GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G46419.1

Manuscript received 19 April 2019
Revised manuscript received 26 July 2019
Manuscript accepted 14 August 2019

Published online 6 September 2019

The Aspen paleoriver: Linking Eocene magmatism to the world's largest Na-carbonate evaporite (Wyoming, USA)

Alexander P. Hammond[1], Alan R. Carroll[1], Ethan C. Parrish[1], M. Elliot Smith[2] and Tim K. Lowenstein[3]
[1]Department of Geoscience, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA
[2]School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA
[3]Department of Geological Sciences and Environmental Studies, Binghamton University, Binghamton, New York 13902, USA

ABSTRACT

Deposition of trona, nahcolite, and other Na-carbonate evaporite minerals in lakes is commonly closely associated with active volcanism, suggesting that the excess alkalinity required for their formation may arise from fluid-rock interactions involving hydrothermal waters that contain magmatic CO_2. Paradoxically, the world's largest Na-carbonate occurrence, contained within the Eocene Green River Formation in Wyoming, USA, was not associated with nearby active magmatism. Magmatism was active ~200 km southeast in the Colorado Mineral Belt, however, suggesting that a river draining this area could have supplied excess alkalinity to Eocene lakes. Sedimentologic studies in southwestern Wyoming, along the course of the hypothesized Aspen paleoriver, document fluvial and deltaic sandstone with generally northwest-directed paleocurrent indicators. Sandstone framework grain compositions and detrital zircon ages are consistent with derivation from the Colorado Mineral Belt and its host rocks. These results provide the first confirmation of a fluvial connection to downstream Eocene lakes, and indicate that lake deposits may offer a unique perspective on upstream magmatic and hydrothermal histories.

INTRODUCTION

Large endorheic lakes commonly serve as terminal sinks for regional- to subcontinental-scale rivers. The Great Salt Lake in Utah (United States), for example, receives its largest surface inflow from the Bear River, which has headwaters ~560 km upstream in the Uinta Mountains. The Aral Sea in central Asia receives drainage from the Amu Darya and Syr Darya rivers, both of which flow >2000 km from their headwaters in the Pamir Mountains and Tian Shan, respectively. Lake deposits therefore offer unique, high-resolution stratigraphic archives of past tectonic, magmatic, climatic, and biotic processes, integrated across larger watersheds.

Lacustrine evaporite facies can be especially instructive because they convolve information about drainage networks, climate, and influent water chemistry. Sodium-carbonate evaporite occurrences are comparatively rare (Warren, 2010), in part because they evolve from unusual parent waters in which $[HCO_3^- + CO_3^{2-}]$ initially exceeds $[Ca^{2+} + Mg^{2+}]$ (Hardie and Eugster, 1970). The origin of this excess alkalinity is subject to debate. Waters with elevated Na^+ and HCO_3^- can originate from weathering of volcanic rocks or volcaniclastic sediments via silicate hydrolysis (Jones, 1966), but many evaporative lakes associated with such rocks are not alkaline and do not precipitate Na-carbonate minerals (Earman et al., 2005). CO_2 produced through microbial or thermogenic degradation of sedimentary organic matter could also increase alkalinity, but such mechanisms have not created hyperalkalinity in modern lakes (Lowenstein et al., 2017).

Earman et al. (2005) argued that subsurface fluid-rock interaction caused by injection of magmatic CO_2 into groundwater is critical for generating the alkalinity required to precipitate Na-carbonate evaporite. However, the largest known deposit superficially appears to contradict this hypothesis. Trona (a non-marine evaporite, $Na_2CO_3{\cdot}NaHCO_3{\cdot}2H_2O$) in the Eocene Green River Formation in Wyoming (United States) accounts for ~90% of global commercial soda ash reserves (Bolen, 2018), but is not associated with evidence for nearby, coeval volcanism (Smith et al., 2008b; Chetel et al., 2011). A potential resolution of this paradox would be that the Green River Formation lakes were indirectly influenced by river transport of alkalinity from a distant magmatic center. Trona deposits at Searles Lake in California (United States) offer a potentially useful Quaternary analogue. Fluid-rock interactions occur during hydrothermal circulation through igneous and metamorphic rocks in the western Long Valley caldera, ~300 km to the north. These waters emerge as thermal springs enriched in Na^+ and HCO_3^- (Sorey, 1985; Farrar et al., 1987), which were transported to Searles Lake via surface drainage (Earman et al., 2005; Lowenstein et al., 2016).

