Characterization and reconstruction of Laramide shortening and superimposed Cenozoic extension, Romero Wash–Tecolote Ranch area, southeastern Arizona

Daniel A. Favorito and Eric Seedorff
Lowell Institute for Mineral Resources, Department of Geosciences, University of Arizona, 1040 East Fourth Street, Tucson, Arizona 85721-0077, USA

ABSTRACT

Laramide structures that are exposed along much of the Laramide porphyry copper province of southeastern Arizona have been dismembered and tilted by superimposed Cenozoic normal faults, such that the overall style of shortening (e.g., thin-skinned, low-angle thrusts versus basement-cored, moderate-angle reverse faults) is unclear pending a compelling reconstruction of superimposed extension. This study integrates new geologic mapping in the Romero Wash–Tecolote Ranch area with earlier work and utilizes palinspastic reconstructions of structures related to extension and shortening to determine the geometry of structures in this segment of the Laramide orogenetic belt and their relationship to local products of magmatism and hydrothermal alteration.

Geologic mapping indicates that multiple generations of Cenozoic normal faults can be identified through crosscutting relationships. Near both ends of the study area, the oldest synextensional strata dip vertically, indicating that the area has been tilted 90° eastward during extension. Structural reconstructions of normal faults reveal two reverse faults within the area, the Romero Wash fault and the Tecolote fault. Once restored, both faults originally dipped in opposite directions at moderate angles and demonstrate clear evidence for associated fault-propagation folds. As a result of 90° tilting by Cenozoic normal faulting, the Romero Wash fault became an overturned reverse fault, whereas the Tecolote fault became an apparent normal fault. Constraints from the surface geology and forward models indicate that the Tecolote fault has ~2.8 km of displacement on a fault that had an initial dip of 55°E, whereas the Romero Wash fault has ~0.75 km of displacement on a fault that had an initial dip of 58°W. Considering their relative displacements and orientations, the Romero Wash fault is interpreted to be a backthrust to the Tecolote fault. These results are consistent with the interpretation that Laramide shortening in southeastern Arizona was dominated by basement-cored uplifts. Based on reconstruction of a cross section, the amount of Laramide shortening \( (e = \Delta l/l) \) in the study area was 1.8 km or 20%, and the total amount of subsequent Cenozoic extension \( (e = \Delta l/l) \) was 14.6 km or 200%.

Two stocks of granodiorite, with associated porphyry dikes and related hydrothermal alteration, occur within the study area. Sericitic and propylitic alteration and sparse quartz veins are present without observed potassic alteration. A barren porphyry dike (65.9 ± 0.7 Ma, U-Pb zircon) cuts the Romero Wash fault, limiting the upper age of the fault. Similar dikes nearby are sericitically altered, suggesting that alteration postdates shortening, similar to interpretations reached at the nearby porphyry copper systems of Ray, Resolution, and Kelvin-Riverside.

INTRODUCTION

Porphyry copper deposits form in magmatic arcs that mostly develop in compressional tectonic settings, but the detailed temporal and spatial relationships between shortening and development of porphyry deposits are not clear. Locations where both the timing of porphyry deposit formation and reverse faulting are known are few. Certain deposits globally seem to postdate shortening (e.g., Barton et al., 2005; Nickerson et al., 2010), whereas others appear to have been emplaced during or before shortening (e.g., Perelló et al., 2010; Piquer et al., 2015). Separate questions are whether reverse faults and associated folds play a role in the location of porphyry deposits and the geometry of the intrusions and alteration patterns. It has been proposed that intrusions related to porphyry deposits form in regional transfer zones of reverse faults (Hill et al., 2002; Gow and Waliszé, 2005; Kloppenburg et al., 2010), but other locations such as in hanging-wall anticlines or along fault planes may be plausible (Niemeyer and Munizaga, 2008). The relationship between shortening and porphyry deposit generation has implications for exploration strategies.

With additional work, the nature of shortening, i.e., primarily the geometry, magnitude, and timing of structural features, also could be characterized well in the Laramide porphyry copper belt of Arizona because extension has exposed the Laramide crust at a wide range of crustal depths (Barton et al., 1988; Seedorff et al., 2008). Shortening in the North American Cordillera during the Laramide orogeny (ca. 80–50 Ma) consisted of both thin-skinned, low-angle thrust faults and basement-cored uplifts bounded by variably vergent, moderate-angle reverse faults (DeCelles, 2004). Shortening in the Sevier belt of southern Nevada and central Utah is of thin-skinned, thrust belt geometry (Armstrong, 1988; DeCelles and Coogan, 2006), whereas the foreland area of the central...
Rocky Mountains of Wyoming and Colorado, and perhaps New Mexico and Chihuahua, Mexico, contains basement-cored uplifts (Brown, 1988; Hamilton, 1988; Haenggi, 2002; Seager, 2004; Ersliev and Koenig, 2009). The character of Laramide shortening is least understood in southeastern Arizona. This is where Cenozoic extension and associated sedimentation have resulted in dismemberment, tilting, burial, and local erosion of earlier products of Laramide deformation (Dickinson, 1991). It is also an area where numerous porphyry copper systems were forming broadly contemporaneous with shortening (Titley, 1982). Interpreted Laramide features in this area include many basement-cored uplifts (Davis, 1979; Dickinson, 1991), a few thin-skinned thrusts (Dickinson, 1991; Waldrip, 2008), and local tectonite fabrics (Bykerk-Kauffman and Janecke, 1987). Thus, the structural style of deformation appears to be inhomogeneous within the region, perhaps varying with time or in space.

Although the overall timing of the Laramide orogeny has been broadly characterized, only a few reverse faults or related fabrics in Arizona have tight age constraints (Bykerk-Kauffman and Janecke, 1987; Krantz, 1989; Waldrip, 2008; Nickerson et al., 2010). In addition, the magnitude of shortening in the region also is poorly constrained, in part due to the complications of Cenozoic extension.

This study describes the geology of the Romero Wash–Tecolote Ranch area (~220 km²), located in the southern Tortilla Mountains west of the San Pedro Valley (Fig. 1). The results presented here are based on new field work, with emphasis on structure and alteration, as well as incorporating results of previous maps of Krieger (1974a, 1974b) and Keith (1983). We show that Cenozoic extension has tilted Laramide-age and older rocks in the study area 90° to the east, such that the two main Laramide reverse faults now are an apparent normal fault and an overturned reverse fault. Structural reconstructions indicate that shortening produced a basement-cored uplift bounded by moderately dipping reverse faults with opposing vergence. New radiometric dates and crosscutting relationships constrain the age of reverse faulting. Mapping revealed two small-scale patterns of hydrothermal alteration associated with porphyry dikes, which postdate shortening and may represent the fringe of a larger porphyry system. There is a lack of a close spatial relationship between hydrothermal alteration and reverse faulting, and alteration patterns exhibit a general lack of structural influence.

### REGIONAL TECTONIC AND GEOLOGIC SETTING

The Romero Wash–Tecolote Ranch area is located within a highly extended portion of the southeastern Basin and Range province where mid- to late Cenozoic extension resulted in dismemberment of the Laramide magmatic arc (Dickinson, 1991). Laramide magmatism resulted in numerous porphyry copper systems in southeastern Arizona, making the region one of the largest copper provinces in the world (Titley, 1982). In many places, the porphyry systems were dismembered and tilted by subsequent Cenozoic extension (Wilkins and Heidrick, 1995; Maher, 2008; Nickerson and Seedorff, 2016). Nearby major copper districts include Ray, Superior, Globe-Miami, Christmas, and San Manuel–Kalamazoo (Fig. 1). The center of the study area is ~80 km north of Tucson and 120 km east-southeast of Phoenix. Nearby towns include Dudleyville and Winkelman, both located ~7 km to the west.

Crystalline basement rocks in the southern Tortilla Mountains consist of Proterozoic Pinal Schist that was deposited at ca. 1.7 Ga (Meijer, 2014), which...
subsequently was intruded by various plutons, including the Ruin and Oracle Granites at 1.4 Ga (Conway and Silver, 1989; Dickinson, 1991). Following a period of erosion, rocks of the Proterozoic Apache Group, consisting mostly of fine siliciclastic and lesser carbonate rocks, were deposited on the beveled surface. Next, the Troy Quartzite was deposited, followed by the emplacement of dikes, sills, and sheets of diabase and eruptions of basaltic lava at ca. 1.1 Ga (Wrucek, 1989; Bright et al., 2014). Diabase primarily intruded as sills along stratigraphic horizons in Proterozoic strata and as subhorizontal sheets in the upper ~1 km of the underlying crystalline basement, regardless of basement lithology or fabric (Howard, 1991). After a hiatus of a half-billion years, Paleozoic carbonate and lesser siliciclastic rocks were deposited unconformably over Proterozoic strata.

The Laramide orogeny, commonly defined as spanning the interval from ca. 80 Ma to ca. 50 Ma (e.g., Coney, 1976), has been interpreted to be the result of tectonic basal traction on the lithosphere during a time of subhorizontal subduction (Bird, 1998). The style of Laramide shortening in southeastern Arizona appears to be variable (Fig. 2). Basement-cored uplifts bounded by moderate-angle reverse faults (Davis, 1979; Lawton and Olmstead, 1995) and thin-skinned thrust faults (Waldrip, 2008) are reported, with the dominant style, or spatial and temporal variations in style, yet to be determined. Ductile features related to Laramide shortening, such as tectonite fabrics, have also been documented (Bykerc-Kaufman and Janecke, 1987). Magmas were emplaced throughout the Laramide time interval in southeastern Arizona (e.g., Reynolds et al., 1986). As in most arc settings, magma composition generally became more felsic with time (e.g., Lang and Titeley, 1998). Local sedimentary rocks and mafic Laramide magmatism of the Williamson Canyon volcanics predated shortening (Wilden, 1964). Magmatism associated with porphyry copper deposits ranges in age from ca. 75–60 Ma near the study area (e.g., Seedorff et al., 2005b) but extends to younger ages farther south and east (e.g., Barra et al., 2005; Levelle and Stegen, 2012; Stegen et al., 2016). In the few examples with geologic constraints, these porphyry systems appear to postdate shortening (Manske and Paul, 2002; Barton et al., 2005; Nickerson et al., 2010). Finally, two-mica granites were emplaced from the late Laramide to the mid-Cenozoic (e.g., Gehrels and Smith, 1991; Fornash et al., 2013).

