Rift-wide correlation of 1.1 Ga Midcontinent rift system basalts: implications for multiple mantle sources during rift development

Suzanne W. Nicholson, Steven B. Shirey, Klaus J. Schulz, and John C. Green

Abstract: Magmatism that accompanied the 1.1 Ga Midcontinent rift system (MRS) is attributed to the upwelling and decompression melting of a mantle plume beneath North America. Five distinctive flood-basalt compositions are recognized in the rift-related basalt succession along the south shore of western Lake Superior, based on stratigraphically correlated major element, trace element, and Nd isotopic analyses. These distinctive compositions can be correlated with equivalent basalt types in comparable stratigraphic positions in other MRS localities around western Lake Superior. Four of these compositions are also recognized at Mamainse Point more than 200 km away in eastern Lake Superior. These regionally correlative basalt compositions provide the basis for determining the sequential contribution of various mantle sources to flood-basalt magmatism during rift development, extending a model originally developed for eastern Lake Superior. In this refined model, the earliest basalts were derived from small degrees of partial melting at great depth of an enriched, ocean-island-type plume mantle source ($\varepsilon_{Nd}(1100)$ value of about 0), followed by magmas representing melts from this plume source and interaction with another mantle source, most likely continental lithospheric mantle ($\varepsilon_{Nd}(1100) < 0$). The relative contribution of this second mantle source diminished with time as larger degree partial melts of the plume became the dominant source for the voluminous younger basalts ($\varepsilon_{Nd}(1100)$ value of about 0). Towards the end of magmatism, mixtures of melts from the plume and a depleted asthenospheric mantle source became dominant ($\varepsilon_{Nd}(1100) = 0$ to +3).

Résumé : Le magmatisme contemporain de la mise en place du système du rift Midcontinental, il y a 1,1 Ga, est attribué au soulèvement et à une fusion par baisse de pression d'un panache mantellique localisé sous l'Amérique du Nord. Le long de la rive sud dans la partie occidentale du lac Supérieur, cinq compositions distinctes ont été reconnues parmi les coulées de basalte de la succession basaltique associée au rift, sur le fondement de correlations stratigraphiques établies pour les éléments majeurs et en traces, et les analyses isotopiques du Nd. Ces compositions distinctes peuvent être mises en corrélation avec les types de basalte équivalents qui occupent des niveaux stratigraphiques comparables dans les autres localités du système du rift Midcontinental voisines du secteur occidental du lac Supérieur. On a identifié également quatre de ces compositions à Mamainse Point, c'est-à-dire à plus de 200 km de distance, dans la région orientale du lac Supérieur. Ces corrélations régionales fondées sur les compositions des basaltes fournissent les éléments de base pour déterminer la contribution séquentielle des différentes sources mantelliques au magmatisme des coulées de basalte durant le développement du rift, perfectionnant le modèle développé initialement pour la région orientale du lac Supérieur. Dans ce modèle raffiné, les premiers basaltes formés dérivaient de faibles degrés de fusion partielle à grande profondeur d'un panache mantellique enrichi de type océanique-insulaire ($\varepsilon_{Nd}(1100)$ proche de 0), suivis de magmas composés des liquides de fusion partielle du panache et d'une interaction avec une autre source mantellique, plus probablement issue du manteau lithosphérique continental ($\varepsilon_{Nd}(1100) < 0$). La contribution relative de cette deuxième source mantellique diminuait avec le temps, au fur et à mesure qu'augmentait la proportion de fusion partielle du panache qui finalement est devenue la source dominante alimentant les volumeuses coulées de basalte plus jeunes ($\varepsilon_{Nd}(1100)$ proche de 0). Les derniers stades du magmatisme ont été dominés par les mélanges de magmas dérivés du panache et d'une source appauvrie du manteau asthénosphérique ($\varepsilon_{Nd}(1100) = 0$ à +3).

Introduction

The 1.1 Ga Midcontinent rift system (MRS) contains at least $2 \times 10^6$ km$^3$ of volcanic rocks (Cannon 1992) which were emplaced within about 22 Ma (Davis and Green 1997), and provides an example of a structurally intact continental rift that nearly formed an oceanic basin. The last decade has been a period of intense data gathering about all aspects of the rift. This effort coincided with the publication of rapidly changing concepts regarding the general development of continental rifts, flood-basalt provinces, and mantle plumes (Cox 1980; R.S. White et al. 1987; McKenzie and Bickle 1988; Richards et al. 1989; R.S. White and McKenzie 1989, 1995; Campbell and Griffiths 1990; Arndt and Christensen 1992; R.S. White 1992; Turner and Hawkesworth 1995). Models developed from these concepts suggest that progressive melting of a mantle plume head can produce voluminous flood basalts distributed over a region up to $1 \times 10^6$ km$^2$ or more (e.g., R.S. White and McKenzie 1989; R.S. White 1997). The
sequential compositions of erupted flood basalts derived from melting at this scale provide a basis for evaluating the nature and dynamics of mantle sources during riftting.

Most of the MRS is buried by water or Paleozoic strata, but recent deep crustal seismic reflection, refraction, and gravity profiles (Behrendt et al. 1988; Cannon et al. 1989; Hinze et al. 1990; Hutchinson et al. 1990; McGinnis and Mudrey 1991; Allen et al. 1995) show that it extends to as much as 30 km depth and is segmented into a number of subbasins. High-precision U-Pb zircon dating (Paces and Miller 1993; Davis and Green 1997; Zartman et al. 1997) has constrained the absolute time frame of magmatism and allows for resolution of individual magmatic pulses and hiatuses (Miller et al. 1993; Davis and Green 1997; Zartman et al. 1997) tied to detailed stratigraphy provide the basis for geochemical correlations that allow the nature and interaction of magma sources during development of the Midcontinent rift to be explored.

Abundant geologic, geochronologic, geochemical, and isotopic data for rift basalts on the south shore of western Lake Superior are now available. The relationships observed in this stratigraphic section can be compared with other MRS exposed sections, in particular the well-documented section at Mamainse Point. The correlation of geographically isolated sequences provides a more complete view of the succession of magma types during rift development than can be observed at any one locality. The regional correlation of flood-basalt compositions extends the model for the succession of magmatic sources derived for eastern Lake Superior (Klewin and Berg 1991; Shirey et al. 1994) and leads to a general model for the interaction of mantle and crustal sources such as enriched continental lithospheric mantle of probable Archean age, enriched plume-type mantle, and depleted convecting mantle.

Geological setting

The arcuate 1.1 Ga Midcontinent rift system extends more than 2000 km from Kansas north beneath Lake Superior and then southeast beneath the Michigan basin to the Grenville Front (Fig. 1), cutting across crustal terranes ranging in age from 3.6 to 1.65 Ga (Van Schmus and Hinze 1985; Van Schmus et al. 1987). Recent seismic reflection profiles (Behrendt et al. 1988; Cannon et al. 1989; Allen et al. 1995) show that the deepest portion of the rift subsided along large normal growth faults to a depth of about 30 km, accommodating at least 20 km of rift-related volcanic rocks and 10 km of overlying sedimentary rocks. Broad shallow basins filled with rift-related volcanic and sedimentary rocks flank these deep central graben segments. In the western Lake Superior region, individual central graben segments are asymmetric, alternating across major accommodation or transform zones (Cannon et al. 1989; Allen et al. 1995), whereas in eastern Lake Superior, the central graben is symmetric (Mariano and Hinze 1994). Two basement blocks (White’s ridge and Grand Marais ridge: WR and GMR in Fig. 1) acted as topographic high points as the volcanic basins subsided around them (Allen et al. 1995). Deposition of volcanic flows was reduced near the margins of the rift basin and in the vicinity of these crustal blocks, At about 1060 Ma, a period of compression and thrust faulting inverted the central graben (Cannon et al. 1993a).

