Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

2021

Dear *Geochemistry, Geophysics, Geosystems* editors,

We appreciate the positive assessment that our manuscript received through review. We are also grateful for the suggestions made by the reviewers that have guided revisions. The implementation of these revisions is detailed below and we have attached a track changes PDF with the submission of the revised manuscript. All reviewers' comments below are in italics and our responses are in regular fonts.

Associate Editor Evaluations:

Recommendation: Return to author for major revisions

My main reason for the "major revisions" decision is to try and resolve the physical volcanology issue that reviewer William Rose highlighted. Otherwise, this paper was a real joy to review and I thank you for submitting it to G-Cubed.

Thank you Josh! We appreciate the positive assessment of this work.

Reviewer 1 comments

Ophitic Texture and columnar jointing are ubiquitous for both the Greenstone Flow and the PLV in general. The style and scales are related to cooling rate of the lavas. Because of their thickness and its control by ponding of the lava in the rift valley, there was formation of large and rude columns with dendritic cmx preserving conspicuous ophitic masses, with each cmx including scores of tiny plag. High rates of nucleation for the plag and poor nucleation but healthy growth for the cmx (explained here in more detail: http://www.geo.mtu.edu/KeweenawGeoheritage/BlackLavas/Ophitic_Texture/Ophitic_Texture.html) Paces (1988) showed that thicker PLV flows were more typically marked with ophitic textures, which suggests that slower cooling is part of the story. Overall the Keweenawan lavas are thicker that most flood basalts, and this is especially true of the Greenstone Flow. Given its thickness it may have taken millennia to solidify. The lower ophite in the Greenstone makes up a basal layer which amounts to more than half of the total Greenstone thickness in many places. The lower ophite may be spectacularly jointed, such as at the Palisades and Passage Island at Isle Royale and at the Cliff on the Keweenaw. The Upper ophite is typically much thinner and is located below the amygdaloid and above the pegmatoid zone. It is also ophitic and jointed. The dual jointing likely reflects two colonnades of cooling with the lower ophite growing upward from heat loss at the base of the flow and the upper ophite growing downward from the flow top where heat is lost to the atmosphere and less heat is lost to the top due to conductivity.

During a millennia or more of gradual solidification both ophites form a dendritic mush and the lower ophite is squeezed like a sponge from the massive weight of thick lava above. This leads to in

Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

situ differentiation, with mobile liquid moving upward and forming vesicle cylinders and segregation cylinders above the solidification front. As the rising liquid gets closer to the solidification front of the upper ophite, it forms planar units which we call vesicle sheets or pegmatoids. Vesicle sheets are thinner and are typically closer to the amygdaloid. Moving toward the flow interior the planar segregations are thicker and are termed pegmatoids. Thick pegmatoids may be 10 m or more. Pegmatoid textures are not ophitic, they include much larger plag. In one thin section there could be only one cmx oikocryst, which has hundreds of plag inside. All of this is explained in more detail (and illustrated) in the web material (and also in the field guides). Here are the links:
http://www.geo.mtu.edu/KeweenawGeoheritage/BlackLavas/Stratigraphy/Stratigraphy.html
http://www.geo.mtu.edu/KeweenawGeoheritage/BlackLavas/Basalt_Textures.html
http://www.geo.mtu.edu/KeweenawGeoheritage/BlackLavas/Flow_Features.html
http://www.geo.mtu.edu/KeweenawGeoheritage/IRKeweenawRift/L_Louise.html
http://www.geo.mtu.edu/KeweenawGeoheritage/IRKeweenawRift/Blake_Point.html
http://www.geo.mtu.edu/KeweenawGeoheritage/IRKeweenawRift/Raspberry_I/Raspberry_I.html

Within the PLV, thicker flows (Greenstone, Copper City) have thicker pegmatoids. Altogether the physical pattern within the Greenstone and other PLV flows suggests long lasting thermal control with the final liquid at about 1/3 of the way from the top , where the pegmatoids tend to be.

I feel that the reviewed ms evidence for late intrusion of vesicular pegmatoidal (lines 226-238) into the greenstone flow is weak and not compelling. sect 4.2 does not help.

Non mention of important physical volcanology is a very significant loss, sufficient to make the Greenstone data in this paper inadequate and (in my humble opinion) probably wrong. Overwhelming physical evidence in the Greenstone is consistent with the in situ differentiation of the flow during solidification. Plagioclase size in the pegmatite is more likely because of differing undercooling for the final phase of solidification, so the inference of a late intrusion seems quite speculative. Given that, making an association between the big anorthosite in the Beaver Bay and the Greenstone Flow may be an unnecessary part of this story?

