Confirmation of progressive plate motion during the Midcontinent Rift's early magmatic stage from the Osler Volcanic Group, Ontario, Canada

Nicholas. L. Swanson-Hysell,[1,2] Angus A. Vaughan,[1,3], Monica R. Mustain,[1,4] and Kristofer E. Asp[1,5]

[1]Institute for Rock Magnetism, Department of Earth Sciences, University of Minnesota, Minneapolis, Minnesota, USA

[2]Department of Earth and Planetary Science, University of California, Berkeley, California, USA

[3]Department of Geology, Carleton College, Northfield, Minnesota, USA

[4]Department of Geology and Geography, Illinois State University, Normal, Illinois, USA

[5]Department of Geological Sciences, University of Minnesota, Duluth, Minnesota, USA

Abstract. As the supercontinent Rodinia was assembling ca. 1.1 billion years ago, there was extensive magmatism on at least five Proterozoic continents including the development of the North American Midcontinent Rift. New paleomagnetic data from 84 lava flows of the Osler Volcanic Group of the Midcontinent Rift reveal that there was a significant and progressive decrease in inclination between the initiation of extrusive volcanism in the region (ca. 1110 Ma) and ca. 1105 $\pm$ 2 Ma (the "early stage" of rift development). Paleomagnetic poles can be calculated for the lower portion of the reversed Osler Volcanic Group (40.9°N, 218.6°E, A_{95}=4.8°, N=30) and the upper portion of the reversed Osler Volcanic Group (42.5°N, 201.6°E, A_{95}=3.7°, N=59; this pole can be assigned the age of ca. 1105 $\pm$ 2 Ma). This result is a positive test of the hypothesis that there was significant plate motion during the early stage of rift development. In addition to being a time of widespread volcanism on Laurentia and other continents, this interval of the late Mesoproterozoic was characterized by rapid paleogeographic change.

1. Introduction

Despite being active for more than 20 million years [*Davis and Green*, 1997] and resulting in the thinning of pre-rift crust to less than 10 km [*Cannon*, 1992], the 1.1 Ga Midcontinent Rift failed to dismember Laurentia (cratonic North America). This failure resulted in the preservation of a thick record of rift-related volcanic and sedimentary rocks that gives geoscientists insight into the development of this ancient rift. Most models for the development of the Midcontinent Rift attribute its origin to the upwelling and decompression melting of a mantle plume [*Shirey*, 1997]. On the basis of the great volume of generated magma and interpretation of geochemical data, it is argued that the early stage plateau flood basalts of the rift (ca. 1110-1105 Ma) and the main stage volcanics that erupted into the central basin (ca. 1100-1095 Ma) were both dominated by plume-sourced melts. This deep-plume origin for the rift needs to be considered in conjunction with paleogeographic change that has been inferred to have been ongoing throughout rift development. Fully constraining this paleogeographic change is essential for understanding rift development and for constraining late Mesoproterozoic paleogeographic reconstructions given the centrality of Laurentia's apparent polar wander path to such efforts.

It has long been noted that there is a significant difference in paleomagnetic inclination between the steep (dominantly reversed polarity) magnetizations of the oldest volcanics and intrusives of the Midcontinent Rift and the shallower (dominantly normal polarity) magnetizations from the younger main stage volcanics and intrusives [*Halls and Pesonen*, 1982]. This inclination change has been interpreted either as resulting from rapid plate motion [*Robertson and Fahrig*, 1971; *Davis and Green*, 1997] or as being the result of large non-dipolar contributions to the late Mesoproterozoic geomagnetic field that led to asymmetry across reversals [*Pesonen and Nevanlinna*, 1981]. The interpretation of the record as recording stepwise inclination change across reversals associated with a significant sustained departure from a geocentric axial dipole (GAD) dominated field was challenged by the observation of a progressive decrease in paleomagnetic inclination across multiple geomagnetic reversals up through the succession of Midcontinent Rift lavas at Mamainse Point, Ontario [*Swanson-Hysell et al.*, 2009, 2014]. This progressive decrease in inclination leads to the interpretation of multiple symmetric reversals when the data are considered in stratigraphic context and these results have been used to support the hypothesis that rapid paleogeographic change was ongoing during Midcontinent Rift magmatism [*Buchan*, 2013; *Swanson-Hysell et al.*, 2014]. To date, Mamainse Point is the only succession where a progressive decrease in inclination through an exposure of rift stratigraphy has been reported. At Mamainse Point, much of the decrease in paleomagnetic inclination occurs within the lowermost reversed polarity portion of the stratigraphy that erupted during the early magmatic stage of rift development [*Swanson-Hysell et al.*, 2014]. This result sets up the prediction that other localities in the rift that span the same period of time should also record such a decrease. This work tests that hypothesis with new paleomagnetic data developed in stratigraphic context from the Osler Volcanic Group.

2. Geology and context of the Osler Volcanic Group

2.1. Osler Volcanic Group lithologies

The Osler Volcanic Group overlies the epicontinental sediments of the Mesoproterozoic Sibley Group. The lowest 100 meters of the Osler Volcanic Group contains rift-related sandstones and conglomerates [*Hollings et al.*, 2007a], which are followed by a succession of relatively continuous tholeiitic basalt flows. We studied these flows along the east shore of Simpson Island in the Lake Superior Archipelago. This location has well-preserved basalt flows and exposure of a significant thickness of the Osler Volcanic Group stratigraphy. This location occurs at a great enough distance (> 10 km) from the intrusive St. Ignace Island Complex so that the magnetizations of the flows are apparently unaffected by its emplacement. The St. Ignace Island Complex is dominated by felsic lithologies and was emplaced into the mafic flows of the Osler Volcanic Group near the end of Midcontinent Rift volcanism [*Hollings et al.*, 2007b].

