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Tectonics of the Chupadera Mesa region, central New Mexico

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TECTONICS OF THE CHUPADERA MESA REGION, CENTRAL NEW MEXICO

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Abstract—The Chupadera Mesa region contains structures related to the Ancestral Rocky Mountain orogeny, the Laramide orogeny, late Eocene–Oligocene magmatism, and the Rio Grande rift. Major faults generally strike north, ranging from north-northwest to north-northeast. These include (from west to east) the Hot Springs, Hubbell Springs, and Montosa faults (probable Laramide dextral-oblique reverse faults, the first two of which were reactivated as normal faults during rifting), an unnamed major arcuate normal fault and the Oscura fault, both of which separate the Neogene Trinity Basin (new name) from its footwall uplift in the Oscura Mountains, the Chupadera fault (a probable southward extension of the Picuris–Pecos strike-slip fault of northern New Mexico), and buried faults that bound the western margin of the late Paleozoic Pedernal uplift.

Large north-trending folds include the Prairie Spring anticline, the Torres syncline, the Chupadera anticline, and the Carrizozo anticline. The Prairie Spring, Chupadera, and Carrizozo anticlines owe much of their structural relief to intraformational tectonic thickening of the Yeso Formation, which caused broad arching of overlying strata. This thickening may result from contractile deformation where thrust-sense detachment faults within Permian gypsum and halite beds ramped up-section. It is possible that contractional ramps beneath these anticlines were linked kinematically to extensional, top-east detachment faults exposed east of the Socorro Basin, but this linkage has not been demonstrated. More speculatively, much of the western part of the study area may be allochthonous, with a few kilometers of top-east slip on Permian evaporite successions. Detachment faulting was polygenetic and may have been driven by: (1) gravity-driven gliding during rise of the Laramide Sierra uplift or footwall uplifts of the Rio Grande rift; (2) tectonic end-loading by crustal contraction in the Sierra uplift; or possibly (3) late Eocene–Oligocene volcanism, which (a) caused loading of allochthons by extensive volcanic fields, and (b) increased geothermal gradients that may have weakened potential detachment horizons by dewatering and volume changes during the gypsum–anhydrite transition.

Intrusion of stocks and laccoliths of the Lincoln County porphyry belt caused doming of adjacent strata, and lateral intrusion of mafic dikes into the Yeso Formation caused the development of narrow anticlines in overlying beds. These dike-related anticlines can often be traced for tens of kilometers. Dikes exposed in anticlines are typically tens of meters wide and generally do not cut strata above or below the Yeso Formation. The Oligocene Jones Camp dike may be confined to the Yeso Formation, and thus does not necessarily mark a basement fracture zone in the western part of the Capitan lineament as has been previously suggested. The Capitan lineament, which is marked by an east-trending zone of Cenozoic magmatism and late Paleozoic uplifts in eastern New Mexico and Texas, may terminate westward at the Chupadera fault.

INTRODUCTION

The Chupadera Mesa region of central New Mexico encompasses the area from the east shoulder of the Socorro Basin of the Rio Grande rift eastward to the Lincoln County porphyry belt, and includes the northern Jornada del Muerto, Chupadera Mesa, and the Claunch sag. This vast region (~6500 km^2) exposes rocks ranging in age from Proterozoic to Quaternary, and preserves aspects of most major Phanerozoic episodes of tectonism and magmatism that have affected southwestern North America. The area has received little detailed study, particularly in its southern part within the White Sands Missile Range. Previous work in the Chupadera Mesa region includes mapping and stratigraphic studies (Darton, 1928; Thompson, 1942; Bates et al., 1947; Wilpolt et al., 1946; Wilpolt and Wanek, 1951; Smith and Budding, 1959: Smith, 1964; Weber, 1964; Bachman, 1968), subsurface studies (Hawley, 1986; Broadhead and Jones, 2004) and a regional tectonic overview (Kelley and Thompson, 1964). The present report is of a reconnaissance nature. Because detailed mapping and subsurface data are limited, some interpretations presented herein are speculative and are intended to provide testable hypotheses for future studies.

MAJOR FAULTS

The principal faults in the western part of the study area are the Hot Springs, Montosa, and Hubble Springs faults (Fig. 1). All strike north-northeast and dip steeply west. The Hot Springs and Montosa faults were dextral-oblique reverse faults during the Laramide orogeny (Harrison and Chapin, 1990; Cather and Harrison, 2002; Harrison and Cather, 2004; Cather, 1992; Behr, 1999). The Laramide history of the Hubbell Spring fault is unknown, but may be similar to that of the nearby Montosa fault, to which it is subparallel for ~60 km. Lower Paleozoic isopachs near Truth or Consequences are offset dextrally ~26 km by the Hot Springs fault, mostly during the Laramide (Harrison and Chapin, 1990; Cather and Harrison, 2002). Most of this dextral slip appears to have been transferred to the Nacimiento fault to the north, beneath what is now the Socorro and southern Albuquerque basins of the rift (Cather, 2004). A small component (perhaps 5 km or less; Cather et al., 2006) of the dextral slip on the Hot Springs fault was transferred to the Montosa fault and (possibly) the Hubbell Springs fault. The major sinistral step between the Hot Springs fault and the Montosa and Hubbell Springs faults, in what is now the Socorro Basin of the rift (Fig. 1), constituted a restraining bend in this dextral system. Contractile deformation related to this restraining bend may provide a kinematic explanation for the existence of a Laramide highland (the Sierra uplift; Cather, 1983; Cather, 2009, this guidebook) that exposed large areas of Proterozoic granitic gneiss before it was structurally inverted to form the Socorro Basin during late Cenozoic extension. The Hot Springs and Hubbell Springs faults were reactivated as major west-down normal faults during opening of the Rio Grande rift.

