Evidence of early Miocene synextensional volcanism and deposition in the northern Calico Mountains, central Mojave metamorphic core complex, southern California, USA

Bryan P. Murray1 and Willis E. Hames2
1Department of Geological Sciences, California State Polytechnic University, Pomona, 3801 W. Temple Avenue, Pomona, California 91768, USA
2Department of Geosciences, Auburn University, 2050 Beard Eaves Coliseum, Auburn, Alabama 36849, USA

ABSTRACT

The spatiotemporal link between large-scale continental crustal extension and magmatic activity has been identified by numerous past studies, yet commonly the details of these associations remain unresolved. This study in the central Mojave metamorphic core complex (CMMCC) of southern California (USA) presents new geologic mapping, stratigraphic interpretations, and 40Ar/39Ar geochronology of the Jackhammer and Pickhandle Formations in the northern Calico Mountains to provide additional age constraints on the relative timing of early Miocene volcanism, deposition, and extension. The Jackhammer Formation, the oldest Tertiary stratigraphic unit, is nonconformable with pre-Cenozoic nonmylonitic metasedimentary and plutonic basement rocks and consists primarily of alluvial deposits and primary to reworked silicic tuffs, interbedded locally with basement-derived avalanche megabreccia, lacustrine limestone, and maﬁc lava; in addition, the “Mammut ignimbrite”, an ~130-m-thick crystal-rich welded lapilli tuff, is exposed only in the eastern part of the study area and appears to transition laterally into thinner, nonwelded lapilli tuff ~6 km to the west. The Pickhandle Formation conformably overlies the Jackhammer Formation and consists of: (1) a lower assemblage composed of reddish monomictic debris-ﬂow breccias with porphyritic rhyodacitic clasts and silicic block-and-ash-ﬂow deposits of similar composition; and (2) an upper assemblage of polymictic (metaplutonic basement and rhyodacite) alluvial deposits, primary to reworked lapilli tuff, and local rhyodacitic lava and block-and-ash ﬂows. Rhyodacitic lava domes were emplaced during the ﬁnal stages of Pickhandle Formation deposition, primarily intruded along preexisting normal fault zones. Sedimentary and volcanic lithofacies suggest that the Jackhammer and Pickhandle Formations were deposited in a volcanic vent–proximal alluvial fan system that formed within a half-graben basin bounded on the east by the southwest-dipping “Amphitheatre fault”. Growth strata within the hanging-wall deposits, primarily southwest-directed paleocurrents, and interbedded alluvial debris-ﬂow, basement-derived megabreccia, and lacustrine deposits adjacent to this fault suggest synextensional deposition in an intra-hanging-wall basin that developed during upper-plate extension in the CMMCC. New 40Ar/39Ar ages for six samples of silicic pyroclastic ﬂows and a lava dome from the synextensional Pickhandle and Jackhammer Formations in the Calico Mountains have a mean age of 20.10 ± 0.06 Ma. This age is 3–4 m.y. younger than the maximum age of initial extension determined by previous studies in other areas of the central Mojave, suggesting that CMMCC extension was not a synchronous large-magnitude regional event. Rather, extension and contemporaneous volcanism was more localized and asynchronous across the region, occurring in many smaller extensional basins that eventually culminated in exposure of the CMMCC mylonitic footwall rocks.

INTRODUCTION

Since the latest Paleogene, much of southwestern North America has experienced a complex history of deformation and volcanism related to the development of the Pacific–North American plate margin, including crustal extension, volcanism, and strike-slip faulting (e.g., Atwater, 1970; Dickinson, 1981, 2006; Glazner et al., 2002). The central Mojave Desert region of southern California (USA) provides an excellent record of this complicated deformational history. During the early Miocene, crustal extension and low-angle detachment faulting led to the development of the central Mojave metamorphic core complex (CMMCC), which juxtaposes a mylonitic pre-Tertiary basement footwall against Miocene volcanic and sedimentary rocks in the hanging wall (Fig. 1; Dokka, 1989; Glazner et al., 1989, 2002; Fletcher et al., 1995; Fillmore and Walker, 1996). Prior studies related to core-complex formation indicate a strong spatiotemporal association between large-scale continental crustal extension and magmatic activity (e.g., Coney, 1980; Gans et al., 1989; Lister and Baldwin, 1993), with extension suggested as one mechanism that favors crustal melting and the generation and storage of large silicic magma volumes (e.g., Hildreth, 1981; McKenzie and Bickle, 1988; White and McKenzie, 1989; Wark, 1991; Hanson and Glazner, 1995). However, in the central Mojave Desert region, many details about the relative timing of CMMCC extension, magmatic activity, and basin development remain unresolved. Previous workers utilized regional tectonostratigraphic models to constrain the age of initial extension in the CMMCC to ca. 24 Ma based on the oldest age of...
the early Miocene Pickhandle Formation, a predominately volcaniclastic rock unit interpreted as synextensional supradetachment basin deposits (Fillmore and Walker, 1996). In comparison, thermochronology data from the mylonitic footwall rocks of the CMMCC suggest that the age of initial core-complex extension may postdate these oldest depositional ages by ~3 m.y. (Gans et al., 2005; Wong and Gans, 2009).

Although the timing of the initial CMMCC extension has been based in part upon sedimentological interpretations of the Pickhandle Formation (e.g., Fillmore and Walker, 1996), direct evidence of synextensional deposition (e.g., growth strata) is not well documented. Much of the volcaniclastic rocks of Pickhandle-type deposits found throughout the central Mojave Desert region are interpreted to have been derived from an active silicic volcanic center in the Calico Mountains (Fillmore and Walker, 1996), an ~20-km-long range on the upper plate of the CMMCC ~15 km northeast of Barstow (Figs. 1 and 2); however, limited detailed geologic mapping, volcanic stratigraphy, and geochronology have been completed in this range to date. Given the potential connections between crustal extension and synextensional sedimentation and volcanism, further investigation to assess the validity of these previous interpretations is warranted. This study in the northern Calico Mountains presents new stratigraphic and \(^{40}Ar/^{39}Ar\) geochronology evidence that supports synextensional deposition of the Pickhandle Formation in a normal fault–bounded basin that developed on the upper plate of the CMMCC during the early Miocene, and proposes that extension was also active during deposition of the previously undated underlying Jackhammer Formation; these new age relationships suggests that the tectonostratigraphic correlations used to define the age of initial CMMCC extension may be oversimplistic and in need of reinterpretation.

### GEOLOGIC SETTING

#### Central Mojave Metamorphic Core Complex

Following a period of relative geologic quiescence in the central Mojave Desert during the Late Cretaceous–late Paleogene, tectonic activity, magmatism, and basin development returned to the region around the Paleogene-Neogene boundary (Glazner et al., 2002). During the early Miocene, large-magnitude brittle-ductile crustal extension and coeval magmatism and sedimentation occurred in the central Mojave metamorphic core complex (CMMCC), an ~90-km-long northwest-trending outcrop belt stretching from the Rodman Mountains to The Buttes (Fig. 1; Dokka, 1989; Glazner et al., 1989; Walker et al., 1990; Fletcher et al., 1995). Much of the extension in the CMMCC appears to be related to low-angle detachment faulting, including on the Waterman Hills detachment fault just north of the Calico Mountains.
Barstow (Fig. 2), a low-angle brittle-ductile normal fault that juxtaposes a variably mylonitized footwall consisting of metasedimentary and metavolcanic rocks and synkinematically emplaced intrusions against a hanging wall composed of early Miocene volcanic and coarse-grained clastic rocks (Glazner et al., 1989, 2002; Fletcher et al., 1995).

The precise timing and amount of early Miocene extension in the CMMCC is not clear. Fillmore and Walker (1996) suggested that extension occurred between ca. 24 and 19 Ma based on geochronologic data from synkinematic intrusions and apatite fission-track analyses from the CMMCC footwall (e.g., Dokka and Baksi, 1988; Walker et al., 1990; Glazner et al., 1992) and the depositional ages of the Pickhandle and Barstow Formations (discussed below). Stratigraphic evidence in the Mud Hills indicates that extension appears to have been active by 21 Ma, although it may have initiated earlier (Ingersoll et al., 1996). In comparison, thermochronology studies in the Mitchel Range and Hinkley Hills concluded that the CMMCC has a multiphase extensional history, with rapid cooling ages suggesting that extensional uplift first occurring in the Late Cretaceous–Paleocene at ca. 70 – 60 Ma, followed by a reactivation of extension between ca. 21 and 17.5 Ma (Gans et al., 2005; Wong and Gans, 2009). Alternately, Anderson (2017) proposed that the timing of extension was perhaps much younger and related to the late-stage emplacement of the Waterman Hills granodiorite (Fig. 2), postdating deposition of the Pickhandle Formation and preceding (and possibly concurrent with) the development of the Eastern California shear zone. Offsets of pre-Tertiary markers across the Waterman Hills detachment fault, including a Mesozoic gabbro-diorite complex at Iron Mountain that is correlated to a similar complex in the northern Calico Mountains (Fig. 1), suggest ~40–70 km of northeast-directed normal slip on the detachment fault (Glazner et al., 1989; Martin et al., 1993); however, the amount of slip on the fault may be significantly less, given that total extensional strain in the CMMCC is possibly distributed between the earlier Late Cretaceous–Paleocene extensional
event and later Miocene offset of the fault (Wong and Gans, 2009).

Following this period of crustal extension, strike-slip faulting with transpressional and transtensional faulting became the dominant form of deformation in the region caused by Pacific–North American transform plate boundary tectonics and the development of the Eastern California shear zone (e.g., Glazner et al., 2002). Northwest-trending right-lateral faults are the most prevalent structures found throughout the region, and northeast-trending left-lateral faults are common (Figs. 1 and 2; Glazner et al., 2002). East-west-trending folds are also observed within the central Mojave Desert, with crustal shortening attributed to local transpression related to northwest-trending right-lateral faults (e.g., Dibblee, 1980; Singleton and Gans, 2008) or regional north-south compression (Bartley et al., 1990). In the Calico Mountains, the main geologic structure is the northwest-trending Calico fault (Figs. 1 and 2), which has a maximum right-lateral offset of ~10 km and forms an ~10-km-long restraining bend that resulted in transpressional folding of Barstow Formation lacustrine sediments adjacent to the fault (Fig. 2; Singleton and Gans, 2008).

Middle Cenozoic volcanism in the central Mojave Desert was contemporaneous with large-magnitude extension in the CMMCC (Walker et al., 1995). Volcanic activity in this region has been attributed to several processes related to the development of the Pacific–North American transform plate margin, including slab rollback during subduction of the Farallon plate (e.g., Coney and Reynolds, 1977), the growth of slab windows (e.g., Dickinson, 1997), active asthenospheric upwelling during rifting (e.g., Gans et al., 1989), and/or the northward migration of the Mendocino triple junction (e.g., Glazner and Supplee, 1982). Early studies suggested that the age distribution of volcanic rocks in the central Mojave Desert region exhibited a pattern of south-to-north migration of volcanism over time (Glazner and Supplee, 1982). However, more recent geochronology data have shown that this migration pattern is likely not present given that the oldest volcanic rocks of the region are represented in both the north and south, and volcanism appears to be widespread and episodic (mainly at 22–21 Ma, 19.5–18.5 Ma, and 17.2–15 Ma) with no clear spatial trends (e.g., Gans et al., 2005).

