Geochemistry and tectonic significance of alkalic mafic magmatism in the Yukon–Tanana terrane, Finlayson Lake region, Yukon

Stephen J. Piercey, James K. Mortensen, Donald C. Murphy, Suzanne Paradis, and Robert A. Creaser

Abstract: This paper provides an integrated field and geochemical study of weakly alkalic, ~360 Ma mafic rocks from the Yukon–Tanana terrane in the Finlayson Lake region, southeastern Yukon. These mafic rocks occur as dykes and sills that crosscut older felsic metavolcanic rocks and metasedimentary rocks (Kudz Ze Kayah unit) or as flows interlayered with carbonaceous metasedimentary rocks. The mafic rocks have signatures similar to those of ocean-island basalts, moderate TiO₂ and P₂O₅ contents, elevated high field strength element and light rare earth element contents, and εNd350 = +1.1. A subset of the dykes (group 4b) has similar geochemical characteristics but with higher Th/Nb and lower Nb/U ratios, higher Zr and light rare earth element contents, and εNd350 = –2.8. The geochemical and isotopic attributes of these rocks are consistent with formation from either lithospheric or asthenospheric sources during decompression melting of the mantle, with some rocks exhibiting evidence for crustal contamination (group 4b). The alkalic basalts are interpreted to represent ~360 Ma ensialic back-arc rifting and basin generation. It is envisioned that east-dipping subduction, represented by slightly older magmatic suites (Fire Lake unit), was disrupted by subduction hinge roll-back, westward migration of arc magmatism, and the onset of back-arc extension. Decompression melting of the mantle associated with back-arc generation resulted in mantle melting and the formation of the alkalic basalts. The spatial association of this mafic magmatism with crustally derived felsic volcanic rocks and contained volcanogenic massive sulphide mineralization suggests that the associated deposits (Kudz Ze Kayah, GP4F) formed within an ensialic back-arc environment.

Résumé: Cet article présente une étude intégrée de données de terrain et de géochimie de roches mafiques, ~360 Ma, faiblement alcalines, du terrane Yukon–Tanana dans la région du lac Finlayson, dans le sud-est du Yukon. Ces roches mafiques se présentent sous forme de dykes et de filons-couches, qui recoupent des roches métavolcaniques et des roches métasédimentaires (unité Kudz Ze Kayah) plus âgées, ou sous forme de coulées interstratifiées avec des roches métasédimentaires carbonées. Les roches mafiques ont des signatures semblables à celles des basaltes d’îles océaniques, des teneurs modérées en TiO₂ et P₂O₅, de hautes teneurs en éléments à champ électrostatique élevé et en éléments de terres rares légers, ainsi qu’une valeur de εNd350 = +1,1. Un sous-ensemble des dykes, (groupe 4b), a des caractéristiques géochimiques similaires mais avec un rapport Th/Nb plus élevé, un rapport Nb/U plus faible et une plus haute teneur en Zr et en éléments de terres rares légers, ainsi qu’une valeur de εNd350 = –2,8. Les caractéristiques géochimiques et isotopiques de ces roches concordent avec une formation de source lithosphérique ou asthénosphérique durant la fusion de décompression du manteau, alors que quelques roches montrent des évidences d’une contamination crustale (groupe 4b). Les basaltes alcalins représentaient l’extension d’arrière-arc ensialique et la génération de bassins, ~360 Ma. On croit que la subduction à pendage vers l’est, représentée par des suites magmatiques légèrement plus âgées (unité Fire Lake), a été perturbée par le repositionnement de la charnière de subduction, la migration vers l’ouest du magmatisme d’arc et le début d’une extension d’arrière-arc. La fusion de décompression du manteau, associée à la génération d’arrière-arc, a conduit à la fusion du manteau et à la formation des basaltes alcalins. L’association spatiale de ce
Introduction

The origins and tectonic setting of mafic magmatism within the Yukon–Tanana terrane (YTT) of the northern Canadian Cordillera have been problematic. Central to these problems has been the stratigraphic grouping of mafic rocks without regard to stratigraphic context, geochemistry, or tectonic setting (e.g., Anvil Allochthon; Tempelman-Kluit 1979). There has also been contradictory nomenclature of YTT-associated mafic rocks. For example, some workers have correlated mafic rocks of the YTT with the Anvil Allochthon or Anvil Assemblage, considering them allochthonous with respect to the YTT (Tempelman-Kluit 1979). Other workers have considered some YTT mafic rocks to be stratigraphically part of the YTT, whereas other YTT mafic rocks were considered allochthonous and correlated with the Slide Mountain terrane (e.g., Mortensen and Jilson 1985; Mortensen 1992).

