The Paleogene California River: Evidence of Mojave-Uinta paleodrainage from U-Pb ages of detrital zircons

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ABSTRACT

U-Pb age spectra of detrital zircons in samples from the Paleogene Colton Formation in the Uinta Basin of northeastern Utah and the Late Cretaceous McCoy Mountains Formation of southwestern Arizona (United States) are statistically indistinguishable. This finding refutes previous inferences that arkosic detritus of the Colton was derived from cratonic basement exposed by Laramide tectonism, and instead establishes the Cordilleran magmatic arc (which also provided sediment to the McCoy Mountains Formation) as the primary source. Given the existence of a north-south–trending drainage divide in eastern Nevada and the north-northeast direction of Laramide paleoflow throughout Arizona and southern Utah, we infer that a large river system headed in the arc of the Mojave region flowed northeast ~700 km to the Uinta Basin. Named after its source area, this Paleogene California River would have been equal in scale but opposite in direction to the modern Green River–Colorado River system, and the timing and causes of the subsequent drainage reversal are important constraints on the tectonic evolution of the Cordillera and the Colorado Plateau.

INTRODUCTION

Reconstructions of regional paleodrainage provide direct evidence of paleogeography and landscape evolution, in turn constraining tectonic models and informing isotopic analyses of past climate and altitude that are affected by the source of surface waters. In the North American Cordillera, Paleogene drainage patterns indicated by paleoflow measurements and sedimentary provenance have been used to infer paleotopography and episodes of tectonic transition (e.g., Dickinson et al., 1986; Elston and Young, 1991; Goldstrand, 1994; Henry, 2008; Lawton, 1986; Surdam and Stanley, 1980; Young and McKee, 1978).

Only recently have studies begun to unravel the areal extent of Laramide watersheds. Oxygen, strontium, and lead isotope records from Eocene Green River lake deposits have demonstrated that the lakes (in southern Wyoming, northwest Colorado, and northeast Utah; Fig. 1) received inflows from a large northern drainage beginning ca. 50 to ca. 49 Ma, which tapped areas at least as distant as central Idaho (Carroll et al., 2008; Chetel et al., 2010; Davis et al., 2009). Thus, at times during the Paleogene, southward-flowing rivers were integrated along >1000 km of the Cordillera from central Idaho to the Uinta Basin in Utah. In contrast, paleoflow directions in southern Utah and Arizona were consistently to the north and northeast during the early Paleogene, and the source of rivers has been generally assumed to reside in the proximal hinterland west of the Sevier thrust belt (e.g., Elston and Young, 1991; Goldstrand, 1994; Lawton, 1986; Young and McKee, 1978). A notable exception is the deltaic Colton Formation of the southern Uinta Basin, the large volume (>10^3 km^3) and arkosic composition of which, along with the geometry of foreland structures, led some of us (Dickinson et al., 1986) to propose a more distal source in the exposed Precambrian basement of south-central

