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Rapid emplacement of massive Duluth Complex intrusions within the North American Midcontinent Rift

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ABSTRACT

The Duluth Complex (Minnesota, USA) is one of the largest mafic intrusive complexes on Earth. It was emplaced as the Midcontinent Rift developed in Laurentia's interior during an interval of magmatism and extension from ca. 1109 to 1084 Ma. This duration of magmatic activity is more protracted than is typical for large igneous provinces interpreted to have formed from decompression melting of upwelling mantle plumes. While the overall duration was protracted, there were intervals of more voluminous magmatism. New $^{206}Pb/^{238}U$ zircon dates for the anorthositic and layered series of the Duluth Complex constrain these units to have been emplaced ca. 1096 Ma in <1 m.y. (duration of 500 ± 260 k.y.). Comparison of paleomagnetic data from these units with Laurentia's apparent polar wander path supports this interpretation. This rapid emplacement bears similarities to the geologically short duration of well-dated large igneous provinces. These data support hypotheses that call upon the co-location of lithospheric extension and anomalously hot upwelling mantle. This rapid magmatic pulse occurred >10 m.y. after initial magmatism following >20° of latitudinal plate motion. A likely scenario is one in which upwelling mantle encountered the base of Laurentian lithosphere and flowed via "upside-down drainage" to locally thinned lithosphere of the Midcontinent Rift.

INTRODUCTION

The Midcontinent Rift represents a protracted tectonomagmatic event in the interior of Laurentia (the North American craton). Voluminous outpouring of lava and emplacement of intrusions accompanied rift development (Fig. 1). Magmatic activity initiated at ca. 1109 Ma and continued until ca. 1084 Ma (Swanson-Hysell et al., 2019). Preserved thicknesses of the volcanic successions range from nearly 10 km for partial sections exposed on land (Green et al., 2011) to ~25 km under Lake Superior (Cannon, 1992). These volcanics and associated intrusions are much more voluminous than is typical for tectonic rifting. Analysis of seismic data leads to an estimate that total eruptive volume exceeded 2×10^6 km^3, with a greater volume added to the lithosphere as intrusions and a magmatic underplate (Cannon, 1992). The ~25 m.y. duration of Midcontinent Rift volcanism is much longer than is typical for large igneous province emplacement associated with decompression melting of an upwelling mantle plume. Well-dated large igneous provinces, such as the Central Atlantic magmatic province (Blackburn et al., 2013), the Karoo-Ferrar large igneous province (Burgess et al., 2015), and the Deccan Traps (Schoene et al., 2019; Sprain et al., 2019) had durations of <1 m.y. for the bulk of their magmatism. An explanation for prolonged volcanism in the Midcontinent Rift could attribute rift initiation and initial volcanism to plume arrival, with continued volcanism resulting from rift-driven asthenospheric upwelling. However, the most voluminous period of magmatism occurred >10 m.y. after initial flood volcanism during an interval known as the "main magmatic stage" (Vervoort et al., 2007). Main-stage magmatism has been attributed to an upwelling mantle plume based on the large volume and geochemical signatures (Nicholson and Shirey, 1990; White and McKenzie, 1995).

Pioneering Midcontinent Rift geochronology utilized $^{207}Pb/^{206}Pb$ dates on zircon from volcanics (Davis and Green, 1997) and intrusions (Paces and Miller, 1993) to illuminate the magmatic history. Subsequent advances in U-Pb geochronology enable higher-precision $^{206}Pb/^{238}U$ dates to be used when chemical abrasion methods have mitigated Pb loss (Mattinson, 2005). U-Pb dates developed using these methods have led to an updated chronostratigraphic framework for Midcontinent Rift volcanics (Swanson-Hysell et al., 2019; Fig. 2). With these higher-precision constraints, the timing and tempo of magmatic activity within the rift can be reevaluated: Was it continuous or punctuated by pulses? Key to evaluating this question is the timing of emplacement of intrusive rocks, particularly the largest intrusive suite—the Duluth Complex (Fig. 1). With its arcuate area of 5630 km^2, the tholeiitic Duluth Complex (Minnesota, USA) is the second-largest exposed mafic intrusive complex on Earth (Miller et al., 2002). It was emplaced as sheet-like intrusions into the base of a comagmatic volcanic succession, with the majority of its volume associated with the anorthositic series and the layered series of gabbroic and troctolitic cumulates (Miller et al., 2002; Fig. 1). We present $^{206}Pb/^{238}U$ zircon dates from the Duluth Complex, as well as from the Beaver Bay Complex (Fig. 1), to improve constraints on the duration of intrusive magmatism and contextualize it with the chronology of volcanism.

