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Jeffrey M. Amato

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STRUCTURAL RELATIONSHIPS IN THE FLORIDA MOUNTAINS, SOUTHWESTERN NEW MEXICO—A REVIEW

JEFFREY M. AMATO
Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003; amato@nmsu.edu

Abstract—Despite several previous detailed structural investigations of the Florida Mountains, the nature of low-angle faults there remains controversial. Paleozoic sedimentary rocks lie in both fault contact and nonconformably over the Cambrian Florida Mountains pluton. All rocks are complexly faulted. The structural controversies in the region include (1) the relative importance of steep, basement-involved block faulting versus low-angle thin-skinned thrusts during the Laramide orogeny; (2) the relative importance of strike-slip versus reverse motion on the south Florida Mountains fault (SFMF); and (3) the validity of a thrust model that attempts to explain the younger-on-older relationships. Resolution of these controversies will require more detailed structural studies, particularly along the SFMF and other major structures, as well as thermochronologic investigations of the exhumation history of the Florida Mountains pluton on either side of the SFMF. An additional consideration is the possibility that these structures represent reactivation of normal faults formed during a regional Jurassic extensional event documented in other areas. Tertiary normal faulting resulted in tilting of the range ~25° to the northeast. Perhaps several of the normal faults interpreted by other workers as forming during the Laramide event are in fact related to Tertiary Basin-and-Range extension.

INTRODUCTION

Several intriguing structural relationships are present in the complexly faulted Gym Peak area of the Florida Mountains, southwestern New Mexico (Fig. 1). The Florida Mountains are an important component of late Mesozoic/early Cenozoic tectonic models for southwestern New Mexico and southeastern Arizona, yet interpretations of the structural relationships are controversial. Unresolved questions include: (1) What was the structural style of Laramide deformation here? (2) Why do structures mapped as thrust or reverse faults commonly exhibit younger-on-older relationships? (3) What is the relative importance of strike-slip versus reverse motion on the range's major structure, the south Florida Mountains fault? This paper reviews the structural and petrologic relationships of the Florida Mountains, summarizes existing geochronologic data, evaluates previously published tectonic models, and offers suggestions for future work.

GEOLOGIC OVERVIEW

The Florida Mountains were previously mapped by Darton (1917), Corbitt (1971), Brown (1982), Clemons and Brown (1983), and Clemons (1985), with the latter two publications compiled and slightly revised by Clemons (1998). This area has been the subject of two previous NMGS outings: the 21st Field Conference (Corbitt and Woodward, 1970) and the 39th Field Conference (Mack and Clemons, 1988). Exposures include Cambrian plutonic rocks overlain by Paleozoic sedimentary rocks, Tertiary conglomerates, and Tertiary volcanic rocks (Figs. 2, 3). A major structure termed the south Florida

