Ice-crystal traces imply ephemeral freezing in early Permian equatorial Pangea

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ABSTRACT

Delicate impressions in lacustrine strata of the lower Permian (lower Cisuralian) Usclas Formation record ephemeral freezing in equatorial Pangea. These sediments accumulated in the paleoequatorial and intramontane Lodève Basin (southern Massif Central, France) during peak icehouse conditions of the Late Paleozoic Ice Age. Experimental replication of these features supports the interpretation that they are ice-crystal molds. Evidence for films of ice in marginal-lacustrine sediment at such low latitudes and inferred low to moderate altitudes (1–2 km) calls for a reevaluation of climate conditions in eastern equatorial Pangea. Ephemeral freezing implies either cold tropical temperatures (~5 °C cooler than the Last Glacial Maximum) and/or lapse rates that exceeded those of the Last Glacial Maximum. Extreme continentality of the Lodève Basin would have amplified seasonality, albeit the climatic forcing(s) necessary to have promoted cold temperatures in equatorial Pangea remain enigmatic.

INTRODUCTION

The Graissessac-Lodève Basin is a small continental rift basin in France’s Massif Central (Fig. 1). Delicate crystal molds in multiple bedding-plane exposures of the lower Permian Usclas Formation have been interpreted to record traces of either gypsum crystals, implying evaporative conditions (Odin, 1986), or ice crystals, implying ephemeral freezing (Becq-Giraudon et al., 1996) during the Late Paleozoic Ice Age (LPIA). We documented and characterized the primary morphologies of these features and conducted laboratory analyses to empirically reproduce sediment impressions left by freezing of water-saturated mud. The paleoenvironmental conditions of formation (ephemeral freezing) implied by these results demand a reevaluation of climate models in low-latitude, early Permian Pangea.

BACKGROUND

Pangean assembly resulted in uplift of the Central Pangean Mountains, which spanned the equator from North America (the Appalachian-Ouachita-Marathon belt) through Western Europe (the Variscan belt). Syn-orogenic extension in the late stages of the Variscan orogeny (ca. 300 Ma) produced several rift basins (Burg et al., 1994) that remained within the equatorial belt throughout the Permo-Carboniferous (Fig. 1; Domeier and Torsvik, 2014; Evans et al., 2014; Kent and Muttoni, 2020). Among them, the Lodève Basin (southern Massif Central) preserves a late Carboniferous–Permian record of regional paleoequatorial climate from apex to collapse of the LPIA.

The frequency of ice-contact deposits across southern Gondwana implies that Asselian–Sakmarian (early Permian; ca. 288–295 Ma) time records the most intense phase of the LPIA (e.g., Soreghan et al., 2019). Semiarid climates and periglacial-proglacial conditions at paleoequatorial latitudes have also been hypothesized in both western (Ancestral Rocky Mountains; Soreghan et al., 2008, 2014) and eastern (Variscan paleomountains; Julien, 1895; Becq-Giraudon et al., 1996; Pfeifer et al., 2020) Pangea. However, these claims remain controversial because they imply colder conditions than models can replicate (e.g., Heavens et al., 2015).

The lower Permian (lower Cisuralian) Usclas Formation (Lodève Basin) consists primarily of organic-rich mudstone and tan siltstone of lacustrine origin (variable water depth; Pochat and Van Den Driessche, 2011). Delicate, stellate features occur on multiple bedding-plane exposures here and in coeval strata of the nearby Gabian-Neffies Basin (Montenat and Dolle, 1986) and Germany (Martinstein-Nahe; Reineck, 1955). Features with similar attributes—although rare in the geological record (Table 1, and references therein)—have been interpreted as ice-crystal traces, with low-latitude examples dating exclusively from the upper Carboniferous–lower Permian.

METHODS

We measured three detailed sections of the Usclas Formation (totaling 5.4 m; Fig. 1) containing abundant delicate impressions, at centimeter-scale resolution. The impressions were classified into three morphologies. Thin sections were made of representative samples and compositional analyses (energy dispersive spectroscopy) were acquired with an electron probe microanalyzer. We conducted experiments to freeze mud (saturated with distilled water or dilute NaCl solutions) in order to simulate ice-crystal growth and test the hypothesis that the features represent ice traces (experimental set up and variables are provided in Appendix S1 in the Supplemental Material).