The Absaroka and Challis volcanic provinces in Wyoming and Idaho, respectively, lie to the north of the Green River Formation, but neither appears to have drained into Eocene lakes during evaporite deposition (Chetel et al., 2011). Lowenstein et al. (2017) instead hypothesized that the Colorado Mineral Belt (CMB), a large magmatic and hydrothermal province ~200 km southeast of Eocene Lake Gosiute (Wyoming; Fig. 1), could have supplied excess alkalinity. Smith et al. (2014) previously proposed such a paleoriver and named it after the town of Aspen, Colorado, but its existence has remained conjectural until now. Our study presents new sedimentological and provenance data that test the hypothesized fluvial connection between the CMB and Lake Gosiute.

GEOLOGIC SETTING

The Green River Formation was deposited by freshwater to hypersaline lakes that occupied the segmented Laramide foreland east of the Sevier fold-and-thrust belt, in what is now Wyoming, Colorado, and Utah (Dickinson et al., 1988; Smith et al., 2008b; Fig. 1). Recent studies

CITATION: Hammond, A.P., et al., 2019, The Aspen paleoriver: Linking Eocene magmatism to the world's largest Na-carbonate evaporate (Wyoming, USA): Geology, v. 47, p. 1020–1024, https://doi.org/10.1130/G46419.1

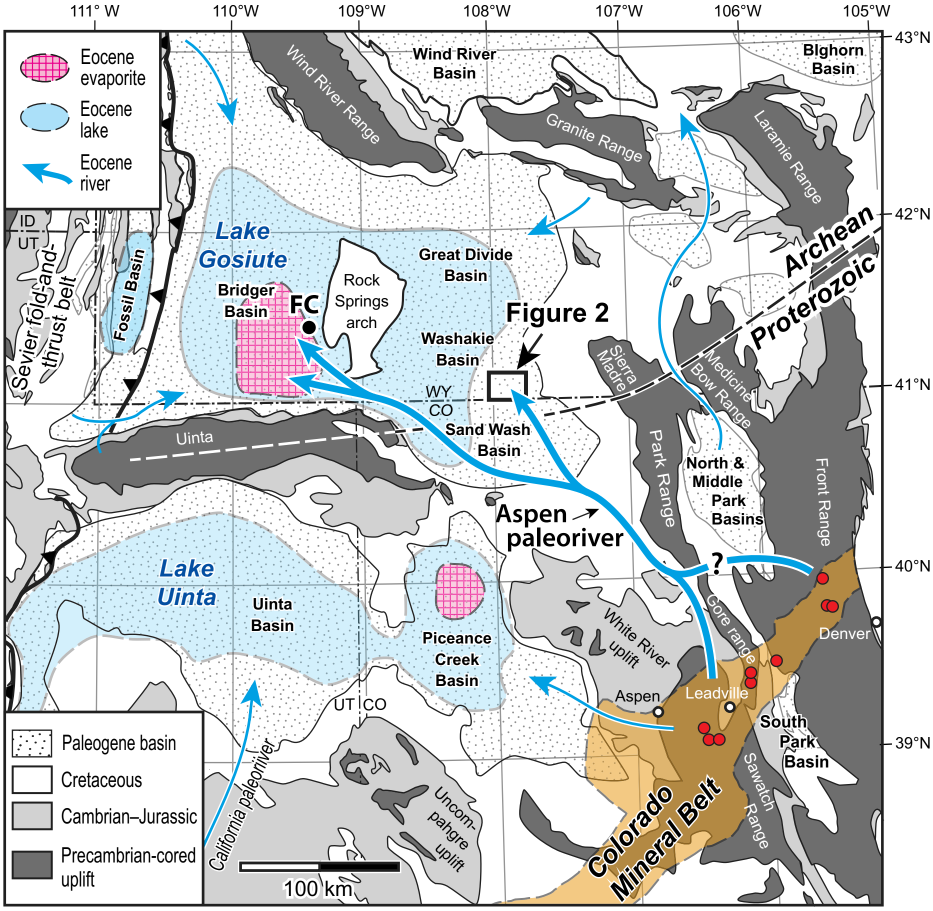

Figure 1. Schematic paleogeography of the western United States at ca. 51 Ma (modified from reconstructions of Smith et al., 2008b, 2014). Dashed line denotes approximate boundary between the Archean Wyoming province and Proterozoic terranes to the south. Red circles are areas with reported radioisotopic age determinations falling within analytical uncertainty of 51 Ma (Klein et al., 2010). FC—Firehole Canyon locality; ID—Idaho; UT—Utah; WY—Wyoming; CO—Colorado.

have demonstrated that the lakes received drainage from regional paleorivers as long as 700 km (Davis et al., 2010; Chetel et al., 2011; Dickinson et al., 2012). Intercalated volcanic tuffs establish a detailed chronology of evaporite deposition (Smith et al., 2008b). The giant Na-carbonate evaporite deposits in Wyoming occur principally within the Wilkins Peak Member in the Bridger Basin, which was deposited by Lake Gosiute between ca. 51.6 and 49.8 Ma.

