Structure, chronology, kinematics, and geodynamics of tectonic extension in the greater Catalina metamorphic core complex, southeastern Arizona, USA

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ABSTRACT

Oligocene and early Miocene displacement on the Catalina–San Pedro detachment fault and its northern correlatives uncovered mylonitic fabrics that form the greater Catalina metamorphic core complex in southeastern Arizona, USA. Gently to moderately dipping mylonitic foliations in the complex are strongly lineated, with a lineation-azimuth average of 064–244° and dominantly top-southwest shear sense over the entire 115-km-long mylonite belt. Reconstruction of detachment fault displacement based on a variety of features indicates 40–60 km of displacement, with greater displacement in more southern areas. Widespread 26–28 Ma volcanism during early extensional basin genesis was followed by 24–26 Ma granitoid magmatism. Cooling of footwall mylonites continued until 22–24 Ma, as indicated by \(^{26}Ar/^{26}Ar\) mica dates. Lower temperature thermochronometers suggest that footwall exhumation was still underway at ca. 20 Ma. Tectonic reconstruction places a variety of unmetamorphosed supracrustal units in the Tucson and Silver Bell Mountains above equivalent units that were metamorphosed and penetratively deformed in the Tortolita and Santa Catalina Mountains. This restored juxtaposition is interpreted as a consequence of older Laramide thrust burial of the deformed units, with northeast-directed thrusting occurring along the Wildhorse Mountain thrust in the Rincon Mountains and related but largely concealed thrusts to the northwest. Effective extensional exhumation of lower plate rocks resulted from a general lack of internal extension of the upper plate wedge. This is attributed to a stable sliding regime during the entire period of extension, with metamorphic core complex inflation by deep crustal flow leading to maintenance of wedge surface slope and detachment fault dip that favored stable sliding rather than internal wedge extension.

INTRODUCTION

Structural styles of large-magnitude continental extension vary dramatically. In many metamorphic core complexes, lack of internal extension in upper plate rocks during detachment faulting resulted in efficient exhumation of deeply formed mylonitic fabrics (e.g., Pain, 1985; Murphy et al., 2002; Little et al., 2007, 2019; Spencer, 2011; Spencer et al., 2016). In contrast, extension in other areas, in some cases synchronous and along strike with exhumation of a metamorphic core complex, produced highly extended tilt-block arrays without any exposure of mylonitic fabrics below detachment faults (e.g., Proffett, 1977; Anderson, 1977, 1978; Chamberlin, 1983; Grubensky, 1989; Richard et al., 1990; Nickerson et al., 2010; Favorito and Seedorff, 2017, 2020). This contrast is plausibly explained as the difference between stable and unstable sliding of the upper plate during extension where unstable sliding resulted in extensive extension of the upper plate, although in many areas it is uncertain if detachment faults actually underlie the tilt blocks because these faults are not exposed. This terminology of stable and unstable sliding is derived from critical taper theory, also known as “critical Coulomb wedge theory,” which models an upper plate with a wedge shape in cross section as composed of non-cohesive material such as dry sand or highly fractured rock (Dahlen, 1984; Xiao et al., 1991). Analog sandbox models confirm that contrasting stable versus unstable extension results from differences in surface slope, fault dip, and the friction coefficients of the wedge material and the underlying fault surface (Dahlen, 1984; Xiao et al., 1991). In this article we present data constraining the geometry, chronology, and kinematics of Oligocene to lower Miocene extensional detachment faulting, mylonitic fabric development, and uplift and exhumation of the greater Catalina metamorphic core complex in southeastern Arizona (Fig. 1). We also evaluate the relationship between extension and magmatism and conclude by identifying geodynamic factors that appear to have promoted stable rather than unstable sliding of the upper plate.

Another aspect of this study concerns the relationship between detachment faulting and older thrust faulting. A previous study determined that the Catalina–San Pedro detachment fault, which uncovered the Catalina core...
Figure 1. Simplified geologic map shows the extent of mylonitic fabrics in the greater Catalina metamorphic core complex, Oligocene to Miocene sedimentary and volcanic rock units, major faults, and pre-Oligocene rock units divided into those below and above the Catalina–San Pedro detachment fault. All detachment faults shown, except for the San Xavier–Ajo Road detachment fault, are considered part of the Catalina–San Pedro detachment fault system. Also shown are depth-to-bedrock contours from Richard et al. (2007). Abbreviations in the Santa Catalina and Rincon Mountains: PP—Pusch Peak; ML—Mt. Lemmon; MB—Molino Basin; MM—Mica Mountain; RP—Rincon Peak. Mts—Mountains, Mtn—Mountain.
complex, formed partly within calcareous metasedimentary rocks in the footwall of the Wildhorse Mountain thrust in the eastern Rincon Mountains (Spencer et al., 2019). Deeply buried carbonates would have formed a weak zone in the crust, and detachment fault localization in such rocks would be expected if they had been tectonically buried to temperatures of ~200–300 °C (Singleton et al., 2018). Reconstruction of 40–60 km of detachment fault displacement in the Catalina metamorphic core complex places a variety of weakly metamorphosed to unmetamorphosed rock units in the Tucson and Silver Bell Mountains above metamorphosed and penetratively deformed Paleozoic and Mesoproterozoic strata and associated units in the Tortolita and Santa Catalina Mountains. In this study we propose that much of the Catalina metamorphic core complex formed the lower plate of one or more Laramide thrust faults and that detachment fault initiation occurred in close association with this thrust system, possibly because tectonically buried carbonates formed a weak zone in the pre-extension crust.

Geologic Setting

Basement in southeastern Arizona consists of 1.6–1.8 Ga granitic, gneissic, and schistose rocks intruded by ca. 1.4 Ga granites (Richard et al., 2000a), with thin overlying strata of the Mesoproterozoic Apache Group and associated 1.1 Ga diabase sills and dikes (Shride, 1967; Wrucke, 1989). Paleozoic strata that blanket much of southwestern North America and are well displayed in the Grand Canyon are thin (~1–2 km), as is characteristic of Paleozoic strata within the transtensional arc that extends across much of cratonic North America (Sloss, 1988). Jurassic subduction-related magmatism and latest Jurassic to Cretaceous tectonic extension associated with the Bisbee Group were followed by Laramide (50–80 Ma) thrust faulting, voluminous subduction-related magmatism, and porphyry copper mineralization (e.g., Dickinson et al., 1989; Leveille and Stegen, 2012). Eocene (55–35 Ma) peraluminous magmatism produced heterogeneous pegmatitic leucogranite that is exposed primarily in metamorphic core complexes (Fornash et al., 2013; Davis et al., 2019; Chapman et al., 2021). Multiple subhorizontal sills and irregular bodies of pegmatitic leucogranite, with screens and inclusions of Proterozoic crystal-line rock, form much of the Catalina metamorphic core complex (e.g., Drewes, 1974, 1977; Keith et al., 1980; Force, 1997; Ferguson et al., 2002). A penetrative, high-temperature, crystalloblastic (non-mylonitic) fabric, characterized by sub-horizontal lithologic layering and preferred orientation of minerals including micas, is cut by pegmatites that are variably involved in the flattening deformation (Fig. 2A). The youngest pegmatites are only weakly affected by this high-T deformation, while much of the older rock consists of banded gneiss. Oligocene to early Miocene WSW–ENE tectonic extension, mylonite genesis and exhumation by detachment faults, and widespread subduction-related magmatism were followed by Miocene to Pliocene NNW–ESE extension and high-angle normal faulting that produced much of the modern Basin and Range topography (Fig. 1; Spencer and Reynolds, 1989; Dickinson, 1991; Davis et al., 2004; McQuarrie and Wernicke, 2005).

The greater Catalina metamorphic core complex encompasses mylonitic rocks in the Rincon, Santa Catalina, Tortolita, Suizo, and Picacho Mountains, the Durham Hills, and Desert Peak (Fig. 1). The metamorphic core complex is a 115-km-long, dominantly top-southwest mylonitic shear zone with features characteristic of tectonic extension, including strongly linedated mylonites, mylonitic fabrics characterized by high degrees of grain-size reduction, position below a top-southwest extensional detachment fault, and thermochronologic evidence for cooling and exhumation during tectonic extension. Footwall rocks directly below the detachment fault are characterized by sequentially developed chloritic breccia, cataclastite, and iron oxide-stained brittle fractures overprinting footwall mylonitic fabrics and other igneous and metamorphic footwall rocks (e.g., Davis, 1980; Davis et al., 1986; Reynolds and Lister, 1987). Rocks above the detachment fault include tilted Oligocene to lower Miocene Miocene calcareous and clastic units deposited in syn-tectonic basins that locally include mylonitic debris shed from the rising core complex (Dickinson, 1991). The lower plate in the Rincon Mountains has a corrugated form, with corrugation axes parallel to extension direction (Fig. 3), as do many other core complexes (e.g., Spencer and Ohara, 2014).

Purpose

This paper is primarily an analysis and synthesis of geologic map and geochronologic data produced over the past 40 years that are relevant to understanding the tectonics of mid-Cenozoic extension in the greater Tucson area. Most of the geologic maps that form the primary basis for this review were produced by the Arizona Geological Survey from 1998 through 2010 with funding from the joint state and federal STATEMAP program as specified by the National Geologic Mapping Act of 1992. The first section of this paper summarizes the results of 1846 measurements of mylonitic lineation and foliation in the greater Catalina metamorphic core complex. These measurements are listed in Item S1 in the Supplemental Material1. The second section summarizes geochronologic data related to the magmatic and cooling history of the Catalina metamorphic core complex and surrounding areas. Seventy-nine dates relevant to our analysis are listed in Item S2 (see footnote 1), and seven new U-Pb dates are included, with analytical data provided in Item S3. Data for most U-Pb dates are available in Spencer et al. (2015), while 40Ar/39Ar dates are listed by Spencer et al. (2017) with sources of analytical data specified. This is the first synthesis of geochronologic and thermochronologic data for the entire Catalina metamorphic core complex that incorporates 40Ar/39Ar and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb analyses. The third section evaluates rock types and offset features to arrive at a synthesis of displacements on the greater Catalina–San Pedro detachment fault and its relatives to the northwest, including the Guild Wash fault in the

1Supplemental Material. Item S1: Mylonitic lineation and foliation data. Item S2: Summary of geochronologic dates and sources. Item S3: New U-Pb geochronologic data. Please visit https://doi.org/10.1130/GEOS.5.20334990 to access the supplemental material, and contact editing@geosociety.org with any questions.
Figure 2. Images show mylonitic granitic and gneissic rocks in the Santa Catalina Mountains. (A) Deformed pegmatitic dikes and sills within foliated 1.4 Ga granite in the Catalina forerange. Pegmatite injection, folding, and flattening are interpreted as pre-mylonitic events that occurred during Eocene leucogranite magmatism. Visible part of highway sign is ~1 m high. (B) Strongly mylonitic Eocene leucogranite with streaks of highly comminuted white feldspar and plastically deformed gray quartz, Catalina forerange. Surface is parallel to mylonitic foliation. (C) Photomicrograph, with crossed Nichols, of a mylonitic quartz vein, Babad Do’ag area, Catalina forerange (see Fig. 5 for location). Thin section is cut parallel to lineation and perpendicular to foliation. Straight and thin horizontal zone across the middle of the image, consisting of sheared muscovite, is parallel to foliation and is interpreted as a “C” surface in an S-C mylonite (Lister and Snoke, 1984). Grain elongation from lower right to upper left indicates top-left shearing in a strain regime of recrystallization-assisted dislocation creep (Platt et al., 2015). (D) Same image as in Figure 2C but with quartz plate inserted and microscope stage rotated so that fast and slow directions of quartz crystals and the inserted quartz plate are maximally additive, for greatest birefringence. The fact that maximum birefringence corresponds to stage rotation of 54° from alignment with polarization direction, rather than 45°, indicates that the quartz crystallographic c-axes are tilted forward in the direction of shearing, which yields the same shear sense as is indicated by the grain shape (Spencer, 2006). (E) Field photograph of S-C mylonite from southeastern Santa Catalina Mountains (northwest of Bellota Ranch klippe, which is located on Fig. 5). (F) Same image as in Figure 2E but with red lines to highlight some of the surfaces of flattening (S surfaces) that, with subhorizontal shearing surfaces (C surfaces), indicate top-southwest (top-right) mylonitic shearing.
northern Tortolita Mountains. This analysis requires consideration of Mesozoic thrust faults that were reactivated by the major extensional detachment fault system. This is followed by analysis and discussion that includes evaluation of the following issues: (1) structural styles of upper plate extension, (2) origin of mylonitic fabrics, (3) chronology of magmatism and extension and the relationship between the two, (4) implications for the geometry of thrust faults in the Rincon Mountains area that were dismembered and dispersed by tectonic extension, (5) the relationship of Laramide thrust faulting to the greater Catalina metamorphic core complex, and (6) consideration of geodynamic factors that determined the style and degree of exhumation of the metamorphic core complex.

