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NEW INSIGHT INTO THE HISTORY OF CLASTIC DIKES IN THE WESTERN SAN JUAN MOUNTAINS, SOUTHWESTERN COLORADO

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Abstract—Clastic dikes crosscut Paleozoic to Mesozoic strata in the western San Juan Mountains near Placerville and Ouray. These dikes trend W-NW for hundreds to thousands of meters and vary from tabular masses several meters thick to zones of bifurcating veins and breccia cemented by calcite. Clastic dikes near Ouray are exposed adjacent to, and cross cut, ~65 Ma granodiorite dikes and stocks and are overlain by ~30 Ma volcanic rocks. Near Placerville, clastic dikes crop out along fractures in Permian to Jurassic strata and have similar trends as some late Mesozoic to Cenozoic mafic to intermediate dikes, but are nowhere in direct contact with post-70 Ma intrusive rocks and lava flows. Clastic dikes exposed in the region are matrix- to clast-supported with angular to subrounded pebble- to boulder-sized fragments that are dominated by Proterozoic igneous and metamorphic rocks. A U-Pb detrital zircon-age analysis on a sample of clastic dike near Placerville yields zircon populations that are consistent with reworking of Proterozoic basement (1800 to 1400 Ma) and Paleozoic sedimentary rocks (500 to 350 Ma). Previous and current field investigations, and new fluid inclusion data, lend evidence that clastic dikes in the western San Juan Mountains formed by release of CO_2-charged volatiles at depths greater than 500 m where Proterozoic basement was fragmented, entrained, and transported to higher stratigraphic levels. Herein, we propose that the clastic dikes formed by release of volatiles along deep fractures, from degassing of plutons or mantle melts after 70 Ma.

INTRODUCTION

Numerous studies document clastic dikes in the western San Juan Mountains near Placerville (Haff, 1944; Bush et al., 1959; Bush et al., 1960) and Ouray (Ransome, 1901; Irving, 1905; Spurr, 1923; Burbank, 1930) (Figs. 1, 2, 3). Sandstone "injectites" found in stratigraphic sequences are commonly formed by upward release of over pressurized fluids and remobilized sediments during seismic events (e.g., summary in Braccini et al., 2008). A strong genetic relationship, however, is also noted between igneous intrusions and "clastic injectites" in some geologic settings (e.g., Planke et al., 2005; Moreau et al., 2012).

Hypotheses proposed for the origin of clastic dikes in the western San Juan Mountains are: 1) rapid release of volatiles and gases from nearby plutons (Burbank, 1930; Haff, 1944; Kelley and Silver, 1946; Bush et al., 1959; Bush et al., 1960; Burbank and Luedke, 2008); 2) fracture filling from overlying strata (Ransome, 1901); 3) "friction breccia" related to fault movement (Irving, 1905); and 4) infilling of fracture from upward movement of mud and sand under pressure (Spurr, 1923).

In the area between Sawpit and Placerville (Fig. 2), clastic dikes with trends ~290º are exposed in Permian to Jurassic sedimentary rocks. Numerous felsic to mafic plutons are exposed in this area, but the clastic dikes and plutons are nowhere in direct contact, and a clear genetic relationship with magmatic events is not established. North of Ouray, east-west trending clastic dikes often crop out next to Laramide granodiorite plutons, and in some locations crosscut ~65 Ma dikes and stocks (Burbank and Luedke, 2008; Gonzales, 2015; Fig. 3). Ransome (1901) noted that the clastic dikes exposed near Ouray are closely allied with some zones of mineralization (e.g., upper workings of the Bachelor mine). "Breccia dikes" associated with dioritic intrusive rocks and mineralized breccia pipes are also documented by Kelley and Silver (1946) in the Dunmore fissure system which is located ~8 km (~5 mi) south of Ouray.

Clastic dikes found near Placerville and Ouray (Figs. 2, 3) contain a wide range of detritus with a high proportion of fragments from the Proterozoic basement. Field evidence such as angular fragmentation and stoping of country rock adjacent to the dikes is consistent with the idea that the clastic dikes formed by the release of over-pressurized gas into fractures. The origin of the clastic dikes and the source of detritus in them, however, were unresolved in previous studies. Deciphering the origin and age of the clastic dikes is important to further understand the latest Mesozoic to Cenozoic magmatic history and related events in the region.

In this contribution, we summarize and compare the main features of clastic dikes at Ouray and Placerville with an emphasis on outcrop features and clast compositions. This work formed the basis for a U-Pb age analysis on detrital zircons from a clastic dike exposed near Placerville. Our preliminary results provide insight into the provenance of detritus in the dikes, potential depths at which the dikes originated, and the mechanisms that created them.

