Magmatic activity and plate motion during the latent stage of Midcontinent Rift development

Nicholas L. Swanson-Hysell[1], Seth D. Burgess[2], Adam C. Maloof[3], and Samuel A. Bowring[2]

[1]Department of Earth and Planetary Science, University of California–Berkeley, Berkeley, California 94720, USA
[2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[3]Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA

ABSTRACT

The Keweenawan Midcontinent Rift of North America records significant continental rifting between ca. 1110 and 1085 Ma, and preserves the most detailed paleomagnetic record of plate motion of any continent in Precambrian time. U/Pb dates from extrusive and intrusive rocks of the western Lake Superior Basin suggest a latent stage of reduced magmatic activity from ca. 1106 to 1100 Ma that places constraints on the dynamics of rift development and the record of plate motion. However, it has remained unclear whether this stage is a feature of the entire >2500-km-long rift. The succession of picritic and basaltic lava flows at Mamainse Point in the eastern Lake Superior Basin may be the most continuous and best exposed record of rift-related volcanism and magnetic reversals, but its age and duration relative to the latent stage has been uncertain due to a lack of radioisotopic dates. We present a weighted mean $^{206}Pb/^{238}U$ date of 1100.36 ± 0.25 Ma on zircon crystals isolated from a newly discovered tuff within the upper reversed polarity portion of the stratigraphy below the Great Conglomerate. This date indicates that eruptive activity at Mamainse Point continued during the interval of diminished magmatic activity in the western Lake Superior Basin. This result strengthens the chronostratigraphic framework of rift development while explaining the preservation of additional geomagnetic reversals at Mamainse Point and the record of progressively decreasing paleomagnetic inclination that is indicative of rapid paleogeographic change.

INTRODUCTION

Over a period of ~25 m.y. in the late Mesoproterozoic, more than 2.0×10^6 km^3 of volcanic rocks formed from eruptions in the middle of the Laurentian craton associated with the development of the Keweenawan Midcontinent Rift (Cannon, 1992). Rifting ceased prior to continental dismemberment and the resulting failed rift preserves rocks and structures that can be used to gain insight into the mechanisms and time scale of rifting (e.g., Stein et al., 2011). Paleomagnetic data from these rocks serve as the central record for reconstructing paleogeography at that time, when the supercontinent Rodinia is hypothesized to have been assembling. High-precision temporal constraints on rift rocks and robust chronostratigraphic correlation between extrusive successions are vital for understanding the pace and geometry of rift development and for interpreting the paleomagnetic record.

A popular model for Midcontinent Rift development proposes four stages of magmatism: early (1109–1106 Ma), latent (1106–1100 Ma), main (1100–1094 Ma), and late (1094–1086 Ma) (Fig. 1; Miller and Vervoort, 1996; Davis and Green 1997; Vervoort et al., 2007). U-Pb dates from extrusive (Davis and Green 1997) and intrusive (Paces and Miller, 1993; Vervoort et al., 2007) sequences in the western part of the Lake Superior Basin are primarily within the early or main magmatic stages, leading to the interpretation that the period between them was a latent stage characterized by minimal eruptive activity (Halls, 1974; Miller and Vervoort, 1996; Vervoort et al., 2007). The early stage of magmatism is characterized by magnetizations of steeply reversed polarity, while the main stage of Midcontinent Rift volcanism is characterized by magneti-

