Lithosphere, published online on 27 August 2014 as doi:10.1130/L390.1

Basement-hosted sandstone injectites of Colorado: A vestige of the Neoproterozoic revealed through detrital zircon provenance analysis

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ABSTRACT

Detrital zircon provenance analysis is used to resolve the age of sandstone injectites together with source sandstones that form fault-bounded, tabular bodies within Mesoproterozoic crystalline rocks of the Colorado Front Range. Named Tava sandstone (informal), the unit is a product of liquefaction and remobilization of mature quartz sediment within source bodies having volumes ≥1 × 10^6 m^3 into dikes up to 6 m in width. To surmount the indeterminate age of emplacement, we obtained new U-Pb detrital zircon age data for two source sandstones, three dikes and one sill, for comparison to four Paleozoic arenites. Tava age distributions feature a dominant 1.33–0.97 Ga broad age group and narrow ca. 1.11, 1.44, and 1.70 Ga groups, with several smaller age groups >1.5 Ga. The Tava detrital zircon results are dissimilar to Paleozoic sandstones but closely resemble published detrital zircon reference data for Grenville orogen–derived siliciclastic units of the western United States. The similarity in age distributions is borne out by statistical comparisons among Tava sandstone, Paleozoic samples, and Neoproterozoic strata that reveal a high probability of correlation of Tava sandstone to ca. 800–680 Ma strata deposited during intracontinental extension. We conclude that Tava sandstone is Neoproterozoic in age and provides a new avenue to investigation of Rodinia's terrestrial paleoenvironment.

LITHOSPHERE GSA Data Repository Item 2014333 doi:10.1130/L390.1

INTRODUCTION

Detrital zircon reference curves for North America (Gehrels and Pecha, 2014; Yonkee et al., 2014) provide a new means by which to place age limits upon the deposition of siliciclastic units that lack age control. Age correlation is based upon the premise that contemporaneous units incorporate detrital zircon from regional reservoirs that contain diagnostic zircon age populations. The approach promises to resolve a long-standing problem in Colorado geology (Cross, 1894; Harms, 1965), namely, the age of a regional system of dikes, sills, and source bodies (Fig. 1) formed by liquefaction and remobilization of mature quartz sediment. On the basis of distinctive sedimentological characteristics and geological context, Siddoway et al. (2013) introduced the name Tava sandstone[1] for the formation. Bounded by crystalline host rock (Figs. 2 and 3), the injectite system has defied comprehension because of its indeterminate emplacement age and the uncertain provenance for the constituent mature quartz (e.g., Scott, 1963). Hypotheses for the time of formation span the Phanerozoic Eon.

Injectites ordinarily form within strata undergoing rapid sedimentation (Hurst et al., 2011) in settings prone to transient rapid overpressure events, from earthquakes or other causes (Jonk, 2010). The Colorado Front Range offers one of the only regional-scale examples of injectites within crystalline host rock. Attributes of Tava sandstone are diagnostic of liquefaction and high-energy sediment remobilization: The rock is conglomeratic yet structureless, with nontouching granule- to pebble-sized clasts suspended in a sand matrix, forming tabular dikes and large bodies having volumes of hundreds to millions of cubic meters (Siddoway et al., 2013). The source of voluminous mature sediment, origin of fluid overpressure, and trigger for liquefaction will remain obscure, however, without constraints on paleoenvironment, which will be recognized once the age of formation of the sandstone is resolved.

A maximum age for the Tava sandstone is provided by the 1.09 to 1.03 Ga Pikes Peak Granite (Unruh, et al., 1995; Howard, 2013), which hosts a majority of the dikes and parent bodies (Fig. 1; Siddoway et al., 2013). A minimum age of late Paleozoic is provided by chemical remanent (Kost, 1984; Freedman, 2014) and primary (Dulin and Elmore, 2013) magnetization retained within the hematitic quartz sandstones.

