GEOSPHERE

GEOSPHERE; v. 14, no. 3

doi:10.1130/GES01632.1

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CITATION: Malone, D.H., Stein, C.A., Craddock, J.P., Kley, J., Stein, S., and Malone, J.E., 2018, Maximum depositional age of the Neoproterozoic Jacobsville Sandstone, Michigan: Implications for the evolution of the Midcontinent Rift: REPLY: Geosphere, v. 14, no. 3, p. 1382–1384, doi:10.1130/GES01632.1.

Science Editor: Shanaka de Silva

Received 4 November 2017
Accepted 31 January 2018
Published online 29 March 2018

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Maximum depositional age of the Neoproterozoic Jacobsville Sandstone, Michigan: Implications for the evolution of the Midcontinent Rift: REPLY

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INTRODUCTION

We thank T.J. Bornhorst (2018) for consideration of our work on the Jacobsville Sandstone in northern Michigan. We engaged in this research to advance understanding of the geology of the Lake Superior region. As we began this project, we were fascinated that little attention had been paid to refining the lithostratigraphic and chronostratigraphic understanding of the Jacobsville Sandstone; our work is ongoing. Since publication of Malone et al. (2016a), we have analyzed ~400 additional zircons from 3 Jacobsville Sandstone exposures in Ontario (Canada). We will collect and analyze Jacobsville subsurface occurrences in the next few months.

Bornhorst's comment questioned our sampling and analytical methodologies, and the statistical factors used to determine the Jacobsville maximum depositional age (MDA). He also challenged our interpretations as well as "…far-reaching conclusions …" here. We find these generalizations puzzling, but welcome this opportunity to expand our discussion of the Jacobsville Sandstone in Malone et al. (2016a).

SAMPLING AND ANALYTICAL METHODOLOGY

Our sampling methodology was designed to ensure stratigraphically and geographically diverse Jacobsville Sandstone localities. The sampling localities included basal Jacobsville members at L'Anse and Sturgeon Falls, and upper Jacobsville members near Bruce Crossing and Munising, Michigan. We also sampled the Jacobsville Sandstone, presumably upper, where it is deformed near the Keweenaw fault. Our data indicate that the Jacobsville provenance is distinct in space and time, and that sediment was contributed from source areas in the Grenville, Keweenawan, Midcontinent Granite-Rhyolite, Penokean, and Superior Provinces. Most of the youngest zircons in the data set are from some of the stratigraphically lowest (and thus older) surface exposures of the Jacobsville Sandstone. Thus, it is admissible and necessary to regard all surface occurrences of the Jacobsville as Neoproterozoic in age.

Zircons were separated first by crushing and milling, and then by panning, heavy liquids, and magnetic processes. The equipment was clean and in good working order as each sample was processed. Because our paper was a research note, we only presented a summary of our methodology, and the references cited provided more details.

Cathodoluminescence imaging is not standard for detrital zircon data sets, but high-quality backscatter scanning electron microscopy imaging was the basis for selecting suitable zircons for analysis. Where possible, and for all of the youngest zircon ages in Malone et al. (2016a), core areas of simply zoned, unfractured zircons were analyzed. Thus, we believe that the impact of metamorphic overgrowths (which in our experience are quite rare in detrital data sets) or Pb loss on these zircon ages is minimal and accounted for by the 1σ analytical errors that we report.

We reiterate that concordance information was provided in Malone et al. (2016a), and individual zircons that were more than 80% discordant were not considered further.

JACOBSVILLE STRATIGRAPHY

In Malone et al. (2016a) we did not state or imply that Jacobsville Sandstone deposition was everywhere isochronous. As for most lithostratigraphic units, Jacobsville deposition was diachronous, and it is likely that what is now regarded as part of the Jacobsville Sandstone is stratigraphically much more complex than is currently understood. It is interesting that Bornhorst pointed to decades-old, unpublished and unreviewed Master of Science theses as the bases for the subsurface lithologic distinctions, but considers our peer-reviewed work using standard methodologies as speculative and questionable. Until a comprehensive subsurface study is published, we must rely on what is exposed. Bornhorst stated that the Jacobsville may be as thick as 3000 m from geophysical data. These surveys assumed that only the Jacobsville is between the surface and the basement. Other units, such as the Freda Sandstone, may be present in the subsurface and account for much of this thickness.

Bornhorst (2018) stated "Cannon (1992) estimated the upper age of the Freda Formation...to be ca. 1060–1040 Ma." This statement is misleading; the Freda Formation has not been directly dated. Cannon (1992, p. 46) wrote: "Reverse faulting, known to be synchronous with later phases of sedimentation, has been indirectly dated at about 1060–1040 Ma." We have found no published report that provides objective data demonstrating that reverse faulting is synchronous with sedimentation. Cannon's (1992) assumption was based, so far as we can tell, on the assumption that dated hydrothermal minerals (ca. 1060–1040 ± 20 Ma) in the basalt and the Nonesuch Formation must have formed during faulting. The Jacobsville Sandstone is not present at either of the two sites of dated hydrothermal minerals. It is well known that the Jacobsville Sandstone is intensely deformed near the Keweenawan fault (e.g., Craddock et al., 2017), so some or all of the movement along the Keweenaw fault must have occurred after Jacobsville deposition.

DETERMINATION OF THE JACOBSVILLE MDA

Laser ablation–inductively coupled plasma–mass spectrometry methodologies are standard for many detrital zircon studies. This methodology generates larger data sets with analytical errors of ~2%. As we understand it, Bornhorst's concern is that "…the age dates from these four critical zircon grains should be considered as anomalous until they are proven to be trusted as valid," and that our interpretation "relies upon the assumption that the analytical results are geologically meaningful." The analytical errors for individual analyses were determined using in-house software at the University of Arizona LaserChron Center (see the University of Arizona LaserChron Website, https://sites.google.com/a/laserchron.org/laserchron/home/).