In recent years new stratigraphic mapping, trace element geochemistry, and Nd-isotope geochemistry of mafic rocks in the YTT have led to significant new advances in understanding the tectonic setting and origin of YTT mafic rocks (e.g., Creaser et al. 1997; Grant 1997; Murphy and Piercey 1999, 2000; Murphy 2001; Piercey et al. 1999, 2001a, 2001b). For example, Creaser et al. (1997) and Grant (1997) illustrated that mafic rocks of the Anvil Assemblage had arc-like trace element geochemical and Nd isotopic signatures that were incompatible with them being correlative to basalts of the Slide Mountain terrane, which have mid-ocean-ridge basalts (MORB) like signatures (Nelson and Bradford 1993; Nelson 1993; Plint and Gordon 1997). Recent stratigraphic mapping in the YTT as part of the Ancient Pacific Margin National Geoscience Mapping Program (NATMAP) Project (Murphy 1998, 2001; Murphy and Piercey 1999, 2000; Nelson et al. 2000; Colpron and Yukon–Tanana Working Group 2001) has illustrated the diversity of mafic rocks in the YTT. These studies have shown that mafic rocks are essential constituents of the YTT but are not necessarily stratigraphically or temporally equivalent, nor have they formed in similar tectonic settings (Murphy 1998, 2001; Murphy and Piercey 1999, 2000; Nelson et al. 2000; Colpron and Yukon–Tanana Working Group 2001). Furthermore, geochemical data, on stratigraphically and temporally constrained mafic and felsic rocks in the YTT, illustrate diverse geochemical characteristics for these YTT rocks (Colpron 2001; Piercey 2001; Piercey et al. 2001a, 2002) that reflect processes occurring during mid to late Paleozoic arc magmatism and back-arc basin generation (Nelson et al. 2000; Colpron 2001; Colpron and Yukon–Tanana Working Group 2001; Piercey et al. 2001a, 2001b).

In this paper we present and interpret a regional geological and geochemical dataset for ~360 Ma (late Early Mississippian) within-plate mafic rocks from the Finlayson Lake region. These mafic rocks form part of unit 4 of the Grass Lakes succession, the oldest succession in the Finlayson Lake region, and are both underlain by ~360 Ma felsic rocks (Kudz Ze Kayah unit; Piercey 2001) and crosscut by ~360 Ma granitic rocks (Grass Lakes suite intrusions; Mortensen 1992). The underlying, but broadly coeval, felsic rocks of the Kudz Ze Kayah (KZK) unit host the Kudz Ze Kayah and GP4F volcanic-hosted massive sulphide (VHMS) deposits. The geochemical data provided in this paper imply that within-plate mafic rocks record derivation from enriched mantle sources within an ensialic back-arc-basin setting. Differences between the samples are attributed to different levels of crustal contamination. The combined geological and geochemical dataset presented herein aims to (i) document the geological and geochemical characteristics of these within-plate mafic rocks, (ii) provide insights into the origins and petrogenesis of the YTT-associated mid-Paleozoic within-plate mafic magmatic rocks, and (iii) ascertain the significance of this style of mafic magmatism in the tectonic evolution of the YTT in the northern Cordillera.

Geologic and stratigraphic setting

The YTT in the Finlayson Lake region (Fig. 1) is composed of deformed and metamorphosed (greenschist to lower amphibolite grade) metasedimentary, metavolcanic, and metaplutonic rocks (e.g., Tempelman-Kluit 1979; Mortensen and Jilson 1985) (Fig. 2). Despite the structural and metamorphic overprint on these rocks, a stratigraphically intact sequence consisting of three mid to late Paleozoic unconformity-bound successions has been defined: the Grass Lakes, Wolverine Lake, and Campbell Range successions (Fig. 2) (Murphy 1998, 2001; Murphy and Piercey 1999, 2000). The alkalic rocks of this study occur in the uppermost part of the Grass Lakes succession.

The Grass Lakes succession consists of unit 1, the Fire Lake unit (unit 2), the Kudz Ze Kayah (KZK; unit 3) unit, and unit 4 (Figs. 2, 3). The lowermost part of the Grass Lakes succession consists of pre-365 Ma quartz-rich, non-carbonaceous metasedimentary rocks of unit 1, which are overlain by the ~365–360 Ma mafic dominated arc- and back-arc rocks of the Fire Lake unit (Murphy 1998, 2001; Murphy and Piercey 1999, 2000; Piercey et al. 1999, 2001a). The KZK unit stratigraphically overlies the Fire Lake unit and consists of felsic volcanic and variably carbonate sedimentary rocks (Murphy 1998) (Figs. 2, 3). The KZK unit is stratigraphically overlain by interlayered alkalic basalts and carbonate sedimentary rocks of unit 4 (Murphy 1998) (Figs. 2, 3). Unit 4 mafic rocks occur in a variety of forms including, most commonly, metre-scale layers of chloritic schist interlayered with carbonate phyllitic rocks; locally, volcanic flow textures (massive flows and hyaloclastite) are preserved. Mafic dykes and sills are commonly found near the KZK and GP4F VHMS deposits (Fig. 2). Near these deposits, medium-grained diabase sills are interlayered with carbonate phyllitic and locally preserve fine intergrowths of lath-like pseudomorphed plagioclase and pyroxene and...
cumulate textures. Mafic dykes near the KZK deposits are commonly biotite-rich, weakly altered, and cut the footwall and hanging wall rhyolitic rocks and are therefore interpreted to post-date the hydrothermal system that formed the KZK deposit. Similarly, near the GP4F VHMS deposit (Fig. 2), numerous mafic dykes cut across the felsic volcaniclastic stratigraphy; however, some of the mafic rocks may be interlayered flows or volcaniclastic sedimentary material. Biotite-rich (biotitite) dykes are also sporadically present within the Finlayson Lake region; however, the greatest concentration of the alkalic mafic rocks in the Finlayson Lake region appears to be concentrated near the KZK and GP4F deposits (Fig. 2).