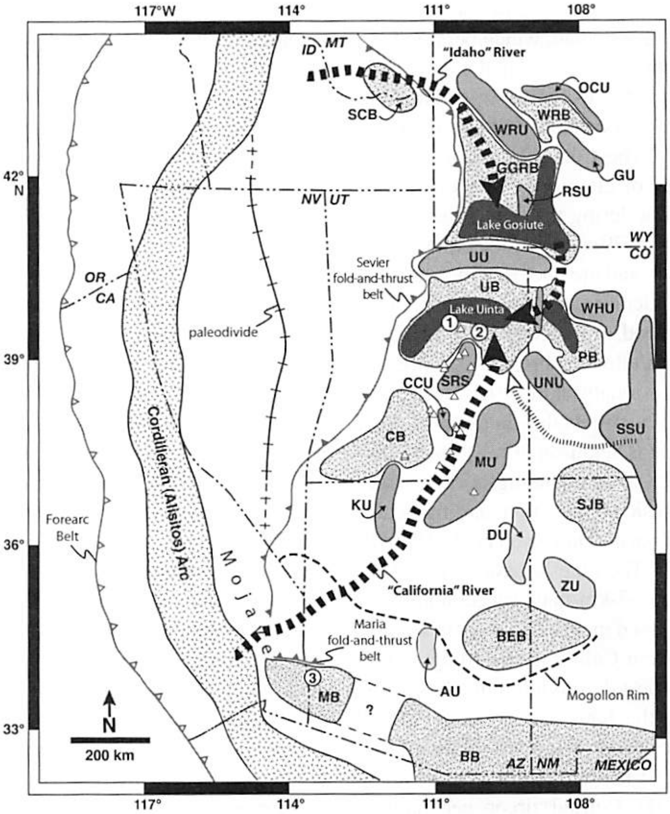

Figure 1. Palinspastic map showing location of Late Cretaceous and Paleogene structures of North American Cordillera and schematic path of inferred California River. Location of samples from Paleogene Colton Formation at Price River and Water Canyons and Late Cretaceous McCoy Mountains Formation are indicated by circles labeled 1, 2, and 3, respectively. Triangles indicate location of Mesozoic control samples (Fig. 2C). Basins are lightly stippled, uplifts are shaded light gray, Green River Lakes are shaded dark gray, and Cordilleran arc is denoted with "v" pattern. AU—Apache uplift; AZ—Arizona; BB—Bisbee Basin; BEB—Baca-Eager Basin; CA—California; CB—Claron Basin; CCU—Circle Cliffs uplift; CO—Colorado; DU—Defiance uplift; GGRB—greater Green River Basin; GU—Granite Mountain uplift; ID—Idaho; KU—Kaibab uplift; MB—McCoy Basin; MT—Montana; MU—Monument warp; NM—New Mexico; NV—Nevada; OCU—Owl Creek uplift; OR—Oregon; PB—Piceance Basin; RSU—Rock Springs uplift; SCB—Sage Creek Basin; SJB—San Juan Basin; SRS—San Rafael swell; SSU—Sawatch-San Luis uplift; UB—Uinta Basin; UNU—Uncompahgre uplift; UT—Utah; UU—Uinta uplift; WHU—White River uplift; WRB—Wind River Basin; WRU—Wind River uplift; WY—Wyoming; ZU—Zuni uplift. Previously proposed (and here abandoned) source of Colton Formation sand from SSU to southern UB is shown as finely dashed line. Also shown are inferred Eocene Idaho River (Davis et. al., 2009; Chetel et al., 2010), north-south–trending Nevada paleodivide (Henry, 2008), forearc belt, the Sevier and Maria fold-and-thrust belts, and Mogollon Rim.

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Geology, October 2010; v. 38; no. 10; p. 931–934; doi: 10.1130/G31250.1; 2 figures; Data Repository item 2010258.

Colorado (Fig. 1). Here we present new evidence from U-Pb analyses of detrital zircons in the Colton Formation that refutes a source within the foreland and, by statistical equivalence with an arc-derived sample from the McCoy Mountains Formation of southwestern Arizona, instead supports the existence of another large-scale river system originating >1000 km away from the Uinta Basin in the Cordilleran arc of the Mojave region of southern California.

GEOLOGIC SETTING

Beginning in Campanian time (ca. 80 Ma), drainage of the Cordilleran foreland was increasingly disrupted by Laramide deformation, and basement uplifts partitioned the foreland into a series of discrete basins (Dickinson et al., 1988). Axial drainage among these intraforeland basins led to the ponding of water in the Green River lakes of Wyoming, Colorado, and Utah, which persisted as hydrologically closed sumps as deformation progressed in the Early and early Middle Eocene until basins were infilled as tectonism waned in the late Middle Eocene (Davis et al., 2009; Dickinson et al., 1988; Surdam and Stanley, 1979).

