# REGIONAL GEOLOGIC SETTING OF THE FORT HANCOCK STUDY AREA, HUDSPETH COUNTY, TEXAS

by

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# EXECUTIVE SUMMARY

The Fort Hancock study area is located within the Basin and Range geologic province in Trans-Pecos Texas. The geologic features of the region record a long history of geologic events. By describing the regional geologic setting, the Fort Hancock study area can be placed within a larger context, and the significance of the site-specific investigations can be more properly understood.

The oldest rocks present in the region are Precambrian crystalline rocks, although none crop out within about 20 mi (32 km) of the proposed repository site. Precambrian rocks are present in the Hueco Mountains to the west and in isolated occurrences on the Diablo Plateau to the north of the study area. In northeastern Chihuahua Precambrian rocks are known primarily from deep exploratory drilling. The Precambrian rocks show evidence of sedimentation, magmatism, metamorphism, and deformation prior to deposition of overlying Paleozoic strata. The greater depth of burial of Precambrian rocks in Chihuahua is interpreted to be a manifestation of Precambrian faulting and subsidence southwest of a structural zone that parallels the Rio Grande. This structural zone, which projects close to the study area, is also coincident with younger geologic structures and has been termed the Texas Lineament.

The Paleozoic history of the region is one of marine sedimentation and, until the late Paleozoic, only mild epeirogenic uplift and subsidence. In the late Paleozoic the Ouachita-Marathon orogenic event produced a belt of strongly deformed Paleozoic strata to the southeast of the study area. Also in the late Paleozoic the major structural highs of the region, such as the Diablo Platform near the study area, were uplifted in the foreland of the Ouachita-Marathon belt. It has been suggested that the late Paleozoic was a time of major displacement on the Texas Lineament, although offset in the vicinity of the study area is difficult to document owing to the limited data on correlative Paleozoic strata across the lineament.

During the Mesozoic the Chihuahua Trough developed as a well-defined depositional basin. The study area lies on the northeastern margin of the Chihuahua Trough near the southwestern edge of the Diablo Platform. This margin of the trough is presumed to have developed along a series of high-angle faults, most of which can only be inferred to exist beneath a cover of younger sediments. In the late Mesozoic and early Tertiary, Laramide deformation of the Chihuahua Trough, the Chihuahua tectonic belt, strongly folded and faulted earlier strata with tectonic transport directions to the east and northeast. Décollement surfaces are thought to have developed in Mesozoic evaporite deposits of the Chihuahua Trough. Localized structures were also formed in more stable areas such as the Diablo Platform. A compressional stress regime may have been present in the Trans-Pecos region until about 30 m.y. ago.

At about 30 m.y. ago the regional stress regime became extensional. Magmatism, both prior to and contemporaneous with extension, was locally important throughout the region, but no magmatic activity younger than 17 m.y. old has occurred in the Trans-Pecos area. The extension resulted in a series of basins related to the Basin and Range Province and the Rio Grande rift. The study area lies within the southeastern arm of the Hueco Basin. The Hueco Basin, or Hueco Bolson, is viewed as an extension of the Rio Grande rift of New Mexico. Regional extension continues to the present day and is manifested by Quaternary fault scarps such as the Campo Grande fault near the study area and the Amargosa fault across the Rio Grande in Chihuahua. The extensional Hueco Basin, similar to other basins in the Rio Grande rift, was infilled with clastic sediments derived both from local sources and from more regional drainage systems. The older bolson sediments exposed in the vicinity of the study area are mostly lacustrine, alluvial fan, and fluvial facies of the Fort Hancock Formation. With the eventual integration of the Rio Grande as a through-flowing system, the higher energy clastic sediments of the Camp Rice Formation were deposited. Younger deposits record a history of alternating stability and episodic incision by the Rio Grande.

The Texas Lineament is commonly projected through the Rio Grande region near the study area where it may be expressed as: a major Precambrian discontinuity; the northwestern arm of the

Paleozoic Marfa Basin; the axis or eastern flank of the Mesozoic Chihuahua Trough; the western margin of the Diablo Platform; the approximate leading edge of Laramide (80 to 50 m.y. ago) thrusting (or the margin of the Chihuahua tectonic belt); or the northwest structural control on the development of the southern portion of the Hueco Basin. There has been intermittent deformation associated with at least some portions of the Texas Lineament from the Precambrian to the present (Horak, 1985), but major periods of activity appear to have been during the Precambrian and the late Paleozoic. Deformation has not been continuous, but the zone has been episodically reactivated by the imposition of regional tectonic stresses during periods of orogenesis.

## INTRODUCTION

This report is a summary of the regional geologic setting of the Fort Hancock study area, Hudspeth County, Texas. It is based on work by staff of the Bureau of Economic Geology and on a review of the published literature. An attempt has been made to stress the more recent published references on the region, but this is not a comprehensive evaluation of the voluminous available literature. The purpose of this discussion is to illustrate the regional characteristics of the setting of the proposed site for a low-level radioactive waste repository and to review the major geologic events that have influenced the development of the geologic framework of the proposed site. This discussion concerns the structural, stratigraphic, and tectonic setting of the Fort Hancock study area. Most emphasis is placed on those characteristics or events that have a direct bearing on the geologic features of the site or site vicinity. For more detailed information on topics that are specifically addressed in contract reports prepared as part of the site investigation, the reader is referred to the appropriate topical reports. The major part of this report is a chronologic summary of the geologic development of the region. Quaternary faulting within the Hueco Bolson and natural resources present near the study area are discussed in more detail following the regional summary.

The rocks exposed in Trans-Pecos Texas and adjacent areas of New Mexico and Mexico record a long sequence of geologic events. The Precambrian and Paleozoic events prepared the stage for the deposition of younger strata present in the study area and probably have imparted a tectonic grain that influenced subsequent deformation. Mesozoic and early Tertiary events are especially important to understanding the geology of the proposed site because they include deposition and deformation of units that now compose the host rocks for much of the deep saturated zone beneath the study area. Tertiary to Recent events include deposition and local deformation of the proposed host units for the repository. These younger events are the best source of information on the locations and rates of the more recently active geologic processes in the vicinity of the study area and are the best guide to evaluating the potential for further geologic modification during the 500-yr period of repository containment.

The Fort Hancock study area lies within the southeastern Basin and Range tectonic province. Adjacent provinces include the more stable Colorado Plateau to the northwest and the southern extension of the Great Plains to the east. The Basin and Range Province of late Cenozoic extensional faults continues well to the south into Mexico (e.g., Stewart, 1978). The discussion of the regional setting of the study area emphasizes the Trans-Pecos Texas, southern New Mexico, and northern Chihuahua portions of the Basin and Range Province. The region discussed here lies north of the postulated Mojave-Sonora megashear (Silver and Anderson, 1974), a possible left-lateral shear zone that separates the North American Precambrian craton from suspect terranes to the southwest. Figure 1 is a geologic map of the 100,000 $mi^2$ (260,000 $km^2$) region that includes the Fort Hancock study area and many of the geologic features discussed in this report.

## PRECAMBRIAN

Precambrian rocks are exposed at scattered localities throughout Trans-Pecos Texas and southern New Mexico and very locally in Chihuahua, but none crop out within 20 mi (32 km) of the proposed site (fig. 1). The distribution of Precambrian rocks in the broader context of the western United States is shown on small-scale geologic maps such as those by Condie (1981, 1986). Precambrian rocks in Chihuahua are present in drillholes at depths in excess of 13,000 ft (4,000 m) southwest of Ciudad Juarez, and in outcrops in the Los Filtros area north of Chihuahua City (Clark, 1984). Muehlberger (1980) suggested that the apparent deep burial of Precambrian rocks in Chihuahua may be related to a Precambrian rifting event at about 1,450 m.y. (Sears and Price, 1978). This is inferred by Muehlberger (1980) possibly to have imparted a northwest-striking tectonic grain that has strongly influenced the location and trends of subsequent tectonic events; this structural belt is referred to as the "Texas lineament."

De Cserna (1976) projected the Grenville-age Precambrian rocks of Texas and southeastern New Mexico into Mexico as the north-south-trending Oxacan structural belt. Condie (1986) suggested that early Proterozoic terranes occur in northeast-trending belts across the southwestern United States, and Grambling and others (1988) interpreted the Proterozoic of New Mexico to be composed of multiple terranes bounded by subhorizontal shear zones locally steepened by folding.

Among the closest outcrops of Precambrian rocks to the study area (fig. 1) are those in the Franklin Mountains, the southern Hueco Mountains, the Pump Station Hills on the Diablo Plateau, and the Allamoore-Van Horn area of Texas (Dietrich and others, 1983). The oldest Precambrian unit in West Texas is the Carrizo Mountain Group of metasedimentary and metaigneous rocks. The age of deposition has been inferred by Denison (1980) to be about 1,200 to 1,300 m.y. ago based on whole-rock Rb-Sr isochrons. The Carrizo Mountain Group has been thrust northward over the Allamoore Formation in the vicinity of Van Horn, Texas. The Allamoore Formation consists of basalts and carbonate rocks that are probably equivalent to metasedimentary units in the Franklin Mountains (Henry and Price, 1985). The overlying Hazel Formation near Van Horn is thought to be correlative with the Lanoria Quartzite in the Franklin Mountains.

Recent ages on probably correlative granites and rhyolites exposed in the Hueco Mountains, Franklin Mountains, and Pump Station Hills (Copeland and Bowring, 1988) indicate that igneous activity culminated by 1,150–1,135 m.y. ago. This is somewhat older than the 1,000 m.y. (possibly related to cooling) assigned by Denison and Hetherington (1969) to these rocks and the age commonly assumed for the Grenville orogenic period of volcanism, intrusion, metamorphism, and thrusting that marks the major Precambrian orogenic episode of the region (Denison, 1980; Muehlberger, 1980; Henry and Price, 1985). The Grenville and possibly earlier events were believed by King and Flawn (1953) and subsequent writers (Muehlberger, 1980) to have established a northwest structural grain in far West Texas that was reactivated in subsequent periods of deformation. Whether these Precambrian events were a significant control on the development of much younger structural features, including the west-northwest-trending Cenozoic extensional faults near the study area, is an issue of continuing discussion among investigators. Brown and Handschy (1984) have also suggested that Paleozoic, Mesozoic, and Cenozoic structural features in Chihuahua may represent reactivations of Precambrian faults.

Younger Precambrian sedimentary rocks were deposited, mildly deformed by uplift and rifting along the craton margin, and eroded prior to deposition of overlying Cambrian (?) and Ordovician strata. The only direct evidence of Precambrian rocks near the study area is the presence of clasts of Precambrian crystalline rocks in the "exotic" gravels (Albritton and Smith, 1965) that are locally found near the base of the Cenozoic Camp Rice Formation (Gustavson, 1990).

## PALEOZOIC

Paleozoic rocks are present in isolated outcrops throughout Trans-Pecos Texas, southern New Mexico, and locally in Chihuahua (fig. 1). Paleozoic strata (fig. 2) have also been intersected in many exploration wells. In southwestern New Mexico up to 11,000 ft (3,300 m) of Paleozoic strata were deposited (Kottlowski, 1971). In the state of Chihuahua, Paleozoic strata are known from only a few scattered outcrops and a few well penetrations (Brown and Handschy, 1984, their fig. 3, p. 165). No Paleozoic formations older than Ordovician crop out in Chihuahua (Bridges, 1974).

## Early through Middle Paleozoic

During the early and middle Paleozoic (Cambrian to Devonian), the region was a passive continental margin undergoing only minor epeirogenic uplift and subsidence and no major structural deformation (Horak, 1985). Passive subsidence of the Pedregosa Basin in Chihuahua permitted deposition of a thick sequence of Paleozoic shelf carbonates. The Tobosa Basin, precursor to the Delaware Basin, developed east of the Diablo Platform, with the study area lying on the western margin of the basin (Mear, 1980; Reaser, 1980). Sedimentation throughout the region was characterized by shallow-marine shelf deposits separated by a series of regional unconformities (Ross and Ross, 1985). These unconformities are shown in figure 2, the chart of regional correlations. Muehlberger (1980) noted the regional nature of the Lower Ordovician unconformity at the top of the Ellenburger Group and the El Paso Formation (LeMone, 1969). LeMone (1969) also described an unconformity at the top of the Upper Ordovician Montoya Group in the Franklin Mountains.

Thickness variations in Cambrian to Devonian strata are cited by Henry and Price (1985) as evidence that the Diablo Platform (fig. 3) was a positive feature during the early Paleozoic, although Muehlberger (1980, p. 116) suggested that the Diablo Platform was "first clearly recognizable" as a structural element in Permian time. The absence of pre-Permian Paleozoic rocks in a well southwest of El Paso is inferred by Brown and Handschy (1984) to indicate that the Burro-Florida-Moyotes Uplift extended south from New Mexico into northern Chihuahua during the early Paleozoic. Southwest of the Pedregosa Basin was another high, the Aldama Platform.

## Late Paleozoic

The relative tectonic quiescence of the early and middle Paleozoic passive margin setting changed to a more active margin in the late Paleozoic with the approach and eventual collision of this edge of the North American plate and the South American-African plate (formation of Gondwana). In West Texas this Appalachian-Ouachita-Marathon orogenic event began in the Mississippian and, based on evidence in the Marathon area (Ross, 1979), culminated in the Early Permian. Sediments deposited in areas not directly affected by active tectonism continued to be mostly carbonates and clastics deposited in a shallow cratonic sea (Henry and Price, 1985). The study area lay well in the foreland of the active orogenic belt.

Among the Trans-Pecos structural features attributed to late Paleozoic tectonism (fig. 3) are the Ouachita-Marathon fold and thrust belt, foreland basins and troughs with north-south-trending axes (King, 1965; Henry and Price, 1985), wrench faults along the Babb and Victorio flexures (Dickerson, 1980), north-side-down monoclines (Dickerson, 1980), and folds of pre-Permian rocks in the Hueco Mountains (Beard, 1985). Translation associated with the Ouachita-Marathon fold and thrust belt is from the southeast to northwest, with deeper-water flysch facies being thrust upon shallow-water limestones, dolomites, and sandstones (King, 1980). Late Permian reefs were in part localized on structural highs.

In New Mexico there is a series of late Paleozoic uplifts, the Deming axis (Turner, 1962) that trends across the southern part of the state to the Diablo Platform in Texas. The northwesterly trend of the uplifts has been interpreted as possible evidence of right-lateral shear in the late Paleozoic along the so-called Texas Lineament (Muehlberger, 1980). The study area lies southwest of the Diablo Platform, near the projection of the Texas Lineament.

Based on work in the Hueco Mountains and previous studies by Wilson (1967, 1972), Pol (1985) interpreted the Pedernal Uplift in New Mexico and the Diablo Platform to have been an emergent landmass during much of the Pennsylvanian. He described the Hueco Mountains area as a tectonically active shallow-marine shelf between the Pedernal/Diablo landmass to the east and the Oro Grande Basin of south-central New Mexico and northern Chihuahua to the west. The study area probably lies near the shelf margin as it existed during the late Paleozoic and part of the Mesozoic (Greenwood, 1971).

Relatively little is known about the effects of the late Paleozoic tectonic event in Chihuahua, but a Permian metamorphic event at Sierra Mojina (Denison and others, 1971), 95 mi (150 km) south of El Paso, is cited as evidence of this period of orogenic activity in Mexico (Muehlberger, 1980). A "probably Leonardian" rhyolite flow is present in the Mina Plomosas area (Bridges, 1974). Brown and Handschy (1984) saw no effects of the Ouachita event in northern or western Chihuahua, and Handschy (1984) suggested that evidence of the Ouachita-Marathon tectonism is restricted to southeastern Chihuahua.

## MESOZOIC

Figures 4 and 5 summarize the Mesozoic stratigraphy and Mesozoic tectonic elements in the region around the Fort Hancock study area. The major event in this region during the Mesozoic was the formation of the northwest-trending Chihuahua Trough in West Texas and adjacent northern Mexico. The Aldama Platform in Chihuahua, the Diablo Platform in Texas, and the Florida Uplift in New Mexico were the major adjacent positive features (fig. 5). Formation of the trough has been inferred to be related to the opening of the Gulf of Mexico (Muehlberger, 1980) and to resulting transform movement on the Mojave-Sonora megashear (Silver and Anderson, 1974; Anderson and Schmidt, 1983). The oldest sediments in the trough are Jurassic evaporites overlain by a thick sequence of Cretaceous marine deposits. Cretaceous deposits thicken markedly into the Chihuahua Trough: from 1,000 to 2,000 ft (300 to 600 m) thick on the Diablo Platform (Henry and Price, 1985) to over 13,000 ft (4,000 m) thick in Chihuahua (DeFord and Haenggi, 1971). No Triassic or Lower Jurassic sediments from Chihuahua have been described (Clark, 1984).

