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QUATERNARY FAULT SYSTEM IN THE TULAROSA AND HUECO BASINS, SOUTHERN NEW MEXICO AND WEST TEXAS

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INTRODUCTION

Many geologists in West Texas and New Mexico are aware of the nearly continuous fault scarps of Quaternary age that border the eastern edge of the Sierra Juarez–Franklin–Organ–San Andres Uplift and western Tularosa and Hueco Basins. Less well-known is the system of comparatively minor faults breaking the surface of the two basins (figs. 1 and 2). These minor faults, which block out a somewhat jumbled array of horsts, grabens and tilted blocks in basin-fill deposits, constitute a swath about 5 to 25 km wide subparallel to the boundary fault of the adjacent uplifts. A major conclusion of this paper is that these faults formed when basin fill warped down in response to localized extension—a pull-apart—beneath the western side of the basins. Although many of the minor faults may be comparatively shallow features, some are not; all have potential for growth as long as movement on the range-boundary fault of the Franklin–Organ–San Andres Uplift continues.

Some of the scarps were recognized years ago. Sayre and Livingston (1945) identified several scarps and depressions in northeastern El Paso and along the Carlsbad highway (U.S. 62-180) as faults, and showed them on their map. Knowles and Kennedy (1958) subsequently acknowledged the presence of scarps in the Hueco Bolson, agreeing with Sayre and Livingston that they were a product of faulting. Only recently has the extent of the fault swarm

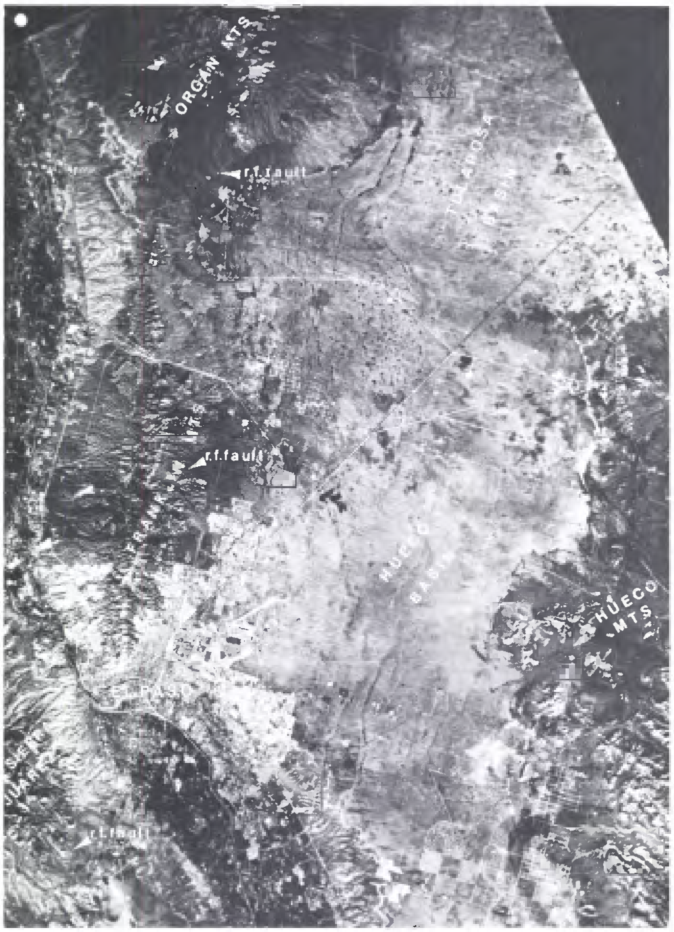

Figure 1. Skylab photo (SL4-92-025) of northern Hueco and southern Tularosa Basins. Faults that break the basin surface are marked by dark lineaments, most of which are aligned, playa-covered depressions at the foot of fault scarps. The range boundary fault scarp of the Juarez–Franklin–Organ uplift is marked (r.f. fault) in three places.

Figure 2. Fault map of northern Hueco and southern Tularosa Basins. Shaded areas are topographically and structurally lowest parts of the basins. The dotted (buried) faults in the northeastern part of the map area and along the western side of the Hueco Mountains are revealed by gravity and aeromagnetic surveys, by drill hole data, or are suggested by stratigraphic studies.

become apparent (Woodward and others, 1978). The present study has revealed a still more remarkable array of fault blocks that provide considerable topographic variety to the floors of the western Tularosa and Hueco Basins—bolson floors usually thought of as "flat."

