

Supporting information for “Primary and secondary red bed magnetization constrained by fluvial intraclasts”

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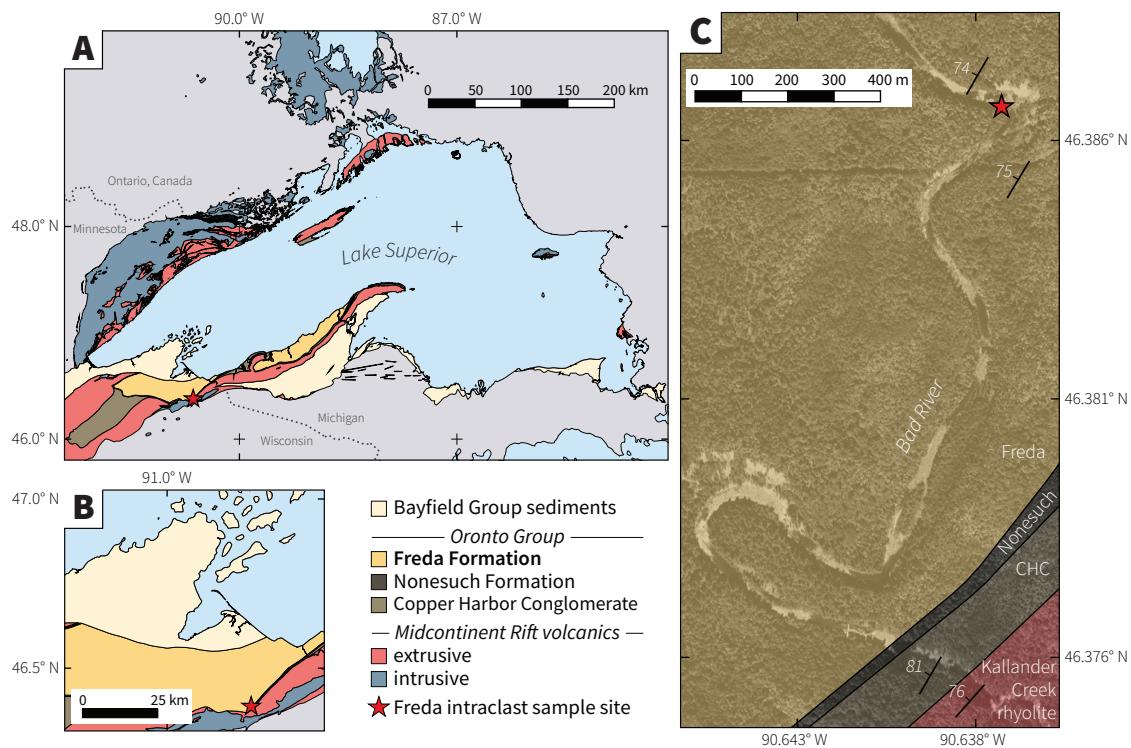


Figure S1. Geological maps of the study region highlighting bedrock units associated with the Midcontinent Rift. The intraclast study location (47.3867°N , 90.6371°W , WGS84) is shown as a red star on the Lake Superior region overview map (A), the zoom-in map of the eastern Ashland syncline (B) and the Bad River (C) for which the geology is overlain on air photo imagery (ESRI World Imagery). CHC stands for Copper Harbor Conglomerate. The geologic map data have been modified from Ontario Geological Survey (2011), Nicholson et al. (2004), and Jirsa et al. (2011).

Text S1: Additional study location information

The intraclast locality in the Freda Formation along the Bad River is within the Ashland Syncline (47.3867°N, 90.6371°W, WGS84; Fig. S1). These outcrop exposures along the Bad River are very fresh as the soil-rock interface dates to retreat from the last glacial maximum which is constrained locally to be 13.2 ± 0.4 thousand years ago based on nearby ^{10}Be exposure dates (Ullman et al., 2015). The outcrops have subsequently been exposed through ongoing river incision (Fig. S1C). The rocks are very well-preserved for their antiquity. In contrast to localities ~ 90 km to the east in the White Pine region, there is a lack of mineralization in the underlying Nonesuch Formation in this region (Stewart and Mauk, 2017). Figure S2 depicts intraclast BRIC-6 in outcrop, drill core and in the lab with the sandstone matrix removed.



