RESEARCH FOCUS

Wastelands of tropical Pangea: High heat in the Permian

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We study the sedimentary record to gain perspective on the range of environmental conditions through Earth's history. Lithology, internal organization, fossil content and composition are used to reconstruct depositional environments, guided by a uniformitarian-approach: physical laws that command Earth systems today have not changed through time. Most Phanerozoic continental sediments indicate surface conditions within the range of modern Earth. This is intuitively obvious, for the fossil record documents vertebrate and plant life on land at least since the Silurian (ca. 440 Ma), and environmental conditions never went outside the limits where these can survive. Occasionally the sedimentary record preserves evidence for conditions too extreme for complex life, outside the modern range. Extraordinarily harsh climatic conditions are documented by Zambito and Bennison (2013, p. 587 in this issue of *Geology*), who use fluid inclusion homogenization temperatures (T_h) in uppermost Lower Permian (ca. 270 Ma) halite beds of the Nippewalla Group (Kansas, United States) as proxies for surface air temperatures. The region was then in the tropics. Average T_h values rise from those typical for the modern tropics (~26 °C) near the base of the Nippewalla Group, to ~40–45 °C in its lower and middle parts, then return to typical values of 21–33 °C toward its top. The zone of peak average T_h includes maximum values of >70 °C, and diurnal variability of >30 °C, both more extreme than recorded on Earth today. Evidence for extremely high surface temperatures during deposition of the Nippewalla Group provides a better understanding of some of the peculiar aspects of the Permian terrestrial record in western tropical Pangea, but also presents paradoxical paleoclimate problems, which can be appreciated only within the broader context of Permian–Carboniferous (P-C) sediments, soils, and plant and animal fossil assemblages.

During the late Paleozoic, the continents were grouped into two large landmasses: Laurasia, moving southward on the Northern Hemisphere, and Gondwana, moving northward on the Southern Hemisphere. At ~340–320 Ma (Early Carboniferous), they collided near the equator to form Pangea (Scotese et al., 1979). Around this time, climate cooled, with continental ice-sheet development documented by proxies collected at high paleolatitudes (near-field) and low paleolatitudes (far-field). There may have been multiple centers of ice-sheet growth, and retreats of variable extent and duration (Isbell et al., 2012). Beginning in the mid-Carboniferous (ca. 327 Ma), ice sheets grew from small centers, reached their acme in the Late Carboniferous–Early Permian (ca. 303–290 Ma), then shrunk again to small ice centers until the end of the "ice house" in the Late Permian (ca. 260 Ma; Fielding et al., 2008). Comparisons between near- and far-field glacial indicators and associated paleoclimate patterns are hampered by a lack of accurate correlations.

Long-term, "classical" Pennsylvanian–Permian sedimentary indicators of paleoenvironments and paleoclimate in terrestrial strata indicate that (1) in the Pennsylvanian, Euramerica had predominant humid, ever-wet "swampy" environments in which vast coal deposits formed; (2) dryer and seasonal, fluvial-dominated, depositional conditions prevailed in the Early Permian, when the red-bed deposits across the central United States formed; and (3) in the late Early Permian, deposits formed under arid eolian-dominated conditions, with locally arid climates that included wet sabkha and playa depositional environments now exposed in the High Plains and Mountain West of the United States. Not all paleotropical basins preserve the entire lithostratigraphic trend, but long-term (10^6–10^7 yr) Pennsylvanian–Permian aridification was complete by the late Early Permian (ca. 270 Ma; Tabor and Poulsen, 2008).