To refine the age of Tava sandstone emplacement, we employed detrital zircon age analysis to test hypothesized correlations (e.g., Vitanage, 1954; Scott, 1963; Dockal, 2005) to Paleozoic mature sandstones (Maher, 1950) and to investigate alternatives. The impetus to resolve the age stems from recognition that the Tava injectite system constitutes a unique element (cf. Jonk, 2010) of a continental environment of the past. We report new detrital zircon data for five granite-hosted Tava sandstones and four Paleozoic quartz arenites, and then we compare the new data sets to each other and to published detrital zircon reference curves for siliciclastic units of the southwest United States. We demonstrate a very strong probability of statistical correlation to detrital zircon age distributions of Neoproterozoic strata deposited during extension/rifting along the proto-Cordilleran margin (Yonkee et al., 2014).

DETRITAL ZIRCON U-Pb GEOCHRONOLOGY SAMPLES

Samples of well-rounded or moderately well-rounded quartz sandstone of 4–6 kg were collected from representative portions of outcrops

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[1]Tava is an indigenous name referencing Pikes Peak.

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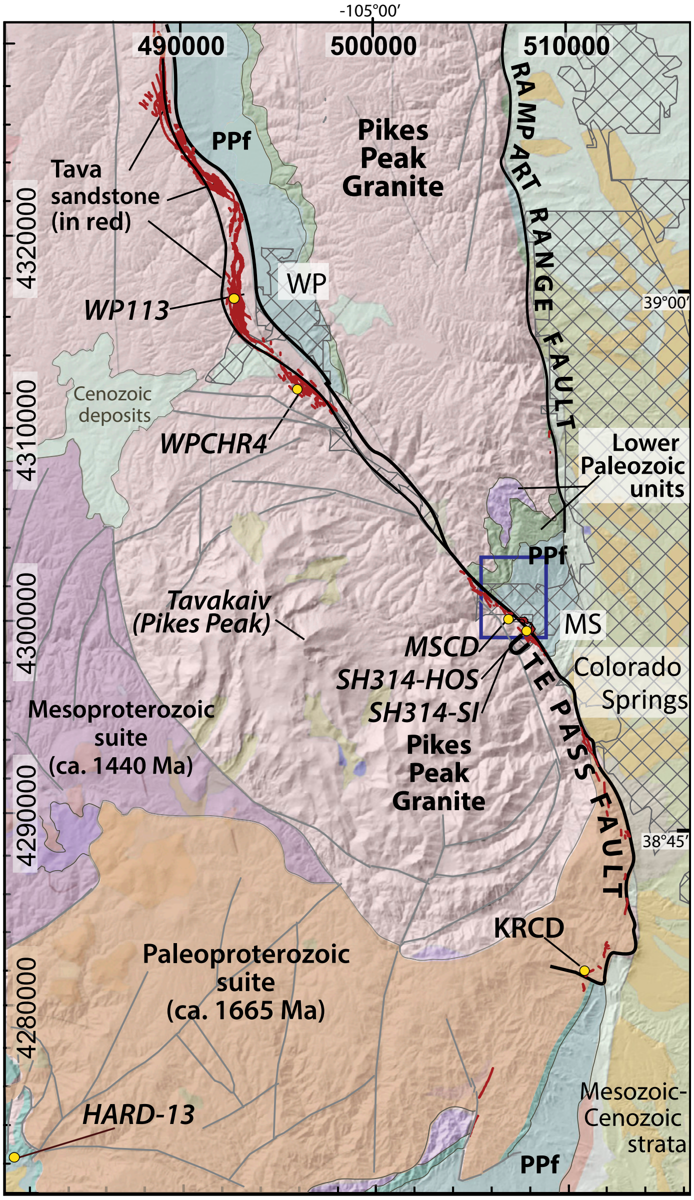

Figure 1. Geological map of southern Front Range, showing Tava sandstone in red. Yellow symbols show sample locations, with IDs, and the blue rectangle encloses the collection area for four of five Paleozoic samples (see Fig. DR1G for geological map inset and sample sites [see text footnote 2]). The fourth sample, HARD-13, was collected from the site labeled in the SW corner of Figure 1. Proterozoic plutonic units are labeled on the map, Pennsylvanian Fountain Formation is abbreviated PPf, and units of other ages are generalized as labeled. Cross-hachured patterns correspond to urban areas (MS—Manitou Springs; WP—Woodland Park). Digital topography is from http://ned.usgs.gov/ and geology base from Green (1992). Map projection: WGS1984, UTM zone 13S.

