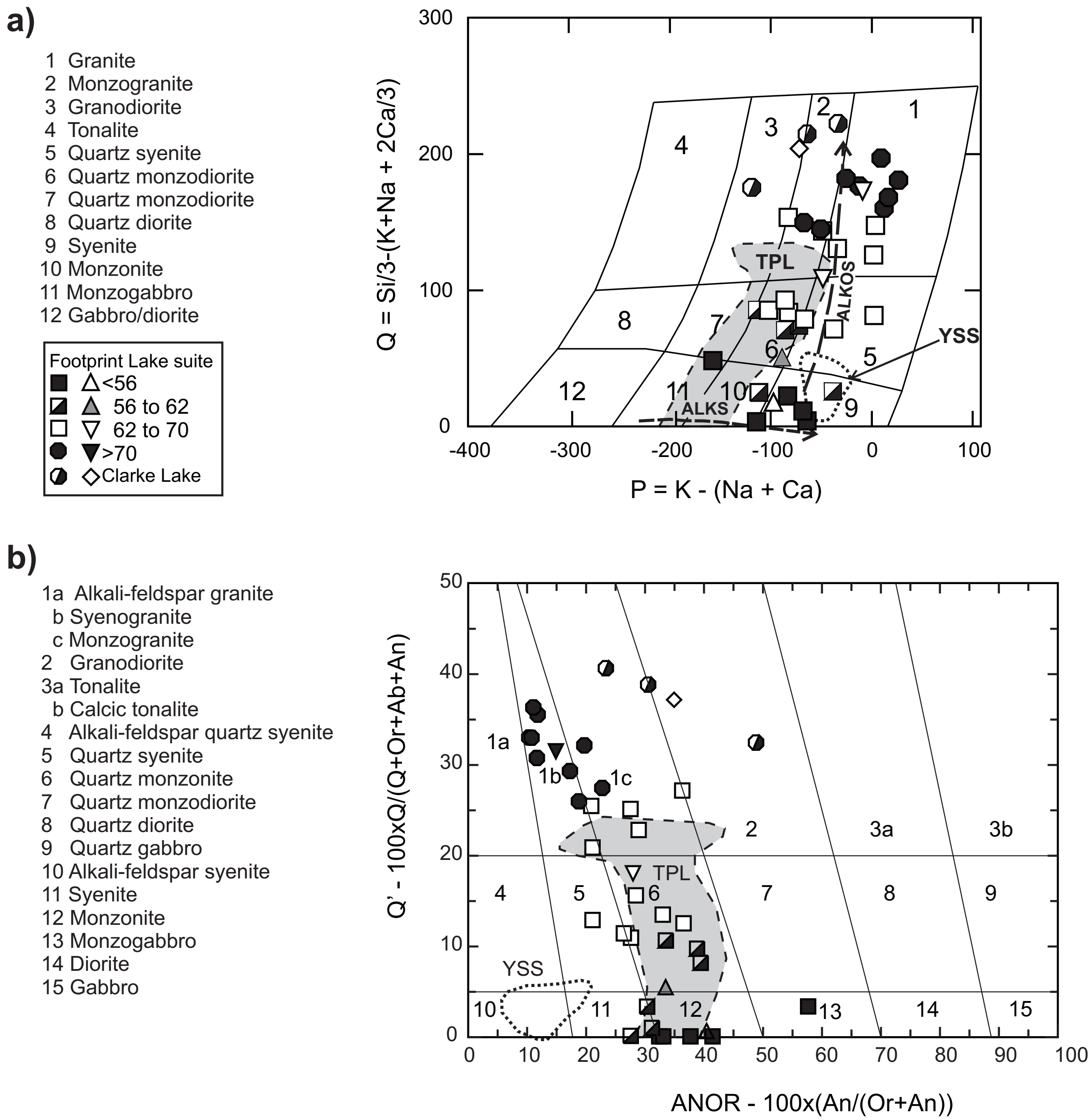


***Figure GS-6-3:*** *Ca. 1885 Ma plutons plotted on major-element–based granitoid classification diagrams. Shown for comparison is the shaded field for Tibetan potassic lava (TBL) derived from data in Williams et al. (2004), and the Yamato syenite suite, Antarctica (YSS) derived from Table 4 of Zhao et al. (1995);* ***a)*** *Debon and Le Fort (1983) Q-P cation plot and trends for ALKS and ALKOS, alkaline-saturated and oversaturated suites are included;* ***b)*** *Streckeisen and LeMaitre (1979) CIPW normative Q′-ANOR plots. Footprint Lake plutonic suite samples were subdivided into four groups based on silica content, each shown by a different plot symbol (left column in legend box), as are the four group averages (right column in legend box). Clarke Lake pluton samples and averages are also plotted. Three samples plotted on the ANOR axis are 1–2% nepheline normative, whereas the Tibetan suite includes five samples that are 3–15% nepheline normative.*

samples that plot on the ANOR axis in Figure GS-6-3b are undersaturated, including up to 2% CIPW normative nepheline. In these diagrams, the Clarke Lake pluton plots separately, as it includes granodioritic compositions. On a $K_2O$ versus $SiO_2$ plot (Figure GS-6-4a), most FLPS samples exhibit very high K or shoshonitic compositions but do trend into the high-K field at >63 wt. % silica contents. In the total alkali–silica diagram of Irvine and Baragar (1971; Figure GS-6-4b), low-silica FLPS samples plot in the alkaline field, whereas high-silica samples cross over into the subalkaline field. In contrast, the Clarke Lake pluton has medium K and is subalkaline.

