ABSTRACT

A shift in the depositional systems and tectonic regime along the western margin of Laurentia marked the end of the Paleozoic Era. The record of this transition and the inception and tectonic development of the Permo-Triassic Cordilleran magmatic arc is preserved in plutonic rocks in southwestern North America, in successions in the distal back-arc region on the Colorado Plateau, and in the more proximal back-arc region in the rocks of the Buckskin Formation of southeastern California and west-central Arizona (southwestern North America).

The Buckskin Formation is correlated to the Lower–Middle Triassic Moenkopi and Upper Triassic Chinle Formations of the Colorado Plateau based on stratigraphic facies and position and new detrital zircon data. Calcareous, fine- to medium-grained and locally gypsiferous quartzites (quartz siltstone) of the lower and quartzite members of the Buckskin Formation were deposited in a marginal-marine environment between ca. 250 and 245 Ma, based on detrital zircon U-Pb data analysis, matching a detrital-zircon maximum depositional age of 250 Ma from the Holbrook Member of the Moenkopi Formation. An unconformity that separates the quartzite and phyllite members is inferred to be the Tr-3 unconformity that is documented across the Colorado Plateau, and marks a transition in depositional environments. Rocks of the phyllite and upper members were deposited in wholly continental depositional environments beginning at ca. 220 Ma. Lenticular bodies of pebble to cobble (meta) conglomerate and medium- to coarse-grained phyllite (subfeldspathic or quartz wacke) in the phyllite member indicate deposition in fluvial systems, whereas the fine- to medium-grained beds of quartzite (quartz arenite) in the upper member indicate deposition in fluvial and shallow-lacustrine environments.

The lower and phyllite members show very strong age and Th/U overlap with grains derived from Cordilleran arc plutons. A normalized-distribution plot of Triassic ages across southwestern North America shows peak magmatism at ca. 260–250 Ma and 230–210 Ma, with relatively less activity at ca. 240 Ma, when a land bridge between the arc and the continent was established.

Ages and facies of the Buckskin Formation provide insight into the tectono-magmatic evolution of early Mesozoic southwestern North America.

INTRODUCTION

Early Mesozoic sedimentary successions in southwestern North America record a shift from a primarily carbonate- and clastic-dominated platform to continental-fluvial depositional systems (Lawton, 1994), coinciding with a change in the tectonic setting of the southwestern margin of Laurentia from passive to convergent (Lawton, 1994; Dickinson and Lawton, 2001). Permian strata from the forearc or arc-proximal areas, exposed in northwestern Sonora (Mexico) and south-central California (USA), record nascent subduction along the western margin of Laurentia (Rains et al., 2012; Dobbs et al., 2016). On the Colorado Plateau, Triassic marginal-marine and fluvial successions are the earliest retro-arc sedimentary record of the development of the early Mesozoic Cordilleran arc (Cadigan, 1971; Stewart et al., 1972b; Riggs et al., 2012, 2016). The Lower–Middle Triassic Moenkopi Formation (Fig. 1) has rare arc-derived detritus (Dickinson and Gehrels, 2008; Riggs et al., 2017), whereas the Upper Triassic Chinle Formation contains abundant volcanic detritus and clasts that record arc magmatism, most plausibly from the Mojave Desert segment of the Cordilleran arc (Riggs et al., 2012, 2016). Variably metamorphosed upper Paleozioc and lower Mesozoic sedimentary successions in western Arizona, southeastern California, and northern Sonora are exposed closer to arc-related plutonic rocks and should therefore provide a record of arc initiation and the earliest sedimentary transport of arc-derived material. The Buckskin Formation (Fig. 1) of west-central Arizona and southeastern California has been tentatively correlated with the Lower–Middle Triassic Moenkopi and the Upper Triassic Chinle Formations based on stratigraphic position and facies (Reynolds and
Spencer, 1989; Hargrave, 1999), and we demonstrate that it preserves a record of the initiation of Cordilleran arc magmatism.

The Buckskin Formation has also been considered critical in understanding patterns of uplift within the arc. Reynolds et al. (1989) documented an early Mesozoic uplift that they speculated was influential in supplying detritus to Upper Triassic and Lower Jurassic Colorado Plateau sedimentary basins, based on an unconformity that separates the Buckskin Formation from the overlying Vampire Formation. The Buckskin Formation therefore provides an excellent opportunity to investigate the influence of the incipient Cordilleran magmatic arc on proximal and regional depositional systems and to enhance our understanding of the paleogeographic region between the arc and the basin system in the back-arc region. This study provides additional stratigraphic detail and uses detrital zircon geochronology to (1) confirm regional correlation of the Buckskin Formation to the Triassic successions of the Colorado Plateau, (2) determine the maximum depositional age of the Buckskin Formation and thus constrain the earliest retro-arc detrital record of early Mesozoic Cordilleran arc magmatism, and (3) relate the detrital zircon record of the Buckskin Formation to early Mesozoic regional tectonics and the influence of the nascent magmatic arc on regional depositional systems.

**BACKGROUND**

**Permo-Triassic Geologic Setting and Paleogeography**

The tectonic development of the Permian–Triassic Cordilleran margin is recorded by the sedimentary successions of basins that developed in response to the Sonoma orogeny and to the incipient Cordilleran magmatic arc (Blakey, 1989; Dickinson, 1992; Miller et al., 1992; Saleeby et al., 1992; Lawton, 1994). Prior to development of the arc, a transcurrent fault (California-Coahuila fault of Dickinson [2000]; Fig. 1) brought dominantly passive-margin tectonism to a close beginning in Pennsylvanian time (see summary in Stevens et al. [2005]) and translated crustal slivers southeastward along the margin (Dickinson, 2000; Saleeby, 2011). A record of earliest arc magmatism is preserved in ca. 275 Ma plutonic suites in the Mojave and Sonoran Deserts (Walker, 1987; Barth et al., 1997; Barth and Woodward, 2006; Arvizu et al., 2009; Riggs et al., 2009; Arvizu and Iriondo, 2015; Cecil et al., 2018). For the most part, these granitic suites intrude Proterozoic crust of the Mojave and Yavapai provinces and overlying Paleozoic miogeoclinal shelfal deposits (Barth et al., 1997; Arvizu et al., 2009; Arvizu and Iriondo, 2015). The Cordilleran magmatic arc formed above an east-dipping subduction zone, likely in response to tectonic conversion of the transcurrent fault that cut across the passive margin in late Paleozoic time (i.e., induced nucleation of subduction; Stern, 2004).

