The Hot Springs fault system of south-central New Mexico—evidence for the northward translation of the Colorado Plateau during the Laramide orogeny

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Abstract

The Hot Springs fault system of southern New Mexico is a major north-northeast-striking zone of deformation that was active during the Laramide orogeny. Much of the fault system is buried beneath basin fill of the Rio Grande rift; however, segments of the system and subsidiary structures are exposed in the southern Fra Cristobal Range and Cutter sag area, and more extensively in the northern Caballo Mountains–Truth or Consequences–Mud Springs Mountains area (Truth or Consequences area). Southward from the Truth or Consequences area, the fault system is covered by late Cenozoic sediments of the Santa Fe Group, but its presence in the subsurface is marked by a prominent lineament on regional gravity and aeromagnetic maps. The geophysical lineament associated with the fault system can be traced for a strike length of over 160 km. North of the Fra Cristobal Range, the Hot Springs fault system may be continuous with dextral faults near Socorro.

Exposures in the Truth or Consequences area show the Hot Springs fault system to consist of an approximately 15 km wide zone consisting of multiple strands that juxtapose differing geologic terranes. Principal faults in this system include: 1) the Hot Springs–Walnut Canyon fault, which juxtaposes the overturned limb of a northwest-trending fault-propagation fold against the overturned limb of a north-trending fault-propagation fold across an approximately 40 m wide, hydrothermally altered shear zone; 2) the Hobbs Canyon fault, which juxtaposes the overturned limb of the northwest-trending fault-propagation fold against gently northeast dipping beds; and 3) the Cross fault, which juxtaposes terranes with differing stratigraphic successions. In the Fra Cristobal Range, a restraining bend in the Hot Springs fault system produced north-striking, east-vergent thrust faults, reverse faults, and overturned folds.

Dextral offset of approximately 26 km on the Hot Springs fault system is indicated by: (1) dextral deflection of Devonian pinch-out trends; (2) offset of four oblique Laramide structures; and (3) offset of transverse linear anomalies on both gravity and aeromagnetic maps. Reconstruction of isopach and facies maps for other lower Paleozoic strata are permissive or supportive of this strike-slip movement. The Upper Cretaceous and early Tertiary(?) McRae Formation, deposited in Cutter sag, is interpreted to be syntectonic and to record transpressional basin development that began in the Late Cretaceous along the Hot Springs fault system.

The Hot Springs fault system is part of a regional strike-slip fault system in southern New Mexico that helped accommodate the decoupling and north–northeast motion of the Colorado Plateau microplate relative to the continental interior during the Laramide orogeny. Other Laramide dextral faults may lie buried beneath the Palomas and Engle Basins, as shown by 35–60 km of dextral deflection of lower Paleozoic pinch-out trends across them. A related strike-slip fault in the Black Range (west of Truth or Consequences), with approximately 3.1 km of dextral strike slip, cuts virtually the entire Eocene Rubio Peak Formation. It is overlain by an unfaulted ash-flow tuff with an $^{40}Ar/^{39}Ar$ age of 34.93 ± 0.04 Ma, indicating that the system became inactive by the early Oligocene.

Introduction

Chapin and Cather (1981) and Hamilton (1981) were the first to postulate regional Laramide strike-slip tectonism along ancient flaws in the Southern Rocky Mountain–Rio Grande rift province, including north-northeast-trending faults in southern New Mexico. Chapin (1983a,b) delineated regional dextral fault zones in central New Mexico and northward along the eastern margin of the Colorado Plateau. [Note, however, that during printing of the regional map by Chapin (1983a, fig. 1) the fault overlay was inadvertently shifted slightly to the south-southeast relative to topography.] He identified the Hot Springs–Walnut Canyon (HSWC) and Montosa–Paloma faults as components in a system of distributed strike-slip faults that accommodated northward translation of the plateau. The Laramide fault system in south-central New Mexico was further defined by Harrison (1989a), who documented 3.1 km of dextral slip on the Chloride fault zone in the Black Range, approximately 50 km west of the HSWC fault. Harrison also demonstrated that the strike-slip fault system was active in the Eocene, but had terminated by early Oligocene.

Seager (1983), Seager and Mack (1986), and Seager et al. (1997) found little evidence in southern New Mexico for Laramide dextral deformation, instead emphasizing the role of northwest-trending basement-cored upthrusts (their Rio Grande uplift). Although we do not dispute the existence of such upthrusts in southern New Mexico, we focus herein on the major north-northeast-striking faults of the Hot Springs system, which collectively may have accommodated as much as 26 km of Laramide dextral slip (Harrison and Chapin 1990).

A regional linear feature present on geophysical maps marks the trace of the Hot Springs fault system (Fig. 1). This lineament is pronounced on bouguer gravity anomaly maps (Decker et al. 1975; Ramberg and Smithson 1975; Cordell et al. 1982; Keller 1983; Gilmer et al. 1986) and appears to owe its origin to both Laramide and Rio Grande rift-related deformation. The Hot Springs fault system also coincides with a north-northeast-trending linear element on aeromagnetic maps (Kucks et al. 2001). Late Tertiary and Quaternary Santa Fe Group sediments overlie the Hot Springs fault system along most of its trace. The main exposures of the fault system are in the northern Caballo Mountains–Truth or Consequences–Mud Springs Mountains area (T or C area)

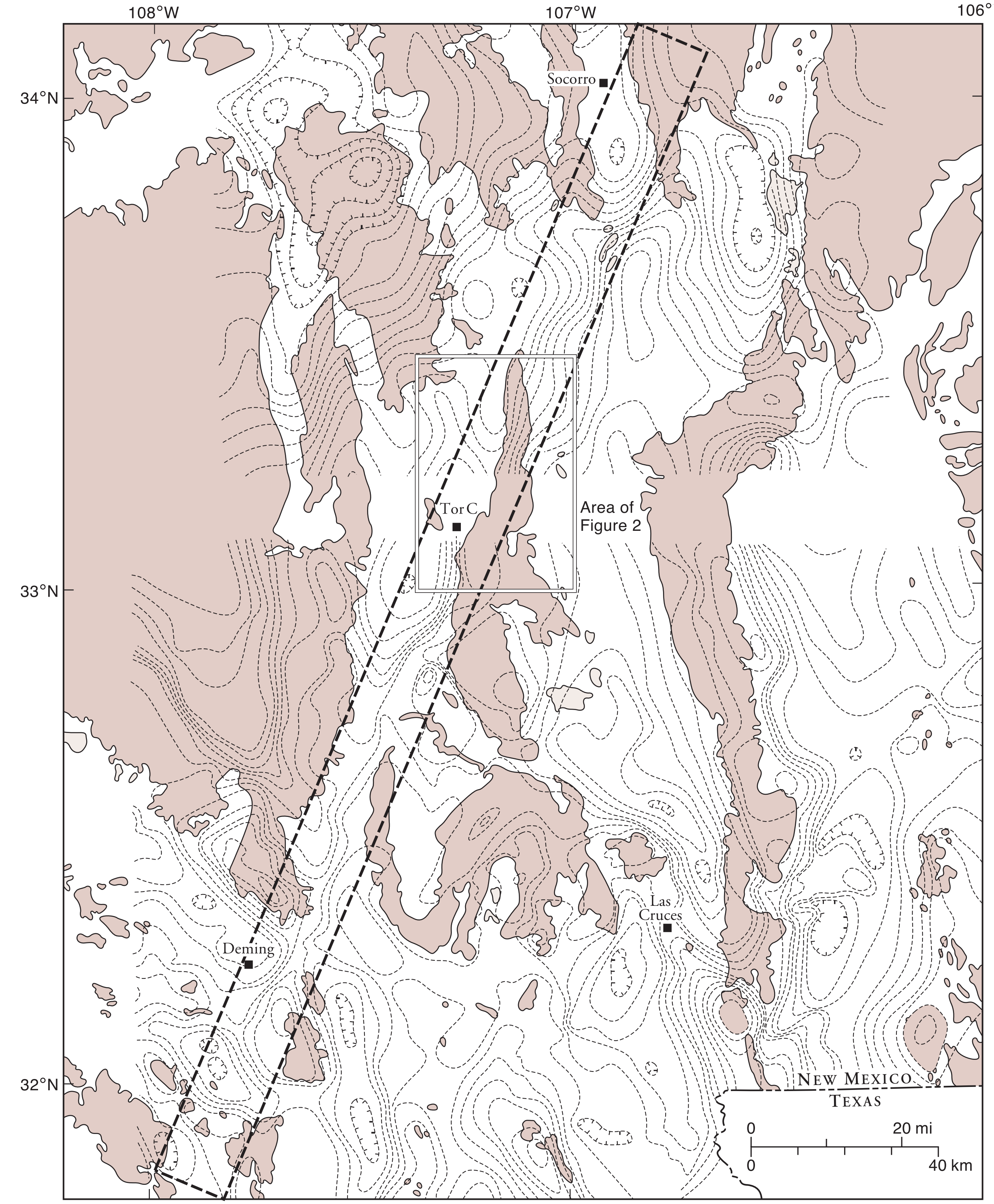


FIGURE 1—Location map for southern New Mexico showing uplifts (shaded areas) and basins (unshaded areas) overlain by bouguer anomaly maps from Ramberg and Smithson (1975) and Keller (1983). Contour interval is 5 mgal in south and 4 mgal in north. The Hot Springs fault system is indicated by dashed box. **T or C**—Truth or Consequences.

and the southern Fra Cristobal Range– Cutter sag area (Fig. 2). These exposures reveal a zone of multiple strike-slip faults and displaced terranes in the Truth or Consequences area, and a transpressive bend adjacent to the southern Fra Cristobal Range.

Truth or Consequences area

In the T or C area (Fig. 3), the Hot Springs fault system is an approximately 15 km wide fault zone consisting of multiple strands that juxtapose differing geologic terranes. The principal structure in this system is the HSWC fault, which locally exhibits a complex cataclastic zone of breccia and sheared rocks that is as much as 40 m wide. Subsidiary faults, folds, and fractures extend for many tens of meters from the main shear zone. Hydrothermal alteration and mineralization consisting of silica, barite, fluorite, and iron-manganese oxides are common and locally intense. Strongly deformed slivers of pre-Cenozoic formations occur at several locations along the fault. Immediately to the north of the T or C area, in the wing dam area of the Elephant Butte Reservoir, Lozinsky (1986) mapped normal fault splays branching from the HSWC fault that cut Santa Fe Group beds, and estimated a down-to-the-west stratigraphic separation of about 1,220 m. However, Lozinsky's (1986) estimation was based on the assumption that similar stratigraphic sequences and thicknesses occur on both sides of the fault. In contrast, gravity modeling across the HSWC fault in the wing dam area by Gilmer et al. (1986) indicates that both the Cretaceous–Paleozoic contact and the Paleozoic–Precambrian contact are downthrown approximately 1 km to the east.

The HSWC fault in the T or C area shows characteristics atypical of a normal fault. We disagree with Mack and Seager's (1995) interpretation that the HSWC fault near Truth or Consequences and the northern Caballo Mountains is a major rift-basin boundary fault. Detailed mapping (Kelley and Silver 1952; Maxwell and Oakman 1990; Lozinsky 1986; R. Harrison unpublished mapping) indicates that the main rift-basin boundary fault along the southern and central Caballo Mountains swings northwestward to become the Mud Springs fault (Fig. 2). This is substantiated by drill data presented in Murray (1958) and Lozinsky (1987). The limited vertical separation of upper Paleozoic strata between the Mud Springs Mountains and northern Caballo Mountains argues against major components of dip slip during Laramide or rift deformations. In the northern Caballo Mountains area, late Tertiary to Quaternary Santa Fe Group sediments locally either bury the HSWC fault or were deposited against an erosional scarp along the fault. Thus, whereas some segments of the HSWC fault were reactivated by Rio Grande rifting, reactivation in the T or C area was minor.