Bornhorst took issue with our only using zircons at the young end of the age spectrum, and that these ages amount to only 0.2% of the 2052 zircons analyzed. The youngest split, whether it is large or small in number, is the only zircon split relevant to the calculation of the MDA.

Determination of the MDA for the Jacobsville Sandstone followed methodologies in Dickinson and Gehrels (2009), who proposed several estimates, including: (1) the youngest single grain, (2) the youngest peak age on the probability density plot, and (3) the mean age of two or more overlapping grains at 2σ. (For additional information on MDA determinations, see the University of Arizona LaserChron Website.) The method for determining the Jacobsville MDA proposed by Bornhorst in his comment has not been validated by peer review and it is not in common usage.

The youngest single grain may be used as an estimate of the MDA when it is not part of subset of ages with overlapping errors (e.g., Craddock et al., 2013; Rainbird et al., 2017). The youngest age peak on the probability density plot provides the most conservative estimate of the MDA and is useful for small data sets. Larger data sets like ours (e.g., He et al., 2017; Malone et al., 2016b) allow use of the weighted mean age of overlapping grains at the young age of the spectrum. This method weights each single grain age by the square of its uncertainty. Thus, ages with the smallest uncertainty affect the calculated age more substantially. The weighted mean average uncertainty is the standard error of the calculated mean. A critical assumption here, as Bornhorst points out, is that each of the grains is truly related in age. To assess this, the mean square of weighted deviates (MSWD) must be determined and evaluated. If the MSWD is <1, which is the case for the Jacobsville Sandstone, the uncertainty of the weighted mean average adequately explains the scatter, and it is reasonable to conclude that the grains have the same true age. Our calculated MDA for the Jacobsville Sandstone, 959 ± 19 Ma, passes this test, making our interpretation that these 4 grains are related by age viable. Our method for determining the MDA is statistically rigorous, and is validated by peer review and extensive usage.

A final check on the reliability of the MDA determination in Malone et al. (2016a) involved using the unmix routine of Isoplot (Ludwig, 2003). This routine further enabled us to determine that the youngest subset of ages is related. Unmix uses a Gaussian distribution that best fits each age group on a particular age peak (a model age), and determined 2 age peaks for the youngest subset of 20 grains, 960 ± 19 and 1017 ± 7 Ma, which further validates the MDA as determined by the weighted mean average.

ORIGIN OF THE 960 Ma ZIRCONS

Because ca. 980–900 Ma zircons are rare in the Neoproterozoic and early Paleozoic stratigraphic record of Laurentia, it would be difficult for zircons of this age to be a contaminant of the larger data set. Any contaminants would more likely be lost in the ubiquitous Grenville age group. Craddock et al. (2013) first reported detrital zircon ages for the Keweenaw rift sequence, including a 933 Ma grain from the basal Jacobsville Sandstone at Little Presque Isle, Michigan. The Konstantinou et al. (2014) study of Cambrian and Ordovician sandstones in Minnesota, Wisconsin, Illinois, and Missouri (sample number (s) = 12, zircon number (n) = ~1500) reported only three zircons in this age range, even though the rocks are more than 400–500 m.y. younger. Zircons in the 980–900 Ma range do not appear in significant numbers in the Laurentian cratonic sedimentary record east of the Transcontinental Arch until the Carboniferous. The Rothschild et al. (2016) study of Chesterian strata in the Illinois Basin reported 37 zircons (s = 4, n = 964) or 3.7% in the 980–900 Ma age range. The Kissock et al. (2018) study of Pennsylvanian strata in Iowa and Illinois found 125 zircons (s = 14, n = ~3051) or 4.1% in the 980–900 Ma age range.

The best interpretation of the provenance of the ca. 959 Ma zircons is a Baltica highland. Sveconorwegian postcollisional granite plutons, ranging in age from ca. 975 to 950 Ma, occur in the basal gneiss complex (Bingen et al., 2008; Bingen and Solli, 2009, and references therein). Similarly, Cawood et al. (2010, and references therein) reported 980–920 Ma ages for crystalline rocks in Scotland, east Greenland, and Svalbard. The relative positions of Laurentia and Baltica in Rodinian paleogeography are well understood (Li et al., 2008; Cawood et al., 2010), as evidenced by structures and ages associated with the Grenville-Sveconorwegian orogeny. Relative to current geography, Baltica was east of Laurentia and adjacent to Greenland. Cawood and Pisarevsky (2017) reported a 1000 km southward translation and 95° clockwise rotation of Baltica between 1100 and 1000 Ma (Weil et al., 1998). The two continents shared a common paleomagnetic pole between 1000 and 900 Ma, and thus were joined at the time of the Jacobsville MDA. Baltica zircons in the Laurentian Carboniferous record can be attributed to Devonian (Acadian) collision of Laurentian and Baltica as Pangea was assembled. Baltica zircons may have been delivered to the Jacobsville depositional systems through fluvial or eolian processes (e.g., Malone et al., 2017).

SUMMARY

We hope that we have ameliorated Bornhorst's concerns regarding Malone et al. (2016a) and the additional papers that he noted (e.g., Craddock et al., 2017). Our data and interpretations are not questionable, speculative, or far reaching. Much or all of the Jacobsville Sandstone surface samples are Neoproterozoic in age, and Jacobsville deposition continued through at least 960 Ma and perhaps much later. Jacobsville deposition occurred after the conclusion of the Grenville orogeny, so Grenville compression cannot adequately explain all phases of the tectonic inversion of the Midcontinent Rift. We hope that these data will stimulate a new cycle of research of the Precambrian geology of the Lake Superior region.

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