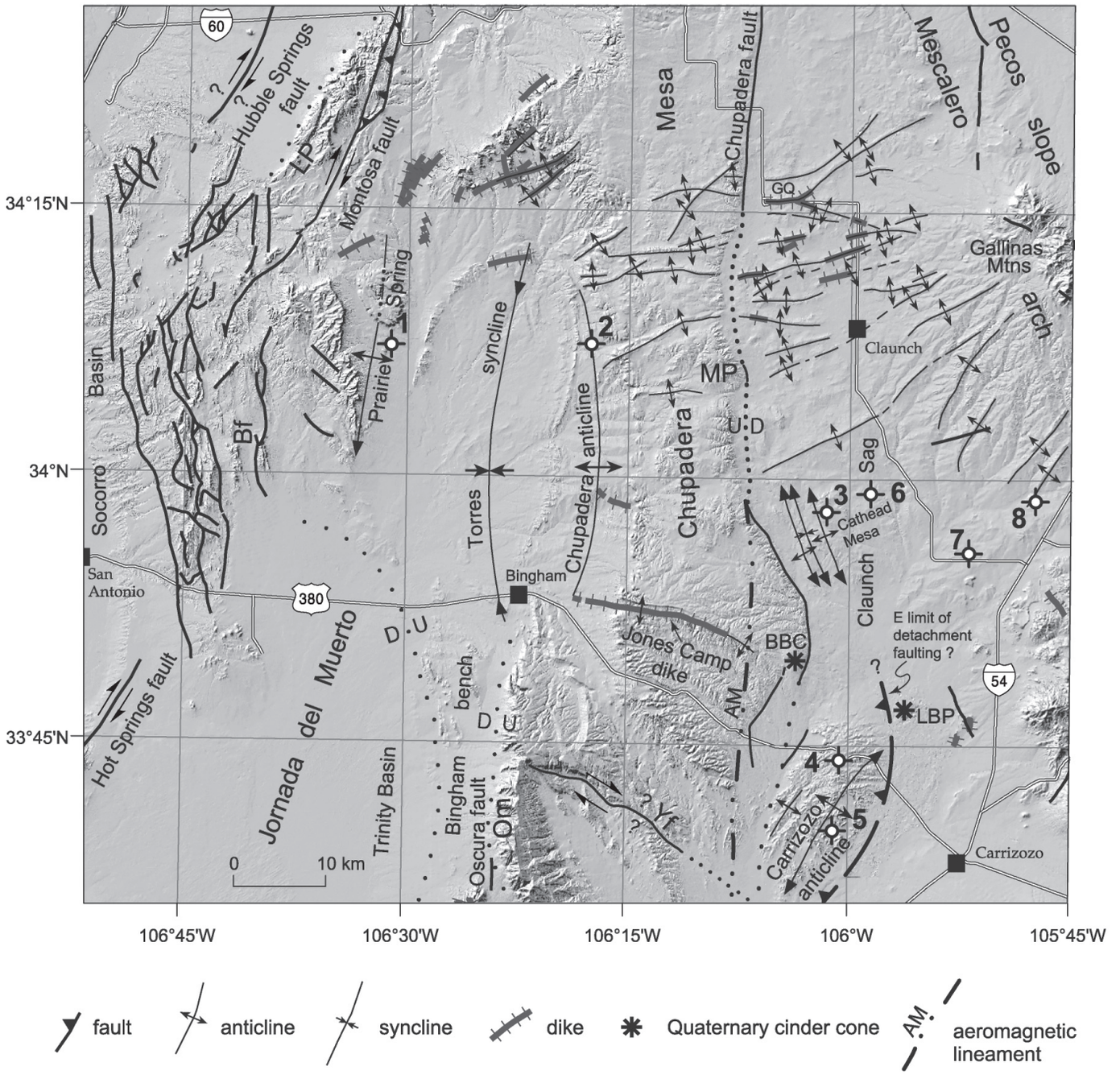


FIGURE 1. Digital elevation model of the Chupadera Mesa region showing selected faults, folds, dikes, cinder cones, petroleum exploration wells, and aeromagnetic lineaments. Abbreviations are Bf, Bustos fault, LP, Los Pinos Mountains; MP, Monte Prieto; GQ, Gran Quivira; BBC, Broken Back Crater; LBP, Little Black Peak; OM, Oscura Mountains, Yf, Yates fault. Wells are (1) Skelly Oil Company No. 1 Goddard, (2) Yates Petroleum Corporation No. 1 McCaw, (3) Manzano No. 1 Cathead Mesa, (4) Standard Oil Co. of Texas No. 1 J.F. Heard-Federal, (5) Texaco No. 1D Federal (USA), (6) Primero No. 1 Dulce Draw State, (7) Primero No. 1 Jackson Ranch Federal, and (8) Manzano No. 1 Spaid Buckle wells..

An asymmetrical, ~30 mgal gravity anomaly in the northern Jornada del Muerto (Plate 3) represents the low-density fill of a late Cenozoic rift basin, herein termed the Trinity Basin (Fig. 1). The sense of asymmetry suggests it is an east-tilted half graben. Healey et al. (1978) calculated the maximum thickness of basin fill to be ~3 km, assuming a 0.4 g/cm^3 density contrast between basin fill and the underlying Paleozoic and Proterozoic basement. Because it is in an area that is internally drained, the fill of the Trinity Basin is unexposed due to lack of incisement. Deposits of a Quaternary closed lake in the southern part of the gravity low (Lake Trinity of Neal et al., 1983, and Hawley, 1993) have been documented by borehole penetrations. These lacustrine deposits are at least 40 m thick and consist largely of bedded gypsum. The Trinity Basin is bounded on the east by a major arcuate fault that

is mostly buried by alluvium and eolian sand, but in places is marked by surficial lineaments visible on satellite imagery.

The Trinity Basin is separated from the Oscura Mountains by a structural bench (herein termed the Bingham bench) on which Pennsylvanian and Permian strata are exposed (Plate 2). The Bingham bench and the Oscura Mountains constitute part of the footwall uplift of the Trinity Basin. The Bingham bench is analogous to the Hubbell bench of the southern Albuquerque Basin that intervenes between the deep basin and the Manzano and Los Pinos mountains (e.g., Connell, 2004). The Bingham bench is separated from the Oscura Mountains by the Oscura fault, which exhibits a maximum of ~2 km of west-down stratigraphic separation (Bachman, 1968). Stratigraphic separation on the Oscura fault decreases to the north and dies out near Bingham.

The Chupadera fault strikes north through the central part of the study area. It forms the west-up structural boundary between Chupadera Mesa and the Claunch sag (Kelley and Thompson, 1964). North and south of Monte Prieto, the trace of the Chupadera fault is obscured by Neogene alluvium that has accumulated in solution-collapse basins. Sinkholes resulting from the dissolution of Permian evaporites are common on Chupadera Mesa and the Claunch sag. They are thought to be the source of the term Chupadera (Spanish for sucker or absorbent). Throughout much of its length, the trace of Chupadera fault is marked by an east-dipping monocline as much as 0.8 km in width (Fig. 2). This monocline may be a fault-propagation fold related to west-up components of slip on the Chupadera fault. Because the fault is typically poorly exposed beneath alluvium at the toe of the monocline, the attitude of the fault has not been determined. Broad monoclines, however, are not typically associated with normal faults, thus the Chupadera fault may be a west-dipping fault with a reverse component of slip.

