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Response: commentary: detecting upland glaciation in Earth's pre-Pleistocene record

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Introduction

As noted in Molén's (2023) comment, our (Soreghan et al., 2022) explicit aim was to provide approaches for detecting the former presence of a glacial influence in upland settings, where preservation of the sedimentologic record is less complete compared to lowland settings. As Soreghan et al. (2022) is a Review paper, we relied primarily on previously published work including our own. We thus provided specific, geographically diverse case studies to illustrate each methodology or data type. Additionally, our paper focused on how to recognize an upland glacial influence on the sedimentary record in *ancient strata*. Molén (2023) seemed to misunderstand our aims, as he began with the statement that we "conducted field research to find evidence of ancient upland glaciation. . . and presented a case study mainly from the. . . Cutler Formation" and then goes on to say that some of the "decisive ones for influence from cold weather" such as ice-crystal imprints are derived from strata other than the Cutler Formation. We do not dispute this, because our focus was not the Cutler Formation. The ice-crystal impressions detailed in our paper are—as stated in the paper—from lower Permian strata of the Lodéve Basin in France (Pfeifer et al., 2021), and these features have also been identified in lower Permian strata of Germany (Reineck, 1955), and Colorado (the Maroon Formation; Voigt et al., 2021). Below we expand on three of the primary points that Molén (2023) raised.

Polygonal network of clastic dikes

Molén (2023) suggested from the few images presented in Figure 5 of Soreghan et al. (2022) that the features we infer as frozen-ground phenomena could be interpreted as "induced by gravity from soft sediment tectonics." The section in question presents a synopsis of Sweet and Soreghan (2008), which documented two intervals within the Pennsylvanian Fountain Formation of a polygonal network of clastic dikes appearing at two different scales. These polygonal networks formed in sand and granule substrate, and sand fills the dikes. Sweet and Soreghan (2008) proposed a frozen-ground mechanism only after considering (and dismissing) other potential mechanisms for the formation of the polygonal network of clastic dikes.

We disagree with Molén's (2023) suggestion that these polygonal networks formed by soft-sediment tectonics because 1) individual cracks taper downward and were passively filled by sediment that matches the overlying strata, and 2) the overlying strata demonstrate no evidence of rapid deposition that would have injected the material into the underlying strata. Indeed, in one of the localities where these cracks occur, overlying strata are eolian, and the material composing the dikes exhibits a composition and texture matching the overlying eolian strata, suggesting that wind-blown material filled open cracks. Potentially, we misinterpreted Molén's (2023) meaning of soft-sediment tectonics implied in his Comment.

Molén (2023) also asserted that the size of the polygonal networks shown in Figure 5 of Soreghan et al. (2022), do not resemble freeze-thaw polygons. Sweet and Soreghan (2008) tabulated published studies to compare dimensions of clastic dikes with polygons of different origins, which showed that the dimensions of the Fountain Formation polygons approximate polygons formed by evaporites, freeze-thaw processes, desiccation, *and* seasonal frost cracking. Part of the issue may stem from Molén's (2023) inference and use of terminology that Soreghan et al. (2022) never used: whereas Molén (2023) applied the phrase "freeze–thaw" polygons to the Fountain Formation features, Sweet and Soreghan (2008; summarized in Soreghan et al., 2022) inferred cracking of already frozen ground, or seasonal frost-crack polygons (Maruszczak, 1987). We recognize that our interpretation of the polygonal network of clastic dikes in the Fountain Formation is controversial; however, Molén cites few images to re-interpret the phenomenon while neglecting to consider the comprehensive data and arguments presented in the original paper (Sweet and Soreghan, 2008).

Frozen or unfrozen rip-up clasts?