Following an extended period of tectonic quiescence, the subducing slab underneath the North American Cordillera steepened from its previously subhorizontal orientation, allowing for a new influx of magmatism from 34–15 Ma (Dickinson, 1991). Because there was no more plate coupling beneath southeastern Arizona after this time, crustal thinning could commence. The majority of extension occurred from 25–15 Ma, and synextensional sediments were deposited during this time in basins created by normal faulting (Dickinson, 1991; Gawthorpe and Leeder, 2000). Tilting associated with normal faulting is recorded by inclined sequences of sedimentary rocks that commonly display fanning-upward dips, indicating growth during slip on normal faults (Maher, 2008). By late Miocene, modern basins began to accumulate sediment that is flat or gently dipping (Scarpboro and Peirce, 1978). Recent dissection of this basin fill has been accompanied by development of piedmont surfaces, stream terraces, and soils of variable maturity.

### GEOLOGIC UNITS

The pre-Cenozoic stratigraphy of the study area generally consists of a thin section of Proterozoic clastic rocks overlain by thinner sections of Paleozoic carbonate and Mesozoic volcanic rocks that have been intruded by various igneous bodies ranging in age from Proterozoic to as young as Cenozoic (Figs. 3 and 4). Important Laramide intrusions include diorite, Smith Granodiorite, and Rattler Granodiorite (Fig. 3). The total thickness of pre-Cenozoic strata is ~1 km in the study area, and a complete section is only observed west of Jim Thomas Wash (Fig. 3).

Cenozoic rocks within the study area consist dominantly of synextensional sedimentary rocks that span from Oligocene to Pliocene and locally range in thickness from 0 to 1.5 km. These rocks include the Oligocene to Miocene Cloudburst Formation, Miocene San Manuel Formation, Miocene to Pliocene Quiburis Formation, and less extensive Cenozoic dikes and other possible intrusions. Stratigraphic horizons here serve as important geologic markers for structural reconstructions, and dated horizons offer temporal constraints on the ages of faulting. Supplemental Text, Part 1, contains descriptions of the various rock types.

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1Supplemental Text. Please visit [http://doi.org/10.1130/GES01381.S1](http://doi.org/10.1130/GES01381.S1) or the full-text article on [www.gsapubs.org](http://www.gsapubs.org) to view the Supplemental Text.
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Figure 3. Geologic map of the study area and regional geologic cross section along line of section AA' with no vertical exaggeration. On the cross section, projected locations of measured bedding attitudes are shown near the surface. Map is based on new mapping and previous work by Krieger (1974a, 1974b), Keith (1983), and Dickinson (2000, 2002).
**STRUCTURAL FRAMEWORK**

### Proterozoic Shear Zones

A pervasive east-northeast–trending quartz ± biotite fabric in Ruin Granite has been mapped northwest of the study area in the Kelvin-Riverside area (Schmidt, 1971). Proterozoic diabase dikes crosscut the foliation (Schmidt, 1971), and similar features in Ruin Granite have been recorded in the Winkelman, Crozier Peak, and Black Mountain quadrangles (Krieger, 1974a, 1974b, 1974d). This deformation was interpreted by Schmidt (1971) to be Proterozoic in age and the result of differential movement within the crystallizing igneous body of Ruin Granite during the final phase of emplacement.

### Laramide Structure

Prior workers in the region have recognized the difficulty of distinguishing Laramide reverse faults from low-angle normal faults in east-central Arizona (Willden, 1964; Krieger, 1974a, 1974b; Richard and Spencer, 1998b; Maher, 2008). Previously identified reverse faults within the study area include the Romero Wash fault. Krieger (1974a, 1974c) interpreted the fault to be a flat section of an east-vergent, thin-skinned thrust that had been subsequently tilted. Dickinson (1991) proposed that this fault may correlate with a similar structure to the southeast, near the mouth of Aravaipa Creek (Young et al., 2009). Just north of the study area near Ray (Fig. 1), the Walnut Canyon thrust (Fig. 2) places Pinal Schist over Proterozoic and Paleozoic strata as young as Naco Formation (Keith, 1986; Richard and Spencer, 1998b). A fold is present in the hanging wall of the fault as an overturned east-vergent anticline with a north-trending fold axis. The fault is interpreted by Richard and Spencer (1998a) as a series of flats and ramps, connecting with the Telegraph Canyon thrust to the west. Evidence for east-vergent Laramide reverse faults and associated folds in Paleozoic and Mesozoic strata is also observed farther north in the Superior district (Manske and Paul, 2002). To the northwest of the study area, in the Christmas quadrangle, several reverse faults and related folds have been identified (Willden, 1964). As in previous examples, an east-northeast vergence direction is suggested.

### Cenozoic Structure

Cenozoic extension within southeastern Arizona is characterized by north-northwest–trending normal faults of varying dip associated with tilt-block homoclines (Dickinson, 1991; Maher, 2008). Synextensional sedimentary rocks with fanning-upward sequences (e.g., Cloudburst Formation and San Manuel Formation) were deposited in the hanging walls of these normal faults. Regions that have undergone tilting due to extension can be subdivided into tilt domains, which are broad areas with rocks tilted roughly in the same direc-
METHODS

This study began with a compilation of previous maps of the area by Krieger (1974a, 1974b), Keith (1983), and Dickinson (2002). Geology of an area from Sample Wash north to Bee Wash (Fig. 3) was primarily mapped using the Anacoda paper- and mylar-based mapping method (Brimhall et al., 2006) at scales ranging from 1:5000 to 1:10,000. Separate overlays were used for lithology, structure, and alteration. Observations on alteration of felsic and mafic mineral sites, magnetite stability, veins, and ore minerals were recorded on the alteration overlay. The structural overlay focused on gathering new bedding orientations, accurate fault traces, fault orientations, and kinematic indicators such as slickenlines. Specific smaller areas in the vicinity of Indian Camp Wash and Tecolote Ranch (Fig. 3) were mapped briefly in order to determine key geologic relationships. Positions of geologic measurements, sample sites, and photographs were acquired using a Garmin GPSMAP 64s. Locations of geologic contacts were determined and recorded using a topographic map with a contour interval of 30 m and a custom GPS grid array. Mapped contacts were plotted over ArcGIS satellite images, and satellite images were used to extend mapped contacts into inaccessible areas.

Preexisting names for topographic and geologic features have been used as much as possible, but new names have been created as needed for reference. The newly named topographic features are Bee Wash and Cow Fence Wash (Fig. 3), and the newly named geologic features include the Dirt, Sand, Cholia, Tecolote, Eagle Wash, Tarantula, Agave, Beehive, Diorite, Northern Ridge, Southern Ridge, Bee Wash, and Horse Hills faults (Fig. 3).

Due to the nature of weathering of local host rocks, primarily of the Ruin Granite, many key faults are poorly exposed, and few direct fault plane measurements could be made. Structure contour maps and three-point problems were used to determine the orientations of most faults. Some fault segments solely involving Ruin Granite were partially mapped in ArcGIS using satellite imagery where fault gouge was apparent. These data were subsequently field checked.

Adobe Illustrator® was used to generate modern-day cross sections. Bedding measurements were projected along strike into sections at the same elevation. Sequential unfaulting and untilting of Cenozoic normal faults were performed using Adobe Photoshop®. Pre-Cenozoic cross sections were then forward-modeled with the Midland Valley Move™ structural modeling software kit, using modern surface contacts and dips as constraints. Adobe Illustrator® was then used to model erosion surfaces and synextensional deposits. Stereonet 9 (Allmendinger et al., 2012) was used to generate and contour equal-area stereonet plots of structural data and to calculate fold axis orientations. Supplemental Text (see footnote 1), Part 2, contains further explanation of reconstruction methods.

Two samples from the study area were collected for U-Pb radiometric age dating. Igneous zircons were analyzed using the laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) method at the University of Arizona LaserChron Center (see Appendix).

DESCRIPTION OF STRUCTURES

The structures described below are ordered by age, from oldest to youngest. Faults that crop out in the study area are divided into descriptively similar sets of faults, which for convenience are numbered from 1 to 5 based on crosscutting relationships, similar orientations, and similar spatially associated folds (Fig. 3). Key data related to each set of faults are tabulated in Table 1.

Shear Zones

Shear zones and associated foliation are found together within the Horse Hills, but foliated rocks without associated shear zones persist at least 1.5 km to the south and 3 km to the west of the Horse Hills (Fig. 5). Both features strike northeast, dip steeply to the southeast or northwest, and affect Ruin Granite and related aplite dikes. Local diabase dikes are not deformed. Foliated granite has aligned biotite and elongated quartz grains. Ruin Granite proximal to shear zones commonly displays moderate to intense chlorite alteration with stable K-feldspar and quartz. In several areas, shear zones appear to crosscut and displace Ruin aplite and pegmatite dikes (Fig. 5). Because crosscutting bodies of diabase are undeformed, this deformation is interpreted to be Proterozoic in age, as others have also concluded (e.g., Schmidt, 1971).

Fault Set 1 and Spatially Associated Folds

Fault set 1 includes faults that do not cut Cenozoic sedimentary rocks, and all of these faults have evidence for fault-related folds.
### Table 1. Characteristics of Faults in the Romero Wash–Tecolote Ranch Area

<table>
<thead>
<tr>
<th>Fault set</th>
<th>Examples of named faults</th>
<th>Strike direction</th>
<th>Present-day dip of faults</th>
<th>Sedimentary rocks with growth relationships to faults of this set</th>
<th>Youngest rocks cut and offset by faults of this set</th>
<th>Exposed crosscutting relationships with faults of older sets</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (youngest)</td>
<td>Smith Wash, Northern Ridge, Southern Ridge Horse Hills, Cowhead Well, Eagle Wash</td>
<td>Primarily NNW</td>
<td>Primarily ENE, steep</td>
<td>Quiburis Formation</td>
<td>Quiburis Formation</td>
<td>Faults cut and offset faults of sets 1, 2a, 3</td>
<td>Jim Thomas syncline is in hanging wall of Hackberry fault</td>
</tr>
<tr>
<td>4</td>
<td>NNW</td>
<td>WSW, steep</td>
<td>Quiburis Formation</td>
<td>San Manuel Formation, possibly Quiburis Formation</td>
<td>Faults cut and offset faults of sets 2a, 2b, 3²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Hackberry, Swim Hole</td>
<td>NNE</td>
<td>WSW, moderate</td>
<td>San Manuel Formation</td>
<td>Upper member of Cloudburst Formation</td>
<td>Faults cut and offset faults of set 2b; no spatial overlap with faults of sets 1, 2a</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>Dirt, Sand</td>
<td>Primarily N</td>
<td>E, shallow</td>
<td>Lower member of Cloudburst Formation</td>
<td>Cretaceous volcanic rocks</td>
<td>No spatial overlap with faults of set 1</td>
<td>Restricted to NW portion of study area</td>
</tr>
<tr>
<td>2a</td>
<td>Beehive, Diorite</td>
<td>E to SSE</td>
<td>Primarily S to SW, moderate</td>
<td>None observed</td>
<td>Williamson Canyon volcanics or Smith Granodiorite</td>
<td>Faults cut and offset faults of set 1</td>
<td>Restricted to NE portion of study area</td>
</tr>
<tr>
<td>1 (oldest)</td>
<td>Romero Wash, Bee Wash, Tecolote</td>
<td>NNW and NE</td>
<td>NNE and NW, moderate</td>
<td>None observed</td>
<td>Romero Diorite</td>
<td>N.A. (oldest set)</td>
<td>Associated fault propagation folds (Tecolote syncline)</td>
</tr>
</tbody>
</table>

Abbreviation: N.A.—not applicable.