zations of relatively shallow normal polarity (Fig. 1). In the Powder Mill Group and the North Shore Volcanic Group, U-Pb dates on extrusive felsic units (Davis and Green, 1997; Zartman et al., 1997) suggest significant hiatuses in volcanism during the time period of the latent stage, during which there was a change from reversed to normal magnetic polarity (Fig. 1). In contrast, the Mamainse Point succession of eastern Lake Superior has been interpreted to represent a more continuous record spanning nearly the entire duration of rift volcanism (Shirey et al., 1994). The Mamainse Point volcanics are exposed close to where the covered southeast arm of the rift intersects the lake (Figs. 1 and 2), and range in composition from picrite to basaltic andesite (Shirey et al., 1994). The interpretation of relatively continuous magmatism at Mamainse Point has stemmed from the presence of multiple geomagnetic reversals that have not been recognized in other extrusive successions (Fig. 1). Major element, trace element, and isotopic data demonstrate that the Mamainse Point polarity zones are distinct; these data and the lack of geological evidence for fault repetition support the interpretation that the succession records three geomagnetic reversals (Klewin and Berg, 1990; Shirey et al., 1994). While the presence of additional reversals may suggest that eruptive activity continued at Mamainse Point during the latent stage magmatic hiatus elsewhere, Midcontinent Rift correlation schemes hypothesize that deposition of an ~300-m-thick conglomerate at Mamainse Point (the Great Conglomerate; Figs. 1 and 2) corresponds to the entirety of the latent magmatic stage (Miller and Vervoort, 1996; Nicholson et al., 1997; Miller, 2007). This correlation model implies that the eastern Lake Superior Basin underwent the same period of extended magmatic quiescence inferred in the west.

Determining the temporal and spatial extent of magmatism within the rift basin and how the succession at Mamainse Point correlates to other records of rift volcanism is essential for the following reasons.

1. In order to evaluate whether initiation, progression, and ultimate failure of the rift were isochronous, we need to determine the comparative histories of the west and east arms.

2. High-volume silicic magmatism in the North Shore Volcanic Group has been argued to be associated with prolonged crustal heating during the hypothesized latent stage (Vervoort et al., 2007). Is the comparative lack of silicic flows further east (Fig. 1) due to contrasting temporal evolution?

3. The paleomagnetic record is used to understand the geometry of the geomagnetic field and the progression of plate motion at this crucial time period of Rodinia assembly. If the additional geomagnetic reversals at Mamainse Point correspond to a period of missing stratigraphy in other successions, then the progressive decrease in paleomagnetic inclination at Mamainse Point provides a strong case for rapid equatorward motion of Laurentia (Davis and Green, 1997; Swanson-Hysell et al., 2009). Alternative correlations complicate this interpretation and could support models of large-scale deviations from dipolar geomagnetic field behavior (Pesonen and Nevanlinna, 1981; Davis et al., 1995).

