Nepheline Syenite from Lyle Lake, Peter Lake Domain (NTS 64E-06)[1]

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The Peter Lake Domain nepheline and nepheline-biotite-sodalite syenite occurrence located at Lyle Lake, Saskatchewan (NTS 64E-06; UTM 613000E 6366000N; Figure 1) is the only known example of silica-undersaturated felsic magmatism in Saskatchewan. This report presents new geological, petrological, and mineralogical data about these rocks.

The region has been geologically mapped by the Saskatchewan Geological Survey at 1:50 000 scale (Lewry, 1976; Lewry *et al.*, 1980); the Lyle Lake area being mapped as metadiorite and monzonite with syenite. MacDougall (1987) mapped the region immediately south of Lyle Lake at 1:20 000 scale. The nepheline syenite occurrence was discovered in 1982 during the course of off-property mineral exploration by the Saskatchewan Mining and Development Corporation (now Cameco; Wittrup, 1983; Waterman *et al.*, 1984). MacDougall (1987) briefly noted the presence of undersaturated rocks in the Lyle Lake area.

The nepheline syenite is found near the Lyle Lake pluton, a Hudsonian post-deformational granitic intrusion (MacDougall, 1987) situated within the Archean Peter Lake Domain close to the boundary with the Hudsonian Wathaman Batholith. The Peter Lake Domain consists of massive to weakly foliated felsic plutonic rocks and a diorite-gabbroic plutonic suite which together have a complex Archean intrusion history (Lewry *et al.*, 1980; Ray and Wanless, 1980; Annesley *et al.*, 1992).

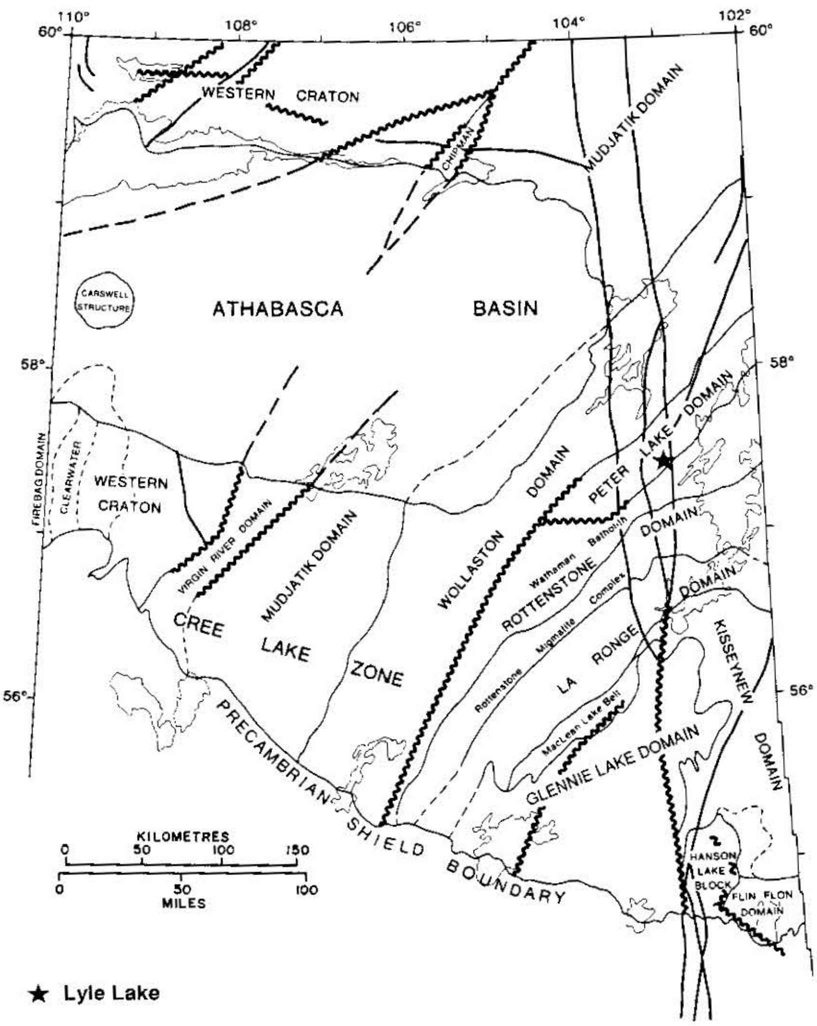

Figure 1 - Geologic map indicating location of Lyle Lake.

1. General Geology

In the vicinity of the study area, three main lithological assemblages are recognized: 1) felsic plutonic rocks of the Peter Lake Domain (Peter Lake Complex), 2) the Wathaman Batholith, and 3) the Lyle Lake Pluton. The felsic plutonic rocks of the Peter Lake Complex range from leucogranite to quartz syenite to quartz monzonite in composition. The rocks are coarse grained and can be foliated or unfoliated. Igneous textures and mineralogy are commonly preserved (Collerson and Lewry,

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1985). Radiometric data indicate Archean ages for the Peter Lake Complex (Ray and Wanless, 1980; Bickford and Van Schmus, 1985; Bickford *et al.*, 1986; Van Schmus *et al.*, 1987) with thermotectonic events at around 2100 Ma and 1850 Ma (e.g. Ray and Wanless, 1980; Van Schmus *et al.*, 1987; Annesley *et al.*, 1992; Bickford *et al.*, 1992).