Wilkins Peak Member facies initially extended across the Bridger Basin and into parts of the Great Divide, Washakie, and Sand Wash Basins. Alluvial facies of the Cathedral Bluffs Tongue of the Wasatch Formation subsequently filled the eastern basins (Smith et al., 2014; Fig. 1). Arkosic alluvial sediment was also deposited episodically across the Bridger Basin during major lake lowstands that recurred on an ~100 k.y. eccentricity time scale (Pietras and Carroll, 2006; Aswasereelert et al., 2013). The resultant deposits are informally designated "marker beds" A–I. They typically range from medium-grained sandstone to siliciclastic mudstone. Each of these marker beds progressively thins, becomes finer-grained, and eventually disappears going from south to north.

The CMB is an ~500-km-long southwest-northeast–trending mosaic of stocks, laccoliths, sills, dikes, and hydrothermal mineral deposits emplaced from ca. 75 to 0 Ma (Fig. 1; Bookstrom, 1990; Klein et al., 2010). Laramide plutonic rocks range in composition from alkaline monzonites and quartz monzonite in the northeast, to calc-alkaline granodiorite in the central CMB. The CMB crosscuts older southeast-northwest–oriented structural trends, and its origin is enigmatic. Chapin (2012) attributed it to dilation of a segment boundary within the underlying, subhorizontally subducting Farallon plate. Igneous ages generally young to the southwest, but few radioisotopic data have been reported for hydrothermal minerals themselves. The detailed timing of hydrothermal activity is therefore based largely on cross-cutting geologic relationships, and in some cases on fission-track annealing ages of apatite and zircon in host rocks (e.g., Bryant et al., 1990). Ages that potentially overlap that of the deposition of the Wilkins Peak Member appear to be limited to the northeastern segment of the CMB (Klein et al., 2010; Fig. 1).

PALEORIVER DEPOSITS IN THE WASHAKIE BASIN

Cathedral Bluffs Tongue sedimentary facies in the southern Washakie Basin (Fig. 2) may be broadly subdivided into three associations. (1) Carbonate-rich, kerogenous mudstone facies containing ostracods occur near the base of the Cathedral Bluffs Tongue, and are interpreted to record profundal to sublittoral lacustrine deposition during expansions of Eocene Lake Gosiute. (2) In contrast, silty red and green mudstone facies are carbonate poor and contain paleosols, desiccation cracks, and carbonaceous debris. They are interpreted as floodplain deposits. (3) Sandstone facies encompass amalgamated beds 1–17 m thick, which are laterally discontinuous over scales of hundreds of meters. Grain size ranges from fine to very coarse sand, with occasional layers of pebbles up to 1 cm in diameter. Bed bases in some cases contain mudstone intraclasts, which are associated with channel scour. Sedimentary structures include planar-parallel lamination, climbing ripples, and trough crossbeds with amplitudes up to 15 cm. Tabular crossbeds reach amplitudes up to 2 m, and shingled sigmoidal bedforms reach 1–3 m. The sandstone facies association is interpreted to represent fluvial to deltaic deposition. The sigmoidal bedforms are interpreted as laterally accreting bars, and 2-m-amplitude tabular crossbeds at one site (Sand Creek delta) are interpreted as downstream-accreting delta foresets. Measured paleocurrent directions based on trough and tabular crossbeds are bimodal in the Wasatch Formation main body (Red Creek site), with modes indicating southeast and northwest transport. The significance of this bimodality is unclear, but it may reflect deposition by higher-sinuosity streams. In contrast, vector mean paleocurrent directions are consistently to the west or northwest in the Cathedral Bluffs Tongue (Fig. 2).