METHODS AND RESULTS

Zircon crystals were chemically abraded prior to analysis by isotope dilution–thermal ionization mass spectrometry (ID-TIMS) (see the

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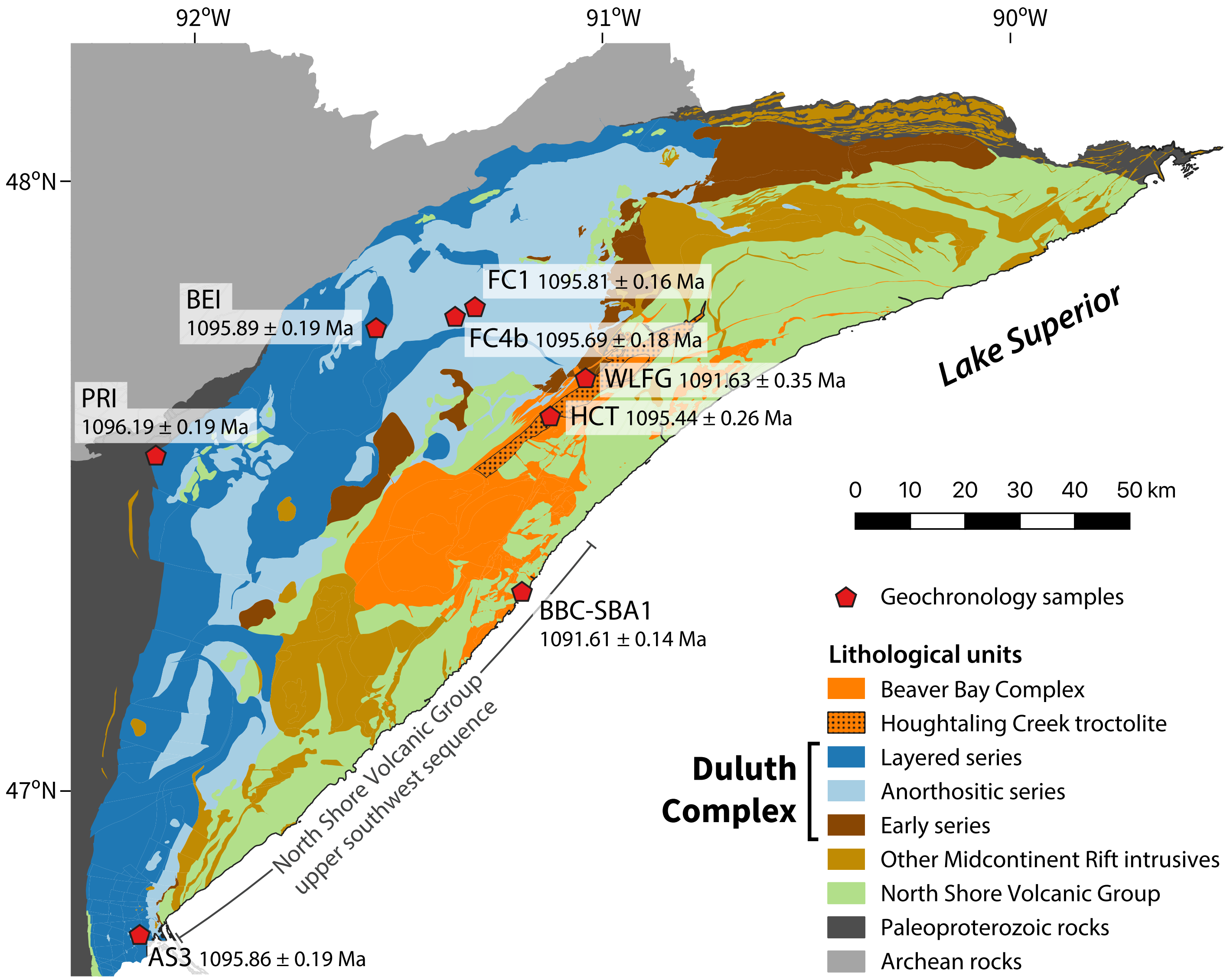

Figure 1. Geologic map of northeastern Minnesota, USA (simplified from Jirsa et al., 2011), highlighting the Midcontinent Rift intrusive complexes and geochronology sample locations. Volcanic and intrusive units dip toward Lake Superior typically at 10° to 20°. U-Pb dates from anorthositic and the layered series of the Duluth Complex (light and dark blue) indicate rapid emplacement in <1 m.y.

