GS2023-6

The Burntwood Lake syenite complex revisited: the site of voluminous carbonatite magmatism in the Kisseynew domain, west-central Manitoba (part of NTS 63N7)

by A.R. Chakhmouradian[1], C.G. Couëslan and T. Martins

In Brief:

- Improved exposure of the Burntwood Lake syenite complex suggest that it is a composite pluton that has been tilted and tightly folded
- Several carbonatite exposures were identified in the northern part of the complex
- Carbonatite is associated with at least three syenite complexes in the Trans-Hudson of Manitoba, which underlines the region's potential for rare-earth element exploration

Citation:

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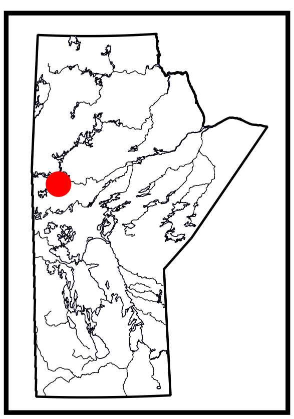

Summary

The Burntwood Lake syenite complex was revisited in 2023 to assess outcrop exposure after a recent forest fire. The complex is one of a series of alkaline igneous complexes in the Trans-Hudson orogen of Manitoba, two of which are known to host carbonatite dikes (the Eden and Brezden lakes complexes). The increased quality and extent of exposures at Burntwood Lake led to the discovery of numerous carbonatite dikes, both in situ and in locally derived boulders. The syenite body is interpreted as a composite pluton that was tilted toward the south and then folded around a southward-plunging isoclinal fold hinge. The current orientation places the more mafic floor of the composite body toward the north, overlain by the more-evolved upper portions of the complex to the south.

Carbonatite exposures were identified in the northern part of the complex over an area of approximately 0.3 km^2 and comprise diffuse, centimetre-scale veins and lenticular pods in the syenite, as well as discrete dikes and 'blows' up to 1 m wide. The carbonatite consists predominantly of calcite, clinopyroxene, apatite and xenocrysts of feldspar, along with accessory amphibole, biotite, titanite and allanite. Coarse-grained dolomite predating calcite was observed at one location. The carbonatite is typically inequigranular and ranges from granoblastic to foliated. Stable carbon and oxygen isotope analyses of carbonate minerals yield ^{13}C-depleted compositions consistent with a mantle source, possibly modified through subduction-related processes. Carbonatites from similar tectonic settings in California and China host several world-class deposits of rare-earth elements. The discovery of carbonatite associated with three syenite complexes in the Trans-Hudson orogen of Manitoba is an important step toward recognizing the Trans-Hudson alkaline-carbonatite igneous province and its potential value for rare-earth–element exploration.

Introduction

A scoping study of the Burntwood Lake syenite complex was undertaken during the summer of 2011 to investigate its potential for rare-earth–element (REE) mineralization (Martins et al., 2011). It was also recognized that the complex could host carbonatite, which had been previously reported from similar geological environments elsewhere (Mumin, 2002; Halama et al., 2005; Hou et al., 2009). During the 2011 field season, outcrops of igneous rock (predominantly, alkali-feldspar syenite) were found to be extensively moss- and lichen-covered and, although a sample of apatite-rich material with elevated concentrations of REEs (~4000 ppm Y + lanthanides) was collected, it was determined that further study of the complex was not feasible due to poor exposure. The discovery of carbonatite and lamprophyre in recently burnt areas at Brezden Lake (Hnatiuk et al., 2022) demonstrated the role of exposure in exploration and mapping, and signalled the importance of revisiting other known sites of alkaline magmatism in the Trans-Hudson orogen. A forest fire burned over the Burntwood Lake complex in the summer of 2022, which provided an impetus for conducting a new scoping study in June of 2023. The principal outcome of this recent work was the discovery of numerous carbonatite dikes, found both in situ and in displaced, locally derived material. The present report is a preliminary summary of these findings and follow-up analytical work conducted thus far.

Regional geology

The Burntwood Lake syenite complex is located in the central Kisseynew domain, approximately 70 km north-northwest of the town of Snow Lake. The Kisseynew domain forms part of the internal zone of the Trans-Hudson orogen in Manitoba, and is flanked by the Lynn Lake domain to the north, Flin Flon domain to the south, and Superior boundary zone to the east (Figure GS2023-6-1).

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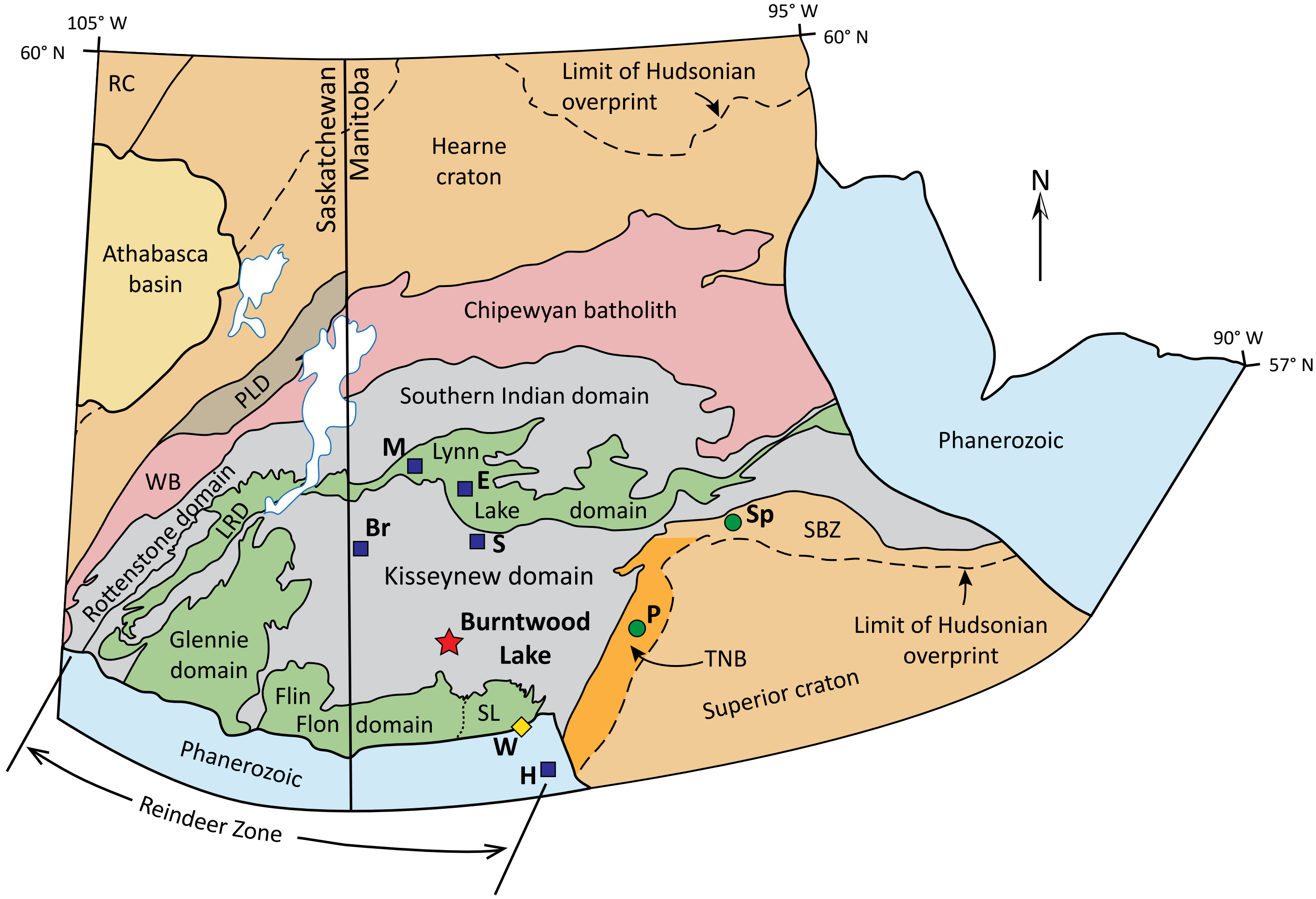

