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SUPERPOSED REVERSE AND NORMAL FAULTS IN THE CENTRAL FLORIDA MOUNTAINS, SOUTHWESTERN NEW MEXICO, AND THEIR IMPLICATIONS FOR POST-CRETACEOUS CRUSTAL DEFORMATION

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Abstract—At Mahoney Park in the Florida Mountains of southwestern New Mexico, field relations demonstrate several generations of faults that offset basement and the Paleozoic section. The oldest faults have reverse separation; they strike east–west and northwest–southeast. The reverse-separation faults emplaced basement granite over Ordovician strata and Silurian dolostone over Devonian Percha Shale. Younger normal faults with approximate east-west strikes cut basement and strata as young as middle to late Eocene. A major NW-trending, moderately dipping normal fault, termed here the Mahoney Park fault, is either contemporary with the steep faults or post-dates them. The steep faults do not cut the Mahoney Park fault, which emplaces Paleozoic sedimentary rocks on footwall basement syenite and offsets the trace of a major reverse-separation basement fault, the South Florida Mountains fault. The Mahoney Park fault is not expressed in surficial deposits flanking the range, whereas north-trending, range-bounding faults form subdued scarps of several meters on the northwest flank of the range. Regional geologic relations suggest that reverse-separation faults are Late Cretaceous to middle Eocene, both predating and postdating deposition of the middle Paleocene to early Eocene Lobo Formation. Rhyolite and granite dikes with U-Pb and $^{40}Ar/^{39}Ar$ ages on groundmass, biotite, and hornblende that range from ~32–25 Ma are emplaced along east-west faults in the Little Hatchet Mountains of southwestern New Mexico and the northern part of the Florida Mountains. The dike ages indicate that the east-west normal faults were active in the Oligocene prior to development of north-trending Basin and Range faults. Some of the extensional faults demonstrably reactivated Laramide reverse faults. The Mahoney Park fault may be time equivalent with the Oligocene faults or alternatively may represent an intermediate phase of post-Oligocene, pre-Basin and Range faulting. Exploitation of some Laramide shortening structures by the east-west faults suggests that north-south extension resulted from gravitational collapse of a high-elevation plateau in Oligocene time.

INTRODUCTION

The style of Laramide crustal deformation in southern New Mexico has long been debated. Kinematic models for shortening include low-angle faults in the sedimentary section (Corbitt and Woodward, 1973) and basement (Drewes, 1980, 1988, 1991), basement-involved strike-slip faults associated with basement uplift (Brown and Clemons, 1983; Seager, 1983; Seager and Mack, 1986; Mack and Clemons, 1988), and basement-cored uplift analogous to the structural style displayed in the Laramide province of the central Rocky Mountains (Seager and Mack, 1986; Seager, 2004; Clinkscales and Lawton, 2015), in part controlled by antecedent rift structure (Lawton, 2000; Clinkscales and Lawton, 2017). Post-Laramide crustal extension likewise is incompletely understood in terms of timing and sequence of extension directions (Clinkscales and Lawton, 2017).

The Florida Mountains of southwestern New Mexico occupy an important location between well-described Laramide structures in southwestern New Mexico and north of Las Cruces in and adjacent to the Rio Grande rift (e.g., Seager, 2004; Clinkscales and Lawton, 2017). In combination with regional relations and geochronology, faults near Mahoney Park in the central Florida Mountains provide insight into the kinematics and timing of regional crustal deformation in southern New Mexico. In this paper, we describe the structural kinematics at Mahoney Park and synthesize previously published observations from the Florida Mountains to propose a combination of Laramide shortening and two phases of later crustal extension to explain structural development of the range.

METHODS

Geologic relations near Mahoney Park on the west range flank (Figs. 1, 2) were mapped during six visits with field courses, ranging from one to five days each, between 2005 and 2011. Field maps made on 1:12,000 scale orthophotos were transferred to a 1:12,000 scale topographic map. Fault planes, commonly exposed in mine adits, were measured and orientations of slickensides noted where present. Line-of-sight measurements (Compton, 1985, p. 35) were made where possible on planar features such as faults that extend across arroyos and on stratification of carbonate strata in order to mitigate the effects of local irregularities in attitude. Faults were classified according to their stratigraphic separation, whether older on younger or younger on older, to properly assess reverse or normal fault style.