**Lower Mesozoic Sedimentary Units in Western Arizona and Southeastern California and on the Colorado Plateau**

**Buckskin Formation**

The Triassic Buckskin Formation is the oldest Mesozoic stratigraphic unit in the deserts of western Arizona and southeastern California. It is thickest and best exposed in the Buckskin and Palen Mountains (Reynolds and Spencer, 1989; Hargrave, 1999), but is also exposed in the Midland syncline region of the
Little Maria Mountains (Fig. 1) and in stratigraphic and structural fragments in other ranges throughout western Arizona and southeastern California (Fig. 1). The Buckskin Formation disconformably overlies the Permian Kaibab Formation (Reynolds et al., 1989; Hargrave, 1999), the uppermost unit of the Paleozoic passive-margin platform succession in the region, along a contact that is well exposed in the Palen Mountains but crops out only locally elsewhere (Stone and Kelly, 1989; Hargrave, 1999). The Buckskin Formation is divided into four members (Figs. 2, 3A, and 3B): (1) the lower member variably consists of quartzose to quartzofeldspathic sandstone and siltstone, phyllite, sandy metapelite, chloritic schist, and gysiferous rocks; (2) the quartzite member is a massive to indistinctly bedded quartzite; (3) the phyllite member variably consists of phyllite, slate, phyllicitic siltstone, micaceous sandstone, and conglomerate; and (4) the upper member is massive to poorly bedded, moderately to well-sorted quartz (Reynolds and Spencer, 1989; Reynolds et al., 1989; Hargrave, 1999). The Buckskin Formation has a structural thickness of as much as 900 m in the Buckskin Mountains (Reynolds et al., 1989) and >500 m in the Palen Mountains. The lower two members of Buckskin Formation have been correlated to the lower two members of the Buckskin Formation. Elsewhere, the unconformity that separates it from the overlying Jurassic Vampire Formation (Reynolds et al., 1987, 1989; Reynolds and Spencer, 1989; Hargrave, 1999). The depositional environments of the lower two members of the Buckskin Formation have been interpreted as shallow marine to marginal marine, whereas the upper two members represent continental fluvial to possibly shallow-lacustrine depositional systems (Hargrave, 1999).

The uppermost Buckskin Formation is regionally truncated by an irregular unconformity that separates it from the overlying Jurassic Vampire Formation (Reynolds et al., 1989). This unconformity is best exposed in the Buckskin Mountains where it cuts downsection from west to east across the upper three members of the Buckskin Formation. Elsewhere, the unconformity reflects erosional removal of all Paleozoic and early Mesozoic rocks, locally exposing Proterozoic basement (Reynolds et al., 1989). Subsequent to the deposition of the Buckskin and Vampire Formations and overlying Jurassic volcanic rocks, the region proximal to the arc experienced several episodes of deformation and metamorphism (Reynolds et al., 1988) that subjected the Buckskin units to lower- to middle-greenschist-facies conditions (Reynolds and Spencer, 1989). These episodes modified the original thicknesses of the members of the Buckskin Formation and destroyed most of the primary sedimentary structures, complicating paleogeographic reconstructions and correlations of Mesozoic units to those of the Colorado Plateau (Reynolds et al., 1989). Sections in which sedimentary structures are preserved provide the basis for environmental interpretations.

**Moenkopi Formation**

The Moenkopi Formation is the oldest regional sedimentary succession of the Triassic Period in southwestern North America and has been interpreted to represent a complex of deposits formed in continental and marine environments (McKee, 1954; Stewart et al. 1972a). The unit is bounded stratigraphically by regional unconformities that generally separate the Moenkopi Formation from both underlying Pennsylvanian or Permian strata and the overlying Chinle Formation on the Colorado Plateau (Stewart et al., 1972a; Pipirigos and O’Sullivan, 1978). Fluvial deposits in the east grade laterally to marine deposits toward the west (Dubiel, 1994; Fig. 4A). Paleocurrent indicators in the Moenkopi Formation primarily record sediment transport toward the northwest and west with a dominant source region to the east (Stewart et al., 1972a; Dubiel, 1994), but also record less-prominent southern and western sources of detritus (Stewart et al., 1972a).

In southern Nevada, northwestern Arizona, and southwestern Utah, the Moenkopi Formation is divided into six members: (1) the Timpoweap Member is variably composed of siltstone, limestone, and a chert-pebble conglomerate; (2) the lower red member comprises horizontally stratified to structureless siltstone; (3) the Virgin Limestone Member is interbedded limestone and siltstone; (4) the middle red member consists of horizontally laminated siltstone with interbedded gypsum layers; (5) the Shnabkaib Member comprises thick beds of red siltstone, gypsum, and some dolomite and limestone; and (6) the upper red member includes laminated siltstone with variable beds of ripple-laminated siltstone and cross-stratified sandstone. These members together represent cycles of transgression and regression (Stewart et al., 1972a).

**Chinle Formation**

A widespread paleosol marks the unconformity between the Moenkopi Formation and overlying strata (Stewart et al., 1972a; Dickinson and Gehrels, 2008). Across the Colorado Plateau, the Upper Triassic Chinle Formation disconformably overlies this paleosol in places and fills deep paleovalleys cut into the Moenkopi in others (Stewart et al., 1972b). Paleocurrent indicators in the Chinle Formation are highly variable but suggest that sediment was dominantly transported toward the northwest, though the abundant volcanic detritus in the deposit implies some sediment transport from the magmatic arc developing to the west and southwest (Stewart et al., 1972b; Blakey and Gubitosa, 1983; Lupe and Silberling, 1985; Lucas and Marzolf, 1993; Riggs et al., 1996; Howell, 2010; Howell and Blakey, 2013).