The morphology and chemistry of paleosols are sensitive indicators of paleoclimate. Generally, in tropical western Euramerica (Kessler et al., 2001; Mack, 2003**;** Tabor et al., 2008; DiMichele et al., 2010), (1) Upper Pennsylvanian paleosols include histosols (i.e., coal), argillisols, and spodosols indicating humid, ever-wet conditions, as well as vertisols and calcic vertisols that indicate soil moisture deficiency and seasonal precipitation; (2) sub-humid seasonal climate in earliest Early Permian (vertisols and calcic vertisols) changed to a semi-arid to arid climate (calcisols and gypsisols) in latest Early Permian time; and (3) climate was dryer in the northern (e.g., the Eagle Basin of Colorado) than in the southern basins (e.g., the Midland Basin of Texas), possibly related to zonal climate differences. Even in the more-humid southern basins of North America, well-developed paleosols essentially disappear in the upper Lower Permian, indicating unfavorable conditions for soil development and plant growth. Paleosol mineral $\delta^{18}O$ and δD values in western Euramerica indicate surface temperatures ranging from relatively cool (~22 ± 3 °C) in the Late Pennsylvanian to substantially warmer (~35 ± 3 °C) from the P-C boundary through Early Permian (Tabor, 2007). Warming across the P-C boundary may have affected fossil floras in tropical western Euramerica (DiMichele et al., 2006).

Long-term floral change in western tropical Euramerica records a prolonged, stepped, trend: (1) Late Mississippian through Middle Pennsylvanian coal swamps were dominated by lycopsids, pteridosperms, and tree ferns, forming wetland ecosystems; (2) in the Late Pennsylvanian (ca. 306–304 Ma), opportunistic tree ferns and pteridosperms became dominant in response to intensified seasonality (DiMichele et al., 2010); (3) the wetland biome was intercalated with a biome dominated by conifers, callipterids, and other seed plants resistant to prolonged periods of dryness during glacial-interglacial cycles (DiMichele et al., 2006); (4) the seasonally dry biome became dominant near the P-C boundary, but cyclic alternation of wet-dry biomes continued through the Lower Permian, with progressively more drought-tolerant assemblages; (5) a macrofloral hiatus in upper Lower Permian strata is coeval with sedimentary indicators of aridity; and (6) a depauperate, drought-resistant and conifer-dominated flora appeared above this hiatus, with its elements otherwise known only from the Late Permian and Mesozoic of Europe (DiMichele et al., 2001).

Pennsylvanian–Early Permian terrestrial tetrapods are best known from western tropical Euramerica. After the Carboniferous rainforests collapsed, endemism and increased tetrapod diversity developed during the Late Pennsylvanian and Early Permian (Sahney et al., 2010). Tetrapod diversity remained high up to the late Early Permian, but a tetrapod record is essentially absent in younger strata of western tropical Euramerica, after a major collapse of amphibians and basal synapsids in the tropics which has been named "Olson's extinction" (Benton, 2012). Thereafter, tetrapods in mid- to high-paleolatitude basins in South Africa and Russia are dominated by therapsids. There is no marine extinction corresponding to Olson's extinction and the Early Permian tropical terrestrial biome collapse.

Permian amphibians were likely ectothermic, but it is unclear whether Permian synapsids were endothermic or ectothermic (Ruben, 1995). Modern large ectotherms (crocodilians, varanids) do not survive sustained temperatures in excess of 40–45 °C (Spellerberg, 1972). Terrestrial endotherms (birds and mammals) experience facultative hyperthermia and death at sustained temperatures of 41–46 °C (e.g., Adolph, 1947). At

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temperatures above 35–40 °C, most modern plants experience protein denaturation, malformed cellular membranes, and greatly diminished CO_2 uptake (Daniell et al., 1969). Woody C_3 plants such as the xeromorphic Permian floras in the western tropics (Montañez et al., 2007) are especially sensitive to the effects of diminished CO_2 uptake at high temperatures (Berry and Downton, 1982). Seedlings of the most drought-tolerant conifers have threshold temperatures (~63 °C; Kolb and Robberecht, 1996) that could not survive the temperatures implied by the T_h values in Zambito and Benison (2013).