Sandstone consists of subangular, poorly sorted arkose to lithic arkose, dominated by monocrystalline quartz and potassium feldspar, which average 50% and 29% of framework grains, respectively. Lithic fragments average 13% of the framework grains, of which 65% are sedimentary, 21% are volcanic, and 14% metamorphic. Detrital zircon U-Pb age distributions are broadly similar in all six samples in this study. Relatively few Archean grains are present in any of the samples; they compose 3.5% of the Wasatch Formation main body sample and <2% of all other samples. All samples exhibit age peaks at 1760–1770 Ma, 1670–1680 Ma, and ca. 1430 Ma, although their relative magnitude varies. Grains with ages of 900–1200 Ma are also present in all samples, but are minor in the Cathedral Bluffs Tongue. All samples also contain

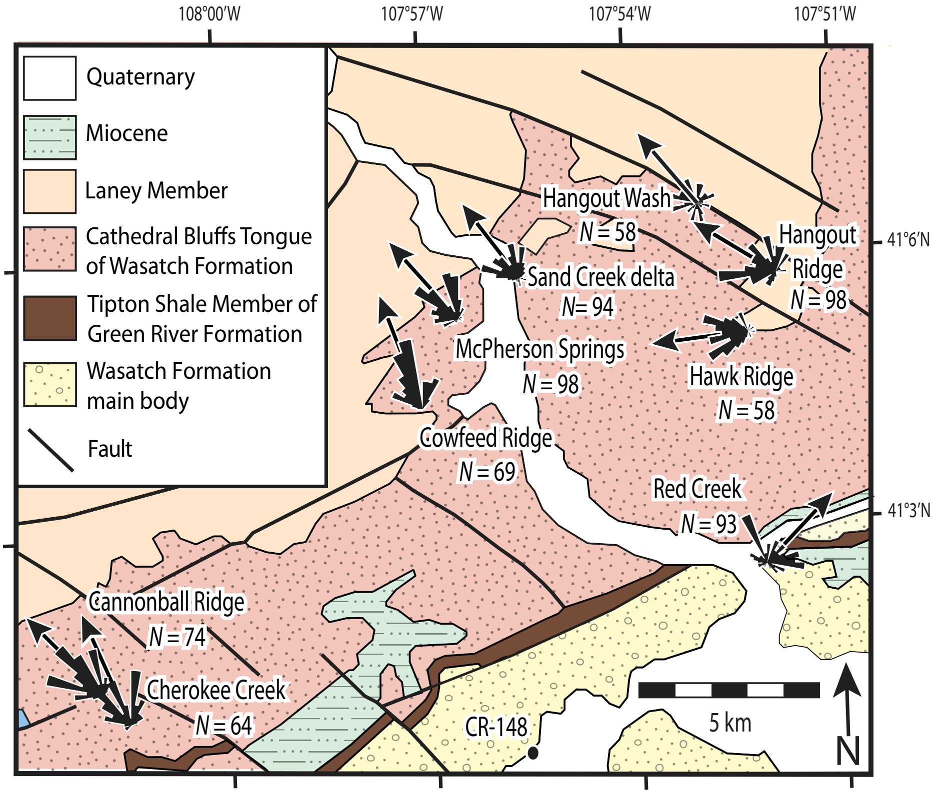

Figure 2. Geologic map of the study area showing geologic formations, faults, paleocurrent rosettes, and mean vector paleocurrent direction at nine locations in the southern Washakie Basin (Wyoming, USA; see Fig. 1 for location). Formations and faults are adapted from Love and Christiansen (1985); see Figure DR1 in the Data Repository[1] for measured sections. Total of 707 paleocurrent measurements were made from planar and trough crossbeds. CR-148—County Road 148 locality.

subordinate 75–500 Ma grains, in approximately equal proportion to the 900–1200 Ma grains. Finally, all samples exhibit multiple peaks <75 Ma. These grains compose ~5% of the Wasatch Formation main body sample and 14%–15% of the Cathedral Bluffs Tongue and Wilkins Peak Member samples. Their detailed distribution varies, but the most prominent peak in all samples occurs at 56–59 Ma.

DISCUSSION AND CONCLUSIONS

Fluvial facies with west- to northwest-directed paleocurrents clearly attest to a paleoriver (or rivers) that entered the Washakie Basin from the southeast. We infer that river transport expanded further west during ~100 k.y. lowstands of Lake Gosiute, crossing the southern end of the Rock Springs arch and depositing finer-grained siliciclastic sediment downstream in the Bridger Basin. The local paleoflow pattern within the Bridger Basin is more ambiguous; measured paleocurrent indicators generally have not yielded consistent directions (Pietras and Carroll, 2006). However, the pronounced northward fining and thinning trends observed within the sandstone marker intervals A–I (Pietras and Carroll, 2006; Smith et al., 2015) strongly imply overall south-to-north transport.

