REGIONAL GEOLOGIC SETTING OF THE EAGLE FLAT STUDY AREA, HUDSPETH COUNTY, TEXAS

by

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EXECUTIVE SUMMARY

The Eagle Flat study area lies near the east limit of 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, we can place the Eagle Flat study area within a larger context, and the significance of the site-specific investigations can be more properly understood. In general, the discussions are arranged chronologically, from oldest to youngest; each characterizes the regional geologic framework and describes how the proposed site at Faskin Ranch fits within that geologic setting.

The oldest rocks in the region are metamorphosed Precambrian sedimentary and igneous rocks. Precambrian rocks crop out about 6 mi (9 km) east of the proposed repository site and are extensively exposed in the hills in the northeast part of the study area and in the Carrizo Mountains east of the Eagle Flat study area. Precambrian rocks are also present in isolated occurrences on the northeast flank of the Eagle Mountains, southeast of the site, on the Diablo Plateau, and in the Franklin Mountains, and in New Mexico. In northeastern Chihuahua, Precambrian rocks are present in limited outcrops but are known primarily from deep exploratory drilling. The Precambrian rocks show evidence of sedimentation, magmatism, metamorphism, and deformation before deposition of overlying Paleozoic and younger strata. The greater depth of burial of Precambrian rocks in Chihuahua is interpreted to be partly a manifestation of Precambrian faulting and subsidence associated with a wide northwest-trending zone that parallels the Rio Grande. This zone, the Texas Lineament, broadly trends through the study area and locally coincides with younger geologic structures.

The Paleozoic history of the region is one of marine sedimentation (fig. 3) 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 that lie about 125 mi (200 km) southeast of the study area. Also in the late Paleozoic, the major structural highs of the region, such as the Diablo Platform north of the study area, were uplifted in the foreland of the Ouachita–Marathon belt, and areas of subsidence such as the Delaware Basin were formed. 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 because of the limited data on correlative Paleozoic strata across the lineament.

During the Mesozoic (fig. 5) the northwest-trending Chihuahua Trough developed in the area of the present international border and extended into northeastern Chihuahua as a well-defined depositional basin. The study area lies on the northeast margin of the Chihuahua Trough near the south 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 produced the Chihuahua tectonic belt of strongly folded and faulted earlier strata with tectonic transport directions to the northeast. Décollement surfaces may have developed in Mesozoic evaporite deposits of the Chihuahua Trough. Localized structures 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 mya.

About 30 mya, the regional stress regime became extensional. Magmatism, both prior to and contemporaneous with extension, was locally important throughout the region. The main period of caldera formation in the Trans-Pecos was between 38 and 32 Ma, and most of the volcanic and shallow intrusive rocks present near the study area, such as Sierra Blanca Peaks and the north Quitman and Eagle Mountain volcanic centers, are related to this period of magmatism. Magmatic rocks in the vicinity of the study area are part of the calcic-alkalic belt, whereas temporally similar rocks farther to the east, such as those in the Davis Mountains and in Big Bend National Park, are part of an alkalic belt. No magmatic activity younger than 17 Ma has occurred in the Trans-Pecos area. Quaternary volcanic rocks are present in southern New Mexico.

The extension resulted in a series of basins related to the Basin and Range Province and the Rio Grande rift. The northwest Eagle Flat basin, in which the proposed site lies, is a subsidiary basin that lies between the much larger basin systems, the southeast arm of the Hueco Bolson to the west and the Salt Basin–Wild Horse Flat–Lobo Valley basins to the east. The Hueco Bolson, or Hueco Basin, is viewed as an extension of the Rio Grande rift of New Mexico. Extension also occurred in the Red Light Draw area, south of the proposed site, and related early extension may account for the deeper parts of the northwestern Eagle Flat Basin. The series of Cenozoic basins (Salt Basin, Wild Horse Flat, Lobo Valley) that occur east of the study area are nearly coincident with the approximate east limit of Basin and Range deformation. The extensional basins, including Eagle Flat basin, were infilled with predominantly siliciclastic sediments (fig. 7) and locally minor evaporite deposits. Faults such as the East Franklin Mountains fault in the Hueco Bolson and the Amargosa fault across the Rio Grande in Chihuahua may have been active in the Holocene. Regional extension continues to the present day and is manifested by historic earthquakes, such as the 1931 Valentine event, although no surface rupturing events have occurred in historic times.

The Texas Lineament is commonly projected through the Rio Grande region near the study area. Regionally, it may be expressed as a major Precambrian discontinuity, the northwest arm of the Paleozoic Marfa Basin, the axis or east flank of the Mesozoic Chihuahua Trough, the south and southwest margin of the Diablo Platform, the approximate leading edge of Laramide (80 to 50 Ma) thrusting (or the margin of the Chihuahua tectonic belt), or the northwest structural control on the development of the southeast part of the Hueco Bolson. Intermittent deformation has occurred that is associated with at least some northwest-trending fractures ascribed by some to the Texas Lineament from the Precambrian to the late Cenozoic, but major periods of activity appear to have occurred during the Precambrian and the late Paleozoic. Deformation has not been continuous, but structures in the zone have been episodically reactivated by the imposition of regional tectonic stresses during periods of tectonism.

The proposed Faskin Ranch site lies in the west part of the Eagle Flat study area within northwest Eagle Flat basin. It lies northeast of the leading edge of major Laramide thrusting on the downwarped southwest margin of the Diablo Plateau. As is true throughout the Trans-Pecos, there is no volcanism younger than 17 Ma anywhere near Faskin Ranch. Cenozoic basin fill is as much as 700 ft (210 m) thick and as old as ~12 Ma in the vicinity of the proposed site. Beneath basin-fill sediments, the Cretaceous strata dip gently to the southwest. In the Cretaceous, bedrock covered by Cenozoic basin-fill sediments, between the proposed site and outcrops of Cretaceous strata to the southwest, there are several inferred faults. These faults are down dropped to the northeast. One fault is inferred to occur in bedrock beneath the proposed site. It is unknown whether this fault displaces the deep basin-fill sediments, but no evidence exists that it is present in the shallow subsurface. Calcic soils, paleomagnetic chronostratigraphic boundaries, and stratigraphic horizons that can be projected without offset all are evidence that no recognizable fault ruptures have occurred within at least 780,000 yr B.P. The surface of the basin has been very stable in the late Cenozoic, as is indicated by the mature calcic soils that have developed. No Quaternary fault scarps have been identified either at the proposed site or elsewhere in northwest Eagle Flat basin. One fissure has been recognized about 1.5 mi (~2.4 km) west of the proposed site, but none have been found to occur on the proposed site. Current rates of erosion and deposition are slow and will not impact the stability of the natural surface.

INTRODUCTION

This report summarizes the regional geologic setting of the Eagle Flat study area, Hudspeth County, Texas. The Eagle Flat study area is the six 7.5-minute quadrangle area designated by the Texas legislature within which the Texas Low-Level Radioactive Waste Disposal Authority is to attempt to locate a technically suitable site for the Texas low-level radioactive waste repository. The Faskin Ranch site is the proposed site for the repository, located within the study area, in northwestern Eagle Flat basin. This report is based on a review of the published literature and work by staff of the Bureau of Economic Geology. It is an expanded and updated version of a previous contract report (Raney and Collins, 1990). An attempt has been made to stress the more recently 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 characteristics of the regional setting of the proposed Faskin Ranch 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 Eagle Flat study area. Those characteristics or events that have a direct bearing on the geologic features of the site or site vicinity have been emphasized. For more detailed information on topics that are specifically addressed in reports prepared as part of the site investigation, the reader is referred to the appropriate topical reports. Late Cenozoic faulting in the region and sedimentation within the late Cenozoic basins are summarized here and discussed in more detail in the referenced reports. The main part of this report chronologically summarizes the geologic development of the region.

The rocks exposed in Trans-Pecos Texas and adjacent areas of New Mexico and Mexico record a long sequence of geologic events. Precambrian and Paleozoic events prepared the stage for the deposition of younger strata present in the study area and probably 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 comprise the host rocks for much of the deep, saturated zone beneath the study area. Late Tertiary to Quaternary events include formation and deposition of sediments in basins such as the northwest Eagle Flat basin, the proposed location of the repository. These younger events are the best source of information on the rates of the more recently active geologic processes within the study area and are the best guide to evaluating the potential for further geologic modification of the repository area.

The Eagle Flat 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 (Stewart, 1978; Henry and Aranda-Gomez, 1992; among others). The discussion of the regional setting of the study area emphasizes Trans-Pecos Texas, but also includes the southern New Mexico and northern Chihuahua parts of the Basin and Range Province. The region discussed here lies north of the postulated Mojave–Sonora megashear (Silver and Anderson, 1974), a possible Mesozoic left-lateral shear zone that separates the North American Precambrian craton from suspect terranes to the southwest. Figure 1 shows major tectonic features of the region, and figure 2 is a geologic map of the 100,000-mi^2 (260,000-km^2) region that includes the Eagle Flat study area and many of the geologic features discussed in this report. It is included to illustrate the continuity of geologic units between the United States and Mexico. The reader is also referred to the Van Horn–El Paso (Dietrich and others, 1983) and Marfa (Twiss, 1979) 1:250,000-scale geologic maps of the Texas part of the region.

PRECAMBRIAN

Precambrian rocks are exposed at scattered localities throughout western Trans-Pecos Texas and southern New Mexico and very locally in Chihuahua (fig. 2). Precambrian rocks crop out about 6 mi (9 km) east of the proposed repository site on the lower flanks of Eagle Flat Mountain and are extensively exposed in the Streeruwitz, Bean, and Millican Hills north of Interstate Highway 10 and in the Carrizo Mountains 20 mi (32 km) east-southeast of Faskin Ranch. Precambrian rocks are also present in isolated occurrences on the northeast flank of the Eagle Mountains, the west edge of the Wylie Mountains, the Van Horn Mountains, on the Diablo Plateau to the north of the study area, in the Hueco Mountains to the northwest, and in the Franklin Mountains near El Paso. In northeastern Chihuahua, Precambrian rocks are known

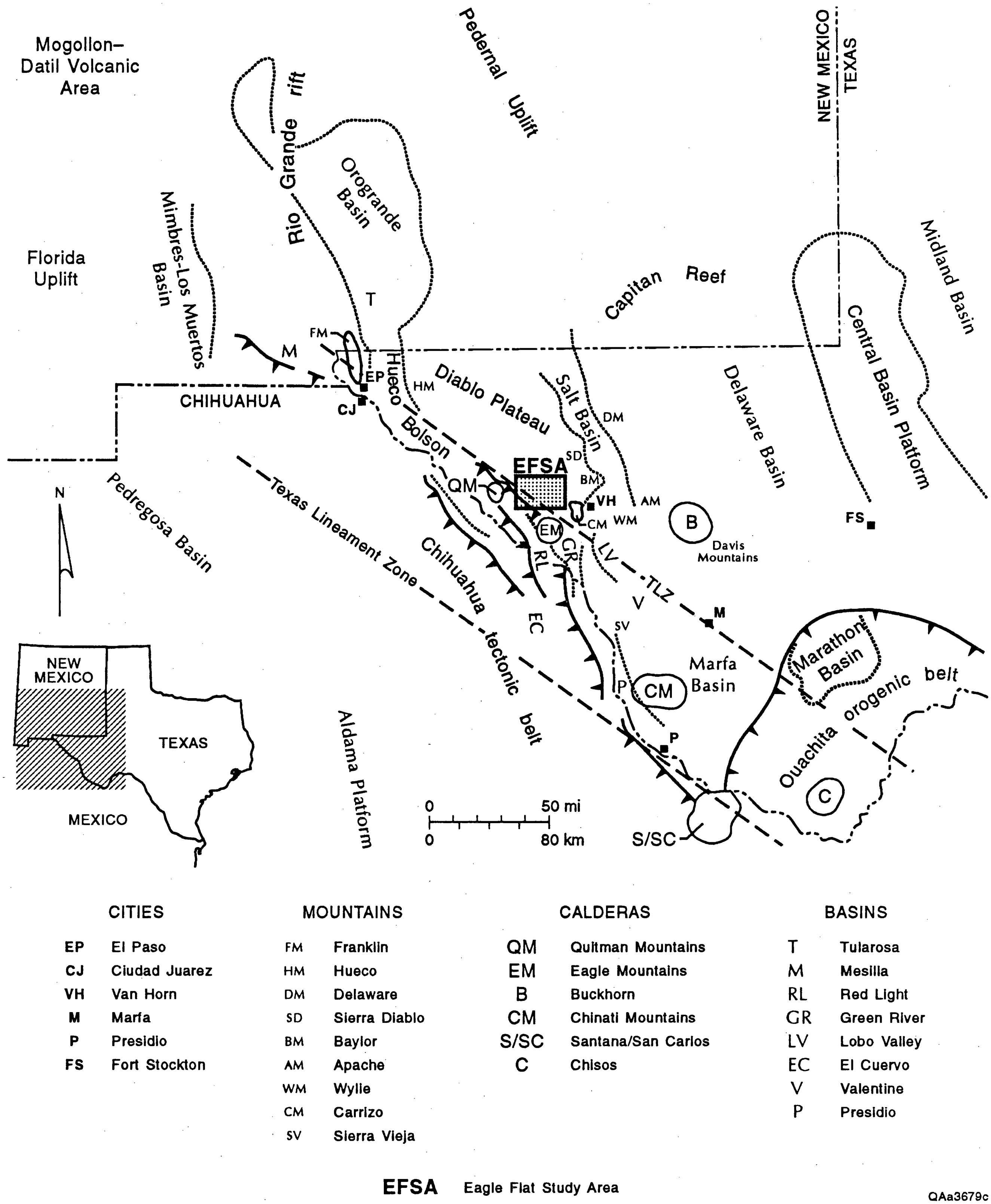

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Figure 1. Map showing major regional tectonic features of West Texas and adjacent areas of New Mexico and Mexico. Figure modified from Keller and Peeples (1985), Goetz and Dickerson (1985), and Muehlberger and Dickerson (1989).