Along the east shore of Simpson Island, where we measured stratigraphic sections (Fig. 1), the stratigraphic succesion is dominated by basaltic lava flows with typical thicknesses of ca. 5 meters. For the 105 flows in the measured stratigraphic sections (that represent a subset of the total stratigraphy) where there is sufficient exposure of the flow base, interior and top to determine thickness, the median flow thickness is 4.9 meters with a first quartile thickness of 2.0 meters and third quartile thickness of 9.8 meters (details are provided in the supporting information). Minor interflow siltstone and conglomerate occur between some flows and provide constraints on paleo-horizontal that were utilized for structural corrections of paleomagnetic data (Fig. 1). The red-brown siltstone beds are generally centimeters to tens of centimeters thick while the conglomerate beds can be up to several meters in thickness. Clasts in the conglomerate beds are basaltic in composition and are primarily pebble-sized, but can range up to 10 cm in diameter. Within the stratigraphic sections, individual flows can be distinguished by their characteristic transition in texture moving up through the flow: pipe vesicles at the base of flows, to massive basalt, to massive basalt with some amygdules, to a highly amygdaloidal texture at the top of the flows. There is well-preserved pahoehoe flow-banding on some flow tops. Using our measurements of bedding orientation, we estimate that slightly over 3000 meters of the Osler Volcanic Group is exposed on Simpson Island (Fig. 1).

2.2. Angular unconformity and associated paleomagnetic reversal

Southwest of Simpson Island in the Nipigon Strait region there is exposure on Puff Island, which contains an angular unconformity marked by a conglomerate that separates underlying flows of reversed magnetic polarity from overlying flows of normal magnetic polarity [*Halls*, 1974]. This unconformity is stratigraphically higher than the top of the exposure at Simpson Island where all studied flows have reversed magnetic polarity. Only ca. 110 stratigraphic meters of normally magnetized flows are exposed south (i.e. stratigraphically above) of the unconformity on Puff Island before the sequence is covered by Lake Superior. This unconformity has been interpreted to be due to a period of quiescence of local volcanism [*Halls*, 1974]. *Halls* [1974] was the first to suggest that such quiescence may have been widespread throughout the Midcontinent Rift—an idea that is now incorporated into models of rift development that utilize interpretations of the distribution of U-Pb dates and has been termed the "latent stage" [*Vervoort et al.*, 2007]. As occurs in sequences across the Midcontinent Rift, the lower reversed flows studied paleomagnetically by *Halls* [1974] have a steeper inclination, in an absolute sense, than the younger normal flows above the unconformity. The missing time evidenced by the angular unconformity likely correlates with the missing time inferred from radiometric dates on units within the North Shore Volcanic Group and the Powder Mill Group [*Davis and Green*, 1997; *Zartman et al.*, 1997]. In these rift successions, the stratigraphic intervals where time is inferred to be missing are associated with a switch from reversed to normal magnetic polarity. A new U-Pb date from Mamainse Point (1100.36 ± 0.25 Ma from the upper reversed polarity zone) demonstrates that, in contrast to successions with missing time or condensed stratigraphy, the sequence there is relatively complete thereby preserving additional geomagnetic reversals [*Swanson-Hysell et al.*, 2014].

The paleomagnetic data that *Halls* [1974] developed from Osler Volcanic Group flows were in relatively close stratigraphic proximity below and above the unconformity (as the goal of the study was to confirm the presence of a geomagnetic reversal that had been inferred from aeromagnetic data; *Halls* [1972]). The aeromagnetic data demonstrated that the reminder of the flows below the unconformity (i.e. to the north) and stratigraphically below those studied by *Halls* [1974] are also of reversed magnetic polarity. On the basis of polarity and the geochronology discussed below, the interval has been correlated with the "early stage" of Midcontinent Rift development and the other basal sequences of lava flows within the rift. These early stage flows are interpreted to be plateau lavas that erupted over a broad geographic area prior to significant development of the main central rift graben that underlies present day Lake Superior [*Cannon*, 1992]. Due to being limited to the portion of the succession in close stratigraphic proximity to the angular unconformity, existing data have not permitted evaluation of whether or not there is a progressive change in paleomagnetic inclination through the reversed polarity flows as observed in the "early stage" volcanics at Mamainse Point [*Swanson-Hysell et al.*, 2009].

2.3. Age constraints on the Osler Volcanic Group

In some locales, a quartz-feldspar, porphyritic felsic unit occurs near the base of the Osler Volcanic Group for which a U-Pb zircon date of 1107.5^{+4}_{-2} Ma has been reported

[*Davis and Sutcliffe*, 1985]. This date was obtained from an outcrop of felsic porphyry on Black Bay Peninsula, ca. 40 km to the west of Simpson Island [*Davis and Sutcliffe*, 1985]. This unit was tentatively interpreted as extrusive [*Davis and Sutcliffe*, 1985; *Lightfoot et al.*, 1991] and the date has been interpreted as constraining the time at which Osler Group volcanism commenced. New observations made of a quartz-feldspar porphyry unit on Simpson Island, mapped as equivalent to the unit from which the date was obtained [*Giguere*, 1975], provide additional evidence for the inference made by *Giguere* [1975] that this unit is actually intrusive. On Simpson Island, the basal sedimentary units of the Osler Volcanic Group are overlain by the quartz-feldspar porphyry which itself underlies the basalt flows (Fig. 1). A thin (1-2 mm thick) veneer of basalt is variably present overlying the porphyry. The basalt veneer displays pahoehoe flow banding, which is unlikely to have developed if the flow was originally this thin, implying that the felsic unit intruded into the basalt, cutting into an originally thicker flow. An additional observation is that there are protrusions of porphyry surrounded by host basalt, providing further support for an intrusive relationship. If the Simpson Island intrusion is indeed equivalent to the Black Bay Peninsula unit, this evidence suggests that the 1107.5^{+4}_{-2} Ma date is a minimum age for the eruption of the first Osler basalt flows, rather than an absolute age for that point in the Osler Volcanic Group stratigraphic succession. This unit should be a target for future geochronology.

A sequence of quartz-feldspar phyric rhyolite flows occurs near the top of the magnetically reversed portion of the Osler Volcanic Group at Agate Point (*Davis and Sutcliffe* [1985]; Fig. 3; stratigraphically higher than the highest flow on Simpson Island). *Davis and Green* [1997] obtained a U-Pb zircon date from the Agate Point Rhyolite of 1105 ±

2 Ma which, if the extrusive interpretation is correct, is a robust age for that point in the Osler Volcanic Group stratigraphy.