The Colton Formation in the Uinta Basin is a fluvio-deltaic complex of claystones, siltstones, and sandstones that prograded into Lake Uinta during the Late Paleocene and Early Eocene (Stanley and Collinson, 1979) (sample localities 1 and 2 in Fig. 1). These strata are 0.3–1 km thick and are enclosed by lacustrine facies of the Green River Formation. Lenticular channelforms of nonresistant sandstone are fine to medium grained, micaceous, feldspathic, commonly cross-bedded, and weather red, yellow, or brown. Red, green, or purple silty or sandy mudrocks and occasionally thin (<0.3 m) limestones are interbedded (Peterson, 1976). Paleocurrents flowed to the north and northwest, and the unit thins to the west (Dickinson et al., 1986). The sediment source of the formation has been a longstanding question because of its large volume (>10^3 km^3), arkosic composition, and the scarcity of potential source lithologies near the basin (Dickinson et al., 1986; Picard, 1957).

The Late Jurassic to Late Cretaceous McCoy Mountains Formation is a 4–7-km-thick succession of sandstone, mudstone, and conglomerate exposed in an east-west–trending belt in southwestern Arizona and southeastern California (Harding and Coney, 1985; Tosdal and Stone, 1994). Earliest deposition in the basin was related to lithospheric extension during the Jurassic (Spencer et al., 2010). Deposition renewed in the Late Cretaceous with deformation in the east-west–trending Maria fold-and-thrust belt along the northern margin of the McCoy Basin (Barth et al., 2004). Detrital zircon geochronologic data reported in this study were derived from a sandstone sample collected from the uppermost (siltstone) member of the McCoy Mountains Formation in the southern Dome Rock Mountains of western Arizona (Spencer et al., 2010) (locality 3 in Fig. 1); the member consists of siltstone, feldspathic sandstone, and minor conglomerate, and is stratigraphically above a tuff dated as 79 Ma (Tosdal and Stone, 1994). Diverse conglomerate clasts and southward paleocurrent measurements (Harding and Coney, 1985) indicate that sources of sediment were the Maria fold-and-thrust belt and the active Cordilleran magmatic arc to the northwest.

U-PB AGE SPECTRA

U-Pb ages of detrital zircons in samples from the Colton and McCoy Mountains Formations were determined using the laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) methodology of Gehrels et al. (2008). Full U-Pb analytical data, concordia diagrams, and combined histograms and/or probability-distribution plots are available in the GSA Data Repository[1] (Table DR1; Figs. DR1–DR6). Of 248 detrital zircon grains that provided acceptable U-Pb ages and had uncertainties that either overlapped concordia or were close enough to meet standard acceptance criteria (Dickinson and Gehrels, 2008a), 131 grains were younger than 275 Ma and 117 grains were older than 275 Ma, the age of the oldest magmatic arc assemblages along the Cordilleran margin (Dickinson and Gehrels, 2008a, 2008b, 2009).

The two Colton Formation samples contain age populations that appear similar to the Upper McCoy Mountains Formation sample, particularly for grains older than 275 Ma (Figs. 2A and 2B). Kolmogorov-Smirnoff (K-S) statistics substantiate the visual similarity of the three samples (Press et al., 1986). Where P values calculated by the K-S test are >0.05, there is <95% confidence that the compared grain populations were not sampled at random from the same parent population (where P = 1 represents statistical identity). As should be expected of two samples from the same formation, the P value for the two Colton samples is quite high,

