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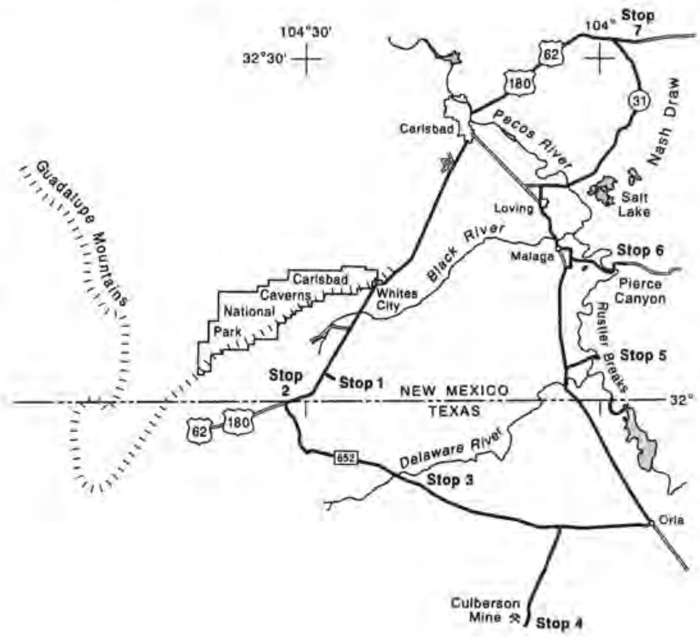
FIRST-DAY ROAD LOG FROM CARLSBAD TO WHITES CITY, ORLA, LOVING, POTASH ENCLAVE AND RETURN TO CARLSBAD

GEORGE S. AUSTIN, JAMES M. BARKER, JOSEPH E. CRAWFORD, JOHN W. HAWLEY, DAVID LOVE, SPENCER G. LUCAS and JIM W. ADAMS

THURSDAY, OCTOBER 7, 1993

Assembly point: Parking lot of the Carlsbad Civic Area, National Parks Highway, Carlsbad, New Mexico.
Departure time: 7:30 a.m.
Distance: 205.8 mi
Stops: 7



SUMMARY

The first segment of the Day 1 and 2 tours, via US-62/180 to the New Mexico-Texas state line, crosses the northwestern Delaware Basin along the southeastern base of the Guadalupe Mountains. The Day 1 tour emphasizes the Delaware Basin; Day 2 focuses on the Capitan Reef (Escarpment); Day 3 covers the shelf.

Day 1 Stops 1 and 2 and two optional stops (miles 22.9 and 25.7) introduce the main Upper Permian—Ochoan units (Castile, Salado and Rustler Formations). Emphasis is on dissolution and related phenomena that affected this evaporite-dominated sequence since its deposition. Two minipapers (Hawley) review the geomorphic history and late Cenozoic stratigraphy and introduce the mechanisms of formation of zones of soil-carbonate (caliche-calcrete) prominent in the local surficial deposits (late Miocene to Pleistocene). A minipaper (Crawford) on Stop 1 describes paleokarst features and related selenite of the Yeso Hills portion of the (Castile) Gypsum Plain. Sulfide/barite/fluor-ite deposits of the Delaware Basin are discussed in Hill's minipaper. Minipapers at Stop 2 by Anderson, Leslie et al. and Watkinson and Alexander relate to the origin and morphology of the State Line Gypsum Outcrop (middle to upper Castile Formation).

The second segment of Day 1 is from US-62/180 southeast to Orla, Texas, via Texas Farm-Road 652, across the Gypsum Plain and the Rustler Hills. Two stops examine features with similar origins but very different scales. Stop 3 is at the "Castiles," conical hills of secondary biogenic limestone/sulfur developed in the Castile Formation, as discussed in a condensation of Brown and Loucks (1988) on the Gypsum Plain. Stop 4 is at the Culberson Sulphur Mine, a world-class Frasch sulfur/limestone deposit of biogenic origin in the Salado and Castile Formations. Minipapers by Klemmick (Pokorny sulfur deposit), Guilinger (Phillips Ranch Sulphur Mine) and Davis (Phillips Ranch hydrology) cover aspects of smaller local deposits. A minipaper (Hawley) discusses the upper Neogene valley and depressions fills of the Orla area.

The third segment of Day 1 from Orla north to the Known Potash Leasing Area (KPLA) and Stop 7 is via US-285, NM-31 and US-62/180 with excursions. Three stops examine the Rustler Breaks (or Bluffs) along the Pecos River (Stop 5 excursion), the geology at Pierce Canyon (Stop 6 excursion) and the Permian-Triassic Boundary at the "Hill B" breccia pipe (Stop 7). Two related minipapers cover post-tectonic reheating history via vitrinite data (Barker and Pawlawicz) at Stop 5 and red bed age and nomenclature at Pierce Canyon (Hawley, Love and Lucas) at Stop 6. Olsen's minipaper discusses the role of the BLM in managing the Potash area. Wallace discusses the ground-water quality in the Carlsbad reef aquifer.

The final segment from Stop 7 traverses the KPLA and oil fields via US-62/180 to Carlsbad, then south to the Civic Center.

OVERVIEW OF THE GEOMORPHIC HISTORY OF THE CARLSBAD AREA

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The combination of tectonic, surface-fluvial and subsurface-dissolutional processes acting for at least the past 12 to 13 Ma has produced a very complex system of landforms and valley and depression fills in the Carlsbad area (Fig. 1.1). These units are still incompletely char-acterized and understood, particularly in terms of absolute chronology of events (provisional summary in Fig. 1.2). Calcisol development and soil-geomorphic relationships are discussed in the following minipaper.

The area's topographic relief and variable climate within a general semiarid-continental setting are *primarily* controlled by Basin-and-Range tectonism (Miocene to present) superimposed on Laramide (early Tertiary) epirogenic uplift of the southern Rocky Mountain region (Gregory and Chase, 1992). Products of these deep-seated forces form the major elements of the modern landscape visible in the Sacramento, Guadalupe and Delaware Mountains (Basin and Range province—Sacramento section) and adjacent parts of the lower Pecos Valley (southern Great Plains). Relict highlands formed on mid-Tertiary volcanic and intrusive centers flank the western mountains to the north and south, respectively, in the Sierra Blanca–Capitan and Davis Mountain areas. Significant topographic relief between the mountain and plains regions, in the order of several thousand feet, had developed by the late middle Miocene Ma). Local relief has since been accentuated by major differential movement along the western boundary fault zones of the Sacramento, Guadalupe and Delaware Mountain blocks.

The action of surface streams and associated mass wasting is the *second* major geomorphic process involved in development of the present landscape. Landforms of the Carlsbad area are of particular interest because they contain an excellent (but still poorly documented) record of the evolution of a surface drainage system that was ancestral to the modern lower Pecos. In highland areas this record is very spotty and exists mainly as valley-border erosion surfaces with thin and discontinuous veneers of alluvium and colluvium. In contrast, because of the solution-subsidence process discussed below, a significant part of the history of upland denudation is still preserved as thick fills beneath the plains and valley lowlands of the region; however, much of that record still remains to be deciphered.

Solution-subsidence, the *third* major component of the geomorphic system, is the process that gives much of the lower Pecos Valley region its unique character. Dissolution of parts of the thick Ochoan evaporite sequence that originally filled the Delaware Basin and overlapped much of the Capitan reef and Northwestern Shelf area has long been recog-nized as having played a major role in landscape evolution (Lee, 1925; Adams, 1944; Maley and Huffington, 1953; Bachman, 1976, 1980, 1984, 1987; Anderson et al., 1978; Kelley, 1980; Anderson, 1982b). Karst landscapes are also extensive in parts of the Northwest Shelf underlain by gypsiferous units of the Guadalupian upper San Andres Formation and the Artesia Group. In terms of large-scale dissolution phenomena. removal of halite and gypsite/anhydrite zones in the Salado

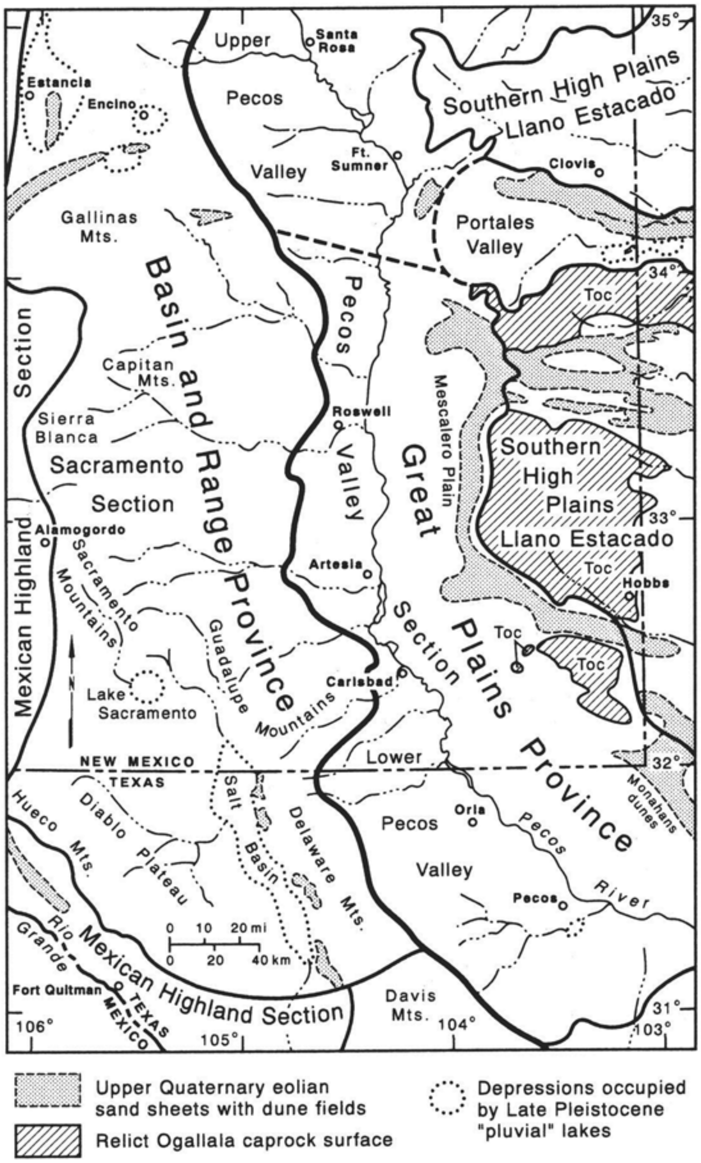

FIGURE 1.1. Index map to major geomorphic features of the Carlsbad, New Mexico area.

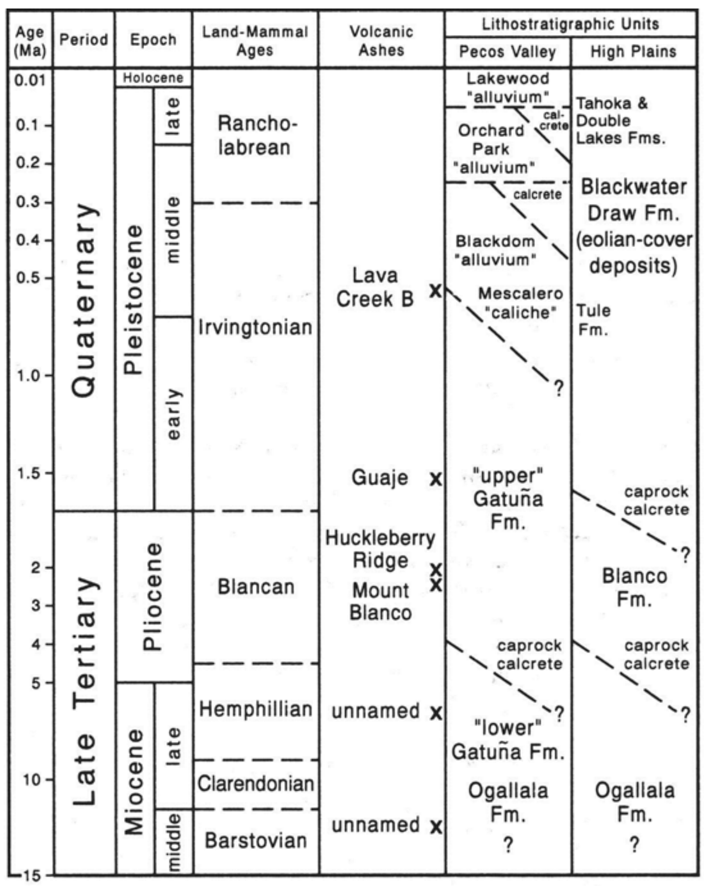

FIGURE 1.2. Chart summarizing Late Cenozoic stratigraphy of the Carlsbad, New Mexico area.

Formation and parts of the Castile and Rustler Formations has had the most profound geomorphic effect. Bachman (1984) considered that two major intervals of erosion and evaporite dissolution have occurred since the late Permian, the first in Triassic and Jurassic time prior to the last (Early Cretaceous) marine incursion and the second during the Cenozoic (primarily late Tertiary and Quaternary). The most spectacular landforms of the Carlsbad area, Guadalupe Ridge and the Reef Escarpment, are primarily exhumed features with most of their Ochoan cover removed by a combination of dissolution and erosion (King, 1948; Hayes, 1964). Much of the exhumation occurred in the late Cenozoic as a result of the tectonic and fluvial processes just outlined. Miocene and younger fills in the largest solution-subsidence depressions of the northern Delaware Basin range from about 1100 ft in southern Eddy County, New Mexico to 1900 ft in Reeves County, Texas (Maley and Huffington, 1953; Kelley, 1980; Bachman, 1984; Hawley, Powers and Holt, this volume).

