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

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Introduction

Soreghan et al. (2023) defended earlier work done from 2008 and onwards by different coauthors (e.g., some of the following quoted by Soreghan et al. (2023), and others not quoted; Sweet and Soreghan, 2008; Sweet and Soreghan, 2010; Soreghan et al., 2008; Soreghan et al., 2014; Soreghan et al., 2022; Keiser et al., 2015; Sweet and Brannan, 2016; Smith et al., 2018), on interpretations of glaciation in the Late Paleozoic tropics, as an answer to comments by Molén (2023a).

Soreghan et al. (2023) wrote "… the intent of our paper was to present and integrate a wide variety of data to assess consistency with an upland glacial influence", i.e., to start with a former interpretation and then present data in such a way that they are not at odds with this interpretation. The two main geological features advanced as proxies for glaciation were patterned ground and surface mictrotextures.

Patterned ground: polygonal network of clastic wedges

Many geological processes may create clastic wedges and polygons, with a surficial appearance similar to frost-created features, like wetting and drying, (non-freezing) thermal contraction, in gilgai, sedimentary compaction, gravitational loading, small scale tectonics, flexure over an uneven surface, volume change during cementation, in sheeting joints, and almost any volume change in sediments, and it is not always clear cut how to interpret different features (e.g., Butrym et al., 1964; Everett, 2006; Van Vliet-Lanoë et al., 2004; Van Vliet-Lanoë, 2005; Dixon, 2009; Van Loon, 2009; Superson et al., 2010; Robinson et al., 2017; Molén, 2023b). Such processes have on occasions been misinterpreted as permafrost features (e.g., Butrym et al., 1964; Eyles and Clark, 1985). As permafrost undergoes degradation, significant changes occur that impact the formation and appearance of these fissures, necessitating a nuanced understanding of how to differentiate between those found in non-frozen sediment and those present in perennially-frozen sediment (e.g., French, 2018). But, the papers referred to by Soreghan et al. (2023) do not document such detailed data, and therefore the data presented here is also more general.

True ice wedges are commonly 1) V-shaped vertically 2) arranged in polygonal patterns, 3) filled from above (and display vertical lamination), 4) associated with deformations in the flanking sediments, and 5) display vertically standing stones, if stones are present (Butrym et al., 1964). Soreghan et al. (2023) acknowledge that their interpretation of their documented polygonal network of sand wedges is

