Cenozoic structural evolution of the Catalina metamorphic core complex and reassembly of Laramide reverse faults, southeastern Arizona, USA

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ABSTRACT

This study investigates the Late Cretaceous through mid-Cenozoic structural evolution of the Catalina core complex and adjacent areas by integrating new geologic mapping, structural analysis, and geochronologic data. Multiple generations of normal faults associated with mid-Cenozoic extensional deformation cut across older reverse faults that formed during the Laramide orogeny. A proposed stepwise, cross-sectional structural reconstruction of mid-Cenozoic extension satisfies surface geologic and reflection seismologic constraints, balances, and indicates that detachment faults played no role in the formation of the core complex and Laramide reverse faults represent major thick-skinned structures.

The orientations of the oldest synextensional strata, pre-shortening normal faults, and pre-Cenozoic strata unaffected by Laramide compression indicate that rocks across most of the study area were steeply tilted east since the mid-Cenozoic. Crosscutting relations between faults and synextensional strata reveal that sequential generations of primarily down-to-the-west, mid-Cenozoic normal faults produced the net eastward tilting of ~60°. Restorations of the balanced cross section demonstrate that Cenozoic normal faults were originally steeply dipping and resulted in an estimated 59 km or 120% extension across the study area. Representative segments of those gently dipping faults are exposed at shallow, intermediate (~5–10 km), and deep structural levels (~10–20 km), as distinguished by the nature of deformation in the exhumed footwall, and these segments all restore to high angles, which indicates that they were not listric. Offset on major normal faults does not exceed 11 km, as opposed to tens of kilometers of offset commonly ascribed to “detachment” faults in most interpretations of this and other Cordilleran metamorphic core complexes. Once mid-Cenozoic extension is restored, reverse faults with moderate to steep original dips bound basement-cored uplifts that exhibit significant involvement of basement rocks. Net vertical uplift from all reverse faults is estimated to be 9.4 km, and estimated total shortening was 12 km or 20%. This magnitude of uplift is consistent with the vast exposure of metamorphosed and foliated cover strata in the northeastern and eastern Santa Catalina and Rincon Mountains and with the distribution of subsequently dismembered mid-Cenozoic erosion surfaces along the San Pedro Valley. New and existing geochronologic data constrain the timing of offset on local reverse faults to ca. 75–54 Ma.

The thick-skinned style of Laramide shortening in the area is consistent with the structure of surrounding locales. Because detachment faults do not appear to have resulted in the formation of the Catalina core complex, other extensional systems that have been interpreted within the context of detachments may require further structural analyses including identification of crosscutting relations between generations of normal faults and palinspastic reconstructions.

INTRODUCTION

The Laramide orogeny (ca. 80–50 Ma) of the North American Cordillera resulted in both thick- and thin-skinned shortening (e.g., Erslev, 1986; Pfiffner, 2017). Both structural styles were largely limited to distinct geographic regions (DeCelles, 2004); thin-skinned deformation developed in the Sevier fold and thrust belt (Armstrong, 1968; DeCelles and Coogan, 2006) and thick-skinned deformation developed in the Laramide province (Brown, 1988; Hamilton, 1988; Erslev and Koenig, 2009); however, some overlap in structural style has been documented (Craddock et al., 1988; Schmidt et al., 1988; Younger and Weil, 2015). The style and magnitude of shortening during the Laramide orogeny in southeastern Arizona, USA, is unclear (DeCelles, 2004) primarily due to the effects of superimposed mid-Cenozoic extension that dismembered, tilted, and concealed older reverse faults (Dickinson, 1991). Authors have interpreted both thick- and thin-skinned Laramide shortening in the region (e.g., Davis, 1979; Barton et al., 2005; Waldrip, 2008; Arca et al., 2010; Spencer et al., 2019), which suggests that the structural style in southeastern Arizona may be inhomogeneous (Fig. 1). However, recent studies in highly extended locales have shown that previously identified thin-skinned thrusts are basement-cored uplifts with moderate-angle reverse faults (Favorito and Seedorff, 2012, 2020), which is consistent with the geology of nearby areas that have undergone minor extension (Davis, 1979; Favorito and Seedorff, 2018). This
suggests that interpretations of thin-skinned thrusts elsewhere in the region (Fig. 1) also may be better interpreted as basement-cored uplifts once Cenozoic extensional deformation is restored.

In addition to contrasting shortening styles, authors have proposed contrasting styles of extensional deformation (cf. Wernicke and Burchfiel, 1982) throughout southeastern Arizona to explain highly extended areas (i.e., 100%–300% extension), all of which contain normal faults that presently dip at low angles. In several areas along the San Pedro Valley, authors have interpreted extension in terms of domino-style block faulting (Barton et al., 2005; Nickerson et al., 2010; Fajardo, 2015; Favorito and Seedorff, 2017; Favorito and Seedorff, 2020). In this interpretation, multiple generations of originally high-angle normal faults have rotated to lower angles and progressively tilted and extended blocks of the upper crust (e.g., Proffett, 1977; Gans and Miller, 1983; Mandl, 1987; Richardson et al., 2019; Seedorff et al., 2019a). Conversely, variations on low-angle detachment and rolling hinge models (e.g., Wernicke, 1981; Buck, 1988; Wernicke and Axen, 1988; Whitney et al., 2013) typically have been used in recent decades to explain intense crustal extension and related ductile tectonic fabrics in the Santa Catalina and Rincon Mountains (Dickinson, 1991;
Though not exposed in the study area, Jurassic strata consist of redbeds and shallow crystalline basement were intruded by dikes and sills at ca. 1.1 Ga (Bright et al., 2014). Paleozoic strata include carbonate and lesser siliciclastic rocks (Bryant, 1968). Within the study area, the combined Proterozoic-Paleozoic cover sequence measures ~1.8 km thick, and the majority of the section consists of Paleozoic carbonate rocks. Though not exposed in the study area, Jurassic strata consist of red beds and volcanic rocks (Beatty, 1987). From the Late Jurassic to mid-Cretaceous, the region underwent intracontinental rifting to form the Bisbee basin (Bilodeau, 1982; Dickinson et al., 1983; Dickinson and Lawton, 2001). Strata of the Bisbee Group consist of basal Glance Conglomerate overlain by mainly clastic strata. The thickness of these strata varies regionally according to proximity to normal fault-bounded depocenters, and the greatest observed thickness is ~3 km. Limited data suggest a local thickness of at least 1 km (Lingrey, 1982; Dickinson, 1991).

The Laramide orogeny involved widespread contractional deformation during a broad inboard sweep of magmatism, which coincided with the building of a new arc, the Laramide arc, following termination of the Sierra Nevada arc (Coney, 1976; Krantz, 1989; Barton, 1996; Seedorff et al., 2019b). Geologic features are typically attributed to northeast-directed, flat-slab subduction under the Cordillera (e.g., Dickinson and Snyder, 1978; Jacobson et al., 2017; Chapman et al., 2020); however, an alternate model involving island arc accretion over a west-dipping subduction zone has also been proposed (e.g., Sigloch and Mihalynuk, 2017; Hildebrand, 2019). The start of the Laramide arc in the study area is marked by the intrusion of intermediate magmas with associated extrusive equivalents such as the Muleshoe Volcanics at ca. 75 Ma (Goodlin and Mark, 1987; Spencer et al., 2015), which locally measure ~1 km thick. These volcanic rocks are commonly folded, which suggests that regional shortening began after ca. 75 Ma. Synorogenic sedimentary rocks largely consist of conglomerates that were presumably deposited in the footwalls of reverse faults (Dickinson, 1991), and the thickest local exposures measure ~2 km. Intermediate to felsic intrusions were emplaced during the middle of the Laramide orogeny (75–60 Ma), and several resulted in the formation of large porphyry copper deposits in the surrounding region (Titley, 1982; Leveille and Stegen, 2012; Seedorff et al., 2019b; Favorito and Seedorff, 2020). The end of the Laramide orogeny is marked by the intrusion of two-mica granites of the Wilderness suite, dated at ca. 57–46 Ma, which primarily crop out in the Catalina-Rincon area (Keith et al., 1980; Fornash et al., 2013). The mid- to late Cenozoic was characterized by intermediate to felsic magmatism and significant crustal extension (Dickinson, 1991). Proposed tectonic triggers include collapse of a topographically elevated region no longer under compression (Coney and Harms, 1984; Sonder et al., 1987) that was facilitated by heat of the upwelling asthenosphere as a result of slab steepening and subsequent foundering (e.g., Coney and Reynolds, 1977; Dickinson, 2002). In some areas of high extension, ductile shear fabrics were exhumed in the footwall of regional normal fault systems, which created metamorphic core complexes. The Catalina core complex is a type locality of such features (Coney, 1980). Synextensional strata were deposited in half-grabens created by normal faults and typically display fanning-upward dips, which indicate tilting during fault offset (Dickinson, 1991; Gawthorpe and Leeder, 2000). Within the Catalina-Rincon area, synextensional units are divided according to the geography of specific basins, age, and composition (Dickinson, 1991). These strata consist largely of siliciclastic sedimentary rocks and lesser felsic to intermediate volcanic rocks that range in age from early Oligocene to late Pliocene. Concurrent with extension, intermediate to felsic plutons were intruded, such as the Catalina and Tortolita Mountains Granites, both of which crystallized at ca. 26–25 Ma, the latter of which was overprinted by extensional shear fabrics (Banks, 1980; Ferguson et al., 2003; Spell et al., 2003; Fornash et al., 2013; Ducea et al., 2020). By the late Miocene, the majority of extension had occurred, and basins had accumulated gently dipping to flat-lying sediment (Scarborough and Peirce, 1978).

**Structural Framework**

**Bisbee Rift**

The Bisbee rift in southeastern Arizona primarily involved west-northwest–striking and northwest-striking normal faults (Titley, 1976; Bilodeau et al., 1987; Dickinson, 1991). Only one such normal fault has been potentially identified in the general study area within the northwestern Santa Catalina Mountains.
by Janecke (1987). Strata of the Bisbee Group are not present north of the Santa Catalina Mountains, which suggests that the east-west-trending structural edge of the Bisbee basin was within or just north of the Santa Catalina Mountains (Dickinson and Lawton, 2001).

Laramide Shortening

Several Laramide reverse faults have been documented within the study area (Fig. 1), most of which have been interpreted as originally low-angle, thin-skinned thrusts (Bykerk-Kaufman, 1990, 2008; Waldrip, 2008; Spencer et al., 2019), but the structural style of several have not been previously interpreted (Fig. 1). Reverse faults are present in the Santa Catalina, Rincon, and Galiuro Mountains, and they typically crop out along strike over short distances (~1–5 km) before they are either cut by younger faults, intruded by younger igneous units, or buried by younger sedimentary rocks. Some authors have proposed that these fault segments were originally part of a single continuous thrust sheet, or “overthrust,” that spanned the study area (e.g., Drewes, 1981; Keith and Wilt, 1985; Waldrip, 2008; Arca et al., 2010; Spencer et al., 2019). Kinematic indicators such as S-C foliations in granitic rocks, offset markers, outcrop-scale folds, and stretched phacoids indicate a top-to-the-northeast vergence of the fault system (Bykerk-Kaufman and Janecke, 1987; Waldrip, 2008). These authors have interpreted that the modern orientations of these faults have only been affected by relatively minor Cenozoic extension-related tilting. In the southern Galiuro Mountains, Waldrip (2008, p. 15) interpreted 25° of east-northeast tilting based on the average orientation of intermediate-age synextensional strata (Galiuro Volcanics); in the northeast Catalina-Rincon area, Bykerk-Kaufman (1990, p. 77) interpreted 30° of east-northeast tilting based on an assumed original orientation of the San Pedro fault of N30°W 10°W.

In specific areas directly north and south of the study area where Cenozoic extension and related tilting is minimal, northwest-striking, moderate-angle, thick-skinned basement-cored uplifts have been documented (Fig. 1; Davis, 1979; Favorito and Seedorff, 2018). Similar structures have also been documented in highly extended and tilted areas farther to the north-northwest (Barton et al., 2005; Nickerson et al., 2010; Favorito and Seedorff, 2017, 2020; Richardson et al., 2019).

Cenozoic Extension

The Catalina-Rincon area is characterized by a high degree of extensional deformation and related development of a metamorphic core complex (Davis, 1980; Arca et al., 2010; Davis, 2013). Normal faults dominantly strike north-northwest, and extension was west-southwest-directed (Dickinson, 1991). Normal faults that presently dip at low, moderate, and high angles are present throughout the study area.

Fanning-upward sequences of synextensional strata, ranging in age from ca. 33 Ma to ca. 5 Ma, accumulated in the hanging walls of normal faults (Dickinson, 1991). The oldest of these units are the early Oligocene to Miocene Pantano Formation and Oligocene Mineta Formation, both of which are steeply to moderately east-dipping (Fig. 2). As currently defined, the Pantano Formation only crops out southeast of the Santa Catalina–Rincon Mountains, and the Mineta only crops out northeast of the range. Moderately east-dipping Galiuro Volcanics of late Oligocene age overlie the Mineta Formation (Fig. 2). Farther to the north near San Manuel, the late Oligocene Cloudburst Volcanics rest on Proterozoic Oracle Granite and are steeply east-dipping. The moderately east-dipping Miocene San Manuel Formation overlies both Oligocene volcanic units. The youngest synextensional unit is the Miocene to Pliocene Quiburis Formation, which is typically gently east-dipping to horizontal (Fig. 2).

Normal faults that currently dip at moderate to low angles, such as the Catalina, San Pedro, Cloudburst, Soza Mesa, and Teran Wash faults, are interpreted to be the oldest Cenozoic structures and responsible for the majority of extension in the Catalina-Rincon area (Fig. 2). Previous authors have interpreted these structures as detachment faults (Wernicke, 1981; Wernicke and Burchfiel, 1982; Lister and Davis, 1989) that initiate at moderate to low angles and become nearly horizontal with depth (Lingrey, 1982; Dickinson, 1991; Arca et al., 2010; Spencer et al., 2019). A variety of different structural Cenozoic configurations for the study area have been suggested (Dickinson, 1991; Arca et al., 2010; Spencer et al., 2019), some of which involve more than one detachment. Net slip estimates on these systems range from 20 km to 30 km (Dickinson, 1991) to as much as ~60 km (Spencer et al., 2019).

Steeply dipping normal faults are considered to be the youngest Cenozoic structures. Authors typically group these structures as “Basin and Range” faults and propose they represent a distinctly separate style of extension from detachment faulting (e.g., Dickinson, 1991; Davis et al., 2004) that is analogous to domino-style block faulting (e.g., Proffett, 1977; Mandl, 1987). Estimated offset on faults of this type is considerably less than that attributed to earlier detachment faults and typically ranges from a few hundred meters to a few kilometers (Dickinson, 1991). Flexural uplift and related tilting of rocks in the footwall of these faults are observed, specifically for the Pirate fault and Martinez Ranch faults (Fig. 2), both of which cut the Catalina fault. Davis et al. (2004) interpret that both the isostatic uplift during earlier detachment faulting and the later flexural response from younger Basin and Range faults contributed to the exhumation of the Catalina core complex. Similar flexure and related tilting by the Teran Wash and Soza Mesa faults in the Galiuro Mountains are suggested by Spencer et al. (2019).

In the northernmost portion of the study area, at San Manuel, Fajardo (2015) interpreted Cenozoic extension to be the result of multiple generations of originally steeply east-dipping normal faults that tilted blocks of the upper crust ~65° E (i.e., domino-style block faulting). In this interpretation, there is no difference in structural style between the oldest, currently low-angle faults and the younger, currently steep faults. Strugatskiy (2008) made analogous
Figure 2. Geologic map of the Santa Catalina Mountains, Rincon Mountains, southern Galileu Mountains, and southern Black Hills. Primarily based on Dickinson (1991) with additional data from Creasy and Theodore (1975), Banks (1976), Benson (1981), Grover (1982), Balcer (1984), Goodlin and Mark (1987), Drewes (1996), Ferguson et al. (2001), Richard et al. (2001, 2005), Spencer et al. (2000, 2001, 2009a, 2009b, 2009c, 2011, 2015), Skotnicki and Siddoway (2001), Bolm et al. (2002), Orr et al. (2004a, 2004b), Bykerk-Kauffman (2008), Waldrip (2008), Gootee et al. (2009), Pearthree et al. (2009), and Favorito and Seedorff (2018). Map updates include revised fault traces and contacts and new fault attitudes from structure contour mapping and three-point problems.
interpretations of Cenozoic extension in the eastern Rincon and southern Galiuro Mountains.