**MYLONITIC SHEAR ZONES**

Lineated mylonitic fabrics overprint much of the lower plate of the Catalina–San Pedro extensional detachment fault and similar, related faults to the northwest such as the Guild Wash fault on the northern flank of the Tortolita Mountains (e.g., Davis, 1980; Davis et al., 2019). Mylonitic fabrics are better developed on the southwestern flanks of the ranges and are rare or absent low on the northeastern flanks, which reflects overall tilting to the northeast and greater uplift on southwestern range flanks. The general northeast dip of Paleozoic strata, widely exposed on the northeastern flank of the Santa Catalina Mountains, is consistent with northeast tilting of the entire range (e.g., Force, 1997; Byker-Kaufman, 2008).

The mylonitic fabric in the Catalina metamorphic core complex is readily identified by its well-developed lineation and grain-size reduction. Feldspars are commonly broken and where strongly mylonitic are crushed and smeared into streaks (Fig. 2B), while quartz grains were subjected to a combination of brittle and crystal-plastic deformation. In thin section, grain-size reduction is especially apparent in vein quartz where quartz grains are broken into numerous subgrains and reduced to ~10–50 μm diameter, but grain boundaries are sutured, and quartz-crystal C-axes have a strong preferred orientation and are slightly tilted in the direction of shearing (Figs. 2C–2D). In outcrop, the older, non-mylonitic, crystalloblastic fabric is distinguished from the mylonitic overprint because the mylonitic fabric is well lineated but the older crystalloblastic fabric is not. Indeed, some of the mylonitic fabrics appear as L-tectonites, while most of the non-mylonitic gneiss and leucogranite are not lineated at all. Grain-size reduction in the mylonitic rocks is unlike the older foliation in which mica appears to have grown parallel to lithologic layering rather than being crushed and shredded (Fig. 2C). The mylonitic fabric is generally well developed at high structural levels where it is, or was, within a few tens to perhaps 100–300 m of the overlying detachment fault. It is weak, discontinuous, or absent in deep canyons where the nonlined or weakly lineated crystalloblastic fabric in gneissic rocks was conflated with the mylonitic fabric by Ducea et al. (2020). Well-developed mylonitic lineations have a gentle plunge and a similar, ~064–244° trend along the southwest flank of the entire 115-km-long shear zone (Fig. 4; Item S1, see footnote 1). Dominantly top-southwest shear sense is apparent from S-C mylonites and asymmetric tails on feldspar porphyroclasts (Figs. 2E–2F; Perry, 2005; Spencer, 2006; Davis, 2013; Spencer and Constenius, 2020).

Complex shear zone geometries and, in the Santa Catalina Mountains, opposite shear sense on opposite sides of the forerange arch, indicate that mylonitic fabric development was not simply the result of unidirectional displacement on a single inclined normal-shear zone. In the southeastern Santa Catalina Mountains, mylonitic foliation and lithologic layering in host gneiss and layered pegmatitic leucogranites define an antiform, known as the “forerange arch,” which has an axis that plunges gently toward ~280° (Fig. 5A; Reynolds and Lister, 1990; Naruk and Byker-Kaufman, 1990; Force, 1997). The south side of the antiform is characterized by strong mylonitic foliation and lineation at high structural levels, whereas the north side is only moderately deformed with a general lack of ultramylonites characterized by extreme grain-size reduction. Shear sense is dominantly top-southwest on the south side of the arch and top-northeast on the north side (Figs. 5B–5C). The
Figure 4. Lower hemisphere stereonet projection shows primary eigenpoles for 20 sets of mylonitic lineation measurements, which represent 1428 measurements listed in Item S1 (see text footnote 1) from the greater Catalina metamorphic core complex, excluding the Molino Basin and Windy Point shear zones. Box with numbered axes represents all data. Eigenpoles are plotted rather than Fisher vectors because lineations are lines, not vectors. Plot and eigenpoles were generated with Stereonet 10.0 (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013).

Davis and Lister (1988; Reynolds and Lister, 1990; Naruk and Vectors. Plot and eigenpoles were generated with Stereonet 10.0 (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013). Within the Molino Basin shear zone, lineation trend, at ~065° at the arch crest, is more northerly at progressively greater distances to the north such that the lineation trend is 40° more northerly 4 km north of the arch axis (Fig. 5C).

The Windy Point shear zone, located well above the mylonitic front, is characterized by subhorizontal mylonitic foliation with a top-southwest shear sense (Fig. 5; Force, 1997; Davis et al., 2019). It projects southward from Windy Point into the air and toward the crest of the forerange arch. Correlation with mylonitic fabrics on the south side of the arch is suggested by foliation alignment and by the consistent mylonitic lineation trend along a curved path, with the mylonitic fabrics between the Windy Point shear zone and the south flank of the forerange arch now removed by erosion (Fig. 5C). At its northernmost exposures along the range crest, the mylonitic fabric is weakly developed and rarely apparent, and the shear zone projects northward into the air.

The Molino Basin shear zone strikes eastward toward the Bellota Ranch klippe (Fig. 5A), which is a remnant of the upper plate of the Catalina–San Pedro detachment fault that consists of Paleozoic carbonate and quartzite and mid-Cenozoic clastic strata. Mylonitic foliation generally weakens to the east and dies out within a few kilometers east of the klippe. Lineation trend is even more northerly in the Bellota Ranch area than in the Molino Basin shear zone. Shear sense is dominantly top-southwest, but the shear zone incudes top-northeast shear-sense indicators (Bykerk-Kaufman, 2008; Spencer and Constenius, 2020) and thus appears to have elements of both the Molino Basin shear zone and the Windy Point shear zone. To the south in the Rincon Mountains, mylonitic lineations parallel the curved crest of Tanque Verde Ridge (Fig. 3; Spencer et al., 2019). The map view curvature of mylonitic lineation trends in the Rincon Mountains is gradual compared to that in the Santa Catalina Mountains, with opposite directions of curvature in the two ranges (Fig. 6). All three lines plotted in Figure 6 are consistent with vertical axis rotation of rock masses above or below the mylonitic shear zones with the different slopes of the lines indicating different radii of curvature for the different shear zones.

The Guild Wash fault on the northern flank of the Tortolita Mountains and its equivalents directly to the north in the Suizo Mountains and Durham Hills (Fig. 7) are characterized by a mylonitized footwall with chloritic breccia as is typical of extensional detachment faults (Banks, 1980; Ferguson et al., 2002; Spencer et al., 2002; Richard et al., 2002). The mylonitic foliation that extends over much of the Tortolita Mountains dips northward beneath the Guild Wash fault with a roughly subparallel orientation, but the fabric is discordant in detail. Furthermore, a small area of mylonitic fabric in the hanging wall near the western edge of the range appears to be a displaced fragment of the shear zone (Ferguson et al., 2002). In the northeastern corner of the range, the Carpas Wash shear zone is characterized by a lineated mylonitic fabric that is separated from the eastern end of the Guild Wash fault by less mylonitic to non-mylonitic rocks (Fig. 7). The north-northwest–striking Indian Springs fault truncates the mylonites associated with the Guild Wash fault, and it appears that the Carpas Wash shear zone is the offset continuation of the mylonitic shear zone (Fig. 7). The Carpas Wash shear zone is also cut by a non-mylonitic dacite dike dated at 25.1 ± 1.2 (2σ) Ma (Item S2, see footnote 1; Ferguson et al., 2002; Spencer et al., 2003a). These relationships indicate that mylonitization in the Carpas Wash shear zone occurred before ca. 25 Ma and was followed by offset on the Indian Springs fault, which was in turn followed by displacement on the Guild Wash fault.

The lineated mylonitic fabric that overprints ca. 25 Ma plutons is indistinguishable from the mylonitic fabric that affects older rock types along the main mylonite zone. Mylonitic fabrics overprint the Tortolita and Wild Burro Canyon plutons in the southern Tortolita Mountains, granodiorite and diorite in the Durham Hills, and the Barnett Well Granite in the Picacho Mountains (Fig. 8). These granitoids are all dated by U-Pb zircon isotopic analysis at 24.2–25.7 Ma (Fig. 8; Item S3). With a few exceptions, lineation orientations are similar...
Figure 5. (A) Map of the south side of the central and southeastern Santa Catalina Mountains shows leucogranite and gneiss, undivided (orange) and metasedimentary rocks (blue). Each arrow shows the average trend and plunge direction of several mylonitic lineation measurements. (B) Mylonitic lineation plunge versus distance from the crest of the forerange arch for measurements between the two blue lines in Figure 5A. Distance is measured perpendicular to arch crest. Positive plunge corresponds to southwestern plunge, and negative plunge corresponds to northeastern plunge. (C) Mylonitic lineation trend versus distance from the axis of the forerange arch for measurements between the two blue lines in Figure 5A. Distance is measured perpendicular to arch crest. Northeast-plunging lineations were transposed to the southwest quadrant (+180°). Data are from Item S1 (see text footnote 1).
elsewhere within the Catalina metamorphic core complex (Fig. 4). Some of the variation in lineation trend and plunge apparent in Figure 4 can be attributed to late Cenozoic normal faulting and associated tilting, especially in the Suizo Mountains and Durham Hills, which are cut by late Cenozoic, high-angle normal faults (Fig. 1). In contrast to Ducea et al. (2020), we emphasize that there is no apparent difference between mylonitic lineation character and orientation within ca. 25 Ma granitoids and older rocks that are far from the granitoids and their thermal aureoles.

**MAGMATIC AND THERMAL HISTORY**

Geochronologic data are outlined below to assess the relationship between extension and magmatism and to identify the chronology of tectonic exhumation and associated footwall cooling. Sixty-seven dates in the 15–35 Ma age range are included in this analysis, including all available 40Ar/39Ar dates of volcanic rocks and U-Pb zircon dates of granitic plutons (Figs. 8–10; Item S2, see footnote 1). Because of large uncertainties in K-Ar and fission-track dates, these dates were only used for specific rock types or geographic areas where high-precision data were lacking. Much of the geochronologic and thermochronologic data utilized here are from Arizona Geological Survey (AZGS) open-file reports and AZGS digital-information series reports and include seven new U-Pb dates reported in Item S3.