Figure GS2023-6-1: *A schematic map of major tectonic elements in the Manitoba–Saskatchewan segment of the Trans-Hudson orogen (modified from Lewry et al., 1990; Maxeiner et al., 2021; Manitoba Geological Survey, 2022). The location of the Burntwood Lake syenite complex is indicated with a red star. Blue squares indicate the locations of high-potassium to shoshonitic syenite complexes in the Trans-Hudson orogen. Green circles indicate the locations of Paleoproterozoic, late-orogenic carbonatite magmatism in the Superior boundary zone. The yellow diamond indicates the location of anorogenic carbonatite magmatism. Abbreviations: Br, Brezden Lake; E, Eden Lake; H, Huzyk Creek; LRD, La Ronge domain; M, McVeigh Lake; P, Paint Lake; PLD, Peter Lake domain; RC, Rae craton; S, Suwannee River; SBZ, Superior boundary zone; SL, Snow Lake subdomain; Sp, Split Lake; TNB, Thompson nickel belt; W, Wekusko Lake; WB, Wathaman batholith.*

The central Kisseynew domain is underlain by Burntwood group metagreywacke intruded by large plutons, sheets and lenses of felsic to ultramafic rocks (Zwanzig, 2008). The Burntwood group was deposited between 1860 and 1840 Ma (Machado et al., 1999; Murphy and Zwanzig, 2021) into what has been variously interpreted as a back-arc, inter-arc or fore-arc basin (Ansdell et al., 1995; Zwanzig, 1997; Zwanzig and Bailes, 2010). The detritus was largely derived from the adjacent, juvenile magmatic arcs, as indicated by prominent, overlapping detrital zircon age peaks of 1870–1850 Ma in probability plots (Zwanzig and Bailes, 2010; Murphy and Zwanzig, 2021).

Rocks of the central Kisseynew domain attained upper amphibolite– to granulite-facies metamorphic conditions. The migmatitic Burntwood group rocks contain zones of coarse, garnet- and cordierite-rich diatexite (Zwanzig, 2008). Gordon (1989) estimated peak metamorphic conditions of 750 ±50 °C and 5.5 ±1.0 kbar at ca. 1815 Ma for the central Kisseynew domain. However, estimated peak metamorphic conditions as high as 900 °C and 12 kbar at ca. 1800 Ma were reported by Growdon (2010). Large-scale, recumbent isoclinal folds predated peak metamorphism in this part of the domain, and were subsequently refolded during the regional metamorphism (Gordon, 1989; Zwanzig, 2008).

It is possible that the Burntwood intrusive suite was recognized as early as 1971 and interpreted as quartz monzonite–granite crosscut by aplite and pegmatite dikes and surrounded by amphibolitized metasedimentary rocks (unit 15 of McRitchie, 1971). However, the description provided in that report can also potentially refer to hornblende-biotite granite that is common in some parts of the intrusion. Syenitic rocks were decisively identified in McRitchie (1987, 1988), but were not revisited for more detailed work until 2011. Several other syenite complexes of shoshonitic affinity occur within the Trans-Hudson orogen of Manitoba (McRitchie, 1988; Chakhmouradian et al., 2008; Couëslan, 2023). The Burntwood Lake, Brezden Lake, Suwannee River and Huzyk Creek intrusions occur within the Kisseynew domain, whereas the Eden Lake and McVeigh Lake complexes occur within the Lynn Lake domain (Couëslan, 2005; Chakhmouradian et al., 2008; Martins et al., 2011, 2012; Hnatiuk et al., 2022; Martins and Couëslan, 2022; Couëslan, 2023). Granitoid rocks within these complexes typically range in composition from alkali-feldspar syenite (referred to as monzonite in some reports) to clinopyroxene melasyenite and leucocratic quartz syenite. Spatially associated lamprophyres have been reported at Brezden and McVeigh lakes, and carbonatite dikes crosscutting syenites have been reported at Brezden and Eden lakes (Mumin, 2002; Couëslan, 2005; Chakhmouradian et al., 2008; Hnatiuk et al., 2022). The latter intrusion hosts REE-rich apatite (up to 8 wt. % REE) and late, hydrothermal REE mineralization (Chakhmouradian et al., 2008; Mumin, 2010). The syenite complexes within the Trans-Hudson orogen have been the subject of exploration for Zr, REE, Th and U, with the majority of activity centred on Eden Lake (McRitchie, 1989; Mumin, 2010).

Results from 2023 scoping study: new data on the Burntwood Lake complex

Silicate rocks

The 2022 forest fire resulted in much better exposure in the Burntwood Lake area, with a significantly reduced cover of lichen and moss relative to 2011. The improved exposure enabled a better understanding of the structural relations among different rock types, particularly in recessed areas. In the text that follows, we provide a synthesis of the presently available field data combined with preliminary laboratory observations. The Burntwood Lake syenite complex is interpreted as a phacolithic syenite intrusion measuring approximately 1.4 by 2.4 km and hosted by Burntwood group diatexite and associated peraluminous granite (McRitchie, 1987). The intrusion is deformed, with two south-southeast-trending 'roots' partially wrapping around a shallow, north-plunging synformal fold hinge (Figure GS2023-6-2). A steep east-northeast-dipping, axial planar gneissosity is variably developed, but most pronounced along the flanks and within the hinge zone of the intrusion. Contacts between the syenite and the country rock are sharp, but locally metasomatized (McRitchie, 1987).

The syenite is a compositionally and texturally heterogeneous body that was broadly subdivided by Martins et al. (2011) into a pink-beige phase and a brick red phase. The readily apparent difference between the two phases is the colour of feldspar and relative abundance of albite and quartz, which are generally more common in the pink-beige variety. It is noteworthy, however, that some pink-beige syenite undoubtedly represents the brick red phase affected by bleaching at the contact with carbonatite (see 'Carbonate rocks', below). Clinopyroxene is the dominant mafic mineral in the syenite (Figure GS2023-6-3a), although amphibole is locally common and biotite was observed as an accessory phase (2–4 vol. %) in quartz syenite (Figure GS2023-6-3b, c). Where all three minerals are present, amphibole typically forms partial reaction rims on fractured and resorbed clinopyroxene, and is, in turn, replaced by biotite (Figure GS2023-6-3d).