The Chihuahua Trough includes the northeastern two-thirds of Chihuahua, the westernmost Rio Grande region of Texas, the southwestern border region of New Mexico, and the southeastern corner of Arizona (Brown and Handschy, 1984). The deep northwest-trending axis of the trough lies mostly in northeastern Chihuahua but extends into Texas near El Paso and the study area

(Brown and Handschy, 1984) and possibly continues south to the vicinity of Big Bend National Park (Muehlberger, 1980; Henry and Price, 1985) where similar structures are present east of the park. The trough is asymmetric with a steeper northeastern flank.

The transition from the northeastern margin of the Chihuahua Trough to the southwestern edge of the Diablo Platform lies near the study area but is not exposed. The margin is inferred to be a series of pre-Cretaceous, large-displacement, southwest-dipping normal faults (Henry and Price, 1985). Uphoff (1978) used well data to infer the presence of a fault near Clint, Texas, that was interpreted to be one of these trough-bounding structures. The trough appears to have localized subsequent Laramide deformation and may account for the northwest trend of Basin and Range extensional faults in the vicinity of the Fort Hancock study area.

Northeast of Casas Grandes, Chihuahua, near Sierra El Capulin and Cerro El Chile, volcanic rocks (andesites and pyroclastics) are interbedded with Cretaceous marine sediments (Clark, 1984). Upper Cretaceous volcanic rocks are also present to the south near Chihuahua City. In Texas, the oldest evidence of Cretaceous volcanism is present in the Upper Cretaceous San Carlos Sandstone and Aguja Formation (Henry and Price, 1989), which contain ash, probably from volcanism in Mexico.

Mesozoic rocks present near the Fort Hancock study area (fig. 1) are mostly Lower Cretaceous marine limestones and clastics (Albritton and Smith, 1965). The Cox Sandstone and the overlying Finlay Limestone form prominent outcrops along the erosional escarpment of the Diablo Plateau north of the study area and are present on Campo Grande Mountain and in small hills in the footwall of the Campo Grande fault. Other Lower Cretaceous units, the Bluff Mesa Limestone, Yucca Formation, and the Kiamichi Formation are locally present in outcrop or have been penetrated in holes drilled in the study area as part of the current evaluation, or in the vicinity of the study area for petroleum exploration. Most of the Cretaceous strata thicken into the depositional basin to the south and southwest of the study area. The bolson units at the study area overlie an erosional surface developed on these Cretaceous units.

## MESOZOIC–CENOZOIC TRANSITION

The transition from the Mesozoic to the Cenozoic (Late Cretaceous to Eocene) was a time of major change in the region that includes the study area. The Laramide orogenic event transformed this part of the crust from a shallow-marine environment to an emergent, compressional continental margin. These effects are inferred to be the result of interactions between the North American and Farallon-Kula plates (Horak, 1985; Hamilton, 1987). North- and northwest-trending thrust faults and folds composing the Chihuahua tectonic belt developed along the northeastern margin of the Chihuahua Trough, with the deformation perhaps resulting from uplift of the trough and mostly northeastward sliding of Cretaceous strata on older evaporite units (Gries and Haenggi, 1971; Gries, 1980). The Diablo Platform was deformed by high-angle reverse faulting, local strike-slip faulting, and monoclinal folding but was otherwise little disturbed by Laramide tectonism (Henry and Price, 1989). Two directions of principal horizontal stress, east-west and N60°E, have been noted (Berge, 1981; Horak, 1985; Henry and Price, 1989). The northeast-southwest principal horizontal stress is most common in the Chihuahua tectonic belt, and the east-west stress is inferred not only from north-south oriented faults and fold axes but also from east-west-trending dikes in east-central New Mexico (Horak, 1985). Laramide-age igneous activity, probably post-folding, occurred in New Mexico, Arizona, and northern Mexico (Coney and Reynolds, 1977).

The leading edge of Laramide thrusting is present in the subsurface near the southern margin of the study area. Strongly folded rocks are present on Campo Grande Mountain southeast of the proposed site and in the high ranges in Mexico across the Rio Grande to the south. The monocline in Cretaceous rocks that marks the transition to the Diablo Plateau north of the study area, and whose gently dipping south flank underlies much of the study area, may be a Laramide structure. There is no direct evidence on timing of Laramide tectonism in the study area, but no rocks younger than Cretaceous are present that were deformed by this period of compression.

Regionally the timing of Laramide deformation is not closely constrained, but it began no earlier than the Late Cretaceous, perhaps at 80 m.y. ago. Laramide thrust faulting and folding appear to have ceased by about 50 m.y. ago (Price and Henry, 1985), and Laramide compressive stress appears to have waned by about 30 m.y. ago (Henry and Price, 1989). In the Big Bend area of Trans-Pecos Texas the major period of deformation is thought to have occurred in the late Paleocene (Wilson, 1971). In other areas researchers have proposed that more than one major episode of deformation occurred (e.g., Berge, 1981; Henry and Price, 1989).

## CENOZOIC

Laramide compression dominated the early Cenozoic (see above), but between about 30 m.y. ago and the present the region has been characterized by extensional tectonics, continental sedimentation (fig. 6), and local volcanism. The specifics of the Cenozoic stratigraphy, faulting, and Quaternary geomorphology as they relate to the study area and the proposed site are described in other contract reports written by staff of the Bureau of Economic Geology (Baumgardner, 1990; Collins and Raney, 1990; and Gustavson, 1990). Reports on topics related to regional geophysics and seismicity are being written concurrently by staff of the Department of Geological Sciences at The University of Texas at El Paso. The following discussion presents a broad overview and sets the regional context for the Bureau studies of the Cenozoic geology.

Regional extension and related volcanism occurred during the Cenozoic across much of the western United States. This tectonism is presumably related to earlier subduction along the western margin of the North American plate and residual thermal effects (Horak, 1985). The resulting Basin and Range Province includes the region surrounding the Fort Hancock study area. Cenozoic extensional basins of the region are shown in figure 7.

The Rio Grande rift is generally viewed as the north-south zone of Cenozoic extension and high heat flow that bisects New Mexico and may include related portions of the Basin and Range Province in Trans-Pecos Texas and northern Mexico. It has been argued, primarily based on geophysical data, that the Rio Grande rift is similar to, but distinct from, the "true" Basin and Range. Because of the apparent structural and stratigraphic continuity of the northwest-trending portion of the southeast Hueco Basin, in which the Fort Hancock study area is located, with the north-trending Hueco Basin near El Paso, the study area is inferred to lie in an extension of the Rio Grande rift within the Basin and Range Province. This is in agreement with heat flow data (Seager and Morgan, 1979; Henry and others, 1983). Seager and Morgan (1979) also noted that basins associated with the Rio Grande rift, like the Hueco Basin, tend to be deeper than nearby grabens associated with Basin and Range extension. Gravity data (Ramberg and others, 1978; Keller and Peeples, 1985) have been interpreted to indicate that it is common for some of the basins in New Mexico and Trans-Pecos Texas to contain about 9,500 ft (3 km) or more of basin-fill sediments.

The Cenozoic stratigraphy (fig. 6) of the basins of West Texas and New Mexico has been described by many authors (e.g., Albritton and Smith, 1965; Strain, 1966; Hawley and others, 1969; Groat, 1970; Stevens and Stevens, 1985; Gustavson, 1990), but correlations both within and between basins are difficult because of the scarcity of reliable age determinations. Most studies are based on investigations of available outcrops and geophysical data with limited samples from drilling, and the early history of basin development and sedimentation is not well defined. The oldest documented episode of Basin and Range extension in West Texas occurred about 24 m.y. ago (Henry and Price, 1986), somewhat more recently than that associated with the Rio Grande rift in New Mexico. A change in extension direction (from ENE to WNW) and a possible change to a lower strain rate at about 10 to 13 m.y. ago has been proposed for New Mexico and possibly Trans-Pecos Texas (Zoback and others, 1981; Golombek, 1983; Henry and Price, 1986).

The Hueco Basin deposits and the Cenozoic structural and depositional development of the study area are described in detail in other contract reports (Baumgardner, 1990; Collins and Raney, 1990; Gustavson, 1990) and summarized below. The sediments within the basins accumulated by lateral infilling from adjacent highlands and from more regional stream systems associated with the ancestral Rio Grande (Strain, 1966; Hawley and others, 1969). The early history appears to be one of a series of closed basins, locally and perhaps episodically integrated, that at various times received sediments from a river system that flowed generally from north to south and was not through-flowing to the Gulf of Mexico but terminated in the closed basins of northern Chihuahua and in part in the Hueco Basin. Although some standing bodies of water may have persisted as perennial lakes, ephemeral desert lakes or playas were more typical. Lacustrine muds and minor evaporite deposits are common in many sections. Sediment input from adjacent highlands was of local and episodic occurrence related to ephemeral drainages from restricted drainage basins. Proximal to distal alluvial fan deposits of locally derived materials are commonly present especially near basin margins. Local eolian reworking of the finer sediments is suggested, but no extensive eolian deposits are recognized.

In the study area the oldest Cenozoic sediments in outcrop, the Fort Hancock Formation, are probably upper Pliocene (fig. 6). Somewhat older but undated strata have been penetrated by drilling, and a much thicker Tertiary section is known to be present to the southwest of the study area in the hanging wall of the Campo Grande fault. Overlying the Fort Hancock Formation is the commonly coarser grained Camp Rice Formation. The initiation of Camp Rice deposition, about 2.5 m.y. ago, appears to be coincident with the integration of the southern Rio Grande with the northern ancestral Rio Grande and the initiation of a through-flowing river system in the Hueco Bolson. Deposits of gravels with clasts derived from rocks that do not crop out near the study area are evidence of the through-flowing river system (Albritton and Smith, 1965). Deposits that overlie the Camp Rice Formation record a history of deposition and downcutting related to the Rio Grande and periods of stability during which calcic soils were developed.

Fault scarps related to late Cenozoic faulting are common throughout much of the New Mexico–Trans-Pecos–Chihuahua region that includes the study area. The Quaternary fault of most significance to the proposed site is the Campo Grande fault, which is described in detail by Collins and Raney (1989, 1990) and Barnes and others (1989a). Across the Rio Grande in Chihuahua is the southwestern boundary fault of the Hueco Basin. This fault was mapped and described by Muehlberger and others (1978) as a 30- to 40-mi (50- to 60-km) -long Quaternary fault scarp. It has recently been named the Amargosa fault (Barnes and others, 1989b; Keaton and others, 1989).

The Amargosa fault has not been studied in as much detail as the Campo Grande fault, but it is generally similar in character to the East Franklin Mountains fault (fault 16, fig. 8) that bounds the Hueco Basin near El Paso. An expanded discussion of the Quaternary faulting of the Hueco Basin area is presented later in this report. Seismicity of the region is discussed in a separate contract report (Doser, 1990).

In addition to the Quaternary scarps associated with the Hueco Basin (Muehlberger and others, 1978) and its northern continuation (Tularosa Basin) (Seager, 1980; Machette, 1987), Muehlberger and others (1978) and Goetz (1980) recognized a well-developed system of scarps associated with the Salt Basin and its probable structural extensions to the north and south. The largest historic earthquake in Texas, the 1931 Valentine earthquake, was probably associated with a seismically active fault in this structural zone. Much has also been written about the Cenozoic fault scarps of southern and southwestern New Mexico (e.g., Machette and others, 1986; Gile, 1987). Quaternary fault scarps are also present throughout northern Chihuahua. These are little studied (Morrison, 1969) but are part of the evidence indicating the probable continuation of the Rio Grande rift into Chihuahua (Gries, 1979).

Volcanism and other igneous activity (fig. 1) that either apparently predates, or coincides with, Basin and Range tectonism in the region that includes the Fort Hancock study area has been described by many authors. Magmatism occurred in the Trans-Pecos region from about 48 to 17 m.y. ago. The main period of caldera-related magmatism was between 38 and 32 m.y. ago, with caldera formation continuing in adjacent Chihuahua until about 28 m.y. ago (Henry and McDowell, 1986). Those in the Finlay Mountains, closest to the study area, were emplaced about 47 m.y. ago (Henry and McDowell, 1986; Matthews and Adams, 1986) and produced structural doming of the earlier strata (Albritton and Smith, 1965).

In contrast to the Trans-Pecos region of Texas, magmatism associated with the Rio Grande rift of New Mexico has continued into the Holocene (Seager and others, 1984). Most authors (Baldridge and others, 1984) recognize two major pulses of volcanism associated with rifting: an early magmatic pulse between 30 and 18 m.y. ago and a pulse about 5 m.y. ago. There are also some notable volcanic centers (Jemez) whose eruptions are not coincident with either pulse. In addition, development of the Mogollon-Datil volcanic field (active about 43-20 m.y. ago) of southern and southwestern New Mexico may be related to Cenozoic extension, although it is not strictly part of the Rio Grande rift (Baldridge and others, 1984). Volcanic rocks associated with the Rio Grande rift are of diverse composition and have no simple pattern of distribution that may be related to the evolution of the rift.

## QUATERNARY FAULTS OF THE HUECO BASIN

Faults that offset Quaternary sediments are common in the northwest-trending Hueco Basin (fig. 8). Gravity studies by Wen (1983) and Keller and Peeples (1985) indicate that the Hueco Basin is composed of two subbasins that are referred to in this report as the northwest and southeast Hueco Basins (fig. 9). The northwest Hueco Basin is composed of normal faults that generally strike northward, whereas normal faults of the southeast Hueco Basin strike northwestward (fig. 8). The Fort Hancock study area is located within the southeast Hueco Basin.

Seager (1980) described the northwest Hueco Basin as an asymmetric, west-tilted graben (fig. 10a). The southeast Hueco Basin has a similar geometry (fig. 10b). The deepest parts of the basin are bound by major faults that define a large (about 15.5 mi [25 km] wide) graben, segregated into northwest and southeast portions (fig. 10). Intragraben faults also exist, and some faults also occur outside the large grabens. The following discussion summarizes the geometries, offsets, lengths of surface expressions, fault-scarp morphologies, and amounts of offset during the last surface ruptures of selected surface faults shown in figure 8.

Nomenclature of Quaternary stratigraphic units in the study region is shown in figure 6. Terminology referring to fault offset and scarp morphology is illustrated in figure A-1. Morphometric data for fault scarps are in tables A-1 and A-2, and the locations of selected field stations referred to in this report are in figures A-2 and A-3.

## Faults of the Northwest Hueco Basin

Faults of the northwest Hueco Basin strike northward and have been mapped and discussed by numerous researchers. Faults bounding the Franklin Mountains have been reported by Richardson (1909), Sayre and Livingston (1945), Lovejoy (1971, 1972), Harbour (1972), Lovejoy and Hawley (1978), Lovejoy and Seager (1978), and Machette (1987). Numerous faults that occur east of the Franklin Mountains (within the northwest Hueco Basin) have been described by Seager (1980), Henry and Gluck (1981), and Sergent, Hauskins, and Beckwith (1989). Faults of this northwest Hueco Basin area, as well as surrounding areas, also have been mapped during regional mapping investigations by Woodward and others (1978), Dietrich and others (1983), and Henry and Price (1985).

The most distinct fault scarp in the northwest Hueco Basin is the East Franklin Mountains fault (Machette, 1987) (fault 16, fig. 8) that bounds the northwest Hueco graben on the west. Fault 16 trends along the east flank of the Franklin Mountains and has also been referred to as the East Boundary fault by Lovejoy (1971, 1972). En echelon to fault 16 is fault 19 (fig. 8), which trends along the southeastern part of the Franklin Mountains and is inferred to strike southward toward the eastern flank of Sierra De Juarez in northern Chihuahua. Fault 19 was not studied for this report because its surface expression either is mostly covered by Rio Grande alluvium or has been disturbed by construction of buildings and roads in El Paso.

