Evidence for a Late Cretaceous to Paleogene basement-involved retroarc wedge in the southern U.S. Cordillera: A case study from the northern Chiricahua Mountains, Arizona

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Abstract

Late Cretaceous to Paleogene contractional deformation in the southern U.S. Cordillera is commonly attributed to the Laramide Orogeny, in part because of the prevalence of moderate- to high-angle, basement-involved, reverse faults. However, it is unclear if the tectonic models developed for the archetypal Laramide foreland belt in the U.S. Rocky Mountain region are applicable to the southern U.S. Cordillera. New geologic mapping of the northern Chiricahua Mountains in southeast Arizona, U.S.A. indicates the presence of an originally sub-horizontal thrust fault, the Fort Bowie fault, and a thin-skinned ramp-flat thrust system that is offset by a younger thrust fault, the Apache Pass fault, that carries basement rocks. Cross-cutting relationships and new geochronologic data indicate deformation on both faults occurred between 60 and 35 Ma. A biotite ^{40}Ar/^{39}Ar plateau age of 48 Ma from the hanging wall of the basement-involved Apache Pass fault is interpreted to record erosion related to reverse fault movement and rock uplift. The presence of thrust faults in southeast Arizona raises the possibility of a latest Cretaceous – Eocene retroarc orogenic wedge that linked the Sevier and Mexican thrust belts to the north and south, respectively. Basement-involved deformation does not rule out the presence of a retroarc wedge and many Cordilleran orogenic systems include basement-involved thrusting.

Introduction

The tectonic processes and style of deformation that characterize Late Cretaceous to Eocene age contractional deformation in the southern U.S. and northern Mexican Cordillera remain uncertain. Prior to the 1980s, contractional deformation in this region was recognized to be contemporaneous to the Laramide Orogeny in the U.S. Rocky Mountain region (ca. 80-40 Ma; Guzman and de Cserna, 1963; Coney, 1976; 1978; Armstrong, 1974; Dickinson and Snyder, 1978), but considered tectonically distinct. This distinction was based on early structural studies that emphasized the prevalence of low-angle thrust faults in southern Arizona, U.S.A (Ransome, 1904; Darton, 1925; King, 1939; 1969; Moore et al., 1941; Gilluly, 1956; Sabins, 1957a; Cooper and Silver, 1964; Hayes and Landis, 1964) and models that proposed the existence of a regionally extensive fold and thrust belt, analogous to the Sevier thrust belt (Corbitt and Woodward, 1973; Drewes, 1978; 1981b). This structural style (i.e., thin-skinned) is generally considered at odds with the Laramide foreland belt (Fig. 1), an area of thick-skinned deformation and large basement uplifts bounded by moderate- to high-angle, major reverse faults (see review in Weil and Yonkee, 2023). The leading proponent of the fold and thrust belt tectonic model for the southern U.S. was Harald Drewes of the U.S. Geologic Survey, who produced geologic maps for many of the mountain ranges in southeast Arizona and southwest New Mexico (e.g., Drewes, 1971; 1972; 1981a; 1982; 1984; 1985; 1986; 1991; 1996).

Despite the initial emphasis on low-angle thrust faults, basement-involved uplifts bounded by high-angle reverse faults were also recognized in the southern U.S. Cordillera (Jones, 1963; 1966; Mayo, 1966) and during the late 1970s and 1980s, many of the structures previously identified as thrust faults were reinterpreted as other types of contacts (Davis et al., 1979; Seager, 1983; Seager et al., 1986; Dickinson, 1984; Krantz, 1989). Of particular importance was the recognition of metamorphic core complexes and low-angle detachment faults during this time (e.g., Davis et al., 1980), leading to a re-interpretation of previously identified thrust faults as low-angle normal faults (cf., Dickinson, 1984), and a repudiation of the structural models of Drewes (1978; 1981b; 1988). The apparent absence of low-angle thrust faults, yet presence of basement-cored uplifts bounded by reverse faults, ultimately led to the prevailing paradigm for “thick-skinned” uplifts in the region (e.g., Amato et al., 2017; González-León et al., 2017; Clinkscales and Lawton, 2018; Favorito and Seedorf, 2017; 2018; 2022; Caylor et al., 2021; Trzinski and Chapman, 2023) and has contributed to the hypothesis that the southern U.S. Cordillera is part of the Laramide foreland belt and was affected by the Laramide Orogeny (Fig. 1). There is ongoing debate concerning the tectonic causes of the Laramide Orogeny as well as whether the Laramide foreland belt, defined primarily by structural style (Weil and Yonkee, 2023), is representative of the spatial extents of the Laramide Orogeny (Saleeby, 2003; Seager, 2004; Liu et al., 2010; Jones et al., 2011; Humphreys et al., 2015; Tikoff et al., 2023; Schwartz et al. 2023).

A recent review by Favorito and Seedorf (2022) suggested that *all* Late Cretaceous to Eocene age contractional deformation in southeast Arizona is thick-skinned and is characterized by regional-scale basement-cored uplifts bounded by moderate-angle reverse faults, consistent with the Laramide foreland belt. That review represents the culmination of the structural reinterpretations away from earlier fold and thrust belt models. To support their argument, Favorito and Seedorf (2022) presented structurally restored cross-sections from four key locales, including the northern Chiricahua – southern Dos Cabezas Mountains (Fig. 2). In this study, we revisit that location and present new geologic mapping to investigate the structural style of Late Cretaceous to Eocene age contractional deformation. In contrast to Favorito and Seedorf (2022), we recognize a major, low-angle thrust fault and propose that this structure is an unambiguous example of thin-skinned deformation in southeast Arizona. This finding has implications for the tectonic processes that produced Late Cretaceous to Eocene age deformation and challenges the notion that the southern U.S. Cordillera is characterized by a single style of contractional deformation. It also raises the question of what the exact relationship is between contractional deformation in the southern U.S. Cordillera and the surrounding tectonic provinces, including the Mexican fold and thrust belt, the Sevier thrust belt, and the archetypal Laramide foreland belt in the U.S. Rocky Mountain region (Fig. 1). We explore the possibility that the southern U.S. Cordillera could be characterized as a retroarc orogenic wedge, similar to the Sevier orogenic wedge to the north and the Mexican orogenic wedge to the south (DeCelles and Mitra, 1995; DeCelles, 2004; Long et al., 2015; Fitz-Díaz et al., 2018). These features have been interpreted to have an overall wedge shape that tapers toward the foreland, where deformation primarily involves sedimentary rocks, and thickens toward the hinterland, where deformation commonly involves basement rocks (e.g., Davis et al., 1983).