The *fourth* major geomorphic process, which is also unique to the Carlsbad area, resulted in formation of an extensive cavern system in the Capitan Limestone and associated reef facies of Guadalupian Age. The major role played by sulfuric acid in cave formation and the evolution of the Guadalupe Mountains' caverns was recently described in detail by Hill (1987). Cavernous "porosity" along the reef trend has influenced not only the genesis of land-surface forms in mountain up-lands but also the development of subsidence features such as breccia pipes in the southern Great Plains area (Bachman, 1980; Baumgartner et al., 1982; Snyder and Gard, 1982; Johnson, 1989).

The oldest Cenozoic sedimentary unit preserved in the Great Plains region of southeastern New Mexico and adjacent parts of Texas is the Ogallala Formation of late Miocene and early Pliocene age (Darton, 1928a, 1928b; Hawley, this volume). The constructional surface of the formation, with its prominent caprock-caliche zones, is best preserved in the Llano Estacado area of the High Plains south of the Canadian Valley where it locally has a thick cover of Plio-Pleistocene eolian deposits (Blackwater Draw Formation; Gustayson, 1990). Southwest-ernmost High Plains outliers in Lea County (about 30 mi east of Carls-bad) are 600 to 1000 ft above the Pecos Valley floor.

According to the "classic" Ogallala depositional model (Se!lards et al., 1932, fig. 51; Nye, 1933; Seni, 1980), the formation is primarily a piedmont apron of coalescent alluvial fans that prograded eastward from a nearly continuous chain of western mountains extending from Colorado to Trans-Pecos Texas. The distal part of this inferred apron extended across the eastern New Mexico—western Texas area where it is now preserved beneath the surface of the Southern High Plains. Ogallala deposition ceased in early Pliocene time when source area drainage was diverted into an evolving system of valleys cut by the ancestral Canadian and Pecos Rivers.

Recent research on the late Neogene geology of the Llano Estacado region, reviewed in Gustayson (1990) and discussed by Hawley (this volume) demonstrate that many earlier interpretations of Ogallala depositional history must be revised. The formation is primarily a complex of valley-filling fluvial deposits interbedded with eolian sediments; fan-piedmont facies are very minor constituents. Locally, solution-subsidence depression fills, including playa-lake beds, are also major components. Ongoing research supports early observations by Bretz and Horberg (1949a), Horberg (1949), Leonard and Frye (1962), Kelley (1971, 1980) and Reeves (1972) that an ancestral lower Pecos drainage system heading in east-central New Mexico existed near its present position throughout Ogallala time. Eolian facies dominate much of the formation downwind (northeast) of this and other contributing fluvial systems. Basal parts of older Pecos Valley fills that appear to be Ogallala correlatives include the "quartzose conglomerate" of Meinzer et al. (1926) and much of the Gatufia Formation mapped in the Delaware Basin (discussed below).

Nye (1933, p. 11-12) defined a stepped-sequence of geomorphic surfaces (both erosional and constructional) that flank the modern Pecos floodplain in the Roswell artesian-basin segment of the lower Pecos Valley. The only post—High Plains surface recognized by Nye east of the valley is the Mescalero plain, a broad undulating surface locally covered by eolian deposits ("Mescalero Sand") and disrupted by many solution-subsidence depressions. This surface is separated from the Llano Estacado by the "Mescalero ridge" escarpment. Relict and shallowly buried parts of the Mescalero plain, which stabilized in the late Pliocene (?) to middle Pleistocene, are characterized by a caprock-calcrete unit that has been designated the "Mescalero caliche" by Bachman (1976, 1980). Nye (1933) correlated the Mescalero plain with the Diamond A plain, a poorly preserved piedmont surface west of the Pecos Valley that is primarily an erosional feature cut on carbonate rocks of the Sacramento uplift. Projected gradients of these two surfaces, neglecting subsequent solution-subsidence effects, place them from 300-500 ft above the modern valley floor.

Valley fills and erosion-surface veneers genetically associated with the Mescalero and Diamond A plains have long been referred to as the Gatufia Formation (Lang, 1938; Vine, 1963; Bachman, 1976, 1980, 1981, 1984; Powers and Holt, this volume). Questions raised by Kelley (1971, 1980) and Reeves (1972) about the maximum age and uncertainty in correlation of at least the lower part of the Gatufia section are also addressed by Hawley (1984, this volume) and are discussed at several optional and scheduled Day 1 stops (mi 25.7, mi 97.1 and Stop 6).

The lower three surfaces of Nye's (1933) valley-border sequence developed during the past 0.6 Ma after stabilization of the Mescalero surface and formation of an integrated "upper and lower" Pecos Valley system that extended from the southern Sangre de Cristo range to the Pecos—Rio Grande confluence (Reeves, 1972; Hawley, et al., 1976, table 3; Bachman, 1976, 1980; Gustayson et al., 1990, pl. 5). As originally described in the Roswell artesian basin (Fiedler and Nye, 1933; Morgan, 1938), these geomorphic surfaces comprise the Blackdom and Orchard Park "terraces" graded, respectively, to inferred river base levels 60-80 and 20-50 ft above the modern valley floor and the Lakewood "terrace" 10-30 ft above the Pecos floodplain.

Hawley et al. (1976) proposed a climate-process model for the development of such valley-border sequences throughout the Rio Grande and Pecos Valley system in the eastern Basin and Range and southern Great Plains provinces. Episodic changes in precipitation-runoff, stream discharge, erosion-sedimentation potential, ground-water recharge, rate of dissolution and effectiveness of vegetative cover and soil-forming processes are all tied to major glacial-interglacial cycles of the Qua-ternary Period. In this model, a river with glaciated headwaters (such as the Pecos) incises and widens the middle reaches of its valley during waxing- and full-glacial (pluvial) intervals. During waning glacial and much of interglacial time more sediment is delivered from local tributary drainage basins than the master fluvial system can transport and the floors of the river and major tributary valleys aggrade.

The Lakewood terrace and modern floodplain surfaces of latest Wisconsin and Holocene age are clearly products of the last (and ongoing) glacial-interglacial cycle. The Orchard Park and Blackdom surfaces and associated alluvial fills of the Roswell basin were interpreted by Hawley et al. (1976, table 3) as being deposited during the two or three glacial-interglacial cycles inunediately preceding the Wisconsin glacial stage (>0.1 Ma). Maximum age of the "type Blackdom" is constrained by presence of a 0.6 Ma volcanic ash lens in Gatufia beds underlying the youngest part of the Mescalero surface (Bachman, 1980, 1981). Hawley et al. (1976) also pointed out that ongoing solution-subsidence is a major factor complicating geomorphic interpretations in the Pecos Val-ley area.

Horberg (1949) mapped possible correlatives of the Blackdom—Orchard Park—Lakewood sequence along the Pecos and Black River Valleys of the Carlsbad area, and Jelinek (1967) tentatively correlated these units with surfaces in the (upstream) Fort Sumner area. Since no detailed research has ever been done on the Quaternary stratigraphy, geomorphic history and soil-geomorphic relationships throughout the Pecos Valley area of New Mexico and western Texas, such correlations should be regarded as provisional at best (compare with research in the Rio Grande Valley described by Gile et al., 1981; and Machette, 1985). Inferred ages and suggested names of valley-border surfaces are used where appropriate in road log sections of this volume.

SOME PRINCIPLES OF CALCISOL DEVELOPMENT AND SOIL-GEOMORPHIC RELATIONSHIPS IN SOUTHEASTERN NEW MEXICO

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The following brief discussion of soils and soil-geomorphic relationships is adapted from a review paper by McGrath and Hawley (1987). Emphasis is on general soil-forming factors and characteristics of pedogenic horizons of carbonate accumulation. The basic principle of soil development in arid and semiarid regions is that precipitation does not remove free cations from the soil during most years. Thus, the soil solution becomes concentrated and alkaline. Weathering pro-ceeds at an extremely slow rate. Gile and Grossman (1979), Gile et al. (1981), Machette (1985) and Monger et al. (1991a) provided much information on soils and soil-geomorphic relationships in the arid to semiarid landscapes of the southern New Mexico region. The general application of soils in geomorphology and Quaternary geology is dis-cussed in detail by Birkeland (1984) and Birkeland et al. (1991).

Parent materials and soil landscapes. Basin and valley fills and upland alluvial deposits of southeastern New Mexico are primarily derived from carbonate rocks, sandstone, mudstone and gypsite of Paleozoic age, Mesozoic sandstone and mudstone and Cenozoic igneous and nonmarine sedimentary rocks (Hawley, this volume). Upper Tertiary-Quaternary stratigraphic units in the Carlsbad area include alluvial, colluvial, lacustrine and eolian sediments deposited in two contrasting geomorphic settings: (1) a complex of stream valleys and solution-subsidence basins in the Pecos Valley section and adjacent parts of the High Plains, (Great Plains province) and (2) intermontane basins and adjacent highlands (mountains and plateaus) of the tectonically active Basin and Range province (Sacramento section). The most ancient soil landscapes are on relict geomorphic surfaces that have been essentially stable for hundreds of thousands to several millions of years. These surfaces include stream terraces and plateau plains remnants that predate early to middle Pleistocene entrenchment of the present Pecos drainage system (Hawley, this volume).

Present and past climates and vegetative cover. The Pecos Valley and lower mountain and plains surfaces of the Carlsbad area have an arid to semiarid climate with mean annual precipitation of about 8-16 in. (20-40 cm) and mean annual temperature of about 58-63°F (14—17°C). Cooler and moister conditions existed during Wisconsin and earlier Pleistocene glacial-pluvial stages (Hawley, 1993; Swift, 1993). Interglacial temperature and moisture regimes are typified by the wann-dry Holocene and late Sangamon intervals (past 10,000 yrs and about 0.12 to 0.13 Ma) but are probably not typical of long-term Quaternary environments in this part of the southern Great Plains and southeastern Basin and Range provinces (Ashbaugh and Metcalf, 1986; Harris, 1987, 1989; Betancourt et al., 1990). Temperature and moisture regimes during much of Quaternary and Pliocene time (past 5 Ma) were probably intermediate between full-glacial and interglacial environments, but they appear to have always been in the semiarid-temperate range.

The present vegetative cover is dominated by desert shrubs, grasses, annuals, cacti and trees of the pifion-juniper zone. During the Pleistocene glacial-pluvial intervals, grasslands and mixed forest-grassland were much more extensive at lowland sites. Faunal influence on pedogenesis includes subsurface activity of insects and bunowing vertebrates; ubiquitous soil microorganisms also play a major, but often poorly documented, role in desert soil formation.

Swface soil horizonation. Surface soil horizons in the area tend to (1) be low in organic matter except on valley floors and on higher undissected basin and plains surfaces; (2) have variable (alkaline to slightly acid) soil solutions; (3) be easily eroded at many sites with sparse vegetative cover; (4) have a thin surface crust at such sites; (5) be exposed to extreme temperature variations; and (6) receive atmospheric fallout (aerosol contributions). Subsurface horizons have fewer oscillations in temperature and soil solution, but are wetted to different depths by each precipitation event. Calcite precipitates in the subsurface of all arid-region soils. Biologic, including microbial, processes are very important factors influencing carbonate precipitation (Monger et al., 1991b). Clay translocation occurs, as indicated by horizons of silicate-clay accumulation (argillic horizons) that are preserved in the upper parts of soil profiles in a few areas, but secondary carbonate commonly disrupts alluvial clay coatings or engulfs argillic horizons (Monger et al., 1991a). Clay neoformation and silica translocation is possible if soil solution exists for a long enough time at great enough concentrations (McGrath and Hawley, 1987; Monger and Daugherty, 1991a, b). Some common horizonation sequences observed are shown in Fig. 1.3. For additional information on soil-horizon and fabric nomenclature, see Soil Survey Staff (1975, 1981), Brewer (1976), Cornell University Agronomy Department (1986) and Birkeland et al., (1991).

Caliche is the common term used to describe near-surface accumulations of secondary calcium carbonate of both pedogenic and nonpedogenic origin in the American Southwest (Bretz and Horberg, 1949b; Aristarain, 1970; Reeves, 1970; Gardner, 1972; Frye et al., 1974). Nonpedogenic varieties of caliche (or calcrete) formed mainly by precipitation of calcite by deeply percolating subsurface water in both the vadose and underlying saturated (ground-water) zones. Many fanglomerates, conglomerates and sandstones in valley- and basin-fill deposits have been cemented by this process, and, where exposed, may be misinterpreted as pedogenic carbonate horizons. These rocks are also transitional to travertine deposits in areas of active or prior spring discharge (Bachman and Machette, 1977; Carlisle et al., 1978; Barker, 1983).

Bates and Jackson (1980) defined *calcrete* as a "calcareous duricrust" and a *duricrust* as "a general term for a hard crust . . . or layer in the upper horizons of a soil in a semiarid climate." Calcrete (Lamplugh, 1902; Goudie, 1973) is now commonly used as a synonym for indurated forms of caliche in the southwestern United States (Machette, 1985). The general term "calcic soil," introduced by Bachman and Machette (1977), refers to all soils with readily identifiable amounts of alluvial carbonate in the B-horizon position, whether nonindurated or indurated (Bk and Bkm horizons; previously designated Bca, Cca and Ccam horizons). Soils with calcic and petrocalcic horizons are now included in this category (Machette, 1985; Gile, 1987). Mack et al. (1993) have recently designated such soils as "Calcisols."