### Stratigraphic Framework of the Central Mojave Desert

The middle Cenozoic stratigraphic units of the Calico Mountains and the surrounding region of the central Mojave Desert were first described by McCulloh (1952) and formally defined by Dibblee (1967). The Jackhammer Formation is the oldest middle Cenozoic stratigraphic unit and rests nonconformably on a relatively low-relief erosional surface cut into the underlying basement complex of Mesozoic plutonic rocks and Paleozoic metavolcanic and metasedimentary rocks (McCulloh, 1952, 1960, 1965). The Jackhammer Formation is discontinuous and relatively thin where exposed, with the thickest exposures found at the type section in the vicinity of Jackhammer Gap (Figs. 1 and 2; McCulloh, 1952; Dibblee, 1994; Fillmore and Walker, 1996). Previous radiometric dating of the Pickhandle Formation indicates an early Miocene age, bracketed between 23.7 and 18.9 Ma (Burke et al., 1982; Walker et al., 1995; Fillmore and Walker, 1996); additional 40Ar/39Ar ages by Singleton and Gans (2008) in the southeastern Calico Mountains suggest that the age of volcanic and intrusive rocks of the Pickhandle Formation in this area is 19.3–19.0 Ma. Due to its coarse-grained nature and outcrop proximity to the CMMCC, previous studies suggested that the Pickhandle Formation—and possibly the Jackhammer Formation—represent synextensional supradetachment-basin deposits (Fillmore et al., 1994; Fillmore and Walker, 1996). Studies in the southeastern Calico Mountains recognized that extensional faults are not common (possibly due to reactivation as strike-slip faults), yet those present are typically northwest-trending, steeply (≥45°) southwest-dipping normal faults with small offsets (<50 m) resulting in only 5% total magnitude of northeast-southwest extension (Singleton and Gans, 2008). These faults are likely related to CMMCC extension, given that they are present in the Pickhandle Formation but are rare in the overlying stratigraphic units (Singleton and Gans, 2008).

Fillmore and Walker (1996) studied the sediment dispersal patterns and provenance interpretations of the regional Pickhandle-type deposits (excluding the Calico Mountains) and subdivided the unit into two assemblages: (1) a lower volcanic assemblage of primary and fluvially reworked volcanlastic deposits (“lower Pickhandle”), interpreted to be sourced from an intrasbasal volcanic center in the Calico Mountains, and (2) an upper nonvolcanic assemblage of lacustrine, fluvial, and...
rock-avalanche deposits (“upper Pickhandle”). The depositional contact between the lower and upper Pickhandle is gradational to slightly disconformable. Compared to the lower Pickhandle, the upper Pickhandle is dominated by epiclastic deposits derived primarily from pre-Tertiary basement plutonic sediment sources and lacks much of the volcanic detritus found in the lower Pickhandle (Walker et al., 1995; Fillmore and Walker, 1996; Ingersoll et al., 1996). This provenance distinction has led several authors to classify the upper Pickhandle as the Mud Hills Formation based on the change in sediment source from intrabasinal volcanics to extrabasinal plutonics (Dokka et al., 1991; Ingersoll et al., 1996); while this distinction is useful for some localities, for this study the nonvolcanic assemblage will be referred to as the “upper Pickhandle” to avoid confusion and to give preference to the earlier naming schemes used at the Jackhammer Gap type locality (McCulloh, 1952) that is located in this study area (Fig. 2). Nevertheless, these previous studies suggested that the transition from lower Pickhandle volcaniclastic to upper Pickhandle plutonlastic sedimentation occurred sometime ca. 21.5 Ma due to a waning of volcanism and/or an increase in extensional exhumation rates in the region as Pickhandle Formation deposition progressed (Walker et al., 1995; Fillmore and Walker, 1996).

The Barstow Formation overlies the Pickhandle Formation in a slight angular unconformity and likely represents postextensional fine-grained lacustrine deposits (Fillmore and Walker, 1996; Ingersoll et al., 1996). It is composed primarily of fine-grained lacustrine deposits and interstratified tuffs; a basal fluvial conglomerate-sandstone unit (Owl Conglomerate Member) is locally observed in the Mud Hills, where this formation has been studied extensively (e.g., MacFadden et al., 1990; Woodburne et al., 1990; Ingersoll et al., 1996). The age of the fine-grained lacustrine rocks of the Barstow Formation in the Mud Hills is bracketed between ca. 17 and 13 Ma, however the Owl Conglomerate Member may be as old as 19.3 Ma (MacFadden et al., 1990; Woodburne et al., 1990). Fine-grained lacustrine rocks of the Calico Member of the Barstow Formation were deposited in the southeastern Calico Mountains following 19.0 Ma Pickhandle Formation volcanism and before subsequent dacite volcanism in the Yermo volcanic center at 16.9 Ma (Singleton and Gans, 2008); these fine-grained rocks are older than the lacustrine section in the Mud Hills, but are possibly age-equivalent with the Owl Conglomerate Member of the Barstow Formation.

### LITHOLOGY AND STRATIGRAPHY OF THE NORTHERN CALICO MOUNTAINS

New geologic mapping (Figs. 3 and 4) and measured stratigraphic sections (Fig. 5) from this study provide the basis for the following lithologic descriptions and depositional interpretations of the rocks in the northern Calico Mountains presented here. Five stratigraphic subdivisions are defined in this study area (from oldest to youngest): (1) pre-Cenozoic metasedimentary and plutonic basement rocks; (2) the Jackhammer Formation, consisting mainly of silicic volcaniclastic deposits; (3) the lower Pickhandle Formation, composed of monomictic rhyodacitic volcaniclastic breccias; (4) the upper Pickhandle Formation, which primarily consists of polymictic volcaniclastic and epiclastic deposits; and (5) syn- to post-Pickhandle silicic lavas and subvolcanic intrusions. These subdivisions are consistent with established stratigraphic nomenclature used in previous studies in the Mojave Desert region (e.g., McCulloh, 1952; Dibblee, 1967; Fillmore and Walker, 1996), with the characteristics of these rock units in the northern Calico Mountains described below.

The use of volcanic-volcaniclastic terminology in the literature is often ambiguous; the terminology used here is based on those of Fisher and Schmincke (1984), Fisher and Smith (1991), Sigurdsson et al. (2000), and Jerram and Petford (2011). Following Fisher and Schmincke (1984), the term “volcaniclastic” refers to all fragmental rocks composed predominantly of volcanic detritus, including: (1) pyroclastic fragmental deposits, inferred to have been directly derived from an eruption, e.g., pyroclastic air fall, ignimbrites, block-and-ash flows, autoclastic flow breccias; (2) reworked fragmental deposits, inferred to result from limited transportation of unconsolidated eruption-derived fragmental deposits, e.g., a block-and-ash-flow deposit that transitions downslope into debris-flow and fluvial deposits; and (3) epiclastic deposits, consisting of volcanic fragments inferred to have been derived from erosion of pre-existing rocks. When the distinctions cannot be made, the general term “volcaniclastic” is applied. Delicate pyroclastic detritus (pumice, glass shards, or euhedral crystals) cannot be derived from erosion of preexisting volcanic rocks, so their presence in fluvial or debris-flow deposits indicates that at least some of the deposit consists of reworked unconsolidated primary pyroclastic material, suggesting broadly coeval explosive volcanism. Similarly, if a debris-flow deposit is dominated by one volcanic clast type, it can be inferred to record reworking of a block-and-ash-flow deposit or flow breccia. However, the presence of multiple volcanic clast types is not proof of an epiclastic origin because a wide variety of volcanic clast types can become incorporated into an eruption-triggered debris flow (i.e., lahar); in that case, a distinction between reworked and epiclastic cannot be made, and the deposit is simply classified as a volcaniclastic debris-flow deposit.

### Pre-Cenozoic Basement

The Jackhammer and Pickhandle Formations are deposited nonconformably on a pre-Cenozoic basement of nonmylonitic metamorphic and plutonic rocks. The basement rocks were not the focus of this study, but brief descriptions are included here as potential sediment sources for the overlying formations. The oldest rocks in the study area are late Paleozoic low- to medium-grade metamorphic and metavolcanic rocks of the Coyote Group, originally mapped and described in detail by McCulloh (1952). In the study area, this group consists of a moderately (~50°) southeast-dipping section of white to dark gray fine-grained quartzite, gray phyllite, reddish-brown marble, and greenish-black metabasalt exposed on the northwestern flanks of the Calico Mountains (Fig. 3; McCulloh, 1952, 1960; Dibblee and Minch, 2008).
Figure 3. (Continued on following three pages.)
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Lithology

- Alluvium (Qa)
- Older alluvium (Qoa)
- Landslide breccia (Qls)
- Calico Mountains dacitic lava (Tcmd)
- Unconformity

Pickhandle Formation

- Upper Pickhandle Formation (volcaniclastic, undifferentiated)
  - Hypabyssal intrusions (unsaturated)
  - Red porhyritic rhyodacitic intrusion
  - Gravelly rhyodacitic ash flow and dome
  - Flow-banded light gray rhyodacitic lava and/or intrusion
  - Reworked silicic tuff
  - Fluvial sandstone and conglomerate
  - Silicic block-and-ash flow

- Lower Pickhandle Formation (undifferentiated)
  - Rhyodacitic debris-flow breccia
  - Rhyodacitic block-and-ash flow

Jackhammer Formation

- Lower Jackhammer Formation (undifferentiated)
  - Mammut silicic welded ignimbrite
  - Tuffaceous debris-flow conglomerate, fluvial sandstone, and nonwelded tuff
  - Lacustrine limestone
  - Avalanche megabreccia
  - Conglomeratic sandstone
  - White bedded tuff
  - Matrix-supported debris flow conglomerate

Pre-Cenozoic basement

- Mesozoic plutonic rocks—Larrea complex (McCulloh, 1960)
- Paleozoic metasedimentary & metavolcanic rocks—Coyote Group (McCulloh, 1952)

Contacts & Faults

- Contact—certain
- Contact—approximately located
- Contact—concealed
- Contact—referred from aerial imagery
- Fault—approximately located
- Fault—concealed
- Fault—referred from aerial imagery
- Syncline axis—approximately located

Symbols

- /\ Strike and dip of inclined bedding
- \ Strike and dip of inclined flow banding in igneous rock
- /\ Strike and dip of inclined ignimbrite compaction foliation
- \ Trend and plunge of mineral lineations
- \ Fault dip direction
- \ Trend and plunge of slip lineation on a fault surface
- U: up, D: down
- Fault sense-of-slip directions
- Location of \(^{40}\text{Ar}/^{39}\text{Ar} \) age (Table 1; or cited reference)
- Measured stratigraphic section location (Figure 5)

Figure 3 (continued). Geologic maps and lithostratigraphic correlation key of select areas of the northern Calico Mountains. Map area locations are shown in Figures 2 and 13. Mapping was conducted at 1:12,000 scale using U.S. Geological Survey 7.5′ quadrangle topographic maps and aerial imagery. Contour interval is 40 feet (20 feet south of 35° N). Map projection: North American Datum of 1927 (NAD27), Universal Transverse Mercator (UTM) zone 11 (coordinates in black; latitude and longitude are in blue). (A) Jackhammer Gap. Locations of measured sections 1–3 (Fig. 5) are shown. (B) Amphitheatre Canyon. Map has been rotated 45° from true north. Locations of cross-sections A-A′ and B-B′ (Fig. 4) and measured section 4 (Fig. 5) are shown. (C) East of Calico Peak, south of Amphitheatre Canyon. Black box denotes location of inset detailed map area in lower left, which shows the location of cross-section C-C′ (Fig. 4) and measured section 5 (Fig. 5).
Figure 4. Cross-sections A-A′ and B-B′ from Amphitheatre Canyon (Fig. 3B) and cross-section C-C′ from east of Calico Peak (Fig. 3C), showing the depositional relationships in the synextensional half-graben basin bounded by the Amphitheatre fault. Sections are the same scale as Figure 3, with no vertical or horizontal exaggeration. Rock units inferred above the topographic profile (brown line) are indicated by subdued color shades. Bedding orientations from strike and dip measurements are shown with black tick marks and are emphasized with thin gray dashed marker lines. Arrows indicate fault sense-of-slip. Colors, geologic unit labels, and contact line types are the same as in Figure 3.
**LITHOLOGY**