Coeval with and crosscutting the KZK unit and unit 4 are the \(360 \text{ Ma}\) (Mortensen 1992) K-feldspar porphyritic to megacrystic granitoids of the Grass Lakes suite (Figs. 2, 3). These intrusions are interpreted to represent the subvolcanic intrusive complex to the felsic volcanic rocks associated with the KZK unit VHMS mineralization (Murphy and Piercey 1999). The stratigraphic relationship of unit 4 to the essentially coeval KZK unit and Grass Lakes suite granitoids (Figs. 2, 3) suggests that the alkalic rocks of the study are \(360 \text{ Ma}\).

The rocks of the Grass Lakes succession, and the entire Finlayson Lake region, have been subject to various degrees of deformation, but most of the deformation post-dates the formation of the rocks in this paper. In the Late Pennsylvanian, rocks of the Fire Lake unit were displaced approximately 30 km from the west-southwest to their present position east-northeast along the Money Creek thrust (Figs. 1, 2; Murphy and Piercey 2000; Murphy 2001; Murphy et al. 2002). The dominant fabric in the Finlayson Lake region is related to Cretaceous ductile deformation and low-displacement, southwest-vergent folding and thrusting (Murphy 1998). A Mississippian event of uncertain kinematics has affected the Grass Lakes succession; however, this event also post-dated the formation of the Grass Lakes succession and is interpreted to represent an intra-arc deformation episode (e.g., Colpron and Yukon–Tanana Working Group 2001).

**Lithogeochemistry and neodymium-isotope geochemistry**

**Sampling and analytical methods**

Samples of mafic volcanic and subvolcanic rocks in this study were collected during 1:50 000 scale regional mapping, and all samples were analyzed at the laboratories of the Geological Survey of Canada, Ottawa (Table 1). Based on field interpretations, most of the schistose and massive aphyric (greenstone) rocks samples are interpreted to be of volcanic origin. Samples that had relict phenocrysts of plagioclase have been interpreted to be either plagioclase-phyric flows or high-level intrusions. In both of these cases
it is interpreted that these rocks represent, or were very close to, liquid compositions. All samples had weathered edges removed by a diamond saw and were pulverized in a steel jaw crushe. Most of the pulverized material was crushed in a tungsten carbide mill; three samples were pulped in a Cr-steel mill and are denoted as such in Table 1. Samples that have been crushed by Cr-steel likely have excess Cr values, whereas those crushed by tungsten carbide likely have excess Ta. Throughout the paper Ta is not used during geochemical discussions, and the three Cr-contaminated samples are not included in discussions when Cr is used. Powders from the aforementioned steps were used in all analytical techniques.

The majority of major elements were determined on fused beads by X-ray fluorescence (XRF), with the exception of...
H₂O and CO₂, which were analyzed by infrared spectroscopy, and FeO, which was analyzed by modified Wilson titration. Samples analyzed for trace elements were totally dissolved using a combination of nitric, perchloric, and hydrofluoric acids, with a lithium metaborate flux if any residual material existed after the first acid attack. These solutions were then analyzed for trace elements using a combination of inductively coupled plasma – emission spectrometry (ICP–ES: Cr, Ni, Co, Cu, Zn, Ba, La, Pb, Sc, Sr, V, Y, Yb, and Zr if >100 ppm) and inductively coupled plasma mass spectrometry (ICP–MS: remaining rare earth elements (REE), Cs, Rh, Th, U, Ga, Hf, Ta, and Zr if <100 ppm). Further details on the methodology can be obtained from the Geological Survey of Canada at <http://132.156.95.172/chemistry>. Analytical precision calculated from repeat analyses of internal basaltic reference materials is given as percent relative standard deviation (%RSD = 100 × standard deviation/mean) and yielded values of 0.43–6.52% for the major elements; 0.72–8.80% for the transition elements (V, Ni, Cr, Co); 2.21–5.92% for the high field strength elements (HFSE; Nb, Zr, Hf, Y, Sc, Ga); 2.35–6.96% for the low field strength elements (LFSSE) Cs, Rb, Th, and U, but slightly higher for Ba and Sr (1.49–15.75%); 2.15–6.47% for the REE (La–Lu); and 1.12–98.12% for Cu, Pb, and Zn (Piercey 2001). Concentrations of the latter elements were close to detection limits in the internal reference materials, however, leading to decreased precision and high %RSD values (Piercey 2001). Two samples were analyzed for their Nd isotopic composition at the University of Alberta radiogenic isotope facility. Samples were analyzed by thermal ionization mass spectrometry (TIMS) using the preparation and error treatment methodology of Creaser et al. (1997). Values for the Geological Survey of Japan Shin Etsu Nd standard yielded an average value of 143Nd/144Nd = 0.512106 with an analytical uncertainty of ±0.000012 (1σ), which is interpreted to be the minimum uncertainty estimate of the 143Nd/144Nd for any particular sample. The Nd isotopic data presented here are normalized to 143Nd/144Nd = 0.512107 for the Geological Survey of Japan Shin Etsu standard (R.A. Creaser, unpublished data), which is equivalent to 0.511850 for the La Jolla standard (Tanaka et al. 2000). Although the age of the mafic rocks is ~360 Ma, the initial εNd values were calculated at 350 Ma to facilitate comparison with other YTT Nd isotopic data (Grant 1997; Creaser et al. 1997). This is further justified as the variations between εNd,550 and εNd,350 are insignificant within the timescale of the evolution of the Sm–Nd system (<0.1 c unit; e.g., Hamilton et al. 1983; Goldstein et al. 1984). Results of the Nd isotopic analyses are presented in Table 2.