Despite the importance of integrating the Mamainse Point succession into chronostratigraphic correlation schemes, radioisotopic dates have been difficult to obtain due to a lack of zircon-bearing extrusive volcanic rocks.
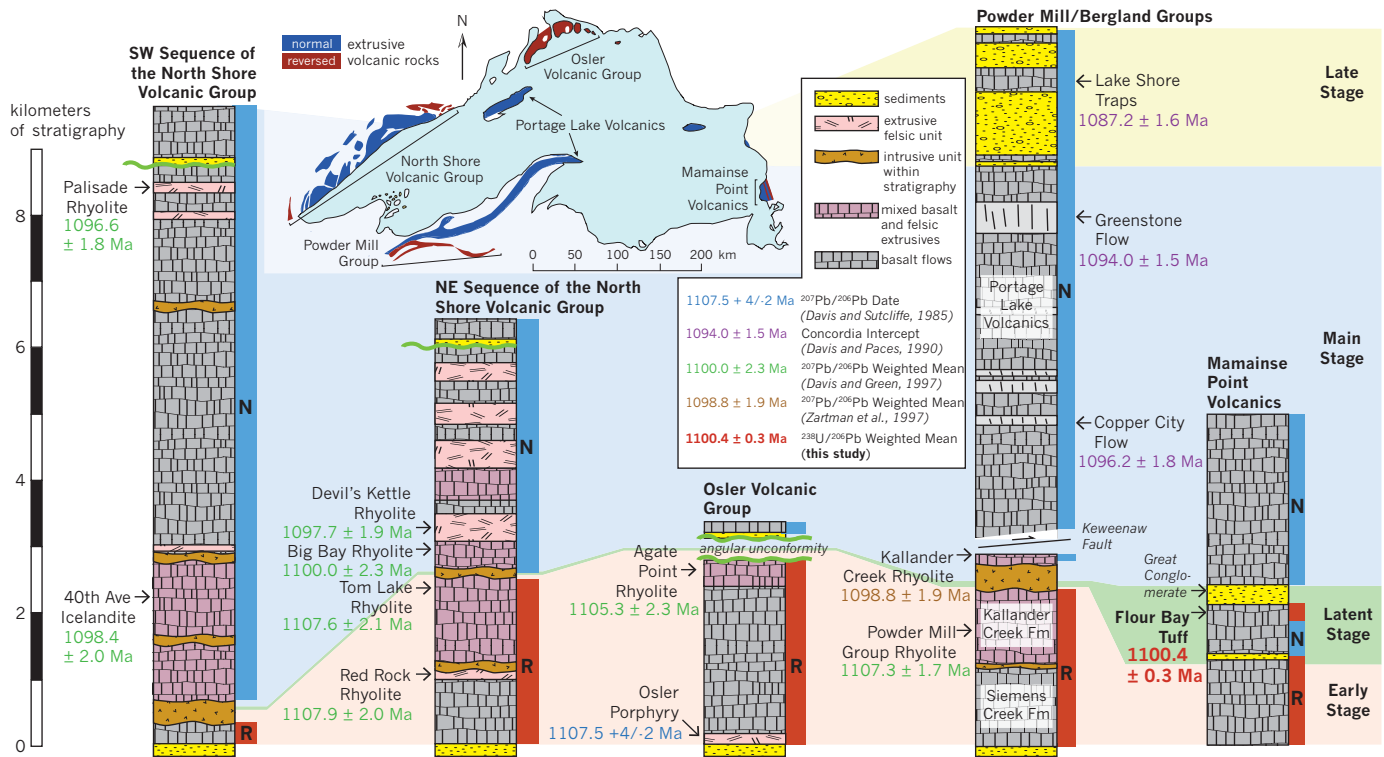
Figure 1. Summary lithostratigraphic columns across the Midcontinent Rift. Lithostratigraphy adapted from Davis and Green (1997) for the North Shore Volcanic Group, Hollings et al. (2007) for the Osler Volcanic Group, Cannon and Nicholson (2001) for the Bergland Group, and Hubbard (1975) for the Powder Mill Group. Dates are colored by reference (weighted mean dates were recalculated). Correlation using the new Flour Bay tuff date shows the middle reversed and normal polarity zones at Mamainse Point to be missing from other successions, commonly in association with unconformities at the time of the latent stage. Comparisons between dates are complicated by the change in the assumed ratio of $^{238}U/^{235}U$; however, the $^{207}Pb/^{206}Pb$ date of 1102.4 ± 0.69 Ma for the Flour Bay tuff calculated with the previously assumed ratio also supports the correlation shown here.

PALEOMAGNETIC DATA AND AGE CONSTRAINTS FOR THE MAMAINSE POINT STRATIGRAPHY

Due to the large changes in paleomagnetic inclination throughout Midcontinent Rift development (Davis and Green, 1997; Swanson-Hysell et al., 2009), paleomagnetic data can be used to provide chronostratigraphic constraints through comparison of undated paleomagnetic poles to poles constrained by radioisotopic dates. Swanson-Hysell et al. (2009) presented paleomagnetic data obtained from 72 lava flows within the Mamainse Point stratigraphy. Here we present data from an additional 27 flows (Fig. 2; Table DR2 in the GSA Data Repository[1]) that reinforce positive reversal tests on the three reversals in the succession (described in the Data Repository).

