

# Paleohydraulics of cyclonic storm deposits suggest that the equatorial climate of Earth in the Pennsylvanian was not cold

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## ABSTRACT

Earth has experienced extreme past climates, and recent studies posit a controversial hypothesis that a cold global climate, including tropical low-altitude glaciation, existed in the Pennsylvanian Period. Paleohydraulic analysis of storm-generated, hummocky bedforms in shallow marine Pennsylvanian deposits of the Ancestral Rocky Mountains of Pangea allows for reconstruction of wave parameters, which reflect paleoclimate because physical marine conditions and ocean–atmospheric linkages are highly latitude- and temperature-dependent. The results indicate large waves and gale to hurricane strength winds of cyclonic storms, driven by high Coriolis vorticity and high sea-surface temperatures. These refute both published extremely low paleolatitude (<5°) estimates for the Colorado (USA) region, and the idea of a cold equatorial Pennsylvanian climate, the latter of which has profound implications for biological, geochemical, and oceanographic reconstructions.

## INTRODUCTION

The late Paleozoic ice age (LPIA), one of the most extreme glacial intervals of the Phanerozoic, profoundly influenced Earth's coupled atmospheric–oceanic–biological systems (Montañez and Poulsen, 2013). LPIA climate dynamics, including glacial–interglacial intervals, are an analog for Pleistocene glaciations and modern climate conditions. Prior to the mid-2000s, prevailing models suggested that a warm equatorial region coexisted with high-latitude glaciers during the Moscovian Stage (ca. 315–307 Ma; e.g., Angiolini et al., 2007). However, geologic evidence was used to support low-altitude glaciations at 500–1000 m, and episodic, widespread cold equatorial conditions (e.g., Soreghan et al., 2008a, 2008b). Estimates of low-latitude sea-surface temperatures (SSTs) for the Moscovian vary significantly. Vêrand and Veizer (2019), Scotese et al. (2021), and Song et al. (2019) provided  $\delta^{18}\text{O}$  estimates of  $\sim 10$ – $16$  °C, consis-

tent with a cold tropical region. However, recalibrations of these data yielded revised values of  $\sim 22$ – $26$  °C and  $14$ – $20$  °C for the latter two studies, respectively (Grossman and Joachimski, 2022). In addition, Chen et al. (2016; Fig. S1 in the Supplemental Material<sup>1</sup>) suggested temperatures of  $20$ – $22$  °C for the Moscovian, and Judd et al. (2024, their figure S20) proposed  $22$ – $27$  °C for the entire Pennsylvanian. All  $\delta^{18}\text{O}$  paleotemperature reconstructions support a Moscovian warming episode between two pulses of the LPIA (Montañez and Poulsen, 2013) (Fig. S1). If the warm SST temperatures are correct, the paleoequator would have been closer to modern values, contradicting geologic evidence used to support cold equatorial temperatures.

Much of the evidence for a cold equatorial climate comes from Colorado (USA), particularly from the Middle Pennsylvanian (Atokan to Desmoinesian  $\approx$  Moscovian) Fountain Formation, terrestrial deposits of the Ancestral Rocky Mountains of Pangea (Soreghan et al., 2008b; Sweet and Soreghan, 2008, 2010a, 2010b). We address the paleoclimate controversy with a new approach to paleoclimate reconstruction; namely, the state of the sea. This is a significant

paleoclimate indicator because the sea state and ocean–atmospheric linkages are highly latitude-dependent. Specifically, maximum wind speeds, and ultimately the size of surface gravity waves, of cyclonic storms are directly linked to SSTs and climatic gradients. We present an analysis of storm deposits in thin marine intervals within generally coarse-grained, alluvial through fan delta deposits of the Fountain Formation. We analyzed stratification produced by hummocky bedforms (i.e., hummocky cross stratification [HCS]), which form in storms, typically under high-energy, wave-dominated, combined flows. Our findings indicate SSTs exceeding  $26.5$  °C and storm systems requiring significant Coriolis vorticity, a combination irreconcilable with climate reconstructions and current paleolatitude estimates for the central Rocky Mountain region.