The Chupadera fault can be traced for at least 90 km, and may be part of a much larger fault system if probable links to faults to the north and the south are considered (Cather and Harrison, 2002; Cather et al., 2006). Despite its great length, stratigraphic separation on the fault is only ~110 m or less (Kelley and Thompson, 1964). Perhaps because of this modest separation (the fault juxtaposes different parts of the Permian San Andres Formation in most places), Bates et al. (1947) did not map it as a fault but as a topographic escarpment (the Monte Prieto scarp). Kelley and Thompson (1964) were the first to recognize the structural nature of this escarpment, and coined the term Chupadera fault. This term has been employed by some subsequent workers (Cather, 1991; Cather and Harrison, 2002; Cather et al., 2006), but others have used the term Monte Prieto–Liberty Hill structural zone (Hawley, 1986; Broadhead and Jones, 2004).

The trace of the Chupadera fault is notably linear except near Broken Back Crater where it curves ~8 km to the east. This curvature may be the result of Cenozoic top-east sliding of upper-plate strata along younger detachment faults in the evaporites of the Yeso Formation (see below). A north-trending aeromagnetic anomaly (Plate **4**; Fig. 1) suggests the Chupadera fault maintains its linear trend in the basement beneath the detachment. Tectonic thickening of the Yeso Formation in the Carrizozo anticline may mark the toe of the detachment (see below).



FIGURE 2. View to northwest across Aguila Canyon from 0402262E, 3749460N (NAD 1927) showing anticlinal crest of broad monocline ~800 m west of the trace of the Chupadera fault. Strata on monocline dip east (right) ~5–10°.

Where the Chupadera fault crosses the north edge of Chupadera Mesa ~13 km north of Gran Quivira, another top-east separation of the fault along detachments in the upper Yeso Formation may exist. The Chupadera fault can be traced northward to the base of the Glorieta Sandstone near Round Top Draw, but does not appear to cut the underlying Yeso Formation. About 4 km to the west, however, the lower-plate position of the fault in the Yeso Formation may be marked by the anomalously straight drainage of Chavez Draw. Unpublished reconnaissance mapping by the writer indicates the Yeso–Glorieta contact in Chavez Draw is unfaulted, and can be traced across the valley in western part of sec. 31, T. 3 N., R. 8 E. Because of poor exposure of the Yeso Formation, however, the geometry of the Chupadera fault at the north edge of Chupadera Mesa is inadequately constrained. More work is needed.

The Chupadera fault may have hosted major strike slip, as it appears to be a principal southward extension of the Picuris–Pecos fault of north-central New Mexico (see discussion in Cather and Harrison, 2002, Cather, 2004, and Cather et al., 2006). Unlike the Picuris–Pecos fault (e.g., Cather et al., 2006), the Chupadera fault does not show unambiguous lateral offsets of aeromagnetic features, perhaps because of the lack of strong magnetic contrast (i.e., granite vs. quartzite) in the Proterozoic basement and magnetic overprinting by Cenozoic intrusions. The Picuris–Pecos fault exhibits well-documented evidence for ~37 km of dextral separation of Proterozoic lithotypes and structures (Miller et al., 1963). Dextral slip occurred mostly during the Ancestral Rocky Mountain and Laramide deformations (Cather et al., 2006; Cather et al., 2007), causing at least 30 km of dextral separation since the Middle Pennsylvanian (Dunbar et al., in press). Strike slip on the Chupadera fault may explain why a fault of this length (≥ 90 km) exhibits only modest stratigraphic separation (≤ 110 m). If the stratigraphic separation were solely the result of dip slip on the fault, the scaling ratio between fault displacement and fault

length (≤ 0.0012) is one or two orders of magnitude too low (see Schultz and Fossen, 2002, their fig. 1).

The Claunch sag (Kelley and Thompson, 1964) is the structurally low area between the Chupadera fault and the intrusions of the Lincoln County porphyry belt. The Claunch sag is a broad, shallow, west-tilted structural basin, bounded on the west by the Chupadera fault. Because the dip direction of the Chupadera fault is not definitively known, the structural style of the Claunch sag is unclear. It may be a shallow half-graben of Neogene age, which would suggest that the Chupadera fault dips eastward. Perhaps more likely, the Claunch sag is an exhumed Laramide tilted block that was tectonically loaded on its west side by reverse components of slip on the Chupadera fault. This would require the fault to dip westward, as does its probable extensions to the north and south (the Picuris–Pecos and Jarilla faults).

The Mescalero arch (Kelley, 1971) is a broad, low-relief anticlinorium that passes north-northwest through the Gallinas Mountains region. It divides the west-tilted Claunch sag from the gently east-dipping homocline of the Pecos slope on the east. It corresponds approximately with the buried western margin of the late Paleozoic Pedernal uplift (Kelley, 1971). Sparse well penetrations indicate syndepositional control of Pennsylvanian and Lower Permian stratal thicknesses by faults along this margin of the Pedernal uplift (Broadhead and Jones, 2004). These same faults were reactivated during development of the Mescalero arch, probably during the Laramide orogeny, and later served to localize stocks and laccoliths of the Lincoln County porphyry belt.

The Capitan lineament is an east-trending tectono-magmatic feature in Texas and eastern New Mexico. From east to west it encompasses the late Paleozoic Red River uplift and the Matador arch of Texas (Ewing, 1990), the late Paleozoic Roosevelt uplift and the Oligocene Camino del Diablo dikes east of Roswell, the Oligocene Capitan stock, and, in the study area, the Quaternary cinder cones of Little Black Peak and Broken Back Crater and the Oligocene Jones Camp dike (Kelley, 1971). The Capitan lineament is generally interpreted as a basement fracture zone (Kelley and Thompson, 1964; Kelley, 1971, Chapin et al., 1978, Cather, 1991), although no surficial faults mark its trend in New Mexico. The extension of the Capitan lineament westward beyond the Chupadera fault is questionable as the Jones Camp dike may be a rootless lateral intrusion that is restricted to the Yeso Formation (see below).

MAJOR FOLDS

Four broad, north-trending folds are present in the study area. The western three of these folds (Prairie Spring anticline, Torres syncline, and Chupadera anticline) are evenly spaced (~10 km between their axes) and terminate northward at approximately the same latitude (Fig. 1). The Torres syncline and Chupadera anticline terminate southward near the latitude of Bingham, but the southern end of the Prairie Spring anticline is faulted and obscured by Neogene alluvium. Stratal dips on the limbs of all three folds are gentle (generally ~5–20°). The Prairie Spring and Chupadera anticlines are somewhat asymmetrical, with their steep limbs facing the Torres syncline. Structural relief on the top of the Yeso Formation between the Torres syncline and the flanking anticlines is ~0.5 km.