The Wathaman Batholith, a large synkinematic K-feldspar megacrystic quartz monzonitic intrusion (Van Schmus *et al.*, 1987; Meyer *et al.*, 1992), forms the southeastern boundary to the Peter Lake Domain. It is also interpreted as intruding the Archean gneisses of the Peter Lake Domain (e.g. the Middle Lake and Ettle Creek granites). Meyer *et al.* (1992) suggest that most of the batholith formed between 1865 and 1850 Ma. Lyle Lake is located approximately 5 km north of the boundary of the Peter Lake Domain with the Wathaman batholith.

The Lyle Lake pluton is a post-deformational concentric annular intrusion (MacDougall, 1987) composed of a discontinuous outer envelope of coarse-grained granite, an inner ring of more alkaline material that is quartz syenitic to granitic in composition, and a core of fine-grained granite. Marginal apophyses and dykes of aplitic syenite to quartz syenite that crosscut the coarse-grained granite and quartz syenite are also present at the margins of the pluton. The pluton has not yet been radiometrically dated.

The coarse-grained granite of the Lyle Lake pluton is gneissic to unfoliated containing dominant potassium feldspar with plagioclase and subordinate quartz. Coarse-grained biotite is present as are trace to minor amounts of amphibole, chlorite, and pyrite (MacDougall, 1987). The quartz syenitic to granitic phase of the pluton is fine to medium grained, unfoliated, and is strongly potassium feldspar dominant. Subordinate quartz and plagioclase are present as are minor quantities of biotite and fluorite. Trace amounts of pyrite and pyrrhotite were noted by MacDougall (1987). The fine-grained granitic core of the pluton is unfoliated and is also strongly potassium feldspar dominant with subordinate quartz and plagioclase and minor quantities of biotite and amphibole. The apophyses and dykes of aplitic syenite to quartz syenite are very fine grained, equigranular, pink rock consisting primarily of potassium feldspar with minor plagioclase.

The undersaturated syenites are exposed approximately 900 m northwest of the main outcrop area of the Lyle Lake pluton, along the north shore of Lyle Lake and toward a small lake (locally called 'Fluorite Lake') 400 m northeast of Lyle Lake. No contacts with other rock types have been exposed and their relationship to the Lyle Lake pluton is uncertain. Approximately 700 m west of Fluorite Lake, these rocks are apparently bounded by a syenite to quartz syenite body whose relationships to the undersaturated rocks and to the Lyle Lake pluton are also uncertain (Waterman *et al.*, 1984). From traverse information, the nepheline syenites cover at least 3 km^2. The undersaturated rocks can be subdivided into two units: coarse-grained to pegmatitic nepheline syenite both with and without coarse-grained fluorite (referred to herein as nepheline syenite), and medium-grained nepheline-biotite-sodalite syenite (referred to herein as nepheline-sodalite syenite). Both units are leucocratic, contain extremely rare amphibole, and lack pyroxene. No contacts between these units have been observed.

U-Pb radiometric dating of the undeformed Lyle Lake nepheline syenites is complicated by the presence of significant quantities of common lead in the zircons. Two samples of turbid, blastic zircon from these rocks (PL-91-05, and -07) were undateable due to the excess common lead present (T.E. Krogh, pers. comm., 1992). A zircon age of 1830 ±20 Ma has been obtained, however, from clear, cracked, and partly turbid zircons from the nepheline syenite (L.A. Clark, pers. comm., 1992).

2. The Lyle Lake Nepheline Syenites

The nepheline syenite is white to greyish and is generally coarse grained, but locally contains narrow (10 to 15 cm) bands of pegmatitic material of similar mineralogy that are gradational into non-pegmatitic nepheline syenite. It is composed of albite, potassium feldspar, and nepheline in varying proportions with up to 60 percent nepheline (Table 1). Fluorite, biotite, scapolite, zircon, allanite/epidote, and magnetite are ubiquitously found in minor to trace quantities. Coarse-grained zircon is typical of this unit, appearing as highly dispersed brown subhedral to euhedral blastic metamict grains. Such grains are surrounded by a magnetite and biotite-free zone that shows a distinctive radial fracture pattern. Overall texture of this unit is porphyritic/xenomorphic granular to hypidiomorphic granular due to the coarse, euhedral to subhedral fan-shaped habit of the albite phenocrysts (clevelandite) and the large, dispersed zircon crystals. Biotite, magnetite, and titanite are typically found intimately associated in scattered knotted aggregates. Feathery natrolite is found as a late-stage mineral in rare veins.

The nepheline-sodalite syenite is a leucocratic medium-grained hypidiomorphic granular rock. It is composed of albite with subequal amounts of potassium feldspar, nepheline, and biotite (Table 1). Sodalite and andradite garnet are ubiquitous minor components in this unit. Magnetite is conspicuous by its infrequent presence and fluorite, titanite, apatite, and zircon are found only as fine- to medium-grained accessory phases. Biotite occurs as disseminated flakes and with andradite in knotted aggregates with associated fluorite, zircon, titanite, apatite, and rare fine-grained magnetite.