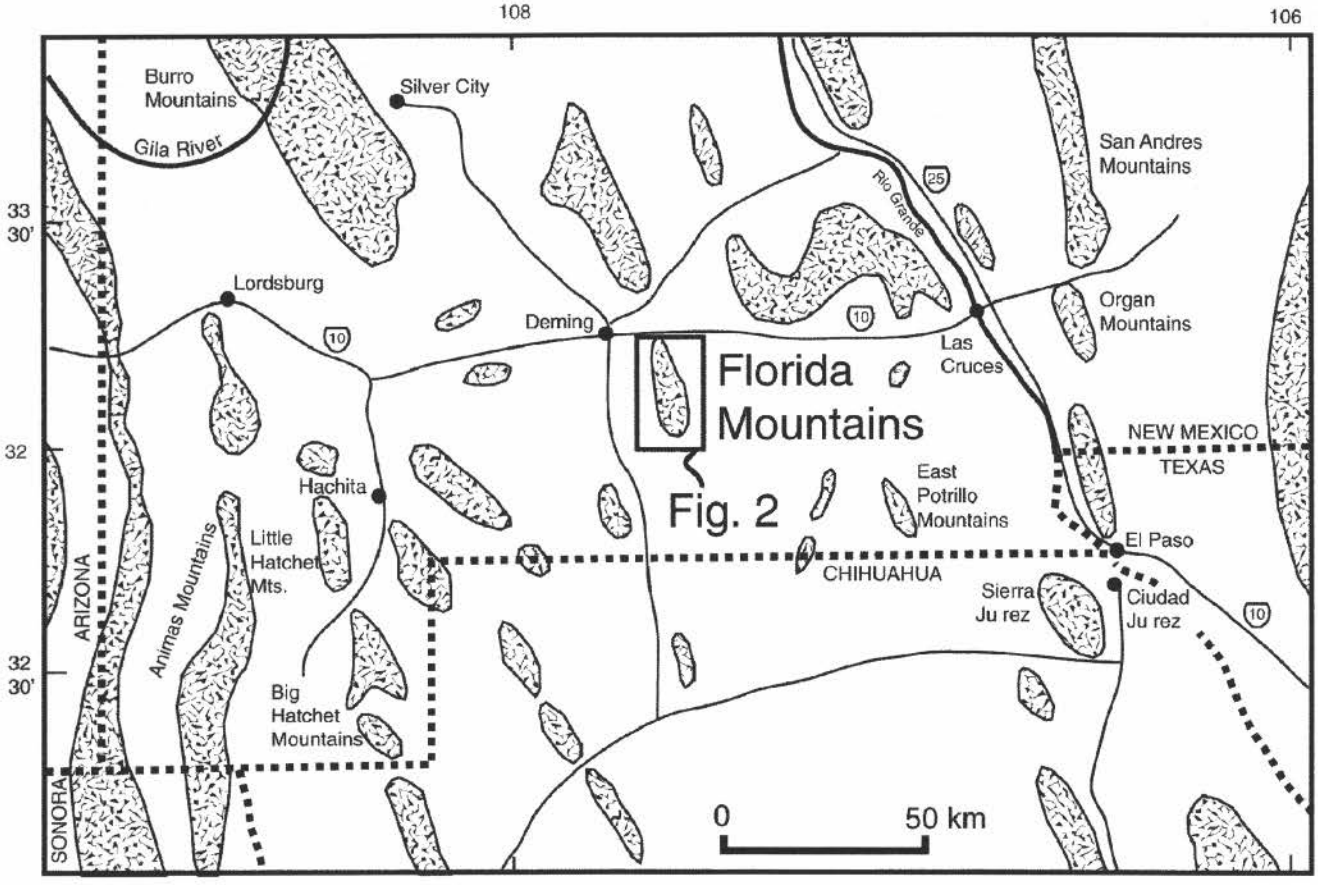


FIGURE 1. Important geographic localities in the vicinity of the Florida Mountains (after Drewes, 1988).