The lower, volcaniclastic part of the Chinle Formation in northern Arizona is broadly divided into four distinct units that reflect continental depositional environments: (1) the Shinarump Conglomerate and Mesa Redondo Member are thin but extensive, cross-stratified, fine- to coarse-grained sandstone with lenses of conglomerate; (2) the Blue Mesa and Bluewater Creek Members are claystone to clay-rich sandstone and siltstone; (3) the Sonsela Member comprises siliceous conglomeratic sandstone; and (4) the Petrified Forest Member is a variable bentonitic mudstone to sandstone unit that is the thickest and most extensive member of the Chinle (Stewart et al., 1972b; Woody, 2006; Martz and Parker, 2010). The upper part of the formation comprises the Owl...
a) Palen Mountains
Jurassic(? ) Vampire Formation

Phyllite member

Quartzite member

Upper member

Lower member

Permian Kaibab Formation

3-4 m beds, fine to medium grained

1-8 m beds; fine to medium grained

basal cgl w/ 1-3 cm quartzite clasts

0.5-2 m; interbedded very fine grained phyllitic quartzite and fine grained phyllite

float blocks dominated by gypsiferous phyllite

b) Buckskin Mountains
Jurassic(? ) Vampire Formation

Explanation

Quartzite, light grey; calcareous; weakly to strongly foliated

Phyllite, pale to blue green or grey to pink-grey; weakly to strongly foliated

Quartzite, white to silvery blue-green or greenish-white, grey, brown; may be calcareous

Quartzite, grey to green, thin to thick bedded; may be calcareous or foliated

Metaconglomerate, silvery green; pebble- to cobble-size quartzite clasts

Gypsiferous phyllite, silvery blue-green; weakly to strongly foliated

Marble, grey to light pink, weakly to strongly foliated

Covered interval; underlying pattern shows likely substrate lithology

Coarsening-upward sequence

Zircon sample

indistinct 3-4 m bed following local quartz-clast layers; clasts < 3 cm

fine to medium grained

very fine to medium grained

quartzite clasts < 5 cm

interbedded very fine to coarse grained, 2-5 m

distinct 10-20 cm porcellanite beds common

interbedded quartzite and phyllite

1-3 m interbeds of non-gypsiferous quartzite

interbedded 2-3 m fine-grained quartzite and 1 m micaceous quartzite

Buckskin-Rawhide detachment fault

phyllite and quartzite

Figure 2. Composite stratigraphic logs of the Buckskin Formation in the Palen Mountains and Buckskin Mountains; scale in meters. See Table 1 for sample numbers and locations of starred zircon samples. Grain size designations: vf—very fine; f—fine; m—medium; c—coarse; vc—very coarse; p—pebble; co—cobble. See Sanchez (2015) for detailed stratigraphic logs. cgl—conglomerate.
Figure 3. Buckskin Formation. (A) Panoramic view of overturned Buckskin Formation (overturned) at Palen Pass, Palen Mountains. Rounded hills with poor exposure are characteristic of the fine-grained and gypsiferous lower member. Yellow-orange lines indicate contacts between units. Photo taken at 33.90837°N, 115.06376°W, looking east. Flat bench in foreground is ~100 m in length. (B) Phyllite, quartzite, and upper members. Photo taken at 34.21007°N, 114.00854°W, looking west-northwest. Cliff of resistant upper Buckskin Formation is ~10 m high.

Figure 4. (A) Facies patterns in the Moenkopi and lower Buckskin Formations, after Stewart et al. (1972a). The lower Buckskin Formation correlates well with quiet-water facies of the Moenkopi Formation; note that facies follow a northeast trend. (B) Facies patterns in the Chinle Formation, after Stewart et al. (1972b); note that facies in the terrestrial Chinle Formation are more haphazard. Buckskin Formation facies have broad stratigraphic similarities to Chinle Formation members.
The protolith of gypsiferous phyllite beds is interpreted to be packages of Quartzite Member

Church Rock Members are similar to the overlying uppermost Triassic and fluvial, floodplain, and lacustrine settings (e.g., Stewart et al., 1972b; Lawton, 1994; Dickinson and Gehrels, 2008; Howell and Blakey, 2013; Fig. 4B).

**LITHOSTRATIGRAPHY AND DEPOSITIONAL SETTING OF THE BUCKSKIN FORMATION**

**Lower Member**

Detailed descriptions and stratigraphic sections of the Buckskin Formation are available in Sanchez (2015), with additional descriptions in Reynolds and Spencer (1989), Stone and Kelly (1989), and Hargrave (1999). The structural thickness of the lower member (Fig. 3A) varies between 100 and 400 m, and the stratigraphic thickness is 100–200 m. The lower member includes resistant, fine-grained quartzite as well as variably fine- to medium-grained phyllite, calcareous quartzite, gypsiferous phyllite, gypsum, and phylilitic quartzite (Fig. 2). In thin section, rocks of the lower member consist of poorly to moderately well-sorted detrital grains in a matrix of quartz, chlorite, white mica, and epidote. Monocrystalline, angular to subrounded quartz makes up as much as 60% of grains. Quartz grains show some evidence of strain, with undulose extinction, formation of subgrains, and locally incipient formation of quartz ribbons. Feldspar (5%–35%; microcline, albite, and plagioclase), zircon (<1%), and spinel (<1%) are also present. Laminations in thin sections are defined by variations in the size of quartz and feldspar grains.

The protolith of the fine-grained quartzite is interpreted as quartz siltstone with calcite cement. Protoliths of the coarser units of the basal portion of the lower member are calcareous subarkosic arenites and subfelspathic wackes. The protolith of gypsiferous phyllite beds is interpreted to be packages of gypsiferous mudstone.

**Quartzite Member**

The structural thickness of the quartzite member is 0–45 m, and the measured stratigraphic thickness is 10–20 m. The member is highly resistant and exposed in characteristic bands that stand out above finer-grained surrounding units (Fig. 3B). Rock types are very fine- to fine-grained, thickly bedded, epidote-rich quartzite (0.5–1 m) or calc-silicate rock. A distinctive section of porcellanite beds (10–20 cm) that locally interfingers with calcareous quartzite beds (20–40 cm) crops out ~4.5 m below the top of the member. Exposures of this unit pinch and swell along strike.

Thin-section examination shows that the quartzite member is composed of quartz, calcite, and epidote, and less commonly, muscovite, feldspars, biotite, chlorite, and oxide minerals. Where best exposed, in the Palen Mountains, the porcellanite unit consists of extremely fine-grained muscovite (sericite) and chlorite in a bluish groundmass (chlorite?).

The protolith of the quartzite member is hypothesized to be a calcite-cemented quartz siltstone or mudstone. Coarser units within the quartzite have calcite-cemented subfelspathic wacke protoliths. The porcellanite beds are interpreted to be a very-fine-grained, water-lain ash-fall tuff or muddy claystone.