¹Age relationship between fault sets 2b and 2a is uncertain.

²Crosscutting relationship observed in Putnam Wash quadrangle (Dickinson, 2000).

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**Romero Wash Fault System**

This fault system is located along the eastern side of the study area (Figs. 3, 5, and 6) and includes the Romero Wash fault and Bee Wash fault (Table 1). In the Romero Wash area (Fig. 5), the Romero Wash fault strikes ~N25°W, dips 28°–36°E, and places older Ruin Granite on younger Apache Group and diabase. From Cow Fence Wash to Sample Wash, Romero Diorite intrudes along the fault. The eastern dike contact is intrusive, and the western contact is either brecciated or covered by alluvium. In the Romero Wash area, breccia along this contact occurs in the Romero Diorite and rocks in the footwall of the fault and is characterized by angular clasts up to tens of cm in diameter surrounded by clay fault gouge (Fig. 7). Locally, this zone of breccia and gouge is ~5–10 m wide. These relationships indicate that the western dike contact is the fault plane. Structure contour mapping of this surface (Fig. 8) shows that the Romero Wash fault is approximately planar. Due to relative offsets of diabase and Apache Group just southeast of Bee Wash, the Romero Wash fault is interpreted to continue northward through the Bee Wash area (Figs. 3 and 6). Here, the Romero Wash fault strikes N25°W to N, dips 55°–80°E, and places older Apache Group and diabase on younger Apache Group and diabase. In rare exposures of the fault within this area, there is a zone of fault breccia and gouge roughly 1 m wide. At Cow Fence Wash (Fig. 5), an unaltered Smith Granodiorite porphyry dike, with a U-Pb zircon age of 65.87 ± 0.69 Ma, crosscuts the Romero Wash fault; therefore, the Romero Wash fault must be Laramide or older.

The Bee Wash area (Fig. 6) is also the only location where the Bee Wash fault is exposed. This fault has a similar orientation to the Romero Wash fault locally and also places older rocks on younger rocks.

In the Romero Wash area, Apache Group strata dip vertically to steeply to the east (Figs. 9A and 5). Along E-W cross sections that contain the Romero Wash fault, there is little to no variation in beddind orientation (Fig. 10), suggesting that there is no folding here—only tilting. In the Bee Wash area, Apache Group strata strike N-S and dip either upright east, vertical, overturned west, or doubly-overturned east, i.e., rotated over 270° (Figs. 6, 9B, and 9C). This change in bedding orientation occurs locally around the Romero Wash and Bee Wash faults, as shown in roughly E-W cross sections (Figs. 11 and 12), indicating the presence of fault-related folds. Stereonet analyses of the southern Bee Wash area indicate rocks have been folded about an axis of N18°E 37° and the average interlimb angle is 74° (Fig. 9C). Only one outcrop with an obvious fold was found in the Pioneer Formation (Fig. 13). Fold axes here averaged N26°E 38°, closely matching stereonet results.

A map-scale syncline also has been observed southwest of Flying UW Ranch (Fig. 3). It is unclear, however, whether this is a fault-related fold because the present geometry of the syncline (Krieger, 1974a; Keith, 1983) predicts a reverse fault dipping to the west, but no direct evidence for such a fault was observed.

**Tecolote Fault and Spatially Associated Folds**

The Tecolote fault (Table 1) is located east of Tecolote Ranch (Fig. 3) and occurs in relatively flat topography with sparse exposure. The fault strikes N40°E to N10°E and dips 41°W. The Tecolote fault places younger Apache Group and diabase on older Ruin Granite. The fault cuts a dacite porphyry dike and an unclassified intermediate to felsic dike that had intruded Apache Group strata in the hanging wall (Fig. 3). In the rare locales of good exposure (Fig. 14), a zone of fault breccia and gouge roughly 10–15 m wide is present. Clasts here are commonly angular and several tens of cm in diameter.
Figure 5. Geologic map of the Romero Wash area. Based on new mapping and previous work by Krieger (1974a), Keith (1983), and Dickinson (2002). Location for this figure is shown in Figure 3.
Figure 6. Geologic map of the Bee Wash area. Based on new mapping and previous work by Krieger (1974a), Cornwall and Krieger (1975), Keith (1983), and Dickinson (2002). Location for this figure is shown in Figure 3.
Folds associated with the Tecolote fault affect rocks of the Apache Group on the northwestern side of the fault (Fig. 3). Here, the strike of bedding ranges from N-S to E-W and dips north upright, east upright, vertical, and overturned west (Figs. 3 and 9D). The axis of the fold calculated by stereonet analysis is N20°W 50° (Fig. 9D). The calculated axial plane is N48°E 70°W, and the interlimb angle is 70°. The axial plane was estimated by assuming a simple bisector of the two relatively planar fold limbs. The Ruin Granite–Apache Group contact is clearly folded (Fig. 3), and the dacite dike appears to be folded.

**Fault Set 2a**

The major faults within fault set 2a are the Beehive fault and the Agave fault (Table 1). The majority of faults within this set occur east of Eagle Wash in the northeastern portion of the study area (Figs. 3 and 6). Major faults of this set primarily strike S30°E to E-W, dip ~35°–65°S, and place older rocks on younger rocks or vice versa. Some faults of set 2a are mantled by the upper member of the Cloudburst Formation (Figs. 3 and 6), so faults of this set were active before deposition of the upper member of the Cloudburst Formation. No synextensional deposits appear to be directly related to this fault set.
Figure 9. Lower-hemisphere equal-area stereonet plots of poles to bedding and fold axes for (A) Romero Wash area (Fig. 5); (B) Bee Wash area north of line of latitude 32°59’30″N (Fig. 6); (C) Bee Wash area south of line of latitude 32°59’30″N (Fig. 6); and (D) Tecomote syncline (Fig. 3). A plane of best fit to bedding poles is shown in nets where folding is present. Plots were generated with the program Stereonet 9 (Allmendinger et al., 2012).

Figure 10. Geologic cross section across the Romero Wash area along line of section BB’ shown in Figure 5, with no vertical exaggeration. Projected locations of measured bedding attitudes are shown near the surface.
Figure 11. Geologic cross sections across the southern Bee Wash area along line of section CC’ shown in Figure 6, with no vertical exaggeration. Projected locations of measured bedding attitudes are shown near the surface.

Figure 12. Geologic cross sections across the northern Bee Wash area along line of section DD’ shown in Figure 6, with no vertical exaggeration. Projected locations of measured bedding attitudes are shown near the surface.
Fault Set 2b

Fault set 2b consists of the Dirt and Sand faults (Table 1), which occur west of Jim Thomas Wash. These faults primarily strike north and place younger Apache Group and diabase on older Ruin Granite (Fig. 3). The precise location of these faults is uncertain due to a majority of their contacts being granite-on-granite in topographic lows with significant alluvial cover. Because of this, dips are also uncertain, but they are estimated to be ~20°E because of the attitudes of similar faults only a few km to the north near Ripsey Wash (Nickerson et al., 2010, p. 308–309). The Dirt fault and Sand fault appear to be crosscut by a N-S-trending fault that likely belongs to fault set 4 (Fig. 3). Restoration of offset along this younger fault indicates that the Dirt fault and Sand fault are likely separate, parallel faults, with the Dirt fault being structurally higher. Exposures and associated crosscutting relationships are not definitive, but it appears that the faults of set 2b were active during or in part before all of the deposition of the lower member of the Cloudburst Formation. This is supported by similar strikes between these faults and lowest Cloudburst strata as well as the ~70° cut-off angle between these features. Similar relationships are observed just north of the field area (Nickerson et al., 2010).

Fault Set 3

The Hackberry and Swim Hole faults constitute fault set 3 (Figs. 3 and 6; Table 1). These faults strike N20°–30°W, and the Swim Hole fault dips ~25°–33°W. No exposures of the Hackberry fault in the field area were adequate to obtain a reliable attitude on the fault surface, although to the north, Dickinson (1995, 1996, 2001) documented dips ranging from 55° to 30°. Consequently, a structure contour map was made for the fault based on the intersection of topography with the trace of the fault for a length of ~1 km, which yields a dip of ~28°W (Fig. 15) The Swim Hole fault places younger Apache Group and diabase on older Pinal Schist, and the Hackberry fault places structurally higher Ruin Granite intruded by diabase sheets on structurally lower Ruin Granite without diabase.

Fault Set 4

Major faults within set 4 include the Cowhead Well, Eagle Wash, and Indian Camp faults (Fig. 3; Table 1). These faults generally strike N40°W to N-S and typically dip 50–60°W. The Cowhead Well fault, despite its moderate dip, is grouped into this fault set because it cuts the Camp Grant fault, a fault that most resembles those of set 3, located to the southeast in the Putnam Wash quadrangle (Dickinson, 2000). The Camp Grant fault is, in turn, regarded as the northern continuation of the San Manuel fault (Hansen, 1983; Dickinson, 2000).

Figure 13. Photograph in the southwestern Bee Wash area 200 m north of section CC′, showing folded shale beds of the Pioneer Formation involved in an originally east-vergent anticline in the hanging wall of the Romero Wash fault. Its presently synformal geometry was produced by tilting associated with later normal faults. Beds are highlighted with dashed purple lines. Doubly-overturned beds dipping SSE are on the left, and overturned beds dipping NW are on the right. Image is facing N60°E.

Figure 14. Photograph of the Tecolote fault where an intermediate to felsic dike is cut by and currently lies above Ruin Granite.
Fault Set 5

Primary faults within set 5 include the Smith Wash and Lopez Ranch faults. These faults strike N15°W to N and dip steeply to the east (Fig. 3; Table 1). The Southern Ridge and Northern Ridge faults may be related to the Smith Wash fault tipping southward (Fig. 3).