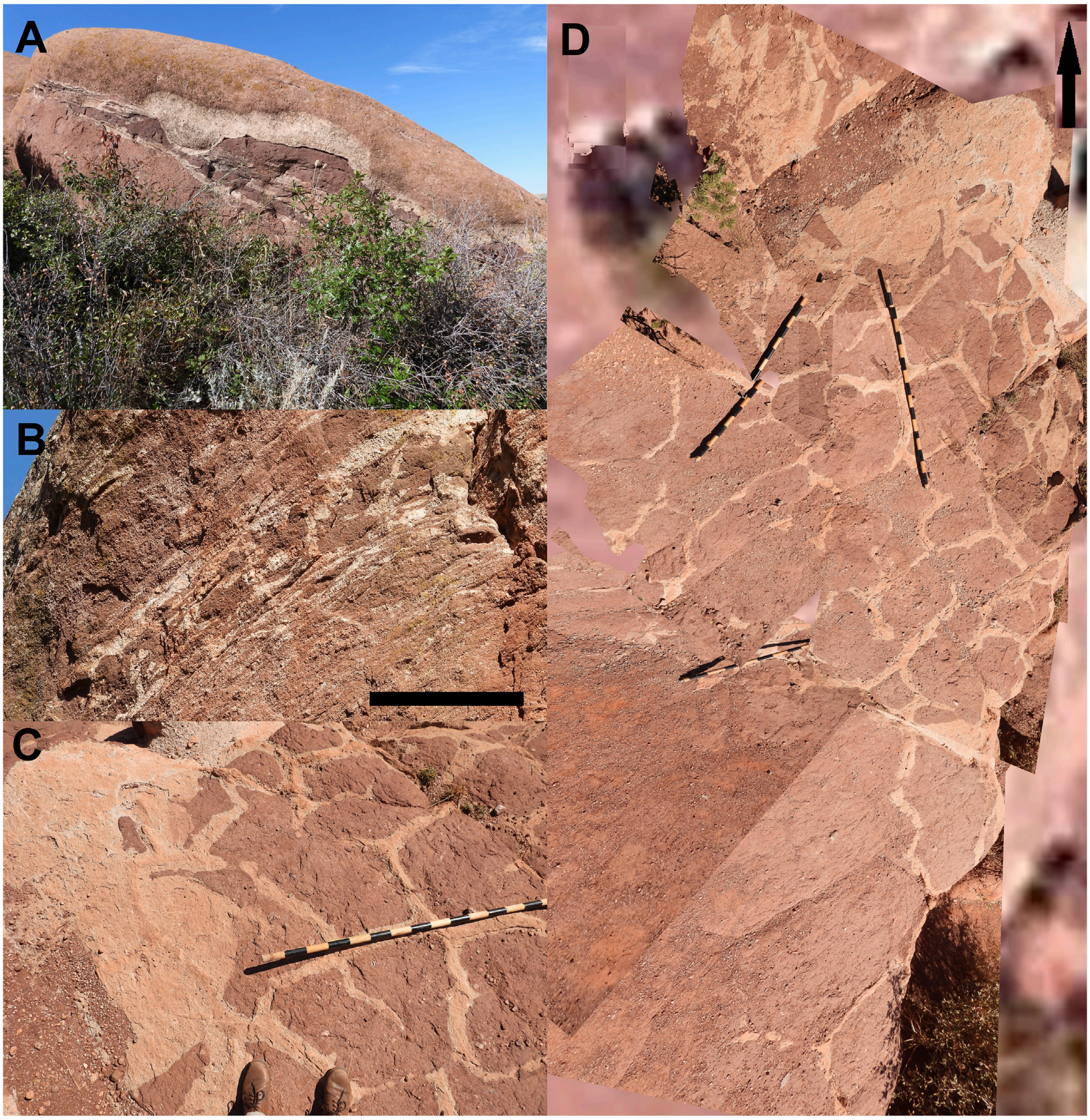

FIGURE 1
Fountain formation in **(A, B)** Red rocks park and **(C, D)** Manitou springs. There is a good dirt road passing the research area in Manitou Springs, and the polygons can even be seen on google earth. **(A)** Example of evidence of movement (streaks of sediments, channels and/or small scale tectonics/flows) in the sediments (N 39 40′21.54″, W 105 12′21.71″). **(B)** A small area of sand injections. (N 39 40′19.49″, W 105 12′27.35″. Scale is approximately 1 m). **(C)** Details showing the irregular and very different sizes of the sand injections/polygons, which here is similar to, but not as varied, as other similar structures that are visible along the dirt road. The irregular appearances were not much discussed in the work by Soreghan et al. (2022) nor Sweet and Soreghan (2008). **(D)** Mosaic of the complete outcrop pictured by Soreghan et al. (2022) plastered on top of the Google Earth view. (Arrow is north. Matching errors, including on the meter stick, is because the area is not perfectly flat. N 38 51′51.66″, W 104 53′53.70″) (Photographs by Edmond W. Holroyd, III).

controversial, but they defend their interpretation as of probably periglacial origin, referring to studies by Sweet and Soreghan (2008). Except for the above five criteria, which were only in part documented, other features were documented by Soreghan (references as of above) which are at odds with a periglacial interpretation of the sand wedges.