## METHODS

This study involved compilation of previous maps combined with new mapping in key locales focusing on accurate fault attitudes, kinematic indicators, and orientations of strata and foliation, as well as new U-Pb zircon geochronology. Specific study areas include the northeastern Rincon Mountains and southern Galiuro Mountains (locations of more detailed geologic maps are shown in Fig. 2) with most new work focusing on the geology near section line AA’ (Fig. 2). Measurement positions were recorded using a Garmin GPSMAP 64S. Detailed mapping of reverse fault outcrops was combined with structure contour mapping (and less commonly three-point problems) to determine accurate fault geometries. Newly named faults include the Vail, Ant, Mineta, Gardner, and Tuff faults. Certain fault segments that were previously interpreted as separate faults have been reinterpreted as single faults due to similar orientations, crosscutting relations, rocks involved, and projections along strike. These include the Bellota Ranch and Italian Trap allochthons (Dickinson, 1991), which are both renamed the Italian Trap fault. The Teran Basin fault (Goodlin and Mark, 1987) is renamed the Soza Mesa fault. Structural reconstructions began with the creation of a cross section through the geologic map using Adobe Illustrator. This section was then imported into Midland Valley Move™ to carry out a sequential structural reconstruction of normal faults. The resulting restored section prior to Cenozoic extension demonstrates the original geometries of Laramide reverse faults, which were then verified in Move™ by 2-D forward structural modeling. Finally, the restored positions of outcrops and faults were combined with results from forward modeling to create a cross section that represents a possible structural configuration of the area before Laramide shortening.

## DESCRIPTION OF STRUCTURAL FEATURES

### Laramide Reverse Faults and Map-Scale Folds

Previous authors have identified Laramide reverse faults throughout the study area (Bykerk-Kaufman, 1990, 2008; Dickinson, 1991; Gehrels and Smith, 1991; Richard et al., 2005; Waldrip, 2008; Spencer et al., 2011, 2019). These faults currently place older rocks on younger rocks, are typically flat or dipping at low angles to the east or west, and dominantly strike to the northwest, although northeasterly and east-west–striking faults are also present. These faults include faults of set L1 and possibly those of set L2 (Fig. 2). Faults of set L2 present very complex and enigmatic field relations (Janecke, 1987; Dickinson, 1991; Force, 1997) that require further detailed study before fault type and history can be confidently interpreted. Dominantly north-northwest–trending folds related to mapped reverse faults are documented in the southern Galiuro Mountains (Figs. 2–3; Goodlin and Mark, 1987; Waldrip, 2008). The pervasiveness and wide range of sizes of mapped folds (wavelengths of 10–400 m), particularly in Bisbee Group and other Mesozoic strata, makes estimation of cut-off angles between reverse faults and older strata difficult (Fig. 3). Where strata are not foliated, cutoff angles typically range from 25° to 60° (Figs. 3–4; Table 1).

Across the study area, deformation in the hanging walls and footwalls of reverse faults ranges from brittle to semi-ductile (Figs. 4–6, Table 1), which suggests that reverse faults collectively represent a range of Laramide paleodepths. Laramide synorogenic strata include the American Flag Formation in the northeastern Santa Catalina Mountains (Fig. 2; Janecke, 1987) and the Cascabel Formation in the southern Galiuro Mountains (Figs 3; Goodlin and Mark, 1987). Where data are available, tectonic fabrics and folds indicate that reverse faults are east- to northeast-vergent (Figs. 3–6; Bykerk-Kauffman and Janecke, 1987; Smith, 1989; Waldrip, 2008; Spencer et al., 2019); however, the Edgar fault has been interpreted as possibly southwest-vergent due to geometric relations between faults and strata (Bykerk-Kauffman, 1990).

### Pre-Cenozoic Normal Faults

As indicated by crosscutting relations, some normal faults in the study area (fault set L3) are not related to mid-Cenozoic extension (Janecke, 1987; Bykerk-Kaufman, 1990). These include the Evans fault, each of which places younger rocks on older rocks (Fig. 2). The Evans and Gardner faults dip gently to the northeast and east at 10°–20°. The Evans fault is cut by the Wilderness Granite that crystallized at 57–46 Ma and cuts the Edgar reverse fault (Bykerk-Kaufman, 2008), which suggests that the Evans fault was active during the Laramide orogeny (Bykerk-Kaufman, 1990). The Gardner fault is cut by the San Pedro fault, which may be the oldest mid-Cenozoic normal fault in the area. This relation does not, however, preclude a mid-Cenozoic age for the Gardner fault. Because this fault involves only brittle rocks and the San Pedro involves deeply exhumed ductile rocks in its footwall, we infer the Gardner fault may not be related to the onset of mid-Cenozoic extension and instead formed during the Bisbee rift or Laramide orogeny. Additional study of this fault is required to test this hypothesis.

### Cenozoic Normal Faults

Using crosscutting relations and similar fault orientations, Cenozoic normal faults have been grouped into distinct fault sets (Fig. 2) from oldest (1a) to youngest (6). Determining the relative timing relations between certain fault sets (i.e., sets 1b and 2) is difficult given the lack of exposed crosscutting relations. Key fault data are summarized in Table 2. Most normal faults strike north-northwest and dip to the west (Fig. 2). In the study area, younger faults...
Figure 3. Geologic map of the Soza Mesa and Teran Basin area. Based on new mapping and previous work by Grover (1982), Goodlin and Mark (1987), Dickinson (1991), Waldrip (2008), and Spencer et al. (2015). Map updates include revised fault traces and contacts, new fault attitudes from structure contour mapping and three-point problems, and new bedding measurements in strata located 0–3 km west of the Teran Wash fault.
Figure 4. Geologic map of the Soza Canyon area. Based on new mapping and previous work of Byker-Kauffman (2008) and Spencer et al. (2009a). Map updates include revised fault traces and contacts, new fault attitudes from structure contour mapping and three-point problems, and new bedding, foliation, and fold axis measurements across the area.
TABLE 1. CHARACTERISTICS OF REVERSE FAULTS

| Fault name          | Present-day strike direction | Present-day average dip | Oldest exposed rocks in hanging wall in contact with fault | Youngest exposed rocks in footwall in contact with fault | Deformation present in rocks of hanging wall and/or footwall (Ignoring Proterozoic deformation) | Folds                                             | Present-day shear-sense direction of tectonic fabric |
|---------------------|------------------------------|-------------------------|-----------------------------------------------------------|---------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------|
| Loma Alta           | N64°W                         | 0-1°SW                  | Proterozoic granite                                       | Bisbee Group                                            | Variably crenulated and warped bedding, possible overturned strata5                      | Possible large-scale folding due to overturned strata | N.A.                                            |
| Edgar               | N65°W                         | 28°E                    | Lower Proterozoic clastic rocks                           | Lower Paleozoic clastic rocks                           | Penetrative foliation, lineation4                                                        | Outcrop-scale ductile folds                      | Top-to-the-east                                 |
| Youelcy             | N43°W                         | 25°E                    | Proterozoic Pinal Schist                                  | Bisbee Group                                            | Penetrative foliation, lineation4                                                        | Outcrop-scale ductile folds                      | Top-to-the-east                                 |
| Roble Spring        | N30°W                         | 18°E                    | Proterozoic Pinal Schist                                  | Bisbee Group                                            | Brittle, uncommon crenulated and warped bedding4                                         | Uncertain                                        | Top-to-the-east                                 |
| Wildhorse Mountain  | N79°E                         | 33°5'S                  | Proterozoic granite                                       | Upper Paleozoic carbonate rocks                         | Penetrative foliation, lineation, especially proximal to fault plane4                     | Outcrop-scale ductile folds                      | Top-to-the-east                                 |
| Little Rincon       | N48°W                         | 25°W                    | Proterozoic granite                                       | Lower Paleozoic clastic rocks                           | Penetrative foliation, lineation, especially proximal to fault plane4                     | Uncertain                                        | Top-to-the-east                                 |
| Hot Springs         | N33°W                         | 13°W                    | Bisbee Group                                             | Cascabel Formation                                      | Variably foliated, primarily in shaly horizons5                                          | Outcrop-scale folds, large-scale isoclinal fold in hanging wall ~50 m wide | Top-to-the-east                                 |
| Kelsey Canyon       | N5°E                          | 7°E                     | Proterozoic Pinal Schist                                  | Bisbee Group                                            | Mainly brittle fracturing                                                                  | Uncertain                                        | N.A.                                            |

Note: N.A.—not applicable.

1Brittle fractures are present in footwall and hanging wall rocks in all examples.
2Orientation uncertain given near horizontal dip of fault and lack of observed fault plane exposures.
3Penetrative deformation is present in footwall rocks.
4Penetrative deformation is present in both hanging wall and footwall rocks.

Dip steeply, whereas older faults dip gently. In addition, the majority of faults presently display a down-dip sense of offset; however, some do not.

In the Catalina-Rincon area, faults that presently dip at low angles to the east include faults of sets 1a and 1b (Table 2; Figs. 2). These faults currently place either younger rocks on older rocks or place non-foliated rocks on foliated rocks (i.e., structurally deeper rocks), which suggests normal offset. Kinematic indicators in lineated footwall rocks of the San Pedro fault (set 1b) suggest top-to-southwest sense of shear, as demonstrated in Happy Valley (Spencer et al., 2011, 2019). This suggests that the fault and fabrics are related, have rotated through horizontal, and presently have an up-dip sense of slip (Lingrey, 1982). Similar observations have been made for some faults of generation 1b such as the Italian Trap fault (Benson, 1981). Other faults such as the Espiritu Canyon shear zone generally lack lineated fabrics, and pervasive outcrop-scale folds that developed in its hanging display indicate top-to-southwest shear according to new field measurements (Fig. 4). Shear in these unlined rocks is not definitively linked to fault offset, however, and may be related to Eocene magmatism (Spencer et al., 2019). Faults of set 1a and 1b appear to merge in some areas, but more typically faults of set 1a are cut by those of 1b, which indicates that the latter is younger (Fig. 2).

The Soza Mesa fault and Cloudburst fault are grouped into fault set 2 because both currently dip at shallow angles to the east or west, are cut by faults of set 3, and cut and/or bound Oligocene volcanic rocks of likely the same age (Dickinson, 1991; Table 2; Fig. 2; Galliso Volcanics and volcanic lower member of the Cloudburst Formation). The Cloudburst fault, like faults of sets 1a and 1b, has rotated through horizontal as demonstrated by Fajardo (2015). Limited direct data demonstrate that fault set 1b is older than set 2. However, interpretation of these structures and their relation to synextensional strata provides key insights into their relative timing (see section entitled “Cenozoic normal fault generations”).

Faults of set 3 currently dip moderately to the west, cut faults of sets 1b and 2, are cut by faults of set 4, and appear to have bounded the deposition of the Miocene San Manuel Formation and time-equivalent upper Pantano Formation (Table 2; Fig. 2).

Faults of sets 4 and 5 are both steeply dipping and rarely interact with one another except, perhaps, in the south-central portion of the study area (Table 2; Fig. 2). These limited crosscutting relations are consistent with the timing of similarly oriented fault sets at San Manuel (Fajardo, 2015) and the Romero Wash area located 30 km north-northwest of San Manuel (Favorito and Seedorff, 2017). Crosscutting relations are also limited for faults of set 6 (Table 2; Fig. 2), but work from Favorito and Seedorff (2020) in the Ray-Superior area, located 60 km north-northwest of San Manuel, suggests these faults are the youngest.

Cenozoic Map-Scale Antiforms and Synforms

Mapped Cenozoic antiforms and synforms are mainly present along the southwestern flank of the Santa Catalina–Rincon Mountains. These structures are defined by the change in dip of foliated Wilderness and Oracle Granite
Tectonic Fabrics

Two main sets of these features are present, and both are largely restricted to the footwall of the Catalina fault. One set consists of synforms and antiforms with mainly southwest-plunging fold axes that mirror the overall geometry of the Catalina fault; one example is the Tanque Verde Ridge antiform (Fig. 2). These are referred to as corrugations or mega-mullions (Dickinson, 1991) and are interpreted to be the result of extreme slip on the Catalina fault (Spencer, 1999; Spencer et al., 2019). The other set has fold axes that trend northeast in the Santa Catalina–Rincon Mountains to the northeast in the southern Gallo Suite Granite mylonites. The intensity of this fabric is greatest proximal to the Catalina fault and decreases toward the northeast (Davis, 2013; Fig. 2). Foliation near the Catalina fault is typically subparallel to the fault to slightly less inclined and is gently folded about northeast- and mid-Cenozoic extension may be responsible for a large degree of fabric development (Bykerk-Kauffman, 1990; Spencer et al., 2019; Ducea et al., 2020). Fabrics and folds are described below in localities moving from the southwest related to the Laramide orogeny and others during mid-Cenozoic extension, and deformation type and intensity vary as a function of location (Dickinson, 1991). Furthermore, Paleogene igneous activity and related crustal flow prior to mid-Cenozoic extension may be responsible for a large degree of fabric development (Bykerk-Kauffman, 1990; Spencer et al., 2019; Ducea et al., 2020). Fabrics and folds are described below in localities moving from the southwest

### Figure 5.
Geologic map of the southern exposure of the Youcty reverse fault. Based on new mapping and previous work by Bykerk-Kauffman (2008) and Spencer et al. (2009a). Map updates include revised fault traces and contacts, new fault attitudes from structure contour mapping and three-point problems, and new foliation and fold axis measurements.
Figure 6. Photos of deformation in Bisbee Group strata caused by Laramide shortening. Photo-facing direction is shown in bottom left corner. (A) Unmetamorphosed and foliated mudstone with boudinaged sandstone lenses located at Hot Springs Canyon in footwall of Hot Springs Canyon reverse fault. (B) Recumbent fold of unmetamorphosed unfoliated sandstone located in Hot Springs Canyon. (C) Unmetamorphosed and weakly foliated mudstone with large boudins of sandstone. Located near Soza Canyon in the hanging wall of the San Pedro fault and footwall of Roble Spring reverse fault. (D) Overturned fold of unmetamorphosed, unfoliated sandstone located at Roble Spring in the hanging wall of the San Pedro fault and footwall of the Roble Spring reverse fault. (E) Metamorphosed, strongly foliated, and folded siliciclastic rocks. Folds are east-vergent. Located in the footwall of the Youcay reverse fault and footwall of San Pedro fault. (F) Metamorphosed, strongly foliated, and folded siliciclastic and carbonate rocks of the Bisbee Group (labeled Kb) and Wilderness Granite dikes (labeled Tw, sampled TW-5 location in Fig. 5). Folds within Bisbee rocks and the dike margins are east-vergent, largely shearing into the page (outcrop is sloping toward viewer at ~40°), and share similar trend and plunge to mapped folds in Figure 5. Located in the footwall of the Youcay reverse fault and footwall of San Pedro fault.
TABLE 2. CHARACTERISTICS OF MID-CENOZOIC NORMAL FAULTS

| Fault set | Faults | Present-day strike direction | Present-day average dip | Strata with growth relationships to faults of this set | Youngest rocks cut and offset by faults of this set | Exposed crosscutting relationship with older Cenozoic fault sets |
|-----------|--------|-----------------------------|------------------------|------------------------------------------------------|-------------------------------------------------|---------------------------------------------------------------|
| 6 (youngest) | Sky | WNW and ENE | N and S, steep | None clearly documented | Uncertain | Cuts faults of sets 2 and 4 |
| 5 | Martinez Ranch | NNW | E, steep | Possibly Quiburis Formation | Quiburis Formation | Cuts faults of sets 1a, 1b, 2, 3, and 4 |
| 4 | Pirate, County Line, Cowhead Well, White Ridge, Tuff | NNW and NNE | W, steep | Quiburis Formation | Quiburis Formation | Cuts faults of sets 1a, 1b, 2, and 3 |
| 3 | Catalina, San Manuel, Teran Wash | NW | W, moderate | San Manuel Formation and upper Pantano Formation | Upper Cloudburst Formation, Galiuro Volcanics | Cuts faults of sets 2 and 1b |
| 2 | Cloudburst, Star Flat, Soza Mesa, Ant | NW | W, shallow | Cloudburst Formation and possibly Galiuro Volcanics | Mineta Formation | Cuts faults of set 1a |
| 1b (oldest) | San Pedro, Vail, Sierra Blanca | NW and NE | W, moderate to shallow | Mineta Formation and lower Pantano Formation | Cascabel Formation | Not applicable (oldest set) |
| 1a (oldest) | Espiritu Canyon shear zone, Italian Trap | NW and NE | W, shallow | Mineta Formation and lower Pantano Formation | Bisbee Group | Not applicable (oldest set) |

northwest-trending fold axes. Kinematic indicators, such as lineations, small-scale folds, and S-C fabrics, indicate that this fabric was the result of top-to-the-southwest normal displacement (Reynolds and Lister, 1990; Naruk and Bykerk-Kauffman, 1990). This fabric largely involves the 57–46 Ma Wilderness Granite and therefore is considered younger than Laramide deformation. Most authors ascribe this deformation to normal shear on the Catalina fault and core complex generation; however, recent work by Ducea et al. (2020) has demonstrated the existence of an Eocene southwest-directed, pre-extensional fabric that is interpreted to reflect crustal flow during extensive magmatism. The degree to which this fabric is present throughout the range and has been overprinted by younger fabrics related to core complex generation requires further investigation. Geobarometric analyses by Ducea et al. (2020) indicate that the mostly undeformed 25–26 Ma Catalina Granite formed at 6 ± 2 km depth. This granite is located just beneath mylonitic deformation in the core complex and is thought to be synchronous with and facilitated development of fabrics related to the Catalina fault. Earlier studies suggest that these fabrics formed at depths of 8–12 km (Anderson et al., 1988) or as deep as 15 km (Anderson, 1988).