- Clast-supported conglomerate
- Matrix-supported conglomerate
- Trough cross-bedded conglomerate
- Clast-supported breccia
- Matrix-supported breccia
- Avalanche megabreccia
- Massive sandstone
- Trough cross-bedded sandstone
- Horizontally stratified sandstone
- Fluvially reworked silicic tuff
- Nonwelded silicic ignimbrite
- Welded silicic ignimbrite
- Silicic block-and-ash flow
- Silicic lava flow
- Vitrophyre
- No exposure or covered

**Paleocurrent direction from trough limbs**

- (n = number of measured limbs)

**Paleocurrent direction from clast imbrications**

- (n = number of measured clasts)

**CONGLOMERATE CLAST COMPOSITION**

- Metamorphic (undifferentiated)
- Metabasic (undifferentiated)
- Pink silicic tuff
- Gray welded tuff
- White to tan silicic tuff
- Reddish-brown silicic porphyritic volcanic
- Reddish-brown to gray silicic volcanic
- Flow-banded red silicic volcanic
- Basaltic to andesitic volcanic
- Granite conglomerate

**GRAIN SIZE**

- cl—Clay
- s—Silt
- vf—Very fine sand
- f—Fine sand
- m—Medium sand
- c—Coarse sand
- v—Very coarse sand
- p—Pebble
- b—Boulder

**Sample height**

- (n = number of clasts)

**Section 1**

- 280 m
- 260 m

**Section 2**

- 38.15 ± 0.15 Ma

**Section 3**

- 38.15 ± 0.15 Ma

**Figure 5. (Continued on following page.)**
Section 4

Figure 5 (continued). Measured stratigraphic sections of the Jackhammer and Pickhandle Formations at Jackhammer Gap (sections 1–3), north of Amphitheatre Canyon (section 4), and east of Calico Peak (section 5) showing lithologies, paleocurrent data, and conglomerate clast counts. Thick gray dashed lines indicate stratigraphic correlations between the sections. Thin dashed lines for measured stratigraphic units indicate uncertainty in grain size and bedding thickness determination due to limited exposure. Colors and geologic unit labels are the same as in Figure 3. Inset annotated photograph shows the rock units of the Jackhammer and Pickhandle Formations at the location of section 4; vertical relief of exposure is ~250 m.
On the northeastern side of the Calico Mountains (Fig. 3B), the Paleozoic metamorphic rocks are intruded by probable Late Jurassic–to-Cretaceous-age plutonic rocks identified as the Larrea complex (McCulloh, 1960; Lane Complex of McCulloh, 1952; Dibblee and Minch, 2008). These rocks are primarily dark-colored medium-grained hypidiomorphic biotite-hornblende diorite, however compositions ranging from gabbro to quartz diorite have been reported for the rock unit (McCulloh, 1952). Several ~4-5-m-thick light gray medium-grained granodiorite dikes intrude the diorite in the Amphitheatre Canyon area east of the Amphitheatre fault (Fig. 3B); these dikes are mapped with the Mesozoic rocks for this study, however, their ages are unknown. Glazner et al. (1989) correlated the Mesozoic plutonic rocks in the Calico Mountains to a similar gabbro-granite complex in the Iron Mountains (Fig. 1); this possible correlation provided a primary piercing point for their estimate of 40 km of normal slip on the Waterman Hills detachment fault.

Jackhammer Formation

The Jackhammer Formation is the oldest Cenozoic rock unit in the Calico Mountains, exposed in discontinuous outcrops in the northern part of the range where it is deposited on the nonconformity surface with the underlying nonmylonitic metaplutonic basement (Fig. 3). Four stratigraphic sections were measured through the Jackhammer Formation to analyze stratigraphic characteristics and lateral facies variations (Fig. 5, sections 1-4): three measured sections are located near Jackhammer Gap (Fig. 3B), and reworked tuff and lapilli tuff, Jackhammer Gap (Fig. 3B). Several distinct lithofacies are identified in the Jackhammer Formation, which are grouped into three main assemblages for this study (discussed below): intercalated conglomerates, sandstones, and mafic lavas (“lower Jackhammer”), bedded reworked tuff and localized basement-derived megabreccia (“middle Jackhammer”), and reworked tuff and lapilli tuff, tuffaceous sandstone, welded ignimbrite, and localized megabreccia and lacustrine limestone (“upper Jackhammer”) (Figs. 3, 5, and 6).

Lower Jackhammer

The lowest stratigraphic subdivision of the Jackhammer Formation in the study area is a conglomeratic sandstone and conglomerate unit (Tjc; Fig. 3). These rocks are generally reddish-gray to tan colored, thinly to medium-bedded, crudely cross-stratified granule-pebble conglomeratic sandstones that are interbedded with clast-supported pebble-cobble conglomerate lenses that are laterally continuous for less than a few meters. Amalgamated small channel-fill structures with basal concave-up erosional surfaces cut into underlying sediments are common in this rock unit (Fig. 6A). Clasts are moderately to poorly sorted, subrounded to subangular, metamorphic rock fragments (quartzite, metabasalt) similar in appearance to the underlying Paleozoic basement. Clast compositions and textures of unit Tjc vary laterally between the Jackhammer Gap and Amphitheatre Canyon areas, with the latter locality having more angular to subangular, massive, matrix-supported conglomerates with granule-cobble (to ~35 cm) white silicic volcanic and volcanioclastic fragments and lesser (~10%) metamorphic fragments. The lithofacies of unit Tjc are interpreted as sandy-gravel bedforms with scour-fill structures and gravel bars and/or lag deposits, with the coarse-grained conglomerates in the Amphitheatre Canyon area interpreted as debris-flow deposits. This lithofacies assemblage suggests that this stratigraphic unit was deposited in a proximal streamflow-dominated alluvial fan system or outwash braidedplain (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009), with the provenance of this unit being from the underlying Paleozoic metamorphic basement and a localized silicic volcanic source in the east.

Overlying and interfingerling with the conglomeratic sandstone unit Tjc are mafic-intermediate lava flows (unit Tjv; Fig. 3). These lavas are medium gray with 5%-10% phenocrysts (plagioclase ± hornblende ± clinopyroxene). Locally, the lavas are amygdaloidal and have basal autochthonous flow breccias above red thermally altered rocks. The thickest exposures of unit Tjv are in Jackhammer Gap east of Fort Irwin Road, where the lavas are complexly interstratified with unit Tjc (Fig. 3A). A vent source for these volcanic rocks has not been identified; one tentative source could be a minor northeast-trending mafic dike (unit Tji) of similar appearance to the nearby lava flows that crosscuts the Paleozoic basement west of Fort Irwin Road (Fig. 3A). Although further study evaluating unit Tjv is warranted, this unit is tentatively interpreted as dike-fed mafic to intermediate lava flows erupted into the fluvial channels carved during deposition of the conglomeratic sandstone unit (Tjc).

The conglomeratic sandstone (unit Tjc) and mafic lava (unit Tjv) units are absent west of Fort Irwin Road in Jackhammer Gap and are not recorded in the measured stratigraphic sections, where stratigraphic subdivision Tjdf was deposited directly on the Paleozoic basement (Fig. 3A). Unit Tjdf consists primarily of light gray, massive, weakly consolidated, very poorly sorted, matrix-supported silty-sandy conglomerates with angular to subangular pebble-boulder clasts of metamorphic basement rock. In measured section 2 (Fig. 5), the top of the matrix-supported conglomerate unit Tjdf consists of a reddish-gray granule conglomerate similar in appearance (and possibly correlative) to rocks of the conglomeratic sandstone unit (Tjc) to the east; below this sandstone, the matrix-supported silty-sandy conglomerate has a reddish matrix that grades downward into the unit’s typical gray color and is interbedded with a white bedded tuff layer (unit Tjt; described below). The rocks of unit Tjdf are interpreted as debris flows deposited in a proximal debris flow–dominated alluvial fan system (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009). The reddish matrix in the upper part of the unit may represent a paleosol horizon that developed during a depositional hiatus, which was later buried due to lateral migration of the fluvial conglomeratic sandstone unit (Tjc). The matrix-supported debris-flow unit (Tjdf) was likely incised during its depositional history, as evident by the discontinuous outcrops of white bedded tuff (unit Tjt) and megabreccia (unit Tjb; discussed below) that appear to infill erosional channels.
Figure 6. Photographs of Jackhammer Formation lithofacies in Jackhammer Gap (Fig. 3A). Length of hammer used for photographic scale is 38 cm. (A) Amalgamated channel-fill structures in unit Tjc conglomerates and conglomeratic sandstones, with the end of the hammer located at the base of a channel scour fill. (B) White thinly bedded reworked silicic tuff with a 20-cm-thick gray very coarse-grained tuffaceous sandstone scour-fill structure at 23 m in measured section 1 (Fig. 5). (C) Annotated photograph of the rocks of measured section 1 (Figs. 3A and 5). Avalanche megabreccia unit Tjb thickens in the direction of the viewer and pinches out on the backside of the hill, where tuffaceous debris-flow and sandstone deposits (unit Tjst) overlie unit Tjt. Width of the photograph is ~75 meters. (D) Base of the avalanche megabreccia (unit Tjb) with metaplutonic basement and silicic ignimbrite boulders, at 22 m in measured section 2 (Fig. 5). (E) Top of avalanche megabreccia unit Tjb at 45 m in Jackhammer Gap measured section 2 (Fig. 5), with a large 5-m-diameter marble boulder (unit Pm) protruding from the top of the deposit, which is buried by the overlying conglomerate (unit Tjst). (F) Interbedded reworked tuff, tuffaceous sandstones, and conglomerates of unit Tjst at 75 m in section 2 (Fig. 5). Arrow points to a 0.25-m-thick massive matrix-supported pebble-cobble conglomerate composed primarily of subangular biotite-hornblende diorite clasts, interpreted as a debris-flow deposit derived from Mesozoic basement (unit Mzi).
Middle Jackhammer

An ~30-m-thick white bedded tuff unit (Tjt) is observed interbedded with breccias and conglomerates in the Jackhammer Gap stratigraphic sections 1 and 2 and is deposited directly on Paleozoic basement rocks northwest of section 1 (Figs. 3A, 5, and 6B–6C). This unit is also locally present in a thin outcrop over basement plutonic on the footwall of the Amphitheatre fault, directly beneath lower Pickhandle Formation rocks (Fig. 3B). Unit Tjt consist primarily of white thinly bedded reworked silicic tuff with ~10% phenocrysts (plagioclase + biotite ± hornblende), ~5% pink granule silicic volcanic lithic fragments, and ~5% small lapilli-sized pumice fragments. At the base of the unit in section 1 (Fig. 5), an ~8-m-thick primary (nonreworked) tuff of a similar composition with a 0.5-m-thick basal vitrophyre is deposited over the megabreccia unit Tjb (described below). Interbedded with the bedded reworked tuffs are tuffaceous sandstones and conglomeratic sandstones that are thinly to medium bedded (locally thickly laminated) with scour-fill structures (Fig. 6B) and are moderately sorted and medium to very coarse grained with granule-pebble–rich lenses that extend laterally as much as 10 m. Clasts in these tuffaceous sandstones are typically subangular to subrounded metasedimentary fragments. Immediately northwest of section 1 (Fig. 3A), sandstones are less common in the white bedded tuff unit, and there is a greater abundance of interbedded greenish-gray siltstones. The white bedded tuff unit (Tjt) likely represents the eruptive products of distal silicic explosive volcanism deposited in the channels of the active alluvial fan system, where low-to-moderate-energy fluvial flow reworked the volcaniclastic deposits. Lateral facies variations between sections 1 and 2 and to the northwest of section 1 (Figs. 3A and 5) suggest that a major channel for unit Tjt deposition was centered around section 1 where the coarsest-grained (i.e., highest-energy) tuffaceous sandstones with scour-fill channel structures are concentrated; to the east and particularly to the northwest, the unit becomes finer grained and more horizontally stratified, interpreted as the channel-margin overbank or floodplain deposits (e.g., Miall, 1985, 1996). Garrison and Reynolds (2015) reported fossils of freshwater gastropods (Lymnaea sp. and Menetus sp.), water reeds, and root traces in the white bedded tuff unit Tjt (their basal Pickhandle Formation) and interpreted that deposition occurred in a lacustrine environment with quiet, slow-moving water and abundant vegetation; these depositional conditions can also be satisfied with the fluvial overbank-floodplain interpretation proposed here, which is preferred due to the presence of channelized deposits.