We echo Bill's appreciation of the tremendous thickness of the Greenstone Flow as stated in the web material. His points regarding the cooling of the flow and the formation of ophitic texture are all on point and certainly not in conflict with anything we present. He takes issue with the model of Doyle (2016) that there may have been the injection of a pulse of evolved magma into the Greenstone Flow during crystallization. Instead, he favors the classic model that the entirety of the flow and its textural and compositional variation can be attributed to in situ differentiation. In this work, our contribution is primarily focused on resolving the precise age of the intrusive Beaver River diabase and the anorthosite xenoliths therein, to explore their synchronous temporal relationship and magmatic association with the previously well-documented and precisely dated Greenstone Flow (Lane, 1899, 1911; Cornwall, 1951; Doyle, 2016; Swanson-Hysell et al., 2019). Together these data demonstrate a major ca. 1092 Ma pulse of magmatic activity. We wish that Bill had engaged with more facets of our scholarship.

Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

However, returning to Bill's critique of the composite model, he makes good points in favor of the internal differentiation model. There are also intriguing points made by Doyle (2016) where abrupt lithologic changes and inclusion relationships in addition to the more evolved geochemistry led them to interpret that there was a a secondary, more highly evolved pulse of magma intruded into the core of the Greenstone Flow. However, in both Bill's preferred model and in the Doyle model there is in situ fractionation leading to the coarsest-grained granophyric gabbro lenses.

To address this input, we have made edits to the section on the geologic background of the Greenstone Flow that seeks to more clearly introduce the in situ differentiation model without giving preference to either model in that section. That paragraph now reads:

According to the mineralogical and textural attributes, the Greenstone Flow can be divided into four zones from bottom to top — a lower ophitic zone, a "pegmatoid" or heterolithic zone, an upper ophitic zone, and an amygdaloidal zone Cornwall (1951). The heterolithic zone contains lenses to layers of coarse-grained granophyric gabbro that are referred to in the literature as "pegmatoid." Zircon crystallized in these layers have enabled the heterolithic zone to be targeted for U-Pb geochronology Davis and Paces (1990); Swanson-Hysell et al. (2019). A ^{206}Pb/^{238}U zircon date of 1091.59 ± 0.27 Ma for the Greenstone Flow was developed from a sample from this zone in Swanson-Hysell2019a. The Greenstone Flow is typically interpreted to represent emplacement of a single body of magma that then underwent in situ differentiation Huber (1973); Davis and Paces (1990). Doyle2016a favored a distinct model where the emplacement of the Greenstone Flow started with voluminous eruption of olivine tholeiitic magma, forming the ophitic zones which while still crystallizing further inflated due to subsequent injection of a more evolved basaltic magma to form intergranular gabbro in the heterolithic zone. They considered this progression to be more consistent with observed abrupt lithologic changes from the ophitic zone to the heterolithic zone over centimeter to meter scales, inclusion relationships between evolved and ophitic Greenstone Flow lithologies, and remnant blocks of initially crystallized ophitic basalt interlayered with evolved lithologies within the heterolithic zone which contains the pegmatoids. In both the Doyle2016a model of multiple magma injections and the model of in situ differentiation, it is migration of the most evolved and volatile-rich melts within the interior of the flow in the final stages of flow crystallization that led to the formation of some aplite dikes and the coarsest segregations. Both models also indicate a single basaltic magma source with the distinct of whether differentiation is occurring within an evolving magma chamber or solely within the crystallization flow.

Reviewer 2 comments

Overall, this is a very well done, compelling study, establishing a very convincing link between anorthosites and (really large) anorthosite cumulates as the magma supply to voluminous diabase flows in the North American mid-continent rift. The combination of paleomagnetic data,

Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

high-precision geochronology, and supporting geochemistry all provide robust evidence for the conclusions made.

Thank you Bernie! We appreciate the positive assessment of this work.

The tilt correction: lines 354, 538, etc. It would be better to note some of the uncertainty in using these igneous fabrics/structures as paleohorizontal. These include original dip of the flows, as well as possible imbrication of mineral alignment associated with flow or emplacement direction. Including the in-situ and tilt-corrected directions in a figure, along with mention of the specific correction, would better illustrate the uncertainty in this portion of the data analysis. The dips, and therefore the amount of directional change in the tilt-corrections is not large (10-15 degrees from the supplement)- so the impact of errors in these corrections is likely small. This is, however, the only real weakness in the whole set of data.

Indeed tilt correcting the paleomagnetic directions is one crucial step of the paleomagnetic data analyses. The bedding orientation results, together with the paleomagnetic mean directions before and after tilt correction are now directly presented in the paleomagnetic result section as well as in the paleomagnetic result table in the main text. The text in section 3.2 related to the tilt correction procedure is also updated to address our confidence in the tilt correction while acknowledging uncertainty in interpreting the igneous fabric orientations as paleohorizontal.