## GEOLOGIC SETTING AND STUDY AREAS

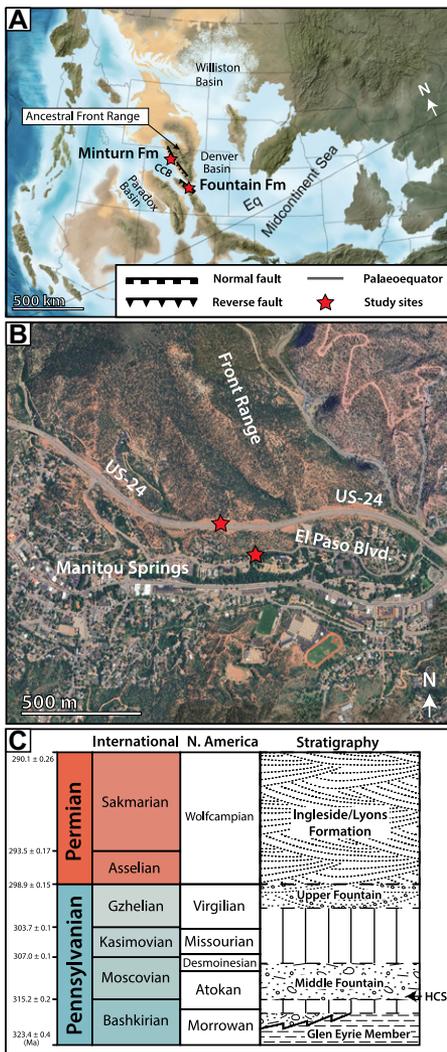
The Pennsylvanian Ancestral Rocky Mountain orogeny produced a series of highlands and basins within the western equatorial region of Pangea (Sweet and Soreghan, 2008, 2010b; Fig. 1A). The Ancestral Front Range uplift faced the mid-continental seaway to the east and the Central Colorado Basin to the west. Thick alluvial fan and fan-delta deposits prograded into these marine basins, including the  $\sim 600$ -m-thick Minturn Formation to the west (Maples and Suttner, 1990; Houck 1997; Myrow et al., 2008; Sweet and Soreghan, 2010b) (Fig. 1A), which was deposited during an eustatic rise (Inola transgression) in the early Desmoinesian (Houck, 1997). The formation contains an  $\sim 19$ – $35$ -m-thick prodeltaic unit of green silty shale and fine sandstone hyperpyc-

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<sup>1</sup>Supplemental Material. Section S1: Detailed paleohydraulic calculations. Section S2: Bedform boundary criteria. Section S3: Discussion of alternative gravity wave sources. Section S4: Discussion of geologic evidence for a cold tropical Pennsylvanian climate. Figures S1–S6 and Tables S1–S2. Please visit <https://doi.org/10.1130/GEOL.S.30888599> to access the supplemental material; contact [editing@geosociety.org](mailto:editing@geosociety.org) with any questions.

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**Figure 1. (A)** Pennsylvanian (Moscovian) paleogeography map of the western United States with uplifts and sedimentary basins (modified from Myrow et al. [2008], Sweet [2017], and Blakey and Ranney [2008]). Minturn Formation (Fm) and Fountain Formation locations are shown with the paleoequator (Eq). Palaeoequator data are provided in Table S2 (see footnote 1). CCB—Central Colorado Basin. **(B)** Fountain Formation study area near Manitou Springs, Colorado. **(C)** Pennsylvanian–Permian strata in Manitou Springs, Colorado. Black vertical lines in the stratigraphy indicate a depositional hiatus. Black arrow shows the stratigraphic position of the studied hummocky cross stratification (HCS) bed (modified from Sweet and Soreghan [2010a]).

nal flow deposits with HCS (Lamb et al., 2008; Myrow et al., 2008).