In the T or C area, the HSWC fault strikes N20°–30°E, and typically dips from 65° to 90° to the northwest. However, dips of 80–90° to the southeast are present at several places along the fault and are interpreted to reflect the presence of large horizontal mullions. Numerous slickenside surfaces with subhorizontal striations exist on the main fault and subsidiary faults where they cut Paleozoic rocks (Fig. 4a); kinematic indicators (Riedel and conjugate Riedel shears) suggest dextral slip on north-northeast-striking surfaces and sinistral slip on east-northeast surfaces. These strike-slip motions are interpreted to be the result of a northeast-directed maximum principal stress. Numerous fault surfaces with shallowly plunging slickenlines also occur in Precambrian rocks on the west side of the HSWC fault (Fig. 4b). Kinematic indicators suggest dextral slip on surfaces that strike to the northeast, north, and northwest, and sinistral slip on east-striking surfaces. These are consistent with Riedel and conjugate Riedel shears that formed during right-lateral shearing along the HSWC fault under a northeast-directed maximum principal stress.

Individual faults of the Hot Springs fault system display complexities in stratigraphic and structural juxtaposition that cannot be reconciled by dip-slip faulting alone. A significant feature of the HSWC fault is that it juxtaposes the overturned limb of a northwest-trending fault-propagation fold against the overturned limb of a north-trending fault-propagation fold (Fig. 3, sections A–A' and B–B'). This geometry could not have been produced by normal or thrust faulting and cannot be balanced without invoking significant strike-slip movement along the HSWC fault. Lozinsky (1986) described right-lateral drag features along the fault and suggested approximately 460 m of right-lateral strike slip based on apparent offsets of the Paleozoic section along an eastern strand of the fault. However, restoration of his suggested slip does not alleviate the balancing problem. As described later, a much greater amount of strike-slip movement, approximately 26 km, is indicated for the HSWC fault system.

The Truth or Consequences fault is about 1 km west of the HSWC fault (Fig. 3). This fault and another between it and the HSWC fault were described first by Kelley and Silver (1952) as buried structures that parallel the HSWC fault. Their existence was inferred from offsets of the northwest-striking overturned beds observed in scattered outcrops in the town of Truth or Consequences and drill data. An exposure of strongly altered (Mn and Fe oxides, and silica) Ordovician Montoya Group along the Truth or Consequences fault has vertical shear surfaces that strike N22°E and contain slickenside striations that rake 15° to the southwest.

The Hobbs Canyon fault, located approximately 3 km west of the Truth or Consequences fault (Fig. 3), is covered by Santa Fe Group sediments. Its presence is inferred from juxtaposition of the southwest-dipping overturned limb of the northwest-trending fault-propagation fold against northeast-dipping beds in the Mud Springs Mountains (Fig. 3). Such structural relations require a tear fault, or strike-slip fault, between these two areas.

The Mud Springs Mountains contain additional structures indicative of regional strike-slip deformation. The Mud Mountain fault is a north-northwest-striking, vertical structure (Maxwell and Oakman 1990). At several locations, drag folds adjacent to the fault indicate dextral oblique slip. At other locations on this fault, subhorizontal slickenside striations with rakes as low as 20° occur (R. Harrison unpublished mapping). Both transpressive and transtensional features along this fault indicate right-lateral motion (R. Harrison unpublished mapping). The Cross fault dips steeply and parallels the HSWC fault (Fig. 3). It intersects the Mud Mountain fault in an intensely deformed area containing low-angle thrust faults and overturned bedding (Maxwell and Oakman 1990). Although no kinematic indicators have been found on the Cross fault, localization of overturned bedding near a left-stepping bend in the fault (Maxwell and Oakman 1990), suggests dextral components of slip.

The Cross fault also juxtaposes terranes of differing stratigraphic sequences. North of the fault, approximately 100 m of Upper Ordovician through basal Pennsylvanian section is absent and marked by the basal Pennsylvanian unconformity (Maxwell and Oakman 1986). A more complete stratigraphic section, including Devonian strata, is preserved to the south of the Cross fault.

Evidence for magnitude of dextral slip

Displaced terranes

As first noted by Kelley and Silver (1952), the belt of northwest-striking overturned beds near Truth or Consequences is similar in many respects to the belt of northwest-striking overturned beds in the Apache Gap area, southern Caballo Mountains. Also, geologic terranes west of the HSWC fault are locally dissimilar to the geologic terrane east of the fault in the northern Caballo Mountains. Three differing geologic terranes occur in the Truth or Consequences area, separated by the Cross fault, the Hobbs Canyon fault, and the HSWC fault. All three terranes possess unique geologic characteristics. However, characteristics of all T or C area terranes

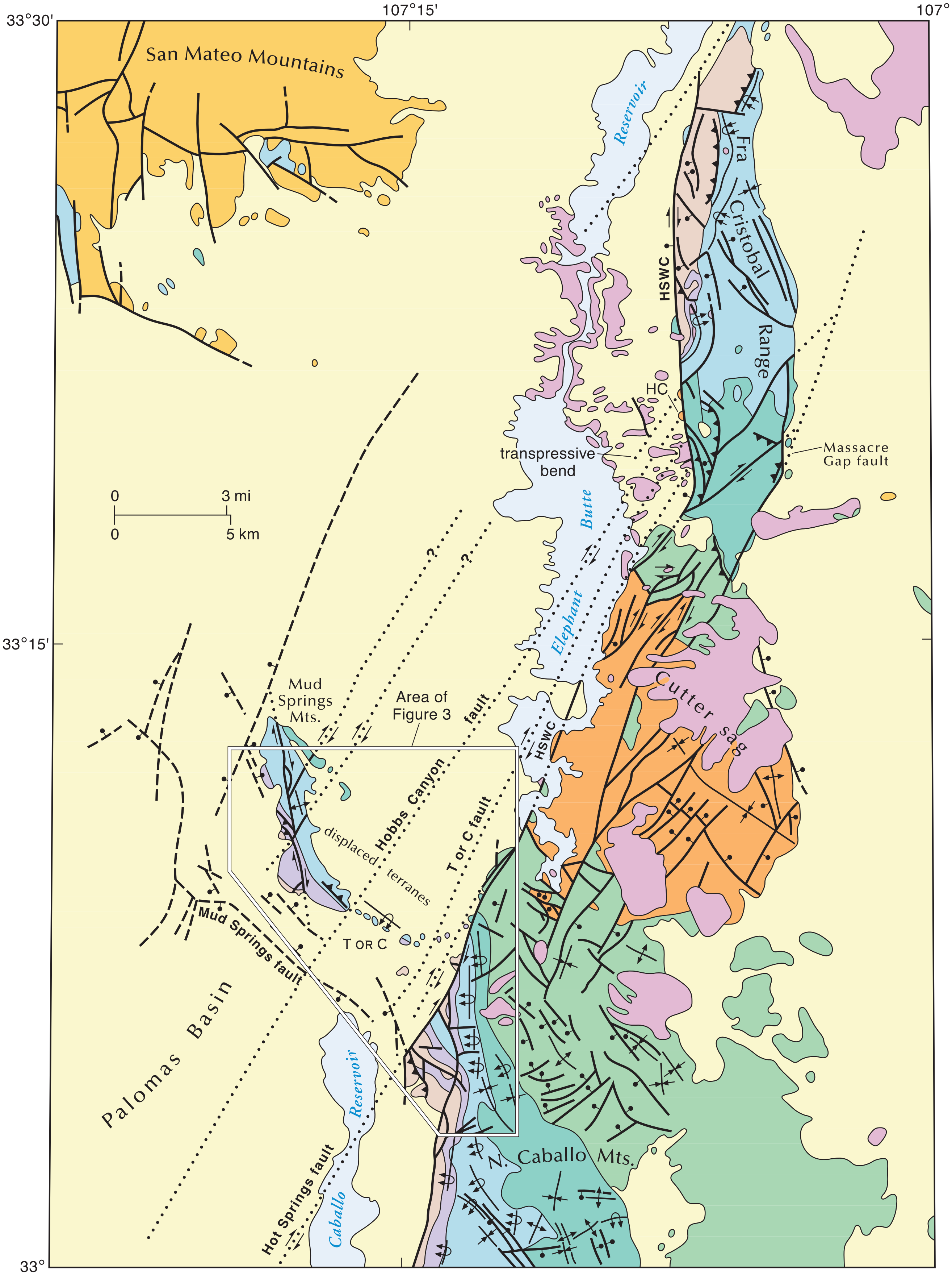


FIGURE 2—Generalized geologic map of the T or C area (northern Caballo Range, city of Truth or Consequences, Mud Springs Mountains), Cutter sag, and Fra Cristobal Range. Adapted and simplified from Van Allen et al. (1983); Lozinsky (1986); Maxwell and Oakman (1990); Foulk (1991); R. Harrison (unpublished mapping). **HSWC**—Hot Springs–Walnut Canyon fault. **HC**—Hackberry Canyon, discussed in text.

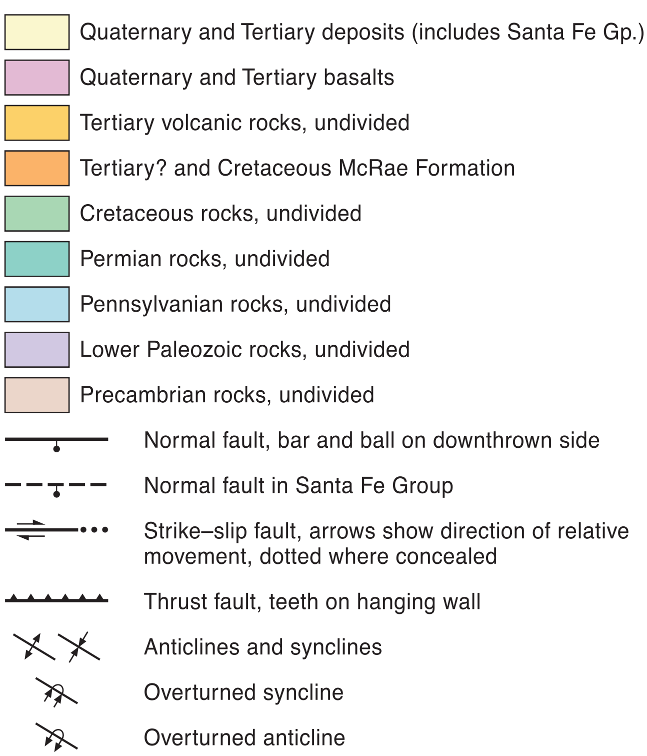
occur in the Apache Gap area (AG in Fig. 5) in the southern Caballo Mountains, approximately 26 km to the south-southwest of the T or C area. We interpret the geologic terranes in the T or C area to have been displaced from their original position adjacent to the southern Caballo Range by strike-slip faulting along the Hot Springs fault system to their present position adjacent to the northern Caballo Range.

"Terrane A" is the northern Mud Springs Mountains, northwest of the Cross fault (Fig. 3). A unique geologic characteristic of this terrane is an unusually well developed basal Pennsylvanian unconformity. Maxwell and Oakman (1986) determined that the upper portion of the Ordovician Cutter Dolomite, the entire Devonian and Mississippian sections, and the Lower Pennsylvanian Sandia Formation of Hill (1956) or the lower part of the Red House Formation of Kelley and Silver (1952) are absent below the unconformity. Immediately southeast of the Cross fault, the unconformity is much diminished and only Mississippian strata are absent.