The presence of thick-skinned deformation in the southern U.S. Cordillera is often cited to support tectonic models that interpret contractional deformation in this region to be related to the Laramide Orogeny and low-angle subduction (cf., Weil and Yonkee, 2023). The most widely cited geodynamic model for the Laramide Orogeny proposes that flat-slab to shallow subduction of the Farallon plate conjugate of the Hess Rise, an oceanic plateau, is responsible for the contractional deformation associated with the Laramide Orogeny in the southern U.S. and northern Mexican Cordillera (Liu et al., 2010). This geodynamic model is a slightly younger and slightly smaller version of the model suggesting that flat-slab to shallow subduction of the Farallon plate conjugate of the Shatsky Rise, another oceanic plateau, was responsible for the Laramide Orogeny in the archetypal Laramide province in the central to northern U.S. Rocky Mountain region (e.g., Saleeby, 2003; Liu et al., 2010; Humphreys et al., 2015; Copeland et al., 2017). Models suggesting the subduction of two oceanic plateaus are appealing because it could explain Late Cretaceous to Paleogene age ("Laramide age"), thick-skinned deformation ("Laramide structural style") in both the U.S. Rocky Mountain region (e.g., Wyoming) and in the southern U.S. and northern Mexican Cordillera (e.g., Arizona, New Mexico, Sonora, Chihuahua). However, recent studies have called into question the applicability of the Hess oceanic plateau model for the southern U.S. Cordillera (e.g., Schwartz et al., 2023) as well as the Shatsky oceanic plateau model for the U.S. Rocky Mountain region (e.g., Carrapa et al., 2019; Tikoff et al., 2023). Demonstrating that Late Cretaceous to Paleogene contractional deformation in the southern U.S. Cordillera is not uniformly thick-skinned emphasizes the need consider alternative tectonic models for the region, independent of models developed for the central to northern U.S. Rocky Mountain region.

Geologic Setting and Previous Interpretations

The southern Dos Cabezas Mountains and northern Chiricahua Mountains (Fig. 2) are located in the southern Basin and Range province and are bounded on the northeast by a major normal fault system that has tilted the ranges down to the southwest during the Miocene (Drewes et al., 1985). The two ranges are part of a single, continuous mountain block separated by Apache Pass, the site of the infamous encounter between U.S. Army Lieutenant George Bascom and Chiricahua Apache leader Cochise that triggered the Apache Wars in the late 1800s (Roberts, 1994). Apache Pass is now part of the Fort Bowie National Historic Site (Fig. 3), which was mapped as part of this study. Sabins (1957a; 1957b) first described the local stratigraphy and produced the first detailed geologic map of the area.

Stratigraphy

Basement rocks include the Paleoproterozoic Pinal Schist (ca. 1.6 Ga; Meijer, 2014) and Mesoproterozoic granitoids (ca. 1.4 Ga; Trzinski et al., 2021). Basement rocks are unconformably overlain by a Paleozoic (Cambrian to lower Permian) passive margin sequence with a cumulative thickness of ~2 km (Sabins, 1957b). Upper Jurassic to mid-Cretaceous strata of the Bisbee Group (Dickinson and Lawton, 2001) were deposited unconformably on the Paleozoic section and Proterozoic basement. The geometry of this unconformity is variable throughout the study area, but is generally an angular unconformity with bedding dip discordance of ≤ 15°. This unconformable relationship is interpreted to record fault block uplift and erosion associated with the Mexican Border rift system that produced a series of northwest-trending rift basins collectively called the Bisbee Basin (Lawton et al., 2020). The Bisbee Group are the sedimentary rocks deposited in this basin. The basal unit of the Bisbee Group is the

Upper Jurassic Glance Formation, a carbonate-clast dominated cobble conglomerate that is ≤ 20 m thick in the study area and thins toward the southeast. For this report, the two successively younger units of the Bisbee Group, the Lower Cretaceous Morita Formation and the mid-Cretaceous Mural Formation, were treated as a single map unit (Km, see Figs. 4 and 5). The Morita-Mural unit is predominantly composed of shale, siltstone, and limestone and may be partially or wholly correlative with the Crystal Cave Formation, as defined by Lawton and Olmstead (1995) in the southern Chiricahua Mountains. The thickness of the combined Morita and Mural Formations in the study area is ≤ 130 m and thins toward the southeast. The uppermost unit of the Bisbee Group is the mid-Cretaceous Cintura Formation, which is ~750 m thick based on exposures located immediately east of the study area where the entire section is exposed south of Wood Mountain (Trzinski et al., 2021). In the study area, the top of the Cintura Formation is truncated everywhere by faults except on the western flank of Rough Mountain where it is unconformably overlain by the ca. 28 Ma volcanic Faraway Ranch Formation (Pallister and du Bray, 1997) (Fig. 3) and in the Dug Road Mountain area, where it is overlain by Cretaceous(?) age volcanic rocks (Fig. 3). Lastly, the youngest stratigraphic units consist of Cenozoic volcanic rocks associated with caldera-forming eruptions from ca. 35-26 Ma (du Bray et al., 2004). Volcanism is part of the regionally extensive mid-Cenozoic (late Eocene – Oligocene) ignimbrite flare-up and is related to the roll-back and/or foundering of the Farallon slab (Farmer et al., 2008). The study area is intruded by numerous small granitic to rhyolitic plutons, dikes, and sills (~35 Ma; this study) related to this magmatic event.

Structural Geology

There have been several interpretations of the structural geology of the study area, starting with the first comprehensive geologic mapping (1:62,500 scale) of the area by Sabins (1957a) who identified the presence of two major reverse faults; the Apache Pass fault and the Fort Bowie-Wood Mountain fault. Sabins (1957a) interpreted the Fort Bowie-Wood Mountain fault to originally be a low-angle thrust fault that juxtaposed Paleozoic strata structurally above Bisbee Group rocks. He interpreted the thrust fault to have been offset by the Emigrant Canyon fault (Fig. 3), with the Fort Bowie fault to the west and the Wood Mountain fault to the east. Based on the apparent surface offset relationships, Sabins (1957a) interpreted the Emigrant Canyon fault as a left-lateral strike-slip fault. Sabins (1957a) also reported that the Fort Bowie fault was truncated by the Apache Pass fault (Fig. 4) making it the older of the two structures. The Apache Pass fault was interpreted to be a high-angle reverse fault, dipping steeply to the southwest and placing Proterozoic basement rocks structurally above Paleozoic and Bisbee Group strata.