During Eocene time and before the beginning of tectonic extension in the Oligocene, southern and western Arizona were highlands that shed sediments northeastward onto what is now the Colorado Plateau and southwestward toward the continental margin (e.g., Peirce et al., 1979; Cather and Johnson, 1984; Spencer and Reynolds, 1989; Abbott and Smith, 1989; Potochnik and Faulds, 1998). Eocene leucogranite emplacement at mid-crustal depths represents the only apparent geologic activity prior to Oligocene extension and magmatism (Davis et al., 2019). The earliest indication of renewed tectonic and magmatic activity in the greater Tucson area consists of a 33.47 ± 0.08 (2σ) Ma tuff interbedded with the Whitetail Conglomerate in the central Galiuro Mountains (Krieger, 1968) and a welded tuff dated at 33.01 ± 0.38 (2σ) Ma at the base of tilted clastic strata south of the Rincon Mountains (Figs. 9, 10A, and 11; Spencer et al., 2001). Neither of these necessarily indicates initial extension, as the tuff in the Galiuro Mountains is interbedded with strata that are still subhorizontal, and the tuff in Cienega Basin rests directly on bedrock or on a minor amount of conglomerate. These tuffs could be far-traveled products of explosive volcanism from farther east in the Mogollon-Datil volcanic field (McIntosh et al., 1992), an area that was many tens of kilometers closer prior to province-wide extension (Kruger et al., 1995; McQuarrie and Wernicke, 2005).

Initiation of extension is most clearly revealed by deposition of coarse, clastic sediments in tilted fault blocks above the Catalina–San Pedro detachment fault and its correlatives, and above the San Xavier detachment fault southwest of Tucson. Tilted and faulted conglomerate and sandstone within the Pantano Formation in Cienega Basin south of the Rincon Mountains contain two ash beds, both ~300 m above the base of the strata, which are dated at 26.44 ± 0.09 (2σ) Ma and 27.50 ± 0.09 (2σ) Ma (Fig. 11; Spencer et al., 2001; Peters et al., 2003). At Star Flat, northeast of the Tortolita Mountains, an ash...
Basalt of Three Buttes (lower Miocene)
Rock-avalanche breccia (lower Miocene)
Conglomerate and sandstone upper unit (lower Miocene)
Conglomerate and sandstone (Oligocene to Miocene)
Mafic to dacitic volcanic rocks (Oligocene to Miocene)
Granitic rocks (Cretaceous to Oligocene)
Granitic and gneissic rocks (Proterozoic to Eocene)
Granitic rocks and Pinal Schist (Proterozoic)

Figure 7. Geologic map and cross section of the north flank of the Tortolita Mountains, the Suizo Mountains area, and Durham Hills are shown. Mylonitic foliation is sparse in the Durham Hills. See Figure 1 for location. Simplified from Spencer et al. (2002), Richard et al. (2002), and Ferguson et al. (2002). c—hanging-wall cutoff at base of Oligocene volcanic rocks.
Figure 8. Simplified geologic map of the Catalina metamorphic core complex shows locations of thermochronologic samples from footwall crystalline rocks that were analyzed by the $^{40}$Ar/$^{39}$Ar method and from fault rocks that were analyzed by the K-Ar method. Six Oligocene plutons and U-Pb dates are also shown with names in red and dates in parentheses. Dates and sources are listed in Items S2–S3 (see text footnote 1).
Figure 9. Simplified geologic map of the region around the Catalina metamorphic core complex shows locations of samples from volcanic and hypabyssal rocks that were dated by ⁴⁰Ar/³⁹Ar (sanidine and biotite) and U-Pb (zircon) methods. Porphyritic andesite lava is shown in the subsurface east of the Sierrita Mountains, where its location is well defined by drilling (Richard et al., 2003a). Oligocene plutons are numbered as follows: 1—Picacho Reservoir Hornblende Granitoid (Richard et al., 1999); 2—Barnett Well Granite (Richard et al., 1999); 3—porphyritic granodiorite of the Durham Hills (Richard et al., 2002); 4—pluton of Wild Burro Canyon (Ferguson et al., 2002); 5—Tortolita Mountains Granite (Ferguson et al., 2002); 6—Catalina quartz monzonite (Keith et al., 1980); 7—Stronghold Granite (Drewes, 1987). Dates and sources are from Items S2–S3 (see text footnote 1). Item S3 includes new U-Pb zircon data for plutons numbered 1, 2, and 7 and a 25 Ma tuff (green triangle, upper center).
Tertiary volcanic rocks and potentially were created. A tilted sequence of clastic strata and rock avalanche breccia above the San Xavier detachment fault in the Sierra Mountains southwest of Tucson contains a tuff dated at 27.49 ± 0.15 (2σ) Ma (Fig. 13; Spencer et al., 2017). The Exxon State (321) deep drill hole in the deepest part of Tucson Basin penetrated a welded tuff at 2.6 km depth that was dated at 26.9 ± 0.2 (2σ) Ma (Houser et al., 2005). This tuff overlies ~150 m of clastic strata that are interpreted as similar in age and reflecting early basin genesis (Houser et al., 2005). These five dates indicate that extensional faulting and basin genesis were underway at 26–28 Ma.

The age of widespread volcanism in the greater Tucson area is indicated by geochronologic data from widely distributed lava flows, tuffs interbedded with lava flows, and shallow intrusions. Eleven of 15 dates from such rocks fall in the range of 25.7–28.2 Ma (Fig. 10B). In addition, five K-Ar dates from widely distributed, distinctive plagioclase-porphyritic andesite known locally as “turkey-track porphyry” (Cooper, 1961) cluster around 27–28 Ma (Figs. 9 and 10C). This was the time when volcanic activity was most widespread in the greater Tucson area. In contrast, 10 U-Pb dates from seven granitic plutons are all in the range of 24.4–25.8 Ma, which is distinctly younger than the previous episode of widely distributed volcanism (Fig. 10D; Items S2–S3, see footnote 1; Fornash et al., 2013; Spencer et al., 2015; Ducaze et al., 2020).

The chronology of cooling of footwall mylonites is derived from several geochnrometers. Cooling through ~300–400 °C (Reiners and Brandon, 2008) is revealed by 17 ⁴⁰Ar/³⁹Ar dates of muscovite and biotite from mylonitic footwall rocks in the Santa Catalina and Tortolita Mountains (Figs. 8 and 10E; Item S1, see footnote 1; Spell et al., 2003; Terrien, 2012; Spencer et al., 2017). Two of these dates, 28 ± 1 (2σ) Ma and 28.72 ± 0.07 (2σ) Ma, are from northeastern areas that are weakly mylonitic to non-mylonitic but are adjacent to the Windy Point and Capars Wash mylonitic shear zones, respectively. ⁴⁰Ar/³⁹Ar mica dates are progressively younger to the southwest in both ranges, with five dates at 22–24 Ma near the southern or southwestern foot of the ranges (Spell et al., 2003; Terrien, 2012). Three samples of illite and one of cataclasite from fault zone rocks along the Catalina–San Pedro detachment fault at the western foot of the Rincon Mountains yielded K-Ar dates of 20.9–21.4 Ma, which indicates some combination of cooling and termination of fault zone processes that led to illite and cataclasite genesis (Damon and Shafiqullah, 2006; Figs. 8 and 10F). Cooling through fission-track apatite annealing temperatures of ~110 °C occurred at ca. 20 Ma based on analysis of four samples: three from the Catalina foreland and one from the bottom of adjacent Hitchcock Canyon in the main range (Fayon et al., 2000; Fig. 10G).

A tuff on the northern flank of the Tortolita Mountains, dated at 19.68 ± 0.30 (2σ) Ma, is interbedded with conglomerate that is tilted ~2–10° to the east (Figs. 7 and 10A; Spencer et al., 2002). This tuff, and an isolated tuff on the western flank of the Tortolita Mountains dated at 17.69 ± 0.17 (2σ) Ma, (Fig. 7 and 10A; Ferguson et al., 2002), are not clearly associated with detachment faulting and associated basin genesis.

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**Figure 10. Normalized age-probability plots show isotope geochronologic and fission-track dates from the Catalina metamorphic core complex and surrounding areas. Within each curve the area beneath the curve representing each date is the same, while the height of the curve for each date is proportional to analytical precision. Abbreviations: n—number of dates; Ttr—Oligocene volcanic intrusions; Tv and Tt—Oligocene and Miocene volcanic rocks and potentially far-traveled tuffs, respectively; gr—granite and gneissic rocks of the detachment fault footwall; W—Whitetail Conglomerate; C—Cienega Basin; 2 indicates two almost identical dates represented by one peak in Figure 10A. Sample locations are shown in Figures 8–9 and listed in Items S2–S3 (see text footnote 1). Normalized age probability plots were created with a Microsoft Excel®-based program provided by the Arizona LaserChron Center at the University of Arizona. Because plots of high-precision ⁴⁰Ar/³⁹Ar dates were smoothed by the Microsoft Excel® program, which was written for generally older and less precise U-Pb dates, data were plotted by multiplying the dates by 100 and then dividing the horizontal axis numbers by 100 after the plots were created.**
Figure 11. Geologic map shows the southwestern flank of the Rincon Mountains. Map data are from Spencer et al. (2001), Richard et al. (2001, 2005), and Ferguson et al. (2001). Three unlabeled red dots near the southern edge of the map area represent 40Ar/39Ar dates that overlap with the labeled 26.44 Ma date within 1σ analytical uncertainty and are thought to represent the same tuff bed (Peters et al., 2003; Spencer et al., 2017).
**DETACHMENT FAULT DISPLACEMENT**

**Rincon Mountains–Johnny Lyon Hills**

A previous study of the Rincon Mountains area identified evidence that a segment of a thrust fault now exposed in the western Rincon Mountains had been displaced 34–38 km to the southwest by the Catalina–San Pedro detachment fault from a position adjacent to an equivalent thrust fault in the lower plate of the detachment fault in the northern Johnny Lyon Hills (Fig. 14; Spencer et al., 2019). Modern separation between these features is ~40 km, but 2–6 km of this separation is estimated to have resulted from minor extensional faulting of the lower plate of the detachment fault in the San Pedro River Valley and erosional retreat of the thrust-fault trace in the Johnny Lyon Hills.

Consideration of additional displacement necessary to restore the trailing edge of the main mass of the upper plate wedge, now represented by the axis of Tucson Basin, to an original position adjacent to the Johnny Lyon Hills, indicates another ~20 km of extension. The northwest-dipping Santa Rita normal fault, apparent in seismic reflection profiles in southern Tucson Basin, where it dips ~20° to the northwest, appears to have accommodated this additional extension (Fig. 1; Johnson and Loy, 1992). This fault, which has Quaternary surface offset (Pearthree and Calvo, 1987), is inferred to merge northward with the Catalina–San Pedro detachment fault (Wagner and Johnson, 2006, 2010), but alternative geometries are possible in the subsurface where, for example, late Cenozoic offset could be linked to offset on the Pirate Fault through a buried right-lateral strike-slip fault (Fig. 1). Regardless of the geometry and displacement history of the Santa Rita fault and its relationship to the detachment fault, total displacement of ranges west of Tucson Basin relative to ranges to the north and east reflects movement associated with both faults and is estimated at 54–58 km (Spencer et al., 2019).

**Santa Catalina–Tortolita–Tucson Mountains**

The Santa Catalina and Rincon Mountains form a single fault block below the Catalina–San Pedro detachment fault. Metamorphosed and penetratively deformed Mesoproterozoic, Paleozoic, and Mesozoic strata are exposed almost continuously along the northeastern flanks of both ranges (e.g., Byker-Kauffman, 2008; Force, 1997; Spencer et al., 2009a, 2009b, 2011). This belt of supracrustal rocks is truncated westward by the Pirate fault (Figs. 15 and 16A–16B) but appears farther west, where it extends across the Tortolita Mountains (Fig. 16C; Skotnicki, 2000; Ferguson et al., 2002). The entire 85-km-long belt of metasedimentary rock units, from the southeastern Rincon Mountains to the western Tortolita Mountains, was largely or entirely exhumed by mid-Cenozoic displacement on the Catalina–San Pedro detachment fault.