In addition to discrete crystals distributed uniformly throughout the rock, clinopyroxene also occurs in mafic-rich zones within the syenite (melasyenite; Martins et al., 2011), including in relatively equant or irregularly shaped clots and discontinuous layers or lenses up to 15 cm in thickness (Figure GS2023-6-4a). These zones are dominated by dark green clinopyroxene and typically enriched in colourless, fine-grained apatite. Fine-grained rocks consisting of nearly massive apatite were also identified in narrow discontinuous zones up to 30 cm wide at two locations (Figure GS2023-6-4b). At one of these locations, the apatite-rich rock and host red syenite are crosscut by beige quartz syenite with abundant amphibole oikocrysts (Figure GS2023-6-3b). Outcrops containing abundant mafic- or apatite-rich rocks are typically recessed because of the susceptibility of clinopyroxene to fragmentation and erosion.

In many places across the northern part of the Burntwood Lake complex, mafic clots are so abundant as to give the host syenite a leopard-skin appearance. Orthogonal exposures of such areas suggest that clots are cross-sections of small lenticular pods defining a shear-induced lineation. Large fragments of mafic rock are commonly disaggregated and crosscut by pegmatite or syenite dikes, in which case the crosscutting felsic rock is typically enriched in clinopyroxene crystals (Figure GS2023-6-4a, c). Along the sublongitudinal shear zone in the northern part of the complex (Figure GS2023-6-2), mafic horizons are stretched into isolated or stacked lenticular bodies, whereas syenite is fragmented and locally boudinaged (Figure GS2023-6-4d). Assuming that clinopyroxene- and apatite-dominant lithologies represent early igneous products (cumulates), their folding, accompanied by a penetrative axial planar foliation, is in agreement with the overall structural interpretation of the syenite pluton by McRitchie (1987).

In the southern part of the Burntwood Lake pluton, pink-beige syenite is more common than farther north, and no evidence of bleaching was observed. In addition, the syenite is crosscut by numerous pegmatite dikes and, closer to the contact, contains rafts and xenoliths of biotite granite and randomly oriented metasedimentary rocks presumably derived from the Burntwood group. It is thus possible that 'unit 15' of McRitchie (1971) refers to the earlier granite phase predating the syenites. Fine-grained quartz syenite near the eastern contact with the Burntwood group contains fluorite and fluorite-quartz veinlets up to a few centimetres in width. The present authors concur with the earlier interpretation of Martins et al. (2011) that the fluorite-bearing syenite represents an evolved intrusive phase, which was probably emplaced near the roof of the Burntwood Lake pluton.

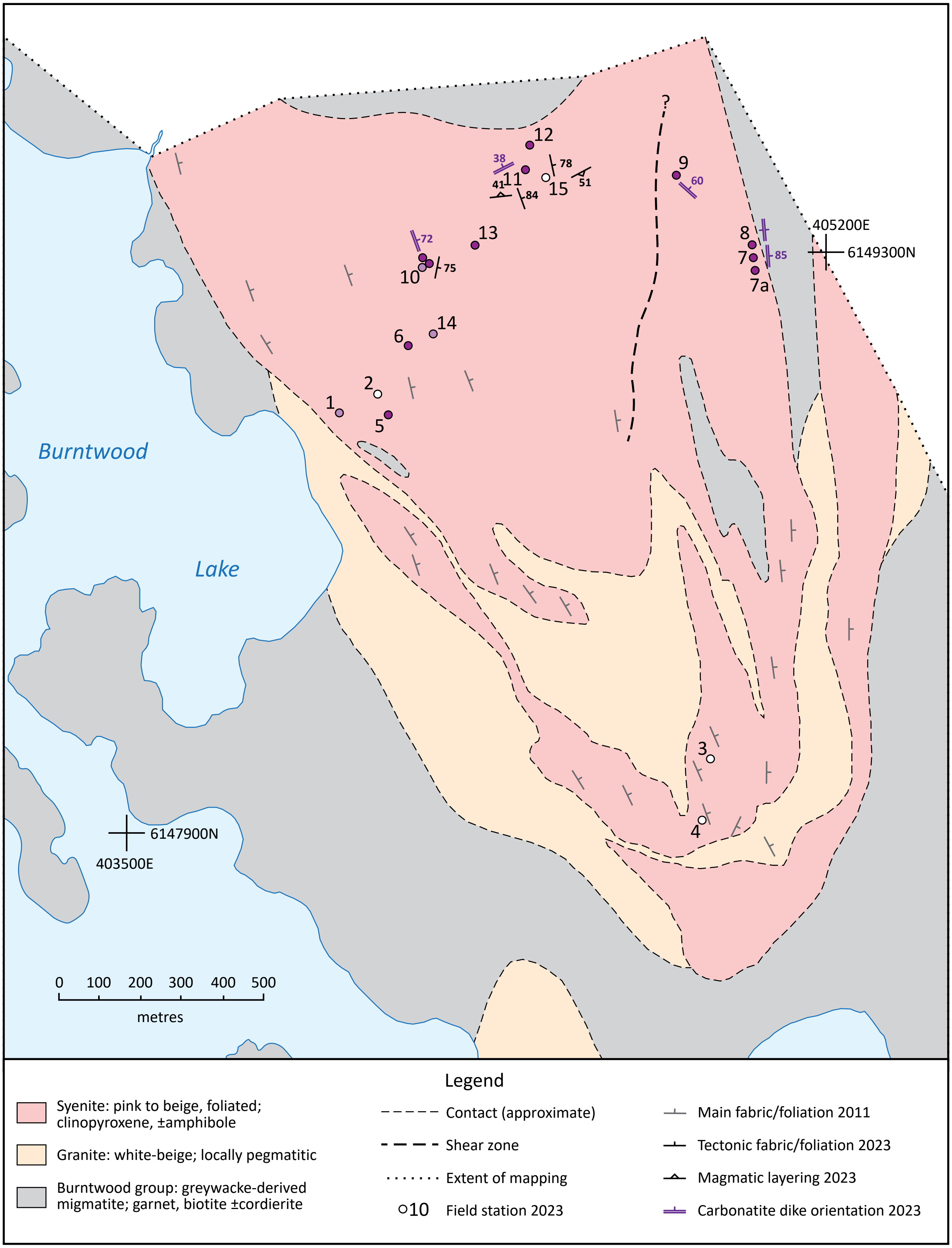

Figure GS2023-6-2: *Simplified geological map of the Burntwood Lake syenite, modified after McRitchie (1987) and Martins et al. (2011). Light purple stations indicate the occurrence of carbonatite in locally derived boulders, dark purple stations indicate carbonatite in outcrop. Stations without colour indicate no observed carbonatite. All co-ordinates are in UTM Zone 14, NAD83.*

