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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. 298–295 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[1]).

[1]Supplemental Material. Appendices S1–S4. Please visit https://doi.org/10.1130/GEOL.S.14925237 to access the supplemental material, and contact editing@geosociety.org with any questions.

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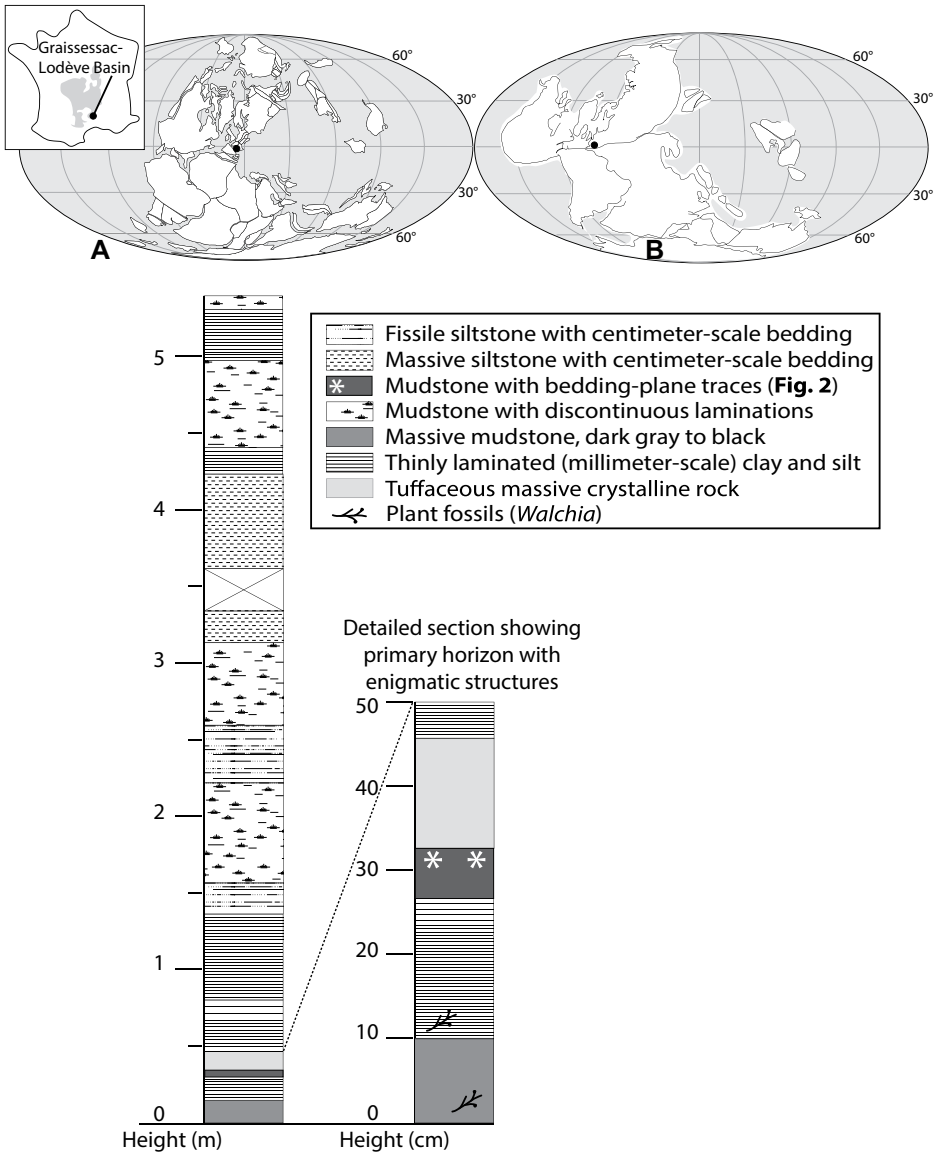

Figure 1. (Top) Early Permian (ca. 290 Ma) paleogeographic reconstructions of Domeier and Torsvik (2014) (Pangea, A) and Kent and Muttoni (2020) (Pangea, B). Black dots show equatorial location of the Graissessac-Lodève Basin (southern margin of the French Massif Central; gray shading on inset map) at ~0°–2°S (A) to 0°–2°N (B), consistent with published paleomagnetic data from the Lodève Basin (Evans et al., 2014). Proximity to the Paleotethys ocean varies substantially, though both suggest a relatively continental position (e.g., Molli et al., 2020). (Bottom) Stratigraphic section (concatenation of three exposures) of the Usclas Formation, Lodève Basin. Detailed log on right shows bottom 0.5 m at centimeter-scale resolution where most of the enigmatic structures are found (white asterisks).