Rift-related volcanic and sedimentary rocks, called the Keweenawan Supergroup, are present at the surface only in the Lake Superior region, primarily along the margins of the rift (Fig. 1). Southeast and southwest of Lake Superior, rift-related rocks are covered by Paleozoic sedimentary rocks; samples are available only from drill core. Most of the exposed outcrop of MRS volcanic and sedimentary rocks occur in western Lake Superior (Fig. 1). Volcanism was dominated by subaerial tholeiitic basalts flows with lesser intermediate and rhyolitic rocks.

Historically, a regionally recognized shift in magnetic polarity from reversed to normal has provided a ready correlation tool (e.g., Halls and Pesonen 1982). Recent high-precision U-Pb zircon ages have constrained the rift’s duration of magmatism from about 1108 to about 1086 Ma and placed the regionally recognized magnetic polarity shift at about 1100 Ma (Miller et al. 1995a; Davis and Green 1997). Recognition of other magnetic reversals in the section and the acquisition of zircon ages have clarified the overall time frame for rift development and magmatism, but also have raised new questions. Tools such as stratigraphically controlled geochemical and isotopic data have become increasingly important in identifying regional correlations.

A reasonably complete stratigraphic section of MRS volcanic and sedimentary rocks about 17 km thick is preserved in northern Michigan and Wisconsin on the southern margin of the lake (Fig. 2). Although the outcrop is discontinuous, detailed mapping and sampling provide the basis for regional correlation of geochemical and isotopic data with well-documented stratigraphy, constrained by magnetic polarity and precise U-Pb geochronology.

Sampling and analytical techniques

Over a period of more than 10 years, several hundred MRS samples have been collected around Lake Superior by United States Geological Survey personnel and analyzed for major and trace elements by United States Geological Survey laboratories, using inductively coupled plasma – atomic emission spectrometry (ICP–AES), rapid rock, X-ray fluorescence spectrometry (XRF), and instrumental neutron-activation analysis (INAA) techniques as described in Baedeker (1987). From this suite, nearly 70 volcanic samples from the south shore of western Lake Superior and 35 samples from elsewhere around Lake Superior have been analyzed for Sr, Nd, and Pb isotopic composition. Concentrations of Rb, Sr, Nd, and Sm were determined by isotope dilution along with isotopic compositions of Sr, Nd, and Pb at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, following procedures similar to those given in Carlson (1984) and Nicholson and Shirey (1990). These largely unpublished results, in addition to published and unpublished chemical data provided by J.C. Green based on three decades of research on the North Shore Volcanic Group, as well as the chemical analyses and (or) Nd isotopic data reported by Brannon (1984), Dosso (1984), Sutcliffe (1987), Paces (1988), Paces and Bell (1989), Nicholson and

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Shirey (1990), Klewin and Berg (1991), Lightfoot et al. (1991), and Shirey et al. (1994), provide the basis for the subsequent discussion.

**South shore of western Lake Superior**

A review of the detailed stratigraphy of the south shore of western Lake Superior is important at this point, in light of recent geochemical distinctions made within the earliest formations (Nicholson and Shirey 1992; Nicholson et al. 1994), a newly refined age for the early flows (Davis and Green 1997) and new ages for some of the youngest units on the south shore (Zartman et al. 1997), and the recent recognition of a possible additional magnetic reversal in this section. These newly acquired refinements provide constraints on the nature and duration of rift magmatism, particularly the earliest magmas, and provide critical criteria with which to draw correlations with other stratigraphic sections throughout the rift.

**Stratigraphy**

In Wisconsin and Michigan, the basal unit of the Keweenawan Supergroup is the Bessemer Quartzite, a thin lacustrine sandstone (Fig. 2). Overlying the Bessemer is the basal volcanic unit, the Siemens Creek Volcanics (SCV), which consists of two informally defined upper and lower members. The lower member contains only basalt, including a newly recognized picrite. The upper member is dominated by basalt but includes minor basaltic andesite and andesite. No rocks with SiO$_2$ > 57 wt.% have been found in this formation.
The lower member is thin (<50 m thick), has limited regional extent, and is distinctive because it contains augite phenocrysts, a rarity among younger MRS basalts, including those of the upper member of the SCV. The upper member is more widespread than the lower member and considerably thicker (up to 1.5 km). Near Ironwood, Michigan, the augite-phyric basalts of the lower member disappear to the east and the basalts that directly overlie the Bessemer Quartzite are upper Siemens Creek flows that do not contain augite phenocrysts. Pillows formed in the basal few basalt flows that directly overlie the Bessemer Quartzite, regardless of whether the flow composition is lower or upper Siemens Creek. The SCV is characterized by reversed magnetic polarity (Palmer and Halls 1986). No ages have been determined for the SCV, but by correlation with the earliest ages from the compositionally similar units of the Osler Group and the Nipigon sills north of Lake Superior, volcanism was probably initiated about 1 108 Ma (Davis and Green 1997).

The Kallander Creek Volcanics (KCV) overlies the SCV, and also has been informally divided into upper and lower...
members. Both members range from basalt to intermediate rocks and rhyolite. The lowermost 1.5 km of the KCV consists of flood basalt, with minor andesite and rhyolite. The basalts typically have plagioclase phenocrysts, which, in some flows, form large radiating clusters. A rhyolite flow near the top of the lower KCV gives an age of 1107.3 ± 1.6 Ma (Davis and Green 1997). The upper member (about 2 km thick) is dominated by andesite and is considered to be the extrusive products of a localized magmatic system (Cannon et al. 1993b). On the east side of the Mellen Intrusive Complex, a thick and laterally extensive rhyolite at the top of the upper member of the KCV yields a date of 1099.0 ± 2.6 Ma (Zartman et al. 1997). The Mellen granite and Mellen gabbro, which intrude the KCV, have ages of 1101.5 ± 2.9 and 1102.1 ± 3.5 Ma, respectively (Zartman et al. 1997).

Volcanic rocks in the KCV are reversely polarized, with two exceptions (Fig. 2), both of which have been recognized during reconnaissance fieldwork in the last 2 years. There appears to be a thin interval of flows with normal polarity at the base of the upper member. The stratigraphic thickness of this interval has not yet been delineated and exposure is limited; however, most of the upper KCV elsewhere has reversed magnetic polarity. The second exception occurs at the top of the formation. Historically, the regionally recognized shift in magnetic polarity from reversed (lower Keweenawan) to normal (upper Keweenawan) has been placed at the boundary between the KCV and the overlying Portage Lake Volcanics (PLV) on the south shore (e.g., Books 1968). However, a recent reconnaissance survey of magnetic polarity identified the shift from reversed to normal polarity as occurring a few flows below the 1099 Ma rhyolite that forms the top of the KCV. This age corroborates ages that forms the top of the Keweenaw Peninsula. Near the Mellen Intrusive Complex, a thick and laterally extensive rhyolite at the south shore appears in Table 1. Five distinctive flood-basalt compositions are recognized and designated basalt types I-V, in order to ease the comparisons among detailed stratigraphic successions at various localities.