**Phyllite Member**

The structural thickness of the phyllite member is as much as 60 m; the stratigraphic thickness is 20 m. Rock types include variable fine- to coarse-grained, non-calcarenite phyllite, phylilitic quartzite, and pebble to cobble metaconglomerate. The rock has a distinctive blue-green tint in most exposures. Visible grains in hand sample include quartz, chlorite, muscovite, and magnetite, as well as oblong-shaped “clasts” composed of muscovite and fine magnetite (identified by Hargrave [1999]).

Near the base, a thin metaconglomerate unit contains subrounded to subangular quartzite pebbles and cobbles (<10 cm). The middle portion of the member consists of fine-grained phylilitic quartzite that is overlain by an upper portion of alternating phyllite and coarse-grained (locally conglomeratic) phyllite. The phyllite member commonly has beds 0.05–1 m thick and a millimeter-scale pervasive foliation imparted by post-depositional metamorphism and deformation.

In thin section, rocks of the phyllite member show poor sorting and consist primarily of angular to subrounded monocrystalline quartz (30%–60%) and muscovite (30%–40%) grains. Chlorite, feldspars, epidote, and magnetite are also present in the rock in smaller percentages. Zircon is present in small amounts (<3%), generally clustered in pods or concentrations of chlorite and muscovite.

The mineral assemblages of the phyllite member imply that the protoliths are probably micaceous quartz wacke and subfelspathic wacke. Hargrave (1999) interpreted “clasts” of muscovite that include groups of zircon grains to be metamorphosed pumice clasts. The sedimentary protoliths of the phyllite member are volcanogenic.

**Upper Member**

The upper member (Figs. 2 and 3B) has a structural thickness >300 m; the stratigraphic thickness is uncertain due to folding within the member (Reynolds and Spencer, 1989). It consists of massive, variably calcareous, fine- to medium-grained quartzite and calc-silicate rock. Beds of phylilitic quartzite and pebble to (local) cobble metaconglomerate are present in lesser proportions.
Clasts within the metaglomerate are subrounded to rounded quartzite. The upper member is locally characterized by coarsening-upward successions. Thin sections reveal moderate to poor sorting and mineralogy that consists dominantly of monocristalline subrounded to subangular quartz. Biotite, chlorite, muscovite, and epidote are also common grain types. The samples from the Palen Mountains are relatively more arkosic (15%–30% feldspar grains) than those from the Buckskin Mountains (0%–10% feldspar grains). The protoliths of the upper member are interpreted as calcite-cemented subarkosic quartz arenite and micaceous quartz arenite. The calcareous nature of the upper member contrasts strongly with the composition of the phylite member.

Depositional Setting of the Buckskin Formation

The rocks of the Buckskin Formation commonly lack distinct preserved sedimentary structures, and relict small-scale sedimentary structures in many cases have been overprinted by post-depositional metamorphic and deformational events. Depositional environments are interpreted using observed or inferred sedimentary features, particularly mineral constituents, grain size, degree of sorting, preserved lamination and bedding characteristics, cement types, and stratigraphic context.

Gypsiferous siltstone beds in the lower portion of the lower member were deposited in restricted bodies of water (evaporative basins), such as sabkhas or restricted marine basins (cf. Douglas and Goodman, 1957; Schreiber and El Tabakh, 2000); low levels of precipitation and enhanced seasonality during Early Triassic time would have promoted the formation of gypsum in isolated bodies of water (Parry, 1993). This interpretation is supported by the poor to moderate sorting, pervasive calcite cement, and the horizontal laminations and bedding in other rocks of the lower member, which suggest deposition in a marginal-marine environment or very low-profile fluvial system. The fine-grained, horizontally laminated siltstone-mudstone facies may represent quiet-water deposition with little to no influence of currents, likely on a shallow-marine shelf and/or in tidal flats and levees. Coarser-grained units (subfeldspathic wacke) represent more fluvial-dominated, tidal-channel, or deltaic depositional settings.

Fine-grained, thinly bedded quartz siltstone and subfeldspathic wacke of the quartzite member also lack sedimentary structures (except for bedding), are fine grained, and have calcite cement. These features suggest a continuation of the relatively calm-water marginal-marine depositional setting. Less common, coarser-grained subfeldspathic wackes may have been deposited in deltas and tidal channels. Porcellanite near the top of the quartzite member was likely deposited from ash fall or as a slack-water claystone, while the interfering relation between it and the calcareous siltstone suggests reworking in a low-energy, nearshore environment. If the ash-fall interpretation is correct, this porcellanite is the first direct evidence of arc-derived volcanic ash reaching the basin.

During Early Triassic time, the Buckskin depositional system was probably an estuarine environment affected by tidal and fluvial currents. Evaporative basins may have formed in the estuary or on shallow tidal flats that promoted formation of the gypsum.

The phyllite member represents a distinct change in depositional setting of the Buckskin Formation based on the compositional dominance of quartz, muscovite, and magnetite grains and the lack of pervasive calcite cement in the two lower members. The wide range in grain size (fine to cobble), the composition, and the lenticular bedding of the phyllite member suggest deposition by fluvial or alluvial processes, including gravel bars and sand sheets for coarser beds and floodplains and levees for finer beds. The coarse-grained micaceous quartz wacke and subfeldspathic wacke beds of the member are distinct from the fine-grained, quartz-rich units of the underlying members. We infer that the phyllite member was deposited in a continental fluvial environment that tapped an active volcanic source region.

The upper member comprises calcite-cemented subarkosic quartz arenite and micaceous quartz arenite. The calcite cement, especially in contrast to the underlying phyllite member, suggests deposition in a deltaic environment adjacent to a lake, or possibly in a shallow-marine environment.

The phyllite and upper members of the Buckskin Formation reflect deposition dominantly to wholly continental systems. Although a shallow-marine environment cannot be ruled out, we prefer a lacustrine interpretation for parts of the upper member as part of a complex fluvial system with channel avulsions, crevasse splays, and shallow lakes (Stewart et al., 1972b; Lawton, 1994; Dickinson and Gehrels, 2008; Howell and Blakey, 2013).