Supplemental Material[1]). Weighted means were calculated from multiple single zircon dates (Fig. 2; Table 1). These $^{206}Pb/^{238}U$ dates can be compared to one another, and to the volcanic dates of Swanson-Hysell et al. (2019), at the level of analytical uncertainty (*X* uncertainty in Table 1) given that all dates were developed using EARTHTIME tracer solutions (Condon et al., 2015). This 2σ analytical uncertainty will be reported when dates are discussed. External uncertainties and mean squared weighted deviation (MSWD) values are reported in Table 1.

The Duluth Complex anorthositic series comprises plagioclase-rich gabbroic cumulates varying from anorthositic gabbro to anorthosite. Samples FC1 and FC4b are from gabbroic anorthosite exposures near the former logging town of Forest Center (Minnesota). A weighted mean $^{206}Pb/^{238}U$ date for sample FC1 of 1095.81 ± 0.16 Ma is calculated based on 10 single zircon dates (Table 1). This date is indistinguishable from a weighted mean $^{206}Pb/^{238}U$ date for sample FC1 of 1095.97 ± 0.22 Ma developed by Ibañez-Mejia and Tissot (2019). Our new sample FC4b date is indistinguishable from these sample FC1 dates with a weighted mean $^{206}Pb/^{238}U$ date of 1095.69 ± 0.18 Ma based on dates from seven zircons. These dates are indistinguishable from the weighted mean $^{206}Pb/^{238}U$ date of 1095.86 ± 0.19 Ma developed from chemically abraded zircons of anorthositic-series sample AS3 collected in the city of Duluth (Schoene et al., 2006; Fig. 2; Table 1). Zircon grains from these anorthositic-series samples are commonly used as U-Pb standards.

The layered series of the Duluth Complex is a suite of stratiform troctolitic to gabbroic cumulates emplaced as discrete intrusions (Fig. 1). Sample PRI is an augite troctolite from the Partridge River intrusion, which is at the base of the complex in contact with underlying Paleoproterozoic metasedimentary rocks (Fig. 1). Data from six zircons result in a weighted mean $^{206}Pb/^{238}U$ date of 1096.19 ± 0.19 Ma (Fig. 2). Sample BEI is an olivine gabbro from the Bald Eagle intrusion. This intrusion has been

[1]Supplemental Material. Individual zircon dates, paleomagnetic site mean directions, and additional method details. Please visit https://doi.org/10.1130/GEOL.S.12935057 to access the supplemental material, and contact editing@geosociety.org with any questions. Paleomagnetic data and interpreted directions are available in the Magnetics Information Consortium (MagIC) database (https://earthref.org/MagIC/doi/10.1130/G47873.1). Geochronological data are available at https://www.geochron.org associated with International Geosample Numbers (IENSH000H, IENSH000I, IENSH000J, IENSH000 K, IENSH000L and IENSH000 M). Code associated with statistical tests and data visualization is available in a Zenodo repository https://doi.org/10.5281/zenodo.4012382.