GEOLOGIC SETTING

The Florida Mountains constitute a tilted fault block delineated by north-striking Neogene normal faults (Fig. 1; Clemons,

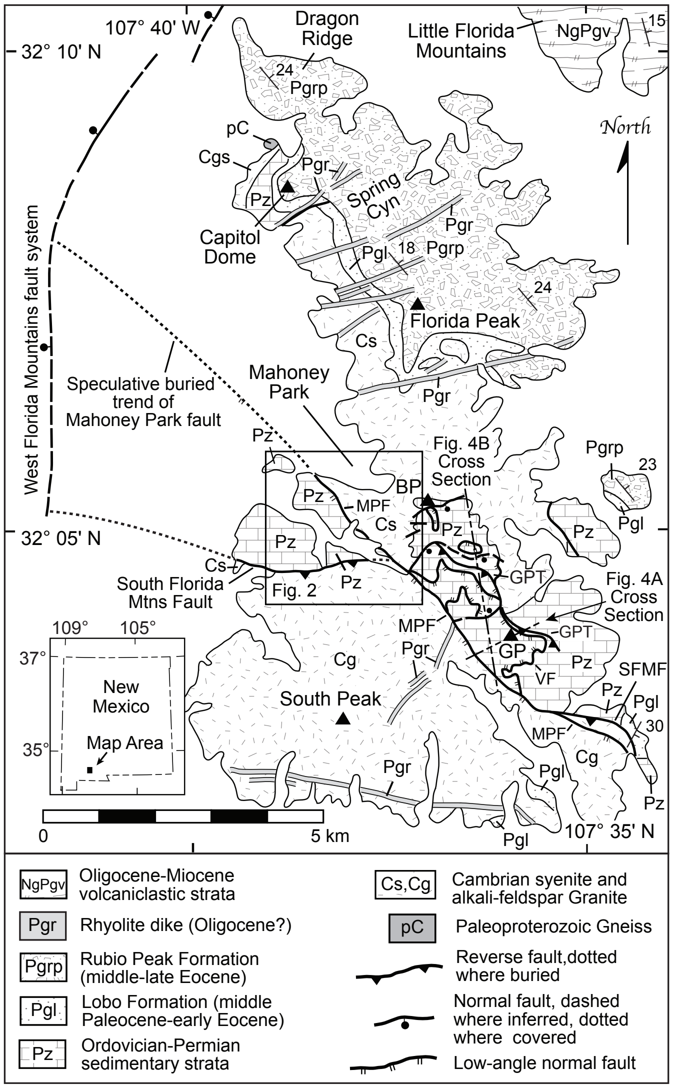

FIGURE 1. Generalized geologic map of the Florida Mountains, modified from Clemons and Mack (1988) and Clemons (1998). BP, Baldy Peak; GP, Gym Peak; GPT, Gym Peak thrust; MPF, Mahoney Park fault; SFMF, South Florida Mountains fault; VF, Victorio fault. Map of Figure 2 indicated by large rectangle, cross sections of Figure 4 by bold dashed lines.

1998). The southern part of the range is dominated by granitic basement that is thrust over faulted lower Paleozoic carbonate strata along the South Florida Mountains fault (SFMF). A northwest-striking, moderately dipping normal fault, here termed the Mahoney Park fault, emplaces the Paleozoic strata on syenite at Mahoney Park in the central part of the range and offsets the trace of the SFMF. Paleozoic strata in the central high part of the range are deformed by low-angle and high-angle faults (Brown, 1982; Brown and Clemons, 1983). Paleozoic strata overlie granitic rocks at Capitol Dome in the northern part of the range, where the Paleozoic section and basement alike are overlain by the Paleogene Lobo and Rubio Peak formations.

Plutonic rocks that constitute the basement in the map area (Fig. 2) consist of unnamed Cambrian syenite in the vicinity of Mahoney Park and alkali-feldspar granite south of the SFMF (Clemons, 1998). A sample of syenite (05FM1) from the southeast edge of Mahoney Park (Fig. 2) yielded a U-Pb Concordia age of 509±4 Ma (n=4; MSWD= 0.7; Amato and Mack, 2012). North of Capitol Dome, related middle Cambrian alkali-feldspar granite intrudes orthogneiss (Fig. 1; Clemons, 1998) with an interpreted age of 1623±14 Ma (U-Pb zircon; Amato and Mack, 2012).

Paleozoic rocks in the vicinity of Mahoney Park include the Bliss Sandstone, El Paso Formation, Montoya Formation, Fusselman Dolomite, Percha Shale, and Rancheria Formation (Fig. 2; Clemons, 1998). In the southeastern part of the study area, the Bliss Sandstone unconformably overlies the middle Cambrian syenite (Fig. 2). The Bliss Sandstone consists of cross-bedded and laminated angular, medium- to coarse-grained feldspathic sandstone. A section of approximately 30 m is present in the map area southeast of Mahoney Park and an incomplete section is present directly north of the SFMF (Fig. 2). The age of the Bliss Sandstone in the Florida Mountains is not yet established, but because it overlies coarsely-crystalline syenite of ~509 Ma (Amato and Mack, 2012), it is likely that the unit is Early Ordovician (see discussion in Mack, 2004). Accordingly, the Bliss Sandstone is indicated as Ordovician on the geologic map (Fig. 2).