In the Jackhammer Gap area, a megabreccia (unit Tjst) interfingers with the white bedded tuff unit (Figs. 3A, 5, and 6C). This unit is a very poorly sorted, massive clast-supported boulder breccia with a gray very coarse sand matrix and fractured, angular clasts averaging 0.5 m diameter (as much as 5 m diameter) composed of metamorphic (quartzite, phyllite, marble, metabasalt), plutonic (biotite-hornblende diorite), and volcaniclastic (pink silicic tuff, white bedded tuff) rocks (Figs. 6D–6E). Clast compositions vary up section, with a greater abundance of white bedded tuff and less metasedimentary clasts observed near the base of the deposit. The thickness and maximum clast size of unit Tjst show significant lateral variation over its 400-m-long outcrop, with a 25 m thickness in section 2 that increases northwestward toward section 1, where it interfingers with the white bedded tuff unit Tjt before pinching out to a 2-m-thick deposit with clasts averaging 0.1 m diameter (as much as 3 m diameter) within section 1; the megabreccia is not exposed farther northwest of section 1 nor southeast of section 2 (Figs. 3A, 5, and 6C). Based on textural characteristics and outcrop localization, the megabreccia unit Tjst is interpreted as a rock avalanche (e.g., Yarnold, 1993; Blair and McPherson, 2009) deposited into the paleochannel that the white bedded tuff unit Tjt was depositing in. The sediment source for the avalanche deposit was the adjacent pre-Cenozoic metaplutonic basement rocks and older Cenozoic volcanic and volcaniclastic rocks, including the white bedded tuff unit (Tjt) of the Jackhammer Formation and possibly the Lane Mountain quartz latite welded tuff (e.g., McCulloh, 1952; Burke et al., 1982), suggesting a significant amount of erosional relief along the margins of the paleochannel.

Upper Jackhammer

The uppermost stratigraphic subdivision of the Jackhammer Formation is a light gray tuffaceous sandstone, conglomerate, and lapilli-tuff unit (Tjst). In the Jackhammer Gap area, this stratigraphic unit is deposited over the avalanche megabreccia unit Tjb at the location of the measured sections 1–3 (Figs. 5, 6C, and 6E) but is directly deposited over units Tjt and Tjv-Tjc to the west and east, respectively, of the measured sections (Fig. 3A). The lower part of unit Tjst is composed primarily of light gray, medium-bedded, very poorly sorted, clast-supported pebble-cobble silty conglomerates with scour-fill structures and subangular to subrounded metamorphic and silicic volcaniclastic clasts. The lower part of the subdivision transitions upward into medium-bedded, poorly sorted tuffaceous sandstones and reworked tuff with subrounded fine-grained sand to granule clasts with trace pebble-cobble fragments of a similar provenance to the lower part of the unit; trace white pumice fragments are found as clasts. The upper part of unit Tjst consists primarily of thickly bedded matrix-supported tuffaceous granule-pebble conglomerate that transitions upsection into medium- to thickly bedded reworked lapilli tuffs with pinkish pumice fragments, broken euhedral biotite (to 2 mm diameter) and quartz (to 1 mm diameter) phenocrysts, and angular to subangular (trace subrounded) metamorphic and silicic volcaniclastic lithic fragments (Fig. 5); limited nonwelded primary lapillii tuffs with similar compositions are present. Overall, the rocks of the upper part of the Jackhammer Formation (unit Tjst) are interpreted as tuffaceous debris flows, fluvial sandstones, and reworked silicic lapilli tuffs, likely deposited in a fluvial environment that was part of a proximal debris flow–dominated alluvial fan system (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009).

The lithofacies of the upper part of the Jackhammer Formation vary laterally between the measured sections in Jackhammer Gap described above (Figs. 3A and 5, sections 1–3) and the exposures in the Amphitheatre Canyon area (Figs. 3B and 5, section 4). In the latter, the Jackhammer Formation consists primarily of an ~130-m-thick welded
ignimbrite, herein named the “Mammut ignimbrite” after a pachyderm-shaped rock outcrop located in Amphitheatre Canyon (Fig. 7A). The Mammut ignimbrite (unit Tjd) has a gray, glassy, eutaxitic groundmass, is crystal-rich (30%–40%) with euhedral embayed quartz (to 3 mm diameter), biotite (to 2 mm diameter), plagioclase ± sanidine ± hornblende phenocrysts, and has 5%–10% white fiamme (<1 cm long) and 5%–20% reddish silicic volcanic, gray metamorphic, and trace plutonic accidental lithic fragments (mostly 0.5–5 cm diameter, maximum ~50 cm) (Fig. 7B). The Mammut ignimbrite has a densely welded lower part that passes upward into a less densely welded upper part and exhibits normal coarse-tail grading of accidental lithic fragments and inverse coarse-tail grading of pumice; based on vertical changes in the degree of welding, two cooling units of the Mammut ignimbrite are interpreted in measured section 4 (Fig. 5). A thin 1-m-thick nonwelded top of this ignimbrite is present in measured section 4 (Fig. 5) but is generally absent in other parts of the study area, suggesting some removal and redeposition of the less-consolidated upper portions of the ignimbrite. Based on a similar stratigraphic position, McCulloh (1952) tentatively correlated the upper section of the Jackhammer Formation in Jackhammer Gap area, this deposit is interpreted as a proximal volcaniclastic debris flow; unit Tjd has a densely welded lower part that passes upward into an upper nonwelded top of this ignimbrite with angular reddish-gray rhyodacitic volcanic clasts; however, the clasts of unit Tjd are angular to subangular reddish-brown mud to very coarse-grained sand matrix (Fig. 7A). The breccia clasts have a very similar appearance and phenocryst assemblage to the red rhyodacitic lavas and subvolcanic intrusions in the Calico Mountains that crosscut the Pickhandle Formation (units Tir and Tpl; described below), but the direct provenance of these clasts has not been determined. The maximum measured clast size in unit Tjd varies laterally between the exposures in Jackhammer Gap and in Amphitheatre Canyon (0.8 m versus 1.25 m diameter, respectively). In the Jackhammer Gap section 3, the breccias are both clast supported and matrix supported, and the unit is twice as thick compared to the lower Pickhandle rocks in section 4 north of Amphitheatre Canyon (Fig. 5). Around Amphitheatre Canyon, matrix-supported breccias dominate, and the deposits thicken and coarsen with increased proximity to the Amphitheatre fault (Figs. 3B, 4, and 8B). Interbedded with the massive breccias in the Amphitheatre Canyon area (Figs. 3B and 5) is a volcaniclastic deposit (unit Tplv) of a similar appearance to the breccias with large (0.5–1 m) reddish-gray rhyodacitic volcanic fragments; however, the clasts of unit Tplv are surrounded by a reddish-gray ash matrix of similar composition to the clasts with broken euhedral biotite crystals. This unit is interpreted as a pyroclastic block-and-ash-flow deposit; unit Tplv is not present in Jackhammer Gap, suggesting the volcanic source was more proximal to the northeastern Calico Mountains.

The depositional setting of the lower Pickhandle Formation is interpreted as a proximal volcanic debris apron (e.g., Manville et al., 2009) or a proximal debris flow–dominated alluvial fan system (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009) adjacent to an active silicic volcanic system. The monomictic breccias of unit Tplb are interpreted as volcaniclastic debris flows derived from local volcanic rocks, although it is unclear whether they were deposited concurrently with eruptions (i.e., lahars) or represent epiclastic deposition of

Pickhandle Formation

The Pickhandle Formation in the Calico Mountains is subdivided into two main assemblages (after Fillmore and Walker, 1996): a lower reddish volcaniclastic assemblage (“lower Pickhandle”) and an upper tan volcaniclastic, epiclastic, and volcanic assemblage (“upper Pickhandle”). Descriptions of the various lithofacies and stratigraphic relationships observed in the Pickhandle Formation during this study are summarized below.

Lower Pickhandle

The lower assemblage of the Pickhandle Formation in the northern Calico Mountains is deposited primarily conformably over the uppermost Jackhammer Formation and nonconformably on pre-Cenozoic basement rocks east of the Amphitheatre fault (unit Tpl; Fig. 3). The lower Pickhandle generally consists of a monotonous section of reddish-brown, massive, thickly to very thickly bedded, very poorly sorted monomictic cobble-boulder breccias (unit Tplb) with angular to subangular red porphyritic rhyodacitic volcanic clasts in a light reddish-brown mud to very coarse-grained sand matrix (Fig. 8A). The breccia clasts have a very similar appearance and phenocryst assemblage to the red rhyodacitic lavas and subvolcanic intrusions in the Calico Mountains that crosscut the Pickhandle Formation (units Tir and Tpl; described below), but the direct provenance of these clasts has not been determined. The maximum measured clast size in unit Tplb varies laterally between the exposures in Jackhammer Gap and in Amphitheatre Canyon (0.8 m versus 1.25 m diameter, respectively). In the Jackhammer Gap section 3, the breccias are both clast supported and matrix supported, and the unit is twice as thick compared to the lower Pickhandle rocks in section 4 north of Amphitheatre Canyon (Fig. 5). Around Amphitheatre Canyon, matrix-supported breccias dominate, and the deposits thicken and coarsen with increased proximity to the Amphitheatre fault (Figs. 3B, 4, and 8B). Interbedded with the massive breccias in the Amphitheatre Canyon area (Figs. 3B and 5) is a volcaniclastic deposit (unit Tplv) of a similar appearance to the breccias with large (0.5–1 m) reddish-gray rhyodacitic volcanic fragments; however, the clasts of unit Tplv are surrounded by a reddish-gray ash matrix of similar composition to the clasts with broken euhedral biotite crystals. This unit is interpreted as a pyroclastic block-and-ash-flow deposit; unit Tplv is not present in Jackhammer Gap, suggesting the volcanic source was more proximal to the northeastern Calico Mountains.