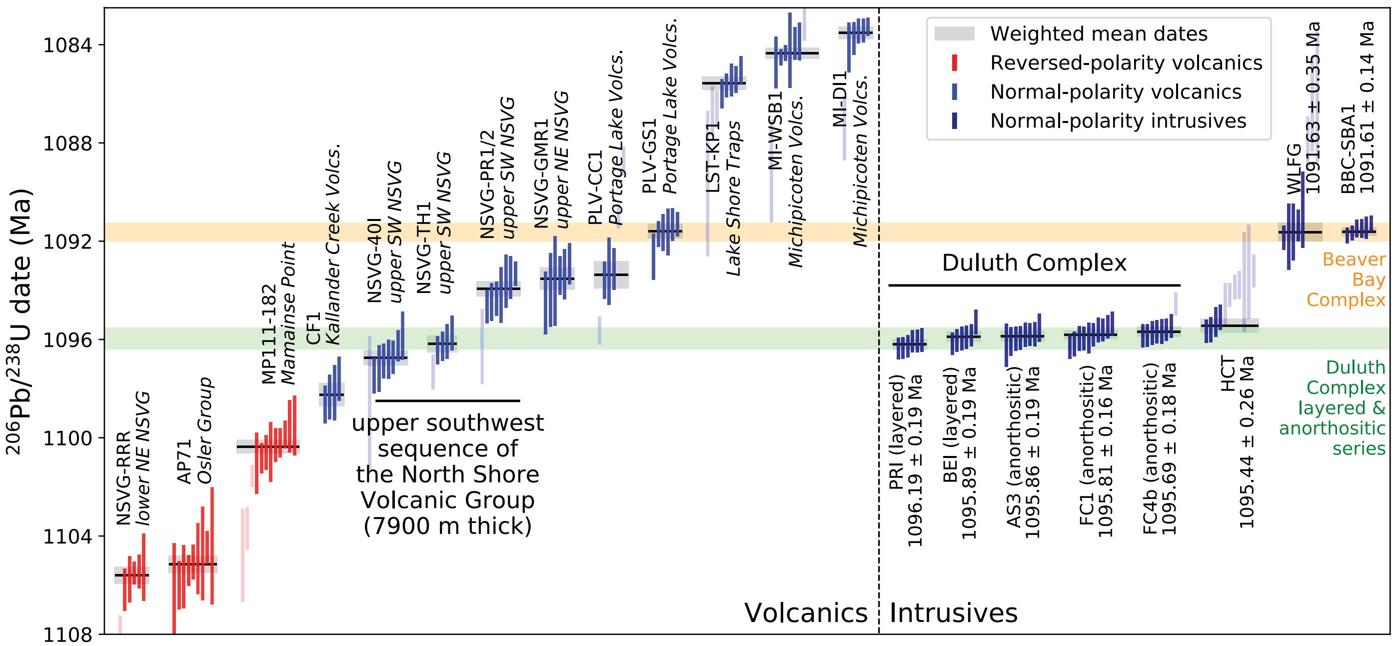

Figure 2. Date bar plot of chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) ^{206}Pb/^{238}U zircon dates for Midcontinent Rift volcanics and intrusives. Dates for volcanics and sample BBC-SBA1 are from Fairchild et al. (2017) and Swanson-Hysell et al. (2019); sample AS3 date is from Schoene et al. (2006). Each vertical bar represents the date for an individual zircon, while horizontal lines and gray boxes represent weighted means and their uncertainty. Dates are colored by the geomagnetic polarity recorded by the unit or sequence of lavas. NSVG—North Shore Volcanic Group; Volcs.—Volcanics.

interpreted as one of the youngest layered-series units based on cross-cutting relationships inferred from aeromagnetic data (Miller et al., 2002). Dates from six zircons of sample BEI result in a weighted mean ^{206}Pb/^{238}U date of 1095.89 ± 0.19 Ma (Fig. 2).

The Beaver Bay Complex is a suite of dominantly hypabyssal intrusions that cross-cut the North Shore Volcanic Group (Fig. 1). Sample HCT is an augite troctolite from the Houghtaling Creek troctolite macrodike (Miller et al., 2001). In contrast to the internally consistent dates from the layered- and anorthositic-series samples, ^{206}Pb/^{238}U zircon dates from sample HCT have more dispersion, which we interpret as resulting from Pb loss not fully mitigated by chemical abrasion. After excluding individual dates that trend away from concordia, dates from four concordant zircons result in a weighted mean ^{206}Pb/^{238}U date of 1095.44 ± 0.26 Ma (Fig. 2). A sample of ferrodiorite was collected as sample WLFG from the Wilson Lake ferrogabbro of the Beaver Bay Complex. This plug-shaped zoned intrusion was emplaced into the Duluth Complex roof zone. Variable-intensity chemical abrasion was applied to sample WLFG zircons, with hotter and longer dissolution yielding more concordant data with older ^{206}Pb/^{238}U dates (Table S1 in the Supplemental Material). After excluding those interpreted to have unmitigated Pb loss, dates from five zircons result in a weighted mean ^{206}Pb/^{238}U date of 1091.63 ± 0.35 Ma (Fig. 2). This date is indistinguishable from the 1091.61 ± 0.14 Ma ^{206}Pb/^{238}U date developed from an aplite within a Silver Bay intrusion of the Beaver Bay Complex (sample BBC-SBA1 of Fairchild et al., 2017; Figs. 1 and 2).