DESCRIPTION OF THE FAULTS

In general, the floors of the Tularosa and Hueco Basins slope westward, about 2.3 and 3.2 m/km respectively, to closed depressions near the base of the Franklin and Organ Mountains. Modifying this slope, however, are the fault scarps mapped on Figure 2, which extend from highway 70, south of Lake Lucero, southward to the Rio Grande valley below El Paso. Although the scarps probably continue farther in both directions, they are masked by depositional and erosional effects of Lake Lucero and the Rio Grande. Most of the fault system parallels the frontal fault zone of the Franklin-Organ Uplift with remarkable fidelity. Where the frontal fault is embayed or bulges outward, the basin faults duplicate the trend; this seems to indicate a genetic linkage of the two fault systems. Only 3 to 5 km wide in the western Tularosa Basin, the system widens southward to embrace the entire width of the Hueco Bolson east of El Paso. Many pairs of faults outline narrow horsts and grabens, especially in the Tularosa Basin; these are expressed on the ground as linear hills or depressions bounded by relatively gentle slopes mantled with sand. Most scarps in the Hueco Basin east of El Paso face east, and these as well as other east-facing scarps in the system are antithetic to the general westward slope of the basin floors. Longest faults in the system can be traced on topographic maps or aerial photos for at least 30 km, and less certainly for nearly 40 km. However, many appear to be short, 5 to 7 km or less. All are curving or somewhat angular in trend, and a few divide into multiple faults along their length. There is little continuity in structural relief along strike: horsts may pass into grabens, or west-facing scarps may be replaced with east-facing ones. Heights of scarps range from 3 to 7 m to as much as 28 m. Scarp-slope angles are generally less than 15 degrees, mostly because the material composing them is relatively unconsolidated sand, silt, clay and minor gravel of the Camp Rice Formation. Caliche, which represents soil on the bolson floor, caps most of the fault blocks but provides only modest resistance to erosion. Consequently, the faults are not striking features of the landscape; instead they form low, rounded scarps or rounded, elongated hills or shallow depressions marked by alluvial flats or small playas. Some scarps also have distinct linear vegetation breaks across them, presumably due to mounding of groundwater behind the faults (C. Henry, personal communication, 1980). These are best seen on aerial photos, but the fault blocks themselves are most clearly revealed on topographic maps such as Newman, Newman SW, or Fort Bliss SE 7½ minute quadrangles.

AGE OF THE FAULTS

Regretably, the time of latest movement on any faults in the system within the two basins has not been established with any precision. About all that can be said is that the faults are younger than about 0.5 m.y., based on offset of both uppermost beds of the Camp Rice Formation and the soil developed on it. The faulted deposits contain land mammals as well as local volcanic ash layers, the former identified by Strain (1966; 1969a,b) as middle Pleistocene in age, the latter as about 0.7 m.y. old by Hawley (1978). The Camp Rice is no younger than the 0.2 to 0.25 m.y. old dates obtained on basalt flows above the Camp Rice Formation west of the Mesilla Valley (Hoffer, 1971; Hawley and others, 1976). More recent unpublished dates from the basalts indicate the Camp Rice Formation may be no younger than 0.5 m.y.

Due to the efforts of L. Gile and M. Machette, the time of most recent movement on the Franklin-Organ frontal fault is well established. Their studies near White Sands Missile Range headquarters indicate movement within the last 4,000 to 5,000 years. By comparing soil development on the youngest faulted fan and on the oldest unfaulted fan, Gile arrived at the mid-Holocene date (unpublished report); Machette (personal communication, 1980) corroborated Gile's conclusion by investigating scarp-slope angle and scarp height relationships (after Bucknam and Anderson, 1979).

The most recent scarp, up to 9 m high, extends for at least 35 km along the mountain front. Successively higher scarps displace successively older generations of fans; oldest fans, thought to be of late Pliocene or early Pleistocene age, exhibit scarps about 90 m high. Clearly, the older scarps are composite, the result of repeated movement on the frontal fault for the last 2 to 3 m.y. Similar relationships are likely to exist elsewhere along the Franklin-Organ-San Andres frontal fault, as well as evidence for Holocene movement.

