Tectonics

RESEARCH ARTICLE

10.1029/2018TC005180

Key Points:

- Laramide reverse faults measuring at least 50 km in combined strike length were discovered
- Moderate restored dip of reverse faults, fault-propagation folds, and high degree of basement involvement indicate thick-skinned shortening
- Stratigraphic and structural data suggest that arching related to a regional-scale reverse fault tilted the area during the Laramide

Correspondence to:

D. A. Favorito,
dfavorito@email.arizona.edu

Citation:

Favorito, D. A., & Seedorff, E. (2018). Discovery of major basement-cored uplifts in the northern Galiuro Mountains, southeastern Arizona: Implications for regional Laramide deformation style and structural evolution. *Tectonics*, 37, 3916–3940. <https://doi.org/10.1029/2018TC005180>

Received 9 JUN 2018

Accepted 19 SEP 2018

Accepted article online 23 SEP 2018

Published online 23 OCT 2018

Discovery of Major Basement-Cored Uplifts in the Northern Galiuro Mountains, Southeastern Arizona: Implications for Regional Laramide Deformation Style and Structural Evolution

Daniel A. Favorito¹ and Eric Seedorff¹

¹Lowell Institute for Mineral Resources, Department of Geosciences, University of Arizona, Tucson, AZ, USA

Abstract The Laramide orogeny is poorly understood in southeastern Arizona, largely because of complex structural overprinting by mid-Cenozoic extension that occurred over large areas. This study integrates new geological mapping with previous work, combined with structural reconstructions and forward modeling, to determine the primary structural style, timing, evolution, and kinematics of Laramide shortening in the northern Galiuro Mountains. Cenozoic normal faulting in the study area is minor and has only resulted in up to 13° of eastward tilting, as indicated by the gentle dips of synextensional strata. Detailed mapping has revealed newly identified reverse fault systems measuring at least 50 km in combined strike length. Each major fault strikes north-northwest, dips moderately to the west, places older rocks on younger, and has related fault-propagation folds. Once restored to their original orientation, reverse faults range in dip from 38° to 47°. These moderate dips of faults combined with related folds, the significant degree of basement involvement, and cover sequence lacking obvious penetrative deformation indicate that these faults are thick-skinned, basement-cored uplifts. Forward modeling and Cenozoic erosion surfaces suggest regionally extensive Laramide-age tilting to the west-southwest and gentle folding, possibly caused by a regional-scale reverse fault underlying the study area. These results are consistent with the interpretation that Laramide shortening in southeastern Arizona was primarily characterized by thick-skinned tectonics. Kinematic indicators, folded basement rocks, north-northwest strikes of reverse faults, and lack of evidence for basin inversion suggest that preexisting basement faults and fabrics had little or no effect on the subsequent structural evolution.

Plain Language Summary The Late Cretaceous to early Eocene Laramide orogeny was a period of crustal shortening in the North American Cordillera that involved two different styles of reverse faulting. One style involves low-angle thrusts that typically slip parallel to bedding planes in layered rocks, whereas the other style involves faults that cut across bedding at moderate angles and continue downward through underlying crystalline basement rock. In southeastern Arizona, the style of Laramide shortening is debated and not well understood, in part because most of the region has undergone subsequent Cenozoic extension that has significantly rotated, dismembered, and buried most faults formed during Laramide crustal shortening. This study examines a newly discovered set of Laramide reverse faults that extend for more than 50 km along strike and that have only been affected by minor extension. Results from field mapping and structural modeling indicate that these faults are basement-involved, moderate-angle reverse faults. Because the upper crustal architecture across the region is largely consistent, the region as a whole may be characterized by moderate-angle reverse faults. Thus, nearby Laramide faults that have been previously interpreted as low-angle thrusts deserve reexamination.

1. Introduction

The Laramide orogeny (ca. 80–50 Ma) of the North American Cordillera consisted of both thin-skinned and thick-skinned contractional deformation (DeCelles, 2004). The Sevier fold-and-thrust belt spans from western Montana, through central Utah, to southeastern California, and is characterized by extensive thin-skinned deformation with low-angle thrust faults and related fault-bend folds (Armstrong, 1968; DeCelles & Coogan, 2006). The foreland Laramide province borders the Sevier belt to the east and extends from southern Montana to New Mexico and possibly into Chihuahua, Mexico (Brown, 1988; Haenggi, 2002; Hamilton, 1988; Seager, 2004). Deformation here consists of thick-skinned, basement-cored uplifts (Kellogg et al., 2004),

which other workers term arches (e.g., Erslev, 1993), bounded by moderate-angle reverse faults and related fault-propagation folds (Erslev, 1986). Each style of shortening typically formed in distinct geographic areas, although both structural styles overlap and interact in northwestern Wyoming and southwestern Montana (Craddock et al., 1988; Schmidt et al., 1988).

The style of Laramide deformation in southeastern Arizona in many places is obscured due to the effects of superimposed Cenozoic extensional tectonics. Throughout much of the region, normal faulting has dismembered, rotated, and concealed Laramide reverse faults (Dickinson, 1991; Favorito & Seedorff, 2017); however, in certain subregions the effects of extension are relatively minor (e.g., Davis, 1979). Individual mountain ranges or groups of ranges are commonly affected by similar amounts of extension. In areas affected by normal faults of a single polarity (e.g., east-dipping faults), the magnitude of extension is directly related to the degree of tilting of the oldest local synextensional strata (Stewart, 1975; Thompson, 1960). In ranges affected by normal faults with variable dip directions and moderate to high degrees of Cenozoic extensional tilting, the style of reverse faulting, magnitude of shortening, and kinematics of reverse faulting commonly is obscured, and a compelling reconstruction of superimposed extensional faulting is a prerequisite for assessing the style of contraction (e.g., Favorito & Seedorff, 2017).

Laramide shortening in southeastern Arizona has been interpreted as thin-skinned in some studies and thick-skinned in others (e.g., Davis, 1979; Drewes & Thorman, 1978; Favorito & Seedorff, 2017; Waldrip, 2008). This indicates that either the style of reverse faulting is regionally varied or that previous interpretations of structural style in certain areas are incorrect. In addition, several reverse faults in southeastern Arizona may have yet to be identified, largely due to the obscuring effects of Cenozoic extension. The most prominent practical applications arise because the area largely coincides with the porphyry copper province of southwestern North America (Titley, 1982).

The complexity and uncertainty of shortening in southeastern Arizona has sequestered it from discussion on Laramide Cordilleran-scale tectonics (DeCelles, 2004). In addition to uncertain deformation styles, the timing of shortening is not well understood (Krantz, 1989), as only a few reverse faults have age constraints (e.g., Favorito & Seedorff, 2017; Gehrels & Smith, 1991). Understanding both the timing and structural style can help provide insight into the deformation history of the region and how it relates to the tectonic evolution of the North American Cordillera. Perhaps one of the most interesting unresolved tectonic questions concerning southeastern Arizona is the origin of high topography at the end of the Laramide that ultimately may have led to mid-Cenozoic gravitational collapse and core complex development (e.g., Coney & Harms, 1984; Sonder et al., 1987; Spencer & Reynolds, 1990). Did shortening of the upper crust build topography prior to extension or did some other mechanism, such as lower crustal flow (e.g., McQuarrie & Chase, 2000), play a more important role? To answer this question, the structural style, magnitude, and areal extent of reverse faults must be determined.

This study describes the structural geology of the northern Galiuro Mountains, located northeast of Tucson and southeast of Phoenix on the eastern boundary of the San Pedro Valley (Figure 1). The research area encompasses roughly 300 km² and is bisected by the Aravaipa Valley. Results presented here are based on new field work in combination with data from previous mapping. The study area has only been affected by minor Cenozoic extension, making it an excellent location to characterize Laramide shortening and to develop a more straightforward structural reconstruction compared to highly extended areas. Map patterns and forward modeling of structures indicate the presence of two previously unidentified and significant basement-cored uplifts, each bounded by a moderately west-dipping reverse fault. Together, these two faults form a fault system that likely continues for a total distance of at least 50 km along strike. Crosscutting relationships between Laramide volcanic and plutonic rocks provide age constraints on shortening and relative timing between local porphyry copper generation and contractional deformation.

2. Geologic Setting

The Galiuro Mountains are located within the Basin and Range province of southeastern Arizona. Even though the San Pedro Valley and Tortilla Mountains, located immediately west of the Galiuro Mountains, have been highly extended and tilted by middle to late Cenozoic extension (Barton et al., 2005; Dickinson, 1991; Favorito & Seedorff, 2017; Maher, 2008; Nickerson et al., 2010), the Galiuro Mountains are cut by only a few normal faults and are only mildly extended (Creasey et al., 1981; Dickinson, 1991). Nearby towns

Figure 1. Geologic map of the study area. Based on new mapping and previous work by Simons (1964), Willden (1964), Krieger (1968a, 1968b, 1968c), Keith (1983), Bolm et al. (2002), and Gootee et al. (2009). Significant map updates include identification of reverse faults and addition of bedding and foliation measurements in units Tv and Tw. Cross section AA' is Figure 3, and cross section BB' is Figure 8. Inset figure shows the location of the study area and the style of Laramide reverse faults in southeastern Arizona as interpreted by the authors cited.

include Mammoth and Dudleyville, and nearby Laramide porphyry copper deposits include Copper Creek, San Manuel-Kalamazoo, Chilito, and Christmas (Leveille & Stegen, 2012), each of which is no farther than 15 km from boundaries of the study area.

Crystalline basement rocks within the study area include Pinal Schist formed at 1.7 Ga (Conway & Silver, 1989; Meijer, 2014) that has been intruded by anorogenic granite that crystallized at 1.4 Ga (Anderson, 1989). Following a period of erosion, a series of dominantly siliciclastic rocks were deposited over the basement. These rocks include the Mesoproterozoic Dripping Springs Quartzite, Mescal Limestone, and Troy Quartzite (Wrucke, 1989). Diabase sills and dikes (1.1 Ga) were then emplaced into the sedimentary sequence and the upper few hundred meters of the underlying crystalline basement (Bright et al., 2014; Howard, 1991). As a result of intrusion of sills, the Mesoproterozoic section has been inflated, clastic rocks locally were metamorphosed to quartzite or hornfels, and original dolomite was locally hydrothermally altered (Wrucke, 1989). Individual diabase sills range in thickness from several meters to a few hundreds of meters and in total commonly comprise half of any structural section of Mesoproterozoic rocks (Krieger, 1968a, 1968b, 1968c). Within the study area, this section ranges in total thickness from 200 to 550 m, including the magmatic inflation component.

Paleozoic rocks rest unconformably on the Proterozoic section and mainly consist of carbonate and lesser siliciclastic rocks. These units include the Bolsa Quartzite, Abrigo Formation, Martin Formation, Escabrosa Limestone, and Naco Group (Krieger, 1968a). The Paleozoic section in the study area is 500 to 650 m thick. Mesozoic clastic rocks that unconformably overly Paleozoic rocks crop out in isolated patches throughout the study area and do not exceed a total thickness of 130 m. These include an undivided Mesozoic sedimentary unit (variably iron oxide-rich conglomerate, sandstone, and siltstone) and the Late Cretaceous Pinkard Formation (Krieger, 1968a). These rocks likely do not correlate with sedimentary rocks of the Cretaceous Bisbee rift basin farther to the south. Instead, the undivided Mesozoic unit may represent Triassic back-arc sedimentation related to erosion of the Cordilleran arc (Riggs et al., 2013), and the Pinkard Formation likely represents deposition on the southwestern edge of the western interior basin of North America (Hayes, 1970).