"Terrane B" is also in the Mud Springs Mountains and lies between the Cross fault and the Hobbs Canyon fault (Fig. 3). This terrane has a relatively complete stratigraphic section for the region, including a Devonian section (Maxwell and Oakman 1990; Hill 1956). The presence of Devonian rocks there is unique in the Truth or Consequences area; there are no Devonian strata in the northern Caballo Mountains (Harley 1934; Thompson 1942; Kelley and Silver 1952; Mason 1976; Lozinsky 1986). In the Apache Gap area of the southern Caballo Range, however, a Devonian section is present (Kelley and Silver 1952; Seager et al. 1982). Another possible connection between terrane B and the Apache Gap area is that both locations contain abundant fossils in the Bat Cave Formation of the Ordovician El Paso Group, whereas elsewhere in the region the formation is only sparsely fossiliferous (Kelley and Silver 1952).

"Terrane C" lies between the Hobbs Canyon fault and the HSWC fault. The belt of northwest-striking overturned beds present in this terrane is unique in the T or C area. The closest occurrence of a similar-striking structure is the overturned belt southeast of Apache Gap in the southern Caballo Mountains, approximately 26 km to the south.

We note also that the Chavez Canyon fault, a Laramide reverse fault in the Salado Mountains 23 km west of Truth or Consequences (Seager and Mayer 1988), projects eastward along strike toward the northern Caballo Mountains where no Laramide structures of similar orientation are present. The Chavez Canyon fault is well north of the northernmost Laramide structure of similar strike in the Caballo Mountains (Longbottom fault; Seager and Mack 2004).



Gravity data

Harrison and Chapin (1990) argued that geophysical, structural, and stratigraphic data in southern New Mexico were either supportive or permissive of 26 km of right-lateral strike-slip on the Hot Springs fault system. Figure 5 is a strike-filtered residual gravity anomaly map of southwestern New Mexico, southeastern Arizona, and northernmost Chihuahua from DeAngelo and Keller (1988) that has been modified by restoring 26 km of right-lateral movement along the Hot Springs fault system. DeAngelo and Keller (1988) filtered north-south-trending anomalies from their map, and thus it emphasizes the gravity fabric that is orthogonal to the Hot Springs trend and the trend of major rift basins. Although these gravity anomalies largely reflect the geometry of late Tertiary basins and uplifts, many such late Tertiary features have been reactivated or inverted from Laramide and older features (e.g., Seager and Mack 2003; Nelson 1993). The 26 km of restoration aligns several prominent northwest-trending gravity features across the Hot Springs fault system. Similar restorations on a bandpass-filtered (15–125 km) magnetic anomaly map of DeAngelo and Keller (1988), as well as the regional bouguer anomaly map of Ramberg and Smithson (1975) also produce alignments of geophysical highs and lows across the Hot Springs fault system (Harrison and Chapin 1990).

Structural alignments

Many geologists have recognized Laramide contractile structures, such as fault-propagation folds, high-angle reverse faults, and thrust faults in southern New Mexico (Kelley and Silver 1952; Zeller 1970; Corbitt and Woodward 1973; Drewes 1978; Woodward and DuChene 1981; Seager 1983; Seager and Mack 1986; Chapin and Nelson 1986; Nelson 1993). With the exception of the north-striking deformation belts in the northern Caballo Mountains and Fra Cristobal Range, major Laramide structures in southern New Mexico strike northwest to west-northwest, orthogonal to the Hot Springs trend. The overturned belt in terrane C in the T or C area is one of these northwest-striking Laramide structures, as is the overturned belt southeast of Apache Gap in the southern Caballo Mountains.

Several other Laramide structures south of the T or C area are realigned by 26 km of restoration. Figure 6a is a map of southwestern New Mexico showing Laramide structures in their present-day configuration, and Figure 6b shows the location of these structures after restoration of 26 km of right slip along the Hot Springs fault system. This restoration aligns several Laramide structures that cross the Hot Springs fault system in southern New Mexico.

Structures 1W and 1E in Figure 6 are the Truth or Consequences and southern Caballo Mountains structures described previously. Structures 2W and 2E are located in the southern Cooke's Range and the Florida Mountains, respectively, and are characterized as northwest-striking high-angle reverse faults that exposed in Laramide time a broad area of Precambrian and Paleozoic rocks (Corbitt and Woodward 1973; Brown 1982; Clemons 1985; Clemons and Brown 1983; Seager 1983; Seager and Mack 1986). Laramide

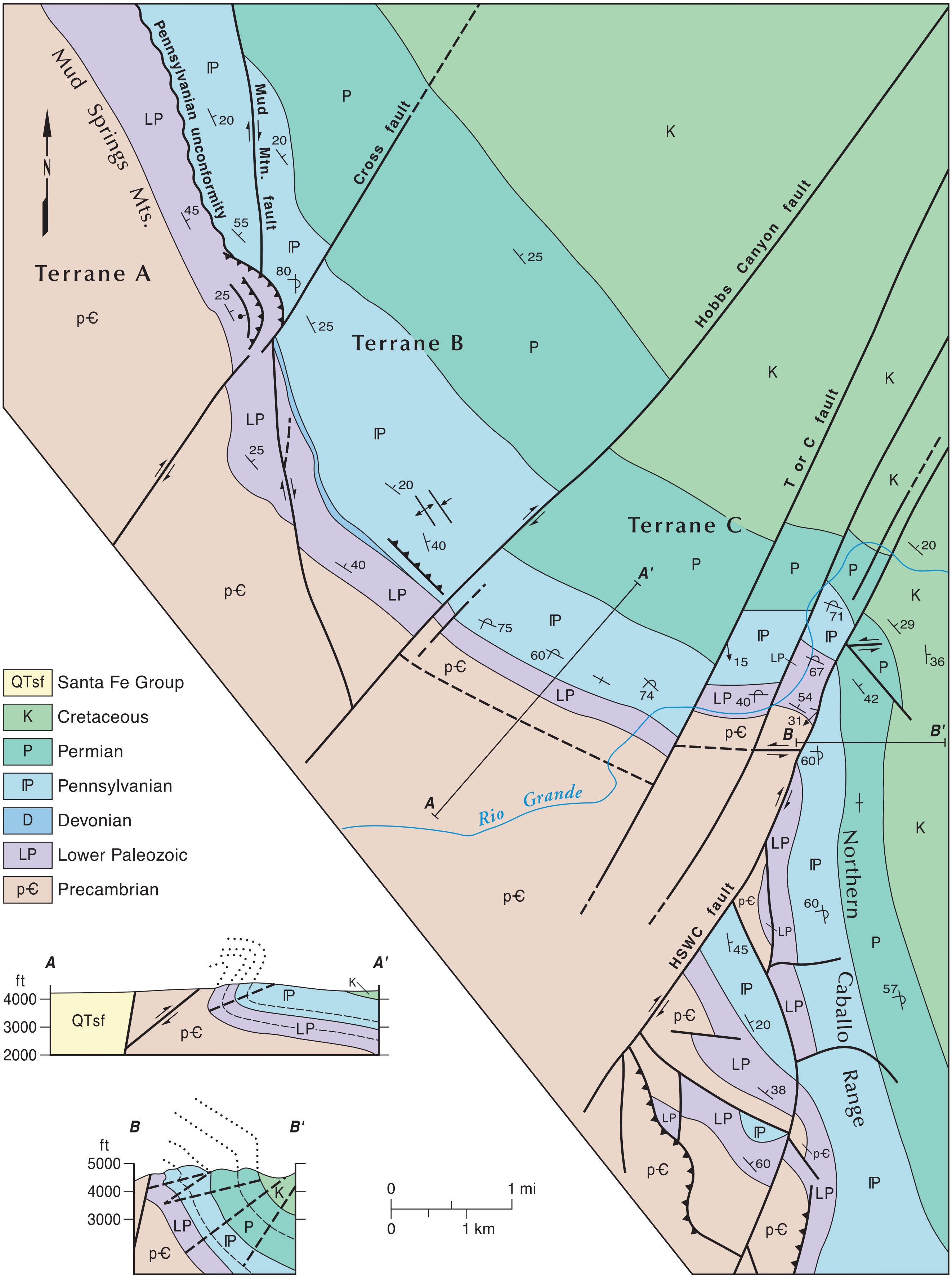
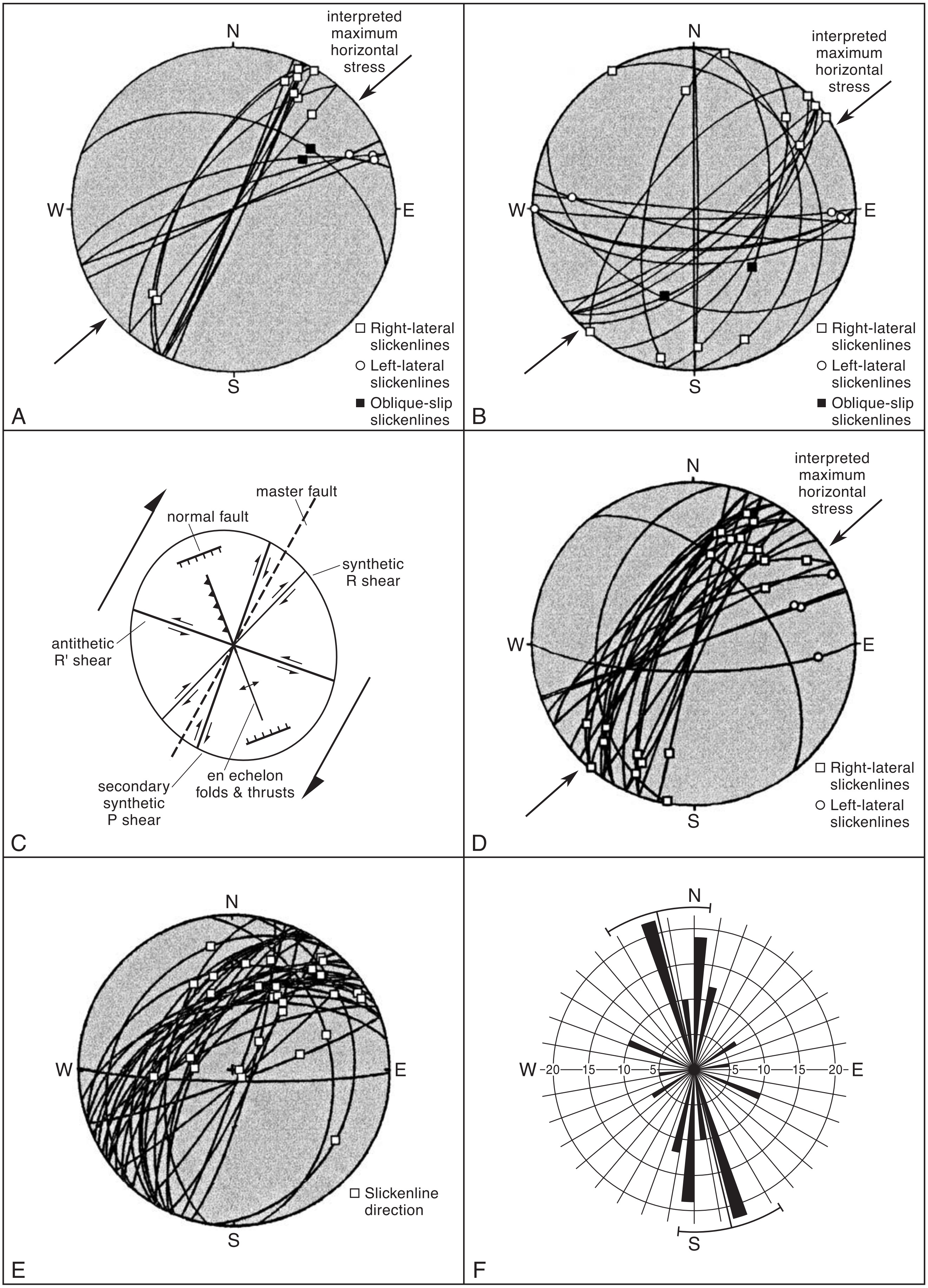