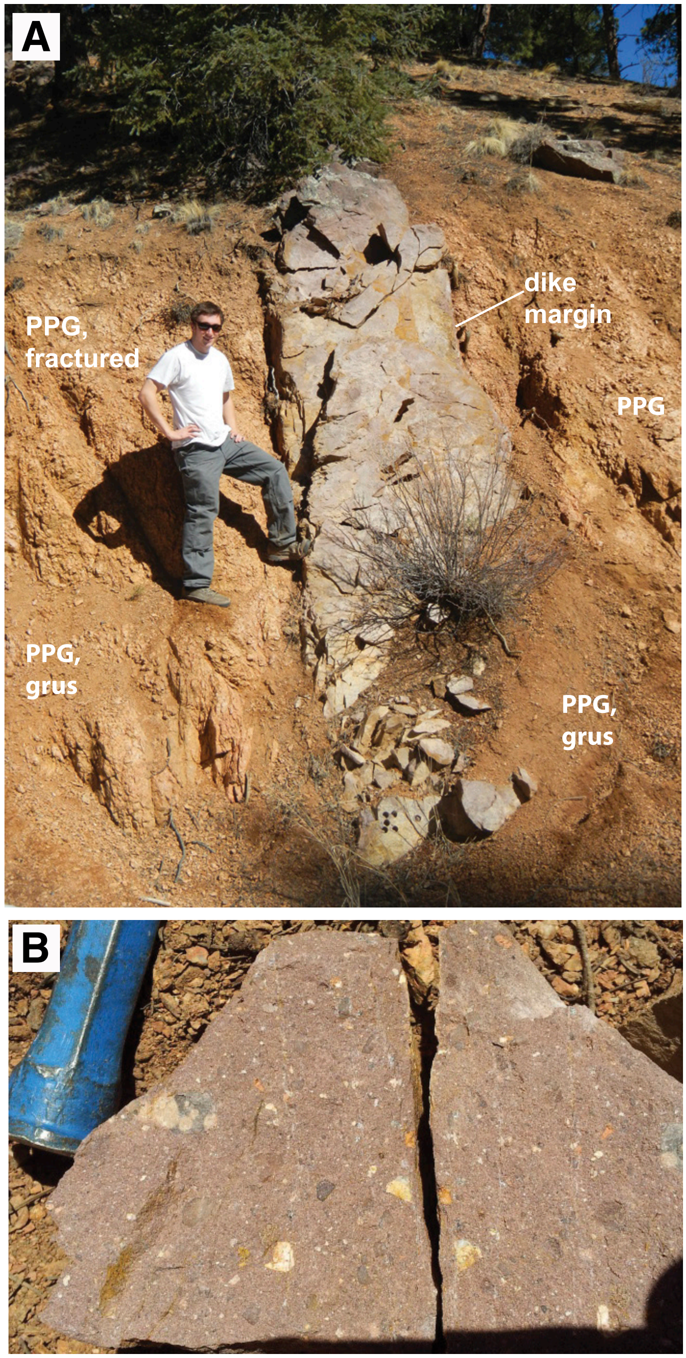

Figure 2. (A) Field photograph of Tava sandstone dike, 1.5 m wide, hosted by Pikes Peak Granite (PPG; detrital zircon sample WP113). (B) Hand sample of WP113 exhibiting dispersed pebbles within unsorted, ungraded matrix of moderately fine sand. Chisel head is 1.5 cm across.