The features (Soreghan et al., 2022, Soreghan et al., 2023; Sweet and Soreghan, 2008) refer to are incipient (Figure 1), in general outside of the range of freeze and thaw polygons, and present in superimposed horizons. In Quaternary periglacial areas, polygon diameters may be between 1 and 59 m, wedge depth 0.25–80 m, and wedge width 0.1–10 m, or more (Eyles and Clark, 1985;

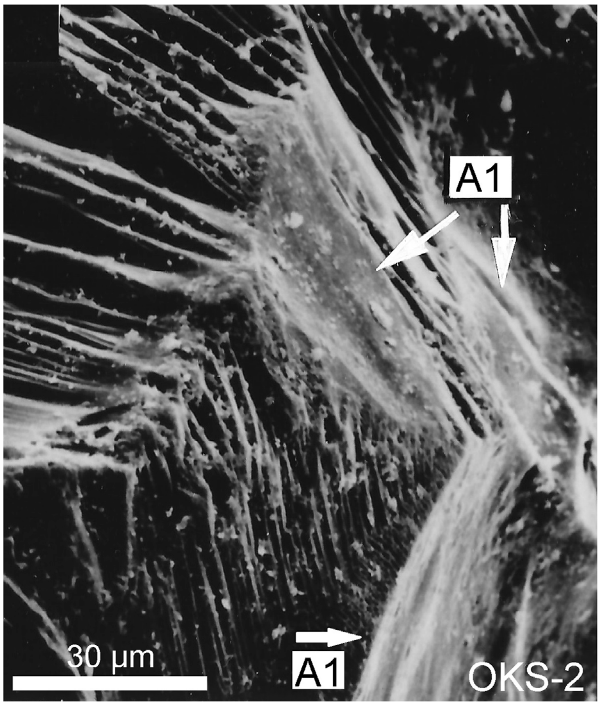

FIGURE 2
Typical glaciogenic surface microtextures, i.e., fractures displaying steps that have been irregularly abraded (arrows showing larger abraded areas, A1), on a grain transported by a thin mountain glacier, probably not more than 50–250 m in thickness, Okstindene, Västerbotten County, Sweden (Molén, 2014).

Murton, 2013; Bertran, 2022), while those documented by Sweet and Soreghan (2008) were 15–78 cm in diameter, 13–61 cm in depth, and 3–22 cm in width. But polygons and ice- and sand wedges do of course always start as small and incipient. A longer or more severe climatic deterioration discussed but not suggested in this area by Soreghan et al. (2022), would induce structures more similar to those close to Pleistocene alpine glaciers or inland ice caps. Furthermore, smaller wedge polygons often occur in finer material (Murton, 2013; Andrieux et al., 2016; Bertran, 2022), and not in coarse sandstone and granule conglomerate as is the case for the structures documented by Sweet and Soreghan (2008). Areas of smaller polygons, more similar in size to those documented by Sweet and Soreghan (2008), may be a subdivision within larger polygons (Bertran et al., 2014; Andrieux et al., 2016; Bertran, 2022). However, the structures documented by Sweet and Soreghan (2008) are not a subdivision of larger polygons.

Except for the size, Quaternary examples are still different in appearance compared to those documented by Sweet and Soreghan (2008), i.e., the latter do not display clear deformations in flanking sediments nor vertical lamination - and only in one locality the sediments are interpreted to be eolian which may not preserve evidence of vertical lamination. Laminae in the host sediment (where present) "commonly are truncated and rarely bent upward at wedge walls" (p. 198, Sweet and Soreghan, 2008), and there is only one presented example of upward bent wedge walls. Quaternary polygons and wedges commonly display both vertical and horizontal lamination, embedded strata of organic material, and commonly upturned and downturned laminae in the wedge walls (Murton, 2013; Andrieux et al., 2016; Bertran et al., 2018; Wolfe et al., 2018; Bertran, 2022). Undeformed strata, which are the most prevalent appearance in the areas studied by Sweet and Soreghan (2008), would be rare and difficult to explain if present in permafrost areas (Murton, 2013), but Sweet and Soreghan (2008), p. 201) refer to special conditions "… that the hosting stratum was massive and/or lacked high water content" in their complete research area. Also, at least some of their documented "frozen-ground" fractures are tapering off upwards (Sweet and Soreghan, 2008; Soreghan et al., 2014), similar to structures produced by soft sediment tectonics (Butrym et al., 1964). There is no undulation or slumping in the sediments next to the wedges, which is a common feature of frozen ground (Sweet and Soreghan, 2008).