**Alteration–metamorphism and element mobility**

Although attempts were made to collect least altered samples, field and petrographic data on the mafic rocks of the study area indicate that they have been affected by low-grade hydrothermal alteration (seawater alteration) and (or) greenschist-facies regional metamorphism. Even though primary volcanic–intrusive features are readily observable at both outcrop scale (e.g., cumulate textures) and thin-section scale (e.g., relict plagioclase), the primary mineralogy of the rocks has largely been replaced. In particular, petrographic examination indicates that the matrixes of the rocks have been replaced by an assemblage of chloride, tremolite–actinolite, quartz, muscovite, titanite, epidote, and carbonate. Precursor plagioclase and mafic phenocrysts have been replaced by carbonate, muscovite and epidote, and chloride and tremolite–actinolite, respectively. The greenschist-facies metamorphic and seafloor conditions that these samples have experienced imply a high probability that most major elements (e.g., SiO₂, Na₂O, K₂O, CaO) and LFSE (Cs, Rb, Ba, Sr) have been mobilized to various degrees (MacLean 1990). The likelihood of element mobility is supported by the metamorphic mineral assemblages present in the rocks, and the high volatile contents (H₂O + CO₂ = 2.4–14.6%; Table 1). In contrast, the major elements Al₂O₃, TiO₂, and possibly P₂O₅, the transition elements, HFSE, REE, and Th were likely immobile under the aforementioned conditions (e.g., Pearce and Cann 1973; Wood 1980; MacLean 1990; Rollinson 1993; Jenner 1996). To test if these elements have remained immobile during alteration and metamorphism, we have plotted the Al₂O₃/Na₂O alteration index (Spitz and Darling 1978) against key compatible elements, compatible element ratios, and incompatible element ratios used throughout this paper (Fig. 4). In all of these diagrams it is clear that there is very little correlation, if any, between these elements and the...
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Table 1. Geochemical data for weakly alkaline mafic rocks from unit 4 of the Grass Lakes succession.
Table 2. Neodymium-isotope geochemical data for mafic rocks from unit 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Suite</th>
<th>143Nd&lt;sup&gt;a&lt;/sup&gt;</th>
<th>144Nd&lt;sup&gt;b&lt;/sup&gt;</th>
<th>147Sm&lt;sup&gt;c&lt;/sup&gt;</th>
<th>εNd&lt;sub&gt;143Nd&lt;/sub&gt;</th>
<th>εNd&lt;sub&gt;144Nd&lt;/sub&gt;</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P98-9b</td>
<td>Group 4</td>
<td>0.512505 (07)</td>
<td>0.1151</td>
<td>+1.1</td>
<td>–0.41</td>
<td>–2.6</td>
<td>9.50</td>
<td>49.90</td>
</tr>
<tr>
<td>P98-2</td>
<td>Group 4</td>
<td>0.512364 (07)</td>
<td>0.1395</td>
<td>–2.8</td>
<td>–0.29</td>
<td>–5.3</td>
<td>8.88</td>
<td>38.48</td>
</tr>
</tbody>
</table>

<sup>a</sup>Uncertainties in the last two decimal places are given in parentheses and are at the 2σ level.

<sup>b</sup>Calculated using 143Nd/144Nd of chondritic uniform reservoir (CHUR) = 0.512638 and 147Sm/144Nd = 0.1966 (Hamilton et al. 1983).

<sup>c</sup>Chondrite normalized to values of Sun and McDonough (1989).
degree of alteration and metamorphism (Fig. 4). Given these constraints, it is inferred that the elements shown in Fig. 4 have been controlled by processes other than alteration and metamorphism and have remained immobile during the latter processes (e.g., Pearce and Cann 1973; Wood 1980; MacLean 1990; Rollinson 1993; Jenner 1996). Given the likelihood of mobility of some elements (e.g., LFSEs), discussions in this paper rely primarily on immobile element systematics. Throughout this paper Zr is chosen as a fractionation index, as this element behaves incompatibly during the fractionation of basaltic liquids and is immobile during low to moderate grades of alteration and metamorphism (e.g., MacLean 1990).