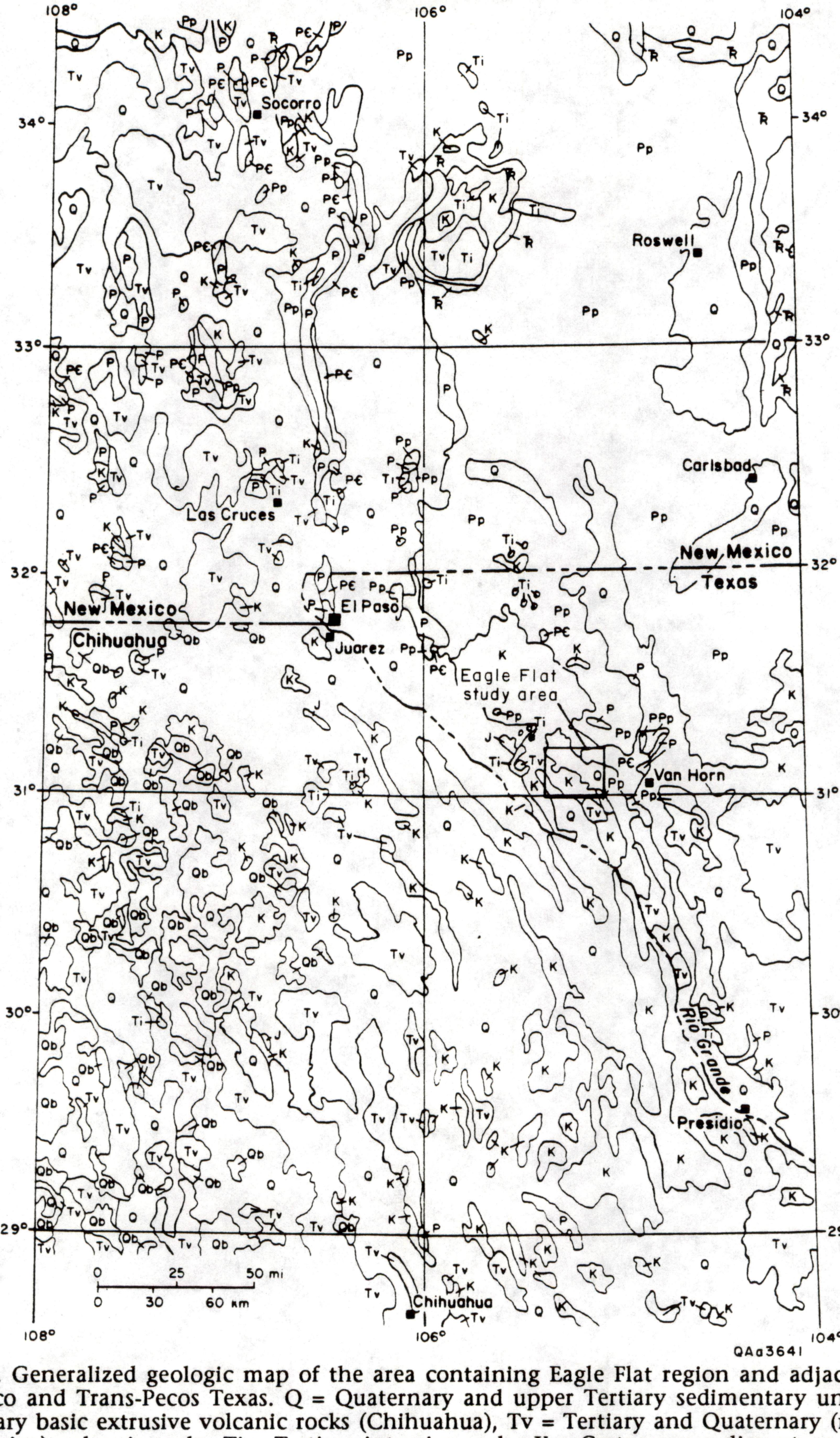

Figure 2. Generalized geologic map of the area containing Eagle Flat region and adjacent areas of Mexico and Trans-Pecos Texas. Q = Quaternary and upper Tertiary sedimentary units, Qb = Quaternary basic extrusive volcanic rocks (Chihuahua), Tv = Tertiary and Quaternary (mostly in New Mexico) volcanic 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, and PC = Precambrian rocks undivided. Map modified from Oetking and others (1967) (New Mexico), Renfro and others (1973) (Texas), and Dirección General de Geografía del Territorio Nacional (1981) (Chihuahua).

primarily from deep exploratory drilling. Precambrian rocks in Chihuahua are intersected by drill holes 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 apparently deep burial of Precambrian rocks in Chihuahua may be related to a Precambrian rifting event at about 1,450 Ma (Sears and Price, 1978). Muehlberger (1980) thought this rifting 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" or the "Texas Lineament zone" (Muehlberger and Dickerson, 1989). 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) and Soegaard (1993).

In the western Trans-Pecos the older Precambrian rocks, generally 1.4 to 1.0 Ga, are assigned to the Mid-Proterozoic Grenville province on the basis of age (Muehlberger and others, 1966). In the study area, rocks of the Grenville province are commonly viewed as having been accreted to the North American craton at about 1.2 to 1.1 Ga along the Grenville front (Elston and Clough, 1993). Precambrian sedimentary rocks in the Franklin Mountains are interpreted to have been deposited in a shallow-marine environment inland from the Grenville front. DeCserna (1976) projected the Grenville-age Precambrian rocks of Texas and southeastern New Mexico into Mexico as the north-south-trending Oaxacan structural belt. Condie (1986) suggested that early Proterozoic terranes occur in northeast-trending belts across the southwestern United States (see also Ewing, 1990; Soegaard, 1993), and Grambling and others (1988) interpreted that the pre-Grenville Proterozoic of New Mexico is composed of multiple terranes bounded by subhorizontal shear zones locally steepened by folding.

Grenville-age rocks within and adjacent to the study area are separated into two major packages, the Carrizo Mountain Group and the Allamoore Formation, by the Precambrian Streeruwitz thrust fault (King and Flawn, 1953; see figure 5 in Soegaard, 1993). The Carrizo Mountain Group, in the hanging wall of the thrust, crops out mainly in the Carrizo Mountains and less extensively in the Van Horn Mountains, the Wylie Mountains, and on the north edge of the Eagle Mountains. Small outcrops also occur near exposures of the Streeruwitz thrust in the western Millican Hills and southern Streeruwitz Hills (Eagle Flat Mountain). Precambrian rocks, possibly related to the Carrizo Mountain Group, were encountered at a depth of about 14,350 ft (~4,375 m) by the Border State 11 exploration well located about 6 mi (~9.5 km) southwest of the proposed site (Osburg and others, 1985). The Carrizo Mountain Group is presumed to underlie the site beneath a wedge of Permian and Cretaceous strata and Cenozoic basin-fill sediments at depths in excess of 1,500 ft (>450 m). Projections of Precambrian rocks beneath the study area and the proposed site are shown in the regional cross section (plate 1).

The Carrizo Mountain Group, 1.4 to 1.33 Ga according to U-Pb zircon dates (Soegaard and others, 1991; Roths, 1993), is the oldest sequence of Precambrian rocks in the Trans-Pecos region. The U-Pb dates agree with previously published whole-rock Rb-Sr dates (Denison, 1980; Reynolds, 1985) reported on rhyolites, which indicate a minimum age of the metasediments of about 1.2 to 1.3 Ga, and unpublished U-Pb data (1.37 Ga) on a rhyolite by Patchett and Ruiz (1989). The Carrizo Mountain Group is comprised of greenschist- to amphibolite-grade metasedimentary rocks interbedded with bimodal metaigneous rocks. Metamorphic grade increases to the south, Van Horn Mountains, and east, Wylie Mountains (King and Flawn, 1953; Bristol and Mosher, 1989). Roths (1993) interpreted the Carrizo Mountain Group as a remnant of a Precambrian rift basin; Bristol and Mosher (1989) suggested that the Carrizo Mountain Group formed in a back-arc basin that was initially under compression but that later became extensional. The polyphase deformation of the Carrizo Mountain Group has been interpreted to indicate northwest-directed, oblique convergence along the margin of the North American craton (Bristol and Mosher, 1989).

Rocks in the footwall of the Streeruwitz thrust, the Allamoore Formation (King and Flawn, 1953), are well exposed in the Streeruwitz, Bean, and Millican Hills in the northeast part of the study area and in adjacent areas to the east. The Allamoore Formation includes at least 1,000 ft (300 m) of lower greenschist facies, interbedded limestones, pyroclastics, volcanic flows, phyllites, talc, and rare quartzites (Roths, 1993). The talc deposits of the Allamoore District (see

Seni and Raney, 1992) are hosted by the Allamoore Formation and are the only mineral deposits in the study area currently undergoing significant production. The Allamoore Formation is probably equivalent to metasedimentary units in the Franklin Mountains (Henry and Price, 1985). Data obtained by Roths (1993) on the Allamoore Formation are interpreted to indicate that Allamoore sediments were deposited in an arc environment between 1,290 and 1,250 Ma. The Allamoore Formation is unconformably overlain by volcanic flows, volcanic litharenites, agglomerates, and pillow breccias, previously assigned to the Allamoore Formation (King and Flawn, 1953). These rocks have recently been informally referred to as the Tumbledown Formation (Roths, 1993; Callahan, 1992).

Unconformably overlying the Allamoore and Tumbledown Formations is a series of conglomerates, sandstones, and siltstones that comprise the Hazel Formation, which may be correlative with the Lanoria Quartzite in the Franklin Mountains (Denison and Hetherington, 1969; Dietrich and others, 1983). Analyses of the Lanoria Quartzite (Patchett and Ruiz, 1989), however, suggest derivation from older (~1.8 Ga) Precambrian terrains. Conglomerates in the Hazel contain angular clasts as much as "several tens of meters across" (Roths, 1993, p. 16) mostly of lithologies present in the underlying Allamoore and Tumbledown Formations, but also including boulders of granite and rhyolite. U-Pb zircon dates on the granite and rhyolite boulders (Roths, 1993), both approximately 1.12 Ga, place a maximum age on deposition of the Hazel Formation.

Paleomagnetic studies (Elston and Clough, 1993) suggest a correlation with ~1,100- to 1,080-Ma rocks of the Lake Superior region. The Hazel is interpreted to be a synorogenic clastic wedge with a southerly source that was deposited in a strike-slip basin (Soegaard and Callahan, 1993). Soegaard and others (1991) and Soegaard and Callahan (1993) described the Hazel as a greater than 8,000-ft (>2,500-m) thick sequence of alluvial fan and eolian sediments deposited in a foreland basin developed north of the fold and thrust belt (Carrizo Mountain Group–Allamoore and Tumbledown Formations). Continued crustal shortening folded the foreland basin sequence and emplaced thrust sheets of Allamoore Formation on the Hazel Formation.