OVERVIEW OF CLASTIC DIKES IN THE WESTERN SAN JUAN MOUNTAINS

Clastic dikes found between Placerville and Sawpit ((Haff, 1944; Fig. 2) mostly crop out in the Permian Cutler and Triassic Dolores formations although several small segments are mapped in the Jurassic Entrada Sandstone (Bush et al., 1959;

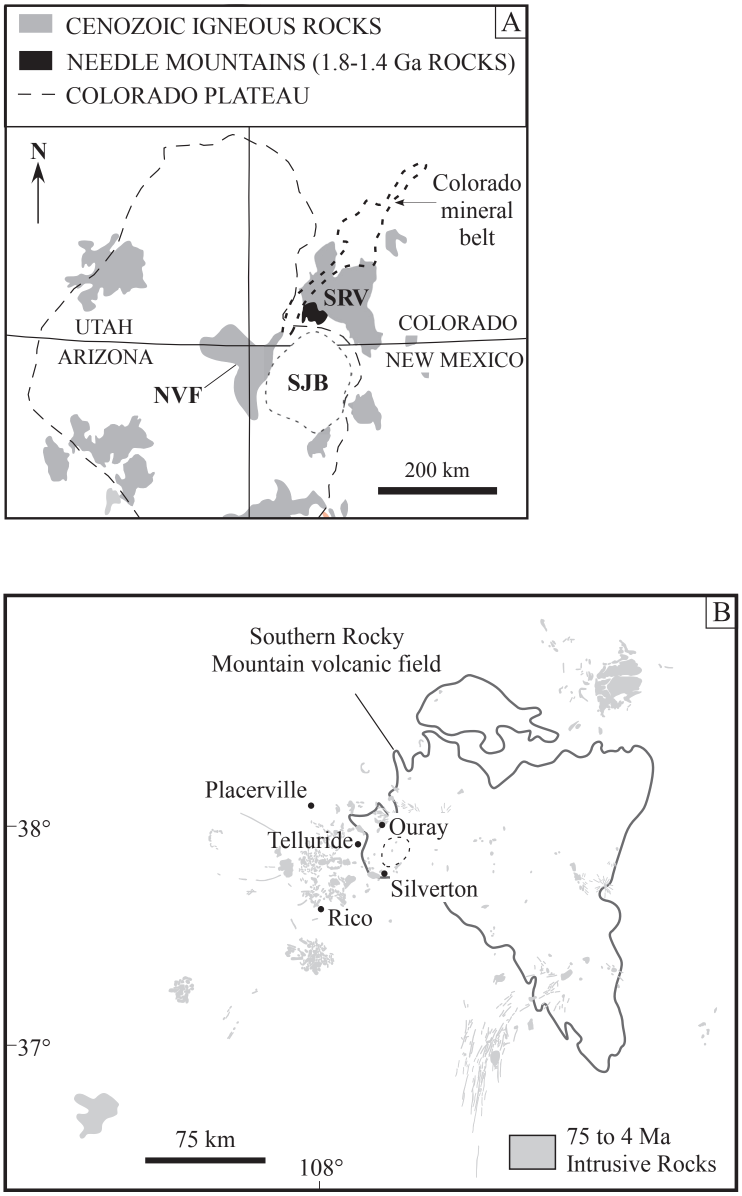

FIGURE 1. **A.** Generalized regional map showing major geographic and geologic provinces in the region: Southern Rocky Mountain volcanic field (SRV), San Juan Basin (SJB), and Navajo volcanic field (NVF); **B.** The general distribution of latest Mesozoic to Pliocene intrusive rocks (shown in gray) in the western San Juan Mountains (modified after Cunningham et al., 1994). The dashed line marks the approximate boundary of the Silverton caldera. The boundary shown for the Southern Rocky Mountain volcanic field delineates the magmatic locus of the field.

Bush et al., 1960). The dikes trend ~290º and dip 90º to 85º SW. Southeast of Placerville the clastic dikes terminate on north-trending and east-dipping normal faults (Fig. 2). This structural relationship led Bush et al. (1960) to argue that the clastic dikes were Tertiary in age, and possibly post-Miocene.