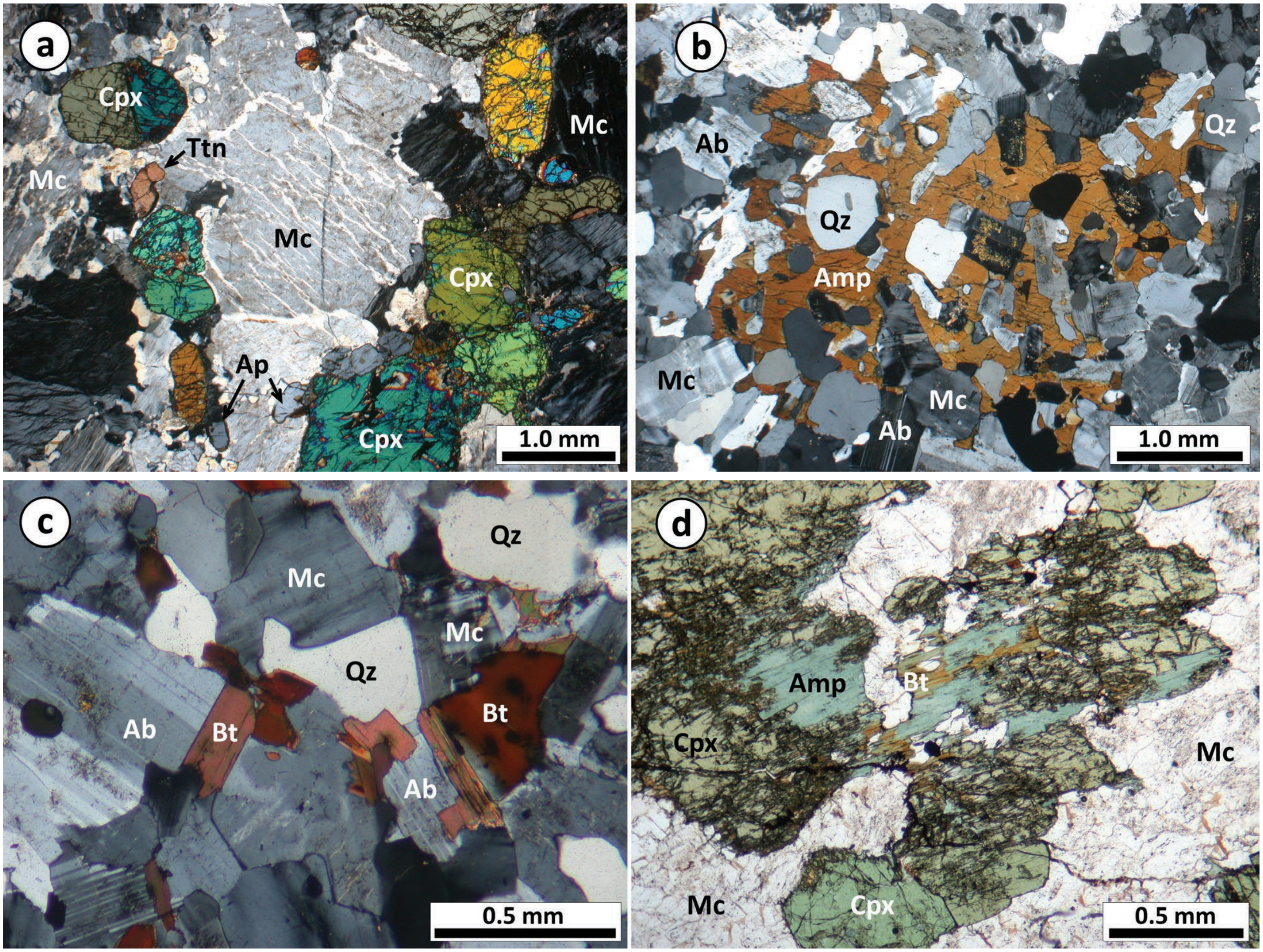

Figure GS2023-6-3: *Selected textural characteristics of the Burntwood Lake syenites:* ***a)*** *euhedral clinopyroxene, accessory apatite and titanite associated with microcline-perthite in mesocratic alkali-feldspar syenite, cross-polarized light (XPL);* ***b)*** *amphibole oikocryst containing inclusions of microcline, albite and quartz in leucocratic quartz syenite, XPL;* ***c)*** *accessory interstitial biotite in quartz syenite, XPL;* ***d)*** *resorption and replacement of clinopyroxene by amphibole and biotite in mesocratic alkali-feldspar syenite, plane-polarized light (PPL). Abbreviations: Ab, albite; Amp, amphibole; Ap, apatite; Bt, biotite; Cpx, clinopyroxene; Mc, microcline-perthite; Qz, quartz; Ttn, titanite.*

Carbonate rocks

Many occurrences of carbonate-rich rock and carbonate-bearing syenite were discovered in outcrop and as float in the northern part of the syenite complex, over a total area of 0.3 km^2 (Figure GS2023-6-2). Discrete trends of these rocks could, in some cases, be traced in outcrop over a distance of 70–80 m. Carbonate-bearing rocks were not observed south of stations 5 and 7 (Figure GS2023-6-2), although less time was spent exploring that part of the Burntwood Lake pluton. The newly discovered rocks range from vuggy, weathered red syenite with diffuse pods and veins of carbonate a few centimetres in width, to discrete dike-like bodies and 'blows' (cf. Wilson and Head, 2007) of predominantly carbonate rock up to 1 m across (Figure GS2023-6-5). In most cases, their emplacement was clearly structurally controlled, and confined to either contacts between different silicate units or steeply dipping linear features generally aligned with the fabric in the host syenite (Figure GS2023-6-5a, b). Wide 'blows', comprising predominantly coarse-grained calcite and albitized microcline, were observed at six locations and appear to be restricted to coarse-grained syenite (Figure GS2023-6-5c). Contacts between the veins and (mela)syenites are diffuse, owing to the presence of interstitial carbonate in the hostrocks and of numerous felsic xenoliths and xenocrysts of feldspar, clinopyroxene and quartz in the veins. The exocontact zone of fine-grained carbonate veins is typically bleached, presumably due to conversion of microcline-perthite to albite (see below).

Several varieties of carbonate-rich rock were identified based on their modal composition and textural characteristics. Their colour ranges from light pink to white and grey; most varieties are extremely inequigranular, but some of the veins (e.g., at stations 1 and 7) comprise more-or-less uniform saccharoidal material with abundant syenite xenoliths. Mineralogically, all of