The Tucson Mountains represent the exposed top of the upper plate of the Catalina–San Pedro detachment fault where the fault projects southwestward.
Figure 13. Geologic map shows the east side of the Sierrita Mountains. The Pima Mine porphyry copper deposit is thought to have been displaced from a position above the Twin Buttes Mine deposit by 11.5 km displacement above the San Xavier detachment fault, with displacement of upper plate rocks toward 344° and southward tilting of both upper and lower plates (Cooper, 1960; Stavast et al., 2008). If the San Xavier North deposit is displaced from above the Pima Mine deposit, another 4.3 km displacement is indicated, for a total of 15.8 km displacement. Map data are from Ferguson et al. (2003), Johnson et al. (2003), Richard et al. (2003a), Spencer et al. (2003b), and, for the Sierrita porphyry copper deposit, Dan Aiken (2007, personal commun.).

MAP UNITS
Quaternary deposits
- Mine tailings
- Mine dump
- Quaternary deposits
Oligocene-Miocene strata
- Volcanic-lithic sandstone and conglomerate
- Andesite and dacite lava
- Porphyritic andesite
- Rock-avalanche breccia
- Conglomerate and sandstone
Laramide granitoids
- Sierrita Granite
- Ruby Star Granodiorite
- Esperanza rhyodacite porphyry
- North Sierrita porphyry
- Sierrita breccia
- West Sierrita porphyry
- Esperanza quartz-monzonite porphyry
- Ruby Star Granodiorite, biotite granite phase
- Diorite
Laramide porphries and related units
- Esperanza rhyodacite porphyry
- North Sierrita porphyry
- Sierrita breccia
- West Sierrita porphyry
- Esperanza quartz-monzonite porphyry
- Ruby Star Granodiorite, biotite granite phase
- Twin Buttes porphyry suite
Mesozoic rocks
- Demetrie Volcanics (76 Ma)
- Harris Ranch Quartz Monzonite
- Red Boy Rhyolite (76.8 Ma)
- Angelica Arkose
- Ox Frame Quartzite
- Ox Frame Rhyolite (172 Ma)
- Ox Frame Andesite
- Cretaceous andesite
Pre-Mesozoic rocks
- Paleozoic carbonate, quartzite, and phyllite
- Proterozoic granitoids

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Figure 14. Geologic map shows the Rincon Mountains, Johnny Lyon Hills, and southern Galiuro Mountains. Two vectors show the restoration path for the Loma Alta thrust and Sentinel Butte (Spencer et al., 2019). The 18-km-long green line, parallel to mylonitic lineation above the Wildhorse Mountain thrust fault, separates the Wildhorse Mountain fault from the projected trace of the base of Oligocene strata. The buried trace of the Kelsey Canyon thrust fault is inferred to be down-dip from the eastern end of this green line. That buried thrust trace, which was at Earth's surface before Oligocene burial and tilting, would have projected down dip for ~18–20 km to depths where quartz was deformed under crystal-plastic deformation conditions to form the Laramide mylonitic fabric above the Wildhorse Mountain thrust. Inferred 8–15 km depths for this mylonitization, and the ~18–20 km separation between mylonitic fabrics and the buried thrust trace along the green line trending parallel to Laramide mylonitic lineation, suggest original thrust dip of ~25–50°.
Conglomerate and minor sandstone (Oligocene to lower Miocene) - pattern indicates oxidative alteration

Volcanic and sedimentary rocks (Oligocene to lower Miocene)

Laramide intrusive rocks (50-80 Ma) (peraluminous granites not shown)

Sedimentary rocks and 1.1 Ga diabase (Mesoproterozoic to Paleozoic)

Upper-plate bedrock (Paleoproterozoic to Cretaceous)

Lower-plate bedrock (Paleoproterozoic to Eocene) - pattern indicates mylonitic fabric

Fault system: unspecified

Catalina - San Pedro

Ripsey - Camp Grant - Teran

Figure 15. Geologic map of the northern Catalina metamorphic core complex area shows vector restorations of extension and, for a transect through the Santa Catalina Mountains, possible vector restorations for earlier Laramide thrust emplacement of the Amole pluton over the Santa Catalina Mountains. The tail end of the black vector at the western edge of the Amole pluton shows the inferred center of the base of the pluton where it is truncated by the down-dip projection of the Catalina–San Pedro detachment fault. The 5 km length of the black vector represents extension on the late Cenozoic Pirate fault, which is inferred to have displaced the Tucson Mountains relative to the Santa Catalina Mountains. Note also that Cenozoic conglomerate and sandstone have generally been divided into separate units by previous workers (San Manuel Formation and Cloudburst Formation primarily, e.g., Dickinson [1991]) but are divided here only by degree of oxidative alteration.
Figure 16. (A) Simplified geologic map of the northwestern Santa Catalina Mountains and southern Tortolita Mountains shows locations of Figures 16B–16C. Labels not included in legends for Figures 16B–16C are as follows: Tv—Oligocene volcanic rocks; Kg—Cretaceous granitoids; Pzs–Ya—Paleozoic and Mesoproterozoic supracrustal rocks and 1.1 Ga diabase sills. (B) Geologic map of the northeastern margin of the 25 Ma Catalina quartz monzonite shows the syncline that parallels the intrusive contact (simplified from Suemnicht, 1977, and Spencer et al., 2000). (C) Geologic map of the belt of Paleozoic and Neoproterozoic metasedimentary rocks at the northern margin of two 24–25 Ma plutons (simplified from Skotnicki, 2000, and Ferguson et al., 2002).

Tortolita Mountains Granite (~24 Ma)
Pluton of Wild Burro Canyon, western phase (~24.7 Ma)
Pinal Schist (Paleoproterozoic)

Quartzite, calc-silicate and sericitic schist, and marble (Paleozoic)
quartzite, calc-silicate and sericitic schist, and carbonate (Cambrian)quartzite, siltstone, and carbonate of the Apache Group, and Sierra Ancha diabase (Mesoproterozoic)
from the southwestern flank of the Santa Catalina Mountains to beneath Tucson Basin (Fig. 15). In simplified view, the Tucson Mountains consist of a single fault block tilted to the northeast, with a stratigraphic sequence that extends upward from minor exposures of Paleozoic sedimentary rocks at the western edge of the range, through Jurassic and Cretaceous volcanic and sedimentary units, to the thick intracaldera fill of the ca. 73 Ma Cat Mountain tuff and related volcanic units and breccias that make up most of the range (Lipman, 1993). Overlying Oligocene volcanic rocks at the northern and southeastern edges of the range dip ~20° to the northeast beneath Tucson basin and project downdip toward the southwest-dipping detachment fault (Lipman, 1993; Spencer, 2003). The simplest view is that this tilted section was originally contiguous with the tilted Mesoproterozoic through Cretaceous strata on the northern flank and crest of the Santa Catalina Mountains and was displaced from this position by detachment faulting. This interpretation is difficult to reconcile, however, with the penetratively deformed and metamorphosed character of the Santa Catalina supracrustal units as compared to unmetamorphosed strata in the Tucson Mountains (e.g., Mayo, 1966; Risley, 1987).

An alternative reconstruction is that the Tucson Mountains formed part of a thrust plate that overlay the metasedimentary rocks on the northeastern flank of the Santa Catalina Mountains. These rock units in the Santa Catalina Mountains were subjected to greenschist-grade metamorphism and penetrative deformation that increases in intensity from northeast to southwest. Subhorizontal foliations and east–west-trending lineations are defined by aligned phyllosilicates, pressure shadows, flattened mineral grains, new mineral growth, aligned phenocrysts, and deformed pebbles (Bykerk-Kauffman, 1983, 1990; Janecke, 1986). A variety of structures indicate top-east shearing and section attenuation across the entire area, however, which indicates that the tectonic setting of penetrative deformation is not well understood. This deformation affected the 69 Ma Leatherwood Granodiorite and largely but not entirely preceded emplacement of Eocene leucogranites (Bykerk-Kauffman, 1987). Restoration of 50–60 km of detachment fault displacement would place Tucson Mountains bedrock over the metasedimentary units on the northeastern flank of the Santa Catalina Mountains, which is consistent with metamorphism and deformation in the lower plate of a thrust but not necessarily associated with thrust movement.

The ca. 73 Ma Amole Granite and its granodiorite border phase in the northwestern Tucson Mountains (Lipman, 1993) should have a deep-seated equivalent in the footwall of the Catalina–San Pedro detachment fault. Restoration of ~28 km of detachment fault displacement places the Amole Granite above the granite of Alamo Canyon in the western Santa Catalina Mountains (Fig. 15; Spencer and Pearthree, 2004), but U-Pb dates indicate that the granite of Alamo Canyon is 2–6 m.y. younger (Fig. 17). Restoration of an additional 20 km places the Amole Granite above the Leatherwood Granodiorite near the crest of the Santa Catalina Mountains, but the Leatherwood Granodiorite is also too young to be a match (Figs. 15 and 17). The Rice Peak porphyry in the northern Santa Catalina Mountains is about the same age as the Amole Granite (Figs. 15 and 17), but it is a hypabyssal rock with a fine-grained matrix (Creasey, 1967; Force, 1997). It thus appears that there is no obvious root zone for the Amole Granite in the Santa Catalina Mountains.

If penetrative deformation and metamorphism in the 85-km-long belt of metasedimentary rocks in the Rincon, Santa Catalina, and Tortolita Mountains are related to tectonic burial below the Wildhorse Mountain thrust in the Rincon Mountains and its relatives to the northwest, and thrusting is younger than the ca. 73 Ma Amole pluton as suggested by penetrative deformation of the 69 Ma Leatherwood Granodiorite, then any attempt to find the roots of the Amole pluton must also consider thrust displacement. The amount and direction of thrust displacement are poorly constrained. If the thrust is correlative with the Wildhorse Mountain thrust in the Rincon Mountains, then displacement was toward 067°, as is indicated by mylonitic lineations along the thrust zone (Spencer et al., 2019). Approximately 20 km of thrust displacement toward 067° would be necessary for tectonic burial of metasedimentary
units on the northeastern flank of the Santa Catalina Mountains, as this is the approximate maximum width of the belt (Fig. 15, green restoration vector). If thrust displacement was toward ~090°, as suggested by lineation and shear sense in footwall metasedimentary rocks (Byker-Kauffman and Janecke, 1987), displacement would have to be at least ~28 km to cover the metasedimentary footwall in the Santa Catalina Mountains. Restoration of either of these thrust displacements, following restoration of detachment displacement, places the Amole pluton in areas occupied by younger granitoids or buried by upper Cenozoic basin fill (Figs. 8 and 15). The absence of the Amole pluton root zone in the Santa Catalina Mountains is thus consistent with the interpretation of significant Laramide thrust displacement of pre-Cenozoic Tucson Mountains bedrock relative to pre-Cenozoic Santa Catalina bedrock. It is also consistent with the concept that detachment faulting occurred approximately spatially coincident with the thrust fault.

**Cloudburst–Star Flat–Guild Wash**

The upper plate of the Guild Wash fault in the northwestern Tortolita Mountains consists of Proterozoic crystalline rocks overlain by Oligocene to Miocene mafic to intermediate lava flows and overlying conglomerate that are tilted moderately to steeply to the northeast (Figs. 7 and 15). This fault block is bounded to the north by the Suizo Mountain detachment fault, which represents the northward continuation of the Guild Wash fault. This geometry indicates that the upper plate of the Guild Wash fault is a thin, tilted slab that forms a synformal keel with an axis that is approximately parallel to displacement as indicated by footwall mylonitic lineations on both sides of the keel (Fig. 7).