Cenozoic Folds

The Jim Thomas syncline, located along Jim Thomas Wash (Fig. 3), is an example of a Cenozoic fold (Dickinson, 2002). It primarily involves units as young as the San Manuel Formation, with dips of strata ranging from horizontal to dipping gently to moderately to the east or west. The fold measures 10 km along its axis and consistently trends north-northwest along the strike of the Hackberry fault. The southern end of the syncline plunges gently to the north, whereas the northern end, which is beyond the study area, plunges to the south. The estimated axial plane is oriented almost due north and dips 85°W. The interlimb angle is ~120°.

VEINS, ALTERATION, AND MINERALIZATION

Styles and Distribution of Alteration and Veins

Hydrothermally altered rocks crop out in the vicinity of Smith Wash in two main areas, both of which are proximal to Smith Granodiorite stocks (Fig. 16). The primary host rock for alteration is Ruin Granite, with a smaller areal extent of alteration in the Smith Granodiorite. The two main alteration styles present are sericitic and propylitic, both of which are characteristic of the upper levels of porphyry-style copper systems (e.g., Seedorff et al., 2005a). There are local quartz veinlets, but no clear evidence for potassic alteration was observed.

Sericitic alteration within the field area is characterized by quartz-pyrite veins with sericitic envelopes that are clearly related to Smith Granodiorite porphyry dikes that are of Laramide age. These veins range from 1 to 2 mm to a few cm wide, occur in abundances ranging from roughly 2–20 veins per meter, strike roughly E-NE, and dip steeply N or S (Fig. 17A).

South of Smith Wash (Fig. 16), sericitic alteration is confined to a broad area of veins around a stock of unaltered Smith Granodiorite. Porphyry dikes that appear to emanate eastward from this stock are moderately sericitically altered or fresh. North of Smith Wash (Fig. 16), sericitic alteration is confined to a narrow region of veins around and within a stock of Smith Granodiorite and related porphyry dikes. A breccia pipe is located within the western portion of this stock, and it contains subangular cobble- to boulder-sized clasts of Smith Granodiorite that are intensely sericitized and appear to have been rotated. Rare quartz veinlets occur in clasts of the breccia.
Figure 16. Map of the distribution of hydrothermal alteration within the Smith Wash area. Location for this figure is shown in Figure 3.
Propylitic alteration within the field area is characterized by K-feldspar (relict), epidote, chlorite, and hematite. Associated veins include carbonate, epidote, and chlorite veins. In general, this alteration is present distal to the two centers of sericitic alteration (Fig. 16). Calcite-siderite veins occur throughout the study area, primarily near faults, and may be a more distal expression of propylitic alteration. These veins range from several mm to 1 m in width, strike E-NE, and dip steeply N or S. The similar orientation of the calcite-siderite veins to sericitic veins indicates that both types of veins may be part of the same hydrothermal system (Fig. 17).

Copper Mineralization

Primary copper mineralization has only been observed in a small number of locations. Chalcopyrite either occurs in veins in diorite, in calcite-siderite veins, or rarely in sericitically altered Ruin Granite. Oxidized copper minerals such as malachite and chrysocolla have been observed in the Ruin Granite and Pioneer Shale near the Romero Wash fault and in diabase where it is cut by the Smith Granodiorite. Near Smith Wash, copper-oxide minerals occur in clasts of Ruin Granite that are hosted by Smith Granodiorite igneous breccia and in northwest-striking faults. One occurrence of exotic copper conglomerate was found near the southern Smith Granodiorite stock. Here, pebble-sized clasts of Ruin Granite are cemented by copper oxide.

Crosscutting Relationships between Faulting and Alteration

Within the main area of alteration, the Diorite and Southern Ridge faults crosscut altered rocks. Most minor faults within Figure 7 likely offset alteration, but these features were not mapped in detail. An exception to this is located west of the southern stock of Smith Granodiorite, where propylitic alteration appears to be concentrated along a minor E-W–striking fault. Near Cow Fence Wash (Figs. 5 and 16), a barren Smith Granodiorite porphyry crosscuts the Romero Wash fault. This porphyry dike is similar, if not identical, in original composition to sericitically altered porphyry dikes a few hundred meters north. This suggests that the Romero Wash fault predates hydrothermal alteration.

U-Pb GEOCHRONOLOGY

Table 2 shows results of U-Pb zircon geochronology for one sample from this study and one sample collected and analyzed by S.E. Runyon (2016, personal commun.), both of which are located in the eastern half of the study area (Figs. 5 and 16). Sample Ksg-p of Smith Granodiorite porphyry was chosen for dating because it cuts the Romero Wash fault. U-Pb ages were obtained from microanalysis of zircons by the laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) method at the University of Arizona.
Sample Ksg-p yielded an age of $65.9 \pm 0.7$ Ma, and sample Ksg-s yielded an age of $69.8 \pm 2.4$ Ma (Table 2). These ages confirm that the Smith Granodiorite is a Laramide intrusion.

### **INTERPRETATIONS**

#### Identification of Laramide Faults

The Romero Wash fault, which belongs to fault set 1 (Table 1), is cut by a Laramide dike (Fig. 5), making it a pre-Cenozoic structure. The Tecolote fault is included in fault set 1 primarily on the basis of similar style of associated folds (i.e., overturned beds). Using these relationships, the Tecolote fault is also inferred as a pre-Cenozoic structure. Because the other known period of pre-Cenozoic deformation within the region occurred during the early Mesoproterozoic, and the Romero Wash and Tecolote faults cut late Mesoproterozoic diabase, these faults are inferred to be of Laramide age.

Faults belonging to fault set 2a (Table 1) may also be Laramide faults. These faults cut rocks as young as Smith Granodiorite Ruin Granite and diorite, and some are mantled by the upper member of the Oligocene to Miocene Cloudburst Formation (Figs. 3 and 6). This suggests these faults may be related to the deposition of the lower Cloudburst Formation (i.e., fault set 2b). However, once restored, these faults have opposite dips and dissimilar strikes compared to those of fault set 2b (discussed later), indicating these fault sets are not related, and thus fault set 2a is not related to the lower Cloudburst Formation using this reasoning.

Because fault set 2a is likely older than the upper Cloudburst, and not related to the Oligocene lower Cloudburst, this fault set must be pre-Cenozoic because the Cloudburst marks the beginning of Cenozoic extension within the study area (Dickinson, 1991). These faults may be late Laramide in age, because they clearly postdate fault set 1 (Laramide) and cut many, if not all, Laramide units. In order to understand the initial orientations and configuration of these Laramide faults, the effects of Cenozoic normal faulting must be restored. Hence, an interpretation of Laramide structures follows the interpretation of the Cenozoic structural evolution below, i.e., addressing faults of sets 2b through 4.

### Cenozoic Normal Fault Generations

The normal faults that crop out in the field area can be grouped into four separate generations using crosscutting relationships, and an additional generation is interpreted to be present based on relationships exposed north of the field area (Table 3). Faults belonging to sets 2b, 3, 4, and 5 are Cenozoic normal faults because they cut all Laramide features (Fig. 3), have Cenozoic synextensional sedimentary rocks in their hanging walls, display normal stratigraphic separation, and, in many exposures, cut and offset Cenozoic rocks or have Cenozoic rocks in their hanging walls. The initial dip of each fault and the amount of tilting associated with each generation of faults can be estimated using structural reconstructions of faults and the angular relationship between synextensional strata and faults of various generations (Fig. 18). The initial dip of a fault is determined by the cut-off angle between the fault and the oldest related synextensional stratum. An exception to this is the second generation of faults (Table 3); not one example of this generation of faults crops out in the study area (discussed below). The amount of tilting produced by a given fault generation is inferred to be roughly equal to the range of dips of synextensional strata associated with that fault generation.

#### Generation 1

The first generation of Cenozoic normal faults consists of faults from set 2b (Table 3), because faults of sets 1 and 2a are Laramide faults (see above). The normal faults of generation 1 generally lack crosscutting relationships with younger faults, as only one fault from set 4 (see generation 4 below) cuts faults of set 2b (Fig. 3). As noted earlier, the crosscutting relationships within the field area are not definitive, but a reasonable hypothesis is that faults of set 2b were active during or in part before all of the deposition of the lower member of the Cloudburst Formation and controlled the half-grabens in which the sedimentary lower member of the Cloudburst Formation accumulated. The Dirt and Sand faults of set 2b are overturned normal faults (i.e., they initiated as west-dipping normal faults but have been rotated through horizontal and now dip east), with estimated present-day easterly dips of $-20^\circ$. Considering that the oldest strata within the lower member of the Cloudburst Formation dip $90^\circ$E, this implies a bedding-to-fault angle, and ultimately a fault initiation angle, of $70^\circ$ (Fig. 18). The net amount of tilting associated with this fault generation is $40^\circ$E (Fig. 18).

### TABLE 2. U-Pb AGES OF IGNEOUS ROCKS IN ROMERO WASH–TECOLOTE RANCH AREA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Rock type</th>
<th>Local host of intrusion</th>
<th>Structural relationships</th>
<th>Age (Ma)</th>
<th>2σ (Ma)</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ksg-p</td>
<td>32°56.818'</td>
<td>110°51.200'</td>
<td>Smith Granodiorite porphyry</td>
<td>Ruin Granite and Apache Group</td>
<td>Crosscuts Romero Wash fault</td>
<td>65.9</td>
<td>0.7</td>
<td>Inherited core age of 1414 ± 29 Ma</td>
<td>S.E. Runyon (2016, personal commun.)</td>
</tr>
<tr>
<td>Ksg-s</td>
<td>32°58.104'</td>
<td>110°52.134'</td>
<td>Smith Granodiorite</td>
<td>Ruin Granite and diorite</td>
<td>No known relationship to structures</td>
<td>69.8</td>
<td>2.4</td>
<td>Inherited core age of 1442 ± 16 Ma</td>
<td>This study</td>
</tr>
</tbody>
</table>

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**Favorito and Seedorff** | Characterization and reconstruction of Laramide shortening and superimposed Cenozoic extension
Evidence from stratigraphic relationships and the structure north of the field area indicates the presence of a second generation of faults, which was active after generation 1 and before subsequent generations (Table 3). As noted above, faults of set 2b were active before deposition of the upper member of the Cloudburst Formation and probably bound half-grabens that were forming during deposition of the lower member of the Cloudburst Formation (see generation 1). Likewise, faults of set 3 in the study area likely bounded the half-grabens in which the sediments of the San Manuel Formation accumulated (see generation 3 below). There are no synextensional faults exposed in the field area, however, that account for deposition of growth beds of the upper Cloudburst Formation (Table 3), which are bound above and below by thick sections exhibiting homoclinal dips that therefore lack evidence of fault-related growth (Maher et al., 2004). Consequently, faults of an intermediate generation are presumed to have been involved during the deposition