During the Laramide orogeny (ca. 80–50 Ma), pronounced structural shortening occurred throughout the Cordillera (Coney, 1976; Krantz, 1989). Tectonic explanations include low-angle subduction of the Farallon slab eastward beneath continental North America (e.g., Dickinson & Snyder, 1978; Jacobson et al., 2017) or suturing of an archipelago against continental North America above a west-dipping subduction zone (e.g., Sigloch & Mihalynuk, 2017). In southeastern Arizona, authors have interpreted that Laramide reverse faults include both moderate-angle reverse faults bounding basement-cored uplifts (e.g., Davis, 1979; Favorito & Seedorff, 2017) and low-angle thrusts (e.g., Drewes & Thorman, 1978; Waldrup, 2008). The dominant shortening style remains enigmatic, and additional major reverse faults may yet be discovered. In addition, several reverse faults throughout the region have not been explicitly characterized in terms of structural style (Krantz, 1989; Spencer, Cook, et al., 2009; Spencer et al., 2011; Willden, 1964). Laramide rocks in the region consist of various intrusions, volcanic piles, and volcanoclastic synorogenic strata (Dickinson, 1991). Locally, in the northern Galiuro Mountains, the Laramide arc rocks include the Williamson Canyon Volcanics, diorite, Glory Hole Volcanics, Copper Creek Granodiorite, and intrusive rhyolite (Krieger, 1968a, 1968b). Intermediate to felsic intrusions, ranging in age from ca. 75 to 60 Ma, are associated with significant porphyry copper deposits throughout the San Pedro Valley (Seedorff et al., 2005). The Copper Creek deposit is located within the study area and is related to the Copper Creek Granodiorite. The end of the Laramide in southeastern Arizona is marked by the intrusion of two-mica granites exposed in the Santa Catalina Mountains dated at 57–46 Ma (Fornash et al., 2013).

The mid to late Cenozoic is characterized by significant extension and an influx of magmatism, perhaps associated with steepening of the Farallon slab and transition to a strike-slip continental margin (Coney & Reynolds, 1977; Dickinson, 1991). Movement on normal faults produced half-graben basins where synextensional strata accumulated (Gawthorpe & Leeder, 2000). Within the field area, mid-Cenozoic rocks include late Oligocene Whitetail Conglomerate and overlying Galiuro Volcanics, and early Miocene Hell Hole Conglomerate (Dickinson, 1991). Late Cenozoic rocks include the late Miocene to Pliocene Quiburis Formation, which represents basin fill associated with range-bounding normal faults (Dickinson, 1998, 2002).

3. Structural Framework

The majority of the study area was originally mapped by Krieger (1968a, 1968b, 1968c). Krieger identified numerous faults but interpreted many of them to be nearly vertical and rarely distinguished between reverse and normal offset. Only three minor reverse faults, ranging from 0.2 to 2 km in strike length, were previously documented (Keith, 1983; Krieger, 1968a, 1968b). The largest of these, the Bolsa fault (Figure 2), was interpreted by Krieger (1968a) as either a low-angle thrust or landslide block. In his compilation map, Dickinson (1991) interpreted the Brandenburg fault and the northern segment of the Holy Joe fault (Figures 1 and 2) as high-angle normal faults.

Cenozoic extension in the northern Galiuro Mountains has resulted in minor tilting. Normal faults here are uncommon, are widely spaced, and generally have minor offset (Creasey et al., 1981; Dickinson, 1991). Evidence for tilting comes from the orientation of bedding in the late Oligocene Galiuro Volcanics, which comprise most of the range in outcrop, and scattered, slightly older, synextensional deposits. Bedding in both units strikes north-northwest and dips at shallow angles (10–20°) to the east-northeast. The lack of significant Cenozoic extension and associated tilting in the map area indicates that the modern attitudes of Laramide faults are close to their original attitudes, unlike in nearby areas where Cenozoic extension has rotated certain Laramide faults through horizontal or through vertical (e.g., Favorito & Seedorff, 2017; Richard & Spencer, 1998a).

There are several nearby locales where significant Laramide structures have been documented. In the Romero Wash area near the town of Winkelman, located 20 km west of the study area (location 6 in Figure 1), Favorito and Seedorff (2017) interpreted that basement-cored uplifts bounded by moderate-angle faults had been dismembered and tilted by a complex sequence of Cenozoic normal faults. Extension resulted in 90° of eastward tilting, significantly complicating original Laramide fault geometry. Once restored, the reverse fault at Tecolote Ranch is west vergent and strikes roughly north. Just west of the Ray copper deposit, located 40 km northwest of the study area, the Walnut Canyon and Telegraph Canyon thrusts (location 2 in Figure 1) were interpreted by Richard and Spencer (1998b) to be part of a thin-skinned east-vergent thrust sheet. Like near Romero Wash, this area was also effected by complex Cenozoic normal faulting, tilting rocks by more than 60° to the east (Richard & Spencer, 1998a, 1998b). Thin-skinned, east-vergent thrusts have also been interpreted 40 km south-southeast of the study area (location 10 in Figure 1) in the southern Galiuro Mountains (Waldrip, 2008). A proposed regional thrust sheet, ~6 km thick, is invoked to explain penetrative deformation observed in footwall rocks. This thrust is possibly thought to be linked to other reverse faults observed in the northern Catalina Mountains, such as the Edgar and Youtcy faults (locations 8 and 9 in Figure 1), as suggested by northeast-directed Laramide shear fabrics (Bykerk-Kauffman & Janecke, 1987; Gehrels & Smith, 1991).

4. Methods

This study includes a compilation of previous maps (Bolm et al., 2002; Gootee et al., 2009; Keith, 1983; Krieger, 1968a, 1968b, 1968c; Simons, 1964; Willden, 1964), in addition to remapping of certain areas at a scale of 1:10,000 with particular focus on locating fault traces accurately and acquiring fault and bedding orientations and kinematic indicators. The positions of measured structural features and lithologic contacts were recorded using a Garmin GPSMAP 64s. ArcGIS satellite imagery was used to append both remapped and inaccessible areas. Three-point solutions using a digital elevation model in Google Earth were used to determine the orientation of bedding planes in certain areas where distinct beds and contacts could confidently be traced. For ease of reference, new informal names are applied to previously unnamed geographic features, including the Diabase and Lost Hammer Washes. Likewise, certain previously unnamed geologic features are assigned informal names, as shown in Figures 1, 2, 6, and 7. The names are used as reference points in this discussion and include the Brandenburg, Holy Joe, Troy, and Bolsa faults. Each is named after geographic landmarks or associated geologic units. Due to the general lack of exposures of fault planes in outcrop, three-point problems and structure contour mapping were used to determine the orientations of faults. In order to estimate the amount of slip on faults, the thickness of the stratigraphic column for each area was calculated using data from local exposures because the thickness of diabase sills varies by hundreds of meters across the field area.

Final maps and cross sections were created using Adobe Illustrator®. Laramide folds unrelated to local reverse faulting were created in Midland Valley Move™ by hand. These were then unfolded using the Move™ 2-D

Figure 2. Geologic map of the Brandenburg area. Based on new mapping and previous work by Krieger (1968a). Location is shown in Figure 1. Significant map updates include identification of reverse faults and fold axes, new fault orientation measurements, and addition of bedding and foliation measurements east of the Brandenburg fault. Only prominent fold axes are shown and extended under cover. The axial traces of folds related to the Brandenburg fault likely continue to the northwest, but their location is uncertain.

Figure 3. Geologic cross section across the Brandenburg area along line of section AA' shown in Figures 1 and 2, with no vertical exaggeration. Projected locations of measured bedding attitudes are shown near the surface. Unit Ybdd includes the Barnes Conglomerate, Dripping Springs Quartzite, and diabase. Cenozoic erosion surface is emphasized by the irregular lower contact of Whitetail Conglomerate (Tw).

unfolding module with the flexural slip method in order to verify line length and area balance. Forward modeling of reverse fault offset and related folding was achieved using the Move™ 2-D move-on-fault module and trishear method. Stereonet 10 (Allmendinger et al., 2012) was used to plot and contour structural data, to restore structures to their original orientations, and to calculate fold axes, interlimb angles, and axial planes.

5. Description of Structures

5.1. Brandenburg Reverse Fault System

This reverse fault system is located in the northwestern portion of the study area and includes the Brandenburg fault, Bolsa fault, and other minor faults (Figures 1–3 and Table 1). All faults strike north to north-west and are moderately or steeply inclined. The longest fault is the Brandenburg fault, and it was originally mapped by Krieger (1968a) as a generic unclassified fault, later reinterpreted by Dickinson (1991) as a high-angle normal fault. No outcrops of a discrete fault surface were found, but fault breccia is present in several locations. Breccia zones are typically 5–15 m wide and contain angular clasts ranging in size from a few centimeters to several meters wide with lesser fault gouge (Figures 4a and 4b). In some areas, the fault zone is characterized by intense clay and iron-oxide alteration (Figure 4b). Even though fault exposure is minimal, the fault trace was accurately located between Diabase Wash and Carrico Spring using breccia zones and differences in lithology (Figure 2). The fault generally strikes north-northwest and dips moderately to the west. Along most of the exposed strike length of the fault, an anticline is present in the hanging wall, and a syncline is present in the footwall (Figures 2, 3, and 5a and Table 1). Both folds are gently north-plunging. Less commonly, the footwall contains a synclinal bend instead of a syncline (Figure 2). The axial trace of these folds and proximity to the fault indicate that they formed as a result of reverse fault offset. Within the anticline and syncline, the Pinal Schist-Barnes Conglomerate contact is clearly folded (Figures 2 and 3).

Just north of Diabase Wash, the Brandenburg fault is interpreted to link to a more northwesterly striking reverse fault segment under Cenozoic cover (Figures 1 and 2). Paleozoic and Mesozoic rocks in the northwestern section of the mapped area (Figure 2) are steeply inclined to overturned, strongly suggesting the continuation of the reverse fault system.

The Bolsa fault is west of the Brandenburg fault and was originally interpreted by Krieger (1968a) as either a low-angle thrust or landslide block. It strikes northwest and dips steeply to the east (Figures 2 and 3 and Table 1). Fault exposures are limited, and the lack of topography along the fault trace results in an uncertain dip estimation. Most strata near the fault are gently folded, and tight folds are present near the western tip of

Table 1
Characteristics of Reverse Faults

Fault	Brandenburg	Bolsa	Holy Joe	Troy
Strike ^a	N10°W	N53°W	N21°W	N44°W
Dip ^a	37°W	50°E ^b	30°W	50°E
Oldest rocks in hanging wall in contact with fault	Diabase hosted by Pinal Schist	Diabase hosted by Dripping Springs Quartzite	Pinal Schist	Diabase hosted by the lower unit of Troy Quartzite
Youngest rocks in footwall in contact with fault	Naco Group	Abrigo Formation	Mesozoic sedimentary rocks	Upper Troy Quartzite
Approximate strike length (km)	13.5	2.3	30	2.1
Maximum exposed offset (km)	1.1	0.2	2.0	0.2
Fault-related folds	Variable: anticline/syncline pair and lesser monoclines	Anticline/syncline pair	Variable: anticline/syncline pair and lesser monoclines	Anticline/syncline pair
Overtaken fold limbs	Common	Uncommon	Common	Uncommon
Fold axis trend/plunge ^{a,c}	N27°W, 10°	N42°W, 2°	N17°W, 4°	N46°W, 8°
Axial plane strike and dip ^{a,c}	N15°W, 40°W	Uncertain	N10°W, 30°W	N51°W, 63°W
Fold interlimb angle ^{a,c}	74°	Uncertain	43°	97°
Relationship to younger rocks	Mantled by Cenozoic Whitetail Conglomerate and Cenozoic Gila Formation	N.A.	Mantled by Laramide Glory Hole Volcanics and Cenozoic Gila Formation	N.A.
Relationship to other faults	Cut by minor E-W normal faults	Backthrust of the Brandenburg reverse fault	Cut by minor E-W normal faults	Cut by the Holy Joe fault and a minor E-W normal fault

Note. N.A. = not available.

^aValues that represent average orientation where fault offset is greatest. ^bValue is uncertain due to limited topography over fault exposure. ^cCalculated using stereonet analyses.

the fault (Figures 2 and 5b). Stereonet analyses indicate a gentle northward plunge for these folds (Figure 5b). Other minor reverse faults within the Brandenburg system are located north of the Bolsa fault, and many have fault-related folds (Figure 1).