Esteban (1976, 1977), with particular reference to "vadose pisolite and caliche" in the Guadalupe Mountains—Permian Basin region, defined "caliche" as follows:

> Caliche (calcrete) cotmnonly is defined as fine grained, chalky to well-cemented calcareous (calcite) deposits that formed as a soil in or on previously existing sediments, soil, or rocks in semiarid temperate environments. . .
>
> Caliche is a vertically zoned subhorizontal carbonate deposit, normally developed with three main rock types: I) massive-chalky, 2) nodular-crumbly and 3) laminated and/or pisolitic compact crust or caprock. The position and development of these rock types in the vertical sequence (profile) and laterally is highly variable. The only usually consistent relationship is that the massive-chalky rock grades downward into original rock or sediment through a transition zone, both with strong evidence for in-place alteration and replacement of the original rock or sediment. Colors are commonly white and light brown, but red and black may be important.

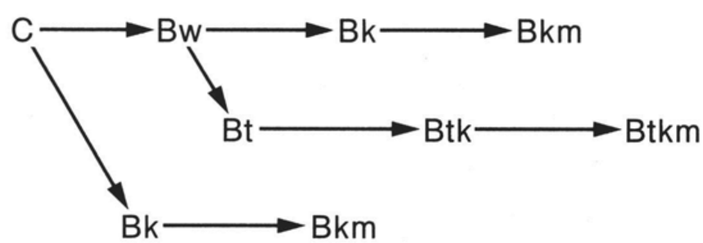

FIGURE 1.3. Parent material **(C)**, with continued addition of aerosols to a stable geomorphic surface, transforms to cambic **(Bw)** to calcic **(Bk)** to petrocalcic **(Bkm)** horizons, *or* from cambic **(Bw)** to argillic **(Bt)** to argillic overprinted with calcic **(Btk)** to petrocalcic **(Btkm)** horizons, *or* directly to calcic **(Bk)** to petrocalcic **(Bkm)** horizons.

The predominant caliche fabric is a clotted, peloidal micrite with microspar channels and cracks. Accessory fabrics are poorly laminated micrite, karst products and rhizocretions. Microspar areas usually show evidence of replacement or relict grains and of other primary and earlier diagenetic microfabrics.

Morphological and genetic sequences of soil-carbonate accumulation. Gile (1961, 1975, 1977) and Gile et al. (1965, 1966) developed many of the fundamental principles of carbonate horizon genesis and classification in soils of arid and semiarid regions. Their model for soil-carbonate accumulation is described by a bimodal, four-stage (I-IV), morphogenetic sequence for both gravelly and nongravelly parent sediments (Gile et al., 1966). Bachman and Machette (1977) and Machette (1985) expanded this scheme to a six-stage morphogenetic sequence, with stages V and VI used to characterize very strong and morphologically complex pedogenic calcretes (caprock caliches) of the American Southwest. This scheme, as adapted by McGrath and Hawley (1987) is presented in Table 1.1.

Stages I and II are initial phases of soil-carbonate illuviation and result in the formation of weaker Bk horizons that usually are not diagnostic in soil classification. Nonindurated carbonate accumulations that qualify for calcic horizon designation commonly exhibit stage III morphology. A nearly continuous fabric of carbonate-coated clasts and carbonate-filled voids (K-fabric of Gile et al., 1965) and initial development of irreversible cementation (induration) characterize the stage III-IV transition. This incipient phase of petrocalcic horizon and calcrete formation may be followed by stage IV, which is characterized by an indurated layer of dense, multiple-laminar K-fabric that caps the massive to nodular "carbonate-plugged" horizon. Stage IV marks the initial formation of "caliche profile" as defined by Lovelace (1972). Stage V includes development of a thicker "caprock caliche" layer, with several multiple-laminar subhorizons, followed by initial fracturing of this zone and development of coarse-platy structure and zones of brecciation and/ or dissolution. Recementation and laminar coating of brecciated ma-terial and solution-rounded fragments to form a pisolitic fabric and additional cycles of brecciation and cementation characterize stage VI. Very long intervals of soil-landscape stability (>105 to 106 yrs) and major changes in paleohydrologic conditions are reflected in the thickness and complexity of the caprock layer in calcretes with stage V and VI morphology.

Soils with petrocalcic horizons, IV to VI, are widely developed on Plio-Pleistocene geomorphic surfaces in this region and "calcic soils" with weaker expression of pedogenic carbonate (stages I to III) are nearly ubiquitous on younger Quaternary surfaces that are not formed on highly gypsiferous parent materials (Machette, 1985). Petrocalcic horizons (pedogenic calcretes) with stage IV to V morphology are extensively preserved on surfaces of mid-Pleistocene to late Pliocene age (e.g., Orchard Park and older surfaces of the Carlsbad-Roswell area; Fiedler and Nye, 1933; Bretz and Horberg, 1949b; Horberg, 1949; Bachman, 1976; Hawley, this volume). Stage VI calcretes are almost everywhere restricted to soils that started to form in Pliocene to late Miocene time (1.7 to 7 Ma). The only extensive soil landscape of this age (relict and buried) preserved in the Southwest is on the Southern High Plains (Llano Estacado) of Texas and New Mexico. However, ancient soils with stages V and VI carbonate morphologies are locally preserved throughout the Pecos Valley section and the Basin and Range Province from Trans-Pecos Texas to southern Nevada (Bretz and Hor-berg, 1949b; Gile, 1961; Reeves, 1970; Gardner, 1972; Lattman, 1973; Machette, 1985; Hawley, this volume).

Mileage

0.0 Begin at the Carlsbad Civic Center parking lot. **Turn left** (southwest) onto US-62/180 (National Parks Highway). Zero mile point for each day trip is at Milepost 32, 0.1 mi southwest of the Civic Center. The Day 3 tour via Hidalgo Road to right follows Dark Canyon Draw to mouth of Dark Canyon at the eastern tip of the Guadalupe Mountains (1:00-2:00). The Dark Canyon area, mapped by Motts (1962), marks the northernmost exposed Guadalupian Capitan Limestone and reef. The Hackberry Hills about 2 mi to the northwest (3:00) are local antiforms capped by Tansill Formation (uppermost Artesia Group). The underlying Yates Formation is locally exposed in these structures. Guadalupian rocks form the upper units of the Northwestern Shelf sequence that is the major focus of Day 3. **0.5**

1.2 South Carlsbad Field (gas wells) to the west in secs. 25 and 36, T22S, R26E. Production is from Pennsylvanian Strawn (discovered in 1970) and Morrowan strata (1969).

TABLE 1.1. Stages of carbonate accumulation in gravelly and nongravelly morphogenetic sequences of calcrete development.

Stage and general character	Diagnostic carbonate morphology: Gravelly sequence	Nongravelly sequence
I Weakest expression of macroscopic carbonate	Thin, discontinuous coatings on gravel clasts	Few filaments or faint coatings on ped surfaces
II Carbonate segregations separated by low-carbonate fabric	Continuous coatings on clasts, some interclast fillings	Few to common nodules
III Carbonate essentially continuous; plugged horizon forms in last part	Many interpebble fillings	Many nodules and internodular fillings
	Upper part of horizon essentially plugged	
IV Laminar horizon develops over plugged horizon; incipient calcrete formation; forms caprock layer up to 20 in. thick	Indurated laminar horizon over plugged horizon; thin upper zone of platy structure over zone with massive to nodular structure; grades downward into gravelly or nongravelly material with stage III morphology; incipient "caliche profile" of Lovelace (1972) and pedogenic calcrete	
V Multiple laminar horizon develops in upper part of profile; incipient development of degradational features; forms caprock layer up to 2 m thick	Thick, well-indurated upper horizon; platy to tabular structure with multiple laminar internal fabric; zones of dissolution, brecciation, and recementation locally present; dry bulk densities up to 2.2 g/cm^3, with discontinuous upper zones 2.2-2.7 g/cm^2.	
VI Brecciation, dissolution and recementation of upper, multilaminar horizon; multiple generations of calcrete formation and degradation; forms cap rock layer up to 13 ft thick	Very thick, well-indurated, upper horizon; tabular to platy structure, with pisolitic and multilaminar internal fabric; secondary silica common; dry bulk densities 2.2-2.7 g/cm^3	

Strawn production is from a depth of 10,400 ft with a cumulative 0.5 million barrels of oil (MMBO) and 32.4 billion ft3 of gas (BCFG). Morrow production is from a depth of 11,200 ft with a cumulative 0.08 MMBO and 235.4 BCFG. **0.8**

2.0 Milepost 30. Carlsbad Airport Terminal to right. **0.3**

2.3 Low gravelly ridge with large borrow pit to left is tour Stop V of Esteban (1977, G73-77) at a representative "caliche profile, probably Pleistocene." This pedogenic calcrete (stage V morphology, see previous minipaper by Hawley) is formed on thin, gravelly to loamy older valley-fill alluvium unconformable on deformed sandstones to mudstones of the Gaturia Formation "quartzose conglomerate" unit. **0.4**

2.7 Caliche pit road to left; entering Carlsbad West quadrangle mapped by Motts (1962). **0.3**

3.0 The major rise 3 to 5 mi west is the concave-west eastern edge of the Guadalupe escarpment, here termed the Cueva escarpment, exposing the largely shelf dolomite of the Tansill Formation. The arcuate lower hills in the middle ground are the Frontier Hills, mostly composed of Ochoan Rustler Formation. The topographic relief between the Cueva escarpment and the Frontier Hills is mainly due to dissolution of evaporites in the basal Rustler and underlying Salado Formation. The Salado-Rustler dissolution residue overlies the Castile Formation, the basal Ochoan unit in the Delaware Basin, here near its shelf-edge pinchout. Guadalupian and Ochoan strata dip gently east. **0.4**

3.4 Stage V calcrete surface in shallow bar ditch to right. **2.1**

5.5 Roadside park and New Mexico Port of Entry station to right. **0.5**

6.0 Milepost 26. Water well at ranch to right penetrated 304 ft of older valley fill (Hendrickson and Jones, 1952). To the right (west) are the Dark Canyon (discovered in 1952), Frontier Hills (1989) and Carlsbad South (1969) pools in secs. 21 and 22, T23S, R26E. Dark Canyon (Delaware) production is from a depth of 1880 ft with a cumulative total 0.07 MMBO. Frontier Hills (Strawn) production has a cumulative 0.08 MMBO and 7.4 BCFG. Carlsbad South (Morrow) production is from a depth of 11,200 ft with a cumulative 0.08 MMBO and 235.4 BCFG. **0.5**

6.5 Dark Canyon Road (Eddy County-408) to right joins Day 3 route at the mouth of Dark Canyon. Day 3, Stop 1 is 3 mi to the west. Continue to southwest on US-62/180. **1.6**

8.1 Crossing Cass Draw. Low ridges 1 mi to the west (11:00 to 4:00) formed on the Culebra Dolomite Member of the Rustler Formation. Route ascends an alluvial slope at the base of the Guadalupe escarpment that grades to Horberg's (1949) Orchard Park plain. Thin calcrete-capped gravels overlie soft rocks of an Ochoan Castile-Salado-lower Rustler sequence, with most of the Salado and Rustler evaporites removed by dissolution (Fig. 1.4). **0.9**

9.0 Milepost 23. Roadcut through the Culebra Dolomite Member (Rustler Formation); entering Carlsbad Cavern East quadrangle mapped by Hayes (1957). The Culebra, named by Adams (1944), is a grayish-pink, cryptocrystalline porous dolomite, here underlain by up to 150 ft of residual gypsum and reddish siltstone and claystone that are a dissolution residue of the Salado and basal Rustler Formations. **2.2**

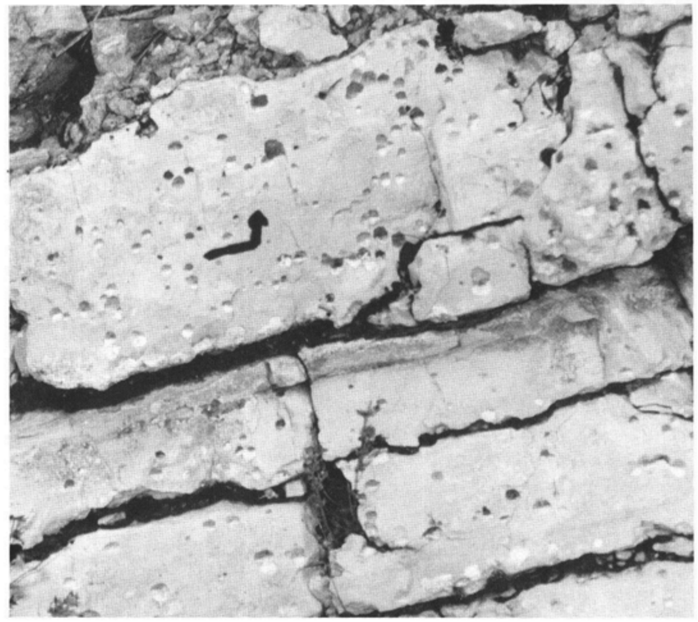

FIGURE 1.4. Culebra Dolomite with abundant anhydrite molds showing geopetal fabrics that are in the lower part of the mold that parallel the tile of the beds in this roadcut. The anydrite dissolution and partial fill occurred prior to the tilting of the strata. The arrow shows present "UP" direction.