Scarps of the East Franklin Mountains fault (fault 16) are commonly compound scarps (fig. A-2), and usually the steepest slope angles are between 13 and 23° (fig. 11a and table A-1). Multiple rupture events during the Quaternary have caused older Quaternary surfaces to be offset more than younger surfaces. Scarp heights commonly vary between 18 and 128 ft (5.5 and 39 m), owing to the different ages of faulted Quaternary sediments along the fault trace (table A-1). Middle Pleistocene sediments (Jornada I surface, fig. 6) are offset at least 105 ft (32 m) (fig. 12). In a previous study Machette (1987, his table 1, p. 44) reported scarp slope angles between 10 and 26°

and scarp heights between 6.5 and 195 ft (2 and 60 m). Machette (1987, p. 27) also reported that late Pleistocene to Holocene sediments (Issachs Ranch or younger alluvium [fig. 6]) are offset by the East Franklin Mountains fault across a 12 ft- (3.7 m-) high scarp. Machette (1987, p. 27) suggested that the youngest scarps along the East Franklin Mountains fault are early Holocene or latest Pleistocene in age (about 10,000 to 5,000 years old), on the basis of scarp morphology.

The East Franklin Mountains fault (fault 16, fig. 8) has a surface trace of about 14.2 mi (23 km) and is approximately 50 mi (80 km) from the proposed repository site in Hudspeth County (table 1). Multiple faulting events since the middle Pleistocene are indicated by compound fault scarps and greater offsets on increasingly older sediments. Amount of offset during the last rupture event was from approximately 5.5 to 10 ft (1.7 to 3.0 m), assuming that the steepest parts of compound scarps reflect the latest single rupture event.

Scarps of intragraben faults and major faults that bound the east side of the northwest Hueco graben (fig. 8) are not as distinct as the East Franklin Mountains fault scarp. Windblown sand usually covers the scarps. Scarp profiles were studied for faults 1, 2, 3, 4, 5, and 17 (fig. 8). The intragraben faults (faults 1, 2, 3, and 17) are commonly downthrown to the east, whereas the major faults that bound the northwest Hueco graben on the east (faults 4 and 5) are downthrown toward the west (fig. 8). Scarp slope angles are low (2 to 4.5°) and scarp heights are between 5 and 23.6 ft (1.5 and 7.2 m) (fig. 11 and table A-1). Fault offsets of possible middle Pleistocene deposits that are capped with Stage IV to V caliche (Machette, 1985) are unknown because eolian deposits usually cover the scarps, and alluvium and windblown sand overlie the middle Pleistocene deposits on the down-thrown fault blocks. Studies of these faults (faults 1, 2, 3, 4, 5, and 17) indicate that minimum offsets of probable middle Pleistocene sediments are greater than 6.5 to 18 ft (2 to 5.5 m) (fig. 12).

Intragraben surface faults are common in the northwest Hueco Basin (figs. 8 and 10). The lengths of these fault traces (including faults 1, 2, 3, and 17) are about 8 to 13 mi (12 to 21 km). Distances of these faults from the proposed waste repository in Hudspeth County range between about 27 and 44 mi (43 and 70 km) (table 1). The steep part of a sand-covered and subtle compound scarp of fault 3 suggests the amount of offset of the last surface rupture was at least 3 ft (1 m) (table 1). Faults on the east side of the northwest Hueco graben that are downthrown toward the west include faults 4 and 5. Lengths of the surface traces of these faults are between 6 and 7 mi (10 and 11 km), and these faults are 37 and 26 mi (60 and 42 km) from the proposed site for the low-level radioactive waste repository (table 1). The amounts of offset during the last ruptures of these faults are unknown.

Surface fault traces of faults outside the northwest Hueco graben (west of faults 16 and 19 and east of faults 4 and 5) have been mapped in the Franklin and Hueco Mountains. Bedrock that crops out in these areas is commonly covered by Quaternary alluvium. Faults that displace bedrock in these areas generally do not have distinct scarps. It is not known if faults in the mountain areas have moved during the Quaternary. The structural and depositional setting of the area indicates most Quaternary fault movement and coincident deposition has occurred within the graben area (fig. 10a). The presence of fault 6 (fig. 8) indicates some Quaternary fault movement has occurred outside the main northwest Hueco graben. Fault 6 is downthrown to the east and is within the northwest Hueco topographic basin, although it is outside the main Hueco graben (fig. 8). Fault 6 has a subtle, sand-covered scarp similar to faults 1, 2, 3, 4, 5, and 17.

## Faults of the Southeast Hueco Basin

Faults of the southeast Hueco Basin strike northwestward and have been mapped and discussed by Bell (1963), Milton (1964), Albritton and Smith (1965), Strain (1966), Jones (1968), Jones and Reasor (1970), Barnes and others (1989a, b), Keaton and others (1989), Sergent, Hauskins, and Beckwith (1989), and Collins and Raney (1989, 1990). Faults of this southeast Hueco Basin area also have been mapped during regional geologic investigations by Woodward and others (1978), Dietrich and others (1983), and Henry and Price (1985). Some small faults inferred near Alamo, Camp Rice, and Diablo Arroyos by Dietrich and others (1983) could not be found in the field and are not shown in figure 8.

The most distinct fault scarp in the southeast Hueco Basin is fault 14 (fig. 8), a major fault that bounds the southeast Hueco graben on its southwest flank in Chihuahua. Fault 14 is at the base of Sierra de San Ignacio, Sierra de la Amargosa, and Sierra San Jose del Prisco, and has been called the Amargosa fault by Barnes and others (1989a) and Keaton and others (1989). The Amargosa fault is composed of en echelon fault strands, has a surface trace of about 43.5 mi (70 km), and is approximately 15.5 mi (25 km) from the Fort Hancock study area (table 1). This fault strikes approximately N40-50°W, dips 75 to 80° northeastward, and appears to have had mostly vertical offset where we studied it, although Barnes and others (1989a) and Keaton and others (1989) reported graben-like extensional features along the fault as evidence for lateral components of fault slip. Scarp-slope angles of the Amargosa fault (fault 14) are steeper than those of other faults of the Hueco Basin. Slope angles are between 19 and 27°, and scarp heights vary between 105 and 9 ft (32 and 2.8 m) (fig. 11 and table A-2). The ranges in scarp heights are due to multiple rupture events during the Quaternary that have caused older Quaternary surfaces to be offset more than younger surfaces.

At a location west of Porvenir, Chihuahua, four Quaternary surfaces are offset by the Amargosa fault (figs. 13 and A-2, locations 221, 222, 223, and 225). The oldest of these surfaces (Q1, fig. 13) is composed of piedmont deposits, has a Stage IV to V caliche (Machette, 1985), is estimated to be middle Pleistocene age and is offset about 78 ft (24 m). The younger Quaternary surfaces (Q2, Q3, Q4, fig. 12) are arroyo terraces and are estimated to be of late Pleistocene age. Two of these younger surfaces, Q2 and Q3 (fig. 13), have Stage III-IV caliche, and the youngest terrace (Q4) has Stage II calcic development. Surfaces Q2, Q3, and Q4 are offset 21, 13, and 8 ft (6.5, 4, and 2.5 m), respectively. The varying amounts of offset of these three late Pleistocene surfaces indicate at least three fault events since the formation of Q2. Surface ruptures have had between 5 and 8 ft (1.5 and 2.5 m) of offset per event. An important field observation made at this area is that both scarp profiles of Q2 and Q3 have steep single slope angles of about 20° rather than compound slopes, even though multiple surface ruptures have occurred. This relationship may be due to a relatively short length of time between ruptures, to the composition of the faulted sediments, or some unknown factors. This field observation indicates not all steep single slope scarps in this area are due to single rupture events. Northwest of the area mapped in figure 13, at field location 220 (fig. A-2), sediments with Stage II calcic development and of late Pleistocene (?) age are vertically offset 14.5 ft (4.5 m). It is unknown if the steep single slope scarp (slope angle as much as 20°) resulted from one or multiple surface rupture events. Barnes and others (1989a) interpreted vertical offsets of 8 to 14.5 ft (2.5 to 4.5 m) per rupture event for the Amargosa fault (fault 14, fig. 8). In the area west of Porvenir (fig. 13), young, probably Holocene sediments (Q5 and Qal on fig. 13) are not faulted, although relationships mapped on aerial photographs (fault 14, fig. 8) suggest that young (possibly Holocene) sediments may be offset elsewhere along the Amargosa fault trend, particularly at location 230 (fig. A-2), near the central part of the Amargosa fault.

Scarps of intragraben faults and major faults that bound the northeastern side of the southeast Hueco graben (figs. 8 and 9b) are not as distinct as the Amargosa fault scarp (fault 14). Faults 15, 10, and 13 (fig. 8) are the main faults that bound the northeastern side of the southeast Hueco graben. Fault 15 (fig. 1), the Campo Grande fault, has a surface trace of about 28 mi (45 km), and is approximately 2.5 mi (4 km) from the center of the Fort Hancock study area. The Campo Grande fault is the closest fault to the study area that has demonstrable Quaternary displacement. Part of this fault was mapped by Albritton and Smith (1965) and Strain (1966). Strain (1966) named it the Campo Grande fault after Campo Grande Mountain, a prominent hill on the footwall fault block. The Campo Grande fault has been mapped and discussed by Barnes and others (1989b), Sergent, Hauskins, and Beckwith (1989), and Collins and Raney (1989, 1990). The latter researchers have described the fault in detail.

The Campo Grande fault (fault 15, fig. 8) is composed of en echelon fault strands that are 1 to 6 mi (1.5 to 10 km) long and have strikes of N25°-75°W. Dips are between 60 and 90° southwest. Grooves on fault planes indicate mostly dip-slip movement. Fault scarps have been modified by erosion of the footwall and deposition on the hanging wall. Erosion-resistant caliche (Stages IV to V) at the surface aids in preserving scarp heights of between 5 and 38 ft (1.5 and

11.5 m) and scarp slopes of 4 to 17° (fig. 11). Successively younger units cut by the Campo Grande fault have less displacement. The middle Pleistocene Madden Gravel (fig. 6) is offset by all the fault strands that compose the Campo Grande fault; the Madden Gravel has a maximum vertical offset of about 33 ft (10 m) (fig. 12). The late Pleistocene age Ramey Gravel (fig. 6) is offset as much as 10 ft (3 m) by several fault strands, although some Ramey deposits overlie fault strands and are not faulted. The younger late Pleistocene age Balluco Gravel (fig. 6) and Holocene sediments are not offset by the Campo Grande fault. On the downthrown block of one fault strand, faulted calcic horizons (1.6 to 3 ft [0.5 to 1.0 m] thick; Stage III) with vertical separations of 3 to 6.5 ft (1 to 2 m) indicate at least five episodes of movement, deposition, and surface stabilization since the middle Pleistocene. Maximum vertical offset during the last faulting event was about 3 to 5 ft (1 to 1.5 m).

Fault 10 (fig. 8), another major fault that bounds the northeastern side of the Hueco graben, lies southeast of the Campo Grande fault (fault 15, fig. 8). Fault 10 has a locally covered surface trace of 9.3 mi (15 km), and the shortest distance between it and the proposed repository site is about 6.2 mi (10 km) (table 1). This fault strikes N30-60°W and dips about 60° to 85° southwestward. Where the scarp is preserved it has a height between 5.5 to 8 ft (1.7 to 2.5 m) and a compound slope with the steepest slope angle of as much as 15°. Erosion-resistant caliche helps preserve the scarp. Middle Pleistocene Madden Gravel sediments are offset as much as 10 ft (3 m) indicating that fault 10 has been less active than fault 15 (Campo Grande fault) since the middle Pleistocene (figs. 8 and 12). Much of the trace of fault 10 is covered by unfaulted late Pleistocene and Holocene sediments. The approximate amount of vertical offset on fault 10 during the last surface rupture was about 2 ft (0.6 m), if the steep parts of compound scarps reflect the latest single rupture event.

Fault 13 (fig. 8) is another main fault that bounds the northeastern side of the southeast Hueco graben. Fault 13 was informally named the Caballo fault by Jones (1968), and it flanks the west side of the Quitman Mountains. It has a surface trace of about 30 mi (48 km), strikes N20-40°W, dips southwestward, and its shortest distance to the proposed repository site is about 30 mi

(48 km). The scarp of the Caballo fault is well dissected and difficult to distinguish along most of the fault trace, although at location 205 (fig. A-2) a compound scarp was measured to be 34 ft (10.5 m) high. The steep part of the compound slope is 15° (fig. 11, table A-2). South of location 205 (fig. A-2) as much as 79 ft (24 m) of offset was estimated for the middle Pleistocene Madden Gravel (figs. 6 and 12), although erosion of sediments along the fault trace makes precise measurement difficult. Offset of the late Pleistocene age Ramey Gravel is 23 ft (7 m), and the younger late Pleistocene age Balluco Gravel (fig. 6) is not faulted. The approximate amount of vertical offset during the last surface rupture was about 5.5 ft (1.7 m), determined by assuming that the steep parts of compound scarps reflect the latest single rupture event.

Intragraben faults of the southeast Hueco Basin have neither scarps that are as distinct nor surface traces that are as long as those of the main faults bounding the graben. Faults 7, 8, 9, 11, and 12 are intragraben faults that were studied (fig. 8). Fault 7 has a surface trace of 6.2 mi (10 km) and is about 8 mi (13 km) from the proposed repository site (table 1). Middle Pleistocene Madden Gravel (fig. 6) is offset about 59 ft (18 m) (fig. 12). Fault 8 has a surface trace of about 2 mi (3 km) and is 7.4 mi (12 km) from the proposed site. The middle Pleistocene Madden Gravel (fig. 6) is offset 13 ft (4 m) at fault 8 (fig. 12). Fault 9 is 10.5 mi (17 km) from the proposed site, has a surface trace less than 0.5 mi (0.8 km) long, and is overlain by unfaulted middle Pleistocene Madden Gravel (table 1 and fig. 12). The top of the Pliocene Fort Hancock Formation (fig. 6) is offset only 29.5 ft (9 m) at fault 9. Fault 11 has a surface trace of less than 1 mi (1.5 km), is 13.6 mi (22 km) from the proposed repository site, and offsets middle Pleistocene Madden Gravel about 6.5 ft (2 m) (Albritton and Smith, 1965). Fault 12 has a surface trace of about 5.5 mi (9 km), is about 37 mi (61 km) from the proposed repository site (table 1), and displaces the late Pleistocene age Ramey Gravel (fig. 6) 45 ft (13.8 m).

Surface faults outside the southeast Hueco graben have been mapped in the mountain ranges that bound the basin and along the Diablo Plateau escarpment. These faults do not have distinct scarps, and they offset Mesozoic and Paleozoic bedrock. It is unknown if these faults have moved during the Quaternary. The structural and depositional setting of the area indicates that most

Quaternary fault movement and coincident deposition occurred within the graben (fig. 10b). Fault 18, which has been called the Rim fault by Sergent, Hauskins, and Beckwith (1989), is located between 2.5 and 5.6 mi (4 and 9 km) north of the proposed repository site at the Diablo Plateau escarpment (fig. 8). The fault has a surface trace of about 5.6 mi (9 km) and strikes westward, oblique to the northwest striking and southwest dipping monocline that defines the Diablo Plateau escarpment in this area. Fault 18 (Rim fault) has several fault strands, and its geometry varies from being a fault with as much as 65 ft (20 m) of vertical offset to being a flexure associated with only minor faults of <3 ft (1 m) vertical offset. The main fault plane dips about 75 to 85° southward. Cretaceous limestone and sandstone bedrock adjacent to the fault is highly fractured, and many of the fracture surfaces and bedding planes have striations with orientations that range from horizontal to vertical. Striations on the main fault plane range from trending parallel to the dip of the fault to trending oblique to the fault plane dip (rakes as small as 65°). Unfaulted alluvium (possibly as young as Holocene) overlies the fault where it projects westward into the Hueco Basin.

## Local Stress Field

The Hueco Basin is within the southeast part of the regional Basin and Range-Rio Grande Rift Stress Province (Zoback and Zoback, 1980) (fig. 14). The regional least principal horizontal stress direction of this stress province is west-northwestward, although local variations in the stress field may occur (Zoback and Zoback, 1980). There have been no in situ stress measurements of the stress field in the Hueco Basin to determine what variations may exist. On the basis of the orientation of grooves on the fault plane of the Campo Grande fault (fig. 8, fault 15), the closest fault to the proposed repository site, extension (least principal horizontal stress direction) was determined to be northeastward during the last fault movement (late Pleistocene). This direction is different from the regional west-northwestward direction characteristic of the stress province. Preexisting zones of crustal weakness might have affected the occurrence and geometry of Quaternary faults in the Hueco Basin.