**Results**

The unit 4 mafic rocks are characterized by basaltic affinities (Fig. 5c) (Zr/TiO₂ = 50.3–92.2; Table 1) and weakly to moderately alkalic Nb/Y ratios (Nb/Y = 0.36–2.96; Table 1). The weak to moderate alkalinity of the rocks is also reflected by their elevated TiO₂ (1.53–4.82%) and P₂O₅ contents (0.16–0.80%; Table 1), which show a positive correlation with increasing Zr, suggesting incompatibility of all of these elements during fractionation (Figs. 6a, 6b); in contrast, Zr exhibits a negative trend with the compatible elements Ni, Cr, and Sc (Figs. 6c, 6d, 6e). The Al₂O₃/TiO₂ ratios of the mafic rocks (4.20–9.26; Table 1) are lower than primitive mantle (~21) and normal mid-ocean-ridge basalts (N-MORB = 11) but lie between those of ocean-island basalts (OIB = 5) and enriched MORB (E-MORB = 9.5; Sun and McDonough 1989) (Table 1).

The immobile trace element features of the unit 4 mafic rocks are plotted in a series of discrimination diagrams and primitive mantle normalized and chondrite-normalized plots in Figs. 7–9. Based on the Th–Nb–light rare earth element (LREE) relationships in primitive mantle normalized plots, unit 4 rocks can be subdivided into two groups. The group 4a samples are characterized by positive Nb anomalies (Nb/Nb* > 1) relative to Th and La (Fig. 7), whereas the group 4b samples have weakly negative Nb anomalies (Nb/Nb* < 1) relative to Th and La (Fig. 7). It should be noted that these geochemical groups can only be distinguished geochemically, as there are no distinguishable differences between them based on field observations or thin sections. The group 4a samples are characterized by smooth, downward-sloping profiles (Fig. 7a) with signatures similar to those of OIB (Fig. 7a). The group 4b samples have similar downward-sloping profiles, but the group 4b samples have negative Nb anomalies and higher Th/Nb values (Fig. 7b; Table 1). The downward-sloping profiles of the two groups in Fig. 7 are echoed by the REE profiles (Fig. 8), with both groups exhibiting LREE enrichment (La/Smₙ = 1.94–3.70) and fractionation of the middle REE from the heavy rare earth elements (HREE) (Gd/Ybₙ = 1.40–3.86).

In various discrimination diagrams most of the samples have within-plume affinities. The elevated TiO₂ contents of the unit 4 mafic rocks are reflected by the samples lying on the OIB–MORB boundary in the Ti–V plot (Fig. 9a). In the Th–Nb–Zr plot, groups 4a and 4b separate systematically, with the group 4a samples lying largely in the field for OIB with their positive Nb anomalies (Nb/Nb* = 1.11–1.81) and low Th/Nb (0.07–0.10), whereas the group 4b samples are displaced towards the Th apex, reflecting their negative Nb anomalies (Nb/Nb* = 0.67–0.90) and higher Th/Nb ratios (0.14–0.22) (Fig. 9b; Table 1). Furthermore, the group 4b samples have Th/Nb ratios that correlate with Zr and La/Sm and have higher Th/Yb at a given Nb/Yb content than the group 4a suite of rocks, typical of rocks that have been contaminated by continental crust (Figs. 10a–10c). Although U can be mobile under oxidizing fluid conditions (Brenan et al. 1995), the strong correlation of U with immobile Nb suggests that U has been immobile and that the Nb–U systematics of the rocks reflect primary values. There is a strong separation in Nb/U ratios between the group 4a samples (Nb/U = 34–68) and the group 4b samples (Nb/U = 17–35), which are displaced towards values for continental crustal reservoirs (Nb/U = 12; Fig. 10d). Both group 4a and group 4b samples have similar and largely chondritic (~36) to slightly superchondritic (>36) Zr/HF ratios (e.g., Eggins et al. 1997), ranging from 36.6 to 46.7 (average = 41.7) and from 35.7 to 57.1 (average = 43.6), respectively (Table 1).

A sample from the group 4a mafic volcanics yielded εNd₃⁵₀ = +1.1 and fSm/Nd = -0.41, and a group 4b sample yielded εNd₃⁵₀ = –2.8 and fSm/Nd = –0.29 (Table 2). These εNd₃⁵₀ values are much lower than those for the depleted mantle (DM) reservoir at 350 Ma which has a value of εNd₃⁵₀ = +9.5 and fSm/Nd = +0.09 (Goldstein et al. 1984).