While it can be helpful to present the paleomagnetic directions and poles before tilt correction, given the rich amount of paleomagnetic information already presented in Fig. 8, we believe that having only the tilt-corrected paleomagnetic pole positions from the Beaver River diabase and the anorthosite xenoliths can help clarify our results. Nevertheless, we have now added the mean pole positions of the Beaver River diabase, anorthosite xenoliths before and after tilt correction into the Supporting Information text in the revised manuscript. In addition, the bedding orientation compilation as well as the paleomagnetic direction data before and after tilt correction are included in the *AX_BD_pmag* and *AX_BD_Orientations* Python Jupyter notebook in the code repository.

Another suggestion would be to add plots of magnetization versus thermal demagnetization treatment temperature, to illustrate the unblocking temperature behavior of these rocks. In the cooling history discussion (Fig 9)- cooling durations of 1000 yrs at relatively high temperatures are mentioned. Comparing that duration, its proposed temperature, and the laboratory unblocking temperatures (Pullaiah et al., 1975) would be a useful extension of that discussion.

Plots of magnetization versus thermal demagnetization treatment temperature have been added. Reference to those plots are added to the cooling history discussion section for clarity. In addition, a summary of the thermal demagnetization results including the steps of thermal demagnetizations used to fit for the characteristic remanent magnetizations is included in a *AX_BD_pmag* Python Jupyter notebook in the code repository.

Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

Line 497: When speculating on the minimum size of the magma conduit, given the size of the anorthosite cumulate blocks, I would note this is likely a significant underestimate, if you consider the effects of clogging those pipes with numerous cumulate blobs?

Yes. We agree with this interpretation that our estimated Beaver River diabase magma conduit size could be much smaller than the true size of the conduits. This is why we state that the "the Beaver River diabase conduits must have been of at least the width of the anorthosite short axis diameters" (line 48-49 of original manuscript) in the introduction and mention that the "The large anorthosite xenoliths within the Beaver River diabase require that conduits feeding the magma to the surface had widths that exceeded 150 meters." (line 574-575 of original manuscript).

Line 75 change "more roughly constrains" to "provide less precise estimates of"

This change has been incorporated into the manuscript.

Line 187: rather than friction, perhaps abrasion, or ablation

This is a good suggestion. In the updated manuscript "friction" is replaced by "abrasion".

Line 291: change "sampled standard" to "sampled using standard"

We can be more specific about the sample collection description here. Now this sentence is changed into "We collected paleomagnetic cores that are 1-inch in diameter along the southern and eastern Beaver Bay Complex......"

Additional edits

Additionally we recognize that it is necessary to add discussions about the proposed intrusive - extrusive magmatic relationship in context of the Midcontinent Rift basin geometry - that this proposed connection allows an interpretation that the Greenstone Flow could have extended for $\sim$250 km from the lake shore of northern Minnesota to the Keweenaw Peninsula. This makes the Greenstone Flow comparable to some of the longest lava flows in the Columbia River Basalts and those in the Deccan Traps. This additional discussion text is added in discussion section 4.2.

Sincerely,

Yiming Zhang
PhD candidate of Earth and Planetary Science
University of California, Berkeley

Yiming Zhang
PhD candidate
307 McCone Hall, Berkeley, CA 94720
yimingzhang@berkeley.edu

References

Cornwall, H. R., 1951, DIifferentiation in lavas of the Keweenawan Series and the origin of the copper deposits of Michigan: Geological Society of America Bulletin, vol. 62, p. 159, doi:10.1130/0016-7606(1951)62[159:dilotk]2.0.co;2.

Davis, D. W. and Paces, J. B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent Rift system: Earth and Planetary Science Letters, vol. 97, pp. 54–64, doi:10.1016/0012-821x(90)90098-i.

Doyle, M., 2016, Geologic and geochemical attributes of the Beaver River Diabase and Greenstone Flow: Testing a possible intrusive-volcanic link in the 1.1 Ga Midcontinent Rift: Master's thesis, University of Minnesota.

Huber, N., 1973, The Portage Lake Volcanics (Middle Keweenawan) on Isle Royale, Michigan: Tech. rep., United States Geological Survey.

Lane, A. C., 1899, Geological report on Isle Royale, Michigan: Geological Survey of Michigan, vol. 6, p. 281.

Lane, A. C., 1911, The Keweenaw series of Michigan: Michigan Geological and Biological Survey Publication 6, vol. 2, p. 983.

Swanson-Hysell, N. L., Ramezani, J., Fairchild, L. M., and Rose, I. R., 2019, Failed rifting and fast drifting: Midcontinent Rift development, Laurentia's rapid motion and the driver of Grenvillian orogenesis: GSA Bulletin, vol. 131, pp. 913–940, doi:10.1130/b31944.1.