The PLV and all younger Keweenawan formations have normal magnetic polarity. The PLV is exposed laterally for about 200 km from the Mellen Intrusive Complex east to the tip of the Keweenaw Peninsula. Near the Mellen Intrusive Complex, the PLV disconformably overlies the KCV (Hubbard 1975) and is concordantly overlain by the Copper Harbor Conglomerate. Where the PLV is exposed along the Keweenaw Peninsula and in northern Wisconsin, it consists of 3–5 km of subaerial tholeiitic basalt flows with minor rhyolites and few intermediate rocks, but is truncated by the high-angle reverse Keweenaw fault (Fig. 1). Seismic reflection profiles across Lake Superior suggest that the thickness of the PLV rocks may have been 6–7 km near the axis of the rift (Cannon et al. 1989). Two stratigraphically separated basalt flows from the PLV on the Keweenaw Peninsula yield ages of 1094.0 ± 1.5 and 1096.2 ± 1.8 Ma (Davis and Paces 1990).

The Porcupine Volcanics overlies the PLV in the vicinity of the Porcupine Mountains in Michigan (Fig. 1), and consists of basalt, abundant andesite, and rhyolite (Johnson and White 1969; Hubbard 1975; Cannon and Nicholson 1992). This unit has a lateral extent of about 35 km and maximum thickness of at least 4 km. The overlying Copper Harbor Conglomerate thins dramatically where the Porcupine Volcanics is present. A rhyolite at the top of the Porcupine Volcanics yields an age of 1093.8 ± 1.4 Ma (Zartman et al. 1997).

The Chengwatana Volcanics, which lies in the Ashland syncline to the west of the Mellen Intrusive Complex (Fig. 1), occupies the same stratigraphic position as the PLV, which lies to the east of the Mellen Intrusive Complex (Fig. 2). The Chengwatana Volcanics is at least 14 km thick on the southeast limb of the syncline (Allen et al. 1995), although the true thickness is unknown due to truncation by the Lake Owen fault. A Chengwatana rhyolite near the Lake Owen fault yields an age of 1094.6 ± 2.1 Ma (Zartman et al. 1997), an age comparable to the upper part of the PLV.

Near the base of the Copper Harbor Conglomerate, both in the Porcupine Mountains area and off the north shore of the Keweenaw Peninsula, a few to several dozen basaltic andesite to andesite flows are interspersed within the conglomerate (Paces and Bornhorst 1985). North of the Keweenaw Peninsula these flows are informally called the Lake Shore traps (Lane 1911), and one flow yields an age of 1087.2 ± 1.6 Ma (Davis and Paces 1990).

**Geochemistry**

To provide a consistent basis on which to compare magma compositions among formations, only those samples with SiO2 < 53 wt. % are considered in the following discussion. Regional hydrothermal alteration that accompanied native copper deposition clearly affected the mobile alkali elements (e.g., Paces 1988; Nicholson 1990). However, less mobile trace and major elements can be used to characterize basalt compositions. A summary of average compositions for basalts in each formation east of the Mellen Intrusive Complex on the south shore appears in Table 1. Five distinctive flood-basalt compositions are recognized and designated basalt types I–V, in order to ease the comparisons among detailed stratigraphic successions at various localities.

Compared to basalts from other south shore formations, the basalts of the lower member of the SCV (basalt type I) are characterized by substantially lower Al2O3, the highest MgO content, the largest MgO range (8–17 wt. %), and the steepest rare earth element (REE) slopes (Table 1). They have the highest Cr and Ni abundances and moderately high incompatible trace element abundances (Fig. 3). One sample from this unit collected just west of the Mellen Intrusive Complex is picritic (MgO = 16.9 wt. %; Mg# = 0.72, where Mg# = molar Mg/(Mg + Fe)) and is the only MRS picritic identified on the south shore. A single basalt sample from this unit has been analyzed for Nd isotopic composition and yields an εNd(100) value of −0.6.

Basalts of the upper SCV (basalt type II) are characterized by higher Al2O3, lower TiO2 and MgO, and lower chondrite-normalized Ce/Yb (CeYb) than basalts in the lower Siemens Creek, and still have low heavy REE (HREE) abundances (Table 1). Compatible and incompatible trace element abundances are less overall than for the lower SCV. In addition, the upper SCV basalts show slight negative Nb and Ta anomalies (Fig. 3), in contrast to the smooth incompatible trace element pattern of the lower SCV basalts. Six samples analyzed for Nd isotopic composition yield an average εNd(100) value of −3.6 (range = −1.5 to −6.9).
Table 1. Average basalt compositions for formations on the south shore of western Lake Superior.

<table>
<thead>
<tr>
<th>Siemien Creek Volcanics</th>
<th>Kallander Creek Volcanics</th>
<th>Low TiO₂ Basalts</th>
<th>High TiO₂ Basalts</th>
<th>Porcupine Volcanics</th>
<th>Late second-phase basalts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower (n = 5; basalt type I)</td>
<td>Upper (n = 18; basalt type II)</td>
<td>Lower (n = 10; basalt type III)</td>
<td>Upper (n = 7)</td>
<td>Low TiO₂ (n = 31; basalt type IV)</td>
<td>High TiO₂ (n = 8)</td>
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<tr>
<td>SiO₂</td>
<td>48.62±1.28</td>
<td>51.20±1.35</td>
<td>50.92±1.25</td>
<td>49.37±1.04</td>
<td>48.56±1.10</td>
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<td>TiO₂</td>
<td>2.41±0.26</td>
<td>1.70±0.22</td>
<td>3.62±0.63</td>
<td>2.99±0.93</td>
<td>1.70±0.22</td>
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<tr>
<td>Al₂O₃</td>
<td>9.92±1.40</td>
<td>15.13±0.99</td>
<td>14.28±1.01</td>
<td>14.06±1.26</td>
<td>16.81±0.66</td>
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<tr>
<td>Fe₂O₃</td>
<td>2.08±0.11</td>
<td>1.71±0.11</td>
<td>2.05±0.20</td>
<td>2.20±0.25</td>
<td>1.75±0.12</td>
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<tr>
<td>CaO</td>
<td>11.77±0.61</td>
<td>9.68±0.60</td>
<td>11.64±1.11</td>
<td>12.48±1.44</td>
<td>10.44±0.68</td>
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<tr>
<td>MgO</td>
<td>0.22±0.01</td>
<td>0.18±0.01</td>
<td>0.18±0.03</td>
<td>0.24±0.02</td>
<td>0.19±0.05</td>
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<tr>
<td>MnO</td>
<td>11.06±3.06</td>
<td>6.77±1.06</td>
<td>4.08±0.99</td>
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<td>FeO</td>
<td>10.30±1.29</td>
<td>9.82±0.93</td>
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<tr>
<td>Na₂O</td>
<td>2.06±0.86</td>
<td>2.74±0.50</td>
<td>4.18±0.96</td>
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<td>2.68±0.74</td>
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<td>K₂O</td>
<td>1.28±0.29</td>
<td>0.84±0.50</td>
<td>1.40±0.73</td>
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<tr>
<td>P₂O₅</td>
<td>0.28±0.06</td>
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<td>0.54±0.10</td>
<td>0.45±0.17</td>
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<td>100.00</td>
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<tr>
<td>Mg#</td>
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<td>0.56</td>
<td>0.39</td>
<td>0.46</td>
<td>0.58</td>
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</table>