An alternative granitoid rock geochemical classification scheme (Frost et al., 2001) employed herein is three-tiered: 1) based on either an FeO/(FeO+MgO) or $FeO^{total}/(FeO^{total}+MgO)$ versus $SiO_2$ diagram (Figure GS-6-5a), a suite is either ferroan or magnesian; 2) based on an $Na_2O+K_2O$–CaO (alkali-lime index) versus $SiO_2$ diagram, a suite is either alkalic, alkali-calcic, calcalkalic or calcic (Figure GS-6-5b); and 3) based on aluminum saturation index (ASI = Al/(Ca–1.67P+Na+K; Shand, 1943), a suite is either peraluminous (ASI >1.0), metaluminous (ASI <1.0), or, if Na + K >Al, peralkaline (not shown). In this classification scheme, the FLPS is magnesian, alkalic (mafic samples) to alkali-calcic (felsic samples) and metaluminous. In contrast, the Clarke Lake pluton is magnesian, calcic and metaluminous.

According to Frost et al. (2001), magnesian alkalic compositions, like FLPS mafic end members, are uncommon, their only cited example being the Yamato syenite

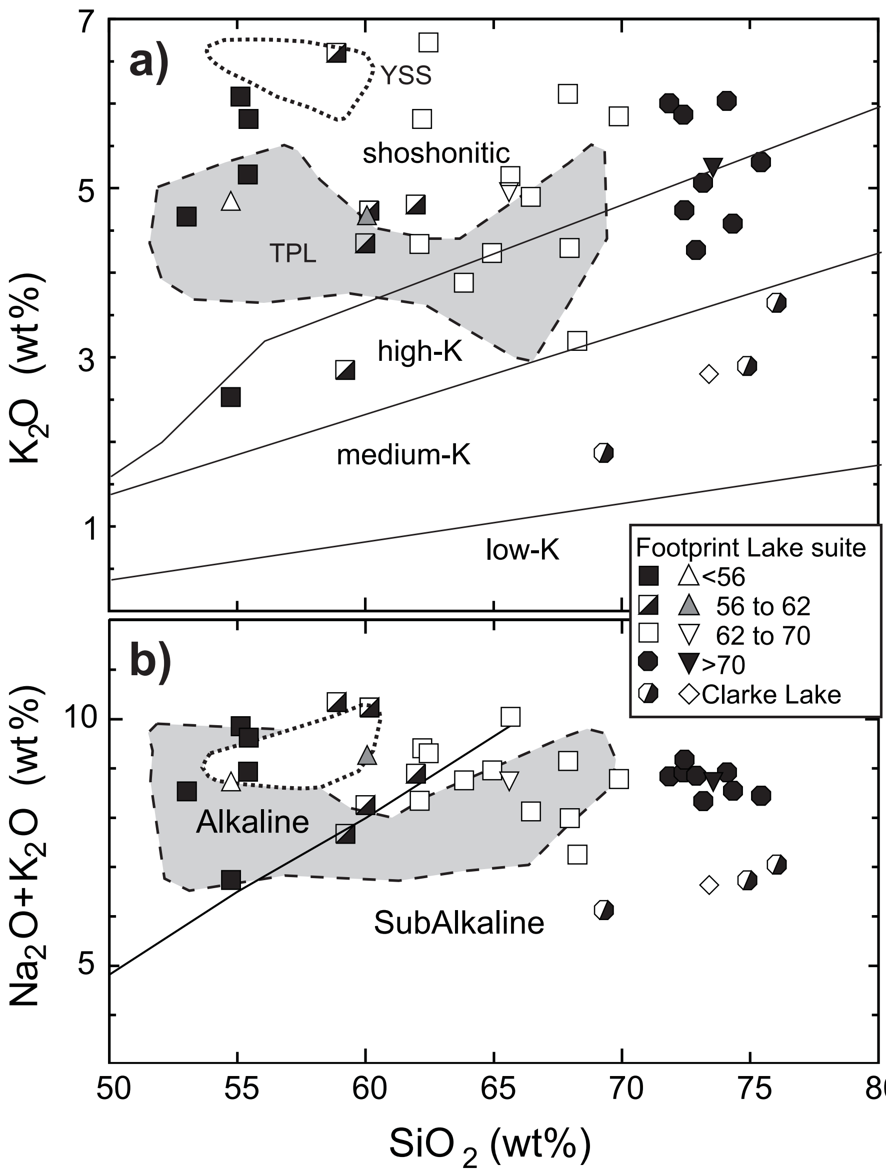


***Figure GS-6-4:** Ca. 1885 Ma plutons plotted on the **a)** $K_2O$ versus $SiO_2$ diagram that includes the low-, medium- and high-K suite boundaries from LeMaitre (1989) and the high-K–shoshonitic suite boundary from Peccerillo and Taylor (1976); **b)** $K_2O+Na_2O$ versus $SiO_2$ diagram that includes the Irvine and Baragar (1971) alkaline–subalkaline suite boundary. Plot symbols and shaded fields as in Figure GS-6-3 and its included legend.*