Overlying the Hazel Formation are the Van Horn Sandstone and younger Paleozoic marine sedimentary strata. For purposes of this discussion, the Precambrian/Cambrian Van Horn Sandstone is described in the following section on the Paleozoic.

Precambrian outcrops elsewhere in the Trans-Pecos (Franklin Mountains and within or adjacent to the Diablo Plateau), outside the Van Horn Mobile Belt (Flawn, 1956), appear not to have been as directly involved in the Grenville orogeny and lie cratonward of the Grenville front. The Franklin Mountains contain outcrops of weakly metamorphosed shallow-marine sediments and volcanic rocks (Castner Marble, Mundy Breccia, Lanoria Quartzite, and Thunderbird Group) that are of Grenville age and that may correlate with the Allamoore and younger Precambrian rocks of the Van Horn Mobile Belt. These units are intruded by rhyolite dikes, granitic dikes and plutons (Red Bluff Granite), and basalt and diabase dikes. Rhyolites and granites from the Franklin Mountains and similar rock types in the Hueco Mountains and Pump Station Hills were intruded about 1,086 to 1,135 Ma. (Copeland and Bowring, 1988; Roths, 1993).

The Grenville and possibly earlier events were thought by King and Flawn (1953), King (1965), and subsequent writers (such as Muehlberger, 1980) to have established a northwest structural grain in far West Texas that was reactivated in subsequent periods of deformation. The degree to which this Precambrian fabric controlled the development of much younger structural features is an issue of continuing discussion among investigators. Brown and Handschy (1984) also suggested that Paleozoic, Mesozoic, and Cenozoic structural features in Chihuahua may represent reactivations of Precambrian faults. West of Van Horn and in the east part of the study area, a series of east-west- to west-northwest-trending faults cut Precambrian and locally younger strata. These features are of appropriate orientation and location to be elements of the Texas Lineament (Muehlberger, 1980).

One fault possibly related to the lineament, the Grapevine fault, is one of the few faults near the study area that has demonstrable strike-slip displacement. The Grapevine fault (analysis of Kwon, 1990; reported by Soegaard and Nielson, 1993, field trip stop #2) near

Tumbledown Mountain was studied to document net-slip, dip-slip, and strike-slip components of displacement. Using the offset of the axis of the Hackberry Creek anticline, a Precambrian fold in the Hazel Formation, the results are 4,619 ft, 2,037 ft, and 4,144 ft (1,408 m, 621 m, and 1,263 m), respectively. The displacement was *left-lateral* with a normal dip-slip component (26-degree plunge of net slip). The same authors interpreted offset of the Ordovician Bliss Sandstone to imply 3,755 to 9,523 ft (1,125 to 2850 m) of subsequent *right-lateral* displacement on the Grapevine fault. In studies of the same Grapevine fault, King (1965, p. 102–103) inferred "about half a mile" (~750 m) of *left-lateral* displacement on the basis of offset of features in the Hazel Formation; King probably interpreted offset of the Bliss Sandstone on the fault as due to *dip slip* (see also King and Flawn, 1953, p. 117).

PALEOZOIC

Paleozoic rocks crop out throughout Trans-Pecos Texas, southern New Mexico, and at a few localities in Chihuahua (fig. 2). Paleozoic strata (fig. 3) have also been intersected in many exploration wells. LeMone and others (1983a) presented isopach maps of preserved Paleozoic strata for much of the region of interest. In southwestern New Mexico, as much as 11,000 ft (3,300 m) of Paleozoic strata was 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). Although no Paleozoic formations older than Ordovician were identified in Chihuahua by Bridges (1974), Dyer and Reyes (1987) described a Cambro-Ordovician to Permian section in east-central Chihuahua about 65 mi (~100 km) east-northeast of Ciudad Chihuahua. In Texas, Paleozoic strata, especially Permian formations, are extensively exposed in the northern (Hueco Mountains to Cornudas area) and eastern Diablo Plateau (Sierra Diablo, Baylor Mountain and vicinity), the Delaware Basin to the northeast, and in the Marathon area. Smaller exposures are present on the west side of the Franklin Mountains, locally in the Malone and Finlay Mountains, the Streeruwitz Hills, the northeast

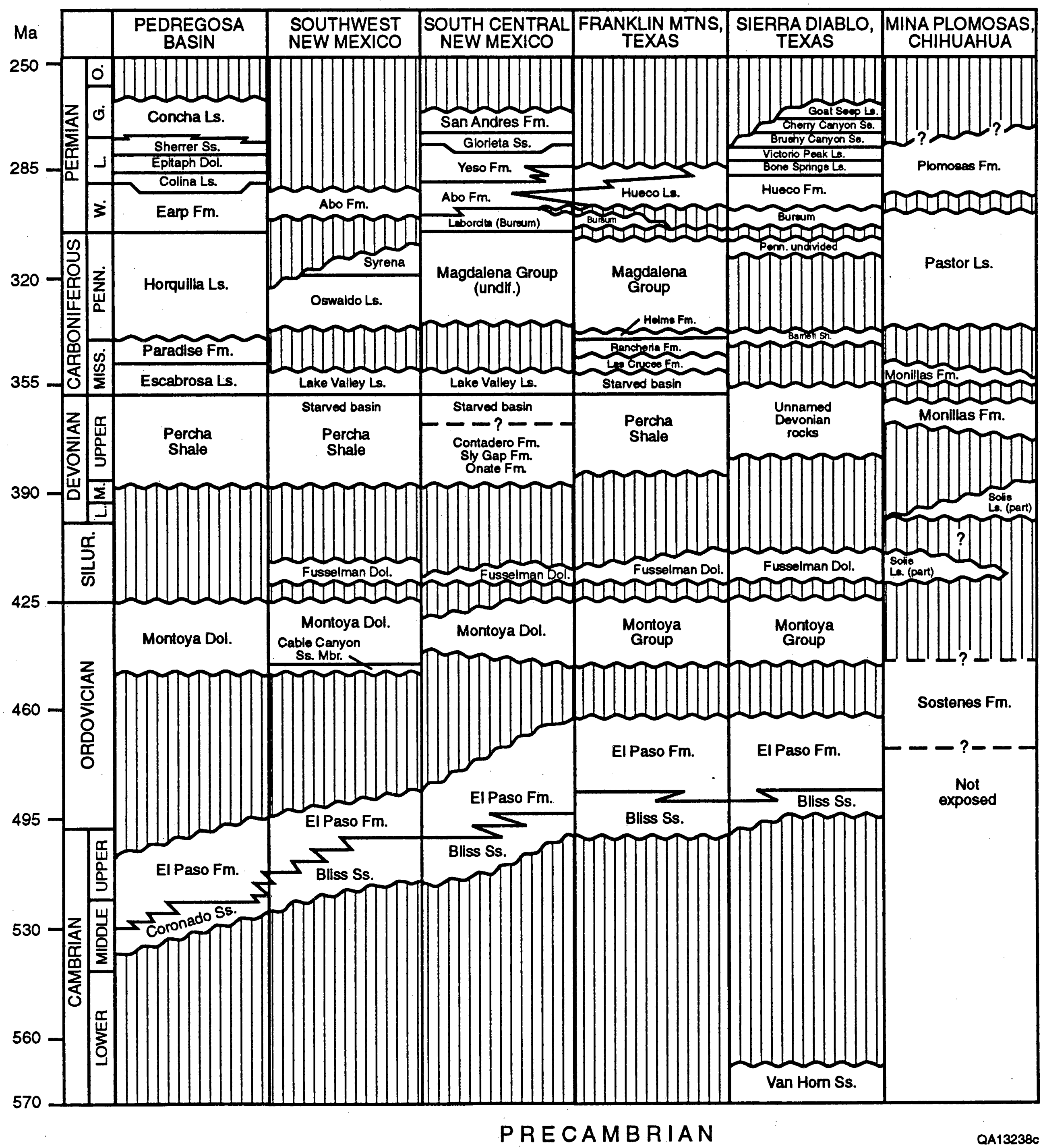

Figure 3. Chart of regional Paleozoic stratigraphy. After Ross and Ross (1985).

flank of the Eagle Mountains, the southern Carrizo–northern Van Horn Mountains, and in the Wylie Mountains (Dietrich and others, 1983; Twiss, 1979). Farther to the south, Permian rocks are also present on the flanks of the Chinati Mountains.

Early through Middle Paleozoic

The geologic record of transition from Precambrian to Paleozoic is incomplete. The Van Horn Sandstone, present in the Beach Mountain–Baylor Mountain area, north and west of Van Horn, is the oldest unit of possible Paleozoic age present in the region. King (1965) considered the Van Horn to be of possible Precambrian age; Ye and Soegaard (1993, p. 63), on the basis of subsidence history analysis, suggested the Van Horn Sandstone was deposited "immediately prior" to thermal subsidence 510 mya; Elston and Clough (1993) cited their previous lithostratigraphic correlation of the Van Horn Sandstone with the Early and Middle Cambrian Tapeats Sandstone of Arizona. In any case, the Van Horn unconformably overlies the Hazel Formation (~1.0 Ga) and is unconformably overlain by the Ordovician Bliss Sandstone and younger Paleozoic units. The Van Horn truncates folds and faults of the Hazel and older units and was tilted at low angles and faulted before deposition of the Bliss (King, 1965). McGowen and Groat (1971) interpreted the Van Horn Sandstone as an alluvial fan system deposited by braided channels. Ye and Soegaard (1993) suggested that the Van Horn was deposited as a braided channel complex, not as an alluvial fan, and that the Hazel Formation–Van Horn Sandstone couplet records a rift-drift succession deposited earlier than 510 mya.

During the early (post-Van Horn Sandstone) and middle Paleozoic (Devonian), the region was a passive continental margin undergoing only minor epeirogenic uplift and subsidence with no major structural deformation (Horak, 1985). Ye and Soegaard (1993), on the basis of subsidence curves determined for shallow-marine strata of the Van Horn area, suggested that subsidence rates decreased from the Early Ordovician to Early Pennsylvanian. Clearly, subsidence locally decreased markedly after the late Mississippian as uplifts occurred in the foreland of the Ouachita orogenic belt.

Passive Paleozoic subsidence resulted in formation of the Tobosa Basin, Cambrian to Mississippian (fig. 4), precursor to the Permian (Delaware and Midland) basin, east of the Diablo Platform, and other late Paleozoic features. The proto-Chihuahua Trough and Pedregosa (Devonian–Pennsylvanian) basins developed to the west (Goetz and Dickerson, 1985), where a thick sequence of Paleozoic shelf carbonates were deposited. Because the preservation and outcrop of early to middle Paleozoic strata is limited (LeMone and others, 1983a), the extent of these basins is poorly known. Sedimentation throughout the region, and extending well into Mexico and southern Arizona (Goetz and Dickerson, 1985), was characterized by shallow-marine shelf deposits separated by a series of regional unconformities (fig. 3). 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) also described unconformities at the top of the Silurian strata and at the top of the Upper Ordovician Montoya Group in the Franklin Mountains.

Thickness variations in Cambrian to Devonian strata were cited by Henry and Price (1985) as evidence that the Diablo Platform (fig. 4) 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 was 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.