Northeastern Santa Catalina–Rincon Mountains

The northeastern flank of the Santa Catalina–Rincon Mountains contains a complex array of intensely metamorphosed and foliated strata and intrusions, all of which occur in (or project into) the footwall of the San Pedro fault (Figs. 2 and 4–5). Rocks in the hanging wall of the San Pedro fault are typically undeformed or only contain brittle deformation with the exception of limited foliation developed in Bisbee strata. Within the footwall of the San Pedro fault, bedding planes in sedimentary rocks are transposed, and granitic basement rocks range from slightly foliated to strongly mylonitic (Figs. 6E–6F; e.g., Lingrey, 1982; Bykerk-Kauffman, 1990). Only strata north of latitude 32° 21′ contain discernable bedding planes (Fig. 2), although most of this area is strongly foliated (Bykerk-Kauffman, 1990). Both top-to-the-southwest and top-to-the-east shear senses have been documented (Figs. 4–5) with the latter interpreted as a result of Laramide compression (Bykerk-Kauffman and Janecke, 1987; Smith, 1989) and the former as a result of Cenozoic extension (Lingrey, 1982) and pre-extensional magmatism (Spencer et al., 2019).

Laramide tectonic fabrics. Within the northeastern Santa Catalina Mountains, Proterozoic through Mesozoic strata in the footwall of the San Pedro fault are metamorphosed and foliated (Fig. 2), and metamorphic grade ranges from lowermost greenschist to amphibolite facies at 1–3 kbar (Lingrey, 1982). Late Cretaceous intrusions and small dikes of Paleogene Wilderness Granite are also foliated, whereas the main body of the Wilderness Granite is largely undeformed (Bykerk-Kauffman and Janecke, 1987). The intensity of penetrative deformation and metamorphic grade decreases toward the northeast and increases toward bodies of Wilderness Granite. Strata are variably deformed as a function of lithology; weak units exhibit strong foliation, lineation, and transposed bedding (Bykerk-Kauffman, 1990). Lineation trends east, and kinematic indicators, such as S-C fabrics, outcrop-scale shear zones, sheath folds, and offset markers, consistently indicate east-directed shear (Figs. 2 and 4–5; Bykerk-Kauffman and Janecke, 1987). Because rocks of the Leatherwood suite, which crystallized between 75 Ma and 64 Ma, display the tectonic fabric, and most rocks of the Wilderness suite, dated at 57–46 Ma, are undeformed, Bykerk-Kauffman and Janecke (1987) interpreted the fabric to be related to regional deformation during the Laramide orogeny. Because small dikes of Wilderness Granite are locally sheared and display incipient mylonitic foliation parallel to foliation developed in the country rock, these dikes are interpreted to have been intruded during late stages of deformation.

Similar tectonic fabrics have been documented in the southeastern Rincon Mountains at the Little Rincon reverse fault (Fig. 2). Here, the fabric increases in intensity toward the fault and displays top-to-the-northeast shear. Cross-cutting relations and ages of dikes that interact with the fabric indicate that it formed late in the Laramide orogeny (ca. 66–51 Ma; Smith, 1989; Gehrels and Smith, 1991). Other rocks displaying a Laramide tectonic fabric are located roughly 8 km north-northeast of the Little Rincon reverse fault. The fabric here is developed in the hanging wall of the Wildhorse Mountain reverse fault.
(Fig. 2) and indicates top-to-the-northeast sense of shear on the fault (Spencer et al., 2009b, 2019). Even though there are no direct age constraints on this fabric, its spatial association with a reverse fault implies that it formed during Laramide compression (Spencer et al., 2019).

New structural measurements in the northern Rincon Mountains from this study are consistent with the Laramide tectonic fabric documented by Bykerk-Kaufman and Janecke (1987). Small-scale, tight to isoclinal folds developed in rocks of the Bisbee Group dominantly display top-to-the-northeast sense of shear and have fold axes that trend parallel to the strike of the Youcty reverse fault (Figs. 5 and 6E–6F). Bedding here appears to be transposed because the axial planes of folds are parallel to foliation and rocks are commonly boudinaged. Other kinematic indicators, such as S-C fabrics variably developed in Oracle Granite and Dripping Springs Quartzite, also indicate top-to-the-northeast sense of shear (Fig. 5). Small-scale folds and foliation increases in intensity toward small granitic dikes and folds appear to be less common tens of meters from the dikes. Because of the relatively low modern dip of the Youcty fault and small areal exposure of rocks in its footwall and hanging wall, it is uncertain if the fabric intensity increases or decreases toward the fault (Bykerk-Kaufman, 1990). The fabric here may be related to offset on the fault, as foliation is subparallel to the fault plane. Timing relations between this fabric, offset on local reverse faults, and intrusive units are discussed in depth in Appendix A.

In all of the examples discussed above, tectonic fabrics are present in rocks that are located within the deeply exhumed footwall of the San Pedro fault (Fig. 2). However, some deformed rocks of the Bisbee Group in the Soza Mesa area are within the hanging wall of the San Pedro fault (Fig. 4). These rocks are not metamorphosed and are variably deformed as a function of lithology and location (Figs. 6C–6D). In this area, strata typically become slightly more deformed moving from east to west. Deformation consists of boudins of sandstone beds pinched out within shale, uncommon transposition of weak, almost unconsolidated, shaly units, and warped bedding planes (Fig. 6). The base of the Mineta Formation (the mid-Cenozoic erosion surface) projects only 0.1–2 km above these rocks (Fig. 4). Consequently, this deformation probably occurred at shallow depths (e.g., 1–4 km). The similarity of this deformation to that observed at Soza Mesa (discussed below under “Southern Galiuro Mountains”) suggests that it formed during Laramide compression.

Cenozoic tectonic fabrics. Tectonic fabrics of Cenozoic age are well documented in the northeastern Rincon Mountains (Fig. 2) by Lingrey (1982). Like previous locales discussed above, ductile tectonic fabrics here are within the footwall of the San Pedro fault, whereas the hanging wall is characterized by brittle deformation (Figs. 2 and 4–5). Proterozoic through Mesozoic strata are metamorphosed to lower greenschist to locally lower amphibolite (low pressure) facies, are strongly foliated/transposed, and typically contain asymmetric overturned tight (and in some places isoclinal) folds with axial planes parallel or subparallel to foliation. These folds occur at various scales ranging from several centimeters to ~300 m in wavelength and typically indicate top-to-the-southwest shear (Lingrey, 1982). Mid-Cenozoic granites and Proterozoic granitic basement rocks that underlie foliated strata are generally undeformed and only display foliated and lineated mylonitic fabrics in local exposures (Lingrey, 1982). Metamorphism here is older than the undeformed Barney Ranch quartz monzonite, which is dated at 28.0 ± 1.1 and 270 ± 0.9 Ma (K-Ar biotite; Drewes, 1974), and other undeformed andesite dikes of Oligocene age (Lingrey, 1982).

Lineations in these fabrics are typically absent except at the northwestern corner of Happy Valley (Spencer et al., 2011). Here, Oracle Granite that is structurally positioned a few tens of meters beneath the San Pedro fault displays mylonitic foliation and lineations formed by southwest-directed shear. Farther to the east, these lineations appear to die out. These relations suggest that the fabric and fault are related (Spencer et al., 2019). Fabrics that display no lineation are instead interpreted to have formed as a result of regional magmatism prior to extension (Spencer et al., 2019). This is because Eocene intrusions are inferred to be an important heat source during metamorphism and penetrative deformation (Lingrey, 1982), and extension is interpreted to have started ca. 26 Ma (Spencer et al., 2019). However, this interpretation relies upon the precise age of the “Eocene” intrusions, most of which in the eastern Rincon Mountains have yet to be dated. Furthermore, extension likely started prior to ca. 26 Ma, as older mid-Cenozoic volcanic strata were dated at ca. 33 Ma (Spencer et al., 2001). Finally, even though magmatism seems to have played a role in thermally weakening these rocks, the source(s) of stress that induced shearing are less clear if extension is interpreted to postdate these fabrics by several million years.

North of Happy Valley, similar unlined fabrics are observed at Soza Canyon (Figs. 2 and 4). Within the footwall of the San Pedro fault and hanging wall of the Espiritu sheath zone, strata are foliated and transposed (Spencer et al., 2009a). Outcrop-scale folds in these rocks largely indicate top-to-the-southwest shear according to the trend of newly mapped fold axes and fold asymmetry (Fig. 4); for that reason, we interpret the fabric as Cenozoic.

Finally, linedate fabrics are observed within the hanging wall of the Italian Trap fault, which involves three klippen that are roughly aligned northwesterly (Fig. 2). The central klippe was studied by Benson (1981). Rocks in the footwall, primarily Wilderness Granite and lesser Oracle Granite, are undeformed except directly adjacent to the fault, where they are mylonitized (Benson, 1981). Rocks in the hanging wall are Paleozoic carbonate units and possibly Mesozoic strata that are foliated, linedated, and metamorphosed to greenschist facies. Asymmetric folds within these rocks have subhorizontal fold axes that trend northwest-southeast and display a top-to-the-southwest sense of shear that is consistent with offset on the Italian Trap fault. It is not clear if this fabric is solely related to one period of deformation; however, some fabric component must be younger than the ca. 57–46 Ma Wilderness Granite because these rocks display the fabric (Benson, 1981).

Southern Galiuro Mountains

In the southern Galiuro Mountains (Figs. 2–3), unmetamorphosed strata of the Bisbee Group are variably deformed during Laramide compression (Goodlin and Mark, 1987; Waldrip, 2008). This deformation is most intense between
Hot Springs and Sierra Blanca Canyons and is only weakly developed to the north and south. The intensity of deformation appears to increase toward the Hot Springs fault (Fig. 3). Here, sandstone beds are bounded in shale, the beds of weak shaly units are transposed, and foliation is variably developed (Figs. 6A–6B). Folds include large- to small-scale (3–10 m wavelength on average), tight to isoclinal folds with axial planes that are typically subparallel to foliation (Goodlin and Mark, 1987). Stretched phacoids in localized shear zones of the Kelsey Canyon fault and a large-scale isoclinal fold in the hanging wall of the Hot Springs fault indicate a top-to-the-northeast sense of shear on these reverse faults (Waldrip, 2008). Movement on these reverse faults is interpreted to be the main cause of the deformation. Even though younger rocks such as Muleshoe Volcanics and Cascabel Formation are deformed by map-scale folds (Fig. 3), likely during Laramide shortening (Goodlin and Mark, 1987), small-scale deformation features such as foliation and folds in these units are absent, perhaps due to the greater strength of these rocks compared to shale of the Bisbee Group.

### DISTRIBUTION AND GEOCHRONOLOGY OF SYNEXTENSIONAL STRATA

Cenozoic synextensional strata crop out throughout the study area and in the greater San Pedro region (Fig. 2). They provide geologic markers to restore normal fault offset, to estimate the amount of extension-related tilting, and to determine times when individual basins were forming. Understanding the relative ages of strata is critical for interpreting the Cenozoic structural evolution of a given locale (e.g., Dickinson, 1991).

#### Regional Relations between Relative Ages and Amount of Tilting of Synextensional Strata

Throughout the greater San Pedro region, synextensional formations display distinctive ranges of fanning-upward dips (e.g., Formation A dips 70°–50°E, Formation B dips 50°–30°E, etc.), with greater dips typically correlating with older ages (Figs. 2–4 and 7). For example, from San Manuel (Fig. 7A; Fajardo, 2015) to Ripsey Wash (Maher et al., 2004; Richardson et al., 2019) and Ray-Superior (Fig. 2; Richard and Spencer, 1988; Favorito and Seedorff, 2020), where nearly complete synextensional records are documented, the oldest synextensional strata in each specific locale always dip most steeply, and progressively younger strata display shallower dips. This is because extension in each locale was primarily accomplished via multiple generations of crosscutting faults with a single polarity (down-to-the-west), each of which tilted upper crustal blocks eastward by 35°–15° on average. Conversely, had extension instead been the result of fault generations of variable polarity, the dip of strata might not correlate to the age of a given formation. Moreover, basins continued to fill after slip on the graben-bounding fault(s) had ceased, which stacked subparallel beds without fanning-upward relations until slip began on faults of a new generation (e.g., Maher et al., 2004).

### Local Relations between Synextensional Strata

Within the study area, several formations overlap in time (Dickinson and Shafiqullah, 1989; Dickinson, 1991). Historically, these formations were in part divided by subbasins (individual half-grabens that are perhaps bound by different normal faults), as discussed by Dickinson (1991). Because most normal faults within the study area are down-to-the-west, we can use the inclination of strata as a first-order guide to relative age in the absence of other data (Fig. 2). Even though more detailed mapping and geochronology is needed to fully relate these units to one another, available ages and orientations of strata do suggest fundamental relations (Fig. 8).

#### Early Oligocene Strata

The oldest local synextensional strata are the Pantano and Mineta Formations (Figs. 2, 4, and 8; Dickinson, 1991). Both units rest on rhyolitic tuff. The tuff that underlies the Pantano is dated at 33.01 ± 0.76 Ma (40Ar/39Ar sanidine; Spencer et al., 2001). The tuff under the Mineta Formation, located along Cañada Atravesada (Fig. 4), is dated at 25.1 ± 0.6 Ma (K-Ar groundmass feldspar; Dickinson and Shafiqullah, 1989). However, according to Dickinson (1991), this age is most likely spurious, as a date from the overlying Galiuro Volcanics is 26.9 ± 5.8 Ma (K-Ar plagioclase; Dickinson and Shafiqullah, 1989). Therefore, the basal tuff at Cañada Atravesada is likely older than ca. 27 Ma. Similar composition, texture, and probable overlap in age suggest that both units mark the onset of extension at 34–35 Ma as stated by Dickinson (1991). This is further suggested by the relatively steep, northeastward dip of the base of each unit, as observed south of I-10 in the Pantano Formation (Fig. 2) and in the eastern Rincon and southern Galiuro Mountains in the Mineta Formation (Fig. 7).

#### Mid- to Late Oligocene Strata

The Mineta Formation is overlain by the Galiuro Volcanics (Figs. 2–4 and 8; Dickinson, 1991), the base of which has been dated at 29.8 ± 0.5 Ma (40Ar/39Ar biotite; Spencer et al., 2017), and rocks near the top were dated at 22.8 ± 0.5 Ma (K-Ar groundmass feldspar; Dickinson and Shafiqullah, 1989). The lower volcanic member of the Cloudburst Formation (Fig. 2), which is lithologically similar to portions of the Galiuro Volcanics (Dickinson, 1991), ranges in age from 29.3 ± 0.6 Ma (K-Ar whole rock) to 22.8 ± 0.5 Ma (K-Ar groundmass feldspar; Dickinson and Shafiqullah, 1989). The upper sedimentary member of the Cloudburst Formation is largely older than 22.5 ± 0.5 Ma (K-Ar sanidine) according to the age of a rhyolite clast in a tuff breccia intercalated within the
Figure 7. Dip data for mid-Cenozoic synextensional strata grouped by locality and formation. Each data set shows the range (outer bars), median (center line), mean (black square), interquartile range (large rectangle), outliers (circle), total count (n), and standard deviation (σ). Oldest formations are listed at the bottom of each plot. Where upper and lower contacts are observed, formations are roughly subdivided into upper and lower halves. Data for the basal several hundred meters of the oldest formation in each area are shown. For all localities, only bedding planes that dip to the east are plotted even though some bedding planes dip to the west. The latter commonly occur proximal to faults or inferred buried faults, which implies they have been folded and therefore are not useful for determining tilting amounts. Tucson basin area is not included due to scarcity of measurements and little geochronologic control. (A) San Manuel area. Data from Spencer et al. (2009c) and Orr et al., (2004a). Tsm data points in hanging wall of San Manuel fault (Fig. 2) are excluded due to uncertain stratigraphic position relative to upper and lower halves of Tsm defined in the footwall. (B) Northeast Rincon Mountains. Data from Spencer et al. (2009a), Spencer et al. (2011), and new measurements (Fig. 4). Units “Tcg” and “Tcu” from Spencer et al. (2011) are not included due to less certain age. West-dipping “Tsmv” from Spencer et al. (2009a) is excluded. (C) Soza Mesa and Teran Basin area. Data from Waldrip (2008), Goodlin and Mark (1987), Grover (1982), and new measurements (Fig. 3). Only includes data from hanging wall of Soza Mesa fault (Fig. 2) due to less Cenozoic net tilting east of the fault. Upper contact of unit Tg was not observed, and data are inferred to represent mostly lower and middle section. West-dipping Tsm is excluded. (D) Cienega Basin. South- and west-dipping data points and Tp of uncertain age were excluded. Lower Tp includes “Tpl” from Spencer et al. (2001) and “Tdl” from Ferguson et al. (2001). Upper Tp includes “Tpu” and “Ta” from Spencer et al. (2001), “Td” and “Ta” are from Ferguson et al. (2001) and Richard et al. (2001). Unit Tw refers to the Unit of Wakefield Canyon in Spencer et al. (2001), which is likely Miocene to Pliocene in age (Quibriz Formation equivalent), and west-dipping strata are excluded here as they appear to be related to forced-folding associated with a blind normal fault at depth.
uppermost strata (Dickinson, 1991). Due to similar composition and overlap in age, the Cloudburst Formation and Galiuro Volcanics were likely part of the same igneous complex. Finally, lavas in the middle of the Pantano Formation at Ciénega Gap (Fig. 2) are dated at 28.7 ± 1.1 Ma (K-Ar biotite; Marvin et al., 1973), and a tuff interbedded with conglomerate in the upper Pantano Formation was dated at 26.44 ± 0.09 Ma (40Ar/39Ar sanidine; Peters et al., 2003), which suggests that the middle and at least part of the upper Pantano Formation are also synchronous with the previously mentioned strata (Fig. 8; Dickinson, 1991).