11.2 Junction with NM-396 to left and alternate road to Pierce Canyon area (Stop 6) via Black River village. This route has been logged by Powers and Martin (1990) and emphasizes geology and hydrology of Delaware Basin evaporites and the Waste Isolation Pilot Plant (WIPP) project. Continue on US-62/180 along the base of the Guadalupe Escarpment, which is basically an exhumed reef "held up by the resistant Capitan Limestone" (Hayes, 1964, p. 46) with most of the Ochoan evaporite cover (Castile-Salado-Rustler) removed. Hayes and Bachman (1979) found no Cenozoic faults along the base of the Guadalupe and Cueva escarpments proposed by Kelley (1971). See Day 2 road log and Hawley (this volume). **0.2**

11.4 Jurnigan Draw, which dissects the Guadalupe escarpment, to right. Siliceous pebbles scattered on the summit of Guadalupe Ridge from here to above Slaughter Canyon (opposite Milepost 6) were originally considered to be remnants of the upper Tertiary Ogallala Formation (Bretz and Horberg, 1949a; Horberg, 1949). Field studies (Hayes, 1964; Hawley, this volume) indicate that these deposits are residuum from a lower Cretaceous unit (Cox Sandstone?) since eroded from Guadalupe Ridge. Conglomeratic sandstone fissure-fills, described as "dikes" in the Jurnigan Draw and Slaughter Canyon area by Hayes (1964, p. 38), are all that remain of this marine sedimentary cover. No evidence suggests the Guadalupe Ridge was a site of Ogallala deposition. It was instead a local upland source terrane, at least as early as late Miocene, for depocenters in an ancestral lower Pecos River valley generally coinciding with the present Pecos, Black and Delaware river valleys. **2.6**

14.0 Milepost 18. Crossing the piedmont apron of older alluvial deposits at the foot of the Guadalupe escarpment. Horberg (1949) correlated this calcrete-capped geomorphic surface with the middle Pleistocene Blackdom plain of Fiedler and Nye (1933). The underlying deposits, mapped as Pleistocene "gravels" by Hayes (1957), appear to correlate with the thick "older" valley fill described above in the Carlsbad West quadrangle. **1.5**

15.5 Apache Canyon Trading Post to right. **0.3**

15.8 Entering Whites City. **0.4**

16.2 Junction with NM-7 that leads right to Carlsbad Caverns National Park. Day 2, Stop 1 is at the mouth of Walnut Canyon (2:00) just beyond Whites City. Continue southwest on US-62/180. **0.4**

16.6 Crossing Walnut Canyon Draw. 0.1

16.7 Sign-State line 16 mi, El Paso 145 mi. Route descends into the Black River valley across a broad erosion surface, primarily cut into the Castile Formation, here with a thin veneer of Quaternary alluvium. **2.8**

19.5 Approaching the Black River; roadcuts ahead are in older valley fill, mainly gypsiferous sands, silts and channel gravels, commonly well-cemented with secondary calcite. Deformation is due to solution subsidence along the Black River. Calcretes were formed in the phreatic and lower-vadose zones and are not pedogenic features; however, many of the terraces preserved along the Black River Valley are capped with well-developed (stage IV or V) pedogenic calcretes. "A sulfur exploration hole in the valley to the west showed about 61 m of fill over bedrock" (Powers and Martin, 1990, p. 10). Sares (1984) and Sares and Wells (1986) detailed the Pliocene and Quaternary deposits and the geomorphic history of the evaporite karst development on the Castile Formation in this part of the upper Black River and (tributary) Chosa Draw drainage basins. Sares and Wells (1986) correlated their oldest valley-fill unit, which includes both highest terrace remnants and thick basal deposits of inner valley areas, with the "Plio-Pleistocene" Gatufia Formation of Bachman (1976, 1980, 1981, 1984). Hawley (this volume) correlates the oldest part of the Black River valley fill ("quartzose conglomerate") with the upper Miocene Ogallala Formation. **0.3**

19.8 Crossing Black River. The headquarters for Carlsbad Caverns to the north is on top of Guadalupe Ridge. Rattlesnake Canyon (2:00) cuts the Guadalup escarpment to the northwest. **0.2**

20.0 Milepost 12. Roadcuts ahead are in high-level, Black River terraces with calcrete zones. **0.8**

20.8 This undulating surface is formed on erosional remnants of the highest Black River Terrace, here about 100 ft above the river channel. The thin fill is gravelly calcrete (stage IV-V) capping an erosion surface on the Castile Formation. **0.9**

21.7 Washington Ranch Road (Eddy County-418) to right. For the next 8 mi the route crosses the Yeso Hills at the northwestern edge of the Gypsum Plain (discussed at mile 51.9, Stop 3). This complex surface is developed on the Castile Formation and includes a few outlying remnants of the Rustler Formation (mostly Culebra Dolomite Member) and underlying Salado and Rustler residual deposits. Karst features of the Gypsum Plain were described in detail by Olive (1957), Sares (1984) and Sares and Wells (1986). Continue on US-62/180. **1.3**

23.0 Milepost 9. Prepare to turn left ahead at optional stop. 0.1

23.1 **OPTIONAL STOP.** Dillahunty Road (Eddy County-424) to left. CP Hill, a prominent "karst/mound dome," is 1.8 mi to the southeast (10:00). This Rustler-capped feature and the surrounding area have been drilled extensively during sulfur exploration (Powers and Holt, this volume).

Lang's (1947) locality of "Comanche rocks" and fossils is about 400 ft to the left, just south of Eddy County Road 424 (NE '1/4 SE1/4 NW '/4 sec. 31, T25S, R25E). Coarse fragments of fossiliferous Lower Cretaceous (Albian) sandstone and limestone are scattered on the Castile Formation at this locality (Hayes, 1964). Lang (1947, p. 1472) suggested that these fragments were "trapped . . . in a deep sink or cavernous channel which later collapsed and they have been preserved there while the enclosing rocks were eroded away." The exotic lower Cretaceous clasts at this site could also be general cor-relatives of the fissure-filling sandstones noted at mile 11.4. Bachman (1980) suggested that the basal Creta-ceous in this area completely mantled a regional un-conformity on progressively older units from east to west.

Other exotic materials include scattered siliceous pebbles and angular clasts of dark igneous rock (Bretz and Horberg, 1949a). Hayes (1964, p. 40) also noted that fragments of "trachyandesite are scattered on the surface about 1000 ft southeast of U.S. Highway 62 at this point." Lamprophyre dikes here, first described by Pratt (1954) in NMGS Guidebook 5, are discussed at road log miles 25.7 and 172.2.

The fragments of Lower Cretaceous rocks include oyster packstone blocks and numerous fossils of echinoids and the gryphaeid bivalve *Texigryphaea.* The texigryphaeas belong to a small species that occurs in the Muleros and Mesilla Valley Formations at Cerro de Cristo Rey near El Paso, a correlative of the Fort Worth and Denton Formations of the Washita Group (Bose, 1910; Strain, 1976). Correlative fossils and strata also are present in the Cornudas Mountains, 65 mi west (see Kues and Lucas, this volume). **1.2**

24.3 Roadside Park, with an overview of Washington Ranch gas field, to right **(OPTIONAL STOP, Days 1 and 2).** This site overlooks the upper Black River Valley extending to the base of the Guadalupe Escarpment. The south-southeast-trending Huapache monocline crosses the escarpment near the mouth of Slaughter Canyon (2:00). New and Ogle Caves are in the lower part of the canyon. The Huapache monocline is downwarped to the east over a Pennsylvanian thrust zone. The monocline affects late Guadalupian rocks and "it appears that minor post-Guadalupe, probably Tertiary, movement has taken place along the old zone of weakness" (Hayes, 1964, p. 42). Ochoan rocks in Black River Valley extend from Rattlesnake Canyon (4:00) to Big Canyon (1:00) and are deeply buried by the "Pleistocene gravel" unit of Hayes (1964, p. 38). The thickness of the upper Cenozoic alluvial deposits probably exceeds 300 ft in the large fans that spread from Black, Double and Slaughter Canyons. This valley fill could be as old as late Miocene (Hawley, this volume). 1.1

25.4 Bottomless Lakes Road to right leads to a partly flooded sink-hole complex in the Castile on the Black River valley floor. The mouth of Slaughter Canyon is at 2:45 beyond the natural gas field. **0.3**

25.7 **OPTIONAL STOP.** Road cut to left is at the northwest edge of a large collapse feature in the Castile Formation. A core of dense carbonate rocks (Culebra?) is flanked by steeply dipping conglomerate beds composed mainly of rounded carbonate clasts derived from the Guadalupe Mountains. Rubble in the roadcut contains red to orange clasts of siltstone and gypsum derived from Salado and basal Rustler dissolution residue. Bretz and Horberg (1949a, p. 489) and Horberg (1949, p. 470) originally described the deformed "limestone conglomerate" here and noted trace amounts of quartzite pebbles. They suggested that this high-level deposit (about 150 ft above the Black River) was a remnant of a former extensive Ogallala cover. As mentioned at mile 11.4, field evidence does not show that this cover extended to the Guadalupe Ridge, where residual siliceous gravels have been observed (Hayes, 1964; Hawley, this volume). Bachman (1976, 1980) considered that the oldest gravels in this area were remnants of a post-Ogallala, Gaturia deposit.

The highway for the next mile crosses the northeast-southwest trend of three deeply weathered and very poorly exposed igneous dikes (Hayes, 1957). The features were originally mapped by Pratt (1954) and initially noted by Darton (1928a, p. 61): "In 1925 I found a dike cutting the Castile Gypsum. Examination by C. S. Ross shows that, although considerably decomposed, it is a lamprophyre of basaltic habit." This is the approximate position of the 32 Ma lamprophyre dike described by Calzia and Hiss (1978).

The dike zone is about 100 mi long and 1 mi wide and consists of a series of small, parallel intrusions (also see mile 172.2 comments). The following description of dikes near the Yeso Hills paraphrases the observations of Pratt (1954, p. 143-146). The walls of the dikes are not distinct and are obscure on the ground. Seen from the air, however, the occurrence is relatively conspicuous. The three separate dikes appear as long, narrow patches of rust-colored earthy material studded with occasional sharp, small fragments of dark-colored, fine-grained igneous rock. They range in width up to 20 ft and in length up to about 0.5 mi. The zone of intrusions mapped by Pratt (1954) in T24S, R24E consists of a series of small, subparallel, en echelon intrusions trending east-northeast and roughly coinciding with the trend of the Capitan Reef. The dike rocks were described for Pratt (1954) by Peter H. Masson of Humble Oil & Refining Company. He classed one specimen from the south wall midway along the outcrop of the northernmost dike as an alkali trachyte. Another specimen from the wall of the highway cut across the eastern end of the northernmost dike was also identified as a trachyte porphyry. Both specimens were vesicular, indicating near-surface crystallization. Traces of bismuth, copper and lead were detected by chemical analysis of specimens from this same dike. The igneous material at Lang's Cretaceous fossil locality (mile 22.9) was also examined by Masson, who identified it as trachyandesite. All of Masson's findings place these igneous rocks in the same petrographic category as other Tertiary intrusives in this region. **0.3**

26.0 Milepost 6. Roadcut in the Castile Formation, with typical interlaminated gypsum and calcite exposed to the left and biogenic replacement zone of secondary limestone in cut to right. Prepare for left turn ahead. **0.8**

26.8 **Turn left (southeast)** across cattle guard onto gravel road to K Hill (Stop 1A) and the Yeso Hills selenite occurrence (Stop 1B); see following minipaper by Crawford. Continue 1.5 mi to turnaround point in the saddle southeast of the hill and retrace route 0.2 mi to Stop 1A. **1.7**

28.5 **STOP 1A: K Hill.** After stop, retrace route toward the highway for 1.0 mi and then turn right (northeast) 0.2 mi to the selenite occurrence. **1.2**

29.7 **STOP 1B: Yeso Hills selenite occurrence.**

K HILL AND YESO HILLS SELENITE OCCURRENCE

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K Hill is a paleokarst erosional remnant within a 1 mi-wide, northeast-trending, solution-subsidence depression within the Castile Formation (Olive, 1957). The hill is about 55 ft high and is in the S1/2 sec. 13, T26S, R24E, Eddy County, New Mexico. Use care near steep prospect pits and the 16-ft shaft sunk into the top of the hill.

K Hill is largely covered by cobble and boulder-size, matrix-supported, breccia clasts embedded in granular gypsum and selenite of the upper Rustler Formation and possibly of the Salado Formation. The breccia clasts are karstic slump debris from the Culebra and Magenta Members of the Rustler Formation (Figs. 1.5, 1.6). The Culebra is brown micritic-to-silty dolomite with scattered spherical vugs and locally contains thin, red to gray chert beds. The Magenta is typically interlaminated gray-brown dolomitic mudstone and gypsum.

A rotated, downdropped karst block comprising the eastern part of the hill preserves the uppermost Permian Dewey Lake Formation in contact with the basal Cretaceous (Lower Albian) Cox Formation. The Dewey Lake, an orange-brown to red fine-grained quartz sandstone with white mica and dark opaque minerals, hosts faint, pale reduction spots. These spots are much more obvious in this formation elsewhere. The Fe-oxide concretions and cubic pseudomorphs after pyrite scattered over much of the hill are probably weathered out of the Dewey Lake

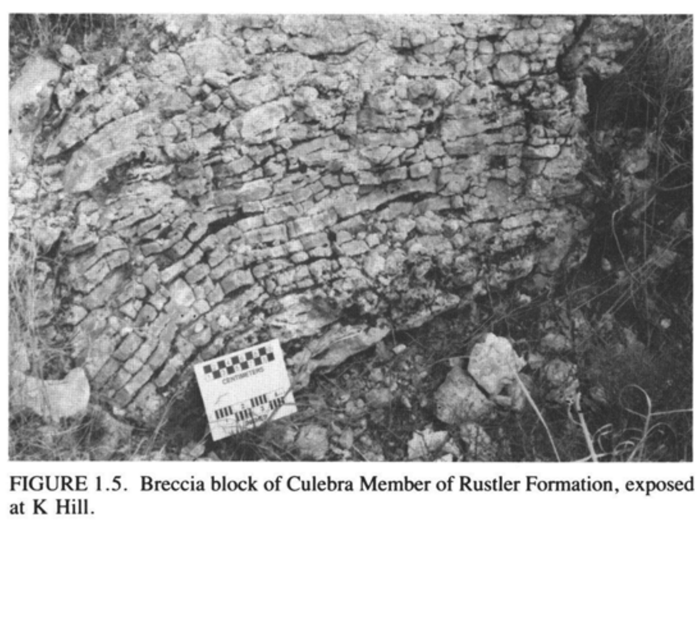

FIGURE 1.5. Breccia block of Culebra Member of Rustler Formation, exposed at K Hill.