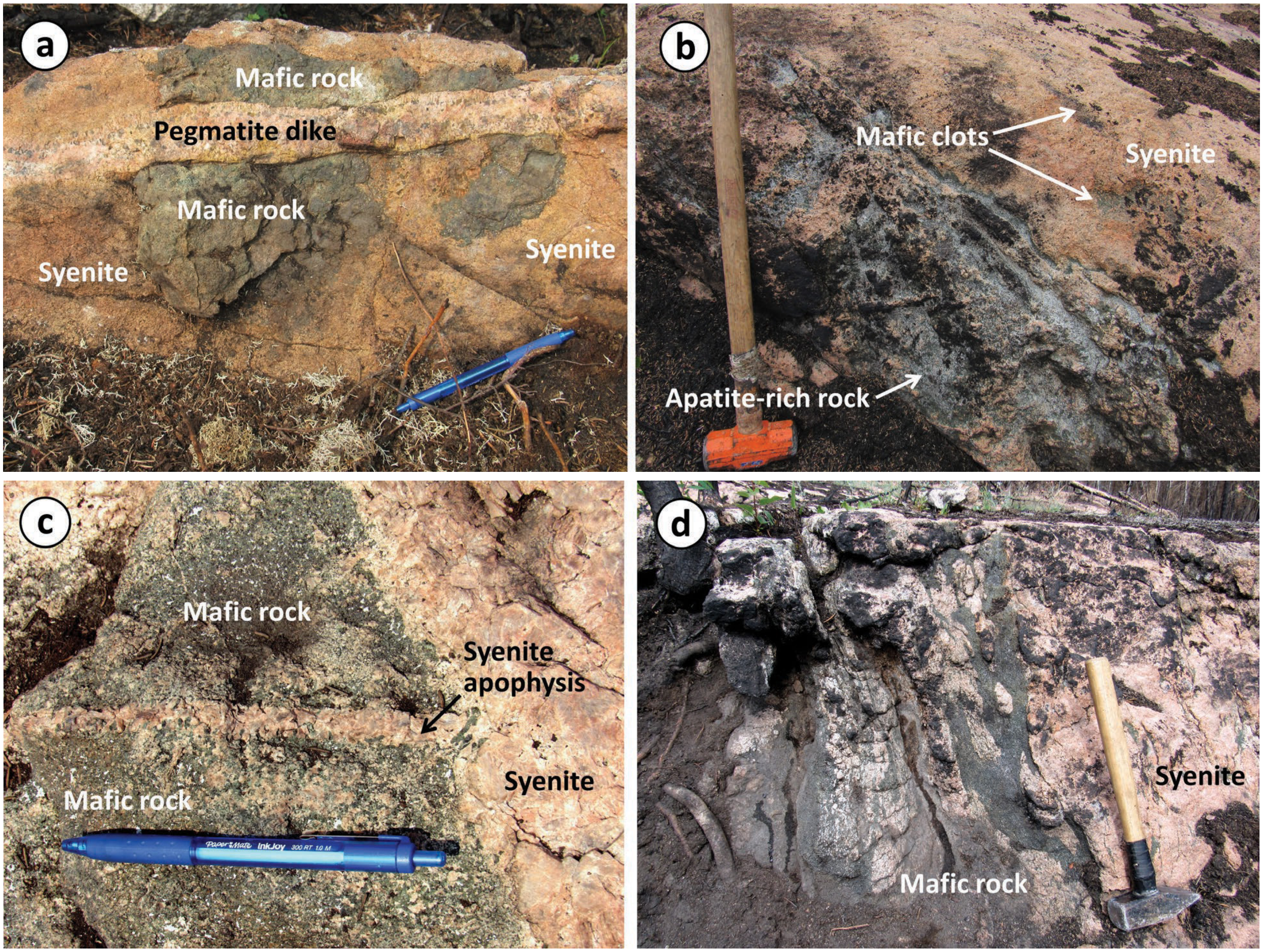

Figure GS2023-6-4: *Field relations of mafic silicate rocks in the Burntwood Lake complex:* ***a)*** *partially disaggregated xenolith of mafic rock (melasyenite) in coarse-grained leucocratic alkali-feldspar syenite, both rocks are crosscut by pegmatite;* ***b)*** *apatite-rich rock and mafic clots hosted by leucocratic syenite;* ***c)*** *mafic xenolith in alkali-feldspar syenite, note syenite apophysis crosscutting the mafic rock, and comb-like structure of clinopyroxene crystals within the apophysis;* ***d)*** *sheared mafic rock comprising stacked and attenuated lenses.*

the samples examined using polarizing microscopy comprise calcite, apatite and xenocrysts of microcline-perthite. Dolomite was observed only at station 10 as coarse porphyroclasts in a finer-grained mesostasis. Calcium clinopyroxene (diopside to aegirine-augite) occurs in the majority of veins and is represented both by sub- to euhedral crystals and by fragmented, resorbed xenocrysts derived from the host (mela)syenite (Figure GS2023-6-6a, b). In several localities, clinopyroxene xenocrysts are partially overgrown by acicular bluish-green amphibole, whereas their unaltered sub- to euhedral counterparts show no evidence of resorption or replacement and typically have a darker colour arising from a greater Na+Fe (aegirine) content. Microcline-perthite xenocrysts are very common in all veins and exhibit partial mesh-like and peripheral replacement by clear albite (Figure GS2023-6-6c). This type of texture, accompanied by clinopyroxene alteration to amphibole is well known in sodic fenites (e.g., Figure GS2023-6-6d).

Typical accessory minerals in the veins include subhedral, zoned crystals of allanite and titanite measuring up to 2.5 and 1.0 mm, respectively (Figure GS2023-6-6a, b). Allanite is most common in endocontact zones, where it forms partial overgrowths on silicate xenocrysts and is associated with fibrous amphibole and albite. Titanite is comparatively less abundant and occurs as discrete grains in clinopyroxene-rich rocks. Accessory biotite is scarce, but makes up 3–4 vol. % of the grey carbonate rock at station 13. The mineral occurs as deformed platy crystals showing strong normal pleochroism in shades of brown, which implies an elevated Fe^{2+} (annite) content.

Microscopically, the examined samples range from nearly equigranular granoblastic rocks with a mosaic texture (Figure GS2023-6-6e) to strongly foliated varieties with coarse calcite or, less commonly, dolomite porphyroclasts enveloped in dynamically recrystallized fine-grained material (Figure GS2023-6-6f). Such ‘core-and-mantle’ structures are invariably accompa-