The El Paso Formation, a succession of dolostone and limestone with characteristic mottled texture, gradationally overlies the Bliss Sandstone (Clemons, 1998). No complete sections of the El Paso Formation are present in the map area, but it is approximately 380 m thick on the east flank of the range (Fig. 1; Clemons, 1998). It locally overlies Cambrian syenite near Baldy Peak (Fig. 1), probably as a result of onlap of the lowermost part of the Paleozoic stratigraphic section onto irregular paleotopography. The El Paso Formation is Early Ordovician in age throughout southern New Mexico and West Texas (Clemons, 1998).

The Montoya Formation, which is late Middle to Late Ordovician in the Florida Mountains (Clemons, 1998), is a succession of sandy dolostone, mottled dolostone and limestone, and cherty limestone that unconformably overlies the El Paso Formation. A complete section is present southwest of Mahoney Park, where it is about 70 m thick.

The Fusselman Dolomite unconformably overlies the Montoya Formation and consists of light- to dark-gray weathering dolostone in the area of Figure 2. It contains gray chert nodules near its base and is locally extensively brecciated in the map area. A complete section of the Fusselman Dolomite is not present in the map area, where its upper part is eroded or overthrust by Cambrian granite in the southwestern part of the area. The Fusselman Dolomite ranges from Silurian to Early or Middle Devonian in the Florida Mountains (Clemons, 1998).

The Percha Shale, which is late Middle to Late Devonian in the Florida Mountains (Clemons, 1998), forms incomplete fault-bounded exposures in the Mahoney Park area (Fig. 2). It consists of platy to fissile light- to dark-gray, gray- to pink-weathering shale, commonly fractured and cut by calcite veins. It forms slopes and strike valleys. The Percha Shale is present about 200 m north of the SFMF, where it is overthrust by the El Paso Formation (Clemons (1998). Small exposures elsewhere in the map area were included by Clemons (1998) in a tectonic breccia unit, composed mostly of pervasively fractured Fusselman, or were not recognized by Clemons (1998) due to poor exposure.