On the eastern side of the Ancestral Rocky Mountain Front Range, the Fountain Formation is locally >1400 m thick (Fig. 1A; Lamb et al., 2008). The ~575-m-thick lower and middle parts (Sweet and Soreghan, 2010b) record coalesced alluvial fans, braid plains, and fan delta environments (Suttner et al., 1984; Maples and Suttner, 1990; Sweet and Soreghan, 2010a, 2010b; Sweet, 2017). An ~18-m-thick, basal,

Morrowan to lower Atokan (Suttner et al., 1984) Glen Eyrie Member consists of shale, sandstone, and coal (Sweet and Soreghan, 2010a, 2010b; Fig. 1C). An unconformity separates the lower Fountain from the middle part, which is middle Atokan to late Desmoinesian (Moscovian) (Sweet and Soreghan, 2010b; Fig. 1C).

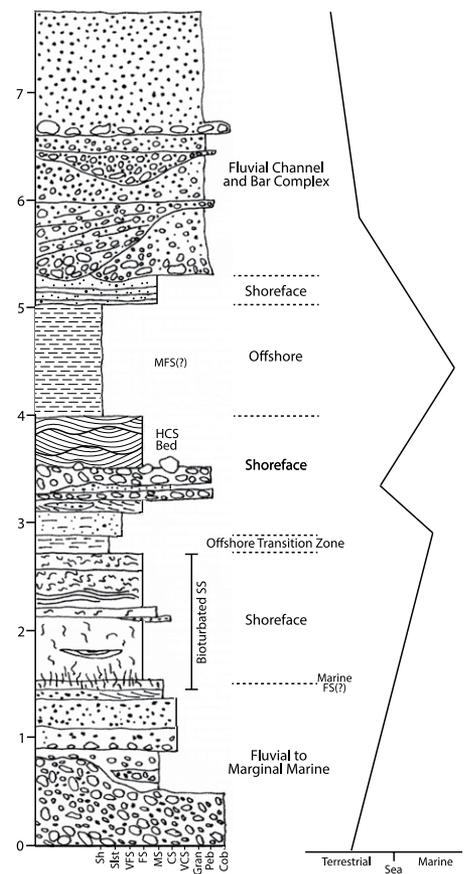
### HCS IN THE MINTURN AND FOUNTAIN FORMATIONS

HCS in the Minturn and Fountain Formations (Myrow et al., 2008; Sweet and Soreghan, 2010b) is used to constrain the sea state during storms for the Pennsylvanian units on both sides of the Ancestral Front Range. Myrow et al. (2008) described HCS in the Minturn Formation, on the west side of the Ancestral Front Range, which was deposited close to shore (<~30 m depth) but below the shoreface zone of the delta front (>10 m), in accordance with modern studies of shorefaces in various parts of the world (e.g., Valiente et al., 2019). Preserved hummocky bedforms have bedform spacing (i.e., crest-to-crest distance) that are generally >1 m and reach a maximum of ~2 m.

The lower and middle Fountain Formation, on the east side of the Ancestral Front Range, have a series of marine–nonmarine cycles with HCS beds (Maples and Suttner, 1990), including an interval exposed in the Manitou Springs area (Fig. 1B; ~76–82 m; Sweet and Soreghan, 2010b, their fig. 4) that rests ~16 m above the lower–middle member unconformity. It consists of thick, pebble-to-cobble conglomerate with lenticular channel forms and coarse lags, bioturbated and laminated sandstone, and silty shale (Fig. 2). An ~50-cm-thick, fine-grained (125 μm) sandstone bed with low angle (<20°), curved laminae and erosional surfaces typical of HCS directly overlies cobble conglomerate (Fig. 3) and contains a suite of marine trace fossils in its upper ~10 cm. This is one of six HCS beds noted by Sweet and Soreghan (2010b) in this part of the section. The bed preserves complete bedform geometries of the hummocky bedforms from which spacings of hummocks and swales were measured. The spacings range from 3.2 m to 3.92 m (Table S1 in the Supplemental Material). The bed was deposited in a shoreface above the offshore transition zone to mud, thus indicating a possible maximum depth of ~30 m (Valiente et al., 2019).