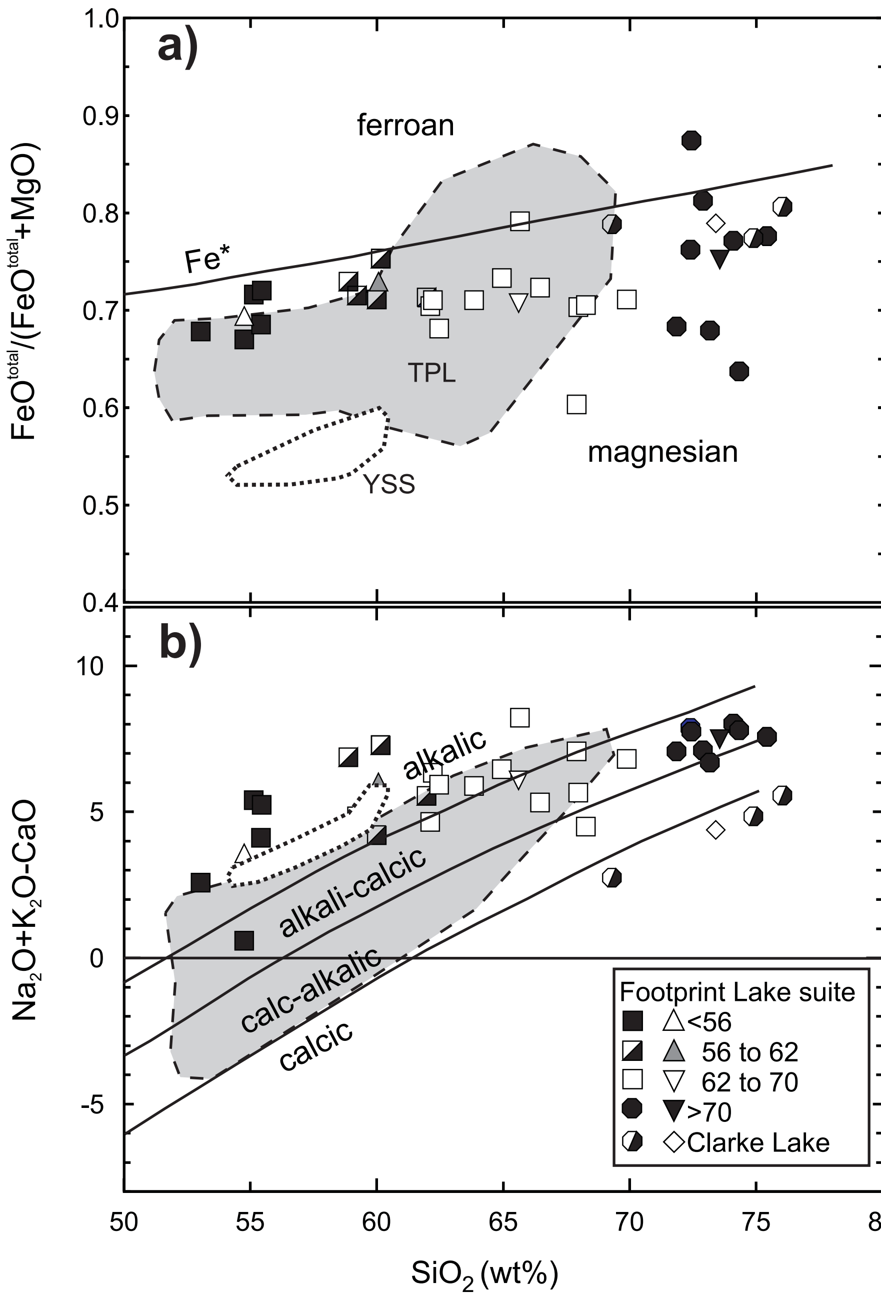


***Figure GS-6-5:*** *Ca. 1885 Ma plutons plotted on granitic rock classification diagrams of Frost et al. (2001);* ***a)*** *FeO$^{total}$/(FeO$^{total}$+MgO) versus SiO$_2$ classification diagram is shown with the boundary between ferroan and magnesian plutons (based on the alkali-lime classification of Peacock, 1931); and* ***b)*** *Na$_2$O+K$_2$O–CaO versus SiO$_2$ classification diagram is shown with the ranges for the alkalic-calcic, calcalkalic and calcic rock series, based on the alkali-lime classification of Peacock (1931). Together with the aluminum saturation index (ASI, not shown; Shand, 1943), these plots constitute a three-tiered geochemical scheme for granitoid rocks (see text for discussion). Plot symbols and shaded fields as in Figure GS-6-3 and the included legend.*

suite (YSS), East Antarctica (Zhao et al., 1995). Fields for the YSS included in the major-element–based plots (Figures GS-6-3, -4 and -5) indicate it to be consistently more potassic, but similarly quartz-poor and alkali-rich as the two FLPS groups with the lowest silica. In the Frost et al. (2001) classification, the YSS is markedly more magnesian but identically alkalic as lower-silica FLPS samples (Figures GS-6-5a and -5b). Frost et al. (2001) found magnesian, alkali-calcic compositions, like FLPS felsic components, to be mainly restricted to inboard of Cordilleran batholiths. A possible modern analogue for FLPS magmatism mentioned, but not elaborated on, by Frost et al. (2001) is Neogene high-K lava of the Tibetan plateau. Comparison fields for this, based on data of Williams et al. (2004), overlap fairly closely in Figures GS-6-3 and -4 with <70% silica samples of the FLPS.

However, equivalents of FLPS high-silica plutonic end members are absent and Tibetan lava tends to be less potassic and more calcic, such that it belongs to a magnesian alkali-calcic to calcalkalic suite (Figure GS-6-5b). Also, five of the Tibetan samples contain 3–14 wt. % CIPW normative nepheline so that, in Figure GS-6-3b, they should be shown in the undersaturated F′–ANOR classification diagram of Streckeisen and LeMaitre (1979).

An important conclusion of Frost et al. (2001) was that magnesian granitoid rocks, like the FLPS, reflect a close affinity to relatively hydrous, oxidizing magma or source regions, consistent with a broadly subduction-related origin. Also, as they found that plutonic suites generally follow subparallel alkali-lime trends during differentiation, suites that cross these trend lines, as does the FLPS (Figure GS-6-5b), may reflect mixing of multiple magmas. Similar crossing by the FLPS of igneous suite classification boundaries in Figure GS-6-4a and -4b is further evidence that FLPS components are not related by fractional crystallization.

### *Trace elements*

As would be predicted from their wide major-element compositional range, the Footprint Lake plutonic suite (FLPS) also exhibits a large range in trace-element compositions (Table GS-6-1). Normalized extended-element plots for FLPS silica-grouped averages (*see* Figures GS-6-3, -4 and -5) are shown in Figure GS-6-6a. Of note is that all normalized patterns 1) are roughly parallel, 2) are markedly enriched in large-ion lithophile elements (LILE; e.g., Rb, Ba, K) and high field-strength elements (HFSE; e.g., Zr, Ti), 3) are heavy rare-earth element (HREE) depleted, and 4) exhibit well-developed negative Nb, Sr and P anomalies. Averages for the three lower-silica FLPS groups compare most closely with, and are more enriched in all normalized elements (other than Rb and Th) than the >70 wt.% silica FLPS sample average. Also, patterns of this high-silica average and that of the Clarke Lake pluton overlap closely. The low-silica FLPS field shown in Figure GS-6-6a is compared with patterns for the Yamato syenite suite and Tibetan lava in Figure GS-6-6b and -6c. In their trace-element patterns, low-silica FLPS samples overlap fairly well with the similar silica content of the Yamato syenite suite and Tibetan lava. In detail, the closest match is with lower-silica Tibetan lava, as higher-silica lava tends to be more enriched in Rb and Th, and depleted in Nb, Sr and P, whereas Yamato syenite is more enriched in Rb, Ba, P and Y.