3. Methods

We collected oriented samples for magnetic laboratory measurements during the course of measuring stratigraphic sections (Fig. 1). Each site consists of an individual lava flow from which we collected 6 to 10 small (2 cm diameter) rock cores with a hand-held drill. These small core samples were oriented with a magnetic and sun compass, when possible, such that their spatial orientation is known. To minimize the visual impact of collecting these small cores along the pristine Lake Superior shoreline, we knocked out the portion of the outcrop from which they were collected.

At the Institute for Rock Magnetism, specimens were prepared from the samples and subjected to progressive thermal or alternating field (AF) demagnetization (Fig 2A). Initial results on sister specimens demonstrated the simplicity of the magnetizations and the similarity between results obtained through thermal and AF demagnetization (Fig 2A). Low-temperature remanence experiments were run on representative samples and loss of remanence across the Verwey transition demonstrates that the magnetic mineralogy is dominated by low-titanium magnetite (e.g. Fig 2B). These results revealed the ability of AF demagnetization to isolate the characteristic remanent magnetization (ChRM) held by magnetite with relatively small and variably present overprints being effectively removed by low-field AF steps. Given these results, the majority of flows were studied with AF demagnetization alone.

4. Results and Discussion

Flow means from the data generated for 84 flows of the Osler Volcanic Group are summarized in Figures 1 and 3 and in a table in the supporting information. To consider whether the flows of the Osler Volcanic Group record progressive paleogeographic change, we take the approach of grouping and comparing data from the lower third of the sequence (0 to 1041 meters; 30 flows), the middle third of the sequence (1041 to 2083 meters; 20 flows) and the upper third of the sequence (2083 to 3124 meters; 34 flows). To test whether these subsets of the data could have been drawn from a common mean, we apply both the Watson V_w test with Monte Carlo simulation [*Watson*, 1983] and the bootstrap test for a common mean [*Tauxe*, 2010]. Full details associated with these statistical tests are provided in the supporting information. The results from these common mean statistical tests show that the directions from the lower third of the sequence cannot be distinguished from those from the middle third, nor can the directions from the upper third of the sequence be distinguished from those in the middle third. In contrast, directions from the lower third of the sequence can be distinguished from those of the upper third at the 95% confidence level. This result can be seen visually in Figure 3 as the α_{95} ellipses associated with the directional means and the A_{95} ellipses associated with the pole means do not overlap. The statistically significant difference between the populations of flow means in the lower and upper third of the stratigraphy, combined with the result that the middle third data has a mean that is an intermediate direction between the lower and upper means, supports the hypothesis that progressive plate motion was ongoing throughout the eruption of the Osler Volcanic Group with Laurentia moving to lower latitudes (see reconstruction Fig. 3). The paleomagnetic poles calculated and used in the paleogeographic reconstruction in Fig. 3 are: lower third Simpson Island Osler Group (40.9°N, 218.6°E, A_{95}=4.8°, N=30); middle third Simpson Island Osler Group (42.7°N, 211.3°E, A_{95}=8.2°, N=20) and the upper portion of the reversed Osler Group (41.6°N, 205.4°E, A_{95}=4.8°, N=34). Stratigraphic subgroups of the Simpson Island data can be made in many different ways than this approach of dividing the stratigraphic sequence into thirds. For example, comparing the 17 flows in the lowermost 500 meters against the 17 flows in the uppermost 500 meters demonstrates that those populations are dramatically different such that the bootstrap test for a common mean shows their x, y and z components to be distinct at the 99% confidence level (see supporting information for details). Comparing the 41 flows in the lower half of the stratigraphic succession to the 43 flows in the upper half of the stratigraphic succession also reveals a statistically significant, but relatively small, difference between the populations (see supporting information for details). We focus on the lower, middle and upper third grouping in our analysis making the judgement that such an analysis strikes the balance between considering the possibility of change through the stratigraphy while binning enough data over thick enough intervals to not to be significantly biased by under-averaging secular variation. In this grouping, each bin contains >100 meters of relatively thin pahoehoe basalt flows.

The paleomagnetic data developed by *Halls* [1974] come from the Osler Volcanic Group in the Nipigon Straits region. The data were obtained from the uppermost part of the stratigraphic succession below the angular unconformity on Puff Island that separates the flows of reversed polarity from younger flows of normal polarity. The *Halls* [1974] data of reversed polarity (N=25, http://earthref.org/MAGIC/9518) comes from a portion of the stratigraphy that should correlate with the upper third of the sequence at Simpson Island.

Given that the flows are dominantly thin pahoehoe lavas and that the *Halls* [1974] study area was ca. 30 km eastward in the vicinity of the Nipigon Strait, those data should be comprised of distinct individual cooling units from the Simpson Island flows. Watson and bootstrap tests for a common mean between the *Halls* [1974] data of reversed polarity and data from the upper third of the stratigraphy at Simpson Island are positive indicating that the populations of directions cannot be distinguished from one another—consistent with this stratigraphic correlation. In contrast, tests for a common mean between the reversed polarity *Halls* [1974] data and the lower third of the Simpson Island stratigraphy fail. This result indicates that the populations are statistically distinct, building on the result that there was significant paleogeographic change recorded by the Osler Volcanic Group. Given that the data from the upper third of the stratigraphy on Simpson Island correlate stratigraphically and share a common mean with the Halls (1974) data from the Nipigon Straits region, we can calculate a mean paleomagnetic pole for the upper portion of the reversed Osler Volcanic Group stratigraphy (42.5°N, 201.6°E, A_{95}=3.7°, N=59). This pole can be assigned an approximate age of 1105 ± 2 Ma using the date from the Agate Point rhyolite [*Davis and Green*, 1997].

These new data from 84 flows of Osler Volcanic Group from the early stage of the Midcontinent Rift bolster evidence from the succession at Mamainse Point that the decrease in inclination through the history of the rift is a progressive change rather than a step-wise change across reversals. The interpretation of a step-wise change of inclination across reversals has been used to argue for reversal asymmetry at the time that was proposed to result from significant deviation from an axial dipole geomagnetic field [*Pesonen and Nevanlinna*, 1981]. The observed progressive change in inclination is more consistent with the hypothesis that inclination decrease is a result of fast equatorward motion of Laurentia [*Davis and Green*, 1997; *Swanson-Hysell et al.*, 2009]. The poles calculated from the stratigraphic groupings of the Osler Volcanic Group at Simpson Island fit the progression along the path resulting from from the lowermost reversed polarity zone at Mamainse Point, Ontario. These data sets combined indicate that there was significant plate motion during the early magmatic stage of North American Midcontinent Rift development.