To summarize, features of wedges and polygons mentioned by Soreghan et al. (2022), are:

> *Thin, not widening much upwards (Sweet and Soreghan 2008, Figures 10A–B; Soreghan et al., 2022; Figure 5C).
> *Some become wider downwards (Sweet and Soreghan, 2008, Figures. 6A–B, 10D; Soreghan et al., 2022, Figure 5B), which indicate sand injections from below and not frost phenomena (Butrym et al., 1964).
> *Some display an appearance of dessication fractures, and are also bent (Sweet and Soreghan, 2008; Figures 6C–F). The latter may indicate slight horizontal movement of the sediments, and display similarities to cuspidate injectites and hydrofractures produced by horizontal movement of unconsolidated granular material (Philips, 2006; Festa et al., 2016). Dessication fractures may originate in sediments with <10–15% clay (Cordero et al., 2021; Wang et al., 2023), and liquefaction only in sediments <14% clay (Świątek et al., 2023), i.e., displaying a similar clay content as the sediments documented by Sweet and Soreghan (2008) of <14%.
> *The appearance of the sections are "spasmodic" wherever they are visible in the areas, i.e., displaying many kinds of thick and thin injections and not a more regular pattern (e.g., Figures 1C, D), which would not be if the features were slowly produced by freeze and thaw phenomena (Sweet and Soreghan, 2008, Figure 10G). The appearance of these and the complete outcrop is similar to features originating by hydrofracturing, which could be a result of deposition from sediment gravity flows (Mandl et al., 1987; Philips, 2006; Denis et al., 2010; Pisarska-Jamroży et al., 2024).

Quartz grain surface microtextures

The SEM work on surface microtextures by Soreghan et al. (2022), Soreghan et al. (2023) uses the correct definitions, but selectively use only parts of a classification scheme, and do not refer to the combination of surface microtextures necessary for a correct identification. Apparently single surface microtextures, whatever size or number of ocurrences on single grains, appear to have been recorded as a basis for their interpretations, not using overall descriptions of the surfaces and statistics (Mahaney, 2002; Molén, 2014). Single occurrences of small scale surface microtextures commonly have little value and may be misidentified. The problems with this were clearly outlined by Molén (2014) referring to operator variance that sometimes differed between 0% and 100% detection on the same samples, even though the researchers still had the same interpretations of the depositional environment. (Soreghan et al., 2022) and other papers by the same group, e.g., Sweet and Soreghan, 2008) commonly mark surface microtextures on only a few grains, but the entire grain surfaces show, e.g., solitary fractures or those typical of weathered grains released from bedrock and no abrasion, i.e., these grains had to have been missed by any nearby glaciers because they acquired no irregular abrasion. They showed typical non-glaciogenic grains but proposed (probable) nearby glaciers (e.g., Sweet and Soreghan, 2010; Keiser et al., 2015). They provided no evidence of regular (fluvial) or irregular (glacial) abrasion (e.g., different kinds of "edge rounding") and therefore misidentified grains that commonly originate from release from bedrock or simple fracturing without providing evidence of glaciation or (glacio-) fluvial abrasion (e.g., Sweet and Brannan, 2016; Soreghan et al., 2014; Soreghan et al., 2022; Smith et al., 2018). A typical glaciogenic quartz sand grain is shown in Figure 2.