The north-south extent of the Prairie Springs, Torres, and Chupadera folds is similar to that of the previously mentioned restraining bend in Laramide dextral faults near the Socorro Basin (Fig. 1). It is possible that these folds formed, in part, as a far-field response to contractile deformation in this restraining bend. It is clear, however, that tectonic thickening of the Yeso Formation, probably caused by detachment faulting, is responsible for much of the supra-Yeso structural relief on the Prairie Spring and Chupadera anticlines. The structural relief of these anticlines measured on units below the Yeso Formation thus may be significantly less than the ~0.5 km relief measured at the top of the Yeso Formation. Quantification of sub-Yeso structural relief, however, is hindered by a lack of borehole data in the Torres syncline.

The Chupadera anticline owes much of its structural relief to intraformational tectonic thickening of the Yeso Formation. Numerous small-scale folds in Yeso Formation strata are exposed in the core of the Chupadera anticline and are readily visible in satellite imagery (Fig. 3). These folds trend north, plunge variably but gently, have wavelengths of ~500–1500 m, and generally have limb dips of ~20–50°, but subvertical beds are locally present. Although not well enough exposed for quantitative line-length evaluation in cross section, it is clear that beds in the Yeso Formation in the Chupadera anticline have been shortened far more than the overlying Glorieta–San Andres beds, and that these differing strain domains are separated by the evaporite-bearing beds of the upper Yeso Formation. A partial thickness of the Yeso Formation in the northern part of the anticline is given by the Yates No. 1 McCaw Federal well, which was collared in the Yeso Formation and penetrated 610 m of Yeso strata (Broadhead and Jones, 2004). Approximately 100 m of Yeso strata have been eroded from above the collar elevation of this well, based on the cross-sectional geometry of the Chupadera anticline. The total thickness of the Yeso Formation in the northern part of the Chupadera anticline (~710 m) is thus much thicker (by a factor of 2.3–3.4) than that of Yeso exposures nearby to the west (299 m; Colpitts, 1986) and north (~207 m; Bates et al., 1947). Such rapid thickness changes are unusual in the Yeso Formation, which, except for areas flanking the late Paleozoic Orogrande basin in southern New Mexico, are typically 2–5 m/km (Mack and Dinterman, 2002; their fig. 4). Tectonic thickening of the Yeso Formation in the Chupadera anticline thus may account for much or all of the ~0.5 km structural relief between the anticline and the Torres syncline to the west. An undeformed igneous dike cuts folded Yeso strata in the east-central part of the Chupadera anticline (Figs. 1, 3). This dike is undated but is almost certainly late Eocene or Oligocene in age, and thus indicates the Yeso folds and the Chupadera anticline are Laramide structures.

The Yeso Formation in the Prairie Spring anticline is also unusually thick. The Skelly No. 1 Goddard well was collared in the Yeso Formation and penetrated 314 m of Yeso strata near the central part of the anticline (Broadhead and Jones, 2004). About 120 m of Yeso strata have been eroded from this part of the anticline based on the cross-sectional geometry of the fold, giving a

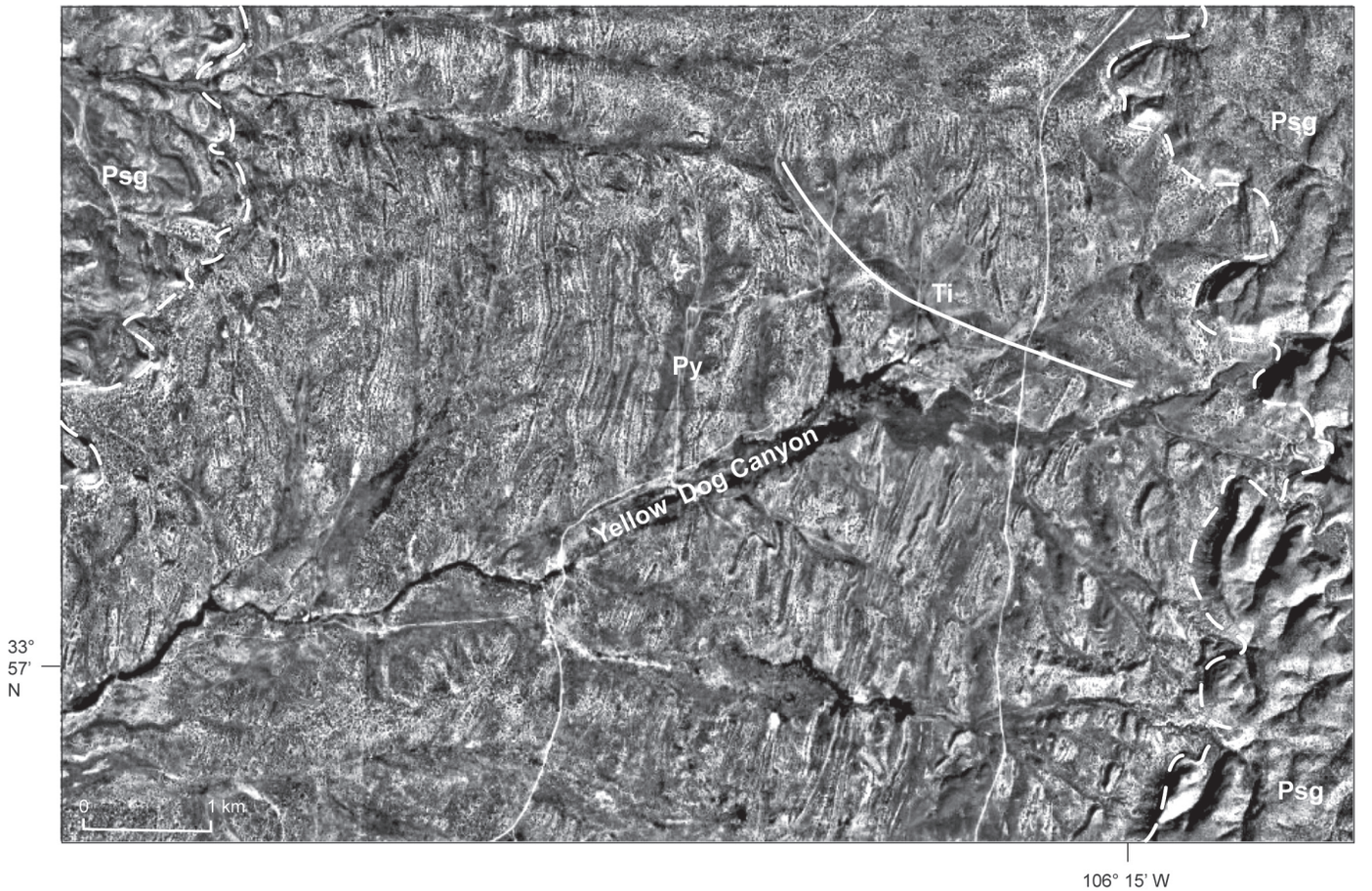


FIGURE 3. Landsat image of strongly folded beds of Yeso Formation (Py) in the central part of the Chupadera anticline. Note gently dipping (~10–20°) beds of the Glorieta Sandstone and San Andres Formation (Psg) on west and east limbs of anticline and undeformed igneous dike (Ti). Dashed line is approximate Yeso–Glorieta contact.