At present, the duration of Osler Volcanic Group volcanism remains poorly constrained given the uncertainties on the ages and the lack of a dated unit that can firmly be demonstrated to be extrusive near the base of the group. This reality makes it difficult to go from the plate motion inferred from the Osler Volcanic Group poles to a rate estimate based on that motion alone. An alternative approach is to use the new mean pole for the upper part of the reversed Osler stratigraphy in conjunction with a pole developed from normal magnetized volcanics of the main magmatic stage. The main magmatic stage pole we use here is calculated using data developed by *Tauxe and Kodama* [2009] from lava flows of the southwest limb of the North Shore Volcanic group between the dated 40th Ave icelandite and the Palisade rhyolite (35.8°N, 182.1°E, A_{95}=3.1°, N=47; see details in supporting online information). The pole's age can be taken to be the mean of the the two dated units that bracket it (1098.4 ± 1.9 Ma for the 40th Ave icelandite and 1096.6 ± 1.7 Ma for the Palisade rhyolite; *Davis and Green* [1997]). We take a Monte Carlo simulation approach to determine rate uncertainty between the pair of poles where a large number of random draws are taken for age from a Gaussian distribution and for pole position from a Fisherian distribution allows for the 95% confidence range of a rate estimate to be determined (Fig. 4; code and further details are provided in the supporting materials). Using these poles, this approach yields an estimated rate of latitudinal change of 24.0 cm/yr with a 95% range of 16.3 to 39.1 cm/yr (Fig. 4) and supports previous arguments that Laurentia's rate of motion likely exceeded 20 cm/yr during the period of rift development [*Davis and Green*, 1997; *Swanson-Hysell et al.*, 2009]. Note that what is being considered is latitudinal change and that the rate estimate is therefore a minimum. Future geochronology with higher precision has the potential to significantly reduce the uncertainty of such rate estimates. Regardless, given that latitudinal drift rates are typically well-below 10 cm/year throughout the Phanerozoic [*Torsvik et al.*, 2012], this motion can be considered to be quite rapid. The rate likely exceeded that of India's motion between ~70 and ~50 Ma at rates between 13 and 18 cm/year which represents the fastest well-constrained sustained motion of continental lithosphere in the Mesozoic and Cenozoic Eras[*van Hinsbergen et al.*, 2011; *Torsvik et al.*, 2012].

From the beginning of Midcontinent Rift extrusive volcanism in the early magmatic stage (ca. 1110 to 1105 Ma) to the voluminous volcanism associated with the main magmatic stage of rift development (ca. 1100 to 1095 Ma) there was ca. 25° of latitudinal motion of Laurentia. The latitudinal change implied by the lower third Simpson Island Osler Volcanic Group pole to the North Shore Volcanic Group pole described above is 26.7° with the Osler Volcanic Group poles being on the first part of this trajectory during the early magmatic stage. The voluminous volcanism appears to have been concentrated in the Lake Superior region both during the early magmatic stage and during the eruption of the thick main stage volcanics in the central graben. Arguments for a plume-origin for Midcontinent Rift volcanism have argued that a plume is necessary to explain isotopic signatures in lava flows (Nd isotopes, *Nicholson et al.* [1997]; Re-Os data, *Shirey* [1997]) and as a heat source for generating the large volumes of basaltic magma associated with the rift [*Cannon*, 1992]. If a long-lived plume was in a fixed position relative to Earth's spin axis and did not become significantly diverted upon reaching the lithosphere, large relative motion of Laurentia could make it unable to continue to be a source of melt to the rift. One possibility is that Laurentia and a deep-seated mantle plume traveled in unison to lower latitudes as a result of large-scale rapid true polar wander. The motion implied by Keweenawan Track poles has been interpreted as a result of true polar wander [*Evans*, 2003; *Mitchell et al.*, 2012]. To reconcile an interpretation of rapid plate motion through differential plate tectonic motion, rather than true polar wander with a continued plume contribution, *Davis and Green* [1997] proposed that a plume head drifted with continental lithosphere. This idea can be considered in the context of the model of "upside-down drainage" for positively buoyant plume material wherein relief at the base of the lithosphere directs lateral flow [*Sleep*, 1997; *Ebinger and Sleep*, 1998]. Given the significant lithospheric thinning associated with rifting, plume material could continue to be directed into the rift sustaining magmatism despite ongoing plate motion. Such lateral flow could also explain the widespread coeval volcanism recorded by mafic intrusions throughout SW Laurentia [*Heaman and Grotzinger*, 1992; *Weil et al.*, 2003]. Whether lateral flow beneath continental lithosphere is feasible on this scale depends on the paleogeographic configuration at the time and whether continuous continental lithosphere extended beyond cratonic Laurentia as part of a nascent Rodinia supercontinent.

At the same time that the Midcontinent Rift was initiating in Laurentia the following igneous provinces were emplaced on four other cratons:

1. the Umkondo large igneous province of the Kalahari Craton (many ID-TIMS U-Pb dates on zircon and baddeleyite between 1112 and 1108 Ma; *Hanson et al.* [2004])

2. thick and extensive gabbro-norite (GN) dikes exposed in the southwest Angola portion of the Congo Craton (one of which has an ID-TIMS U-Pb date on baddeleyite of 1110.3 ± 2.5 Ma; *Ernst et al.* [2013])

3. the Mahoba suite of dikes of the India Craton (one of which, the "Great Dike of Mahoba" has an laser ablation U-Pb date on zircon of 1112.7 ± 7.4 Ma; *Pradhan et al.* [2012])

4. a putative ca. 1110 Ma large igneous province in the southwest portion of the Amazonia craton inferred from dates on two widely separated intrusions (ID-TIMS U-Pb date on baddeleyite from the Rincón del Tigre intrusion of 1110.4 ± 1.8 Ma and a sill within Aguepeí sediments with a ID-TIMS U-Pb date on baddeleyite of 1111.5 ± 1.5 Ma *Hamilton et al.* [2012])

This contemporaneous voluminous volcanism on five late Mesoproterozoic cratons is coincident with the onset of Laurentia's rapid plate motion. This temporal correlation suggests that this time period was characterized by particularly vigorous plume activity, that in addition to driving large igneous province development may be connected to the driving forces that resulted in rapid plate motion and/or true polar wander.