FIGURE 1.6. Collapse breccia block of Magenta Member of Rustler Formation, K Hill. Scale is 6 in.

FIGURE 1.8. Cretaceous Cox Formation breccia blocks showing clasts of sandstone and conglomerate in matrix composed of same material. Outcrop on southeast part of K Hill. Scale is 6 in.

and occur within irregular calcite veinlets within this unit. Because this steeply dipping unit is exposed in the shaft at the top of the hill just below the Cox contact, it is the only unit for which a true thickness measurement (at least 13 ft) can be made. Outcrops immediately northeast of the shaft contain Dewey Lake fragments in the basal Cox. Because its stratigraphic position and petrology are slightly different from typical Dewey Lake, it is possible that this unit is the Lower Cretaceous Yearwood Formation.

Cox Formation remnants up to 5 ft thick are stratigraphically above the Dewey Lake near the shaft and are smaller karst blocks forming the southeast flank of the hill. The Cox is brown to red-brown coarse-grained crossbedded sandstones and conglomerates (Fig. 1.7). Sand grains are commonly well-rounded and frosted. The relationship of the conglomeratic zones to the finer-grained facies suggests coastal-fluvial to shallow-marine deposition. The conglomeratic facies are calcite- and silica-cemented pebbles of varicolored chert, fine-grained sandstone, purple-red metaquartzite, bull quartz, oncolitic limestone and fossiliferous carbonates. Blocks exposed on the southeast flank of the hill show an unusual relationship in which rounded to subangular cobbles of sandstone and conglomerate of Cox affinity are embedded in an indurated matrix composed of the same material (Fig. 1.8). This texture suggests that (1) the cobbles are possibly older than Cox (i.e., Triassic), (2) the cobbles represent Cox that underwent Cenozoic stream com-minution and subsequently fell into karstic voids through sinks, or (3) the Cox Formation was occasionally consuming itself in a meandering, high-energy transport of detrital materials.

K Hill formed by post-Cretaceous collapse of post-Castile or post-Salado rocks into a karstic void developed within the evaporitic water-soluble lithologies of the Castile Formation. Later-stage erosion and ground water dissolution of the surrounding Castile, as shown by the solution subsidence depression, left the feature as an insoluble remnant. The preservation of these rocks, which are relatively far from correlative outcrops, indicates that upper Rustler, Dewey Lake and Cox units once covered this area. Another possibility from solution and collapse is that breccias preserved at K Hill formed within the Salado Formation and did not penetrate into the Castile Formation. The breccias would effectively be sitting on an upper Castile surface in which all surrounding and overlying Salado has been eroded or dissolved.

The Yeso Hills selenite occurrence is a high-purity lenticular gypsum deposit subcropping within an area of about 3.2 acres in the NE1/4 sec. 14, T26S, R24E, Eddy County. Complexly interlocking, cleavable masses of selenite are exposed sporadically across the northern boundary fault of a northeast-trending solution-subsidence depression expressed in the Castile Formation. An excavated trench is toward the base of the slope immediately south of and structurally below the boundary scarp. The best natural exposures of selenite crystal masses may be traced from the trench northward along the channel of an arroyo that breaks through the low scarp (Fig. 1.9). Many of the crystals show twinning along what is probably the b-axis.

About 315 yd3 of selenite were excavated from the 100-ft-long trench and, according to N. **T.** Berry of Carlsbad, the selenite was quarried as a substitute raw material for the manufacture of capacitors during

FIGURE 1.7. Collapse breccia block of quartzarenite and conglomerate facies of Cox Formation, K Hill.

FIGURE 1.9. Selenite crystals in arroyo north of Yeso Hills quarry. Striations are due to weathering. Scale is 6 in.

World War II. The largest crystal in the deposit, 18 ft long and 6 ft wide, forms part of the northwestern wall of the trench. Most of the area around the trench is covered with cleavage folia from crystals that were equally large before extraction. Because of remarkable clarity and aesthetic beauty, local individuals continue to use selenite as decorative stone in landscaping.

This selenite deposit may have been formed by localized hydration of anhydrite along a solution-subsidence boundary fault in which upwelling waters from the Delaware Mountain Group contacted Castile evaporites. The hypothesis of artesian flow as a factor in forming solution-subsidence troughs on the Gypsum Plain was presented by Olive (1957). Local ponding of ground water in a karst void or network of fractures or faults against a mass of anhydrite is one explanation for such an apparently isolated selenite occurrence. As the Castile anhydrite hydrated to gypsum by contact with this water, the process of gypsum crystallization may have proceeded by diffusion along crystal boundaries, permeating into the host rock and advancing the gypsum/anhydrite interface concentrically as a migrating reaction front. The volume change induced by the anhydrite-to-gypsum transformation may have subsequently filled all voids, with the force of crystallization inducing the interlocking fabric evident in outcrop. Although the selenite deposit is apparently within the Castile Formation, no remnant calcite laminations are preserved within the crystals.

Another possible origin for selenite is a modification of simple hydration of anhydrite that involves oxidation of hydrogen sulfide to sulfuric acid. This is similar to a process described by Hill (1987) to account for other related chemical effects in caves of the Guadalupe Mountains. Acid attack on carbonate laminations, which locally constitute 10 to 50% of the Castile Formation, produced selenite and carbon dioxide, which was degassed from the system. The hydrogen sulfide migrated upward into contact with oxygenated meteoric ground water in the Castile, or was generated in place along a fault by sulfate-reducing bacteria. A sulfur isotope value of 15.1%0 8' from this deposit (Carol A. Hill, personal comm. 1992) is on the higher end of normal values for the Castile Formation and suggests a complex isotope fractionation process if the hydrogen sulfide was biogenic. Without further evidence, any relation between the nearby Tertiary Trachyte dikes and the selenite occurrence is speculative. Possibly the intrusives provided heat to initiate local ground water convection that would hydrate anhydrite to gypsum. They also could have provided a hydraulic dam that impounded ground water in contact with the Castile Formation. The indicated local hydraulic gradient and the coincidence of the deposit with the subsidence-depression boundary fault does not favor the latter.

SULFIDE/BARITE/FLUORITE ORE DEPOSITS, DELAWARE BASIN, NEW MEXICO AND WEST TEXAS

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Most geologists who have studied the Delaware Basin know about the caves of the region, but are not aware that sulfide/barite/fluorite, Mississippi Valley-type (MVT) ore deposits also exist around the margins of the basin (Fig. 1.10). Hill (1993) described more than 15 mines/prospects in just the Guadalupe Mountains section of the basin. Most of these had not been visited for more than 60 years.

Despite differences in location (Guadalupe, Apache, Glass Mountains and Fort Stockton area; Fig. 1.10) and occurrence (along structural and stratigraphic traps, faults and igneous intrusives), the sulfide deposits around the Delaware Basin appear to be genetically related. All are mineralogically simple (pyrite, usually sphalerite, calcite, dolomite) and most have sulfur isotope values ranging from VS — 9 to + *5‰* and carbon-oxygen isotope values ranging from 8"C —15 to *—5‰;* 8"0 =7" —10 to —3%c. In the Guadalupe Mountains, the ore deposits occupy the same structural (anticlines) and stratigraphic (base of the Yates Formation) positions as to do many of the caves.

Hill (1993) proposed that the origin of the MVT sulfide deposits in the Guadalupe Mountains is related to the degassing of the Delaware Basin, where H2S moved from basin to carbonate reef margin and there accumulated in structural and stratigraphic traps (Fig. 1.11). Sulfide mineralization (Hill, 1993) occurred in the Oligocene to Miocene, when these traps were still within the reduced zone (Fig. 1.11A). Later (late Miocene-Pleistocene), as the mountains rose and regional base level dropped, the large cave passages dissolved by a sulfuric acid mechanism where the trapped H2S gas was oxidized at or near the water table (Fig. 1.11B). Using the Delaware Basin as a model, Hill (1993) proposed that the origin of all MVT deposits may be related to the degassing of basins rather than the compaction or dewatering of basins.

Return to highway. 0.5

30.2 **Turn left (southwest) on US-62/180. 0.1**

30.3 Milepost 5. Crossing northeast-southwest-trending solution valley (Olive, 1957) that extends eastward through the Stop 1 area. **1.7**

32.0 Outcrop of biogenic limestone on both sides of the road, trending northeast-southwest along the southern boundary of a solution valley. This linear outcrop is developed within the Castile Formation. **0.3**

32.3 Milepost 3. Crossing northwestern edge of the Yeso Hills overlooking the upper valley of the Black River drainage system. Turnout ahead on right. **0.8**

33.1 **STOP 2: State line gypsum outcrop.** Park at top of the hill on the right shoulder. Taking care to stay off the highway, walk along roadcut to examine exposures. A thick section of much of the upper and middle part of the Castile Formation is exposed on both sides of the highway. These evaporites were deposited about 7 or 8 mi from the western edge of the basin. The following introductory discussion is primarily taken from Brown and Loucks (1988). See also following minipapers by Anderson, Alexander and Watkinson, and Leslie et al.

The Castile Formation is the lower Ochoan (Upper Permian) evaporite deposited in the Delaware Basin following deposition of the Bell Canyon Formation. The section exposed in this road cut correlates to the middle portion of the Castile Formation (Anderson and Kirkland, 1987). At this outcrop, most of the Castile Formation consists of couplets of white to gray gypsum laminae, 1/16 to Va in. thick, interbedded with sub-millimeter, dark brown, calcite laminae. Larger scale sedimentary cycles are also apparent in outcrop. In the upper part of the outcrop, cycles consist of the following three lithologies: a thin 0/4 to V2 in.) basal limestone bed, an interval 0.5-2 ft thick consisting of thinly laminated, gypsum-calcite couplets and a capping lithology of thin- to medium-bedded to nodular gypsum, 2 to 10 in. thick. Larger scale cycles may also be apparent in outcrop, but are difficult to identify because of weathering.

The gypsum-calcite couplets have been interpreted as seasonal varves by Anderson et al. (1972), based on the predictable change in mineralogy and upon well-documented correlation of the laminae over tens of miles. Varved evaporites were originally believed to have formed only in restricted, highly saline, deep-water basins (Dean and Anderson, 1978). Postulated water depths of initial Castile deposition range from about 600 ft to over 1800 ft. Evaporite deposition is believed to have been initiated when circulation to the Delaware Basin was greatly re-