FIGURE 3—Interpretive geologic map of the T or C area . Except for cross section **A–A′**, Santa Fe Group sediments of the Palomas Basin and faults cutting the Santa Fe Group are not shown. Adapted from Kelley and Silver (1952); Lozinsky (1986); Maxwell and Oakman (1986a, 1990); R. Harrison (unpublished mapping).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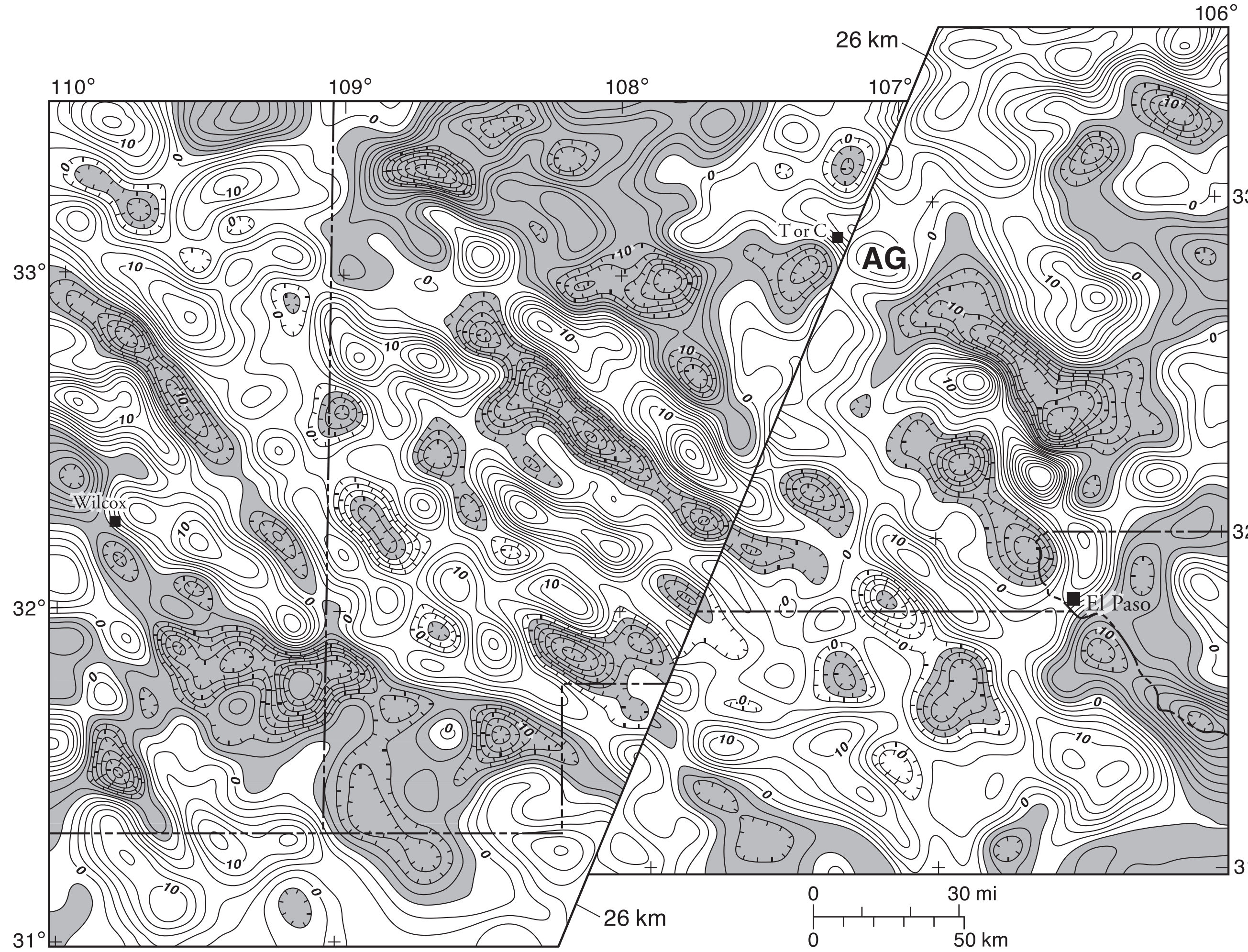

FIGURE 5—Strike-filtered residual gravity anomaly map of southwestern New Mexico (after DeAngelo and Keller 1988) with 26 km (16 mi) of strike slip restored along the Hot Springs fault system. **AG**–approximate location of the Apache Gap area in southern Caballo Mountains. Shaded areas are values less than – 2.0 mgals.

orogenic fanglomerate deposits derived from uplift and erosion related to these two structures are similar in age (Paleocene to early Eocene), petrofacies, and facies distribution (Seager and Mack 1986). Our reconstruction of movement on the Hot Springs fault system implies these structures perhaps were once continuous and formed the northeast margin of the Laramide Burro uplift.

In a similar way, structures 3W and 3E (Fig. 6), which are Laramide features in the Snake Hills and Tres Hermanas Mountains, respectively, can also be restored across the fault. Deformation at both locations has been described as west-northwest-striking, low-angle thrust faults in lower Paleozoic strata (Corbitt and Woodward 1973; Woodward and DuChene 1981; we note, however, that W. R. Seager [2001, oral comm.] disputes the presence of thrust faults in the Snake Hills). Restoration (Fig. 6b) realigns these structures that are today approximately 26 km apart.

South of the border in Chihuahua, numerous elements of Laramide deformation have been recognized (Corbitt 1988). While there appears to be right-lateral offset across the Hot Springs fault system, particularly between a 20-km-wide, west-northwest-trending fold belt in Sierra Palomas (4W in Fig. 6) with a similar fold belt in the Sierra Chinos (4E in Fig. 6), the amount of offset is less than 26 km. A similar smaller offset of gravity anomalies also is present in this area (Fig. 5). These relationships suggest that a portion of the strike-slip movement may have been taken up by differential shortening on the orthogonal contractile structures.

Piercing-line analysis of lower Paleozoic pinch-outs

Several lower Paleozoic units pinch-out to the north in south-central New Mexico. These pinch-out trends, defined by the ultimate northern limit of each unit, form linear elements that may serve as piercing lines to delimit the magnitude of strike-slip faulting (e.g., Cather 1999). In this analysis, we use the term *deflection* (sensu Cather 1999) in a nongenetic sense to describe the apparent separation of pinch-out trends. Deflections may be either of tectonic or sedimen-

FIGURE 4—**A**. Stereonet showing structural data from Paleozoic rocks along the HSWC fault in Truth or Consequences area. Fault surfaces are shown as great circles and rakes of slickenlines as point data. **B.** Stereonet showing structural data from Precambrian rocks adjacent to HSWC fault. Fault surfaces are shown as great circles and rakes of slickenlines as point data. **C**. Strain ellipse for northeast shortening and associated right-lateral shear. **D**. Stereonet of structural data from HSWC fault at mouth of Hackberry Canyon (HC in Fig. 2) in the southern Fra Cristobal Range. Fault surfaces are shown as great circles and rakes of slickenlines as point data. **E**. Stereonet showing structural data from detached blocks of Permian San Andres Formation and Upper Cretaceous-lower Tertiary? McRae Formation in the southern Fra Cristobal Range (from Foulk 1991). Fault surfaces are shown as great circles and rakes of slickenlines as point data. **F**. Rose diagram showing strike of fold axial surfaces in the northern Caballo Range (data from Mason 1976 and Kelley and Silver 1952).

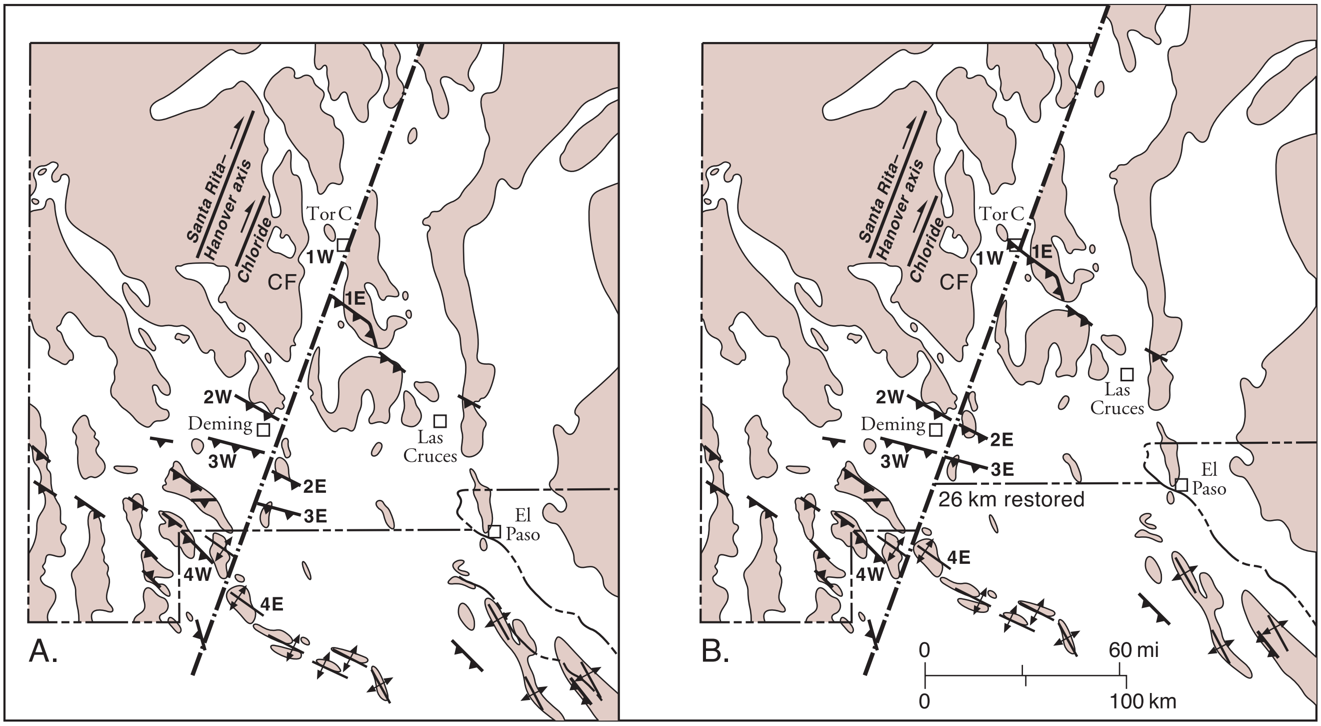

FIGURE 6—Maps of southwestern New Mexico, northern Chihuahua, and extreme western Texas showing: **A**. Present locations of northwest-striking Laramide thrusts and fold belts; and, **B**. Locations after restoration of 26 km of strike slip along the Hot Springs fault system. Also shown are the locations of the Santa Rita–Hanover axis and Chloride strike-slip zones, and Copper Flat (**CF**) intrusive. Shaded areas are uplands, unshaded are late Cenozoic basins.

tary origin, or both. Deflections confidently may be inferred to be of strike-slip origin (i.e., true separations) only where control points are closely juxtaposed across faults of known or suspected strike-slip history (see discussion in Cather 1999, pp. 852–853).