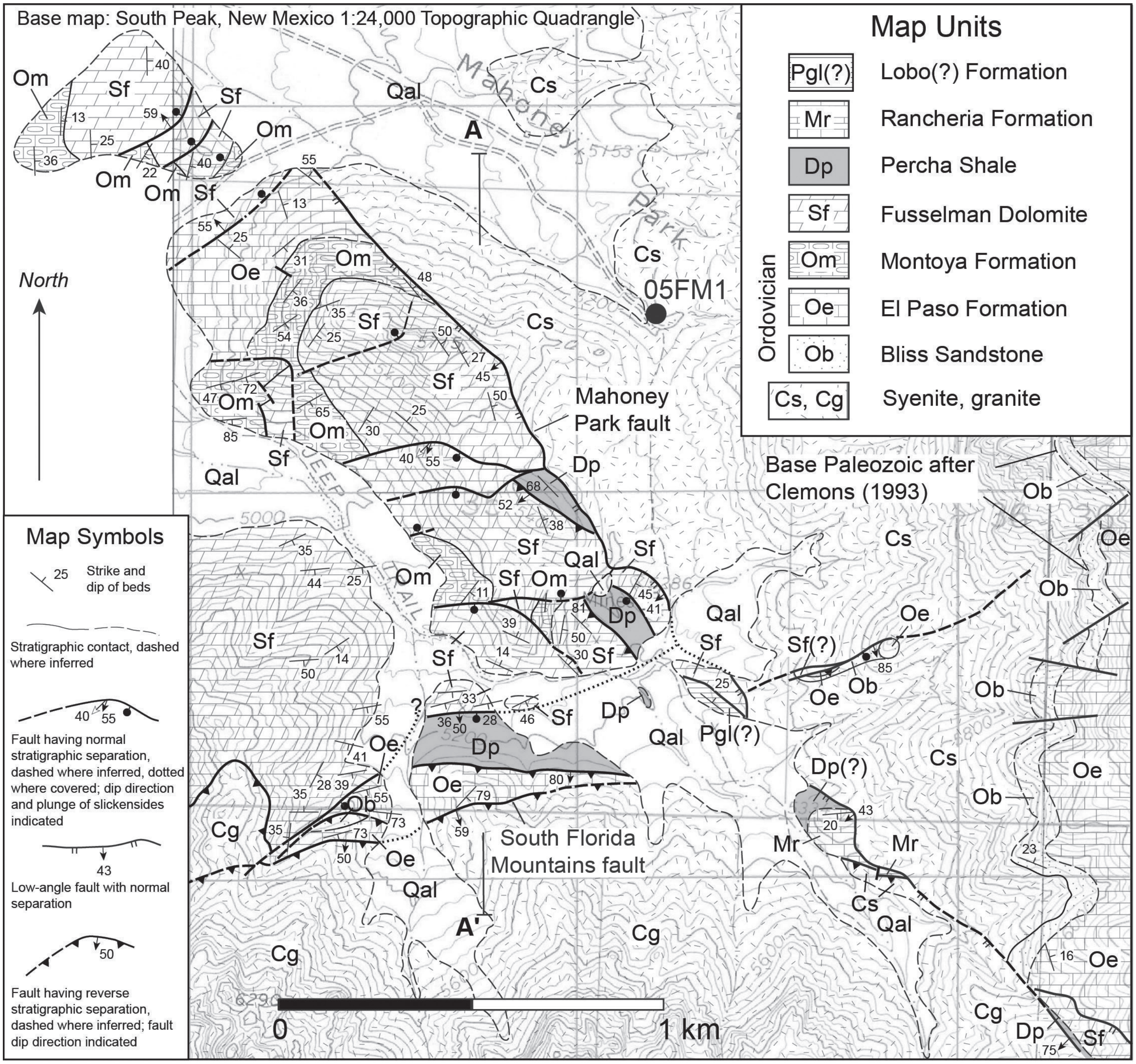

FIGURE 2. Geologic map of Mahoney Park and vicinity. Location of map indicated in Figure 1. 05FM1, location of geochronology sample from Amato and Mack (2012) described in text.

Crinoid-rich, medium-gray limestone of the Mississippian Rancheria Formation crops out southeast of Mahoney Park (Clemons, 1998). The Rancheria Formation consists of platy, locally laminated mudstone to crinoidal grainstone with laminar gray chert nodules to 20 cm thick. It forms a single group of outcrops in the southeast part of the study area adjacent to the Mahoney Park fault.

Paleogene sedimentary, volcanic and volcaniclastic rocks dominate the northern part of the Florida Mountains (Fig. 1). The Lobo Formation directly overlies Proterozoic orthogneiss, Cambrian granitic rocks, and folded lower Paleozoic strata in the vicinity of Capitol Dome (Clemons, 1998). It unconformably overlies Cambrian granitic rocks in the central part of the range and Permian limestone in the southeastern part of the range (Fig. 1; Clemons, 1998). It is overthrust by basement granite along the SFMF in the southeastern part of the range. Subcrop and cross-cutting relations thus indicate that the Lobo Formation was deposited late in the history of Laramide shortening (Mack and Clemons, 1988). At all localities except in the southeasternmost exposure, the formation forms a homoclinal section that dips NE 20°–40° (Fig. 1; Clemons, 1988; De los Santos et al., 2018). The formation consists of a local basal conglomerate as much as 6 m thick overlain by a thick succession of flaggy tan sandstone and pale gray siltstone. The upper part of the formation consists of red-weathering siltstone and lenticular pebbly sandstone and an upper boulder conglomerate that contains cobbles and boulders of sandstone, quartz arenite, limestone, and pebble conglomerate derived in part from the Lower Cretaceous Bisbee Group, which is not exposed in the Florida Mountains. At Capitol Dome, the Lobo Formation is interpreted as middle Paleocene to early Eocene in age (~60–52 Ma; De los Santos et al., 2018).

The Rubio Peak Formation concordantly overlies conglomerate at the top of the Lobo Formation. The Rubio Peak Formation consists of subordinate andesite flows and dominant andesite breccia (Clemons, 1998). Like the Lobo Formation, the Rubio Peak Formation forms a homoclinal section that dips NE 18°–24° and extends at least as far south as a small Rubio Peak outcrop east of the map area of Figure 2 (Fig. 1). The Rubio Peak Formation in the Florida Mountains is not directly dated, but hornblende $^{40}Ar/^{39}Ar$ ages of 46.3±0.3 Ma and 40.2±0.3 Ma were reported from an andesite clast in a volcanic breccia and an andesite flow in the Cookes Range, about 40 km to the NNW (McMillan, 2004), indicating that the Rubio Peak Formation is middle to late Eocene. A small exposure of oncoidal limestone and feldspathic sandstone in the central part of the map area is provisionally included in the Lobo Formation (Fig. 2).

Rhyolite dikes intrude rocks as young as the Rubio Peak Formation in the Florida Mountains (Fig. 1; Clemons, 1998; McLemore and Dunbar, 2000). Dikes measured as part of this study on the east side of the range strike N65–75E, dip 65º–75° S, and commonly occupy normal faults (Clemons, 1998; De los Santos et al., 2018). The dikes are as much as 7.5 m thick. Oligocene-lower Miocene volcaniclastic rocks of the Little Florida Mountains, directly north of the Florida Mountains (Fig. 1), have $^{40}Ar/^{39}Ar$ ages on andesite and rhyolite ranging from ~33 to 24.4 Ma (McLemore and Dunbar, 2000). The dikes do not appear to cut these volcaniclastic rocks. A rhyolite dike in the Rubio Peak Formation in the head of Spring Canyon (Fig. 1) yielded a $^{40}Ar/^{39}Ar$ groundmass age of 25.4 Ma (McLemore and Dunbar, 2000).

STRUCTURAL GEOLOGY OF MAHONEY PARK AREA

Intricately faulted Paleozoic strata and subjacent syenite basement are present west and south of Mahoney Park in the central Florida Mountains (Fig. 2). Both normal- and reverse-separation faults are present in the Mahoney Park area.