Note: Due to limitations of space, individual analyses cannot be reported here and instead are represented by averages, which are used to define the five distinctive flood-basalt compositions. Individual analyses are available on request from the first author. Major elements are reported in weight percent on an anhydrous basis, assuming FeO(Fe₂O₃ + FeO) = 0.85, and trace elements in parts per million as analyzed. Uncertainties on the averages are 1σ. Mg#, Mg/Fe + Mg (mole percent); Ce₀/Yb₀, chondrite-normalized Ce/Yb; n, number of samples.
The lower KCV contains the most evolved basalts in the south shore section, as evidenced by these basalts having the highest overall TiO₂ content, the lowest MgO, Cr, and Ni, and the lowest average Mg#. This compositional group (basalt type III) has a chondrite-normalized incompatible trace element pattern that is very similar to that of the lower SCV, but elemental abundances are higher (Fig. 3). Only one sample of the lower KCV has been analyzed for Nd isotopic composition, yielding an εNd(1100) value of -0.9.

Basalts of the upper KCV have a major element composition similar to that of basalts from the lower KCV, with high TiO₂ and low MgO, but are less fractionated than the lower KCV and have higher Mg#, Cr, Ni, and Sc (Table 1). However, there is a marked contrast between the two units in incompatible trace element composition (Fig. 3), with the upper KCV basalts showing negative Nb and Ta anomalies, which are not present in the lower KCV. In addition, the REE slopes are distinctly different, and the upper KCV basalts have higher HREE than the lower KCV basalts (Fig. 3). Four samples of the upper KCV yield a narrow range around an average εNd(1100) value of -1.5 (Table 1).

The exposed PLV basalts can be divided into two groups based on major and incompatible trace element composition, informally described as high-TiO₂ (> 2.5 wt. % TiO₂) and low-TiO₂ (< about 2.0 wt. % TiO₂) basalts (Nicholson 1990). The low-TiO₂ PLV basalts are high in alumina (Table 1), and some samples have Mg#’s as high as 0.66. With the exception of one group of younger basalts, the low-TiO₂ PLV basalts have the lowest abundances of incompatible trace elements of any basalt group (Table 1). The high-TiO₂ PLV basalts are somewhat more differentiated (lower Mg#) and have higher incompatible trace element abundances. Slopes of REE patterns are similar for both compositional groups (CeNy/YbN = 2.6 and 2.7), and both compositional groups have similar average εNd(1100) values (+0.4 vs. +0.6; Table 1). The laterally extensive low-TiO₂ basalts make up at least 90% of the PLV, whereas the far less abundant high-TiO₂ basalts are geographically localized. Therefore, for the purposes of this discussion, the low-TiO₂ PLV basalt composition is taken to be representative of basalt type IV. The average upper KCV basalt composition is nearly identical to that of the high-TiO₂ PLV basalts (Fig. 3), differing only in εNd(1100) value (Table 1).

Basalts of the Porcupine Volcanics are relatively enriched in Th and Ba compared with other basalt types (Table 1) and have relatively high incompatible trace element abundances and distinct negative Nb and Ta anomalies (Fig. 3). In contrast to other MRS basalts, these basalts have strongly negative εNd(1100) values (< -10; Table 1), suggesting that these rocks represent crustally contaminated compositions.

Preliminary evaluation of chemical analyses of basalts from the Chengwatana Volcanics on the southeast limb of the Ashland syncline suggests that the distinctions between low- and high-TiO₂ basalts determined for the PLV can be applied to this unit as well. The bulk of the Chengwatana Volcanics is high-alumina basalt and, for the purposes of this discussion, the PLV and Chengwatana Volcanics will be considered correlative. However, there is a basalt composition in the upper part of the Chengwatana that has not been recognized in the PLV. This composition, informally called the “late second-phase” basalt (Table 1), refers to a group of basalts about 0.5 km thick near the top of the formation. This composition (basalt type V) has only been recognized in a few dikes elsewhere on the south shore, but flows of similar composition appear at the top of the North Shore Volcanic Group (NSVG) in Minnesota. Although chemical and isotopic data are limited for this unit on the south shore, it does represent a distinctive composition characterized by high Mg#, low incompatible trace element abundances, and positive εNd(1100) values (+2.2; Table 1).

Correlations in western and central Lake Superior

It is only within the last decade that a critical body of stratigraphically well-controlled geochemical and isotopic data for exposed MRS magmatic rocks has been amassed. These data coupled with more than two dozen high-precision U–Pb zircon ages (Fig. 4) and the recognition of multiple changes in direction of magnetic polarity now allow correlations to be drawn on a regional scale (Fig. 5). An important result of the high-precision zircon dating effort is the recognition that rift magmatism was episodic over a period of about 22 Ma (Fig. 4) (Miller et al. 1995a; Davis and Green 1997).

First magmatic phase: about 1108–1105 Ma

The oldest ages determined for MRS magmatic rocks are 1108.2 ± 0.9 Ma for the basaltic and peridotitic Logan sills (Davis and Sutcliffe 1985; Davis and Green 1997) and

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1108 ± 1 Ma for the alkaline Coldwell Complex in Ontario (Heaman and Machado 1992). At the base of the Osler Group is a rhyolite that has been dated at 1107.5\(^\pm\)4 Ma (Davis and Sutcliffe 1985). Numerous ages for rhyolites and plutonic rocks in the NSVG cluster between 1107 and 1108 Ma (Fig. 4); a rhyolite in the KCV yields an age of 1107.3 Ma, and a rhyolite near the top of the central suite in the Osler Group has been dated at 1105.3 Ma (Davis and Green 1997).

The three basalt compositional groups erupted during the first phase of magmatism on the south shore of Lake Superior are also found in other localities around western Lake Superior (Fig. 5). The augite-phryic flows of the lower SCV are products of the first preserved erupted MRS magma (basalt type I), a distinctive magma composition exposed elsewhere only in western Lake Superior. Flows of this earliest phase are found at the base of the Keweenawan Supergroup on the south shore (lower SCV), as the basal units in the Ely’s Peak (Kilburg 1972) and Grand Portage areas (Green 1972, 1977, 1995) of the NSVG, and as the basal unit (lower suite) of the Osler Group in Ontario (Lightfoot et al. 1991) (Fig. 5). This unit is generally less than 100 m thick and overlies a quartz sandstone. The basal flows are commonly pillowved, indicating eruption into what was probably a shallow lake. On Black Bay Peninsula, the lower suite is about 750 m thick and overlies a thin conglomerate (McIwaine and Wallace 1976; Lightfoot et al. 1991). The basal augite-phryic unit everywhere has reversed magnetic polarity (Green and Books 1972; Halls 1974; Halls and Pesonen 1982; Palmer and Halls 1986). The chemical composition of this unit is consistent among localities (low Al\(_2\)O\(_3\) and HREE, smooth, broadly concave-down, chondrite-normalized trace element pattern; Fig. 6), as is the Nd isotopic composition, which yields an average \(c_{Nd}(1100)\) of -0.1 (\(n = 10\) samples) with a narrow range (-0.7 to +0.7; Fig. 7).