5. Conclusion

Lava flows of the Osler Volcanic Group below the Puff Island unconformity erupted during the early magmatic stage of Midcontinent Rift development during a time interval characterized by reversed magnetic polarity. New paleomagnetic data from 84 Osler Volcanic Group lava flows reveal a significant decrease in paleomagnetic inclination through the sequence of lava flows. These results support the hypothesis that the difference between the steep paleomagnetic inclinations characteristic of the early magmatic stage and the relatively shallower inclinations of the main magmatic stage throughout the rift are the result of rapid plate motion that was progressively recorded by the Osler Volcanic Group.

Acknowledgments. The Ontario Ministry of Natural Resources granted permits for work to be conducted in the Lake Superior Archipelago Conservation Reserve. Pete Hollings of Lakehead University along with Dorothy Campbell and John Scott of the Ontario Geological Survey provided an introduction to the geology of the Lake Superior Archipelago. This work benefitted from discussions with Robert Cundari, Josh Feinberg and Henry Halls. Reviews from Trond Torsvik and an anonymous referee led to significant improvements of the manuscript. Julie Bowles, Mike Jackson and Peat Solheid provided support for measurements at the Institute for Rock Magnetism. This research was supported by NSF EAR-1045635 to N.L.S.-H. and the NSF-funded Research Experiences for Undergraduates program in the Department of Earth Sciences at the University of Minnesota that supported A.A.V. and M.R.M.. This is IRM contribution #1312.

References

Buchan, K. L. (2013), Key paleomagnetic poles and their use in Proterozoic continent and supercontinent reconstructions: A review, *Precambrian Research*, *238*(0), 93–110, doi:http://dx.doi.org/10.1016/j.precamres.2013.09.018.

Cannon, W. F. (1992), The Midcontinent rift in the Lake Superior region with emphasis on its geodynamic evolution, *Tectonophysics*, *213*(1-2), 41–48, doi:10.1016/0040-1951(92)90250-A.

Davis, D., and J. Green (1997), Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution, *Canadian Journal of Earth Science*, *34*, 476–488, doi:10.1139/e17-039.

Davis, D., and R. Sutcliffe (1985), U-Pb ages from the Nipigon plate and northern Lake Superior, *Geological Society of America Bulletin*, *96*, 1572–1579, doi:10.1130/0016-7606(1985)96¡1572:UAFTNP¿2.0.CO;2.

Ebinger, C. J., and N. H. Sleep (1998), Cenozoic magmatism throughout east Africa resulting from impact of a single plume, *Nature*, *395*(6704), 788–791.

Ernst, R. E., E. Pereira, M. A. Hamilton, S. A. Pisarevsky, J. Rodriques, C. C. G. Tassinari, W. Teixeira, and V. Van-Dunem (2013), Mesoproterozoic intraplate magmatic 'barcode' record of the Angola portion of the Congo Craton: Newly dated magmatic events at 1505 and 1110 Ma and implications for Nuna (Columbia) supercontinent reconstructions, *Precambrian Research*, *230*(0), 103–118, doi:10.1016/j.precamres.2013.01.010.

Evans, D. (2003), True polar wander and supercontinents, *Tectonophysics*, *362*, 303–320, doi:10.1016/S0040-1951(02)000642-X.

Giguere, J. F. (1975), Geology of St. Ignace Island and adjacent islands, District of Thunder Bay, Canada, *Tech. rep.*, Ontario Geological Survey.

Halls, H. (1974), A paleomagnetic reversal in the Osler Volcanic Group, northern Lake Superior, *Canadian Journal of Earth Science*, *11*, 1200–1207, doi:10.1139/e74-113.

Halls, H., and L. Pesonen (1982), Paleomagnetism of Keweenawan rocks, *Geological Society of America Memoirs*, *156*, 173–201, doi:10.1130/MEM156-p173.

Halls, H. C. (1972), Magnetic studies in northern Lake Superior, *Canadian Journal of Earth Sciences*, *9*(11), 1349–1367, doi:10.1139/e72-123.

Hamilton, M. A., G. R. Sadowski, W. Teixeira, R. E. Ernst, and A. S. Ruiz (2012), Precise, matching U-Pb ages for the Rincon del Tigre mafic layered intrusion and Huanchaca gabbro sill, Bolivia: Evidence for a late Mesoproterozoic LIP in SW Amazonia?, in *Geological Association of Canada Annual Meeting Abstracts*, vol. 35.

Hanson, R., J. Crowley, S. Bowring, J. Ramezani, W. Gose, I. Dalziel, J. Pancake, E. Seidel, T. Blenkinsop, and J. Mukwakwami (2004), Coeval large-scale magmatism in the Kalahari and Laurentian Cratons during Rodinia assembly, *Science*, *304*, 1126–1129, doi:10.1126/science.1096329.

Heaman, L. M., and J. P. Grotzinger (1992), 1.08 ga diabase sills in the Pahrump group, California: Implications for development of the Cordilleran miogeocline, *Geology*, *20*(7), 637–640, doi:10.1130/0091-7613(1992)020¡0637:GDSITP¿2.3.CO;2.

Hollings, P., P. Fralick, and B. Cousens (2007a), Early history of the Midcontinent Rift inferred from geochemistry and sedimentology of the Mesoproterozoic Osler Group, northwestern Ontario, *Canadian Journal of Earth Sciences*, *44*(3), 389–412, doi:10.1139/e06-084.

Hollings, P., M. Smyk, and L. Heaman (2007b), Preliminary investigations of the ∼1 Ga St. Ignace Island Complex, northern Lake Superior, Ontario, *Geological Association of Canada/Mineralogical Association of Canada Program with Abstracts*, *32*, 39.

Lightfoot, P. C., R. H. Sutcliffe, and W. Doherty (1991), Crustal contamination identified in Keweenawan Osler group tholeiites, Ontario: A trace element perspective, *The Journal of Geology*, *99*(5), 739–760, doi:10.1086/629536.