Detachment faults to the east at Star Flat and in the Black Hills displace clastic and volcanic rocks similar to those in the Guild Wash area, except that lower plate rocks are not mylonitic and upper plate rocks include little or no crystalline rock (Figs. 12 and 18). Sedimentation was approximately synchronous in all three areas as indicated by similar dates from tuffs in clastic and volcanic sequences in the three areas (from west to east, 26.39 ± 0.07 (2σ) Ma, 26.33 ± 0.1 (2σ) Ma, and 26.1 ± 0.4 (2σ) Ma; Items S2–S3, see footnote 1). Underlying detachment faults in all three areas were correlated with the Catalina–San Pedro detachment fault by Dickinson (1991). This correlation disallows correlation of the Cloudburst detachment fault with the low-angle Camp Grant fault to the north because the Camp Grant fault projects below Proterozoic crystalline rocks in the Black Mountain area, whereas a correlated Cloudburst–Star Flat fault lies structurally above (Fig. 15).

The upper plate of the Cloudburst detachment fault is bounded to the south by the steeply north-dipping Turtle fault, which is cut and displaced by younger movement on the San Manuel fault (Fig. 18). Dickinson (1991) interpreted the Turtle fault as lateral ramp in the Cloudburst detachment, whereas Spencer et al. (2018) interpreted it as a younger, high-angle normal fault that offset the Cloudburst fault (Fig. 18). In either case, correlation with the greater Catalina–San Pedro fault system is geometrically permissible. If the Cloudburst detachment fault cuts the Turtle fault and projects southward beneath the Santa Catalina Mountains (Fig. 18), then it can’t be correlated with the greater Catalina–San Pedro detachment fault system but can be correlated with the Camp Grant fault to the north (Fig. 15) and the Teran Basin and related faults to the southeast (Fig. 14; Favorito and Seedorff, 2021). Underground mining and drilling in the San Manuel porphyry-copper ore body did not identify any candidates for the Cloudburst fault at paleodepths approaching 1 km (Lowell, 1968; Force et al., 1995), so if it does continue southward in the subsurface, it must curve sharply downward (Fig. 18) and project southward beneath the Santa Catalina Mountains.

If the Guild Wash, Star Flat, and Cloudburst detachment faults are correlative, then estimates of displacement can be made by reconstructing the hanging-wall cutoff where the steeply southwest-dipping basal depositional contact of Oligocene volcanic rocks with Proterozoic crystalline rocks is truncated by the Guild Wash and Suizo detachment faults. This cutoff, shown in two locations with the label “c” (for “cutoff”) on Figure 7, would restore to a position at least as far east as the eastern edge of the footwall of the Cloudburst fault (36–41 km) but not farther east than the basal depositional contact of Oligocene volcanic rocks in the Galiuro Mountains (54 km; Fig. 15). A potential issue with this reconstruction is that the northern (Suizo) cutoff restores to a position in the San Pedro River Valley where Mesozoic, Paleozoic, and Mesoproterozoic strata rest on Proterozoic crystalline rocks and are cut by the Lookout Mountain thrust fault, but these supracrustal units and the thrust fault are not represented in the pre-Cenozoic bedrock above the Guild Wash and Suizo detachment faults. Restoration of 45–50 km would place the cutoff over concealed bedrock under the San Pedro River Valley and away from pre-Cenozoic, supracrustal rocks on the flanks of the valley, although the only rationale for this reconstruction is the lack of alternatives.

Extension that occurred on younger faults that cut the Guild Wash–Star Flat–Cloudburst detachment fault system is included in the 45–50 km displacement estimate and so would have to be subtracted from the estimate to determine detachment fault displacement rather than total extension. One of these faults, the San Manuel fault, has ~2 km displacement where it is crossed by the reconstruction vector (Spencer et al., 2018). Displacement on the others is likely comparable or less except for the Camp Grant fault and its buried continuation to the south in the hanging-wall block of the younger Cowhead Well fault (Fig. 15). The Camp Grant fault probably has less than ~5 km displacement because it does not obviously offset steeply dipping Paleozoic and Mesoproterozoic strata in the footwall block to the east of the fault trace relative to similar strata in the hanging-wall block to the north–northwest. Finally, normal faults within crystalline rocks in the upper plate of the Guild Wash fault (Fig. 7) are not included in the 45–50 km reconstruction but would add perhaps several kilometers to displacement at the southwestern part of the detachment fault system. In summary, we estimate a total of 45–50 km of displacement on the correlated Guild Wash–Star Flat–Cloudburst detachment fault. This estimate includes a few kilometers of post-detachment extension.
conglomerate - Quiburis Formation (upper Miocene to Pliocene)
rhyolite (23.2 ± 0.4 Ma)
conglomerate - San Manuel Fm. (Oligocene to lower Miocene)
conglomerate
mafic lavas and conglomerate
granodiorite porphyry (~68 Ma) Oracle Granite (1.43 Ga)

tuff

Figure 18. Geologic map and cross sections of the Black Hills north of the Santa Catalina Mountains are shown. See Figure 1 for location. Map sources include Greasey (1967), Dickinson (1993), Orr et al. (2004), and Spencer et al. (2018). Cross sections are from Lowell (1968) and Spencer et al. (2018), with modifications from labeled sources. Cross section B–B′ extends beyond the boundaries of the map. On cross section C–C′, small circle with dot indicates displacement toward the viewer while the small circle with the x indicates displacement away from the viewer.
west of the Black Hills but does not include perhaps comparable detachment-related extension southwest of the hanging-wall cutoff points in the northern Tortolita Mountains.

Black Mountain–Durham Hills–Picacho Mountains

The Picacho Mountains make up the northwesternmost component of the greater Catalina metamorphic core complex. A southwest-dipping detachment fault between the Picacho Mountains to the north and Picacho Peak to the south is exposed only at one small klippe at the southern end of the Picacho Mountains (Richard et al., 1999). Restoration of 26 km of extension would be necessary to place volcanic rocks at Picacho Peak over 25 Ma mylonitic granitoids in the Durham Hills (Fig. 15). Greater restored displacement would be necessary to place the Durham Hills at the 8–15 km depths typical of mylonitization, which indicates total displacement of at least ~40 km (a 45°-dipping fault requires 14 km of displacement to uncover rocks elevated from 10 km depth to the surface during faulting; e.g., Osterle et al., 2021). Cenozoic mylonitic fabrics are absent in the Black Mountain massif (Krieger, 1974; Skotnicki, 1999; Orr et al., 2002; Spencer et al., 2002), which has yielded several Eocene to Mesoproterozoic 40Ar/39Ar and K-Ar biotite and muscovite dates (Fig. 15; Reynolds et al., 1986; Spell et al., 2003) that are consistent with a shallow crustal location near the breakaway of the detachment system. Total displacement of 40–50 km seems likely based on this analysis.

Farther north, the Grayback fault is one of two large, west-dipping, low-angle normal faults that cross the Gila River (Fig. 15; Richard and Spencer, 1997; Nickerson et al., 2010; Runyon et al., 2019). Just north of the Gila River, the Grayback fault dies out upward into tilted conglomerate that is overlain by volcanic rocks that are dated nearby at ~16–21 Ma (McIntosh and Ferguson, 1998; Richard and Spencer, 1998), which indicates that displacement ended before ca. 21 Ma. Fault displacement was estimated at 17 km (Richard and Spencer, 1997). To the south, the Grayback fault extends across the Ninetysix Hills and is buried farther south by alluvial cover (Skotnicki, 1999). Southward continuation of the buried fault along the range front of the Ninetysix Hills and westward dip beneath the Durham Hills is ruled out because restoration of >10 km of extension on such a fault would place the mylonitic ca. 26 Ma Durham Hills Granite above non-mylonitic 1.4 Ga granite that makes up the Black Mountain massif. An alternative is that the Grayback fault continues southward and displaces the Picacho Mountains relative to the Durham Hills. A 5.5-km-deep drill hole in this area crossed a chloritic breccia zone at 3.9 km depth that could represent the buried Grayback fault (Fig. 15; Reif and Robinson, 1981), but this correlation would require a steep dip for the Grayback fault that is unlike its gentle dip farther north. A third alternative is that the Grayback fault extends over the Picacho Mountains and represents some of the displacement on the greater Catalina–San Pedro detachment fault system and its northern representative on the southern flank of the Picacho Mountains.

Analysis and Discussion

Deformation within the Upper Plate

Restoration of amounts of extension outlined above places mylonitic rocks beneath ranges ~20–50 km to the southwest (Fig. 19). The Tucson, Roskruge, Waterman, Silver Bell, Sawtouo, and Slate Mountains, which form the exposed top of the thick part of the upper plate of the detachment system, are cut by few normal faults generally with minor displacement (Blacet et al., 1978a, 1978b; Lipman, 1993; Beikman et al., 1996; Sawyer, 1996; Ferguson et al., 1999a, 1999b; Richard et al., 2000b; Skotnicki and Pearthree, 2000; Mizer, 2018). The Sierra Hills, which restore to a position above the southwestern Rincon Mountains, are similarly unaffected by normal faulting except for the top-north San Xavier detachment fault that, before extension, would have projected down dip toward the Molino Basin shear zone (Fig. 19). Areas underlain by the brittle, deeper part of the Catalina–San Pedro detachment fault, rather than its deeper projection into a mylonitic shear zone, are most relevant to inferences about geodynamics based on critical taper theory. The Tucson, Waterman, Silver Bell, and Sawtouo Mountains are all reconstructed to positions above the Catalina–San Pedro detachment fault rather than above deeper mylonites (Fig. 19). The fact that none of these areas is significantly affected by extensional faulting is consistent with stable sliding of thicker parts of the upper plate during detachment fault displacement.

Upper plate rocks that represent the tapered end of the upper plate wedge are widely exposed on the southwestern flank of the Rincon Mountains (Fig. 11) or at least did represent the tapered end until displacement on concealed normal faults produced the deep axis of the Tucson Basin and left the wedge tip perched on the side of the Rincon Mountains (Wagner and Johnson, 2008; Spencer et al., 2019). In the northwestern part of the map area of Figure 11, near Rincon Creek, a single, southwest-side-down fault interpreted as a normal fault places tilted conglomerate on the southwestern side of the fault against Mesozoic and older bedrock to the northeast. Another fault to the east, within the synformal keel formed by the detachment fault, could be a normal fault with east-side-down displacement, but the fault is not sufficiently exposed to determine dip. A normal fault south of Cienega Creek could be related to detachment faulting, but its north–south strike is characteristic of younger normal faults that are unrelated to detachment faulting (e.g., Davis et al., 2004). Widely exposed Oligocene to Miocene clastic strata in the Cienega Creek area are generally tilted less than ~40° and are cut by only a few faults with minor displacement (Fig. 11). One of these faults, an east-dipping fault that displaces Oligocene porphyritic andesite in its hanging-wall block, could be a reverse fault.

Extensional faults within upper plate rocks are apparent north of Guild Wash and in the San Pedro River Valley. The Guild Wash allochthon is a tilted slab that is broken by several normal faults, although fault displacement and lateral extent are uncertain within extensive areas of low-relief crystalline rock (Fig. 7; Ferguson et al., 2002). A variety of fault blocks are displaced by the Catalina–San Pedro detachment fault in the San Pedro River Valley, and some of these fault blocks are affected by multiple generations of normal
faulting. Many of these consist of, or are capped by, conglomerate and sandstone deposited during detachment faulting (Lingrey, 1982; Dickinson, 1991; Spencer et al., 2009b, 2011, 2018). Extended and tilted pre-Cenozoic bedrock in the San Pedro River Valley forms a trivial amount of the total rock mass of the upper plate of the Catalina–San Pedro detachment fault.