The depositional setting of the lower Pickhandle Formation is interpreted as a proximal volcanic debris apron (e.g., Manville et al., 2009) or a proximal debris flow–dominated alluvial fan system (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009) adjacent to an active silicic volcanic system. The monomictic breccias of unit Tplb are interpreted as volcaniclastic debris flows derived from local volcanic rocks, although it is unclear whether they were deposited concurrently with eruptions (i.e., lahars) or represent epiclastic deposition of
Figure 7. Photographs of Jackhammer Formation lithofacies in Amphitheatre Canyon (Fig. 3B). (A) Distinctive rock outcrop of the Mammut ignimbrite in Amphitheatre Canyon that inspired the name of this rock unit. Height of creosote bush in foreground is ~1 m. (B) Closeup of eutaxitic texture in welded basal section of Mammut ignimbrite. This ignimbrite is crystal rich (30%–40% phenocrysts) with 5%–20% reddish silicic volcanic, gray metamorphic, and trace plutonic accidental lithic fragments (mostly 0.5–5 cm, maximum ~50 cm). (C) Depositional contact between the tuffaceous sandstone, conglomerate, and lapilli-tuff unit (Tjst) and the overlying densely welded Mammut ignimbrite (unit Tjm) with subvertical columnar jointing normal to the contact. In comparison to the rocks in Jackhammer Gap, unit Tjst in this area has greater bedding thicknesses and increased amounts of interbedded sandstones and breccias. Students in the foreground for scale (red box). (D) Very thinly bedded lacustrine limestone (unit Tjl) with a possible soft-sediment deformation structure to the left of the scale. (E) Interfingering avalanche breccia (unit Tjb) and tuffaceous sandstone (unit Tjst) deposited over the Mammut ignimbrite (unit Tjm) in Amphitheatre Canyon, near the middle of cross-section B’-B’ (Figs. 3B and 4).
previously erupted volcanic material. The presence of an interbedded block-and-ash flow (unit Tplv) suggests the former, implying that the rocks of the lower Pickhandle were deposited during a period of active silicic volcanism in the Calico Mountains, with volcaniclastic deposition on the aprons surrounding the volcanic edifices. Compared to the Amphitheatre Canyon area, the decreased clast size and greater abundance of clast-supported breccias in Jackhammer Gap suggest further fluvial reworking of the volcaniclastic deposits farther away from the volcanic vent.

**Upper Pickhandle**

The upper assemblage of the Pickhandle Formation in the Calico Mountains is a primarily volcaniclastic unit of variable lithologies, distinguished from the lower Pickhandle by its light tan color and polymict clast compositions (Fig. 5). In general, where undifferentiated (unit Tpu; Fig. 3), the deposits in the upper Pickhandle consist of thinly to thickly bedded reworked silicic lapilli tuffs and tuffaceous breccias, conglomerates, and sandstones (Figs. 5 and 9A). Most conglomerates are matrix supported, with subangular to subrounded pebble-cobble metasemidetrital, plutonic, and silicic volcanic clasts, suggesting a locally derived nonmylonitic basement and silicic volcanic sediment source. Clast-supported conglomerates and trough cross-bedded sandstones with basal scour-structures are also common in this unit. Thin reddish rhyodacitic lava flows (unit Tpul; described below) are locally interbedded in the undifferentiated upper Pickhandle Formation (Figs. 3B and 9B).

In the northeastern Calico Mountains, the rocks of the upper Pickhandle are subdivided into several distinct mappable lithofacies associations (Figs. 3B–3C). The lowest stratigraphic subdivision is a pyroclastic breccia (unit Tpuv) composed of white angular rhyodacitic blocks as large as 1 m diameter surrounded by a white ashy matrix of the same composition with 1–2 mm euhedral biotite crystals (Fig. 9C) that is interpreted as a silicic block-and-ash flow. The known distribution of this unit is restricted to the area east of Calico Peak along cross-section C-C’ and west of Amphitheatre Canyon (Figs. 3B–3C and 4). Where exposed, the block-and-ash-flow is at least 50 m thick (Fig. 5, section 5) and is deposited on an older dacitic lava or intrusion (unit Tiod; described below). Deposited above the white block-and-ash flow unit Tpuv is a predominantly epiclastic sandstone-conglomerate unit (unit Tpus; Figs. 9C–9D) with interbedded reworked silicic lapilli tuffs (unit Tput1 where differentiated and mappable); where unit Tpuv is not present, unit Tpus is deposited on the lower Pickhandle. The deposits of the sandstone-conglomerate unit (Tpus) are primarily reddish-brown to tan pebble-cobble conglomerates that are matrix supported, massive, medium to thickly bedded, and poorly sorted with subrounded to angular plutonic, metasemidetrital, and rhyodacitic volcanic clasts derived from a local nonmylonitic basement and silicic volcanic source. Interbedded with the conglomerates are medium- to very coarse-grained trough cross-stratified and horizontally stratified sandstones of a similar provenance. Basal bedding planes for both the conglomerates and sandstones are typically concave-up erosive surfaces indicating channel scour-fill structures; large multistory channel structures are also present in this stratigraphic unit (Fig. 9D). Extending laterally, farther west from the Amphitheatre fault, unit Tpus becomes more tuffaceous, thinner bedded, and less coarse grained. This stratigraphic subdivision is interpreted as debris-flow and braided-fluvial deposition in a proximal distributary zone of an alluvial fan system or an outwash braidplain (e.g., Miall, 1985, 1996; Blair and McPherson, 1994, 2009).

The uppermost volcaniclastic unit mapped in the upper Pickhandle Formation is a light tan primary to slightly reworked lapilli tuff (unit Tput2; Figs. 3B–3C and 9E). This >50-m-thick nonwelded ignimbrite is a massive cliff-forming unit where nonreworked, consisting of 10%–15% creamy yellow long-tube pumice fragments as much as 5 cm long, 5% phenocrysts (~1 mm biotite and quartz), and 5% accidental metaplatecic basement and silicic volcanic lithic fragments as large as 30 cm diameter. Above the massive lapilli tuff section, unit Tput2 transitions upsection into a clast-supported tuff breccia with angular light gray rhyodacite blocks (~0.2 m, as much as 0.5 m diameter), interpreted as a block-and-ash flow or a co-ignimbrite lag breccia (Fig. 9F). In comparison, the lower section of unit Tput2 exhibits evidence of fluvial deposition above the white block-and-ash flow unit Tpuv.
Figure 9. Photographs of upper Pickhandle Formation lithofacies. (A) Cliff-forming greenish-gray tuffaceous pebble-cobble conglomerate with overlying white tuffaceous sandstone, at 268 m in Jackhammer Gap measured section 3 (Fig. 5). (B) Silicic lava (unit Tpul; Fig. 3) interbedded with upper Pickhandle volcanioclastic rocks (not pictured) in Amphitheatre Canyon, showing flow-top breccia (lf), white tuff layer (wt), and monomictic breccia (mb). Breccia (mb) is clast supported with flow-banded dacitic boulders (as large as 1 m) similar in appearance to underlying lava (lf). (C) White silicic block-and-ash flow deposit (unit Tpuv) with blocks as large as 1 m below red fluvial sandstone (unit Tpus) at the location of cross-section C-C' (Figs. 3C and 4). (D) Multistory channels in reddish alluvial conglomerate-sandstone (unit Tpus) and interbedded reworked lapilli tuff (unit Tput1) east of Calico Peak (Fig. 3C). Inset photograph shows a closeup of the scour-fill relationship between the uppermost Tpus sandstone channel in the main photograph and underlying unit Tpus rocks. Length of hammer in photograph is 38 cm. (E) Looking northwest, east of Calico Peak near the location of cross-section C-C' (Figs. 3C and 4) at the intraformational angular unconformity in the upper Pickhandle Formation between moderately (~20°–30°) east-dipping reddish alluvial conglomerate and sandstone (unit Tpus) below gently (~20°) northwest-dipping tan reworked lapilli-tuff (unit Tput2). Emplaced over unit Tput2 is a red porphyritic lava dome (unit Tir). Total vertical relief of image is ~100 m. (F) Tuff breccia with gray dacitic fragments in the upper part of unit Tput2, interpreted as a block-and-ash flow deposit or a co-ignimbrite lag breccia.
reworking, including a greater degree of sorting and medium to very thick bedding. Unit Tpul2 is interpreted as an ignimbrite erupted into the alluvial fan depositional system by a basin-proximal explosive volcanic source. Initial eruptive products were reworked by fluvial processes in the basin system, followed by an increased amount of pyroclastic material that was erupted faster than it could be reworked.

**Syn- to Post-Pickhandle Volcanic Rocks**

During and shortly following deposition of the Pickhandle Formation in the study area, several silicic domes and lavas were emplaced (Figs. 3 and 10). At least four different volcanic units are identified in the study area, described here from relatively oldest to youngest. The oldest volcanic unit is a light gray to white dacitic lava and/or hypabyssal intrusion (unit Tiod), distinguished by its light color and platy flow banding, and has 5%–30% phenocrysts of plagioclase (to 3 mm), biotite, and trace quartz. In comparison to the other volcanic units, unit Tiod does not hold up the high topography in the Calico Mountains and is mainly found in the low-lying areas on the northwestern flanks of the range. In the area east of Jackhammer Gap (Fig. 3A), unit Tiod intrudes the Paleozoic basement, Jackhammer Formation, and lower Pickhandle Formation; west of Amphitheatre Canyon (Fig. 3B), the white block-and-ash-flow unit Tpul and light tan lapilli tuff unit Tpul2 are deposited on top of unit Tiod (Fig. 10A).

The most common volcanic assemblage in the northern Calico Mountains is red porphyritic rhyodacitic lava flows (unit Tird) and associated lava flows (unit Tpul) (Fig. 10). These rocks are distinguished by their red-lavender porphyritic texture with 25%–30% phenocrysts of euhedral plagioclase, biotite, and quartz (typically 1–2 mm in diameter, as much as 5 mm) and flow-banded groundmass. The lava domes and subvolcanic intrusions (unit Tird) typically exhibit subvertical flow banding that transitions laterally into slightly lower dip angle. Where the outer margins of a lava dome are preserved, autoclastic flow breccias are present (Fig. 10B). These domes intrude the upper Pickhandle Formation volcaniclastic rocks, with intrusion-induced folding of these deposits adjacent to the domes. At least one dome was erupted during upper Pickhandle deposition as a buttress unconformity between upper Pickhandle tuffaceous sedimentary rocks that overlie and infill the brecciated upper margin of unit Tir (Fig. 10B). The rocks identified as lava flows (unit Tpul) are identical in appearance and phenocryst assemblage to the lava domes (unit Tir) except they exhibit irregular subhorizontal flow banding with compressional folding. The typical vertical sequence of unit Tpul (>100 m thick) consists of a dark gray to black basalt vitrophyre with localized brecciation that transitions into a dark red, coherent, flow-banded interior, which grades upsection into a light gray to white flow-banded upper section with a brecciated top (Fig. 10C). Like the lava domes, these flows are younger than much of the upper Pickhandle Formation and flowed over much these deposits after they were tilted or faulted (Fig 10A).