total Yeso Formation thickness of ~434 m. This is significantly thicker than the unfaulted Yeso section exposed at Sierra de la Cruz ~16 km to the west (299 m thick; Colpitts, 1986). The Prairie Spring anticline thus may also be related in part to tectonic thickening of the Yeso Formation. Satellite imagery shows the presence of anomalously folded Yeso beds in the southwestern part of the Prairie Spring anticline, reminiscent of those in the Chupadera anticline. The Prairie Spring anticline folds Triassic strata but predates the Neogene sediments that bury the southern end of the anticline. Thus it may have developed during the Laramide or mid-Tertiary magmatism.

The greatest known thickness of the Yeso Formation in New Mexico occurs in the Carrizozo anticline. The Yeso Formation is 1300 m thick in the Standard of Texas No. 1 J.F. Heard Federal well in the northern part of the anticline (Broadhead and Jones, 2004). This is far thicker (2.6 times) than the Yeso Formation exposed in the southern Oscura Mountains ~25 km to the west (490 m; Bachman, 1968), and twice the maximum thickness of the Yeso Formation anywhere else in New Mexico (Mack and Dinterman, 2002). The underlying Bursum–Abo stratigraphic interval in the Carrizozo anticline is also somewhat thicker than it is in the Oscura Mountains ~25 km to the west or in the Claunch sag ~30 km to the north (Table 1). Pennsylvanian strata appear to systematically thicken southward toward the late Paleozoic Orogrande basin, but are not unusually thick in the Carrizozo anticline.

The great thickness of the Permian strata in the Carrizozo anticline is, at least in part, the result of tectonic thickening. The Texaco No. 1D Federal (USA) well was collared in the Yeso Formation and penetrated 1190 m of Yeso strata near the center of the anticline. A continuous dipmeter log from 500–7540 feet depth in this well shows strongly disturbed bedding attitudes associated with thick evaporite beds throughout much of the Yeso Formation (Broadhead and Jones, 2004) and locally in the underlying Abo Formation and Madera Group (logs are available from the New Mexico Library of Subsurface Data, New Mexico Bureau of Geology and Mineral Resources). This disturbed bedding (Fig. 4) is presumably the result of folding and faulting similar to that exposed in the Chupadera anticline to the northwest. The strong deformation of the Yeso Formation in the Carrizozo anticline indicates the unusual thickness of the unit cannot be explained solely by syndepositional thickening, although it is possible that weak strata deposited in an evaporitic depocenter may have localized subsequent tectonic thickening. It is unlikely that bedding disturbance by evaporite dissolution was an important effect, as this process would tend to thin the Yeso Formation rather than

TABLE 1. Comparison of thicknesses of Pennsylvanian, Bursum–Abo, and Yeso strata in the Carrizozo anticline with adjacent areas

Unit	Carrizozo anticline		Oscura Mountains	Claunch sag
	Heard-Fed[2]	Fed (USA)[3]		
Yeso Fm	1300 m	1190+ m	490 m[1]	449–530 m
Bursum and Abo Fms	588 m	580 m	~297 m	384–520 m
Pennsylvanian strata	410 m	548+ m	280[4]–670[5] m	0–149 m

[1]Thickness from outcrop data of Bachman (1968); all other thickness data are from Broadhead and Jones (2004). Claunch sag thicknesses are from Primero No. 1 Dulce Draw State, Manzano No. 1 Cathead Mesa, Primero No. 1 Jackson Ranch Federal, and Manzano No. 1 Spaid Buckle wells. [2]Standard Oil Co. of Texas No. 1 J.F. Heard-Federal. [3]Texaco No. 1D Federal (USA). [4] northern Oscura Mountains. [5]southern Oscura Mountains.

contribute to the observed thickening.

Abrupt changes in bedding orientation, here interpreted as faults, occur in the Yeso Formation at depths (below surface) of 963, 1080, 1744, 1861, 1926, 2486, 2660, 2943, 3239, 3291, 3776, and 3900 feet, the last occurring at the contact between the Yeso and Abo formations. Discontinuities in bedding dip of the Abo Formation are present at 4198 and 4538 feet depth, and at 5908, 6242, 6318 feet depth in the Madera Group. The faults responsible for these bedding-dip anomalies are probably thrust faults, due to their association with tight folding and an overthickened section. Tectonic thickening of the Yeso Formation may account for much or all of the structural relief on the Carrizozo anticline. This possibility was also noted by Kelley and Thompson (1964, p. 116), "…the anticline may be nonexistent or only a terrace below the Yeso. There is also some possibility that the apparently thick section is due to folding or a low-angle fault which may have duplicated the section."

The development of the Carrizozo anticline is only constrained to be post-Permian and pre-Quaternary. It is possible that it is related to a Laramide regional detachment system that developed on the east flank of the Laramide Sierra uplift (see below), but this would require the east-west extent of the detachment system to be ~80 km. Perhaps more likely the Carrizozo anticline formed at the contractional toe of a detachment that slid eastward off the Oscura Mountains as they rose during Neogene (mostly Miocene) extension. The northwest-striking Yates fault (Kelley and Thompson, 1964; Fig. 1; Plate 2) in the Oscura Mountains trends toward the southern end of the Carrizozo anticline and may represent a tear fault on the southwest side of the detachment. The Yates fault is exposed along strike for 21 km, yet does not cut down-section into rocks older than Pennsylvanian at the western front of the Oscura Mountains (Bachman, 1968). This down-section limit of the fault corresponds approximately to the lowest stratigraphic level of disturbed bedding in the Texaco No. 1D Federal (USA) well in the Carrizozo anticline. It is speculated here that the Yates fault slipped dextrally during Neogene uplift and eastward tilting of the Oscura Mountains, and marked the southwestern edge of top-southeast detachment faults in the Pennsylvanian and (principally) the Permian section.