The clastic dikes at Placerville (Fig. 2) are exposed along strike for ~2.4 km (~1.5 mi) and range from several centimeters to 2 m wide (~6.5 ft). The margins of the dikes are usually distinct against the red clastic rocks of the Cutler Formation, but the contact zones in places are marked by angular fragments of country rock torn from the walls, pulverized, and incorporated into the dikes. The clastic dikes are mostly distinct tabular features, but some segments are defined by bifurcating and branching fractures, filled with calcite, that extend up to several meters on strike. The dikes vary from matrix to clast supported with angular to subrounded fragments set in a grayish white to brown matrix dominated by quartz, plagioclase, perthitic feldspar along with lesser biotite, muscovite, chlorite, and zircon. Haff (1944) also reported apatite, hornblende, and tourmaline in the sandy matrix. The groundmass is typically cemented with calcite and opaque oxides and some clasts are replaced by calcite; in a few outcrops small patches of malachite were noted.

Clasts in the Placerville dikes are typically less than a few centimeters up to 15 cm in maximum dimension, and are dominated by pieces of medium- to coarse-grained Paleozoic sandstone and fragments of Proterozoic rocks. A clast count (n = 100) (method of Howard, 1993) in one outcrop determined the following clast types and proportions: sandstone (n = 42), phyllite or shale (n = 30), Proterozoic quartzite (n = 4) and granite (n = 11), and equigranular diorite (n = 13). Although none were observed in this investigation, Haff (1944) reported non-fossiliferous limestone fragments in the clastic dikes. He also noted the alignment of “elongate and tabular” lithic fragments with the dike margins which he interpreted as evidence of “forcible intrusion or injection” of the clastic material. In a 10-m-long section of one clastic dike at Placerville, we discovered three rounded fragments that spanned the entire 0.3-m width of the dike. The fragments are Proterozoic porphyritic granite, quartzite of the Uncompahgre Group, and granodiorite. These boulders are encased in dike material, and appear to have been transported with the matrix. Fragments of this size, however, were not observed elsewhere in the Placerville dikes so were are cautious in interpreting them as “injectite” fragments.

Clastic dikes exposed just north of Ouray (Fig. 3) are near vertical and trend ~90˚, but the trends are quite variable in some outcrops. These dikes crop out in Permian to Cretaceous sedimentary rocks, and some are adjacent to ~65 Ma granodiorite dikes (Gonzales, 2015). At a few locations, north of Ouray, granodiorite to diorite dikes exhibit fragmentation from the release of magmatic volatiles; these dikes appear to be transitional phases between unfragmented graniodiorite dikes and the clastic dikes. Previous mapping showed (Luedke and Burbank, 1962; Luedke and Burbank, 1981) that the clastic dikes locally crosscut and stoped the granodiorite plutons, but do not extend into the Oligocene San Juan Formation. These relationships demonstrate that the Ouray clastic dikes were emplaced between 65 and 30 Ma (Burbank and Luedke, 2008; Gonzales, 2015).

The clastic dikes at Ouray vary in thickness from several centimeters up to 3 m (~9.8 ft); in some outcrops the breccia grades into bifurcating calcite-filled fractures. Outcrops are matrix to clast supported with rounded to angular fragments ranging from less than 2 cm to 35 cm. The fragments are dominated by Proterozoic rock types: 1) phyllite and quartzite of