On the Pearce (1996) Rb–Nb+Y tectonomagmatic discrimination diagram (Figure GS-6-7a), low-silica FLPS samples plot almost exclusively within the overlap area between volcanic-arc (VAG) and postcollisional (post-COLG) granite. In contrast, most high-silica FLPS samples plot on this diagram within the VAG field, straddling its boundary with syncollisional (syn-COLG) granite. In the Nb-Y diagram (Figure GS-6-7b; Pearce et al.,1984), low-silica FLPS samples straddle the WPG–VAG+syn-COLG granite boundary, whereas high-silica samples exhibit lower Nb and Y contents. The field of Tibetan lava on these diagrams corresponds fairly closely to that of low-silica FLPS samples, though this lava ranges to slightly higher Rb, Y and Nb contents. The Yamato syenite suite field overlaps with only the most enriched FLPS samples. In summary, Rb, Nb and Y contents of the low-silica FLPS samples correspond most closely to postcollisional granitoid rocks, whereas the high-silica samples plot in the field of volcanic-arc granite.

A notable feature of the FLPS, and also of the Tibetan potassic lava, is that they are enriched in Th and have elevated chondrite-normalized La/Yb ratios (mainly >10 ppm and >20, respectively; Figure GS-6-8). Yamato syenite has lower $(La/Y)_{cn}$ but similarly high Th. On this diagram, there is almost no overlap between ca. 1885 Ma plutonic samples and the field of more than 300 samples from the ca. 1.90 and 1.83 Ga Flin Flon Domain granitoid plutons (data from Whalen et al., 1998). This enrichment in Th is not accompanied by high U, such that the FLPS exhibits average Th/U values of 17.4–20.0 in low-silica samples and 13.9 and 12.1 in high-silica samples and in the Clarke Lake pluton (Table GS-6-1). This characteristic was noted during U-Pb zircon dating when it was found that FLPS zircon Th/U ratios were distinctively high, typically greater than 1 and with values ranging up to 2.7 (Percival et al., 2007). The whole-rock Th/U ratios for compared alkaline suites (Figure GS-6-6b and -6c) are also high: YSS = 4.0–7.0 and Tibet = 5.9–6.4, but much lower than for the FLPS. Another significantly enriched trace element in the FLPS is Zr, which ranges from 822 to 159 ppm. Using the model of Watson and Harrison (1983), high calculated zircon saturation temperatures of 780–880ºC (Table GS-6-1) were obtained for the FLPS and Clarke Lake pluton, temperatures that help explain a paucity of xenocrystic zircon in the three dated samples from these plutons (Percival et al., 2007)

### *Nd isotopes*

Tracer isotopic analyses were conducted using the Nu Plasma™ multicollector inductively coupled plasma–mass spectrometer (ICP-MS) at the Geological Survey of Canada. Samarium and neodymium were analyzed using an array of fixed Faraday collectors in static multicollector mode. The isotopic ratios were corrected for spike contribution and mass discrimination by numeric solution of the isotope dilution equations with exponential normalization. Quality control was performed by monitoring the uniformity of nonradiogenic isotopic ratios and by analyzing of the La Jolla Nd and Ames Sm standards. Analytical results are presented in Table GS-8-2 of Percival et al. (2006) for two Footprint Lake plutonic suite (FLPS) samples and one Clarke Lake pluton sample.

**Table GS-6-1: Geochemical averages for the Footprint Lake plutonic suite and the Clarke Lake pluton.**

| Suite/ pluton | FLPS | FLPS | FLPS | FLPS | Clarke Lake |
|---|---|---|---|---|---|
| Silica interval | <56 | >56–<62 | >62–<70 | >70 | |
| No. averaged | N = 5 | N = 5 | N = 11 | N = 8 | N = 3 |
| $SiO_2$ | 54.8 | 60.0 | 65.6 | 73.3 | 73.4 |
| $TiO_2$ | 1.39 | 0.98 | 0.69 | 0.20 | 0.20 |
| $Al_2O_3$ | 18.81 | 18.42 | 16.44 | 14.28 | 13.13 |
| $Fe_2O_3$ | 2.00 | 1.20 | 0.93 | 0.51 | 1.30 |
| FeO | 5.30 | 4.44 | 3.00 | 1.00 | 2.05 |
| MnO | 0.10 | 0.08 | 0.05 | 0.01 | 0.07 |
| MgO | 3.16 | 2.13 | 1.60 | 0.53 | 0.86 |
| CaO | 5.17 | 3.34 | 2.68 | 1.29 | 2.27 |
| $Na_2O$ | 3.58 | 4.08 | 3.49 | 3.27 | 3.23 |
| $K_2O$ | 5.16 | 5.00 | 5.25 | 5.49 | 3.41 |
| $P_2O_5$ | 0.57 | 0.30 | 0.25 | 0.09 | 0.07 |
| LOI | 0.60 | 0.52 | 0.53 | 0.35 | 0.53 |