Flows from the lower 600 m (227.0°E, 49.5°N, A_{95} = 5.3°, N = 24; lower R pole 1 in Table DR3) of the Mamainse Point stratigraphy yield virtual geomagnetic poles (VGPs) that pass the Watson V_w and bootstrap tests for a common mean with data from the Siemens Creek Formation volcanics (n = 10; sites 15–24 of Palmer and Halls, 1986, from the panel with the most robust tilt correction). The Siemens Creek Volcanics are older than 1107.3 ± 1.7 Ma, on the basis of a U-Pb date on a rhyolite from the overlying Kallander Creek Formation (Fig. 1; Davis and Green, 1997). Flows from the 1000 m of the upper normal polarity zone immediately above the Great Conglomerate (183.1°E, 33.7°N, A_{95} = 2.0°, N = 27) yield VGPs that pass tests for a common mean with data from flows of the North Shore Volcanic Group (N = 47; Tauxe and Kodama, 2009) between the 40th Avenue icelandite and Palisade rhyolite (U-Pb dates of 1098.4 ± 2.0 Ma and 1096.6 ± 1.8 Ma, respectively; Fig. 1; Davis and Green, 1997). These comparisons suggest that the lowest reversed polarity zone at Mamainse Point corresponds to the early magmatic stage, while the uppermost normal polarity zone at Mamainse Point corresponds to the main magmatic stage (Fig. 1).
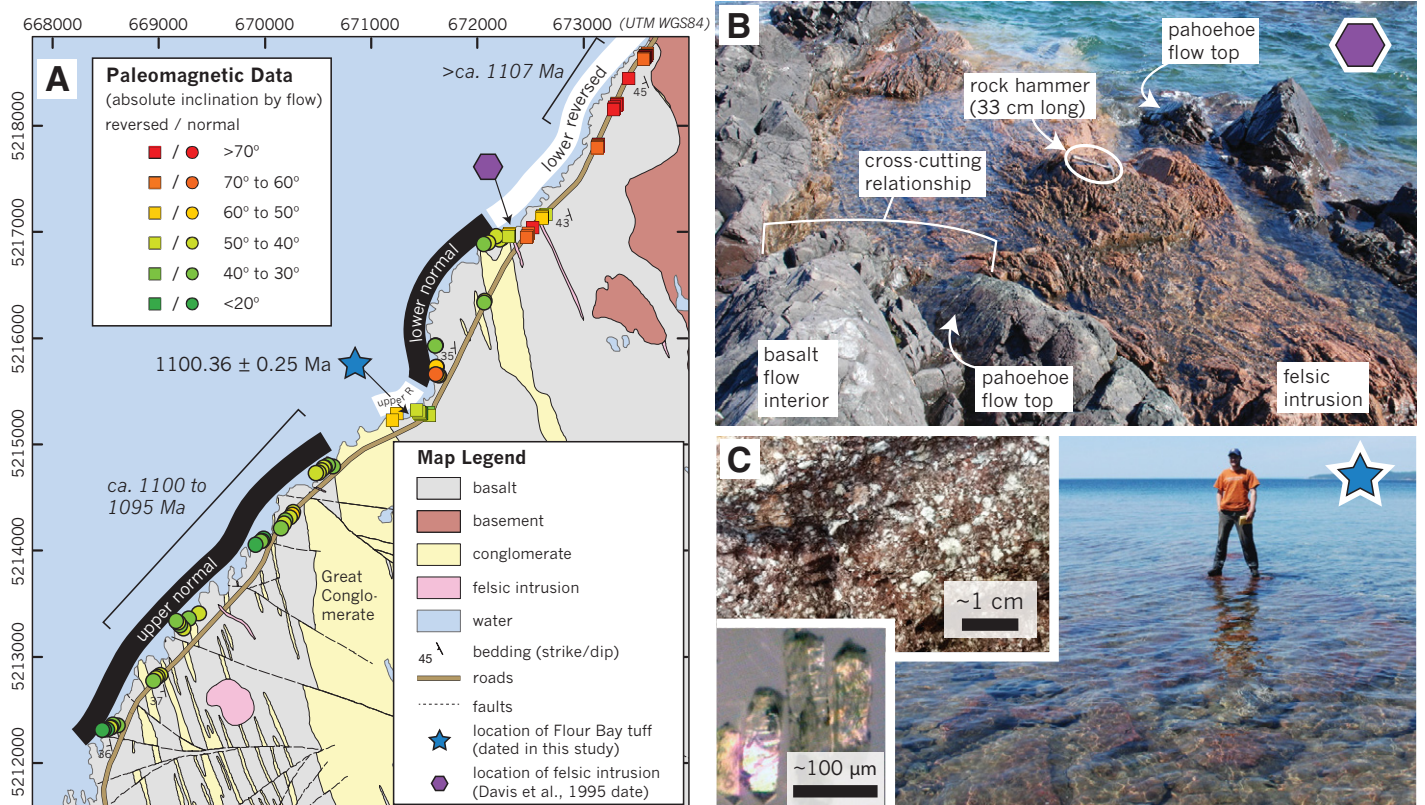
Previously Dated Unit within the Mamainse Point Succession