In the Trans-Pecos region, lower to middle Paleozoic strata are exposed in the Franklin Mountains, Hueco Mountains, and the Van Horn area (Sierra Diablo–Cox–Goat–Beach–Baylor Mountains). The lower Paleozoic sedimentary rocks are the shallow-marine equivalents of the deep-marine strata present in the Marathon area to the southeast (Ye and Soegaard, 1993) and

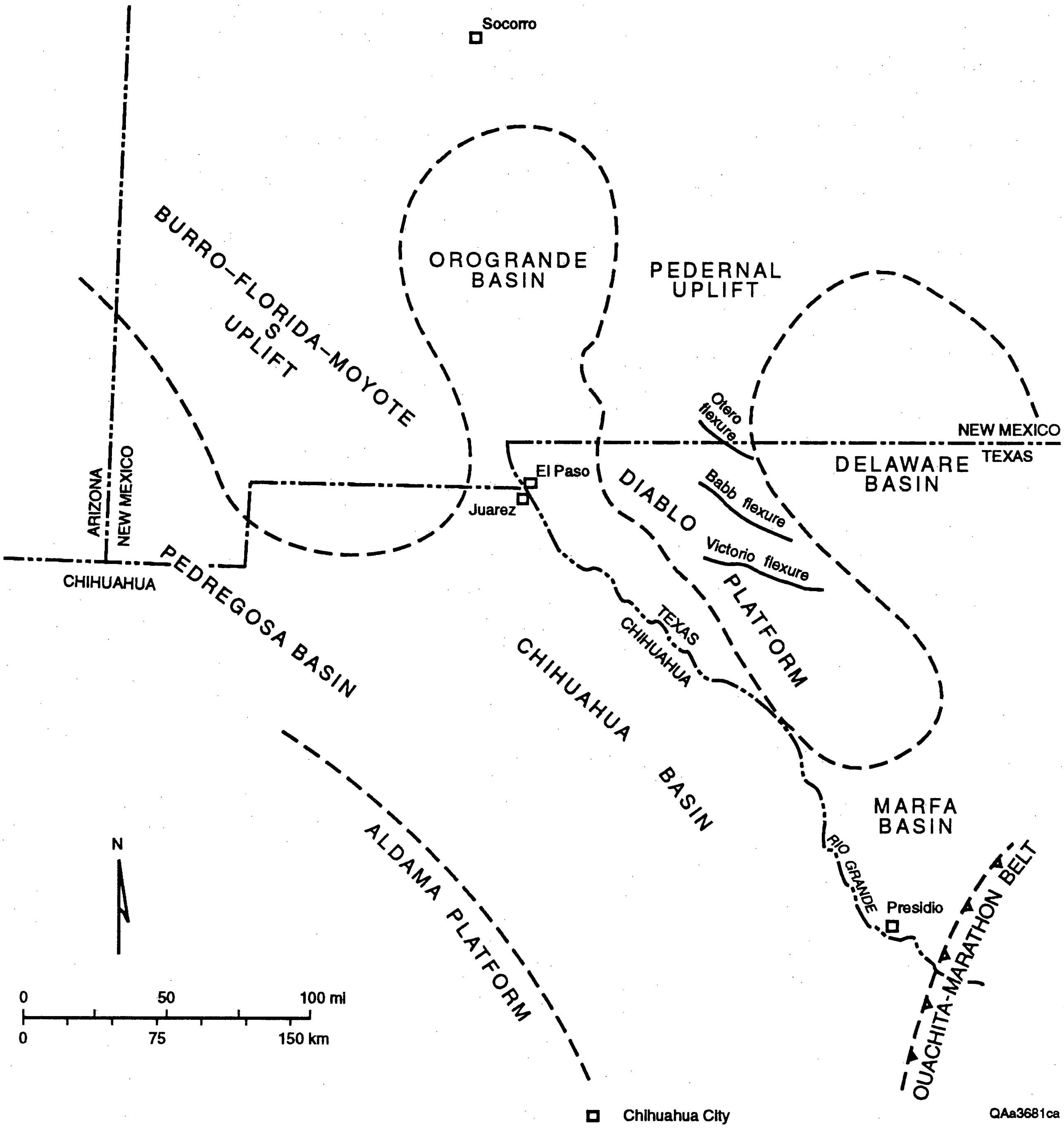

Figure 4. Generalized map of Paleozoic tectonic setting. Tectonic elements generalized from several sources, including Gries (1980), LeMone and others (1983b), and Brown and Handschy (1984).

the Solitario. In the Eagle Flat study area, Permian and younger strata lie on the erosional unconformity at the top of the Precambrian. An outcrop of Van Horn Sandstone (possibly Cambrian), near Goat Mountain in the northern Bean Hills quadrangle, is the only Paleozoic formation older than Permian present in outcrop or known from drilling. It is assumed that all pre-Permian strata younger than the Van Horn Sandstone, and including most of the Van Horn Sandstone itself, eroded from the Eagle Flat study area before Permian time (see LeMone and others, 1983a).

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 the North American plate and the South American–African plate (formation of Gondwana). This Appalachian–Ouachita–Marathon orogenic event began in West Texas in the Mississippian and, according to evidence in the Marathon area (Ross, 1979), culminated in the Early Permian. A subsidence history analysis of Paleozoic sediments in the Van Horn area (Ye and Soegaard, 1993) suggests that, after a long period of decreasing subsidence rates, the rate of subsidence increased from Late Pennsylvanian to Early Permian (Leonardian). 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 Eagle Flat study area lay well in the foreland of the active orogenic belt.

Among the Trans-Pecos structural features attributed to late Paleozoic tectonism (fig. 4) are the Ouachita–Marathon fold and thrust belt, foreland basins and troughs having north-trending axes (King, 1965; Henry and Price, 1985), the Diablo Platform (Muehlberger, 1980), inferred wrench faults along the Babb and Victorio flexures (Dickerson, 1980), north-side-down monoclines (Dickerson, 1980), folds of pre-Permian rocks in the Hueco Mountains (Beard, 1985), the Permian Basin (Delaware Basin, Central Basin Platform, Midland Basin), and the

Hillside fault (King, 1965). Translation associated with the Ouachita–Marathon fold and thrust belt was from southeast to northwest. Deeper-water flysch facies were thrust upon shallow-water limestones, dolomites, and sandstone (King, 1980; Ross and Ross, 1985). Late Permian reefs were partly localized on structural highs.

In New Mexico a series of late Paleozoic uplifts (the Deming axis [Turner, 1962]), trends across the south 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 Texas Lineament (Muehlberger, 1980), although few specific structural features having this sense of displacement have been documented. The Eagle Flat study area lies on the south edge of the Diablo Plateau, near the projection of the Texas Lineament.

Pennsylvanian strata, poorly exposed at the margins of the Diablo Plateau, have been removed by pre-Permian erosion at many locations. On the basis of 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 a partly 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 Orogrande Basin of south-central New Mexico and northern Chihuahua to the west. Cys and Gibson (1988) described the Diablo Platform as a stable carbonate shelf during most of the Pennsylvanian, but local uplifts developed in the northern platform in the Late Pennsylvanian. The study area probably lies near the shelf margin as it existed during the late Paleozoic and part of the Mesozoic (Greenwood, 1971). King (1965; his figure 3) showed the study area located on the southwest margin of the Diablo Platform during the Permian.

The west margin of the Delaware Basin (east edge of the Diablo Platform [fig. 4]) is in part approximately coincident with the Cenozoic Salt Basin–Wild Horse Flat extensional basins. The west edge of the Diablo Platform is approximately coincident with the east margin of the Chihuahua and Pedregosa basins, the Mesozoic Chihuahua Trough and the Cenozoic Hueco Bolson. The east and west boundaries of the Diablo Platform, as defined in the Paleozoic, probably influenced the location of Mesozoic and subsequent tectonic elements of the Trans-Pecos.

The part of the large Tobosa Basin (figs. 1 and 4) lying northeast and east of the study area was transformed into, from west to east, the Delaware Basin, the Central Basin Platform, and the Midland Basin. The western Delaware Basin is of most concern in this review. This region had been relatively stable from Cambrian through Mississippian time, but in the Late Mississippian and Early Pennsylvanian the tectonic features of the present Permian Basin formed (Cys and Gibson, 1988). Maximum subsidence in the Delaware Basin during the Pennsylvanian occurred on the east side of the basin along the north-trending, west edge of the Central Basin Platform (Cys and Gibson, 1988). Basin asymmetry and deposition of basinal clastics in the center and shelf carbonates on the margins continued into the Permian. During the middle Permian (Guadalupian), reefs, including the world-famous Capitan Reef complex, developed on the margins of the basin. The gradual filling of the basin was completed in the Late Permian (Ochoan) with deposition of evaporites and, at the close of the Permian, shallow-water evaporites and red beds (Cys and Gibson, 1988).

Relatively little is known about the effects of the late Paleozoic tectonic event in Chihuahua (Wilson, 1990), 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 Ouachita–Marathon tectonism is restricted to southeastern Chihuahua.

Late Paleozoic Permian rocks, the Wolfcampian Hueco Limestone, are extensively exposed in the northern Diablo Plateau and southern Sierra Diablo areas. Outcrops of Hueco Limestone are also common in the northeastern study area, southern Carrizo Mountains, northeastern Eagle Mountains, northern Van Horn Mountains, western Franklin Mountains, and the Wylie

Mountains. The closest outcrops of Hueco Limestone to the proposed site are about 2 mi (~3 km) east of northern Faskin Ranch near Railroad tank.

The Hueco Limestone unconformably overlies Pennsylvanian and older rocks in the region. The basal unit is commonly a conglomerate, the Powwow Member (King, 1965), but the formation is primarily a bedded limestone. The Hueco varies in thickness because of both the relief of the surface on which it was deposited and the erosional truncation of its upper surface before deposition of overlying formations. In the Sierra Diablo area, the Hueco Limestone is unconformably overlain by the Bone Spring Limestone and younger Permian units (King, 1965); to the west of the study area in the core of the Finlay Mountains, Permian strata younger than the Hueco are also exposed (Albritton and Smith, 1965). Southeast of Faskin Ranch, on the northeast edge of the Eagle Mountains, the Hueco Formation overlies Precambrian rocks and is unconformably overlain by Cretaceous strata (Underwood, 1963). In the Streeruwitz Hills, northeast of the proposed site, Hueco and younger Cretaceous units directly overlie Precambrian rocks, and no Permian strata younger than the Hueco are present (King, 1965). Permian rocks have been penetrated by deep wells drilled during petroleum exploration southwest of Devil Ridge (see plate 1). Permian strata, presumably the Hueco Limestone, are inferred to underlie the wedge of Cretaceous rocks that occur beneath the Cenozoic basin fill at the proposed site, but no Permian strata have been encountered in drilling associated with the site characterization program (see plate 1).

The Hillside fault (King, 1965) is a west-northwest trending fault of Permian and younger age that occurs in outcrop north of the Carrizo Mountains and projects westerly into the Eagle Flat study area beneath basin-fill sediments. Metarhyolite, present in outcrop south of the fault, occurs as fragments within the Powwow Member of the Hueco Limestone north of the fault. King (1965) inferred that the Hillside fault was active, downthrown on the north, during deposition of the Hueco Limestone. Cretaceous units are also downthrown on the north in excess of 1,000 ft (>300 m), presumably during the Tertiary because "erosional features indicate that it has been inactive since [the late Tertiary]" (King, 1965, p. 114). The westward continuation of the Hillside fault into the study area is undocumented.

A fault of similar trend and generally on the projection of the trace of the Hillside fault was mapped by King (1965) between the Precambrian rocks at the base of Eagle Flat Mountain in the southern Streeruwitz Hills and low knobs of Hueco Limestone to the west and southeast. As noted by King, this inferred fault is downthrown to the south, unlike the Hillside fault. On plate 1, we have inferred a west-northwest-trending fault, downthrown on the south, that is the north-bounding fault of the northwest Eagle Flat graben. If the Hillside fault projects through the Eagle Flat area (see plate 1), it appears to have much less displacement here than in its type area. Cretaceous units crop out only 2 mi (3 km) to the southwest near Grayton Lake, which implies that the strata are either downfaulted or downwarped to the south.

Projection of the Hillside fault through the Sierra Blanca area is difficult. Moody and Hill (1956) suggested that the Hillside fault correlated with a high-angle fault between Texan Mountain and Flat Mesa. This fault, mapped by Albritton and Smith (1965), has a strike generally similar to that of the Hillside fault, although related faults strike more northerly and displacements are much less. Studies by Albritton and Smith (1965) and King (1965) both dismiss Moody and Hill's (1956) interpretation of large, left-lateral, strike-slip displacement along the Hillside fault and structures of similar trend in the Eagle Flat region. Although noting the importance of northwest trends to many tectonic features of the region and previous interpretations of the Hillside fault as part of the Texas Lineament (Moody and Hill, 1956), the workers cited earlier argued that essentially no field evidence exists to support the interpretation that this is zone of great lateral offset in the Eagle Flat area.