To explain the anomalous thickness of the Yeso Formation in the Carrizozo, Chupadera, and Prairie Spring anticlines, I propose a model for the structural development of these anticlines that involves detachment faulting. In these anticlines, outcrop and borehole data indicate a dominance of contractile deformation. A possible detachment geometry for intra-Yeso tectonic thickening in these anticlines is depicted in Figure 5, with folding and thrust faulting resulting from the detachment faults climbing up-section in the direction of upper-plate transport. Tectonic thickening of the Yeso Formation, in turn, caused broad anticlinal warping of the overlying strata. Contractional deformation in the Carrizozo, Chupadera, and Prairie Spring anticlines is not locally balanced by extension, suggesting they may be part of a regional detachment system.

REGIONAL DETACHMENT FAULTING?

Detachment faulting is widespread in the evaporitic strata of the Yeso and San Andres outcrops east of the Socorro Basin (Smith, 1983; Cather, 2009, this guidebook). Gypsum, commonly in beds meters to tens of meters thick, is the dominant evaporite mineral, but bedded halite also occurs in the Yeso Formation in central and

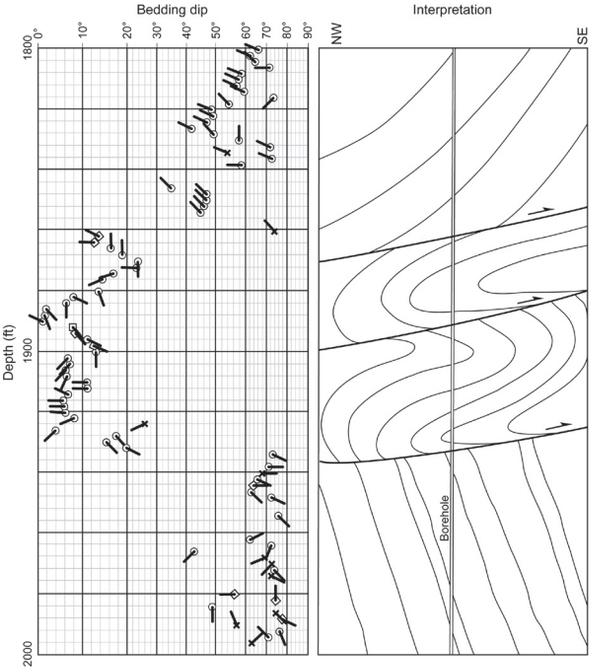


FIGURE 4. Continuous dipmeter log and interpretation for part of the Yeso Formation in the Texaco No. 1D Federal (USA) well in the central Carrizozo anticline. Data quality indicated by symbols: open circles = excellent; open squares = good; open diamond = fair; X = poor (Pirson, 1977). See text for discussion.

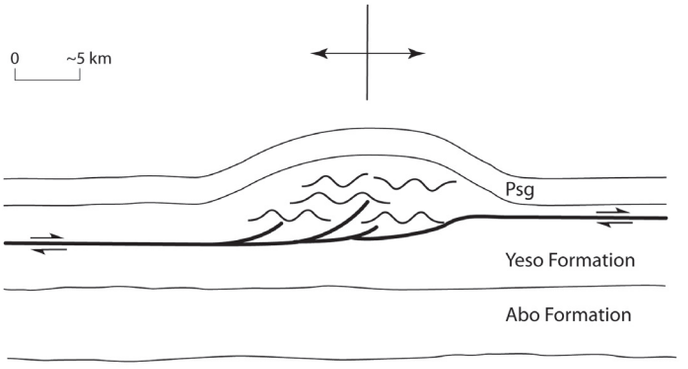


FIGURE 5. Model for development of broad anticlines by contractional deformation of the Yeso Formation due to up-section ramping of detachment fault. Psg, Glorieta Sandstone and San Andres Formation. Great vertical exaggeration. See text for discussion.

east-central New Mexico (Mack and Dinterman, 2002). Bedded halite has been documented in the Manzano Oil No. 1 Cathead Mesa well in the Claunch sag and in the Standard of Texas No. 1 Heard Federal well on the Carrizozo anticline (Fig. 1). The latter well penetrated about 300 m aggregate thickness of halite in intervals ~30–100 m thick, although chaotic bedding complicates the interpretation of the true halite thickness in this well (Broadhead and Jones, 2004). Halite does not survive in surficial exposures of the Yeso Formation, but molds of halite crystals are common in the Yeso exposures in central New Mexico and show that evaporitic concentration of brines was sufficient to precipitate halite over a broad region.

It is plausible, but untested, that detachment faults in the Permian section were kinematically linked over a broad region of central New Mexico. On the east flank of the Socorro Basin, detachment faulting is generally top-to-the-east and steps down-section in the direction of upper plate transport, resulting in normal-fault geometries that excise stratigraphic section (see Cather, 2009, fig. 8, this guidebook). These extensional detachment faults may represent a breakaway zone, and there is no evidence that they were balanced locally by shortening. Approximately 20–80 km to the east, probable detachment-related thrusting and folding occurred in the Prairie Springs, Chupadera, and Carrizozo anticlines, and possible top-east dismemberment of the Chupadera fault by younger detachment faults near Broken Back Crater and at the north end of Chupadera Mesa was described above. If detachment faults within Permian evaporites were linked regionally, then extension on detachments on the east flank of the Socorro Basin may have been balanced by contraction in anticlines far to the east, much like the extension in the breakaway zone of a landslide is balanced by shortening at the toe.

Such broad lateral continuity of detachment faulting is speculative. To test this idea, it will be necessary to examine in detail the Yeso Formation exposures in the region for evidence of bedding-parallel shear fabrics (Fig. 6). In areas where stratal excision or repetition due to the ramping of detachment faults occurs, the role of detachment faults is reasonably apparent. Where faults are parallel to bedding and do not cut up or down section, however, detachment faults are easily overlooked. On the east flank of the Socorro Basin, detachment faults were not noted in the relatively well-studied Yeso exposures there (including the original type section of the unit) until detailed mapping by C.T. Smith and his students at New Mexico Tech in the 1980s (Smith, 1983; Maulsby, 1981; Bausch, 1982; Fagrelius, 1982; Colpitts, 1986; Craig, 1992; Linden, 1990).