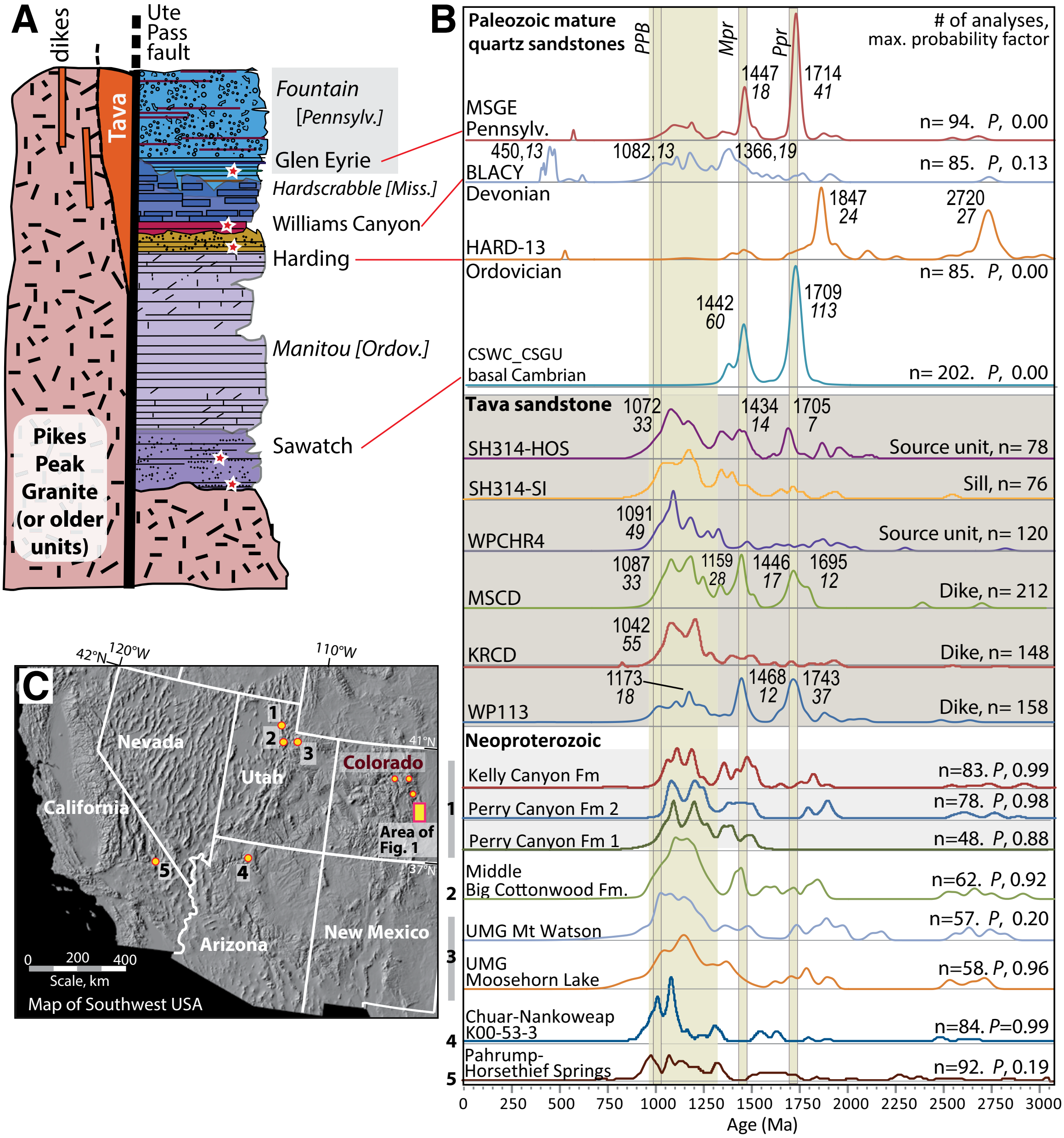

Figure 3. (A) Tectonostratigraphic diagram for southern Front Range, illustrating the spatial-structural relationship of Tava sandstone to the Ute Pass fault and Paleozoic strata. Sampled Paleozoic strata are labeled. (B) Age distribution plots comparing detrital zircon results for Tava sandstone and Paleozoic quartz arenites with detrital zircon reference curves for Neoproterozoic siliciclastic units. Formation names appear on the left. Equal-area curves were constructed by summing all ages and uncertainties, and normalizing by the number of analyses (shown on the right). Continuous age-probability domains and peak ages were calculated at 2σ uncertainty using a University of Arizona LaserChron Center (ALC) routine: Selected peaks are labeled in Ma, with number of analyses in italics. The right column displays the highest *P* values determined from Kolmogorov-Smirnoff (K-S) statistical comparison (see Table DR1, parts 12–15 [see text footnote 2]) of the detrital zircon age data for the specified formation to Tava sandstone (UMG—Uinta Mountain Group). The age span for detrital zircons of Grenville provenance is demarcated by the broad band in tan. Age span for local igneous sources corresponds to narrow bars (PPB—Pikes Peak Batholith, Mpr—Mesoproterozoic plutons, Ppr—Paleoproterozoic plutons). (C) Locations for detrital zircon reference data on digital landform map (pubs.usgs.gov/imap/i2206/) of southwest Unites States. Rectangle symbol within Colorado corresponds to area of Figure 2. Site numbers correspond to labels on left side of part B. For interpreted Neoproterozoic paleogeography of the reference sites, see Yonkee et al. (2014, their Fig. 12). Circle symbols within Colorado correspond to additional Tava sandstone sites, identified on the basis of DZ populations (C. Siddoway and G. Gehrels, personal data).