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 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];

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		Hänzschel, 1935	
Modern	Illinois, USA	41.5	150	loess		Udden, 1918	A
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	SL	sand-mud		Dionne, 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	HI
Middle Permian	New Mexico, USA	9.2	SL	limestone	surface	Lang, 1937	G
Lower Permian	Germany	3.9	~300	silt-clay	surface	Reineck, 1955	
Lowe Carboniferous	De L'aïr, Niger	–50	<300	mud-silt	surface	Lang et al., 1991	L
Upper Devonian	New York, USA	–33	SL	sand-mud	base	Clarke, 1917	
Upper Ordovician	Libya	–62	<300	mud	surface	Girard et al., 2015	K
Upper Ordovician	Morocco	–80	<300	sandy mud	surface	Nutz et al., 2013	J

See Appendix S3 (see text footnote 1) for photos and references. Paleolatitudes are converted from modern latitudes using the paleogeography of Torsvik et al. (2012; and the calculator at http://paleolatitude.org, and paleoaltitude estimations are approximate. SL— paleoaltitudes around sea level.

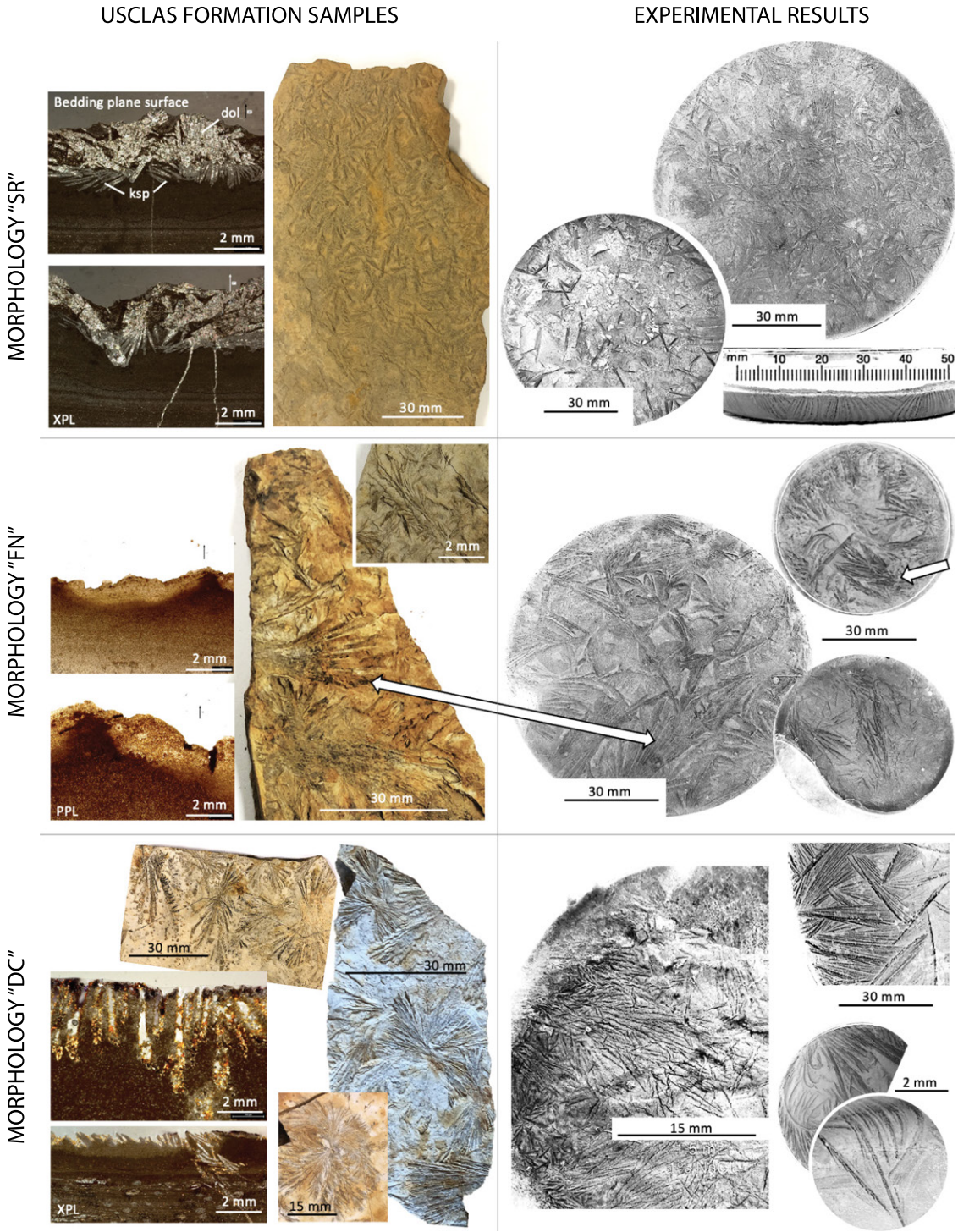

Figure 2. Summary of morphologic characteristics of features from the Usclas Formation (south-central France) (left) adjacent to examples from experimental results (right) that replicate features in each morphology, respectively (SR—stubby rods; FN—fanned needles; DC—delicate, complex). XPL—cross polarized light; PPL—plain polarized light; ksp—potassium feldspar; dol—dolomite.

Barns and Laudise, 1985), so the rate of freezing (relative to natural systems) is also a variable, but not within our experimental design.