### PALEOHYDRAULIC ANALYSIS

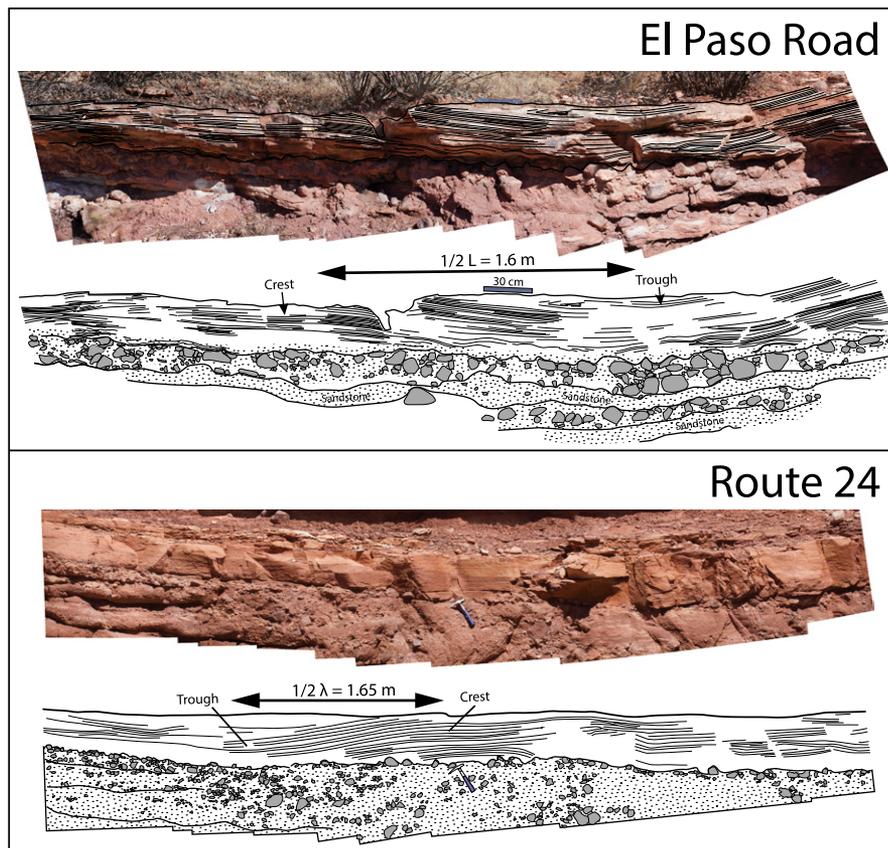
Using hummocky bedform spacings ( $\lambda = 2.0$  m for the Minturn Formation;  $\lambda = 3.2$  m for the Fountain Formation, a conservative minimum estimate), we applied Airy wave theory and the paleohydraulic workflow of Myrow et al. (2008) and Lamb et al. (2012) to estimate wave parameters—height  $H$  (m), period  $T$  (s), and wavelength (m)—using a



**Figure 2. Stratigraphic column and inferred relative sea-level curve of the studied Fountain Formation (Colorado, USA). HCS—hummocky cross stratification; Sh—shale; Sst—siltstone; VFS—very fine sandstone; FS—fine sandstone; MS—medium sandstone; CS—coarse sandstone; VCS—very coarse sandstone; Gran—granule; Peb—pebble; Cob—cobble; MFS—maximum flooding surface.**

semi-empirical wave-forecasting model (Coastal Engineering Research Center, 1984; Text S1) for fetch distances of 1–10,000 km and wind speeds of 1–100 m/s, under inferred water depths of 10–30 m (described above). By excluding breaking waves and capping  $T$  at fully developed seas, we define a solution space ( $H$  versus  $T$ ) for ocean surface gravity waves capable of generating orbital motions needed for the observed bedforms (Fig. 4A; Text S1).

The stability field of hummocky bedforms further reduces the range of possible wave parameter values. We used a grain size of 125 μm (determined from petrographic measurement) and the stability field equations to define bedform phases at specified depths as a function of fetch and wind speed (Fig. 4B; Text S1). The lower energy boundary is the ripple-to-hummocky bedform transition (Pedocchi and García, 2009), and the upper boundary is the transition to upper plane bed conditions, set with a Shields number of  $\theta = 3$ , as used by Lamb et al. (2012) (Text S1; Fig. S3).