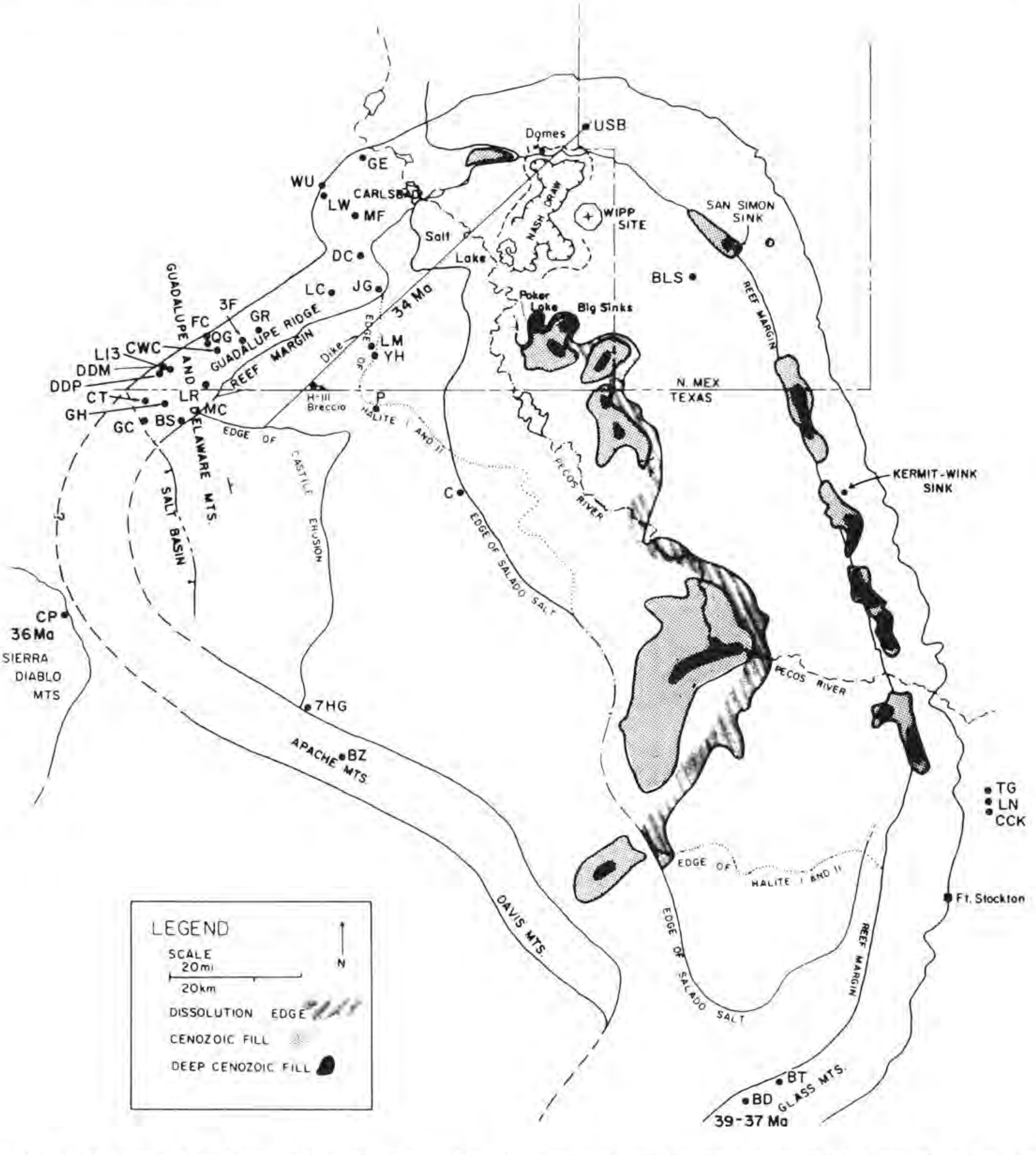

FIGURE 1.10. Location of different types of ore deposits, Delaware Basin, New Mexico and Texas. Counterclockwise from Carlsbad, New Mexico, around and then within the Delaware Basin: GE = Golden Eagle mine, WU = Walt Canyon uranium mine, LW = Little Walt prospect, MF = Middle Fork Waterhole marcasite, DC = Dark Canyon pyrite/marcasite, JG = Jurnigan gossan, LC = Lechuguilla Cave pyrite, GR = Guadalupe Ridge pyrite, 3F = Three Fingers Cave Ridge pyrite, FC = Fir Canyon prospect, QG = Queen of the Guadalupes mine, CWC = Cottonwood Cave, LR = Lonesome Ridge pyrite, L13 = Lucky 13 prospect, DDM = Devil's Den mine, DDP = Devil's Den prospect, MC = McKittrick Canyon pyrite, BS = Bell Springs prospect, GH = Grisham Hunter prospect, CT = Calumet and Tejas mine, GC = Glori Cave fluorite, CP = Cave Peak mining district, 7HG = Seven Heart Gap barite mine, BZ = Buck zinc prospect, BD = Bird mine, BT = Bissett mine, CCK = Comanche Creek, LN = Los Nietos, TG = Texas Gulf, C = Culberson sulfur mine, P = Pokorny sulfur deposit, LM = Leonard Minerals sulfur deposit, YH = Yeso Hills pyrite, BLS = Bell Lake Sink celestite and barite, USB = U.S. Borax mine pyrite (now Mississippi Chemical). From Hill (1993).

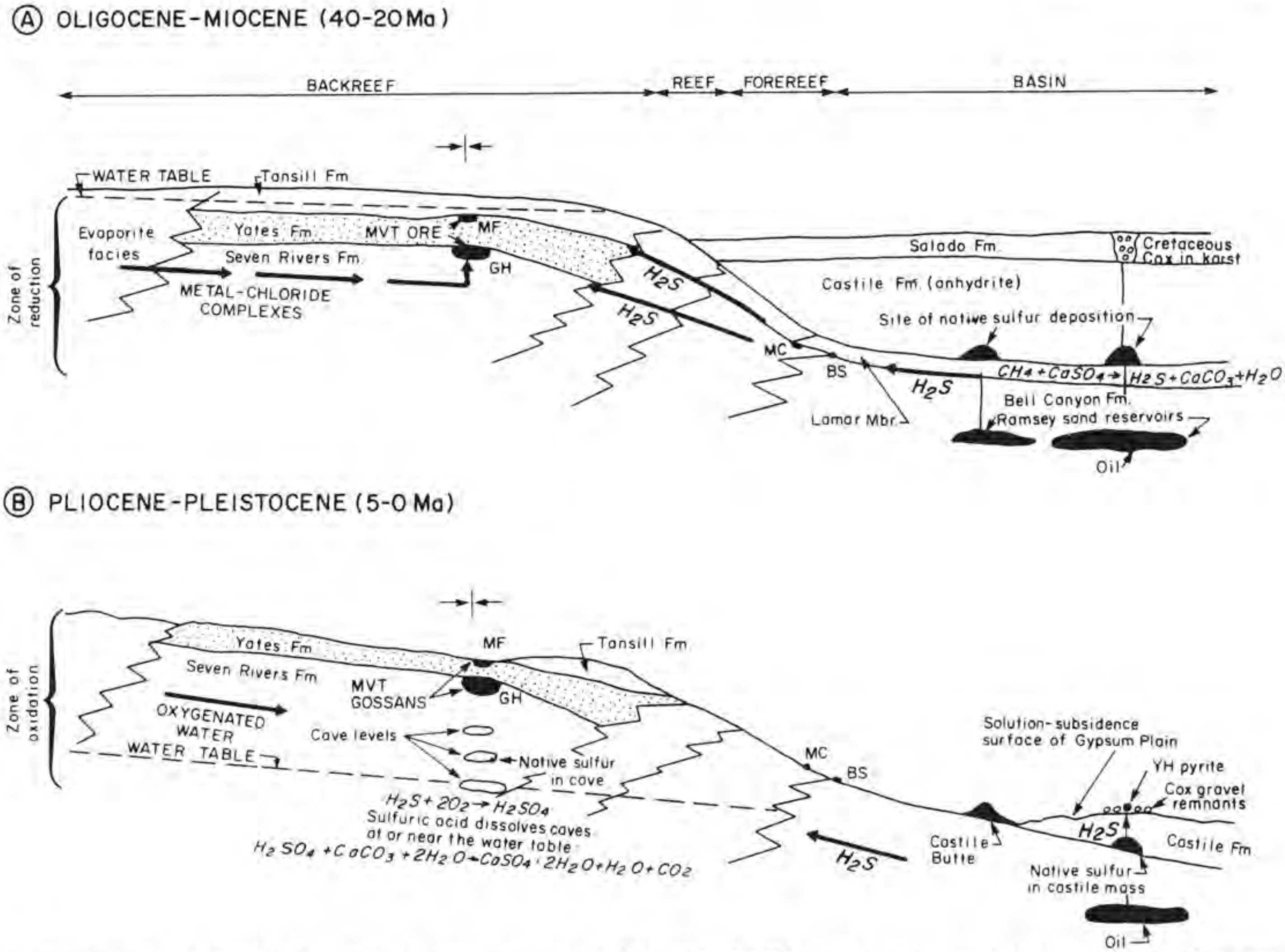

FIGURE 1.11. Idealized model for the formation of sulfide ore deposits, Guadalupe Mountains. This model proposes a genetic connection between hydrocarbons, native sulfur and pyrite in the basin and Mississippi Valley–type (MVT) ore deposits and caves along the carbonate reef margin. A. In the Oligocene to Miocene, at the beginning of uplift of the Delaware Basin, H_2S was generated in the basin by reactions involving hydrocarbons and Castile anhydrite solutions. The H_2S oxidized to native sulfur in the basin and also migrated from basin to reef to there accumulate in structural (anticlinal) and stratigraphic (base of Yates) traps. Metals moved downdip as chloride complexes from backreef evaporite facies and, where they met with the H_2S below the water table in the zone of reduction, they formed MVT ore deposits. B. In the Pliocene-Pleistocene, maximum uplift of the basin caused increased H_2S generation and migration of gas from basin to reef. Cave dissolution occurred in the same structural and stratigraphic position as earlier MVT ore deposits and cave passages were formed where H_2S oxidized to sulfuric acid at or near the water table, in the zone of oxidation. Cave levels correspond to a descending base level. See Fig. 1.10 caption for abbreviations.

stricted near the end of Guadalupian time. If the couplets do represent varves, the entire 1800 ft of the Castile was deposited in about 220,000 yrs. Depth of water in the basin and the existence of an open channel connecting the Delaware Basin to the Permian ocean are issues that are currently being debated.

Early and late deformation fabrics are also evident in outcrop. As noted by Kirkland and Anderson (1970), microfolds with amplitudes on the order of 0.5 in. and related larger folds, are not related to gypsum dehydration or anhydrite hydration. These folds are interpreted as having formed in response to gravity sliding contemporaneous with deposition. Post-lithification features include large folds probably related to dissolution of underlying salt layers and breccia beds formed due to solution collapse of salt and anhydrite beds. The large syncline at the upper end of the outcrop plunges toward the north-northwest, approximately parallel to the present edge of salt dissolution. Late folding can be identified by the brittle behavior of intercalated limestone laminae. Both tectonic and sedimentary folding textures are present (Borns, 1987), suggesting that some events took place before lithification because trains of folds are often out of phase. Robinson and Powers (1987) also portrayed textures of gravity-driven Castile sediments.

THE CASTILE AS A "NONMARINE" EVAPORITE

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After King (1947) showed that the low proportion of halite to anhydrite in the Castile evaporite could be explained by the reflux of brine from the Delaware Basin, the Castile became the classical example of a marine, "deep water" evaporite. Anderson and Dean (in press) have reexamined the distribution of evaporite units, as well as geochemical evidence and they suggest that reflux is not the only way to explain the compositional and stratigraphic relationships of the Castile. According to the alternate explanation, the brine was not a residual of sea water flowing directly into the basin. Rather, it is suggested that chloride recharge was from ground water seeping into the basin from the south, especially during lowstands (Fig. 1.12a), with the brine derived from a partly marine source or from previously deposited evaporites. In this model, the Delaware Basin was a hydrologically closed basin with water level subject to extreme highstands (Fig. 1.12b) and lowstands, a type of response similar to that observed in existing closed basins in western North America.

Support for a closed-basin model can be found in the record of climatic variability that is preserved in the Castile. For example, millennial oscillations in climate and lake level are strongly expressed in the closed hydrologic basins in western North America during the late Pleistocene. Millennial cycles also are dominant in the Castile and determine the incidence and duration of halite accumulation (lowstands). Cycles of precession and eccentricity also are well defined in the Castile and in the record of the ocean and cryosphere over the past million years. The occurrence of climate cycles recognized in the Pleistocene and Holocene does not address the question of marine recharge for the Castile. However, strong expression of the same climatic periodicities within the Castile is consistent with a closed-basin hydrologic setting and meteoric recharge.

More direct evidence for meteoric recharge can be seen in the depletion of "0 in limestone beds along the western margin of the basin (Magaritz et al., 1983) and in rapid, synchronous changes in the seasonal rate of accumulation of calcium sulfate (freshening events) that resulted in beds of laminated limestone. Such events can be traced from the western margin to the center of the basin, suggesting that a significant volume of meteoric recharge entered the basin from the west during those times when water level was at or near a highstand (Fig. 1.12b). Other evidence for meteoric contributions can be found in the low bromine concentrations in halite, which give the Castile an affinity with other nonmarine evaporites. Ground-water recharge of ions derived from preexisting evaporites provides an alternate mechanism to account for the low ratio of halite to sulfate.

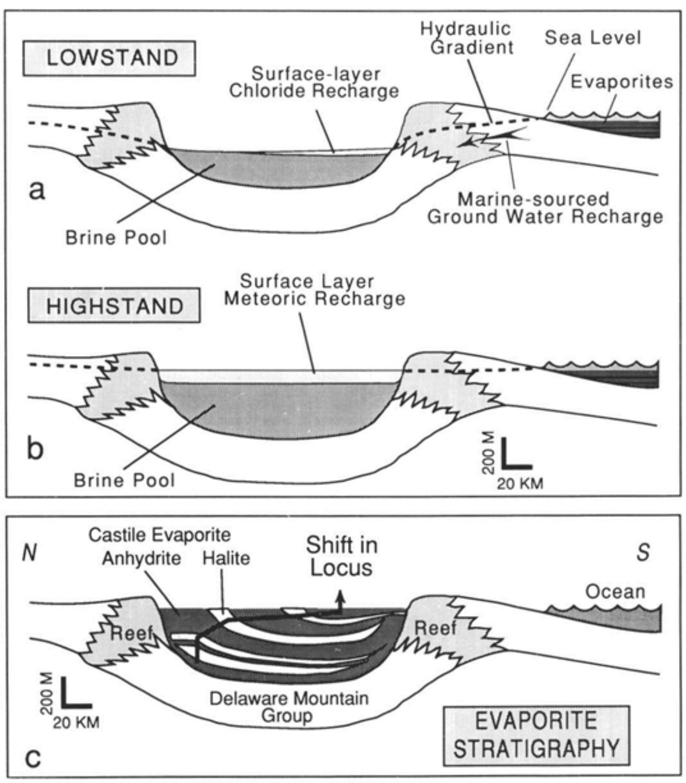

FIGURE 1.12. Cross section through Delaware Basin, showing (a) lowstand and halite mode with ground water entering basin from the south; (b) highstand and anhydrite mode with meteoric recharge entering from the west; and (c) shift in locus of halite accumulation. Shift began when basin was about half filled with sediment, suggesting that drawdown was accompanied by lateral displacement of halite accumulation.

The geometrical relationships of stratigraphic units provides indirect evidence for ground-water recharge and for large changes in water level within the Delaware Basin. For example, as the basin filled with sediment there was a southward shift in the locus of thick accumulation of halite (Fig. 1.12c) that can best be explained if water level was initially drawn down to a minimum pool several hundred meters below the basin rim (Fig. 1.12a). Reflux during such lowstands seems unlikely. Also, beds of laminated halite are thicker to the north, implying that seasonal accumulation of halite was less continuous in the south, even during lowstands, as would be expected if chloride entered the basin in ground water.

Although no single line of evidence eliminates direct marine inflow as a source for the brine, the strong response to climate forcing, combined with evidence for drawdown and meteoric contributions, leaves the clear possibility that the Delaware Basin was isolated from the sea.