**Discussion**

**Petrogenesis**

Deciphering the origin of mafic magmatism within the YTT requires distinguishing between mantle source features versus superimposed features related to fractional crystallization and (or) other open-system processes (e.g., crustal contamination). For the most part, compatible element contents, such as Ni, Cr, and Sc, provide us with significant information about the fractionation history of mafic rocks. Compared to Zr, the incompatible element fractionation monitor, the compatible elements Ni, Cr, and Sc exhibit an inverse relationship (Fig. 6). This is consistent with fractional crystallization of olivine, spinel, and clinopyroxene. These compatible element features, however, provide little information on the source or subsequent contamination history of the unit 4 mafic rocks. In contrast, the immobile and high to moderate incompatible-element characteristics of these rocks are largely unaffected by fractional crystallization and thus can provide evidence bearing on the mantle source region(s), tectonic setting, and the between-suite characteristics of the mafic rocks (e.g., Pearce 1983; Pearce and Peate 1995). For example, the low Al₂O₃/TiO₂ ratios and high TiO₂ and P₂O₅ values suggest that these rocks have been derived from an enriched mantle source region, similar to OIB, at low degrees of partial melting (e.g., LaFleche et al. 1998). Likewise, an OIB-like source is further supported by the HFSE and REE characteristics and primitive mantle normalized patterns of the group 4a rocks (Fig. 7). The slight variation from OIB in the group 4b signatures likely reflects crustal contamination of an OIB-type magma, as indicated by the Nd isotopic data and crustally sensitive incompatible element systematics (see the following text).

Rocks with alkalic affinities and OIB signatures are found in a variety of continental margin settings including continental rifts (Goodfellow et al. 1995) and continental arc rift settings (van Staal et al. 1991; Shinjo et al. 1999), and there is
Fig. 4. Key compatible elements (a, b), compatible element ratio (c), and incompatible element ratios (d-h) used throughout this paper against the Al2O3/Na2O alteration index (Spitz and Darling 1978). Further details provided in the text.
considerable debate as to whether alkalic rocks in these environments come from asthenospheric or subcontinental lithospheric mantle sources. For example, numerous workers have shown that magmas derived from enriched asthenospheric mantle can yield rocks with enriched OIB-like trace element signatures (e.g., Sun and McDonough 1989; van Staal et al. 1991; Shinjo et al. 1999). Other workers have shown, however, that the subcontinental lithospheric mantle (SCLM) is strongly enriched in incompatible trace elements (Pearce 1983; McDonough 1990; Hawkesworth et al. 1990; Menzies 1990). Some workers have also suggested that small volumes of alkaline magatism represent melts of dominantly lithospheric origin (e.g., LaFlèche et al. 1998), whereas larger volumes represent asthenospheric-derived melts (e.g., McKenzie and Bickle 1988). The geochemical data from unit 4 are compatible with either an asthenospheric or SCLM source region. For example, the geochemical attributes of the unit 4 rocks are similar to those of interpreted asthenospheric mantle derived mafic rocks in the modern Okinawa Trough back-arc basin (Shinjo et al. 1999) and back-arc basin basalts in the Ordovician Bathurst Mining camp (van Staal et al. 1991). Equally viable, however, is a lithospheric source. For example, the low εNd350 value of the group 4a sample, as compared with the DM reservoir at 350 Ma (+9.5), is a feature present in some SCLM-derived magmas (Hawkesworth et al. 1990; Menzies 1990). The relatively minor volume of magma associated with the unit 4 alkalic magmatism in the Finlayson Lake region, as inferred from the field distributions of the rocks (Fig. 2), is also partly supportive of an SCLM source (e.g., LaFlèche et al. 1998). The latter, however, may be a function of the large volumes of felsic volcanic rocks associated with these mafic rocks which may have effectively prevented the surface expression of large volumes of mafic magmatism. For example, these felsic rocks are interpreted to have formed from basaltic underplating (Piercey et al. 2001b) of continental crust, and as such the unit 4 magmas may have solidified in subvolcanic magma chambers below these felsic volcanic rocks and did not erupt on surface. Both suites, therefore, are consistent with either asthenospheric or SCLM origins.

The group 4a and 4b suites have strong geochemical similarity; however, the group 4b rocks have weak negative Nb anomalies (Fig. 7), which point to the role of an additional component in their genesis. Negative Nb anomalies are common features of rocks associated with subduction zones and incipient back-arc basins, due to the influx of LFSE into the mantle source regions from the subducted slab (Hawkins 1995; Pearce and Peate 1995; Shinjo et al. 1999). Negative Nb anomalies, however, are also common to the bulk and upper continental crust (e.g., Taylor and McLennan 1985; Wedepohl 1995), and rocks contaminated by continental crust can also exhibit such anomalies. In the case of the group 4b suite, numerous lines of field and geochemical evidence argue against an arc origin for their negative Nb anomalies. Their very high HFSE and REE contents and OIB-like signatures (Fig. 7) are dissimilar from those of most arc rocks (e.g., Pearce and Peate 1995). Also, unit 4 alkaline rocks are associated with abundant HFSE-enriched (A-type) felsic rocks, with extensional synvolcanic faults (Murphy and Piercey 2000) and VHMS mineralization, all of which are interpreted to have formed in an ensialic back-arc rift or back-arc basin (Piercey et al. 2001b). Given these constraints, the negative Nb anomaly is unlikely to reflect formation of these rocks within an arc environment proper. Nevertheless, a subducted slab component may have played a role in the genesis of these rocks. High LFSE/Nb values have been recognized in back-arc lavas of modern back-arc environments where they have been attributed to fluids or melts from the subducted slab metasomatizing the back-arc mantle (Hawkins 1995; Shinjo et al. 1999). If the negative Nb anomalies of the group 4b suite are from a subducted slab component, then this slab component must have contained evolved continental crustal material to account for the εNd350 = −2.80 value in the group 4b sample.