The composition and textural immaturity of sandstone in the Washakie and Bridger Basins are consistent with first-cycle derivation from Proterozoic crystalline rocks in the Front, Gore, and/or Sawatch Ranges of Colorado. The presence of sedimentary lithic grains likely indicates recycling of Paleozoic–Mesozoic strata flanking Precambrian-cored uplifts. Volcanic lithic grains may have been derived from CMB volcanic rocks. Preserved extrusive rocks of Laramide age are generally scarce within the CMB, however, either because they were never widespread or because of later erosion.

The scarcity of Archean detrital zircon grains clearly demonstrates that few if any grains were derived directly from Wyoming province basement. Conversely, detrital peaks with Yavapai-Mazatzal province and "anorogenic" granite ages are consistent with derivation from Proterozoic basement in central Colorado. The 900–1200 Ma and 75–500 Ma zircons are inferred to derive primarily from reworking of Paleozoic–Mesozoic strata (cf. Dickinson et al., 2012). Some or all of the Archean grains likely share the same origin. Detrital zircon grains with 55–66 Ma ages are consistent with igneous ages in the northeast segment of the CMB (Bookstrom, 1990; Klein et al., 2010). Magmatic ages of 60–66 Ma are widely reported from the CMB between the cities of Denver and Aspen. CMB ages of 55–60 Ma are less common, but have been reported between Denver and Leadville, Colorado. The variation in Paleogene detrital zircon age distributions reported here may reflect changes in the Aspen paleoriver headwaters through time, or alternatively could reflect grain size–related differences in hydrodynamic sorting of zircon grains of different ages.

Taken together, the results of this study confirm the existence a fluvial connection between the CMB and Lake Gosiute. Riverine transport of excess alkalinity to Lake Gosiute is more difficult to prove, primarily because the detailed history of the CMB is much less well known than that of the Green River Formation. The youngest detrital zircon ages reported here predate the onset of evaporite deposition by ~3–4 m.y. (Fig. 3), which on its face might suggest that hydrothermal activity ceased before evaporite deposition began. Several other factors could also account for this temporal gap, however, including inheritance of older zircon cores, low zircon fertility in exposed igneous rocks, and the time required to unroof newly emplaced intrusive bodies. More significantly, the timing of Laramide hydrothermal activity is only loosely known. Bryant et al. (1990) postulated that a hydrothermal event occurred at 52.1 ± 4.4 Ma near Aspen, based on localized fission-track annealing of zircon in a mineralized porphyry, but other similar studies are scarce. The late Cenozoic history of the CMB clearly demonstrates that hydrothermal activity need not be associated with coeval detrital zircon. No intrusive rocks younger than 5 Ma are exposed anywhere in the CMB today. Modern hydrothermal "soda springs" are nonetheless common, and have chemistries similar to the waters that provided excess alkalinity to Searles Lake (Evans et al., 1986; Lowenstein et al., 2016). Alkali-olivine basalt <5 Ma does occur in within the CMB (Klein et al., 2010). Detrital zircon grains <30 Ma are absent from Holocene river samples collected downstream, however (Kimbrough et al., 2015), reflecting the limited areal extent of basalt flows, their low zircon fertility, or both.

Based on the above arguments, the CMB cannot be excluded as the source of excess alkalinity that enabled downstream Na-carbonate evaporite deposition. A simple numerical model shows that thermal spring discharge equal to 1%–10% of the total runoff to Lake Gosiute could account for the observed mass of trona (Fig. 4). Additional studies are needed to fully elucidate the detailed history of Laramide

[1]GSA Data Repository item 2019361, Figure DR1 (measured sections), Table DR1 (sandstone petrography), and Table DR2 (detrital zircon age data), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