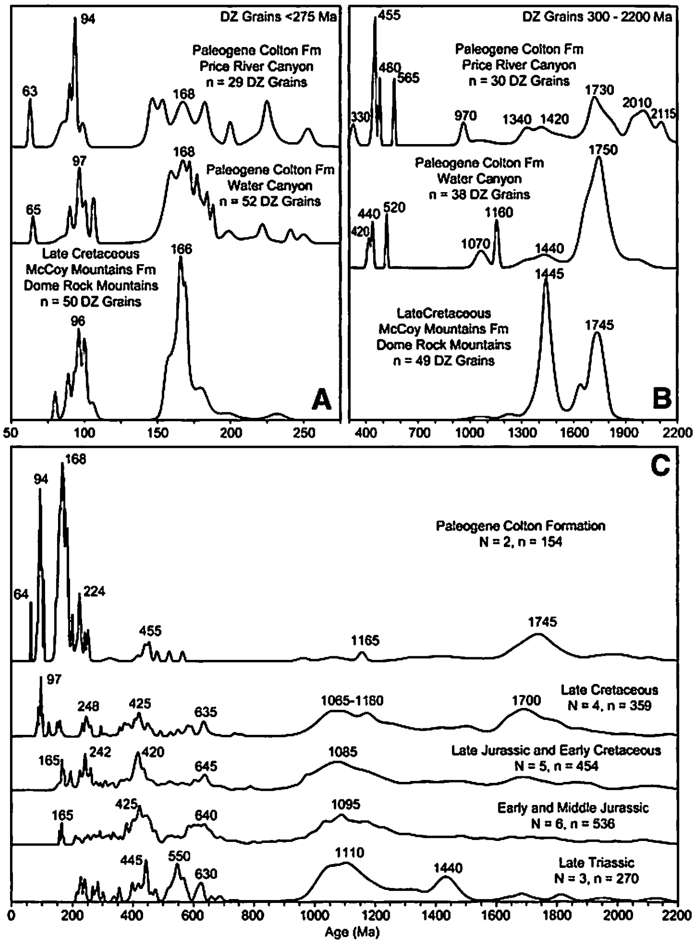

Figure 2. Normalized U-Pb age spectra (age-probability plots) of detrital zircons (DZ) in samples from Paleogene Colton Formation and Late Cretaceous McCoy Mountains Formation. A: Younger than 275 Ma. B: Between 300 and 2200 Ma. C: Comparison of spectra of combined Colton samples with control samples from Mesozoic units present in central Utah (see Fig. 1) omitting grains older than 2200 Ma (3%–8% of total grains). N—number of samples; n—number of U-Pb grain ages. Mesozoic samples composited: Late Cretaceous—CP33, CP34, CP39, CP40 (Dickinson and Gehrels, 2008b); Late Jurassic and Early Cretaceous—CP32, CP35, CP36, CP41, CP52 (Dickinson and Gehrels, 2008b); Early and Middle Jurassic—CP1, CP43, CP45, Jenw, Jnnw, Jwnw (Dickinson and Gehrels, 2009); Late Triassic—CP42, CP44, CP47 (Dickinson and Gehrels, 2008a).

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[1] GSA Data Repository item 2010258, Figures DR1–DR3 (age-bin histograms and age-distribution curves), Figures DR4–DR6 (concordia diagrams), Figure DR7 (<2200 Ma age spectra of samples), and Table DR1 (sample locations) and Table DR2 (U-Pb analytical data), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

0.75. More surprising, when the two Colton samples are combined into a single population and compared with the McCoy Mountains sample, the resulting P value is 0.23. Thus, the samples are statistically indistinguishable for the purpose of assessing provenance relations (Dickinson and Gehrels, 2009).