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### RESULTS

**Morphological Documentation of Delicate Traces**

The Usclas Formation (Fig. 1) comprises massive to locally laminated, thinly bedded mudstone to tuffaceous mudstone (mode 25–30 µm; see Appendix S2). The bedding-plane traces (occurring as both molds and casts) exhibit three morphologies (Fig. 2) designated as “SR” (stubby rods), “FN” (fanned needles), and “DC” (delicate, complex), albeit these represent a continuum. Morphologies FN and DC (most common) co-occur and present as molds. Morphology SR presents as casts. All impressions contain secondary minerals (Fig. 2): Potassium feldspar replaces dolomite in SR, and potassium feldspar lines molds of FN and DC. Morphology SR forms composite, rod-like, stubby needles (6–10 mm), wherein bundles commonly intersect at 60°, 90°, or 180°. Morphology FN consists of needles (2–5 mm) occurring most commonly as fans radiating at 60°–120°; less common are feather-like features (as long as 20–25 mm) that fan in preferred directions from a linear center with rare curvature. Morphology DC consists of delicate blades that form well-developed 60°–120° semi-radial “bow-tie” to full 360° radial fans. Some fans comprise straight needles (3–10 mm), while others are feather-like to dendritic, with smaller curved branches emanating from the main needles.

### Laboratory Simulation of Ice Growth in Sediment

Morphologies of experimental ice (formed at −15 °C in saturated to supersaturated mud) match the scale and form of bedding-plane impressions from the Usclas Formation (Fig. 2). The variable that most influences morphology is sediment water saturation, with a secondary influence from water chemistry. Morphology SR generally forms in mud saturated or supersaturated (for shorter, deeper impressions) with distilled water; FN forms in mud with very dilute NaCl (0.1%–0.5%)–saturated conditions, and DC forms in mud saturated or super-saturated with 0.5%–1% NaCl solution. Note that natural growth rates are much slower (0.01–0.1 in/hr [0.2–2.5 mm/hr];

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**TABLE 1. SUMMARY OF EXISTING INTERPRETATIONS OF ICE CRYSTAL TRACE MARKINGS (MODERN–ANCIENT)**

| Time       | Location       | Paleo-latitude | Paleo-altitude (m) | Substrate     | Bed              | Citation       | Figure S2 panel |
|------------|----------------|----------------|--------------------|---------------|------------------|----------------|-----------------|
| Modern     | Germany        | 49.8           | SL                 | mud           |                  | Hänschel, 1935 | A               |
| Modern     | Illinois, USA  | 41.5           | 150                | loess         |                  | Udden, 1918    |                 |
| Modern     | Northeast USA  | 42.3           | SL                 | clay          |                  | Shaler et al., 1806 |                 |
| Modern     | Northwest Idaho, USA | 46.7 | 500             | loess         |                  | Mark, 1932     |                 |
| Modern     | Tidal Bay, California, USA | 47.3 |              | sand-mud      |                  | Dinné, 1985    |                 |
| Pleistocene| Utah, USA      | 40.2           | 1500               | fine sands    | surface          | Mark, 1932     | DE              |
| Upper Cretaceous | South Dakota, USA | 46.7 | SL                  | silt-clay    | surface          | Udden, 1918    |                 |
| Upper Cretaceous | Texas, USA     | 33.8           | SL                 | lime-clay    | surface          | Udden, 1918    |                 |
| Middle Permian | New Mexico, USA | 9.2            | SL                 | limestone    | surface          | Lang, 1937     | G               |
| Lower Permian | Germany        | 3.9            | ~300               | silt-clay    | surface          | Remeik, 1955   |                 |
| Lower Permian | De Laï, Niger  | 50             | ~300               | mud-silt     | surface          | Lang et al., 1991 | L              |
| Upper Devonian | New York, USA  | 33             | SL                 | sand-mud     | base             | Clarke, 1917   |                 |
| Upper Devonian | Libya          | 62             | ~300               | mud          | surface          | Girard et al., 2015 | K              |
| Upper Devonian | Morocco        | 80             | ~300               | sandy mud    | surface          | Nutz et al., 2013 | J              |

See Appendix S3 (see text footnote 1) for photos and references. Paleo-latitudes are converted from modern latitudes using the paleogeography of Torsvik et al. (2012; and the calculator at http://paleolatitude.org, and paleolatitude estimations are approximate. SL—paleo-latitudes around sea level.
Furthermore, the common morphological features that define both ice-crystal traces from modern mudflats (e.g., Table 1; Figs. S2A–S2C) and inferred ice-crystal traces from the ancient record (e.g., Table 1; Figs. S2D–S2L) reinforce this interpretation. Generally, these characteristics include straight, tapered, needle-like traces in bundled to radial habits that exhibit intersecting or overlapping patterns. Experiments reproduced (in size and form) the defining characteristics of each morphology (Fig. 2), including the short, high-relief features of morphology SR, 60°–120° fans of FN, and delicate, radial blades and dendritic branches of DC. DC morphologies visually replicate irrefutable ice-crystal traces from modern playas (e.g., Fig. S2C). FN morphologies resemble shapes of both modern (e.g., Fig. S2B) and inferred Pleistocene ice-crystal traces (e.g., Figs. S2D and S2E) and cryostructures (e.g., Fig. S2F). The rod-like forms of SR resemble *Fucoides graphica* features referenced in early interpretations of peritidal ground ice (Hall, 1843; Clarke, 1918).