**Figure 18. Diagram of each normal fault generation (colored) with associated synextensional formations. Average modern dips of each fault generation and modern range of dips for synextensional strata are given. The cut-off angle (red) between the oldest synextensional strata and the modern fault dip is the inferred angle of initiation for a given fault generation. The range of dips for synextensional strata associated with a given fault generation (black bold) is equal to the amount of tilting produced by that given fault generation. The values presented are based on observed attitudes of Cenozoic strata and normal faults within the map area, coupled with the structural reconstructions, except for generation 2. Generation 2 is based on an assumed cut-off angle of 60°, which implies a dip of 10°W (see text for discussion).**

**TABLE 3. CURRENT AND RESTORED ORIENTATIONS OF TERTIARY NORMAL FAULTS**

<table>
<thead>
<tr>
<th>Normal fault generation</th>
<th>Fault set</th>
<th>Synextensional sedimentary unit</th>
<th>Predominant dip of synextensional sedimentary rocks</th>
<th>Estimated net tilting associated with each generation</th>
<th>Expected direction of concurrent tilting of fault blocks</th>
<th>Fault</th>
<th>Present strike&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Present dip&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Maximum offset (km)</th>
<th>Restored strike</th>
<th>Restored dip</th>
<th>Characterization of fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (youngest)</td>
<td>5</td>
<td>Quibiris Formation</td>
<td>5–0°E</td>
<td>5–0°E</td>
<td>Westward</td>
<td>Smith Wash</td>
<td>N10°W</td>
<td>60°E</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Normal fault</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Quibiris Formation</td>
<td>10–0°E</td>
<td>10–0°E</td>
<td>Eastward</td>
<td>Indian Camp Wash</td>
<td>N10°W</td>
<td>60°W</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Normal fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Horse Hills</td>
<td>N20°W</td>
<td>60°W</td>
<td>0.5</td>
<td>N20°W</td>
<td>70°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eagle Wash</td>
<td>N16°W</td>
<td>54°W</td>
<td>1.7</td>
<td>N16°W</td>
<td>64°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cowhead Well</td>
<td>N35°W</td>
<td>40°W</td>
<td>1.9</td>
<td>N33°W</td>
<td>50°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>San Manuel Formation</td>
<td>30–10°E</td>
<td>30–10°E</td>
<td>Eastward</td>
<td>Hackberry</td>
<td>N25°W</td>
<td>28°W</td>
<td>1.5</td>
<td>N23°W</td>
<td>58°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Swim Hole</td>
<td>N20°W</td>
<td>29°W</td>
<td>1.9</td>
<td>N20°W</td>
<td>59°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td>2</td>
<td>N.A.</td>
<td>Upper member of Cloudburst Forma</td>
<td>50–30°E</td>
<td>50–30°E</td>
<td>Eastward</td>
<td>Tortoise&lt;sup&gt;2&lt;/sup&gt;</td>
<td>N20°W</td>
<td>10°W</td>
<td>2.7</td>
<td>N20°W</td>
<td>60°W</td>
<td>Normal fault</td>
</tr>
<tr>
<td>1 (oldest)</td>
<td>2b</td>
<td>Lower member of Cloudburst Forma</td>
<td>90–50°E</td>
<td>90–50°E</td>
<td>Eastward</td>
<td>Sand</td>
<td>N5°E</td>
<td>20°E</td>
<td>1.3</td>
<td>N29°W</td>
<td>72°W</td>
<td>Overturned normal fault</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dirt</td>
<td>N5°E</td>
<td>20°E</td>
<td>N.A.</td>
<td>N29°W</td>
<td>72°W</td>
<td>Overturned normal fault</td>
</tr>
</tbody>
</table>

Abbreviation: N.A.—not applicable.

<sup>1</sup>Restorations based on untilting about an axis of N20°W; minor faults and faults with no reliable strike and dip are excluded.

<sup>2</sup>Eastward dips of synextensional strata are not included because they appear to be the result of folding associated with normal faulting, not just tilting.

<sup>3</sup>Faults with variable strike and dip are averaged.

<sup>4</sup>Using average orientations closest to line AA (Fig. 3).

<sup>5</sup>This fault inferred; see text.
of the Cloudburst Formation in the study area and can be inferred on an old published seismic-reflection survey in a region nearby (figs. 1–12 of Barton et al., 2005).

Beds near the base of the upper Cloudburst Formation in the map area have quite variable dips, commonly between 30°E and 50°E, and to the north near Hackberry Wash dip ~50°E (Maher et al., 2004). Assuming a bedding-to-fault angle of ~60° (i.e., possibly the expected angle of an initially steeply west-dipping fault) with beds at the base of the upper Cloudburst Formation that currently dip ~50°E, then the present-day attitude of second-generation faults might be expected to be ~10°W, as discussed further in the reconstruction below. A set of faults with similar orientation is observed a few kilometers to the north near Ripsey Wash (Nickerson et al., 2010, p. 308–309). The net amount of tilting associated with this fault generation is 20°E (Fig. 18). The primary fault within this generation is the Tortoise fault (Fig. 19E; Table 3).

Generation 3

The faults of set 3, the Hackberry and Swim Hole faults, constitute the faults of this generation (Table 3). Faults of generation 2 cut and offset faults of generation 1, and faults of generation 2 are cut by faults of generation 3. As noted earlier, both faults clearly cut and offset and thereby postdate the upper member of the Cloudburst Formation, and the San Manuel Formation is in the hanging walls of both the Swim Hole and Hackberry faults (Fig. 3). Therefore, the Hackberry and Swim Hole faults probably controlled the half-grabens in which the sediments of the San Manuel Formation accumulated. The Swim Hole fault dips ~29°W, and bedding in the San Manuel Formation in the hanging wall of the Swim Hole fault dips ~30°E, which defines a bedding-to-fault angle of ~59° (Fig. 18). The Hackberry fault displays similar relationships. The net amount of tilting associated with this fault generation is 20°E (Fig. 18).

Generation 4

This generation includes all faults from set 4 (Table 3). They consistently dip steeply west. Faults within this generation, such as the Eagle Wash fault, make a bedding-to-fault angle of ~85° with beds of the Quibiris Formation (Fig. 18). Because the majority of these faults dip to the west, typically at 55°–60°, and the Quibiris Formation ranges in dip from flat to 10°E, this fault generation is inferred to have an overall net tilt of 10°E (Fig. 18).

Generation 5

This fault generation is composed of the primarily steeply east-dipping faults of set 5 (Table 3). These faults are interpreted to be the youngest due to relationships observed to the northwest (Nickerson et al., 2010) and because the Smith Wash fault is a prominent range-bounding fault. Tilting associated with this fault set appears to be minimal because these faults are steeply dipping at 60°, as expected for the initiation angle for normal faults (Table 3).

Amount of Net Cenozoic Tilting

The principal evidence for the net amount of tilting during Cenozoic time is the orientation of the oldest synextensional strata, i.e., rocks of the Oligocene to Miocene Cloudburst Formation. The attitudes of the underlying pre-Cenozoic strata in most places are similar to those of the Cloudburst Formation (Fig. 3). Therefore, the pre-Cenozoic rocks in those places were subhorizontal at the time the basal beds of the lower Cloudburst Formation unit were deposited, i.e., at the inception of extension when faults of Cenozoic normal fault generation 1 initiated. West of Jim Thomas Wash (Fig. 3), the lower Cloudburst Formation strikes ~N20°W and dips as steeply as vertical. At the eastern side of the field area, just north of Romero Wash, the upper member of the Cloudburst Formation strikes ~N10°W and dips as much as 85°W (Table 2). Together, these two locales indicate the field area has been tilted ~90° to the east during Cenozoic extension. The axis of net rotation is ~N20°W because the majority of tilted Cenozoic strata strike in this direction.

Structural Reconstructions

Choice of Cross Sections, Goals, and Assumptions

A regional section along AA′ (Fig. 3) has been reconstructed in order to determine the possible Cenozoic structural evolution of the study area (Fig. 19). Reconstructions along BB′ (Fig. 20) and CC′ (Fig. 21), considerably shorter sections by comparison, draw on the results from the reconstruction along AA′. The main goal of each reconstruction is to make a stepwise restoration of the effects of Cenozoic normal faulting and associated tilting, ultimately to determine the orientation and distribution of Laramide structures. Without evidence to the contrary, the unexposed portions of faults here are assumed to be approximately planar or curvilinear projections of the exposed portions, following observations made in the field and seismic evidence from earthquakes on numerous normal faults around the world (e.g., Jackson and White, 1989). The reconstructions of normal faults assume rigid-body deformation in order to avoid complexity, even though active normal faults display hanging-wall and footwall flexure (e.g., Stein et al., 1986; Roberts and Yielding, 1994). In addition, without data to the contrary, pure dip-slip displacement is assumed, even though faults can have components of oblique slip and rotation within the fault plane itself (e.g., Seedorf et al., 2015).
Figure 19. Structural reconstruction along line of section AA’ moving forward in time from Laramide time (before shortening) to modern. Modern topography for rocks older than the lower Cloudburst Formation is shown by bold black line. Erosion surfaces are represented by dotted lines, and eroded rocks for a given time are transparent. Note that in (A) reverse fault tip shown as red dot, and area of tri-shear deformation defined by dashed red lines. Fault propagation to slip ratio for Técolote fault = 2.0. In (B), apparent dip of Técolote fault in restored cross section is slightly steeper than the true restored dip reported in Table 4 because the strike of the fault rotates during the restoration. In (C)-(G), faults that have moved and underwent tilting are bold, and the locations of future faults are dashed. Step (H) involves no faulting but demonstrates erosion that produces the modern cross section.
Section AA′ was chosen for a structural reconstruction because it intersects the Tecolote syncline and includes most sets of faults and key geologic markers. The section is oriented normal to the strike of most faults and of Proterozoic to Cenozoic strata (Fig. 3). The Sand fault of generation 1 (see above) has been projected into the cross section from the northwestern corner of the map area (Fig. 3). The Swim Hole fault has also been projected from north of the line of section (Fig. 3). Continuous, E-W–striking Proterozoic to Laramide age dikes within the vicinity of AA′ provide proof for the absence of additional significant faults at the present surface across the majority of the cross section (Fig. 3). The exposure of a thick sill of diabase near the center of the section (Fig. 3) provides a key constraint on the reconstruction, as it has to restore to relatively shallow levels within the Ruin Granite (see above). This indicates that this block is not part of the deeper levels of the Ruin Granite.