THE CASTILE FORMATION: A CONTINUING PARADOX

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The Upper Permian (Ochoan) Castile Formation consists of laminated couplets of anhydrite and calcite/organic material, interbedded with massive to poorly laminated halite (Anderson et al., 1972). The Castile Formation ranges in thickness from under 300 m in the west of the basin where halite has been removed to over 600 m in the east. The Castile Formation was deposited in an embayment of the Permian Basin (the Delaware Basin) during a period of restricted circulation with marine waters, causing a rapid increase in salinity and consequent precipitation of evaporite minerals. The laminites display a number of cyclicities on different scales, which have been related to orbital forcing by Anderson (1982).

At the base of the Ochoan in the Delaware Basin is an upward transition from marine finely laminated carbonate and siltstone to massive sulfate and laminated carbonate/sulfate couplets. This implies a significant change in both sediment supply and in paleohydrological conditions in the basin. The change in lithology occurs over 1 m of section (Cys, 1978) indicating a rapid change in conditions in the basin. The Castile Formation passes upwards into the Salado Formation, which is lithologically similar although halite is more abundant. A slight angular unconformity is possible between the two formations.

The Castile Formation has been the subject of several studies in the past few decades and a reasonably well-constrained depositional model has been developed to account for the basinwide distribution of millimetric laminations (Anderson et al., 1972; Dean and Anderson, 1978; and others). The deep-water, stratified basin in which carbonate and sulfate minerals are precipitated in evaporitic surface waters and subsequently deposited over the basin floor as a thin pelagic cover is an established model that has been applied to numerous other examples of evaporite basins in geologic history.

Recent studies have begun to develop the interpretations further while retaining the basic interpretations of the original model. That the millimetric laminations were deposited in a deep (i.e., below wave base) setting is well established. There is increasing evidence, however, that at certain times water levels in the basin were sufficiently low to allow growth of crusts of gypsum (selenite) on the basin floor. Cycles of upwards-increasing lamina thickness have been recognized (Dean and Anderson, 1978), which are topped by intervals of relatively coarse, nodular sulfate. The coarse sulfate deposits have in some cases formed as displacive nodules within the uppermost laminites and appear to be a synsedimentary or very early diagenetic phase of sulfate growth. The growth of selenite crusts is, in most cases, overprinted and obscured by nodular sulfate. The texture of the crusts is preserved only in the presence, within a coarse sulfate bed, of apparent selenitic terminations, picked out by impurities and inclusions within the sulfate. Growth of these crusts requires supersaturation of basin waters with respect to gypsum at the basin floor and therefore a fully mixed water column. The growth of nodular sulfate within the uppermost laminites also requires supersaturation of the waters at the basin floor.

The constraints upon water depth during growth of sulfate at the basin floor are narrow, because supersaturation of the water column with respect to sulfate is controlled by evaporation at the surface. It is unlikely that a water column greater than a few tens of meters could be fully homogenized by surface processes in a small basin. The basin is thus unlikely to have been filled with water if the present interpretation of basin paleotopography (over 200 m) is accepted. Although it is possible that some tectonic movements did take place in the Ochoan, the basin must still have been relatively deep at the onset of evaporite deposition. The implication for the depositional environment of the Castile Formation is that the basin was only partially filled, at least before deposition of the third cycle (200 m of sulfates and halite in the east of the basin). This interpretation of the thick-bedded sulfate leads to a conflict in paleoenvironmental interpretations only in terms of ***absolute*** water depths in the Delaware Basin. The deep-water environ-ment does not require the basin to be full during deposition, only that a stratified water body is developed.

If the basin was not filled during deposition of the evaporites, then some evidence of exposure of the basin margins (karstification, tray-ertines) might be expected. This part of the model has yet to be tested, because suitable outcrops or cores are not available and the evidence, as such, could be open to a number of interpretations.

In the upper parts of Halite 2, examined in the Union Oil Core 37- 4 University well, halite appears to be replacing nodular sulfate at the top of a number of salinity cycles. The nodular form of the sulfate suggests that it precipitated at or just below the basin floor as gypsum before being partly replaced by anhydrite. It is possible that there was a grain-size control on the replacement, with more fine-grained crystals being replaced while only the outer rims of coarser, lenticular masses were altered.

The replacement of the remaining gypsum by halite also took place during very early diagenesis, while the sediments were still accessible to basin waters. Most of the halite has replaced sulfate while retaining the lenticular nodular form of the original gypsum. Some halite crystals within laminated Castile have good cubic form and are clearly replacive. Halite crystals are commonly concentrated along particular laminae and some have a diamond profile, suggesting the original presence of glaub-erite.

As yet, no mechanism exists for the replacement of sulfate by halite in a deep-water setting. Such textures have only been described from very shallow environments where evaporative surface brines are in contact with the sediment (Hovorka, 1991; Schreiber and Walker, 1992). It is possible that by the end of the second cycle, the basin was sig-nificantly shallower in the north of the basin around borehole PDB-03 (Anderson and Dean, in press). However, the association of the halite replacement fabrics with normally laminated Castile again presents a paradox in the possible interpretation of water depths.

CASTILE MICROFOLDING

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The state-line outcrop of the Castile Formation exhibits superb ex-amples of multilayer fold systems in anhydrite/calcite bilaminate rock and stimulates debate on the origin of the folds. For succinct discussions of the regional context and stratigraphy, possible sedimentological con-ditions of deposition and the paleoclimatic record, see Anderson and Kirkland's (1987) excellent guide and minipapers in this volume by Anderson and Leslie et al. More in-depth discussions of folding are given by Kirkland and Anderson (1970) and Alexander and Watkinson (1989).

Observations of the folding of the Castile Formation are based on our own field work at the state-line outcrop (Alexander and Watkinson, 1989), coupled with study of core samples very kindly made available to us by R. Y. Anderson and on observations made by Kirkland and Anderson (1970).

The outcrop consists of alternating laminae of brown calcite and gray-white anhydrite. The anhydrite layers are as much as 5 nun thick with a mean thickness of 1.1 mm. The brown calcite-rich rayers, con-taining organic material plus intermittently distributed anhydrite crys-tals, are on average 0.4 nun thick and as much as 1.2 nun thick. All structural indications are that the anhydrite layers were the more com-petent layers during the folding deformation. The anhydrite layers fre-quently have a cuspate-lobate fold form (Ramsay and Huber 1987 p. 403; Fig. 1.13). We see no evidence of interlayer slip such as bedding-plane slickensides or striae and thus assume that the layer contacts remained bonded during deformation.

One of the most striking features of the state-line outcrop, described by Kirkland and Anderson (1970, figs. 8 and 9; Anderson and Kirkland, 1987), is the occurrence of the small-scale folds in concentrated zones or pods. The pods are located predominantly in the hinge zones of larger-scale folds (wavelengths approximately ..?-1 m), in both the syn-clinal and anticlinal hinges (Fig. 1.14). The outline shapes of these concentrated zones of microfolds are typically either elongate along the layering or elongate in a direction parallel to the axial-plane trace of the folds, at a high angle to the layering. This observation provides the motivation for a useful way of communicating the details of the dis-tribution of the ininor folds—continuity of folds in terms of components of along-the-layer and across-the-layer systems (Watkinson and Alex-ander, 1979).

Even within the pods of microfolds, not all anhydrite layers are folded. In some cases, both thicker layers (4-5 mm) and thinner layers (<1 mm) remain essentially unfolded adjacent to folded layers. This creates systems of folds that have a long lateral continuity compared to the across-the-layer component. Fig. 1.13 illustrates typical examples of fold systems with many folds laterally but involving only one or two competent layers. The folds die out in a variety of ways; some decrease in both amplitude and wavelength and others die out with an increased wavelength (or, more correctly, span, if only one fold exists of one size) and decreased amplitude.

In contrast to systems with obvious lateral continuity compared to the across-the-layer continuity, other systems involve harmonic folding of many layers, in many cases with short lateral extent and in most cases in the hinge zone of the large folds. The obvious end member of this type of system is a kink fold, which occurs rarely in the Castile

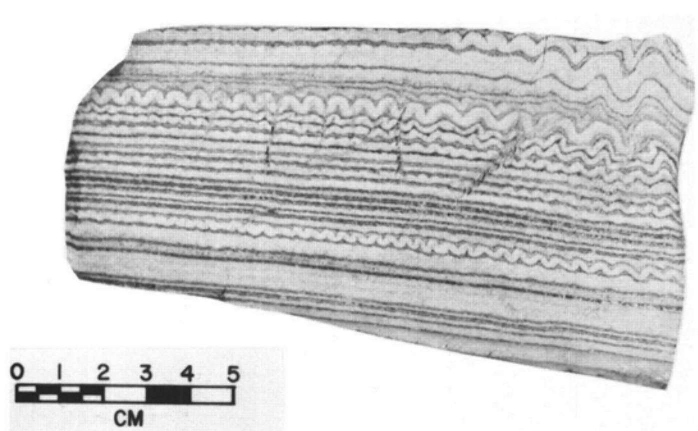

FIGURE 1.13. Multilayer folds exhibiting components of both along-the-layer folding and minor across-the-layer folding in the upper right-hand corner.

FIGURE 1.14. Dendriform pattern of along-the-layer and across-the-layer components typical of hinge zones or larger folds.

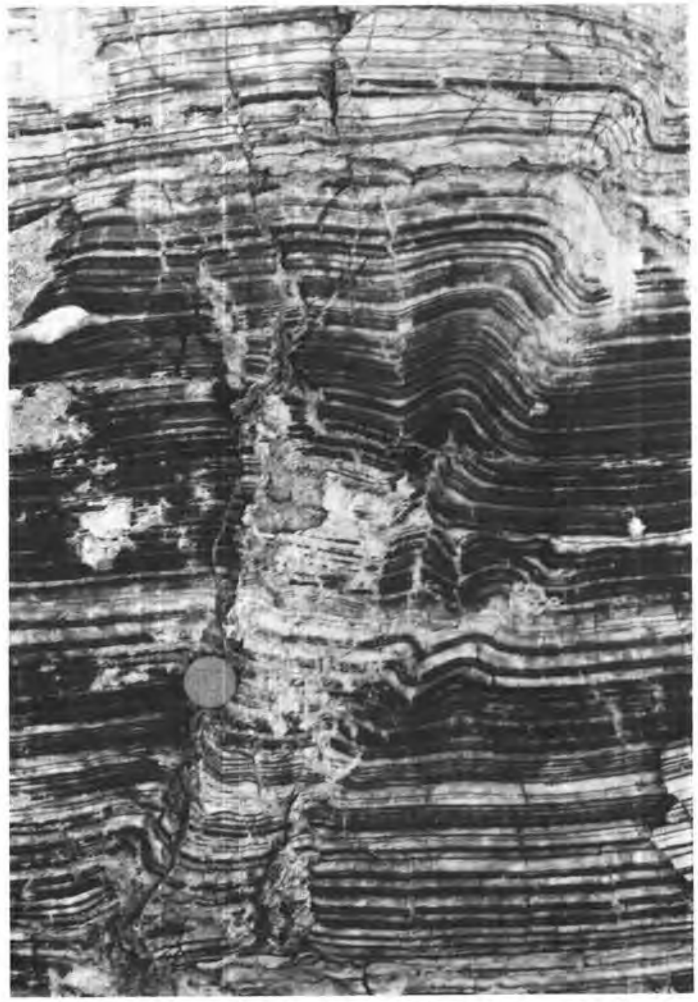

FIGURE 1.15. One of the few chevron/kink-like folds observed at the state-line outcrop.

sequence (Fig. 1.15). The tendency for extensive across-layer systems to develop is greater where all layer thicknesses or layer-couplet (anhydrite/calcite laminae) ratio thicknesses remain constant, that is, with no markedly thicker or thinner beds. As expected in these more homogeneous multilayer sequences, the folding tends to be a chevron to sinusoidal type (Fig. 1.15), rather than the typical rounded, cuspate inner arc, buckle type of the single layer folds. In detail, many of the zones of microfolding show multilayer folds with several layers folding out laterally, farther along the layer than others; this creates dendriform patterns of fold distribution (e.g., Fig. 1.14). Some zones occur where all of the layers are folded. More commonly, the folds occur harmonically within multilayer packets, with some folds harmonic across several multilayer packets. In general, the multilayer folds are disharmonic (out of phase) across either anomalously thick layers (either anhydrite or calcite) or thin layers that remain unfolded. Figs. 1.16 and 1.17 show some typical examples of fold patterns. Compared to the folded layer(s), the adjacent unfolded layer or layers may be both thicker or thinner (Fig. 1.17). There are examples where one interface of a thicker layer may be perturbed as a cusp interface, but not the other.

Other deformation in the outcrop is distinct from the orderly folding (see also Borns, 1983, fig. 7). "Disrupted" zones may be related to hydration effects of anhydrite to gypsum. Also the layering is reorganized locally to form nodular aggregates.

Previous work (Alexander and Watkinson, 1989) leads us to conclude that the folds must be tectonic in origin, based largely on systematic relationships of folds at different scales. The trend of the folds does not appear to be related to paleoslope in the basin, but apparently parallels the trend of the "major belt of Tertiary faulting west of the erosional edge of the Castile Formation" (Anderson and Kirkland, 1987, p. 458). The low-strain nature of the Castile outcrop is compatible with the notion that we are observing the early expressions of a once-spreading fold system in the multilayers. Localized initiation and spatial propagation may typify fold systems (Cobbold, 1976; Watkinson, 1976).

The existence of unfolded planar layers, mostly thicker, but some thinner than folded layers (Fig. 1.17) is often used to appeal to a sedimentary/diagenetic origin of the folds. However, Wollkind and Alexander (1982) have shown analytically that some layers may remain "stabilized" to fold perturbations, creating internal fold geometries (Biot, 1965). The planar layers have uniformly thickened, as has been carefully demonstrated by Kirkland and Anderson (1970). Therefore, the folds have not "detached" off undeformed layers, as has been proposed for a soft-sediment origin. Also, the folds are strikingly periodic and regular, although only locally developed, especially when compared to those observed in modern-day sabkha environments (Shinn, 1983).