that are uniform in respect to the highest quartz abundance (mineralogically mature), grain size, and clast composition. Collection sites for Tava sandstone were selected at intervals of ~18 km along the southern Ute Pass fault (Fig. 1). One sample site (KRCD) comes from a dike within Mesoproterozoic granodiorite above a subhorizontal segment of the Ute Pass fault. Sites of two parent bodies (SH314-HOS, WPCHR4) and two dikes (MSCD, WP113) border a subvertical portion of the Ute Pass fault that juxtaposes Pikes Peak Granite against shallowly inclined Cambrian through Pennsylvanian strata (Keller et al., 2005). One parent sandstone contains a sill (SH314-SI; Siddoway et al., 2013), which was also sampled. Four samples of Paleozoic mature sandstone (Maher, 1950) come from the downthrown side of the fault (Fig. 3A; Fig. DR1G[2]) in Manitou Springs, Colorado, and a fifth (HARD-13) was obtained from a U.S. Highway 50 road cut west of Canon City, Colorado.

Sample Descriptions

Tava Sandstone

Tava sandstone samples consist dominantly of quartz, with accessory (total <5%) feldspars, micas, magnetite, and zircon. They were collected from massive uniformly structureless, hematitic sandstone consisting of fine to moderately fine sand supporting isolated rounded quartz granules and pebbles (0.5–3 mm; Fig. 2B). Zircons in the samples are mainly colorless to light pinkish, transparent, well-rounded to subangular grains that are 125–250 mm in long dimension. Subrounded prismatic and semispherical grains are present, forming <5% of the sample. Oscillatory zoning, when observed in backscatter electron (BSE) images, usually is off-center and truncated at grain margins. Sample WPCHR4 contains some deeper-colored, rounded zircons and grains reaching 350 mm in size. Sample KRCD contains abundant tiny rounded grains and angular fragments <20 mm, too small to be analyzed.

Paleozoic Sandstones

The Lower Sawatch Formation (Lower to Middle Cambrian; Fig. 3A) consists of white-weathering, thin- to medium-bedded mature coarse quartz arenite with <5% feldspar. Basal beds rest nonconformably on Pikes Peak Granite, which in places abuts core stones in the granite (Siddoway et al., 2013). Texturally uniform samples were obtained at 0.30 m (CSGU) and 2.2 m (CSWC) above the Great Unconformity, from parallel-laminated beds that lack dune-scale trough cross-stratification, avoiding concentrations of pebbles. Zircons in both samples are clear, colorless to light pinkish, and well rounded, with sizes ranging from 75 to 150 mm.

The Harding Sandstone (Ordovician) is a medium-bedded grayish-white, poorly cemented, fine-grained sandstone. The unit is not present near the Ute Pass fault, so a sample was collected from a fresh road cut in a location SW of Pikes Peak (Fig. 1). The detrital zircon sample (HARD-13) consists of transparent, well-rounded and some subrounded grains with a narrow size range of 100–150 mm.

The Williams Canyon Formation (Devonian) is a carbonate with few beds of competent muscovite-bearing white orthoquartzite. Sample BLACY-13 was obtained from an ~2-m-thick, massive bed. A majority of detrital zircons are well-rounded small grains, ~75 mm, with few large subrounded semiprismatic elongate grains, ~225 mm in length.

The Glen Eyrie member of the lower Fountain Formation (Pennsylvanian) consists of medium-thin beds of poorly cemented, mature quartz arenite alternating with thin-bedded organic-rich shale and siltstone. Uniformly coarse-grained, well-rounded, friable quartz sandstone was collected (MSGE). Zircons consist of small (60–120 mm), light-colored, transparent, rounded grains and prismatic to rounded-subhedral grains; moderately dark, well-rounded grains; and few subhedral prismatic grains exhibiting oscillatory zoning in BSE.