ORIGIN OF FAULTS

A brief account of the known or inferred geometry of the Hueco and Tularosa Basins would be a useful preface to discussion of the origin of the fault system that displaces the basin surface. Semi-diagrammatic cross-sections through each basin illustrate the essential features (fig. 3). Both basins are asymmetric, west-tilted grabens, deepest along their western margin according to available gravity, aeromagnetic and drill hole data (Mattick, 1967; Bath, 1977; Healey and others, 1978). Mattick's (1967) gravity model predicts as much as 2750 m of bolson fill in the western Hueco bolson and drill holes confirm at least half of that near El Paso and at

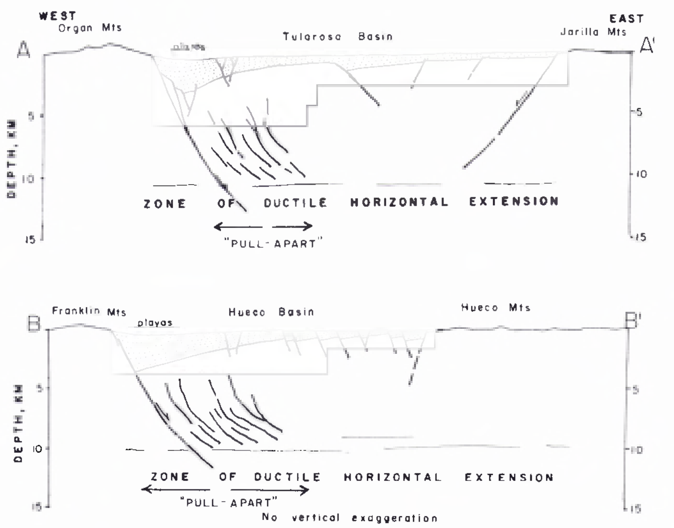

Figure 3. Cross-sections of the Tularosa and Hueco Basins constructed using available gravity, aeromagnetic, drill-hole and geologic data (see text for data sources and Figure 2 for location of sections). Dotted pattern indicates late Cenozoic basin fill. Downbending of basin fill is thought to be a result of localized pull-apart beneath the western part of the basins. The width of the flexed zone, indicated by the width of the fracture system (figs. 2 and 4), suggests that the pull-apart zone is wider beneath the Hueco Basin than beneath the Tularosa Basin.

Newman (King, 1935). Near White Sands Missile Range headquarters about 2400 to 2750 m of bolson fill is consistent with gravity data of Seager and Brown (1978) and Healey and others (1978); drilling has proven at least 1800 m (Doty and Cooper, 1970).

By comparison with their western counterpart, the eastern boundary faults of both grabens have much less displacement as indicated by geologic, drill-hole, and especially gravity data. Nevertheless, the eastern boundary fault of the Tularosa Basin, west and southwest of the Jarilla Mountains, is clearly revealed by gravity and aeromagnetic surveys (Bath, 1977; Healey and others, 1978). Judging from the lack of scarps this fault is inactive. In the case of the Hueco Basin, an eastern boundary fault, or a series of stepped fault blocks, is indicated along the irregular western edge of the Hueco Mountains by drill-hole data between the main mountain mass and bedrock outliers. Elevation differences of various Permian formations between the escarpment and outlying hills also suggests down-to-the west faulting, and west-facing scarps are discontinuously present just west of the westernmost bedrock hills (C. Henry, personal communication, 1980). Figure 2 shows the location of all known or inferred faults along the eastern side of the grabens.

Clearly, subsidence has been greatest and most rapid beneath the western part of both basins, in areas adjacent to the Organ–Franklin boundary fault. The westward inclination of the surface of the basins indicates that asymmetry is continuing to develop as a result of Quaternary faulting along the range front (King, 1935; Sayre and Livingston, 1945). It is worth repeating here that the system of minor faults in the Tularosa Basin is comparatively narrow, lies just east of the depressions along the western edge of the basin, and comprises a rather disorderly but closely spaced array of horsts, grabens and tilted blocks. In contrast, the fault system in Hueco Bolson extends across the entire width of the basin, but individual faults are comparatively widely-spaced, and nearly all are antithetic to the westward tilt of the basin. With this setting in mind, we turn to a possible explanation for the faults.

The clay model experiments of E. Cloos (1968) reveal structures strikingly similar to those observed in the Tularosa and Hueco Basins (figs. 4A and 4B). Most obvious is the swarm of tension fractures, antithetic faults, and shallow horsts and grabens created by extension where the clay cake bent down into the "master fault" of the model; these may be analogous to the faults in the western Tularosa Basin, which may have formed by similar downbending of the bolson fill of the Tularosa Basin. Notice that in the model, as well as in the Tularosa Basin, unfaulted topographic as well as structural depressions lie between the "master" fault at the edge of the graben and the zone of minor antithetic rifts. The wider zone of more uniformly spaced antithetic faults in the Hueco Basin may indicate a much broader zone of downbending than is apparent either in the model or in the western Tularosa Basin.

The closely spaced, low-angle, antithetic faults in the lower half of the clay model apparently reflect a less-brittle response to extension relative to upper parts of the model. (Initially steep fractures, these faults subsequently rotated into low-angle attitudes as downbending of the clay progressed.) Such faults may be expected at depth within both basins (and are shown diagrammatically on Figure 3). However, judging from their length, many of the faults that break the basin surfaces may also extend deep into the upper crust.