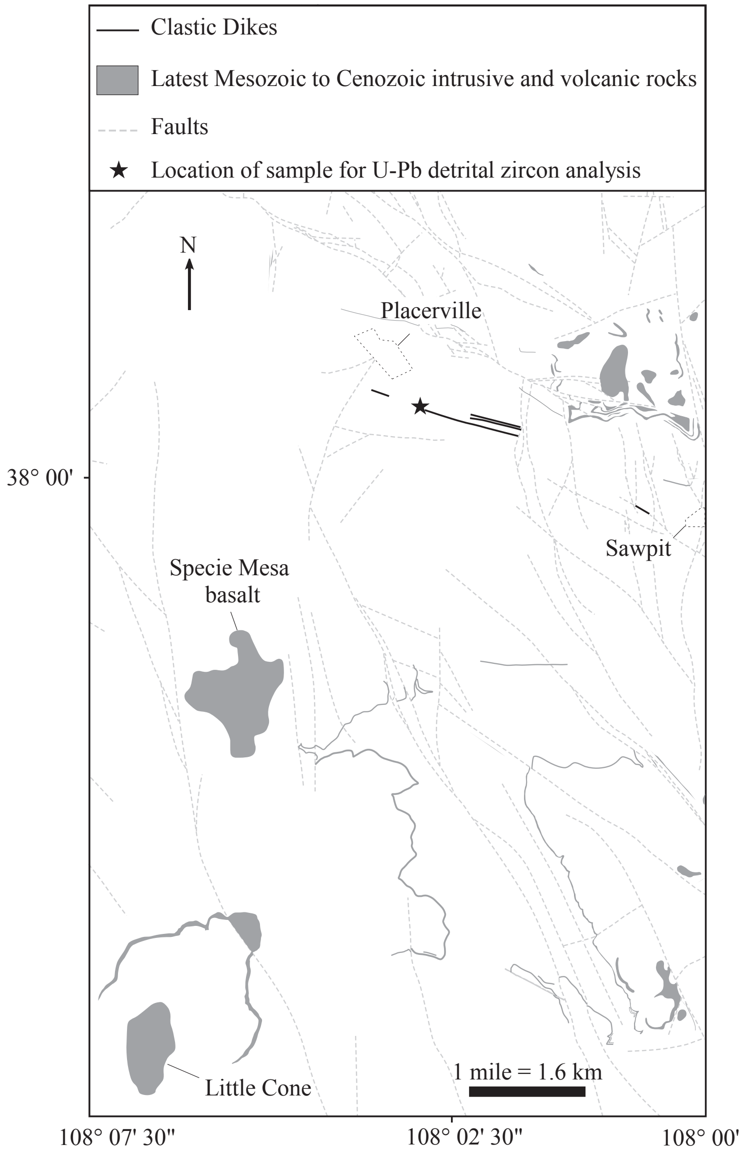

FIGURE 2. General geology in area around Placerville showing the relationship of clastic dikes to latest Mesozoic to Cenozoic plutons and Specie Mesa lava flow, and faults. The area colored white on the figure represents undivided Paleozoic to Mesozoic sedimentary rocks.

the Uncompahgre Formation, 2) 1.7 to 1.4 Ga granites, and 3) minor felsic to mafic gneiss and schist that are similar to rocks in the 1800-1750 Ma Irving Formation and Twilight Gneiss (Gonzales and Van Schmus, 2007). A 100-point clast count on a single outcrop identified clasts of Proterozoic granite and diorite (n=53), Uncompahgre quartzite (n=16) and phyllite (n=19), and sandstone (n=12). Although the contacts with the country rock are generally sharp and well defined, angular fragments of adjacent rocks are often incorporated into the clastic dikes. The matrix of the clastic dikes consists of medium- to very coarse-grained sand and granules composed mostly of quartz, biotite, and feldspar (Burbank and Luedke, 2008). The rocks also contain secondary calcite, chlorite and epidote which imparts a green tinge to most outcrops; in a few locations minor pyrite, chalcopyrite, and malachite were noted. Compared to the Placerville dikes, the matrix in the Ouray dikes is much finer grained.

Field evidence establishes that clastic dikes in the western San Juan Mountains are not "sandstone" dikes formed by remobilization of sediment from Paleozoic to Mesozoic strata. We argue that Proterozoic fragments in the clastic dikes were forcefully stoped from depths over 500 m (~1600 ft) below the modern exposed surfaces (depths shown in cross sections by Bush et al., 1959 and Luedke and Burbank, 1962) by pressurized volatiles that transported material along existing fractures or newly developed pathways related to dike emplacement. The types and proportions of basement rocks are similar in many respects to xenoliths found in dikes and breccias associated with diatremes of the ~25 Ma Navajo volcanic field (e.g., Condie and Selverstone, 1999).

DETRITAL ZIRCON U-PB ANALYSES

U-Pb ages of detrital zircons can constrain the provenance of detritus in sedimentary rocks and clastic dikes (e.g., Siddoway and Gehrels, 2013) by matching the ages of zircon populations with the detrital-zircon ages in potential source rocks. For the clastic dikes in the western San Juan Mountains, constraining the sources is complicated by the fact that these features breached and recycled rocks from the Proterozoic basement into Mesozoic strata.

We sampled about 15 kg of rock from the most extensive of the clastic dikes (Fig. 4) near Placerville on Highway 145 at location 38.008309 N, 108.045394 W (indicated by star on Fig. 2). Only the matrix material was selected for processing to avoid biasing the sample with given clast types. Zircon crystals were extracted from the sample at The University of Arizona LaserChron Center by standard methods; an in-depth discussion of these methods is provided at *https://drive.google.com/file/d/0B9ezu34P5h8eTU9PaUczTGc5elk/view*. Zircon separates were mounted onto a 1-in-diameter epoxy puck along with fragments or loose grains of Sri Lanka, FC-1, and R33 zircon crystals that were used as primary standards. The surface of the epoxy mounts was sanded down to a depth of ~20 microns, polished, imaged using a Gatan Chroma cathodoluminescence (CL) detector coupled to a Hitachi S2400 scanning electron microscope, and cleaned prior to isotopic analysis.