Pinch-out trends for individual units were determined using exposures and well control on a coherent structural block (Jornada block) that consists of the Jornada del Muerto syncline and the inward-tilted ranges that comprise its eastern (San Andres Mountains) and western (Fra Cristobal Range and Caballo Mountains) limbs. Other than the Jornada Draw fault, which is a Pliocene–Pleistocene feature (Seager and Mack 1995), the Jornada block is not cut by major, throughgoing faults and thus is a suitable locale for determination of pinch-out trends. In this analysis, we extrapolate the trends defined on the Jornada block to areas of poor control to the west where such trends are less well defined. We consider only the zero isopach of each unit because the pinch-outs that define them have been precisely mapped by previous workers in ranges east of the Hot Springs fault system. The location and trend of other, nonzero isopach lines are typically less precisely known because they have been interpolated between widely spaced control points (e.g., Kottlowski 1963). Our map (Fig. 7) differs from the isopach maps of Kottlowski (1963) primarily in that we have included additional data from Furlow (1965) in the eastern San Mateo Mountains and refinements to pinch-out locations near Mockingbird Gap by Bachman (1968).

Bliss, El Paso, and Montoya—The Bliss Sandstone (Cambrian–Ordovician) and overlying El Paso and Montoya Groups (Ordovician) are all beveled to zero thickness beneath Pennsylvanian strata within a few kilometers of each other in the Mockingbird Gap area (Bachman 1968) and in the Fra Cristobal Mountains (Van Allen et al. 1983; McCleary 1960). The Sun Victorio Land and Cattle No. 1 well (Fig. 7) in the northern Jornada del Muerto penetrated substantial thicknesses of these units and thus delimits the pinch-out trend on the south in this area. West of the Hot Springs fault system, significant thicknesses of Bliss, El Paso, and Montoya strata crop out in the central Sierra Cuchillo (Jahns 1955) and in the eastern San Mateo Mountains (Furlow 1965). These control points require a sharp dextral deflection of the pinch-out trend across the Engle Basin of approximately 35 km.

Devonian strata—The northernmost limits of Devonian strata (Percha Shale, Oñate, and Sly Gap Formations) east of the Hot Springs fault system form a northeast-trending line that is defined by exposures in the northern San Andres Mountains (Bachman 1968) and the Caballo Mountains (Kelley and Silver 1952; Seager and Mack 2004) and is bracketed by wells in the Jornada del Muerto (Fig. 7). West of the Jornada block, exposures of Devonian strata in the southern Mud Springs Range (Maxwell and Oakman 1990) require an acute, closely constrained, dextral deflection of at least 26 km across the Hot Springs fault system. Devonian strata exposed in the central Sierra Cuchillo (Jahns 1955) require a dextral deflection of at least 60 km from the pinch-out trend defined to the east of the Palomas Basin. North of these pinch-out trends Devonian strata have been removed by Middle Mississippian–Early Pennsylvanian erosion.

Fusselman Dolomite—The northward pinch-out of the Fusselman Dolomite (Silurian) is present along an east-northeast-trending line that is defined by exposures in the central San Andres Mountains (Kottlowski 1963) and in the Caballo Mountains (Seager and Mack 2004) and is bracketed by well penetrations in the Jornada del Muerto. The Fusselman is not present in the Mud Springs Range, giving an upper limit of about 26 km on any possible deflection across the Hot Springs fault system. Outcrops of the Fusselman Dolomite in the southern Sierra Cuchillo (Kottlowski 1963) require a dextral deflection of nearly 60 km from the pinch-out trend defined on the Jornada block.

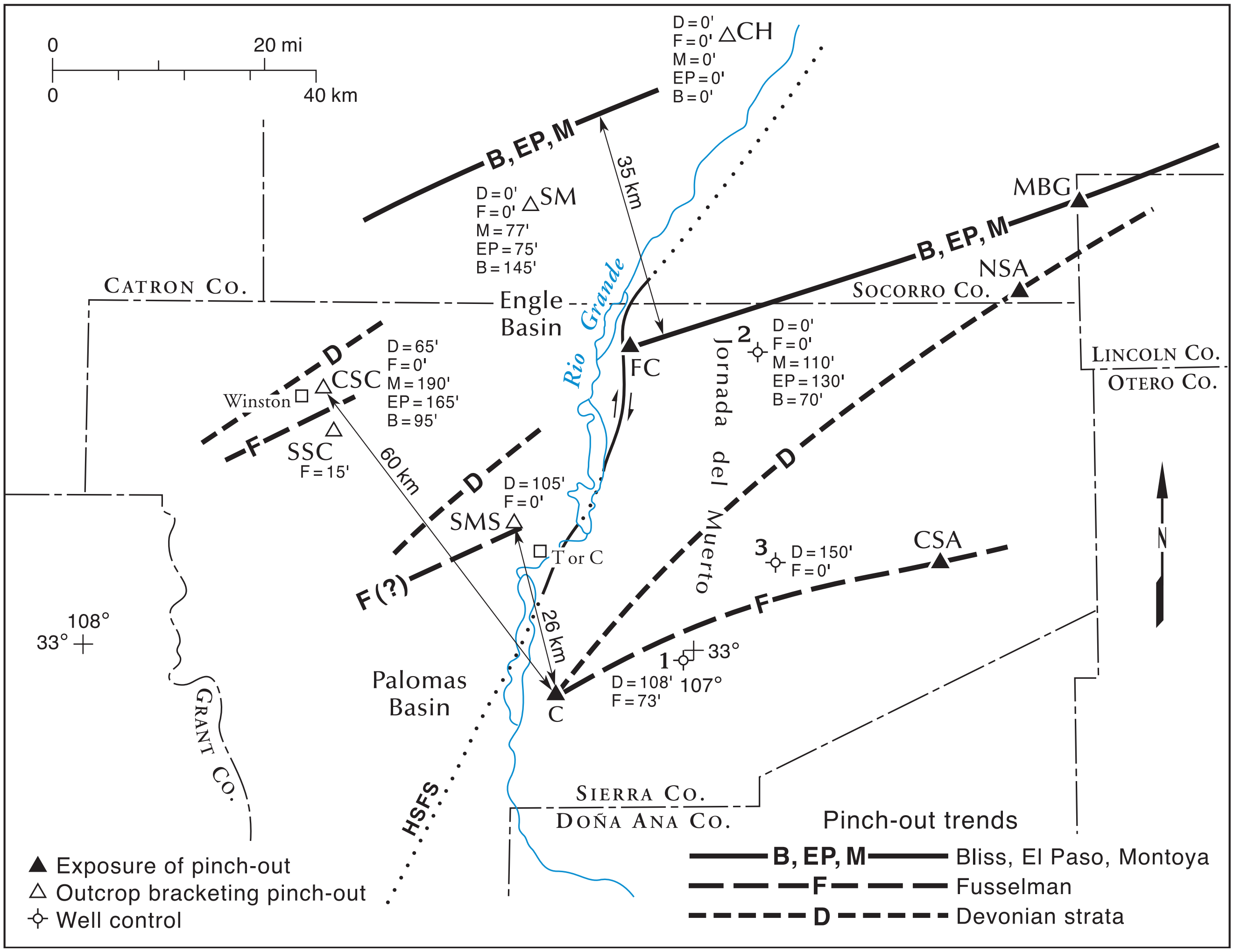

FIGURE 7—Map showing easternmost limit of Hot Springs fault system, control points, and pinch-out trends of lower Paleozoic units in south-central New Mexico. Units are **B**, Bliss Sandstone (Cambrian); **EP**, El Paso Group (Ordovician); **M**, Montoya Group (Ordovician); **F**, Fusselman Dolomite (Silurian); **D**, Devonian strata (includes Percha Shale, Oñate, and Sly Gap Formations). Thickness is in feet. Localities are **CH**, Chupadera Mountains; **SM**, San Mateo Mountains (Eaton Ranch); **CSC**, central Sierra Cuchillo; **SSC**, southern Sierra Cuchillo; **FC**, Fra Cristobal Range; **MBG**, Mockingbird Gap; **NSA**, northern San Andres Mountains; **SMS**, southern Mud Spring Mountains; **C**, Caballo Mountains; **CSA**, central San Andres Mountains. Well control: **1**, Sunray Mid-Continent New Mexico Federal No. 1; **2**, Sun Victorio Land and Cattle No. 1; **3**, Exxon No. 1 Beard Federal; **HSFS**, approximate east limit of Hot Springs fault system. Stratigraphic data are from Kottlowski (1963) except for in San Mateo Mountains (Furlow 1965) and northern San Andres Mountains–Mockingbird Gap area (Bachman 1968).

Unlike the zero isopachs for previously described units (Bliss, El Paso, Montoya, and Devonian strata), which were determined by bevelling beneath the basal Pennsylvanian section, the northern limit of the Fusselman was determined by pre-late Devonian erosion.

Discussion—All lower Paleozoic units discussed in the previous sections have relatively linear northeast to east-northeast-pinch-outs on the Jornada block, and all exhibit prominent, nearly right angle, dextral deflections of varying magnitudes in areas to the west. Several possibilities exist to explain these deflections, but Laramide dextral offset appears to be the most plausible alternative.

Because pinch-outs of lower Paleozoic units in south-central New Mexico are related to erosional bevelling beneath Pennsylvanian or Devonian strata, they cannot be solely the result of irregularities in original sedimentary onlap and thinning. Major tectonic offsets (strike-slip or dip-slip) during early Paleozoic time in south-central New Mexico are unlikely. This region was characterized during the early Paleozoic by deposition of gently southward-thickening sediments, which lack rapid lateral facies transitions, internal angular unconformities, and conglomerate that characterize syntectonic sediments. Most workers have described early Paleozoic deformation in south-central New Mexico as epeirogenic (Kelley and Silver 1952; Seager and Mack 2003).

Pennsylvanian sedimentation and the nature of the basal Pennsylvanian unconformity in southern New Mexico were certainly influenced by Ancestral Rocky Mountain orogenesis. The T or C area, however, was located on the relatively stable western shelf of the Orogrande Basin. Sedimentary thicknesses, clastic ratios, and sand-shale ratios are reasonably similar throughout the region adjoining the T or C area (Kottlowski 1960). Several areas near the Hot Springs fault system display evidence for significant local relief at the base of the Pennsylvanian section. In the Red Hills area 30 km south of Truth or Consequences, Pennsylvanian strata overlie the El Paso Group (Seager and Mack 2004). Approximately 5 km east of the Red Hills, across the Apache and Caballo faults, Pennsylvanian beds overlie Percha or Montoya strata, suggesting modest (100–150 m) depths of Middle Mississippian to Early Pennsylvanian erosion due to west-up faulting or flexure across these structures. North of the Cross fault in the Mud Springs Mountains, the Percha Shale and uppermost Montoya Group are cut out beneath basal Pennsylvanian strata, and the overlying Pennsylvanian Red House Formation is somewhat thinner there than across the fault to the south, giving a total stratigraphic thinning of ~100 m (Maxwell and Oakman 1986, 1990). In the Mud Springs Mountains, however, it is not clear if these differing stratigraphies resulted from Pennsylvanian deformation or subsequent Laramide strike-slip juxtaposition, or both. Although we acknowledge the possibility of Pennsylvanian dip-slip or strike-slip tectonism in the T or C area, we feel that such tectonism was modest at best, as shown by lack of rapid lateral facies transitions, scarcity of conglomerate, and lack of intraformational angular unconformities in Pennsylvanian strata. For these same reasons we question the conclusions of Furlow (1965), who interpreted the dextral deflection of Cambrian–Ordovician pinch-outs east of the San Mateo Mountains to be the result of Late Mississippian to Early Pennsylvanian arching and erosion in the Caballo–Fra Cristobal area. The arching hypothesis also cannot explain why a similar magnitude of dextral deflection exists between the Caballo Mountains and the Sierra Cuchillo for the pinch-outs of both the Fusselman Dolomite and Devonian strata. Of these two, only the Devonian pinch-out is determined by the basal Pennsylvanian unconformity.