The amount of offset on faults has been estimated by measuring the offset of geologic contacts. In several cases, displacements are estimated from fault exposures north of the line of section where the same faults cut rocks with reliable markers, such as near Hackberry Wash and the Tea Cup–Grayback pluton (e.g., Seedorff and Maher, 2003; Barton et al., 2007; Nickerson et al., 2010). Faults that have geologic markers that offer tight constraints in the field area on the amount of offset include the Romero Wash, Dirt, Swim Hole, Hackberry, and Horse Hills faults. Faults with poor constraints include the Eagle Wash, Tarantula, and Cholla faults.

The amount of tilting associated with each generation of faults was determined by restoring the bedding of the oldest synextensional sedimentary rocks associated with each fault to horizontal (Fig. 18). Faults that have been involved in structural reconstructions have qualitative uncertainty values for both the amount of offset and amount of tilting. The uncertainty in the amount of offset is largely based on the presence of reliable contact markers, and tilting uncertainty is based on the degree of exposure and the accuracy and consistency of dips of faults and their associated synextensional sedimentary strata. The Swim Hole, Horse Hills, and Romero Wash faults have an estimated uncertainty in offset of ±5%, the Bee Wash, Hackberry, and Dirt faults ±20%, Cholla and Tecolote faults ±30%, and the Eagle Wash, Tarantula, and Tortoise faults ±50%. The estimated uncertainty in the amount of tilting for Cenozoic fault generations is fair for generations 2 and 3 (±20%) and good for generations 1 and 4 (±10%). The estimated uncertainty in the net tilting is only ±5%.

The challenge of dealing simultaneously with both Laramide shortening and Cenozoic extension also complicates the assignment of uncertainties in structural reconstructions. An iterative approach was used to produce a viable cross-sectional reconstruction (Supplemental Text Material [see footnote 1], Part 2). This results in a degree of internal circularity within the reconstruction because the extensional structure and the pre-extensional structural model are not mutually independent (e.g., Pepe et al., 2016). Thus the regional reconstruction shown here is not unique; nonetheless, it provides a testable hypothesis.
Results of Stepwise Reconstruction of Normal Faults

A structural reconstruction of Cenozoic normal faults along a regional line of section AA’ (Fig. 3) indicates that the study area has been progressively dismembered and tilted eastward by four separate generations of normal faults (Fig. 19; Table 3). This is directly supported by the geometric relationships between faults and related synextensional deposits observed in the field (Fig. 18). In addition, the restoration provides estimates of the amount of offset for Cenozoic and Laramide faults that lack exposures of offset markers (Tables 3 and 4). The initial and final stages of reconstruction of the Cenozoic normal faults indicate a total of 14.6 km or 200% extension ($e = D/l$) of the study area during the Cenozoic. The fifth generation of Cenozoic normal faults is ignored because these faults do not intersect the line of section AA’. The reconstruction presented here closely resembles Proffett’s (1977) reconstruction of the Yerington district, Nevada, where rocks had been rotated steeply westward by multiple sets of crosscutting normal faults.

Figure 21. Structural reconstruction along line of section CC’. (A) Restored geologic cross section along line of section CC’ during Laramide time, before reverse faulting. Reverse fault tip shown as red dot, and area of tri-shear deformation defined by dashed red lines. (B) Geologic cross section after reverse faulting and intrusion of the Rattle Granodiorite and before Cenozoic extension. Fault propagation to slip ratio = 3.4 for the Romero Wash fault and 4.8 for the Bee Wash fault. Modern topography is shown by bold black line.

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Fault Nomenclature: Original versus Present-Day

The presence of multiple generations of Cenozoic normal faults, with large amounts of net tilting (~90°E), produces complications in interpreting earlier deformation. Indeed, even the descriptive nomenclature for faults can be confusing because of the extreme amount of net tilting achieved by Cenozoic extension.

In the terminology we employ, a fault is overturned if it has been rotated through horizontal, which (1) reverses the dip direction of the fault, (2) reverses the slip direction of the fault, but (3) maintains the relative ages of units above and below the fault. Therefore, a normal fault rotated through horizontal becomes an overturned normal fault, and a reverse fault rotated through horizontal becomes an overturned reverse fault. In contrast, we use the modifier apparent for faults that have rotated through vertical. After rotating through vertical, (1) the dip direction of the fault reverses, (2) the slip direction of the fault reverses, and, most importantly, (3) the relative ages of units above and below the fault are also reversed. Because of the third characteristic, a fault that originally was a normal fault becomes an apparent reverse fault, and a fault that originally was a reverse fault becomes an apparent normal fault. The maps presented here use symbols that are consistent with this terminology (see legends of Figs. 3, 5, and 6).

Whether a fault is normal or reverse ordinarily is regarded as a descriptive classification. To use the traditional classification directly, however, requires the assumption that the present-day orientation is similar to the original one. In this study area, that assumption clearly is false; so the more complicated nomenclature described above is needed. This nomenclature effectively acknowledges both the original and present-day orientations of the fault and thus contains a component of structural interpretation. The implicit component of interpretation to classify structures here is analogous to using an overturned bedding symbol on an outcrop that lacks a facing indicator but confidently can interpret these structures.

Laramide Normal Faults

The faults of set 2a, located on the eastern side of the study area, presently strike almost east-west, and some of them, although normal faults, are now apparent reverse faults (i.e., they initiated as normal faults with a westerly component of dip but have been rotated through vertical and currently have a steep easterly component of dip). Map relationships previously discussed indicate these faults are likely late Laramide in age. Once restored, major faults within fault set 2a strike roughly S27°E and dip 65°NNE (Table 4) and appear to be normal faults. This dip direction is nearly opposite of the restored orientations of faults belonging to fault set 2b (Table 3), further indicating that these two sets are not related.

Laramide Reverse Faults

The structural reconstruction along section AA’ (Fig. 19) demonstrates the kinematic evolution of the study area from the late Laramide to present day; showing how rocks here underwent 90° of eastward rotation through a series of down-to-the-west normal faults. Using these results regarding the structural history of the region, detailed sections along BB’ at Romero Wash (Fig. 20) and CC’ at Bee Wash (Fig. 21) were structurally reconstructed, even though only one normal fault generation is exposed at the surface in each cross section. Reconstructions along these sections, combined with results from section AA’, are used to gain further insight into the geometry of Laramide reverse faults within the study area.

Tecolote Fault. Presently, the Tecolote fault is an apparent normal fault because it places younger Apache Group rocks on older Ruin Granite (Fig. 3). Once restored to its original orientation (Fig. 19; Table 4), the Tecolote fault is a west-vergent Laramide reverse fault that places older rocks on younger rocks, strikes roughly north-northeast, and dips moderately at ~55°E. Structural reconstructions indicate ~2.8 km of displacement and 2.5 km of vertical uplift (Fig. 19). The Tecolote syncline, located to the west of the Tecolote fault (Fig. 3), is interpreted to be a fault-propagation fold in the footwall of the fault. Once the fold is rotated 90°E, the eastern limb of the fold is overturned, and the western limb is nearly horizontal (Fig. 22; Supplemental Files 12 and 23). Because the basement-cover interface is clearly folded (Fig. 3), the reverse fault tip is interpreted to have initiated deep in the basement ~1.8 km below the interface (Fig. 19A), as indicated by forward models. In addition, the modern orientation of the axis of the fold, N22°E 50°′CC′, is nearly identical to fault-related folds associated with the Romero Wash fault near Bee Wash, which had an average fold axis of N18°E 37°′CC′ (Fig. 9C). This suggests these folds formed in the same compressional regime.

Using average orientation of the Romero Wash fault in the Romero Wash area.

1Restorations based on untilting 90°W about an axis of N20°W; minor faults and faults with no reliable strike and dip are excluded.
2Using orientation of northernmost exposure of the Tecolote fault.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Fault set</th>
<th>Present strike</th>
<th>Present dip</th>
<th>Offset (km)</th>
<th>Restored strike</th>
<th>Restored dip</th>
<th>Modern characterization of fault</th>
<th>Original characterization of fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beehive</td>
<td>2</td>
<td>S15°E</td>
<td>50°S</td>
<td>&gt;1.0</td>
<td>S26°E</td>
<td>64°N</td>
<td>Apparent reverse fault</td>
<td>Down-to-the-NNE normal fault</td>
</tr>
<tr>
<td>Diorite</td>
<td>2</td>
<td>S13°E</td>
<td>47°S</td>
<td>&gt;0.2</td>
<td>S26°E</td>
<td>66°N</td>
<td>Apparent reverse fault</td>
<td>Down-to-the-NNE normal fault</td>
</tr>
<tr>
<td>Romero Wash</td>
<td>1</td>
<td>N25°W</td>
<td>32°E</td>
<td>0.75</td>
<td>N17°W</td>
<td>58°W</td>
<td>Overturned reverse fault</td>
<td>East-vergent backthrust</td>
</tr>
<tr>
<td>Tecolote</td>
<td>1</td>
<td>N10°E</td>
<td>41°W</td>
<td>2.8</td>
<td>N04°E</td>
<td>55°E</td>
<td>Apparent normal fault</td>
<td>West-vergent reverse fault</td>
</tr>
</tbody>
</table>

1Restorations based on untilting 90°W about an axis of N20°W; minor faults and faults with no reliable strike and dip are excluded.
Romero Wash fault system. Presently, the Romero Wash fault is an overturned reverse fault that places older Ruin Granite on younger Apache Group but with a down-dip sense of displacement (Fig. 10). The Romero Wash fault system is interpreted to have a strike length of 11 km and may have accommodated the most displacement where it is buried under Cenozoic cover, just east of Smith Wash (Fig. 3). Reconstruction along section AA′ (Fig. 19) indicates that the Romero Wash fault was a backthrust to the Tecolote fault due to their opposing vergence directions and because the Romero Wash fault has significantly less displacement than the Tecolote fault. Once restored to its original orientation (Fig. 20), the Romero Wash fault is an east-vergent Laramide reverse fault that places older rocks on younger rocks, strikes roughly north-northwest, and dips moderately to the west.

At Romero Wash, the Romero Wash fault presently dips on average 32°E. Reconstruction along section BB′ (Fig. 20) indicates ~0.75 km of displacement and an original dip of 58°W. Here, the Romero Wash fault has a consistent bedding cut-off angle of ~55°, and there is no evidence for fault-related folding (Fig. 9A). South of Romero Wash, displacement on the Romero Wash fault appears to approach zero between Sample and Swingle Washes. However, south of this area, the Romero Wash fault splits into two reverse faults that appear to continue southward under Cenozoic cover (Fig. 3).