Based on additional geologic mapping (1:24,000 scale), Drewes (1981a; 1982; 1984) interpreted the presence of several additional thrust faults that he referred to as “strands.” He renamed the Fort Bowie-Wood Mountain fault of Sabins (1957a) the middle strand of the Hidalgo thrust fault. North of this fault, he interpreted the lower strand of the Hidalgo thrust fault to be a bedding-parallel thrust fault at the Paleozoic-Proterozoic contact. Moreover, Drewes suggested that this structure was reactivated by the northeast strand of the Apache Pass fault. South of the middle strand of the Hidalgo thrust fault, Drewes (1981a; 1982) interpreted the upper strand of the Hidalgo thrust fault to be a bedding-parallel thrust fault below Bisbee Group rocks and above upper Paleozoic strata. Drewes (1981a; 1984) renamed the Apache Pass fault of Sabins (1957a) the southwest or central strand of the Apache Pass fault and interpreted this structure to be a strike-slip fault. South of this structure, he interpreted the west strand of the Apache Pass fault to be a bedding-parallel fault located below Cenozoic volcanic rocks and above Cretaceous Bisbee Group rocks.

In the southern Chiricahua Mountains, approximately 20 km southeast of the present study area, Lawton and Olmstead (1995) presented a regional geologic map (approximately 1:100,000 scale) that reinterpreted the Apache Pass fault and Wood Mountain fault as major reverse faults and abandoned the usage of the Hidalgo thrust fault and the strand terminology of Drewes (1981a; 1982; 1984). Reverting to the interpretation of Sabins (1957a), Lawton and Olmstead (1995) indicated that the lower strand of the Hidalgo thrust fault, upper strand of the Hidalgo thrust fault, and west strand of Apache Pass fault of Drewes (1981a; 1982; 1984) are stratigraphic unconformities. The most recent structural analysis of the area was undertaken by Favorito and Seedorff (2022) who presented a structural cross-section (1:1,000,000 scale) through the Apache Pass area. Their cross-section was constructed using the geologic mapping and structural data of Drewes (1981a; 1982; 1984), but no additional mapping was performed to validate and verify the map relationships. Following Sabins (1957a) and Lawton and Olmstead (1995), Favorito and Seedorff (2022) interpreted the Apache Pass fault to be a high-angle reverse fault and interpreted the bedding-parallel “strands” of Drewes (1981a; 1982; 1984) to be unconformities. Favorito and Seedorff (2022) interpreted the Wood Mountain fault to be a southeast extension of the Apache Pass fault and suggested that the Emigrant Canyon fault offsets the Apache Pass fault, not the Fort Bowie-Wood Mountain fault. Favorito and Seedorff (2022) suggested that the Fort Bowie fault (Sabins, 1957a; Drewes, 1981a; 1984) was a depositional contact and reinterpreted the Bisbee Group rocks previously mapped (Sabins, 1957a; Drewes, 1981a; 1984) north of the fault as either Paleozoic strata or Proterozoic basement.

New Geologic Mapping and Structural Interpretation

To help resolve competing structural interpretations and investigate how contractional deformation is expressed in the region, we undertook new geologic mapping, conducted over the last 8 years. Collectively, we estimate >500 human-hours, ~60 days, were spent geologic mapping in the field. We present a new sub-regional geologic map (Fig. 3) based on reconnaissance 1:24,000 mapping and two detailed geologic maps (Figs. 4 and 5) based on 1:10,000 mapping of key areas. Two cross-sections, oriented transverse to structural strike, were constructed through the detailed mapping areas (Fig. 6).

Fort Bowie fault

Our results are consistent with the structural interpretations and geologic mapping of Sabins (1957a) and indicate that the Fort Bowie fault is a thrust fault that is truncated to the northwest by the Apache Pass fault and truncated to the southeast by the Emigrant Canyon fault (Fig. 3). Several lines of evidence support this interpretation. In the central part of the study area, progressively younger Paleozoic strata in the hanging wall are truncated against the fault toward the northwest, whereas the fault is sub-parallel to bedding of the Cintura Formation in the footwall. The position of the fault is at approximately the same stratigraphic level within the Cintura Formation along strike. This stratigraphic cutoff relationship suggests that the exposed portion of the fault is characterized by a hanging wall ramp and footwall flat. It is unclear if displacement on the fault was pure dip-slip or had a translational component. Hanging wall ramp cuts up stratigraphic section at a low angle relative to bedding (< 15°) toward the north. Assuming that bedding in the Cintura Formation was sub-horizontal during movement of the Fort Bowie fault, the original geometry of the fault can be estimated by unfolding bedding, presumably tilted by Cenozoic normal faulting (cf., Favorito and Seedorff, 2022). Because the fault is parallel to bedding of the Cintura Formation in the footwall, the original orientation of the fault is interpreted to also have been sub-horizontal. Similarly, in the Marble Canyon area (Fig. 3), the Fort Bowie fault and Cintura Formation bedding (in the footwall) are overturned, both dipping steeply toward the northeast.

In the Fort Bowie area, the Paleozoic section in the hanging wall is folded into an isoclinal anticline with an overturned northern limb (Figs. 4 and 6). We interpret this structure as a hanging wall anticline in the Fort Bowie thrust sheet. Despite the abundance of overturned beds, Drewes (1984) suggested this structure was an upright synform with bedding-parallel reverse faults located between each unit to explain the apparent older-on-younger stratigraphic relationships. All stratigraphic units are present and in the correct order, albeit overturned, and we did not observe evidence for faulting between units. Based on our mapping, the average strike and dip of Bisbee Group rocks in the in the Fort Bowie area is 129 58 SW (n=44; Fig. 4B). Restoration of Cenozoic normal fault block rotation using this average orientation suggests that the overturned, isoclinal fold was originally recumbent. The axial plane of the fold, determined using bedding orientation of Paleozoic strata, has a strike and dip of 123 69 SW (n=36; Fig. 4C). Restoration of tilting using the average Bisbee Group bedding orientation suggests that the original strike and dip of the axial plane was 107 15 S. Assuming that shortening direction was orthogonal to the axial plane of this fold, we estimate the shortening azimuth to have been ~017°.

In the Emigrant Canyon area, rocks in the footwall of the Fort Bowie fault are folded into an open, box-like syncline that plunges steeply to the west (Figs. 5 and 6). In this area, the Cretaceous section nonconformably overlies basement rocks and the unconformity is a structural marker that records folding of basement rocks into a synclinal structure. Basement rocks occupy the up-plunge (i.e., structurally deepest) portion of the fold, which is offset by the north-south striking Emigrant Canyon fault. The southern limb of the syncline is truncated against the Fort Bowie fault. We interpret this structure as a footwall syncline related to movement on the Fort Bowie fault. Restoration of the original orientation of this syncline is not straightforward as it has experienced at least two periods of tilting. These include uplift and down-to-the west tilting in the hanging wall of the Emigrant Canyon fault (see section on Emigrant Canyon fault below) and uplift and down-to-the south tilting of the entire Chiricahua Mountain block, presumably during Basin and Range (Miocene?) normal faulting. Footwall uplift across the Emigrant Canyon fault exposed the synclinal structure and contributed to its steep westward plunge.