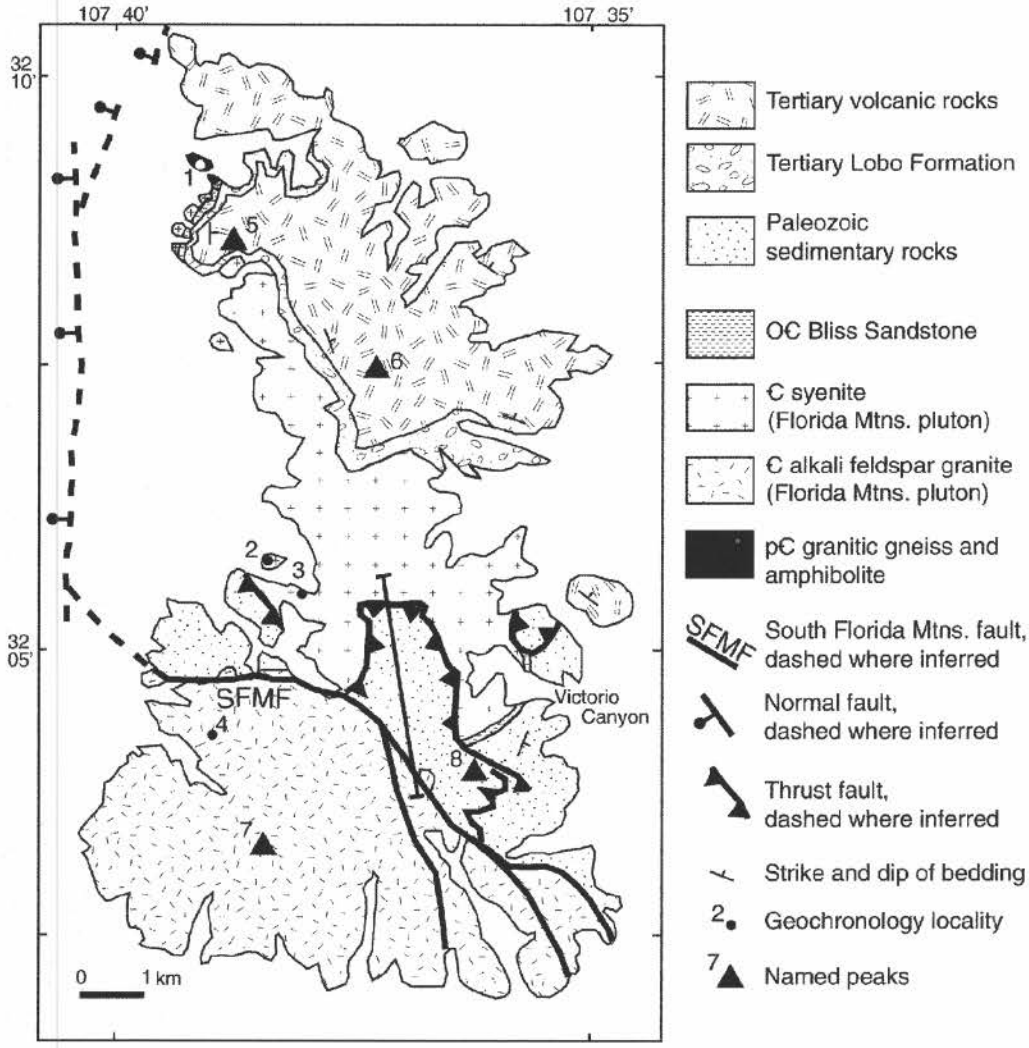


FIGURE 2. Simplified geologic map of the Florida Mountains. Geochronology localities include: (1) granitic gneiss, $^{207}Pb/^{206}Pb$ zircon age of 1550–1570 Ma (Evans and Clemons, 1988); (2) syenite, $^{40}Ar/^{39}Ar$ biotite cooling age of 491 ± 5 Ma (Ervin, 1998); (3) syenite, U-Pb zircon age of 514 ± 3 Ma (Matheny et al., 1988); (4) alkali feldspar granite, U-Pb zircon age of 503 ± 10 Ma (Evans and Clemons, 1988). Named peaks include: (5) Capitol Dome; (6) Florida Peak; (7) South Peak; (8) Gym Peak. High-angle, south Florida Mountains fault consists of several steep splays in the southeastern part of the range. Line is shown for cross-section in Figure 3. Geology after Evans and Clemons (1988).

Mountains fault (SFMF) cuts the Florida Mountains pluton and the Paleozoic sedimentary section. Mack and Clemons (1988) interpreted the structures of the Florida Mountains as "intra-uplift" in origin, with the main fault of this uplift present in the southern Cookes Range to the north. Key geologic relationships are reviewed here. For a more complete discussion, see Clemons (1998).

Precambrian plutonic rocks

Precambrian rocks are rare in the Florida Mountains. Limited exposures of Precambrian orthogneiss and amphibolite are locally exposed in the Capitol Dome area of the Florida Mountains (Clemons, 1998). The orthogneiss has a $^{207}Pb/^{206}Pb$ zircon age of 1550–1570 Ma (Evans and Clemons, 1988).