**Early to Mid-Miocene Strata**

The Miocene San Manuel Formation (Figs. 2 and 8) contains a basal olivine-bearing lava dated at Three Buttes at 21.0 ± 0.5 Ma (K-Ar whole rock, Banks et al., 1978) and at Putnam Wash at 22.1 ± 0.5 Ma (K-Ar groundmass feldspar, Dickinson and Shaﬁqullah, 1989). Tilted beds of the San Manuel Formation can be at least as young as the date on a rhyodacite tuff at Ripsey Wash of 17.5 ± 1.0 Ma (K-Ar biotite, Berry et al., 1976), and a tuff interbedded with conglomerate in the upper Pantano Formation is overlain by the late Miocene to Pliocene Quiburis Formation (Dickinson and Shafiqullah, 1989). Tilted beds of the San Manuel Formation at Ciénega Gap (Fig. 2) are dated at 28.7 ± 1.1 Ma (K-Ar biotite; Marvin et al., 1973), and a tuff interbedded with conglomerate in the upper Pantano Formation was dated at 26.44 ± 0.09 Ma (40Ar/39Ar sanidine; Peters et al., 2003), which suggests that the middle and at least part of the upper Pantano Formation are also synchronous with the previously mentioned strata (Fig. 8; Dickinson, 1991).

**STRUCTURAL INTERPRETATION**

**Cenozoic Tilt Domains**

Understanding the tilting history of rocks at various localities across the study area during Cenozoic extension is critical for carrying out a structural reconstruction of the region and assessing its structural evolution. Assuming roughly horizontal deposition, the inclination of the oldest synextensional strata that depositionally overlie pre-Cenozoic rocks in a given area is equal to the net amount of tilting the area has undergone by Cenozoic normal faults (Figs. 7 and 9–10). Additionally, the orientation of pre-Cenozoic strata also indicates the amount of net Cenozoic tilting for given areas assuming these rocks were not tilted during Laramide shortening. Net tilting directions are inferred to be orthogonal to the average strike direction of the oldest synextensional units. For example, in the northeastern Rincon Mountains, synextensional strata typically strike northwest, which suggests a northeastward tilt direction (Fig. 2). This is largely consistent with the orientation of the corrugations or “mega-mullions” of the southwestern Catalina-Rincon range front, whose axes trend southwest, parallel to the extension direction (Dickinson, 1991). Net Cenozoic tilting across the study area ranges from 5°–70°E, and the majority of the central area is highly tilted, whereas the easternmost area is nearly upright (Fig. 9).

Estimating net tilting across the study area is complicated by the fact that the original distribution of certain early synextensional deposits appears to have been limited geographically at least according to modern outcrops (Figs. 2 and 9). For example, the Mineta Formation and likely age-equivalent lower Pantano Formation (Fig. 8) were probably not deposited north of the Mogul fault, as suggested by the absence of these strata here and because the lower...
Figure 9. Simplified geologic map of the study area that displays data used to estimate maximum net tilting in the region due to Cenozoic extension (contoured in blue). All tilting is approximately northeast-directed. Orientations of strata within pre mid-Cenozoic bedrock appear to have not been tilted by any deformation events prior to Cenozoic extension. Orientations of oldest Cenozoic strata (Oligocene) are the most reliable data points for determining maximum tilt in a given area. Tilt domain lines are dashed, transparent, and assumed to be evenly spaced where there are no data, which possibly results in oversimplification of tilt domain boundaries; however, this may be appropriate given the large scale of the map. Orientations of Miocene and younger strata are not displayed, as they only indicate intermediate tilting magnitudes.
member of the Cloudburst Formation was deposited on Oracle Granite at San Manuel (Fig. 2). In the southern Galiuro Mountains, the original distribution of the Mineta Formation is also uncertain. Even though these rocks do not crop out at Soza Mesa (Fig. 3), buried half-grabens here may contain this unit given their proximity to Teran Basin and the Sierra Blanca fault (Fig. 2). Strata of the Mineta Formation at Teran Basin would project northwest along strike into the Soza Mesa area. These rocks were probably not deposited northeast of the area, as pre-Cenozoic rocks there are depositionally overlain by Galiuro Volcanics (Figs. 2 and 9). Net tilting at Soza Mesa is likely less than at the Teran Basin area (Figs. 9–10), as prior work has demonstrated that the central and northern Galiuro Mountains (Fig. 2) are only tilted ~10°–20°E by Cenozoic extension (Creasey et al., 1981; Dickinson, 1991; Favorito and Seedorff, 2018). Further difficulty in estimating net tilting is apparent due to the lack of oldest basal synextensional strata (Mineta and lower Pantano Formations) in certain areas (Figs. 2 and 9–10). This is particularly true for the northern Santa Catalina Mountains, where the young Quiburis Formation is the only Cenozoic unit present (included in “Basin fill, alluvium, talus” unit QTs in Fig. 2). Additionally, pre-Cenozoic strata here are largely not useful for estimating net Cenozoic tilting, as unfoliated units are complexly folded, perhaps by Laramide compression. Despite this lack of local control, synextensional strata of the adjacent Soza Canyon and San Manuel areas, both of which are steeply tilted ~60°–70°E by Cenozoic extension (Figs. 2, 4, and 10), project into this area, which suggests that it is also tilted by a similar amount. This tilting estimate is further suggested by the similar orientation of pre-Cenozoic faults in the
Soza Canyon area and northern Santa Catalina Mountains assuming that these faults did not change orientation along strike (Figs. 2 and 10).

In some areas, Cenozoic strata are steeply inclined and indicate significant tilting, but their precise ages are uncertain due to the lack of local radiometric dates. For example, at Happy Valley, a Cenozoic conglomerate of unknown age was deposited on Paleozoic units (Figs. 2 and 9). Because the unit dips steeply at ~60° east-northeast near the depositional contact, similar to the dip of Oligocene strata of the Mineta Formation roughly 10 km to the north, these strata may belong to the Mineta Formation. This early age is further suggested by the fact that clasts within the conglomerate are not composed of metamorphosed or mylonitic rocks (Spencer et al., 2011). Nonetheless, the dips of this conglomerate suggest steep eastward tilting locally. Even though the exposure of this conglomerate is limited, the orientation of unmetamorphosed Paleozoic strata in the hanging wall of the San Pedro fault is consistent with this amount of tilting (Figs. 2; see Spencer et al., 2011). In areas where Paleozoic strata appear not to have been folded, they commonly dip 45°–70°E, similar to the local basal conglomerate of potentially Oligocene age.

Finally, other areas contain identified synextensional units that generally represent the onset of extension, but the bases of these units are not observed locally, and therefore maximum tilting estimates are uncertain. Within the central Santa Catalina–Rincon Mountains, exposures of fault-bounded Mineta Formation in the hanging wall of the Mineta fault indicate moderate to significant eastward tilting (Fig. 2). The precise amount of tilting cannot be estimated because it is unknown where these exposures belong in the stratigraphic sequence and if any fault-related shearing rotated these strata to lower angles. Within the northeastern Tucson basin, 2-D seismic reflection data along line CX12A (Figs. 2 and 11) reveal steeply dipping Pantano Formation. The base of these strata is not evident, but the steepest observed strata dip ~50°E. This indicates a minimum of 50°E tilting here and potentially more considering that strata fan upward to the east and the basin deepens to the west.

Cenozoic Normal Fault Generations

On the basis of crosscutting relations between normal faults and synextensional strata, normal fault sets (Table 2) are interpreted to represent temporally distinct generations of curviplanar down-to-the-west normal faults that initiated as steeply dipping (~60°) and progressively tilted the study area eastward at

![Figure 11. Seismic profile for line CX12A across the northeastern Tucson Basin and southern Santa Catalina Mountains (Fig. 2), adapted from Arca et al. (2010). No vertical exaggeration. Seismic processing follows that of Arca et al. (2010) with the addition of implicit finite-difference time migration using 70% of the smoothed interval velocities, linear-prediction noise removal (F-X deconvolution), and time-depth conversion using 95% of smoothed root mean square (RMS) stacking velocities. (A) Uninterpreted stacked section; surface units are shown at top of section (Fig. 2). (B) Interpreted section. Mylonitized basement and younger intrusive units are below the Catalina fault (Yom = mylonitized Oracle Granite; Twm = mylonitized Wilderness Granite). Note the fanning-upward sequence of the Pantano Formation (Tp) above the Catalina fault (each stratum reflection is colored orange). This indicates that the area has been tilted at least 50°E during Cenozoic extension. Steepest dipping strata here may correspond to the steeply dipping strata of the early or middle Pantano in Cienega Gap (Figs. 2 and 9). Moderately to shallowly dipping strata (i.e., 30°E or less) here may correspond to the upper Pantano, as those rocks at Cienega Gap dip at 30°E or less. These rocks therefore may be related to offset on the Catalina fault, and their cutoff angle with the Catalina fault suggests an original fault dip of ~45–50°W. Estimation of cutoff angle is difficult because the precise ages of these strata are unknown, the Catalina fault plane appears to have possibly been modified by minor flexure and folding related to younger crosscutting normal faults, and the depth correction is not constrained by drill hole data. Additionally, the seismic section may not be aligned with the true dip of the Catalina fault as implied by the geologic map (Fig. 2), which suggests that its true dip across the section may be slightly greater (~2–3°) than shown here.](image-url)
variable magnitudes (Table 3; Fig. 10). Normal faults are interpreted as curvilinear (i.e., variable in strike but showing little change in dip with depth) as opposed to listric because shallow, intermediate, and deep normal fault exposures restore to high angles if one assumes a rigid, relatively planar footwall (Figs. 10–12). The relative structural depth of each fault exposure is given by the intensity and nature of deformation of rocks exhumed in its footwall. For example, deep exposures of faults exhumed intense mylonitic deformation in their footwall. Across the study area, fanning-upward sequences record gradual tilting of normal faults to lower angles (Figs. 7 and 10), and individual units provide tilting estimates for certain generations of normal faults (Table 3). Normal tilting for each normal fault set is mainly determined by the angular difference between the uppermost and lowermost strata that accumulated during fault offset; however, in some cases, the angular difference between faults of consecutive sets can also indicate net tilting. As originally high-angle normal faults slip in this interpretation, they gradually tilt to lower angles until slip on a fault is no longer mechanically favorable or the state of stress changes (Table 3; Fig. 10). After this, a new generation of high-angle faults is formed, and the process repeats. This interpretation is similar to the extensional styles documented in locales just to the north such as San Manuel (Fajardo, 2015), Romero Wash (Favorito and Seedorff, 2017), Kelvin-Riverside (Nickerson et al., 2010), and the Ray-Superior area (Barton et al., 2005; Favorito and Seedorff, 2020), to the southwest at Sierrita (Stavast, 2006), and just south in the Santa Rita

| Normal fault generation | Fault set | Syntectonic units | Predominant range of dips of syntectonic strata | Estimated maximum tilting related to fault generation | Tilling direction of fault blocks | Fault | Cenozoic tilt axis | Magnitude of net Cenozoic tilting | Present-day strike | Present-day dip | Estimated offset (km) | Restored strike | Restored dip | Modern characterization of fault |
|------------------------|----------|------------------|-----------------------------------------------|-----------------------------------------------------|---------------------------------|-------|-----------------|-----------------------------|-----------------|-----------------|-----------------------------|----------------|-------------|-----------------------------|
| 5                      | 5        | Possibly Quiburis Formation | 0°–5°W                                      | 5° Westward                                         | Martinez Ranch                  | N5°W | 5°             | N5°W                        | 55°E            | > 1.8°          | N5°W                        | 60°E           | Normal fault |
| 4                      | 4        | Quiburis Formation     | 0°–10°E                                    | ~ 10° Eastward                                       | Pirate County Line Cowhead Well | N15°E | Uncertain      | N15°E                       | N2°E            | > 4.4°          | N15°E                       | 63°W           | Normal fault |
| 3                      | 3        | San Manuel Formation and upper Pantano Formation | 10°–30°E                                    | ~20° Eastward                                        | Catalina                          | N33°W | 30°           | N38°W                       | 18°W            | 11°             | N35°W                       | 48°W           | Normal fault |
| 2                      | 2        | Cloudburst Formation and possibly Galiuro Volcanics | 65°–30°E at San Manuel 40°–25°E near Soza Mesa | ~35° Eastward                                        | Cloudburst                        | N15°W | 45°           | N17°W                       | 4°              | 3.1°            | N15°W                       | 61°W           | Overturned normal fault |
| 1 (oldest)             | 1a and 1b| Mineta Formation and lower Pantano Formation | 70°–50°E in Rincon Mtns 40°–25°E near Soza Mesa | ~20° Eastward                                        | Espiritu Canyon shear zone       | N30°W | 70°           | N18°W                       | 20°E            | 10.2°           | N35°W                       | 51°W           | Overturned normal fault |
|                        |          |                  |                                              |                                                     | Italian Trap                      | N30°W | 70°           | N33°W                       | 19°E            | 10.2°           | N29°W                       | 51°W           | Overturned normal fault |
|                        |          |                  |                                              |                                                     | Sienna Blanca                    | N45°W | 50°           | N22°W                       | 8°              | 13°             | Uncertain                   | N31°W          | 62°W          | Overturned normal fault |

Note: N.A.—not applicable.

1 More than one range is shown for generations 1 and 2 to demonstrate regional variability of tilting.
2 Estimated based on the orientation of the oldest related syntectonic strata.
3 Fault dips represent an average of measured dips and dips derived from structure contour maps.
4 From Davis et al. (2004).
5 Inferred based on the strike of the fault.
6 Inferred from regional dip of the Quiburis Formation.
7 From Spencer et al. (2011).
8 From Spencer et al. (2009c).
9 From structural reconstruction along section AA (Fig. 11).
10 From Fajardo (2015).
11 Present-day fault orientations and Cenozoic tilt axis orientations are from exposures near section AA (Fig. 2).
12 San Pedro, Espiritu Canyon shear zone, and Italian Trap faults are all interpreted to be part of the same fault system and therefore offset listed for each represents the entire system.

TABLE 3. MID-CENOZOIC NORMAL FAULT GENERATIONS AND RESTORED ORIENTATIONS OF MID-CENOZOIC NORMAL FAULTS
Mountains (R.E. Greig, 2020, personal commun.). Extension in these nearby areas, particularly at San Manuel, can provide insight into certain Cenozoic fault generations studied here because fault generations there largely involve the same synextensional strata (Figs. 2 and 10).

Tilting produced from each normal fault generation is complex and likely varied in magnitude across the study area and especially along strike as tips of individual faults were approached (Table 3; Fig. 9). This is primarily because tilting related to normal fault offset is largely limited to the area that encompasses the moving fault (or fault sets), and the area outside of this does not tilt or move vertically. Without the full exposure of Cenozoic units across the study area, it is difficult to estimate precisely how much each locale was tilted by each generation of normal faults. However, the maximum amount of Cenozoic tilting across the study area can be determined with more certainty (Fig. 9).