# NATURAL RESOURCES

The following is a discussion of known occurrences of geologic natural resources (mineable minerals, industrial materials, and oil and gas) in the vicinity of the study area. Ground-water resources are discussed in a separate contract report (Mullican and Senger, 1990). Occurrences of currently economic deposits or accumulations of geologic natural resources are not known to be present beneath the study area or in lands adjacent to the study area.

## Mineable Minerals and Industrial Materials

The closest major prospect to the study area of potentially mineable minerals is the beryllium deposit (Rubin and others, 1987) at Sierra Blanca Peaks, approximately 17 mi (28 km) southeast of the study area. The Sierra Blanca Peaks may also represent a large-tonnage, low-grade resource of rare earths and thorium. Early exploration (McAnulty, 1980) discovered widespread mineralization (fluorite, beryllium, uranium, and tin). No evidence of similar mineralization is known near the study area.

Other prospects in the vicinity include small occurrences of base and precious metals and fluorspar mineralization in the Quitman Mountains, small gypsum prospects in the Malone Mountains, and small uranium occurrences in the Hueco and Quitman Mountains (Albritton and Smith, 1965; Price and others, 1983). U.S. Borax, Inc., drilled three holes to test a geophysical anomaly (induced polarization) for possible copper mineralization in the Finlay Mountains, but the anomaly was determined to be due to pyrite mineralization; no base metals were encountered. Deposits of metallic and nonmetallic minerals in the Sierra Diablo region, east of the study area, are discussed by King (1965). Scattered mineral occurrences are present in Chihuahua (Clark and Ponce, 1983), but no major prospects are present in the portion of Chihuahua closest to the study area. McAnulty (1971) presented a discussion of the mineral potential in the Chihuahua tectonic belt.

Deposits of sand, gravel, and caliche are abundant throughout the region and have been locally developed in the Fort Hancock area. Existing excavations are very limited. Because these materials are so common and of such low unit value, there is no apparent reason why similar deposits in the Fort Hancock study area should be subject to development, especially because there are equally good deposits that are much closer to current centers of population. Clay has been mined from the Fort Hancock Formation east of the site near Finlay for use as drilling mud (Albritton and Smith, 1965), and similar low-grade deposits can be found throughout the region, including the study area. There appears to be nothing unique about the clays in the bolson deposits beneath the study area that makes them especially attractive for exploitation. The greater thickness of low-clay overburden at the study area, the distance to rail transportation, and the abundance of the clay resource throughout the area underlain by the Fort Hancock Formation, all indicate that development of clay deposits beneath the study area is unlikely. Outcrops of igneous rock and Cretaceous limestone have been locally quarried for use in nearby construction projects, but there are no known outcrops of either rock type in the study area.

## Oil and Gas

The region around the study area has been explored for possible hydrocarbon accumulations. The area has been crossed by many seismic surveys, and a few exploration wells have been drilled, but no production of oil or gas has resulted from these activities. The main targets have apparently been structural targets in the Laramide-deformed Cretaceous and Paleozoic rocks. The two closest wells to the study area are a shallow well drilled by Black Oil Company near the old spillway to the dam at Cavett Lake, about 3 mi (4.5 km) west of the study area and the Haymond Krupp Oil and Land Company Thaxton 1 well drilled west of Campo Grande Mountain, about 4 mi (6.5 km) southeast of the study area.

The Black Oil Company well drilled through a shallow cover of bolson sediments and into a few hundred feet of Cretaceous rock. The presumed target was a trap associated with the Laramide overthrust belt. The Thaxton 1 well was almost 7,000 ft (2,130 m) deep. It penetrated a thick Cretaceous section and bottomed in Permian rocks; a thrust fault was crossed at about 1,390 ft (420 m) below surface. The presumed target was in Paleozoic rocks, but the structurally repeated Cretaceous section prevented adequate testing of the Paleozoic strata at relatively shallow depth. No hydrocarbons were produced from either well. Other wells have been drilled in the region within 25 mi (40 km) of the study area, but no commercial production has occurred. Descriptions of some of the exploration wells are found in Albritton and Smith (1965), Pearson (1980), and Veldhuis and Keller (1980); data on many of the wells are unavailable.

Additional untested prospects may be found in the broader region that includes the study area (e.g., Greenwood, 1971, Chihuahua; and LeMone, 1985, southern Hueco Mountains), but exploration results have so far been discouraging. Mesozoic and Cenozoic faulting that may have ruptured potential reservoirs, moderate to high heat flow (Taylor and Roy, 1980), and the relative paucity of marine organic shales to serve as source rocks and seals (Pearson, 1980) may reduce the chances for successful exploration.

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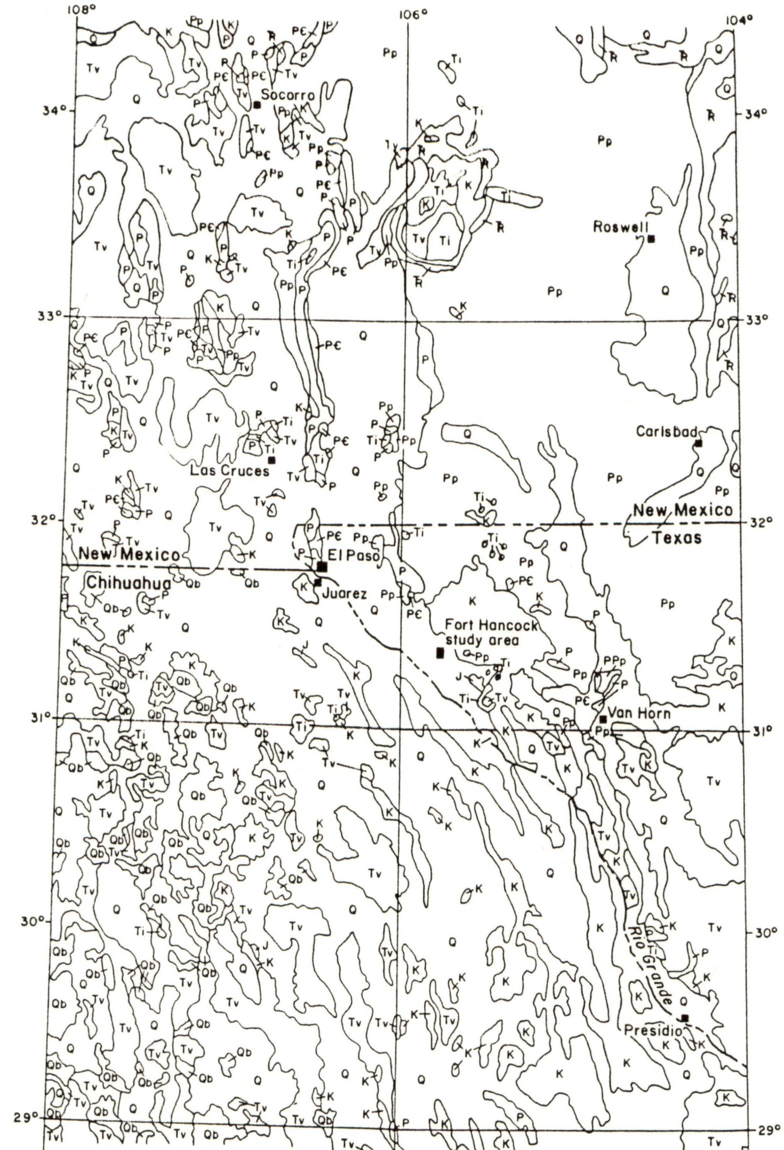


Figure 1. Generalized geologic map of the region containing the Fort Hancock study area (FHSA). Map units are: Q - Quaternary and upper Tertiary sedimentary units; Qb - Quaternary basic extrusive volcanic rocks (Chihuahua); Tv - Tertiary and Quaternary (mostly in New Mexico) volcanic rocks; Ti - Tertiary intrusive rocks; K - Cretaceous sedimentary rocks; J - Jurassic sedimentary rocks; Tr - Triassic sedimentary rocks; Pp - Permian sedimentary rocks; P - Paleozoic rocks undivided; PC - Precambrian rocks undivided. Map modified from Oetking and others (1967) (New Mexico); Renfro and others (1973) (Texas); and Direccion General de Geografia del Territorio Nacional (1981) (Chihuahua).

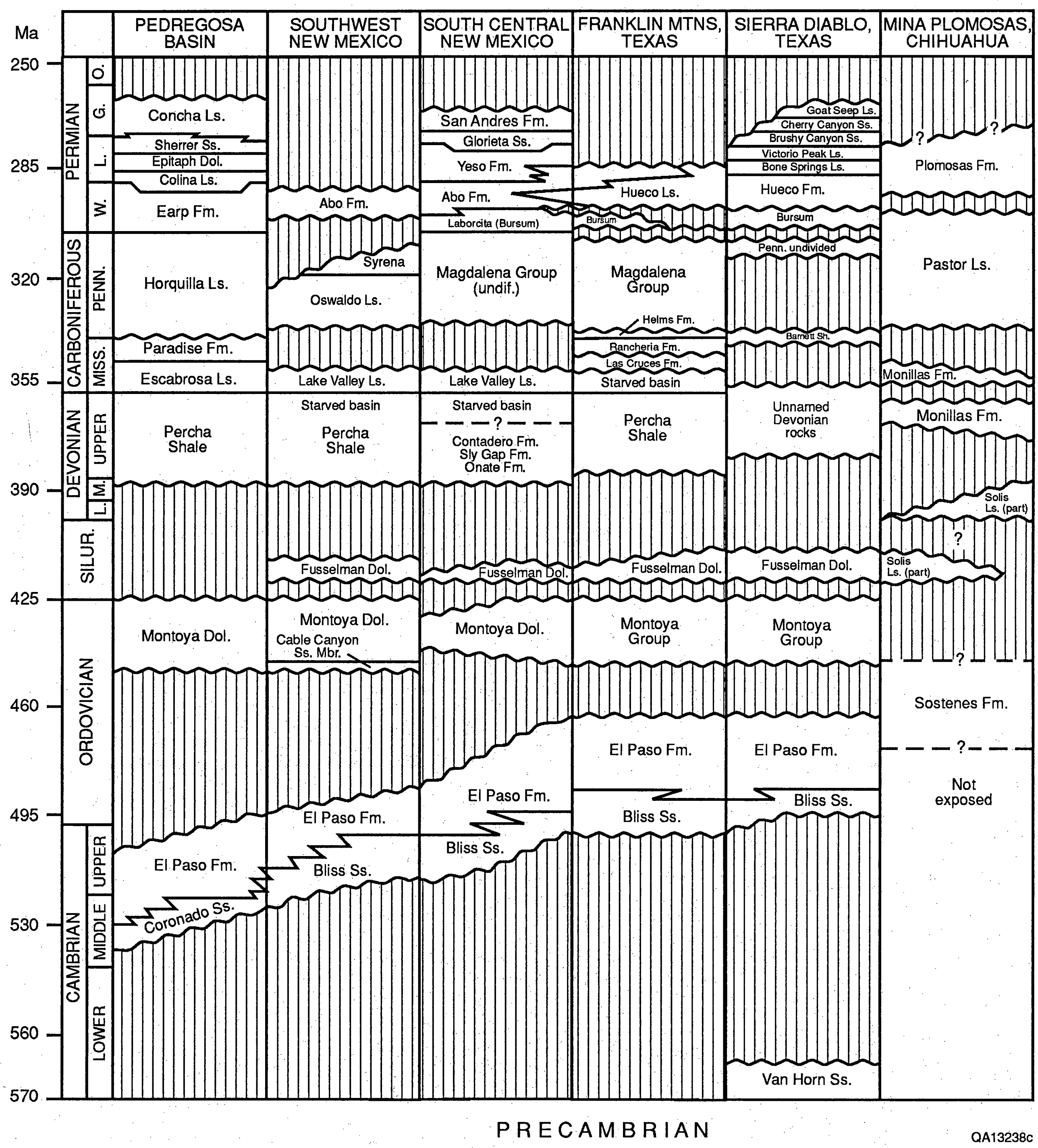


Figure 2. Chart of regional Paleozoic stratigraphy. After Ross and Ross (1985).

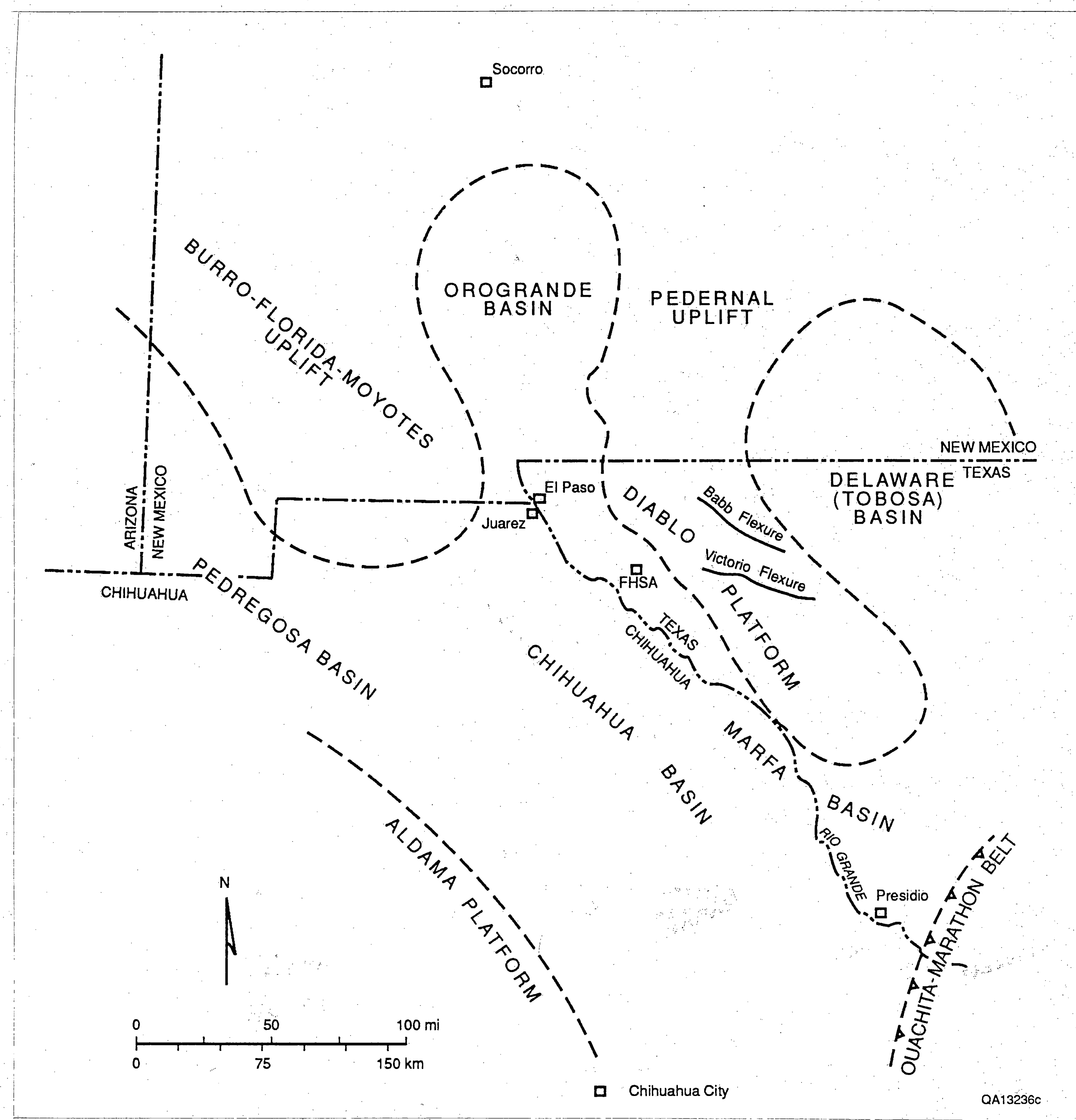


Figure 3. Generalized map of Paleozoic tectonic setting. Tectonic elements generalized from several sources, including Gries (1980), LeMone and others (1983b), and Brown and Handschy (1984). FHSA = Fort Hancock study area.