MESOZOIC

Figures 5 and 6 summarize Mesozoic stratigraphy and tectonic elements in the region and the Eagle Flat study area. The major event in this region during the Mesozoic was the formation

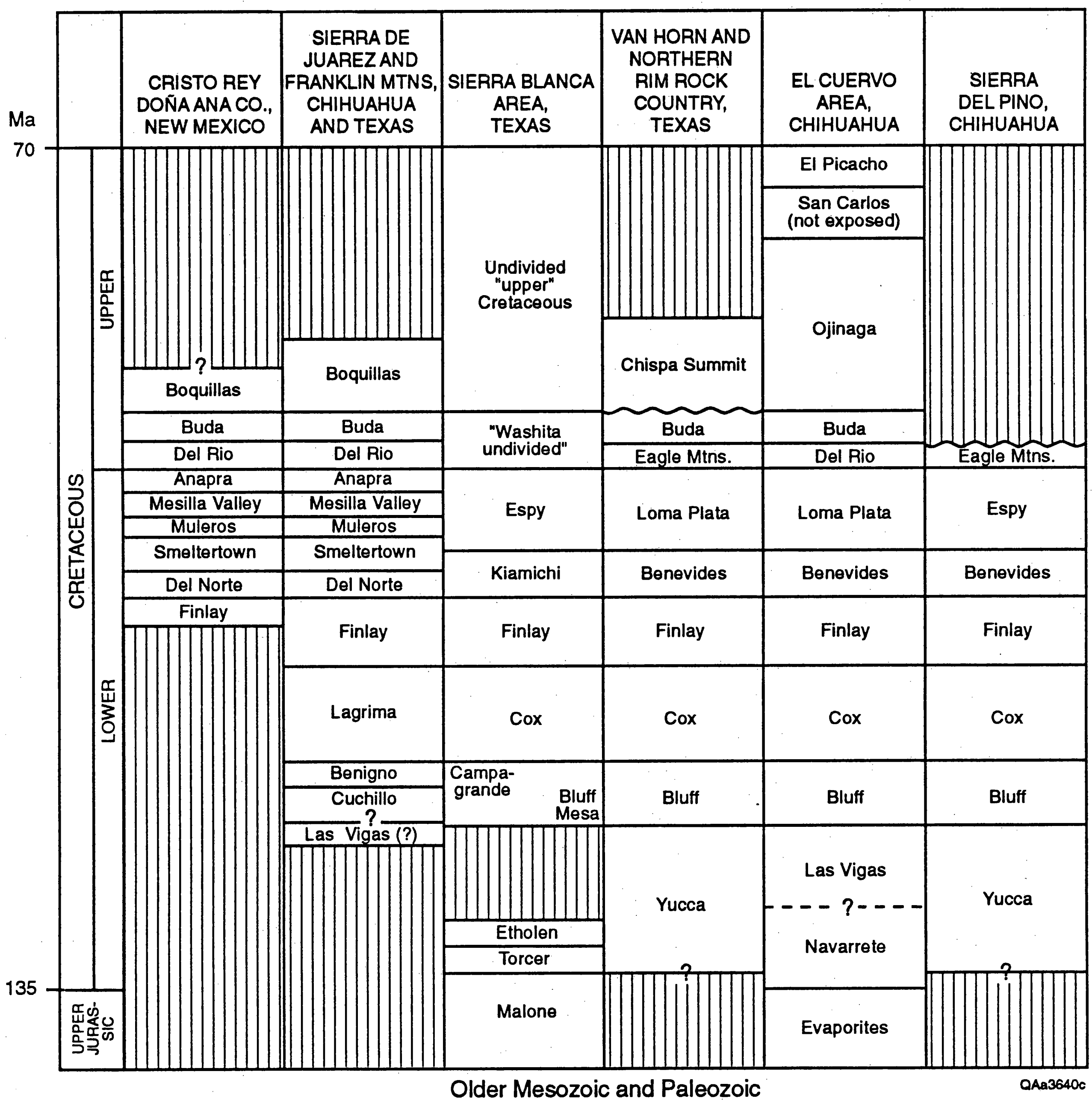

Figure 5. Chart of regional upper Mesozoic stratigraphy. Modified from Underwood (1980) and LeMone and others (1983b).

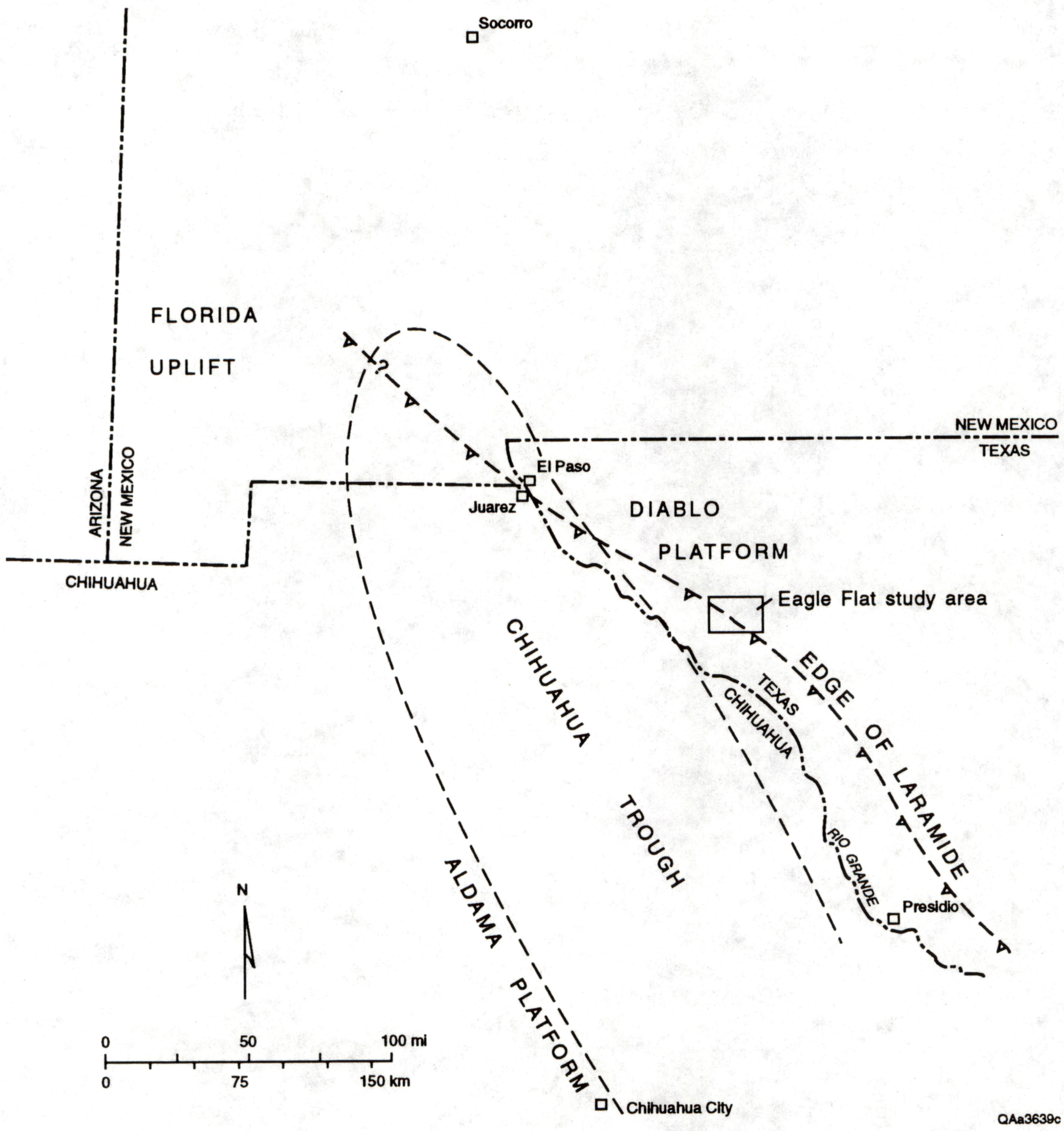

Figure 6. Generalized map of Mesozoic–Laramide tectonic setting. Tectonic elements from several sources, including Wiley and Muehlberger (1971), Navarro and Tovar (1974), and Brown and Handschy (1984). EFSA = Eagle Flat study area.

of the north- to 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. 6). Formation of the trough has been inferred to be related to the opening of the Gulf of Mexico (Muehlberger, 1980) and to the resulting transform movement on the Mojave–Sonora megashear (Silver and Anderson, 1974; Anderson and Schmidt, 1983). The oldest sedimentary strata in the Mesozoic trough are Jurassic(?) evaporites overlain by a thick sequence of Cretaceous marine deposits. Jurassic(?) and Cretaceous rocks thicken markedly into the Chihuahua Trough: from 1,000 to 2,000 ft (300 to 600 m) on the Diablo Platform (Henry and Price, 1985) to more than 13,000 ft (>4,000 m) in Chihuahua (DeFord and Haenggi, 1971). No Triassic or Lower Jurassic sediments have been described in Chihuahua (Clark, 1984). In southeastern New Mexico, well outside the Chihuahua Trough, Permian strata are unconformably overlain by lithologically similar Triassic rocks. Triassic rocks are locally exposed in Texas near the Pecos River (mostly in Loving, Ward, and Crane Counties) and are also present along the northwest edge of the Marathon uplift.

The Chihuahua Trough includes the northeastern two-thirds of Chihuahua, the westernmost Rio Grande region of far west Texas, the southwest border region of New Mexico, and the southeast corner of Arizona (Brown and Handschy, 1984). The deep north- to northwest-trending axis of the trough lies mostly in northeastern Chihuahua but extends into Texas near El Paso (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 asymmetric trough has a steeper northeast flank.

The transition from the northeast margin of the Chihuahua Trough to the southwest edge of the Diablo Platform lies near the study area but is not exposed. The Sierra Blanca area was emergent during the Triassic and much of the Jurassic (Albritton and Smith, 1965). The margin of the trough 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, 20 mi (32 km) southeast of El Paso, that was interpreted to be one of the trough-bounding structures. The trough appears to have localized subsequent Laramide deformation and may account for the northwest trend of Cenozoic Basin and Range extensional faults in the southeastern Hueco Bolson and Red Light Draw.

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 volcanoes in Mexico.

Mesozoic rocks present in the vicinity of the Eagle Flat study area (fig. 2; see also Dietrich and others, 1983; Twiss, 1979) are mostly Cretaceous marine limestones and clastics (Albritton and Smith, 1965), with strata inferred to be Jurassic by Albritton and Smith (1965) present only in the Malone Mountains west of Sierra Blanca. The Jurassic(?) strata unconformably overlie Permian rocks, Briggs Formation, but are conformably overlain by Lower Cretaceous strata, the Torcer Formation (Albritton and Smith, 1965). Subsequent workers (Longoria and Tickner, 1989) interpreted the upper part of the Malone Formation as Lower Cretaceous and inferred that the previously reported Jurassic ammonites are reworked fauna. No age-diagnostic fossils have been found in the lower Malone Formation. Elsewhere, the Cretaceous overlies Permian and older rocks along an erosional unconformity.

The Cretaceous strata present in the Eagle Flat study area (see fig. 5 for generalized stratigraphy) are a series of marine limestones, sandstones, and shales. These have been generally well mapped and described by previous authors (Underwood, 1963; Albritton and Smith, 1965; King, 1965), although each author has devised a slightly different terminology. The Cretaceous formations are, from oldest to youngest: Yucca Formation, Bluff Mesa Limestone, Cox Sandstone, Finlay Limestone, Kiamichi Formation, rocks of Washita age, and an unnamed sandstone and siltstone (terminology of Albritton and Smith, 1965). Underwood (1963) correlated his Benevides Formation with the Kiamichi Formation and subdivided the

Washita-age rocks into, from oldest to youngest, the Espy Limestone, Eagle Mountains Sandstone, and Buda Limestone. King (1965) divided the stratigraphy into "southwestern" and "main" parts of his map area. King's southwestern terminology resembles that of Albritton and Smith (1965) except that King correlates the strata above the Washita Group with the Eagle Ford Formation. In the main part, King maps no Cretaceous strata younger than the Washita Group and refers to all Cretaceous strata older than the Cox Sandstone as the Campagrande Limestone. Albritton and Smith (1965) mapped the Campagrande Formation only in areas west of the Eagle Flat study area, such as the Finlay Mountains, but recognized that it was generally correlative to the Bluff Mesa, which they mapped only in areas south of the Devil Ridge thrust. The Cenozoic basin-fill units at the proposed site overlie an erosional surface developed on these Cretaceous units.