Generation 1

Fault sets 1a and 1b are grouped into fault generation 1 because both are nearly parallel, place younger rocks on older rocks, and appear to possibly merge into one another in certain areas (Figs. 2 and 4). Because the study area has undergone only eastward tilting, it would follow that the normal faults that have undergone the greatest tilting would be the oldest. Because of this, faults of sets 1a and 1b are interpreted as older than faults of set 2. This is further indicated by the geometric relation between Mineta Formation resting in the hanging wall of faults of sets 1a and 1b. The tuff at the base of the Mineta Formation is likely ca. 34 Ma (Fig. 8), and this unit forms a steep cutoff angle (~55°) with faults of sets 1a and 1b near section AA’ (Fig. 2). Assuming these faults originally dipped at steep angles (as is demonstrated for all other Cenozoic fault sets here and to the north at San Manuel, for example), it would suggest that the San Pedro fault (set 1b) is intruded by an undeformed andesite dike dated at 27 ± 1.1 Ma (U-Pb zircon; Arca et al., 2010), which is consistent with the interpretation that the San Pedro fault predates the Galiuro Volcanics. Based on the observed range of dips (70°–50°) in the Mineta Formation at the Soza Canyon area (Figs. 4 and 10), we estimate 20° of maximum tilting associated with fault generation 1; however, there is notable scatter in these dip measurements that makes this estimate imprecise.
We interpret the majority of top-to-southwest post-Laramide tectonite fabrics (both lineated and unlined) in the northeastern Rincon Mountains and near the Italian Trap klippen to be the result of shear on generation 1 normal faults. This is because most of these tectonites are proximal to these faults in 3-D and display a pervasive top-to-southwest shear sense that is consistent with fault offset. Lineation in these fabrics is most well developed proximal to the San Pedro fault north of Happy Valley (Spencer et al., 2019) and the Italian Trap fault (Benson, 1981). The fabrics die out to the east, perhaps because paleodepth decreases in this direction, considering that the area is tilted steeply eastward. Magmatism appears to have played an important role in facilitating this deformation (Lingrey, 1982), but the dikes and plugs that interact with the fabric have yet to be dated. Radiometric dates on undeformed dikes that cut this top-to-southwest tectonite may help further constrain the age of this fabric and the potential relation to local normal faults. Nonetheless, due to the lack of robust timing constraints, it may be possible that the unlined fabric is unrelated to Oligocene normal-sense shear and core complex formation, as proposed by Spencer et al. (2019), but the close geometric association between the two suggests a connection.

Faults of set 1a are interpreted as deep footwall splays of fault set 1b due to the different apparent paleodepths of footwall rocks, similar geometry, close spatial association, and crosscutting relations. The San Pedro fault (set 1b) exhumes rocks that were perhaps 5–10 km deep at the start of extension, is mainly characterized by brittle deformation such as brecciation, and rocks in its hanging wall are brittlely deformed (Lingrey, 1982). Faults of set 1a, which are only exposed in the footwall of the San Pedro fault, include semi-brittle faults that contain ductilely deformed strata and locally mylonitic igneous rocks in their hanging walls (Figs. 2 and 4). This suggests that faults of set 1a represent deeper structural levels than faults of set 1b. Both faults appear to merge into one another in map view in certain areas and especially east of White Ridge (Fig. 4), which suggests they are part of the same fault system. In other places, faults of set 1b appear to cut faults of set 1a and possibly represent adjustments in the geometry of the ductile shear zone over time.

**Generation 2**

Faults of this generation appear to cut the Oligocene Galiuro Volcanics and time-equivalent lower Cloudburst Formation (Table 3; Fig. 10). Alternatively, these faults may instead be synchronous (at least partially) with deposition of these units; however, fanning-upward sequences are difficult to identify with confidence. Even though there are no clearly related synextensional strata to directly constrain tilting related to normal fault generation 2 within the central study area, faults of the same generation are observed at San Manuel (Figs. 2 and 10). Here, this fault generation is synchronous with at least the upper member of the Cloudburst Formation, which indicates ~30°E of local tilting related to normal fault offset (Fajardo, 2015). Within the northeastern Rincon Mountains, the top of the Mineta dips ~50°E on average and the base of the San Manuel Formation (which overlies Cloudburst Formation at San Manuel) dips ~30°E, which suggests that near section AA’, this fault set resulted in a maximum tilting of ~20°E (Figs. 7 and 10). In the southern Galiuro Mountains, maximum tilting related to fault generation 2 is difficult to estimate because the base of the San Manuel Formation is not exposed. If we assume the latter dips ~30°E, then tilting related to fault generation 2 here may be only 10°–15° because the base of the Galiuro Volcanics locally dips at ~40°–45°E (Figs. 3–4 and 10).

**Generation 3**

These faults are related to the deposition of the San Manuel Formation and upper Pantano Formation (Table 3; Fig. 10). At San Manuel and in the northeastern Rincon Mountains, the San Manuel Formation involves a fanning-upward sequence with dips ranging from 30°–10°E, which suggests 20°E of Cenozoic tilting related to offset on faults of generation 3 (Figs. 2 and 7). At Cienega Gap, north of highway I-10, a similar range of eastward, upward fanning dips is also observed in the upper Pantano Formation, which suggests a similar magnitude of tilting here. Such relations within the Tucson Basin are obscure, as both east- and west-dipping synextensional strata are observed. However, seismic line CX12A (Figs. 2 and 11) reveals moderately east-dipping Pantano Formation in the hanging wall of the Catalina fault. The age of these layers is uncertain, so it is unknown which layers are related to fault offset, but they are consistent with eastward tilting. In the southern Galiuro Mountains, the base of the San Manuel Formation is not observed, and the orientations of strata are scattered and may have been affected by fault-related folding (Fig. 3). Consequently, these data do not appear to be useful in estimating local tilting related to fault generation 3. Finally, the base of the San Manuel Formation is exposed just northwest of the Wildhorse Mountain fault (Fig. 2), where it dips 25–30°E, which is consistent with dips of the San Manuel and Upper Pantano Formations at Cienega Gap.

**Generation 4**

This fault generation is related to the deposition of the Quiburis Formation (Table 3; Fig. 10). The dip of this unit ranges from gently east- to gently west-dipping (Fig. 2). East-dipping strata are typically steeper, which suggests growth during offset on down-to-the-west normal faults. The range of dips locally suggests a maximum tilting of 5°–10°E for the study area (Fig. 7). Similar interpretations were made elsewhere along the San Pedro Valley such as at San Manuel (Fajardo, 2015) and in the Romero Wash area (Favorito and Seedorff, 2017).

**Generations 5 and 6**

No clearly documented synextensional strata appear to be related to faults of generations 5 and 6; however, some gently west-dipping strata of the Quiburis Formation may be related to the down-to-the-east faults of...
generation 5 (Table 3). Because of this, some minor tilting may be associated with fault generation 5, but given the fairly steep dip of these faults (Fig. 10), it is negligible. Tilting related to faults of generation 6 is also negligible considering the modern steep orientation of these faults.

Style of Laramide Shortening

By restoring Cenozoic tilting, the original geometry of reverse faults in the study area can be interpreted (Table 4; Figs. 10 and 12). The restored reverse faults typically strike north-northwest and dip moderately to steeply west. The range of restored dips is consistent with the typically moderate to high cutoff angles observed between these faults and older strata (Fig. 10). Due to the originally moderate to steep angle of reverse faults and their significant involvement of basement rocks, these faults are interpreted as thick-skinned, basement-cored uplifts. It is difficult to determine if these faults resulted in large-scale folds because the rocks involved are either crystalline basement, which lacks discernable markers, or strata of the Bisbee Group, which contain abundant small-scale folds. The latter would require more detailed mapping of stratigraphic subunits to discern any large-scale folding. One notable exception to this is a well-developed overturned fold of Bisbee strata in the hanging wall of the Hot Springs reverse fault (Waldrip, 2008).

Vergence Direction of Laramide Reverse Faults

Once reverse faults are restored to their original orientation, the average strike is N30°W (Table 4; Fig. 12). Because all reverse faults dip to the west-southwest, their vergence direction is inferred to be east-northeast and perpendicular to the restored strike of the faults. Top-to-the-east-northeast shear indicators associated with shortening (Bykerk-Kauffman and Janecke, 1987; Gehrels and Smith, 1991; Spencer et al., 2019) largely restore to west-southwest plunging and maintain their east-northeast sense of shear (Fig. 12). This further supports the interpretation that Laramide reverse faults in the study area were mainly east-northeast-vergent.

STRUCTURAL RECONSTRUCTION

Cross section AA’ has been reconstructed at different scales using Midland Valley Move™ (Figs. 13–14) to test the interpretation that multiple generations of originally steeply dipping normal faults progressively tilted rocks in the study area. The location of section AA’ has been chosen due to its intersection with most major structures (Fig. 2); however, some key structures and units are projected into the section. In addition, several inferred faults were added to the reconstruction that do not presently crop out, perhaps due to erosion or burial, as they are needed to restore key strata. Offset and related tilting for each normal fault generation (Table 3; Fig. 10) was restored sequentially excluding generation 6 because these faults have minor offset and are oriented parallel to the section. Within each stage of the reconstruction, the northwestern and southeastern vertical edges of the section only move laterally as extension progresses and do not undergo any tilting or deformation (Fig. 13).

Fault corrugations are not considered because the reconstruction is a 2-D solution (Dickinson, 1991). Corrugations may result from the linkage of variably oriented fractures during the birth of a fault, which are geometrically exaggerated when such faults are exposed at the surface at low inclinations (Jackson and White, 1989; Peacock, 2002). Alternatively, they may reflect down-dip stretching and warping of the fault surface by minor horizontal shortening perpendicular to the extension direction (e.g., Mancktelow and Pavlis, 1994; Spencer, 1999; Singleton, 2013). Within the reconstruction, we

| Fault name         | Present-day strike direction | Present-day average dip | Estimated offset (km) | Cenozoic tilt axis | Magnitude of Cenozoic tilting | Restored strike | Restored dip | Restored hanging wall shear-sense direction |
|--------------------|------------------------------|-------------------------|-----------------------|--------------------|-------------------------------|-----------------|-------------|-------------------------------------------|
| Loma Alta          | N64°W                        | 0–1°SW                  | 1.3°                  | N30°W              | 70°                           | N31°W           | 71°         | east-northeast                           |
| Edgar              | N65°W                        | 25°E                    | >2°                   | N40°W              | 70°                           | N24°W           | 45°         | east-northeast                           |
| Youlcy             | N43°W                        | 25°E                    | 2.8°                  | N30°W              | 70°                           | N22°W           | 46°         | east-northeast                           |
| Roble Spring       | N30°W                        | 18°E                    | 5°                    | N35°W              | 70°                           | N37°W           | 52°         | east-northeast                           |
| Wildhorse Mountain | N79°E                        | 33°S                    | >1.8°                 | N15°W              | 50°                           | N64°W           | 59°         | east-northeast                           |
| Little Rincon      | N48°W                        | 25°W                    | >0.6°                 | N15°W              | 50°                           | N29°W           | 72°         | east-northeast                           |
| Hot Springs        | N33°W                        | 13°W                    | 2.3°                  | N25°W              | 45°                           | N27°W           | 58°         | east-northeast                           |
| Kelsey Canyon      | N5°E                         | 7°E                     | 1°                    | N45°W              | 60°                           | N50°W           | 55°         | east-northeast                           |

1Based on the orientation of the oldest local synextensional strata and/or orientation of pre-Cenozoic strata that do not appear to have been folded.

2Orientation uncertain given near horizontal dip of fault and lack of observed fault plane exposures.

3Estimated offset based on kinematic modeling results along section AA (Fig. 13).

4Estimated offset based on observed stratigraphic separation and restored dip of fault plane.

5Tilt axis orientation and magnitude are uncertain due to lack of local data.
Figure 13. Structural reconstruction of Cenozoic extension along section AA’. In each time panel, the transition from brittle material to ductile material is shown. This thermal boundary is reset after each normal fault generation and is determined by measuring ~12 km downward from mean topography. Erosion is displayed, and rocks below the reset thermal boundary are faded. Ductile material exhumed by normal fault offset is shown by units M1-M4. Mylonites are formed within this exhumed ductile material proximal to related normal faults. A sketch of mylonites exhumed to the modern surface are shown in stage F, which provides a potential genetic explanation for the Catalina Forerange Arch (Fig. 16). Jurassic and younger intrusive units are not shown for simplicity. In each stage, the edges of the section only move laterally. Future faults are dashed. Inferred Cenozoic normal faults are labeled in the time frame prior to offset. The left-most block of each section is pinned. (A) Before offset on normal fault generation 1. (B1) Offset on normal fault generation 1. Deposition of Mineta Formation and lower Pantano Formation. See Figure 14 for detailed reconstruction of fault generation 1. (B2) Thermal boundary reset, exhumation of ductile material M1 is shown. Continued erosion, and deposition of Galiuro Volcanics. Before offset on normal fault generation 2. (C1) Offset on normal fault generation 2. Deposition of Cloudburst Formation and middle Pantano Formation. (C2) Thermal boundary reset, exhumation of ductile material M2 is shown. Before offset on normal fault generation 3. (Continued on following page.)
Figure 13 (continued). (D1) Offset on normal fault generation 3. Deposition of San Manuel Formation and upper Pantano Formation. (D2) Thermal boundary reset, exhumation of ductile material M3 is shown. Before offset on normal fault generation 4. (E1) Offset on normal fault generation 4 and deposition of Quiburis Formation. Mylonitic material has now been exhumed to the surface. (E2) Thermal boundary reset, exhumation of ductile material M4 is shown. Before offset on normal fault generation 5. (F) Offset on normal fault generation 5. Continued erosion and deposition of Quaternary basin fill. Mylonitic foliation formed during stages B1, C1, and D1 is shown near the surface in the eastern and central Rincon Mountains; see Figure 16 for more detailed depiction and explanation.
Figure 6E, F

Espiritu Canyon shear zone

San Pedro fault

Italian Trap fault

Mineta fault

Figure 14. (Continued on following page.)
Figure 14 (continued). Structural reconstruction of Cenozoic extension along section AA’ within the northern Rincon Mountains with a focus on the complex evolution of the San Pedro fault system. The left-most block in each section is pinned. The upper and lower boundaries of sections A–E only represent a viewing window into the specified area through time, and section F displays a dismemberment and variable tilting of that viewing window. As a consequence, sections A–E do not demonstrate tilting or area balance, which is fully depicted in Figure 13. Jurassic and younger intrusive units are not shown for simplicity. Deformation fabrics listed in Proterozoic outcrops do not include earlier Proterozoic deformation (i.e., Pinal Schist). (A) Before offset on the first fault segment of generation 1, shown as dashed. Paleo-up direction is shown by black arrow at left of the section. Representative locations of photographs in Figure 6 are displayed as white rectangles. (B) Initial offset on the San Pedro fault, which includes the Espiritu Canyon shear zone (deeper structural equivalent), deposition of the Mineta Formation (Tm), and erosion of the hanging wall. Offset on the Espiritu Canyon shear zone segment near the Youcty fault (Fig. 2) is now fully restored. (C) Offset on the San Pedro fault, which includes the formation of a horse block. The down-dip portion of the fault involves Italian Trap fault and a splay of the Espiritu Canyon shear zone. Offset on the San Pedro fault at Espiritu Canyon (Fig. 2) is now fully restored. (D) Offset on the Mineta fault that is interpreted as a hanging-wall splay of the San Pedro fault. All strata presently above the Italian Trap fault (Fig. 2) are now fully restored. Complete section of Mineta Formation has been deposited. (E) Deposition of the Galiuro Volcanics, offset on the Cloudburst fault, and deposition of the upper member of the Cloudburst Formation (Tcs). (F) Offset on remaining normal fault generations and deposition of the San Manuel Formation (Tsm) and later basin fill (TQ). On west-side of section, minor flexure-related tilting is related to variable offset on normal faults of generation 4 (Fig. 13). On eastern side of section, minor flexure-related tilting is related to variable offset on normal faults of generation 3 (Fig. 13). Normal faults of generation 3 are not shown in this figure because they do not crop out within the section. All foliation measurements shown indicate top-to-the-southwest transport except for foliation located directly below the Youcty fault, which indicates top-to-the-east-northeast transport.
group all post-Proterozoic intrusions with Proterozoic basement rock for simplicity, as the latter largely contains the former (Figs. 13–15). Nonetheless, in some areas across the range, notable intrusions of Leatherwood Suite and Wilderness Granite intrude deeply buried sedimentary rocks (Fig. 2).