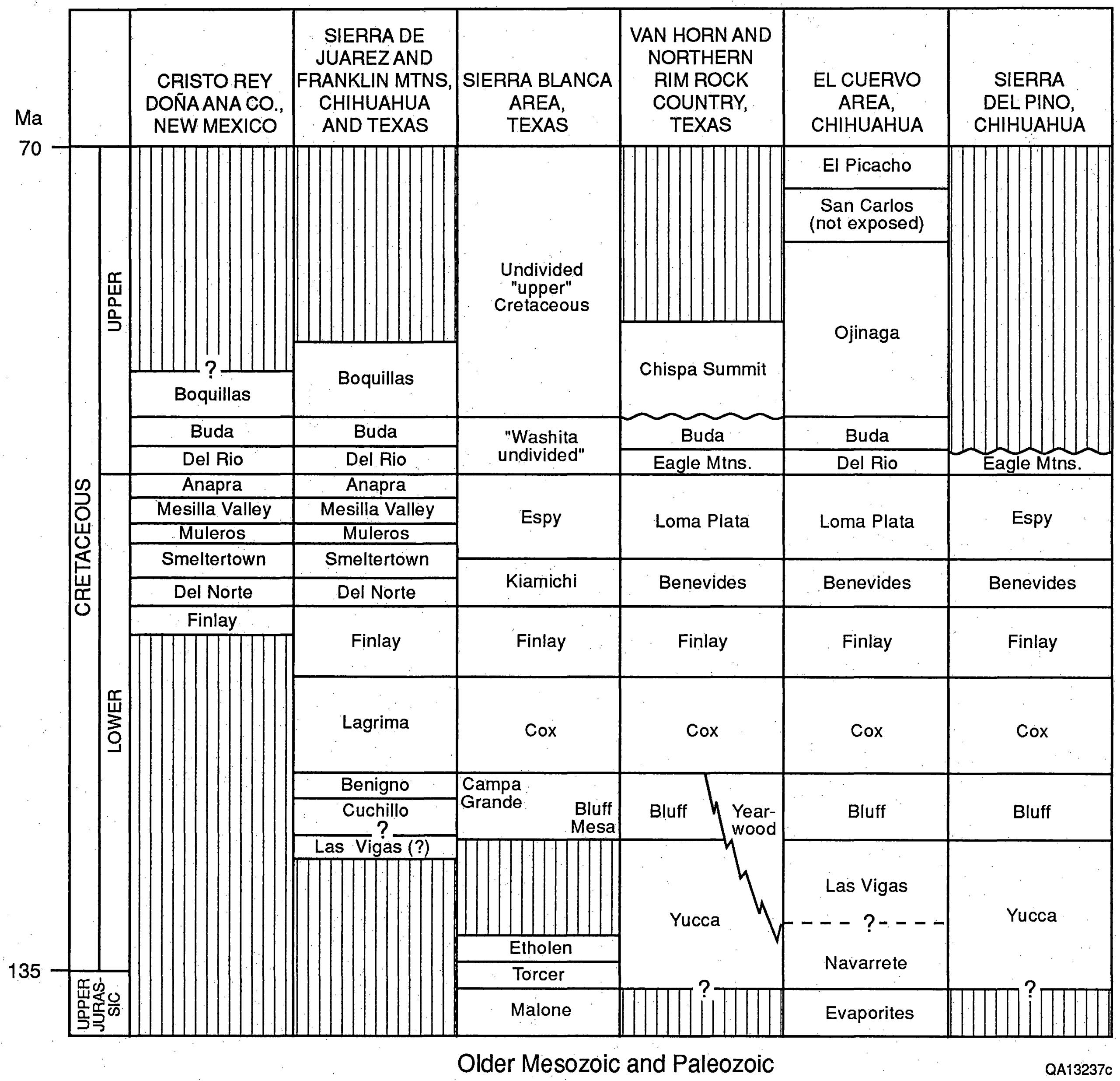


Figure 4. Chart of regional upper Mesozoic stratigraphy. Modified from Underwood (1980) and LeMone and others (1983a).

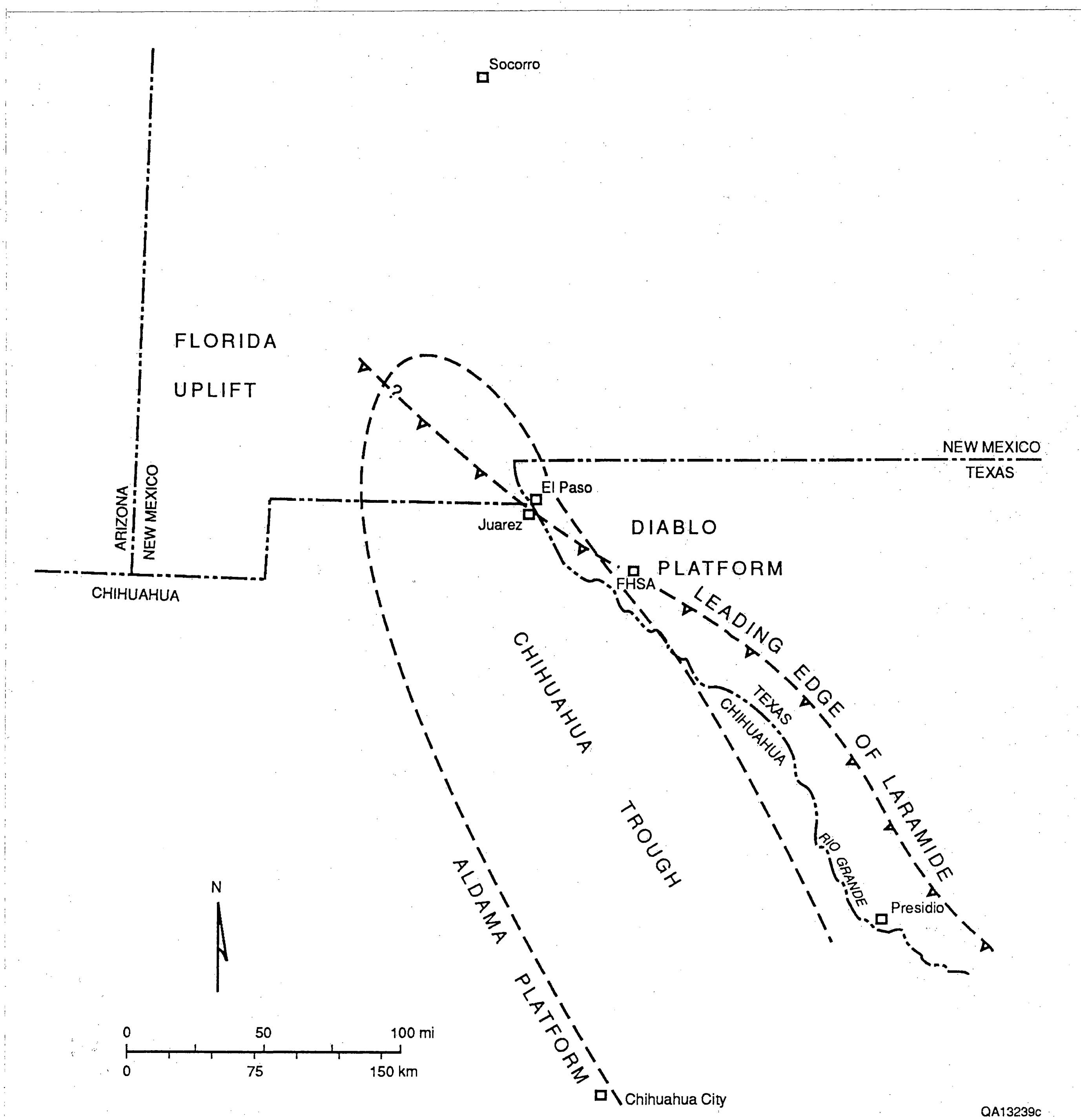


Figure 5. Generalized map of Mesozoic/Laramide tectonic setting. Tectonic elements from several sources, including Wiley and Muehlberger (1971), Navarro and Tovar (1974), and Brown and Handschy (1984). FHSA = Fort Hancock study area.

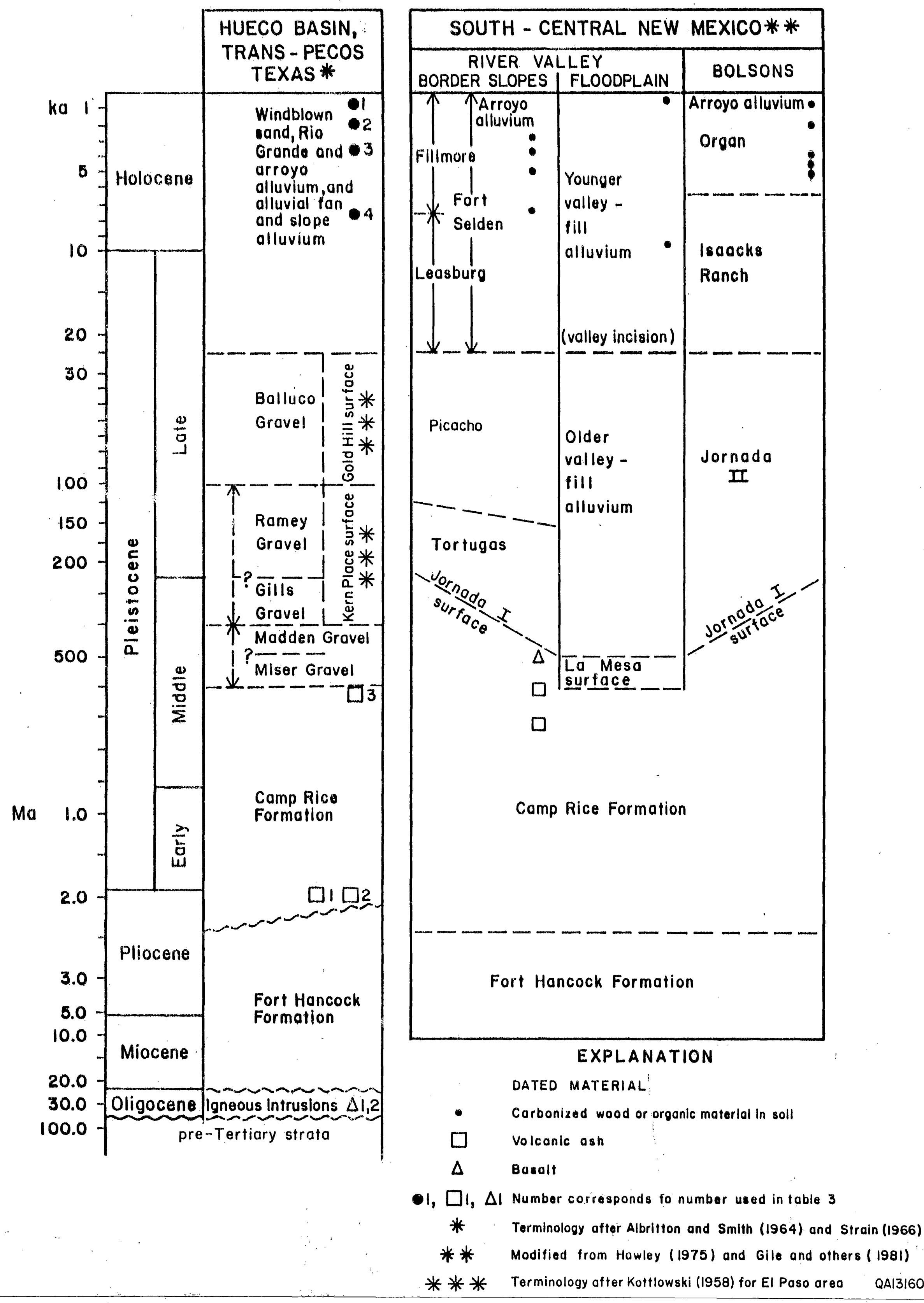


Figure 6. Cenozoic stratigraphy of basin-fill deposits of the Hueco Basin, Trans-Pecos Texas and south-central New Mexico. Modified from Collins and Raney (1990). Table 3 in explanation refers to table 3 of Collins and Raney (1990).

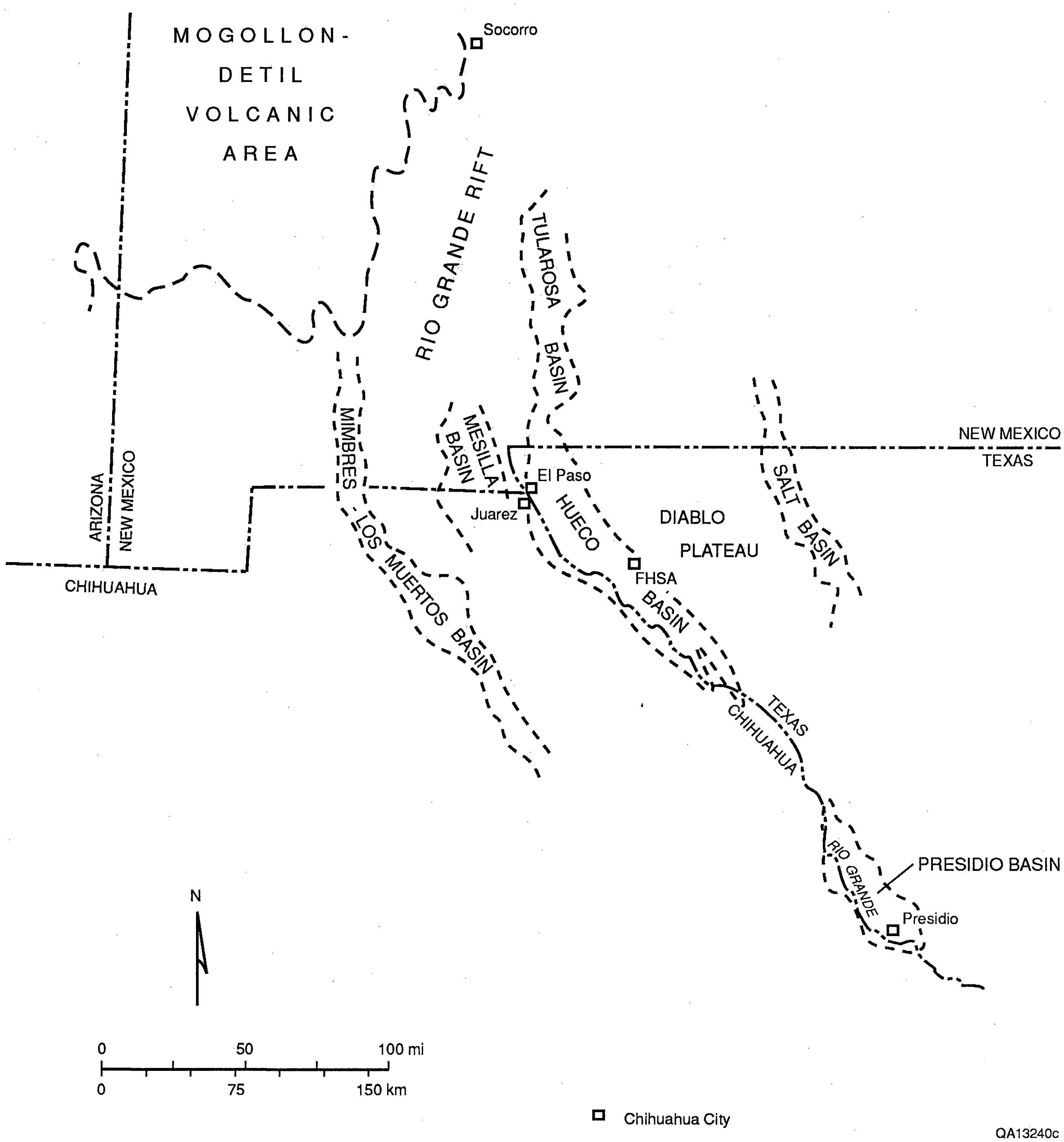


Figure 7. Generalized map of late Cenozoic tectonic setting. Tectonic elements generalized from Oetking and others (1967) and Woodward and others (1978). FHSA = Fort Hancock study area.