DISCUSSION

Interpretation of Usclas Formation Features as Ice-Crystal Traces

Empirical replication of the observed Usclas Formation morphologies using fully saturated mud beneath a film (≤1.5 mm thick) of water (with as much as 1% NaCl) corroborates the interpretation that these features represent ice-crystal molds. 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, higher-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

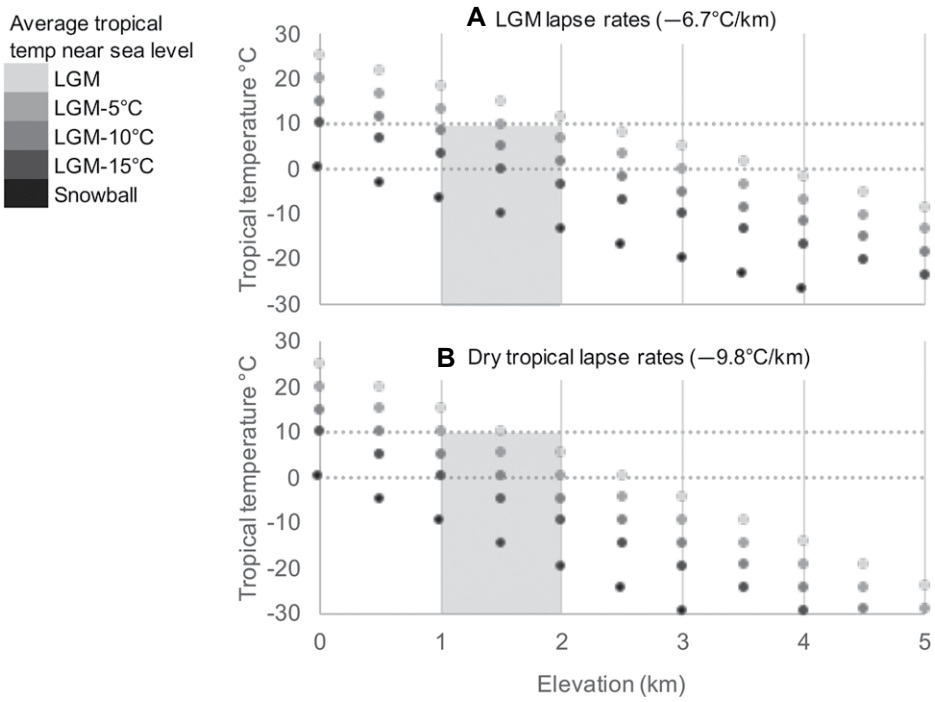

Figure 3. Plots of possible tropical temperature conditions in the Permian at different elevations using the same adiabatic lapse rate as the Last Glacial Maximum (LGM) (–6.7 °C/km; Loomis et al., 2017) (A) and "dry" tropical lapse rate (–9.8 °C/km; MacLennan et al., 2020) (B). Gray zone represents possible paleoelevations (within error) of the Lodève Basin at ca. 295 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).

ratio) are fluid saturation of the mud and water depth. Water chemistry also influences crystal shape, with more complex (curved, feathery, dendritic) forms (Fig. 2, morphology DC) resulting from dilute NaCl solutions (0.1%–1%). Previous observations of ice crystallization in both laboratory (e.g., Allan, 1926; Mark, 1932; Reineck, 1955) and natural settings (e.g., Figs. S2A–S2C; Table 1; Reineck and Singh, 1980) also emphasized the influence of water saturation of the host sediment on crystal size and morphology. Deposition of the Usclas Formation coincides with rapid subsidence (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, pyramidic 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.

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 paleoshorelines of the Usclas Formation lake, and is common in modern playa lakes in climates subject to freezing temperatures (e.g., Fig. S2C) 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 temperatures, or (2) assuming low elevations, markedly cooler equatorial conditions than even those of the Last Glacial Maximum (LGM). Perennial freezing conditions exist in the tropics today (with glaciers descending to ~4500 m elevation; Porter, 2001) and existed during the LGM (with glacial expansion to ~3500 m elevation, or very rarely, as low as 2400 m in high-precipitation regions; Kaser and Osmaston, 2002; Hastenrath, 2009). In the southern Massif Central, paleoelevations at the time of Usclas Formation deposition (ca. 295–290 Ma) can be approximated (1–2 km; Fig. 3) within the spatial and temporal bounds of existing data. The crustal thickness in the southern Massif Central ca. 308 Ma was ~45 km (~30 km of present-day Variscan crust plus ~15 km overburden removed by ca. 285 Ma; Rabin et al., 2015; Pfeifer et al., 2018). Assuming a ratio of 1:6 for isostatic compensation of thickening, this corresponds to an elevation of ~2500 m, but subsequent extensional subsidence to gravity collapse (300–290 Ma; Burg et al., 1994) would have further reduced the mean elevation of the Lodève Basin by ~500–1500 m (Sonder et al., 1987, Wolfe et al., 1998).

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 paleoclimatic change during this time. For example, LPIA climate simulation of peak icehouse conditions shows that pCO_2 <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 pCO_2 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-Carboniferous) record and calls for further investigation of evidence for anomalously cold equatorial temperatures and explanations thereof.

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