METHODS

Sample selection, processing, and analysis procedures, described in the GSA Data Repository (see footnote 2), are according to Gehrels et al. (2008) and Gehrels (2011). Samples were analyzed for U-Pb isotopes at the University of Arizona LaserChron Center (ALC) following protocols of Gehrels et al. (2008). Analysis involved ablation of zircon with a New Wave DUV193 excimer laser while isotope ratios were measured with a Nu high-resolution–inductively coupled plasma–mass spectrometer (HR-ICP-MS). BSE images were used to identify uniform regions for laser analysis, avoiding inclusions, cracks, and mineral zonation. The time-resolved $^{206}Pb/^{238}U$ ratio of standards versus unknowns was used to monitor data quality throughout acquisition. In order to obtain a representative detrital zircon age distribution (Vermeesch, 2004), a minimum of 100–125 analyses per sample were acquired in a random manner avoiding the tendency to select grains on the basis of descriptive criteria. In addition, targeted analyses were performed on three samples in an effort to detect grains of all ages, including the youngest age. We targeted oscillatory zoned, subhedral to euhedral grains within samples WPCHR4 and WP113, and zircons extracted from the magnetic mineral fractions of sample KRCD.

Isotopic information, data-quality parameters, and ages of acceptable analyses are reported in Table DR1, parts 1–10 (see footnote 2). Concordia diagrams (Fig. DR1 [see footnote 2]) generated with Isoplot (Ludwig, 2012), and normalized and relative probability density plots of age distributions (Fig. 3B) with peak and range values were calculated using ALC's online spreadsheet computation tools (laserchron.org). Age distributions for the 11 study samples were compared to each other as a test of the validity of a Paleozoic age for Tava sandstone, and further compared against published detrital zircon reference data (Fig. 3B). For those formations showing strong similarity on the basis of normalized detrital zircon age distributions, we performed Kolmogorov-Smirnoff (K-S) statistical analysis for a quantitative measure of the probability of correlation between the samples' age distributions (Table DR1, parts 12–17 [see footnote 2]). The K-S test incorporates ages with analytical uncertainty, plus the proportion of analyses constituting each age peak, to compute a probability of correlation factor, P. Statistical similarity is shown by P values ≥0.05, up to $P = 1.0$, which signifies indistinguishable age distributions. Commonly P values for correlated units are 0.40–0.75.

RESULTS

All Tava detrital zircon samples contain a prevalent ca. 1330–970 Ma group of U-Pb ages for zircons that form a broad peak in age distribution diagrams (Fig. 3B), superimposed by a narrow age peak at ca. 1.1 Ga. Three of six Tava samples display sharply defined older peaks at ca. 1.7 and 1.4 Ga. All analyses younger than 800 Ma were highly discordant, not replicable from targeted analysis, and therefore insufficient to define a detrital zircon age population (Dehler et al., 2010; Gehrels, 2011) that would reduce the maximum age that is already known from crosscutting relationships.

The K-S statistical test for probability of correlation of U-Pb age distributions among Tava detrital zircon samples yields P values that range from

[2]GSA Data Repository Item 2014333, detrital zircon U-Pb geochronologic data for mature quartz sandstones of the Colorado Front Range, and statistical comparisons to detrital zircon reference data of the western United States, is available at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

0.23 to 1.00 (Table DR1, part 13 [see footnote 2]). Parent sample SH314-HOS yields P = 0.823 when compared to its crosscutting sill SH314-SI, and P = 0.986 for the proximal dike (MSCD). Parent samples WPCHR4 and SH314-HOS also show a high probability of correlation, P = 0.725. In contrast, the northernmost dike, WP113, which contains the same age groups as the other Tava samples, yields low P values of 0.30–0.00 when compared to other Tava samples (Table DR1, part 13 [see footnote 2]). Its lower probability of correlation reflects the lower abundance of detrital zircon ages that fall within the 0.97–1.33 Ga group (<30% of this sample; Table DR1, part 1 [see footnote 2]) versus older age groups (Fig. 3B).