The second composition (basalt type II), exemplified by the upper Siemens Creek basalts, also can be correlated with basalts of similar composition in the NSVG, the Osler Group, and possibly at Ely’s Peak. Everywhere these basalts have reversed magnetic polarity. On the northeast limb of the NSVG, basalts with this composition are found in the upper part of the Grand Portage lavas and in the overlying Hovland lavas (Fig. 5). This compositional group forms the basal lavas west of Grand Portage, where the augite-phryic flows pinch out, much as the upper SCV forms the basal flows on the south shore, where the lower SCV is absent. South shore and north shore representatives of this compositional group show similar chondrite-normalized trace element patterns, including slightly negative Nb and Ta anomalies, which distinguish these rocks from the lower Siemens Creek and lower Kallander Creek compositions (Fig. 6). This compositional type differs from most other MRS basalt units by its broad range of \(c_{Nd}(1100)\) values (-1.4 to -6.9; Fig. 7) and negative average \(c_{Nd}(1100)\) of -3.8 (\(n = 14\) samples).

On Black Bay Peninsula, the central suite overlies the basal augite-phryic basalts. Although much of the central suite has been shown to be affected by variable amounts of crustal contamination (Lightfoot et al. 1991), the most primitive representatives of the central suite are broadly comparable to the upper Siemens Creek composition (Fig. 6), as would be expected from its stratigraphic position. Nd isotopic data have not yet been published for the central suite.

On the south shore, the third basalt composition (basalt type III) is represented by the lower member of the KCV, which overlies the SCV. The lower KCV has higher Al\(_2\)O\(_3\) and TiO\(_2\) and very low MgO, suggesting substantial fractionation, but is otherwise similar geochemically to the lower Siemens Creek (Figs. 3, 6). No augite phenocrysts are present, but large tabular plagioclase phenocrysts are common (Green 1982). This composition is also present in the Grand Portage and Hovland lavas on the northern end of the north shore (Fig. 5). An age of 1107.3 Ma from the top of the lower KCV is indistinguishable from the 1107.7 Ma age determined for the top of the Hovland lavas. This composition is also present in the Ely’s Peak area, but may be intercalated with flows of the lower Siemens Creek composition (Kilburg 1972). Only a few representative chemical analyses are available for the Osler Group (Lightfoot et al. 1991), but this composition does not appear to be present (or possibly is overprinted by crustal contamination). Everywhere these basalts have reversed magnetic polarity. At Ely’s Peak and on the south shore, this composition has an \(c_{Nd}(1100)\) of about -0.6 (\(n = 3\) samples; Fig. 7).
Evidence for a volcanic hiatus: 1105–1100 Ma
A compilation of high-precision U−Pb zircon ages for MRS magmatic rocks (Fig. 4) suggests that after an early period of volcanic eruptions and emplacement of intrusions, there was a period of diminished magmatic activity from at least 1105 Ma until about 1100 Ma in western Lake Superior (Miller et al. 1995a; Davis and Green 1997). This apparent hiatus is best documented within the NSVG where on the northeast limb, within about 100 m of stratigraphy, there is an apparent 7 Ma gap between the top of the Hovland basalts.
Fig. 6. Comparison of trace element patterns for each of the five distinctive mantle-derived basalt compositions identified in both western and eastern MRS. Solid symbols represent average compositions for the south shore, north shore, and Osler Group in western Lake Superior. Open symbols identify specific groups recognized on Mamainse Point. Data source for Mamainse Point in eastern Lake Superior is Shirey et al. (1994). Data sources for western Lake Superior are as follows: (a) Brannon (1984), Nicholson (1990), and J.C. Green and S.W. Nicholson, unpublished data; Normalizing factors as in Fig. 3; (b) Brannon (1984), Nicholson (1990), and S.W. Nicholson, unpublished data; (c) J.C. Green and S.W. Nicholson, unpublished data; (d) Lightfoot et al. (1991), and J.C. Green and S.W. Nicholson, unpublished data; and (e) Kilburg (1972), Lightfoot et al. (1991), and J.C. Green and S.W. Nicholson, unpublished data.

Fig. 7. Compilation of initial $\epsilon_{Nd}$ data for MRS rocks with $SiO_2 < 55$ wt.\% for western and eastern Lake Superior. Data sources include S.W. Nicholson (unpublished data), Brannon (1984), Paces and Bell (1989), Nicholson and Shirey (1990, 1992), and Shirey et al. (1994). The fields labeled CC, CLM, PM, and DM represent the estimated Nd compositions various source reservoirs would have had at 1100 Ma. CC, field for Archean crust; CLM, field for continental lithospheric mantle (Shirey 1997); PM, plume; DM, depleted asthenospheric mantle source (like that of modern mid-ocean-ridge basalt) (Nicholson and Shirey 1990; Shirey et al. 1994).

(1107 Ma) and the base of the overlying Chicago Bay flows (1100 Ma) (Davis and Green 1997). Intrusion of the Duluth Complex obscures any volcanic stratigraphy that might have been erupted in this time interval on the southwest limb.

On the south shore, there is no obvious break in stratigraphy within the 3.5 km thick KCV that might mark a hiatus in volcanism, although outcrop becomes increasingly sparse upsection. The top of the 1.5 km thick lower KCV is about 1107 Ma and, given that the Mellen Intrusive Complex was emplaced into the lower and upper KCV about 1102–1101 Ma (Zartman et al. 1997), the earliest upper KCV lavas had to have erupted by 1102 Ma. Thus, any volcanic hiatus on the south shore could be as much as 5 Ma (1107–1102 Ma).

In the Osler Group, the Agate Point rhyolite at the top of
the reversely polarized central suite has been dated at 1105 Ma (Davis and Green 1997). Most of the upper suite is also magnetically reversed, and a 10 m thick conglomerate separates those flows from a few overlying flows of normal magnetic polarity (Halls 1974). The reversely polarized flows make up a stratigraphic thickness of nearly 3000 m. If the magnetic reversal in the Osler Group took place at about 1100 Ma based on ages in the NSVG and KCV, then only about 600 m accumulated during the period between the youngest dated eruption of the central suite (1105 Ma) and the magnetic reversal (1100 Ma).

Thus, there is an apparent diminishing of flood-basalt eruptions in several localities around western Lake Superior from about 1105 to about 1100 Ma. Based on available ages, the duration is apparently about 5–7 Ma in any given locality, but localized magmatic systems (individual central volcanoes and emplacement of plutons) may have been active during this time (e.g., the upper member of the KCV and related Mellen Intrusive Complex, and perhaps parts of the central and upper suites of the Osler Group).

**Second magmatic phase: 1100–1094 Ma**

Beginning at about 1100 Ma, after the period of relative magmatic quiescence, flood-basalt volcanism and emplacement of large intrusions resumed dramatically around the rift (Fig. 4). This phase of MRS volcanism is the best exposed phase in western Lake Superior and is represented by the normally polarized PLV on the south shore and Isle Royale (Huber 1973; Paces 1988; Nicholson 1990), the normally polarized sections of the southwest and northeast limbs of the NSVG (Brannon 1984; Dosso 1984; Green 1972, 1982, 1983), and the few flows of normally polarized volcanic rocks at the top of the Osler Group (Lightfoot et al. 1991). Much of the Duluth Complex was intruded about 1099 Ma, followed shortly by the Beaver Bay Complex (Paces and Miller 1993).