Basal Bisbee Group Unconformity

The angular unconformity at the base of the Bisbee Group records highly variable degrees of erosion throughout the Dos Cabezas and northern Chiricahua Mountains (Fig. 3). The changes in unconformity position reflect paleotopography, uplift, and erosion related to the Late Jurassic to Early Cretaceous Mexican Border Rift system (Lawton et al., 2020). This deformation event precedes contractional deformation and is not the focus of the current study, but it does produce some structurally complex map relationships. For example, at the easternmost end of the Fort Bowie fault, near its termination against the Emigrant Canyon fault, Paleozoic rocks are in thrust contact with basement rocks, producing an apparent younger-on-older structural relationship. However, along-strike to the west, this map relationship returns to an expected older-on-younger relationship with Paleozoic strata thrust against Cretaceous Bisbee Group rocks. In addition to along-strike changes, the stratigraphic position of the unconformity is commonly different across the Fort Bowie fault. This complicates structural restoration and the use of the unconformity as a piercing point, but also implies that displacement was large enough to juxtapose regions with distinct erosional levels.

Emigrant Canyon fault

The Emigrant Canyon fault was interpreted by Sabins (1957a) and Drewes (1982) to be a left-lateral strike slip fault with ~2 km of displacement. Our results suggest that the Emigrant Canyon fault is primarily a down-to-the east normal fault that offsets steeply south-dipping strata, resulting in the apparent left-lateral offset in map view (Fig. 3). The stratigraphic offset of lower Paleozoic strata (e.g., Cambrian Bolsa Formation) can be produced with ~2 km of dip slip fault displacement on the Emigrant Canyon fault (Fig. 3). The Emigrant Canyon fault is a north-to-northwest-striking structure, at a high-angle to the west-northwest strike of the main range-bounding normal fault flanking the northern end of the range (Drewes, 1984). However, this strike direction is generally consistent with the main range-bounding faults in southeast Arizona and southwest New Mexico (Fig. 2). In the Emigrant Canyon area, the Emigrant Canyon fault locally cross-cuts ca. 35 Ma (this study, see Geochronology section below) granitic rocks (map unit Tg; Fig. 5) and Oligocene volcanic rocks on the southern flank of Rough Mountain (Fig. 3). A small normal fault in the Emigrant Canyon area also offsets the ca. 35 Ma granitic rocks. These observations suggest that normal faulting occurred after intrusion of map unit Tg (< ~35 Ma). The granitic rocks (map unit Tg) cross-cut the footwall syncline associated with the Fort

Bowie fault and cross-cut the Fort Bowie fault itself (e.g., westernmost exposure of Fort Bowie fault in Figure 5). This suggests that fault displacement and deformation (i.e., folding of the footwall) related to the Fort Bowie fault is older than ~35 Ma.

Apache Pass fault

Our results are consistent with previous interpretations of the Apache Pass fault as a large, basement-involved reverse fault that currently dips steeply to the southwest (Sabins, 1957a; Favorito and Seedorff, 2022). In the Fort Bowie area, in the vicinity of cross-section A-A', the Apache Pass fault has an average strike and dip of 135 75 SW, consistent with previous direct measurements of fault dip that range from 65-85° SW (Sabins, 1957a; Drewes, 1984; 1985). Like the Fort Bowie fault, the Apache Pass fault was tilted during mid-Cenozoic normal faulting and the original orientation of the fault can be estimated by restoration (rotation of tilted beds to a horizontal position) of Bisbee Group bedding in the footwall. Northwest of where the Fort Bowie fault is truncated by the Apache Pass fault, the orientation of the Apache Pass fault is sub-parallel (≤ 15°) to bedding of the Bisbee Group in the footwall (Figs. 3 and 4). This suggests the presence of a footwall flat or low-angle thrust ramp, similar to the structural relationship between the Fort Bowie fault and the Bisbee Group in its footwall. Moreover, this structural relationship is present along the entirety of the exposed length (~15 km) of the fault, suggesting that the near bedding-parallel orientation of the fault is not a local feature. Unfolding of bedding in the Bisbee Group in the Fort Bowie area (average strike and dip = 129 58 SW) suggests an original strike and dip of the Apache Pass fault of 148 18 SW.

Our estimate of original fault dip angle is lower than the estimate of Favorito and Seedorff (2022; their Fig. 6C) who suggested an original, near-surface dip of ~45° after restoration of Bisbee Group bedding (restored by rotation of tilted Bisbee Group bedding to a horizontal orientation). However, Favorito and Seedorff (2022; their Fig. 6D) suggested that the present-day bedding in the Bisbee Group has a regional dip of ~30°, significantly less than the average dip of 67° (n=16) reported by Drewes (1984; 1985) near the trace of the cross-section drawn by Favorito and Seedorff (2022) and significantly less than the average dip angle of Bisbee Group bedding exposed anywhere along the trace of the Apache Pass fault. To our knowledge, there are no corroborating field observations which justify the reduced dip angle of Bisbee Group bedding presented in Favorito and Seedorff (2022). To honor the structural data of Drewes (1984; 1985), Favorito and Seedorff (2022) suggested the presence of a small (displacement = ~500 m), southwestward-verging, blind reverse fault in the footwall that locally increased the dip angle of the Bisbee Group rocks near their cross-section (their Fig. 6D). There is no evidence for folded rocks related to this fault in the footwall of the Apache Pass fault along the trace of the cross-section presented in Favorito and Seedorff (2022) and there is no evidence for related folding along strike to the northwest or southeast. Instead, the Paleozoic section and Bisbee Group rocks in the footwall of the Apache Pass fault form a relatively homoclinal panel for >15 km along strike. For these reasons, we prefer our interpretation that the Apache Pass fault was originally a low-angle thrust fault (see Cross-Section Reconstruction section below). Even if bedding in the Bisbee Group was regionally tilted prior to fault displacement (e.g., 20° SW), the structural relationship between the Apache Pass fault and Bisbee Group indicate that the fault formed at an orientation sub-parallel to the regional dip of bedding, consistent with a footwall flat or low-angle ramp.

Southeast of the Fort Bowie area, the Apache Pass fault and the rock units in its hanging wall and footwall are continuously exposed along strike until the truncation of the fault against the Emigrant Canyon fault. South of Emigrant Canyon, the Apache Pass fault appears to be minimally offset by the Comet Spring fault and it is unclear if the Apache Pass fault is offset by the Red Mountain fault because of the presence of a Cenozoic intrusion that obscures the structural relationships (Fig. 3). Changes in the erosional depth of the unconformity at the base of the Bisbee Group on either side of the Red Mountain and Comet Spring faults are interpreted to reflect paleotopography associated with Jurassic age extensional deformation and erosion related to the Mexican Border rift.