Paleomagnetic data from the layered series (37 sites) and the anorthositic series (11 sites) near Duluth were published by Beck (1970) (Fig. 3). Site directions of the layered and anorthositic series share a common mean, consistent with their overlapping U-Pb dates. In order to pair paleomagnetic data with geochronology, oriented cores were collected and analyzed from the sites of samples FC1, FC4b, and HCT. Magnetization was measured on a 2G DC-SQUID magnetometer at the University of California, Berkeley. Samples underwent alternating-field or thermal demagnetization steps, and fits were made using PmagPy software (Tauxe et al., 2016; https://github.com/PmagPy/). While Beck (1970) did not implement tilt corrections, the Duluth Complex and overlying lavas dip toward Lake Superior, and paleomagnetic data need to be corrected for this tilt. We compiled abundant

TABLE 1. SUMMARY OF CA-ID-TIMS ^{206}Pb/^{238}U DATES FROM MIDCONTINENT RIFT INTRUSIONS, MINNESOTA, USA

Sample ID, locality, and lithology	Group	Latitude Longitude	^{206}Pb/^{238}U date (Ma)	Uncertainty (2σ)			MSWD	*n*/*N*
				X (m.y.)	*Y* (m.y.)	*Z* (m.y.)		
PRI—Partridge River intrusion; augite troctolite	Duluth Complex (layered series)	47.5480°N 92.1074°W	1096.19	0.19	0.36	1.15	0.45	6/6
BEI—Bald Eagle intrusion; olivine gabbro	Duluth Complex (layered series)	47.7516°N 91.5680°W	1095.89	0.19	0.36	1.15	1.59	6/6
AS3—Duluth, gabbroic anorthosite	Duluth Complex (anorthositic series)	46.7621°N 92.1590°W	1095.86	0.19	0.36	1.15	0.43	8/8
FC1—Forest Center; gabbroic anorthosite	Duluth Complex (anorthositic series)	47.7827°N 91.3266°W	1095.81	0.16	0.34	1.14	1.44	10/10
FC4b—Forest Center; gabbroic anorthosite	Duluth Complex (anorthositic series)	47.7677°N 91.3753°W	1095.69	0.18	0.35	1.14	0.34	7/8
HCT—Houghtaling Creek troctolite; augite troctolite	Beaver Bay Complex	47.6009°N 91.1497°W	1095.44	0.26	0.40	1.16	1.13	4/11
WLFG—Wilson Lake ferrogabbro; ferrodiorite	Beaver Bay Complex	47.6620°N 91.0619°W	1091.63	0.35	0.46	1.18	0.74	5/8
BBC-SBA1—Silver Bay intrusion; aplite	Beaver Bay Complex	47.3143°N 91.2281°W	1091.61	0.14	0.30	1.2	1.0	6/6

Note: CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry. *X* is 2σ analytical uncertainty; *Y* is 2σ uncertainty also incorporating tracer calibration for comparison to U-Pb dates not developed using EARTHTIME-calibrated tracer solutions (Condon et al., 2015); *Z* is 2σ uncertainty including *X* and *Y*, as well as ^{238}U decay constant uncertainty (0.108%; Jaffey et al., 1971). This *Z* uncertainty needs to be utilized when comparing to dates using other decay systems (e.g., ^{40}Ar/^{39}Ar, ^{187}Re-^{187}Os. MSWD is the mean squared weighted deviation; *n* is the number of individual zircon dates included in the calculated sample mean date; *N* is the number of individual zircons analyzed for the sample. All dates are from this study with the exceptions of samples AS3 (Schoene et al., 2006) and BBC-SBA1 (Fairchild et al., 2017).