The assertion by Soreghan et al. (2023), that for the method by Molén (2014) to be relevant it "requires observation of the entire grain surface" goes against their own observations where they actually have pictured "entire" grain surfaces (i.e., what is shown by SEM), and also against the work of most published SEM work on surface microtextures (e.g., Mahaney, 2002; Molén, 2014; Molén, 2017; Molén, 2023b; Molén and Smit, 2022). Their assertion, shown from their microphotographs, that apparent ocurrences of only single small scale surface microtextures have to be documented, and commonly minute evidence of abrasion, goes against the work by Mahaney (2002), Molén (2014) and others (e.g., Ma et al., 2024). Soreghan et al. (2023) also missed the Molén (2014) reference in their reference section.

Conclusion

The Fountain Formation (which is the formation displaying patterned ground), close to Denver, Colorado, United States, displays evidence of injection of sand, including clastic dikes. The areas displaying geologic features with appearances superfically similar to polygons and ice wedges are insignificant. There is evidence of sediment movement, and on occasions these movements have induced fracturing of the beds and imposed sediment injection. The polygons are in general a direct match to different appearances of non-glacial soft sediment structures, e.g., small scale tectonically induced structures, displaying possible indications of sediment gravity flow deposition, and in detail they only superficially resemble permafrost structures.

The surface microtextures in the area display evidence of, e.g., release from bedrock but not from glaciation.

Soreghan et al. (2023) stated that their work may present "the most widely held views in this area of research, drawn from extensive outcrops." Although their interpretations of geological features are perhaps the most widely held views of other areas, their study concerns only a small area with no extensive outcrops, and the geological features from that area display no evidence of glaciation.

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Conflict of interest

Author MM was employed by Umeå FoU AB.

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References

Andrieux, E., Bertran, P., Antoine, P., Deschodt, L., Lenoble, A., Coutard, S., et al. (2016). Database of pleistocene periglacial features in France: description of the online version. *Quaternaire* 27, 329–339. doi:10.4000/quaternaire.7717

Bertran, P. (2022). Distribution and characteristics of Pleistocene ground thermal contraction polygons in Europe from satellite images. *Permafr. Periglac. Process.* 33, 99–113. doi:10.1002/ppp.2137

Bertran, P., Andrieux, E., Antoine, P., Coutard, S., Deschodt, L., Gardère, P., et al. (2014). Distribution and chronology of Pleistocene permafrost features in France: database and first results. *Boreas* 43, 699–711. doi:10.1111/bor.12025

Bertran, P., Andrieux, E., Bateman, M., Font, M., Manchuel, K., and Sicilia, D. (2018). Features caused by ground ice growth and decay in Late Pleistocene fluvial deposits, Paris Basin, France. *Geomorphology* 310, 84–101. doi:10.1016/j.geomorph.2018.03.011

Butrym, J., Cegla, J., Dżułyński, S., and Nakonieczny, S. (1964). New interpretation of periglacial structures. *Folia Quat.* 17, 1–34.

Cordero, J. A., Prat, P. C., and Ledesma, A. (2021). Experimental analysis of desiccation cracks on a clayey silt from a large-scale test in natural conditions. *Eng. Geol.* 292, 106256. doi:10.1016/j.enggeo.2021.106256

Denis, M., Guiraud, M., Konaté, M., and Buoncristiani, J.-F. (2010). Subglacial deformation and water-pressure cycles as a key for understanding ice stream dynamics:

evidence from the Late Ordovician succession of the Djado Basin (Niger). *Int. J. Earth Sci.* 99, 1399–1425. doi:10.1007/s00531-009-0455-z

Dixon, J. C. (2009). "Aridic soils, patterned ground, and desert pavements," in *Geomorphology of desert environments*. Editors A. J. Parsons, and A. D. Abrahams (Dordrecht: Springer), 101–122. doi:10.1007/978-1-4020-5719-9_5

Everett, K. R. (2006). "Cryoturbation structures," in *Structural geology and tectonics. Encyclopedia of Earth science*. Editor C. Seyfert (Berlin, Heidelberg: Springer), 177–183. doi:10.1007/3-540-31080-0_25

Eyles, N., and Clark, B. M. (1985). Gravity-induced soft-sediment deformation in glaciomarine sequences of the upper proterozoic Port Askaig Formation, Scotland. *Sedimentology* 32, 789–814. doi:10.1111/j.1365-3091.1985.tb00734.x