Cross-Section Reconstruction

Cross-section A-A' was expanded and schematically restored in four partial retro-deformational steps to help illustrate the structural relationships and structural evolution of the region (Fig. 7). In the first step, the cross-section was rotated to remove the tilt of Bisbee Group strata in the footwall of the Fort Bowie fault (bedding rotated to a horizontal orientation) to illustrate the original dip of the Fort Bowie and Apache Pass faults and the recumbent orientation of the hanging wall anticline. In the second step, the hanging wall of the Apache Pass fault was unfolded using the orientation of Bisbee Group bedding (unfolded to a horizontal orientation) in the hanging wall. This step helps to illustrate the displacement of Paleozoic strata and Bisbee Group rocks by the Apache Pass fault. In the third step, ~12 km of slip on the Apache Pass fault was removed to restore the Fort Bowie thrust sheet. The amount of estimated slip for the Apache Pass fault is constrained by the dip of the fault and surface geology that indicates a ~4 km thick panel of Proterozoic basement rocks are present in the hanging wall of the fault.

The fourth retro-deformational step removes ~20 km of slip on the Fort Bowie fault to restore the overturned hanging wall anticline to its (inferred) overturned footwall syncline counterpart. The amount of estimated slip on the Fort Bowie fault is constrained by the presence of Permian age rocks (e.g., Colina Formation) in the hanging wall that are truncated by the Fort Bowie fault (Fig. 4). Where exposed (e.g., Red Mountain area, Fig. 3), Permian age rocks are not present beneath the basal Bisbee Group unconformity in the hanging wall of the Apache Pass fault. As a result, the location of the truncated Permian age rocks on the other side (footwall) of the Fort Bowie fault must be located at a distance greater than the reconstructed distance between the exposures of the basal Bisbee Group unconformity in the Apache Pass fault hanging wall. This distance is ~15 km in the plane of cross-section A-A' and is shown by two vertical blue arrows in Figure. 7. A final retro-deformation step, unfolding of the anticline-syncline pair is not shown, but indicates another ~5 km of horizontal shortening (~25 km total estimate) for the Fort Bowie fault. This slip estimate is conservative and could be an underestimate because the position of Permian age rocks beneath the basal Bisbee Group unconformity is unknown, presumably located in the subsurface in Sulphur Springs valley to the southwest of the Dos Cabezas-Chiricahua Mountains (Fig. 2).

Geochronology and Thermochronology Methods and Results

Zircon U-Pb

Zircon U-Pb laser ablation (LA)-ICPMS analyses were conducted at the University of Arizona Laserchron Center using a Photon Machines 193 nm excimer laser coupled to a Thermo-Fisher Element2 single collector ICPMS following the procedures of Gehrels et al. (2008). A laser spot diameter of ~25 μm was used. Data was reduced using FC-1 as the primary zircon standard and SL and R33 as secondary standards. See Gehrels and Pecha (2014) for reporting on long-term reproducibility of standard ages. Common Pb was estimated from the measurement of

^{204}Hg, after subtraction of backgrounds, and corrected for all analyses using the model of Stacey and Kramers (1975). Age uncertainties were calculated at the 2σ level by adding in quadrature the standard deviation of single spot dates and the average single spot date uncertainty.

Zircon separated from sample DC-D1, a fine-grained rhyolitic dike that cross-cuts the Apache Pass fault (Fig. 4), yielded a range of U-Pb dates including a population of Mesoproterozoic to Paleoproterozoic dates (1.4-1.6 Ga) and a population of late Eocene dates (35.9-34.7 Ma). We interpret the Proterozoic dates to represent inherited, xenocrystic zircon and the Eocene dates to represent the crystallization age of the dike. Two of the Eocene dates display minor discordance (Fig. 8) that we interpret to reflect imprecise LA-ICPMS measurements of ^{207}Pb, which occurs in very low concentrations for Cenozoic age samples (cf., Vermeesch, 2021) (Fig. 8A). The weighted mean $^{206}Pb/^{238}U$ age of the dike is 35.2 ± 0.6 Ma (n=6, MSWD=0.88). Zircon from sample DC-Tg1, a small pluton that intrudes along the trace of a normal fault on the northwest flank of Wood Mountain (Fig. 3), yielded a range of U-Pb dates with a single large population of late Eocene to early Oligocene dates (33.0-36.5 Ma). Excluding outliers and discordant data, the weighted mean $^{206}Pb/^{238}U$ age of the pluton is 34.8 ± 0.7 Ma (n=15, MSWD=0.93) (Fig. 8B). Complete analytical results are presented in Supplementary Data Table 1.

Zircon and apatite (U-Th)/He

Apatite (U-Th)/He (AHe) and zircon (U-Th)/He (ZHe) analyses were performed at the University of Arizona Radiogenic Helium Dating Laboratory following the procedures of Reiners et al. (2004). Apatite and zircon grains were packed into Nb tubes, placed into a planchet, and degassed by a diode or CO_2 laser at temperatures in the range of 1100–1250°C for

15-minute extraction intervals, and subsequently re-extracted at higher laser power and temperature until He yields were below 2–3% of the total. Standards include Durango apatite (date range = 31.9-27.5 Ma) and Fish Canyon Tuff zircon (date range = 27.1-29.7 Ma). After degassing, apatite and zircon grains were dissolved and parent nuclide concentrations were measured by isotope dilution with a ^{233}U-^{239}Th spike on a Thermo-Fisher Element2 SC-ICP-MS. Alpha ejection corrections were applied following the equations presented in Farley and Stockli (2002) for apatite and Hourigan et al. (2005) for zircon.

ZHe and AHe data were collected from three Proterozoic granitoids, samples APPS-X3, APF-D1, and DC-Yg1, collected from the hanging wall of the Apache Pass fault. Individual grain ZHe dates range from 20.5-24.6 Ma for APPS-X3, and 22.4-34.4 Ma for APF-D1. For each of these samples, there is no apparent correlation between date and eU (effective Uranium concentration) or Rs (spherical radius) (Figs. 8C and 8D). The weighted mean ZHe date for APPS-X3 is 27.2 ± 1.7 Ma and 27.2 ± 5.0 Ma for APF-D1. Individual grain AHe dates from sample DC-Yg1 range from 22.5-40.5 Ma. There is no apparent correlation between AHe date and eU and a weak positive correlation (R^2 = 0.56) between AHe date and Rs (Figs. 8C and 8D). The weighted mean AHe date for sample DC-Yg1 is 26.0 ± 11.0 Ma. Complete analytical results are presented in Supplementary Data Tables 2 and 3.