On the Keweenaw Peninsula 5–6 km of PLV is preserved, all normally polarized. Two basalt flows stratigraphically separated by about 2.5 km yield ages of 1094 and 1096 Ma (Davis and Paces 1990). The low-TiO₂ Portage Lake flood basalts (basalt type IV: high Al₂O₃, low REE abundances; Fig. 6), which make up about 90% of the formation, are remarkably consistent in their chemical and Nd isotopic composition over a very large outcrop area (Keweenaw Peninsula to Isle Royale) as well as a substantial stratigraphic thickness (Huber 1973; Paces 1988; Nicholson 1990). This compositional type has $\varepsilon_{\text{Nd}(100)}$ values of +1.0 to −0.6 (Table 1) and average $\varepsilon_{\text{Nd}(1100)}$ of +0.4 (n = 8 samples with one outlier at −2.2). High-TiO₂ PLV basalts (about 10% of the formation) are more fractionated than the low-TiO₂ PLV basalts but also have a narrow range of $\varepsilon_{\text{Nd}(1100)}$ values of +1.5 to 0.0 (Table 1), with an average $\varepsilon_{\text{Nd}(1100)}$ of +0.6 (n = 4 samples). Chemical data are sparse for the few normally polarized flows at the top of the Osler Group, but those reported by Lightfoot et al. (1991) are similar to the composition of low-TiO₂ PLV basalt. This correlation is corroborated by the single Nd isotopic analysis available, which yields an $\varepsilon_{\text{Nd}(1100)} = −0.2$.

On the southwest limb of the NSVG, nearly 10 km of stratigraphy is preserved, of which about 9 km is normally polarized. More than 6 km of these normally polarized flows was erupted between about 1098 and 1096 Ma (Davis and Green 1997), suggesting that the bulk of the PLV may be slightly younger than the bulk of the NSVG on this limb. Brannon (1984) analyzed 160 successive flows (about 4 km thick in total), providing excellent compositional coverage for nearly half of the stratigraphic thickness of the southwest limb. Both low- and high-TiO₂ basalts are well represented in this section, whereas intermediate and felsic flows are few and confined to the lower part. Brannon (1984) reported $\varepsilon_{\text{Nd}(1100)}$ values for basalts and basaltic andesites that range from +1.9 to −1.1 (n = 12 samples, with one outlier at −5.9), comparable to the values determined for the PLV (Paces and Bell 1989; Nicholson and Shirey 1990).

The northeast limb of the NSVG differs substantially from the southwest limb in two fundamental ways. First, the entire stratigraphic section is condensed into about 6.5 km. Of the 4 km of normally polarized rocks, the lowermost several hundred metres was erupted between about 1100 and 1098 Ma, and the remaining 3 km is broadly time equivalent to the bulk of the southwest limb. Second, rhyolites make up at least 25% of the section (Green 1995; Vervoort and Green 1997), and intermediate rocks are abundant. Green (1995) attributes much of the chemical variation observed in this region to the development of crustal magma chambers in which mantle magmas ponded, fractionated, and variably assimilated Archean country rock. For three mafic samples in the Keweenawan reference suite (Basaltic Volcanism Study Project 1981) collected on this limb, Dosso (1984) reported $\varepsilon_{\text{Nd}(1100)}$ values ranging from −0.9 to −9.5, demonstrating a much broader range than is typical for this unit elsewhere. Vervoort and Green (1997) show that the rhyolites in this section become progressively more contaminated by older material with time. They suggest that large crustal magma chambers, such as may be represented by intrusions in the Duluth Complex, produced prolonged crustal heating and melting, substantially affecting mantle melts emplaced into the crust.

A late flood-basalt composition occurs near the top of the volcanic sequence and has been recognized in the Schroeder and Lutsen basalts at the top of the NSVG, in some dikes that cut older MRS units on the south shore, near the top of the Chengwatana on the south shore, and possibly as a few flows near the top of the PLV on the Keweenaw Peninsula (Paces 1988). This composition (basalt type V) is more primitive than other MRS basalt compositions, with the highest average Al₂O₃ content and the lowest incompatible trace element abundances (Table 1; Fig. 6). When taken as a group, these samples are displaced towards more positive $\varepsilon_{\text{Nd}(1100)}$ values (+1.3 and +3.4; n = 2 south shore samples) compared with the Portage Lake equivalent rocks (Fig. 7). Miller et al. (1995b) have recently suggested that the Schroeder–Lutsen basalts at the top of the NSVG may represent the northwest edge of the PLV, erupted beyond the central rift graben. If so, their composition as indicated here implies that they were erupted near the end of the accumulation of the PLV, not at its beginning. Ages for the late basalts at the top of the NSVG and in the Chengwatana would provide much needed constraints on the minimum age of flood-basalt volcanism and would facilitate correlations between the north and south shores of western Lake Superior.

As the second phase of flood-basalt volcanism waned...
around 1094 Ma, upper crustal magma chambers developed locally near or at the top of the Portage Lake or equivalent rocks, most notably in the Porcupine Mountains area (about 1094 Ma) of the south shore (W. S. White 1968; Green 1977; Nicholson et al. 1991). These central volcanoes produced abundant intermediate and rhyolitic rocks. Even the most mafic volcanic rocks associated with the Porcupine Volcanics have $\varepsilon_{Nd}(1100)$ values around $-10.0$ ($n = 8$ samples), suggesting substantial interaction with crustal sources.

**Volcanism during thermal subsidence: about 1087 Ma**

Flood-basalt volcanism waned abruptly after about 1094 Ma (Fig. 4). Two outcrop areas in western Lake Superior record the period of sedimentation that followed volcanism; one is the south shore, where late-stage compression has exposed a portion of the central graben, and the other is the stratigraphically equivalent section on Isle Royale, also an upthrust section of the central graben. Very minor volcanism occurred after flood-basalt volcanism ceased. Sedimentation was well established on the south shore when the few flows of the Lake Shore traps were erupted near the base of the Copper Harbor Conglomerate. Davis and Paces (1990) report an age of about 1087 Ma for one of these flows. This is close to the age of a rhyolitic body (about 1086 Ma) preserved on Michipicoten Island in eastern Lake Superior (Palmer and Davis 1987). In addition, there is a small andesite (the Bear Lake body) that intruded the Freda Sandstone on the Keweenaw Peninsula, although this intrusion has not been successfully dated.

**Regional comparison between western and eastern Lake Superior**

**Stratigraphic and geochemical correlation**

We have shown that the stratigraphic succession of five distinct flood-basalt compositions recognized on the south shore can be generally correlated with well-documented stratigraphic successions elsewhere around western Lake Superior. However, a comparison of the south shore sequence and the succession of basalt compositions reported for Mamainse Point (Shirey et al. 1994) and Michipicoten Island (Annells 1974) in eastern Lake Superior points up several important differences.