Figure S2. Photos of intraclast BRIC-6: in the field within coarse sandstone (A), at the top of an oriented drill core sample (B) and prepped with the matrix sandstone removed on a quartz glass disk (C). The numbered divisions on the rulers in A and C are both in centimeters. Panel A shows multiple siltstone intraclasts. The one marked with the λ is the clast sampled as BRIC-6.

Text S2: Additional details concerning petrographic methods and data

Microscopic observations were made using a Zeiss EVO-LS10 scanning electron microscope (SEM) in the Energy Geosciences Division of Lawrence Berkeley National Laboratory. This instrument has a paired Oxford Instruments X-Max X-ray energy dispersive spectrometer (EDS) that was used to estimate elemental abundance at submicron-sized spots at specified points and in a mapped grid (Fig. S3). Within the Department of Earth and Planetary Science at UC Berkeley, a Zeiss EVO-10 Variable Vacuum SEM with paired electron backscatter diffraction (EBSD) detector was used to collect EBSD patterns for targeted grains (Fig. S3). These EBSD patterns were fit to a catalog of silicate and oxide minerals using OIM Analysis software.

The mineralogical interpretations based on the petrographic data articulated in the main text, including a predominance of hematite and an overall lack of magnetite among the oxide grains, are consistent with those of Vincenz and Yaskawa (1968) on samples from the Freda Formation. Additional Fe-Ti oxides in the intraclasts were identified as rutile and ilmenite. Some of the hematite grains retain primary exsolution textures consistent with an igneous origin rather than