Overall, the undersaturated rocks are unaltered. Feldspars are not sericitized and nepheline does not show evidence of alteration to cancrinite, but trace amounts of hematite can be found with magnetite in a small number of samples. Allanite/epidote has been altered, to varying degrees, to chlorite.

a) Mineralogy

The dominant mineral in the undersaturated syenites is albite (Table 1). In the nepheline syenite it occurs

Table 1 - Modal compositions of selected samples of nepheline and nepheline-sodalite syenite, Lyle Lake. Symbols: tr, trace amounts; -, not observed.

Sample[1]	4a	4b	4c	6	7b	9	11	15
Rock Type[2]	1	1	1	1	1	1	2	2
Albite (vol.%)	60	35	55	40	30	40	35	35
K-feldspar	5	2	7	35	45	40	20	20
Nepheline	25	60	30	20	15	10	15	10
Biotite	2	-	tr	tr	1	tr	15	20
Plagioclase	-	-	-	3	3	2	-	-
Fluorite	2	1	1	tr	tr	5	tr	1
Andradite[3]	-	-	-	-	-	-	8	8
Sodalite	-	-	-	-	-	-	5	5
Scapolite	5	tr	5	tr	2	tr	-	-
Magnetite	1	1	1	1	1	1	tr	tr
Allanite/Epidote	tr	tr	tr	tr	tr	tr	tr	tr
Zircon	tr	tr	1	-	tr	-	tr	tr
Titanite	-	-	-	-	-	-	1	1
Apatite	-	-	-	-	-	-	tr	tr
Hematite[4]	tr	tr	-	-	-	-	-	-

Notes:
1. Full sample number is prefixed with PL-91-
2. Rock type code: 1, nepheline syenite; 2, nepheline-sodalite syenite
3. Ti-rich andradite melanite
4. Probably secondary

predominantly in the clevelandite habit. Phenocrysts can exceed 30 mm in length, are subhedral to euhedral, and form fan-shaped porphyritic aggregates of tabular to trapezoidal crystals (Figure 2a). They display closely spaced albite twinning and cross-hatched twinning, as well as patches without twinning. Albite in the nepheline-sodalite syenite is only rarely found in the clevelandite habit. The laths are up to 8 mm in length, display closely spaced albite twinning, and have a wavy, irregular perthitic exsolution texture. Albite compositions are similar for the nepheline syenite and the nepheline-sodalite syenite, averaging $Ab_{99.1}An_{0.3}Or_{0.6}$. The albite in the nepheline-sodalite syenite tends to have a slightly higher An content than that of the nepheline syenite (0.46% versus 0.11%); Or contents are the same.

Potassium feldspar in the nepheline syenite occurs as groundmass and is fine grained, anhedral to subhedral, and untwinned. It displays a granoblastic polygonal texture (Figure 2b) and a crude morphological grain alignment. Compositions average Or_{95} with negligible An content. The potassium feldspar in the nepheline-sodalite syenite is similar with the exception that the granoblastic polygonal texture is only rarely found.

Minor quantities of fine-grained discrete grains of subhedral to euhedral albite-twinned plagioclase are also found disseminated in the groundmass of the nepheline syenite. These grains are likely albite as they cannot be distinguished from the albite laths found in the nepheline-sodalite syenite.

Nepheline occurs as coarse to much finer subhedral to anhedral, predominantly interstitial grains which contain numerous inclusions of mica, apatite, and opaque minerals. The nepheline weathers recessively, giving a typically pock-marked appearance to the weathered syenite. In some samples of nepheline syenite, nepheline can make up 60 percent of the sample, although it generally makes up about 10 to 30 percent of both the nepheline syenite and the nepheline-sodalite syenite. The average bulk composition of the nepheline in both the nepheline syenite and the nepheline-sodalite syenite is $Ne_{73}Ks_{24}Qtz_3$, which is typical for plutonic nepheline (Edgar, 1984) and falls near the projection of Barth's (1963) 'natural nepheline composition plane' in the system Ne-Ks-Qtz. Non-essential elements such as calcium, iron, and barium are only found in low to very low concentrations. However, barium tends to be slightly enriched in the nepheline-sodalite syenite compared to the nepheline syenite (0.05% versus 0.01%). Other than possibly barium, there is no significant compositional variation between samples or rock type.

Sodalite is found as a minor constituent only in the nepheline-sodalite syenite as fine-grained anhedral disseminations throughout the unit. It is chemically quite pure showing little compositional variation, with trace quantities only of barium and calcium.

Biotite is the only mafic mineral found in these rocks apart from extremely rare amphibole in the nepheline-sodalite syenite. It occurs as fine-grained, anhedral to subhedral flakes disseminated throughout both syenite units, but is associated with magnetite in the nepheline syenite, and in clots intimately associated with andradite garnet, fluorite, apatite, titanite, zircon, and rare magnetite in the nepheline-sodalite syenite. In these mafic clots, biotite is poikilitically encased by garnet in places and in these cases is strongly corroded and embayed. Where the biotite is located adjacent to magnetite in the nepheline syenite, iron diffusion has resulted in the presence of magnetite along the cleavage planes in the biotite. Two different varieties of biotite are recognizable. In the nepheline syenite, it shows light yellowish brown to intense dark brown/black pleochroism whereas in the nepheline-sodalite syenite, it shows pale yellowish-green to dark green pleochroism. The difference is ascribed to the higher Ti content of the brown variety (e.g. Deer *et*