Reverse faults in the map area trend approximately E–W and NW–SE. The reverse-separation SFMF strikes E–W in the southern part of the map area. It dips 50°–59° south and emplaces Cambrian granite on Ordovician and Silurian strata (Figs. 2, 3). Imbricated Ordovician and Devonian strata are present beneath the SFMF. The trace of the SFMF is offset ~4.5 km to the SE by the Mahoney Park fault; at the far SE corner of the range, the offset eastern part of the SFMF emplaces granite over upper Paleozoic strata and the Lobo Formation (Fig. 1; Clemons, 1998). Two segments of a NW-trending reverse-separation fault are present in the central part of the study area, where Fusselman Dolomite is emplaced over Percha Shale. The fault segments dip ~50°, and are offset by an east-trending normal fault. Both reverse fault trends indicate that the Percha Shale was an important detachment horizon during shortening.

Reverse faults are locally associated with small-scale to map-scale folds whose axes parallel the fault traces. Ordovician strata occupy a tight faulted syncline north of the SFMF, where El Paso beds adjacent to the fault are probably overturned (Fig. 3), although inadequate facing indicators preclude positive identification of overturning. East of the map area, small-scale folds with north-northwest-trending axes are present in the El Paso Formation of the hanging wall of the Gym Peak thrust (Fig. 4A) on the crest of the range, with El Paso strata locally overturned adjacent to the fault. On the east side of the range, a map-scale overturned panel of overturned Ordovician strata, also associated with the northwest-striking Gym Peak thrust, strikes northwest and dips southwest (Fig. 4B; Brown, 1982; Brown and Clemons, 1983).

The reverse faults in Paleozoic strata are cut by normal-separation faults that trend NW, NE and E–W, with moderate dips of about 55° to both NW and SE (Fig. 2). These normal faults are truncated by, or sole into, the Mahoney Park fault and thus are restricted to the hanging wall of the fault (Fig. 3). The Mahoney Park fault extends through the study area, juxtaposes Ordovician through Mississippian hanging-wall strata above syenite, cuts the hanging wall of the SFMF with a consistent fault plane attitude of ~N40W 40–45° SW, and continues to the southeastern part of the range (Figs. 1, 2, 3). As noted above, the trace of the SFMF is offset to the SE by the Mahoney Park fault. The Mahoney Park fault has a minimum vertical displacement of 500 m on the basis of offset Ordovician strata exposed along the range crest and has no expression in surficial deposits west of the Florida Mountains. Slickensides were not observed on the Mahoney Park fault, which was interpreted as a younger-over-older thrust by Clemons (1985, 1998).

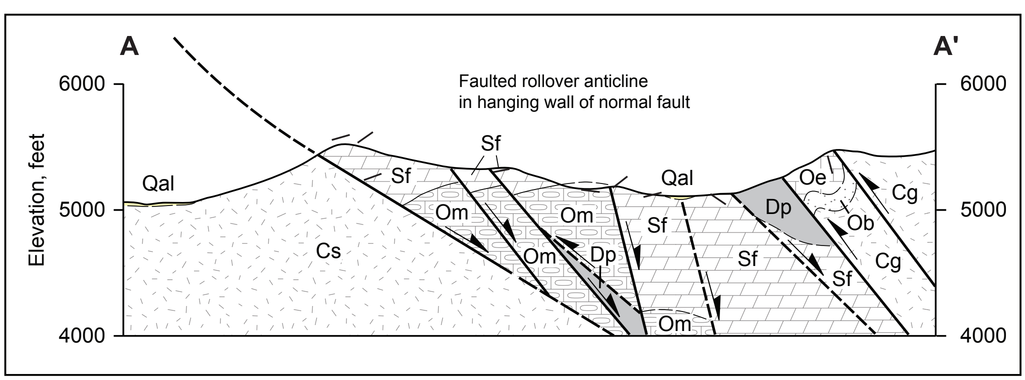

FIGURE 3. Cross-section A-A’ across Mahoney Park and South Florida Mountains faults. Line of section indicated in Figure 2.