Whereas the extension indicated by the fault system appears to be caused by downbending of the basin fill, the origin of the downbending itself poses a more significant problem. An analogy can readily be drawn again between Cloos' models and the Tularosa and Hueco grabens. In Cloos' models the clay bent down to fill the gap created when the clay slab was pulled apart at its base. An analogous zone of active horizontal extension can be inferred beneath the topographically lowest and structurally deepest part of the Hueco and southern Tularosa basins—that is, along their western margin (fig. 3). Downbending of the basin fill into this "pull-apart" zone resulted, and stretching of the basin fill across the downwarp created the fault system shown in Figures 1 and 2.

Considerable geophysical evidence suggests that a widespread zone of ductile horizontal extension does underlie the Basin and Range Province and Rio Grande rift in the middle to upper crust.

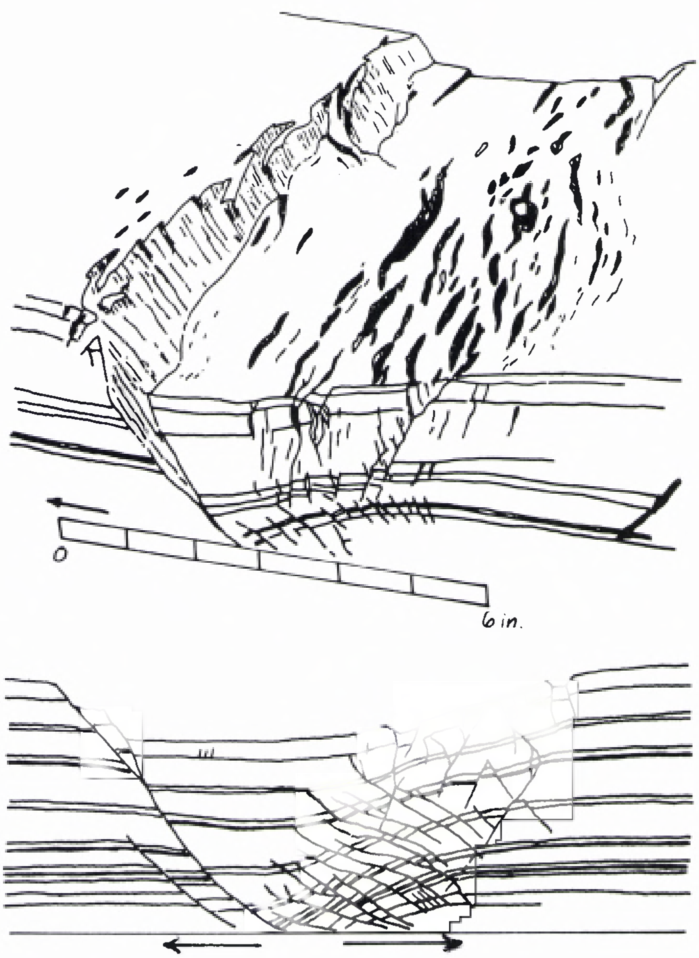

Figure 4. Graben models in clay produced by E. Cloos (1968). (A) In this model the clay cake was extended by pulling horizontally a thin tin sheet located beneath the left half of the model; the right half of the model remained stationary. Extension cracks and minor antithetic rifts formed on the downbent part of the clay cake; these appear to duplicate the structural pattern of the western Tularosa and Hueco Basins. (B) Two overlapping tin plates beneath this clay model were extended horizontally to create the graben. Note here how the lowest part of the down-faulted surface of the clay lies between the master fault and the zone of flexing and fracturing. The same relationship is apparent between the range front fault of the Franklin–Organ Uplift, the playa-filled depressions and the zone of fracturing in the western Tularosa and Hueco Basins (figs. 2, 3). In both of Cloos' models flexing in the downdropped block appears to have resulted when pull-apart of the clay slab left a gap that had to be filled from above.

The general lack of earthquake foci below about 8 to 10 km beneath the Basin and Range (with few deeper than about 15 km) suggests that a transition from brittle to ductile crust takes place within that depth range (Thompson, 1959, 1966; Stewart, 1971; Smith and Sbar, 1974). In fact, Shurbet (1960), Mueller and Landisman (1966), Braile and others (1974) and Smith and others (1975) postulated the existence of low-seismic velocity (reduced rigidity) upper crust material between 6 and 15 km depth, and Shurbet and Cebull (1971) suggested that it is within this zone that horizontal ductile extension takes place beneath the Basin and Range Province. Earthquake foci disappear at similar depths beneath the Rio Grande rift (A. Sanford, personal communication, 1980), although a low-velocity zone has yet to be identified. Nevertheless, it seems likely that a zone of horizontal ductile extension is present beneath the rift. Narrow zones of "pull apart" within this zone of extension are thought to create asymmetric grabens such as the Hueco and western Tularosa Basins (see Stewart, 1971, 1978 for development of this idea).