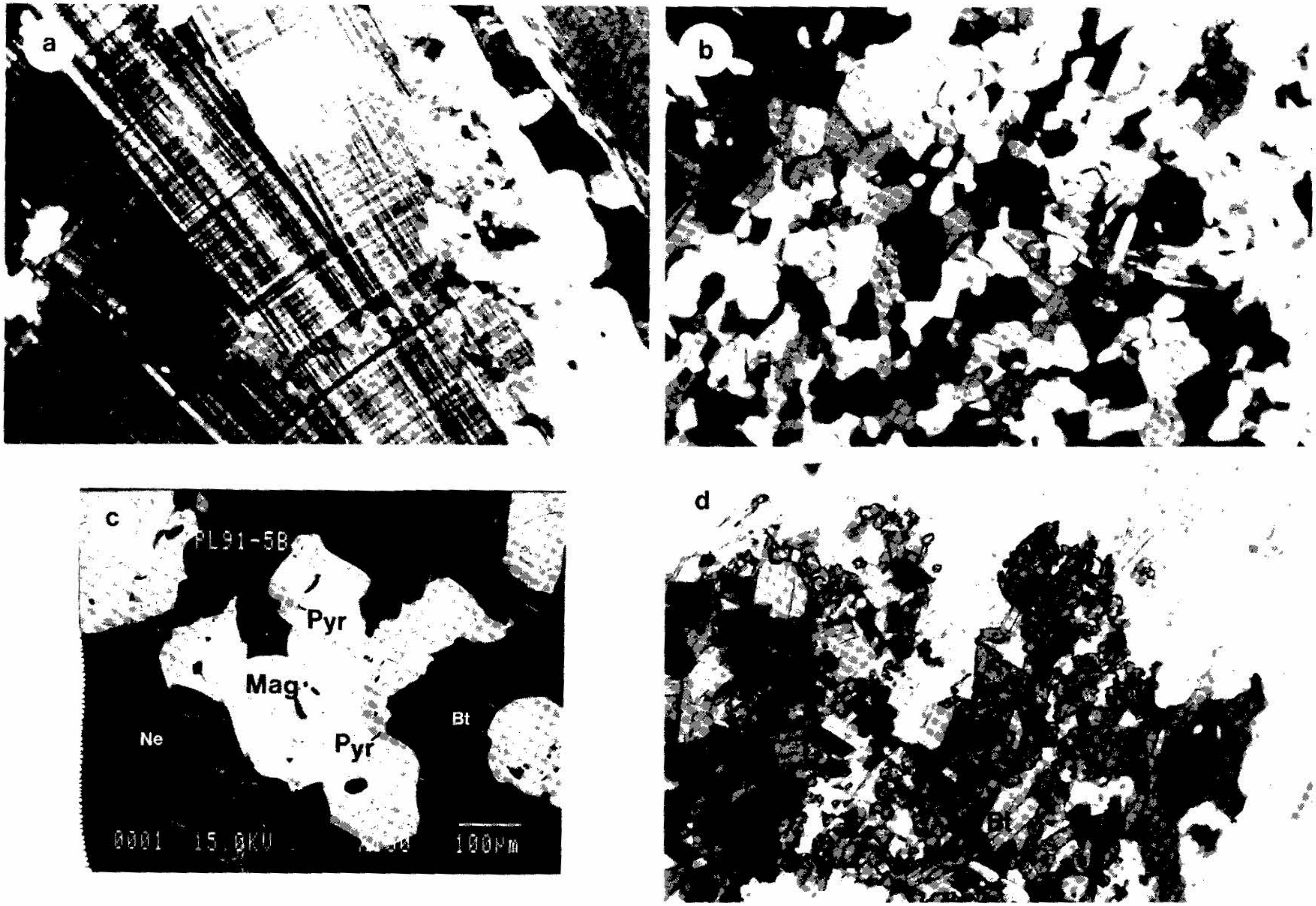

Figure 2 - (a) clevelandite albite in nepheline syenite, (b) potassium feldspar showing granoblastic polygonal texture in nepheline syenite, (c) backscatter electron image of magnetite (Mag) with composite inclusions of pyrophanite solid solution (Pyr) in nepheline syenite; Bt=biotite, Ne=nepheline, (d) garnet-biotite-titanite aggregates in nepheline-sodalite syenite; Grt=garnet, Sph=titanite. All photomicrographs are at 40x magnification with a horizontal field of view of 4.5 mm; backscatter electron image is at 150x magnification.

al., 1978; see below). Biotite is found in much greater quantities in the nepheline-sodalite syenite.

The biotites range in composition from titaniferous, manganiferous biotite in the nepheline syenite to slightly titaniferous Mg-rich biotite in the nepheline-sodalite syenite (nomenclature after Rock, 1982). Biotite in the nepheline syenite is distinctly aluminum-, manganese- and titanium-rich relative to that from the nepheline-sodalite syenite, whereas biotite from the latter unit has a higher phlogopite content (Mg value of 0.55 versus 0.42) and is somewhat more fluorine-rich. Biotites from the two syenite units differ in Al and Mg content, however, both are aluminous intermediate members of the annite-phlogopite series. These biotites are not of unusual composition with respect to the wide compositional range recorded for biotite associated with nepheline syenite (e.g. Rock, 1978, 1982; Mitchell and Platt, 1982; Wolff, 1987; Bhaumik *et al.*, 1990; Stähle *et al.*, 1990; Wallace *et al.*, 1990).