Biotite $^{40}Ar/^{39}Ar$

An $^{40}Ar/^{39}Ar$ step-heating analysis was conducted at the University of Arizona Noble Gas Lab on following the procedures of Schaen et al. (2021). A biotite aliquot of ~2 mg was separated from a Proterozoic granitoid (sample APPS-X3), collected from the hanging wall of the Apache Pass fault (Fig. 3), packed into a planchet, and degassed by a CO_2 laser at power levels between 0.5% and 50% for a series of steps between 1 and 10 minutes in duration. Argon isotopes were measured with an ARGUS VI noble gas multi-collector mass spectrometer with an Alder Creek sanidine analytical standard (1.1851 ± 0.0004 Ma; Schaen et al., 2021). Complete analytical results are presented in Supplementary Data Table 4.

The first steps (< 7% cumulative $^{39}Ar_K$) and last steps (> 99% cumulative $^{39}Ar_K$) yielded anomalously old ages that suggest the presence of excess ^{39}Ar (McDougall and Harrison, 1999). The remaining heating steps (7-99% cumulative $^{39}Ar_K$) yielded dates ranging from 47 to 50 Ma with uncertainties < 0.05 Ma and were used to calculate a weighted mean plateau age of 48.2 ± 0.9 Ma, using the amount of $^{39}Ar_K$ released during each step as the weighting factor (Fig. 8E). We calculated age uncertainty by adding in quadrature the standard deviation of single step dates and the average step uncertainty, which provides a conservative estimate of age uncertainty at the 2σ level. Although the range of single step dates is relative narrow (within 3 Myr), dates generally increased as the heating steps increased, which can be interpreted as diffusive loss of radiogenic ^{40}Ar at low cumulative % Ar release (McDougall and Harrison, 1999). Steps at higher cumulative % Ar release (66-96% cumulative $^{39}Ar_K$) visually define a sub-plateau with a weighted mean age of 49.2 ± 0.2 Ma, using the same weighting and uncertainty calculations described above.

Timing of fault movement and interpretation of thermochronology data

There are two main contractional structures in the northern Chiricahua – southern Dos Cabezas Mountains, the Fort Bowie-Wood Mountain fault and the Apache Pass fault. The Fort Bowie fault is truncated by the Apache Pass fault at its northern terminus and the Apache Pass fault is cross-cut by ca. 35 Ma rhyolitic dikes (e.g., sample DC-D1; Fig. 8). The footwall syncline associated with the Fort Bowie fault is also cross-cut by ca.35 Ma granitic intrusive rocks (e.g., sample DC-Tg1). This places an upper age constraint of ~35 Ma on the movement of these two faults. Immediately to the east of the study area, on the northern flank of Wood Mountain, the Wood Mountain Fault places Paleozoic rocks structurally above synorogenic volcaniclastic rocks as young as ~60 Ma (Trzinski et al., 2021). This places a minimum age of displacement of ~60 Ma on the movement of the Fort Bowie-Wood Mountain fault as well as the Apache Pass fault that cross-cuts the Fort Bowie fault. Trzinski et al. (2021) suggest that the volcaniclastic rocks on Wood Mountain are synorogenic, therefore displacement along the Fort Bowie-Wood Mountain fault must have initiated or have been ongoing by ~60 Ma.

Additional constraints on the timing of movement on the Apache Pass fault come from thermochronology data. Single aliquot ZHe and AHe dates from Proterozoic rocks in the hanging wall of the Apache Pass fault display a dominant date population centered on ~28 Ma (Fig. 8C). This is the same age as widespread volcanism in the Chiricahua Mountains (Pallister and du Bray, 1997) and is slightly younger than the ~35 Ma intrusive rocks dated in this study. We interpret the AHe and ZHe dates to reflect post-magmatic cooling and suggest that the Proterozoic rocks exposed in the hanging wall of the Apache Pass fault have experienced temperatures high enough (ca. 200 °C, Reiners and Brandon, 2006) to have reset the AHe and ZHe systems.

The weighted mean age of the biotite $^{40}Ar/^{39}Ar$ analysis (~48 Ma) from the hanging wall of the Apache Pass fault is within the 60-35 Ma age range for movement on the fault based on cross-cutting relationships. We interpret the $^{40}Ar/^{39}Ar$ plateau age to reflect cooling related to rock uplift and erosion of the hanging wall of the Apache Pass fault. Proterozoic rocks in the hanging wall of the Apache Pass fault likely did not experience temperatures in excess of ca.

325-350 °C, the effective closure temperature of the biotite $^{40}Ar/^{39}Ar$ thermochronology system for cooling rates of 1-10 °C/Myr (Reiners and Brandon, 2006), during late Eocene to Oligocene magmatism. There is a relatively subtle increase in apparent $^{40}Ar/^{39}Ar$ step dates (47 to 48 Ma) at < 65 % cumulative Ar release (Fig. 8E). This could be interpreted as minor diffusive loss of Ar associated with reheating during later periods of magmatism, consistent with the interpretation of the thermally reset AHe and ZHe dates. In this case, the sub-plateau age (~49 Ma) may be a more accurate estimate of the timing of rapid cooling through the closure temperature window. Alternatively, the sample may have experienced slow cooling through a partial retention zone. In this case, the entire plateau age (~48 Ma), or range of step dates, may be the more accurate estimate of the time of cooling. It is difficult to estimate cooling rates and assess the validity of our interpretations with a single $^{40}Ar/^{39}Ar$ sample. Nonetheless, based on the available data, we suggest that movement on the Apache Pass fault was ongoing by 48-49 Ma. Erickson (1981) reported two Eocene biotite K-Ar dates (50.3 ± 1.5 Ma and 53.2 ± 1.5 1.6 Ma) from Proterozoic rocks in the hanging wall of the Apache Pass fault in the Dos Cabezas Mountains northwest of the study area. Erickson (1981) hypothesized that these samples may have been thermally reset by intrusive rocks in the subsurface (not exposed), but they could also be related to rock uplift and erosion in the hanging wall of the Apache Pass fault.

Structural Relationships and Tectonic Implications

The results of this study have broad implications for the tectonics of the southern U.S. and northern Mexican Cordillera. The northern Chiricahua – southern Dos Cabezas Mountains have been suggested to be one of the "type" localities for thick-skinned deformation associated with moderate- to high-angle reverse faults (Favorito and Seedorff, 2022). The presence of thick-skinned deformation in the southern U.S. Cordillera is one of the main arguments for associating this part of the Cordillera with the Laramide Orogeny and geodynamic models that involve flat-slab subduction (cf., Weil and Yonkee, 2023). However, new detailed geologic mapping in the northern Chiricahua Mountains suggests that they contain an unambiguous example of low-angle thrust faulting in the region – the Fort Bowie fault and associated structures. Could this feature be representative of a regionally extensive thrust belt, equivalent to the Sevier thrust belt to the north or the Mexican fold and thrust belt to the south?