**Figure 3. Photographs and sketches of the hummocky cross stratification (HCS) bed in the Fountain Formation along El Paso Road and U.S. Route 24 in Manitou Springs, Colorado (USA). The bed directly overlies an interval of clast-supported boulder conglomerate. Measured half-wavelength of the hummocky bedforms is 1.6 m ( $\lambda = 3.2$  m) at El Paso Road, and 1.65 m ( $\lambda = 3.3$  m) at U.S. Route 24. Hammer is 30 cm long.**

For the Fountain Formation, at 20 m depth, the waves would require wind speeds of  $\sim 27$ – $30$  m/s, which is close to the minimum wind speed of Category 1 hurricanes (33 m/s); at 30 m depth, the required wind speed is  $\sim 23$ – $38$  m/s (Fig. 4B). Maximum wind speeds (Fig. 4B) yield minimum fetch values, which for the Fountain Formation are  $\sim 174$  km for 30 m depth and  $\sim 596$  km for 20 m depth (Fig. 4B). At shallower depths, (i.e., 10 m) upper plane bed conditions dominate, precluding HCS. Using a paleogeographically constrained maximum fetch (500 km; Sweet and Soreghan, 2008, 2010b), minimum wave heights are 5.4–7.0 m with periods of 10.7–11.3 s. Minimum fetch values yield maximum wave heights of 5.5–7.9 m and minimum periods of 10.6–10.7 s (Table S1).

For the Minturn Formation, hummocky bedforms could develop under a wider range of wind speeds. At wind speeds of 33 m/s and 50 m/s (weak and medium-strength hurricanes; see Lamb et al., 2008), minimum fetches are  $\sim 126$  to  $\sim 36$  km, respectively. At these wind speeds, estimated minimum wave heights are 3.4–6.6 m. These estimates, alongside those for the Fountain Formation, align with near-hurricane or hurricane-strength winds. Collectively, the large waves and hurricane-strength winds

required for these bedforms in the Pennsylvanian deposits suggest formation during intense cyclonic storms (Myrow and Southard, 1996). Tsunami waves are dismissed because the Fountain strata lack any of the hallmark characteristics of tsunamites (Fujiwara and Kamataki, 2007; Text S3). Other alternative mechanisms (e.g., monsoons, trade winds) are dismissed as incapable of generating the necessary wave heights and periods (Text S3; Fig. 4A) for the meter-scale HCS observed in both formations. The Fountain Formation would have required significantly longer (up to an order of magnitude) fetch distances, under the same depth and wind speed conditions, since the possible orbital velocities approach the transition to upper plane bed (Fig. 4B). These fetch estimates for the Central Colorado Basin and Midcontinental Sea scale well with ocean basin sizes on paleogeographic maps (Fig. 1A).