The geochemical and isotopic features of the group 4b samples can be explained equally by crustal contamination of group 4a magmas during emplacement. Numerous lines of geochemical evidence support this hypothesis. For example, in Th/Yb–Nb/Yb space (Fig. 10), the group 4a samples have a within-plate enrichment trend with variable amounts of enriched (OIB-like) components in their source. In contrast, group 4b samples lie on a distinctly different trajectory with higher Th/Yb values at a given Nb/Yb value (Fig. 10). In Fig. 10, samples that have been influenced by Th enrichment, either through subducted slab metasomatism or crustal contamination, exhibit vertical increases with higher Th at a given Nb content than rocks that have not been influenced by Th enrichment (e.g., Pearce 1983). Crustal contamination is further supported by Th/Nb–Zr systematics, with group 4b samples showing higher Th/Nb at a given Zr content, typical of magmas that have undergone crustal contamination (Fig. 10). In contrast, the group 4a samples have lower Th/Nb at a given Zr content, typical of uncontaminated mafic magmas (Fig. 10). A similar distribution exists in Th/Nb–La/Smp space, where group 4a samples show a flat distribution with constant Th/Nb values with variable La/Smp contents, and group 4b samples exhibit an increase in Th/Nb values with increasing La/Smp (Fig. 10). Similarly, the Nb/U systematics of group 4a (Nb/Uavg = 51.39) samples lie primarily within the array for oceanic basalts (Nb/U = 47 ± 10; Hofmann et al. 1986), whereas the Nb/U values for the group 4b samples are much lower (Nb/Uavg = 21.17), and similar to crustal values.
Fig. 6. Zr plots against (a) TiO₂ and (b) P₂O₅ illustrate the incompatible nature of these elements during magma evolution. The inverse relationships between Zr and Cr, Ni, and Sc are consistent with spinel, olivine, and clinopyroxene crystallization, respectively. Symbols as in Fig. 4.

(Nb/U = 12.09, Taylor and McLennan 1985; Nb/U_upper crust = 10.40 and Nb/U_lower crust = 12.15, Wedepohl 1995) consistent with interaction with continental crust (Fig. 10). Lastly, group 4b samples contain greater average contents of crustally enriched immobile trace elements, including Zr, Hf, and the LREE, relative to the group 4a suite (Table 1). Taken together, both suites of rocks from the KZK unit are consistent with formation from lithospheric or asthenospheric
sources; however, the group 4b suite of mafic rocks probably experienced crustal contamination either en route to the surface or within crustal-level subvolcanic magma chambers.

**Tectonic setting**

The geological and geochemical attributes of alkalic rocks from the YTT support a continental arc rift to ensialic back-arc rift – back-arc basin setting (Piercey et al. 2001b). Numerous workers have used geological, geochemical, and isotopic techniques to illustrate that the Devonian–Mississippian evolution of the YTT was a product of west-dipping continental arc magmatism, possibly built on the distal edge of the North American margin (e.g., Mortensen 1992 and references therein; Creaser et al. 1997, 1999; Grant 1997; Piercey et al. 1999, 2001a, 2001b). In the Finlayson Lake region, arc magmatism is recorded primarily by the rocks of the 365–360 Ma Fire Lake unit and Money Creek thrust sheet (e.g., Grant 1997; Piercey et al. 2001a, 2001b). In the Finlayson Lake region, arc magmatism is recorded primarily by the rocks of the 365–360 Ma Fire Lake unit and Money Creek thrust sheet (e.g., Grant 1997; Piercey et al. 2001a, 2001b) which lie to the south and west of the area of alkalic magmatism. At ~360 Ma (oldest U–Pb age of A-type Grass Lakes granitoid; Mortensen 1992), this arc was rifted and incipient ensialic back-arc basin development occurred (Piercey et al. 2001b). Piercey et al. (2001b) suggested that this rifting was due to westward migration of an east-dipping subduction zone (cf. Mortensen 1992). The alkaline basalts from this study are likely the manifestations of this arc-rifting event, with them forming as a result of decompression partial melting (e.g., McKenzie and Bickle 1988) of either enriched lithospheric or asthenospheric mantle sources. The spatial association of alkaline basalts with HFSE-enriched felsic rocks further suggests the possibility that the alkaline magmas formed during this arc-rifting event may have provided the heat engine to drive crustal partial melting, which formed the associated felsic rocks (e.g., Huppert and Sparks 1988).

This period of arc rifting in the Finlayson Lake region and westward migration of YTT arc magmatism is broadly coincident with the interpreted opening of the Slide Mountain Ocean (Nelson 1993; Nelson and Bradford 1993; Creaser et al. 1999) and rifting, alkaline magmatism, clastic sedimentation, and exhalative Pb–Zn–Cu sulphide deposit formation within the North American miogeocline (Mortensen and Godwin 1982; Mortensen 1982; Gordey et al. 1987; Paradis et al. 1998). It is suggested that arc-rifting in the YTT in the Finlayson Lake region may have been in response to, or induced the, initial opening of the Slide Mountain Ocean (e.g., Nelson 1993; Nelson and Bradford 1993; Creaser et al. 1999). Coincidentally, the far-field stresses from the YTT rifting and Slide Mountain Ocean opening resulted in the rifting, magmatism, and exhalative sulphide deposit formation in the North American miogeocline (e.g.,

**Fig. 7.** Primitive mantle normalized plots of (a) group 4a and (b) group 4b samples. Primitive mantle values from Sun and McDonough (1989). Symbols as in Fig. 4.