In conclusion, lithological, paleopedogenic, and paleontological data define a P-C trend toward increased aridity, completed by late Early Permian, with conditions exceedingly unfavorable for complex life in terrestrial basins of western tropical Euramerica during the latest Early Permian. Zambito and Benison show exceedingly high temperatures may have been part of these conditions, and lethal temperatures are particularly useful in framing the significance of their high T_h values. Precise chronometric correlation among the terrestrial basins of western tropical Pangea is not yet possible, and it is unclear whether the extreme T_h values reported by Zambito and Benison reflect regional surface temperatures. However, extremely high surface air temperatures over the western tropical basins of Euramerica would provide environmental forcing for the observed collapse of the seasonally dry plant biome and extirpation/extinction of amphibians and synapsids near the end of the Early Permian.

Zambito and Benison provide ancient climate dynamics that are typically neither captured by other proxies (e.g., Tabor and Poulsen, 2008) nor considered at such time scales (e.g., Peyser and Poulsen, 2008). If the T_h values correspond to seasonal high temperatures, the results have important implications for the Permian "ice house." Surface air temperatures of ~40–45 °C in the area of deposition of the Nippewalla Group halite at a paleolatitude of ~10° would correspond to seasonal temperatures well above freezing at the Permian poles. Either the Permian equator-to-pole temperature gradient was significantly larger than the modern gradient of ~0.4 °C per degree of latitude, or there were distinct non-glacial episodes during the Early Permian (Isbell et al., 2012).

The mechanisms responsible for such high surface air temperatures in the low-latitude tropics are not known, but the paleoclimatic pattern is similar to that modeled in Early Permian general circulation models, including a substantial rise in atmospheric CO_2 (Peyser and Poulsen, 2008; Paulsen et al., 2007). Those scenarios indicate that the western tropics should have become increasingly dry and arid in response to higher atmospheric CO_2; an intriguing twist offered by Zambito and Benison is that the arid tropics were at times very wet (albeit saline).

REFERENCES CITED

Adolph, E.F., 1947, Tolerance to heat and dehydration in several species of mammals: The American Journal of Physiology, v. 151, p. 564–575.

Benton, M.J., 2012, No gap in the Middle Permian record of terrestrial vertebrates: Geology, v. 40, p. 339–342, doi:10.1130/G32669.1.

Berry, J.A., and Downton, J.S., 1982, Environmental regulation of photosynthesis, *in* Gindgee, ed., Photosynthesis: Development, Carbon Metabolism and Plant Productivity: New York, Academic Press, p. 263–343.

Daniell, J.W., Chappell, W.E., and Couch, H.B., 1969, Effect of sublethal and lethal temperatures on plant cells: Plant Physiology, v. 44, p. 1684–1689, doi:10.1104/pp.44.12.1684.

DiMichele, W.A., Mamay, S.H., Chaney, D.S., Hook, R.W., and Nelson, W.J., 2001, An Early Permian Flora with Late Permian and Mesozoic Affinities from North-Central Texas: Journal of Paleontology, v. 75, p. 449–460, doi:10.1666/0022-3360(2001)075<0449:AEPFWL>2.0.CO;2.

DiMichele, W.A., Tabor, N.J., Chaney, D.S., and Nelson, W.J., 2006, From wetlands to wet spots: Environmental tracking and the fate of Carboniferous elements in Early Permian tropical floras, *in* Greb, S.F., and DiMichele, W.A., eds., Wetlands through time: Geological Society of America Special Paper 399, p. 223–248.

DiMichele, W.A., Cecil, C.B., Montanez, I.P., and Falcon-Lang, H.J., 2010, Cyclic changes in Pennsylvnianian paleoclimate and effects on floristic dynamics in tropical Pangea: International Journal of Coal Geology, v. 83, p. 329–344, doi:10.1016/j.coal.2010.01.007.

Fielding, C.R., Frank, T.D., Birenheier, L.P., Rygel, M.C., Jones, A.T., and Roberts, J., 2008, Stratigraphic imprint of the Late Palaeozoic ice age in eastern Australia: A record of alternating glacial and nonglacial climate regime: Journal of the Geological Society of London, v. 165, p. 129–140.