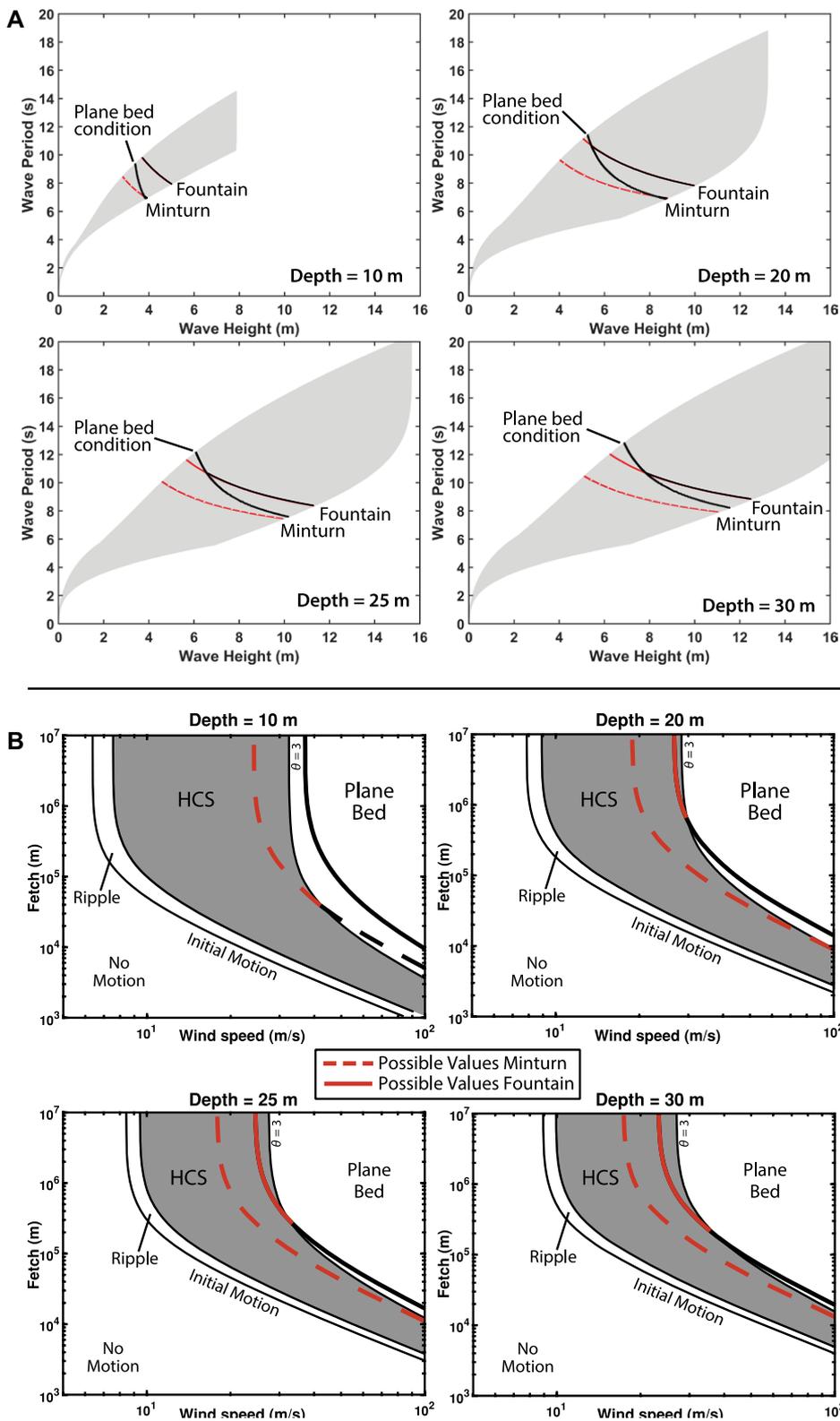
## DISCUSSION

Tropical cyclonic storms require suitable dynamic and thermal potentials (Gray, 1998), which exist at low latitudes and warm surface waters, and their intensities vary directly with SSTs (Cione and Uhlhorn, 2003). However, cyclones are exceptionally rare at latitudes

$< 5^\circ$  due to insufficient Coriolis-driven vorticity (Studholme et al., 2022; Fig. S2). Paleogeographic reconstructions place the Minturn Formation site at a maximum latitude of  $\sim 5^\circ\text{N}$  and the Fountain Formation site near the equator with an average of  $3.6^\circ\text{N}$  ( $\sigma = 0.63$ ) (Table S2). The paleolatitudinal data for the Fountain Formation are thus at odds with the existence of large cyclonic storms necessary for the deposition of HCS. We propose a higher-latitude position,  $> 5^\circ\text{N}$ , but  $< \sim 10^\circ\text{N}$  because the epicratonic seaway to the north was a confined, shallow basin (Fig. 1) that was only at  $\sim 10^\circ\text{N}$  latitude by the Middle Pennsylvanian (Text S3). This paleogeography rules out swell from extratropical storms outside the landlocked basin as a mechanism for HCS in the Fountain Formation.