5.2. Holy Joe Reverse Fault System

The Holy Joe reverse fault system is located in the central and southwestern portions of the study area and includes the Holy Joe fault, Troy fault, and other minor faults (Figures 1 and 6–8 and Table 1). These faults strike west-northwest to north-northwest and are moderately or steeply dipping. The Holy Joe fault is the longest fault in the system and was originally mapped by Krieger (1968b) as a generic unclassified fault. Dickinson (1991) interpreted the northern segment of the fault as a high-angle normal fault and the southern segment as a stratigraphic contact. Within the mapped area, the northern half of the fault (Figure 7) crops out in several locales, whereas the southern half is almost always buried (Figure 6). The fault zone is typically characterized by a 10- to 15-m-wide area of fault gouge and angular clasts ranging in size from several centimeters to about half a meter wide (Figures 4c and 4d). Intense to moderate clay and iron-oxide alteration is present in some fault outcrops (Figure 4d). Slickenlines were found on only one fault exposure and have an average trend and plunge of S66°W, 28° (Figure 5c). The northwestern segment of the fault strikes west-northwest and dips moderately to the south, and strata here are not folded (Figure 7). The central portion of the fault strikes more northwesterly and dips at a slightly lower angle to the southwest, and a monocline is present in the footwall of the fault (Figure 7). Finally, the southern segment of the fault strikes north-northwest and dips at moderate angles to the west (Figures 6 and 8 and Table 1). Here, a syncline is present in the footwall, and an anticline is indicated in the hanging wall by the folded Pinal Schist-Barnes Conglomerate contact. These folds plunge gently to the north (Figure 5c).

The Troy fault is located north of the Holy Joe fault and was not identified by previous authors (Figure 7). No exposures of the fault surface were found. This fault strikes northwest, dips steeply to the east, has

Figure 4. Photographs of reverse faults and related breccia. Camera facing direction is given in the bottom left corner. (a) Brecciated diabase in the footwall of the Brandenburg fault. Located 0.5 km south of Carrico Spring (Figure 2). (b) Brecciated and strongly iron-oxide altered Escabrosa Limestone in the hanging wall of the Brandenburg fault. Located 1 km north of Carrico Spring (Figure 2). (c) Outcrop of the Holy Joe fault (red dashed line) where Proterozoic granite overlies diabase. Brecciation is minor. Located in Mud Spring (Figure 7). (d) Outcrop of the Holy Joe fault where brecciated Proterozoic granite overlies strongly clay-altered diabase. Located in Holy Joe Wash southeast of Mud Spring (Figure 7).

fault-related folds (Figure 5d), and is cut by the Holy Joe fault (Figure 7 and Table 1). Other minor reverse faults within this system are located to the north and south of the Holy Joe fault (Figure 1). The maps of Krieger (1968b) do not indicate the presence of folds associated with these faults.

5.3. Regional Homocline

Within the study area, strata of the Glory Hole Volcanics, Whitetail Conglomerate, Hellhole Conglomerate, and Galiuro Volcanics strike northwest and dip gently (10–15°) to the east (Figures 1, 2, and 6). Due to the similar orientation of these units, they are all considered to be part of a regional homocline (Figure 9a and 9b). Younger rocks of the Quiburis Formation typically dip to the west, indicating that they are not part of the homocline (Figure 1). Near the Brandenburg fault, the homocline has an average orientation of N32°W, 13°E (Figure 9a), and near the Holy Joe fault, the homocline has an average orientation of N28°W, 13°E (Figure 9b).

5.4. Regional Folds

Virtually all rocks older than Glory Hole Volcanics that have not been folded by local reverse faults have been gently folded about gently north-northwest plunging axes (Figure 9c). On average, these beds are oriented N56°E, 6°N (Figure 9c). A clear example of these gentle folds is exposed at Brandenburg Mountain (Figure 1) where Proterozoic and Paleozoic sedimentary rocks are gently folded into a northwest plunging syncline measuring ~4 km in wavelength. Open synclines of similar wavelength are also exposed in the Brandenburg area (Figures 1 and 2) and north of Holy Joe Peak (Figure 1). These rocks are angularly unconformable with overlying rocks such as Laramide Glory Hole Volcanics and Cenozoic Galiuro Volcanics and Whitetail Conglomerate (Figures 1, 2, 6, and 7).

Figure 5. Lower-hemisphere equal-area stereonet plots of poles to bedding for units older than Laramide Glory Hole Volcanics and younger than Pinal Schist and reverse fault slickenlines for the (a) Brandenburg fault (Figures 1 and 2), (b) Bolsa fault (Figure 2), (c) Holy Joe fault (Figures 1, 6, and 7), and (d) Troy fault (Figure 7). Planes of best fit to bedding poles are shown, and from these, fold axes were calculated and plotted. The average fault orientation and axial plane orientation where fault offset is greatest are shown. Plots were created with the program Stereonet 10 (Allmendinger et al., 2012).

6. Interpretations

6.1. Timing of Laramide Structures

6.1.1. Reverse Faults

Timing of reverse faults can be constrained using crosscutting relationships between reverse faults and Mesozoic and Cenozoic rocks (Table 1). Just north of the Bolsa fault, rocks as young as Pinkard Formation are steeply inclined and commonly overturned due to fault-related folding (Figures 1 and 2). Just north of the study area in the southeastern corner of the Christmas quadrangle, Williamson Canyon Volcanics are clearly folded in the form of the Deer Creek syncline that measures ~3 km in wavelength (Keith, 1983; Willden, 1964). This fold is likely Laramide in age because these Cretaceous strata are overlain in angular unconformity by Cenozoic rocks, and the southern fold limb is overturned (Figures 2 and 9). Therefore, the Williamson Canyon Volcanics are the youngest rocks that have been involved in Laramide shortening within the region and consequently represent a lower limit on the age of shortening.

Just south of Lost Hammer Wash (Figure 6), the Holy Joe fault is overlapped by Laramide Glory Hole Volcanics. This geologic relationship demonstrates that the Glory Hole Volcanics postdate contractional deformation here and therefore represent an upper limit on the age of shortening. As shorthand, all units older than Glory Hole Volcanics will now be referred to as *preshortening strata*.

U-Pb zircon analyses (Mizer, 2018) date the Williamson Canyon Volcanics at 73.9 ± 2.5 Ma and the Glory Hole Volcanics at 63.0 ± 0.6 Ma. Using these ages, the timing of shortening within the region is limited to 73.9–63.0 Ma.

Figure 6. Geologic map of the southern Holy Joe area. Based on new mapping and previous work by Krieger (1968b). Location for this figure and full line of section BB' is shown in Figure 1. Note direction of north arrow. Significant map updates include remapping of units Ki and Mzs, reinterpretation of the northern Kg contact, identification of reverse faults and fold axes, new fault orientation measurements, and addition of bedding and foliation measurements throughout the area.

The relative timing between reverse faulting and porphyry copper generation can also be determined within the study area. Because the Copper Creek Granodiorite, the progenitor of the Copper Creek deposit, intrudes the Glory Hole Volcanics, shortening here predates porphyry copper generation.

6.1.2. Regional Folds

Regional folds within the study area that are not directly related to local reverse faulting involve Proterozoic through Laramide rocks. The oldest unit that has not been affected by this folding is the Glory Hole Volcanics.

Figure 7. Geologic map of the northern Holy Joe area. Based on new mapping and previous work by Krieger (1968b). See Figure 6 for map units and symbols. Location for this figure is shown in Figure 1. Note direction of north arrow. Significant map updates include identification of reverse faults and fold axes, new fault orientation measurements, and addition of bedding and foliation measurements throughout the area.

In the Holy Joe area (Figures 1 and 6), this unit consistently dips gently to the east, whereas older rocks such as Escabrosa Limestone dip to the west. This indicates that regional folding must be older than Glory Hole Volcanics (63.0 Ma) and therefore is Laramide in age. The timing relationship between regional folding and local reverse faulting is unclear. The orientation of fold axes of both the regional folds and folds that are closely associated with reverse faulting are similar (Figures 5 and 9c), suggesting that they formed in response to the same compressional forces from 73.9 to 63.0 Ma. It may be possible that regional folding predated, was concurrent with, or postdated local reverse faulting.

6.2. Cenozoic Tilting: Direction, Amount, and Timing

The orientation of Cenozoic and postshortening Laramide strata (Figure 9) indicates the study area has been tilted during mid-Cenozoic extension. The postshortening units of the Glory Hole Volcanics, Whitetail Conglomerate, Galiuro Volcanics, and Hellhole Conglomerate are part of a north-northwest striking and gently eastward dipping homocline (Figure 9). Due to original horizontality, strata of these units were most likely deposited with little or no inclination; therefore, their present-day inclination is the result of tilting related to mid-Cenozoic extension. The tilting axis for a given area is interpreted to parallel the strike of the homocline, and the magnitude of tilting is equal to the dip of the homocline (Figure 9 and Table 2).

The oldest Cenozoic stratum in the study area is the late Oligocene synextensional Whitetail Conglomerate (Figure 2), and this unit is interpreted to represent the start of extension. Extension continued through the Miocene, as indicated by the inclined early Miocene Hell Hole conglomerate (Figure 2). By late Miocene time, the majority of extension-related tilting likely had already taken place, as suggested by the relatively flat lying (Bolm et al., 2002) attitude of late Miocene to Pliocene Quiburis Formation (Figure 2).

Cenozoic units within the study area likely record all extension and related tilting that occurred locally since the Laramide because the start of the start of Cenozoic extension within southeastern Arizona began in the Oligocene according to Dickinson (1991) and the base of the Whitetail Conglomerate is late Oligocene in age. In addition, we are certain that there was no net Cenozoic tilting before or after the deposition of the Whitetail Conglomerate because bedding attitudes in the overlying late Oligocene Galiuro Volcanics and underlying Laramide Glory Hole Volcanics are similar.

6.3. Restored Orientations of Laramide Structures

In order to restore the effects of Cenozoic extension within the study area, rocks must be rotated about the Cenozoic tilting axis but in the opposite direction (Table 2).

6.3.1. Regional Folds

Once beds of all preshortening units are restored to their pre-Cenozoic orientations, they predominately dip gently to the west (Figure 10b) and have a mean orientation of N5°W, 15°W. Even though in the present day these strata constitute gentle folds in cross section, once restored, they appear as a gently folded homoclinal block resembling a strip of bacon. Therefore, this deformation will be referred to as *Laramide westward tilting*.

Figure 8. Geologic cross section across the southern Holy Joe area along line of section BB' shown in Figure 1 and partially in Figure 6, with no vertical exaggeration. Projected locations of measured bedding attitudes are shown near the surface. Unit Ybdd includes units the Barnes Conglomerate, Dripping Springs Quartzite, and diabase (Figure 6), unit Ytl includes the lower Troy Quartzite and diabase, unit Ytu includes the upper Troy Quartzite and diabase, and unit Mes includes the Escabrosa Limestone and Mesozoic sedimentary rocks. Unit Ks is Laramide synorogenic sedimentary rocks. Even though this type of rock is not exposed in the study area, synorogenic sedimentary rocks do crop out 15 km to the southwest of section BB' in the Mammoth quadrangle as the American Flag Formation (Force, 1997; Spencer, Gootee, et al., 2009). Cenozoic erosion surface is emphasized by the irregular lower contact of Tv. Postshortening Laramide erosion surface is emphasized by the irregular lower contact of Kg.

6.3.2. Reverse Faults

Using local Cenozoic tilting axes and magnitudes, the Brandenburg, Holy Joe, Troy, and Bolsa faults were rotated westward to their pre-Cenozoic orientations (Figure 10a and Table 2). Once restored, all reverse faults generally retain their modern strike, with the Holy Joe and Brandenburg faults dipping $\sim 12^\circ$ steeper and the Bolsa and Troy faults dipping $\sim 12^\circ$ more shallowly (Table 2). At the end of the Laramide, all reverse faults within the study area were moderately dipping at angles ranging from 38° to 47° . Restored fold axes associated with these faults plunge gently to the north-northwest (Figure 10a and Table 2).

The restored inclination of reverse faults may not be the original angle of fault formation because the timing between regional Laramide tilting and local reverse faulting is unclear. If regional tilting predated local reverse faulting, then the pre-Cenozoic restored orientations are likely the original angles of fault formation. However, if regional tilting postdated or was concurrent with local reverse faulting, then the original orientation of faults would range from 38° to 55° , as indicated by results from forward models that will be discussed in a later section. Regardless of timing, these faults originally formed at moderate angles, and for simplicity, regional tilting is assumed to predate local reverse faulting.