U-Pb geochronology of zircons was conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008; Gehrels and Pecha, 2014). The analyses involved ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 15 microns at selected points. The ablated material was carried by helium into the plasma source of an Element2 HR ICPMS, which sequences rapidly through U, Th, and Pb isotopes. With the laser set to an energy density of ~5 J/cm^2, a

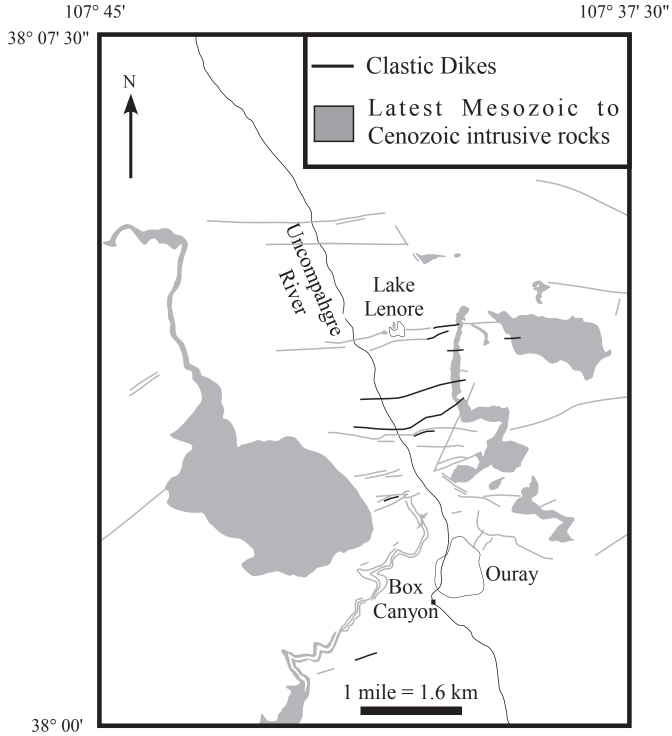

FIGURE 3. General geology in vicinity of Ouray showing the relationship of clastic dikes to latest Mesozoic to Cenozoic plutons, and faults. Light gray lines represent dikes and sills. The area colored white on the figure is undivided Paleozoic to Cenozoic sedimentary, and Cenozoic volcanic rocks. Modified after Burbank and Luedke (2008).

repetition rate of 8 Hz, and an ablation time of 10 seconds, ablation pits were ~12 microns in depth. Following analysis, data reduction was performed with an in-house Python decoding routine and an Excel spreadsheet (E2agecalc) to generate the final dataset. A complete set of U-Pb zircon age data is available in the NMGS data repository.

RESULTS

Detrital zircons (n =102) from the Placerville sample (Fig. 2) define several discrete peaks on the age-probability plot (Fig. 5). Most of the zircons (n=93) were ultimately derived from 1815 to 1389 Ma bedrock sources (Fig. 5), comparable in age to 1800 to 1400 Ma basement rocks in southwestern Colorado (Gonzales and Van Schmus, 2007). Zircons ages from 1815 to 1693 Ma (n=25) fall in the spectrum of ages (1800 to 1690 Ma; Gonzales and Van Schmus, 2007) for Paleoproterozoic metamorphic rocks and syn- to post-orogenic granites. The dominant group of zircon ages from 1472 to 1389 Ma (n=65) are similar in age to ~1.4 Ga granitic to gabbroic intrusive rocks in the Needle Mountains. The possible sources of three zircon ages (1679 Ma, 1668 Ma, 1318 Ma) are uncertain since exposed rocks of this age are not documented in the region. A smaller population of zircons define a distinct probability peak with ages from 524 to 494 Ma (n=8), and an age of 374 Ma was determined for a single zircon (Fig. 5).

DISCUSSION

We agree with previous interpretations (Burbank, 1930; Haff, 1944; Kelley and Silver, 1946; Bush et al., 1959; Bush et al., 1960; Burbank and Luedke, 2008) that the clastic dikes exposed near Placerville and Ouray formed by rapid subsurface release of gas which transported Proterozoic to Mesozoic sedimentary clasts to the point of deposition. The dominance of Proterozoic clasts (Haff, 1944; this study) and zircons in the clastic dikes indicate that gas migrated through basement rocks at depths in excess of 500 m (Placerville, Bush et al., 1959) to 1000 m (Ouray, Luedke and Burbank, 1962; Luedke and Burbank, 1981) below the current level of exposure.