The first significant difference is that the basal augitephyric unit (lower Siemens Creek composition, basal type I) has not been recognized on Mamainse Point (Berg and Klewin 1988; Klewin and Berg 1990, 1991; Massey 1980, 1983), Alona Bay and Cape Gargantua (Massey 1980), or Michipicoten Island (Annells 1974) in eastern Lake Superior. Instead, at Mamainse Point, the basal unit (group 1) has some chemical characteristics that are similar to the upper SCV composition (basalt type II; Figs. 6, 7), although picrites are found in this group at Mamainse Point (Berg and Klewin 1988), but not in the equivalent unit in western Lake Superior. Incompatible trace element abundances of group 1 at Mamainse Point are among the lowest of MRS basalt compositions, and distinct negative Ta and Nb anomalies appear in group 1 (Klewin and Berg 1991) as they do in the similar upper SCV basalts (Fig. 6). Isotopically, the upper SCV and group 1 are also comparable: an average $\varepsilon_{Nd}(1100)$ value of about $-4$ determined for group 1 on Mamainse Point (Shirey et al. 1994) is the same as the average for upper SCV equivalent rocks in western Lake Superior (Table 1).

The second significant difference is that group 2 rocks on Mamainse Point have no direct correlative unit on the south shore of western Lake Superior. The incompatible trace element pattern of group 2 rocks is similar to the pattern for the basalt type II (Fig. 6), except that the Nb and Ta anomalies are smaller (Klewin and Berg 1991; Shirey et al. 1994). Yet, isotopically, group 2 rocks have $\varepsilon_{Nd}(1100)$ values ($-0.6$ to $-2.0$) that are close to those of the lower Siemens Creek and the lower Kallander Creek units (Fig. 7).

Basalt compositions in groups 3–5 at Mamainse Point were postulated to reflect a progressive increase in the amount of crustal contamination (Klewin and Berg 1991; Shirey et al. 1994; Shirey 1997). Given that the crustal component overprints the mantle signature, it is difficult to evaluate the original mantle magma type. Because the effects of crustal contamination are strongly dependent on the age and composition of the local basement rocks, direct compositional correlation with units on the south shore is not possible. However, the stratigraphic position and magnetic polarity of groups 3–5 as well as the association with the Great Conglomerate suggest that these flows could be time equivalent to the KCV.

Groups 6 and 7 rocks at Mamainse Point are stratigraphically and chemically correlative with the PLV (and equivalent north shore rocks, basal type IV) and the late second-phase basalts (basalt type V), respectively (Figs. 6, 7). Group 6 rocks are most similar to high-TiO$_2$ PLV basalts, including slight Nb and Ta anomalies (Fig. 6) and $\varepsilon_{Nd}(1100)$ values that center around 0 (Fig. 7). Group 7 rocks, like the youngest NSVG basalts, are more primitive compositions and have trace element abundances lower than in most other units. The slight Nb and Ta anomalies present in group 6 rocks are diminished or absent in the group 7 (Klewin and Berg 1991) and later NSVG basalts. Groups 6 and 7 basalts have $\varepsilon_{Nd}(1100)$ values that range from 0 to +3 (Fig. 7).

Group 8 rocks of Mamainse Point have no stratigraphic equivalent on the south shore of western Lake Superior. However, despite their stratigraphic differences, the chemistry (Fig. 6) and isotopic characteristics ($\varepsilon_{Nd}(1100) = -0.4$ to $-1.7$) of group 8 rocks are equivalent to those of the lower Kallander Creek unit (basalt type III), suggesting that their origins are similar.

**Correlation based on absolute age**

The correlation between western and eastern Lake Superior outlined above is based on stratigraphic, geochemical, and isotopic similarities coupled with shifts in magnetic polarity. Regional correlations based on magnetic polarity have been complicated by the presence of two additional reversals ($R-N-R-N$) at Mamainse Point that are generally not recognized elsewhere around Lake Superior (Halls and Pesonen 1982). However, if the newly recognized normal magnetic interval on the south shore is correlated with the lower normal interval at Mamainse Point, then group 5 basalts at Mamainse Point could be time equivalent to the normally polarized flows at the bottom of the upper KCV. This correlation supports the inference that the Great Conglomerate at Mamainse Point was deposited during the period of diminished volcanic activity that preceded the
attributed to the emplacement of a mantle plume beneath
The massive volcanism of the Midcontinent rift has been
White North America the sections, and that these compositions appear more or less
of well-documented but geographically distinct stratigraphic
Hutchinson et al. 1990; Nicholson and Shirey 1990; R.S.
51 6
that the uppermost magnetic reversal at Mamainse Point is
Discussion
ations can be recognized in as widely dispersed a distribution
Klewin and Berg 1990; Shirey et al. 1994).
Second-phase volcanism
No equivalent rocks
−12 to −9 Porcupine Volcanics PM + CC
−10 to +4 Late second-phase basalts PM + DM
−1 to +2 Portage Lake Volcanics PM

First-phase volcanism
−2 to −1 Upper Kallander Creek PM ± CC
−1 to 0 Lower Kallander Creek PM
−7 to −1 Upper Siemens Creek PM + CLM
−1 to +1 Lower Siemens Creek PM

Notes: Source abbreviations: PM, plume; CLM, continental lithospheric mantle; DM, depleted mantle; CC, continental crust.

Table 2. Proposed correlation of MRS magma types between western and eastern Lake Superior and their inferred source reservoirs (based on stratigraphic position and geochemical and Nd isotopic characteristics of basalts with SiO₂ < 53 wt. %).

<table>
<thead>
<tr>
<th>Western Lake Superior, south shorea</th>
<th>Eastern Lake Superiorb</th>
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<tr>
<td>εNd(1100) Stratigraphic position Sources</td>
<td>εNd(1100) Stratigraphic position Sources</td>
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<td>No equivalent rocks</td>
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<tr>
<td>−12 to −9 Porcupine Volcanics PM + CC</td>
<td>−2 to +4 Group 7 PM + DM</td>
</tr>
<tr>
<td>−10 to +4 Late second-phase basalts PM + DM</td>
<td>0 to +2 Group 6 PM + DM</td>
</tr>
<tr>
<td>−1 to +2 Portage Lake Volcanics PM</td>
<td>No equivalent rocks</td>
</tr>
</tbody>
</table>

|  | −9 to −3 Groups 3−5 PM + CC |
| −2 to −1 Upper Kallander Creek PM | −5 to 0 Groups 1, 2 PM + CLM |
| −1 to 0 Lower Kallander Creek PM | No equivalent rocks |
| −7 to −1 Upper Siemens Creek PM + CLM | |
| −1 to +1 Lower Siemens Creek PM | |

Data include published analyses for Portage Lake Volcanics (Nicholson and Shirey 1990) and the authors’ unpublished data for the Siemens Creek, Kallander Creek, and Porcupine volcanics and a few late basalts. Also included in the initial ε ranges are several unpublished Nd analyses from the North Shore Volcanic Group for rocks supplied by J.C. Green which are equivalent to the Siemens Creek, lower Kallander Creek, and late basalts.

Local assimilation.

second phase of volcanism in western Lake Superior, and
and that the uppermost magnetic reversal at Mamainse Point is
correlative with the regionally observed shift from reversed
to normal magnetic polarity (Klewin and Berg 1990; Shirey
et al. 1994).