Mitchell, R. N., T. M. Kilian, and D. A. D. Evans (2012), Supercontinent cycles and the calculation of absolute palaeolongitude in deep time, *Nature*, *482*(7384), 208–211, doi:10.1038/nature10800.

Nicholson, S., S. Shirey, K. Schultz, and J. Green (1997), Rift-wide correlation of 1.1 Ga Midcontinent rift system basalts: implications for multiple mantle sources during rift development, *Canadian Journal of Earth Science*, *34*, 504–520, doi:10.1139/e17-041.

Pesonen, L., and H. Nevanlinna (1981), Late Precambrian Keweenawan asymmetric reversals, *Nature*, *294*, 436–439, doi:10.1038/294436a0.

Pradhan, V. R., J. G. Meert, M. K. Pandit, G. Kamenov, and M. E. A. Mondal (2012), Paleomagnetic and geochronological studies of the mafic dyke swarms of Bundelkhand craton, central India: Implications for the tectonic evolution and paleogeographic reconstructions, *Precambrian Research*, *198–199*(0), 51–76, doi:10.1016/j.precamres.2011.11.011.

Robertson, W., and W. Fahrig (1971), The great Logan Loop - the polar wandering path from Canadian shield rocks during the Neohelikian era, *Canadian Journal of Earth Science*, *8*, 1355–1372, doi:10.1139/e71-125.

Shirey, S. B. (1997), Re-Os isotopic compositions of Midcontinent rift system picrites: implications for plume –lithosphere interaction and enriched mantle sources, *Canadian Journal of Earth Sciences*, *34*(4), 489–503, doi:10.1139/e17-040.

Sleep, N. H. (1997), Lateral flow and ponding of starting plume material, *Journal of Geophysical Research: Solid Earth*, *102*(B5), 10,001–10,012, doi:10.1029/97JB00551.

Swanson-Hysell, N. L., A. C. Maloof, B. P. Weiss, and D. A. D. Evans (2009), No asymmetry in geomagnetic reversals recorded by 1.1-billion-year-old Keweenawan basalts, *Nature Geoscience*, *2*, 713–717, doi:10.1038/ngeo622.

Swanson-Hysell, N. L., S. D. Burgess, A. C. Maloof, and S. A. Bowring (2014), Magmatic activity and plate motion during the latent stage of Midcontinent Rift development, *Geology*, doi:10.1130/G35271.1.

Tauxe, L., and K. Kodama (2009), Paleosecular variation models for ancient times: Clues from Keweenawan lava flows, *Physics of the Earth and Planetary Interiors*, *177*, 31–45, doi:10.1016/j.pepi.2009.07.006.

Tauxe, L. (2010), *Essentials of Paleomagnetism*, University of California Press.

Torsvik, T. H., R. Van der Voo, U. Preeden, C. Mac Niocaill, B. Steinberger, P. V. Doubrovine, D. J. J. van Hinsbergen, M. Domeier, C. Gaina, E. Tohver, J. G. Meert, P. J. A. McCausland, and L. R. M. Cocks (2012), Phanerozoic polar wander, palaeogeography and dynamics, *Earth-Science Reviews*, *114*(3–4), 325–368, doi:10.1016/j.earscirev.2012.06.007.

van Hinsbergen, D. J. J., B. Steinberger, P. V. Doubrovine, and R. Gassmöller (2011), Acceleration and deceleration of india-asia convergence since the cretaceous: Roles of mantle plumes and continental collision, *Journal of Geophysical Research: Solid Earth*, *116*(B6), doi:10.1029/2010JB008051.

Vervoort, J., K. Wirth, B. Kennedy, T. Sandland, and K. Harpp (2007), The magmatic evolution of the Midcontinent rift: New geochronologic and geochemical evidence from felsic magmatism, *Precambrian Research*, *157*, 235–268, doi:10.1016/j.precamres.2007.02.019.

Watson, G. S. (1983), Large sample theory of the Langevin distribution, *Journal of Statistical Planning and Inference*, *8*(3), 245–256, doi:10.1016/0378-3758(83)90043-5.

Weil, A., J. Geissman, M. Heizler, and R. Van der Voo (2003), Paleomagnetism of Middle Proterozoic mafic intrusions and Upper Proterozoic (Nankoweap) red beds from the Lower Grand Canyon Supergroup, Arizona, *Tectonophysics*, *375*, 199–220, doi:10.1016/S0040-1951(03)00339-1.

Zartman, R., S. Nicholson, W. Cannon, and G. Morey (1997), U-Th-Pb zircon ages of some Keweenawan Supergroup rocks from the south shore of Lake Superior, *Canadian Journal of Earth Science*, *34*, 549–561, doi:10.1139/e17-044.