**Fig. 8.** Chondrite-normalized plots of (a) group 4a and (b) group 4b samples. Chondrite values from Sun and McDonough (1989). Symbols as in Fig. 7.
The interpretation that these events are related to the westward shifting of the focus of YTT arc magmatism is also strongly supported by recent mapping, geochronology, and fossil ages from the YTT as part of the Ancient Pacific Margin NATMAP Project. These data illustrate that following YTT arc rifting in the Finlayson Lake region, the majority of subsequent arc magmatism occurred in the western portions of the YTT (Nelson et al. 2000; Colpron and Yukon–Tanana Working Group 2001; Colpron 2001; Roots and Heaman 2001). Furthermore, in the Finlayson Lake region, post-arc-rift volcanic and intrusive rocks have geological and geochemical features consistent with formation in a back-arc type environment (Piercey et al. 2001b, 2002). Collectively, these studies illustrate a complex history of magmatism and tectonic activity along the margin of North America during the Devonian–Mississippian.

The YTT exhibits complex interrelationships between mid-Paleozoic magmatism, large-scale tectonics, and metallogenic evolution. The results of this study illustrate that alkalic mafic magmatism in the YTT of the Finlayson Lake region is a manifestation of arc rifting and is broadly coeval with VHMS deposit formation (Kudz Ze Kayah, GP4F deposits; Murphy and Piercey 2000) and HFSE-enriched felsic magmatism (Piercey et al. 2001b). These relationships suggest that arc rifting and subsequent extension were important regional-scale mechanisms that promoted hydrothermal system generation within the Finlayson Lake district. The association of alkalic mafic rocks with HFSE-enriched felsic rocks (Piercey et al. 2001b) may be a regional-scale tectonomagmatic relationship that identifies potential VHMS-bearing stratigraphy within the YTT and similar continent-margin bimodal-volcanic siliciclastic VHMS environments.

Conclusions

The conclusions of this study are as follows:

1. Devonian-Mississippian (~360 Ma) mafic rocks (unit 4) in the Finlayson Lake region are spatially associated with VHMS mineralization and HFSE-enriched felsic volcanic rocks. These alkalic rocks occur as sills and dykes that crosscut felsic volcanic rocks and mafic flows that are interlayered with variably carbonaceous sedimentary rocks.

2. All of the mafic rocks have alkalic, ocean-island basalt like geochemical signatures with high TiO$_2$ and P$_2$O$_5$ contents and elevated high field strength element and light rare earth element contents. A subset of the mafic rocks (group 4b) has similar geochemical characteristics but with higher Th/Nb and Nb/Nb$^*$ ratios, lower Nb/U ratios, and higher Zr and LREE contents; a group 4b sample yielded an $\varepsilon$Nd$_{350}$ value of –2.8 compared with a value of +1.1 in a group 4a sample. The geochemical and isotopic features of the alkalic rocks are consistent with formation from either lithospheric or asthenospheric sources during decompression melting of the mantle. The group 4b mafic rocks are interpreted to be equivalent to the group 4a suite but have been contaminated by continental crust.

3. The alkalic basalts of this study are interpreted to represent magmatism associated with ~360 Ma ensialic back-arc rifting and basin generation within the Yukon–Tanana terrane. We speculate that Devonian-Mississippian east-dipping subduction was disrupted in the Finlayson Lake region by subduction hinge roll-back, westward migration of arc magmatism, and the onset of back-arc extension. Decompression melting of the mantle associated with back-arc generation resulted in melting and the formation of the studied alkalic basalts. The spatial association of this mafic magmatism with volcanic-hosted massive sulphide mineralization suggests that the associated deposits (Kudz Ze Kayah, GP4F) formed within an ensialic back-arc rift to back-arc basin environment.

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Fig. 10. Trace element plots that illustrate the differences between the group 4a and 4b samples. The sympathetic relationships of Th/Nb with (a) Zr and (b) La/Sm in group 4b are consistent with them having experienced crustal contamination. In Th/Yb–Nb/Yb space (c) (modified after Pearce 1983 and Stern et al. 1995), the group 4b samples exhibit a distinct crustally influenced trajectory. The Nb/U ratios of the group 4a samples lie within the field for modern oceanic basalts (Nb/U = 47 ± 10; Hofmann et al. 1986), whereas the group 4b samples have a value that is lower and consistent with crustal influence (Nb/U ≈ 12; Taylor and McLennan 1985). Symbols as in Fig. 4. N-MORB, normal mid-ocean-ridge basalt; OIB, ocean-island basalt (Sun and McDonough 1989); LCC, BCC, and UCC, lower, bulk, and upper continental crust, respectively (Taylor and McLennan 1985).

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References