Magnetite is abundant as fine- to coarse-grained anhedral to subhedral interstitial grains disseminated singly, commonly associated with biotite, through the nepheline syenite, but is found only as rare, fine-grained dispersed grains in the nepheline-sodalite syenite. When found in the latter rock type, a corona of andradite garnet around the magnetite is found. Intergrowths of ilmenite-pyrophanite solid solution (referred to herein as pyrss) are common in magnetite from the nepheline syenite but are absent in magnetite from the nepheline-sodalite syenite.

Magnetites from both types of syenite are homogeneous in composition and lack significant accessory element contents; magnetite from the nepheline syenite contains a slightly higher titanium content. The magnetites are Mn-bearing, with magnetite from the nepheline syenite being significantly richer in MnO than that from the nepheline-sodalite syenite (0.30 to 1.28% versus $<0.25\%$). The relatively high Mn content of the magnetite is characteristic of felsic undersaturated complexes (Neumann, 1974; Rock, 1978; Mitchell and Platt, 1982; Wallace *et al.*, 1990; Benoit and Sclar, 1991; Frost and Lindsley, 1991). The presence of pyrss intergrowths and the low proportion of ulvöspinel component in the magnetite indicate that oxidation-exsolution (Buddington and Lindsley, 1964) has likely occurred. The strong partitioning of Mn into the rhombohedral oxide phase (pyrss), under conditions of subsolidus oxidation-exsolution (Haggerty, 1976), is reflected by the presence of the pyrophanite-rich ilmenite intergrowths in the magnetite (cubic phase).

Pyrss in magnetite from the nepheline syenite (Figure 2c) is typically found as both internal and external composite inclusions (nomenclature from Haggerty, 1976, 1991). Pyrss as very fine discrete grains is rarely observed and is intimately associated with clots of magnetite. The pyrss is highly enriched in MnO, as seen in ilmenite-pyrophanite from other alkaline rocks (e.g. Mitchell and Platt, 1982; Wolff, 1987; Mandarino and Anderson, 1988; Valentino *et al.*, 1990; Wallace *et al.*, 1990; Benoit and Sclar, 1991; Frost and Lindsley, 1991), with MnO contents consistently greater than 35 wt.%.

This MnO content is equivalent to greater than 78 percent of the pyrophanite end-member, giving an average composition of $[(MnTiO_3)_{87}(FeTiO_3)_{13}]$. Accessory elements are found only in trace quantities.

Garnet occurs only in the nepheline-sodalite syenite (Table 1) as yellowish-brown, fine-grained, anhedral to rarely subhedral, generally isotropic grains associated almost exclusively with the knotted aggregates of biotite (Figure 2d). It is in part poikilitic, enclosing biotite and titanite. Such biotite commonly exhibits strong corrosion and embayment. Other accessory fine-grained minerals, such as titanite, apatite, zircon, and fluorite occur predominantly with these aggregates of garnet and biotite. When present, fine- to medium-grained magnetite is entirely enveloped by garnet.

Garnet compositions are calcium- and iron-rich, containing nearly 80 percent andradite molecule and greater than 18 percent grossular molecule. As these garnets contain greater than one percent TiO_2 (averaging 3.5 percent schorlomite molecule), they can be properly termed melanite garnet. They also contain minor concentrations of Mn, V, and F.

Zircon is found in minor to trace quantities in both syenite varieties (Table 1). It has two modes of occurrence: a) fine-grained, yellow-brown, altered, spherical crystals associated with or located within biotite, and b) large (medium- to coarse-grained), dark brownish to black, turbid, inclusion-rich, dominantly metamict and isotropic, blastic grains up to 20 mm in size that are typically surrounded by a biotite- and magnetite-free zone characterized by a metamictization-induced radial fracture pattern. The latter mode of occurrence is typical of the nepheline syenite but is only rarely seen in the nepheline-sodalite syenite. Coarse-grained zircons are commonly fractured, with potassium feldspar filling the fractures, and are rich in inclusions of uranothorite. At least two generations of zircon growth are indicated by the presence of narrow, homogeneous, inclusion-free, non-metamict rims on the turbid, substantially metamict cores of these zircons.

Chemically, the zircons can be subdivided into three groups: 1) fine-grained zircons from the nepheline syenite, 2) coarse-grained, blastic zircons from the nepheline syenite, and 3) fine-grained zircons from the nepheline-sodalite syenite (Table 1). The two groups of fine-grained zircons exhibit significant differences in Hf, Fe, Ca, Th, U, and Tb contents. A zircon of this type from the nepheline syenite shows a normal Zr/Hf ratio of 37 and low Fe, Tb, Ca, Th, and U contents. Zircons from the nepheline-sodalite syenite reveal extremely high Zr/Hf ratios (>175) due to low Hf contents, moderate quantities of Fe and Ca, and variably low to high quantities of U, Th, and Tb.