In summary, there are several features in the Chupadera Mesa region that are best explained by detachment tectonics within the Permian evaporite section. These are: (1) widespread, top-east, low-angle normal faults east of Socorro; (2) intra-Yeso Formation thickening due to folding and thrust faulting in the Prairie Spring, Chupadera, and Carrizozo anticlines; and (3) possible top-east truncation and transport of the Chupadera fault by the upper plate of the detachment. These features may be all linked within a regional detachment system, but more work will be needed to test this. Detachment faulting was polygenetic and began in the Laramide, as shown by an undeformed dike that cuts folded Yeso beds in the Chupadera anticline (Fig. 3). Late Eocene–Oligocene volcanism may have reactivated earlier Laramide detachments, due to loading of allochthons by extensive volcanic fields near Socorro and Sierra Blanca. Additionally, increased geothermal gradients during volcanism may have weakened potential detachment horizons by dewatering and volume decreases related to the gypsum-anhydrite transition. The thickness of the section above the Yeso Formation to the top of the Cretaceous section was ~800–1200 m, and with perhaps an additional 300 m of Laramide deposits that were largely restricted to the Carthage–La Joya basin in the western part of the study area (Cather, 2009, this guidebook). Thus it is possible that gypsum dehydration to anhydrite, which commonly occurs at ~50° C (P.A. Scholle, 2009, oral commun.), may not have occurred until rapid burial and heating during late Eocene–Oligocene magmatism in most of the study area. Subsequent Neogene rift-related extension on the Bustos fault (Cather and Osburn, 2007) and possible gravity-driven sliding off of rising footwall uplifts contributed additional top-east shear to the detachment system.

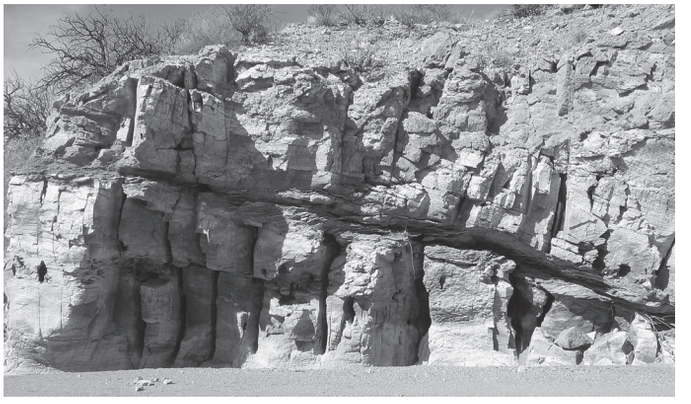


FIGURE 6. View to north of shear zone in gypsum beds of the upper Yeso Formation. Shear zone is ~0.5 m thick. West-dipping fabric indicates top-east (top to right) shear. Note that shear zone cuts down-section to east in its footwall, indicating normal slip. Photo by Gary Axen in Arroyo de las Cañas, ~ 12 km southeast of Socorro, New Mexico.

INTRUSION-RELATED FOLDING

Two types of intrusion-related folds occur in the Chupadera Mesa region: (1) broad domes near stocks and laccoliths of the Lincoln County porphyry belt, and (2) narrow anticlines associated with dike intrusion of the Yeso Formation. Stocks and laccoliths of the Lincoln County porphyry belt are late Eocene–Oligocene in age (~38.2–26.5 Ma old; Allen and Foord, 1991). These intrusions caused broad doming of strata adjacent to them. Such domes commonly extend up to several kilometers from the margin of individual intrusions, and exhibit as much as several hundred meters of structural relief (Woodward, 1991).

Mafic dikes are widespread in the study area. They occur mostly (estimated >80%) in the Yeso Formation; dikes are notably much less common in subjacent and superjacent strata. As first described by Bates et al. (1947), dikes that intrude the Yeso Formation are commonly associated with narrow anticlines in that unit and the overlying beds of the Glorieta Sandstone and the San Andres Formation. Folding apparently occurred as a result of intrusion of the dikes themselves (Fig. 7), which are commonly tens of meters wide and locally as much as ~200 m wide. Following initial dike propagation, overlying beds apparently were forced upward and outward by magmatic inflation as the dike became wider, causing the limbs of the growing anticline to diverge away from the axial dike. This divergence probably caused extension along the crest of the anticline. The crestal areas of dike-related anticlines are commonly faulted, but the nature of these faults has not been adequately studied.

Although not all anticlines are eroded deeply enough to expose their cores, I have observed sufficient examples of dikes associated with anticlines to be convinced that most or all of the narrow anticlines in the study area originated in this manner. A similar conclusion was reached by Bates et al. (1947, p. 40), "The presence of large dikes below observed arches, the absence of arches away from the dike areas, and the parallelism of folds and dikes, indicate that the folds were produced by dike intrusion." Anticlines are generally ~100–500 m wide and can by traced for as much as 30 km along their trends (Fig. 1). Where the erosionally resistant strata of the Glorieta Sandstone and lower San Andres Formation are at the land surface, dike-related anticlines typically form long, slightly arcuate ridges. An example of this is at Gran Quivira, where the ancient pueblo lies on an anticlinal ridge. Roadcuts east and west of the pueblo expose a dike ~70 m wide in the core of the anticline. In other areas where erosion has breached the Glorieta Sandstone, weakly resistant beds of the Yeso Formation form a valley along the anticlinal trend, as at the Jones Camp dike (Fig. 8).

Many dikes in the Chupadera Mesa–Claunch sag area appear to have been intruded laterally into the Yeso Formation over great distances. This interpretation is supported by (1) the abundance of dikes in the Yeso Formation relative to underlying and overlying beds, (2) the great length of dike-related anticlines, and (3) the radial distribution of many dikes and dike-related anticlines in the Claunch sag and central Chupadera Mesa relative to the laccolithic center in the Gallinas Mountains (Fig. 1). These radial dikes are undated, but presumably are similar in age to the Gallinas laccolith (K/Ar age 29.9 Ma; Perhac, 1970). Several dike-related anticlines stitch the Chupadera fault (Fig. 1), and thus preclude major post-Oligocene strike slip on the fault.

Many of the dikes in the study area appear to have propagated from parts of the magmatic system in the Gallinas Mountains area that were sufficiently shallow to allow exploitation of the weak rocks of the Yeso Formation. Dikes were largely confined to the Yeso Formation because of the abundance of weak rocks (shale, gypsum and halite) in that unit. These lithotypes exhibit

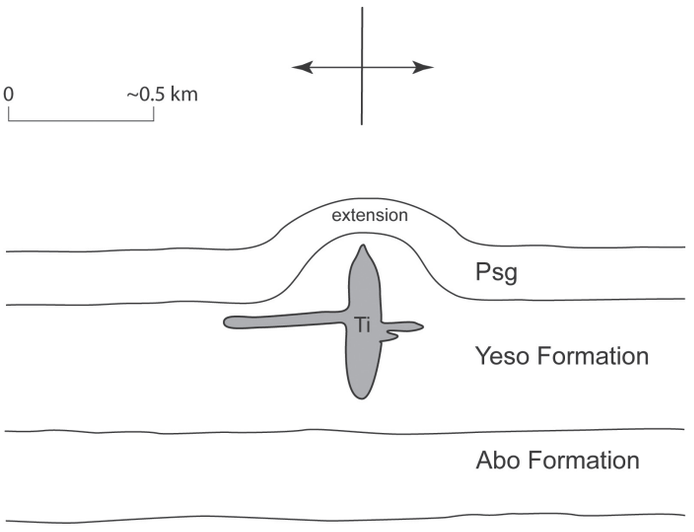


FIGURE 7. Schematic cross-section showing relationship between dikes and narrow anticlines in the study area. Note that dikes are interpreted to be generally rootless, and in some cases may have propagated laterally in the Yeso Formation for tens of kilometers. Psg, Glorieta Sandstone and San Andres Formation. Great vertical exaggeration.