Crustal deformation in the T or C area was much more profound during the Laramide orogeny than during the earlier Ancestral Rocky Mountain event. Local relief associated with Eocene paleocanyons in the region was at least 1 km (Seager et al. 1997), and exposure of Precambrian rocks during this time indicates at least 4 km of structural relief between basins and uplifts. Because late Paleozoic deformation was relatively mild in the T or C area, we infer that most or all of the dextral displacement of stratigraphic and structural features described in this report is of Laramide origin. We note that the involvement in strike-slip deformation of rocks as young as Upper Cretaceous near Truth or Consequences, and as young as Eocene near Chloride, is compatible only with Laramide deformation.

Woodward et al. (1997) invoked several of the lower Paleozoic isopach maps of Kottlowski (1963) as an argument against major Laramide strike-slip along the eastern Colorado Plateau boundary. Woodward et al. (1997) did not, however, utilize the data of Furlow (1965) or Bachman (1968) in their analysis, nor did they specifically analyze the many dextral deflections associated with the Hot Springs trend on Kottlowski's maps. Woodward et al. (1997) also cited the distribution of oolitic hematite facies in the Bliss Sandstone (Kottlowski 1963, fig. 3) as evidence against major Laramide strike-slip. This aspect of Kottlowski's map, however, was derived from the earlier work of Kelley (1951), whose compilation failed to encompass occurrences of Bliss hematitic oolites in the Fra Cristobal Mountains (McCleary 1960), San Mateo Mountains (Furlow 1965), and in the Mud Springs Mountains (Hill 1956; Maxwell and Oakman 1990). Interestingly, in a later paper Woodward et al. (1999) argued for 125 km of Ancestral Rocky Mountains dextral offset on north-striking faults in central New Mexico, despite their earlier statements that lower Paleozoic isopach patterns prohibit such subsequent offsets.

West of the Jornada block, the magnitude of individual pinch-out deflections increases with increased spacing between control points (Fig. 7). The geographically closest juxtaposition of pinch-out control points brackets the Hot Springs fault system between the Caballo and Mud Springs ranges, where the maximum Fusselman deflection and the minimum Devonian deflection converge at about 26 km, a value that is in accord with our estimation of offsets of structural features and regional geophysical anomalies. The next most closely constrained deflection is the Bliss–El Paso–Montoya pinch-out trends between the Fra Cristobal and San Mateo ranges. These right-angle, approximately 35-km deflections encompass the Engle Basin, which includes the Hot Springs fault system in its eastern part. The broadly constrained 60-km deflection of the Fusselman and Devonian pinch-outs across the Palomas Basin also includes the Hot Springs fault system in its eastern part.

The origin of the additional dextral pinch-out deflections beyond the 26-km value that we attribute to the Hot Springs fault system is unknown. Very little is known about the subsurface geology of the Engle and Palomas Basins; it is possible that additional Laramide faults lie buried beneath them. Although the existence of buried Laramide strike-slip faults beneath these basins is entirely speculative, we note that the net dextral deflections of lower Paleozoic pinch-outs across the Engle (35 km) and Palomas (60 km) Basins are comparable with the maximum allowable offsets of Mesozoic piercing lines in the Albuquerque Basin to the north (40–60 km; Cather 1999).

The Hot Springs fault system north of the Truth or Consequences area

Segments of the Hot Springs fault system are exposed northward in the Cutter sag–Fra Cristobal Range area (Fig. 2). The Cutter sag is a northwest-trending structural depression that separates the northern Caballo Mountains from the Fra Cristobal Range (Fig. 2). Amid numerous normal faults related to the late Tertiary Rio Grande rift, Bushnell (1953) and Thompson (1955, 1961) were the first to recognize right-lateral, strike-slip kinematic indicators along segments of the HSWC fault in the Cutter sag area. Bushnell (1953) mapped both right- and left-lateral offsets on faults east of and parallel to the HSWC fault. In addition to numerous right-lateral drag folds, Thompson (1961) described closely spaced, northwest-trending en echelon synclines and anticlines adjacent to the HSWC fault. These en echelon folds are interpreted as kinematic indications of right slip on the HSWC fault (see Fig. 4c). Lozinsky (1986) also noted drag folds indicative of right-lateral slip along the HSWC fault in the Cutter sag area.

East of the HSWC fault in the Cutter sag, Bushnell (1953) estimated the McRae Formation (Upper Cretaceous–(?)lower Tertiary) to be approximately 1,000 m thick. Lozinsky (1986) estimated a more conservative thickness of approximately 500 m. Immediately west of the HSWC fault, subsurface drill data indicate that the McRae is generally absent and only locally attains a thickness of 27 m (Lozinsky 1987). It has been suggested that this is possibly the result of pre-Santa Fe Group uplift and erosion (Lozinsky 1987). An alternate explanation is that Cutter sag is a syntectonic basin that formed in response to curvature along the HSWC fault. In this interpretation, the HSWC fault forms the western boundary of Cutter sag, and the thinness of the McRae Formation on the west side of the fault is due to diminished subsidence during deposition. This idea is supported by the gravity model of Gilmer et al. (1986) that shows the HSWC fault as the western boundary fault to Cutter sag with approximately 1 km of McRae fill east of the fault. An analogy is the Ridge Basin that developed along the San Andreas fault system during the Miocene and Pliocene (Crowell 1974). Figure 8 is a block diagram from Mitchell and Reading (1986) that illustrates the tectonic setting of such a basin.

The Fra Cristobal Range contains some of the most complexly deformed rocks found in southern New Mexico. The many detailed geologic maps that cover parts or all of the range have given rise to varied structural interpretations

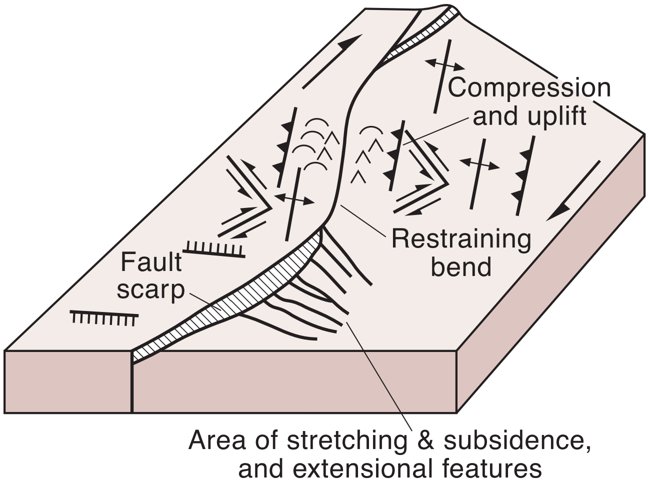

FIGURE 8—Block diagram illustrating the relationship between curvature of a strike-slip fault and closely adjacent extensional basin and uplift, with superimposed tectonic pattern (after fig. 14.48 in Mitchell and Reading 1986). Compare with geologic map of Figure 2; areas of compression and uplift correspond to restraining bend area in southern Fra Cristobal Range and area of subsidence and extension corresponds to Cutter sag.

(Cserna 1956; Jacobs 1956; McCleary 1960; Thompson 1961; Warren 1978; Van Allen et al. 1983; Lozinsky 1986; Hunter 1986; Chapin 1986; Foulk 1991). A combination of compressional "thick-skinned" basement-involved Laramide deformation and "thin-skinned" Laramide deformation (Chapin and Nelson 1986; Nelson and Hunter 1986; Foulk 1991; Nelson 1993) over-printed by normal faulting related to development of the Rio Grande rift have contributed to the structural complexity of the area. An additional contributing factor to the structural complexity of this area may have been the role of strike-slip faulting along the HSWC fault.

Many geologists have noted that the HSWC fault bends to a northerly strike and bifurcates adjacent to the southern Fra Cristobal Range where it becomes the western boundary fault of the range (Kelley and Silver 1952; Thompson 1961; Warren 1978; Van Allen et al. 1983; Lozinsky 1986). In a right-lateral strike-slip regime such a bend is restraining, and in the southern Fra Cristobals produced an area of transpression characterized by imbricate, décollement-style thrusting and folding. Nelson and Hunter (1986) and Nelson (1993) described this style of deformation as thin-skinned Laramide deformation in the area where the HSWC fault bends. Fold hinges and axial planes in this area provide a shortening direction and are dominantly northwest-southeast to north-south in the area (Nelson and Hunter 1986; Nelson 1993). Nelson (1993) postulated that thrusting propagated from the west. The thin-skinned thrust faulting has been recognized across the entire east-west extent of the southern Fra Cristobal Range, a distance of more than 4 km, and involves strata as young as Late Cretaceous (Foulk 1991; Nelson 1993). Geologic mapping by Foulk (1991) along the eastern margin of the southern Fra Cristobal Range suggests the possibility that the entire range is underlain by low-angle thrust faults.

While acknowledging that a restraining bend on a strike-slip fault could not be ruled out as responsible for the observed thin-skinned thrusting in the southern Fra Cristobal Range as suggested by Harrison and Chapin (1990), Nelson (1993) related the thrusting to a hypothetical basement-cored fold to the west, now buried beneath the Rio Grande rift. Such a basement-cored fold (thick-skinned deformation) is observed north of the thin-skinned thrusting (Kelley and Silver 1952; Jacobs 1956; McCleary 1960; Van Allen et al. 1983; Chapin and Nelson 1986; Nelson 1993), however, no thin-skinned thrusting has been recognized east of this basement-cored fold (Jacobs 1956; McCleary 1960; Van Allen et al. 1983; Chapin and Nelson 1986; Nelson 1993).

The HSWC fault, as stated earlier, bends northward and becomes the range's western boundary fault, known as the Walnut Canyon (or West Vein) fault, which was reactivated by Rio Grande rifting. The Walnut Canyon fault is strongly mineralized in most places and only displays characteristics of its late Cenozoic reactivation as a normal fault. In the arroyo at the mouth of Hackberry Canyon (HC in Fig. 2), however, in the hanging wall (west side) of the Walnut Canyon fault, pebble conglomerates of the Upper Cretaceous Ash Canyon Member of the Crevasse Canyon Formation are exposed. The exposures are limited to about 100 m along arroyo walls and to an approximate height of 5–6 m. There, the Ash Canyon strata are overlain unconformably by Santa Fe Group sediments. Depicted in the geologic mapping of Warren (1978), these exposures are adjacent to the area of thin-skinned thrusting. Many steeply dipping shear surfaces with well-developed sub-horizontal slickenside striations occur in the Ash Canyon beds; these faults do not cut the Santa Fe Group. The shear surfaces form two conjugate sets: a dominant north-northeast-striking set containing kinematic indicators of dextral slip, and a lesser east-northeast- to east-west-striking set containing sinistral kinematic indicators (Fig. 4d). We interpret these faults to be part of the Laramide Hot Springs system that has not been substantially re-activated by Rio Grande rifting.