Florida Mountains pluton

The Florida Mountains pluton consists of syenite and alkali-feldspar granite (Evans and Clemons, 1988) lying in both fault contact and nonconformably below the Paleozoic section. Because the Florida Mountains pluton is exposed on either side of the SFMF, the age and compositional relationships of the pluton could help constrain the magnitude and direction of offset along the fault. The pluton consists of syenite and alkali feldspar granite. The syenite is restricted to northeast of the SFMF, whereas alkali-feldspar granite is common south of the fault but rare north of the fault (Fig. 2; Clemons, 1998). Mafic enclaves of hornblende gabbro (Brookins et al., 1978) are common south of the fault but have been reported in only a few localities north of the fault (Ervin, 1998). The alkali-feldspar granite and syenite phases are similar in composition (Brookins et al., 1978); in fact, there is significant major-element geochemical overlap between the two units (Ervin, 1998, figs. 14–15), suggesting that the mapped boundaries do not accurately reflect the distribution of the two rock types. Ervin (1998) used field, petrographic, and geochemical data to argue that the two bodies are cogenetic.

The intrusive age of the pluton on either side of the fault is considered to be the same within error. A sample of alkali-feldspar granite south of the SFMF (Fig. 2) yielded a U-Pb zircon age of 503 ± 10 Ma (Evans and Clemons, 1988). A sample of syenite north of the SFMF (Fig. 2) yielded a U-Pb zircon age of 514 ± 3 Ma (Wallin, unpublished data, 1987, reported in Matheney et al., 1988). This contradicts the earlier suggestion by Clemons (personal commun. in Seager, 1983) that the ages of the pluton on each side of the fault are different. K-Ar dates from hornblende in the mafic enclaves range from 530–555 Ma (Brookins, 1974), which is older than the intrusive age of the host rock and thus likely the result of excess Ar. Hornblende from the syenite yielded K-Ar dates of ~420 Ma (Brookins, 1974), but this date is younger than the overlying sedimentary rocks and therefore also suspect. More recent $^{40}Ar/^{39}Ar$ dating of hornblende from the syenite gave a hump-shaped plateau, suggesting some disturbance of the K-Ar system, but a plateau age (using ~50% of the spectrum) of 486 ± 5 Ma can be calculated (Ervin, 1998). A biotite from the same rock (Fig. 2) yielded a $^{40}Ar/^{39}Ar$ plateau age of 491 ± 5 Ma (Ervin, 1998), suggesting cooling through about 300–350°C (Harrison et al., 1985) about 10–25 Ma following intrusion.

Paleozoic sedimentary rocks

The Paleozoic section in the Florida Mountains includes rocks from Cambro–Ordovician age (Bliss Sandstone) through the Permian Hueco

Limestone (Fig. 3). Pennsylvanian strata are absent, leading to the suggestion by Kottlowski (1958) that the Florida Mountains area was an island in a Pennsylvanian ocean. The lowermost Paleozoic unit deposited nonconformably on the Florida Mountains pluton is the Bliss Sandstone. Regionally, including areas east and north of the Florida Mountains, this unit contains latest Cambrian fossils (Flower, 1969), although in the Florida Mountains, Early Ordovician (Canadian) gastropods are the oldest fauna reported (Flower, personal commun, 1970, in Corbitt and Woodward, 1973). Duration of the Early Ordovician is now considered to be approximately 490–470 Ma (Cowie and Bassett, 1998). Taking into consideration the U-Pb data and the age of the overlying sediments, the time interval between intrusion of the pluton and its exhumation could range from as little as 10 Ma to almost 50 Ma.

Tertiary rocks

Tertiary conglomerates and volcanic rocks overlie the Paleozoic section (Fig. 3) on an angular unconformity and dip approximately 25° NE as the result of tilting associated with Basin-and-Range deformation (Brown, 1982; 1983). Restoring the section to its pre-Basin-and-Range attitude is necessary for the interpretation of what have been inferred to be Laramide structures. The Lobo Formation is an early Tertiary (Paleocene–Eocene) conglomerate (Mack and Clemons, 1988; Clemons, 1998) unconformable on the Florida Mountains pluton in exposures near Florida Peak and also near Capitol Dome. Tertiary volcanic rocks include the Rubio Peak Formation (Eocene), rhyolite dikes, one of which yielded a K-Ar feldspar date of ~29 Ma, and miscellaneous tuffs and flows of Miocene–Oligocene age (Clemons, 1998). The rhyolite dikes are mapped as cutting the Florida Mountains pluton. A north-northeast striking Tertiary range-bounding fault has been mapped on the west side of the range (Clemons, 1998).