Empirical results show that the primary controls on crystal morphology (notably, aspect...
formation morphologies, but inconsistencies in scale (Appendix S4) can exhibit a fan-like or fibrous gypsum, halite, barite, and other saline minerals textures of gypsum crystals (e.g., Magee, 1991) traces, however, are inconsistent with the typical interpretation. The ability to empirically reproduce all three (SR, FN, DC)—together with its ice-crystal morphologies (Appendix S3)—leaves ice as the most parsimonious and conservative explanation for the formation of these features.

**Paleoclimate Implications for the Early Permian**

Empirical replication of ice-crystal molds supports the inference that the ice crystals formed in—at most—very shallow films (<2 mm) of water and displaced sediment downward and outward during growth. This is consistent with ephemeral freezing along paleo-shorelines of the Usclas Formation lake, and is common in modern playa lakes in climates subject to freezing temperatures (e.g., Fig. 2C) but unknown in low-elevation equatorial regions. Ephemeral freezing during cold seasons and at equatorial latitudes during the early Permian implies either (1) substantial elevation to enable freezing at elevations (Pfeifer et al., 2018) as well as fine (Appendix S2) sediment deposition (ash), enhancing preservation of the delicate traces (as in a Lagerstätte).

Odin (1986) interpreted the bedding-plane traces in the Usclas Formation as the result of evaporite (gypsum) crystallization, supported by other evidence for shallow water and dry conditions (e.g., desiccation features) elsewhere in this unit. The morphologies of the Usclas Formation traces, however, are inconsistent with the typical prismatic, pyramidal habits or “brain-like” textures of gypsum crystals (e.g., Magee, 1991) and cubic habits of common halite. Rare forms of gypsum, halite, barite, and other saline minerals (Appendix S4) can exhibit a fan-like or fibrous nature somewhat similar to individual Usclas Formation morphologies, but inconsistencies in scale and form preclude an origin as evaporite minerals (Appendix S4). Additionally, all three morphologies (SR, FN, DC) co-occur in the Usclas Formation, which is also inconsistent with any one alternative interpretation. The ability to empirically reproduce all three (SR, FN, DC)—together with the striking resemblance to a variety of modern ice-crystal morphologies (Appendix S3)—leaves ice as the most parsimonious and conservative explanation for the formation of these features.

Figure 3. Plots of possible tropical temperature conditions in the Permian at different elevations using the same adiabatic lapse rate as the Last Glacial Maximum (LGM) (−6.7 °C/km; Loomis et al., 2017) (A) and “dry” tropical lapse rate (−9.8 °C/km; MacLennan et al., 2020) (B). Gray zone represents possible paleoelevations (within error) of the Lodève Basin at ca. 285 Ma during Usclas Formation deposition (see discussion in text). Average tropical temperatures near sea level range from LGM temperatures (lightest gray) to 15 °C cooler than LGM (darkest gray). LGM minus 15 °C is the coolest end of the range of estimates proposed by Soreghan et al. (2014) (0–15 °C cooler than LGM) to have −1000 m glacial conditions in western equatorial Pangea. Dotted horizontal lines represent average equatorial near-surface mean annual temperatures (MATs) (0–10 °C) that could support upland glaciation in low-latitude Pangea (Feulner, 2017).