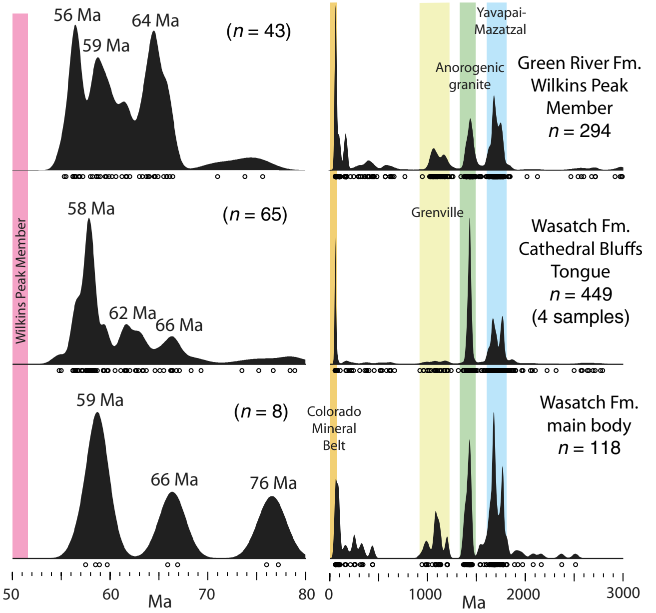

Figure 3. Kernel density estimates based on detrital zircon ages reported in this study (cf. Vermeesch, 2012). A total of 861 detrital zircon U-Pb ages were measured at the Arizona LaserChron Center (Tucson, Arizona, USA), based on five samples from Washakie Basin and one sample from Firehole Canyon in Bridger Basin, Wyoming (Fig. 1; see Table DR3 [see footnote 1] for full data). Vertical scale on each plot is an expression of the relative probability of encountering a particular zircon age in each sample. Circles beneath each plot indicate the measured ages of individual zircon grains. Plots on the left were calculated with bandwidth = 1 m.y., plots on the right with bandwidth = 10 m.y. Four Cathedral Bluffs Tongue (Wasatch Formation) sandstone samples were combined in one plot due to their geographic proximity, similar petrographic composition, and similar detrital zircon age distributions.

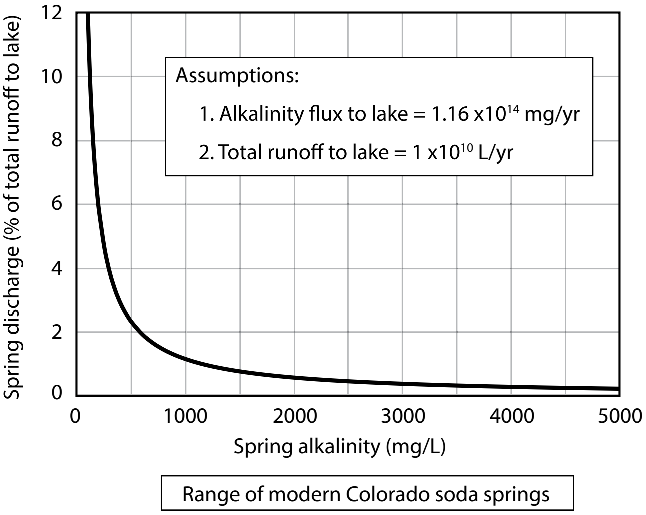

Figure 4. Thermal spring alkalinity versus discharge rate required to account for trona deposits of the Wilkins Peak Member of the Green River Formation, Wyoming, USA. Based on this analysis, spring discharge representing ~1%–10% of total runoff to the Eocene Lake Gosiute (Wyoming) could have supplied the excess alkalinity required to precipitate the preserved mass of trona. Total runoff to the lake was estimated by Doebbert et al. (2010, 2014) based on mass balance modeling of Lake Gosiute (Utah). Alkalinity flux is based on the Smith et al. (2008a) calculation of trona accumulation rate in the lower Wilkins Peak Member (subject to ± 21% uncertainty). Data for modern CO_2-rich soda springs in Colorado were reported by Evans et al. (1986).

hydrothermal activity in time and space. Ironically, the best evidence for this history may come not from the CMB itself, but from further investigation of its downstream influence as recorded stratigraphically within the Green River Formation. For example, $^3He/^4He$ isotope ratios within fluid inclusions of evaporite deposits might provide evidence for mantle input to magmatic fluids. The potential relationship of CMB magmatism to Na-carbonate evaporite deposits in the Piceance Creek and Uinta Basins (Fig. 1) also needs further investigation. More generally, this study points to the utility of lake deposits in helping to interpret complex magmatic histories and the broader evolution of continental landscapes.

ACKNOWLEDGMENTS

We thank S.P. Peters, S.R. Meyers, and P.E. Brown for their helpful comments and insights. I. Dammann provided invaluable assistance in the field, and I. McBrearty provided computational support. M. Pecha helped obtain data at the University of Arizona LaserChron Center (Tucson, Arizona, USA). We also thank the anonymous reviewers of this paper and of an earlier version. Funding was provided by National Science Foundation grants EAR-1812741, EAR-1813278, and EAR-1813350, a Geological Society of America Student Research Grant, and the Department of Geoscience, University of Wisconsin–Madison.