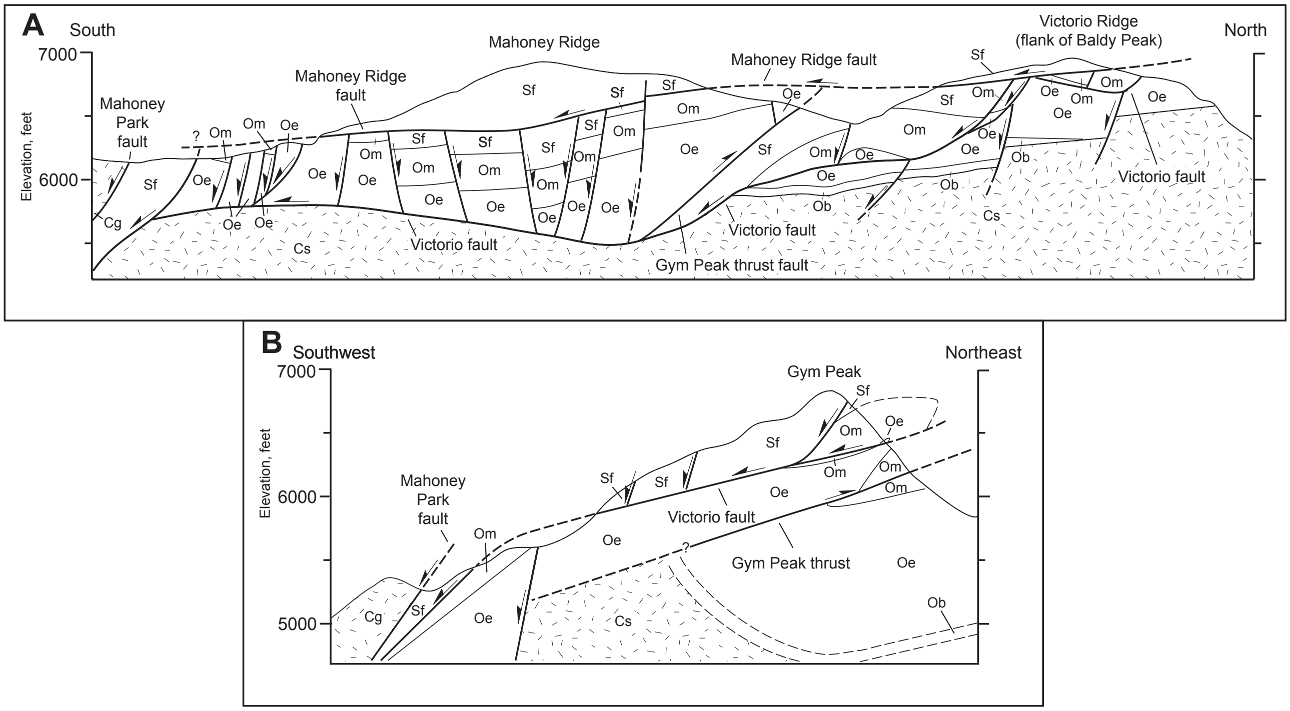

FIGURE 4. Cross sections of high Florida Mountains southeast of Figure 2 map area. Section locations indicated on Figure 1. Sections are redrawn and reinterpreted, with stratigraphy simplified, from Brown and Clemons (1983). **A**) Reverse faults and low-angle Victorio fault system on range crest of Florida Mountains. Mahoney thrust of Brown and Clemons (1983) is termed the Mahoney Ridge fault, revised slightly to distinguish it from the Mahoney Park fault of this paper. **B**) Cross section from Mahoney Park fault across Gym Peak. Overturned Ordovician strata occupy forelimb of a fault-propagation fold developed above Gym Peak thrust. See text for further description of relations. Explanation: Cg, Cs, Cambrian granite and syenite; Ob, Bliss Sandstone; Oe, El Paso Formation; Om, Montoya Formation; Sf, Fusselman Dolomite.

Contradictory stratigraphic displacements along parallel faults within the Mahoney Park fault zone resulted from normal offset of an older reverse-faulted domain. Between offset traces of the SFMF, the fault zone contains a panel of syenite that preserves reverse stratigraphic separation with Devonian shale, and a nearby parallel, southwest-dipping normal-separation fault that emplaces Silurian dolostone over El Paso Formation (southeasternmost corner of Fig. 2, Fig. 4A). The normal fault is a southeastward continuation of the Mahoney Park fault that cut the hanging wall of the SFMF, but with inadequate displacement to compensate the older reverse movement. Alternatively, it could have reactivated part of the older reverse fault, which locally retains its older-over-younger stratigraphic separation.

Normal faults that cut Neogene basin-fill deposits delineate the western edge of the Florida Mountains (Clemons, 1998). The West Florida Mountains fault system trends NNE adjacent to the central and northern parts of the range (Fig. 1) and displaces alluvial and eolian deposits to form a subdued 2- to 3-m scarp (Clemons, 1984, 1985, 1998). The fault system is estimated to have moved as recently as late Quaternary time (< 130 ka; USGS Quaternary Fault and Fold Database of the United States). The range-bounding fault system is inferred to cut the Mahoney Park fault (Fig. 1).

DISCUSSION

Cross-cutting relations indicate the following relative chronology for fault systems at Mahoney Park: (1) Reverse-separation faults; (2) east-west normal faults that cut basement, possibly coeval with northwest and northeast-trending normal faults in the upper plate of Mahoney Park fault; (3) NW-trending Mahoney Park fault; and (4) north-trending range-bounding fault system. The reverse-separation faults are cut by steeply to moderately dipping normal faults, which are in turn truncated at the Mahoney Park fault (Fig. 3). Slip on the normal faults in the upper plate of the Mahoney fault may be related to slip on the main fault, and thus could be the same age as the Mahoney Park fault, as observed in other low-angle extensional systems (e.g., Davis and Lister, 1988).