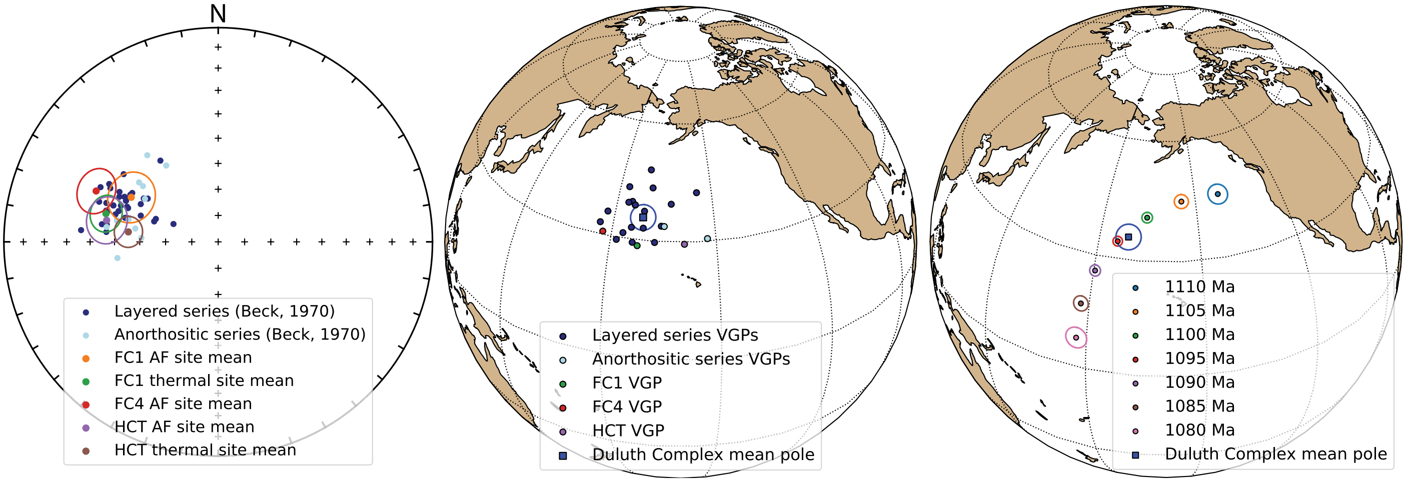

Figure 3. (Left panel) Tilt-corrected site mean paleomagnetic directions from anorthositic and layered series sites of Beck (1970) and from FC1, FC4, and HCT sites (see Fig. 1 and Table 1). AF—alternating field. (Center panel) Virtual geomagnetic poles (VGPs) for sites with 95% confidence angle α_{95} <15° give mean pole of: 35.6°N, 188.7°E, *N* = 24, A_{95} = 3.1, *k* = 92, where *k* is Fisher's precision parameter. (Right panel) Duluth Complex pole shown with synthesized pole path developed from Midcontinent Rift (MCR) volcanic poles.

igneous-layering orientations, which are similar to the tilt of overlying lavas and interflow sediments, and use them for tilt correction.

Rapid progression of poles within the apparent polar wander path (APWP) enable these paleomagnetic data to give chronological insight. Pole positions from the early stage of rift magmatism are different from those of main-stage lavas (Fig. 3). The similar position of Duluth Complex layered- and anorthositic-series virtual geomagnetic poles (VGPs) is consistent with contemporaneous emplacement, and they can be combined into a mean pole (Fig. 3). This pole can be compared to a synthesized APWP developed using an Euler pole inversion of chronostratigraphically controlled volcanic poles (Swanson-Hysell et al., 2019). The Duluth Complex pole lies between the 1100 Ma and 1095 Ma path positions with the 95% confidence angle (A_{95}) of the pole overlapping with the two-angular-standard-deviations ellipse of the 1095 Ma path position. This result is consistent with a ca. 1096 Ma age for the layered and anorthositic series and strengthens the correlation with the volcanics.

DISCUSSION

Our new U-Pb dates, together with paleomagnetic data, imply that the bulk of the Duluth Complex layered series and anorthositic series were emplaced in <1 m.y. The differences between the anorthositic series and sample BEI layered series dates are all within uncertainty of no difference. The Partridge River intrusion layered series date is slightly older, with an age difference from the rest of the anorthositic and layered series dates that is distinct from zero at 95% confidence. Taking this oldest date of 1096.19 ± 0.19 Ma for sample PRI and the youngest date of 1095.69 ± 0.18 Ma from sample FC4b yields a duration of overall emplacement of the layered and anorthositic series of 500,000 ± 260,000 years (2σ). This emplacement was coeval with eruption of the North Shore Volcanic Group upper southwest sequence, which comprises ~7900 m of lavas and is the thickest exposed Midcontinent Rift volcanic succession (Fig. 1; Green et al., 2011; Swanson-Hysell et al., 2019). This rapid emplacement of the bulk of the Duluth Complex together with coeval North Shore Volcanic Group eruptions require a large pulse of melt generation ca. 1096 Ma.