REFERENCES CITED

Aswasereelert, W., Meyers, S.R., Carroll, A.R., Peters, S.E., Smith, M.E., and Feigl, K.L., 2013, Basin-scale cyclostratigraphy of the Green River Formation, Wyoming: Geological Society of America Bulletin, v. 125, p. 216–228, https://doi.org/10.1130/B30541.1.

Bolen, W.P., 2018, Soda ash, *in* Mineral Commodity Summaries 2018: Reston, Virginia, U.S. Geological Survey, p. 152–153.

Bookstrom, A.A., 1990, Igneous rocks and carbonate-hosted ore deposits of the central Colorado mineral belt, *in* Beaty, D.W., et al., eds., Carbonate-Hosted Sulfide Deposits of the Colorado Mineral Belt: Society of Economic Geologists Economic Geology Monograph 7, p. 45–65.

Bryant, B., Naeser, C.W., and Stegen, R.J., 1990, Reconnaissance fission-track geochronology of the Aspen mining district, central Colorado, *in* Beaty, D.W., et al., eds., Carbonate-Hosted Sulfide Deposits of the Central Colorado Mineral Belt: Society of Economic Geologists Economic Geology Monograph 7, p. 301–307.

Chapin, C.E., 2012, Origin of the Colorado Mineral Belt: Geosphere, v. 8, p. 28–43, https://doi.org/10.1130/GES00694.1.

Chetel, L.M., Janecke, S.U., Carroll, A.R., Beard, B.L., Johnson, C.M., and Singer, B.S., 2011, Paleogeographic reconstruction of the Eocene Idaho River, North American Cordillera: Geological Society of America Bulletin, v. 123, p. 71–88, https://doi.org/10.1130/B30213.1.

Davis, S.J., Dickinson, W.R., Gehrels, G.E., Spencer, J.E., Lawton, T.F., and Carroll, A.R., 2010, Paleogene California River: Evidence of Mojave-Uinta paleodrainage from U-Pb ages of detrital zircons: Geology, v. 38, p. 931–934, https://doi.org/10.1130/G31250.1.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, https://doi.org/10.1130/0016-7606(1988)100≤1023:PAPSOL≥2.3.CO;2.

Dickinson, W.R., Lawton, T.F., Pecha, M., Davis, S.T., Gehrels, G.E., and Young, R.A., 2012, Provenance of the Paleogene Colton Formation (Uinta Basin) and Cretaceous–Paleogene provenance evolution in the Utah foreland: Evidence from U-Pb ages of detrital zircons, paleocurrent trends, and sandstone petrofacies: Geosphere, v. 8, p. 854–880, https://doi.org/10.1130/GES00763.1.

Doebbert, A.C., Carroll, A.R., Mulch, A., Chetel, L.M., and Chamberlain, C.P., 2010, Geomorphic controls on lacustrine isotopic compositions: Evidence from the Laney Member, Green River Formation, Wyoming: Geological Society of America Bulletin, v. 122, p. 236–252, https://doi.org/10.1130/B26522.1.

Doebbert, A.C., Johnson, C.M., Carroll, A.R., Beard, B.L., Pietras, J.T., Rhodes Carson, M., Norsted, B., and Throckmorton, L.A., 2014, Controls on Sr isotopic evolution in lacustrine systems: Eocene Green River Formation, Wyoming: Chemical Geology, v. 380, p. 172–189, https://doi.org/10.1016/j.chemgeo.2014.04.008.

Earman, S., Phillips, F.M., and McPherson, B.J.O.L., 2005, The role of "excess" CO_2 in the formation of trona deposits: Applied Geochemistry, v. 20, p. 2217–2232, https://doi.org/10.1016/j.apgeochem.2005.08.007.