A $^{207}Pb/^{206}Pb$ zircon date of 1096.2 ± 1.9 Ma was reported by Davis et al. (1995) from a felsic unit within the lower reversed zone at Mamainse Point that was interpreted to be an extrusive flow. Davis and Green (1997, p. 482) considered the implications of this date if the unit was extrusive, but stated "it has not been possible to publish these data due to the difficulty in establishing beyond doubt the eruptive nature of the dated unit." In the literature, the dated unit has both been accepted as extrusive (Heaman et al., 2007), and questioned as such (Nicholson et al., 1997). An extrusive interpretation for the unit (1) implies that all geomagnetic reversals within the Mamainse Point succession occurred during, or after, the main magmatic stage, in conflict with the consistently normal polarity of that stage elsewhere in the rift, and (2) suggests significant reversal asymmetry, as high paleolatitudes implied by data low in the Mamainse Point stratigraphy would postdate the relatively low implied paleolatitudes of normally magnetized strata elsewhere in the rift (Davis and Green, 1997).

New field observations document a crosscutting relationship with the felsic unit both overlying and underlying the pahoehoe flow top of a single basalt flow (Fig. 2B). This relationship demonstrates that the unit is intrusive and imperfectly intruded along a preexisting flow boundary. The

Figure 2. A: Geological map of Mamainse Point modified from Giblin (1969) and Swanson-Hysell et al. (2009). Coordinates are Universal Transverse Mercator (UTM) zone 16 in World Geodetic System 1984 (WGS1984). The oldest flows are in contact with Superior Province basement and are younger to the west. Symbols at each flow with paleomagnetic data indicate polarity and magnetic inclination. Italicized ages come from paleomagnetic pole comparisons (see text). B: Photograph of felsic unit dated by Davis et al. (1995). Due to the crosscutting relationship with the lava flows, this felsic intrusion wedged apart the labeled pahoehoe flow top. C: Photographs of the Flour Bay tuff (location shown in A), including a hand-sample, four dated zircon crystals, and the outcrop expression in July 2011.

date of 1096.2 ± 1.9 Ma provides a minimum age constraint on the lower reversed polarity zone at Mamainse Point.

New Age Constraint for the Mamainse Point Succession

Low lake levels recently led to improved exposure in Flour Bay, revealing a crystal-rich tuff below the Great Conglomerate within the upper reversed polarity zone (Fig. 2; Fig. DR3). This tuff yielded abundant euhedral zircons that we treated with the chemical abrasion method prior to acquiring U-Pb isotope dilution thermal ionization mass spectrometry data (Figs. DR1 and DR2; see the Data Repository for methods and data). Data from nine grains yield a weighted mean $^{206}Pb/^{238}U$ date of 1100.36 ± 0.25/0.42 Ma (mean square of weighted deviates, MSWD = 1.4), a weighted mean $^{207}Pb/^{235}U$ date of 1100.82 ± 0.31/0.33 Ma (MSWD = 0.63), and a weighted mean $^{207}Pb/^{206}Pb$ date of 1101.51 ± 0.64/0.69 Ma (MSWD = 0.63). Three of the 12 analyzed grains were not used in the calculation of the weighted means based on distinctly older $^{206}Pb/^{238}U$ dates. The uncertainties associated with the dates are reported as ± X/Y, where X is the internal (analytical) uncertainty in the absence of all external errors, and Y incorporates the U-Pb tracer calibration error for comparison to U-Pb dates developed with different tracers.