Two additional Pickhandle-related subvolcanic units locally intrude the rocks of the upper Pickhandle in the Amphitheatre Canyon area (Fig. 3B). One is a light gray to white rhyodacite (unit Tiw), which intrudes the uppermost part of measured section 4 and comprises peak 39S5T and two prominent peaks to the south (Figs. 3B and 5, section 4 photograph). This rock has a light gray to white, aphanitic to very fine-grained phaneritic groundmass with 30%–40% phenocrysts of euhedral plagioclase + biotite ± sanidine (as much as 2–3 mm diameter). This intrusion cross-cuts and drag folds the bordering Pickhandle deposits, and an apparent roof pendant of upper Pickhandle with numerous jasper veins is located on peak 39S5T, implying that unit Tiw is younger than these volcaniclastic rocks (Fig. 3B). The second subvolcanic unit in the study area is a gray rhyodacitic intrusion (unit Tig) that is localized in the area west of measured section 4 (Fig. 3B). This rock has a porphyritic texture, with 10% plagioclase + quartz + biotite ± sanidine phenocrysts as much as 2 mm diameter in a gray groundmass. This intrusion cross-cuts the upper Pickhandle Formation and the red porphyritic lava flow (unit Tpul) to the southeast and appears to be the youngest Pickhandle-related volcanic unit identified in the northern Calico Mountains. Intrusive bodies and dikes similar in appearance to unit Tig were identified during reconnaissance mapping in the area between Jackhammer Gap and Amphitheatre Canyon where they cut unit Tiod and the Pickhandle Formation; further mapping is needed in this area to confirm these relationships.

**AGE CONSTRAINTS**

**Methodology**

Argon–argon ($^{40}$Ar/$^{39}$Ar) ages were obtained for feldspar and biotite from a total of nine volcanic rock samples collected from various stratigraphic levels of the Pickhandle and Jackhammer Formations in the northern Calico Mountains (Fig. 1; Table 1; Table S1†). These ages were obtained using laser extraction methods in the Auburn Noble Isotope Mass Analysis Laboratory (ANIMAL; Auburn University, Auburn, Alabama, USA). Specific details of the laboratory procedures and methods (including specific methods, standards, and values for decay constants) are provided in Table S1. Feldspars were analyzed by fusion of single crystals (SCTF) and by incremental heating of approximately three to four crystals. For plagioclase samples, the incremental heating results are generally preferred and are presented in Table S1, in view of their relatively low K content and the relatively low radiogenic yields of the SCTF analyses (typically <50%). Regression of the isotopic data for all analyses yields ages similar to the model age results of the plateau and with a trapped extraneous component of modern atmosphere. One sample was found to have abundant sanidine, and the age presented for it is the SCTF result. Five of the samples also provided biotite that was analyzed by incremental heating of three to four crystals for each. The ages obtained for biotite plateaus were statistically indistinguishable from the corresponding plagioclase ages of these samples. Results in Table 1 are presented with the combined result of the plagioclase and biotite ages as applicable. All ages are quoted at the 2σ confidence level unless indicated otherwise.

| Supplemental Material. Table S1: $^{40}$Ar/$^{39}$Ar analytical results. Please visit https://doi.org/10.1130/GEOS.1432510 to access the supplemental material, and contact editing@geosociety.org with any questions. |
Figure 10. Photographs of syn– to post–Pickhandle Formation volcanic units. (A) Annotated panoramic photograph looking southwest from 513980E 3875200N toward peak (X) at 514000E 3874000N (Fig. 3B; Universal Transverse Mercator, North American Datum 1927 zone 11S coordinates). Yellow thick dashed lines are faults (dotted where buried; fault slip sense: U—up; D—down). Red medium dashed lines are intrusive and/or flow contact. White long-dashed lines are depositional contacts. Photograph shows a red silicic dome and lava flow (unit Tpul) intruding through a preexisting normal fault on left, flowing over southeast-tilted upper Pickhandle Formation (units Tput2 and Tpus); flow-banding orientations are indicated by thin white short-dashed lines. Also shown in the photograph is a red porphyritic silicic dike (unit Tir) that is also intruding though two preexisting normal faults: the fault in the foreground downdropped units Tpul and Tpu, prior to emplacement of unit Tir. Students in the foreground for scale (black box) are standing on the downdropped block, with ~300 m vertical relief from the black box to the peak (X). (B) Depositional contact between the brecciated outer margin of a red rhyolitic intrusion and an overlying light tan tuffaceous conglomerate of the upper Pickhandle. The tuffaceous matrix from the overlying deposit infills the pore spaces between red breccia clasts. Length of hammer in photograph is 38 cm. (C) View looking north toward peak 4264T (Fig. 3C) at a complete section of a unit Tpul lava flow. The base of unit Tpul is a dark gray to black vitrophyre that changes upsection into a dark red flow-banded coherent interior. The top of unit Tpul transitions from dark red to a light red to white. A younger red silicic dome (unit Tir) intrudes and flows over unit Tpul, which is deposited over unit Tput2 (see Figs. 3C and 4). The coherent interior thickens to the left, indicating the vent direction is likely to the west. Total vertical relief of photograph is ~200 m.
Figure 11. $^{40}$Ar/$^{39}$Ar age spectra for the nine samples analyzed for this study (Table 1). Ages of the samples were determined by the best multigrain incremental heating plateau for plagioclase or biotite for each sample; exception is sample BM165-17-5, which was determined using the sanidine single-crystal total fusion (SCTF) mean age (inset probability density plot). Ages in bold correspond to the preferred age results as discussed in the text and Table 1. Details of each analysis given in Table S1 (see footnote 1). MSWD—mean square of weighted deviates.
Results

Age results are presented in the present study for three samples from previously undated Jackhammer Formation (Fig. 1; Table 1). From the base, two samples of the welded Mammut ignimbrite in Amphitheatre Canyon (unit Tjm; samples BM126-14-2 and BM163-23-2) yield combined ages for plagioclase and biotite of 19.49 ± 0.42 Ma and 19.84 ± 0.14 Ma, respectively. One sample collected from a nonwelded silicic lapilli tuff interbedded with reworked lapilli tuff and tuffaceous conglomerates near the top of the formation in Jackhammer Gap section 3, 42 m (Figs. 3A and 5) measured 20.18 ± 0.15 Ma.

Four samples were dated from the volcaniclastic rocks of the Pickhandle Formation (Fig. 1; Table 1). Beginning from its base, a sample of plagioclase from the lower Pickhandle reddish rhyodacitic block-and-ash flow (unit Tplv; sample BM126-14-3) yields an age of 20.17 ± 0.38 Ma. Two samples were dated from the upper Pickhandle Formation (unit Tpu) where it is directly deposited over the lower Pickhandle. One sample of plagioclase from a reworked silicic lapilli tuff above the base of the upper Pickhandle Formation (unit Tpu; sample BM126-6-3) in Jackhammer Gap measured 20.13 ± 0.36 Ma.

TABLE 1. \(^{40}\text{Ar} / ^{39}\text{Ar}\) GEOCHRONOLOGY OF VOLCANIC ROCKS IN THE NORTHERN CALICO MOUNTAINS, CALIFORNIA (USA)

| Sample  | Unit    | Description                                                                 | Age ± 2\(\sigma\) | Mineral  | Method   | MSWD  | UTM (E) | UTM (N) |
|---------|---------|------------------------------------------------------------------------------|-----------------|----------|----------|-------|---------|---------|
| BM166-1 | Tiw     | Light gray rhyodacitic intrusion, Amphitheatre Canyon (Fig. 3B)             | 19.39 ± 0.32    | Plagioclase | Plateau | 0.57  | 514810 | 3874382 |
| BM166-3 | Tir     | Red porphyry rhyodacitic lava dome intrusion, peak 4264T (Fig. 3C)         | 20.34 ± 0.24    | Plagioclase | Plateau | 1.4   | 515897 | 3873194 |
| BM164-5 | Tpu     | Nonwelded silicic lapilli tuff, directly above unit Tpl (Fig. 3B)          | 19.85 ± 0.40    | Plagioclase | Plateau | 2.6   | 514679 | 3875265 |
| BM164-1 | Tpuv    | White silicic block-and-ash flow fragment (Fig. 3C)                        | 19.97 ± 0.10    | Sanidine/plagioclase | SCTF | 0.78  | 516095 | 3873011 |
|         |         |                                                                               | 20.02 ± 0.08    | Biotite  | Plateau | 1.3   | 508877 | 3877383 |
| BM126-2 | Tpu     | Reworked silicic lapilli tuff, near base of upper unit; Jackhammer Gap    | 20.13 ± 0.36    | Plagioclase | Plateau | 1.3   | 508877 | 3877383 |
| BM126-4 | Tplv    | Reddish-brown rhyodacitic block & ash flow fragment; section 4, 152 m    | 20.17 ± 0.38    | Plagioclase | Plateau | 0.80  | 514198 | 3875483 |
| BM166-2 | Tjst    | Nonwelded silicic lapilli tuff, near top of formation below unit Tpl;     | 20.18 ± 0.15    | Biotite  | Plateau | 0.53  | 509078 | 3877549 |
| BM126-4 | Tjm     | Welded "Mammut" ignimbrite; section 4, 100 m (Figs. 3B and 5)             | 19.49 ± 0.42    | Plagioclase | Plateau | 1.18  | 514167 | 3875546 |
| BM166-2 | Tjm     | Welded "Mammut" ignimbrite, Amphitheatre Canyon (Fig. 3B)                 | 19.82 ± 0.14    | Plagioclase | Plateau | 1.6   | 515585 | 3874446 |
| BM126-4 | Tjm     | Welded "Mammut" ignimbrite; section 4, 100 m (Figs. 3B and 5)             | 19.76 ± 0.12    | Biotite  | Plateau | 1.6   | 515585 | 3874446 |

Notes: Preferred age results as discussed in the text are presented in bold. Samples are listed in relative stratigraphic order (youngest to oldest). Dashes (—) under “Mineral” column indicate the combined results of feldspar and biotite ages for the sample. Abbreviations: SCTF—single crystal total fusion; MSWD—mean square of weighted deviates. Universal Transverse Mercator (UTM; E—east, N—north) coordinates are based on the North American Datum of 1927 (NAD27) zone 11. Map unit labels correspond to Figure 3. Details of each analysis are given in Table S1 (see text footnote 1).
section 3 (Fig. 5) yielded an age of 20.13 ± 0.36 Ma. One sample from a white silicic block-and-ash flow (unit Tpul; sample BM165-17-5) collected within the upper Pickhandle Formation east of Calico Peak provided sanidine and biotite with a combined age of 20.02 ± 0.08 Ma. An additional sample from the upper Pickhandle Formation is a nonwelded silicic lapilli tuff collected near Amphitheatre Canyon (unit Tp; sample BM164-30-5), which has an age of 19.92 ± 0.20 Ma.

Two samples were dated from intrusive units that appear to be broadly coeval with or postdating the stratigraphy of the upper Pickhandle Formation (Fig. 11; Table 1). A sample dated from the red porphyritic rhodacitic lava dome (unit Tir; sample BM165-16-3) that holds up peak 4264T and covers the stratigraphy of the upper Pickhandle Formation east of Calico Peak (Fig. 12) produced a combined age of 20.10 ± 0.06 Ma (n = 6, mean square of weighted deviates [MSWD] = 1.8, with 12% probability of fit). We suggest this mean age represents the primary result obtained in this study.

Considering the results for all samples represented in Table 1, five of the samples from the Pickhandle Formation and the lapilli tuff from the top of the Jackhammer Formation have a mean age of 20.10 ± 0.06 Ma (n = 6, mean square of weighted deviates [MSWD] = 1.8, with 12% probability of fit). We suggest this mean age represents the primary period of explosive and effusive volcanism in the study area, resulting in contemporaneous emplacement of silicic block-and-ash flows, non-welded tuffs, and lava domes in the section as sampled. The exclusions from this mean are a younger intrusive unit (unit Tiw; sample BM165-1-1) and the two samples from the welded Mammut ignimbrite. The J-values for these samples are constrained sufficiently to rule out flux variations as possible sources of error (see supporting information in Table S1 [footnote 1]), and because the anomalously young results for the base of the section are identical for two samples, they appear robust.