Evans, W.C., Presser, T.S., and Barnes, I., 1986, Selected soda springs of Colorado and their origin, *in* Subitzky, S., ed., Selected Papers in the

Hydrologic Sciences 1986: U.S. Geological Survey Water-Supply Paper 2310, p. 45–52.
Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Janik, C.J., Winnett, T.L., and Clark, M.D., 1987, Hydrologic and geochemical monitoring in Long Valley Caldera, Mono County, California, 1985: U.S. Geological Survey Water-Resources Investigations Report 87-4090, 71 p., https://doi.org/10.3133/wri874090.
Hardie, L.A., and Eugster, H.P., 1970, The evolution of closed-basin brines, *in* Morgan, B.A., et al., eds., Fiftieth Anniversary Symposia: Mineralogy and Petrology of the Upper Mantle; Sulfides; Mineralogy and Geochemistry of Non-Marine Evaporites: Mineralogical Society of America Special Paper 3, p. 273–290.
Jones, B.F., 1966, Geochemical evolution of closed basin water in the western Great Basin, *in* Ran, J.L., ed., Proceedings of the Second Symposium on Salt: Cleveland, Northern Ohio Geological Society, p. 181–200.
Kimbrough, D.L., Grove, M., Gehrels, G.E., Dorsey, R.J., Howard, K.A., Lovera, A.A., House, P.K., and Pearthree, P.A., 2015, Detrital zircon U-Pb provenance of the Colorado River: A 5 m.y. record of incision into cover strata overlying the Colorado Plateau and adjacent regions: Geosphere, v. 11, p. 1719–1748, https://doi.org/10.1130/GES00982.1.
Klein, T.L., Evans, K.V., and DeWitt, E.H., 2010, Geochronology database for central Colorado: U.S. Geological Survey Data Series 489, 13 p., https://doi.org/10.3133/ds489.
Love, J.D., and Christiansen, A.C., compilers, 1985, Geologic map of Wyoming: Reston, Virginia, U.S. Geological Survey, 3 sheets, scale 1:500,000, https://doi.org/10.3133/70046739.
Lowenstein, T.K., Dolginko, L.A., and García-Veigas, J., 2016, Influence of magmatic-hydrothermal activity on brine evolution in closed basins: Searles Lake, California: Geological Society of America Bulletin, v. 128, p. 1555–1568, https://doi.org/10.1130/B31398.1.
Lowenstein, T.K., Jagniecki, E.A., Carroll, A.R., Smith, M.E., Renaut, R.W., and Owen, R.B., 2017, The Green River salt mystery: What was the source of the hyperalkaline lake waters?: Earth-Science Reviews, v. 173, p. 295–306, https://doi.org/10.1016/j.earscirev.2017.07.014.
Pietras, J.T., and Carroll, A.R., 2006, High-resolution sequence stratigraphy of an underfilled lacustrine basin: Evidence for tectonic controls on the saline Wilkins Peak Member of the Green River Formation, Wyoming: Journal of Sedimentary Research, v. 76, p. 1197–1214, https://doi.org/10.2110/jsr.2006.096.
Smith, M.E., Carroll, A.R., and Mueller, E.R., 2008a, Elevated weathering rates in the Rocky Mountains during the Early Eocene Climatic Optimum: Nature Geoscience, v. 1, p. 370–374, https://doi.org/10.1038/ngeo205.
Smith, M.E., Carroll, A.R., and Singer, B.S., 2008b, Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States: Geological Society of America Bulletin, v. 120, p. 54–84, https://doi.org/10.1130/B26073.1.
Smith, M.E., Carroll, A.R., Scott, J.J., and Singer, B.S., 2014, Early Eocene carbon isotope excursions and landscape destabilization at eccentricity minima: Green River Formation of Wyoming: Earth and Planetary Science Letters, v. 403, p. 393–406, https://doi.org/10.1016/j.epsl.2014.06.024.
Smith, M.E., Carroll, A.R., and Scott, J.J., 2015, Stratigraphic expression of climate, tectonism, and geomorphic forcing in an underfilled lake basin: Wilkins Peak Member of the Green River Formation, *in* Smith, M.E. and Carroll, A.R., eds., Stratigraphy and Paleolimnology of the Eocene Green River Formation, Western U.S.: Dordrecht, Springer, p. 61–102, https://doi.org/10.1007/978-94-017-9906-5_4.
Sorey, M.L., 1985, Evolution and present state of the hydrothermal system in Long Valley caldera: Journal of Geophysical Research, v. 90, p. 11,219–11,228, https://doi.org/10.1029/JB090iB13p11219.
Vermeesch, P., 2012, On the visualization of detrital age distributions: Chemical Geology, v. 312, p. 190–194, https://doi.org/10.1016/j.chemgeo.2012.04.021.
Warren, J.K., 2010, Evaporites through time: Tectonic, climatic and eustatic controls in marine and nonmarine deposits: Earth-Science Reviews, v. 98, p. 217–268, https://doi.org/10.1016/j.earscirev.2009.11.004.

Printed in USA