This correlation appears to satisfy much of the available
stratigraphic, geochemical, and isotopic data. However, the
only U−Pb zircon age available for Mamainse Point is a date
of about 1096 Ma for a volcanic rock near the top of the
lowermost reversed section (Davis et al. 1995). This age
appears to be too young relative to the rock’s inferred stratig-
graphic position based on the geochemical correlation out-
lined above. At the present time it is unclear whether this age
was determined on a flow, a tuff, or a dike. Our interpreta-
tion is consistent with this being a younger intrusive rock. If
it proves be the age of an extrusive rock, reinterpretation of
the regional correlation will be required.

Discussion
The massive volcanism of the Midcontinent rift has been
attributed to the emplacement of a mantle plume beneath
North America (e.g., R.S. White and McKenzie 1989, 1995;
Hutchinson et al. 1990; Nicholson and Shirey 1990; R.S.
White 1997), a model supported by a wide array of geophysical,
geochemical, and geochronologic data. The comparison of
well-documented but geographically distinct stratigraphic
sections of MRS volcanic rocks reveals that five distinct
flood-basalt compositions are common to most if not all of
the sections, and that these compositions appear more or less
in the same stratigraphic order in each locality (Fig. 5).
Factors including plume heterogeneity and the presence or
absence of continental lithospheric mantle and its composi-
tional variability over a broad region may contribute to
observable variations in magma compositions. Thus, it is
remarkable that a sequential progression of basalt composi-
tions can be recognized in as widely dispersed a distribution
of MRS rocks as is seen throughout the Lake Superior basin.
At each locality there are also suites of volcanic rocks
whose chemical and isotopic characteristics reflect abundant
crustal assimilation, obscuring to various degrees the origin-
ral mantle source characteristics. These crust-dominated
suites include the Porcupine Volcanics on the south shore; a
much of the northeast limb of the NSVG; groups 3−5 at
Mamainse Point; and the central suite and lower part of the
upper suite of the Osler Group. The stratigraphic position of
these suites differs among localities and most likely reflects
the influence of local structural features, changes in the
tectonic setting and extension rate, and the effects of the
localized emplacement of intrusions. Because the ages and
compositions of crustal material differ across the region,
there is considerable compositional variation among these
crustally contaminated suites; thus these suites are less useful
for regional correlation than the distinctive flood-basalt com-
positions. Focusing on the regional stratigraphic eruption
sequence of distinctive flood basalt compositions, rather than
on the more localized volcanic products of mid- to upper-
crustal staging chambers, allows construction of a model for
the nature and interaction of mantle sources through time as
the rift developed.

Recent workers (Klewin and Berg 1991; Klewin and
Shirey 1992; Shirey et al. 1994; Shirey 1997) have combined
detailed stratigraphic sampling with careful chemical and
isotopic modelling of MRS volcanic rocks, and proposed a
model for the progression of mantle sources during rifting
based on evidence observed at Mamainse Point. This model
begins with early interaction of plume melts and the con-
tinental lithospheric mantle, followed by melts dominated
largely by the plume component, and finally the mixing of
depleted mantle and plume components near the end of mag-
matism. (Table 2). The compiled data from western Lake
Superior now allow this model to be tested more broadly.
What is unaccounted for in this model developed for
Mamainse Point is the source of the initial magma type found
as basal units around western Lake Superior (the augitephryic basalts and picrite). Based on inversion of rare earth element data from the lower suite in the Osler Group, R.S. White and McKenzie (1995) calculated that this initial magma type represents small-degree partial melts that last equilibrated with a garnet-bearing residue. These earliest melts have chemical characteristics that are analogous to modern ocean-island basalts (Fig. 8), and $\varepsilon_{Nd}(100)$ of about 0. They most likely represent melts directly from the plume without any appreciable interaction with other sources.

Combining the results from studies in both western and eastern Lake Superior leads to a unified model for the nature and interaction of magma sources through time as the rift developed. As the ascending plume head approached the base of the lithosphere and began to melt, high-MgO melts were produced at depths of more than about 75 km (R.S. White and McKenzie 1995). A few of these earliest melts were erupted through extensional fractures in the lithosphere without much interaction with any other source (basalt type I). Melting began at the bottom of the lithosphere and magmas, which were large-degree partial melts from the plume, interacted with another source, most likely the continental lithospheric mantle (Klein and Berg 1991; Shirey et al. 1994; Shirey 1997). These magmas (basalt type II) were erupted in large volumes (upper Siemens Creek composition, some early NSVG rocks, and Mamainse Point group 1). Melting was still deep, as evidenced by the low HREE abundances and the high CeN/YbN of these units (Table 1; Fig. 6), and REE inversions of groups 1 and 2 compositions at Mamainse Point (R.S. White and McKenzie 1995; R.S. White 1997). Some small-degree partial melts of the plume (basalt type III) underwent fractionation (low MgO, Mg#, Cr, Ni, and Sc, and high TiO2, P2O5, and CeN/YbN), retaining their plume isotopic characteristics (Figs. 7, 8). These highly evolved basaltic magmas were erupted not only early in the rifting cycle (i.e., lower Kallander Creek and equivalent rocks) but also as small-volume eruptions near the end of volcanism (group 8, Mamainse Point).

The first stage of extension and flood-basalt eruption waned, leading to a period of diminished volcanic activity lasting several million years. During this time, the crust was being heated by magmas from the mantle staging in lower-to mid-crustal chambers. These chambers led to localized volcanic centers with abundant intermediate and felsic rocks (central suite and parts of the upper suite in the Osler Group; groups 3–5 at Mamainse Point; upper Kallander Creek on the south shore; some NSVG rocks) and some intrusions (e.g., Mellen Intrusive Complex). At about 1100 Ma the initiation of the second phase of magmatism was marked by renewed extension resulting in growth faults and grabens that quickly filled with an enormous volume of basalt (Portage Lake and equivalent rocks: basalt type IV). These magmas were dominated by the plume component and last equilibrated at shallower levels than the earliest magmas. Assimilation of older (Archean) basement was confined to magmas emplaced along the margins of the rift (e.g., NSVG). As the plume finally dissipated, depleted asthenospheric mantle mixed with the plume component and produced compositions (basalt type V) that progressively became more depleted in incompatible trace elements with time ($\varepsilon_{Nd}(100) > 0$).

The main conclusion of this paper is that throughout the central portion of the MRS there is a similarity in the sequence of basalts derived from mantle source types. Early enriched plume melts interact with continental lithospheric mantle; they are followed in turn by voluminous melts derived chiefly from the plume and finally by mixing of plume-derived melts with depleted upper mantle. That such a parallel progression of mantle sources with magmatic development of the rift can be extended across the central 600 km of the Midcontinent rift is remarkable considering potential heterogeneities that occur in plumes, the geographical extent of the correlation, and the potential differences in the age and composition of the continental lithosphere cut by the MRS. Furthermore, a similar progression is found in other flood-basalt provinces including the North Atlantic (e.g., Gariépy et al. 1983; Dickin 1988; Gill et al. 1988) and the Deccan (e.g., Mahoney 1988; Peng et al. 1994). Thus, this style of interaction between mantle plume, continental lithospheric mantle, and depleted convecting mantle appears to have operated for at least 1.1 Ga in continental settings.
ranging from failed rifts to successful rifts that lead to complete ocean basins.

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**References**


Sutcliffe, R.H. 1987. Petrology of Middle Proterozoic diabases and
system. Annual Review of Earth and Planetary Sciences, 13:
345–384.