Thus, we infer the results of ca. 19.78 Ma for the welded Mammut ignimbrite (unit Tjm) samples reflect loss of some radiogenic 40Ar during a period of high geothermal gradient and elevated temperature from ca. 20.1 Ma to at least ca. 19.78 Ma. In support of this interpretation, we also note that the biotite spectra for these two samples show evidence of 40Ar loss subsequent to ca. 20.1 Ma (Fig. 11).

### GEOLOGIC STRUCTURES RELATIVE TO BASIN DEVELOPMENT

Structural relationships observed in the northern Calico Mountains suggest that extensional deformation occurred both during and after deposition of the Jackhammer and Pickhandle Formations, followed by postdepositional strike-slip fault reactivation. North-northwest–striking faults are the dominant geologic structures in the study area, with subordinate antithetic east-northeast–striking faults (Fig. 3). Where fault slip indicators (e.g., slickenlines) and identifiable offset of stratigraphic units are present, most faults record dip-slip to oblique-slip normal offset. Many faults also exhibit a younger phase of strike-slip offset, indicated by overprinting of the older subvertical slickenlines with subhorizontal lineations. These cross-cutting relationships suggest that most faults in the study area initiated during a period of crustal extension likely related to the development of the CMMCC, with postextensional reactivation of some of the faults during the subsequent development of the Eastern California shear zone and the right-lateral Calico fault system located ~7 km to the southwest of the study area (Fig. 2). Bedding is typically tilted with respect to the major structures, with predominantly east-dipping bedding in the easternmost study area changing to west- to southwest-dipping bedding west of Amphitheatre Canyon to Jackhammer Gap (Fig. 3).

One of the major structures in the study area is the newly named Amphitheatre fault, a high-angle northwest-striking, southwest-dipping normal fault between footwall basement rocks and hanging-wall deposits of the Jackhammer and Pickhandle Formations (Figs. 3B–3C and 4). Evidence of growth strata suggests syndepositional displacement of the Amphitheatre fault, which bounds the northeastern margin of an extensional basin system (Fig. 12). The deposits of the Jackhammer and Pickhandle Formations on the Amphitheatre fault hanging wall thicken and coarsen eastward toward the Amphitheatre fault, with the Jackhammer Formation absent (or thinner) on the footwall block where the lower Pickhandle Formation is deposited directly on nonmylonitic basement Mesozoic plutonic rocks (Fig. 12A). Jackhammer Formation megabreccias intertongue basinward with intercalated lacustrine limestones (unit Tjl) and fluvial tuffaceous debris flows and sandstones (unit Tstj) in the downdropped basin near the Amphitheatre fault (Fig. 7E), suggesting that rock avalanches and debris flows were shed from the uplifted fault scarp into the adjacent basin where an alluvial fan–playa lacustrine system was depositing in the deepest part of the basin next to the Amphitheatre fault. Ponding of the Mammut ignimbrite also occurred in this syndepositional fault depression, with the greater stratigraphic thickness promoting a higher degree of welding; the Mammut ignimbrite thins westward away from the fault toward Jackhammer Gap, where the lapilli tuff was fluvially reworked in the proximal distributary zone of the alluvial fan system. Fanning bedding dips and intraformational angular unconformities are observed within the upper Pickhandle deposits on the hanging wall adjacent to the Amphitheatre fault, further indicating synextensional deposition (Figs. 3B–3C, 4, 9E, and 12).

Many lava domes, lava flows, and related hypabyssal rocks of the red porphyritic rhodacitic unit (units Tir and Tpul) intrude preexisting faults in the study area that offset older Pickhandle deposits (Fig. 10A). In the area west of Amphitheatre Canyon around peak 3862 (524500E 3874500N; Fig. 3B), a vent for lava flow unit Tpul appears to be along the northwest-striking fault truncated by the lava south
Figure 12. Evidence of growth strata in the Pickhandle Formation, suggesting syndepositional extension of the Amphitheatre fault in the northeastern Calico Mountains. Unit labels are the same as in Figure 3. (A) Annotated photograph looking southwest near the eastern end of cross-section B-B’ (Fig. 3B and 4) at eastward-tilted Pickhandle Formation (lower and upper members) on the hanging wall of the Amphitheatre fault (U—up; D—down), which underlie westward-tilted reworked silicic lapilli tuff (unit Tput2) and red rhyodacitic lava (unit Tir). A thin layer of Jackhammer Formation white bedded tuff (unit Tjt) is found on the footwall block, but generally this formation is absent on the footwall of the Amphitheatre fault where the lower Pickhandle Formation (unit Tplb) is deposited directly on basement Mesozoic granitoids (unit Mzi). Width of the photograph is ~0.3 km along the fault. (B) Annotated photograph looking south at the location of cross-section C-C’ (Figs. 3C and 4), showing fanning bedding dips (thin white dashed lines) in the upper Pickhandle Formation (unit Tpus). Unit Tpus dips ~30°E near the base of the unit above the white block-and-ash flow breccia (unit Tpuv), transitioning upsection to ~20°E dip near the top of the unit below the intraformational angular unconformity with the light tan reworked lapilli tuff (unit Tput2). Width of the photograph is ~0.3 km along the ridge. (C) Photograph (top) and interpretation (bottom) of cross-cutting relationships in the upper Pickhandle Formation at the location of cross-section C-C’, west of the Amphitheatre fault (Figs. 3C and 4). Fanning bedding dips in unit Tpus and an intraformational angular unconformity between units Tpuv-Tpus and unit Tput2 are present east of the west-dipping normal fault. On the hanging-wall block, a red dike cut by this fault feeds directly into the red porphyritic rhyodacitic lava dome (unit Tir) that overlies a rhyodacitic lava (unit Tpul). Unit Tput2 is downdropped ~350 ft by the normal fault, with minimal offset of unit Tir. Width of the photograph is ~0.5 km.
of peak 3862. This fault likely provided a conduit for magma ascent and lines up with several smaller lava domes east of Calico Peak (Fig. 3C) that may have been concurrently emplaced; in addition, a younger fault that offsets the lava flow at peak 3862 was subsequently intruded by an elongate unit Tir intrusion (Figs. 3B and 10A). Fault deformation continued following the emplacement of the red porphyritic rhyodacitic unit (units Tir and Tpul), as evident by apparent normal offset of lava flows and domes (e.g., Figs. 4 and 12C).

Sediment dispersal patterns and provenance suggest that deposition in the study area was closely related to concurrent extensional deformation. Paleocurrent measurements were collected from trough-cross limbs in sandstone and conglomerates (method 1 of DeCelles et al. [1983]) and conglomerate clast imbrications in the measured stratigraphic sections and additional isolated outcrops of the Jackhammer and Pickhandle Formations (Figs. 5 and 13). Based on these paleocurrent indicators and assuming no vertical-axis block rotations, paleoflow in the northeastern Calico Mountains adjacent to the Amphitheatre fault was primarily southwest directed (Figs. 5 and 13). Farther west in Jackhammer Gap, paleoflow orientations are consistent with these more fault-proximal deposits, suggesting southwest-directed flow of alluvial systems in the northern Calico Mountains away from an uplifted source region to the northeast (Figs. 5 and 13).

To determine the provenance of the Jackhammer and Pickhandle Formations and to observe possible stratigraphic trends, conglomerate compositional data were collected from several of the measured stratigraphic sections, which consisted of lithologic identification of an average of 75 clasts per conglomerate (Fig. 5); clast compositions were also qualitatively recorded at additional outcrops throughout the study area. Although some conglomerate clasts cannot be identified to specific source localities, many clast types may be attributed with confidence to specific basement or silicic volcanic rock types. Based on these observations, clasts in the Jackhammer Formation were derived primarily from the underlying nonmylonitic basement of Paleozioc metamorphic rocks and Mesozoic granitoids, with additional contribution from intrabasinal erosion of Jackhammer Formation silicic bedded tuff and mafic volcanic rocks and an extrabasinal source of silicic volcanic rocks and welded tuffs possibly derived from the Lane Mountain volcanics found ~5 km northwest of the study area (e.g., McCulloh, 1952; Burke et al., 1982; Dibblee and Minch, 2008). Provenance of the lower Pickhandle Formation indicates derivation from an intrabasinal or basin-proximal rhyodacitic volcanic source, with reworked silicic volcaniclastic rocks (lahars and/or debris-flow deposits) interbedded with silicic pyroclastic deposits (block- and-ash flows). In comparison to the Jackhammer Formation, sediment of the lower Pickhandle indicates either no contribution from a metaplutonic basement source or that clasts derived from this source area were completely inundated by the large input of silicic volcanic fragments filling the basin. Clasts derived from the nonmylonitic metaplutonic basement again appeared during epiclastic deposition of the upper Pickhandle, with a similar proportion of sediments sourced from intrabasinal erosion of Jackhammer and lower Pickhandle Formation rocks. In addition, intrabasinal eruptions of silicic domes, lavas, and pyroclastics (block- and-ash flows, ignimbrites) contributed clasts of volcanic material to the upper Pickhandle Formation.

Mylonitic clasts are notably missing from all rocks in the study area and from tilted Pickhandle Formation rocks deposited on top of the Waterman Hills detachment fault (e.g., Anderson, 2017), although these should be expected if the footwall was exposed during synextensional deposition. The lack of mylonitic clasts suggests that although syndepositional extension was active in the Calico Mountains by ca. 20.1 Ma, either the mylonitic footwall was not exposed at the time and the Waterman Hills detachment fault is a younger feature in the development of the CMMCC, or a drainage divide existed between the detachment fault footwall source and the basins in the Calico Mountains to the east (Fig. 2). The former interpretation is supported by \(^{40}Ar/^{39}Ar\) thermochronology data indicating ca. 21–17 Ma rapid cooling of the Waterman Hills detachment fault footwall (Gans et al., 2005; Wong and Gans, 2009), suggesting that timing of mylonite surface exposure likely occurred after Pickhandle deposition and initial upper crustal extension in the Calico Mountains.