Major elements recalculated to 100% anhydrous

| Suite/ pluton | FLPS | FLPS | FLPS | FLPS | Clarke Lake |
|---|---|---|---|---|---|
| Silica interval | <56 | >56–<62 | >62–<70 | >70 | |
| No. averaged | N = 5 | N = 5 | N = 11 | N = 8 | N = 3 |
| **Trace elements (ppm)** | | | | | |
| Cr | 22 | <10 | 13 | <10 | 17 |
| Ni | <10 | <10 | <10 | <10 | <10 |
| Sc | 16.4 | 8.7 | 10.0 | 2.9 | 8.8 |
| V | 141 | 71 | 68 | 20 | 33 |
| Cu | 12 | <10 | <10 | <10 | <10 |
| Pb | 9 | 16 | 13 | 15 | 21 |
| Zn | 54 | 14 | 27 | 7 | 34 |
| Sn | 2.9 | 3.0 | 1.8 | 1.7 | 1.6 |
| Sb | 0.56 | 0.71 | 1.05 | 0.87 | 0.25 |
| Rb | 87 | 119 | 122 | 153 | 89 |
| Cs | 0.98 | 1.20 | 0.87 | 0.57 | 1.30 |
| Ba | 3056 | 1831 | 1646 | 979 | 1306 |
| Sr | 1470 | 809 | 718 | 355 | 473 |
| Tl | 0.3 | 0.4 | 0.3 | 0.5 | 0.6 |
| Ga | 25.7 | 23.2 | 20.5 | 17.8 | 14.6 |
| Nb | 19.0 | 19.8 | 20.1 | 8.9 | 7.2 |
| Hf | 17.3 | 14.1 | 11.5 | 4.7 | 4.6 |
| Zr | 822 | 616 | 471 | 159 | 181 |
| Y | 23.0 | 21.7 | 21.6 | 9.1 | 9.9 |
| Th | 10.41 | 21.79 | 21.93 | 38.75 | 24.91 |
| U | 0.60 | 1.37 | 1.10 | 2.79 | 2.05 |
| La | 141.6 | 120.7 | 113.9 | 65.1 | 60.4 |
| Ce | 258.3 | 225.9 | 215.4 | 115.2 | 116.6 |
| Pr | 28.6 | 25.6 | 23.8 | 12.0 | 12.0 |
| Nd | 98.6 | 86.8 | 80.0 | 38.1 | 42.1 |
| Sm | 13.21 | 12.53 | 11.23 | 5.86 | 6.31 |
| Eu | 3.37 | 2.47 | 2.01 | 0.92 | 1.00 |
| Gd | 8.30 | 8.03 | 6.78 | 3.61 | 3.89 |
| Tb | 0.98 | 0.94 | 0.87 | 0.45 | 0.43 |
| Dy | 4.57 | 3.95 | 4.14 | 1.88 | 1.92 |
| Ho | 0.78 | 0.78 | 0.73 | 0.30 | 0.33 |
| Er | 1.92 | 1.71 | 1.82 | 0.71 | 0.83 |
| Tm | 0.29 | 0.28 | 0.27 | 0.10 | 0.12 |
| Yb | 1.68 | 1.65 | 1.61 | 0.60 | 0.83 |
| Lu | 0.26 | 0.23 | 0.23 | 0.09 | 0.14 |
| Be | 1.96 | 1.97 | 2.60 | 1.72 | 1.85 |
| Th/U | 17.4 | 15.9 | 20.0 | 13.9 | 12.1 |
| Zir Sat T (ºC)[1] | 868º | 850º | 880º | 780º | 793º |

[1] Zircon staturation temperatures based on model of Watson and Harrison (1983).