**DETRITAL ZIRCON RECORD**

The Buckskin Formation yielded >100 concordant zircon grains from 11 of the 14 samples collected from the lower, phyllite, and upper members in the Buckskin Mountains, Palen Mountains, and Midland syncline and at Plomosa Pass (Fig. 1; Table 1); a sample of the quartzite member yielded only 25 concordant grains (Supplemental Table S1). Samples were crushed and zircon separated by standard methods (e.g., Gehrels, 2000). U-Pb geochronology and trace element geochemistry were conducted by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the laser ablation split-stream (LASS) facility at the University of California, Santa Barbara (UCSB), in 2013 and 2014 using a Nu Plasma high-resolution multi-collector–inductively coupled plasma–mass spectrometer (HR MC-ICP-MS) and a Nu AttoM single-collector ICP-MS (Nu Instruments Ltd., Wrexham, UK), and an Analyte 193 excimer Ar laser-ablation system equipped with a HeLex sample cell (Photon Machines, San Diego, California) using a 24 μm beam. Analytical and procedural details and all analytical data are provided in Supplemental Table S1; all age uncertainties reported are 2σ, and error assessment follows Kylander-Clark et al. (2013). Analyses were evaluated for discordance based on a comparison of 206Pb/238U and 207Pb/235U for Phanerozoic grains, and 206Pb/238U for more ancient samples.

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1The complete data table, which contains isotopic ratios, dates, and uncertainties, is available through the EarthChem library, https://doi.org/10.26022/IEDA/111538. The table is referred to as Supplemental Table S1 herein.
and $^{238}\text{U}/^{206}\text{Pb}$ for Proterozoic grains. Grains that were >10% normally discordant (i.e., $^{235}\text{U}/^{207}\text{Pb}$ age or $^{207}\text{Pb}/^{206}\text{Pb}$ age >10% older than $^{238}\text{U}/^{206}\text{Pb}$ age) or 5% reversely discordant (i.e., $^{238}\text{U}/^{206}\text{Pb}$ age or $^{207}\text{Pb}/^{206}\text{Pb}$ age >5% older than $^{235}\text{U}/^{207}\text{Pb}$ age) were not used in interpretations; these are indicated by “discordant” in Supplemental Table S1.

The basal portion of the lower member of the Buckskin Formation has a distinct distribution of ages that is dominated by late Permian to Early Triassic grains. Of 280 Phanerozoic grains (68% of all grains), 80% are middle Permian–earliest Triassic in age; the weighted average of the youngest grains from the four localities (Fig. 1) yields a maximum depositional age (MDA) of 249 ± 2 Ma with a mean square of weighted deviates (MSWD) of 1.15 (Fig. 5A). Single grains or two-grain groups are as old as 278 ± 3 Ma. The remaining grains within the detrital zircon suite are mostly Proterozoic and Archaean in age, with distinct populations of 1300–1100 Ma, 1400 Ma, and 1800–1600 Ma.

The upper portion of the lower member shows a much greater diversity in ages than the phyllite member (Fig. 5D). The Phanerozoic age distribution has no distinct groupings, with subequal amounts of the Early Triassic and Late Triassic ranges that are common in the lower and phyllite members. Approximately 65% of the total age distribution is Proterozoic grains in broad

### Table 1. Locations for U-Pb Samples

| Member                | Location            | Sample no. | Coordinates (°N) | Coordinates (°E) |
|-----------------------|---------------------|------------|------------------|------------------|
| Buckskin Formation    | Top of upper member | 012414-3   | 34.23981         | -113.97452       |
|                       | Palen Mountains     | 012514-1   | 33.90441         | -115.06417       |
| Basal upper member    | Buckskin Mountains  | 031713-5   | 34.21642         | -114.01752       |
|                       | Palen Mountains     | 031813-1   | 33.90593         | -115.06426       |
| Phyllite member       | Buckskin Mountains  | 031713-4   | 34.21663         | -114.01655       |
|                       | Buckskin Mountains  | 031813-2   | 33.90808         | -115.06253       |
| Quartzite member      | Palen Mountains     | 031813-3   | 33.90847         | -115.06248       |
| Top of lower member   | Buckskin Mountains  | 031713-2   | 34.21715         | -114.01594       |
|                       | Palen Mountains     | 012514-4   | 33.90864         | -115.06158       |
|                       | Buckskin Mountains  | 012314-2   | 34.21754         | -114.01481       |
| Basal lower member    | Buckskin Mountains  | 031713-1   | 34.16202         | -114.18056       |
|                       | Palen Mountains     | 012514-7   | 33.90808         | -115.06280       |
|                       | Midland syncline    | 012614-2   | 33.86315         | -114.82478       |
|                       | Plomosa Pass        | 160510-1   | 33.80980         | -114.08415       |
|                       | Palen Mountains     | 031813-5   | 33.91097         | -115.06271       |
| Moenkopi Formation    | Holbrook Member     | northern Arizona US99 | 35.07558 | -110.93186 |
|                       | northern Arizona Sunset Mtn | 34.77076 | -110.89572 |

**Note:** Datum is WGS84.
Figure 5. Weighted average and probability density plots (PDPs) of ages of the Buckskin Formation using combined member data from Buckskin and Palen Mountains, Midland syncline, and Plomosa Pass. (A) PDP of the basal lower member; inset is a weighted average plot. (B) PDP of the top of the lower member. (C) PDP of the phyllite member; inset is a weighted average plot. (D) PDP of the basal upper member. (E) PDP of the top of the upper member. (F) PDP of the Holbrook Member, Moenkopi Formation, sampled near Winslow, Arizona; inset is a weighted average plot. N—number of samples; n—number of grains; MSWD—mean square of weighted deviates.
ranges of 1200–1000 Ma, 1500–1300 Ma, and 1800–1600 Ma. The uppermost portion of the upper member is dominated by Proterozoic grains, which make up 92% of the entire age distribution (Fig. 5E). No significant age groupings are present in the suite of only 11 Phanerozoic grains. Of 139 Proterozoic grains, 46% of those grains are within a continuous age range of 1500–1130 Ma. Approximately 30% of the grain ages is in the 1800–1600 Ma range, with lesser and subequal amounts of 1200–1000 Ma, 1500–1300 Ma, and >1800 Ma ages.

Thorium/uranium (Th/U) ratios in zircon can be used to gather information about source magmas and, in some cases, isolate areas of likely provenance (Riggs et al., 2013). Th/U ratios in the Buckskin Formation samples are homogeneous, with >95% of Permian and Triassic grains from both the Middle and Late Triassic parts of the formation falling in a range of 0.1–1.2 (Fig. 6).