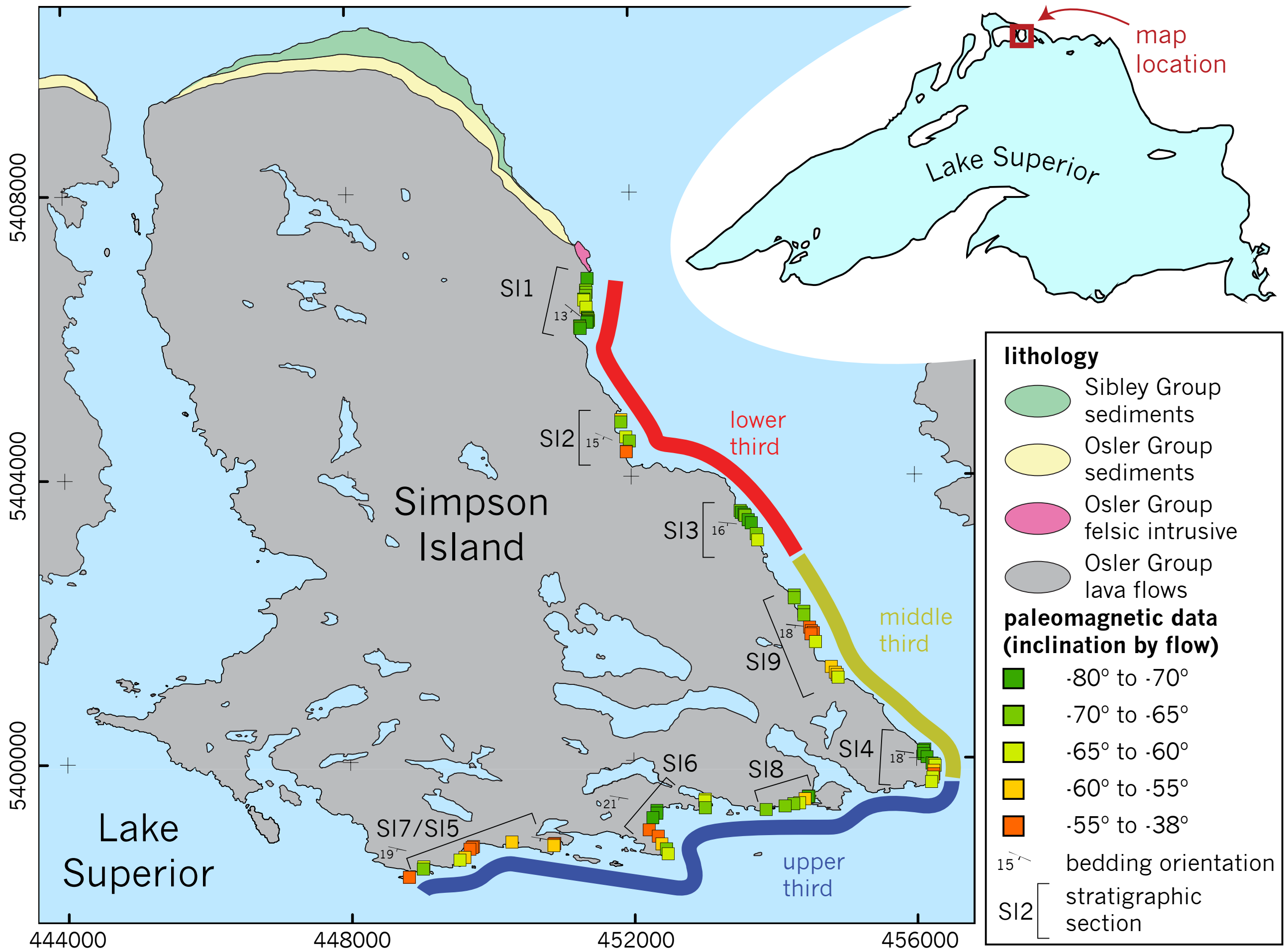

Figure 1. Geological map of Simpson Island in the Lake Superior Archipelago with studied stratigraphic sections and lava flows shown. Data from flows are color-coded by inclination. The lava flows of the Osler Volcanic Group are tilted such that more southward flows are higher in the stratigraphy. The lower, middle and upper thirds divisions of the stratigraphic succession that are used in the text and in Figure 3 are shown. The inset map shows the location of the geological map.

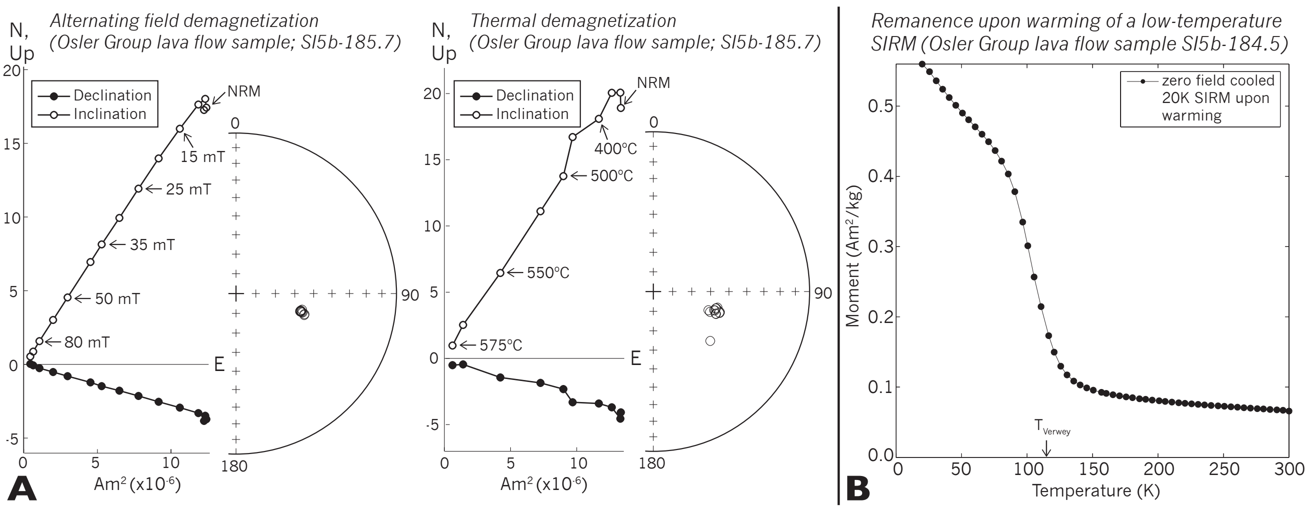

Figure 2. A) Paleomagnetic data for basaltic lava flow sample SI5b-185.7. Alternating field and thermal demagnetization data are shown for sister specimens of this sample in vector component and equal area diagrams. These data reveal a dominantly single-component remanence with both demagnetization protocols isolating the same direction. B) Low temperature demagnetization data from a sample in the same lava flow wherein a saturating isothermal remanent magnetization (SIRM) was imposed at 20K after cooling in a zero field. Subsequent warming of this remanence led to significant demagnetization across temperatures characteristic of the Verwey transition indicating that the magnetic mineralogy of the sample is dominated by low-titanium magnetite.