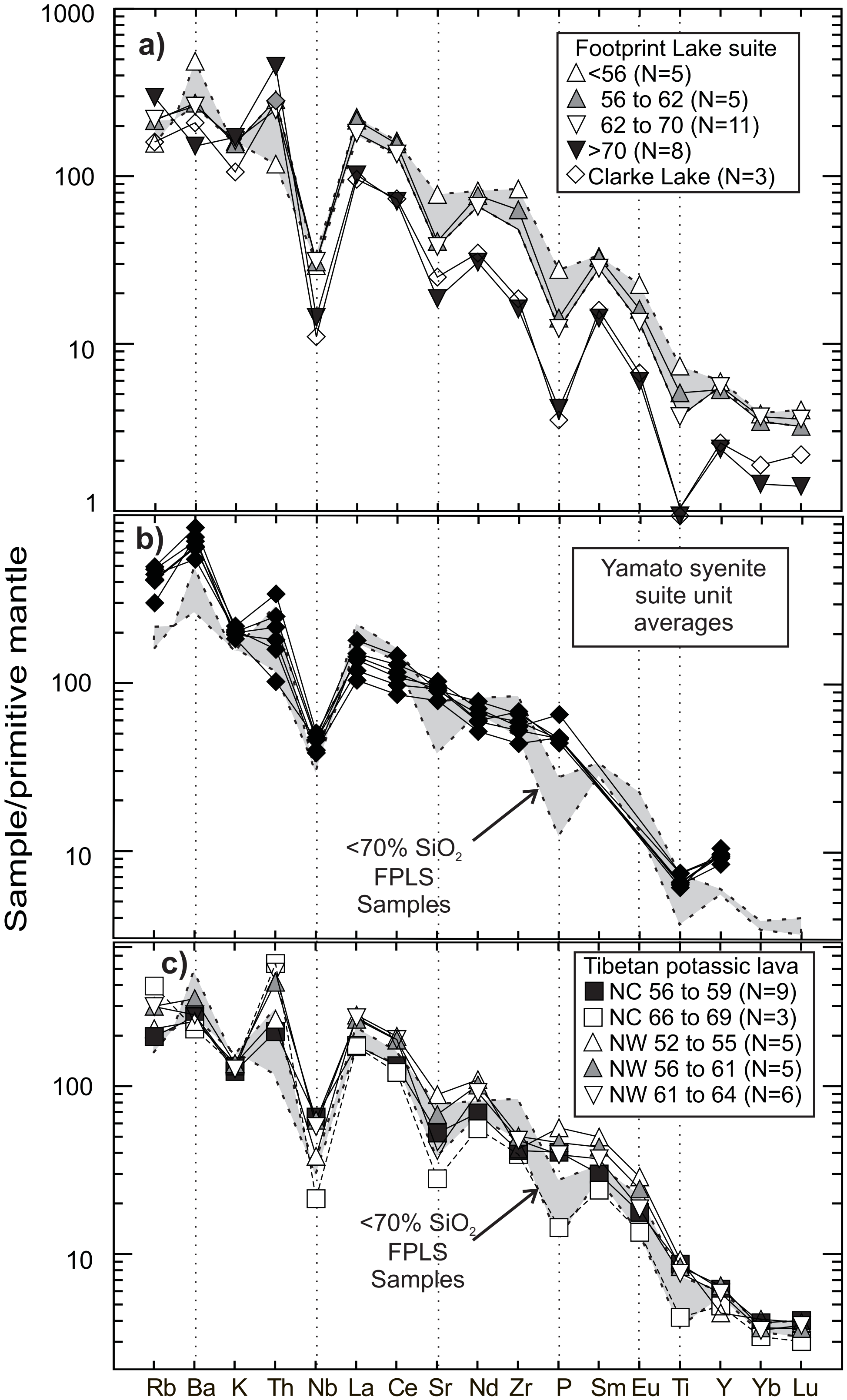


***Figure GS-6-6:*** *Primitive mantle–normalized extended-element plots for **a)** averages for each Footprint Lake plutonic suite (FLPS) silica-based group plus the Clarke Lake pluton, the shaded field outlining the three <70 wt.% silica group averages; **b)** averages for the Yamato syenite suite unit (data from Zhao et al., 1995), HREE data not available; **c)** silica-grouped averages for north-central (NC) and northwest (NW) Tibetan potassic lava (data from Williams et al., 2004). The field for low-silica FLPS samples is also shown in all diagrams. Primitive mantle–normalizing values from Sun and McDonough (1989).*

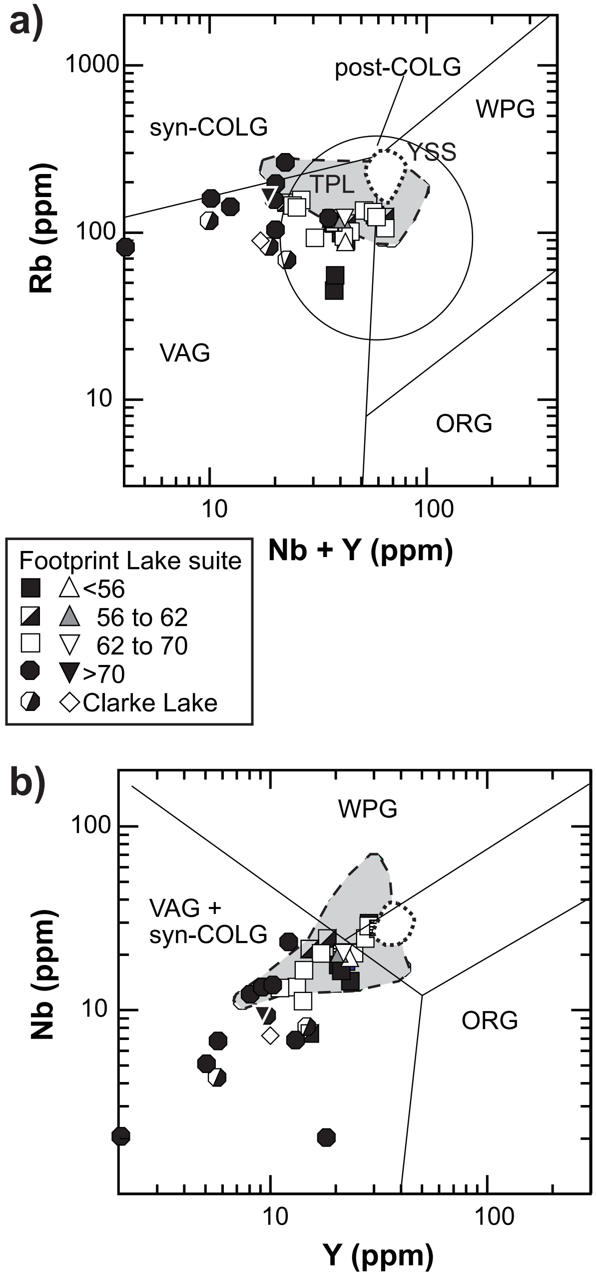


***Figure GS-6-7:*** *Ca. 1885 Ma plutons plotted on granitoid tectonomagmatic diagrams of Pearce et al. (1984):* ***a)*** *Rb versus Y+Nb with the addition of the post-COLG field from Pearce (1996); and* ***b)*** *Nb versus Y. Abbreviations: ORG, ocean-ridge granite; post-COLG, postcollisional granite; syn-COLG, syncollisional granite; VAG, volcanic-arc granite; WPG, within-plate granite. Plot symbols and shaded fields as in Figure GS-6-3 and its included legend.*

Model ages ($T_{CHUR}$; Goldstein et al., 1984) for FLPS plutons 1 and 3 (Figure GS-6-1) are 2.79 and 2.85 Ga, whereas the Clarke Lake pluton (pluton 6) in the Superior Boundary Zone is 2.46 Ga, suggesting crustal contamination was either greater or older within the northeast Kisseynew Domain. Neodymium isotopic data on the former two samples were included in Table GS-8-2 of Percival et al. (2006) but were mistakenly published in an incomplete format. The complete results are being republished here in Table GS-6-2.