■ DISCUSSION

Correlation of the Buckskin Formation to Colorado Plateau Successions

Facies of the Triassic successions of the Colorado Plateau have been delineated primarily by the dominant rock types and sedimentary structures preserved in the rocks (Stewart et al., 1972a, 1972b; Blakey, 1989; Dubiel, 1994). The paucity of sedimentary structures in the Buckskin Formation complicates correlation with the Moenkopi and Chinle Formations, but the regional correlation is guided by the interpreted protoliths, sedimentary features, and detrital zircon ages.

The dominant lithology of the Moenkopi Formation is horizontally stratified sandstone and siltstone interpreted as shallow- to marginal-marine deposits, including primary gypsum deposits (Stewart et al., 1972a; Reif and Slatt, 1979). The lower two members of the Buckskin Formation are interpreted to have been deposited at the interface of marine and fluvial depositional environments and correlate well with these dominant facies of the Moenkopi Formation. The gypsiferous phyllite beds of the lower member are lateral equivalents to interstratified gypsum and siltstone-to-claystone beds, such as the Shnabka Member in the middle of the Moenkopi Formation, which is exposed in the southwestern Utah, northwestern Arizona, and southern Nevada (Stewart et al., 1972a). A reasonable extension of the Moenkopi depositional system to the southwest (e.g., Stewart et al., 1972a; Fig. 4A) aligns the Buckskin depocenter with Moenkopi facies dominated by quiet-water deposits.

The Chinle Formation is interpreted as a wholly continental deposit (Stewart et al., 1972b; Blakey and Gubitosa, 1983). The two upper members of the Buckskin Formation were likely similarly deposited in fluvial depositional systems (Fig. 4B) based on grain-size and bedding characteristics. Conglomeratic beds and the volcanogenic nature of the phyllite member correlate well with the facies in different parts of the Chinle Formation. Coarse-grained units are present in the Shinarump Conglomerate and Mesa Redondo Member at the base of the formation (Stewart et al., 1972b; Blakey, 1989; Dubiel, 1994; Martz et al., 2012), and the Sonsela Member in its middle. The fine-grained units of the phyllite member correlate well with the poorly sorted clay-rich sandstone and bentonitic siltstone facies such as the Petrified Forest Member (Stewart et al., 1972b; Dubiel, 1994).

Hargrave (1999) inferred an erosional unconformity between the quartzite and phyllite members of the Buckskin Formation, based on the sharp contact between those members, the abrupt change in sandstone composition, and a coarse-grained conglomeratic bed at the base of the phyllite member. This unconformity would correlate to the unconformity between the Moenkopi and Chinle Formations of the Colorado Plateau (Tr-3 unconformity of Pipirigos and O’Sullivan [1978]). Fine-grained structureless to horizontally bedded and conglomeratic facies of the upper member may correlate with the Owl Rock Member of the Chinle Formation (Stewart et al., 1972b; Dubiel, 1994; Tanner, 2000).

To further understand the likely correlation between the lower Buckskin Formation and the Moenkopi Formation on the Colorado Plateau, we dated two samples of “tuffaceous sandstone” (Cadigan, 1971) from the Holbrook Member of the upper Moenkopi Formation near Winslow, Arizona (Figs. 1 and 5F; Supplemental Table S1 [footnote 1]). Permian and Triassic grains are acicular with little abrasion, indicating a low amount of transport. Twenty-four grains from the two samples fall within a range of 270–245 Ma (Supplemental Table S1), and the maximum depositional age is ca. 250 Ma (Fig. 5F).

Correlation of the Buckskin Formation and the Triassic units on the Colorado Plateau is indicated by the MDA of the units, although use of MDAs does not
provide member-to-member correlations. The maximum depositional age of ca. 249 Ma for the basal portion of the lower member of the Buckskin Formation is similar to biostatigraphic ages (e.g., McKee, 1954) and our new data from the Holbrook Member. These comparisons, together with the correlation of the gysiferous lower member with the Shnabkaib Member, suggest that the lower and quartzite members of the Buckskin Formation best correlate to middle and upper members of the Moenkopi Formation.

The maximum depositional age of the phyllite member is 220 ± 2 Ma, which is comparable to the 220–230 Ma detrital zircon age distributions from the Chinle Formation (Dickinson and Gehrels, 2008; Heckert et al., 2009; Howell, 2010; Irmis et al., 2011; Ramezani et al., 2011, 2014; Riggs et al., 2012, 2013; Howell and Blakey, 2013; Atchley et al., 2013). A MDA of 220 Ma for the phyllite member corresponds to single-crystal chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) dates of 220 Ma obtained by Atchley et al. (2013) for the top of the Blue Mesa Member or 219 Ma for the basal Sonsela Member (Ramezani et al., 2011). Thus, the phyllite and upper members of the Buckskin Formation likely correlate with the Sonsela or Petrified Forest and Owl Rock Members of the Chinle Formation, rather than the basal Shinarump Conglomerate. These assignments corroborate the interpretations of Hargrave (1999), who used stratigraphic comparisons to make the same correlations.

Thorium/uranium (Th/U) ratios of the zircon crystals support a hypothesis of similar source regions for upper Buckskin Formation and Colorado Plateau formations. Ratios from the lower member of the Buckskin Formation and the Moenkopi Formation are very similar (Fig. 6); although this does not suggest a correlation between units, we infer that magmatic source rocks were part of the same arc complex. Ratios from both units are dominantly within the range of values from Permian and Lower Triassic plutons in the El Paso Mountains in southern California (Cecil et al., 2018). Complementing observations by Riggs et al. (2013), Th/U in grains from our samples of the phyllite member are likewise very similar to those from detrital grains within the Chinle Formation (Riggs et al., 2013, 2016). Triassic plutonic rocks and presumed volcanic equivalents from the Mojave Desert (Barth and Wooden, 2006) are a viable source for these grains based on these ratios.