Favorito and Seedorff (2021) concluded that extension and fault-block tilting in the greater Catalina core complex resulted from several generations of normal faulting on initially steep, planar normal faults. In this model, each fault generation was active until tilting reduced fault dip to the point where a new generation of steeper normal faults became active and caused continued extension and tilting. This would be expected for unstable wedge sliding. This style of extensional faulting is not apparent, however, in any of the many ranges that form the upper plate of the Catalina–San Pedro extensional detachment fault. Furthermore, the large area of exposed upper plate bedrock on the southwestern flank of the Rincon Mountains, which is directly adjacent to a long, exposed segment of the Catalina detachment fault, is cut by only a small number of widely spaced normal faults, and the syn-tectonic sediments in Cienega Basin are only gently to moderately tilted. An older generation of normal faults in the eastern Rincon Mountains is cut by the Catalina–San Pedro detachment fault (Spencer et al., 2011; Gardner fault of Favorito and Seedorff, 2021). This truncation represents the only significant example of multiple generations of normal faults that affected upper plate rocks in the eastern Rincon Mountains before post-detachment normal faulting, and they affect a very small volume of the upper plate. We conclude that there is little evidence of multiple generations of normal faults associated with detachment faulting and that stable wedge sliding was the dominant mode of extension associated with the Catalina–San Pedro extensional detachment fault.

**Mylonites**

Most mylonitic fabrics in metamorphic core complexes are interpreted to represent shearing below the brittle-plastic transition and down-dip from a detachment fault (e.g., Davis et al., 1986). In this interpretation, mylonitic lineations primarily reflect the direction of shearing in the up-dip, strongest part of the crust where large earthquakes nucleate within brittle crust (e.g., Maggi et al., 2000). The dominant ~064–244° orientation of mylonitic lineations over the 115 km distance along the southwestern margin of the greater Catalina metamorphic core complex is consistent with the interpretation that these mylonitic fabrics formed down-dip from a single normal fault or fault system with a strike length of at least 110 km (115 km minus ~5 km of lengthening during post-detachment normal faulting). This fault system, now represented by the Catalina–San Pedro detachment fault, acted in several consecutive fault generations, was specifically applied to the forerange arch with an inferred top-southwest shear sense in the northeast-dipping mylonitic fabrics of the Molino Basin mylonite zone north of the arch crest. In our study, we identified 53 mylonitic shear-sense indicators north of the crest of the forerange arch, 46 of which are top-northeast rather than top-southwest. Furthermore, only two of the top-southwest indicators are located more than 500 m north of the arch crest, compared to 41 top-northeast indicators (see Table S5 in Item S1, footnote 1). The overwhelming abundance of top-northeast shear-sense indicators shows that this shear zone was not directly related to southwest-dipping normal faults as was inferred by Favorito and Seedorff (2021). In addition, we are not aware of any northeast-dipping, top-southwest mylonitic shear zones in the greater Santa Catalina core complex that would support the proposed mylonite geometry of Favorito and Seedorff (2021).

**Chronology**

Two 33–34 Ma tuffs preserved beneath thick clastic sequences in the greater Tucson area are interpreted as pre-dating basin genesis and tectonic extension.
Pre-extension, sub-surface position of mountain peaks

Fault, movement sense unspecified
- Normal fault, ball on downthrown side
- Thrust fault, teeth on upper plate
- Extensional detachment fault, tics on downthrown side

Spencer et al. | Tectonic extension in the greater Catalina core complex

Figure 19. Restoration shows detachment fault displacement of 58 km at the southern end of the Rincon Mountains and 50 km at the southern end of the Picacho Mountains (resulting in 3° rotation of the footwall relative to the hanging wall). The 55 km restoration vector represents restorative displacement of the lower plate of the detachment fault with respect to the upper plate in the middle part of this restoration. Restoration places mylonitic rocks and other features (in magenta) in positions in the middle crust that are beneath basins and ranges to the southwest of their modern exposures. Abbreviations are as follows: PP—Pusch Peak; ML—Mt. Lemmon; MB—Molino Basin; BC—outline of bedrock presently exposed in the Buehman Canyon area of the northeastern Santa Catalina Mountains; MM—Mica Mountain; RP—Rincon Peak. Locations of these features are shown in Figure 1. Dashed green line represents the inferred initial location of the trailing edge of the Catalina–San Pedro detachment fault (equivalent to the breakaway) that encompasses the Lime Peak detachment (Dickinson, 1984) and a possible correlative in the northern Dragoon Mountains (Spencer et al., 1993). The leading edge of the Wildhorse Mountain thrust zone is extended to the southeast to encompass fold and thrust exposures in the Little Dragoon and Dragoon Mountains (Keith and Barrett, 1976a, 1976b; Drewes, 1987; Johnson et al., 2018).
Tuffs dated at 26–28 Ma overlie hundreds of meters of clastic strata within four syn-extensional basins in the greater Tucson area. Sedimentation rates in supradetachment basins are roughly 300–1200 m per m.y. (Friedmann and Burbank, 1995), which indicates that sedimentation could have occurred rapidly since as late as ca. 29 Ma. High rates seem more likely considering that lava flows are abundant in the Star Flat section and rock-avalanche breccias form a significant part of the Sierrita section. We conclude that extension began at 29–33 Ma and was well underway at 26–28 Ma.

Volcanism was widespread at 26–28 Ma, but all seven post-Eocene granitic plutons in the greater Tucson area yielded U-Pb dates of 24.4–25.8 Ma. This discrepancy suggests that heating of the deep crust by mafic magma intrusion over 2–3 m.y. produced conditions necessary for widespread granitoid magmatism. Under such circumstances, it seems likely that felsic magma genesis at depth was more widespread than is indicated by scattered plutons and that the deep crust was heated more generally by igneous activity associated with volcanism. Furthermore, the mylonitic fabrics that affected four of these granitoids indicate that mylonitic shearing occurred after plutons were emplaced at 24–26 Ma.

Seventeen ⁴⁰Ar/³⁹Ar dates of biotite and muscovite from granitic and gneissic rocks in the core complex, all 22–29 Ma, are interpreted as resulting from post-magmatic cooling and/or tectonic exhumation. Five of these dates, all between ca. 23 Ma and 25 Ma, are from widely spaced samples of Eocene and older units collected in the Santa Catalina forerange 7–14 km from the margin of the ca. 25 Ma Catalina quartz monzonite (Fig. 8). These samples are interpreted as reflecting cooling due to tectonic exhumation, although identification of a 25.5 Ma dike in the bottom of a forerange canyon (Ducea et al., 2020) indicates that magmatic heating could have influenced the cooling history of some of these samples.

Along the Catalina detachment fault in the western Rincon Mountains, cooling to temperatures where illite and cataclasite retain argon occurred at ca. 21 Ma, while apatite in the Catalina forerange dropped below the fission-track annealing temperature at ca. 20 Ma (Payon et al., 2000; Damon and Shafiqullah, 2006). Nearly concordant apatite and zircon fission-track dates were interpreted to indicate rapid cooling (Payon et al., 2000). We interpret this chronology to indicate that extension and core complex exhumation were still underway at ca. 20 Ma, well after the end of most magmatism at ca. 24 Ma. The timing of extension termination is unclear. Subaerial exposure of mylonitic rocks in the Catalina forerange and on the southern flank of the Rincon Mountains is indicated by faulted and tilted upper plate conglomerates containing mylonitic clasts at the foot of the ranges (Fig. 11; Dickinson, 1999; Spencer et al., 2001), but these clastic units are undated. A thermochronologic study of similar conglomerate in the Buckskin Mountains in western Arizona indicates that mylonitic rocks forming clasts in tilted upper plate conglomerate had passed through the apatite (U-Pb)/He closure temperature ~1–2 m.y. before subaerial exposure, dispersal, and deposition (Pforer et al., 2018), which indicates rapid exhumation. We conclude that extension began at ca. 29–33 Ma and ended within ~1–3 m.y. years following ca. 20 Ma cooling of the Catalina forerange through fission-track apatite annealing temperatures. This chronology indicates a 10–15 m.y. duration of detachment faulting.

Reconstruction of Detachment Fault Displacement

**Rincon Mountains Area**

At least seven widely spaced thrust- or reverse-fault segments are distributed around the Rincon Mountains and to the east in the southern Galipero Mountains and northern Johnny Lyon Hills (Fig. 14). The Kelsey Canyon thrust fault in the northern Johnny Lyon Hills places 1.65 Ga Johnny Lyon Granodiorite and Paleoproterozoic Pinal Schist over overturned conglomerate and sandstone of the Jurassic–Cretaceous Bisbee Group. The fault now dips eastward, but the dip of beds in overlying Oligocene strata indicates that the pre-Oligocene dip of the thrust fault was gently westward (Fig. 14; Spencer et al., 2009a). The same juxtaposition of rock types characterizes the Loma Alta thrust fault in the Rincon Creek area of the western Rincon Mountains (Fig. 11; Richard et al., 2005). Both thrust-fault segments include thin fault slivers of volcanic-lithic sandstone and conglomerate. Restoration of 40 km of slip on the Catalina–San Pedro detachment fault, along a path that parallels both mylonitic lineation and the adjacent lineation-parallelTanque Verde antiform, places the Loma Alta thrust fault over the Kelsey Canyon thrust fault. At Sentinel Butte, located 2–3 km east of the Loma Alta fault, a small exposure of Mesoproterozoic and Paleozoic strata rests depositionally on Johnny Lyon Granodiorite (Fig. 11). Restoration of 41 km of slip on the Catalina–San Pedro detachment places the Sentinel Butte supracrustal rocks above identical strata that dip steeply eastward on the east side of the Johnny Lyon Hills (Fig. 14). Correlation of a restored Loma Alta fault and Kelsey Canyon fault is thus supported by a diverse suite of matching features and a well-defined displacement vector. Several fault segments with similar juxtapositions of Paleoproterozoic and Mesozoic rock units, including the Roble Spring fault (Fig. 14), are within fault blocks in the upper plate of the Catalina–San Pedro detachment fault in the eastern Rincon Mountains (Spencer et al., 2009b, 2011). We also correlate these thrust-fault segments with the Kelsey Canyon thrust fault.

Approximately 10 km to the southwest of the southern end of the exposed Kelsey Canyon fault, the Wildhorse Mountain thrust in the lower plate of the Catalina–San Pedro detachment fault places Johnny Lyon Granodiorite over penetratively deformed Paleozoic and Mesoproterozoic metasedimentary rocks (Fig. 14). Mylonitic lineation in granodiorite directly above the thrust fault, and top-northeast asymmetric petrofabrics, indicate displacement of the upper plate toward an azimuth of 067° (Spencer et al., 2019). Crystal-plastic deformation of quartz along the Wildhorse Mountain thrust indicates temperatures of deformation greater than ~300 °C, which would be likely at depths of 8–15 km. The trace of the Kelsey Canyon thrust fault was at Earth’s surface in Oligocene time, where the fault trace was buried by Oligocene strata. The lineation-parallel distance between the Wildhorse Mountain thrust and the base of Oligocene strata,
represented by the green line in Figure 14, is ~18 km. The buried thrust-fault trace is inferred to be down-dip from the exposed contact such that the lineation-parallel distance between the buried trace and the Wildhorse Mountain thrust is perhaps 20 km, which suggests an original thrust-fault dip of ~25–50°.

In a recent reconstruction by Favorito and Seedorff (2021), the Loma Alta, Roble Spring, Youtcy, Hot Springs Canyon, and Kelsey Canyon faults were interpreted as a set of five imbricate reverse faults, none with more than ~6 km displacement. The Hot Springs Canyon fault has relatively minor stratigraphic throw, placing Jurassic to Cretaceous strata of the Bisbee Group over Laramide clastic and volcanic strata, and is likely a splay of the structurally higher Kelsey Canyon fault. The interpretation that the other four faults (Loma Alta, Roble Spring, Youtcy, and Kelsey Canyon) represent an imbricate sequence of reverse faults rather than fragments of a single thrust fault broken by Cenozoic extension is not supported by field relationships in which at least two of these faults are preserved in the same Cenozoic fault block (Dickinson et al., 1987; Richard et al., 2005; Bykerk-Kaufman, 2008; Spencer et al., 2009b, 2011) and is therefore highly dependent on a poorly constrained reconstruction of thrust-containing fault blocks that are now dispersed by detachment faulting. In addition, the
fact that Favorito and Seedorff (2021) placed the Loma Alta and Kelsey Canyon faults at the top and bottom, respectively, of their imbricate reverse-fault sequence and therefore initially far apart is particularly inconsistent with the suite of matching features on these two faults.

