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Discussion

Paleozoic reactivation structures in the Appalachian-Ouachita-Marathon foreland: Far-field deformation across Pangea

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1. Introduction

We acknowledge the efforts of the Comment writers to critically review our recent paper "Paleozoic reactivation structures in the Appalachian-Ouachita-Marathon foreland: Far-field deformation across Pangea" and appreciate the opportunity to clarify and explain our work in greater detail. We note that the Comment writers do not anywhere address the essence of our paper: that far-field strain associated the assembly of Pangea contributed to midcontinent deformation along the Kapuskasing-Keweenaw fault (KKF) that is post-Keweenawan (~1 Ga) in age. Instead, they quibble with semantics (sutures vs. structural zones, lithostratigraphic nomenclature, etc.), our interpretations of complex and poorly exposed field relations that conflict with their own interpretations, our understanding and use of the peer-reviewed literature, and most regrettably, our competence and credibility as scientists.

The Comment authors also criticize the validity of Craddock (2017b) as a review paper, and that this contribution, and our recent work in general, has not been adequately reviewed. To insinuate such, in light of relatively minimal expertise in structural geology, tectonics, and far field strain of the Comment writers themselves, only diminishes the integrity of Earth-Science Reviews (ESR) and the important work of its editors and reviewers.

We would like to formally state conditions leading up to the writing of this Reply. In September 2017, after Craddock et al. (2017a) was published three months, the original version of the Comment was submitted and included nearly 15,000 words and it was posted to the ESR website. The original Comment was wrought with personal attacks, which we viewed as extremely biased, territorial, and unprofessional. Consequently, we asked the ESR editors to consider retracting the original Comment. The ESR editors retracted that version of the Comment, and asked the Comment writers to revise before being considered for publication in ESR. The Comment writers submitted their revised work eleven days later, largely intact, but sans the inflammatory introductory paragraphs. We have crafted our Reply to the revised Comment. We note that we did not oppose any of the Comment writers as peer reviewers of our original paper.

In our Reply, we choose to limit our response to a few critical areas addressed by the Comment writers. We choose to proceed this way because we wanted to keep our Reply concise and limited to about 5000 words. We encourage readers of ESR and the Comment writers to contact us directly if they want to discuss our original article, or our Reply to the Comment in more detail. The Comment writers' aim is to "set the record straight". On this point we agree wholeheartedly. Our aim in this Reply is to continue this effort.

1.1. Modern tectonics and uniformitarianism

One of the paradigms of modern tectonics is that tectonic stresses generated at plate boundaries propagate from plate boundary across plate interiors to the distal plate boundary. North America provides an example: Mount and Suppe (1987) reported borehole elongation shape changes along the San Andreas fault (SAF) thereby determining that the principal stress and strain fields include a sub-horizontal shortening axis normal to the SAF. This stress-strain field propagates across North America with the same orientation, but a decreasing magnitude, to Iceland where borehole shape changes and studies of twinned basalt-hosted calcite (Craddock et al., 2004 and references therein) record the same ridge-normal sub-horizontal strain field. These relationships, from a variety of sources, are beautifully represented in the "World Stress Map" (Zoback et al., 1989, and with continuous updates on-line), and the plate motion vectors for North America (DeMets et al., 1990, 2010) are parallel to the shortening orientation, which are parallel to the SKS "fast" anisotropy in the upper mantle (Zandt and Humphreys, 2008).

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The Comment writers seem unaware of these tectonic paradigms, and the work by Craddock (and others) on the propagation of Appalachian-Ouachita stresses preserved by twinned calcite in the Midcontinent published in 1989 (Geology; Craddock and van der Pluijm, 1989), 1993 (Tectonics; Craddock et al., 1993), and 1997 (Science; van der Pluijm, Craddock et al. 1997) that led to the KKF review paper. In the intervening 20 years, we have worked on adding to the field and strain database in North America and Africa (it's a BIG field area!) while synthesizing the literature, ore deposit (MVT) and Earthscope data into the KKF paper to support the observation that the amalgamation of a supercontinent causes deformation within plates, often thousands of kilometers inboard.

1.2. The scientific validity of Craddock et al. (2017b) and the credibility of our research efforts in general

During the last 20 years the authors of Craddock et al. (2017b) have collectively published > 200 peer reviewed articles, dozens of which have focused on the regional geology, structural geology, stratigraphy, and tectonics of the Laurentian Midcontinent (e.g. van der Pluijm et al., 1997; Luczaj, 1998; Craddock and van der Pluijm, 1999; Luczaj and Goldstein, 2000; Craddock and Magloughlin, 2005; Craddock and McKiernan, 2007; Luczaj, 2006; Luczaj et al., 2006; Craddock et al., 2007; Luczaj et al., 2016; Craddock et al., 2013a, 2013b; Konstantinou et al., 2014; Peterson et al., 2015; Kimple et al., 2015; Shaw et al., 2015; Kron et al., 2015; Shaw and Johnston, 2016; Wagle et al., 2016; Malone et al., 2016; Porter et al., 2016; Martin and Malone, 2016; Porter et al., 2017; Craddock et al., 2017b, 2017b; Rose et al., 2017; Kissock et al., 2017; Malone et al., 2017a, 2017b, 2017c; and Luczaj and Huang, 2018).