Figure 9. Lower-hemisphere equal-area stereonet plots of poles to bedding for Laramide Glory Hole Volcanics, Cenozoic Whitetail Conglomerate, and Cenozoic Galiuro Volcanics for the (a) Brandenburg area (Figure 2) and (b) the Holy Joe area (Figures 6 and 7). The unimodal distribution of data in each area suggests homoclinal structures. (c) Poles to bedding for units older than Laramide Glory Hole Volcanics and younger than Pinal Schist that have not been affected by local reverse faults. A plane of best fit to bedding poles is shown, and from this a fold axis was calculated and plotted. Plots were created with the program Stereonet 10 (Allmendinger et al., 2012).

Table 2
Pre-Cenozoic Orientations of Laramide Reverse Faults and Related Folds

Fault	Brandenburg	Bolsa	Holy Joe	Troy
Average orientation of local Cenozoic strata ^a	N32°W, 13°E	N32°W, 13°E	N28°W, 13°E	N28°W, 13°E
Trend of Cenozoic tilting axis ^b	N32°W	N32°W	N28°W	N28°W
Net amount and direction of Cenozoic tilting	13°E	13°E	13°E	13°E
Modern strike and dip of fault ^c	N10°W, 35°W	N53°W, 50°E	N21°W, 30°W	N44°W, 50°E
Restored strike and dip of fault	N15°W, 47°W	N58°W, 38°E	N23°W, 43°W	N48°W, 38°E
Modern trend and plunge of fault-propagation fold axis ^c	N27°W, 10°	N42°W, 2°	N17°W, 4°	N46°W, 8°
Restored trend and plunge of fault-propagation fold axis	N25°W, 9°	N41°W, 4°	N16°W, 1°	N44°W, 12°

^aCenozoic Whitetail Conglomerate and Galiuro Volcanics. ^bAssuming all Cenozoic tilting axes are horizontal. ^cValues that represent where fault offset is greatest.

6.4. Regional Laramide Uplift

The restoration of preshortening strata that have not been affected by local reverse faults strongly indicates that the region was tilted westward during the Laramide (Figure 10b). Further evidence for this tilting is present in the Cenozoic erosion surface north of Aravaipa Valley (Figure 1). At Brandenburg Mountain, Cenozoic volcanic and sedimentary rocks rest on upper Paleozoic carbonate rocks. Moving eastward, the rocks below the erosion surface increase gradually in age (see Krieger, 1968c, for more detailed map). This geometry indicates gentle regional tilting consistent with the restored orientations of preshortening strata. East of Brandenburg Mountain, along the Aravaipa Valley axis, Cenozoic rocks lie on Proterozoic diabase, and moving east, on Pinal Schist. This more abrupt increase in rock age under the erosion surface is likely due to a paleovalley. However, it is still consistent with the notion of westward tilting as older rocks under the erosion surface are encountered eastward upstream.

The pre-Cenozoic orientation of regional and reverse fault-related fold axes also supports the existence of regional Laramide tilting (Table 2). Folds associated with the Brandenburg fault plunge 9° to the north-northwest once restored. This axis was calculated from data at the center of the fault along strike, where fold axes should restore to nearly horizontal. This gentle plunge, which is also observed in folds of the Bolsa and Troy faults, is likely inherited from regional Laramide uplift that is not directly related to local reverse faulting. Even though fold axes associated with the Holy Joe fault restore to nearly horizontal, regional uplift is still expected here due to the common westward pre-Cenozoic restored dip of preshortening strata, as well as

Figure 10. Lower-hemisphere equal-area stereonet plots showing the restored pre-Cenozoic orientations of Laramide structural features. Data from each area were restored according to the local Cenozoic tilting axis orientation and tilting magnitude (Table 2). (a) Restored orientation of Laramide reverse faults (Table 2), reverse fault slickenlines, calculated fold axes of fault-propagation folds associated with each reverse fault, and planes to fold axes. (b) Restored orientation of bedding planes for units older than Laramide Glory Hole Volcanics and younger than Pinal Schist with plane of best fit and fold axis. The original orientations of these beds have not been affected by local reverse faults.

smaller-scale shortening in what has been called a zone of back-limb tightening zone (Erslev, 1986; Erslev, 2005).

The Laramide-age westward tilting of strata is possibly due to a west-dipping regional-scale reverse fault located to the east of the study area. Gravity, seismic, and structural data indicate that thick-skinned reverse faults of this scale, such as the Wind River thrust, likely sole into a subhorizontal detachment at depth (Erslev, 2005; Hall & Chase, 1989). This change in fault dip combined with offset results in gentle tilting of hanging wall rocks in the direction of fault dip. In essence, we hypothesize that the preshortening strata represent the western limb of a large hanging-wall anticline. Because there is a relatively small range of exposure across such a large hypothesized structural feature, the only preshortening strata that we can observe are tilted nearly uniformly and thus appear as a homocline.

Finding proof of such a regional uplift east of the study area is difficult, as most of this area is covered by Cenozoic sedimentary and volcanic rocks and has been dismembered by normal faults (Simons, 1964; Wrucke et al., 2004). However, evidence for such a fault is provided by the Cenozoic erosion surfaces throughout the Santa Teresa Mountains and Pinaleno Mountains, located 40 km east of the study area. Throughout most of these ranges, Proterozoic basement is overlain directly by Cenozoic volcanic rocks (Drewes, 1996; Wrucke et al., 2004), indicating a widespread Laramide uplift that may span 100+ km in strike length. An uplift of such scale could account for the westward Laramide tilting observed in the study area.

6.5. Shortening Style

The moderate restored dip of reverse faults, combined with fault-related folds with relatively small interlimb angles and overturned beds, especially for major faults (Figures 3 and 8 and Tables 1 and 2), argues that these structures represent basement-cored uplifts with related fault-propagation folds, as opposed to thin-skinned low-angle thrusts. A thick-skinned model is also supported by the large extent of basement rocks involved in faulting. This is especially clear in the Holy Joe fault, where the large majority of the rock exposed in the hanging wall is Pinal Schist (Figure 1).

The westward tilting of strata within the region indicates a regional-scale basement-cored uplift east of the study area. This uniform tilting in the hanging wall of major faults is characteristic of thick-skinned arching and is observed in areas of classic Laramide deformation such as the Wind River Range (e.g., Yonkee & Weil, 2017). Therefore, the observed Laramide tilting further suggest that the study area is characterized by thick-skinned shortening.

6.6. Forward Modeling

Forward modeling of the Brandenburg, Bolsa, and Holy Joe faults was carried out using Midland Valley Move™ to further verify the interpretation that Laramide reverse faults here are basement-cored uplifts with related fault-propagation folds (Figure 11). Forward modeling involved creating cross sections and then deforming them according to deformation models available in Move™. If the deformed section matched the data from mapping, then that style of deformation would be a plausible explanation for the structures observed in the field.

The first step in forward modeling was performed in Adobe Illustrator® and involved generating topography for a given line of section with lithology, faults, and the orientation of strata. These data were then rotated gently to the west in order to remove the effects of Cenozoic tilting. The resulting section was exported as an image file and uploaded into Move™. Then, a folded section was drawn in Move™, as seen in a2 and b2 of Figure 11. This stage assumes that regional Laramide tilting predated local reverse faulting. The orientations of strata that were not affected by local reverse faulting were used to constrain this fold geometry. Next, the 2-D move-on-fault module and trishear method were used to forward model reverse fault offset and fault-related folding. The trishear model of Erslev (1991) describes the folding of strata that occurs in a triangular zone in front of a forward-propagating fault tip. Parameters such as fault offset, initial fault-tip position, trishear angle, and propagation to slip ratio were adjusted until the forward model closely matched the geologic data (i.e., lithologic contacts, bedding orientations, axial trace location, and axial plane orientation). The fault propagation to slip ratio for the Brandenburg fault is 2.0, and for the Holy Joe fault it is 1.8. The offset on the Brandenburg fault is 1.1 km, and on the Holy Joe fault it is 2.0 km. Stages a3 and b3 show reverse fault offset, related fault-propagation folding, erosion, and synorogenic sedimentation in dark green. During fault propagation and folding, line length in some units was not maintained due to layer thickening during trishear

Figure 11. Structural reconstruction of geologic cross sections (a) AA' and (b) BB'. Intermediate shortening amounts are shown in a2, b2, a3, and b3. Total shortening for stages a1–a3 equals 0.95 km (18.0%) and for stages b1–b3 equals 2.03 km (17.3%). Extension magnitudes are not given because the lines of section are too short to provide accurate measurements. The location of future reverse faults are shown by dashed lines, the initial fault tips are white dots, and the area of fault-related trishear deformation is outlined in red. Synorogenic sedimentary rocks on the eastern end of b3 are likely from a reverse fault located within the San Pedro Valley (Force, 1997; E. Seedorff, personal communication, November 15, 2017). The location of a future Cenozoic normal fault is shown by a dashed line in stage b4.

deformation; however, area balance in all sections is maintained, disregarding deposition of new strata and erosion. Vertical relief for the Brandenburg section (a3) is 0.6 km, and for the Holy Joe section (b3) it is 1.3 km. Stages a4 and b4 show the deposition of late Laramide and mid-Cenozoic strata after a period of erosion. Finally, a5 and b5 show mid-Cenozoic normal fault offset and related tilting.

The results of forward modeling fault movement closely match data from the field. These results strongly indicate that folds associated with reverse faults formed through progressive offset and forward propagation of the reverse faults, and the region was tilted westward during the Laramide. In order to finally verify the cross sections that were initially drawn (a2 and b2), they were unfolded using the 2-D unfolding module and flexural slip method in Move™. Unfolded sections, as seen in a1 and b1 of Figure 11, retained complete line-length and area balance once restored, further supporting the interpretations. The unfolding module was also used to estimate reverse fault inclinations, given the possibility that Laramide tilting postdated reverse faulting. In this scenario, the Holy Joe fault in section would have formed at an inclination of 38° as opposed to 44° and the Brandenburg fault at 40° instead of 50°.

6.7. Kinematics of Reverse Faults

The transport direction of reverse faults is interpreted to be perpendicular to the restored orientations of fault-related fold axes where the amount of fault offset is greatest (Figure 10b and Table 2). Thus, west-dipping faults have an east-northeast transport direction, and east-dipping faults have a west-southwest transport direction. This is further supported by the restored north-northwest strike of all reverse faults (Figure 10a and Table 2), assuming primarily dip-slip displacement.

Left-lateral oblique slip can only be demonstrated in one outcrop within the northern segment of the Holy Joe fault, where west-southwest plunging slickenlines on a south-dipping fault plane suggest east-northeast transport (Figures 7 and 10a). These slickenlines are roughly perpendicular to the fold axis of the Holy Joe fault where fault offset is greatest, strongly suggesting that they represent the overall transport direction of the fault. Farther to the south, where fault offset increases, the dip of the Holy Joe fault changes to west-southwest (Figure 6). If the transport direction here is assumed also to be east-northeast (as suggested by slickenline measurements), then slip here is primarily dip slip. Assuming a relatively consistent transport direction, the entire east-west striking segment of the Holy Joe fault is likely characterized by left-lateral oblique-slip offset, and the northwest striking segment represents dip-slip offset.

The limited slickenline data for the Holy Joe fault indicate that other reverse faults, such as the Brandenburg, Troy, and Bolsa faults, primarily have dip-slip offset because all of these faults have similar strikes (Figure 1 and Table 1). Together, the restored orientations of reverse faults, related folds, and slickenlines (Figure 10) suggest that Laramide maximum compression within the study area was oriented east-northeast.

6.8. Assessment of Whether Laramide Reverse Faults Reactivated Older Faults

Inverted basin stratigraphy is perhaps the most convincing evidence for the reactivation of older faults (Chapman & Meneilly, 1991; Holdsworth et al., 1997). This is typically observed in normal faults that are reactivated as reverse faults, where older synextensional basin deposits are considerably thicker in the hanging wall than in the footwall (e.g., Lawton, 2000; Marshak et al., 2000). Another common characteristic of reactivated faults is their misalignment with the regional stress field. Due to this misalignment, slip on these faults is commonly oblique (e.g., Johnston & Yin, 2001; Neely & Erslev, 2009; Tindall & Davis, 1999). Reactivated faults also typically lack folds in rocks that predate shortening (Bump, 2003). Conversely, newly formed faults are generally aligned with the regional stress field, their slip is dominantly dip-slip, and the thickness of pre-faulting strata in the hanging wall and footwall is equal ignoring effects of later fault-related folding. In the case of newly formed basement-cored uplifts, the preshortening strata and basement is commonly folded due to the forward and upward propagation of the fault tip (Bump, 2003).