STRUCTURAL GEOLOGY

The Paleozoic section contains several types of brittle structures as well as some folds that are best exposed in the Gym Peak area. All previous workers recognized two classes of faults. The first class includes steep to shallowly dipping faults interpreted to be Late Cretaceous to Early Tertiary in age and associated with Laramide deformation. The second class includes steep normal faults associated with Basin-and-Range deformation. The "Laramide" faults are controversial because they generally place younger strata on top of older rocks, resulting in tectonic elimination rather than duplication, yet they have been interpreted as thrust faults.

Quaternary	alluvium
Tertiary	Pliocene Mimbres Formation
	Oligocene-Miocene volcanic rocks
	Lobo Formation
Permian	Hueco Limestone
Mississippian	Rancheria Formation
Devonian	Percha Shale
Silurian	Fusselman Dolomite
Ordovician	Montoya Formation
	El Paso Formation
Cambrian	Bliss Sandstone
	diamictite
	syenite, alkali feldspar granite
Middle Proterozoic	orthogneiss and amphibolite

FIGURE 3. Stratigraphic chart of rocks in the Florida Mountains (Clemons, 1998). Dashed lines indicate unconformities between units.

According to the maps by Brown (1982), Clemons and Brown (1983) and Clemons (1985, 1998), there appear to be three classes of "Laramide" faults (Fig. 4). The first is represented by the SFMF, a steep (>65°), northwest-striking fault that fans into several subparallel faults to the southeast (Fig. 2; Clemons, 1998). The main trace of the fault places Cambrian granitic rocks over the Paleozoic section. This fault is associated with a breccia zone as much as 60 ft thick (Corbitt and Woodward, 1970), and the breccia separates the Cambrian granite from the Eocene Lobo Formation south of Victorio Canyon (Clemons, 1998).