**Tucson Mountains–Santa Catalina Mountains Reconstruction**

As noted above, total displacement of the tapered end of the upper plate of the Catalina–San Pedro detachment fault in a transect through the Rincon Mountains is estimated at 54–58 km (Spencer et al., 2019). Restoration of this amount of displacement in a transect through the Santa Catalina Mountains places Tucson Mountains bedrock above the northeastern Santa Catalina Mountains. In this restoration, the southwestward increase in penetrative Laramide deformation and metamorphism on the northeastern flank of the Santa Catalina Mountains (Bykerk-Kauffman and Janecke, 1987) corresponds to increasing paleodepth beneath overthrust Tucson Mountains bedrock. The fact that penetratively deformed and metamorphosed Paleozoic and Mesozoic strata are present in the northeastern Santa Catalina Mountains while the same units are unmetamorphosed in the Tucson Mountains supports a reconstruction in which these units were beneath a thrust plate in the northeastern Santa Catalina Mountains whereas correlative units in the Tucson Mountains are part of the upper plate of the thrust. The penetrative deformation of footwall rocks is not necessarily the result of this thrust displacement, however, as this deformation could be a post-burial event. The ca. 73 Ma Amole pluton in the northwestern Tucson Mountains should have a deep-seated equivalent in the footwall of the Catalina–San Pedro detachment fault, but reconstruction of thrust displacement in addition to detachment displacement indicates that the root zone is covered by Cenozoic basin fill or obliterated by younger granitic intrusions that include widespread Eocene leucogranite and the 25 Ma Catalina quartz monzonite. Thrust burial is consistent with relationships in the Rincon Mountains where supracrustal rocks were tectonically buried by the Wildhorse Mountain thrust before detachment fault initiation within weak carbonates. Relicts of this thrust fault are likely lacking in the Santa Catalina Mountains except for small segments of the Youtcy thrust, which is intruded by leucogranites in the easternmost Santa Catalina Mountains (Bykerk-Kauffman, 2008).

**Guild Wash–Cloudburst Correlation and Reconstruction**

Correlation of the Guild Wash, Suizo, and Star Flat faults is indicated by the similarity of upper plate units juxtaposed above bedrock that forms a fault footwall with increasing paleodepth to the southwest. Correlation with the Cloudburst fault is supported by the similarity of upper and lower plate units across a gap of 9 km that is covered by late Cenozoic basin fill. Restoration of displacement on the younger Cowhead Well and Camp Grant normal faults within this gap (Fig. 15) would bring these areas closer together. The basal depositional contact of Oligocene volcanic rocks on Proterozoic crystalline rocks in the Guild Wash area is truncated by the underlying detachment fault. Footwall equivalents of this contact cutoff are unknown but must be east of the Cloudburst fault if the Guild Wash and Cloudburst faults are correlative. Reconstruction of estimated displacement of 45–50 km would place this cutoff above buried bedrock in the San Pedro River Valley, where a footwall cutoff could be present in the subsurface.

**Black Mountain–Durham Hills–Picacho Reconstruction**

Restoration of 26 km of extension is necessary to bring the tapered end of the upper plate of the detachment fault in the Picacho Mountains over the mylonitic Durham Hills. Another 15–25 km would be necessary to restore the Durham Hills and adjacent Suizo Mountains to depths and temperatures of mylonitization, for total displacement of ~40–50 km. The Grayback fault is interpreted as a northern branch of the Catalina–San Pedro detachment fault that would project over the Picacho Mountains. An alternative in which the Grayback fault projects beneath the Picacho Mountains is possible.

**System-Wide Extension and Reconstruction**

Based on the analysis outlined above, we infer that 40–60 km of displacement occurred on the Catalina–San Pedro detachment fault and its northwestern relatives, and that ranges to the west of Tucson, including the Sierrita, Tucson, and Silver Bell Mountains, were displaced by this amount relative to lower plate rocks in the breakaway region. Displacement estimates decrease to the northwest from a maximum of ~60 km in the Rincon Mountains to as little as 40 km for a transect through the Picacho Mountains and Durham Hills. The footwall of the greater Catalina–San Pedro detachment fault is broken and extended to an increasing degree in more northern exposures. Total extension in the system may be similar throughout, but with northward partitioning of extension into different faults, including the Ripsay–Camp Grant fault system located near or within the northern San Pedro River Valley (Fig. 15; Dickinson, 1991; Favorito and Seedorff, 2021).

Restoration of displacement of the greater Catalina–San Pedro detachment system juxtaposes several features that may be related (Fig. 19). In the southern part of this area, reconstruction places the Molino Basin shear zone, with its variably oriented but generally northeast-trending lineations and top-northeast shear-sense indicators, down-dip from the top-north San Xavier detachment fault in the Sierrita Mountains (Richard et al., 2003a) and its western equivalent as the Ajo Road detachment fault and associated mylonitic shear zone (Davis et al., 1987; Gottardi et al., 2020). Differences in lineation orientation and the curvature of lineations in the Molino Basin shear zone indicate that displacements are not strictly related, but a northward component of the displacements could be kinematically related.
Farther north, a reconstruction of 50 km displacement places the west-northwest-striking Mogul fault in the northern Santa Catalina Mountains approximately on strike with the Ragged Top fault in the northern Silver Bell Mountains (Fig. 19). Both faults appear to have south-side-down displacement, at least some of which is mid-Cenozoic, while the Mogul fault has evidence of an older movement history associated with a local mylonitic fabric that affects a Laramide pluton (Spencer et al., 2000; Richard et al., 2003b).

A belt of metamorphosed and deformed Paleozoic and Mesoproterozoic strata in the Tortolita Mountains (Ferguson et al., 2003) is restored to a position beneath the weakly metamorphosed supracrustal rocks in the Silver Bell Mountains (Sawyer, 1996; Mizer, 2018). This juxtaposition would be expected if the northwestern continuation of the Wildhorse Mountain thrust fault or its relatives placed Silver Bell Mountains bedrock over the Paleozoic and Apache Group strata now exposed in the Tortolita Mountains. In the northwestern Santa Catalina Mountains, south of the Mogul fault, Paleozoic and Mesoproterozoic strata are folded into a 10-km-long syncline that parallels the intrusive margin of the 25 Ma Catalina quartz monzonite (Fig. 16B). The belt of metasedimentary strata in the Tortolita Mountains mentioned above, along with Paleoproterozoic Pinal Schist, form a septum between Laramide and Eocene granitoids to the north and 25 Ma granite to the south (Fig. 16C; Ferguson et al., 2002; Skotnicki, 2000). These units form a steeply dipping, lithologically layered sequence with stratigraphic top direction to the south. If these strata were tilted during emplacement of the adjacent 25 Ma granite, as with north-tilting and syncline genesis along the northeastern margin of the Catalina Granite, then the stratigraphic sequence would have been overturned before Oligocene pluton emplacement, as might be expected at deep levels beneath a thrust fault (e.g., Schmidt and Hendrix, 1981).

The Chirreon Wash Granodiorite in the Tortolita Mountains, dated at 69.5 ± 0.5 Ma (U-Pb thermal-ionization mass spectrometry, n = 1; Spencer et al., 2003a), is restored to a position beneath Laramide intrusions in the Silver Bell Mountains that are dated at 64–66 Ma and 71–76 Ma (U-Pb LA-ICPMS, n = 17; Mizer, 2018). The Chirreon Wash Granodiorite has subordinate mafic and felsic phases (Ferguson et al., 2003) that may be different in age than the main phase and related to some of the igneous rocks in the Silver Bell Mountains. If such a relationship were established, it would provide a minimum age of thrust juxtaposition of bedrock in the two ranges.

In the reconstruction of Figure 19, the breakaway of the Catalina–San Pedro detachment fault is shown as coincident with a single thrust fault labeled as the Wildhorse Mountain thrust zone, but there is little evidence for such a strong coincidence of two faults over many tens of kilometers. Thrust faults in the San Pedro Valley are typically broken by younger faults, intruded, or buried, and are nowhere exposed continuously for more than a few kilometers length (Bykerk-Kauffman, 2008; Spencer et al., 2009a, 2009b; Favorito and Seedorff, 2021). The northwestern part of the reconstructed Wildhorse Mountain thrust, northwest of the easternmost Santa Catalina Mountains, is constrained only by the outlines of pre-Cenozoic bedrock exposures correlated with the upper and lower plates of a major thrust zone and by the estimated amount of extension. To the southeast, several thrust faults, folds, and related structures plausibly represent a single thrust system, but the relationship between these different features is uncertain. These structures include the Little Rincon thrust (Smith, 1989; Gehrels and Smith, 1991), a thrust fault in the southern Little Dragoon Mountains that places Pinal Schist over Cretaceous Bisbee Group (Johnson et al., 2018), a complex zone of highly faulted, imbricated, steeply dipping Paleozoic and Mesozoic strata in the northern Dragoon Mountains, with stratigraphic top generally to the northeast (Drewes, 1987), and a northwest-striking syncline in the central Dragoon Mountains that is overturned to the northeast (Keith and Barrett, 1976a, 1976b).

Geodynamics

Critical taper theory models the wedge-shaped upper plates of detachment faults and thrust faults as consisting of rock that is so broken that it behaves as a cohesionless material like dry sand, which can support a surface slope up to the angle of repose (Dahlen, 1984; Xiao et al., 1991). If the coefficient of friction along the underlying fault is less than that within the wedge, then stable sliding of the wedge is possible. Critical taper theory can be used to determine the effective friction coefficients of wedge material and the underlying detachment fault based on measured surface slopes and fault dips in areas of geologically young extension.

Figure 21 shows a stable sliding field determined from the surface slopes and fault dips of several areas of Quaternary detachment faulting and core complex exhumation (Spencer, 2011). Four possible pathways for wedge behavior during tectonic extension are shown in Figure 21A, all of which start with a 45°-dipping normal fault and horizontal Earth surface. Paths a and b reach the extensional margin of the stable sliding field after a history of tilting (path a) or tilting and erosional reduction of surface slope (path b). Following arrival of the wedge configuration at the margin of the stable sliding field, further extension and tilting result in internal wedge extension and elongation of the wedge as the wedge configuration moves along the path represented by the blue arrow. Tilt blocks above the Catalina–San Pedro detachment fault, for example in the Guild Wash–Star Flat–Cloudburst transect, represent areas where the wedge tip was extended after reaching the extensional margin of the stable sliding field. Path c reaches the shortening margin of the stable sliding field, likely because of alluvial fan construction on the wedge tip with sediments derived from a rising core complex, as appears to have happened in western Arizona (Spencer et al., 2016). Continued tilting during detachment faulting results in wedge shortening as the wedge configuration follows the path of the lower blue arrow. Path d represents tilting and erosion where the wedge configuration never reaches the margin of the stable sliding field, and stable sliding is effective for the entire period of extension. This represents our interpretation of wedge evolution during exhumation of the Catalina metamorphic core complex.

In detail, the surface of the wedge was not uniformly sloping, and the underlying detachment fault was not planar. The wedge configuration at the end of
Construction of such a fan could have triggered displacement on a possible reverse fault in Cienega Basin. Most likely, fault dip was greater down-dip from the fault trace, as indicated by the convex-upward form of the core complex, and sediments were derived from tilted upper plate rocks further from the core complex ("f" within the rectangle). Fine-grained strata representing basin interior settings would be intermediate between the two ("e" within the rectangle). Red arrows in Figure 21B represent possible pathways during continued extension and basin evolution, although this is not strictly consistent with critical Coulomb wedge theory, which represents wedges with planar upper and lower surfaces.