Within folds related to the Holy Joe and Brandenburg reverse faults, the basement-cover contact is clearly folded (Figures 2 and 6). This, combined with results from forward modeling (Figure 11), indicates the tip of each reverse fault originated within the Pinal Schist (Bump, 2003). This indicates that both the Holy Joe and Brandenburg faults were newly formed during the Laramide orogeny. The strike and transport direction of these faults are also consistent with original Laramide ages of movement for these structures because they are aligned with east-northeast Laramide compression, as is typical for the North American Cordillera (Erslev & Koenig, 2009). Other indications of fault reactivation are absent. There is no evidence for periods of normal

offset on any reverse fault, and there are no compelling signs of basin inversion. This may in part be due to a lack of fault exposure along strike and depth, but nonetheless, no convincing evidence is present in current exposures.

Even though preexisting faults appear to play no role within the study area, preexisting structural fabrics may have. Within the hanging wall of the east-west trending segment of the Holy Joe fault (Figures 1 and 7), the strike of bedding and foliation within the Pinal Schist as well as the Proterozoic granite-Pinal Schist contact are roughly parallel to the fault; however, the dip of the contact is uncertain. Bedding and foliation in the Pinal Schist typically dip in the same direction of the fault, but they are commonly steeper in inclination by roughly 10–40°. These observations suggest that this Proterozoic structural grain may have had some influence on the orientation of the Holy Joe fault locally. An alternate hypothesis is that the orientation of the fault here is the result of the fault tipping out, and the rough alignment in orientations is only coincidental. However, the change in strike for the Holy Joe fault is very abrupt (Figure 1), indicating that basement control is a possible explanation.

Given the fairly limited exposure of structures in the study area, especially when compared to thoroughly documented uplifts in Wyoming and Colorado, the present geology does not fully exclude the possibility that preexisting faults played a role in forming the major uplifts observed here. Nonetheless, there are observations that indicate preexisting faults played little to no role.

6.9. Regional Extent of Reverse Fault Systems

The regional extent of each reverse fault system can be estimated by analyzing erosion surfaces, bedding orientations, and changes in fault offset along strike. Within the study area, a given area is generally considered to have been significantly uplifted if the following criteria are met: (1) the Laramide and/or Cenozoic erosion surfaces involve Proterozoic rocks and (2) rocks of the same age or older than the Williamson Canyon Volcanics are angularly unconformable with overlying Laramide or Cenozoic rocks. If any of these conditions are not true for a given area, then significant Laramide reverse faulting and uplift likely did not occur there. In addition, fault lengths can be roughly estimated given their offset along strike.

6.9.1. Brandenburg System

The northernmost exposure of the Brandenburg fault has ~1.1 km of offset, the greatest amount for observed for this structure (Figures 2 and 3). Because the maximum displacement generally occurs near the midpoint of a fault, the Brandenburg fault probably continues northward along strike for ~5 km under the Cenozoic cover rocks. This is a reasonable estimate because several kilometers to the south, the Brandenburg fault has little to no offset (Figure 1). The location of the Brandenburg fault under Cenozoic rocks is relatively certain because strata just to the west are steeply inclined to overturned.

6.9.2. Holy Joe System

The westernmost exposure of the Holy Joe fault is near a tip of the fault, that is, where offset approaches 0 m. (Figures 1 and 7). Offset is greatest just south of Lost Hammer Wash (Figure 6). This indicates that the fault probably continues farther to the southwest under the Glory Hole Volcanics, which clearly postdate faulting. Evidence for the continuation of the Holy Joe fault is observed in the southeastern corner of the study area (Figures 1 and 12) where Dripping Springs Quartzite is dipping moderately to steeply overturned and Pinal Schist is mantled by Glory Hole Volcanics. South-southeast of the study area, in the central portion of the Rhodes Peak quadrangle (Gootee et al., 2009), a large ~7 km² outcrop of Pinal Schist is blanketed by Laramide volcanic rocks (Figure 12). Local intrusive relationships, lithology, and location indicate that these rocks correlate with the Glory Hole Volcanics. This erosion surface, combined with the alignment of these rocks with the Holy Joe fault, argues for continuation of the fault. Together, these observations indicate the Holy Joe fault is at least 30 km long.

7. Discussion

7.1. Style of Laramide Reverse Faulting in Southeastern Arizona

Contrasting styles of Laramide shortening have been proposed in southeastern Arizona. Both high-angle reverse faults and low-angle thrusts have been interpreted in areas affected by significant Cenozoic

Figure 12. Geologic map of the Holy Joe fault. Based on new mapping and previous work by Willden (1964), Krieger (1968b), Dickinson (1991), Bolm et al. (2002), and Gootee et al. (2009). Significant map updates include identification of reverse faults.

extension and in areas affected only by minor extension (Figure 1). Basement-cored uplifts bounded by moderate-angle reverse faults have been documented in the central Tortilla Mountains (Favorito & Seedorff, 2017; Nickerson et al., 2010), in a large area centered on the Mustang Mountains (Davis, 1979), and in the Chiricahua Mountains and surrounding ranges (Lawton, 2000; Lawton & Olmstead, 1995). The Salt River area is characterized by monoclines, associated high-angle reverse faults, and extensive northeast Laramide tilting related to regional uplift (Davis et al., 1981; Granger & Raup, 1969; Krantz, 1989; Sandberg & Butler, 1985). Low-angle thrusts have been interpreted in the Catalina Mountains (Bykerk-Kauffman, 2008), southern Galiuro Mountains (Waldrup, 2008), and northern Tortilla Mountains (Richard & Spencer, 1998b). If these assignments of structural style were all correct, then the overall distribution of thin-skinned and thick-skinned reverse faults would appear to be almost random, and there are still several reverse faults throughout the region that have not been characterized in terms of shortening style (Figure 1).

The style of Laramide shortening in well-documented areas surrounding southeastern Arizona is primarily thick-skinned. In southwestern New Mexico and northern Chihuahua, Mexico, northwest-striking basement-cored uplifts formed through reactivation of early Mesozoic normal faults (Haenggi, 2002; Lawton, 2000; Seager, 2004). Uplifts in northern Sonora have not been characterized in terms of structural style; however, Laramide-age tectonism is evident here by the presence of Upper Cretaceous sedimentary basins (Jacques-Ayala et al., 2009). Within the Colorado Plateau to the north, Proterozoic shear zones were reactivated to form moderately-dipping reverse faults and related monoclines of variable strike direction (Davis & Bump, 2009). The structural geology west of southeastern Arizona is considerably more complex due to high degrees of regional metamorphism. In south-central Arizona, Haxel et al. (1984) interpreted

low-angle overthrusts of crystalline rocks, whereas in western Arizona and southeastern California, Tosdal (1990) proposed thick-skinned deformation.

Laramide deformation in the northern Galiuro Mountains is thick-skinned. Major reverse faults here involve basement rocks, formed at moderate angles, and have related fault-propagation folds. West-southwest Laramide tilting, possibly related to a regional-scale reverse fault that may underlie the area and project to the surface toward the east, is suggested by Cenozoic erosion surfaces and the restored orientations of fault-related fold axes. Thick-skinned shortening is expected in the area given that there are no suitable units to form a detachment horizon, and the cover sequence is both thin (~1 km thick) and lacks any obvious penetrative deformation.

Results from this study are largely consistent with the interpretations of Laramide shortening in surrounding regions and with Davis's (1979) interpretation that southeastern Arizona is dominated by thick-skinned deformation. However, there are several significant examples of interpreted thin-skinned deformation throughout the region. It may be possible that Cenozoic extension, more specifically tilting, has obscured the original orientation of many moderate-angle basement-cored uplifts.

7.2. Kinematics of Basement-Cored Uplifts

Regional compression during the Laramide was unimodal and oriented east-northeast (Erslev & Koenig, 2009; Weil & Yonkee, 2012; Yonkee & Weil, 2015), subparallel to the relative motion between the Farallon and North American plates (Wright et al., 2016). Within the North American Cordillera, the average trend of Laramide structures is north-northwest, although the trend of individual faults and uplifts ranges from east-west to north-south. This misalignment of structural trends with the regional compression direction is commonly attributed to reactivation of preexisting weaknesses in basement rock (e.g., Davis & Bump, 2009; Stone, 2002). Kinematic indicators such as slickenlines and shear zones indicate oblique slip along these misaligned structures in the direction of regional contraction (e.g., Johnston & Yin, 2001; Neely & Erslev, 2009; Tindall & Davis, 1999).

The restored north-northwest strike of reverse faults, related folds, and limited slickenline data indicate east-northeast-directed dip-slip offset for all Laramide reverse faults within the study area (Figure 10). Oblique slip can only be demonstrated in the northernmost segment of the Holy Joe fault where the fault tips out and strikes roughly east-west, approximately 80° away from fold axes associated with this fault (Figure 1). Slickenlines in this area indicate an east-northeast slip direction on a southward dipping fault; therefore, left-lateral oblique slip is interpreted. Farther to the southwest, the Holy Joe fault dips west-southwest, perpendicular to fault-related fold axes, indicating dip-slip offset. Together, these observations suggest east-northeast-directed motion along the entire exposure of the fault plane. This interpretation is consistent with Harland's (1971) predictive model for kinematics of curved deformation zones. Both reverse fault transport direction and west-southwest Laramide tilting within the study area are consistent with Erslev and Koenig's (2009) conclusion that Laramide compression was unimodal and directed east-northeast.

Laramide compression directions in southeastern Arizona have not been explored in detail, perhaps due to the uncertainty associated with later Cenozoic tilting (Dickinson, 1991). According to crosscutting relationships with volcanic strata, the age of shortening in the study area is limited to 73.9 to 63.0 Ma. Using this age range, compression directions in southeastern Arizona can be compared to plate motions determined by Wright et al. (2016). The directions are similar, which supports conclusions reached by Yonkee and Weil (2015) that increased plate coupling likely resulted in the development of Laramide basement-cored uplifts throughout the western United States.

Understanding variations in reverse fault kinematics along strike may prove to be important for learning more about the tectonic history of southeastern Arizona because reverse faults here are commonly dismembered, tilted, and covered by Cenozoic extension. Restored fault orientations without kinematic indicators, such as fault-related folds and slickenlines, may not be sufficient to determine the transport direction of faults. This lack of data is common in southeastern Arizona because faults commonly are poorly exposed, and fault-related folding may not be apparent if only basement rocks are exposed (e.g., Nickerson et al., 2010). In southeastern Arizona, Laramide reverse faults and ductile fabrics, regardless of shortening style, are largely interpreted to have either east or northeast transport directions (e.g., Bykerk-Kauffman & Janecke, 1987; Richard & Spencer, 1998a; Waldrup, 2008). East-directed compression may be more consistent with

Sevier-style, thin-skinned deformation for the region, whereas east-northeast-directed compression is more indicative of Laramide-style, thick-skinned tectonics (Yonkee & Weil, 2015). More work concerning precise transport directions for Laramide reverse faults in southeastern Arizona may help shed insight into the primary shortening style for the region.

7.3. Fault Reactivation

Laramide basement-cored uplifts commonly have been interpreted to be the result of reactivation of preexisting crustal weaknesses such as old fault systems (Huntoon, 1993; Magnani et al., 2004; Marshak et al., 2000), lithologic contacts (Tonnonson, 1986), and perhaps other features, such as structural fabrics. Where it has been interpreted that reverse faults reactivated older features in the southwestern United States, the older structural features are usually Proterozoic in age, but in some areas they are as young as Early Cretaceous (e.g., Davis, 1979). Commonly cited evidence includes oblique slip on reverse faults that are misaligned with east-northeast Laramide compression (Johnston & Yin, 2001; Neely & Erslev, 2009; Tindall & Davis, 1999), presence of inverted basin stratigraphy (Huntoon, 1993; Lawton, 2000; Marshak et al., 2000), and unfolded rocks below Phanerozoic cover strata (Bump, 2003). Even though some authors (Marshak et al., 2000; Timmons et al., 2001) claim that regional-scale Laramide reverse faults formed through reactivation of regionally extensive Proterozoic fault systems, others claim that reactivation played at most only a local role (e.g., Caine et al., 2010). The latter is indicated by the independent and systematic change in Laramide reverse fault orientations within the Cordillera (Erslev & Koenig, 2009). In addition, Proterozoic structural grains such as foliation, shear zones, and contacts are not thought to play a significant role because they are commonly cut by Laramide structures at high angles (Erslev & Koenig, 2009; Hamilton, 1988). In general, the trends of major Laramide features align with east-northeast-directed compression, indicating that they are either newly formed features or represent reactivation along favorably oriented older faults (Erslev & Koenig, 2009). However, some major uplifts, specifically the oddly-oriented Uinta (Johnston & Yin, 2001) and Kaibab uplifts (Tindall & Davis, 1999), are more compelling examples of reactivation of older faults.