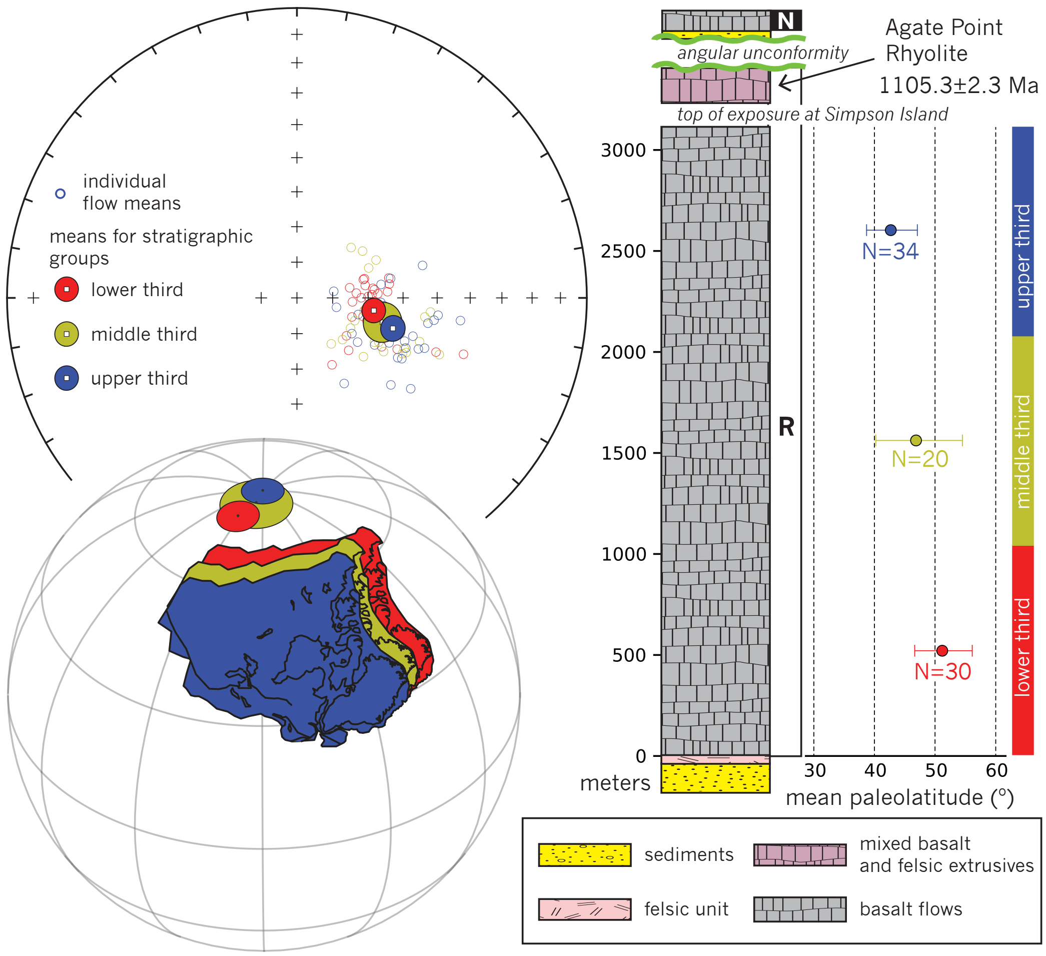

Figure 3. Summary of paleomagnetic data from the Simpson Island exposure of the Osler Volcanic Group. The equal area plot shows the mean directions for each of the individual studied flows (N=84). All studied flows are of reverse polarity such that the plotted directions are in the upper hemisphere of the projection. Means are calculated and plotted on the equal area plot with α_{95} confidence ellipses for flows in the lower third (red; Dec=99.3, Inc=-68.0, α_{95}=3.4, N=30), the middle third (yellow; Dec=105.9, Inc=-64.9, α_{95}=5.9, N=20) and upper third (blue; Dec=107.6, Inc=-61.6, α_{95}=3.5, N=34) of the stratigraphy. The mean paleolatitudes for these portions of the stratigraphy calculated from the Fisher means are also shown on the simplified composite stratigraphy with corresponding 2σ error bars. The paleogeographic reconstruction shows Laurentia's progressive equatorward motion as constrained by the poles from each of the stratigraphic groupings.

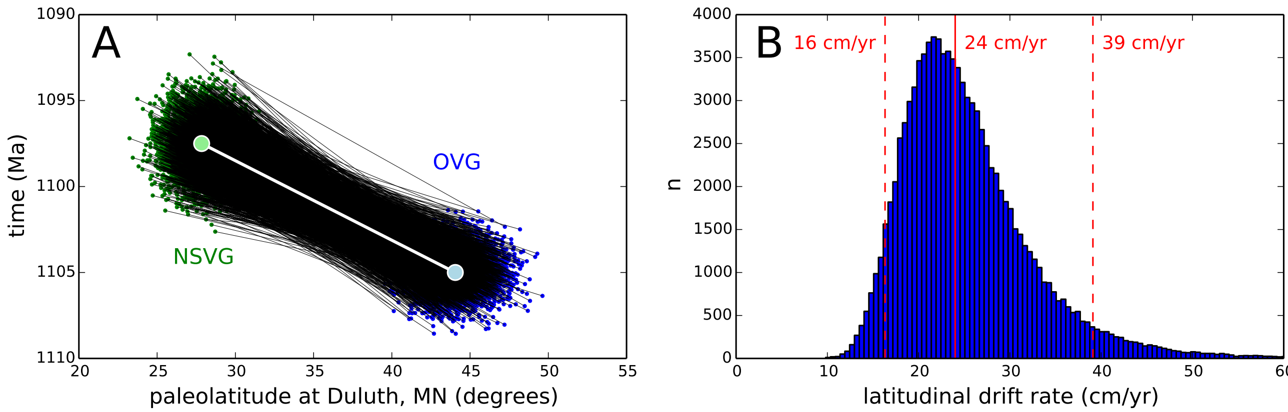

Figure 4. Monte Carlo simulations of rates implied by paleomagnetic and geochronologic data between the Osler Volcanic Group (OVG) and southwest limb of the upper North Shore Volcanic Group (NSVG). In (A), the white outlined points connected by a white line represent the mean paleolatitude (calculated for Duluth, MN) and age of the poles. The green and blue points are 5,000 of the 100,000 simulated pole pairs (OVG and NSVG respectively) used in the analysis and are connected by grey lines which represent the simulated rates. The histogram in (B) shows all 100,000 of the simulated rates that yield the labeled 5 percentile value of 16 cm/yr, median value of 24 cm/yr (also the value as calculated from the means) and 95 percentile value of 39 cm/yr.