Additional evidence for strike-slip faulting is present along the Massacre Gap fault on the east side of the Fra Cristobal Range (see Fig. 2). Adjacent to this fault, a roughly east-west striking thrust fault dips 28° to the south. The fault surface is striated and kinematic indicators show top-toward N30E motion. This is consistent with right-lateral strike slip along the Massacre Gap fault, which we consider to be a branch of the Hot Springs fault system (see Fig. 2).

Curvatures in strike-slip fault systems can produce closely adjacent basins and uplifts with characteristic superimposed tectonic patterns (for examples see: Kingma 1958; Wilcox et al. 1973; Crowell 1974, 1982; Reading 1980; Sylvester 1988). The southern Fra Cristobal Range–Cutter sag area contains such features that are consonant with a restraining bend along a major right-lateral strike-slip fault system. The bend along the HSWC fault corresponds to the area of compression and uplift on the right side of the fault on the diagram. The similar area of uplift and shortening on the west side of the fault has been structurally inverted and now lies buried beneath Santa Fe Group sediments. The Cutter sag corresponds to an area of stretching and subsidence. Thompson (1961) mapped and described numerous northwest-striking normal faults in the western and northern part of Cutter sag that cannot be shown on the scale of Figure 2. These normal faults are associated with asymmetrical folding in beds of the McRae Formation and are cut by northeast-striking normal faults related to Rio Grande rifting (Thompson 1961). We interpret that these northwest-striking faults in the Cutter sag correspond to the extensional features illustrated in Figure 8 in the area of stretching and subsidence. The strike-slip fault illustrated on the diagram is the boundary of the area of stretching and thinning, and shows substantial structural relief over a very short distance. These relationships are similar to those along the HSWC fault and may explain Lozinsky's (1986) observed rapid thinning of the McRae Formation across the structure, as well as the gravity modelling by Gilmer et al. (1986) across the Hot Springs fault.

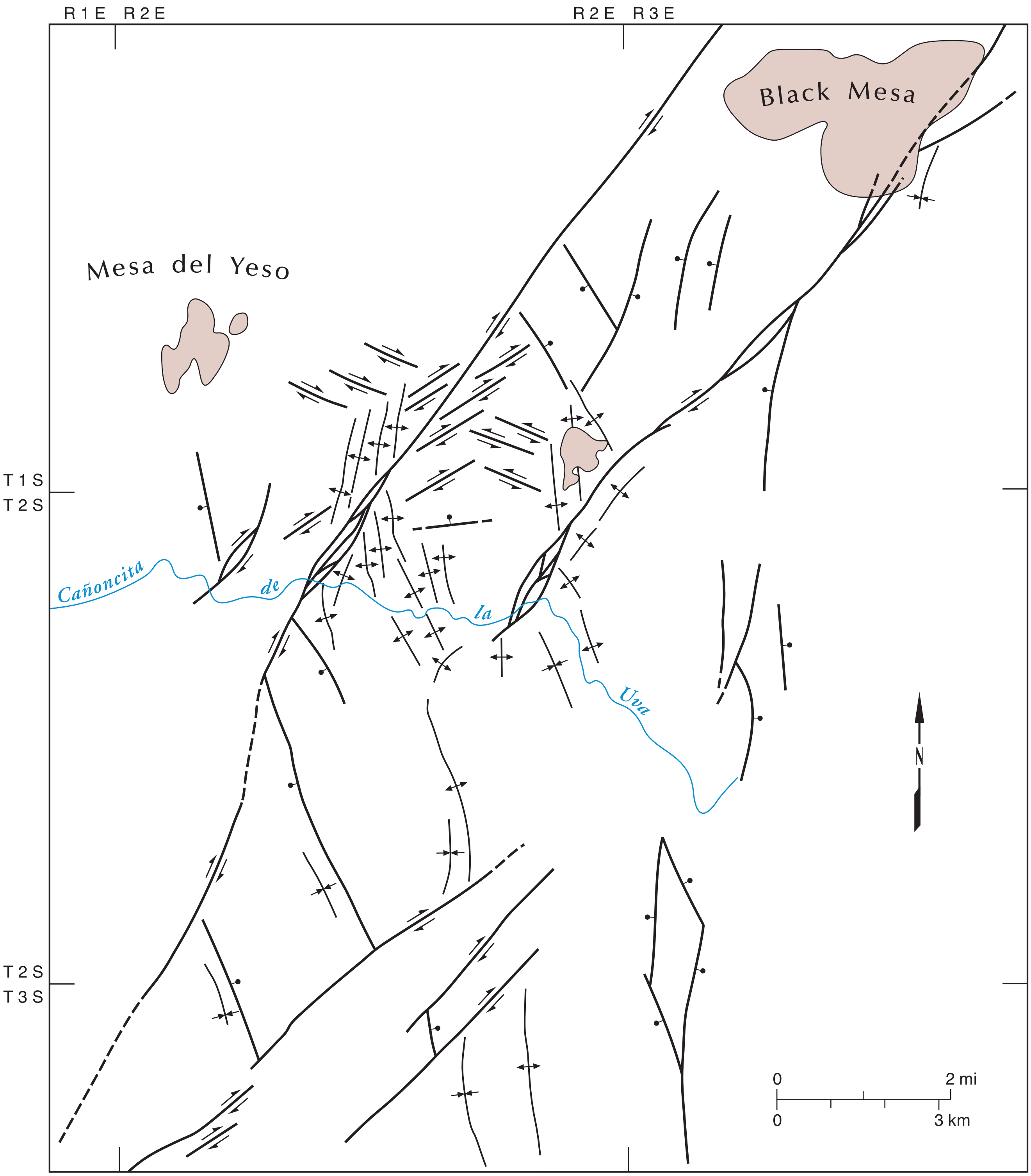

FIGURE 9—Structural map of the Cañoncita de la Uva area, northeast of Socorro showing features related to the Montosa–Paloma fault system (after Colpitts 1986; Brown 1987; and Cabezas 1989). Bar and ball symbols on downthrown side of normal faults, double barred arrows indicate anticlines and synclines, single barred arrows indicate relative motion of strike-slip faults.

To the north, geologic mapping in the area northeast of Socorro (Fig. 9; Colpitts 1986; Brown 1987; Cabezas 1989; Beck 1993; Behr 1999) has documented several north-northeast-striking, dextral oblique faults. These include the Montosa–Paloma, East Joyita, and Cañoncita de la Uva faults. Associated en echelon folds, synthetic Reidel faults, antithetic conjugate Reidel faults, and thrust faults are consistent with dextral shearing. We interpret this fault zone as a northward continuation of the Hot Springs fault zone, as did Chapin (1983a,b).

Discussion

Although interpretable in other ways when considered separately, we feel that the collective structural, stratigraphic, and geophysical discontinuities along the Hot Springs fault system are most reasonably interpreted to be the result of

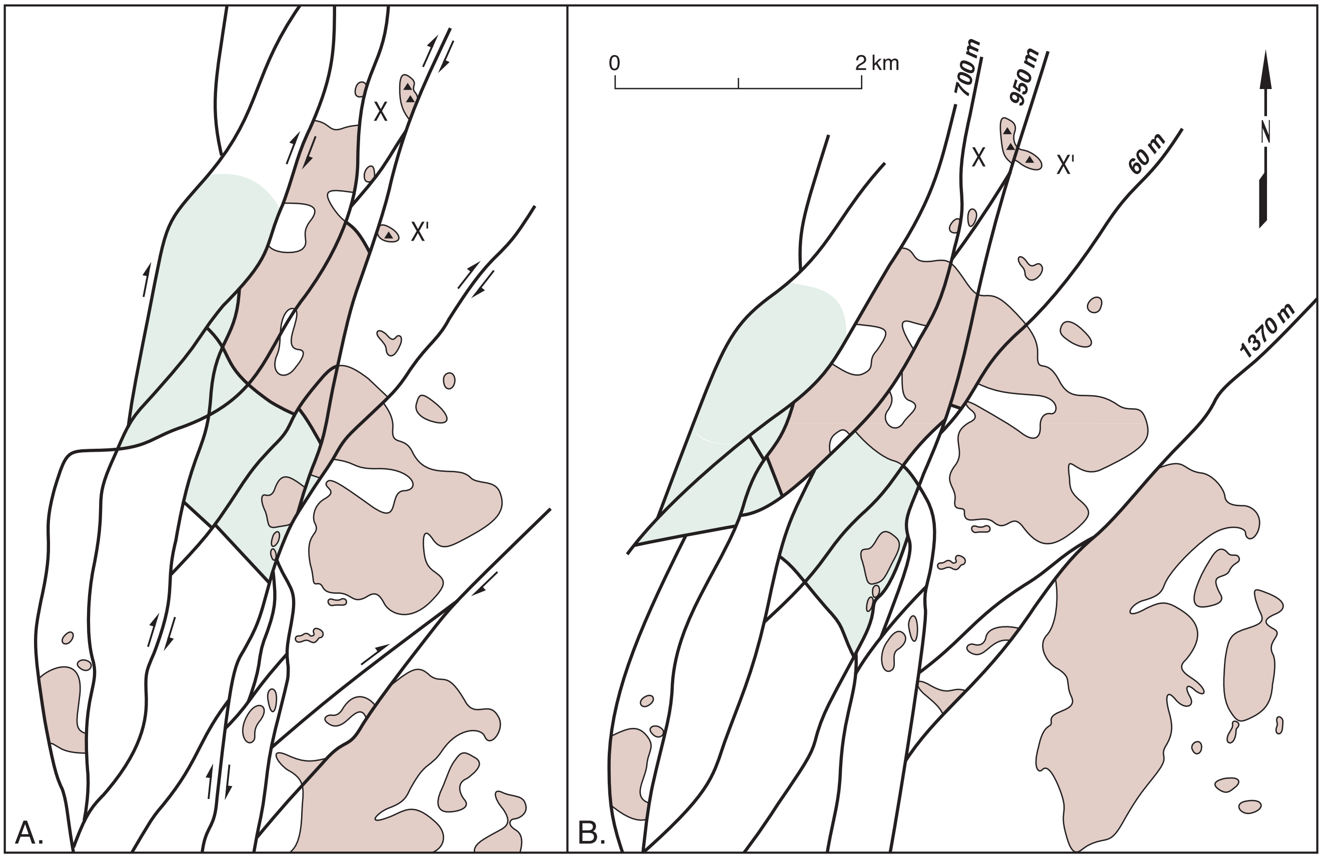

FIGURE 10—Chloride strike-slip fault system in the Black Range, New Mexico (after Harrison 1989a,b); see Figure 6 for location relative to the Hot Springs fault system. Light Brown areas are outcrops of allochthonous blocks of Pennsylvanian Madera Formation within the volcaniclastic Eocene Rubio Peak Formation, green areas are buried allochthonous blocks known from drilling and mine exposures. **A**. Present day map view. **X** and **X′** mark outcrops of distinctive limestone breccia used as piercing points for strike-slip restoration. **B**. Plan view after restoration. When outcrops at **X** and **X′** are juxtaposed, margins of larger limestone blocks are also realigned. Total right-lateral strike slip indicated is approximately 3.1 km.

approximately 26 km of right-lateral strike slip during the Laramide orogeny. The HSWC is the easternmost, and most significant, fault of a north-northeast-trending, right-lateral strike-slip system that is more than 60 km wide in south-central New Mexico (Chapin 1983a,b; Harrison 1989a). Two other structural zones of this system are located in the Black Range, the Chloride strike-slip zone and Santa Rita–Hanover axis (Fig. 6). Other possible strike-slip fault zones are located in the Sierra Cuchillo and Animas uplifts between the Hot Springs and Chloride zones (Harrison 1989a), and additional strike-slip faults may be buried beneath the Palomas and Engle Basins.