General structural relations of the Florida Mountains indicate a late Paleogene age for the Mahoney Park fault. The fault is younger than the Paleocene-middle Eocene Lobo Formation, which is cut by the SFMF in the southeastern part of the range; the SFMF is in turn cut by the Mahoney Park fault. The strike of the Mahoney Park fault parallels the strike of the middle to upper Eocene Rubio Peak Formation in the central part of the range (Fig. 1), but not the more northerly strikes of Oligocene-Miocene strata to the north in the Little Florida Mountains (Clemons, 1998). The parallel strikes of the tilted Rubio Peak Formation, which dips northeast, and the Mahoney Park fault suggest that uplift and tilting of the range were a result of footwall uplift attendant upon fault displacement. Tilting of Eocene strata is greater by about 8° than tilting of fanglomerate in the Little Florida Mountains, indicating that early tilting was underway prior to deposition of the volcaniclastic section in the Little Floridas Mountains. We infer that Rubio Peak tilting represents a back-tilted footwall block coordinate with offset on the Mahoney Park fault, suggesting that fault offset occurred after deposition of the Eocene (post ~40 Ma; McMillan, 2004) Rubio Peak Formation, but predated tilting of the Oligocene (~33 to 24.4 Ma; McLemore and Dunbar, 2000) volcaniclastic strata of the Little Florida Mountains. These field relations imply a late Eocene to Oligocene age for formation of the Mahoney Park fault.

Complex fault relations on the range crest east of the map area (Fig. 1) have been interpreted as low-angle thrust faults that emplaced younger strata over older strata or emplaced Paleozoic strata over basement, roughly coeval with reverse faults that cut basement (Brown, 1982; Brown and Clemons, 1983; Mack and Clemons, 1988). All faults were thus considered a result of Laramide deformation. The rocks and structures of the high Florida Mountains were offset by the Mahoney Park fault and are now exposed in the hanging wall of the fault; therefore, recognition of reverse faults and normal faults of different ages at Mahoney Park permits re-evaluation of the structural history of this part of the Florida Mountains. We interpret the faulting at Mahoney Park as the result of separate tectonic events, rather than as a complex of contemporary Laramide faults.

Reverse-separation faults are present but uncommon on the range crest (Fig. 4). The cross sections of Figure 4, modified only slightly from those of Brown and Clemons (1983), indicate that the Gym Peak thrust and South Florida Mountains fault emplace older over younger rocks. The overturned panel of Ordovician strata in the hanging wall of the Gym Peak thrust system (Fig. 4B) is here interpreted as the forelimb of a northeast-vergent fault-propagation fold. The forelimb is cut by a low-angle normal fault, the Victorio fault (Brown, 1982; Brown and Clemons, 1983; Clemons, 1998), which emplaces younger over older strata. The Gym Peak thrust had a dip ~40–45° southwest prior to northeast tilting of the range. Although equivalence of structural features is not yet established across the Mahoney Park fault, northwest-trending thrust faults in the Paleozoic section of the hanging wall likely represent part of the Gym Peak thrust system.

Low-angle normal-separation faults are common in the high Florida Mountains. The hanging-wall blocks of these faults contain northeast-trending normal faults that are restricted to the hanging walls (Figs. 4A, B); the resulting fault array is like that in the hanging wall of the Mahoney Park fault (Fig. 3). Ordovician-Silurian strata are structurally thinned within fault-bounded horses that form an extensional duplex between the Victorio and Mahoney Ridge faults, which cut the Gym Peak thrust (Fig. 4A). The Victorio fault is a low-angle fault that consistently emplaces younger strata over older strata, indicating significant structural attenuation during displacement. The extensional fault system appears to root into the Mahoney Park fault, or reactivated SFMF, suggesting extensional reactivation of the Laramide fault (Figs. 4A, B). An east-west normal fault reactivated a basement reverse fault adjacent to an asymmetric syncline at Capitol Dome (De los Santos et al., 2018), indicating similar normal reactivation of reverse faults farther north in the range. Amato (2000) likewise suggested that most of the faults on the range crest are normal faults.

Geochronologic data from elsewhere in southern New Mexico shed possible light on the age of the E–W normal faults in the Florida Mountains. A set of east-west trending normal faults is present in the central part of the Little Hatchet Mountains, located 80 km WSW of the Florida Mountains. The normal faults there are intruded by granite, locally highly sheared, ranging in age from 33.8±0.7 Ma to 28.9±0.4 Ma (Clinkscales and Lawton, 2017) and rhyolite ranging 32–26 Ma (Cleary, 2004; Clinkscales and Lawton, 2017). Dated igneous rocks along east-west normal faults elsewhere in New Mexico, in combination with similar east-west trending late Oligocene rhyolite in the Florida Mountains (McLemore and Dunbar, 2000) thus suggest that pre-Basin and Range normal faulting took place during the Oligocene.