Kinematic indicators suggest that reverse faults within the study area formed through primarily dip-slip displacement. The axes of fault-related folds parallel reverse faults, and slickenlines are perpendicular to the overall fault traces (Figures 1, 2, and 6). The average north-northwest strike of reverse faults is consistent with east-northeast Laramide compression. This alignment, combined with mainly dip-slip displacement, indicates that these faults were newly formed during the Laramide and therefore do not represent reactivated older faults. Furthermore, the basement-cover contact in major reverse faults is clearly folded (Figures 2 and 6), indicating that these structures do not likely involve a preexisting fault (Bump, 2003). The lack of basin inversion also is consistent with this interpretation. Only the east-west segment of the Holy Joe fault may have been controlled by a preexisting structural grain, as the fault here is subparallel to Proterozoic foliation, bedding, and the Pinal Schist-Proterozoic granite contact. Finally, west-southwest Laramide tilting indicates that a large regional-scale north-northwest striking reverse fault is present in the region. This orientation suggests that this major fault did not form through reactivation. These results are consistent with the conclusion of Erslev and Koenig (2009) that Laramide reverse fault orientations were largely controlled by the direction of compression.

Careful analysis of fault geometry and kinematics and stratigraphic evidence for two widely separated stages of movement in time would provide more compelling evidence that a given fault was reactivated. (e.g., Holdsworth et al., 1997). Moreover, the fact that certain faults or segments of faults may have evidence for reactivation does not mean that the majority of faults in a region are the result of reactivation, especially where orientations of faults are easily explained solely by Laramide compression.

8. Conclusions

The northern Galiuro Mountains contain previously unidentified Laramide structures that offer insight into the nature of shortening in southeastern Arizona. Not only are the reverse faults and related folds continuously well exposed over several kilometers along strike, they also have been tilted only $\sim 13^\circ\text{E}$ by Cenozoic extension, making the study area one of the most well-preserved, structurally-intact locales of Laramide deformation in the region. Once restored, major Laramide reverse faults dip moderately to the west and place older rocks on younger rocks. This, combined with related fault-propagation folds, the involvement of basement rocks, and the rigidity of cover rocks, indicates that these faults represent thick-skinned basement-

cored uplifts. The maximum offset documented for the Brandenburg fault is 1.1 km, and for the Holy Joe is 2.0 km; however, these estimates may be greater as fault exposures are limited. Stepwise reconstructions estimate that offset on the Brandenburg and Holy Joe faults, combined with folding caused by regional shortening, resulted in 0.6 and 1.3 km of vertical uplift, respectively, and 1.0 km (17%) and 2.0 km (18%) of horizontal shortening. Forward modeling and Cenozoic erosion surfaces indicate the presence of an extensive region of west-southwesterly Laramide tilting, possibly related to a major moderate-angle reverse fault located east of the study area. These results are consistent with interpretations that southeastern Arizona is dominated by thick-skinned basement-cored uplifts (Davis, 1979; Favorito & Seedorff, 2017). Even though this study fills in a large geographic area of Laramide structural uncertainty for the region, there still remain numerous reverse faults that deserve reexamination and potential reinterpretation, and several reverse faults may have yet to be identified.

Despite limited exposure of structures, available data suggest that reverse faults within the study area do not appear to be related to reactivation of preexisting faults. The best evidence is that basement rocks are folded, and there is no convincing evidence for basin inversion along faults. These north-northwest trending reverse faults and related folds are readily explained as structures that were newly formed during east-northeast-directed Laramide compression. Only the east-west striking segment of the Holy Joe fault appears possibly to have been influenced by a Proterozoic structural grain.

Crosscutting relationships between reverse faults and Laramide rocks bracket the age of shortening locally from 73.9 to 63.0 Ma and indicate that shortening predates local porphyry copper generation. Understanding the geometry, kinematics, magnitude, and timing of Laramide structures in southeastern Arizona and how they relate to porphyry systems may prove advantageous for future copper exploration. In addition, the compression direction derived from local structural data is nearly parallel to plate vectors of Wright et al. (2016), supporting the claim that increased plate coupling during the Laramide led to the formation of thick-skinned deformation (Yonkee & Weil, 2015).

Acknowledgments

All the data used are listed in the references. Financial support for this study was provided by the Lowell Institute for Mineral Resources at the University of Arizona and by the Arizona Geological Society J. Harold Courtright Scholarship. Steve Lingrey is thanked for helpful feedback on structural reconstructions and geologic maps. Mark Barton and Jason Mizer are thanked for their geologic insights. Riley Burkart assisted with field mapping. We appreciate the helpful, generous reviews and assistance from reviewers Stephen Richard and Eric Erslev and Editors Sean Long and John Geissman that contributed to an improved manuscript.

References

- Allmendinger, R. W., Cardozo, N., & Fisher, D. M. (2012). *Structural geology algorithms: Vectors and tensors* Cambridge, England: Cambridge University Press.
- Anderson, J. L. (1989). Proterozoic anorogenic granites of the southwestern United States. In J. P. Jenney & S. J. Reynolds (Eds.), *Geologic evolution of Arizona, Arizona Geological Society Digest* (Vol. 17, pp. 211–238). Tucson, AZ: Arizona Geological Society.
- Armstrong, R. L. (1968). Sevier orogenic belt in Nevada and Utah. *Geological Society of America Bulletin*, 79(4), 429–458. [https://doi.org/10.1130/0016-7606\(1968\)79\[429:SOBINA\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1968)79[429:SOBINA]2.0.CO;2)
- Barton, M. D., Brown, J. G., Haxel, G. B., Hayes, T. S., Jensen, E. P., Johnson, D. A., et al. (2005). Center for Mineral Resources: U. S. Geological Survey-University of Arizona, Department of Geosciences Porphyry Copper Deposit Life Cycles Field Conference, Southeastern Arizona, May 21–22, 2002 (50 pp.). U. S. Geological Survey Scientific Investigations Report 2005–5020.
- Bolm, K. S., Lewis, T., Hirschberg, D. M., Pitts, G. S., & Dickinson, W. R. (2002). Spatial digital database for the geology of the San Pedro River Basin in Cochise, Gila, Graham, Pima, and Pinal Counties, Arizona (36 p.). U.S. Geological Survey Open-File Report 02–393.
- Bright, R. M., Amato, J. M., Denyszyn, S. W., & Ernst, R. E. (2014). U-Pb geochronology of 1.1 Ga diabase in the southwestern United States: Testing models for the origin of a post-Grenville large igneous province. *Lithosphere*, 6(3), 135–156. <https://doi.org/10.1130/L335.1>
- Brown, W. G. (1988). Deformational style of Laramide uplifts in the Wyoming foreland. In C. J. Schmidt & W. J. Perry, Jr. (Eds.), *Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt, Geological Society of America Memoir* (Vol. 171, pp. 1–25). Boulder, CO: Geological Society of America.
- Bump, A. P. (2003). Reactivation, trishear modeling, and folded basement in Laramide uplifts: Implications for the origins of intracontinental faults. *GSA Today*, 13(3), 4–10. [https://doi.org/10.1130/1052-5173\(2003\)013<0004:RTMAFB>2.0.CO;2](https://doi.org/10.1130/1052-5173(2003)013<0004:RTMAFB>2.0.CO;2)
- Bykerk-Kauffman, A. (2008). *Geologic map of the southeastern Santa Catalina Mountains, Pima County, Arizona (Map No. CM-08-A)*. Tucson, AZ: Arizona Geological Survey.
- Bykerk-Kauffman, A., & Janecke, S. U. (1987). Late Cretaceous to early Tertiary ductile deformation: Catalina-Rincon metamorphic core complex, southeastern Arizona. *Geology*, 15(5), 462–465. [https://doi.org/10.1130/0091-7613\(1987\)15<462:LCETD>2.0.CO;2](https://doi.org/10.1130/0091-7613(1987)15<462:LCETD>2.0.CO;2)
- Caine, J. S., Ridley, J. R., & Wessel, Z. R. (2010). To reactivate or not to reactivate—nature and varied behavior of structural inheritance in the Proterozoic basement of the eastern Colorado Mineral Belt over 1.7 billion years of Earth history. In L. A. Morgan & S. L. Quane (Eds.), *Through the generations: Geologic and anthropogenic field excursions in the Rocky Mountains from modern to ancient, Geological Society of America Field Guide* (Vol. 18, pp. 119–140). Boulder, CO: Geological Society of America. [https://doi.org/10.1130/2010.0018\(06\)](https://doi.org/10.1130/2010.0018(06))
- Chapman, T. J., & Meneilly, A. W. (1991). The displacement patterns associated with a reverse-reactivated, normal growth fault. In A. M. Roberts, G. Yielding, & B. Freeman (Eds.), *The geometry of normal faults, Geological Society Special Publication* (Vol. 56, pp. 183–191). London, UK: Geological Society of London.
- Coney, P. J. (1976). Plate tectonics and the Laramide orogeny. In L. A. Woodward & S. A. Northrop (Eds.), *Tectonics and mineral resources of southwestern North America: A volume honoring V. C. Kelley, New Mexico Geological Society Special Publication* (Vol. 6, pp. 5–10). Socorro, NM: New Mexico Geological Society.
- Coney, P. J., & Reynolds, S. J. (1977). Cordilleran Benioff zones. *Nature*, 270(5636), 403–406. <https://doi.org/10.1038/270403a0>
- Coney, P. J., & Harms, T. A. (1984). Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression. *Geology*, 12(9), 550–554. [https://doi.org/10.1130/0091-7613\(1984\)12<550:CMCCCE>2.0.CO;2](https://doi.org/10.1130/0091-7613(1984)12<550:CMCCCE>2.0.CO;2)