Considering this question, a reexamination of many of the thrust faults previously identified in the region is warranted. Our findings support the original mapping by Sabins (1957a) that identified the Fort Bowie-Wood Mountain fault as a major thrust fault. Geologic mapping by Drewes (1981a; 1982; 1984) in the study area suggested five additional thrust faults, or fault "strands," none of which are supported by our new mapping. Among the many tens of thrust faults identified by H. Drewes in southeast Arizona and southwest New Mexico, it implies there may be more unrecognized, or misinterpreted, thrust faults. New detailed geologic mapping and structural reconstructions are needed to assess this possibility. Apart from the work of H. Drewes, the Fort Bowie-Wood Mountain fault adds to a growing list of thrust faults identified in southeast Arizona more recently (Gehrels and Smith, 1991; Waldrip, 2008; Arca et al., 2010; Spencer et al., 2019; 2022) and suggests regional thrust faulting may be underappreciated.

A large majority of Late Cretaceous to Eocene age contractional structures identified in southeast Arizona and southwest New Mexico involve basement rocks (Davis et al., 1979, Krantz, 1989; González-León et al., 2017; Clinkscales and Lawton, 2018; Favorito and Seedorf, 2017; 2018; 2022). This suggests that deformation is not predominantly thin-skinned in structural style in this region, but it does not rule out the presence of a thrust belt or orogenic wedge. Many thrust sheets in the Sevier thrust belt involve basement rocks, including the Pavant and Paxton thrust sheets in central Utah (DeCelles and Coogan, 2006), the Wasatch Anticlinorium/Ogden thrust system in the Wyoming salient (Yonkee, 1992), and the Idaho-Montana fold-thrust belt (Parker and Pearson, 2023; Howlett et al., 2024). These structural studies show that the thin-skinned vs. thick-skinned debate is a false dichotomy and the concept that structural style can reliably identify geodynamic processes is a false construct. There are many reasons why thrust belts can involve basement rocks, including inherited structures and changes in sedimentary cover thickness (see review in Lacombe and Bellahsen, 2016). Regardless of the mechanisms, basement-involved fold and thrust belts are common globally, including in the Andean Cordillera where retroarc structural-style varies significantly along strike (Horton and Folguera, 2022). We propose that the southern U.S. and northern Mexican Cordillera can be interpreted as a basement-involved thrust belt or a basement-involved retroarc wedge (Fig. 9), which would distinguish it from the predominantly thin-skinned Sevier thrust belt to the north (e.g., Yonkee and Weil, 2015) and the fold-dominated Mexican thrust belt to the south (Fitz-Díaz et al., 2018), but allow it to become the "missing" segment of the retroarc thrust belt in the broader North American Cordilleran orogenic system (Fig. 1).

In the study area, initial contractional deformation primarily involved shortening of sedimentary cover by slip on the Fort Bowie fault at a relatively shallow decollement position and subsequent contractional deformation occurred at a deeper structural level on the Apache Pass fault (Fig. 7). The transition to deformation at deeper structural levels at any specific position in a thrust belt is a common phenomenon and predicted by critical taper theory for thrust wedges (e.g., Davis et al., 1983; DeCelles and Mitra, 1995). A similar transition from thin-skinned to thick-skinned deformation, has been recognized in parts of the Mexican fold and thrust belt (Fitz-Díaz et al., 2018; Williams et al., 2021) as well as in the Sierra Anibacachi area near the Arizona-Sonora border (González-León et al., 2017) (Fig. 2). Additional structural and geochronology studies in southern U.S. and northern Mexican Cordillera can help test whether regional deformation is consistent with thrust wedge dynamics (e.g., Graveleau et al., 2012).

The presence of thrust faults and the possibility of a thrust belt or orogenic wedge in the southern U.S. Cordillera suggests that the association of deformation in this region with the Laramide Orogeny may need to be reevaluated. More broadly, tectonic models for the Laramide Orogeny that were developed to explain observations in the archetypal Laramide foreland belt in the central to northern U.S. Rocky Mountain region (e.g., Wyoming; Liu et al., 2010) may not be appropriate for the southern U.S. and northern Mexican segments of the Cordillera. Alternative models, including the possibility that the southwest U.S. may represent the northern continuation of the Mexican fold and thrust belt (Fitz-Díaz et al., 2018) should be considered. The Mexican fold and thrust belt propagated eastward (toward the foreland) during Late Cretaceous to Eocene time as a result of ongoing eastward-directed ocean-continent subduction following Early to mid-Cretaceous closure of the Arperos Basin and accretion of the Guerrero superterrane (Martini et al., 2014; 2016; Fitz-Díaz et al., 2018) and has little to no association with low-angle subduction of an oceanic plateau. In this respect, it shares a similar geologic history with the central U.S. Cordillera that experienced closure of marginal oceanic basins and terrane accretion events during the early Mesozoic, followed by continued subduction and a gradual expansion of the retroarc thrust belt toward the foreland, resulting in the Luning-Fencemaker, Central Nevada, and Sevier thrust belts (DeCelles, 2004; Long, 2015).

Finally, the presence of a retroarc thrust belt in the southern U.S. Cordillera would help explain evidence for thickened crust during the Late Cretaceous to Eocene (e.g., the Arizonaplano; Chapman et al., 2020) including the geochemical composition of arc magmatism, metamorphic core complexes, crustal anatexis, and paleoaltimetry data (Licht et al., 2017; Bahadori and Holt, 2019; Chapman et al., 2020; 2021; 2023; Jepson et al., 2022; Kapp et al., 2023).

Conclusions

The southern Dos Cabezas – northern Chiricahua Mountains expose one of the best examples of Late Cretaceous to Eocene thrust faulting in southeast Arizona. Similarly aged thrust and reverse faults elsewhere in the region are commonly inferred based on exposures of basement rocks, but the bounding structures are often only partially exposed for a limited strike-length or covered by alluvium. In contrast, the Fort Bowie fault and Apache Pass fault can be traced along their fault strike for distances of ca. 15 km, and the largely continuous exposures within the mountain range allow for a unique perspective on cross-cutting relationships, including with juxtaposing stratigraphic sections and the relationship to later Cenozoic magmatism. One of these well-documented structures is the Fort Bowie fault, which formed as a sub-horizontal thrust fault and preserves a low-angle (< 15°) hanging wall ramp in upper Paleozoic strata and a footwall flat in Cretaceous strata along its western trace. In the Fort Bowie area, the fault places upper Permian strata structurally above mid-Cretaceous rocks of the Bisbee Group, consistent with a “thin-skinned” structural style. Structural relationships within the hanging wall indicate that there is an overturned, isoclinal, anticline, which in a pre-extensional restored state was a recumbent, northeast-verging fold. Based on the orientation of the axial plane of the hanging wall anticline, we estimate the tectonic transport direction to have been toward the north-northeast. In the Emigrant Canyon area, the Fort Bowie fault places middle to lower Paleozoic strata structurally above Cretaceous Bisbee Group rocks that were deposited unconformably on basement rocks. Basement and Bisbee Group rocks are folded into a steeply plunging, open syncline in the footwall of the fault. We conservatively estimate ~25 km of slip on the Fort Bowie fault, although this is poorly constrained and dependent on our structural interpretation.