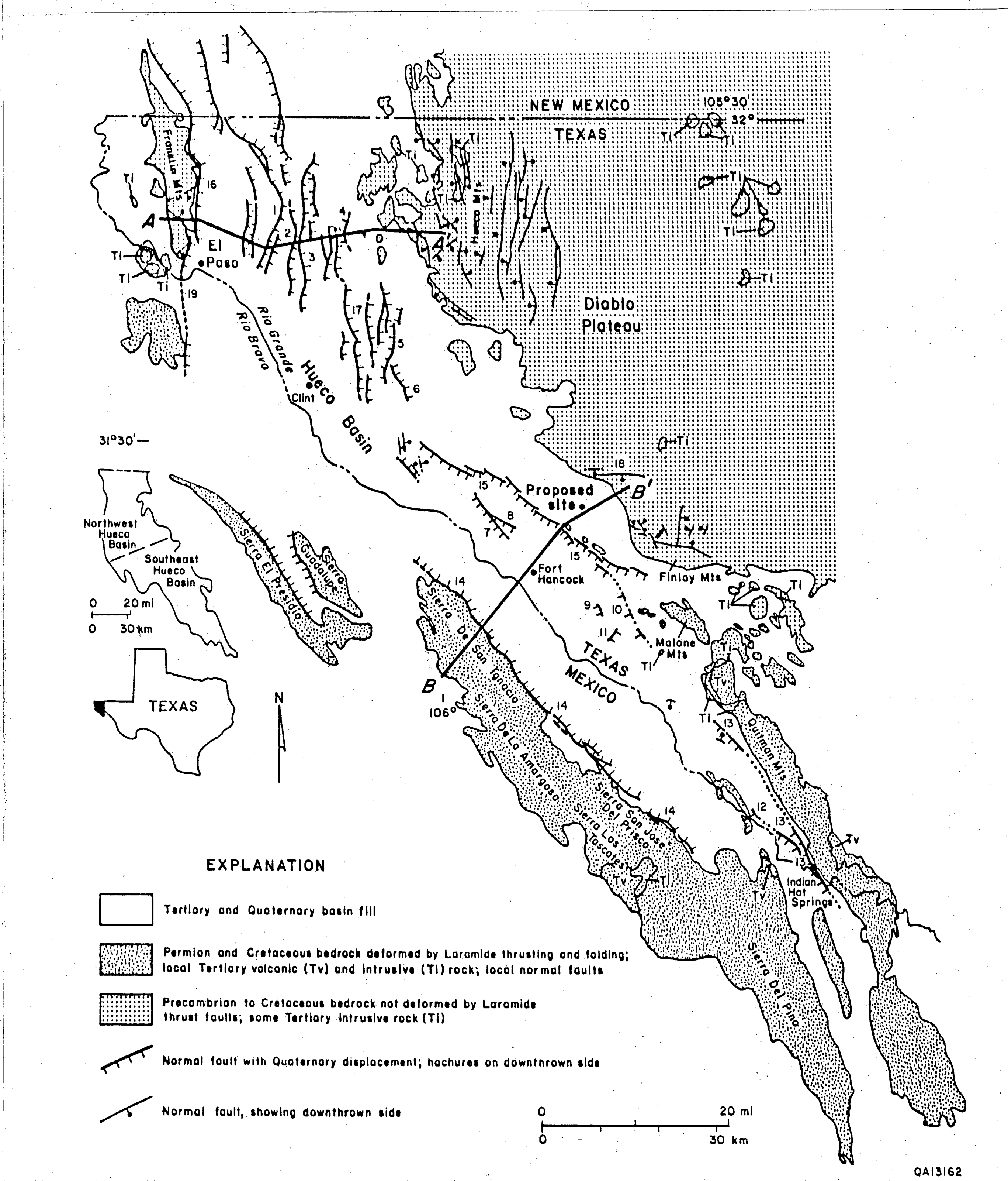


Figure 8. Regional map of surface faults, Hueco Basin, Trans-Pecos Texas. Numbers identify faults discussed in this report. Hachures identify faults that offset Quaternary sediments. It is unknown if some of the other normal faults (bars) in the region have moved during the Quaternary. Map was compiled from Albritton and Smith (1965), Jones and Reaser (1970), Woodward and others (1978), Seager (1980), Dietrich and others (1983), Henry and Price (1985), Collins and Raney (1990), and field and aerial photograph mapping done for this study. See figure 10 for cross sections A-A' and B-B'.

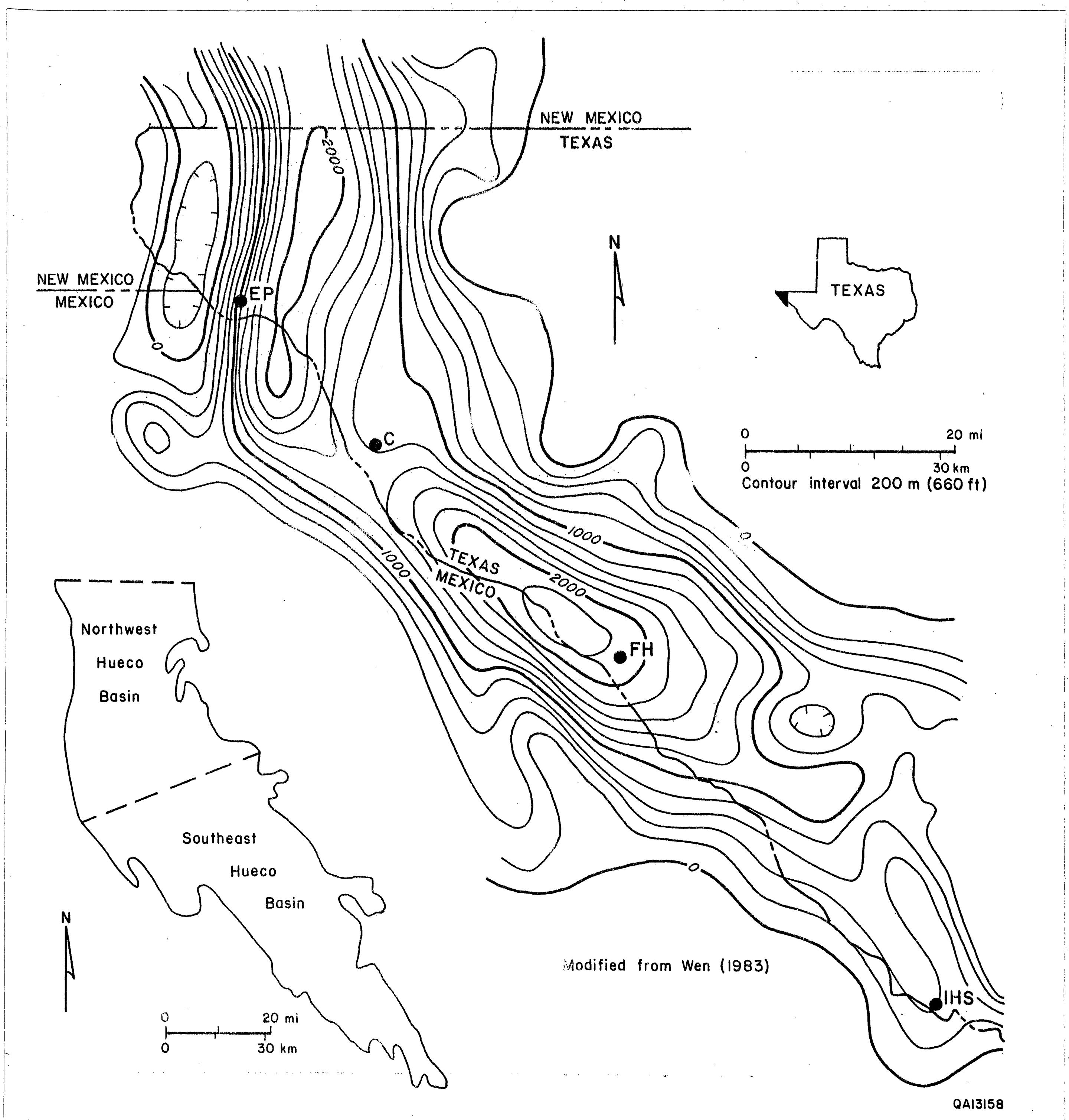


Figure 9. Map of approximate thickness of basin-fill sediments in the Hueco Basin. EP = El Paso; C = Clint; FH = Fort Hancock; IHS = Indian Hot Springs.

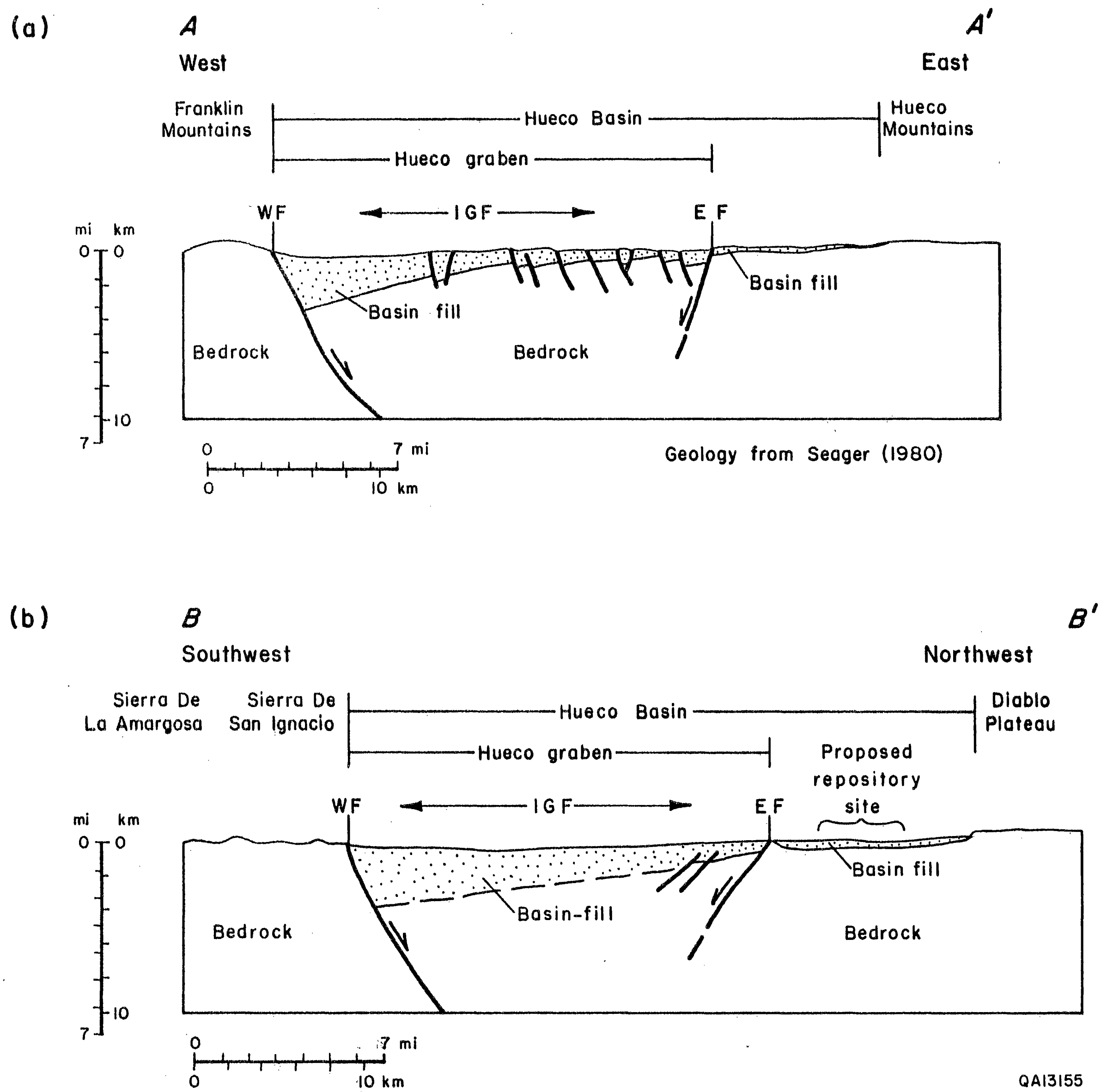


Figure 10. Cross sections of (a) northwest Hueco Basin and (b) southeast Hueco Basin, showing late Tertiary and Quaternary faults. WF = major fault that bounds graben on the west or southwest, IGF = intragraben faults, EF = major fault that bounds graben on the east or northeast. Laramide thrust faults and folds in bedrock not shown.

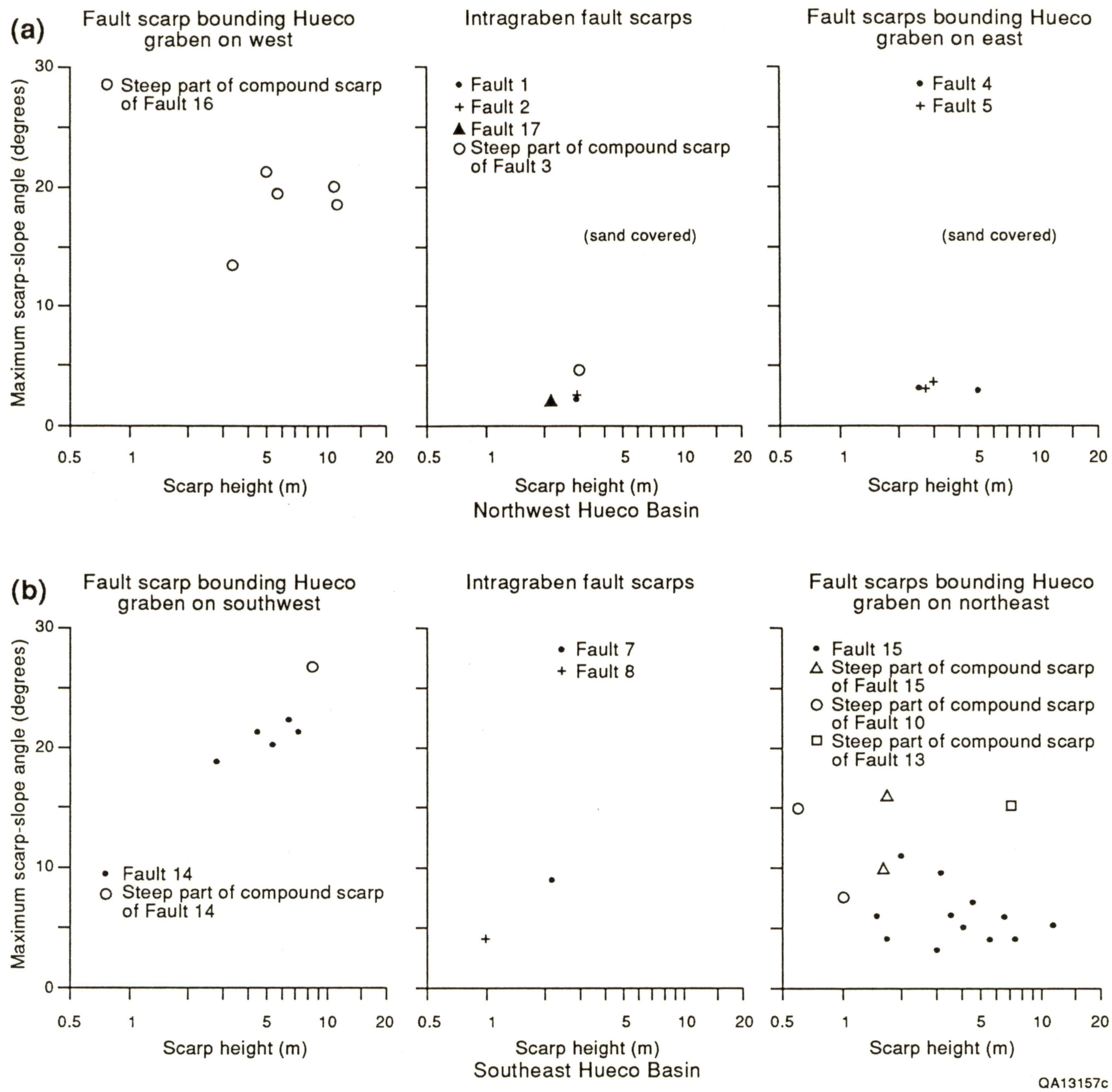


Figure 11. Graphs of scarp heights versus maximum scarp-slope angles for (a) faults of the northwest Hueco Basin and (b) faults of the southeast Hueco Basin.