The large, blastic zircons are generally metamict, with high uranium and very high thorium contents (up to 0.95% U, 1.9% Th). They have high calculated water contents (exceeding 5 wt.%), exhibit normal Zr/Hf ratios (60 to 90), and are enriched in strontium and rare earth elements (REE), including yttrium. The metamict portions of these zircons are appreciably enriched in water, Th, U, REE, Ca, Fe, and Al relative to non-metamict portions. Relative to the fine-grained zircons, the metamict portions of the blastic zircons are calcic, REE-, U- and Th-rich; however, the non-metamict portions are chemically similar to the fine-grained zircon except for a somewhat higher Ca and U content. The rims on the blastic zircons are inclusion-free and close to being chemically stoichiometric with a Zr/Hf ratio of 91.

There are abundant accessory minerals found in the Lyle Lake undersaturated rocks including titanite, fluorite, apatite, allanite/epidote, scapolite, and natrolite. Most are ubiquitous and are found in trace to minor quantities with the exceptions of apatite, occurring only in the nepheline-sodalite syenite; scapolite, occurring only in the nepheline syenite; and natrolite, occurring only as a paragenetically-late vein mineral in the nepheline syenite. Calcite has been observed only in rare, paragenetically-late hairline fractures.

Titanite occurs predominantly in the nepheline-sodalite syenite (Table 1). It is typically found as fine, brown accessory phenocrysts, which are randomly disseminated throughout the rock, and rarely enclosed within nepheline. It is also present in intimate association with the biotite-garnet mafic aggregates as fine-grained anhedral aggregates. It is only rarely seen in the nepheline syenite as very fine grains associated with magnetite. The titanite is of similar composition in the two varities of syenite. It contains significant quantities of Al, Fe, and F as well as appreciable quantities of Nb and Na.

Fluorite is found in both syenite phases but is more abundant in the nepheline syenite (Table 1). Fluorite in this rock type is found in two forms: a medium- to coarse-grained generation with pronounced octahedral cleavage; and a fine-grained, uncleaved generation. Both generations exhibit variability in grain colour. The fine-grained, uncleaved form varies from pale to bright purple and the coarser form from pale brown to pale purple. The latter, fluorite form, is subhedral to anhedral and is found interstitial to, or poikilitically enclosing, albite laths. The fine-grained fluorite occurs as single disseminated grains or as fracture fillings in biotite and rarely in nepheline and feldspar.

Fluorite in the nepheline-sodalite syenite occurs as fine anhedral grains in association with the biotite-garnet aggregates, as fracture fillings in nepheline and feldspar, and as spindles following cleavage in biotite. Coarser-grained fluorite is relatively rare in the nepheline-sodalite syenite giving the impression that the nepheline syenite shows two generations of fluorite, while the nepheline-sodalite syenite contains only one.

Microprobe analyses of fluorite from the nepheline syenite reveal near-stoichiometric CaF_2 with only very minor concentrations of La, Ce, Nd, and Sr. An analysis of fluorite from the nepheline-sodalite syenite, indicated an anomalous composition with an excess of calcium and a deficiency in fluorine.

3. Geochemistry

Selected whole-rock analyses and CIPW norms for the two nepheline-bearing syenites from Lyle Lake are given in Table 2. Little spread is evident in the major elements, especially for the nepheline-sodalite syenite where individual samples are almost chemically indistinguishable. Both syenites are undersaturated in silica with abundant normative nepheline. Normative corundum is ubiquitous in the nepheline syenite indicating a peraluminous nature while normative anorthite and normative pyroxene are absent. The metaluminous nature of the nepheline-sodalite syenite is indicated by the lack of normative corundum. This rock also contains normative anorthite and normative pyroxene. The syenites are, in general, distinguished by high amounts of alkalis and alumina and by low amounts of titania, alkaline earths, and iron. The Na_2O/K_2O ratios for these rocks are uniformly high indicating their strong sodic nature, whereas Fe_2O_3/FeO ratios are high for the magnetite-bearing nepheline syenite and low for the biotitic nepheline-sodalite syenite. Phosphorous content, like the titanium and magnesium contents, is also very low in the nepheline syenite, but the nepheline-sodalite syenite contains significantly higher amounts of each. Magnesium content is very low with respect to iron in the nepheline syenite, and is relatively high in the nepheline-sodalite syenite.

The agpaitic index (molar (Na+K)/Al) for both syenites is consistently at, or close to, but below, unity indicating a miaskitic nature for these undersaturated rock types. Note that the Na_2O/K_2O ratio corresponds to increasing peralkalinity.

Relative to the nepheline-sodalite syenite, the nepheline syenite contains lower Ba, Sr, LREE, Th, Y, Ni, Cr, Cu, Li, and Sc contents (Table 3) and higher contents of F, Rb, Zr, U, V, Ga, and Au. Fluorine levels of up to 9400 ppm have been detected in the nepheline syenite. Incompatible element plots reveal consistent but different patterns for the two rock types. Relative to the nepheline-sodalite syenite, the nepheline syenite pattern shows a strong depletion in Ba, P, and Ti, depletion in Sr and LREE, and strong enrichment in U, Th, and Zr, consistent with increasing fractionation. The Zr/Ti ratio is high in both rock types but is much higher for the nepheline syenite, also consistent with a higher degree of fractionation (LeBas, 1987).