MESOZOIC–CENOZOIC TRANSITION

During the transition from the Mesozoic to the Cenozoic (Late Cretaceous to Eocene) major changes occurred 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 belt of compressional tectonic structures. 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 northeast margin of the Chihuahua Trough. The deformation produced uplift of the trough and mostly northeastward sliding of Cretaceous strata, perhaps on older evaporite units (Gries and Haenggi, 1971; Gries, 1980). The Diablo Platform was locally deformed by high-angle reverse faulting, monoclinal folding, and possible strike-slip faulting, but most strata are nearly flat lying to gently dipping and were little disturbed by Laramide tectonism (Henry and Price, 1989).

In the Big Bend area of Trans-Pecos Texas, the Laramide orogeny began in the Late Cretaceous, peaked in the late Paleocene, approximately 60 mya, and ended in the early Eocene, 55 to 50 mya (Wilson, 1971). In other areas of Trans-Pecos, researchers (Berge, 1981; Henry and Price, 1989; among others) proposed that more than one major episode of deformation occurred. 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; the east-west stress direction is inferred from local north-south oriented faults and fold axes and also from east-west-trending dikes in east-central New Mexico (Horak, 1985). Laramide igneous activity, probably postfolding, occurred in New Mexico, Arizona, and northern Mexico (Coney and Reynolds, 1977). Price and Henry (1984) suggested, on the basis of the east-northeast strike of dikes and veins, that the early (middle Eocene to early Oligocene, 48 to 32 Ma) pulse of magmatism in the Trans-Pecos occurred during the waning stages of residual Laramide compression.

The leading edge of Laramide thrusting, the surface trace of the northeasternmost major thrust sheet (the Devil Ridge thrust), trends northwesterly across the southwest corner of the study area (fig. 6), northeast of Love Hogback and Front Ridge and between Sand Mountain and Yucca Mesa (Underwood, 1963; Albritton and Smith, 1965). The leading edge of Laramide thrusting projects northwesterly between Sierra Blanca Peak and the north end of the Quitman Mountains, beneath the Cenozoic cover of the Hueco Bolson, and south of El Paso between the south end of the Franklin Mountains and Sierra Juarez in Chihuahua (fig. 6). Laramide thrusts are present southeast of the study area in the Eagle and Indio Mountains (Underwood, 1963) and south of the study area in the Quitman Mountains (Jones and Reaser, 1970). Strongly folded Mesozoic rocks are present in the mountains southwest of the Laramide front.

The proposed site at Faskin Ranch lies in the "marginal belt" (Albritton and Smith, 1965, p. 103) between the Devil Ridge thrust to the southwest and the Diablo Plateau to the north. Nearly flat-lying to gently warped Cretaceous strata of the plateau dip southwesterly (2° to 15°) beneath the Laramide thrust sheets. Cretaceous rocks of the marginal belt are locally exposed at

Sand Mountain and in unnamed low hills between Front Ridge and Grayton Lake (Underwood, 1963; Albritton and Smith, 1965) and have been intercepted beneath Cenozoic sedimentary cover in boreholes drilled as part of the characterization studies. Results of drilling are consistent with earlier interpretations by Albritton and Smith (1965) based on outcrops and projections of structure contours. High-angle, northwest-trending normal faults offset Cretaceous and older strata beneath Cenozoic basin fill; faults are downthrown to the northeast. Although no faults of sufficient displacement to juxtapose rocks of different formations were identified in core, fracturing was locally of intensity sufficient to result in lost circulation during drilling. The role of fractures in ground-water flow is discussed in the report on saturated zone hydrology. Correlations of Cretaceous strata in core are based on lithology and on uncommon age-diagnostic fossils. The inferred stratigraphic and structural relationships are shown in cross section on plate 1. The seismic reflection–refraction survey of the site (see report by Paine and others, 1993) was helpful in interpreting depth of bedrock. The survey was optimized for depths of about 300 ft (~100 m). Some internal reflections of limited extent are seen in the basin fill, but no faults are decipherable in either the basin fill or the Cretaceous bedrock.

One normal fault is inferred to lie beneath the proposed site on the basis of three lines of evidence. Stratigraphic data from boreholes YM-17 and YM-62 indicate that a fault, downdropped to the east or northeast, must trend northerly between the two holes; borehole and seismic data identify a steepening in the gradient, down to the northeast, of the bedrock surface (Jackson and others, 1993); Albritton and Smith (1965), on the basis of outcrop data, interpreted several west- to northwest-trending faults, mostly downthrown on the northeast, to lie beneath Cenozoic cover in the area west of the proposed site. The fault beneath the proposed site is related to the faults in the marginal belt described by Albritton and Smith. These faults are presumed to have originated as a result of loading by Laramide thrusting and flexure of the south edge of the Diablo Plateau. They may have been reactivated by later Tertiary extension or, in some cases, originated during Tertiary extension. No evidence was cited by previous workers (Underwood, 1963; Albritton and Smith, 1965) or found during the current investigation that any of these faults displace late Cenozoic sediments, although some of them may have been active during the early extensional history of northwestern Eagle Flat. We have inferred that the fault identified in bedrock between boreholes YM-17 and YM-62 is coincident with the increased gradient on the bedrock–alluvium interface, but similar areas of relief present in the modern topography are mostly not fault controlled. The absence of faulting in the late Cenozoic sediments at the proposed site is discussed further in the following section on the Cenozoic.

Fracturing in the bedrock of the marginal belt, as noted above, is locally of sufficient extent to cause lost circulation problems during drilling, but in the site area the fractures are not interconnected well enough to result in high transmissivities in the deep aquifer or to destroy the confined to leaky-confined character of the aquifer. Fractures are presumed to be locally important to ground-water flow in the aquifer, although the degree to which fractures are interconnected is probably variable.

In Cretaceous limestone and sandstone outcrops southwest of the proposed site, high-angle fractures are commonly of two sets, parallel and orthogonal to the Laramide structural trend. Where developed in limestone, many are filled with calcite. Minor solution widening can be seen locally in surface outcrops. Joint spacing is commonly determined by bed thickness, spacing of several feet (meter-scale) being common in the thick limestone beds. Joints commonly terminate vertically on bedding planes, although some narrow zones of closely spaced joints, northeast-trending in outcrops south of Grayton Lake, for example, appear to cut across several adjoining layers of strata. Locally, narrow fracture zones are about 10 to 15 ft (~3 to 5 m) wide and contain as many as 10 fractures per 3 ft (1 m).

Our observations are generally consistent with those of King (1965) and Underwood (1963). In the Sierra Diablo area, King noted similar steeply dipping, west-northwest and east-northeast trending joints, joint density being controlled by lithology. He also noted that although weathering may have enlarged some joints at the surface, most "narrow and tighten at depth" (p. 115). In the Devil Ridge area, Underwood (1963) mapped many minor displacement (generally less than "a few tens of feet," p. 22) normal faults that trend dominantly northeast along with a subsidiary set that trends northwest. Some of these structures may be joints because "many of the minor faults...are difficult to see on the ground." (p. 22).

In core the joints and fractures are variable in intensity and attitude. Nearly vertical fractures are locally present, but it is unlikely that near-vertical boreholes will intersect near-vertical fractures in a representative fashion. Analysis of fractures in core will either over- or underrepresent the number of nearly vertical fractures present in a rock mass. Nonvertical fractures present in core may be either fractures that formed at some angle to the bedding or fractures that are orthogonal to inclined bedding. Because none of the core is oriented, fracture strikes could not be determined. Some fracture surfaces contain slickenlines, indicating relative movement between the adjoining faces of the fractures, including low-angle features possibly related to Laramide compression, but only minor displacement is inferred because unlike lithologies are not juxtaposed. Fractures are locally weathered near the bedrock–alluvium interface, but below the zone of weathering they are generally smooth, having either a narrow aperture or a filling of sparry calcite or quartz. Locally fractures are closely spaced so that the core is not coherent. Below the zone of weathering, no evidence of solution widening was noted. This may reflect the chemistry of the waters in the aquifer beneath the basin floor because such old waters are probably in near equilibrium with the host rocks.

CENOZOIC

Laramide compression dominated the early Cenozoic (see earlier discussion), but between about 30 mya (Price and others, 1986) and the present, the region has been characterized by extensional tectonics, continental sedimentation, and, until about 17 mya, local volcanism. The specifics of Cenozoic stratigraphy (fig. 7), faulting, and Quaternary geomorphology as they relate to the study area and the proposed site are described in associated reports (Collins and

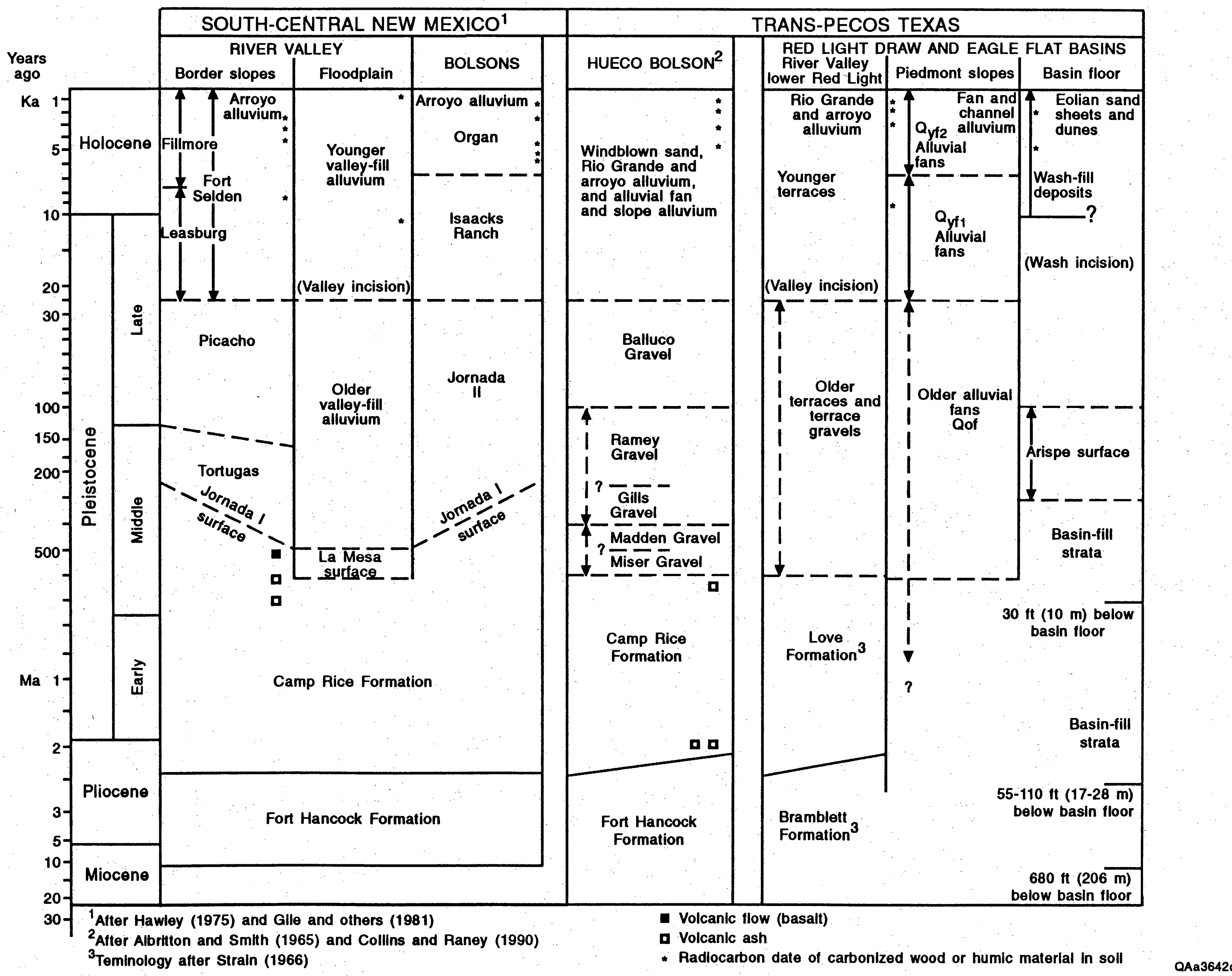

Figure 7. Cenozoic stratigraphy of basin-fill deposits of Trans-Pecos Texas and south-central New Mexico. Figure prepared by Langford (1993).