FIGURE 8. View to west along the trend of the Jones Camp dike from SW/4, Sec. 14, T.5S., R.7E. Dike intrudes weakly resistant beds of Yeso Formation in foreground and in notch on skyline. Note outward dipping beds of Glorieta Sandstone and San Andres Formation on skyline.

lower tensile strengths than nearly all other common rock types (Waltham, 1994), and thus should be the first to fail during magmatic pressurization. Lateral dike propagation may have been driven by magmatic pressure in the Gallinas laccolith. Alternatively, dikes may have propagated downslope by gravity (e.g., Acocella et al., 2006), away from the structurally high Gallinas Mountains magmatic center.

The sources of other dikes in the study area, such as the Jones Camp dike (27.9 ± 1.1 Ma old; Aldrich et al., 1986) and the dikes north of the Torres syncline (30.2 ± 2.0 Ma old; Aldrich et al., 1986) are less clear. They are approximately equidistant from magmatic centers near Socorro and in the Lincoln County porphyry belt, and are contemporaneous with magmatism in both areas. Chamberlin et al. (2002) interpreted them as part of a large Oligocene dike swarm that radiated from the Socorro–Magdalena caldera cluster. At one locality, the Jones Camp dike exhibits shear fabrics along its chilled margin that indicate subhorizontal dike propagation. These fabrics suggest flow from west to east, away from the magmatic system at Socorro (Chamberlin, 2009, this guidebook).

The Jones Camp dike averages ~175 m wide (Bickford, 1980) and can be traced westward through progressively older parts of the Yeso Formation to its termination in the lower part of the formation, which is the approximate lower stratigraphic limit of weak rocks in that unit. It is suggested here that the present westward outcrop limit of the Jones Camp dike is determined by the down-section limit of weak rocks into which it was laterally intruded. If this interpretation is correct, then the present outcrops of the Jones Camp dike may be "rootless" and do not necessarily reflect the westward continuation of the Capitan lineament in the basement.

DISCUSSION

Most of the unusual aspects of the tectonic evolution of the Chupadera Mesa region are attributable to the presence of evaporites in Permian strata, particularly the Yeso Formation. The low shear strength of gypsum and halite relative to other Phanerozoic lithotypes controlled the localization of bedding-plane faults in evaporite strata. On the east flank of the Socorro Basin, these faults step to lower stratigraphic levels in the direction of upper-plate transport, the resulting extensional ramp-flat geometry produced normal faults that excised stratigraphic section and caused tectonic thinning and truncation of upper-plate beds against underlying detachment faults (see Cather, 2009, this guidebook). Where detachment faults step upsection, contractile folding, faulting, and tectonic thickening occurred. Tectonic thickening, primarily in the Yeso Formation, appears to account for much of the supra-Yeso structural relief on the Prairie Springs, Chupadera, and Carrizozo anticlines; subjacent strata may have experienced little or no folding. It is possible that all of the detachment-related features in the study area are part of a single regional system, but this is unproven. Cross-cutting relationships indicate detachments were active during both the Laramide and rift deformations, and possibly during mid-Cenozoic magmatism, but the relative importance of each is unknown.

Interestingly, several aspects of the Lincoln folds (Craddock, 1964; Yuras, 1991), located ~50 km east-southeast of Carrizozo, are similar to the Yeso Formation folds in the cores of the Chupadera and Carrizozo anticlines. These include: (1) development of tight folds in the Yeso Formation but not in overlying beds; (2) the short wavelengths, gentle plunges, and northerly trends of the folds; (3) broad arching of strata above the Yeso Formation (Kelley, 1971). Interpretations of the origin of the Lincoln folds include gravitational gliding (Craddock, 1964), slumping due to increased Pleistocene precipitation and accumulation of glacial outwash (Foley, 1964), encroachment of the structural margin of the Laramide Sierra Blanca Basin (Kelley and Thompson, 1964), and Laramide crustal shortening (Yuras, 1991).

The evaporite-bearing part in the Yeso Formation has been preferentially intruded by Paleogene dikes, probably because of the low tensile strength of gypsum and halite. In some cases, these dikes have propagated laterally tens of kilometers from their sources and produced long, narrow anticlines in superjacent beds. Like the broad, detachment-related anticlines in the area, dikes and their associated anticlines may be generally rootless, as suggested by the low regional abundance of dikes in pre-Yeso beds. Laterally intruded dikes hundreds or thousands of kilometers long have been described in other regions (e.g., Parfitt and Head, 1993, and references therein). To my knowledge, however, this report is the first in which the rheologic control of lateral dike propagation by evaporites has been proposed.

If the detachment-related structures described here are parts of a regionally linked Laramide system, then the size of the central New Mexico allochthon is comparable to the Heart Mountain detachment of Wyoming. Measured from the top of the Yeso Formation to the top of the Cretaceous section, the allochthonous section was ~800–1200 m thick, with perhaps an additional kilometer or so thickness of Paleogene sedimentary and volcanic rocks in the eastern and western parts of the study area prior to deep Neogene erosion. The maximum plausible area of this regional detachment is ~4000 km^2 (this assumes a roughly triangular shape with the east flank of the Socorro Basin, the Carrizozo anticline, and northern Chupadera Mesa at its corners). If the detachment system extended eastward only as far as the Chupadera anticline (i.e., the Carrizozo anticline is part of a separate, younger detachment on the east flank of the Oscura Mountains), then the areal extent was ~1400 km^2. By comparison, the ~50 Ma-old Heart Mountain allochthon of Wyoming is about 2 km thick and encompassed ~3400 km^2 (Hauge, 1993). The leading edge of the Heart Mountain detachment was displaced about 50 km from its original location, probably during a single slip event (Buetner and Craven, 1996). In contrast, the possible regional allochthon in central New Mexico is polygenetic and has been transported eastward only a short distance, probably only a few kilometers, but perhaps a maximum of ~8 km if the apparent top-east separation of the Chupadera fault near Broken Back Crater pertains to a regional detachment system and was not the result of local sliding off the rising Oscura Mountains.

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