Chondrite-normalized REE plots also show distinct patterns for each lithology. The nepheline-sodalite syenite reveals a strongly LREE-enriched pattern as compared to a relatively flat pattern for the nepheline syenite. Abundances of REE in the nepheline syenite are very low, normally totalling less than 50 ppm, compared to over 300 ppm in the nepheline-sodalite syenite.

4. Preliminary Interpretation

Both of the undersaturated syenites show mineral assemblages (albite, K-feldspar, biotite, magnetite, ilmenite, titanite, zircon) typical of miaskitic nepheline syenites that are intermediate in alkalinity. The lack of

Table 2 - Major element contents and CIPW norms of selected samples of nepheline and nepheline-sodalite syenite. mg'=Mg/(Mg+Fe$_t$), Agpaitic Index=(Na+K)/Al, Larsen Index=Si/3+K-Ca-Mg.

	nepheline syenite			nepheline-sodalite syenite		
	PL-91-04	PL-91-05	PL-91-09	PL-91-11	PL-91-13	PL-91-14
SiO_2 (wt %)	56.20	58.30	58.30	60.6	60.2	59.3
TiO_2	0.06	0.05	0.03	0.43	0.44	0.45
Al_2O_3	23.71	22.95	23.72	18.13	18.21	18.65
Fe_2O_3 (t)	2.10	2.32	1.80	3.70	3.85	3.86
Fe_2O_3 (c)	1.21	1.32	1.13	1.25	1.29	1.30
FeO	0.8	0.9	0.6	2.2	2.3	2.3
MnO	0.054	0.066	0.046	0.094	0.107	0.094
MgO	0.057	0.040	0.024	1.52	1.60	1.73
CaO	1.110	0.682	0.666	2.55	2.49	3.08
Na_2O	10.052	10.901	11.313	7.09	7.39	7.37
K_2O	5.80	4.39	4.32	5.18	5.30	5.15
P_2O_5	0.01	0.01	0.02	0.33	0.33	0.40
H_2O	0.5	0.3	0.3	0.6	0.7	0.6
CO_2	0.69	0.43	0.36	0.54	0.51	0.51
S	0.04	0.03	0.01	0.12	0.17	0.17
sum traces	0.495	0.459	0.454	0.653	0.666	0.704
Total	100.80	100.80	101.34	101.25	101.70	101.79
Or	34.35	26.00	25.59	30.66	31.38	30.49
Ab	32.93	45.51	44.68	49.76	47.09	43.71
An				2.31	0.82	2.59
Ne	26.42	23.58	25.86	5.55	8.38	10.08
C	1.54	0.88	1.07			
Di				2.51	3.12	3.94
Hd				1.28	1.54	1.77
Fo	0.11	0.08	0.05	1.86	1.81	1.76
Fa	0.30	0.42	0.14	1.19	1.13	1.00
Mt	1.76	1.92	1.64	1.82	1.88	1.89
Il	0.11	0.09	0.06	0.82	0.84	0.85
Ap	0.02	0.02	0.05	0.78	0.78	0.95
Cc	0.93	0.37	0.18	1.23	1.16	1.16
Fr	0.82	0.66	0.76	0.29	0.35	0.24
Nc	0.68	0.65	0.67			
Pr	0.07	0.06	0.02	0.22	0.32	0.32
Z	0.03	0.14	0.05	0.08	0.07	0.09
mg'	0.02	0.01	0.01	0.26	0.26	0.28
Agpaitic Index	0.96	0.99	0.98	0.95	0.98	0.95
Diff. Index	93.70	95.09	96.12	85.98	86.85	84.28
Colour Index	2.28	2.51	1.89	9.48	10.31	11.22
Larsen Index	12.75	12.22	12.18	11.00	11.04	10.28
norm. plagioclase	0.00	0.00	0.00	4.20	1.56	5.01
Al/(Na+K)	1.04	1.01	1.02	1.05	1.02	1.05
Al/(Ca+Na+K)	0.95	0.96	0.97	0.83	0.81	0.80
Na/(Na+K)	0.72	0.79	0.80	0.68	0.68	0.68
recalc. components						
Qtz	30.90	32.78	31.74	44.64	43.07	42.96
Ne	48.57	51.90	53.34	36.06	37.33	37.72
Ks	20.53	15.31	14.92	19.30	19.60	19.32

pyroxene in the rocks classifies them as miaskites, *sensu stricto* (biotite-nepheline syenites containing albite; Sorensen, 1974). No agpaitic nepheline syenites have been identified at Lyle Lake to date.

Distinct petrochemical trends are shown by the two syenites. The higher MgO, FeO (and FeO/Fe_2O_3) contents in the nepheline-sodalite syenite are attributed to the presence of significant quantities of biotite. Fractionation of P, Ti, Ca, Sr, and Ba is evident from the data in Tables 2 and 3. The distinctly lower contents of these elements in the nepheline syenite, relative to the nepheline-sodalite syenite, is attributed to crystallization in the nepheline-sodalite syenite of apatite (P, Sr), titanite (Ti, Ca), and potassium feldspar (Ba).