Raney, 1993; Jackson and others, 1993; Langford, 1993). Reports on topics related to regional geophysics and seismicity are being written by staff of the Department of Geological Sciences at The University of Texas at El Paso and Dames and Moore. The following discussion presents a broad overview and sets the regional context for characterization studies of Cenozoic geology.

Regional extension and volcanism occurred during the Cenozoic across much of the western United States and adjacent Mexico. This tectonism is presumably related to earlier subduction along the west margin of the North American plate and residual thermal effects (for example, Horak, 1985). The resulting Basin and Range Province includes the region surrounding the Eagle Flat study area. Cenozoic extensional basins of the region are shown in figure 8. Several of these basins have been referred to in the literature as "bolsons." Although some prefer to restrict *bolson* to closed basins having no external drainage, in this report we have attempted to follow the usage of previous authors in the region.

Volcanism and other igneous activity (figs. 1 and 2) that either apparently predates, or coincides with, Basin and Range tectonism in the Trans-Pecos region has been described by many authors (for example, Henry and Price, 1985; Henry and McDowell, 1986; Price and others, 1986). Magmatism occurred in the Trans-Pecos region from about 48 to 17 mya (Price and others, 1986). Magmatism was widespread from middle Eocene to early Oligocene (48 to 32 mya); the main period of caldera-related magmatism was between 38 and 32 mya, caldera formation continuing in adjacent Chihuahua until about 28 mya (Henry and McDowell, 1986). Igneous rocks of this period are divided (Henry and Price, 1984) into a western alkali-calcic belt and an eastern alkalic belt. The alkalic rocks in the Trans-Pecos are inferred to be the easternmost expression of subduction-related magmatism that progressed eastward from the Pacific coast to West Texas as the subducted slab shallowed over time (Price and others, 1986).

The western alkali-calcic belt includes the Eagle Flat study region and the known or suspected calderas of the northern Quitman Mountains, Van Horn Mountains, Wylie Mountains, and, south of the Sierra Vieja, the Chinati Mountains and Infiernito caldera (Price and others, 1986). Other igneous rocks near the study area, such as the rhyolitic laccoliths of

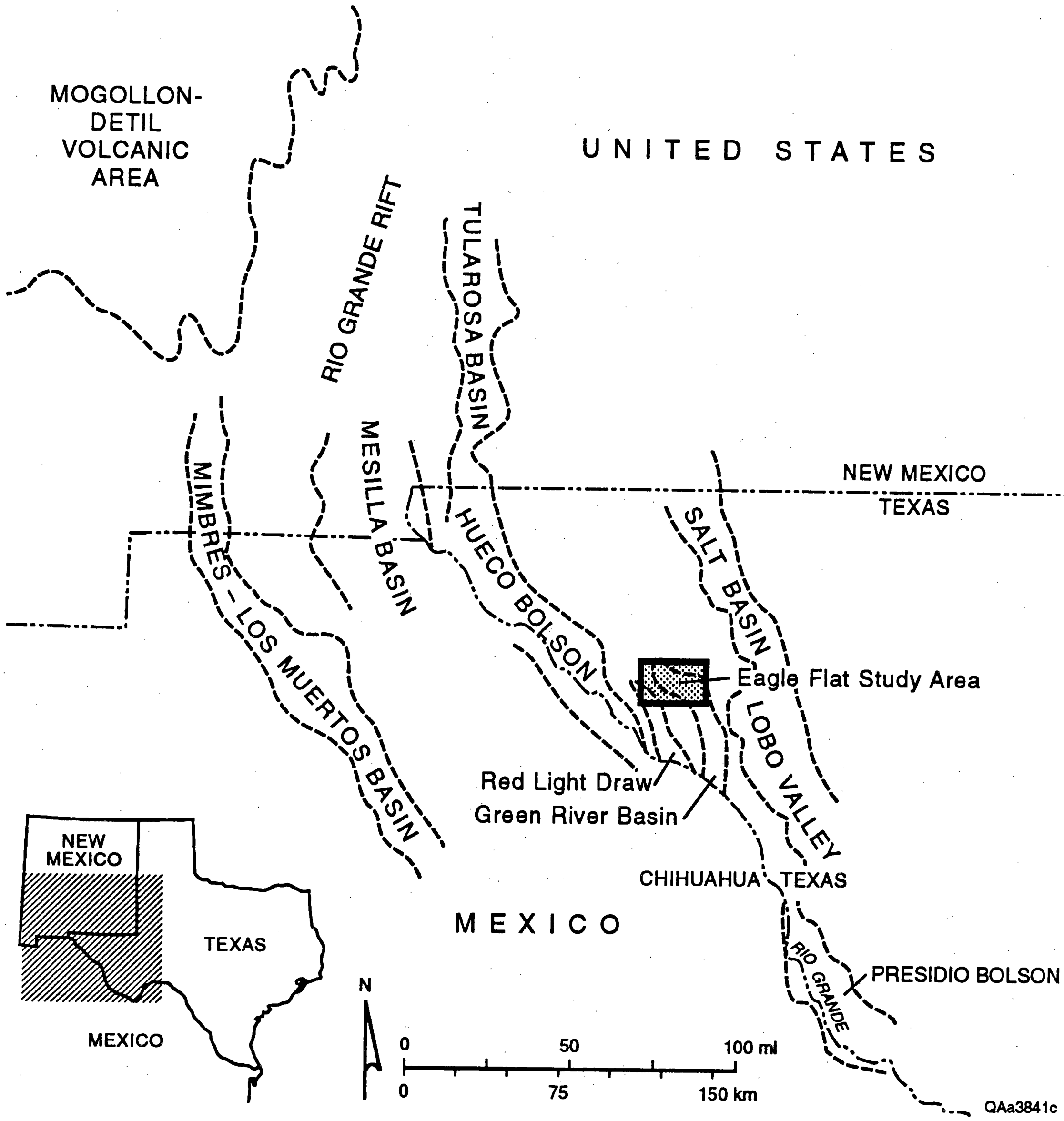

Figure 8. Generalized map of late Cenozoic tectonic setting. Tectonic elements generalized from Oetking and others (1967) and Woodward and others (1978). EFSA = Eagle Flat study area.

the Sierra Blanca Peaks (36 Ma; Henry and McDowell, 1986; see also Mathews and Adams, 1986) and the andesites of the Finlay Mountains (47 Ma; Henry and McDowell, 1986), which produced structural doming of the earlier strata (Albritton and Smith, 1965), are also related to this western belt. The eastern calcic belt includes the igneous rocks of the Davis Mountains, Christmas Mountains and Big Bend area, and the Buckhorn, Paisano, Pine Canyon, and Sierra Quemada calderas (Price and others, 1986).

A small area intruded by rhyolite dikes and sills was mapped by Underwood (1963) 3 to 4 mi (5 to 7 km) south of the proposed site. These are the closest known occurrences of igneous rocks to the site; none were encountered in the drilling associated with this project. A sample from these outcrops was dated by potassium–argon (whole rock) methods and determined to be 36.8 ±1.0 Ma.

From about 31 to 24 mya, during the initiation of regional extension, magmatism was restricted to the southern Trans-Pecos and adjacent Chihuahua (Price and others, 1986). Between 24 and 17 mya, intrusion of alkalic basalts occurred locally throughout the Trans-Pecos, but this magmatism was volumetrically minor (Price and others, 1986). No magmatic events younger than 17 Ma have been identified in the Trans-Pecos. This absence of evidence for post-17-Ma magmatism is consistent with measurements of heat-flow data in the Trans-Pecos (Henry and others, 1989), commonly 1.2 to 1.8 HFU (heat-flow units). The Trans-Pecos values are transitional between the lower values of the craton to the east, ~1.1 HFU, and the higher values, ~2.5 HFU, of the southern Rio Grande rift in New Mexico to the west (Sargent and Bedinger, 1985). The local hot springs and thermal waters of the Trans-Pecos and adjacent Mexico, such as Hot Wells in the southeast Eagle Flat basin, represent deep circulation of meteoric waters and heat-flow convection by ground water (Henry, 1979; Henry and Gluck, 1981). No evidence of any potential for present-day magmatism exists in the Trans-Pecos or in the vicinity of the proposed site.

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 parts of the Basin and

Range Province in Trans-Pecos Texas and northern Mexico. It has been argued, primarily on the basis of geophysical data, that the Rio Grande rift is similar to, but distinct from, the "true" Basin and Range. In contrast to the Trans-Pecos region of Texas, magmatism associated with the Rio Grande rift of New Mexico has continued into the Quaternary (Anthony and Poths, 1992) and Holocene (Seager and others, 1984). Most authors (Baldridge and others, 1984) identify two major pulses of volcanism associated with rifting: an early magmatic pulse that occurred between 30 and 18 mya and a pulse that occurred about 5 mya. Some notable volcanic centers (Jemez caldera) have eruptions that do not coincide with either pulse. In addition, development of the Mogollon–Datil volcanic field (active 32–20 mya) 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 either temporally or spatially related to the evolution of the rift.

Because the structure and stratigraphy of the northwest-trending part of the southeast Hueco Bolson are continuous with those of the north-trending Hueco Bolson near El Paso, it is thought to be an extension of the Rio Grande rift within the Basin and Range Province. This is in agreement with data of many authors (Seager and Morgan, 1979; Henry and others, 1983; among others). Seager and Morgan (1979) also noted that basins associated with the Rio Grande rift, like the Hueco Bolson, 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 some of the basins in New Mexico and Trans-Pecos contain about 9,500 ft (~3 km) or more of basin-fill sediments. Other extensional basins of Trans-Pecos Texas, such as the Salt Basin and related features, Red Light Draw, and Eagle Flat, which includes the proposed site, are shallower and less directly linked to the Rio Grande rift and are here considered to be extensional basins related to the Basin and Range Province (see Henry and others, 1983).

The Cenozoic stratigraphy (fig. 7) of the basins of West Texas and New Mexico has been described by many authors (such as Albritton and Smith, 1965; Strain, 1966; Hawley and others, 1969; Groat, 1970; Hawley, 1975; Gile and others, 1981; Stevens and Stevens, 1985; Gustavson, 1991), but correlations both within and between basins are difficult because reliable age determinations are scarce. This is especially true of subsidiary basins, such as Eagle Flat, that have developed in isolation from the major basins. Most studies are based on investigations of available outcrops and geophysical data using limited samples from drilling, and the early history of basin development and sedimentation is ill defined. The oldest documented episode of Basin and Range extension in West Texas occurred about 24 Ma (Henry and Price, 1986), somewhat more recently than the early extension associated with the Rio Grande rift in New Mexico. A change in extension direction, from east-northeast to west-northwest, and a possible change to a lower strain rate 10 to 13 mya has been proposed for New Mexico and possibly Trans-Pecos Texas (Zoback and others, 1981; Golombek, 1983; Henry and Price, 1986).

The Cenozoic structural and depositional development of the Eagle Flat study area and the neotectonics of the region are described in detail in other reports (Collins and Raney, 1993; Jackson and others, 1993; Langford, 1993). In general, the sediments within the basins accumulated by lateral infilling from adjacent highlands and, in those basins of the Rio Grande rift, from more-regional stream systems associated with the precursor to the ancestral Rio Grande (Strain, 1966; Hawley and others, 1969). The early history (Miocene through early Pliocene) of basins related to the Rio Grande rift appears to be one of a series of closed basins (bolsons), locally and perhaps episodically integrated, that at various times received sediments from a river system that flowed generally from north to south. This river system was not through-flowing to the Gulf of Mexico but terminated in the closed basins of northern Chihuahua and partly in the Hueco Bolson. Although some standing bodies of water may have persisted as perennial lakes of limited duration in the larger basins, ephemeral desert lakes or playas were more typical. Lacustrine muds and minor evaporite deposits occur in the stratigraphic record of the larger basins and less commonly in those basins having smaller drainage areas such as Eagle Flat. Episodic sediment input from adjacent highlands was related to ephemeral drainages in local drainage basins. Proximal to distal alluvial-fan deposits of locally derived materials are common especially near basin margins. An eolian component of the sedimentary fill, of either inter- or intrabasinal origin, is present. Locally extensive eolian deposits are recognized, but much of the eolian material may be reworked into the other deposits.