- Conway, C. M., & Silver, L. T. (1989). Early Proterozoic rocks (1710–1615 Ma) in central to southeastern Arizona. In J. P. Jenney & S. J. Reynolds (Eds.), *Geologic evolution of Arizona, Arizona Geological Society Digest* (Vol. 17, pp. 165–186). Tucson, AZ: Arizona Geological Society.
- Craddock, J. P., Kopania, A. A., & Wiltschko, D. V. (1988). Interaction between the northern Idaho-Wyoming thrust belt and bounding basement blocks, central western Wyoming. In C. J. Schmidt, & W. J. Perry, Jr. (Eds.), *Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt, Geological Society of America Memoir* (Vol. 171, pp. 333–351). Boulder, CO: Geological Society of America. <https://doi.org/10.1130/MEM171-p333>
- Creasey, S. C., Jinks, J. E., Williams, F. E., & Meeves, H. C. (1981). *Mineral resources of the Galiuro wilderness and contiguous further planning areas, Arizona, U.S. Geological Survey Bulletin* (Vol. 1490). Reston, VA: U.S. Geological Survey.
- Davis, G. H. (1979). Laramide folding and faulting in southeastern Arizona. *American Journal of Science*, 279(5), 543–569. <https://doi.org/10.2475/ajs.279.5.543>
- Davis, G. H., & Bump, A. P. (2009). Structural geologic evolution of the Colorado Plateau. In S. M. Kay, V. A. Ramos, & W. R. Dickinson (Eds.), *Backbone of the Americas: Shallow subduction, plateau uplift, and ridge and terrane collision, Geological Society of America Memoir* (Vol. 204, pp. 99–124). Boulder, CO: Geological Society of America.
- Davis, G. H., Showalter, S. R., Benson, G. S., McCalmont, L. S., & Crop, F. W. III (1981). Guide to the geology of the Salt River Canyon region, Arizona. In C. Stone & J. P. Jenney (Eds.), *Arizona Geological Society Digest* (Vol. 14, pp. 48–97). Tucson, AZ: Arizona Geological Society.
- DeCelles, P. G. (2004). Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. *American Journal of Science*, 304(2), 105–168. <https://doi.org/10.2475/ajs.304.2.105>
- DeCelles, P. G., & Coogan, J. C. (2006). Regional structure and kinematic history of the Sevier fold-and-thrust belt, Central Utah. *Geological Society of America Bulletin*, 118(7–8), 841–864. <https://doi.org/10.1130/B25759.1>
- Dickinson, W. R. (1991). *Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona, Geological Society of America Special Paper* (Vol. 264). Boulder, CO: Geological Society of America.
- Dickinson, W. R. (1998). *Facies map of post-mid-Miocene Quiburis Formation, San Pedro trough, Pinal, Pima, Gila, Graham, and Cochise Counties, Arizona (Map No. CM-98-A)*. Tucson, AZ: Arizona Geological Survey.
- Dickinson, W. R. (2002). Depositional facies of the Quiburis Formation, basin fill of the San Pedro trough, southeastern Arizona Basin and Range province. In R. G. Reynolds & R. M. Flores (Eds.), *Cenozoic systems of the Rocky Mountain region* (pp. 1–25). Denver, CO: The Rocky Mountain Section SEPM (Society for Sedimentary Geology).
- Dickinson, W. R., & Snyder, W. S. (1978). Plate tectonics of the Laramide orogeny. In V. Matthews (Ed.), *Laramide folding associated with block faulting in the western United States, GSA Memoir* (Vol. 151, pp. 355–366). Boulder, CO: Geological Society of America.
- Drewes, H. D. (1996). Geology of Coronado National Forest. In E. A. du Bray (Ed.), *Mineral resource potential and geology of Coronado National Forest, southeastern Arizona and southwestern New Mexico, U. S. Geological Survey Bulletin* (Vol. 2083, pp. B17–B41). Washington, DC: U.S. Geological Survey.
- Drewes, H. D., & Thorman, C. H. (1978). Major geologic structures between Lordsburg, New Mexico, and Tucson, Arizona. In J. F. Callender, J. Wilt, & R. E. Clemons (Eds.), *Land of Cochise: New Mexico Geological Society Twenty-Ninth Annual Fall Field Conference Guidebook* (pp. 291–295). Socorro, NM: New Mexico Geological Society.
- Erslev, E. A. (1986). Basement balancing of Rocky Mountain foreland uplifts. *Geology*, 14(3), 259–262. [https://doi.org/10.1130/0091-7613\(1986\)14<259:BBORMF>2.0.CO;2](https://doi.org/10.1130/0091-7613(1986)14<259:BBORMF>2.0.CO;2)
- Erslev, E. A. (1991). Trishear fault-propagation folding. *Geology*, 19(6), 617–620. [https://doi.org/10.1130/0091-7613\(1991\)019<0617:TFPF>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<0617:TFPF>2.3.CO;2)
- Erslev, E. A. (1993). Thrusts, backthrusts and detachment of Laramide foreland arches. In C. J. Schmidt, R. Chase, & E. A. Erslev (Eds.), *Laramide basement deformation in the Rocky Mountain foreland of the western United States, GSA Special Paper* (Vol. 280, pp. 339–358). Boulder, CO: Geological Society of America.
- Erslev, E. A. (2005). 2D Laramide geometries and kinematics of the Rocky Mountains, western U.S.A. In K. E. Karlstrom & G. R. Keller (Eds.), *The Rocky Mountain region: An evolving lithosphere tectonics, geochemistry, and geophysics, American Geophysical Union Geophysical Monograph Series* (Vol. 154, pp. 7–20). Washington, DC: American Geophysical Union.
- Erslev, E. A., & Koenig, N. V. (2009). Three-dimensional kinematics of Laramide, basement-involved Rocky Mountain deformation, USA: Insights from minor faults and GIS-enhanced structure maps. In S. M. Kay, V. A. Ramos, & W. R. Dickinson (Eds.), *Backbone of the Americas: Shallow subduction, plateau uplift, and ridge and terrane collision, GSA Memoir* (Vol. 204, pp. 125–150). Boulder, CO: Geological Society of America.
- Favorito, D. A., & Seedorff, E. (2017). Characterization and reconstruction of Laramide shortening and superimposed Cenozoic extension, Romero Wash–Tocolote Ranch area, southeastern Arizona. *Geosphere*, 13(2), 577–607. <https://doi.org/10.1130/GES01381.1>
- Force, E. R. (1997). *Geology and mineral resources of the Santa Catalina Mountains, southeastern Arizona: A cross-sectional approach, Monographs in Mineral Resource Science* (Vol. 1). Tucson, AZ: Center for Mineral Resources.
- Fornash, K. F., Patchett, P. J., Gehrels, G. E., & Spencer, J. E. (2013). Evolution of granitoids in the Catalina metamorphic core complex, southeastern Arizona: U–Pb, Nd, and Hf isotopic constraints. *Contributions to Mineralogy and Petrology*, 165(6), 1295–1310. <https://doi.org/10.1007/s00410-013-0859-4>
- Gawthorpe, R. L., & Leeder, M. R. (2000). Tectono-sedimentary evolution of active extensional basins. *Basin Research*, 12(3–4), 195–218. <https://doi.org/10.1111/j.1365-2117.2000.00121.x>
- Gehrels, G. E., & Smith, C. H. (1991). U–Pb geochronologic constraints on the age of thrusting, crustal extension, and peraluminous plutonism in the Little Rincon Mountains, southern Arizona. *Geology*, 19(3), 238–241. [https://doi.org/10.1130/0091-7613\(1991\)019<0238:UPGCOT>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<0238:UPGCOT>2.3.CO;2)
- Gootee, B. F., Spencer, J. E., Ferguson, C. A., Richard, S. M., Cook, J. P., & MacFarlane, B. J. (2009). *Geologic map of the Clark Ranch 7 1/2' quadrangle and the west half of the Rhodes Peak 7 1/2' quadrangle, Pinal and Graham Counties, Arizona (Map No. DGM-68)*. Tucson, AZ: Arizona Geological Survey.
- Granger, H. C., & Raup, R. B. (1969). *Geology of uranium deposits in the dripping spring quartzite Gila County, Arizona, U. S. Geological Survey Professional Paper* (Vol. 595). Reston, VA: U.S. Geological Survey.
- Haenggi, W. T. (2002). Tectonic history of the Chihuahua trough, Mexico and adjacent USA, Part II: Mesozoic and Cenozoic. *Boletín de la Sociedad Geológica Mexicana*, 55(1), 38–94. <https://doi.org/10.18268/BSGM2002v55n1a4>
- Hall, M. K., & Chase, C. G. (1989). Uplift, unbuckling, and collapse: Flexural history and isostasy of the Wind River Range and Granite Mountains, Wyoming. *Journal of Geophysical Research*, 94, 17,581–17,593. <https://doi.org/10.1029/JB094iB12p17581>
- Hamilton, W. B. (1988). Laramide crustal shortening. In C. J. Schmidt & W. J. Perry, Jr. (Eds.), *Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt, GSA Memoir* (Vol. 171, pp. 27–39). Boulder, CO: Geological Society of America.

- Harland, W. B. (1971). Tectonic transpression in Caledonian Spitsbergen. *Geological Magazine*, 108(01), 27–41. <https://doi.org/10.1017/S0016756800050937>
- Haxel, G. B., Tosdal, R. M., May, D. J., & Wright, J. E. (1984). Latest Cretaceous and early Tertiary orogenesis in south-central Arizona: Thrust faulting, regional metamorphism, and granitic plutonism. *Geological Society of America Bulletin*, 95(6), 631–653. [https://doi.org/10.1130/0016-7606\(1984\)95<631:LCAETO>2.0.CO;2](https://doi.org/10.1130/0016-7606(1984)95<631:LCAETO>2.0.CO;2)
- Hayes, P. T. (1970). *Cretaceous paleogeography of southeastern Arizona and adjacent areas*, U. S. Geological Survey Professional Paper (Vol. 658-B). Reston VA, U.S. Geological Survey.
- Holdsworth, R. E., Butler, C. A., & Roberts, A. M. (1997). The recognition of reactivation during continental deformation. *Journal of the Geological Society*, 154(1), 73–78. <https://doi.org/10.1144/gsjgs.154.1.0073>
- Howard, K. A. (1991). Intrusion of horizontal dikes: Tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States. *Journal of Geophysical Research*, 96, 12,461–12,478. <https://doi.org/10.1029/91JB00112>
- Huntoon, P. W. (1993). Influence of inherited Precambrian basement structure on the localization and form of Laramide monoclines, Grand Canyon, Arizona. In C. J. Schmidt, R. Chase, & E. A. Erslev (Eds.), *Laramide basement deformation in the Rocky Mountain foreland of the western United States*, GSA Special Paper (Vol. 280, pp. 243–256). Boulder, CO: Geological Society of America.
- Jacobson, C. E., Hourigan, J. K., Haxel, G. B., & Grove, M. (2017). Extreme latest Cretaceous–Paleogene low-angle subduction: Zircon ages from Orocopia Schist at Cemetery Ridge, southwestern Arizona, USA. *Geology*, 45(10), 951–954. <https://doi.org/10.1130/G39278.1>
- Jacques-Ayala, C., Barth, A. P., Wooden, J. L., & Jacobson, C. E. (2009). Provenance and U–Pb geochronology of the Upper Cretaceous El Chanate Group, northwest Sonora, Mexico, and its tectonic significance. *International Geology Review*, 51(9–11), 1051–1077. <https://doi.org/10.1080/00206810902945066>
- Johnston, R. E., & Yin, A. (2001). Kinematics of the Uinta fault system (southern Wyoming and northern Utah) during the Laramide orogeny. *International Geology Review*, 43(1), 52–68.
- Keith, S. B. (1983). *Results of mapping project near Ray, Pinal County, Arizona*, Arizona Bureau of Mines Open File Report (Vol. 83–14). Tucson, AZ: State of Arizona Bureau of Geology and Mineral Technology.
- Kellogg, K. S., Bryant, B., & Reed, J. C. Jr. (2004). The Colorado Front Range—Anatomy of a Laramide uplift. In E. P. Nelson & E. A. Erslev (Eds.), *Field trips in the southern Rocky Mountains, USA*, GSA Field Guide (Vol. 5, pp. 89–108). Boulder, CO: Geological Society of America. <https://doi.org/10.1130/0-8137-0005-1.89>
- Krantz, R. W. (1989). Laramide structures of Arizona. In J. P. Jenney & S. J. Reynolds (Eds.), *Geologic evolution of Arizona*, Arizona Geological Society Digest (Vol. 17, pp. 463–483). Tucson, AZ: Arizona Geological Society.
- Krieger, M. H. (1968a). *Geologic map of the Saddle Mountain quadrangle, Pinal County, Arizona (Map No. GQ-671)*. Reston, VA: U.S. Geological Survey.
- Krieger, M. H. (1968b). *Geologic map of the Hole Joe Peak quadrangle, Pinal County, Arizona (Map No. GQ-669)*. Reston, VA: U.S. Geological Survey.
- Krieger, M. H. (1968c). *Geologic map of the Brandenburg Mountain quadrangle, Pinal County, Arizona (Map No. GQ-668)*. Reston, VA: U.S. Geological Survey.
- Lawton, T. F. (2000). Inversion of Late Jurassic–Early Cretaceous extensional faults of the Bisbee basin, southeastern Arizona and southwestern New Mexico. In T. F. Lawton, N. J. McMillan, & V. T. McLemore (Eds.), *Southwest Passage: A trip through the Phanerozoic: New Mexico Geological Society Fifty-First Annual Fall Field Conference Guidebook* (pp. 95–102). Socorro, NM: New Mexico Geological Society.
- Lawton, T. F., & Olmstead, G. A. (1995). Stratigraphy and structure of the lower part of the Bisbee Group, northeastern Chiricahua Mountains, Arizona, USA. In C. Jacques-Ayala, C. M. González-León, & J. Roldán-Quintana (Eds.), *Studies on the Mesozoic of Sonora and adjacent areas*, GSA Special Paper (Vol. 301, pp. 21–39). Boulder, CO: Geological Society of America.
- Leveille, R. A., & Stegen, R. J. (2012). The southwestern North America porphyry copper province. In J. W. Hedenquist, O. M. Harris, & F. Camus (Eds.), *Geology and genesis of major copper deposits and districts of the world: A tribute to Richard H. Sillitoe*, Society of Economic Geologists Special Publication (Vol. 16, pp. 361–401). Littleton, CO: Society of Economic Geologists.
- Magnani, M. B., Levander, A., Erslev, E. A., Bolay-Koenig, N., & Karlstrom, K. E. (2004). Listric thrust faulting in the Laramide front of north-central New Mexico guided by Precambrian basement structures. In K. E. Karlstrom & G. R. Keller (Eds.), *The Rocky Mountain Region—An evolving lithosphere; Tectonics, geochemistry, and geophysics*, American Geophysical Union Geophysical Monograph Series (Vol. 154, pp. 239–252). Washington, DC: American Geophysical Union.
- Maher, D. J. (2008). *Reconstruction of middle Tertiary extension and Laramide porphyry copper systems, east-central Arizona* (Doctoral dissertation). Tucson, AZ: University of Arizona.
- Marshak, S., Karlstrom, K., & Timmons, J. M. (2000). Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States. *Geology*, 28(8), 735–738. [https://doi.org/10.1130/0091-7613\(2000\)28<735:IOPEFA>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<735:IOPEFA>2.0.CO;2)
- McQuarrie, N., & Chase, C. G. (2000). Raising the Colorado plateau. *Geology*, 28(1), 91–94. [https://doi.org/10.1130/0091-7613\(2000\)028<0091:RTCP>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)028<0091:RTCP>2.0.CO;2)
- Meijer, A. (2014). The Pinal Schist of southern Arizona: A Paleoproterozoic forearc complex with evidence of spreading ridge–trench interaction at ca. 1.65 Ga and a Proterozoic arc obduction event. *Geological Society of America Bulletin*, 126(9–10), 1145–1163. <https://doi.org/10.1130/B31002.1>
- Mizer, J. D. (2018). *Early Laramide magmatism in southern Arizona; U–Pb geochronology of key igneous units and implications for the timing of regional porphyry copper mineralization* (Doctoral dissertation). Tucson, AZ: University of Arizona.
- Neely, T. G., & Erslev, E. A. (2009). The interplay of fold mechanisms and basement weaknesses at the transition between Laramide basement-involved arches, north-central Wyoming, USA. *Journal of Structural Geology*, 31(9), 1012–1027. <https://doi.org/10.1016/j.jsg.2009.03.008>
- Nickerson, P. A., Barton, M. D., & Seedorff, E. (2010). Characterization and reconstruction of multiple copper-bearing hydrothermal systems in the Tea Cup porphyry system, Pinal County, Arizona. In R. J. Goldfarb, E. E. Marsh, & T. Monecke (Eds.), *The challenge of finding new mineral resources: Global metallogeny, innovative exploration, and new discoveries*, Society of Economic Geologists Special Publication (Vol. 15, pp. 299–316). Littleton, CO: Society of Economic Geologists.
- Richard, S. M., & Spencer, J. E. (1998a). *Compilation geologic map of the Ray-Superior area, central Arizona*, Arizona Geological Survey Open-File Report (Vol. 98–13). Tucson, AZ: Arizona Geological Survey.
- Richard, S. M., & Spencer, J. E. (1998b). Laramide structures in the Ray-Globe area, central Arizona (abs.). *Geological Society of America Abstracts with Programs*, 30(6), A35.