Early Mesozoic Sediment-Dispersal Systems

Lower and Quartzite Members

Cordilleran arc signature. Detrital zircon data includes ages that indicate abundant arc-derived grains and suggest that Lower Triassic sediment in the basal portion of the lower member of the Buckskin Formation was transported in drainage systems that originated in active segments of the arc. One system may have originated in or near the El Paso Mountains segment of the Cordilleran arc (Fig. 7A), where ages and Th/U ratios of late Permian–Early Triassic plutonic rocks are well within the range of those of Permian detrital grains (Fig. 6). The primary dispersal system originated in the Mojave Desert segment of the arc, potentially in igneous rocks related to the San Bernardino suite of Barth and Wooden (2006). Plutonic rocks in the Manzanita Springs and Liebre Mountain (Fig. 1) areas are ca. 250 Ma and have Th/U values between 0.3 and 0.6, suggesting a source within older segments of that suite. We agree with previous ideas (Howell and Blakey, 2013; Riggs et al., 2016) that the magmatic

Figure 7. Paleogeography and arc activity during Buckskin Formation deposition, in present-day coordinates. Red arrows depict general paleocurrent trends (after Stewart et al., 1972a; Dickinson and Gehrels, 2008). (A) Basal lower member at 260–255 Ma. Map is offset northward from the following maps to show broader-scale tectonic features. Color gradient reflects the original Moenkopi basin (e.g., Dickinson and Gehrels, 2008). Dashed green arrows depict input of detritus from the El Paso Mountains (northern arrow) and San Bernardino suite (southern arrow). (B) Upper lower and quartzite members at ca. 245 Ma. Note likely magmatism farther north, but highly diminished in Buckskin source areas. Boundary between terrestrial and marine rocks moves northwest. (C) Phyllite member at ca. 220 Ma. Magmatic arc has “shoaled,” causing the Tr-3 unconformity, and fluvial systems from the arc join the dominant northwest-directed transport system. Coarse detritus bypasses the Buckskin depocenter, but Plinian clouds contribute ash. (D) Approximate time of development of the post-Buckskin unconformity with the overlying Vampire Formation (ca. 200 Ma; greyed-out Buckskin depocenter label indicates post-Buckskin time); note the Cordillera-wide lull in magmatism.
arc lay offshore of the Laurentian continent, and suggest that it was some tens of kilometers from the Buckskin basin (Fig. 7A). Zircon grains were transported in tuffaceous turbidites or slurries and reworked by marine currents. We infer that the resultant MDA of ca. 249 Ma very closely approximates the age of the lower member.

**Sonoran arc or El Paso Mountains grains.** In addition to grains that were derived from proximal regions of the arc, 275–265 Ma zircon grains were sourced either in the Sonoran arc (Fig. 1), where plutons range from ca. 275 to 260 Ma (Arvizu et al., 2009; Riggs et al., 2009; Arvizu and Iriondo, 2015) and detrital grains in Permian strata document middle Permian sedimentation (Dobbs et al., 2016), or in older plutons in the El Paso Mountains terrane (Cecil et al., 2018). This latter area has the geographic advantage of being closer, but grains of this age are relatively few in the Buckskin Formation (i.e., ~5% total) and a proximal source might have been expected to swamp the signature more completely if longshore currents were from that direction.

**Eastern and central North American sources.** Early Paleozoic (500–300 Ma) grains were transported by the larger Moenkopi westward-flowing stream systems that originated in and near the Ouachita orogenic belt and the remnant uplifts of the Ancestral Rocky Mountains (Dickinson and Gehrels, 2003, 2008; Gehrels et al., 2011; Leary et al., 2017). Permian ergs in the midcontinent may have stored sand grains (e.g., Lawton et al., 2015); ultimately, they were reworked into the Buckskin basin by eolian or marine currents. Ages in the ranges of 1800–1600 Ma (Yavapai and Mazatzal provinces), 1500–1300 Ma (A-type “anorogenic” granites), and 1300–1000 Ma (Grenville province) are common in North America (Whitmeyer and Karlstrom, 2007).

**Phyllite and Upper Members**

Upper Triassic sediment of the phyllite member (Chinle equivalent) was deposited by stream systems that likely originated in the Mojave Desert segment of the arc (San Gabriel suite; Barth and Wooden, 2006; Fig. 1), based on zircon ages. These systems were linked to a larger drainage system that intersected the Buckskin depocenter and, together with Plinian eruptive clouds, delivered arc-derived detritus to more distal reaches of the greater Chinle depocenter (Fig. 7C; Riggs et al., 2012, 2013). The MDA of 220 ± 2 Ma is interpreted as the age of deposition of the phyllite member.

Deposition of the upper member of the Buckskin Formation marked a change in the primary sediment-dispersal pathways, as suggested by the significant decrease in the input of arc-derived zircon grains. A relative paucity of arc-derived grains in the upper member also suggests a lull in magmatism in latest Triassic time; such a lull has been noted by Barth et al. (2013). This lack of magmatic detritus is also reflected in the comparatively nonvolcanic upper members of the Chinle Formation (Stewart et al., 1972b), which reinforces the suggestion that the uppermost members of the Chinle, and the upper member of the Buckskin, are more likely correlatives with the basal units of the Glen Canyon Group (Dickinson, 2018).

**Early Mesozoic Cordilleran Arc Magmatism**

The Buckskin Formation records two distinct pulses of late Permian to Early Triassic and Late Triassic Cordilleran arc magmatic activity. The first pulse is recorded by the ca. 270–245 Ma zircon grains in the lower member. Distinctly younger grains (ca. 220 Ma) in the phyllite member document the second pulse.

A plot of the distribution of arc-derived ages (ca. 280–200 Ma; Fig. 8) in Triassic units across southwestern North America provides the basis for observations about arc magmatism and sediment dispersal. (1) Two periods of Cordilleran magmatic arc activity supplied detritus to the Buckskin Formation deposition (i.e., ca. 250 Ma and 220 Ma); other pulses of magmatism, however, were sources for other retro-arc successions, particularly during and after formation of the land bridge between the arc and the retro-arc region (ca. 240–235 Ma; e.g., Waterman formation, southern Arizona; Riggs et al., 2013). These variations, especially in upper Buckskin time, may represent changes in the arc and/or integration of river systems over time. (2) The time between the two pulses of more pronounced magmatism (i.e., ca. 245–235 Ma, as seen in all units) does not reflect a complete cessation in magmatism, but a period of reduced activity. This interpretation takes into account plutonism within this range reported by Barth and Wooden (2006). (3) Magmatic activity was continuous in southwestern Laurentia from Permian (ca. 275 Ma) to Late Triassic time (ca. 215 Ma). Age data from other retro-arc units to the north (Davis, 2019) indicate that ca. 250–245 Ma magmatism was common at that latitude.
Early Mesozoic Regional Deformation