Cenozoic deposits in the Eagle Flat study area were described in detail by Jackson and others (1993), and Langford (1993). Due to the generally low gradient of the surface, only the upper few feet of late Cenozoic (generally <500,000 yr old) sediments are exposed in natural outcrops; excavations to about 20 ft (~3 m) in depth provide uncommon opportunities for examining older deposits. Most of what we know of the older Cenozoic stratigraphic record of Eagle Flat comes from boreholes associated with this project (Jackson and others, 1993).

The Hueco Bolson preserves the thickest and most studied basin-fill deposits of the Trans-Pecos. Here the oldest Cenozoic sediments in outcrop, the Fort Hancock Formation, are probably late Pliocene (fig. 7). Older but undated strata have been penetrated by drilling, and a much thicker Tertiary section is known to be present in the deepest parts of the basin (Collins and Raney, 1992). Overlying the Fort Hancock Formation is the commonly coarser grained Camp Rice Formation. The initiation of Camp Rice deposition, at about 2.5 mya, appears to coincide 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 having clasts derived from rocks that do not crop out in the Hueco Bolson 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 (Machette, 1985).

Late Cenozoic fault scarps are common throughout much of the New Mexico–Trans-Pecos–Chihuahua region that includes the study area. For example, Quaternary scarps have been described in the Hueco Bolson (Muehlberger and others, 1978; Keaton and others, 1989;

Collins and Raney, 1990, 1991) and related basins in New Mexico (Seager, 1980; Machette and others, 1986; Gile, 1987; Machette, 1987). Muehlberger and others (1978) and Goetz (1980) identified a distinct system of scarps in the Salt Basin and its probable structural extensions to the south. The largest historic earthquake in Texas, the 1931 Valentine earthquake, was probably associated with a seismically active fault in the Lobo Valley part of this structural zone. Seismicity of the region is discussed in a separate topical report (Keller and others, 1993). Quaternary fault scarps, also present throughout northern Chihuahua, are little studied (Morrison, 1969) but are part of the evidence indicating the probable continuation of the Rio Grande rift–Basin and Range Province into Chihuahua (Gries, 1979) and adjacent regions of Mexico (Henry and Aranda-Gomez, 1992).

Late Cenozoic fault scarps are generally well preserved in the Trans-Pecos, but no evidence exists of any late Cenozoic faulting in the northwestern Eagle Flat basin. The slow rates of sediment accumulation inferred from studies of the basin fill (Jackson and others, 1993) and evidence of surface stability (Langford, 1993) also suggest that any fault scarps of large lateral extent or vertical expression should be readily identifiable. The absence of such scarps, as noted by previous workers in the area (such as King and Flawn, 1953), and which was also noted by us during this investigation, suggests that none has formed for many thousands of years. A near-surface, stage III to IV, fine-grained calcic soil is commonly present in the basin-fill sediments throughout northwestern Eagle Flat basin, but it is nowhere known to be faulted. This suggests that no significant surface rupturing events have occurred for at least several tens of thousands of years. The Quaternary fault closest to the proposed site is the West Eagle Mountains–Red Hills fault in Red Light Draw. This fault and other late Cenozoic faults of the region are discussed in a separate topical report (Collins and Raney, 1993).

The paleomagnetic and basin-fill stratigraphic data (Jackson and others, 1993) provide additional information that suggest no discernible faulting of basin-fill sediments in the vicinity of the proposed site, at least since the top of the Matayama Chron, about 780,000 yr ago. The three boreholes pertinent to this discussion are YM-4, YM-6, and YM-17/53. These provide paleomagnetic data across the north part of the proposed site and cross the projection of the subsurface fault described above. The elevation of the top of the Matayama Chron is 4,347 ft (1,326 m) ±2 ft (±0.6 m) in each of these holes. This near-constant elevation is surprisingly consistent, given the small-scale heterogeneities of the sedimentary package and local variations in rates of deposition, but suggests that no major fault offset of these strata has occurred in the last 780,000 yr. Differences in elevation of other older Chron boundaries are most probably due to local changes in depositional rates or paleomorphology of the surface. Although no evidence of faulting in the older basin fill exists, small-scale offsets cannot be precluded. Similarly, stratigraphic cross sections of the proposed site (Jackson and others, 1993), show beds deeper within the basin fill that correlate across the proposed site and do not appear to have been offset by faults.

In general, extensional faulting probably began at several locations in the Trans-Pecos, probably in the early Miocene, and probably no earlier than the 24-Ma date suggested by Henry and Price (1986). The location and orientation of the early-formed faults probably reflected local stress fields and the trends of preexisting zones of structural weakness. Over time, and with changing stress orientations, some of the early faults and areas of extension continued to develop as the principal centers of extension and eventually formed the major Cenozoic basins of the Trans-Pecos. Other early-formed basins failed to become major centers of extension and exist today as shallower, subsidiary basins of limited extent and less active faulting. The Hueco Bolson is one of the largest and deepest of the Trans-Pecos Cenozoic basins; northwest Eagle Flat is an example of a subsidiary basin that failed to develop as a major center of extension.

The Eagle Flat study area is within the southeast part of the regional Basin and Range–Rio Grande Rift Stress Province (Zoback and Zoback, 1980) (fig. 9). 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 Eagle Flat region to determine what variations

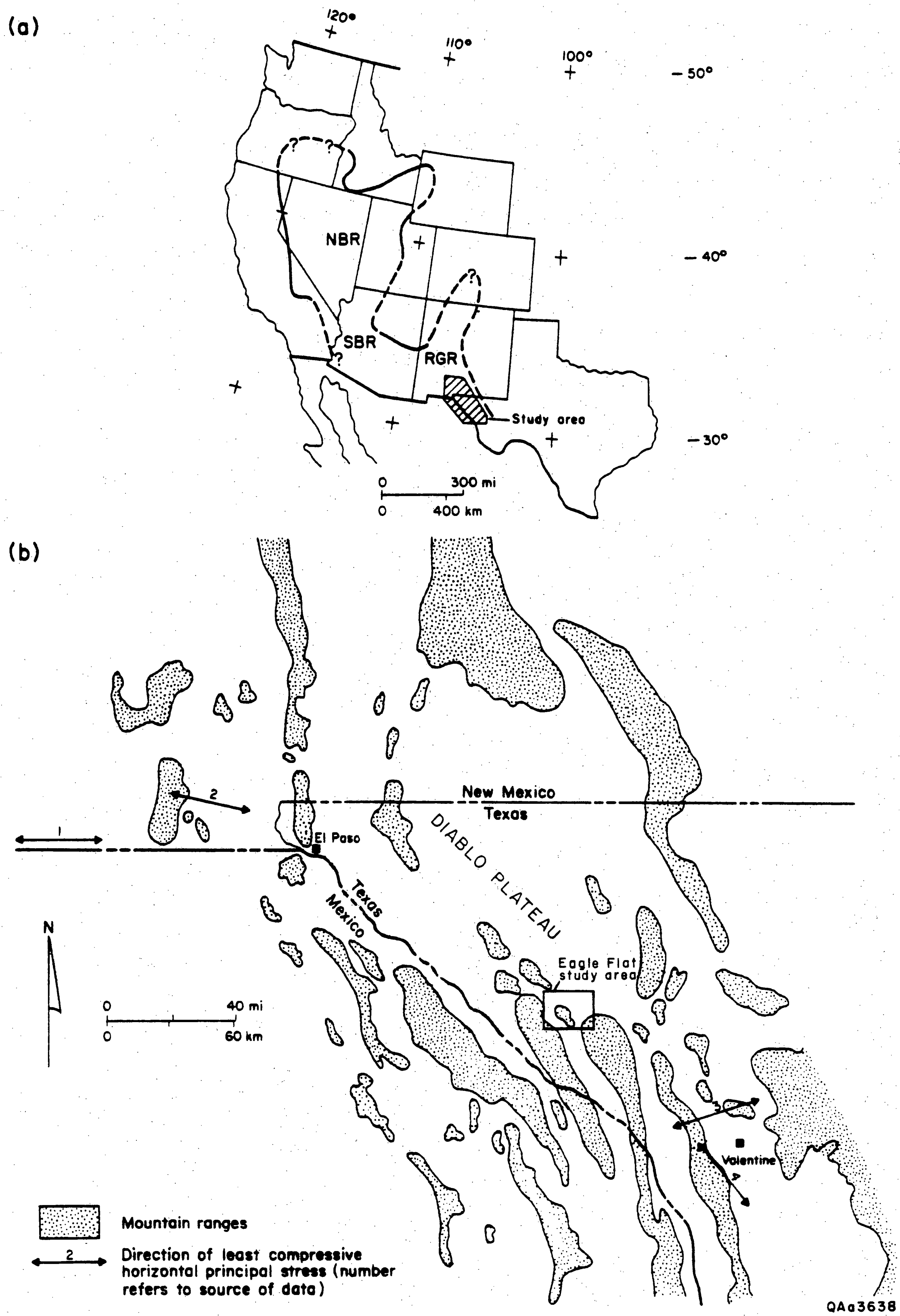

Figure 9. Maps showing (a) approximate boundaries of regional Basin and Range–Rio Grande Rift stress province (modified from Zoback and Zoback [1980]) and (b) measurements of least compressive horizontal principal stress. Measurements 1, 2, and 3 were compiled by Zoback and Zoback (1980), and measurement 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. NBR = northern Basin and Range province, SBR = southern Basin and Range province, RGR = Rio Grande rift.

may exist. On the basis of the orientation of grooves on the fault plane of the Campo Grande fault (Collins and Raney, 1990), extension (least principal horizontal stress direction) was determined to be northeastward during the last fault movement (late Pleistocene). The northwest-striking Mayfield fault of Lobo Valley and the northwest-striking fault bounding the west flank of the Guadalupe Mountains also exhibit evidence of northeastward slip. This direction differs from the regional west-northwestward direction characteristic of the stress province. Variations in the local stress field and preexisting zones of crustal weakness or other inhomogeneities are very important in determining the direction of extension and geometry of specific faults in the region.

Estimates of rates of vertical crustal movement in the Trans-Pecos are not well constrained. Gable and Hatten (their map D; 1983) showed the Eagle Flat study area lying in a zone of vertical movement of 3 to 6 ft (1 to 2 m) per 10,000 yr. This is comparable to that estimated for much of western New Mexico and eastern Arizona and is much less than that shown for areas of the western United States that lie west of the lower Colorado River and Wasatch Front. The Rio Grande rift is shown as having moved 6 to 13 ft (2 to 4 m) per 10,000 yr. Whereas the relative uplift rates of the regions as mapped by Gable and Hatten appear reasonable, the absolute values for the study region seem high, judging from recent studies of late Cenozoic faulting of the Trans-Pecos region (see Collins and Raney, 1993). Henry and others (1989) estimated a much lower average rate of crustal uplift for the Trans-Pecos, 3,600 ft (1,100 m) per 25 Ma or 0.14 ft (0.04 m) per 10,000 yr. Attempts at determining short-term rates of vertical crustal movement by releveling surveys (Reilinger and others, 1980; Ni and others, 1981) have produced questionable results partly because the precision of the early surveys may be in doubt. For example, the total unadjusted apparent uplift at Sierra Blanca was determined to be about 0.24 inch/yr (6 mm/yr) from 1917 through 1957, but the authors (Ni and others, 1981) could not determine whether the apparent uplift was due to a systematic leveling error or to a regional tectonic effect. Related surveys imply a 0.18-inch/yr (4.4 mm/yr) uplift of the Diablo Plateau–Carlsbad, New Mexico, area (Reilinger and others, 1980), subsidence of 0.11 inch/yr

(2.8 mm/yr) near Valentine (Ni and others, 1981), and unspecified subsidence east of Van Horn (Ni and others, 1981) and in the Salt Basin (Reilinger and others, 1980). As noted by Henry and others (1989), the results of the releveling surveys contain large uncertainties and it is unrealistic to extrapolate the inferred rates over long periods of time. More recent surveys in the Davis Mountains and Valentine region, using satellite-based surveying systems, have not shown any detectable rates of vertical crustal movement over a 2-yr period (Roberto Gutierrez, personal communication, 1993).

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