The statistical equivalence of detrital zircon populations in the Colton and McCoy Mountains Formations is strong evidence that the two units share a source in the active Cordilleran magmatic arc. The K-S test is sufficiently rigorous that it is unlikely that even samples derived from different areas of the arc would satisfy it: for example, calculations show that a pair of samples where two age populations are mixed in ratios of 6:4 and 4:6 would fail the test (P = 0.04) (Gehrels, 2010). Moreover, the proportion of Mesozoic zircon grains in the Colton samples is inconsistent with the previously proposed source in Colorado or elsewhere in the foreland. Laramide uplifts in Colorado would contribute only Proterozoic grains and none of the younger than 275 Ma population abundant in the Colton samples. Mesozoic eolianites and associated sedimentary units exposed elsewhere in the foreland (see Fig. 1 for locations of control samples) contain a much larger proportion of Grenville age (1315–1000 Ma) grains, minor but ubiquitous populations of Neoproterozoic (650–550 Ma) and Paleozoic (500–400 Ma) grains, and much fewer grains younger than 275 Ma than our Colton samples (Fig. 2C; Dickinson and Gehrels, 2008a, 2008b, 2009). While recycling of Grenville, Neoproterozoic, and Paleozoic age grains from Mesozoic strata of the Colorado Plateau could account for the few grains of those ages in our Colton samples, no such recycling could account for the abundance of arc-derived grains in the Colton, or for the preponderance of pre-Grenville (1800–1600 Ma) grains in the Proterozoic subpopulation of Colton zircons (Fig. 2C).

DISCUSSION AND CONCLUSIONS

The Colton Formation records a major river that flowed ~1000 km from the Cordilleran magmatic arc rather than draining Laramide foreland uplifts as previously posited. Three lines of evidence support an arc source in the Mojave region of southern California. (1) Paleocurrent measurements, clast compositions, and the distribution of ash-flow tuffs all indicate that a north-south–trending drainage divide existed in eastern Nevada during the Paleogene (e.g., Christensen and Yeats, 1992; Henry, 2008). This divide would have prevented rivers flowing east from the Cordilleran arc in northern California from reaching the Uinta Basin. Cretaceous plutons east of this divide are relatively small, and unlikely to have shed sediment to the southern Uinta Basin. (2) Paleocurrent measurements in numerous studies have shown that Paleogene river networks in southern Utah and Arizona flowed north-northeast (Elston and Young, 1991; Goldstrand, 1994; Lawton, 1986; Young, 2008; Young and McKee, 1978). (3) Detrital zircon age distributions in the Colton and Upper McCoy Mountains Formations are statistically indistinguishable for the purpose of identifying provenance, a relationship unlikely in samples not derived from the same source area.

Considered together, this evidence supports a river system similar in scale but opposite in direction to the modern Green and Colorado Rivers. Others have suggested Laramide paleorivers flowing northeast through Arizona (e.g., Potochnick, 2001), which may have carved an ancestral Grand Canyon (Wernicke, 2009) and then reversed direction as early as to the Cretaceous–Tertiary boundary (Wernicke, 2009) or as late as Miocene time (Potochnik, 2001). Unlike the Cretaceous California River described by Wernicke (2009), however, we find evidence of a river transporting arc-derived sediment from the Mojave region to northeast Utah during the Paleogene, with little addition of sediments from units being eroded in the foreland. Nonetheless, extension and lowering of areas adjacent to the Colorado Plateau alone could not have reversed the direction of a California River debouching in northern Utah (cf. Flowers et al., 2008). Instead, the subcontinental-scale drainage reversal implicates the broader tectonic evolution of the Cordillera, such as post–Early Eocene tilting of the Colorado Plateau. Future work should improve resolution of the river's path and the timing of its reversal, thereby refining topographical constraints on such late Laramide tectonism. In the meantime, our findings compound recent evidence for the large-scale integration of axial drainage in the Cordillera (Chetel et al., 2010; Davis et al., 2008, 2009), indicating that at times in the Paleogene, the Uinta Basin received water and sediment from sources spanning ~1500 km from southern California to central Idaho.

ACKNOWLEDGMENTS

U-Pb analyses of detrital zircon samples at the Arizona LaserChron Center were supported in part by funding from National Science Foundation grants EAR-732436 and EAR-0443387. We thank Richard Young, Chris Henry, and an anonymous reviewer for comments that improved the paper.