The reason for north-south to northeast-southwest extension in the Florida Mountains remains unexplained. Reactivation of somewhat older reverse faults suggests the possibility that Oligocene extension resulted from gravitational collapse of crust that was thickened during Laramide shortening in southern New Mexico.

CONCLUSIONS

Cross-cutting reverse faults and normal faults at Mahoney Park indicate that different faulting events, rather than a single complex system of reverse and strike-slip faults, affected the central part of the Florida Mountains. Late Cretaceous to middle Eocene reverse faults are cut by normal faults that strike E–W to NE–SW; and reverse faults are locally reactivated and modified by NW-striking shallowly- to moderately-dipping normal faults. East-west-striking normal faults are generally restricted to hanging walls of the low-angle faults, although some normal faults continue down into the basement of the range. The low-angle extensional faults created younger-on-older stratigraphic relations previously interpreted to record Laramide crustal shortening. Timing of the various extensional faults remains ambiguous, but it is likely that steep and low-angle faults formed coevally as extensional duplexes. Oligocene rhyolite dikes occupy some E–W normal faults in the Florida and Little Hatchet mountains, indicating that extension was late Paleogene in age. On the west flank of the Florida Mountains, a north-trending, range-bounding normal fault system forms a subdued scarp in unconsolidated surficial deposits and records Neogene Basin and Range extension.

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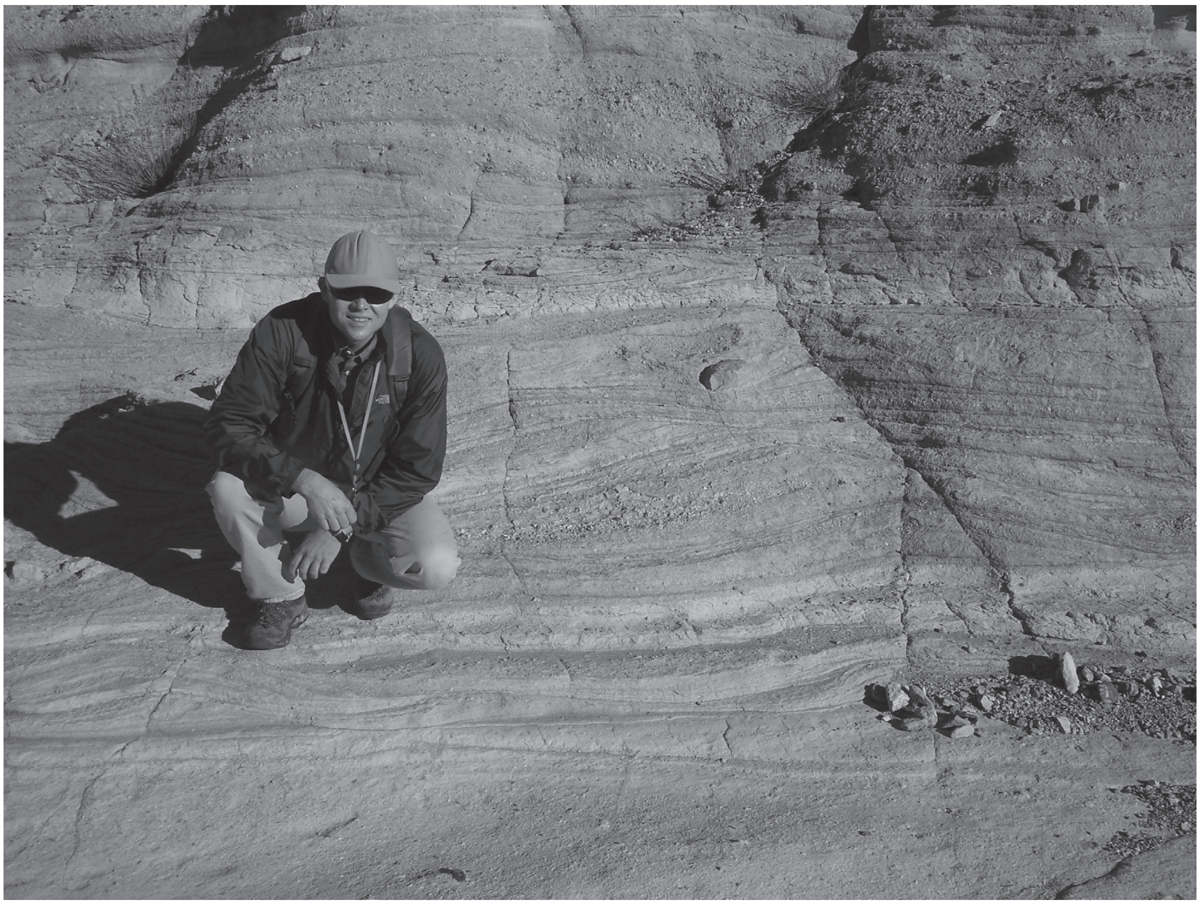

Uppermost Eocene surge deposits south of Foster Canyon. Brian Hampton for scale. Photograph by Greg H. Mack.