The clastic dikes in the western San Juan Mountains are exposed in areas where numerous late Mesozoic to Cenozoic plutons were emplaced. The clastic dikes exposed near Ouray (Fig. 3) show a close spatial relationship to Laramide plutons, and were emplaced sometime between 65 and 30 Ma (Burbank and Luedke, 2008; Gonzales, 2015). An igneous connection with the clastic dikes near Placerville is not as clear. There are numerous post-70 Ma felsic to mafic plutons exposed in near Placerville (Fig. 2), and the proximity and similar trends of the clastic dikes and "andesitic" dikes (Bush et al., 1959) in the area hints at a possible connection.

The results of our detrital zircon analyses reveal that matrix material in the clastic dikes contain a high proportion of Proterozoic zircons, most of which are similar in age to provincial basement rocks. The potential sources of these Proterozoic zircons are: 1) directly from 1.8 to 1.4 Ga crystalline basement or 2) from reworked Proterozoic detritus in Pennsylvanian to Permian conglomerates and sandstones. Present data are unable to resolve the relative proportions of zircons from these potential sources. We contend, however, that crystalline basement made a significant direct contribution to detritus in the clastic dikes, as opposed to recycling of Proterozoic zircons in Paleozoic to Mesozoic strata.

Clasts of Proterozoic rocks are contained in the conglomerates of the Pennsylvanian Hermosa Formation and Permian Cutler Formation. They generally, however, make up <15% of clast populations and are mostly rounded to subrounded fragments of quartzite along with minor granite. In contrast, clast populations in the clastic dikes contain a wider variety of Proterozoic rock types (quartzite, phyllite, granite, felsic to mafic schist and gneiss) which can exceed 75% of all the total clast population in given outcrops.

U-Pb analyses on 34 zircons extracted from a sample of granodiorite exposed at Lone Cone ~6 km (~10 mi) southwest of Placerville reveal that all were inherited from Proterozoic basement. The majority of these xenocrystic zircons (n = 31) yielded ages of 1458 and 1422 Ma while 3 zircons ages of 1767 to 1645 Ma. A crystallization age was not constrained for the stock at Lone Cone, but a sample of similar hornblende granodiorite from a sill ~3 km south of Little Cone (Fig. 2) yielded an Ar/Ar age of ~27 Ma (personal communication with Matt Heizler, 2017). U-Pb analyses on zircons from the Little Cone sample also revealed inherited xenocrysts ranging from 1754 to 1182 Ma. These and previous published data (Gonza-