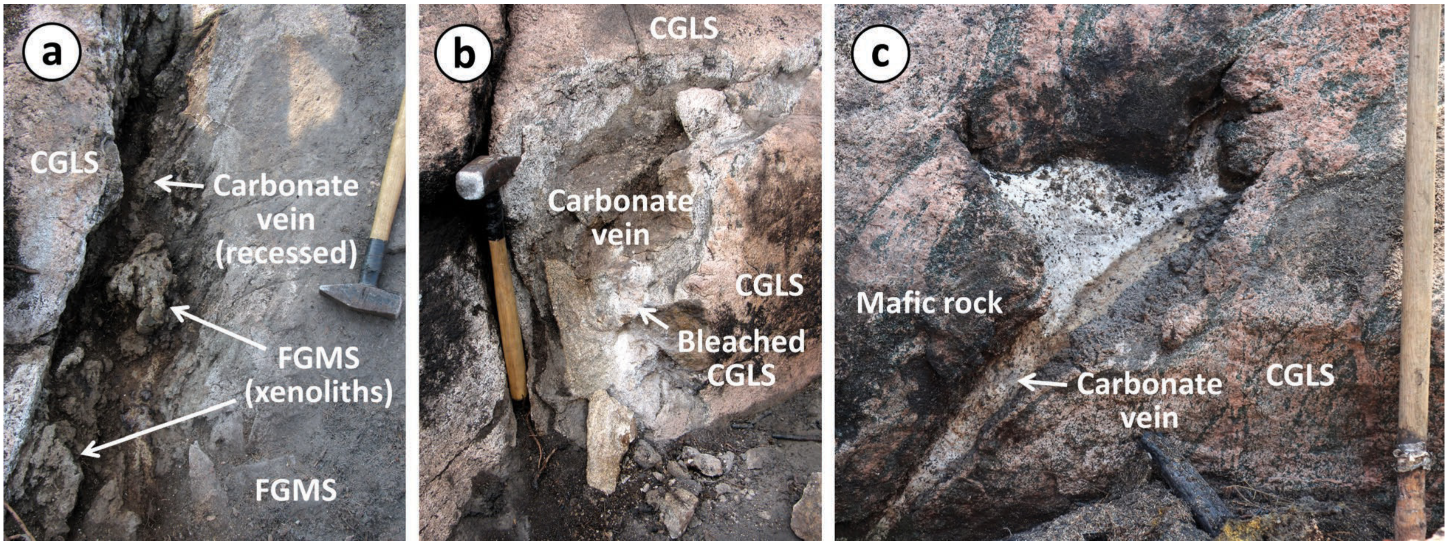

Figure GS2023-6-5: *Field relations of carbonate rocks in the Burntwood Lake complex:* ***a)*** *recessively weathered carbonate vein emplaced at the contact between fine-grained mesocratic syenite and younger coarse-grained leucocratic syenite;* ***b)*** *carbonate vein crosscutting coarse-grained leucocratic syenite, note bleaching of the syenite along the vein contacts;* ***c)*** *carbonate vein with a 'blow' 45 centimetres wide emplaced into coarse-grained leucocratic syenite with numerous mafic clots, sledgehammer handle at right for scale. Abbreviations: CGLS, coarse-grained leucocratic syenite; FGMS, fine-grained mesocratic syenite.*

nied by other evidence of deformation, including undulatory and curtain-like extinction, interrupted and bent polysynthetic twin lamellae in porphyroclasts, foliation-aligned biotite 'fish' and lenticular syenite xenoliths with 'wings' of recrystallized fine-grained calcite. This textural evidence is interpreted to indicate postemplacement ductile flow of the vein material in response to shear stress (Chakhmouradian et al., 2016).

Whole-rock powder samples were prepared from five petrographically distinct carbonate lithologies, including a coarse-grained pink variety with abundant feldspar xenocrysts, fine-grained equigranular white rocks with and without dolomite, and grey varieties with and without biotite. The samples were analyzed at Bureau Veritas Commodities Canada Ltd. (Vancouver, British Columbia) for major and trace elements using X-ray fluorescence and inductively coupled plasma–mass spectrometry, respectively. As can be expected from the available petrographic data (see above in this section), the chemical composition of all five samples is dominated by CaO and CO_2 (35.5–48.1 and 22.5–34.1 wt. %, respectively), whereas SiO_2 and Al_2O_3 concentrations fluctuate significantly (6.1–24.4 and 1.3–5.0 wt. %, respectively) owing to variations in the proportion of silicate xenocrysts in different carbonate veins. The P_2O_5 content is consistently high and reaches 6.1 wt. % (equivalent to 15 wt. % apatite) in the coarse-grained pink rock. Of note are elevated levels of Sr, Ba and REE in all samples; their maximum recorded concentrations are 12 200, 3150 and 4580 ppm, respectively.

Fifteen monomineralic concentrates of calcite and one sample of dolomite (from station 10) were hand-picked under a binocular microscope for stable-isotope analysis. Both fine- and coarse-grained varieties of calcite were extracted from five conspicuously inequigranular rocks. In addition, four mixed samples were prepared for competent fine-grained rocks, where feldspar xenocrysts could not be mechanically separated from calcite. All samples were powdered in an agate mortar, dried at 60 °C for four days and then analyzed by isotope-ratio mass spectrometry. The mass spectrometer was calibrated using calcite standards NBS-18 and IAEA-603 at the beginning, middle and end of each run. To monitor analytical quality, internal standards CHI (calcite) and SIL-MD (dolomite) were analyzed concurrently with 'unknowns', yielding $\delta^{13}C_{VPDB}$ (i.e., carbon isotope ratios with respect to the Vienna Pee Dee Belemnite standard) and $\delta^{18}O_{VSMOW}$ (i.e., oxygen isotope ratios with respect to the Vienna Standard Mean Ocean Water) well within 0.1 per mil (‰) of the accepted values. The results, expressed using the conventional delta notation, are summarized in Figure GS2023-6-7.

All C-O isotope data plot below the 'igneous carbonate box' of Taylor et al. (1967), which has been previously observed in calcite carbonatite from Eden Lake (Chakhmouradian et al., 2008) and Brezden Lake (A.R. Chakhmouradian, unpublished data, 2023). The foliated dolomite-calcite vein from station 10 is characterized by somewhat lower $\delta^{18}O_{VSMOW}$ ratios (7.1–7.6‰) in comparison with calcitic rocks (9.0–10.9‰), but their $\delta^{13}C_{VPDB}$ values overlap (–10.2 to –11.2‰ and –8.3 to –12.8‰, respectively).

Discussion

Preliminary petrogenetic interpretation

Clinopyroxene-rich silicate lithologies observed throughout the northern part of the Burntwood Lake complex during this scoping study can now be confidently interpreted as detached and transported fragments of unexposed cumulate units, ranging from clinopyroxenite to melasyenite in modal composition.