## Discussion

The distinctive and unusual geochemical characteristics of the ca. 1885 K-feldspar–porphyritic Footprint Lake plutonic suite (FLPS) have been documented above. This suite has also been compared to two well-studied suites that could represent younger analogues: the Cambrian Yamato syenite suite (YSS; Zhao et al., 1995) and the Neogene Tibetan lava (Williams et al., 2004). Based on the close similarities demonstrated above, published petrogenetic and tectonic models for these two suites should provide important insights into the FLPS. Zhao et al. (1995) concluded that the Yamato syenitic magma was generated from a parental alkali basaltic magma by multistage fractionation and magma mixing (with crustal melts) processes. They proposed a tectonic model where this magmatism occurred within the hinterland of a Cambrian continental-collision zone, the parental magma being derived by partial melting of a subduction-modified lithospheric mantle source positioned above the deepest part of the subducting slab. For the postcollisional Neogene potassic lava in Tibet, Williams et al. (2004) suggested derivation from subcontinental lithospheric mantle (SCLM) sources, with southern magma representing 1–2% partial melts of a phlogopite+amphibole peridotite and northern lava being 3–4% partial melts of a phlogopite peridotite. Large-ion lithophile enrichment relative to somewhat less enriched HFSE of the magma is attributed to earlier subduction-related SCLM metasomatism and HREE-depletion in the magma is indicative of prior melt extraction, probably related to the initial stabilization of the SCLM. Williams et al. (2004) explained northern Tibetan magmatism and extension as products of episodic convective removal of the lower SCLM and southern magma as being produced by lithospheric erosion associated with slab break-off. A shared feature of the Zhao et al. (1995) and Williams et al. (2004) petrogenetic models is that the more mafic end members of these alkaline suites were derived from SCLM and that their LILE- and HFSE-enriched signatures, typically 4–10 times average continental crust, are mantle-derived features that are highly insensitive to modification by crustal assimilation. As trace-element enrichment includes Nd (60–200 ppm), the evolved or nonradiogenic Nd isotopic signatures exhibited by both these suites were also interpreted as being SCLM derived, not as a product of crustal contamination. Based on quantitative trace-element plus tracer-isotope (Nd-Sr-Pb) modelling, Williams et al. (2004) inferred that the evolved Nd isotopic signatures of Tibetan lava were imprinted on their SCLM sources through metasomatism by both melts and fluids derived from subducted sediments during earlier

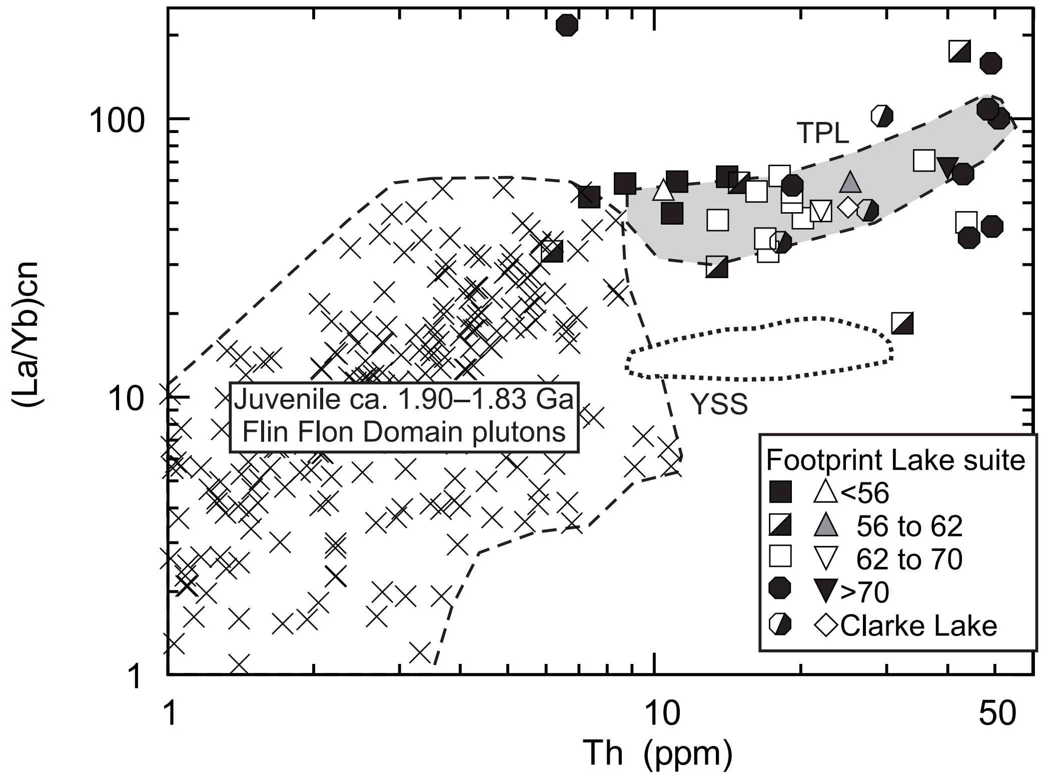


***Figure GS-6-8:*** *Ca. 1885 Ma plutons plotted on a chondrite-normalized (cn) La/Yb versus Th diagram. Also shown is the higher $(La/Yb)_{cn}$ and Th portion of the field for 300 juvenile ca. 1.90– 1.83 Ga Flin Flon Domain arc plutonic rocks (Figure GS-6-1; data from compilation of Whalen et al. (1998). Plot symbols and shaded fields as in Figure GS-6-3 and its included legend. For the Yamato syenite suite, as Yb data was lacking, $Y_{cn}$ was substituted. Chondrite normalizing values from Sun and McDonough (1989).*

**Table GS-6-2: Nd-Sm isotope analysis for the Footprint Lake plutonic suite and the Clarke Lake pluton.**

| Sample number | UTM Zone 14 Easting | Northing | U-Pb age (Ma) | Nd[1] ppm | Sm[1] ppm | $^{147}Sm/^{144}Nd$ [1] | $2\sigma$ [1] | $^{143}Nd/^{144}Nd$ [2] | $2\sigma$ [2] | $\varepsilon^{143}Nd$ [3] | $T_{CHUR}$ (Ma; Goldstein) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Footprint Lake plutonic suite:* | | | | | | | | | | | |
| 25-71-328 | 463212 | 6179568 | 1879 ±13[4] | 70.08 | 9.80 | 0.08453 | 0.00017 | 0.510723 | 0.000011 | -10.90 | 2851 |
| 29-71-412 | 511677 | 6183356 | 1882 ±10[4] | 70.08 | 9.78 | 0.08434 | 0.00018 | 0.510773 | 0.000011 | -9.88 | 2790 |
| 29-71-412 (dupl.) | 511677 | 6183356 | 1882 ±10[4] | 69.43 | 9.69 | 0.08435 | 0.00023 | 0.510770 | 0.000010 | -9.94 | 2793 |
| *Clarke Lake pluton:* | | | | | | | | | | | |
| WX04T-049 | 512854 | 6060194 | 1885 ±5[5] | 47.25 | 7.01 | 0.08964 | 0.00016 | 0.511141 | 0.000033 | -3.31 | 2456 |