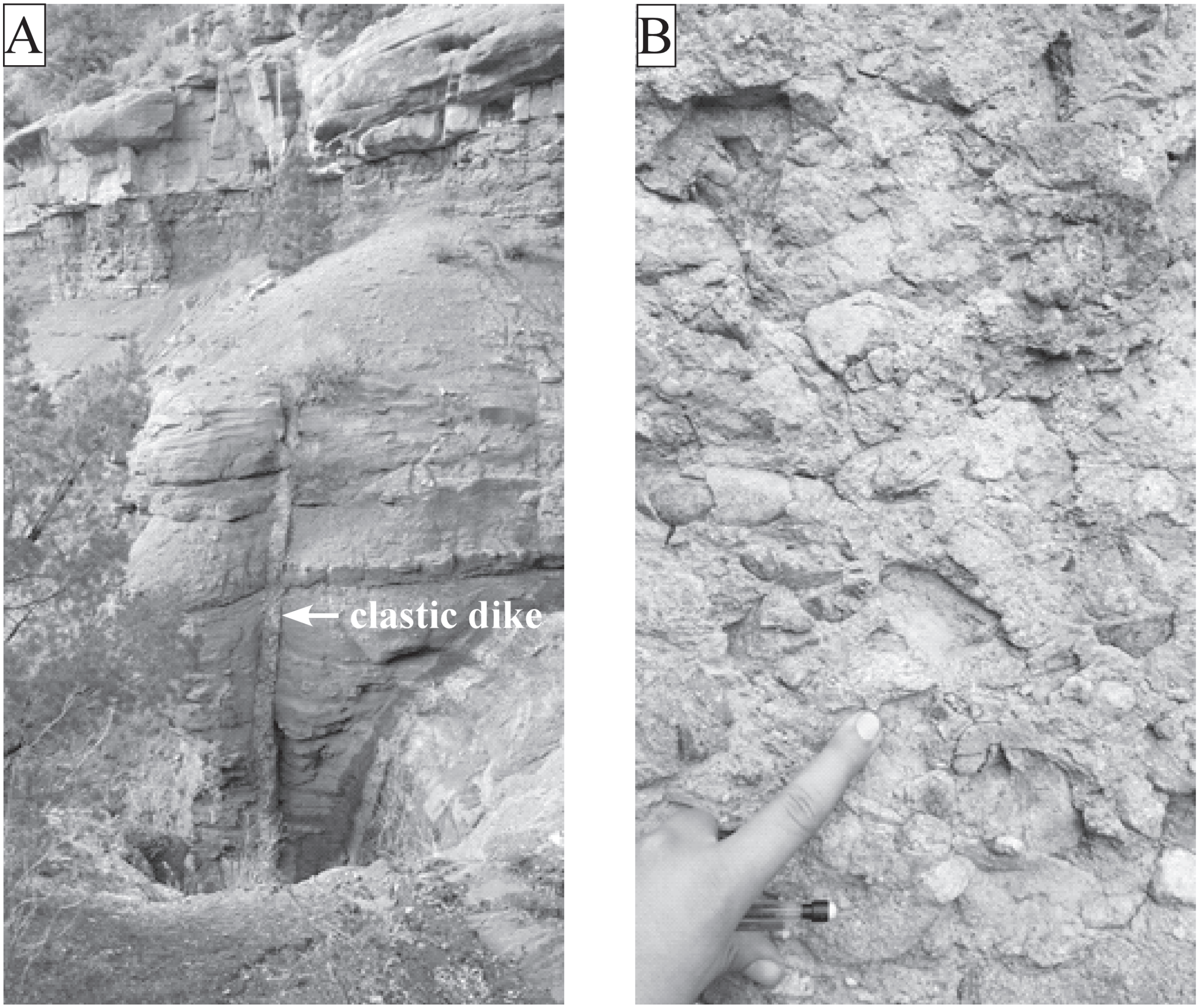

FIGURE 4. **A.** Photograph of a clastic dike, ~0.4 m wide, cutting the Permian Cutler Formation near Placerville. **B.** Close up of outcrop exhibiting dispersed subangular to subrounded pebbles and cobbles within an unsorted and ungraded, coarse sandy matrix.

les, 2015) establish a major contribution of Proterozoic basement to magma production from 75 to 25 Ma. This evidence confirms the presence of 1800 to 1400 Ma basement beneath the Placerville-Ouray area that could contribute fragments and xenocrystic zircons to magmatic volatiles that were released at depth.

The 524 to 494 Ma population peak (Fig. 5), and the single 374 Ma zircon, were probably derived by reworking of detritus in Paleozoic strata. The provenance of zircons is uncertain, but regional detrital zircon studies on Paleozoic to Mesozoic strata offer several different possible sources: 1) a Pan African source for 700 to 500 Ma zircons (Dickinson and Gehrels, 2003); 2) a south-southeasterly source (e.g., Mexico/Texas) for 440-370 Ma zircons (Soreghan et al., 2003; Gehrels et al., 2011); and 3) erosion of Paleozoic bedrock flanking the Appalachian orogenic belt for 640-270 Ma zircons (Dickinson and Gehrels, 2003; Gehrels et al., 2011). Thomas (2011) also noted that zircons found in Paleozoic sedimentary rocks in the area could have come from 664 to 427 Ma plutons in Colorado and New Mexico, and 780 to 485 Ma igneous rocks that formed on the western edge of North America.

The high proportion of calcite in cement, fractures, and vugs found in the clastic dikes is analogous to syn-magmatic calcite-rich breccias associated with minette dikes in the ~24 Ma Navajo volcanic field and 8 to 4 Ma mafic dikes exposed from Rico to Placerville (Gonzales, 2015). Preliminary analyses (n=4) of fluid inclusions in calcite from a clastic dike at Placerville indicate they are nearly pure CO_2 (0.956 to 0.982 ccSTP/cc) with ~15% contribution from mantle He (Rc/Ra = 0.756 to 0.851) (personal commun. with Tom Darrah, The Ohio State University, 2017). These data are consistent with a magmatic contribution to carbonate found in the dikes. The