When normal faults slip in the reconstruction, they rotate to lower angles, and faults with shallower dips typically have greater slip (e.g., Kusznir et al., 1991; Richardson and Seedorff, 2017; Thompson and Parsons, 2016). The edges of the section do not experience deformation and only move out laterally because, as slip progresses, the hanging wall flexes downward due to gravity and the footwall flexes upward due to isostatic unloading (Fig. 13); this phenomenon is observed in active normal faults during each earthquake cycle (e.g., Stein et al., 1988). Within the brittle-ductile transition (300°-400 °C, typically 10–20 km depth for continental crust), rocks behave in a more plastic manner and flow rather than brittlely break. In our interpretive model, offset on the fault gradually decreases down-dip and is compensated by a downward-opening triangular zone of distributed ductile simple shear. Below this zone, rocks flow ductiliy and can migrate laterally in response to blocks rotating at higher levels. Because of this, the hanging walls of normal faults in the reconstruction flex downward, and the footwalls flex upward, as ductile material below either can be evacuated elsewhere or can be moved to fill space.

Normal fault offset was restored in Move™ using the 2-D Move-on-Fault module and fault-parallel flow method where hanging wall rocks are translated parallel to the fault plane (Egan et al., 1997; Kane et al., 1997). Because all normal faults were interpreted as planar, no hanging wall deformation related to offset along fault bends had to be restored. After offset on a certain generation of faults was restored, tilting related to that generation was then restored. To maintain undeformed and level edges of the cross section, and to avoid tilting areas along section AA’ for which there is no evidence for tilting, the section was separated into several distinct segments, each of which were tilted different amounts during each stage of the restoration. Then, flexure of the crust, erosion, and deposition of synextensional strata were schematically drawn in each stage.

Once the restoration of Cenozoic normal faults was carried out (Figs. 13–14), kinematic modeling of reverse fault offset (Fig. 15) was performed to further verify the reconstruction of mid-Cenozoic deformation and to estimate offset on reverse faults (for full methods, see Supplemental File 1: Part 2 of Favorito and Seedorff, 2017). This began with creating a pre-shortening cross section in Move™. The section was then deformed forward in time using the 2-D Move-on-Fault module and the trishare method. The trishare deformation algorithm defines a triangular zone of folding that emanates from a forward-propagating tip of a reverse fault (Erslev, 1991). Because there are limited data regarding reverse fault-related folds in the study area, results represent a schematic approximation of section AA’ after shortening. Other thick-skinned reverse faults located near the study area where reverse fault-related folds are better exposed (e.g., Davis, 1979; Favorito and Seedorff, 2017, 2018, 2020), however, can serve as analogues and provide reasonable parameters for modeling potential fold geometries associated with reverse faults. Examples of key parameters include original fault tip structural depth, angular width of the trishare zone, and fault-propagation-to-slip ratio. Input parameters were adjusted until a reasonable match was reached between the kinematic model of reverse faults (Fig. 15) and the restored section of Cenozoic normal faults (Fig. 13).

Constraints and Uncertainties

Surface geologic data, which include rock types, tectonic fabrics, fault geometries, and sense of shear on faults, serve as direct constraints for the structural reconstruction. Other geologic factors, such as paleotopography (erosion/deposition) and flexural response of the crust, serve to geometrically verify each intermediate stage of the reconstruction (Fig. 13).

Even though the reconstruction honors several types of geologic data and represents a geologically reasonable solution, several Cenozoic normal faults within the reconstruction do not have precise offset estimates due to the lack of suitable geologic markers. In general, there is greater confidence in the net fault offset for each normal fault generation than in the offset on individual faults within each generation, and this is most relevant for generations 1–3 (Fig. 13). Despite this, offset on some faults can be estimated given basic criteria such as fault strike length and the amount of related tilting (Figs. 2 and 10; Table 3). Fault strike length can only be used for relatively young normal faults, as these are typically well-exposed along strike and not dismembered. Faults that dip at lower angles and have evidence of notable related tilting from synextensional strata (Table 3) are expected to have greater slip than those faults with little related tilting (e.g., Thompson and Parsons, 2016). The precise amount of slip, however, cannot be determined, but reasonable approximations can be made by modeling the flexural geometry of the crust during extension as it relates to fault spacing and offset. In addition to uncertain fault offsets, net tilting related to certain fault generations in particular areas is uncertain where map data is lacking.

Modern outcrops must restore to appropriate structural depths and positions relative to faults (Figs. 2 and 13–15). This constraint provides reasonable ranges for the amount of offset estimated for faults without stratigraphic constraints, and more importantly, it guides the net offset for a group of faults in a given generation. All rocks that are older than Laramide shortening must restore to reasonable structural levels given their restored position relative to reverse faults. Laramide synorogenic strata should be deposited in the footwall of reverse faults. Restoration of Cenozoic strata should reveal the geometry of basins created by Cenozoic normal faults. Rocks that are metamorphosed and foliated are restored to appropriate structural depths, and the shear-sense of individual tectonic fabrics is honored (Figs. 12 and 14–15). To honor all of these relations, a pre-shortening normal fault related to the Bisbee rift is interpreted within the reconstruction.

The reconstruction meets all of the above criteria reasonably and is therefore geologically, geometrically, and kinematically admissible. However, the
Cenozoic structural evolution of the Catalina core complex and reassembly of Laramide reverse faults

Shortening = 12 km (20%)
Vertical uplift = 9.4 km

Figure 15. Structural evolution of section AA’ during the Laramide orogeny. The right-most block of each section is pinned. (A) Early during the Laramide orogeny. Pre-existing structural deformation includes inferred normal faults that formed during the Bisbee rift (olive green). (B) Deposition of Muleshoe Volcanics and volcanic rocks of the Tucson caldera. Inferred normal faults (dark blue) are associated with caldera collapse. (C) Results of 2-D kinematic forward modeling of reverse faults (red). Due to limited constraints on folding, and for simplicity, a relatively high propagation-to-slip ratio of 5.0 was chosen for each fault. Each fault tip initiated roughly 1 km below the basement-cover interface. Each tri-shear zone was 30° wide and was bisected by its related reverse fault. Reverse faults were modeled arbitrarily from right to left. Gentle folding in the footwall was drawn in after reverse fault offset to schematically demonstrate possible flexure related to gravitational loading of the hanging wall block. Restored pre-Cenozoic outcrop locations along AA’ are shown as bold colored lines. Deformation fabrics listed in Proterozoic outcrops do not include earlier Proterozoic deformation (i.e., Pinal Schist). Labels of geographic locations are shown in bold text. Jurassic and younger intrusive units are not shown for simplicity.
Results of Structural Reconstruction

Spatial Relation between Individual Reverse Faults

Field observations indicate that reverse faults cut up stratigraphic section at moderate to high angles, which is consistent with their restored orientations (Table 4). Once section AA’ is reconstructed, reverse faults in modern outcrops largely appear to be individual faults if their dips are linearly projected downward (Fig. 15). This projection is reasonable given that reverse fault geometries in the field appear to be dominantly curvilinear (Figs. 2–5). A minor exception to this is the Roble Spring fault, which has been interpreted as a hanging wall splay of the Youtcy fault. This configuration is consistent with their close proximity following restoration (Fig. 15). By restoring the present-day orientation of reverse faults in map view, and given the known structural depths of rocks involved, certain individual reverse faults appear to be part of greater faults or fault systems. The Youtcy and Wildhorse Mountain faults are probably the same fault due to similar strike, dip (Table 4), and metamorphosed/foliated rocks in the footwalls of both faults (Fig. 2). The Edgar fault may be related to this fault system as well, or it may be a subparallel, earlier fault, as indicated by geochronologic data (Bykerk-Kauffman, 1990).

Magnitude of Laramide Uplift

The structural reconstruction suggests that 9.4 km of net minimum vertical uplift was accomplished by reverse faults along section AA’ (Fig. 15). Total shortening is 20% or 12 km. These values likely represent minimum estimates because the structural depth of basement that currently crops out in the hanging wall of these reverse faults is unknown. Such a large-scale net uplift is consistent with fundamental geologic observations throughout the study area. In the northeastern and eastern Santa Catalina–Rincon Mountains, foliated Mesozoic and Paleozoic strata are areally extensive (Fig. 2). These rocks are essentially cover strata over basement, yet they contain tectonic fabrics of lower greenschist to lower amphibolite metamorphic facies that formed at pressures of 1–3 kbar (Lingrey, 1982; Fig. 6), which indicates burial to 3–10 km. This likely occurred via shortening (i.e., structural burial) as suggested by the top-to-northeast shear fabric observed in many of these rocks (Bykerk-Kauffman and Janecke, 1987). Later extension has also created tectonic fabrics in some of these rocks (Lingrey, 1982), but this would have only been possible if they were buried prior to extension. Furthermore, depths of these rocks after shortening are consistent with metamorphic pressure estimates as indicated by the structural reconstruction (Fig. 15C).

Cenozoic Extension and Related Tectonic Fabrics

The structural reconstruction demonstrates a plausible kinematic structural evolution for the study area that involves extension accomplished by a series of mainly down-to-the-west normal faults that gradually rotated blocks of the upper crust eastward (Fig. 13). Results suggest the area was extended 120%, or 59 km, and the majority of extension occurred during offset on faults belonging to generations 1 through 3. Estimation of uncertainty requires end-member solutions to the reconstruction, and the results present here represent a mid-case solution. Nonetheless, rocks must restore to their general positions according to relevant constraints. Because of this, we estimate 10% error (5.9 km) in our determination of extension amount.

Ductile flow within and below the brittle-ductile transition are shown schematically near the surface in the final stage of the reconstruction (Fig. 13F) and in Figure 16. This demonstrates how offset on generation 1 faults could account for the eastward dip of foliated rocks on the eastern limb of the Santa Catalina–Rincon Forerange antiform (Fig. 2) and how offset on generation 3 faults could account for the westward dip of foliated rocks on the western limb. Foliation formed during offset on generation 2 faults would be nearly horizontal in the present day because those faults are roughly horizontal (Fig. 16).

DISCUSSION

Style and Magnitude of Laramide Shortening

Interpretation of both the style and magnitude of reverse faults in southeastern Arizona is complicated by superimposed Cenozoic extension that dismembered, tilted, and concealed older reverse faults (Fig. 1). Previous authors interpreted reverse faults as thin-skinned thrusts (Fig. 1; Drewes, 1981; Bykerk-Kauffman, 1990; Waldrip, 2008; Arca et al., 2010; Spencer et al., 2019), each of which was thought to belong to a single east-vergent regional overthrust sheet measuring ~6 km thick (Waldrip, 2008) or greater (Spencer et al., 2019). South of the study area, where extensional deformation is relatively minor, Davis (1979) interpreted variably vergent, thick-skinned basement-cored uplifts (Fig. 1). Just north of the study area along the San Pedro Valley, mainly east-vergent, thick-skinned reverse faults have been documented in locales that are highly dismembered and tilted by extension (Fig. 1; Barton et al., 2005; Nickerson et al., 2010; Favorito and Seedorff, 2017, 2020; Richardson et al., 2019) and in locales that are relatively unaffected by extension (Figs. 1–2; Favorito and Seedorff, 2018). In the aforementioned highly extended areas, reverse faults previously were interpreted as thin-skinned (e.g., Richard and Spencer, 1998). Structural reconstructions suggest that some east-vergent reverse faults along the northern San Pedro Valley resulted in significant vertical uplift of perhaps as much as 5 km in certain areas (e.g., Favorito and Seedorff, 2020). The mid-Cenozoic erosion surface along the Black Hills and
Tortilla Mountains supports these observations, because most of the rocks underlying oldest Cenozoic strata are Proterozoic basement, which presumably is what led earlier workers (e.g., Turner, 1962; Titley, 1976) to refer to this area as the “Florence uplift.”

In the area of this study, field observations and the structural reconstruction indicate that reverse faults restore to moderate to steep angles and were largely isolated individual faults (Table 4; Figs. 13 and 15). A thick-skinned interpretation is preferred due to the large degree of basement involvement and the original moderate to steep dip of these faults (45°–72°; Table 4). Restored foliation attitudes are also consistent with fault-propagation folds forming during reverse fault offset, which is a typical feature of thick-skinned faults. Once restored, reverse faults appear to result in a combined vertical uplift of 9.4 km, and the restored position of foliated and metamorphosed Proterozoic through Mesozoic strata (Fig. 15) is consistent with an uplift of this magnitude. Near San Manuel, the oldest Cenozoic strata typically rest on basement, which indicates exhumation prior to extension and that the reverse fault system continues to the north through this area (e.g., Davis, 1979). Additionally, reverse faults located southwest of the study area in the Little Dragoon (Johnson et al., 2018) and Dragoon Mountains (Drewes, 1987) may be part of the same system especially due to similar orientations and stratigraphic separations. Such an uplift system may measure roughly 150 km in strike length. Given the slip and strike length relations of known reverse faults (Kim and Sanderson, 2005) and the relatively moderate to steep original dips of these faults, the hypothesized strike length is realistic compared to the estimated magnitude of fault offset and uplift.

The interpretation of thick-skinned, basement-cored uplifts in the study area is consistent with interpretations in the surrounding region and suggests that southeastern Arizona as a whole is characterized by thick-skinned tectonics (e.g., Davis, 1979). As in other nearby locales that were reinterpreted from thin-skinned to thick-skinned (Favorito and Seedorff, 2017, 2020), subsequent multiple generations of crosscutting Cenozoic normal faults appear to be the dominant contributor to complexity and overall geologic uncertainty.

![Figure 16. Structural evolution of the Santa Catalina–Rincon forerange antiform. (A) Simplified diagrams of foliation generated in ductile and brittle ductile rocks during normal fault offset. (A1) Before fault offset. Downward-opening triangular zone represents area of future strain proximal to the fault. This zone becomes larger at depth due to decreased rock strength (i.e., increased ductility). (A2) After minor fault offset and minor east-directed tilting, foliation forms at an angle to the fault plane. Fault offset at depth is absorbed by ductile strain of material below. (A3) After continued fault offset and related east-directed tilting. Foliation proximal to the fault plane is roughly parallel to the fault plane due to focused and continued shear. (B) Cross section of the northern Rincon Mountains along line AAA’ (Figs. 2 and 13F). Foliation is color coded according to the related normal fault. Zone of brittle-ductile shear is shown by dashed lines. Foliation intensity is not depicted in this diagram; intensity generally increases with depth and toward related fault planes. The dips of foliation located 0–4 km east of the Catalina fault are projected from Tanque Verde Ridge to accurately represent the geometry of the antiform (Fig. 2). Foliation formed during offset on the Cloudburst fault is not shown because the fault’s current position suggests it did not influence the formation of the forerange antiform.](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/17/6/1928/5476406/1928.pdf)
Formation of Catalina Core Complex

The Catalina core complex is widely interpreted to be the result of detachment faulting; however, a variety of structural configurations has been proposed. A common feature of all models is that most of the extension is accomplished via one or perhaps two low-angle normal faults, the footwall of which isostatically rises (on the order of 10–15 km) as the hanging wall slides down (i.e., Wernicke, 1981; Wernicke and Burchfiel, 1982; Lister and Davis, 1989). This extension is followed by “Basin and Range” block-style extension, where high-angle normal faults control some of the modern topography and impart small amounts of tilting (Dickinson, 1991; Davis et al., 2004). Tilting of strata during detachment faulting is seldom discussed in detail and is typically interpreted to be the result of offset on kinematically linked, highly listric faults in the hanging wall of the detachment fault (i.e., Dickinson, 1991). These detachment and rolling hinge models propose that the Catalina and San Pedro faults were part of the same detachment surface (Catalina detachment); however, its relation to faults in the southern Galiuro Mountains is debated. Dickinson (1991) proposed that the Catalina detachment connected to the Soza Mesa fault in the southern Galiuro Mountains, where extension is interpreted to have begun and is thus referred to as the “breakaway zone” of the Catalina core complex. Spencer et al. (2019) interpret that the Catalina detachment (and the San Pedro detachment) is the only detachment system in the study area and that the Soza Mesa fault may be related to younger “Basin and Range” faulting. Conversely, Arca et al. (2010) argued that two parallel detachment systems existed; one involved the Catalina fault and possibly the San Pedro fault, and the other involved the Soza Mesa and Teran Wash faults (referred to collectively as the Galiuro detachment).