REFERENCES CITED

Barth, A.P., Wooden, J.L., Jacobson, C.E., and Probst, K., 2004, U-Pb geochronology and geochemistry of the McCoy Mountains Formation, southeastern California: A Cretaceous retroarc foreland basin: Geological Society of America Bulletin, v. 116, p. 142–153, doi: 10.1130/B25288.1.

Carroll, A.R., Doebbert, A., Booth, A.L., Chamberlain, C.P., Rhodes-Carson, M., Smith, E., Johnson, C.M., and Beard, B.L., 2008, Capture of high-altitude precipitation by a low-altitude Eocene lake, western U.S: Geology, v. 36, p. 791–794, doi: 10.1130/G24783A.1.

Chetel, L.M., Janecke, S.U., Carroll, A.R., Beard, B.L., Johnson, C.M., and Singer, B.S., 2010, Paleogeographic reconstruction of the Eocene Idaho River, North American Cordillera: Geological Society of America Bulletin (in press).

Christensen, R.L., and Yeats, R.L., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., et al., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 261–406.

Davis, S.J., Wiegand, B.A., Carroll, A.R., and Chamberlain, C.P., 2008, The effect of drainage reorganization on paleoaltimetry studies: An example from the Paleogene Laramide foreland: Earth and Planetary Science Letters, v. 275, p. 258–268, doi: 10.1016/j.epsl.2008.08.009.

Davis, S.J., Mix, H.T., Wiegand, B.A., Carroll, A.R., and Chamberlain, C.P., 2009, Synorogenic evolution of large-scale drainage patterns: Isotope paleohydrology of sequential Laramide basins: American Journal of Science, v. 309, p. 549–602, doi: 10.2475/07.2009.02.

Dickinson, W.R., and Gehrels, G.E., 2008a, Sediment delivery to the Cordilleran foreland basin: Insights from U-Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau: American Journal of Science, v. 308, p. 1041–1082, doi: 10.2475/10.2008.01.

Dickinson, W.R., and Gehrels, G.E., 2008b, U-Pb ages of detrital zircons in relation to paleogeography: Triassic paleodrainage networks and sediment dispersal across Laurentia: Journal of Sedimentary Research, v. 78, p. 746–754, doi: 10.2110/jsr.2008.088.

Dickinson, W.R., and Gehrels, G.E., 2009, U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment: Geological Society of America Bulletin, v. 121, p. 408–433, doi: 10.1130/B26406.1.

Dickinson, W.R., Lawton, T.F., and Inman, K.F., 1986, Sandstone detrital modes, central Utah foreland region: stratigraphic record of Cretaceous-Paleogene tectonic evolution: Journal of Sedimentary Petrology, v. 56, p. 276–293.

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, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2.

Elston, D.P., and Young, R.A., 1991, Cretaceous-Eocene (Laramide) landscape development and Oligocene–Pliocene drainage reorganization of Transition Zone and Colorado Plateau, Arizona: Journal of Geophysical Research, v. 96, p. 12,389–12,406, doi: 10.1029/90JB01978.

Flowers, R.M., Wernicke, B., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: Geological Society of America Bulletin, v. 120, p. 571–587, doi: 10.1130/B26231.1.

Gehrels, G.E., 2010, Detrital zircon U-Pb geochronology: Current methods and new opportunities, *in* Busby, C.J., and Azor, A., eds., Recent advances in tectonics of sedimentary basins: Hoboken, New Jersey, Blackwell Publishing (in press).

Gehrels, G.E., Valencia, V., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: Geochemistry Geophysics Geosystems, v. 9, Q03017, doi: 10.1029/2007GC001805.

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154, doi: 10.1130/0016-7606(1994)106<0145:TDOUCT>2.3.CO;2.

Harding, L.E., and Coney, P.J., 1985, The geology of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Geological Society of America Bulletin, v. 96, p. 755–769, doi: 10.1130/0016-7606(1985)96<755:TGOTMM>2.0.CO;2.