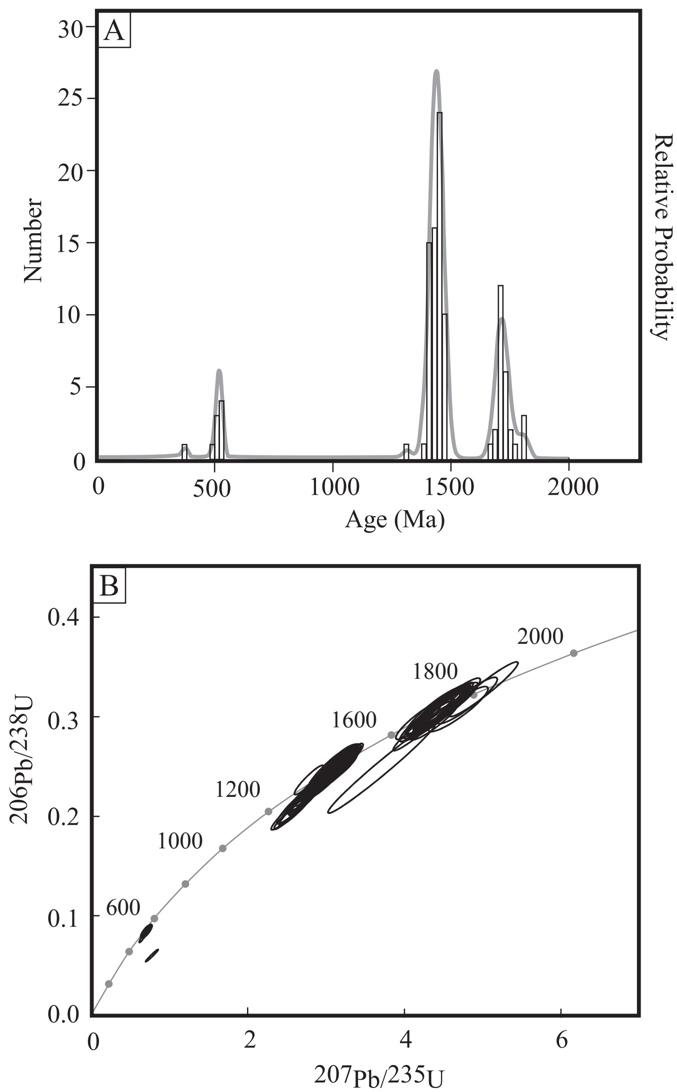

FIGURE 5. **A.** Probability plot for the detrital zircons from the clastic dike sampled at Placerville. Note that the dominant populations are similar to ages of Proterozoic basement in the region; **B.** Concordia plot of the U-Pb data.

release of mantle-derived CO_2-gas in modern thermal springs is documented at Rico about 60 km (~37 mi) south of Placerville (Easley and Morgan, 2013). The eruption of the Specie Mesa basalt at 614±5 ka (Fig. 2) (Gonzales and Lake, 2016) could also have involved the release of high volumes of CO_2-rich gas as indicated by the abundance of calcite in vesicles and vugs. Although more evidence is needed to fully test the relationship between magmatism and the clastic dikes in the region, we propose that these events are directly related. This is further supported by $CO_2/^3He$ ratios of 7.72 to 8.84 x 109 that were measured in the fluid inclusions in calcite samples. These ratios are similar to those reported for gas samples from modern regional geothermal systems which are interpreted as a mixture of asthenospheric mantle, lithospheric, and deep crustal sources (e.g., Karlstrom et al., 2013).

Our working hypothesis is that clastic dikes in the western San Juan Mountains were formed by the release of CO_2-charged volatiles at depths of at least 500 m within the Proterozoic basement. Upward migration of pressurized volatiles stoped overlying Proterozoic to Mesozoic rocks creating the mixture of clastic material that was emplaced along pre-existing or newly developed fractures. Evidence from a variety of geologic settings establish that "sand injectites" are often associated with rapid gas release from igneous intrusions, hydrothermal vents, and subsurface diatreme eruptions into sedimentary successions (e.g., Planke et al., 2005; Svensen et al., 2006; Lock et al., 2007; Wall et al., 2010; Moreau et al., 2012). There is currently not enough evidence to fully constrain the mechanism that led to the formation of clastic dikes in the western San Juan Mountains. Subsurface volatiles could have formed by: 1) expulsion of volatiles from hypabyssal plutons; 2) interaction of magmas with aquifers; or 3) or discharge of gas from asthenospheric and lithospheric mantle melts. In any case, the mechanism that created the clastic dikes required the transfer of volatiles from depths where Proterozoic basement was encountered. The gases released in these events counterbalanced the lithostatic pressure at shallow depths, leading to injection of fragmented material along existing fractures and vertical conduits, and possibly eruptions at the surface along small vents or geothermal springs.

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