Mid-Cenozoic extension in other nearby locales has been studied in detail. Roughly 35 km north of the main study area at San Manuel (Fig. 2), Fajardo (2015) demonstrated that multiple generations of originally steeply west-dipping curviplanar normal faults progressively tilted the area ~65° E. A similar style of extension has been documented in the Tortilla Mountains (Fig. 1, surrounding areas 1–3) around Romero Wash (Favorito and Seedorff, 2017), Hackberry Wash (Maher et al., 2004; Seedorff et al., 2019a), Kelvin-Riverside (Nickerson et al., 2010), Ray (Barton et al., 2005), and west of Ray near Walnut Canyon (Favorito and Seedorff, 2020). In each of these locales, detailed documentation of crosscutting relations between Cenozoic normal faults and related synextensional strata demonstrate well-defined magnitudes of tilting associated with specific generations of normal faults. Most generations of normal faults at each location were originally steeply west-dipping, and faults that presently dip at higher angles typically cut lower angle faults. The Catalina core complex, however, exhibits deeper crustal exposures than the surrounding locales.

The rheology of continental crust (e.g., Kirby, 1983) dictates a downward progression from brittle to semi-brittle to plastic conditions depending on heat flow and other factors (e.g., Gibbons, 1982; Behr and Platt, 2011). Regardless of the proposed mechanism, structural balance must be maintained (e.g., Dahlin, 1989). The means by which balance is achieved in the middle and lower crust is less certain; in certain locales this probably involves important three-dimensional components of crustal flow and magmatism (e.g., Gans, 1987; MacCready et al., 1997). A good first-order approximation of extensional deformation at shallow levels (e.g., <10 km), however, is brittle deformation characterized largely by rigid-body rotations (e.g., Proffett, 1977; Richardson and Seedorff, 2017) supplemented by flexure that probably is achieved by numerous, small-offset fractures (Thompson and Parsons, 2016).

As demonstrated in this study, the Catalina core complex can be modeled thusly, where structural balance is maintained in two dimensions: explicitly in the upper brittle crust in each step and more schematically at deeper levels. Multiple generations of originally steep, down-to-the-west, mid-Cenozoic normal faults extended the area roughly 120% and resulted in net tilting of as much as 70° E. Multiple generations of faults are required by crosscutting relations between normal faults and their relation to synextensional strata (Table 3; Figs. 2 and 9–10) and can yield a balanced structural reconstruction (Fig. 13). The reconstruction also provides a plausible explanation for the intensity, orientation, and distribution of Laramide and Cenozoic tectonic fabrics across the study area (Fig. 14). Furthermore, shallow, intermediate, and deep exposures of normal faults all restore to high angles (Fig. 12), which indicates that they are nearly linear in the down-dip direction (i.e., curviplanar) and not strongly listric.

The interpreted style of extension here is similar to areas to the north, where a more complete succession of synextensional strata and record of crosscutting relations between those strata and normal faults are preserved (e.g., Maher et al., 2004; Barton et al., 2005; Nickerson et al., 2010; Fajardo, 2015; Favorito and Seedorff, 2017, 2020). In fact, some faults within the study area may be equivalent to those observed to the north due to similar orientation, crosscutting relations, and projection along fault strike. Examples of this include the Teran Wash and San Manuel faults and Soza Mesa and Cloudburst faults (Fig. 2). Perhaps the most critical observation for assessing extensional structural style in the study area, and those locales to the north, is that higher angle faults (younger) successively cut and offset lower angles faults (older). This implies that extension was not accommodated by one single detachment but instead by multiple generations of temporally distinct, crosscutting normal faults.

This study suggests that there is no distinction in structural style between core complex formation and “Basin and Range” extension within the study area, as all faults appear to have formed via the same process and differences in the appearances of faults can be attributed to level of exposure. This is consistent with modern earthquake data from the Basin and Range province that records a flexural response of both the hanging wall and footwall during and after normal fault offset (e.g., King et al., 1988; Stein et al., 1988; Thompson and Parsons, 2016). Modern earthquakes in the Basin and Range province, as well as other actively extending areas of continental crust around the globe (e.g., Italy, Greece, and Turkey), rarely record offset on normal faults that dip at low angles (e.g., faults <30°; Jackson, 1987; Jackson and White, 1989; Collettini and Gibbons, 2001). This suggests that normal faults in continental crust generally lock up and are no longer active after they rotate to 30–40° (though they vary in different cases; Richardson and Seedorff, 2017), and if extension is to continue, a new crosscutting fault set that originally dips at steep angles (~60°) would...
need to be generated. The detachment model, therefore, likely does not apply to the Catalina core complex and may not be applicable to other Cordilleran locales of extreme continental extension that have been interpreted as such. The lack of clear crosscutting relations in large areas of deeply exhumed rocks is consistent with detachment and rolling hinge models (e.g., Whitney et al., 2013, Fig 1A); however, this relationship also is predicted by the interpretation in this study (cf. Figs. 2 and 13). The geology of the Catalina core complex and areas to the north is consistent with a single, consistent style of extension involving similar degrees of net tilting along strike regardless of post-Laramide depth of exposure at the modern surface (Figs. 7 and 9).

Timing of Major Normal Faults

Geochronologic data provide insight into the timing of mid-Cenozoic normal faulting and the development of mid-Cenozoic tectonic fabrics within the study area, which are key to understanding the structural evolution and style of mid-Cenozoic extension. Within the northeastern Rincon Mountains, an undeformed andesite dike (27.1 ± 1.1 Ma, U-Pb zircon) intrudes along the San Pedro fault, which provides an upper age limit for slip on this fault (Arca et al., 2010). Structural analyses as a part of this study suggest the San Pedro fault is likely at least as old as the synextensional Mineta Formation, the base of which is likely as old as ca. 34 Ma (Dickinson, 1991). Offset on the Catalina fault is interpreted to be contemporaneous with the emplacement of the largely undeformed 25–26 Ma Catalina Granite (Ducea et al., 2020). This is consistent with abundant low temperature geochronometers that indicate rapid exhumation of the main range directly after, from 25 to 20 Ma (Fayon et al., 2000; Terrien, 2012). Just west of the Catalina Granite in the Tortolita Mountains, the 25–26 Ma Tortolita Granite is overprinted by extensional tectonic fabrics related to the Catalina core complex (Dickinson, 1991; Ferguson et al., 2003). A cooling age of 22.7 ± 0.7 Ma (K-Ar biotite) was obtained near the center of the pluton (Creasey et al., 1977), and another sample roughly ~1 km southwest of its margin yielded a cooling age of 23.69 ± 0.15 Ma (40Ar/39Ar biotite; Spell et al., 2003). K-Ar dating of fault gouge of the Catalina fault suggests that major fault movement occurred between 21.5 Ma and 21 Ma and possibly reflected late stage offset (Damon and Shaﬁqullah, 2006). These geologic relations and radiometric dates imply that the San Pedro fault (ca. 34–27 Ma) is several million years older than the Catalina fault (ca. 26–21 Ma). Certain previous authors have invoked a rolling-hinge model of detachments (Buck, 1988; Wernicke and Axen, 1988; Axen and Bartley, 1997) to explain such temporal discrepancies. In that model, the up-dip portion of the detachment surface eventually becomes inactive after sufficient isostatic uplift of the footwall, which leaves room for only the down-dip portion of the fault to slip.

Structural analyses indicate that the study area formed as a result of multiple generations of normal faults that were active during distinct periods of time (Table 3; Fig. 13). This is indicated by the distinct ages of synextensional strata and their crosscutting relations to fault generations (Fig. 13; Tables 2 and 3), is consistent with prior geochronologic data, and is most evident when comparing timing of offset on the Catalina and San Pedro faults. These data, though not definitive, suggest the San Pedro fault is ~5 m.y. older than the Catalina fault. Such a relation is more simply explained by multiple generations of normal faults as opposed to a rolling-hinge model of detachments (Tables 2 and 3; Figs. 10 and 13).

Estimating Offset on Major Normal Faults

Using various geologic markers, previous authors have estimated a wide range of offsets for major normal faults within the study area. As previously mentioned, authors have typically interpreted the Catalina fault and San Pedro fault as a single detachment surface (e.g., Dickinson, 1991; Spencer et al., 2019). In this interpretation, the estimated offset for the detachment fault varies among authors; however, it typically ranges between 30 km and 60 km (e.g., Naruk, 1987; Krantz, 1983; Dickinson, 1991; Spencer et al., 2019). Markers used to make these estimates include contacts between Proterozoic granite suites, reverse faults, and the distribution of Cenozoic tectonic fabrics. Certain estimates consider that abundant, yet uncertain, slip contributed to the main detachment by hanging wall spays that branch upward from the detachment (Dickinson, 1991). The estimates typically do not explicitly account for the effects of intervening crosscutting faults.

The Catalina and San Pedro faults are two separate faults that belong to different generations of normal faults according to previously discussed geochronologic and crosscutting relations and restored orientations (Table 3; Figs. 2, 10, and 13). Estimated offset for these faults is not well constrained due to the lack of geologic markers that must clearly restore. Nonetheless, the reconstruction of surface geology provides estimates for the amount of offset on both major faults (Fig. 13). The Catalina fault has an estimated offset of 11 km and the San Pedro 10 km. These estimates are only made possible by schematically incorporating normal fault-related flexure in the reconstruction (Fig. 13). Even though there is uncertainty in these offsets (estimated to be ~10%–30% for most faults), the net Cenozoic extension, measured at 120% along section AA’ is relatively certain (on the order of 10%) given the numerous constraints used to reconstruct the section (e.g., surface geology, tectonic fabrics, older faults, synextensional strata). The magnitude of offset on these major faults is far lower than the various estimates for a proposed detachment surface by other authors. However, the combined offsets for faults of generations 1 through 3 (San Pedro through Catalina fault age) equal 63 km, which approximates previous upper-end estimates of offset for the detachment surface.

CONCLUSIONS

The Santa Catalina, Rincon, and southern Galiuro Mountains underwent significant extensional deformation during the mid-Cenozoic. Crosscutting
relations between faults and synextensional strata indicate that the study area was extended via multiple generations of originally steeply dipping, down-to-the-west, curvilinear faults. These faults tilted the majority of the study area an average of ~60° as evidenced by the orientation of the oldest synextensional strata. Structural reconstructions suggest 59 km of extension, or 120%, across the study area. The extensional style documented here is similar to that interpreted in areas just north of the study area along the San Pedro Valley, at Sierrita to the southwest, and in the Santa Rita Mountains to the south, and contrasts with the historically invoked detachment model. These results suggest that the detachment model also may not apply to other areas of extreme crustal extension pending detailed structural reconstructions and further field mapping. Additionally, our reconstructions demonstrate how a metamorphic core complex can be formed without slip on normal faults dipping less than 30°, a point that is supported by modern earthquake data.

Once restored to their original orientations, reverse faults that formed during the Laramide orogeny are moderately to steeply dipping. Because of this and the fact that these faults involve significant basement, these structures are interpreted to represent thick-skinned, basement-based uplifts. Once restored, some reverse faults that are separated across the map appear to have been originally linked when projected along strike. The thick-skinned structural style interpreted here contrasts with the historically interpreted thin-skinned overthrust model, but it is consistent with the structural style of reverse faults in locales surrounding the study area. Total vertical uplift along section AA’ measures 9.4 km, which makes this uplift system perhaps the largest documented in southeastern Arizona. This magnitude of uplift is consistent with the widespread exposure of metamorphosed Proterozoic through Mesozoic strata observed throughout the northeastern and eastern Santa Catalina–Rincon Mountains. In addition, the local preservation of synorogenic strata and a Cenozoic erosion surface along the northern San Pedro Valley are also consistent with such an uplift. Finally, new geochronology of select intrusions indicates that reverse fault offset occurred between 75 Ma and 54 Ma.

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APPENDIX A: GEOCHRONOLOGY OF SELECT INTRUSIONS

Table A1 contains results of U-Pb zircon geochronology for six samples in the study area, all of which were collected in the footwall of the San Pedro fault within the southeastern Santa Catalina and northeastern Rincon Mountains. Ages were obtained through microanalyses of zircons by the laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) method at the University of Arizona LaserChron Center.

These samples were collected to constrain the age of Laramide shortening and fabric development within the study area. All samples crystallized during the Laramide orogeny except for sample KGD-1, which crystallized during the mid-Cenozoic.

Sample Descriptions

KGD-1

Sample KGD-1 was collected from an undeformed and unaltered granodiorite porphyry dike that intrudes foliated, metamorphosed, and folded strata of the Bisbee Group in the footwall of the northernmost exposure of the Youtcy reverse fault (Fig. 2). Sample was chosen for dating to place a lower age limit on the Youtcy reverse fault. It contains 40% phenocrysts in a light- to medium-gray, fine-grained groundmass. Phenocrysts include 65% white feldspar, 1–10 mm; 20% hornblende, 1–3 mm; and 15% biotite, 1–2 mm.

KL-2

Sample KL-2 was collected from a sill of Leatherwood granodiorite that intrudes foliated, metamorphosed, and folded lower Paleozoic strata at the Korn Kab copper prospect (Fig. 2). The sample is foliated and weakly lineated, similar to that of the country rock. Foliation within the sample strikes east-northeast and dips moderately to gently south. Lineation trends east-northeast and plunges gently, and the shear sense is uncertain. Sample was chosen for dating to place an upper age limit on shortening within the general area. It contains 60% phenocrysts in a medium-to dark-grayish green micaceous groundmass. Phenocrysts include 35% white feldspar, 2–4 mm; 30% hornblende, 2–7 mm; 25% quartz, 2–4 mm; and 10% biotite, 1–2 mm.

TW-1

Sample TW-1 was collected from the large sill of Wilderness Granite just north of the Youtcy reverse fault (Fig. 5). The sample is weakly foliated, and nearby rocks of the same sill are either unfoliated or weakly foliated. The foliation in the dike strikes northwest and dips moderately to gently east. The sample was chosen for dating to place a lower age limit on the Youtcy reverse fault, as the sill cuts the reverse fault. The sample is a phaneritic two-mica granite consisting of 40% pink K-feldspar, 4–8 mm; 20% white plagioclase, 2–5 mm; 20% quartz, 2–6 mm; 10% biotite, 1–2 mm; and 10% muscovite, 1–2 mm.

TW-2

Sample TW-2 was collected from a dike of Wilderness Granite that has intruded foliated, metamorphosed, and folded strata of the Bisbee Group within the footwall of the Youtcy reverse fault (Fig. 5). The sample is weakly to moderately foliated, which is made most apparent by stretched quartz. The dike appears to be a boudin within the Bisbee Group, which locally contains outcrop-scale folds that display a top-to-the-east sense of shear. The foliation in the dike strikes north-northwest and dips moderately east similar to that of the host rock. The sample was chosen for dating to constrain the age of the top-to-the-east shear deformation. It consists of 70% white feldspar, 1–2 mm; 28% quartz, 1–4 mm; and 2% biotite, <1 mm.

TW-4

Sample TW-4 was collected from a dike of Wilderness Granite that has intruded Pinal Schist within the hanging wall of the Youtcy reverse fault (Fig. 5). The sample is moderately foliated, which is made most apparent by aligned micas. The foliation in the dike strikes northwest and dips moderately similar to that of the host rock. The sample was chosen for dating to place an upper age limit on the Youtcy reverse fault, as the fault appears to cut the dike. Alternatively, the dike may project above the fault and may have not been cut. Measurements on the dike margins and detailed field mapping are needed to constrain its geometry more accurately. The sample consists of 65% white feldspar, 1–3 mm; 20% quartz, 1–2 mm; 14% muscovite, 1–3 mm; and 1% garnet, 1 mm.
Results

Sample descriptions and analytical results are presented in Table A1 and Figures A1 and A2. Uncertainties shown are at the 2 sigma level and include only measurement errors. Analyses that are ~20% discordant (through comparison of $^{207}$Pb/$^{206}$Pb and $^{206}$Pb/$^{208}$Pb ages) or ~5% reverse discordant are not considered. The resulting ages are determined from the TuffZirc or weighted mean algorithms in Isoplot (Ludwig, 2008). For samples that show a broad range of ages (e.g., young ages of TW-6, the TuffZirc algorithm was used (Fig. A1). This routine finds the set of ages that has the highest degree of clustering and reports the median age and 2 sigma uncertainty of the cluster of ages. This internal uncertainty is then added quadratically to the external uncertainty for the session, and a final uncertainty of the age is reported (at 2 sigma). For samples that yield a relatively restricted range of ages (e.g., ca. 1.4 Ga ages in sample TW-1), the weighted mean algorithm was used. The weighted mean routine calculates the weighted mean (weighting according to the square of the internal uncertainties), the uncertainty of the weighted mean, the external (systematic) uncertainty that corresponds to the ages used, and the final uncertainty of the age (determined by quadratic addition of the weighted mean and external uncertainties).

Sample KGD-1 has an interpreted crystallization age of 27.2 ± 0.3 Ma and shows no sign of inheritance, as the core and rims are the same age. Sample KL2 has an interpreted crystallization age of 7.04 ± 0.8 Ma, and cores indicate inheritance ages of 1433 ± 5 Ma related to Oracle Granite and 1656 ± 12 Ma related to Johnny Lyon Granodiorite (Spencer et al., 2019) or Pinal Schist.