The Fort Bowie fault is truncated by the basement-involved Apache Pass Fault. To the northwest of the fault truncation, the Apache Pass fault places Proterozoic basement rocks structurally above mid-Cretaceous Bisbee Group rocks, and for most of its exposed length, the fault is sub-parallel or at a low-angle to bedding in the Bisbee Group in the footwall. Previous studies suggested this fault originated as a high-angle reverse fault, but restoration of tilted strata suggests that the original fault dip was ~20° SW; thus, we interpret the Apache Pass fault to be a basement-involved thrust fault that post-dates displacement across the Fort Bowie fault. We estimate a minimum of ~12 km of slip on the Apache Pass fault.

Volcaniclastic rocks in the footwall of the Fort Bowie-Wood Mountain fault and new zircon U-Pb dates from felsic dikes that cross-cut the Apache Pass fault indicate that these faults were active between 60 Ma and 35 Ma. New ZHe and AHe analyses of Proterozoic basement rocks in the hanging wall of the Apache Pass fault yielded weighted mean dates of ca. 26-27 Ma and a dominant single-grain date population centered on 28 Ma. These dates are interpreted to reflect post-magmatic cooling following widespread regional magmatism during the Oligocene, including the caldera-forming event in the central Chiricahua Mountains. A single biotite $^{40}Ar/^{39}Ar$ analysis from Proterozoic basement rocks in the hanging wall of the Apache Pass fault yielded a ca. 48-49 Ma plateau age that we interpret to reflect erosion and rock uplift associated with movement on the Apache Pass fault, although the robustness of this interpretation is difficult to assess with a single thermochronometer.

The presence of thrust faults in the southern U.S. Cordillera challenges ideas that Late Cretaceous to Paleogene deformation in the region is only thick-skinned in structural style and raises the possibility that the region could be reinterpreted within a thrust belt or orogenic wedge framework, including a basement-involved retroarc thrust wedge. Although the southern U.S. Cordillera is commonly lumped together with the Laramide Orogeny and tectonic models focused on low-angle to flat-slab subduction of oceanic plateaus, the results of this study suggest it could be related to other tectonic mechanisms and segments of the North American Cordillera, including the Mexican fold and thrust belt. Resolving the deformational history and structural evolution is important for testing competing geodynamic models on drivers for Cordilleran orogenesis.

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Figure Captions

Figure 1: Overview map of the central North American Cordillera that highlights the uncertain relationship between the Sevier thrust belt, Laramide foreland belt, and Mexican thrust belt in the southwest U.S. and northwest Mexico.

Figure 2: Regional geologic map, showing the position of the study area in the Chiricahua Mountains and the location of major, Late Cretaceous to Paleogene age, reverse faults in the region. A schematic cross-section through the Huachuca Mountains (v-v'), Whetstone Mountains (w-w'), Dragoon Mountains (x-x'), Swisshelm Mountains (y-y'), and Chiricahua Mountains (z-z') is presented in Fig. 9. Dashed faults are concealed or inferred

Figure 3: Geologic map the southern Dos Cabezas – northern Chiricahua Mountains based on new 1:24,000 scale mapping undertaken as part of this study. Dashed faults and contacts are concealed (beneath Quaternary rocks) or inferred (beneath all other units). Map projection UTM NAD83 z12.

Figure 4: A) Detailed geologic map of the historic Fort Bowie area (location shown in Fig. 3) based on new 1:10,000 scale mapping undertaken as part of this study. Map units and labels are the same as in Fig. 3 unless otherwise noted. Map projection UTM NAD83 z12. B) Stereonet plot of Bisbee Group bedding in the footwall of the Fort Bowie fault. C) Stereonet plot of Paleozoic strata in the hanging wall of the Fort Bowie fault, including upright bedding, overturned bedding, and the calculated orientation of the axial plane of the overturned anticline.

Figure 5: Detailed geologic map of the Emigrant Canyon area (location shown in Fig. 3) based on new 1:10,000 scale mapping undertaken as part of this study. Map units and labels are the same as in Figs. 3 and 4 unless otherwise noted. K_d: Cretaceous (?) diabase. Dashed faults and contacts are concealed (beneath Quaternary deposits) or inferred (beneath all other units). Map projection UTM NAD83 z12.

Figure 6: Cross-sections A-A' (location shown in Fig. 4) and B-B' (location shown in Fig. 5) showing key structural features, including the hanging wall anticline and footwall syncline associated with the Fort Bowie fault. Ball and stick symbols show apparent dip of bedding in the plane of the cross-section, closed symbols = upright bedding, open symbols = overturned bedding. Quaternary deposits are omitted.

Figure. 7: Schematic restoration of cross-section A-A' (Fig. 6), shown in three retro-deformational steps, based on observations made during geologic mapping. Annotations explain specific drafting decisions for the restored cross section.

Figure 8: Geochronlogy and thermochronology data. A and B) Zircon U-Pb LA-ICPMS data presented on Wetherill concordia diagrams for samples DC-D1 and DC-Tg1 (map unit Tg). C and D) Date-eU (effective Uranium concentration) data and date-Rs (equivalent spherical radius) for apatite (U-Th)/He (AHe) and zircon (U-Th)/He (ZHe) data from Proterozoic rocks collected in the hanging wall of the Apache Pass fault. Error bars are smaller than the symbols in both plots. The kernel density estimate (bandwidth = 2) includes all single-grain (U-Th)/He analyses.

E) Results from a $^{40}Ar/^{39}Ar$ step-heating analysis of biotite from a Proterozoic granitoid collected in the hanging wall of the Apache Pass fault.

Figure 9: A) Schematic cartoon of a composite cross-section through several mountain ranges in southeast Arizona (locations shown in Fig. 2). Normal faults, both Mesozoic and Cenozoic in age, were either restored or ignored to emphasize the possible geometry of Late Cretaceous to Eocene contractional deformation. The regional structural geology is interpreted to be part of a basement-involved, retroarc thrust wedge. The gray dashed line represents an approximate topographic surface. B) Same cross-section as in panel A, but drawn with a thick-skinned structural style (cf., Davis, 1979; Krantz et al., 1989). The geometry of the listric reverse fault and small back-thrust in the Chiricahua Mountains in panel B is modified from Favorito and Seedorff (2022; their Fig. 6C).