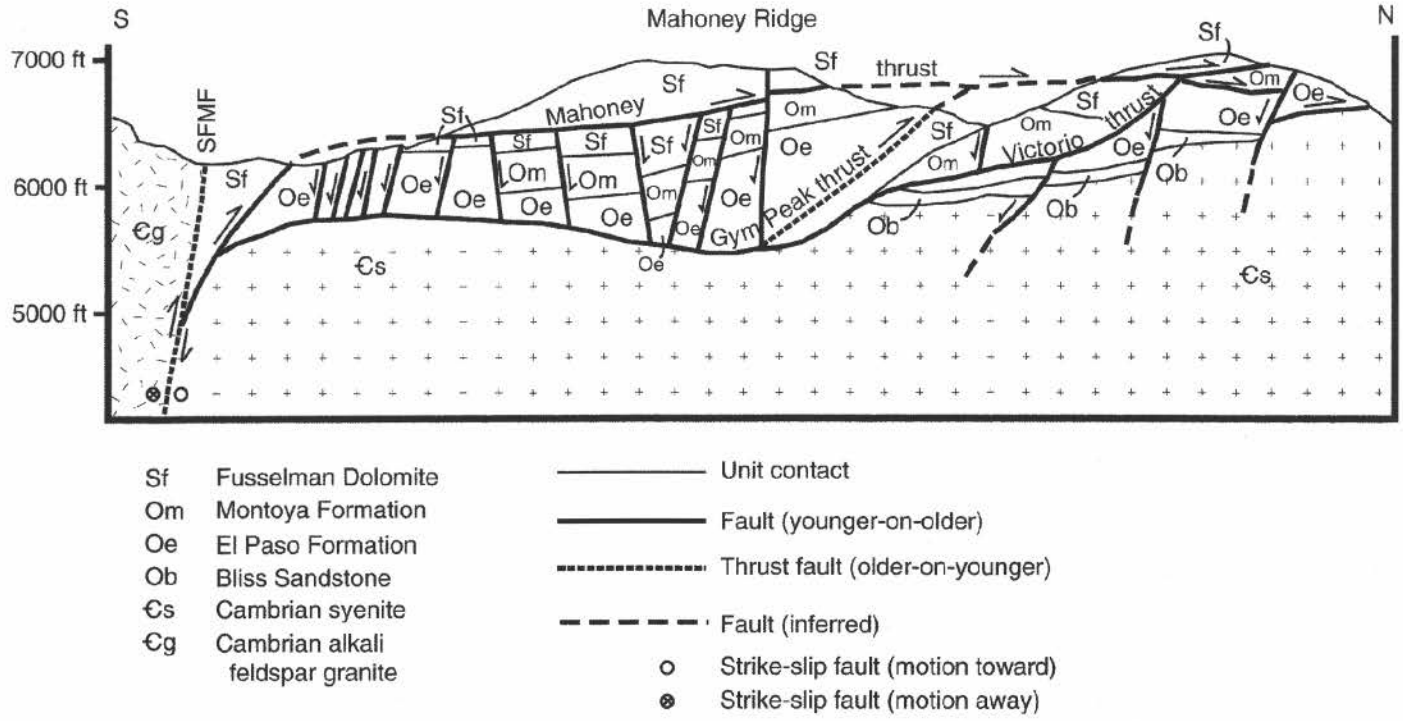


FIGURE 4. Cross-sections of the Mahoney Mine-Gym Peak area simplified (modified from Brown, 1982).

Other splays of the fault cut the Cambrian intrusion.

The second class of faults includes several subparallel low-angle faults that generally place younger strata over older strata (Fig. 4). From deepest structural levels to shallowest, they are the Victorio thrust, Gym Peak thrust, and Mahoney thrust (Clemons, 1998). They all are interpreted to sole into the same steep fault, which is subparallel to the SFMF. In the vicinity of Mahoney Ridge, only the Gym Peak thrust has older-on-younger relationships where the Ordovician El Paso Formation overlies the Silurian Fusselman Dolomite (Fig. 4).

The third class of faults includes steep normal faults that cut the Paleozoic section between the Gym Peak thrust and the Mahoney thrust. In the vicinity of Gym Peak, these faults are interpreted by Clemons (1998) to cut the Fusselman Dolomite but are cut by the Gym Peak thrust. In the vicinity of Mahoney Ridge, they are mapped as both cutting and being cut by the Mahoney thrust, but do not cut the Gym Peak thrust. These normal faults were interpreted by Brown (1983) to be related to the movement of a thrust sheet over irregular basement. When the thrust sheet encounters a structural high in the basement, the passage of the sheet results in normal faults similar to the extension one might expect in the outer limb of a fold, or perhaps analogous to the crevasses in a glacier.

The age of these "Laramide" faults is poorly constrained. Clemons and Brown (1983) indicate that the tectonic breccia found along the SFMF is also found adjacent to the Lobo Formation. However, in the Capitol Dome area the Lobo Formation is interpreted in a cross-section (Clemons, 1998) to lie unconformably on low-angle faults that place the Montoya Formation over the El Paso Formation, a younger on older relationship. These relationships suggest that perhaps the low-angle faults predate the Lobo Formation, but that the latest movement on the SFMF post-dates Eocene Lobo deposition.

Tectonic significance of Florida Mountains faults

The tectonic significance of these faults has been controversial for three reasons, each of which will be briefly addressed. Corbitt and Woodward (1970) and Brown (1982, 1983) agreed that these faults were thrust faults, but disagreed about the fundamental style of faulting and its relationship to the Laramide history of the southwestern United States. Corbitt and Woodward (1970) interpreted the structures as representing the southeastern continuation of the Cordilleran fold and thrust belt as defined by King (1969). This is essentially the "thin-skinned" regional thrusting model also advocated by Woodward and Duchene (1981) and Drewes (1978, 1981, 1988). Brown (1983) and Clemons (1998) noted the steep dips on the SFMF were more compatible with a "thick-skinned," basement-involved block-uplift style of deformation similar to that observed in the Rocky Mountain foreland. Davis (1979) and Seager and Mack (1986) both invoked a basement-cored block uplift model for other parts of southwestern New Mexico and southeastern Arizona, and this appears to be the currently favored hypothesis for the style of Laramide deformation in the region (Miller et al., 1992).