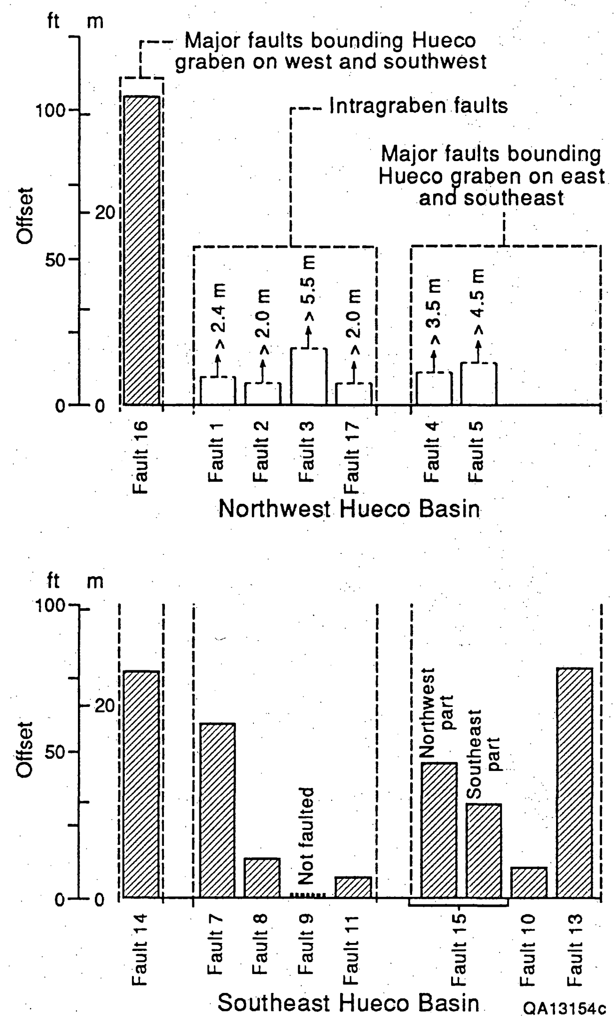


Figure 12. Bar graphs illustrating the amounts of offset on middle Pleistocene sediments for selected Quaternary faults of the Hueco Basin. Fault numbers refer to faults shown in figure 8.

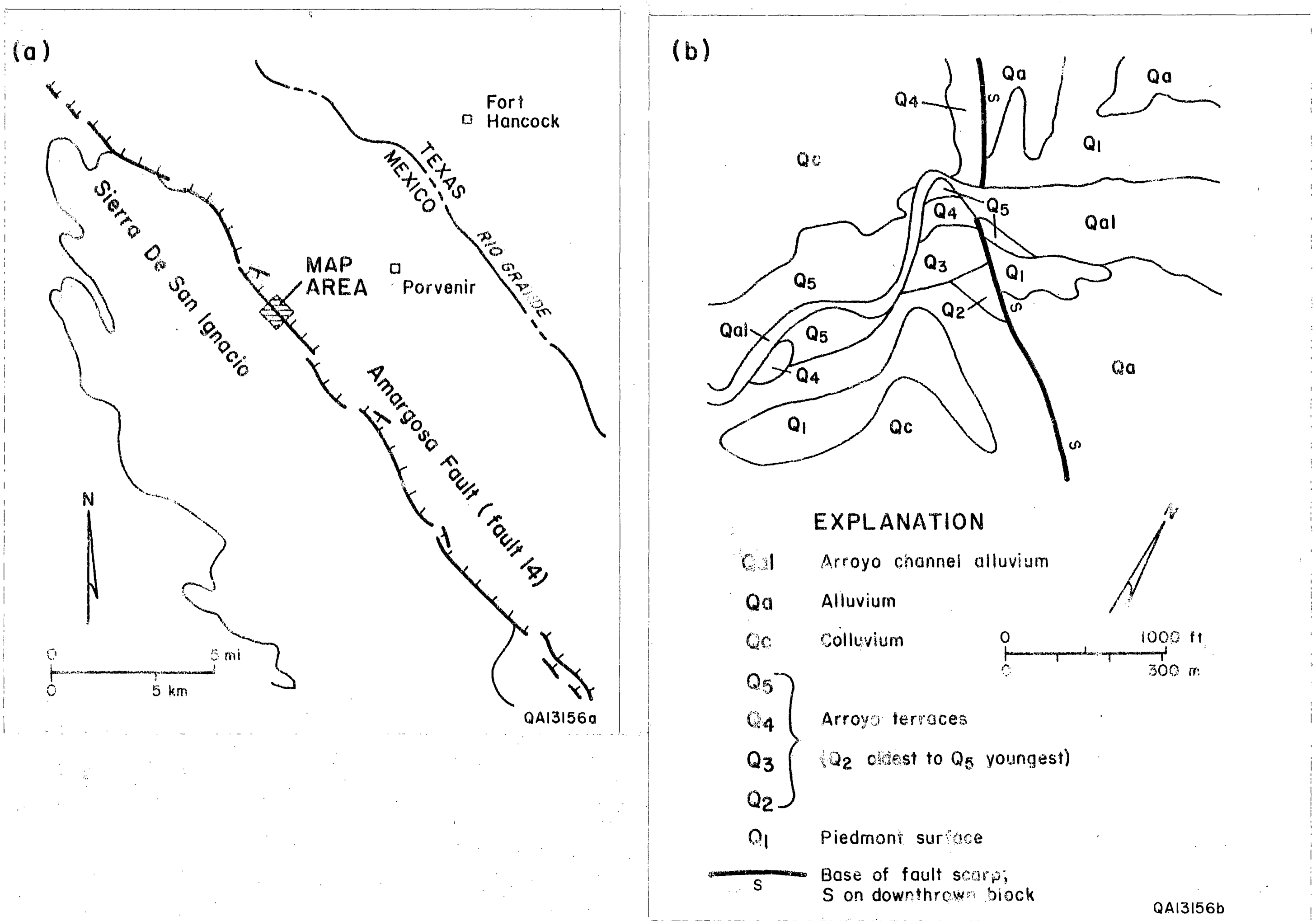


Figure 13. Map of (a) location and (b) geology of an area along the Amargosa fault (fault 14, fig. 8). Q-1 in the hanging wall of the fault was offset by repeated displacement events. The elevation of Q-1 in the hanging wall after each event was the local base level that controlled the development of subsequent terrace deposits (Q-2, Q-3, and Q-4), now preserved only on the foot-wall block. Q-5 is present as erosional remnants on both the foot-wall and hanging-wall blocks.

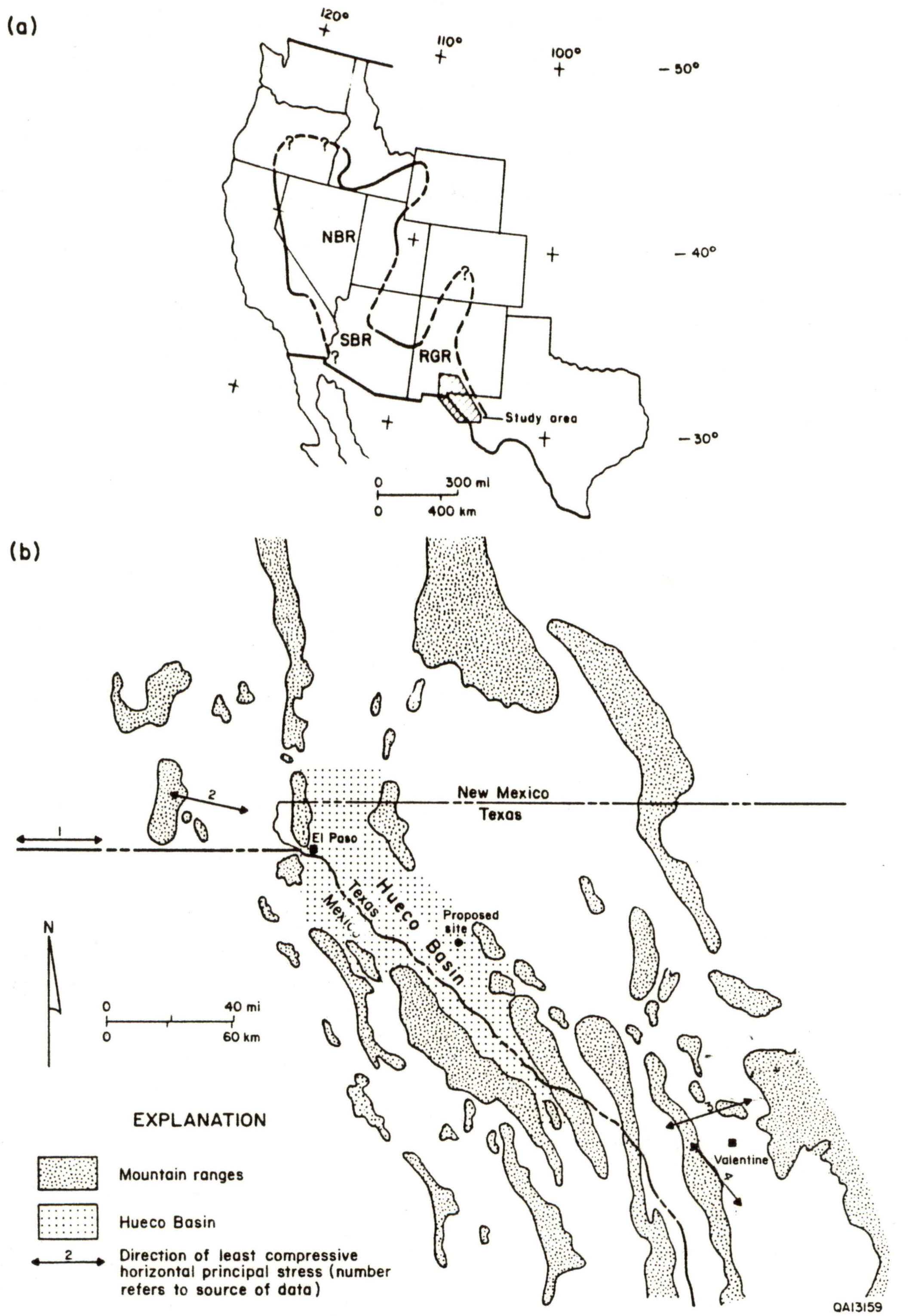


Figure 14. Maps showing (a) approximate boundaries of regional Basin and Range-Rio Grande Rift stress province (modified from Zoback and Zoback [1980]) and (b) measurements of least compressive horizontal principal stress. Measurements 1, 2, and 3 were compiled by Zoback and Zoback (1980), and measurement 4 is from Doser (1987). Measurements 3 and 4 are for the same location, and both were determined from the Valentine earthquake of 1931 using different methods.

**Table 1. Fault characteristics for normal faults of the Hueco Basin that offset Quaternary sediments. Numbers for faults refer to figure 8.**

| | Regional strike | Regional dip direction | Length of surface expression [mi (km)] | Offset of last rupture [ft (m)] | Approximate distance from potential repository [mi (km)] |
|---|---|---|---|---|---|
| **Major faults bounding graben on west and southwest** | | | | | |
| East Franklin Mountains fault (fault 16)* | N10°W–N10°E | E | 14.2 (23) | 5.5 to 9.8 (1.7 to 3) | 51.5 (83) |
| Amargosa fault (fault 14)† | N40°–50°W | NE | 43.5 (70) | 5.2 to 8.2 (1.6 to 2.5) | 15.5 (25) |
| **Major faults bounding graben on east and northeast** | | | | | |
| Fault 4* | N40°W–N20°E | W | 6.2 (10) | not determined | 37.2 (60) |
| Fault 5* | N20°W–N10°E | W | 6.8 (11) | not determined | 26 (42) |
| Campo Grande fault (fault 15)† | N40°–70°W | SW | 28 (45) | 3 to 5 (1 to 1.5) | 2.5 (4) |
| Fault 10† | N30°–60°W | SW | 9.3 (15 ) | 2 (0.6) | 6.2 (10) |
| Caballo fault (fault 13)† | N20°–40°W | SW | 29.8 (48) | 5.5 (1.7) | 29.8 (48) |
| **Selected intragraben faults** | | | | | |
| Fault 1* | N35°W–N30°E | E | 12.4 (20) | not determined | 43.5 (70) |
| Fault 2* | N20°W–N20°E | E | 8 (13) | not determined | 39 (63) |
| Fault 3* | N20°W–N30°E | E | 13 (21) | 3 (1) | 37.2 (60) |
| Fault 7† | N40°–50°W | SW | 6.2 (10) | not determined | 8 (13) |
| Fault 8† | N60°–70°W | SW | 1.8 (3) | not determined | 7.4 (12) |
| Fault 9† | N20°–40°W | SW | 0.3 (0.5) | not determined | 10.5 (17) |
| Fault 11† | N30°–40°E | E | 0.9 (1.5) | not determined | 13.6 (22) |
| Fault 12† | N15°–60°W | SW | 5.5 (9) | not determined | 37 (61) |
| Fault 17* | N25°W–N15°E | E | 7.7 (12.5) | not determined | 26.7 (43) |
| **Fault outside major graben** | | | | | |
| Fault 6* | N10°–50°W | E | 3.7 (6) | not determined | 22.3 (36) |

* Located in northwestern Hueco Basin
† Located in southeastern Hueco Basin

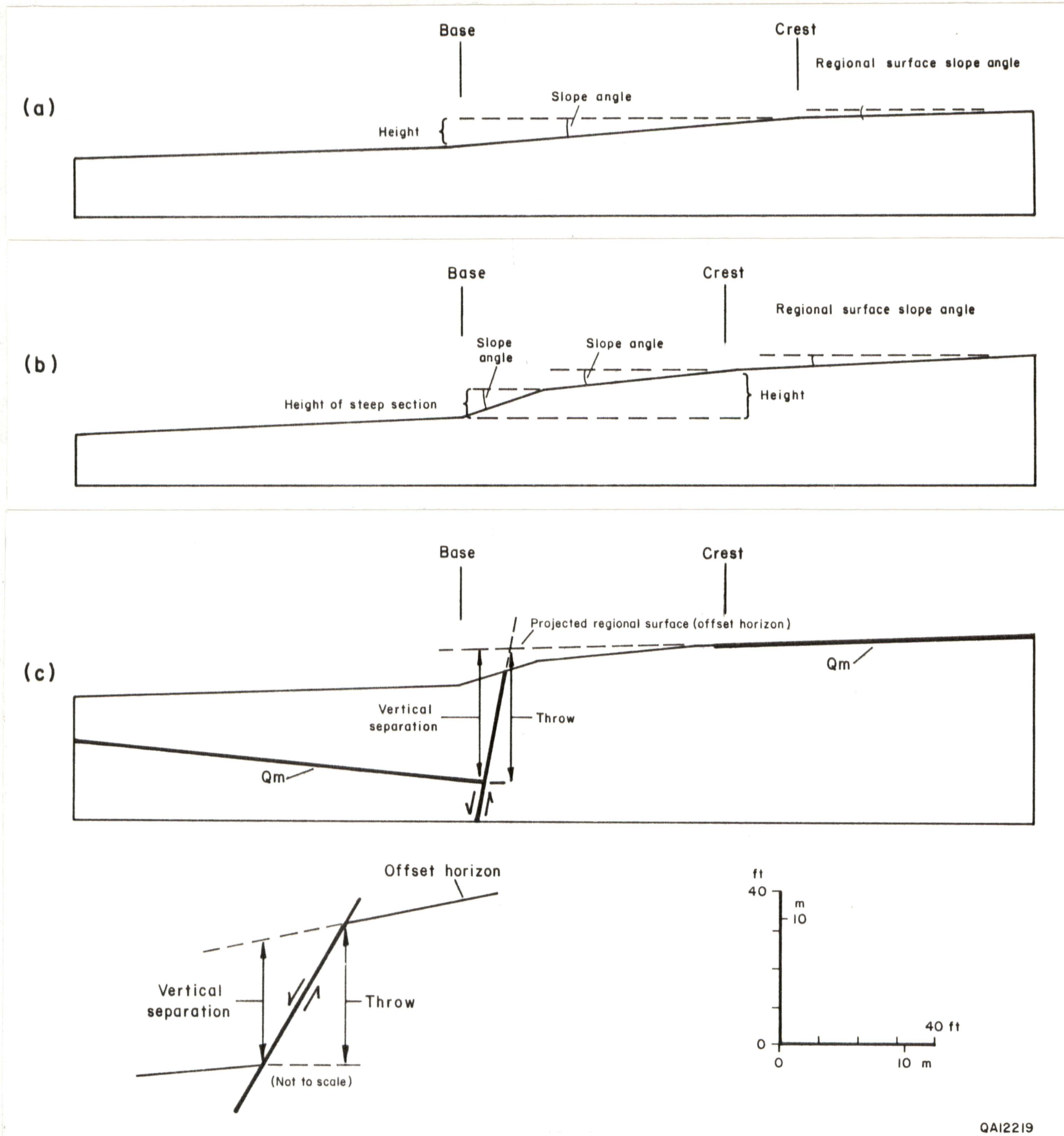


Figure A-1. Fault scarp terminology. (a) Diagram of single-slope scarp. Profile example is from station 17 (fig. A-3) at the Campo Grande fault (fault 15, fig. 8). (b) Diagram of compound-slope scarp (compound scarp). Profile example is from station 14 (fig. A-3) at the Campo Grande fault (fault 15, fig. 8). (c) Diagram showing the small difference between throw and vertical separation of a faulted unit at the Campo Grande fault. The small difference is caused by low slopes of the offset horizon. Profile example is from station 14 (fig. A-3). Inset example is schematic.