**DISCUSSION**

**Volcanic and Tectonic Evolution**

Based on the evidence presented above, the Jackhammer and Pickhandle Formations and coeval volcanic rocks in the Calico Mountains were deposited in a short-lived early Miocene synextensional volcanic vent–proximal alluvial fan system that formed within an intra-hanging-wall basin in the upper plate of the CMMCC. Crustal extension, volcanism, and alluvial deposition was active in the study area by ca. 20.1 Ma based on our oldest age of the Jackhammer Formation. Based on the deep incision and unroofing of the nonmylonitic metamorphic basement that underlies the Cenozoic rocks and from stratigraphic evidence in the nearby Mud Hills, extension likely initiated earlier and was active by ca. 21 Ma (e.g., Ingersoll et al., 1996). The alluvial fan system accumulated in a half-graben basin bounded on the northeastern margin by the southwest-dipping Amphitheatre fault (Figs. 3B–3C and 4), interpreted as an antithetic fault that terminates at depth into the underlying gently northeast-dipping Waterman Hills detachment fault. This structural configuration is very similar to the intra-hanging-wall basin depositional setting interpreted for the Clews Formation in the Alvord Mountains ~25 km east of the Calico Mountains (Fig. 1), where interfinger ing lacustrine and alluvial fan deposits thicken and coarsen eastward toward the east-dipping basin-bounding fault (Fillmore et al., 1994). The distribution of lithofacies in this depositional system is also analogous other fault-bounded basin systems (e.g., Yarnold, 1993; Blair and McPherson, 2009), including the modern Badwater fan in Death Valley and, at a smaller scale, the late Neogene Violin Breccia–Peace Valley Formation in Ridge Basin, both in California (e.g., Crowell, 2003). Extensional deformation was also important to the magmatic development in the study area, given that preexisting normal faults are commonly intruded by syn- to post-Pickhandle...
Figure 13. Generalized geologic map of the northern Calico Mountains showing the locations and directions of paleocurrent data collected from the Jackhammer and Pickhandle Formations. Paleocurrent measurements were collected from trough-cross limbs in sandstones and conglomerates (method I of DeCelles et al. [1983]) and from conglomerate clast imbrications. Inset equal-radius rose diagram for the directional data from all localities (n = 23) suggests a primarily southwestward-directed paleoflow.
silicic domes and lavas, which provided conduits for the emplacement of these volcanic rocks into basin system (Figs. 3B, 10A, and 12C). Extension and volcanism in the northern Calico Mountains was likely waning by ca. 19 Ma, suggested by the lesser degree of deformation to the Pickhandle silicic domes and by post-Pickhandle lacustrine deposition of the Calico Member of the Barstow Formation in the southeastern Calico Mountains (Singleton and Gans, 2008).

In Jackhammer Gap, direct evidence of syn-extensional deposition is limited but is inferred based on observed depositional relationships. In this area, the Jackhammer Formation was deposited in a deeply eroded channel carved into the underlying Paleozoic metamorphic basement. Based on available mapping, it is unclear whether the pre-Cenozoic basement rocks at this locality are part of the footwall or hanging-wall block of the Amphitheatre fault or a related extensional fault, or are simply nonmylonitic upper-plate rocks of the Waterman Hills detachment fault that underlie the Cenozoic deposits; nevertheless, the paleochannel relief was present during deposition to allow local downstream transport of sediments (Figs. 3A and 13). The lowest stratigraphic members of the Jackhammer Formation (units Tjc and Tjv) initially filled this paleochannel east of Fort Irwin Road with sediment derived from the metaplutonic basement rocks and coeval silicic volcanic rocks. Where depositional relationships preserved, the paleochannel was incised an apparent northeast-southwest orientation prior to structural tilt, consistent with the measured paleocurrent directions (Figs. 3A and 13).

The new data presented above for the Jackhammer and Pickhandle Formations in the Calico Mountains challenge the established tectonostratigraphic interpretations related to the development of the CMMCC (e.g., Fillmore et al., 1994; Walker et al., 1995; Fillmore and Walker, 1996). These previous interpretations utilized geochronology and lithofacies distribution models of Pickhandle-type rocks in the central Mojave region stretching from the Gravel Hills to Lead Mountain (Figs. 1 and 14) to suggest that the volcanic-dominated sedimentation of the lower Pickhandle Formation represents synextensional supradetachment deposits derived from an intrabasinal volcanic center located in the Calico Mountains during initial CMMCC extension, followed by waning volcanism and increased epilastic alluvial-lacustrine deposition ca. 21.5 Ma that led to synextensional deposition of the polymictic upper Pickhandle Formation; cessation of CMMCC extension is interpreted to have occurred ca. 19 Ma during deposition of the lacustrine rocks of the Barstow Formation (Fillmore and Walker, 1996). Although these previous workers did not study the Pickhandle Formation in the Calico Mountains, evidence supporting a volcanic center at this locality includes the lower Pickhandle deposits becoming coarser grained and less fluvially reworked with increased proximity to the Calico Mountains, as well as the number of primary lava flows, block-and-ash flows, and volcanic plugs located within the northern Calico Mountains (McCulloh, 1960; Dibblee, 1970; Fillmore and Walker, 1996). However,

### Regional Correlations

The onset of local rhyodacitic volcanism in the northern Calico Mountains (McCulloh, 1960; Dibblee, 1970; Fillmore and Walker, 1996). However, extensions are limited but is inferred based on observed depositional relationships. In this area, the Jackhammer Formation was deposited in a deeply eroded channel carved into the underlying Paleozoic metamorphic basement. Based on available mapping, it is unclear whether the pre-Cenozoic basement rocks at this locality are part of the footwall or hanging-wall block of the Amphitheatre fault or a related extensional fault, or are simply nonmylonitic upper-plate rocks of the Waterman Hills detachment fault that underlie the Cenozoic deposits; nevertheless, the paleochannel relief was present during deposition to allow local downstream transport of sediments (Figs. 3A and 13). The lowest stratigraphic members of the Jackhammer Formation (units Tjc and Tjv) initially filled this paleochannel east of Fort Irwin Road with sediment derived from the metaplutonic basement rocks and coeval silicic volcanic rocks. Where depositional relationships preserved, the paleochannel was incised an apparent northeast-southwest orientation prior to structural tilt, consistent with the measured paleocurrent directions (Figs. 3A and 13).

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### Table: Age Data for the Pickhandle Formation and Associated Strata

| Formation          | Barstow Formation | Upper Pickhandle Formation | Lower Pickhandle Formation | Jackhammer Formation |
|--------------------|-------------------|----------------------------|---------------------------|----------------------|
|                    | 18.9 ± 1.3        | 21.4 ± 0.5                 | 22.4 ± 0.5                | 23.7 ± 0.5           |
| Mud Hills          | 19.3 ± 0.02       | 21.7 ± 0.5                 | 21.7 ± 0.5                | 21.7 ± 0.5           |
| Waterman Hills     |                   | 20.13 ± 0.36               | 20.17 ± 0.38              | 23.0 ± 0.5           |
| Jackhammer Gap     | 19.35 ± 0.15 (intrusive) | 19.0 ± 0.1 to 20.34 ± 0.24 (intrusive) | 19.0 ± 0.1 to 20.34 ± 0.24 (intrusive) | 21.3 ± 0.5 |
| E. Calico Mountains|                   |                            |                           |                      |
| Lead Mountain      |                   | 21.3 ± 0.5                 | 20.17 ± 0.38              |                      |

Figure 14. Compiled age data (in Ma) for the Pickhandle Formation and associated strata in the central Mojave Desert (modified from Fillmore and Walker, 1996), with localities arranged by their relative northwest-to-southeast orientation (see Fig. 1). The localities and ages in bold text are the new ^{40}Ar/^{39}Ar ages from this study (Fig. 1); Table 1), with the ages in italic text from Singleton and Gans (2008). All other ages are from Burke et al. (1982), Woodburne et al. (1990), and Walker et al. (1995). *—The ca. 19.78 Ma age for these welded “Mammut” ignimbrite samples (unit Tjm; Table 1) reflects loss of some radiogenic ^{40}Ar during a period of high geothermal gradient and elevated temperature from ca. 20.1 Ma to at least ca. 19.78 Ma, with biotite spectra showing evidence of ^{40}Ar loss subsequent to ca. 20.1 Ma (Fig. 11). †—Interpretations of the relative timing of tectonic and depositional events in relation to stratigraphic units is after Fillmore and Walker (1996); the new age data from this study are inconsistent with the absolute timing of these interpreted events.
the temporal association of initial CMMC extension with Pickhandle Formation deposition may be misleading because coarse-grained volcaniclastic rocks are not exclusive to synextensional deposition. These types of deposits may form as part of a volcanic debris apron proximal to a volcanic center without requiring any crustal deformation and may display similar stratigraphic relationships as extensional alluvial fan systems, including debris avalanche breccias, channelized cross-bedded fluvial sandstone, and overbank to lacustrine mudstones (e.g., Manville et al., 2009).

Based on provenance, stratigraphy, and geochronology data, our study confirms previous interpretations that the Pickhandle and Jackhammer Formations were deposited during a period of coeval extension and volcanism in the central Mojave and that an active silicic volcanic center was located in the Calico Mountains at ca. 20.1 Ma. However, in detail, these rocks do not fit into the established temporal framework of CMMC extension and related depositional systems (Fig. 14), suggesting that these previous stratigraphic models oversimplify the complex volcanic and extensional history of the central Mojave, which appears to be episodic and overlapping in space and time (e.g., Gans et al., 2005). In the northern Calico Mountains, the ca. 20.1 Ma age of the Pickhandle Formation and the top of the Jackhammer Formation postdates the traditionally inferred regional shift to waning volcanism and polymeric alluvial deposition ca. 21.5 Ma (Fig. 14). In general, the rocks in the Calico Mountains are consistently younger than correlated deposits in the central Mojave (Fig. 14), indicating that the volcanic center located here was likely not the only source of Pickhandle-type rocks in the region. For example, some of the volcanic detritus near the Gravel Hills, where the oldest dated Pickhandle-type rocks are found (Figs. 1 and 14), may have a source from the nearby Black Canyon–Opal Mountain area or from the similar-age Lane Mountain volcanics (McCulloh, 1952, 1960; Dibblee, 1967, 1968; Burke et al., 1982).

Extrapolating stratigraphic relationships and depositional ages from individual basins to the region as a whole to determine the timing of CMMC extension is problematic, particularly because coarse-grained volcaniclastic rocks tend to have more locally derived sources and limited lateral continuity, which make correlations difficult. Therefore, it is possible that the discrepancy in ages and potential miscorrelations of the Pickhandle Formation indicate that CMMC extension was not a large-magnitude regional event occurring synchronously. Rather, extension and contemporaneous volcanism in the central Mojave region was likely more localized and asynchronous, occurring in many smaller extensional basins that eventually culminated in exposure of the CMMC mylonitic footwall rocks.

## CONCLUSIONS

New geologic mapping and 40Ar/39Ar ages indicate that the early Miocene rocks (ca. 20.1 Ma) in the northern Calico Mountains record synextensional volcanism and deposition in a vent-proximal alluvial fan system. The Jackhammer Formation was deposited on deeply eroded nonmylonitic pre-Cenozoic basement rocks and consists of interbedded reworked tuff and lapilli tuff, tuffaceous sandstone, conglomeratic sandstone, and localized basement-derived megabreccia, lacustrine limestone, mafic lavas, and the welded crystal-rich Mammut ignimbrite. The lower assemblage of the Pickhandle Formation is composed of reddish volcaniclastic monomictic debris-flow breccias and silicic block-and-ash-flow deposits of similar composition, sourced from intrabasinal volcanism. The upper assemblage of the Pickhandle Formation is generally polymeric (metaplutonic basement and rhyodacite) alluvial deposits, primary to reworked lapilli tuffs, and local rhyodacitic block-and-ash flows, with silicic domes and lavas emplaced during and following deposition of the upper Pickhandle Formation. The three stratigraphic subdivisions in the study area were deposited in a half-graben basin bounded by the Amphitheatre fault on its eastern margin. Growth strata in the upper Pickhandle Formation adjacent to the Amphitheatre fault document synextensional deposition, and paleocurrent indicators suggest that paleoflow was generally directed toward the southwest away from the Amphitheatre fault footwall and into the adjacent alluvial fan system in the half-graben basin. The Amphitheatre fault half graben represents an intra-hanging-wall basin that developed in the upper plate of the Waterman Hills detachment fault of the central Mojave metamorphic core complex, with extension active by ca. 20.1 Ma (possibly earlier) and waning by ca. 19 Ma.

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