Brown (1982) recognized the controversial nature of "thrust" faults in the Florida Mountains that exhibit younger-on-older relationships and tectonic elimination of strata. There is a long history of interpreting low-angle faults with apparent normal displacement as thrust faults in the Cordillera. Many of these are in the Basin-and-Range province, and were subsequently shown to be low-angle normal faults associated with Tertiary extension (Armstrong, 1972), particularly where associated with metamorphic core complexes. There are, however, several possible geometric explanations for younger-on-older relationships resulting from shortening: (1) faults that cut folds; (2) imbrication of imbricated rocks by a second generation of steeper faults; (3) faults that move along an unconformity (Armstrong, 1972); and (4) reactivation of normal faults as thrust faults. As noted by Brown (1982), conditions (1) and (3) are fulfilled in the Florida Mountains, so it is possible that these faults formed due to shortening. Additional evidence for shortening comes from less-common older-on-younger relationships that do exist (Fig. 3).

Another controversy regarding the nature of the Florida Mountains faults is the importance of strike-slip movement along the SFMF. Brown (1982) observed that restoration of Basin-and-Range tilting results in an 85° SW dip on the SFMF. Typical reverse faults dip about 60–70° (e.g., Price and Cosgrove, 1990), whereas typical strike-slip faults are nearly vertical. Seager (1983) noted that bedding within Paleozoic beds apparently is rotated near the fault in the manner of a large-scale drag fold indicating 5–6 km of right-lateral slip. His interpretation was that this structure was associated with transpression during Laramide deformation. Brown (1983) and Clemons (1998) agreed that strike-slip motion on the SFMF may be significant. Additional geometrical evidence for strike-slip motion comes from the branching of the main trace of the fault into several subparallel faults in a "horsetail splay," a feature common to strike-slip fault systems (e.g., Sylvester, 1988).

DISCUSSION

The work of Davis (1979), Brown (1982), Seager (1983), Seager and Mack (1986), Clemons (1998), and others has shown that the basement-cored uplift model is generally more appropriate than a "thin-skinned," regional overthrusting model for describing the nature of Laramide deformation in southeastern Arizona and southwestern New Mexico. I find the evidence for some component of strike-slip motion along the SFMF compelling and note the similarity of the relationships in the Florida Mountains to classic examples of "positive flower structures" or "palm structures" (Fig. 5). These structures are found along bends in strike-slip fault systems resulting in a local zone of shortening (or extension) associated with a bend in the main fault. Steep faults at depth become shallow at higher structural levels, an observation consistent with relationships described in the Florida Mountains (e.g., the Gym Peak thrust, Fig. 4). Large-scale thrusting associated with this geometry is thought to result from mechanical delamination of a thin "structural flake" from its basement (Sylvester, 1988, p. 1687). In the Florida Mountains, the structural flake is the lower Paleozoic carbonate succession, and the basement is the Florida Mountains pluton. The observation that two phases of what is interpreted to be the same pluton are found