Isbell, J.L., Henry, L.C., Gulbranson, E.L., Limarino, C.O., Fraiser, M.L., Koch, Z.J., Ciccioli, P.L., and Dineen, A.A., 2012, Glacial paradoxes during the late Paleozoic ice age: Evaluating the equilibrium line altitude as a control on glaciation: Gondwana Research, v. 22, p. 1–19, doi:10.1016/j.gr.2011.11.005.

Kessler, J., Soreghan, G., and Wacker, H., 2001, Equatorial aridity in Western Pangea: Lower Permian Loessite and Dolomitic Paleosols in northeastern New Mexico, USA: Journal of Sedimentary Research, v. 71, p. 817–832.

Kolb, P.F., and Robberecht, R., 1996, High temperature and drought stress effects on survival of Pinus ponderosa seedlings: Tree Physiology, v. 16, p. 665–672, doi:10.1093/treephys/16.8.665.

Mack, G.H., 2003, Lower Permian Terrestrial paleoclimateic indicators in New Mexico and their comparison to Paleoclimate Models, *in* Lucas, S.G., et al., eds., New Mexico Geological Society Fall Field Conference Guidebook 54—Geology of the Zuni Plateau: Socorro, New Mexico, New Mexico Geological Society p. 231–240.

Montañez, I.P., Tabor, N.J., Niemeier, D., DiMichele, W.A., Frank, T.D., Fielding, C.R., and Isbell, J.L., 2007, CO_2-Forced Climate and Vegetation Instability during Late Paleozoic Deglaciation: Science, v. 315, p. 87–91, doi:10.1126/science.1134207.

Peyser, C.E., and Poulsen, C.J., 2008, Controls on Permo-Carboniferous precipitation over tropical Pangaea: A GCM sensitivity study: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 268, p. 181–192, doi:10.1016/j.palaeo.2008.03.048.

Poulsen, C.J., Pollard, D., Montanez, I.P., and Rowley, D., 2007, Late Paleozoic tropical climate response to Gondwanan deglaciation: Geology, v. 35, p. 771–774, doi:10.1130/G23841A.1.

Ruben, J., 1995, The evolution of endothermy in mammals and birds: from physiology to fossils: Annual Review of Physiology, v. 57, p. 69–95, doi:10.1146/annurev.ph.57.030195.000441.

Sahney, S., Benton, M.J., and Falcon-Lang, H.J., 2010, Rainforest collapse triggered Carboniferous tetrapod diversification in Euramerica: Geology, v. 38, p. 1079–1082, doi:10.1130/G31182.1.

Scotese, C.R., Bambach, R.K., Barton, C., Van der Voo, R., and Ziegler, A.M., 1979, Palaeozoic base maps: The Journal of Geology, v. 87, p. 217–277, doi:10.1086/628416.

Spellerberg, I.F., 1972, Temperature tolerances of southeast Australian reptiles examined in relation to reptile thermoregulatory behaviour and distribution: Oecologia, v. 9, p. 23–46, doi:10.1007/BF00345241.

Tabor, N.J., 2007, Permo-Pennsylvanian Palaeotemperatures from Fe-Oxide and phyllosilicate $\delta^{18}O$ values: Earth and Planetary Science Letters, v. 253, p. 159–171, doi:10.1016/j.epsl.2006.10.024.

Tabor, N.J., Montañez, I.P., Scotese, C.R., Mack, G.H., and Poulsen, C.J., 2008, Paleosol archives of environmental and climatic history in paleotropical western Euramerica during the latest Pennsylvanian through Early Permian, *in* Fielding, C.R., et al., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper 441, p. 291–304.

Tabor, N.J., and Poulsen, C.J., 2008, Late Paleozoic tropical climate and atmospheric circulation: A review of paleoclimate indicators and models: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 268, p. 181–192, doi:10.1016/j.palaeo.2008.03.052.

Zambito, J.J., IV, and Benison, K.C., 2013, Extreme high temperatures and paleoclimate trends recorded in Permian ephemeral lake halite: Geology, v. 41, p. 587–590, doi:10.1130/G34078.1.

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