Dickinson (2018) speculated that development of the Tr-3 unconformity on the Colorado Plateau was largely due to a transition between major tectonic influences on basin development. In Early–Middle Triassic (i.e., Moenkopi Formation) time, the Sonoma orogenic belt caused down-flexure that resulted in a basin that deepened to the northwest along a gentle plain (Blakey, 1989; Dickinson, 2006); the observation that Buckskin Formation lower and quartzite member facies patterns follow a northeast trend to link with the Moenkopi Formation in southern Nevada and southwestern Utah (Fig. 4A) suggests that this northwest deepening was not influenced by early arc development. Development of the arc in later Triassic time (Chinle Formation) brought about dynamic back-arc subsidence (Lawton, 1994). In terms of arc development, however, the major tectonic change was a transition from an offshore arc that was likely dominantly submarine, although built on continental crust, to a wholly terrestrial arc with fluvial pathways to the retro-arc area (Howell and Blakey, 2013; Riggs et al., 2016). As previously noted, the unconformity within the Buckskin Formation likely marks this same transition in tectonic setting.

Regional Synthesis

The lower and quartzite members of the Buckskin Formation provide the earliest para-autochthonous record of Cordilleran arc magmatism in the westernmost part of the evolving back arc. Our MDA of ca. 250 Ma for the upper Moenkopi Formation corresponds well to the 249 Ma MDA for the basal portion of the Buckskin Formation, although lower Buckskin Formation facies correlate best with middle Moenkopi Formation members (e.g., Shnabkaib Member) in southwestern Utah and Nevada. Although arc-derived zircon grains in samples of the Holbrook Member of the Moenkopi Formation are acicular, suggesting very little reworking and abrasion, these MDAs cannot be used to establish member-to-member correlations.

At the approximate latitude of the Buckskin basin, the evolving magmatic arc was offshore and did not strongly influence depositional patterns in the back arc. The abundance of as much as 25% plagioclase feldspar in lower-member sandstones suggests that volcanic detritus gained access to the depocenter, but the lack of volcanic-lithic clasts of any size indicates that the active arc was some distance to the west or southwest. Subaqueous volcanism in the arc may have provided the sand-size detritus; the alteration and greenschist-grade metamorphism, however, precludes identification of vitriclastic textures that would support this inference. Deposition of the upper part of the lower member and the quartzite member may have occurred during a lull in volcanism at ca. 245–240 Ma (Fig. 8), or they may reflect changing topography as the arc developed. Both members are quartzose, suggesting they were dominantly sourced from reworking of lower-member detritus, with continued input from commonly inferred southwestern sources.

The Tr-3 unconformity between the quartzite and phyllite members suggests passive uplift and “shoaling” of the magmatic arc in latest Middle to early Late Triassic time. Atchley et al. (2013) provided a CA-TIMS date of 227.604 ± 0.082 Ma for the basal Chinle Formation; grains of this age are present in the phyllite member but are older than those used to define the MDA. Volcanic detritus may have mostly bypassed the Buckskin depocenter as dispersal pathways were initially established; although conglomerate lenses are present in the phyllite member, volcanic clasts, which are common in the Chinle Formation conglomerates, are missing.

The strong difference in detrital zircon ages between the Moenkopi- and Chinle-equivalent parts of the Buckskin Formation also points to a change in sediment routing. Zircon grains with ages of ca. 300–500 Ma in the lower two members are most easily considered derived from the Appalachian orogenic belts via late Paleozoic transcontinental river systems proposed by Dickinson and Gehrels (2003). Grains derived from eastern North America are very sparsely represented in phyllite and upper members, however, and the disparity is also reflected in grain ages from the Moenkopi Formation (Supplemental Table S1 [footnote 1]) and data presented by Riggs et al. (2013, 2016) and Howell (2010) on the Chinle Formation.  

The Chinle Formation across the Colorado Plateau is characterized by variable facies distributions (Fig. 4B) influenced by the distribution of the large transcontinental drainage systems and climate patterns (e.g., Stewart et al., 1972b; Dubiel, 1989; Parrish, 1993; Lawton, 1994; Howell, 2010: Atchley et al., 2013; Howell and Blakey, 2013; Dickinson, 2018). Correlation of specific Chinle Formation member facies with the phyllite and upper members of the Buckskin Formation is difficult; depositional ages, however, provide the basis for correlation. These patterns, which show the strong influx of arc detritus through Late Triassic time, support the hypothesis that the upper Buckskin–Chinle basin had a flexural origin that was influenced, in part, by the load of the developing Cordilleran magmatic arc (cf. Lawton, 1994). Pronounced uplift that caused the post-Buckskin unconformity (Reynolds et al., 1989) may be due to deformation within the arc.

CONCLUSIONS

The Lower and Upper Triassic Buckskin Formation in the Mojave Desert of California and Arizona represents the southwestward continuation of coeval Triassic units on the Colorado Plateau and elsewhere. Although rocks are greenschist-facies metamorphosed, we infer depositional environments similar to those in the Moenkopi and Chinle Formations. Marginal-marine facies in the lower and quartzite members of the Buckskin Formation comprise locally gypsiferous, horizontally laminated siltstone and mudstone to medium sandstone interpreted as estuarine and affected by tides and low-profile rivers; these facies correspond well to units in the middle Moenkopi Formation such as the Shnabkaib Member (Fig. 4A). A MDA of 249 ± 2 Ma for the lower member is matched by a MDA of ca. 250 ± 2 Ma for the Holbrook Member of the Moenkopi Formation (Figs. 5A, 5F).
The phyllite and upper members are interpreted as having a continental origin based on a wide range of sorting and grain size, lenticular bedding, and variable composition. These variations suggest a complex fluvial system that included channels and shallow-lacustrine environments. Equivalent middle and upper Chinle Formation units such as the Blue Mesa and Owl Rock Members have discontinuous facies distributions, such that the best correlation is based on zircon data that indicate an age of 220 ± 2 Ma for the phyllite member.

Correlation of Buckskin Formation members with formations on the Colorado Plateau indicates that in Early Triassic time, the effects of the Sonoma orogeny dominated southwestern North America. Only as the magmatic arc became terrestrial and a part of the continental landmass were its effects felt on retro-arc sedimentary patterns.

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