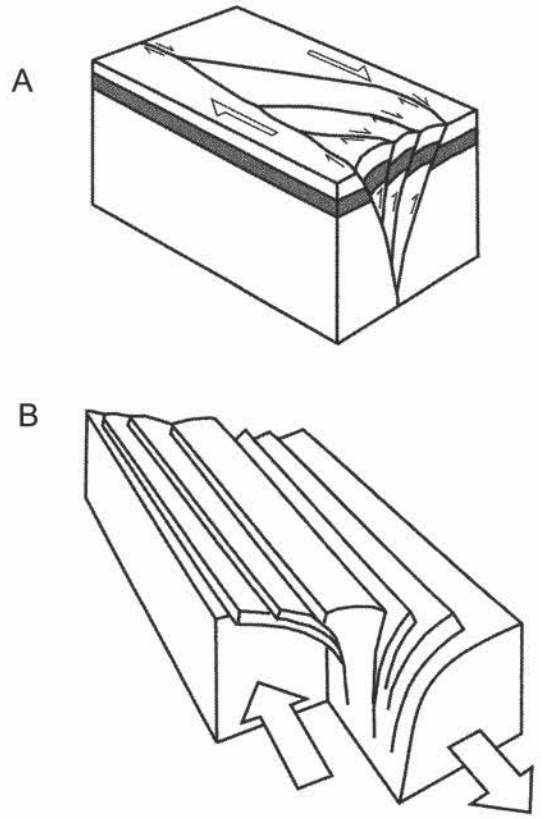


FIGURE 5. Diagrams of flower structures: **A**, vertical displacement predominates; **B**, horizontal displacement predominates (from Sylvester, 1988).

on each side of the SFMF argues for only limited strike-slip displacement.

Brown (1983) and Mack and Clemons (1988) stated that the juxtaposition of granite and syenite on different sides of the fault was difficult to explain by uplift of the granite, but they did not offer any details as to how they came to this conclusion. Granitic plutons are commonly zoned in both the vertical and horizontal dimension (e.g., Bateman and Chappell, 1979; Hildreth, 1981), so it is possible that the granite to the south may represent a deeper phase of the pluton that was juxtaposed against the shallower syenite phase. The greater abundance of mafic inclusions south of the fault suggests that the host alkali-feldspar granite represents a deeper level of a once-contiguous intrusion (Ervin, 1998). This relationship supports arguments for at least some reverse motion on the SFMF. Mack and Clemons (1988) also demonstrate an "unroofing sequence" in the provenance of the Lobo Formation, suggesting a vertical component of motion on the fault necessary to bring the pluton to the surface.

How then, do we reconcile these observations with the abundance of younger-on-older relationships? Conceivably, some sort of positive flower structure could interact with previously formed folds, and the presence of the mechanically strong basement could influence the local development of younger-on-older relationships associated with thrusting. However, it is not a particularly satisfying explanation. The fact that normal faults both cut and are cut by the Mahoney thrust in the vicinity of Mahoney Ridge (Clemons, 1998) is suspicious, and if normal faults are actually more abundant here, it may be that some of the younger-on-older relationships are related to subsequent Tertiary extension, rather than Laramide deformation.

Bayona and Lawton (this volume) and Lawton (this volume) provide evidence for reactivation or inversion of Late Jurassic–Early Cretaceous extensional structures as reverse faults during Laramide deformation in areas such as the Little Hatchet Mountains and Peloncillo Mountains of southwestern New Mexico (Fig. 1) and the Chiricahua Mountains of southeastern Arizona. It is possible that this extensional event also affected the region of the Florida Mountains, forming normal faults that were then partially inverted during compression or transpression. Perhaps the normal faults cut by the Mahoney thrust are not related to transport of the Paleozoic section over an irregular basement complex, but instead are relict structures from the Jurassic–Early Cretaceous extensional event. This would explain the cross-cutting relationship of the Mahoney thrust cutting a series of normal faults in the Mahoney Ridge area, and may provide an explanation for other younger-on-older "thrust" faults.

SUGGESTIONS FOR FUTURE WORK

The detailed mapping of Clemons (1983) and Clemons and Brown (1983) as well as the observations and regional correlations of Seager (1983) provide an excellent summary of the large-scale relationships in the range. Additional data bearing on the geometric controversies regarding the nature of faulting relationships in the Florida Mountains perhaps may be obtained through detailed kinematic analysis of the major structures in the range. Small-scale shear-sense indicators along the SFMF and related faults may provide information on at least the latest slip directions. Thermochronologic studies may help determine the amount and timing of relative uplift of the pluton, but it is possible that all thermochrologic systems will give early Paleozoic cooling ages unrelated to the Laramide history.

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