Festa, A., Ogata, K., Pini, G. A., Dilek, Y., and Alonso, J. L. (2016). Origin and significance of olistostromes in the evolution of orogenic belts: a global synthesis. *Gondwana Res.* 39, 180–203. doi:10.1016/j.gr.2016.08.002

French, H. M. (2018). *The periglacial environment*. Fourth Edition. Hoboken: John Wiley and Sons. doi:10.1002/9781119132820

Keiser, L. J., Soreghan, G. S., and Kowalewski, M. (2015). Use of quartz microtextural analysis to assess possible proglacial deposition for the Pennsylvanian-Permian Cutler Formation (Colorado, U.S.A). *J. Sediment. Res.* 85, 1310–1322. doi:10.2110/jsr.2015.81

Ma, J., Chen, J., and Xu, C. (2024). Sedimentary records of giant landslide-dam breach events in western Sichuan, China. *Front. Earth Sci.* 12, 1414763. doi:10.3389/feart.2024.1414763

Mahaney, W. C. (2002). *Atlas of sand grain surface textures and applications*. Oxford,U.K.: Oxford University Press, 237.

Mandl, G., and Harkness, R. M. (1987). "Hydrocarbon Migration by Hydraulic Fracturing," in *Deformation of sediments and sedimentary Rocks*. Editors M. E. Jones, and R. M. F. Preston (Geological Society Special Publication), 29, 39–53. doi:10.1144/gsl.sp.1987.029.01.04

Molén, M. O. (2014). Asimple method to classify diamicts by scanning electronmicroscope from surface microtextures. *Sedimentology* 61, 2020–2041. doi:10.1111/sed.12127

Molén, M. O. (2017). The origin of Upper Precambrian diamictites; Northern Norway: A case study applicable to diamictites in general. *Geologos* 23, 163–181. doi:10.1515/logos-2017-0019

Molén, M. O. (2023a). Comment to: Detecting upland glaciation in Earth's prepleistocene record. *Front. Earth Sci.* 11. doi:10.3389/feart.2023.1120975

Molén, M. O. (2023b). Glaciation-induced features or sediment gravity flows – an analytic review. *J. Palaeogeogr.* 12, 487–545. doi:10.1016/j.jop.2023.08.002

Molén, M. O., and Smit, J. J. (2022). Reconsidering the glaciogenic origin of Gondwana diamictites of the Dwyka Group, South Africa Gondwana diamictites of the Dwyka Group, South Africa. *Geologos* 28, 83–113. doi:10.2478/logos-2022-0008

Murton, J. (2013). "Permafrost And Periglacial Features: Ice Wedges and Ice-Wedge Casts," in *Encyclopedia of quaternary science* S. A. Elias, and C. J. Mock, Second Edition (Elsevier), 436–451. doi:10.1016/B978-0-444-53643-3.00097-2

Phillips, E. (2006). Micromorphology of a debris flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement. *Quat. Sci. Rev.* 25, 720–738. doi:10.1016/j.quascirev.2005.07.004

Pisarska-Jamroży, M., Woronko, B., Woźniak, P. P., Rosentau, A., Hang, T., Steffen, H., et al. (2024). Deformation structures as key hints for interpretation of ice sheet dynamics - A case study from northeastern Estonia. *Quat. Sci. Rev.* 336, 108788. doi:10.1016/j.quascirev.2024.108788

Robinson, J. E., Bacon, C. R., Major, J. J., Wright, H. M., and Vallance, J. M. (2017). Surface morphology of calderaforming eruption deposits revealed by lidar mapping of Crater Lake National Park, Oregon – Implications for deposition and surface modification. *J. Volcanol. Geotherm. Res.* 342, 61–78. doi:10.1016/j.jvolgeores.2017.02.012