At Bee Wash, the Romero Wash fault and Bee Wash fault presently dip ~60°E (Fig. 6). Reconstruction along section CC′ (Fig. 21) indicates ~0.62 km of maximum displacement for the Romero Wash fault in this location, ~0.41 km for the Bee Wash fault, and an original dip of 30°W for both faults. Both faults appear to pinch out to zero displacement to the north. Fault-related folds appear to be associated with both faults here because bedding orientation changes proximal to both faults in a pattern expected for fault-propagation folds. As with the Tecolote fault, the basement-cover interface is folded here, as indicated by bedding orientations in the Pioneer Formation. The folds here are more open, and this is likely due to the smaller amount of slip on the Romero Wash fault compared with the Tecolote fault. Structural reconstructions along CC′ indicate the reverse fault tip initiated ~350 m beneath the basement-cover interface for the Romero Wash fault and ~120 m beneath the Bee Wash fault (Fig. 21).

The regional reconstruction along section AA′ indicates that the amount of Laramide shortening $(e = \Delta l/l)$ in the study area was 1.8 km or 20% (Fig. 19).

Relationship between Magmatism and Reverse Faulting

Emplacement of Laramide intrusive rocks in the study area generally post-dates reverse fault displacement. Structural reconstruction along section BB′ (Fig. 20) indicates that the Rattler Granodiorite crosscuts the Romero Wash fault. From Cow Fence Wash, moving southward, the laccolith gradually pinches out over a distance of ~1.5 km (Fig. 5). If the gradual pinching out is also assumed in the orthogonal direction, i.e., structurally above and below, the laccolith would continue to a depth of ~1.5 km. If the reverse fault had cut the laccolith, it would have been repeated within the footwall of the fall, but it is not (Figs. 5 and 10), indicating that the laccolith likely cuts the fault. Similar reasoning for the same relationship is seen in the reconstruction along section CC′ (Fig. 21). Other igneous units that crosscut the Romero Wash fault are the Smith Granodiorite porphyry and rhyodacite porphyry (Fig. 5). Smith Granodiorite porphyry also cuts the Tecolote fault, but the Tecolote fault cuts a dacite porphyry within the fault-bounded footwall Tecolote syncline (Tables 3 and 4). This dacite porphyry appears to be folded, which is expected because it is cut by the Tecolote fault.

The only igneous unit with a geometry that appears to be directly affected by reverse faulting is the Rattler Diorite (Figs. 5 and 10), which intrudes along the Romero Wash fault. Because the Rattler Diorite is brecciated along its western contact, which is the Romero Wash fault surface, the unit is interpreted to have intruded between slip events on the fault. All other igneous units appear to have no relationship to the geometry of reverse faults or to the geometry of related folds.

Age of Reverse Faulting

Laramide igneous rocks provide age constraints on reverse faulting in the study area. Previous studies have dated various local igneous units employing K-Ar and fission-track methods, and this study adds new U-Pb zircon age dates...
as a more reliable method for determining ages of crystallization. Because the Romero Wash fault is interpreted to be a backthrust of the Tecolote fault (Fig. 19B), the ages of those two faults should be similar. Crosscutting Smith Granodiorite Porphyry (Fig. 5) brackets the Romero Wash fault to a minimum age of 65.9 ± 0.7 Ma (U-Pb zircon). The dacite porphyry dike near Tecolote Ranch appears to be folded and cut by the Tecolote fault. This unit has an age of 73.1 ± 2.1 Ma (K-Ar hornblende). These ages constrain the age of local reverse faulting to ca. 66–73 Ma assuming the reverse faults are related and thus formed at the same time.

Relationship between Alteration and Reverse Faulting

Geologic evidence indicates that alteration appears to postdate reverse faulting within the study area even though there is no indication of Laramide faults or folds near the two centers of alteration. Alteration is interpreted to postdate reverse faulting because Smith Granodiorite porphyry dikes cut the Romero Wash fault (Figs. 5 and 16). Even though the dike that cuts the fault is unaltered, mesoskopically identical dikes only a few hundred meters away are moderately sericitically altered (Fig. 16). Because the presently east-dipping Romero Wash fault projects under cover to the east (Fig. 3), alteration appears to be hosted within the footwall of the reverse fault. This likely aided in its preservation, just as the Tecolote syncline in the footwall of the Tecolote fault was preserved.

**DISCUSSION**

Styles of Laramide Reverse Faults in Southeastern Arizona

The structural style of reverse faults across southeastern Arizona appears to be variable, as thin-skinned thrusts and basement-cored uplifts have been documented. Waldrip (2008) interpreted the Kelsey Canyon and Hot Spring faults in the southern Galiuro Mountains (Fig. 2) to be low-angle thrusts that are part of a regional overthrust system. Evidence for this includes hanging wall flat-footwall ramp geometries, relatively low footwall cut-off angles (<30°), and transposed Cretaceous strata that suggest burial under a thick thrust sheet. Another possible example of thin-skinned deformation is the Walnut Canyon thrust (Richard and Spence, 198a, 198b), located near Ray (Fig. 2). In contrast, farther to the south, within a large area centered on the Whetstone Mountains (Fig. 2), Davis (1979) interpreted that shortening was accommodated by variably vergent, moderate-angle reverse faults associated with basement-cored uplifts. A prominent example of these faults is the Huachuca fault, which dips at 60° once restored to its original orientation. Other significant reverse faults are located within the Little Rincon Mountains, Santa Rita Mountains, Chiricahua Mountains, and the Christmas and Superior mining districts (Fig. 2), but the style of shortening at these places is not well known. Deeper expressions of shortening are documented in the Santa Catalina Mountains (Fig. 2), where Bykerk-Kaufman and Janecke (1987) dated Laramide tectonite fabrics that indicate east-vergent movement, but their relationship to the two aforementioned, more shallow styles of shortening, is uncertain.

The Romero Wash and Tecolote faults are both examples of moderate-angle Laramide basement-cored uplifts. Currently, the Romero Wash fault is an overturned reverse fault, whereas the Tecolote fault is an apparent normal fault (Fig. 3; Table 4). Once displacement and tilting on Cenozoic normal faults are restored, the Tecolote fault in its original orientation is a regional-scale, west-vergent reverse fault with 2.8 km of displacement and 2.5 km of vertical uplift (Fig. 19B). The Romero Wash fault is interpreted to be a backthrust to the Tecolote fault, with opposing vergence and 0.75 km of displacement. Seismic-reflection data, map relationships, and drill-hole piercements have led authors to interpretations with reverse faults and subsidiary backthrusts in the Front Range of Colorado (Ersliev et al., 2004) and in the Rattlesnake Mountain area of Wyoming (Ersliev, 1993), both of which are classic locales of Laramide deformation. Backthrusts have also been documented in the Sierras Pampeanas in Argentina, a modern analog to the Rocky Mountain foreland, where Garcia and Davis (2004) interpreted blind backthrusts on the basis of map evidence.

Both the Tecolote and Romero Wash faults demonstrate clear evidence for fault-propagation folds (Figs. 19B, 21, and 22). This style of thick-skinned deformation might be expected for this local region because the basement is homogeneous and stiff, dominated by plutonic rocks, and the cover rock sequence is thin, only ~1 km thick (e.g., Mitra et al., 1988; Garcia and Davis, 2004). The results of this study are consistent with Davis’s (1979) conclusion that shortening within southeastern Arizona was accommodated primarily by basement-cored uplifts with associated fault-propagation folds.

The Walnut Canyon thrust is located just northwest of this study area, where we have interpreted basement-cored uplifts to be the shortening style. One might not expect two highly contrasting styles of shortening to be only 20 km apart, perhaps even along strike. Thus, is Walnut Canyon an outlier of thin-skinned shortening in the midst of basement-cored uplifts (Fig. 2), or, in this area of complex extension, might Walnut Canyon be a basement-cored uplift?

Other reverse faults within the region may also deserve further study. Because porphyry deposits form in the shallow crust, understanding the configuration of Laramide reverse faults may allow for the discovery of new deposits in the region. In addition, these faults may aid in the interpretation of known deposits because post-ore reverse faults may cut and offset ore bodies, and pre-ore faults may focus mineralization.

Folding in the Porphyry Copper Belt

Even though the majority of folds observed within the porphyry copper belt of Arizona appear to be related to Laramide reverse faults, some are likely related to Cenozoic normal faults. Understanding the geometry and differences between these two types of fault-related folds is the key to interpreting the structural evolution of a given area and also to determining its exploration potential. Moderate-angle reverse faults can create fault-propagation folds,
where bedding in the footwall and hanging wall are commonly overturned. Normal faults can create drag, reverse drag, roll-over, and transverse folds. All of these types of extensional folds tilt strata gently to moderately and, if not subsequently tilted, have a clear and distinct lack of overturned beds (Schlische, 1995). The largest and most prominent fold within the study area is the Tecolote syncline. Howard and John (1997) suggest that the syncline may be a steeply north-tilted drape fold of cover rock on the down-to-the-west Tecolote fault, which they interpret as a normal fault within a detachment system. They also claim the Tecolote syncline is coaxial with the southern Jim Thomas syncline. Dickinson (2002) built upon this idea, proposing that the Tecolote and Jim Thomas synclines may reflect flat-ramp detachment geometry on the Hackberry fault.

Structural reconstructions from this study indicate that the Tecolote fault is a reverse fault with associated fault-propagation folds (Fig. 19). The Tecolote syncline, once tilted back 90°W to remove the effects of Cenozoic extension, consists of a horizontal western limb and an overturned eastern limb bounded by the Tecolote fault (Figs. 3 and 22). The overturned limb is inconsistent with normal fault-drape folding, and map patterns of bedding attitudes suggest that the Jim Thomas syncline is not coaxial with the Tecolote syncline. The present-day axial plane of the Tecolote syncline is N48°E 70°W, whereas the Jim Thomas syncline axial plane averages almost due north and dips 85°W (Fig. 3). The strikes of the two planes are ~50° apart from one another, further indicating that the two folds probably formed through different processes and are not related. In addition, the interlimb angles differ for the two folds: 70° for the Tecolote syncline and 120° for the Jim Thomas syncline. The Jim Thomas syncline may be a drag fold associated with the Hackberry fault, as suggested by Dickinson (2002). Dickinson proposed that strata were tilted eastward prior to drape folding, which would help explain the synformal shape observed, and that drape folding resulted in the westward dip of the eastern limb of the syncline. This is a reasonable interpretation for the study area because all synextensional sedimentary rocks are expected to be east-dipping due to tilting on down-to-the-west normal faults, and any drape folds that would form on down-to-the-west faults would tilt strata westward. In addition, the relatively large interlimb angle of the Jim Thomas syncline supports this claim. The evidence provided here for the Tecolote and Jim Thomas synclines being separate structures is also inconsistent with Dickinson’s (2002) interpretation that these two structures may reflect flat-ramp detachment geometry of the Hackberry fault.