Henry, C.D., 2008, Ash-flow tuffs and paleovalleys in northeastern Nevada: Implications for Eocene paleogeography and extension in the Sevier hinterland, northern Great Basin: Geosphere, v. 4, p. 1–35, doi: 10.1130/GES00122.1.

Lawton, T.F., 1986, Fluvial systems of the Upper Cretaceous Mesaverde Group and Paleocene North Horn Formation, central Utah: A record of transition from thin-skinned to thick-skinned deformation in the foreland region, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 423–442.

Peterson, A.R., 1976, Paleoenvironments of the Colton Formation, Colton, Utah: Brigham Young University Geology Studies, v. 23, p. 7–35.

Picard, M.D., 1957, Green River and lower Uinta Formation subsurface stratigraphy in central and eastern Uinta basin, Utah, *in* Seal, O.G., ed., Guidebook to the geology of the Uinta basin, Volume 8: Intermountain Association of Petroleum Geologists Annual Field Conference Guidebook, p. 116–130.

Potochnik, A.R., 2001, Paleogeomorphic evolution of the Salt River Region: Implications for Cretaceous-Laramide inheritance for ancestral Colorado River drainage, *in* Young, R.A., and Spamer, E.E., eds., Colorado River origin and evolution: Grand Canyon, Arizona, Grand Canyon Association, p. 17–24.

Press, W.H., Flannery, B.P., Tenkolsky, S.A., and Vetterling, W.T., 1986, Numerical recipes: Cambridge, UK, Cambridge University Press, 818 p.

Spencer, J.E., Richard, S.M., Gehrels, G.E., Gleason, J.D., and Dickinson, W.R., 2010, Age and tectonic setting of the Mesozoic McCoy Mountains Formation in western Arizona, USA: Geological Society of America Bulletin (in press).

Stanley, K.O., and Collinson, J.W., 1979, Depositional history of Paleocene–lower Eocene Flagstaff Limestone and coeval rocks, central Utah: American Association of Petroleum Geologists Bulletin, v. 63, p. 311–323.

Surdam, R.C., and Stanley, K.O., 1979, Lacustrine sedimentation during the culminating phase of Eocene Lake Gosiute, Wyoming (Green River Formation): Geological Society of America Bulletin, v. 90, p. 93–110, doi: 10.1130/0016-7606(1979)90<93:LSDTCP>2.0.CO;2.

Surdam, R.C., and Stanley, K.O., 1980, Effects of changes in drainage-basin boundaries on sedimentation in Eocene Lakes Gosiute and Uinta of Wyoming, Utah, and Colorado: Geology, v. 8, p. 135–139, doi: 10.1130/0091-7613(1980)8<135:EOCIDB>2.0.CO;2.

Tosdal, R.M., and Stone, P., 1994, Stratigraphic relations and U-Pb geochronology of the Upper Cretaceous upper McCoy Mountains Formation, southwestern Arizona: Geological Society of America Bulletin, v. 106, p. 476–491, doi: 10.1130/0016-7606(1994)106<0476:SRAUPG>2.3.CO;2.

Wernicke, B., 2009, The California River and its role in carving Grand Canyon: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 33.

Young, R.A., 2008, Pre-Colorado River drainage in western Grand Canyon: Potential influence on Miocene stratigraphy in Grand Wash Trough, *in* Reheis, M.C. et al., eds., Late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Geologic and biotic perspectives: Geological Society of America Special Paper 439, p. 319–333, doi: 10.1130/2008.2439(14).

Young, R.A., and McKee, E.H., 1978, Early and middle Cenozoic drainage and erosion in west-central Arizona: Geological Society of America Bulletin, v. 89, p. 1745–1750, doi: 10.1130/0016-7606(1978)89<1745:EAMCDA>2.0.CO;2.

Manuscript received 25 March 2010
Revised manuscript received 17 May 2010
Manuscript accepted 24 May 2010

Printed in USA