Crystallization ages reported from Midcontinent Rift rocks primarily have been $^{207}Pb/^{206}Pb$ dates calculated using an assumed $^{238}U/^{235}U$ ratio of 137.88. The $^{207}Pb/^{206}Pb$ date reported here for the Flour Bay tuff uses the new recommended $^{238}U/^{235}U$ ratio of zircon (Hiess et al., 2012). For comparisons with previously published dates, our new date can be recalculated using the legacy $^{238}U/^{235}U$ ratio; doing so yields a $^{207}Pb/^{206}Pb$ date of 1102.4 ± 0.69 Ma, an increase of almost 1 m.y. We regard the $^{206}Pb/^{238}U$ date of 1100.36 ± 0.25/0.42 Ma (n = 9, MSWD = 1.4) as the most precise and

accurate estimate for the age of the Flour Bay tuff. This date provides an age constraint on a paleomagnetic pole calculated from flows of the lower normal and upper reversed polarity zones (189.7°E, 36.1°N, A$_{95}$ = 4.9°, N = 24; Table DR3).

DISCUSSION AND CONCLUSIONS

The new date from the Flour Bay tuff anchors the Mamainse Point stratigraphy in time and indicates that the lava flows below the Great Conglomerate correlate to the period of magmatic quiescence elsewhere in the rift (Fig. 1). Therefore, the conglomeratic unit represents a shorter period of magmatic quiescence than has been hypothesized. This result adds support to the hypothesis that the succession at Mamainse Point is the most complete in the rift. Vervoort et al. (2007) hypothesized that the silicic volcanism in the North Shore Volcanic Group, where rhyolites comprise as much as 25% of the stratigraphy (Fig. 1), could be related to longer term crustal heating during the latent stage that contributed to partial melting in higher levels of the crust. In contrast, at Mamainse Point there is a relative lack of felsic magmatism in a location where the record of volcanism appears to be more continuous, lending support to the hypothesized connection between the latent stage and the abundance of silicic magmatism in the western Lake Superior Basin. The relatively continuous record of magmatism at Mamainse Point is also consistent with the model of the rift as a developing plate boundary (e.g., Merino et al., 2013), as opposed to distinct pulses of magmatic activity across the entirety of the rift.

The dominance of reversed magnetic polarity in older Midcontinent Rift rocks and normal magnetic polarity in younger ones (Fig. 1) has led to much discussion in the literature of the age of a single geomagnetic reversal that occurred during rifting. The multiple reversals through the Ma-

mainse Point stratigraphy demonstrate that referring to a single reversal in the history of the rift is not appropriate. At Mamainse Point, two reversals of the geomagnetic field are recorded in mafic lavas prior to the 1100.36 ± 0.25/0.42 Ma Flour Bay tuff and one afterward (Fig. 1). The temporal correlation of these reversals with latent stage magmatic quiescence in much of the rift explains why these reversals have not been identified in other rift localities (Fig. 1).

There is a significant decrease in paleomagnetic inclination between the reversed polarity rocks of the early magmatic stage and the normal polarity rocks of the main magmatic stage. Interpretation of this inclination difference as a stepwise change led to the hypothesis of geomagnetic reversal asymmetry resulting from large non-dipole contributions to the geomagnetic field in the late Mesoproterozoic (Pesonen and Nevanlinna, 1981). The record at Mamainse Point is not consistent with this hypothesis because it reveals a progressive decrease in paleomagnetic inclination moving upward through the stratigraphy across multiple reversals. Instead, data support the interpretation of significant plate motion of North America from 1110 to 1095 Ma, where the inclination decrease corresponds to decreasing paleolatitude at rates that may have exceeded 20 cm/yr (Davis and Green, 1997; Swanson-Hysell et al., 2009). Successions missing the intervening polarity zones between the early and main magmatic stages, as a result of latent stage magmatic quiescence, will record a stepwise inclination decrease as a result of not recording the progressive paleogeographic change. Reconstructions of the assembly history of Rodinia rely on this record of equatorward plate motion that we can now demonstrate was ongoing throughout rift development.

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