Molén (2023) suggested that the intraclasts presented in Soreghan et al. (2022) more likely formed within sediment gravity flows where sediment was unfrozen prior to transport. We acknowledge that intraclasts composed of non-cohesive sediment can be incorporated into flows through various mechanisms other than ripping up frozen sediment. We also acknowledged in Soreghan et al. (2022) that no single feature in the fluvial facies irrefutably indicates a glacial influence. Rather, the intent of our paper was to present and integrate a wide variety of data to assess consistency with an upland glacial influence. We dedicate only one sentence to the potential for frozen rip-up clasts, and merely state that the features in question appear analogous to features shown by Diffendal (1984). More directly, the facies containing the rip-up clasts illustrated in Soreghan et al. (2022) are interpreted as hyperconcentrated flood flow (HFF), and scour-and-fill deposits. HFFs have sediment support mechanisms similar to gravity flows, but flow does not rely on gravity induced slope failure (see discussion in Soreghan et al., 2009; 2022). Scour-and-fill deposits result from turbulence-dominated flows with a high sediment load, and typically include abundant low-angle scour surfaces (e.g., Smith and Lowe, 1991), as shown in Figure 5I of Soreghan et al. (2022). We acknowledge that the interpretation that rip-up clasts were derived from already frozen ground is simply consistent with the evidence, not mandated by it.

Quartz grain microtextures

Molén (2023) asserts that "a major shortcoming" is our interpretation of microtextures on quartz grains. Microtextural observations can be subjective, so applying a standardized descriptive scheme is essential. We relied on the studies and atlases of Krinsley and Doornkamp (1973) and Mahaney (2002) as a standard, and as demonstrated in multiple previous publications by our groups (e.g., Sweet and Soreghan, 2008; Keiser et al., 2015; Pippin, 2016; Sweet and Brannan, 2016; Smith et al., 2018).

Molén (2023) particularly objected to our statement "More recent work has argued that only large-scale fractures that cover at least one-quarter of the grain surface can be considered glaciogenic, as smaller-scale fractures can be produced in a wide variety of environments (Molén, 2014)." Perhaps we misinterpreted the intent, but Molén (2014) formulated a classification scheme for surface microtextures defined by area of the grain covered, as follows: 1) "large-scale" fractures denote any type of single fracture that covers ≥20–25% of a grain surface, or smaller fractures covering 5%–20% of the surface, such that together these fractures cover >50–55% of the grain; 2) "small-scale" fractures are those that cover −5– ≥20% of the grain surface; and 3) "abrasion" refers to rounded, flattened, polished, or grooved surfaces covering ≥15–20% of the grain area. Percentages of these features are then compared with samples from different environments (Figure 10 of Molén, 2014). Molén (2014; pg. 2031) asserted that abrasion predominates on grains from non-glacial fluvial systems with significant transport distance, whereas large-scale fractures are rare on these grains. This observation led to our statement that abrasion (in Molén's 2014 scheme) occurs in glacial and fluvial environments, but grains from glacial systems also exhibit large-scale fractures. Whereas Molén (2014) focused on development of a scheme to delineate different types of diamictite within a glacial system, our (Soreghan et al., 2022) goal was to explain how to detect any glacial influence on grains during their transportation history. Note that others have cited Molén (2014) and similarly inferred that glaciogenic grains typically exhibit large-scale fractures that cover >25% of the area of the grain (c.f. kalińska et al., 2021).

Molén's (2023) commentary suggests that the SEM images in Sweet and Brannan (2016) only display fractures, not abrasion. However, Sweet and Brannan (2016) followed Mahaney et al. (2001), who building on other studies, assigned suites of microtextures to grain transport environments, and identified numerous microtextures (e.g., troughs, grooves, and edge rounding) that Molén (2014) merged into a single category of abrasion. The methodology proposed by Molén (2014) requires observation of the entire grain surface, which is generally possible when assessing modern to recent sediment, but not practicable for most ancient deposits that have undergone burial diagenesis. Diagenetic alteration and coatings of grain surfaces can obscure transport-induced microtextures (e.g., Sweet and Soreghan, 2010); accordingly, and especially for ancient strata, the methodology pioneered by Mahaney (summarized in Mahaney, 2002) proves more versatile than Molén's approach that requires estimates of the amount of surface area covered by a microtexture.

Final thoughts

We thank Molén (2023) for his comment, as such comments serve to stimulate further discussion, air differences of interpretation, and—potentially—correct flaws. We (Soreghan et al., 2022) tried to summarize means by which it might be possible to infer elusive evidence for upland glaciation in Earth's deep-time record—an inherently interpretative undertaking. Although we disagree with Dr. Molén regarding his preferred methodology and terms, we believe our paper presented the most widely held views in this area of research, drawn from extensive outcrops, on which all interpretations ultimately depend.

Author contributions

The initial response was drafted by DS and further edited by GS, NH, and LP. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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