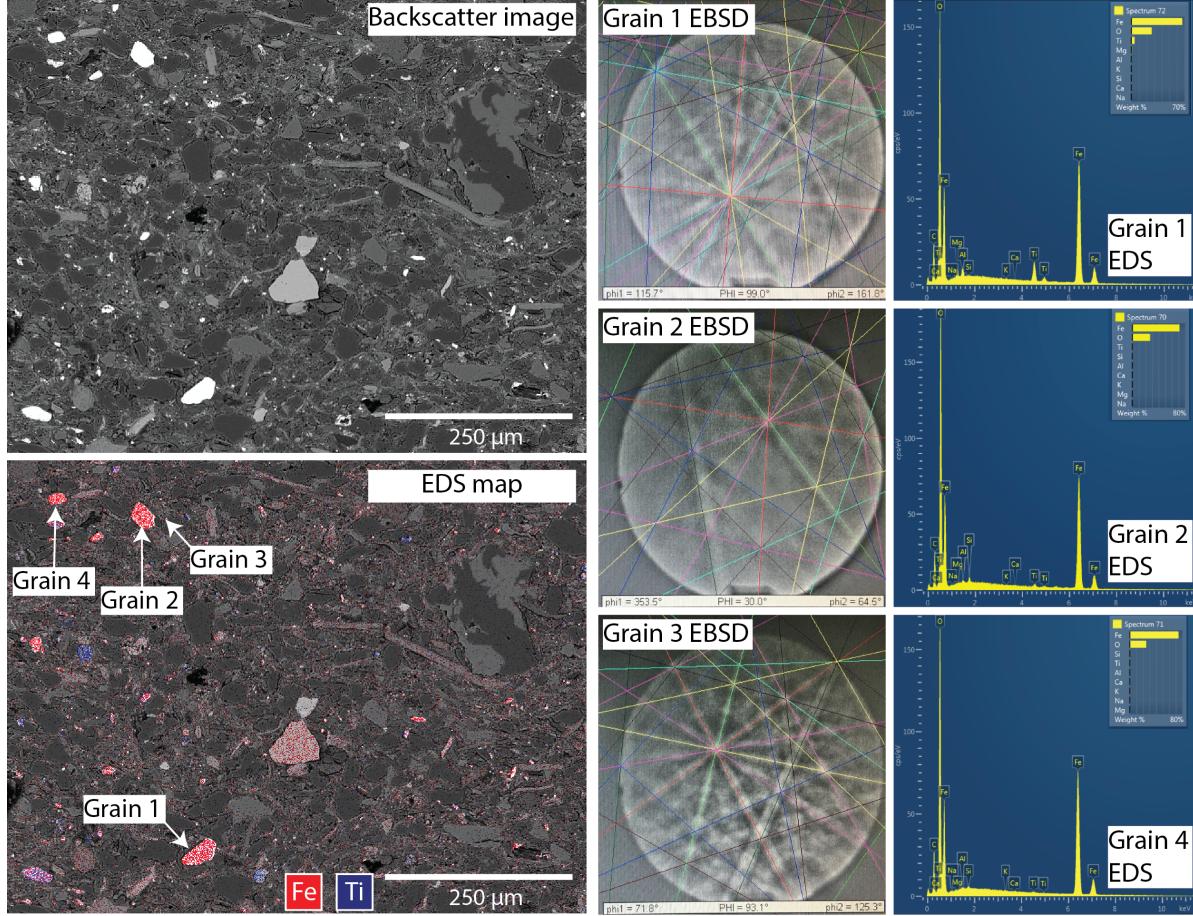


Figure S3. Scanning electron microscopy images and data for sample BRIC-26. The energy-dispersive X-ray spectroscopy (EDS) map shows the distribution of Fe and Ti for the same view as the backscatter image. This map reveals both micron-scale oxide grains (hematite, ilmenite and TiO_2) and disseminated iron within clays and the matrix. EDS spectrum are shown for individual labeled grains as are electron backscatter diffraction (EBSD) images matched with the hematite pattern which identifies the grains. These techniques, along with optical reflected light microscopy, were used to identify the grains labeled as hematite in Figure 1 of the main text.

having formed *in situ* as authigenic grains. Petrographic work on the underlying Copper Harbor Formation identified hematite grains on the scale of 10s of microns, but concluded that it was ambiguous whether these grains were detrital or authigenic (Elmore and Van der Voo, 1982). The dispersion of the paleomagnetic component that is held by such large grains in the Freda intraclasts strongly supports that, in the case of the Freda siltstones, these grains are detrital.

References

- Elmore, R. D. and Van der Voo, R., 1982, Origin of hematite and its associated remanence in the Copper Harbor Conglomerate (Keweenawan), upper Michigan: *J. Geophys. Res.*, vol. 87, pp. 10,918–10,928, doi:10.1029/JB087iB13p10918.
- Jirsa, M. A., Boerboom, T., Chandler, V., Mossler, J., Runkel, A., and Setterholm, D., 2011, S-21 Geologic map of Minnesota-bedrock geology: Tech. rep., Minnesota Geological Survey, URL <http://hdl.handle.net/11299/101466>.
- Nicholson, S. W., Dicken, C. L., Foose, M. P., and Mueller, J. A. L., 2004, Preliminary integrated geologic map databases for the United States: Minnesota, Wisconsin, Michigan, Illinois, and Indiana: U.S. Geological Survey Open-File Report, U.S. Geological Survey, URL <http://pubs.usgs.gov/of/2004/1355/>.
- Ontario Geological Survey, 2011, 1:250 000 scale bedrock geology of Ontario, Miscellaneous Release—Data 126-Revision 1: Tech. rep., Ontario Geological Survey.
- Stewart, E. K. and Mauk, J. L., 2017, Sedimentology, sequence-stratigraphy, and geochemical variations in the Mesoproterozoic Nonesuch Formation, northern Wisconsin, USA: *Precambrian Research*, vol. 294, pp. 111–132, doi:10.1016/j.precamres.2017.03.023.
- Ullman, D. J., Carlson, A. E., LeGrande, A. N., Anslow, F. S., Moore, A. K., Caffee, M., Syverson, K. M., and Licciardi, J. M., 2015, Southern Laurentide ice-sheet retreat synchronous with rising boreal summer insolation: *Geology*, vol. 43, pp. 23–26, doi:10.1130/g36179.1.
- Vincenz, S. A. and Yaskawa, K., 1968, Phenomenon of partial self-reversal in Keweenawan rocks 2. magnetization of upper Keweenawan lavas and sediments and of lower Keweenawan dikes: *Journal of Geophysical Research*, vol. 73, doi:10.1029/JB073i008p02753.