Based on multiple piercing points, the Chloride strike-slip zone (Harrison, 1989a,b) exhibits approximately 3.1 km of right-lateral strike slip (Fig. 10). An $^{40}Ar/^{39}Ar$ age (mean of plateau ages) of 34.9 ± 0.04 Ma (McIntosh 1989; McIntosh et al. 1992) for the oldest unfaulted ash-flow tuff (tuff of Rocque Ramos Canyon of Harrison [1990]) that buries the strike-slip faults provides the oldest constraint on the end of faulting. Also, vertebrate fossil data indicate that the oldest unfaulted volcaniclastic strata are Duchesnean (latest Eocene) to early Chadronian (early Oligocene) in age (Lucas 1983, 1986).

The Santa Rita–Hanover axis is a structural zone 1.5–3.0 km in width that extends for over 50 km in a north-northeast direction (Aldrich 1976), parallel to the Hot Springs fault system. The axis was a structural high during the Late Cretaceous and early Tertiary Laramide orogeny (Elston et al. 1970; Aldrich 1972). Faults along the axis contain horizontal striations and mullions (Jones et al. 1967). Northeast-striking normal faults that join the axis at an acute angle contain dikes of Late Cretaceous and early Tertiary age (Jones et al. 1967; Aldrich 1972). These data are consistent with right-lateral strike-slip faulting along the Santa Rita–Hanover axis (see Fig. 4c). Harrison (1989a, 1998) hypothesized that during the Eocene, gigantic gravity slide blocks of Pennsylvanian limestone present in the Black Range were shed from the structural high along the Santa Rita-Hanover axis into a developing pull-apart graben.

Geologic relationships in southern New Mexico suggest that the Laramide orogeny was a two-stage event and that maximum horizontal paleostress directions rotated counterclockwise from a general easterly direction to a northeasterly direction. This rotation, however, may have occurred earlier (late Campanian?) in southern New Mexico than the late Paleocene to earliest Eocene rotation documented in northern New Mexico and Colorado (Chapin and Cather 1981; Chapin 1983a; Erslev 1999).

Assuming that large fault-propagation folds form nearly perpendicular to the maximum horizontal stress direction, then the north-south to north-northwest-trending fault-propagation fold in the northern Caballo Mountains (Figs. 2, 3) indicates an east to east-northeast paleostress direction. This is supported by the dominant north to north-northwest strikes of axial surfaces of smaller folds in the northern Caballo Mountains (Fig. 4f). A southerly source for the Ash Canyon Member of the Crevasse Canyon Formation in the Cutter sag records Laramide uplift of the ancestral Caballo

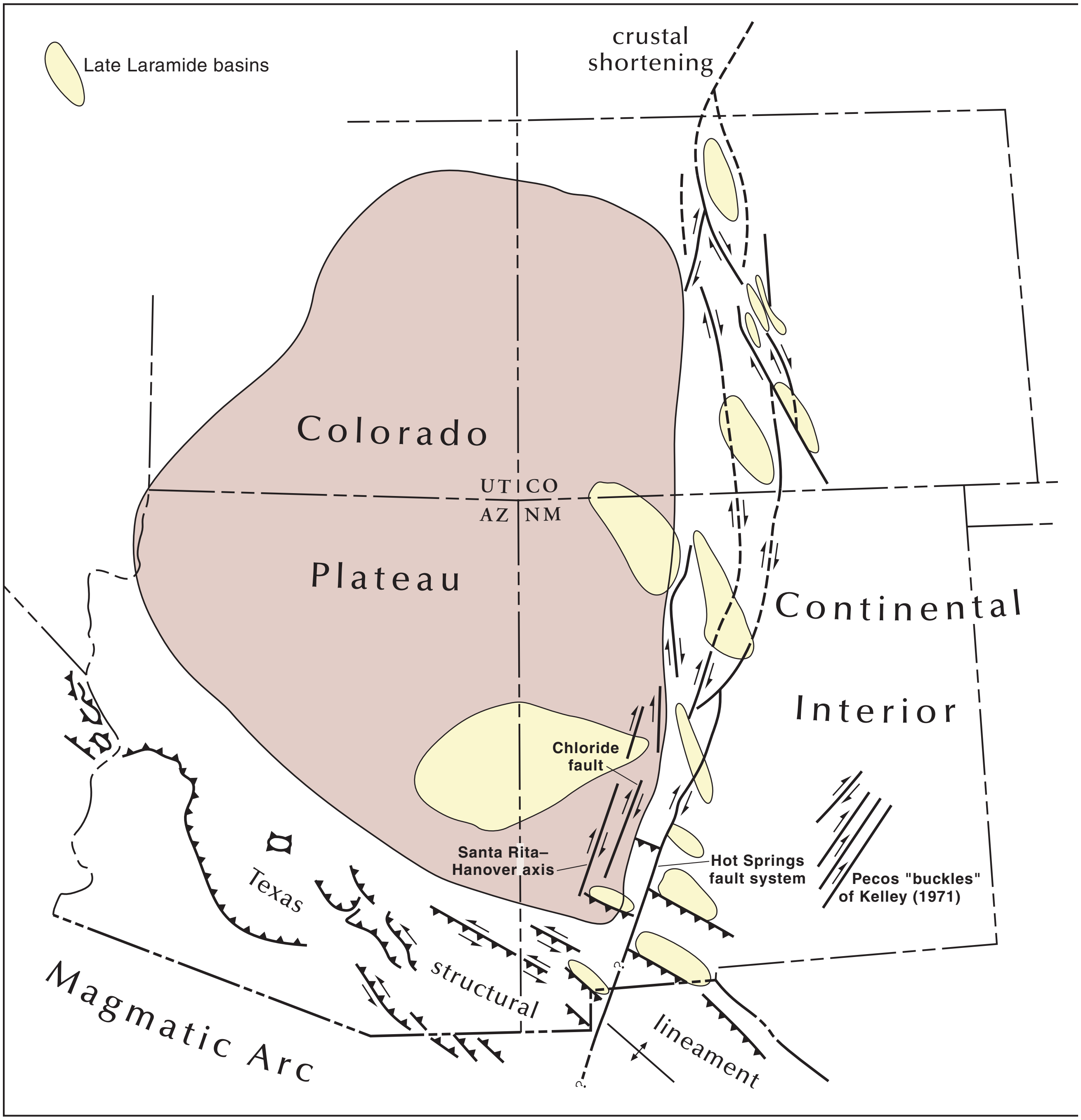

FIGURE 11—Laramide tectonic map of part of the southwestern United States showing the relationship of the Hot Springs fault zone to other tectonic features and demonstrating its role in accommodating the northward translation of the Colorado Plateau (adapted and modified from Davis 1979; Chapin and Cather 1981; Drewes 1980, 1981; Chapin 1983a; Seager and Mack 1986). Note that both compression and left-lateral strike slip occurred in elements of the Texas structural lineament in southwestern New Mexico and southern Arizona, in good agreement with the right-lateral system along the eastern margin of the Colorado Plateau.

Mountains (Hunter 1986) and thus suggests that east to east-northeast shortening was occurring between late Coniacian to early Maastrichtian (88–66 Ma; approximate bracketing ages of Ash Canyon Member [Cather 1991]). This is consistent with an early Laramide greatest principal stress direction of east-northeast, as has been determined elsewhere in the southwestern United States (Rehrig and Heidrick 1976; Heidrick and Titley 1982).

The earliest indication of a northeast-oriented maximum horizontal stress direction is from the emplacement of the late Campanian Copper Flats quartz monzonite stock (CF in Fig. 6), located ~ 32 km southwest of Truth or Consequences and dated by K-Ar at 73.4 ± 2.5 Ma (Hedlund 1974, 1975) and by $^{40}Ar/^{39}Ar$ at 74.93 ± 0.66 Ma (McLemore et al. 1999). Extensional fractures and faults that are synplutonic at Copper Flat show a dominant N34°E orientation (Dunn 1982, 1984) and are interpreted to have formed parallel to the axis of compression (see Fig. 4c). In addition, northeast-striking faults along the Santa Rita–Hanover axis were dilated and intruded by Late Cretaceous dikes (Jones et al. 1967; Aldrich 1972).

The record provided by the syntectonic McRae Formation that was deposited in Cutter sag also indicates that this basin was forming during the Late Cretaceous (Hunter

1986). A late Maastrichtian age is indicated from dinosaur fossils recovered from the lower beds of the McRae Formation (Wolberg et al. 1986; Gillette et al. 1986). If the Cutter sag formed as a result of curvature along the Hot Springs fault zone as we postulate, then strike-slip faulting was initiated in the Late Cretaceous and is consistent with a northeast-directed maximum horizontal stress. The numerous northwest-striking thrust faults and folds in southern New Mexico (see Fig. 6) were most active in the Paleocene to early Eocene (Seager and Mack 1986) and formed under northeast-southwest compression (Chapin and Cather 1981; Heidrick and Titley 1983; Seager and Mack 1986).

As noted by Chapin and Cather (1981), when the Laramide maximum horizontal stress direction rotated counterclockwise to a northeast direction, the orientation of the north-northeast structural fabric in the New Mexico portion of the Southern Rocky Mountains became more favorable for strike-slip reactivation. In southern New Mexico, this rotation may have occurred in Late Cretaceous time (late Campanian?) and coincided with initiation of right-lateral strike-slip faulting along the Hot Springs fault system as indicted by the stratigraphic record in Cutter sag. As discussed previously, cessation is documented to have occurred along the Chloride strike-slip zone by about 34.9 Ma, which serves as a good estimate for the termination of faulting as virtually the entire Eocene intermediate volcanic and volcaniclastic section below the dated unit in the Chloride area is cut by strike-slip faults. An important conclusion derived by Seager and Mack (1986) from their petrofacies analyses of orogenic sediments shed from Laramide uplifts in the Florida Mountains and Cooke's Range (see Fig. 6 for locations) is that deformation along those northwest-trending contractile structures had ceased by the time middle Eocene intermediate volcanism commenced. From the temporal observations in the Chloride area, it must then be concluded that at least some strike-slip faulting along the north-northeast system persisted longer than these other Laramide-age tectonic features. Unfortunately, the timing of cessation of dextral deformation along the Hot Springs fault system is poorly constrained, as critical age relationships are lacking.

What becomes of the Hot Springs fault system to the south of Deming in southern New Mexico is speculative. As indicated earlier, offsets of geophysical and structural features upon which we have based our interpretations appear to diminish in northernmost Chihuahua to perhaps half of the magnitude in the T or C area. Differential crustal shortening on northwest-trending compressional features of the Texas structural lineament (Fig. 11) are the most likely explanation for the discrepancy. Significant strike-slip deformation along the Hot Springs trend may have persisted all the way to the Laramide subduction zone along the southwestern margin of the North American plate.

Summary

The Hot Springs fault system in southern New Mexico is part of an extensive dextral slip system that was active along the eastern margin of the Colorado Plateau during the Laramide orogeny (Fig. 11). Structural relationships in the T or C area document significant amounts of lateral movement on the Hot Springs fault system. The geology of the southern Fra Cristobal Range and Cutter sag area contains features plausibly produced by curvature along a strike-slip fault. The McRae Formation in the Cutter sag is interpreted as a syntectonic deposit that records subsidence at this transpressive bend. Structural, stratigraphic, and geophysical evidence indicate that approximately 26 km of right-lateral slip occurred along the Hot Springs fault system, most or all of which occurred in Late Cretaceous through Eocene time.

Acknowledgments

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