Sample TW-2 has an interpreted crystallization age of 52.7 ± 1.94/–1.64 Ma, and cores indicate inheritance ages of 1437 ± 18 Ma related to Oracle Granite and 1637 ± 12 Ma related to the Johnny Lyon Granodiorite or Pinal Schist.

Due to a lack of a suitable number of analyses, the crystallization age of sample TW-4 is uncertain. Inherited cores of several ages were recorded, which include 116.4 ± 1.3 Ma, 282.8 ± 4.0 Ma, and 1440 ± 10 Ma. The Proterozoic age is related to Oracle Granite. The mid-Cretaceous and Permian ages may represent inheritance from Bisbee Group strata, as these ages nearly overlap with observed detrital zircon populations from the lower Bisbee Group (Peryam et al., 2012). The Paleoproterozoic age is likely inherited from Oracle Granite.

Sample TW-5 has an interpreted crystallization age of 52.75 ± 0.63/–1.1 Ma. It contains multiple inherited core ages, which include 116.2 ± 3.5 Ma, 1429.6 ± 8.4 Ma, 1542.7 ± 6.8 Ma, 2274 ± 15 Ma, and 2534 ± 83 Ma. The Cretaceous age may represent detrital inheritance from the Johnny Lyon Granodiorite. The Paleoproterozoic age is related to Oracle Granite. The Paleoproterozoic and Neoarchean age may represent inheritance from detrital zircons within the Pinal Schist.

Age of ENE-Directed Shear Fabric and Reverse Faults

Results of U-Pb zircon geochronology (Table A1) and crosscutting relations in the field (Figs. 2, 3, 5, and 6) provide constraints on the timing of shortening and related fabrics within the general study area. Sample KL2 of Leatherwood Granodiorite, dated at 7734 ± 6.8/–1.3 Ma, is strongly foliated, and nearby fabrics indicate that this foliation is related to top-to-the-ENE shear (Byker-Kaufman, 2008). This suggests that the fabric is no older than the crystallization age of sample KL2. Another Leatherwood Granodiorite sample, collected in the western Santa Catalina Mountains, has been dated at 68.1 ± 1.2/–2.9 Ma (Fornash et al., 2013), but it is uncertain if it has been foliated and if that foliation was from the same period of shortening in the Rincon Mountains because no sample description was provided. Therefore, that sample is not used as a constraint. Further constraints on the age of the ENE-directed fabric come from dating sample TW-1 at 53.7 ± 0.8/–0.5, which was collected from a largely unfoliated stock of Wilderness
Granite that cuts the Yootcy fault. Because rocks of both the footwall (Bisbee Group) and the hanging wall (Oracle Granite and Apache Group) of the Yootcy fault are strongly foliated and largely have an ENE-directed shear fabric, and the Wilderness stock (TW-1) is largely unfoliated, the fabric must largely predate intrusion of TW-1 (Bykerk-Kaufman and Janecke, 1987). The above observations indicate that the ENE-directed shear fabric largely formed between 77.04 ± 0.8/–1 and 53.7 ± 0.8/–0.5 Ma.

The dating of samples of dikes of Wilderness Granite, samples TW-2 and TW-5, suggests the development of the ENE-directed shear may have persisted after the intrusion of the body dated by sample TW-1. Sample TW-2 has indirect evidence for the ENE-directed fabric, whereas TW-5 has direct evidence for the same fabric (Table A1). TW-2 has an age of 52.57 ± 1.94/–1.64 Ma, whereas TW-5 is dated at 52.75 ± 0.33/–0.94 Ma. The similar compositions and younger ages of these dikes suggest they emanated from the larger stock of Wilderness Granite (TW-1). Because these dikes are younger than TW-1 and display the ENE-directed fabric, deformation continued after the intrusion of TW-1. The weak foliation developed in some parts of the larger stock of Wilderness Granite (TW-1) may be related to ENE-directed shear; however, without definitive kinematic indicators, this remains unclear.

Current evidence cannot definitively link ENE-directed shear fabrics surrounding the Yootcy fault to shear on the Yootcy fault. Fabric intensity does not obviously increase toward the fault, and small-scale folds are better developed proximal to dikes of Wilderness Granite in general. This indicates that, during or after the injection of these dikes, some fabric development may result from regional compressional forces (and/or magmatic intrusion) as opposed to shear on the nearby fault plane. This is supported by the observations that TW-1 cuts the Yootcy fault, is largely undeformed, and is older than TW-5, which is deformed. Therefore, given these complexities, the timing of Laramide shear fabrics may not be representative of the timing of offset on individual reverse faults. There may be significant overlap in the timing of both, but more field observations and geochronologic data are needed to determine this precisely.

Other observations suggest that foliation may have largely existed prior to the intrusion of Wilderness Granite and related dikes. The modern north-northwest strikes of the dikes of Wilderness Granite near the Yootcy reverse fault (Fig. 5) closely resemble their original strikes because the local Cenozoic tilt axis is also oriented north-northwest. This original strike direction of the dikes is not consistent with intrusion during east-north directed compression; otherwise, the dikes would likely strike east-northeast. However, at least one of the dikes (sample TW-5; Fig. 6E) was clearly affected by compression, as it was sheared top-to-the-ENE. These relations suggest that the dikes intruded into foliation planes that were created by offset on the Yootcy fault and then were subsequently sheared due to regional stress probably before cooling to ambient temperatures.

This study provides one new timing constraint on reverse faulting in the area. Because TW-1 cuts the Yootcy fault, the fault must be older than 53.7 ± 0.8/–0.5 Ma. This is consistent with the age of the Cascabel Formation, which was likely sourced by local uplifts bounded by east-vergent reverse faults such as the Yootcy fault. The Muleshoe Volcanics, dated at 74.79 ± 0.39 Ma (Spen cer et al., 2015), underlie the Cascabel Formation and provide a lower age limit. Detrital zircon weighted mean ages indicate that the lower 500 m of the Cascabel Formation is 73.0 ± 2.5 Ma to 72.7 ± 1.1 Ma (Waldrip, 2008), and the youngest tuff layers near the top of the formation are dated at 64.4 ± 1.4 Ma (K-Ar biotite; Grover, 1982). These relations indicate that shortening occurred from 74.79 ± 0.39 Ma to sometime after 64.4 ± 1.4 Ma. Given the timing of ENE-directed fabrics near the Yootcy fault, this shortening may have continued to as late as 53.7 ± 0.8/–0.5 Ma, but this may be too long-lived for the life of a single reverse fault system.

**APPENDIX B: STRUCTURAL RECONSTRUCTION CONSTRAINTS AND UNCERTAINTIES**

Below is an in-depth discussion of various constraints and uncertainties concerning the structural reconstruction (Figs. 13–15).
Figure A1. TuffZirc age plots of the crystallization age of each sample. Each bar represents a single spot analysis. Red bars represent ages used to calculate final age.
Figure A2. Concordia diagrams for U-Pb dates.
Normal Fault Spacing, Related Tilting, and Flexure

Constraints from field observations provide an estimate on the amount of tilting for each generation of normal faults (Table 3; Fig. 10). These data, along with known fault spacing and estimated flexure, are used to estimate net fault offset for a particular fault generation. These data are particularly useful for estimating offset on major faults that lack other local constraints such as the Catalina and Cloudburst faults (Fig. 2). In the case of hypothesized and projected normal faults, i.e., faults that are currently buried or faulting is not fully known. For these faults, only a limited range of possible fault locations exists, as these faults are needed to restore key outcrops (Fig. 15). The poorly known original spacing of these faults does affect estimates of tilting and offset, which further demonstrates the non-uniqueness of the orientations of faults suggested by the data (Fig. 15, see Espiritu Canyon area). Here, flexural bending of upper crustal blocks in each section is shown schematically, and the flexural wavelengths employed are based on field analogues elsewhere in the Cordillera (e.g., Colgan et al., 2008; Van Buer, 2012; Thompson and Parsons, 2016).

Once an initial restoration of a given fault generation was carried out, the section was deformed forward in time to test whether the cross section, given the inputs of fault offsets, fault spacing, and flexural bending related to fault offset, was able to maintain cross sectional edges that only move out laterally and not vertically. The maintenance of these edges directly implies that they are not deformed (Fig. 13) and ensures that either side of the section does not experience broad vertical uplift—an unreasonable outcome of purely extensional settings. This was a common problem encountered during failed restoration attempts (despite surface data being restored). Conversely, vertical subsidence of one side of the section may be plausible, but given the lack of data to support such occurrences locally over such short time intervals (e.g., 3-5 m.y.), it is most simple to model extension where regional borders are maintained. A minor exception to this occurs in the restoration of fault generation 5 (Fig. 13), as flexure related to normal fault offset is not modeled because offsets on faults are minimal and related tilting would be negligible. Once a given stage of the section was deformed forward in time and flexure had been added to make sure the edges of the cross section did not rotate, the elevation difference between the ends of the cross section were compared, and adjustments were made where necessary. If, for example, a down-to-the-west normal fault set was modeled forward in time and the westernmost edge of the section ended structurally higher than the eastern edge (i.e., compensated uplift), this would suggest that either (1) more net fault offset is required for that fault generation, (2) the fault spacing needs to be adjusted, or (3) flexure needs to be adjusted to maintain undeformed and level section edges while nonetheless honoring firm geologic constraints. The amount of offset on faults typically was the most significant geometric parameter that influenced vertical displacement of the edges of the cross section.

Tectonic Fabrics and Structural Depths

Both Laramide and Cenozoic tectonic fabrics help to guide the structural reconstruction (Table 1; Figs. 2–6). These fabrics developed at a range of structural depths from the shallow, near-surface environment to the brittle-ductile transition (Figs. 14–15).

It is unclear if tectonic fabrics of the Laramide orogeny were caused by reverse fault shear, regional compressional stresses, emplacement of magmas, or a combination of these or other factors. Nonetheless, the tectonic fabric and metamorphism that developed in rocks of the foothills and hangingcurtain of the Youcute reverse fault (Figs. 5–6) suggest relatively deep structural burial by offset on a Laramide reverse fault(s) (perhaps 6–8 km depth; Figs. 13–15). Conversely, strata of the Bisbee Group in the footwall of the nearby Roble Spring reverse fault are not metamorphosed and only weakly foliated (Figs. 4 and 6C–6D). Given that the oldest mid-Cenozoic unit, Mineta Formation, does not structurally overlie them and considering the weakness of the carbonate lithology, these rocks were likely not buried deeply by offset on a reverse fault (Figs. 4 and 14–15). Similarly, rocks in the southern Galiuro Mountains are also not metamorphosed, and foliation is only weakly to moderately developed (Figs. 3 and 6A–6B). These rocks were probably buried slightly deeper than those near the Roble Spring reverse fault because penetrative deformation here is somewhat more intense and common (Fig. 15). Finally, the Loma Alta fault in the southwestern Rincon Mountains may project into section AA’ as the fault is currently horizontal (Fig. 2). Rocks here are also not metamorphosed or foliated, which suggests that they were never significantly structurally buried and therefore must restore close to the post-shortening paleosurface (Fig. 15). Like Laramide fabrics, Cenozoic fabrics help guide the depths to which certain outcrops should be restored. Cenozoic fabrics that are lineated are definitively linked to offset on major normal faults, whereas the origin of unlinedated fabrics is less certain and may be more related (or exclusively related) to magmatism (Spencer et al., 2019). In the northern flank of Happy Valley (Fig. 2), a well-developed mylonitic fabric is developed in Oracle Granite a few tens of meters below the San Pedro fault (Spencer et al., 2011; Spencer et al., 2019). This fabric extends 3 km to the east, where it is identified in carbonate rocks a few meters below the fault. Because mylonites are only developed in a small zone proximal to the fault and quickly taper out to the east, this area was probably only slightly above the brittle-ductile transition and perhaps 8–10 km deep. In the restored section of Figure 15, this area would be located a few kilometers below Espiritu Canyon, which is consistent with the observed deformation. Cenozoic fabrics that are not lineated probably restore to depths of 5–7 km in the reconstruction (Fig. 15, see Espiritu Canyon area). This shallowest model is preferred because it implies a lack of lineations if normal fault shear created these fabrics. Regardless, the pervasiveness of this fabric away from faults and relatively shallow restored depth does suggest that magmatism facilitated deformation. Finally, Cenozoic tectonic fabrics are developed in the immediate footwall of Catalina fault (Fig. 2) in a much wider zone than that of the San Pedro fault at Happy Valley. Here, strongly developed mylonites in Proterozoic and Cenozoic granites suggest that this area should restore to deep crustal levels of perhaps 20–25 km (Fig. 15).

Uncertainties

Offset on Individual Faults

Several reverse faults lack precise markers for estimating fault offset, as they contain Proterozoic basement of unknown structural level in their hanging walls (Figs. 2; Table 1). In cases like these, such outcrops of basement are assumed to be near the basement cover interface; therefore, the estimated reverse fault offsets are minimum estimates (Fig. 15). Because the complete Mesozoic stratigraphic section is not observed in the study area (Fig. 2), its true thickness is unknown, which adds additional uncertainty to reverse fault offset estimates.

Several Cenozoic normal faults also do not have geologic markers to constrain the amount of offset. However, offset can be estimated if realistic cross sectional geometries are maintained across each stage of the reconstruction. For some normal fault systems, the complex arrangement of data can make estimates of fault offset and assessment of structural evolution difficult. For example, certain groups of faults share similar orientations and project into one another, which implies that they belong to a single fault system (and possibly a single fault surface); however, stereonets of geologic fabrics across individual faults suggest significantly different offsets on each fault. This is most relevant to the Espiritu shear zone and San Pedro, Mineta, and Italian Trap faults, all of which are interpreted to be part of a single fault system (Figs. 13–14). The Espiritu Canyon shear zone is interpreted as part of a structurally deep horse of the San Pedro fault, and the Mineta fault is interpreted as a hanging wall splay of the San Pedro fault (Fig. 14).
Even though there are uncertainties about the offset of several individual faults, the combined offset of all faults is plausible and honors geologic observations. The amount of offset, spacing of faults, and estimated faulting could be changed to result in other plausible interpretations; however, the final reconstruction would largely resemble what is presented here because of constraints imposed by mapped geologic relations.

**Areal Extent of Cenozoic Tilting**

The net Cenozoic tilting for localities across the study area (Fig. 9) is constrained by geologic observations locally and within the surrounding region (e.g., San Manuel). Even though field data indicate the maximum tilting produced by each normal fault generation (Fig. 10; Table 3), these values are less certain than the net estimates. This applies most directly to the southern Galiuro Mountains (Figs. 2–3). Where section AA’ intersects the Soza Mesa area, there is at least 40°E net tilting as is suggested by the orientation of the oldest Galiuro Volcanics (Figs. 2–3). However, Mineta Formation is located to the south of AA’ at Teran Basin (Fig. 3), which suggests that the oldest generation of normal faults [1] may have tilted the Soza Mesa area more than the younger Galiuro Volcanics suggest and perhaps by 5°–10° more. This uncertainty also applies to the central and western Santa Catalina-Rincon Mountains, where generation 4 faults are hypothesized to result in only 5°E of tilting due to a lack of related faults in this area (Fig. 13).

**Pre-Shortening Normal Fault**

Results from the structural reconstruction suggest that a normal fault formed within the San Pedro Valley prior to shortening, which has perhaps 1–2 km of slip (Fig. 15). Given the apparent timing, this fault may have formed during the development of the Biabe basin. According to reconstruction constraints, the Robie Spring reverse fault likely formed in the hanging wall of the Youtcy fault (Fig. 15). Because of this, rocks in the footwall of the Youtcy fault must connect to rocks in the hanging wall of the Hot Springs fault. To accomplish this connection with realistic fault-related folds, an intervening pre-shortening normal fault appears to be necessary. An alternate way to connect these rocks would be to increase offset on the San Pedro fault by perhaps ~5 km. However, this would not honor geologic observations because this configuration would directly imply that the Kelsey Canyon fault was at the same structural depth as the Youtcy fault. This is unlikely because Bisbee strata in the former location are not metamorphosed or foliated whereas in the latter those strata are metamorphosed and strongly foliated (Fig. 3). This additional configuration would also imply that the southern Galiuro Mountains underwent significantly more post-shortening erosion (approximately an additional 4 km) than the eastern Rincon Mountains as indicated by the restored position of Mineta Formation and Galiuro Volcanics (Fig. 13). Such a configuration would be unreasonable because the eastern Rincon area experienced greater uplift than the southern Galiuro area (according to tectonic fabrics) and thus was more likely to experience greater erosion. In addition, the thick succession of synorogenic strata preserved in the southern Galiuro Mountains (Figs. 2–3) suggests that this area would have been generally more prone to burial than erosion after shortening (Fig. 15).

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