**Relationship between Shortening and Porphyry Copper Generation**

There are few examples where time-space relationships between shortening and porphyry copper generation can be demonstrated, with the scarcity of examples in part due to a lack of detailed observations. Three locales in Arizona contain evidence for such relationships, and they are all located within 50 km of the study area (Fig. 1). Reverse faulting appears to have predated porphyry generation and related hydrothermal alteration at Kelvin-Riverside (Nickerson et al., 2010), Resolution (Manske and Paul, 2002), and Ray (Barton et al., 2005; Maher, 2008). Evidence for porphyry formation following shortening also is observed in the central Andes of Chile at Los Pelambres (Perelló et al., 2012). Nonetheless, there also are several examples of porphyry systems emplaced during and prior to shortening. Examples of Chilean porphyries emplaced during shortening include the Centinela district (Perelló et al., 2010), the Rio Blanco-Los Bronces district (Piquer et al., 2015), and the Potrillosd porphyry (Olson, 1989; Marsh et al., 1997; Niemeyer and Munizaga, 2008). Deposits formed prior to shortening events include the Cadia district of New South Wales, Australia (Holliday et al., 2002), the Kerr-Sulphurets-Mitchell district (Kirkham and Margolis, 1995; Bridge et al., 1996) and the Gibraltar deposit (Bysouth et al., 1995) of British Columbia, and the Aitik deposit, Sweden (Wan-hainen et al., 2003).

Within the Romero Wash–Tecolote Ranch area, barren porphyry dikes crosscut reverse faults (Figs. 5 and 16). Sericitically altered dikes of identical original composition crop out near these barren dikes (Fig. 16), indicating that alteration postdates reverse faulting. This is consistent with the relationships in the three nearby Laramide examples discussed above. In addition, neither the location nor the geometry of the stocks of Smith Granodiorite and their associated alteration patterns appear to have been influenced by any preexisting structure. In all examples documented to date in the Laramide porphyry copper belt of Arizona, porphyry generation and associated hydrothermal alteration postdates reverse faulting at the point of observation. However, future studies may find examples in Arizona with the opposite relative ages—as in Chile—because compression and magmatism in arc settings broadly overlap in time.

Understanding the relationship between shortening and porphyry generation should prove useful for further exploration in a mature region such as the Laramide porphyry belt of Arizona. Until there are more examples of these relationships, the dominant patterns remain elusive.

**CONCLUSIONS**

Cenozoic normal faulting in the Tecolote Ranch and Romero Wash area has provided both an opportunity and a challenge in studying the style of Laramide deformation and its relationship to porphyry generation in southeastern Arizona. Extension here resulted from displacement and tilting on three generations of down-to-the-west normal faults that were mapped at the surface, a fourth generation of down-to-the-west normal faults that is not exposed at the surface but is indicated by stratigraphic and structural evidence, and a fifth generation of down-to-the-east normal faults. The bedding orientations of the oldest synextensional strata present, the lower member of the Hackberry Wash facies of the Cloudburst Formation, indicate that the region underwent ~90° of eastward tilting. Based on a reconstruction of a cross section through the study area, the total amount of Cenozoic extension ($e = \Delta l/l$) was 14.6 km or 200%.

Reverse faults in the field area include the Romero Wash and Tecolote faults. The Romero Wash fault is cut by Laramide dikes, indicating that it is Laramide deformation and its relationship to porphyry generation in southeastern Arizona. Extension here resulted from displacement and tilting on three generations of down-to-the-west normal faults that were mapped at the surface, a fourth generation of down-to-the-west normal faults that is not exposed at the surface but is indicated by stratigraphic and structural evidence, and a fifth generation of down-to-the-east normal faults. The bedding orientations of the oldest synextensional strata present, the lower member of the Hackberry Wash facies of the Cloudburst Formation, indicate that the region underwent ~90° of eastward tilting. Based on a reconstruction of a cross section through the study area, the total amount of Cenozoic extension ($e = \Delta l/l$) was 14.6 km or 200%.
in age. Structural reconstructions indicate that these faults were originally moderate-angle reverse faults that together, resulted in 2.5 km of structural uplift. The Tecolote fault appears to be the fault with the greatest displacement, and the Romero Wash fault has been interpreted as a backthrust of the Tecolote fault due to their opposing vergence directions and difference in amount of offset. Both faults have clear evidence for fault-propagation folds, of which the largest example is the Tecolote syncline. Once restored to its original orientation, this fold appears to have an overturned limb bounded by the Tecolote fault, further evidence that it is related to reverse faulting. The amount of Laramide shortening (ε = ΔL/L) in the study area was 1.8 km or 20%, followed by a small amount of late Laramide extension. The geometry of the area is consistent with the interpretation that shortening in southeastern Arizona was dominated by basement-cored uplifts.

Laramide hydrothermal alteration within the study area is associated with crystallization of Smith Granodiorite porphyry dikes and related stocks. Alteration types include both sericitic and propylitic, with propylitic alteration occurring distal to sericitic alteration. Copper occurrences are limited and typically consist of copper-oxide minerals, with few instances of primary copper mineralization. The lack of exposed potassic alteration, a common feature of porphyry copper systems, indicates the alteration patterns observed may represent the fringe of a larger porphyry system. In one location, a barren porphyry dike crosses the Romero Wash fault, and similar dikes nearby are sericitically altered, indicating alteration postdates reverse faulting. Overall, there is no dike crosscuts the Romero Wash fault, and similar dikes nearby are sericitically altered, indicating alteration postdates reverse faulting. Overall, there is no evidence in the study area that Laramide structures strongly influenced the location or geometry of porphyry intrusion and hydrothermal fluid flow.

APPENDIX. LASER ABLATION–INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY U–Pb ZIRCON GEOCHRONOLOGIC METHODS

Sample Descriptions

Ksg-s

Sample Ksg-s is a Smith Granodiorite porphyry dike that crosscuts the Romero Wash fault just south of Cow Fence Spring (Fig. 5). It was chosen for dating to place an upper age limit on the Romero Wash fault. It contains 40% phenocrysts in a light- to medium-gray, fine-grained groundmass. The phenocryst assemblage consists of 60% plagioclase, 0.5–4 mm; 10% K-feldspar, 0.5–1 mm; 15% biotite/chlorite, 1–2 mm; and 15% hornblende, 2–4 mm. Hydrothermal alteration and weathering have resulted in feldspars being largely replaced by sericite and clay and hornblende and biotite being replaced by chlorite.

Krd

Sample Krd is a Romero Diorite dike that intrudes along the Romero Wash fault and appears to have been brecciated by fault movement. It was chosen for dating to determine the age of the Romero Wash fault. The texture is primarily fine grained, and it contains 5% phenocrysts, of which are mostly potassium feldspar measuring 1–2 mm. The groundmass consists primarily of plagioclase laths, with lesser amounts of biotite, chlorite, and sparse quartz. Hydrothermal alteration and weathering have resulted in feldspars being largely replaced by sericite and clay, and biotite being replaced by chlorite.

Sample Preparation

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples were processed such that all zircons were retained in the final heavy-mineral fraction. A large split of these grains (generally 200 grains) was incorporated into a 1-inch epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts were sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis.

Analytical Methods and Reporting Procedures

U–Pb geochronology of zircons was conducted by laser ablation–multicollector–inductively coupled plasma mass spectrometry (LA-MC–ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008). The analyses involve ablation of zircon with a New Wave UP193HE Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 30 microns. The ablated material is carried in helium into the plasma source of a Nu HR ICPMS, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors with 3 x 1010 ohm resistors for 206Pb, 208Pb, 207Pb, and discrete dynode ion counters for Pb and Hg. Ion yields are ~0.8 mv per ppm. Each analysis consists of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~15 microns in depth.

For each analysis, the errors in determining 206Pb/238U and 206Pb/207Pb result in a measurement error of ~1%–2% (at 2-sigma level) in the 206Pb/207U age. The errors in measurement of 206Pb/208Pb and 206Pb/204Pb also result in ~1%–2% (at 2-sigma level) uncertainty in age for grains that are ~1.0 Ga, but are substantially larger for younger grains due to low intensity of the 206Pb signal. For most analyses, the crossover in precision of 206Pb/238U and 206Pb/207U ages occurs at ca. 1.0 Ga. The 206Hg interference with 206Pb is accounted for by the measurement of 202Hg during laser ablation and subtraction of 202Hg according to the natural 202Hg/204Hg of 4.35. This Hg correction is not significant for most analyses because our Hg backgrounds are low (generally ~150 cps at mass 204).

Common Pb correction is accomplished by using the Hg-corrected 206Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Uncertainties of 1.5 for 206Pb/238U and 0.3 for 206Pb/207Pb are applied to these compositional values based on the variation in Pb isotope composition in modern crystal rocks.

Inter-element fractionation of Pb is generally ~5%, whereas apparent fractionation of Pb isotopes is generally ~0.2%. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 562.5 ± 3.2 Ma (2 sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1%–2% (2σ) for both 206Pb/207Pb and 206Pb/204Pb ages. Concentrations of U and Th are calibrated relative to our Sri Lanka zircon, which contains ~518 ppm of U and 68 ppm Th.

Results

Results are shown in Table 2. Uncertainties shown in this table are at the 1-sigma level and include only measurement errors. Inheritance was tested in the samples by examining both the core and tips of each zircon where possible. The resulting interpreted ages are shown on weighted mean diagrams using the routines in Isoplot (Ludwig, 2008) (Fig. A1). The weighted mean diagrams show the weighted mean (weighting according to the square of the internal uncertainties), the uncertainty of the weighted mean, the external (systematic) uncertainty that corresponds to the ages used, the final uncertainty of the age (determined by quadratic addition of the weighted mean and external uncertainties), and the mean square of weighted deviates (MSWD) of the data set. Figure A2 shows concordia diagrams for the two analyzed samples.

Sample Ksg-p has an interpreted age of crystallization of 65.9 ± 0.7 Ma. Crosscutting relationships indicate that sample Krd cannot be Proterozoic in age. Thus the reported age is interpreted to be the age of inherited zircon grains, which is consistent with the widespread Proterozoic country rock within the study area. The precise age of crystallization for sample Krd is unknown, but it is likely also Laramide in age.
Figure A1. Weighted mean diagram for U-Pb dates. Each red bar represents a single spot analysis, and the mean is shown as a green line. Only results for spots within the tips of zircon grains are shown for sample Ksg-p. MSWD — mean square of weighted deviates.

Figure A2. Concordia diagrams for U-Pb dates. Only results for spots within the tips of zircon grains are shown for sample Ksg-p.


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