Effective exhumation of the footwall of the Catalina–San Pedro detachment fault is indicated by mylonite clasts in tilted upper plate conglomerates due to complete removal of upper plate rock units, by juxtapositions of Oligocene and Miocene sedimentary and volcanic rocks over mylonitic lower plate rocks due to complete removal of pre-Oligocene upper plate rock units, and by widespread exposure of lower plate crystalline rocks in a young and arid landscape. We propose that this effective exhumation resulted from the persistence of a stable-sliding regime for nearly all of the upper plate wedge during the 10–15 m.y. period of extension. Only the initial wedge tip, which represents a trivial fraction of the wedge, was significantly broken apart by normal faults and left as fragments above the subhorizontal detachment fault in the San Pedro River Valley.

Lateral flow of deep crust primarily from the northeast, in response to extensional basin genesis on the southwestern flank of the core complex, is inferred to have inflated the core complex and supported a surface slope above the upper plate wedge that was not steeply downhill toward the rising core complex and at least locally evolved to be downhill away from the core complex (Fig. 20). Core complex inflation also supported a steeper dip to the detachment fault on the flank of the rising core complex. This lateral flow and inflation maintained the extensional wedge in a stable sliding configuration (Fig. 21) and is consistent with the thermal history of the complex. Core complex exhumation began at about the same time as initiation of magmatic heating of the crust, proceeded through a period of widespread granite plutonism, and continued through a period of rapid footwall cooling and subaerial exposure during tectonic exhumation. This type of tectonic behavior is consistent with the rolling hinge model of core complex genesis whereby effective exhumation is supported by a mobile deep crust and a hot, flexible detachment footwall (Spencer, 1984; Wernicke and Axen, 1988; Buck, 1988; McKenzie and Jackson, 2002).

Flow in the deep crust that would have inflated the Catalina metamorphic core complex was not necessarily parallel to the extension direction or derived exclusively from the northeast. Flow directions are not apparent from existing studies, however, and it is uncertain if deep crust that flowed under high-T
CONCLUSIONS

(1) Mylonitic lineations in the greater Catalina core complex trend ~064–244° over most of the complex, especially on the southwestern range flanks. This is interpreted as the direction of early extension on a mid-crustal mylonitic shear zone before cooling due to uplift and transition to brittle shearing. Variations from this trend include curvatures around vertical axes in the Santa Catalina and Rincon Mountains that could have been produced by rotation of fault blocks around steep axes and/or deep crustal flow along curved paths. The Catalina forerange arch is interpreted as the product of top-northeast mylonitic shearing beneath a mylonitic front in the Molino Basin shear zone, northeastern tilting of the Santa Catalina Mountains, and truncation and transposition of the Molino Basin shear zone by the main south-dipping mylonitic shear zone. It is uncertain if early deformation on the two intersecting shear zones was synchronous before truncation of the Molino Basin shear zone terminated its activity.

(2) Mylonitic fabrics in four ca. 25 Ma granitic plutons have the same general lineation orientation and well-lineated character as the dominant mylonitic fabric elsewhere in the greater Catalina metamorphic core complex. This relationship supports the interpretation that all of these fabrics were produced by shearing down-dip from the Catalina–San Pedro extensional detachment fault and is inconsistent with the interpretation of Ducea et al. (2020) that the dominant mylonitic fabric is associated with Eocene peraluminous magmatism.

(3) Favorito and Seedorff (2021) proposed that multiple generations of south-west-dipping normal faults and their downdip projections as mylonitic shear zones resulted in progressive tilting to the northeast so that first-generation mylonitic shear zones were tilted through horizontal and now dip northeast with reverse (top-southwest) shear sense. This structural history was specifically applied to the Molino Basin mylonitic shear zone but is contradicted by our study, in which we identified overwhelming evidence of top-northeast shearing in this shear zone. Furthermore, we did not identify any other shear zones in the greater Catalina metamorphic core complex that would support the multiple shear-zone model of Favorito and Seedorff (2021).

(4) A 33 Ma tuff at the base of the Oligocene Pantano Formation in Cienega Basin is interpreted as derived from a distant source prior to local basin genesis. Extensional basin genesis was underway during 26–28 Ma volcanism. Consideration of extensional basin sedimentation rates (Friedmann and Burbank, 1995) for strata underlying dated volcanic rocks suggests that extension began before ca. 29 Ma. We conclude that extension began at 29–33 Ma.

(5) U-Pb geochronology indicates that all seven granitic plutons in and near the Catalina core complex are 24–26 Ma old and were emplaced after widespread 26–28 Ma volcanism. We interpret this relationship to indicate that 2–3 m.y. of magmatic heating of the deep crust was necessary to trigger ascent of granitic magmas and that heating of the deep crust was more general and widespread than is indicated by the scattered plutons.
(6) Cooling of detachment fault footwall rocks through ~300–350 °C, as indicated by 17 ⁴⁰Ar/³⁹Ar dates from biotite and muscovite in the Tortolita and Santa Catalina Mountains, occurred at 22–29 Ma, with younger dates to the southwest indicating later exhumation to the southwest. Further cooling at ca. 22–20 Ma is indicated by K-Ar dates on fault rocks and fission-track dates from footwall crystalline rocks. Mylonitic clasts in faulted and tilted upper plate conglomerates at the foot of the Santa Catalina and Rincon Mountains indicate that footwall mylonites at least locally were completely denuded during detachment faulting, so it is reasonable to infer that low-temperature cooling was related to tectonic exhumation rather than post-extension erosional exhumation. We conclude that displacement on the Catalina–San Pedro detachment fault ended shortly after 20 Ma.

(7) Upper plate rocks southwest of the axis of the greater Santa Catalina metamorphic core complex are notable because of how little they are affected by NE–SW extensional faulting. This would be expected for stable sliding above the detachment fault. Exhumation of core complex mylonites by stable sliding of the upper plate is a general characteristic of young metamorphic core complexes (e.g., Murphy et al., 2002; Little et al., 2019), including those in the deep sea (e.g., Okino et al., 2004; MacLeod et al., 2009).

(8) Reconstruction of displaced rocks and structures in a transect through the Rincon Mountains indicates ~54–58 km of displacement on the Catalina–San Pedro detachment fault (Spencer et al., 2019). Reconstruction of comparable extension along transects through the Santa Catalina and Tortolita Mountains restores essentially unmetamorphosed supracrustal units in the Tucson and Silver Bell Mountains to positions above metamorphosed supracrustal units of similar age in the Santa Catalina and Tortolita Mountains. This contrast is interpreted to be a consequence of eastward or northeastward Laramide thrust displacement of rock units now exposed in the Tucson and Silver Bell Mountains over similar-age rock units now exposed in the Santa Catalina and Tortolita Mountains. Penetrative deformation in thrust-footwall rocks affected the ca. 69 Ma Leatherwood Granodiorite and indicates that ductile deformation, during thrusting or within the deeply buried footwall of a major thrust fault, occurred after this time.

(9) A reconstruction of Cenozoic extension in and around the Rincon Mountains by Favorito and Seedorff (2021) re-assembled five different thrust-fault segments into an imbricate set of steep reverse faults, of which none had more than ~6 km of displacement. This was done regardless of the fact that two or more imbricate reverse faults are nowhere exposed within a single extension-related fault block, and the sequence of imbricate thrusts is thus dependent on the specifics of reconstruction of extensional faulting. In contrast, our interpretation is that all of these segments were derived from a single thrust fault except for the Hot Springs Canyon fault, which is interpreted as a footwall splay of the main thrust fault. Correlation of the Kelsey Canyon and Loma Alta thrust-fault segments, now 40 km apart, is supported by correlation of a suite of rock types and structures (Spencer et al., 2019). In contrast, the reconstruction of Favorito and Seedorff (2021) places the Loma Alta and Kelsey Canyon faults at the top and base, respectively, of the imbricate reverse-fault sequence, which thus infers that the matching suite of features was initially far apart and associated with different reverse faults. We thus consider their reconstruction to be an artifact of their rejection of a large-displacement detachment fault and a consequence of the specifics of their reconstruction of multiple generations of tilted, initially high-angle normal faults.

(10) We conclude that the ca. 73 Ma Amole pluton in the Tucson Mountains does not have a beheaded root zone in the Santa Catalina Mountains because post-73 Ma, east- or northeast-directed Laramide thrust-fault displacement left the pluton root in an area farther west or southwest that is now obliterated by younger plutons and/or buried by younger deposits.

(11) The tilted contact where Oligocene volcanic rocks rest on Precambrian crystalline rocks in the Tortolita-Suizo Mountains area is truncated by the underlying Catalina–San Pedro detachment fault. A footwall equivalent of this contact is not exposed in the Black Mountain–Black Hills area to the east. Restoration of ~45–50 km displacement is required to place this contact above buried bedrock in the San Pedro River Valley where a footwall equivalent could be present. Farther north, along a transect from the southeastern Picacho Mountains through the Durham Hills, 26 km of detachment fault displacement would be required to bring the trailing end of the upper plate of the detachment fault over the mylonitic Durham Hills. Another 15–25 km of restored displacement on a gently to moderately dipping fault would place the Durham Hills mylonitic rocks at ~8–15 km paleodepth. In conclusion, detachment fault displacement is not well constrained in these two northern transects, but estimated 40–50 km displacement seems likely and is consistent with, although slightly less than, the 50–60 km displacement estimates for the Catalina and Rincon transects. The total denuded area, at ~50 km wide and 110 km long, is 5500 km².

(12) Restoration of 40–60 km displacement on the Catalina–San Pedro detachment fault juxtaposes features not previously considered to be related, including the high-angle Mogul and Ragged Top faults. The top-northeast Molino Basin shear zone is restored to a position down-dip from the top-north San Xavier detachment fault, which raises the possibility that the two structures are related through vector components of their displacements.

(13) Application of critical Coulomb-wedge theory to the displacement history of the largely unextended upper plate of the Catalina–San Pedro detachment fault indicates that the upper plate slid stably off the fault footwall during the entire 10–15 m.y. period of extension. This is possible if lateral flow of deep crust inflated the core complex and supported a steeper fault dip and a wedge-surface slope that dipped away from the rising core complex. According to this analysis, without this deep flow, extension would have produced a rift containing tilted fault blocks, as— for example—in the El Dorado Mountains (Anderson, 1971), rather than a belt of core complexes.
ACKNOWLEDGMENTS

Our research builds on the pioneering contributions of the late Peter J. Coney (1929–1999), who was instrumental in identifying Cordilleran metamorphic core complexes as distinct tectonic features and who highlighted the association of core complexes with crustal extension and magmatism. We also acknowledge the pioneering studies of the late William R. Dickinson (1931–2015), who focused on the relationship between sedimentation and extension in the greater Catalina metamorphic core complex and identified the Catalina-San Pedro detachment fault as a single regional fault system. Other geomorphians who contributed significantly to our understanding of the Catalina metamorphic core complexes include George Davis, Stan Keith, Steve Reynolds, Eric Force, and Gordon Lister. We thank reviewers Andrew Zura and Gary Axen, and Guest Associate Editor David Miller, for thoughtful comments that improved clarity and focus. Many of the field relationships described in our study were revealed by geologic mapping funded by the joint state-federal STATEMAP program specified by the National Geologic Mapping Act of 1992. In particular, we acknowledge Charles Ferguson, Brad Johnson, Steve Skotnicki, and Tim Orr for their detailed geologic maps over large areas of structurally complex geology. Geologic mapping in the greater Tucson area by J. Spencer and S. Richard was supported by the Arizona Geologic Survey under STATEMAP awards 98HQQG0064, 99HQQG0171, 01HQQG0149, 01HQQG0098, 02HQQG0016, 03HQQG014, 07HQQG0102, and 09GQQC0199.

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