Mineralogical and chemical data indicate progressive differentiation from nepheline-sodalite syenite to nepheline syenite. The Mg-rich composition of biotite, lack of amphibole, and the presence of early titanite coexisting with Mg-poor magnetite indicate that the syenites have likely crystallized under relatively oxidizing conditions (Haggerty, 1976). The extent of the spread in the differentiation index (DI) is limited (from around 85 to 97; Table 2), however, the content of normative nepheline does tend to increase with DI. The color index (CI),

Table 3 - Trace element concentrations in selected samples of nepheline and nepheline-sodalite syenite.

	nepheline syenite			nepheline-sodalite syenite		
	PL-91-04	PL-91-05	PL-91-09	PL-91-11	PL-91-13	PL-91-14
Ba (ppm)	58	20	20	1953	1931	2346
Be	13.8	9.3	7.2	9.4	10.1	7.8
Cd	< 1	< 1	< 1	< 1	< 1	< 1
Cl	50			100	70	100
Co	2	1	1	8	8	10
Cr	2	1	1	5	5	7
Cu	5	5	6	28	10	22
F	4000	3200	3700	1700	2000	1500
Ga	34	41	37	22	26	23
Li	18	18	16	61	62	57
Mo	9	6	7	5	5	5
Nb	18	25	17	23	21	20
Ni	2	1	3	12	19	20
Pb	69	50	41	49	66	34
Rb	210	177	177	159	183	153
Sc	< 1	< 1	< 1	3	3	3
Se	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sn	5	5	5	5	5	5
Sr	166	97	97	1587	1415	1854
Th	14	33	15	29	31	33
U	12	25	18	8.6	10.0	10.0
V	11	12	8	5	5	7
W	< 5	< 5	< 5	< 5	< 5	< 5
Zn	92	112	78	99	122	95
Zr	130	710	240	410	360	460
Y	6	7	5	12	12	12
La	27	9	14	102	100	105
Ce	36	13	23	169	176	180
Nd	6	4	4	58	61	62
Eu	0.6	< 0.5	< 0.5	2.8	2.8	3.1
Tb	< 2	< 2	< 2	< 2	< 2	< 2
Dy	1.4	2.2	1.2	4.1	5.4	3.3
Er	1.6	1.4	0.9	0.5	0.5	0.5
Yb	0.79	1.45	1.00	1.75	1.61	1.66
Lu	0.6	0.7	0.5	0.8	1.0	1.0
Au (ppb)	7	2	2	< 1	< 1	< 1
Pd	< 5	< 5	< 5	< 5	< 5	< 5
Pt	< 5	< 5	< 5	< 5	< 5	12

MgO, FeO and FeO/Fe_2O_3, TiO_2 and CaO, and P_2O_5 and Sr are all inversely related to the DI.

The nepheline syenites appear to have a primary magmatic and intrusive origin based on textural evidence, such as the presence of clevelandite albite. There is also no indication of any gradation between the syenites and the country rock, although the lack of contact relations leaves this point somewhat open. No relict or replacement textures due to nephelinization have been observed and there are no indications of the presence of ghost structures of country rocks in the syenites.

Although the nepheline-bearing syenites of the Lyle Lake area have been the subject of this study, the presence in the immediate vicinity of the quartz syenitic to granitic Lyle Lake pluton leads to the consideration of a cogenetic relationship for these lithologies. Analogous situations have been reported from a number of alkaline provinces such as the Larvik-Oslo region in Norway (Neumann, 1980) and the McGerrigle Complex in Quebec (Wallace *et al.*, 1990).

5. Economic Geology

The study area became of exploration interest during the course of reconnaissance mapping by the Saskatchewan Mining and Development Corporation (SMDC; now Cameco) in 1982. One result of this mapping was the discovery of the Lyle Lake nepheline syenite. A follow-up program of mapping and sampling (Waterman *et al.*, 1984) obtained elevated levels of F, Nb, U, Th, and Ce from samples of nepheline syenite. No rare-earth minerals have been observed. When compared with the 'average nepheline syenite' (Gerasimovsky, 1966, 1974), the levels of element enrichment for the REE, B, Sn, Nb, Ta, Ga, Be, Zr, Cl, and Th are typical, if not low. Ba, Sr, and F contents appear to be extremely elevated but are comparable with those from the nepheline syenites of Stjernoy, Norway (Heier, 1964).

As the nepheline syenites described in this report are miaskitic in nature and are characterized by chemically simple minerals such as zircon, magnetite, and ilmenite, the presence of rare metal and REE enrichments are not to be expected (Gerasimovsky, 1966, 1974) and, as noted above, are not found. Agpaitic nepheline syenites, on the other hand, are peralkaline with excess alkalis over aluminum, are characterized by the presence of complex rare-element Zr- and Ti-minerals such as eudialyte and mosandrite, and are commonly highly enriched in incompatible elements such as Zr, REE, Y, Be, Nb, Ta, and U (Sorensen, 1992). From an economic perspective, the miaskitic rocks of the Lyle Lake area are not particularly important for the above reason, but the presence of Hudsonian volatile-rich, undersaturated syenites, however economic, in an otherwise Archean complex, focuses exploration attention on this relatively unexplored region. With only a small part of an apparently large complex having been examined, a more thorough investigation is warranted to examine the area for potentially more economic agpaitic phases.

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