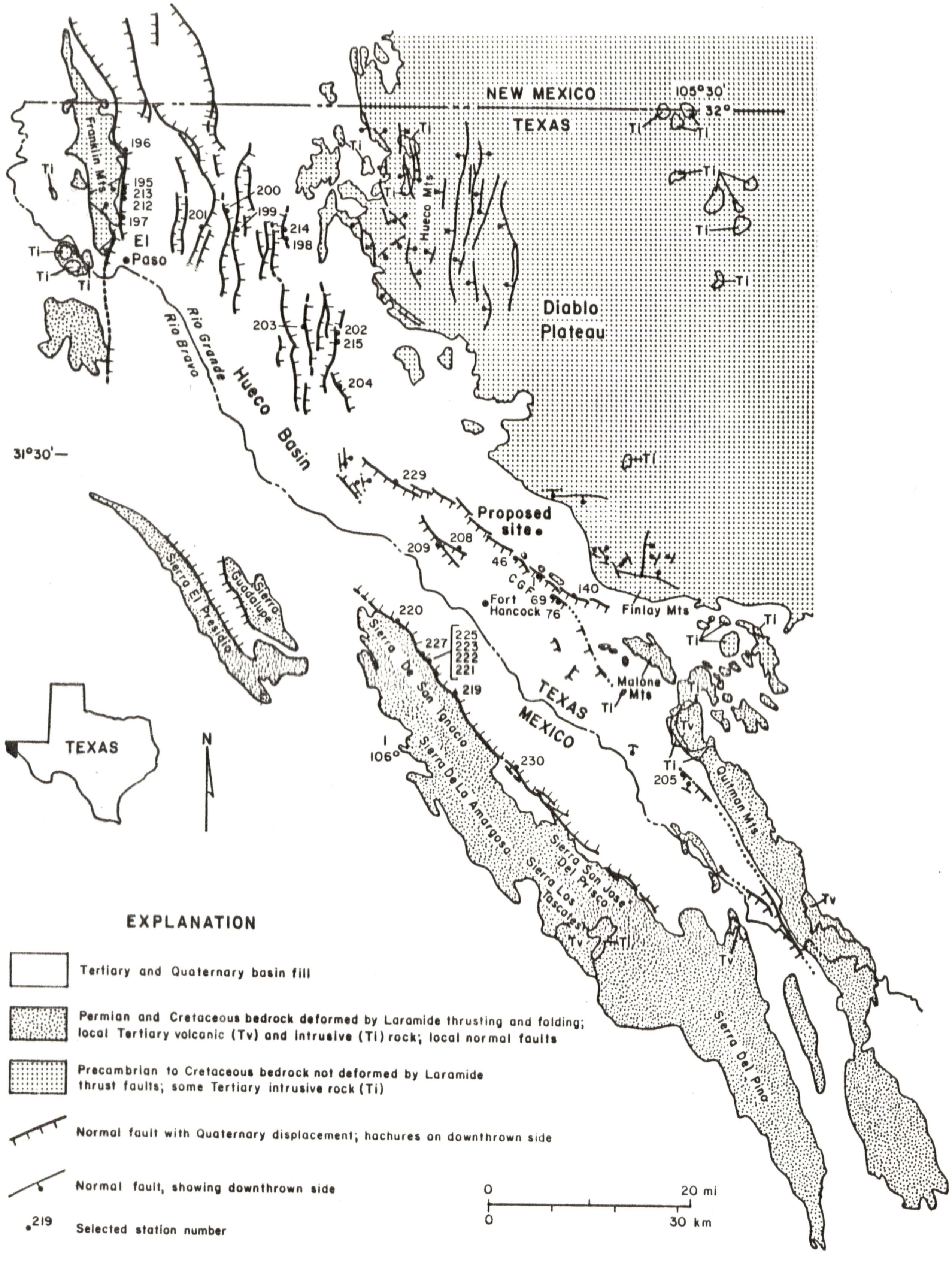


Figure A-2. Regional map of selected field stations discussed in this report. Base map from Collins and Raney (1990).

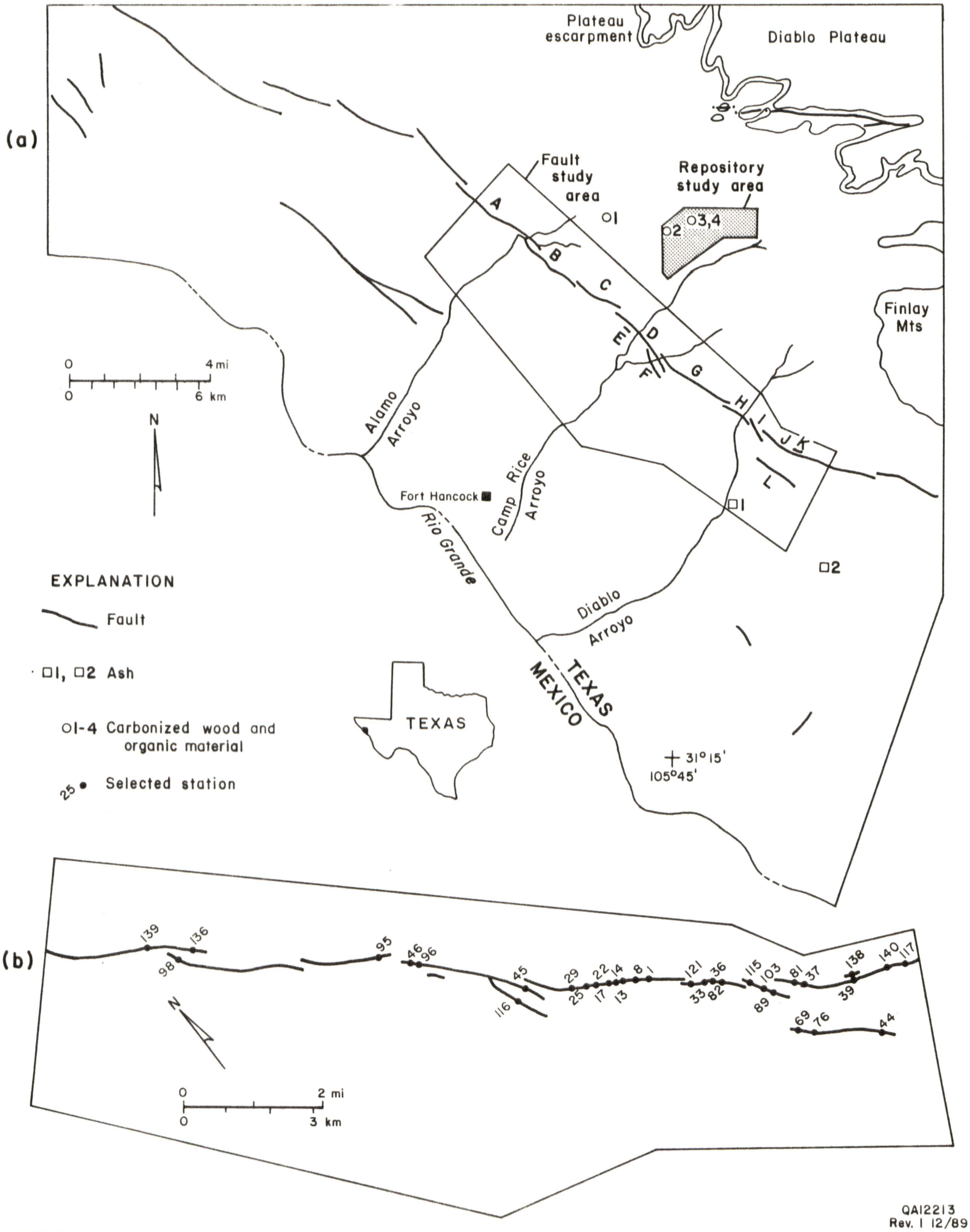


Figure A-3. Maps of (a) location and trace of Campo Grande fault (fault 15, fig. 8) and (b) selected stations discussed in this report. From Collins and Raney (1990).

**Table A-1. Morphometric data for fault scarps of the northwestern part of the Hueco Basin. Station locations are shown in figure A-2. Numbers for faults refer to figure 8.**

| | | | | Compound Scarp | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | steep section | | less steep section | | |
| Profile station | Regional slope angle | Scarp slope (degrees) | Total scarp height (m) | slope (degrees) | height (m) | slope (degrees) | height (m) | Surface unit/Comments |
| **East Franklin Mountains fault (fault 16)*** | | | | | | | | |
| 195 | 5.5 | — | 35 | 20 | 11 | 15 | 24 | Jornada I surface (middle Pleistocene); fault offset is ≥25 m. |
| 196 | 3 | — | 39 | 17 | 11.5 | 9 to 13 | 22 | Jornada I surface (middle Pleistocene); fault offset is ≥32 m. |
| 197 | 6.5 | — | 8.5 | 22.5 | 5 | 16 | 3.5 | Gold Hill surface (late Pleistocene); fault offset is ≥6 m. |
| 212 | 5 | — | 13.7 | 19.5 | 5.8 | 7 to 14 | 7.9 | Kern Place surface (late Pleistocene); fault offset is ≥8.5 m. |
| 213 | 2 | — | 5.5 | 13.5 | 3.3 | 7.5 | 2.2 | Gold Hill surface (late Pleistocene); fault offset is ≥4.5 m. |
| **Fault 1†** | | | | | | | | |
| 201 | 0.5–1 | 2 | 3 | — | — | — | — | Mostly sand covered; Stage IV to V caliche in places; probably covered Jornada I surface. |
| **Fault 2†** | | | | | | | | |
| 200 | 1 | 2.5 | 3 | — | — | — | — | Sand covered; probably covered Jornada I surface. |
| **Fault 3†** | | | | | | | | |
| 199 | 0.5–1 | — | 7.2 | 4.5 | 3 | 2.5 | 4.2 | Sand covered; probably covered Jornada I surface. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Fault 17**† | | | | | | | | |
| 203 | 0.5–1 | 2 | 2.2 | — | — | — | — | Sand covered; probably covered Jornada I surface. |
| **Fault 4**‡ | | | | | | | | |
| 198 | 0.5–1 | 3 | 5 | — | — | — | — | Sand covered; probably covered Jornada I surface. |
| 214 | 0.5–1 | 3 | 2.5 | — | — | — | — | Sand covered; probably covered Jornada I surface. |
| **Fault 5**‡ | | | | | | | | |
| 202 | 0.5–1 | 3.5 | 3 | — | — | — | — | Mostly sand covered; Stage IV to V caliche in places; covered Jornada I surface. |
| 215 | 0.5–1 | 3 | 2.7 | — | — | — | — | Mostly sand covered; Stage IV to V caliche in places; covered Jornada I surface. |
| **Fault 6**§ | | | | | | | | |
| 204 | 0.5-1 | 3 | 1.5 | — | — | — | — | Sand covered; probably covered Jornada I surface. |

* Fault bounds western side of Hueco graben
† Intragraben fault
‡ Fault bounds eastern side of Hueco graben
§ Fault outside the Hueco graben

**Table A-2. Morphometric data for fault scarps of the southeastern part of the Hueco Basin. Station locations are shown in figures A-2 and A-3. Numbers for faults refer to figure 8.**

| | | | | Compound Scarp | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | steep section | | less steep section | | |
| Profile station | Regional slope angle (degrees) | Scarp slope (degrees) | Total scarp height (m) | slope (degrees) | height (m) | slope (degrees) | height (m) | Surface unit/Comments |
| **Amargosa fault (fault 14)*** | | | | | | | | |
| 219 | 2 | 22.5 | 6.6 | — | — | — | — | Stage III to IV caliche; probably late Pleistocene; fault offset of surface is 6 m. |
| 220 | 2 | 20.5 | 5.3 | — | — | — | — | Stage II calcic soil horizon; generally unconsolidated sediment; probably late Pleistocene; fault offset of surface is 4.5 m. |
| 221 | 3.5 to 5.5 | — | 32 | 27 | 8.5 | 7 to 12 | 23.5 | Stage IV to V caliche; probably middle Pleistocene; fault offset is 23.5 m. |
| 222 | 3 to 5 | 21.5 | 7.5 | — | — | — | — | Stage III to IV caliche; probably late Pleistocene; offset of surface is 6.5 m. |
| 223 | 3 | 21.5 | 4.4 | — | — | — | — | Stage III to IV caliche; surface is arroyo terrace formed by incision into surface at station 222; probably late Pleistocene; fault offset of surface is 4 m. |
| 225 | 3 to 4 | 19 | 2.8 | — | — | — | — | Stage II calcic soil horizon; generally unconsolidated sediment; probably late Pleistocene; surface is arroyo terrace formed by incision in surface at station 223; fault offset of surface is 2.5 m. |
| 227 | 1 to 3 | 19.5 | 5.8 | — | — | — | — | Stage III to IV caliche; probably late Pleistocene; fault offset of surface is 5.2 m. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Fault 7**† | | | | | | | | |
| 209 | 1 | 9 | 2.2 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block; fault offset of Madden Gravel is approximately 18 m. |
| **Fault 8**† | | | | | | | | |
| 208 | 1–2 | 4 | 1 | — | — | — | — | Partly sand covered Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block; fault offset of Madden Gravel is approximately 4 m. |
| **Campo Grande fault (fault 15)**‡ **(southeastern part)** | | | | | | | | |
| 1 | 2.5 | 5 | 4 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block; fault offset of Madden Gravel is 9–10 m. |
| 8 | 1 | 4 | 1.7 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 13 | 2.5 | 4 | 5.5 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 14 | 2.5 | — | 3.7 | 17 | 1.7 | 6 | 2 | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 17 | 2 | 6 | 1.5 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 22 | 1.5 | — | 2.5 | 10 | 1.6 | 4 | 0.9 | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 25 | 3 | 7 | 4.5 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| 29 | 2.5 | 6 | 6.5 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 36 | 1 | 6 | 3.5 | — | — | — | — | Ramey Gravel; Stage III to IV caliche; fault offset of Ramey Gravel is 3 m. |
| 46 | 1.5 | 5 | 11.5 | — | — | — | — | Madden Gravel; Stage IV to V caliche; scarp very dissected and eroded; fault offset of Madden Gravel is 10 m. |
| 96 | 1.5 | 4 | 7.3 | — | — | — | — | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block; fault offset of Madden Gravel is 10 m. |
| 103 | 2 | 9.5 | 3.2 | — | — | — | — | Ramey Gravel; Stage III to IV caliche; fault offset of Ramey Gravel is 2.6 m. |
| 115 | 1.5 | 3 | 2 | — | — | — | — | Ramey Gravel; Stage III to IV caliche; thin alluvium deposits cover hanging wall block. |
| 116 | 3 | 11 | 2 | — | — | — | — | Madden Gravel; Stage IV to V caliche; fault offset of Madden Gravel is 1.3 m. |
| **Fault 10‡** | | | | | | | | |
| 69 | 1 | — | 1.7 | 15 | 0.7 | 3 | 1 | Madden Gravel; Stage IV to V caliche; fault offset of Madden Gravel is 1.5 m. |
| 76 | 1 | — | 2.5 | 7.5 | 1 | 3.5 | 1.5 | Madden Gravel; Stage IV to V caliche; alluvium covers hanging wall block. |
| **Fault 13‡** | | | | | | | | |
| 205 | 3–5 | — | 10.5 | 15 | 7 | 11 | 3.5 | Ramey Gravel; Stage III to IV caliche; fault offset of Ramey Gravel is 7 m. |

* Fault bounds southwestern side of Hueco graben
† Intragraben fault
‡ Fault bounds northeastern side of Hueco graben