[1] Sm and Nd concentrations and $^{147}Sm/^{144}Nd$ ratios are corrected for blank of 2 ±2 pg for both Sm and Nd. The uncertainty is propagated into the error of $^{147}Sm/^{144}Nd$ ratio

[2] Nd isotopic ratios are corrected for fractionation relative to the ratio of $^{146}Nd/^{144}Nd$=0.7219, using exponential law and real atomic masses. The $^{143}Nd/^{144}Nd$ isotopic ratios are adjusted to $^{143}Nd/^{144}Nd$ = 0.51186 in the La Jolla standard.

[3] $\varepsilon^{143}Nd$ at the time indicated in the column "U-Pb age (Ma)" relative to the accepted Chondritic Uniform Reservoir with $^{143}Nd/^{144}Nd$ = 0.512636 and $^{147}Sm/^{144}Nd$ = 0.1966.

[4] From Percival et al. (2007)

[5] From Percival et al. (2005)

subduction events. However, without knowing the age and composition of the subducted sediment, they could not constrain the timing of SCLM metasomatism.

An important implication of the above outlined models for FLPS petrogenesis is that its most mafic end members were probably derived from subduction-modified SCLM and that their Archean Nd-model ages are a mantle source characteristic rather than evidence for the presence of, and contamination by, an Archean continental crustal substrate. The FLPS mafic magma source could be either 1) SCLM that was metasomatized by melts derived from Archean sedimentary rocks during a Paleoproterozoic subduction event; or 2) Archean SCLM that was metasomatized during an Archean subduction event. It has been suggested above, based on crossover behaviour, that the FLPS displays on igneous suite classification plots (Figures GS-6-4 and -5) and that low-silica and high-silica components are unlikely to be related by fractionation, but rather may reflect mixing between at least two magma types. If the mafic end member is an alkaline SCLM-derived magma, the simplest felsic end member would be a eutectic minimum crustal melt. Mixing between it and a slightly saturated syenitic magma could have produced the FLPS quartz monzonite to monzo- and syenogranite compositions; however, the trace-element signatures of these mixtures would likely be dominated by the very LILE- and HFSE-enriched mafic end member. While the felsic component could dilute this overall mantle-derived trace-element signature, it is unlikely that it could significantly modify it. This is exactly the behaviour exhibited with increasing silica within the FLPS, where trace-element patterns of mafic through felsic average compositions are roughly parallel but overall trace-element abundances decrease (Figure GS-6-6a). The $T_{CHUR}$ age of 2.46 Ga obtained from the granodioritic Clarke Lake pluton, which is significantly younger than model ages of 2.79 and 2.85 Ga obtained from more mafic FLPS samples, suggests that the crustal source of the felsic end member is younger, maybe even juvenile, depending on how the magma mixing process is modelled. Other coeval granodiorite plutons along the western limit of the Superior Boundary Zone, moreover, have Nd-model ages as old as 2.94 Ga (Zwanzig et al., 2003).

An as-yet open question is how and why did SCLM melting occur to produce the FLPS? The timing of FLPS magmatism overlaps with granodioritic and mafic–ultramafic magmatism on the western Superior margin that included the Molson dike swarm and generated the Thompson Ni deposits, an event attributed by Percival et al. (2005) to an arc–back-arc setting or arc-plume interaction at this time. Molson mafic dikes exhibit komatiitic–tholeiitic compositions (Scoates and Macek, 1978), a magma type generally thought to represent asthenospheric mantle–derived melts. Widespread upwelling of such magma at this time could have provided the thermal flux to partially melt available fertile SCLM sources, producing the FLPS. The presence of the FLPS only in the northeastern Kisseynew Domain and coeval granodiorite and mafic–ultramafic intrusions in the Superior Boundary Zone suggests a different tectonic history for the respective Archean basement rocks and possibly their SCLM.

## Economic considerations

Documentation of the geochemical characteristics of the ca. 1885 Ma Footprint Lake plutonic suite provides a relatively easily identifiable marker unit for the distribution of Superior Province basement (±Ospwagan-like supracrustal rocks) within/beneath the Kisseynew Domain both farther west in Manitoba and into Saskatchewan. These basement culminations are prospective for Thompson-type Ni mineralization. A simple, inexpensive chemical analysis can positively identify other yet unidentified plutons belonging to the FLPS and provide an incentive for Ni exploration.

Worldwide, alkalic plutonic systems have become an attractive exploration target because they can be progenitors to economically significant gold-(copper) deposits, which include high-level epithermal deposits, like those within southwest Pacific arcs (e.g., Lihir and Porgera), and deep-level porphyry deposits, like those within the Mesozoic arcs of British Columbia (e.g., Mt. Polley and Iron Mask; Jensen and Barton, 2000). Thus, the alkalic character of the Footprint Lake plutonic suite makes it prospective for Au ±Cu mineralization.

A further ramification concerns diamond exploration. Recent work (Percival et al., 2006, 2007; Rayner et al., 2006; Zwanzig et al., 2006a, b) has evidenced that Archean crustal basement currently underlies the eastern 60 km of the Kisseynew Domain. This study, which indicates that at ca. 1885 Ma, subcontinental lithospheric mantle (SCLM) characterized by Archean Nd model ages underlay this area, increases the probability that Archean mantle lithosphere is still present, although the extent to which remelting during the ca. 1885 Ma event degraded the thermal structure of the lithosphere is unknown. If present, kimberlitic intrusions within this zone warrant exploration for their diamond potential.

## Acknowledgments

The authors thank N. Brandson for enthusiastic logistical support.

Geological Survey of Canada contribution 20080412.

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