Smith, C., Soreghan, G. S., and Ohta, T. (2018). Scanning electron microscope (SEM) microtextural analysis as a paleoclimate tool for fluvial deposits: A modern test. *GSA Bull.* 130 (7-8), 1256–1272. doi:10.1130/b31692.1

Soreghan, G. S., Pfeifer, L. S., Sweet, D. E., and Heavens, N. G. (2022). Detecting upland glaciation in Earth's pre-Pleistocene record. *Front. Earth Sci.* 10, 904787. doi:10.3389/feart.2022.904787

Soreghan, G. S., Pfeifer, L. S., Sweet, D. E., and Heavens, N. G. (2023). Response: commentary: detecting upland glaciation in Earth's pre-Pleistocene record. *Front. Earth Sci.* 11, 1241577. doi:10.3389/feart.2023.1241577

Soreghan, G. S., Soreghan, M. J., Poulsen, C. J., Young, R. A., Eble, C. F., Sweet, D. S., et al. (2008). Anomalous cold in the Pangaean tropics. *Geology* 36, 659–662. doi:10.1130/G24822A.1

Soreghan, G. S., Sweet, D. S., and Heavens, N. G. (2014). Upland glaciation in tropical Pangaea: Geologic evidence and implications for Late Paleozoic climate modeling. *J. Geol.* 122, 137–163. doi:10.1086/675255

Superson, J., Gębica, P., and Brzezińska-Wójcik, T. (2010). The origin of deformation structures in periglacial fluvial sediments of the Wisłok Valley, southeast Poland. *Process* 21, 301–314. doi:10.1002/ppp.691

Sweet, D. E., and Brannan, D. K. (2016). Proportion of glacially to fluvially induced quartz grain microtextures along the Chitina River, SE Alaska, USA. *J. Sediment. Res.* 86, 749–761. doi:10.2110/jsr.2016.49

Sweet, D. E., and Soreghan, G. S. (2008). Polygonal cracking in coarse clastics records cold temperatures in the equatorial Fountain Formation Pennsylvanian-Permian, Colorado. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 268, 193–204. doi:10.1016/j.palaeo.2008.03.046

Sweet, D. E., and Soreghan, G. S. (2010). Application of Quartz Sand Microtextural Analysis to Infer Cold-Climate Weathering for the Equatorial Fountain Formation Pennsylvanian-Permian, Colorado, U.S.A. *J. Sediment. Res.* 80, 666–677. doi:10.2110/jsr.2010.061

Świątek, S., Belzyt, S., Pisarska-Jamroży, M., and Woronko, B. (2023). Sedimentary records of liquefaction: Implications from field studies. *J. Geophys. Res. Earth Surf.* 128, e2023JF007152. doi:10.1029/2023JF007152

Van Loon, A. J. (2009). Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos* 15, 3–55. Available at: http://hdl.handle.net/10593/155.

Van Vliet-Lanoë, B. (2005). Deformations in the active layer related with ice/soil wedge growth and decay in present day Arctic. Paleoclimatic implications. *Ann. Société Géologique Nord* 12, 77–91.

Van Vliet-Lanoë, B., Magyari, A., and Meilliez, F. (2004). Distinguishing between tectonic and periglacial deformations of quaternary continental deposits in Europe. *Glob. Planet. Change* 43, 103–127. doi:10.1016/j.gloplacha.2004.03.003

Wang, Z., Liu, J., Bu, F., Che, W., Song, Z., Ma, K., et al. (2023). Effects of sand incorporation and temperatures on desiccation cracks, moisture dynamics, and microstructure evolution of sandy slopes' topsoil at multi-scales. *Bull. Eng. Geol. Environ.* 82, 13. doi:10.1007/s10064-022-03035-w

Wolfe, S. A., Morse, P. D., Neudorf, C. M., Kokelj, S. V., Lian, O. B., and O'Neill, H. B. (2018). Contemporary sand wedge development in seasonally frozen ground and paleoenvironmental implications. *Geomorphology* 308, 215–229. doi:10.1016/j.geomorph.2018.02.015