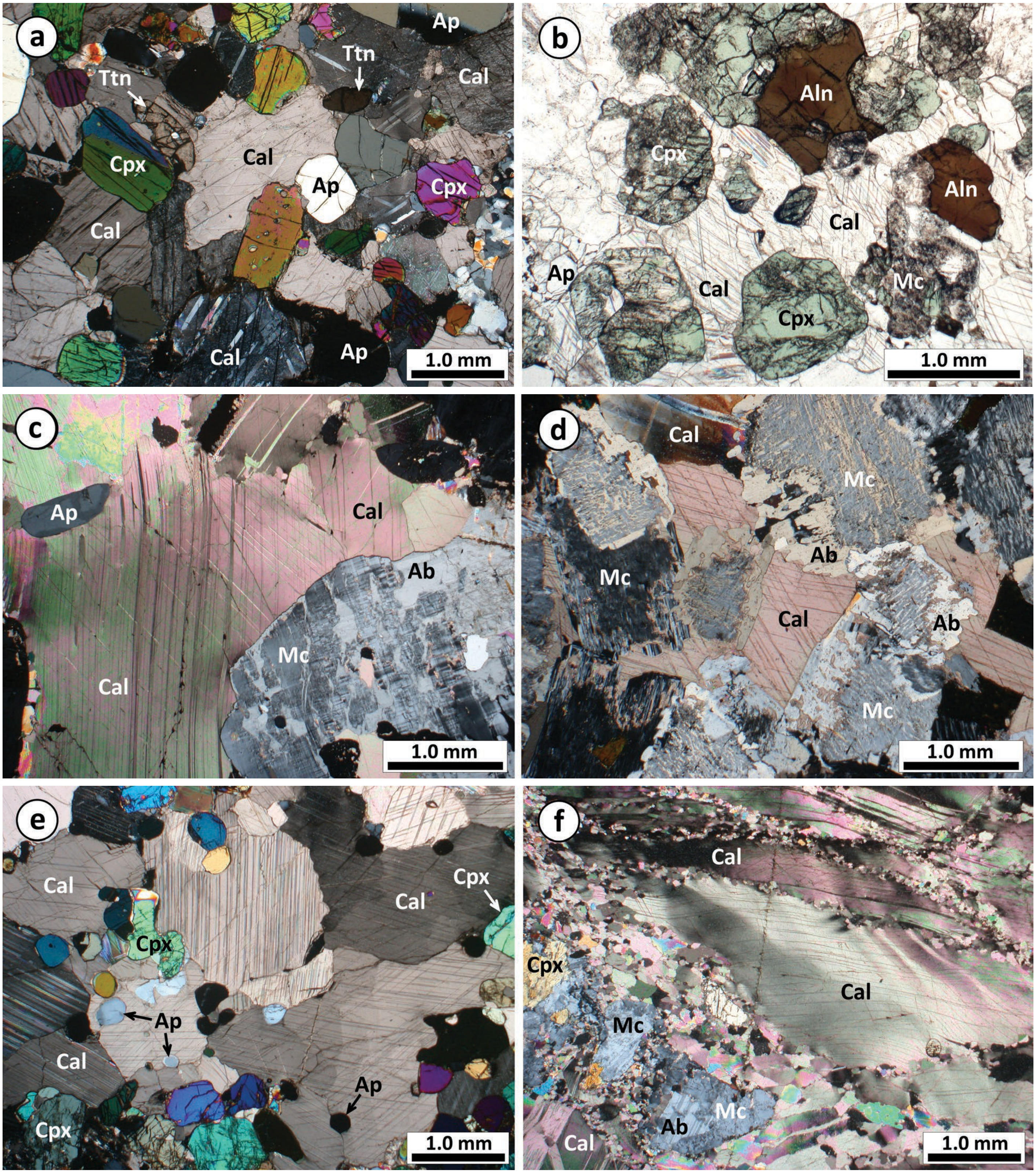

Figure GS2023-6-6: *Photomicrographs of carbonate rocks from the Burntwood Lake complex (a–c, e, f) and Fen complex, Norway (d):* ***a)*** *typical massive carbonate rock composed of calcite, clinopyroxene, apatite and accessory titanite, cross-polarized light (XPL);* ***b)*** *resorbed and altered xenocrysts of clinopyroxene and microcline in a massive carbonate rock; note allanite overgrowths on some xenocrysts, plane-polarized light (PPL);* ***c)*** *microcline xenocryst partially replaced by albite, note undulatory extinction and bent twin lamellae in calcite, XPL;* ***d)*** *typical sodic fenite developed at the contact with calcite carbonatite, from the Fen complex in Norway, XPL (S. Dahlgren and A.R. Chakhmouradian, work in progress) – compare with (c);* ***e)*** *granoblastic texture of nearly equigranular fine-grained carbonate rock, XPL;* ***f)*** *strongly foliated carbonate rock with syenite xenoliths comprising microcline, albite and clinopyroxene (XPL), note 'core-and-mantle' structures and deformation microtextures in calcite porphyroclasts. Abbreviations: Ab, albite; Aln, allanite; Ap, apatite; Cal, calcite; Cpx, clinopyroxene; Mc, microcline; Ttn, titanite.*

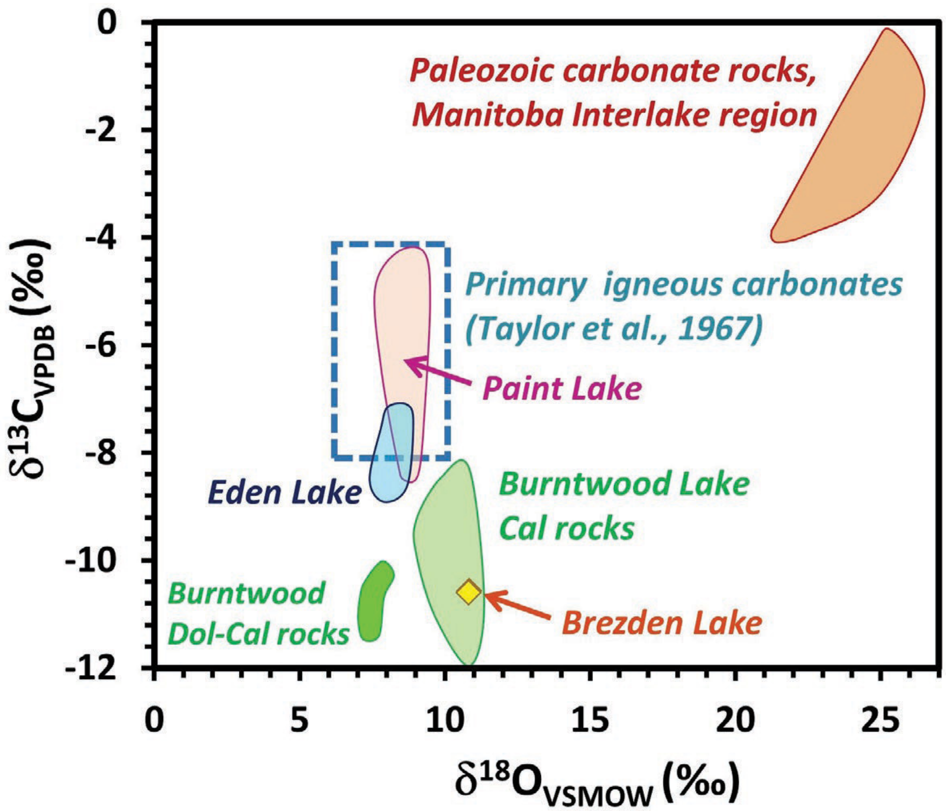

Figure GS2023-6-7: *Variations in carbon (C) and oxygen (O) stable-isotope composition in carbonatites from the Trans-Hudson orogen. The typical compositional range of Paleozoic sedimentary carbonate from the Manitoba Interlake Region and for primary igneous carbonate are plotted for comparison. Abbreviations: Cal, calcitic; Dol-Cal, dolomitic-calcitic. The label for the y-axis is $\delta^{13}C$ Vienna Pee Dee Belemnite ($\delta^{13}C_{VPDB}$), and the label for the x-axis is $\delta^{18}O$ Vienna Standard Mean Ocean Water ($\delta^{18}O_{VSMOW}$); both are expressed in per mil (‰). Source data: Brezden Lake, Paint Lake, Paleozoic sedimentary carbonate, A.R. Chakhmouradian (unpublished data, 2010, 2023); Eden Lake, Chakhmouradian et al. (2008); igneous carbonate, Taylor et al. (1967).*

Their distribution within the more voluminous alkali-feldspar syenite was clearly affected by postemplacement deformation, particularly along the wide shear zone shown in Figures GS2023-6-2 and -4d. The lesser abundance of mafic rocks in the southern portion of the complex, as well as much greater abundance of amphibole- and biotite-bearing quartz syenites, pegmatite dikes and metasedimentary rafts, imply that it represents the upper part of a composite pluton. The complex was tilted toward the south, and folded around a south-plunging isoclinal fold hinge. As a result, the floor of this composite pluton is dipping in an overall southward direction and, hence, more evolved rocks emplaced near the roof are exposed here over a larger area relative to the deeper, more mafic northern part of the complex. This is in contrast to the structural interpretation of a shallow, north-plunging synform by McRitchie (1987). The structural relations among the examined silicate rocks, and their petrographic characteristics, suggest the following emplacement sequence: clinopyroxenite (±apatite cumulate) ⇒ melasyenite ⇒ red alkali-feldspar syenite ⇒ amphibole-bearing quartz syenite (±accessory biotite) ⇒ fluorite-bearing quartz syenite and pegmatite.