Age distributions for Paleozoic sandstones differ from each other and from Tava sandstone, based on visual examination of age spectra (Fig. 3B) and K-S tests (Table DR1, parts 12–14 [see footnote 2]) for all but one sample pairing. Cambrian samples CSGU and CSWC display two distinct, isolated age peaks at ca. 1.70 and 1.44 Ga that resemble well-defined peaks in three Tava samples, but they lack the prominent 1.33–0.97 Ga age group. HARD-13 (Ordovician) displays ca. 1.85 and 2.71 Ga age groups that are absent in others. Ordovician–Devonian samples do contain 1.33–0.97 Ga zircons, albeit in low abundance compared to other ages; hence the K-S P values are low (P = 0.16 and 0.20) when compared to Tava samples. Defined age peaks of ca. 480 Ma distinguish the Devonian and Pennsylvanian samples from the Tava and Cambrian sandstones.

DISCUSSION: TAVA SANDSTONE PROVENANCE AND AGE

A salient feature in Tava sandstone detrital zircon distributions (Fig. 3B; Fig. DR1 [see footnote 2]) is the broad 1.33–0.97 Ga age peak, with sharply demarcated upper and lower bounds and high detrital zircon abundance. The age span and characteristics match the diagnostic detrital zircon population that is derived from the distant Grenville orogen, which is well represented in the global sedimentary record in strata of multiple time periods (Gehrels and Pecha, 2014) but with highest abundance in sedimentary rocks of Neoproterozoic to Cambrian age (Yonkee et al., 2014) due to the volume of sediment and zircon abundance in Grenville sources (Moecher and Samson, 2006; Rainbird et al., 2012). Well-defined age peaks at ca. 1.7 Ga, 1.4 Ga, and 1.1 Ga in Tava sandstone (Fig. 3B: age bands labeled PPB, Mpr, and PPr) likely derive from plutonic sources within the Rocky Mountain region (Van Schmus and Bickford, 1993) and are pervasive in detrital zircon reference data for western U.S. Neoproterozoic rocks (Yonkee et al., 2014). The "shoulder" ages of 940–825 Ma may derive from the porphyry phase of Pikes Peak Granite (Sanders and Hawkins, 1999).

Detrital zircon age distributions for Paleozoic units (Fig. 3B) differ from Tava and from each other, most notably in the lack or low abundance of Mesoproterozoic Grenville-aged zircons. The basal Cambrian sandstone yields no ages younger than 1.30 Ga, a surprising result insofar as the Sawatch Formation rests upon deeply weathered Pikes Peak Granite of ca. 1.0 Ga that might reasonably be expected to have provided detritus. Devonian and Pennsylvanian sandstones exhibit a subdued Grenville-aged peak with gradual slopes suggestive of sediment recycling, albeit with a pronounced 480 Ma age peak that is entirely lacking in the Tava and the Cambrian sandstones. As a consequence of these detrital zircon age differences (Fig. 3B), K-S comparison yields P values of 0.00 for most Paleozoic and Tava samples. Only the Ordovician sample BLACY-13 shows a low probability of correlation (P = 0.6–0.13; Table DR1, parts 12 and 14 [see footnote 2]) because it shares in common a modest quantity of ca. 1.0–1.3 Ga detrital zircons. The overall lack of correspondence in detrital zircon ages and abundances between Paleozoic and Tava sandstone samples provides compelling evidence that Tava sandstone is not Paleozoic in age. Since paleomagnetic evidence rules out the possibility of a Mesozoic or Cenozoic age for Tava sandstone (Kost, 1984; Dulin and Elmore, 2013), we conclude that Tava sandstone formed in Proterozoic time.