A final problem worth brief consideration is the geometry of the western boundary fault of the graben. Recent studies in the Basin and Range Province have focused partly on this problem for range-front faults in general (e.g., Stewart, 1978). Some field and seismic studies support flattening of the faults with depth (Moore, 1960; Hamblin, 1965; Anderson, 1971; Proffett, 1977; L. Russell, 1978 paper presented at Rio Grande rift symposium), while other similar studies and drill hole data indicate the faults are or could be planar to great depths (Meister, 1967; Herring, 1967; Stewart, 1971; Thompson, 1971). However, if fault planes are curved, available fault plane solutions from the Great Basin do not indicate flattening to subhorizontal attitudes (Smith and Sbar, 1974). Although I have no direct evidence from the Tularosa–Hueco Basins, it seems to me that moderate downward flattening is likely, given the behavior of shear fractures as they pass downward through increasingly more ductile rocks. Experimental deformation of rocks as well as shear failure theory shows that, in general, dips of shear fractures decrease (assuming σ_1 is vertical) as confining pressure and temperature (and therefore ductility) increase (Handin and Hager, 1957, 1958; Griggs and Handin, 1960; Handin, 1966). Minimum dips of 45 degrees are expected in perfectly ductile material, although fractures in such material may be obscured by recrystallization. Perhaps range-boundary faults, nearly planar and steeply-dipping in their upper reaches where they pass through brittle rocks, flatten to about 45 degrees—but not to horizontal—as they pass into the more ductile rocks below to 6 to 8 km. Highest parts of the fault surfaces may be nearly vertical (Hamblin, 1965). In the case of the Franklin–Organ–San Andres boundary fault, dips of 68 to 70 degrees have been measured at the modern level of erosion, which is about 1.8 km below the summit of the range.

Actually, the pull-apart process in the zone of horizontal extension is consistent with either downward-curving or planar faults. Curvature seems geometrically and mechanically more realistic, however, and even Cloos' models show some flattening of the master fault as it approaches the zone of horizontal extension at the base of the clay. It seems to me that the observed downbending of Hueco–Tularosa basin fill as well as the inferred curvature of the range-boundary faults are both expectable consequences of ductile flow and a local "pull apart" at 10 to 15 km beneath the western parts of the basins, and this interpretation is shown in Figure 3.

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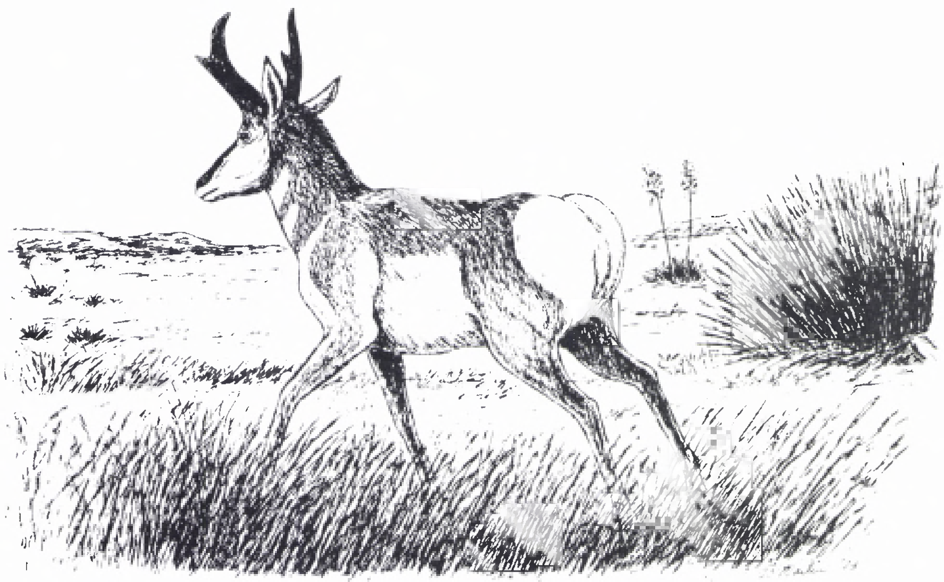

Pronghorn, *Antilocapra americana*.

Green sprangletop plant and spikelet, *Leptochloa dubia*.