Moderate to low elevations (1–2 km) for seasonal freezing in the Usclas Formation implies cooler tropical conditions than most models can replicate for low-latitude Pangea. The climatic forcing(s) necessary to impact tropical precipitation patterns and promote anomalously cold conditions in equatorial Pangea remain poorly understood (Heavens et al., 2015) but likely involved both short- and long-term factors. Average tropical air temperatures (25 °C) and lapse rates (−6.7 °C/km) from the LGM (e.g., Loomis et al., 2017) could not have produced even ephemeral freezing at <2 km elevations (Fig. 3). However, both (1) temperatures averaging −5 °C cooler than the LGM with an LGM lapse rate (Fig. 3A) and (2) LGM temperatures with a dry tropical lapse rate (−9.8 °C/km; MacLennan et al., 2020; Fig. 3B) are consistent with ephemeral freezing at elevations <2 km. The extreme continentality (and thus, seasonality) of the Lodève Basin depicted by its inland position in both Pangea B (Fig. 1; Kent and Muttoni, 2020) and Pangea A (e.g., Molli et al., 2020) would have produced a drier (steeper) lapse rate (Fig. 3B). On longer time scales, orbital variability and volcanism likely amplified paleoclimate change during this time. For example, LPIA climate simulation of peak icehouse conditions shows that pCO2 <150 ppm under a cold summer orbit could have produced near-surface equatorial mean annual temperatures (MATs) of 0–10 °C (Feulner, 2017), consistent with upland glaciation and thus ephemeral freezing at lower elevations. Furthermore, Soreghan et al. (2019) hypothesized that frequent and widespread explosive volcanism in central and western Europe (at low latitude) at ca. 300 Ma may have intensified or sustained cool temperatures, even as pCO2 began to rise. Local evidence in support of coeval volcanism occurs in the Usclas Formation in the form of the altered, ash-like, illite-rich clay mineral compositions of mudstones containing the...
inferred ice-crystal impressions and the tuffaceous units that directly overlie them (Fig. 1).

To date, examples of ice-crystal traces in the low-latitude geological record date exclusively from the upper Carboniferous—lower Permian (Table 1), calling for exploration of a potentially widespread phenomenon that has been long overlooked owing to the seeming implausibility of freezing conditions at relatively low elevations in equatorial latitudes of Pangea.

CONCLUSIONS

Laboratory analyses empirically reproduce sediment impressions left by freezing of water-saturated mud and support the interpretation that morphologically identical features from the lower Permian Usclas Formation (Lodève Basin, France) represent ice-crystal traces. Evidence for films of ice on the paleoshoreline of a low-latitude lake records ephemeral freezing in equatorial Pangea during peak icehouse conditions (LPIA). Given the relatively low elevation (1–2 km) of the Lodève Basin during this time, these conditions require cold tropical temperatures (~5 °C cooler than those of the LGM) and/or lapse rates that exceeded those of the LGM. The forcing(s) necessary to promote cold climate conditions in equatorial Pangea remain enigmatic, but the extreme continentality of the Lodève Basin would have magnified strong seasonality. This work corroborates the presently sparse—yet temporally unique—recognition of low-latitude ice traces in the Phanerozoic (exclusively Permo-Triassic). Temporally unique—recognition of low-latitude ice traces in the Phanerozoic (exclusively Permo-Triassic) corroborates the presently sparse—yet temporally unique—recognition of low-latitude ice traces in the Phanerozoic (exclusively Permo-Triassic). This work corroborates the presently sparse—yet temporally unique—recognition of low-latitude ice traces in the Phanerozoic (exclusively Permo-Triassic).

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REFERENCES CITED

Allan, J.A., 1926, Ice crystal markings: American Journal of Science, v. 1, p. 494–500, https://doi.org/10.2475/ajs.s5-11.6.494.

Barns, R.L., and Laudise, R.A., 1985, Size and perfection of crystals in lake ice: Journal of Crystal Growth, v. 71, p. 104–110, https://doi.org/10.1016/0022-0248(85)90049-X.

Becq-Giraudon, J.-F., Montenat, C., and Van Den Driessche, J., 1996, Hercynian high-altitude phenomena in the French Massif Central: Tectonic implications: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 122, p. 227–241, https://doi.org/10.1016/0031-0182(95)00081-X.

Burg, J.-P., Van Den Driessche, J., and Brun, J.-P., 1994, Syn-to-post-thickening extension in the Variscan Belt of Western Europe: Modes and structural consequences: Comptes Rendus de l’Académie des Sciences Paris, v. 319, p. 1019–1032.

Clarke, J.M., 1918, Strand and undertow markings of the lower Permian Usclas Formation (Lodève Basin, France) represent ice-crystal traces. Evidence for films of ice on the paleoshoreline of a low-latitude lake records ephemeral freezing in equatorial Pangea during peak icehouse conditions (LPIA). Given the relatively low elevation (1–2 km) of the Lodève Basin during this time, these conditions require cold tropical temperatures (~5 °C cooler than those of the LGM) and/or lapse rates that exceeded those of the LGM.

Feulner, G., 2017, Formation of most of our coal took place during the last ice age: Science Advances, v. 3, e1600815, https://doi.org/10.1126/sciadv.1600815.

Porter, S.C., 2001, Glacial forebuilding in the tropics during the Late Quaternary: Geology, v. 29, p. 1076–1079, https://doi.org/10.1130/0091-7613(2001)029<1076:GFITFT>2.0.CO;2.

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