A comparison of U-Pb detrital zircon ages and abundances for Tava sandstone versus those of well-characterized siliciclastic units of western United States supports this hypothesis. Several Neoproterozoic units contain a Grenville-aged peak with secondary peaks at ca. 1.4 and 1.7 Ga attributable to igneous sources in the Rocky Mountains (Yonkee et al., 2104), specifically, the Uinta Mountain Group and middle Big Cottonwood Formation (Dehler et al., 2010), Perry Canyon and Kelly Canyon Formations (Balgord et al., 2013) of Utah, and the Nankoweap Formation of Arizona (Timmons et al., 2005; Fig. 3C). K-S comparisons of detrital zircon age distributions for Tava sandstone versus these formations yield unusually high P values ≥0.67, up to 0.99, for a number of units (Table DR1, part 15 [see footnote 2]). This is remarkable because of the distance that separates the Tava sandstone from the detrital zircon data reference units (Fig. 3C), which makes even the somewhat low but significant probability of correlation of P ~0.20 for Tava sandstone with the Horse Thief Springs Formation, California (Mahon et al., 2014), noteworthy. The similarity in detrital zircon ages and abundances for these formations suggests a common origin for detrital zircons and common age of deposition (in broad terms), and it suggests that Tava sandstone is a component of the record of the Neoproterozoic "great Grenvillian sedimentation episode" (Rainbird et al., 2012). Differences among Tava samples (e.g., WP113) are a possible record of local segmentation of sedimentary distribution systems, perhaps by uplifts of crystalline bedrock undergoing differential erosion.

The sedimentary formations that provide detrital zircon reference data for the Neoproterozoic Era are (1) constituents of a belt of fluvial to marginal marine siliciclastic strata that formed in intracratonic basins on Rodinia ca. 800–740 Ma (Dehler et al., 2012; Yonkee et al., 2014), or (2) parts of a rift assemblage controlled by generally N-S faults ca. 720–660 Ma (Balgord et al., 2013; Yonkee et al., 2014). On the basis of common detrital zircon age characteristics and very high probability of statistical correlation, we conclude that Tava sandstone represents a vestige of the 800–660 Ma intracratonic sediment distribution system and that its age of origin is Neoproterozoic. The intimate association of Tava sandstone with the N-S– to NW-oriented Ute Pass fault and the unusual physical conditions for formation of injectites were most plausibly achieved during seismicity (Jonk, 2010) related to initiation of the ancestral Ute Pass fault, involving rupture of continental crust, propagation of large fracture arrays (Dockal, 2005) and/or mass wasting (Siddoway et al., 2013), and liquefaction and remobilization of available sediment to form injectites. Tectonic exhumation and erosion of exposed crystalline basement may explain the presence of varied amounts of ca. 1.1, 1.4, and 1.7 Ga zircons derived from local igneous sources, with implications for development of a proto–Great Unconformity earlier than has been appreciated, by ca. 680 Ma. The compositional maturity of Tava sandstone (Scott, 1963) and variations in detrital zircon age provenance over small distances between Tava sample sites (this study) are paradoxes that remain to be explained. Because rocks of this age are otherwise unrepresented in the eastern Rocky Mountains, the Tava sandstone represents an illuminating new source of information with promise to deepen the understanding of Rodinia paleotectonics, paleogeography, and paleoclimate.

ACKNOWLEDGMENTS

Enthusiastic thanks go to D. Freedman, S. Shatmeyer, M. Rosales, A. Contreras, A. Cole, S. Elkind, C. Cadow, D. Goverman, and M. Petronis for their contributions. Acquisition of U-Pb data was achieved with the dedicated support of Mark Pecha, N. Giesler, and University of Arizona LaserChron Center (ALC) staff. Mineral separations were carried out by V. Valencia or using University of Wyoming facilities under the supervision of K. Chamberlain. Discussions with Jeff Amato, Carol Dehler, and Jay Temple aided in the identification of suitable detrital zircon reference data sets or field localities. Louisiana State University Geology and Geophysics and the residents of Majestic Park allowed access for sampling. The manuscript received constructive reviews from A. Weil, E. Balgord, and an anonymous reviewer. The National Science Foundation (grant EAR-1032156) supports the ALC and partially funded student users. NSF grant OPP-0944600 funded the training of Colorado College students, and Colorado College provided partial funds for analytical costs.

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MANUSCRIPT RECEIVED 11 MAY 2014
REVISED MANUSCRIPT RECEIVED 7 JULY 2014
MANUSCRIPT ACCEPTED 29 JULY 2014

Printed in the USA

Lithosphere, published online on 27 August 2014 as doi:10.1130/L390.1

Lithosphere

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Lithosphere published online 27 August 2014;
doi: 10.1130/L390.1

Notes