As the writers of the Comment call into question our credibility as scientists, a quid pro quo assessment of their own records on this same subject matter is warranted. Of the 62 references that they cite in the Comment to oppose Craddock et al. (2017b), 28 did not undergo external peer review, as these are abstracts, theses, field guides, geologic maps and survey publications (that did likely experience some level of internal review). Of the 34 peer-reviewed references, five were authored by Craddock et al. (2017b) authors; each of these was published in the last ten years. Each of our papers are in high impact, peer-reviewed journals of international scope. Of the remaining 29 peer-reviewed articles cited by the Comment writers, which is less than half of the total citations offered, only four were published in the last 20 years, and one in the last ten years. The average date of this set of papers is 30 years old. Only one of the recent four peer-reviewed papers that they cite was authored by a Comment writer. Four of the Comment writers did not author a single paper in peer-reviewed work cited in the Comment.

We note that two of the Comment writers have recently presented an abstract that advocates for far field strain in Minnesota. Retzler et al. (2016) clearly indicate they are advocates of inversion of the KKF in the Ordovician in the Twin Cities basin, Minnesota as the result of far-field stresses “from the east”. There they claim the uplifted Twin Cities basin rests atop an uplifted horst. True horsts are bounded by normal faults in an extensional tectonic environment, so we presume Retzler et al. are implying that the Twin Cities basin is actually in the hanging wall of the Douglas and Kapuskasing (Keweenaw) thrusts as reported by Craddock et al. (2017a) and the synorogenic sedimentation perturbations they observe are far-field effects of the Ordovician Taconic orogeny. Curiously, Retzler et al. (2016) is ***not*** cited in the current Comment as that would be hypocritical and negate the intent of the Comment writers.

1.3. Gunflint area

One issue that we choose to respond to deals with our interpretation of the field relations near Gunflint Lake. The geologic map that we reference is Jirsa (2011). It is important to note that this map was published by the Minnesota Geological Survey where Jirsa and several of the other Comment authors work, and that the presumed internal review that this map experienced was by other Comment writers. There is no review acknowledged.

The Comment writers state (bold lettering is our amplification):

> *Nowhere is there a thrust zone along the 5-mile, well-exposed contact between the Paleoproterozoic iron-formation and the Archean substrate. In fact, the contact is **irrefutably** unconformable, as the 2011 reference **clearly** documents. The only major fault portrayed on that publication is the Lookout Fault, which separates Paleoproterozoic iron-formation from Archean metabasalt. Exposures along the fault indicate vertical dip and south-side-up offset, with absolutely no evidence to indicate that this is some sort of nappe-thrust structure. Craddock et al. (2017a) further infer that movement on the “thrust fault” is “post-rift.” This inference is a stretch, as the fault effects Logan intrusions that are ~1115 Ma, but the bulk of Midcontinent rift tectonism and plutonism continued **long** afterward. It is much more likely that the Lookout Fault is related to emplacement of the large mass of Duluth Complex and related intrusions that continued to at least ~1092 Ma.*

It is egregious to state that any interpretation is irrefutable. All scientific hypotheses are, by definition, refutable. To suggest that they aren't blurs the important distinction between observation and interpretation, and amplifies one's personal biases. At Gunflint Lake, Jirsa mapped folds in the Paleoproterozoic Gunflint Formation and several faults of various geometries and slip sense. He mapped some faults that are > 10 km long and show no offset. The cross sections are not taken deep enough (some areas only ~100 m) to show the structural relationship between the underlying gneiss and the folded metasedimentary rocks. Moreover, Jirsa's cross sections to not display irrefutable structural relations that they invoke and cannot be balanced, and are not viable or admissible (e.g. Dahlstrom, 1969; Hossack, 1979). Jirsa speculates that vertical movement of the Lookout Fault is related to the emplacement of the Duluth Complex. Nowhere on his map does the Lookout Fault cut the Duluth Complex, and the Duluth Complex is structurally above this deformed interval. Jirsa maps the Lookout fault to core an anticline. How can an extensional fault core an anticline that formed through compression? Moreover, how is ~9 Ma “long after” anything that happened more than a billion years ago?

It is unlikely the rigid basement gneiss is folded along with and in the same style as the metasedimentary rocks. The mapped geology is consistent these folds being a part of a nappe, and Lookout Fault is consistent with being a thrust ramp that is the basal detachment of this nappe. The 1109 Ma Logan Sills (Davis and Sutcliffe, 1985, note the Comment writers use an age of 1115 Ma for these same rocks) are concordant within the folded Gunflint Formation. As these structures involve Keweenawan rocks, and are compressive, they must be related to the MCR inversion on the footwall of the Douglas (Isle Royale) thrust, or NW-directed thrusting at the base of the Duluth complex, in the late Paleozoic. MCR tectonism was extensional, not compressional. Emplacement of the Logan Sills concordantly after folding is mechanically impossible (e.g. Pollard and Johnson, 1973; Schofield et al., 2012; Magee et al., 2016). Moreover, the Comment states that the Lookout Fault is related to the emplacement of the Duluth Complex. We see this as unlikely, as normal faults associated with such intrusion would occur in structurally high areas above the Duluth Complex. Jirsa (2011) indicates that the Lookout Fault is structurally below the Duluth Complex, which is in conflict with these two events being kinematically linked and “long afterward”. In order for the Lookout Fault to be kinematically linked to the Duluth Complex, the Duluth Complex must also occur locally at depth, which it does not.

The following disclaimer is printed at the base of the Jirsa (2011) map:

> *Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the*