The 1095.44 ± 0.26 Ma age of the Houghtaling Creek troctolite of the Beaver Bay Complex is indistinguishable from the youngest Duluth Complex anorthositic series date. This result indicates that this pulse of voluminous magmatic activity is represented in some Beaver Bay Complex intrusions. A younger pulse of Beaver Bay Complex magmatism postdates North Shore Volcanic Group eruptions, evidenced by units such as the Silver Bay intrusions penetrating the youngest North Shore Volcanic Group lavas, including the 1093.94 ± 0.28 Ma Palisade Rhyolite (Miller et al., 2001; Swanson-Hysell et al., 2019; Fig. 1). The age of this magmatism is constrained by indistinguishable dates of 1091.63 ± 0.35 Ma for the Wilson Lake ferrogabbro and 1091.61 ± 0.14 Ma from the Silver Bay intrusions (Fig. 2; Table 1). This younger Beaver Bay Complex magmatism is coeval with eruption of the >5-km-thick Portage Lake Volcanics that are exposed to the east on the Keweenaw Peninsula and Isle Royale in Michigan (Fig. 2).

Rapid emplacement of the voluminous layered and anorthositic series of the Duluth Complex bears similarities to the geologically short duration (<1 m.y.) of well-dated flood basalt provinces (Burgess et al., 2015; Schoene et al., 2019). This similarity supports the hypothesis put forward by Green (1983), and advanced by others including Cannon and Hinze (1992) and Stein et al. (2015), that co-location of massive magmatism and rifting is the result of lithospheric extension atop decompression melting of an upwelling mantle plume. Contemporaneous heating of Laurentia lithosphere 600 km to the north of the rift is indicated by thermochronologic data from middle- to lower-crustal xenoliths (Edwards and Blackburn, 2018). Basaltic magma was also emplaced throughout the Southwestern Laurentia large igneous province coeval with rift magmatism, including sills >2300 km to the southwest of Duluth (Bright et al., 2014). That such a broad region of Laurentia lithosphere experienced heating and magmatism supports hypothesized large-scale mantle upwelling.

Both the ca. 1108 Ma early stage and ca. 1096 Ma main stage magmatic intervals within the Midcontinent Rift were voluminous and have been interpreted to be the result of a plume-related thermal anomaly. The interpretation that this volcanism is associated with a deep-seated mantle plume needs to be reconciled with the long duration of magmatism and rapid equatorward motion of Laurentia from a latitude of ~54°N at ca. 1108 Ma during early-stage flood basalt eruptions to ~32°N by ca. 1096 Ma (paleolatitudes for Duluth, Minnesota). While some motion could be associated with true polar wander, in which the mesosphere and asthenosphere rotated in conjunction with the lithosphere, paleomagnetic pole positions require a substantial component of plate-tectonic motion (Swanson-Hysell et al., 2019). The pulsed nature of magmatic activity could support an interpretation of multiple upwelling pulses. As postulated by Cannon and Hinze (1992), the initial pulse expressed by ca. 1108 early stage flood basalt volcanism initiated lithospheric thinning. Given the significantly thinned lithosphere in the Midcontinent Rift region, subsequent positively buoyant plume material that encountered

Laurentia lithosphere would have experienced "upside-down" drainage, wherein relief at the base of the lithosphere resulted in lateral and upward flow into the Midcontinent Rift (Sleep, 1997; Swanson-Hysell et al., 2014). Flow of upwelling mantle to locally thin lithosphere would have led to ponding and concentrated decompression melting within the rift. One scenario is that Laurentia was migrating over a plume generation zone (Burke et al., 2008) from which multiple deep-seated mantle plumes upwelled and reached the lithosphere during rift development. The first could have been centered on the present-day Lake Superior region, with the second encountering Laurentian lithosphere and being directed to the rift by upside-down drainage in addition to driving magmatism in southwestern Laurentia. Another scenario is that ca. 1096 Ma magmatism was invigorated by upwelling return flow enhanced by slab avalanche–induced downwelling connected to the rapid plate motion of Laurentia that initiated in the early stage (Swanson-Hysell et al., 2019). Overall, the constraint that both the anorthositic and layered series of the Duluth Complex were emplaced in <1 m.y. requires an exceptional thermal anomaly that led to rapid and voluminous melt generation during the main stage of Midcontinent Rift development.

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