Regarding thermal potentials for cyclonic storms, the case has been made for episodic and widespread cold conditions, including glaciation, regionally within the equatorial Ancestral Rocky Mountains of Pangea during the Pennsylvanian–Permian (e.g., Soreghan et al., 2008b). Reconstructions include glacier termini at 500–1000 m (Soreghan et al., 2008b; Sweet and Soreghan, 2010a) and intensely frozen ground close to sea level (Sweet and Soreghan, 2008). Counterarguments exist for many of these features. For instance, while thick ( $> 700$  m) Pennsylvanian loess deposits in the region have been linked to cold tropical climates (Soreghan et al., 2008a), similar deposits (up to 350 m) occur in temperate settings, e.g., China’s Loess Plateau, refuting the exclusive association to nearby glaciers. Additionally, high-strain quartz microtextures in the Fountain Formation, interpreted as evidence of till and glacial termini at  $\sim 1500$  m elevation (Sweet and Soreghan, 2010a), may instead reflect subcritical deformation. Such deformation occurs under low stresses in a variety of near-surface environments and is amplified by reduction in confining pressure, such as exhumation during the uplift of the Ancestral Rocky Mountains (Eppes and Keanini, 2017).

The strongest purported evidence for a Middle Pennsylvanian cold equatorial climate are polygonal fractures  $> 2$  m deep in braided river facies of the Fountain Formation that Sweet and Soreghan (2008) consider evidence of continuously frozen ground (i.e., permafrost;  $< 0^\circ\text{C}$  ground temperatures) and large diurnal temperature swings of  $10$ – $25^\circ\text{C}$  (see Text S4). A thermal crack origin requires that the cracks (and permafrost) developed “very near sea level” (Sweet and Soreghan, 2008, p. 201), a condition similar to a Snowball Earth scenario. Modern low-elevation permafrost in Alaska exists at latitudes  $> 60^\circ$  (Pastick et al., 2015), and SSTs off the Alaskan coast at these latitudes are  $< 10^\circ\text{C}$  (NOAA). Such SSTs are  $\sim 2.5\times$  lower than all recent estimates for the entire Pennsylvanian ( $20$ – $27^\circ\text{C}$ ; Chen et al., 2016; Grossman



**Figure 4.** (A) Modeled wave height (m) and wave period (s), under water depths of 10, 20, 25, and 30 m using wave-forecasting model (Coastal Engineering Research, 1984) (Text S1). Gray shaded area represents all possible combinations generated from a range of fetch distances (1–10,000 km) and wind speeds (1–100 m/s), constrained by wave-breaking and fully-developed-sea criteria. Combinations of wave heights and periods that would produce orbital diameter estimates for the HCS of the Fountain (solid red) and Minturn formations (dashed red) are constrained by the boundary between upper plane bed and hummocky bedforms. (B) Modeled fetches (m) and wind speeds (m/s) under water depths of 10, 20, 25, and 30 m, necessary to produce waves with estimated orbital diameters for the hummocky bedforms in the Fountain (solid red) and Minturn (dashed red) formations. Outside of the shaded region, HCS bedforms will not form. See Text S2 for additional information.

tion, but the close stratigraphic proximity of HCS and purported permafrost cracks within the lower Fountain makes such an explanation unrealistic. Alternative explanations for the cracks exist, and we believe that one of the “crack” horizons represents spheroidal weathering by reducing fluids along tectonic fractures (Text S4).

Our paleohydraulic analysis of large-scale HCS in the Pennsylvanian strata of Colorado indicates that there were large cyclonic storms in the oceans bordering either side of the Ancestral Rocky Mountain uplifts. These storms, which required warm SSTs, align with recent estimates of Pennsylvanian SSTs (~20–27 °C; Judd et al., 2024) and the timing of the Fountain Formation’s deposition during the early part of a warm interval between the two pulses of the LPIA (Montañez and Poulsen, 2013). The existence of such storms is contradictory to both published low paleolatitude positions and a cold equatorial climate scenario with low tropical SSTs proposed over the past two decades. Thus, our data provide an independent line of evidence that indicates warm LPIA tropical conditions.

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and Joachimski, 2022; Judd et al., 2024), and are incompatible with cyclonic storms, tropical or extratropical, particularly hurricanes, which form at SSTs of >26.5 °C (Tory and Dare, 2015) and upwelling of hot air masses (Studholme et al., 2022). Even during the Ordovician Hirnantian glaciation, one of the coldest

Phanerozoic intervals, tropical SSTs remained at 22–28 °C (Finnegan et al., 2011), close to those of waters off the present-day middle to southern Atlantic coast of North America. One could argue for extremely large temperature fluctuations over short time scales to explain the geologic evidence in the Fountain Forma-

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