The newly discovered carbonate-bearing rocks can be confidently identified as carbonatites based on the currently available evidence. With one exception (station 10), most of these rocks correspond to calcite carbonatite variably contaminated with wallrock silicate material and affected by shearing. The rock at station 10 is also rich in xenoliths and strongly deformed, but comprises similar proportions of dolomite and calcite. The available microtextural evidence (Figure GS2023-6-6c, d) is consistent with metasomatic reworking of syenite xenoliths by carbonatite-derived alkali-rich fluids. Similar metasomatic processes, collectively described as fenitization (Elliott et al., 2018), have been previously documented at Eden and Brezden lakes, which are also in the Trans-Hudson orogen (Chakhmouradian et al., 2008; Hnatiuk et al., 2022). Metasomatic reworking of carbonate rocks by silicate magmas, on the contrary, has not been observed at Burntwood Lake or the other two localities, and, hence, the possibility that the newly discovered carbonate rocks represent rafts of crustal calc-silicate material can be ruled out.

The stable-isotopic signature of the examined samples does not appear to have been modified by wallrock contamination or reaction with metamorphic fluids and is similar to those of calcite carbonatites at Eden and Brezden lakes (Figures GS2023-6-1, -7). The observed depletion in ^{13}C, typical of these rocks, may be related to their derivation from subducted crustal materials or to carbon isotope fractionation in the mantle (Chakhmouradian et al., 2008). The mineralogy, as well as structural relationships with the host syenite, of the Burntwood Lake carbonatites are also similar to their counterparts at Brezden and Eden lakes. At all three localities, large carbonatite bodies (~1 m across) consist predominantly of calcite, clinopyroxene and apatite, and are found in coarse-grained syenite, which is affected by sodic fenitization (Mumin, 2002; Chakhmouradian et al., 2008; Hnatiuk et al., 2022). At all three localities, apatite, titanite and allanite are the principal REE-bearing phases, and the latter is paragenetically linked to wallrock silicate contamination. Allanite is therefore interpreted as the product of reaction between Si-Al–rich, largely feldspathic xenoliths and REE-bearing carbonatitic magma.

The whole-rock trace-element compositions of selected Burntwood Lake syenites reported by Martins et al. (2011) show enrichment in light REE (La–Eu), Ba and other large-ion-lithophile elements, coupled with relative depletion in high-field-strength elements (Ti, Zr, Hf, Nb and Ta). These characteristics are also shared by alkaline igneous rocks at Eden Lake (Couëslan, 2005; Chakhmouradian et al., 2008), Brezden Lake (Martins et al., 2012), Mountain Pass in California (Castor, 2008), Weishan and the Mianning–Dechang metallogenic belt of China (Hou et al., 2009; Zeng et al., 2022). At all these localities, carbonatites are predominantly calcitic in composition and occur in intimate spatial association with silica-saturated syenites. In some cases (e.g., Mountain Pass; Castor, 2008), the petrographic spectrum of associated silicate rocks is wide and ranges from very primitive compositions (e.g., olivine shonkinite) to miaskitic amphibole-quartz syenite. In other cases (Weishan and Mianning–Dechang: Hou et al., 2009; Zeng et al., 2022), the principal silicate constituent is evolved peralkaline quartz syenite. In terms of its diverse petrography, the Burntwood Lake pluton is similar to the Mountain Pass complex, which had a prolonged and complex evolutionary history spanning 60 Ma (Poletti et al., 2016).

The syenite-carbonatite associations in the Trans-Hudson orogen, California and China also share many geochemical characteristics (e.g., enrichment in trace lithophile elements and depletion in high-field-strength elements) and were emplaced in zones of continental plate collision. A large body of trace-element and isotopic evidence has been presented to demonstrate links between this type of magmatism, ocean closure, crust recycling, mantle refertilization and plate-collision processes (e.g., Chakhmouradian et al., 2008; Wang et al., 2019; Çimen et al., 2022; Hou et al., 2023). Well-studied examples elsewhere in the world range in age from ca. 2.0 Ga to 12 Ma (Liu et al., 2015; Djeddi et al., 2021). It is feasible that the composite syenite (±carbonatite±lamprophyre) intrusions in the Paleoproterozoic Trans-Hudson orogen (Figure GS2023-6-1) are broadly coeval and manifest the final stages of plate collision at ca. 1.8 Ga (Corrigan et al., 2009; Salnikova et al., 2019). If so, these complexes represent one of the oldest known and most extensive (~8700 km^2) expressions of collision-related alkaline-carbonatitic magmatism in the world, for which the authors propose the designation 'Trans-Hudson alkaline-carbonatite igneous province'. From a practical standpoint, it is noteworthy here that the Mountain Pass and Chinese carbonatites host economic rare-earth–element mineralization, mostly in the form of bastnäsite ($REECO_3F$).

Recommendations for future work

The wide variety of carbonatite discovered during this scoping study, and its spatial extent, suggest good potential for additional occurrences of these rocks both within the syenite pluton and in its exocontact zone. The collection of additional structural data will be key to reconciling the current geometry of the complex. A thorough characterization of the carbonate rocks, and their relationship to the syenite, would best be accomplished by one or more graduate-level projects. The abundance of these rocks suggests that future investigations should not be restricted to the syenite complex, but should include shoreline mapping in the northwestern Burntwood Lake area. Careful mapping and radiometric dating of discrete intrusive units will be essential to deciphering their temporal relations and ultimately the evolutionary history of the entire complex. The excellent exposures offered by the relatively fresh burn make future field studies time-sensitive, and ideally they should be conducted within the next few years.

Economic considerations

Carbonatites are the most economically important source of light lanthanides (La–Eu) and host the largest known REE deposits, including Bayan Obo in northern China and the aforementioned Mianning–Dechang, Weishan and Mountain Pass mines. China is currently the largest producer of REEs worldwide, supplying some 70% of the global demand (210 000 Mt REE oxide in 2022; Cordier, 2023). The Mountain Pass mine is the second-largest producer, with an annual output of 43 000 Mt REE oxide in the form of bastnäsite and monazite concentrate. However, all of China's current production is exported overseas, whereas the United States currently imports some $200 million worth of REE compounds and metals (Cordier, 2023). Increased demand for REEs, spurred on by the proliferation of low-carbon-footprint transportation, energy and communication technologies, has created a need for new economically viable REE deposits to sustain a reliable REE supply chain outside of the current producers, which are largely dependent on China. This has prompted the Government of Canada to include REEs on the list of critical minerals (Natural Resources Canada, 2022) and support exploration and research efforts focused on REEs under the Targeted Geoscience Initiative and other programs. In addition to revisiting well-known localities of alkaline and carbonatitic magmatism, these programs should be aimed at identifying new targets for critical-metal exploration and new potential metallotects. The discovery of REE-bearing carbonatites at Brezden Lake (Hnatiuk et al., 2022) and Burntwood Lake (this report) is an important step toward recognizing the Trans-Hudson alkaline-carbonatite igneous province and its potential value for rare-metal exploration.

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