- Riggs, N. R., Reynolds, S. J., Lindner, P. J., Howell, E. R., Barth, A. P., Parker, W. G., & Walker, J. D. (2013). The Early Mesozoic Cordilleran arc and Late Triassic paleotopography: The detrital record in Upper Triassic sedimentary successions on and off the Colorado Plateau. *Geosphere*, 9(3), 602–613. <https://doi.org/10.1130/GES00860.1>
- Sandberg, S. A., & Butler, R. F. (1985). Paleomagnetic fold test evidence for Laramide age of monoclinical folding, Salt River Canyon, Arizona. *Earth and Planetary Science Letters*, 73(1), 140–146. [https://doi.org/10.1016/0012-821X\(85\)90041-X](https://doi.org/10.1016/0012-821X(85)90041-X)
- Schmidt, C. J., O'Neill, J. M., & Brandon, W. C. (1988). Influence of Rocky Mountain foreland uplifts on the development of the frontal fold and thrust belt, southwestern Montana. In C. J. Schmidt & W. J. Perry, Jr. (Eds.), *Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt*, *Geological Society of America Memoir* (Vol. 171, pp. 171–201). Boulder, CO: Geological Society of America. <https://doi.org/10.1130/MEM171-p171>
- Seager, W. R. (2004). Laramide (Late Cretaceous–Eocene) tectonics of southwestern New Mexico. In G. H. Mack & K. A. Giles (Eds.), *The geology of New Mexico: A geologic history*, *New Mexico Geological Society Special Publication* (Vol. 11, pp. 183–202). Socorro, NM: New Mexico Geological Society.
- Seedorff, E., Barton, M. D., Gehrels, G., Johnson, D. A., Maher, D. J., Stavast, W. J. A., & Flesch, E. (2005). Implications of new U–Pb dates from porphyry copper-related plutons in the Superior-Globe-Ray-Christmas area, Arizona. *Geological Society of America Abstracts with Programs*, 37(7), 164.
- Sigloch, K., & Mihalynuk, M. G. (2017). Mantle and geological evidence for a Late Jurassic–Cretaceous suture spanning North America. *Geological Society of America Bulletin*, 129(11/12), 1489–1520.
- Simons, F. S. (1964). *Klondike Quadrangle, Graham and Pinal Counties, Arizona*, U. S. Geological Survey Professional Paper (Vol. 461). Reston, VA: U.S. Geological Survey.
- Sonder, L. J., England, P. C., Wernicke, B. P., & Christiansen, R. L. (1987). A physical model for Cenozoic extension of western North America. In M. P. Coward, J. F. Dewey, & P. L. Hancock (Eds.), *Continental extensional tectonics*, *Geological Society Special Publication* (Vol. 28, pp. 187–201). London, England: Geological Society of London.
- Spencer, J. E., Cook, J. P., Lingrey, S. H., Richard, S. M., & Guynn, J. H. (2009). *Geologic map of the Wildhorse Mountain 7½' quadrangle, Cochise County, Arizona* (Map No. DGM-62). Tucson, AZ: Arizona Geological Survey.
- Spencer, J. E., Gootee, B. F., Richard, S. M., & Cook, J. P. (2009). *Geologic map of the Mammoth 7½' quadrangle, Pinal County, Arizona* (Map No. DGM-67). Tucson, AZ: Arizona Geological Survey.
- Spencer, J. E., Lingrey, S. H., Johnson, B. J., Cook, J. P., & Richard, S. M. (2011). *Geologic map of the Happy Valley 7½' quadrangle, Cochise and Pima Counties, Arizona* (Map No. DGM-89). Tucson, AZ: Arizona Geological Survey.
- Spencer, J. E., & Reynolds, S. J. (1990). Relationship between Mesozoic and Cenozoic tectonic features in west central Arizona and adjacent southeastern California. *Journal of Geophysical Research*, 95, 539–555. <https://doi.org/10.1029/JB095iB01p00539>
- Stewart, J. H. (1975). Regional tilt patterns of late Cenozoic basin-range fault blocks, western United States. *Geological Society of America Bulletin*, 91(8), 460–464. [https://doi.org/10.1130/0016-7606\(1980\)91<460:RTPOLC>2.0.CO;2](https://doi.org/10.1130/0016-7606(1980)91<460:RTPOLC>2.0.CO;2)
- Stone, D. S. (2002). Morphology of the Casper Mountain uplift and related, subsidiary structures, central Wyoming: Implications for Laramide kinematics, dynamics, and crustal inheritance. *American Association of Petroleum Geologists Bulletin*, 86(8), 1417–1440. <https://doi.org/10.1306/61EEDCBA-173E-11D7-8645000102C1865D>
- Thompson, G. A. (1960). Problem of late Cenozoic structure of the basin ranges. *Proceedings of the 21st International Geological Congress*, 18, 62–68.
- Timmons, J. M., Karlstrom, K. E., Dehler, C. M., Geissman, J. W., & Heizler, M. T. (2001). Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest-and north-trending tectonic grains in the southwestern United States. *Geological Society of America Bulletin*, 113(10), 0163–0181. [https://doi.org/10.1130/0016-7606\(2001\)113<0163:PMCAE>2.0.CO;2](https://doi.org/10.1130/0016-7606(2001)113<0163:PMCAE>2.0.CO;2)
- Tindall, S. E., & Davis, G. H. (1999). Monocline development by oblique-slip fault-propagation folding: The East Kaibab monocline, Colorado Plateau, Utah. *Journal of Structural Geology*, 21(10), 1303–1320. [https://doi.org/10.1016/S0191-8141\(99\)00089-9](https://doi.org/10.1016/S0191-8141(99)00089-9)
- Titley, S. R. (1982). Geologic setting of porphyry copper deposits, southwestern Arizona. In S. R. Titley (Ed.), *Advances in geology of the porphyry copper deposits, southwestern North America* (pp. 37–58). Tucson, AZ: University of Arizona Press.
- Tonnson, J. J. (1986). Influence of tectonic terranes adjacent to the Precambrian Wyoming Province on Phanerozoic stratigraphy in the Rocky Mountain region. In J. A. Peterson (Ed.), *Paleotectonics and sedimentation: American Association of Petroleum Geologists Memoir* (Vol. 41, pp. 21–40). Tulsa, OK: American Association of Petroleum Geologists.
- Tosdal, R. M. (1990). Constraints on the tectonics of the Mule Mountains thrust system, southeast California and southwest Arizona. *Journal of Geophysical Research*, 95, 20,025–20,048. <https://doi.org/10.1029/JB095iB12p20025>
- Waldrup, W. R. (2008). *Late Cretaceous thin-skinned shortening in southern Arizona* (Master's thesis). Tucson, AZ: University of Arizona.
- Weil, A. B., & Yonkee, W. A. (2012). Layer-parallel shortening across the Sevier fold-thrust belt and Laramide foreland of Wyoming: Spatial and temporal evolution of a complex geodynamic system. *Earth and Planetary Science Letters*, 357–358, 405–420. <https://doi.org/10.1016/j.epsl.2012.09.021>
- Willden, R. (1964). *Geology of the Christmas quadrangle, Gila and Pinal Counties, Arizona*, U.S. Geological Survey Bulletin (Vol. 1161-E). Reston, VA: U.S. Geological Survey.
- Wright, N. M., Seton, M., Williams, S. E., & Mueller, R. D. (2016). The Late Cretaceous to recent tectonic history of the Pacific Ocean basin. *Earth-Science Reviews*, 154, 138–173. <https://doi.org/10.1016/j.earscirev.2015.11.015>
- Wruke, C. T. (1989). The middle Proterozoic apache group, Troy quartzite, and associated diabase of Arizona. In J. P. Jenney & S. J. Reynolds (Eds.), *Geologic evolution of Arizona, Arizona Geological Society Digest* (Vol. 17, pp. 239–258). Tucson, AZ: Arizona Geological Society.
- Wruke, C. T., Bromfield, C. S., Simons, F. S., Greene, R. C., Houser, B. B., Miller, R. J., & Gray, F. (2004). *Geologic map of the San Carlos Indian Reservation, Arizona* (Map No. I-2780). Reston, VA: U.S. Geological Survey.
- Yonkee, W. A., & Weil, A. B. (2015). Tectonic evolution of the Sevier and Laramide belts within the North American Cordillera orogenic system. *Earth-Science Reviews*, 150, 531–593. <https://doi.org/10.1016/j.earscirev.2015.08.001>
- Yonkee, W. A., & Weil, A. B. (2017). Structural evolution of an en echelon fold system within the Laramide foreland, central Wyoming: From early layer-parallel shortening to fault propagation and fold linkage. *Lithosphere*, 9(5), 828–850. <https://doi.org/10.1130/L622.1>