While we favor a tectonic origin for the Castile folding, we point out that many aspects of these fascinating structures still puzzle us. For example, from the correlation of the layering over the basin, a striking feature is that the same layering sequence in different localities has very different fold geometries (see Kirkland and Anderson 1970, fig. 18). Does this mean that the folding is particularly sensitive to subtle changes in layer thickness or composition? Or does some other factor affect the folding, i.e., strain rate, or amount of strain, or fluid content? We still have a lot to learn!

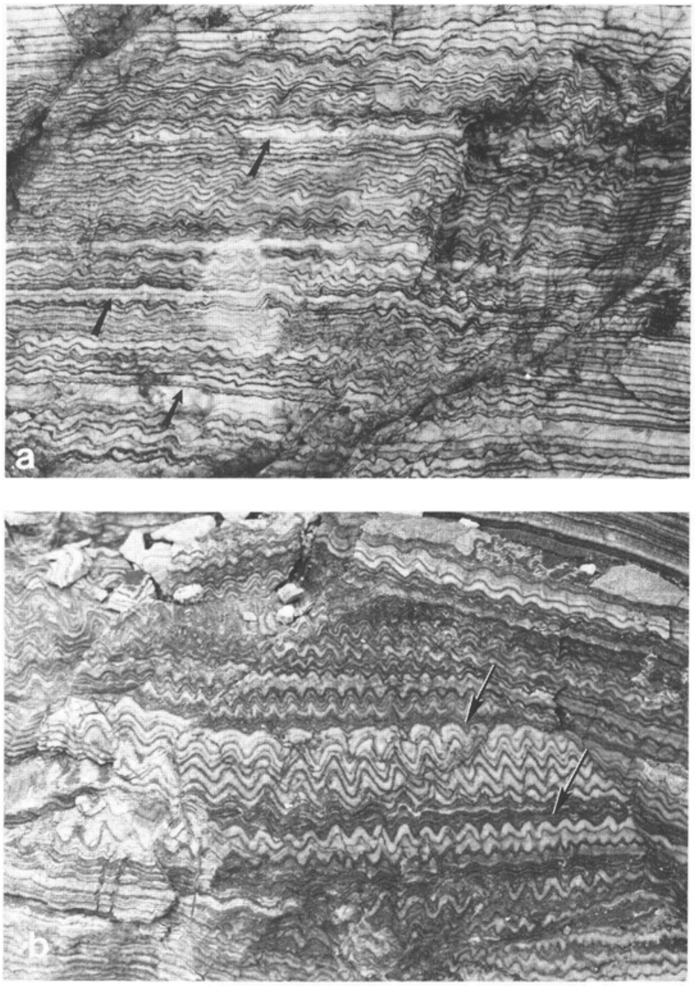

FIGURE 1.16. Examples of styles of multilayer folds. (a) shows internal fold systems bounded by planar interfaces (arrows). (b) shows more pervasive folding, with some disharmony across thicker incompetent layers (dark layers highlighted by arrows).

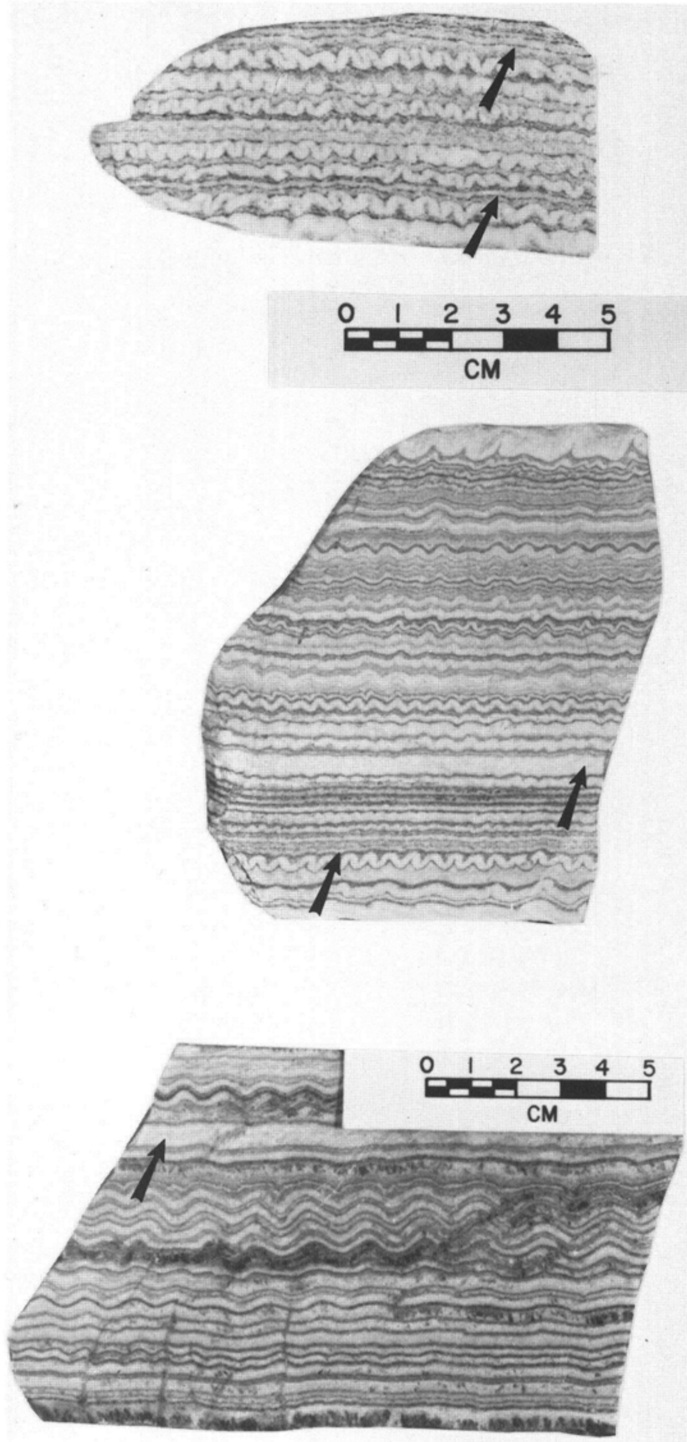

FIGURE 1.17. Examples wherein both "thicker" and "thinner" anhydrite layers remained essentially planar (arrows) whereas layers of "intermediate" thickness folded.

Continue southwest on US-62/180. 0.2

33.3 Milepost 2. Crossing valley floor at western edge of Yeso Hills. McKittrick Canyon Draw joins the upper Black River drainage system about 0.3 mi to the north. Sulfur exploration holes in this area show about 185 ft of alluvial fill. **0.7**

34.0 Ascending to surface of broad alluvial terrace; the distal part of a Pleistocene fan formed at the lower end of McKittrick Canyon Draw. **1.3**

35.3 New Mexico—Texas State Line. Entering Central Time Zone. **Prepare to turn left. 0.1**

35.4 State Line Bar and Cafe on the right and Texas Farm-Ranch 652 on the left. **Turn left onto FR-652** toward Orla. Route continues southeast on Pleistocene alluvial terrace mapped as "Qao, alluvium, colluvium, caliche and gypsite on surfaces dissected by modern drainage" (Bureau of Economic Geology, 1983). 1.0

36.4 Roadcut to left in cobbly terrace gravel on gypsiferous and fine, older valley fill. **1.2**

37.6 Route reenters Yeso Hills area of the Gypsum Plain. Roadcuts ahead in Castile Formation. 1.0

38.6 For the next 4 mi, patches of gravelly calcrete (pedogenic stage IV) form high-level tetTace remnants on the Gypsum Plain. **2.0**

40.6 Junction with FR-1108 to Delaware Springs; bear left and continue on FR-652. **4.5**

45.1 Junction with FR-1165 (pipeline station to left); continue straight on FR-652. **0.2**

45.3 Crossing Alligator Draw, roadcuts in Castile Formation. **2.3**

47.6 Roadcuts in Castile Formation. **0.5**

48.1 Crossing Pokorny sulfur deposit drilled by Addwest Minerals (see minipaper by Klemmick). Valley of Delaware River 1 mi to south follows major, N60°E-trending solution-subsidence trough (Olive, 1957). King (1949; Texas Bureau of Economic Geology, 1983) showed a 2-mi-wide horst with the same trend at the north edge of the valley. This feature is expressed as a salient of Bell Canyon sandstone that extends outward from the eastern base of the Delaware Mountains just south of the highway at this point. 0.2

48.3 Conical "Sulfur Mine Hill" at 3:00 is a "castile" feature (5 mi south-southwest) on the southern rim of "Delaware River" subsidence trough. 1.1

49.4 Northern rim of subsidence trough and roadcut in Castile Formation; crossing valley of Delaware River. 0.2

49.6 Roadcut in Pleistocene terrace deposits, primarily gypsiferous sand, with thin pebble interbeds, capped with well-developed gypsic soil containing a thin, indurated, gyperete. **0.4**

50.0 Bridge over Delaware River. Since at least late Miocene time (past 12 Ma), this and other tributaries to the ancestral Pecos River were part of a surface and subsurface discharge system that shaped much of the topography seen along the route. Past intervals of cooler and moister climate, such as occurred during Pleistocene glacial-pluvial stages, supported much larger sustained discharges than those during the Holocene (past 10,000 yrs). The old Butterfield Stagecoach Line followed the Delaware River. The first waystation east of The Pinery (Guadalupe Pass) was at Delaware Springs about 8 mi west of this point. 0.1

50.1 About 20 ft of solution-subsidence trough fill is exposed in this roadcut. The material is primarily massive gypsite and gypsiferous silt, with discontinuous finely laminated zones exposed near the base of the cut. The age of the deposit is probably middle Pleistocene and forms a prominent intermediate-level terrace on south side of the Delaware River in this area. **1.3**

51.4 Crossing southern rim of solution-subsidence trough. To the north is the small Ed Pokorny oil field that produced 0.00045 MMBO from Delaware sandstone. Prepare to stop on right shoulder of highway. **0.5**

51.9 **STOP 3: "Castiles."** Conical hills on horizon at 11:00 to 1:00 are limestone "castiles" in outcrops of the Castile Formation. Park near the crest of the roadcut through the hills and on the right side of the highway. Assemble on the east side of the most easterly hill on the south side of the highway (Fig. 1.18). At this stop, we examine the origin and structure of a castile. The following discussion is taken from Brown and Louckes (1988).

FIGURE 1.18. View north over highway showing several castiles.

The Gypsum Plain east of the Guadalupe Mountains forms rolling topography punctuated by isolated hills or groups of hills called "castiles" (Adams, 1944). These features resulted from differential erosion of gypsum around areas of secondary limestone. This hill is formed by a V- to U-shaped near-vertical dilce-lilce body of steeply dipping, laminated and brecciated secondary limestone enclosing and surrounded by steeply dipping, laminated gypsum of the Castile Formation and by gypsum breccia. Most dips are near vertical. The roadcut exposes a sharp contact between the gypsum breccia and secondary limestone that dips steeply toward the road. This contact lines up with one of the dike-like bodies weathering to form the hill. The contact may be a fault or a diagenetic contact, but the gypsum is too brecciated to determine if offset occurred. Small amounts of secondary limestone occur within the gypsum breccia (Fig. 1.19). Structure in outcrop and around the hill is not consistent with a simple breccia pipe or fault localization of secondary limestone.

The limestone is formed by bacterial metabolysis of original calcium sulfate and migrating hydrocarbons during Cenozoic uplift, erosion and salt dissolution. The calcium is reincorporated into calcite, hydrocarbons are oxidized to carbonate which is incorporated into the calcite, sulfur is reduced to H2S, and energy is yielded to the bacteria. Locally, economical quantities of sulfur are produced by further reaction of the H2S with actively moving, oxidizing ground water (see Crawford and Wallace, this volume).

Most calcite is locally formed as a volume-for-volume reaction. Laminae and microfolds originally present in precursor anhydrite are perfectly preserved in small areas of the secondary limestone. On a larger scale, porosity is produced because a 20% volume reduction occurs when anhydrite is converted to calcite. This volume difference is accommodated by formation of secondary vugs and by brecciation. Laminae are typically thinner in calcitized rocks than in nearby gypsum, indicating that calcitization took place prior to conversion to gypsum. Anhydrite reaction to calcite without gypsum formation suggests highly saline waters or reactions at higher temperatures.

FIGURE 1.19. Castile Formation brecciated and calcitized south of highway behind easternmost roadcut.

GEOLOGY OF THE POKORNY SULFUR DEPOSIT, CULBERSON COUNTY, TEXAS

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The Pokorny sulfur deposit is located in the northwest corner of the Delaware Basin, in the Rustler Springs sulfur district of west Texas (Fig. 1.20), approximately 35 mi south of Carlsbad, New Mexico, in northeast Culberson County, Texas (Fig. 1.21). To date, 57 sulfur test wells have been drilled by Addwest Minerals delineating a resource of greater than one million long tons (It) of native sulfur.

The Pokorny sulfur deposit was inadvertently discovered by the University of New Mexico while studying climatic cycles and varved strata in the Castile Formation (Davis and Kirkland, 1970). A 905 ft core test, drilled by the University in 1969, intercepted sulfur-bearing bio-epigenetic limestone between 664 and 732 ft, which contained 10 net ft of solid sulfur (NFSS). The deposit, as presently defined, is open-ended in four directions and excellent potential exists to expand reserves to greater than two million It of sulfur (Klemmick, 1992). In addition to drilling, detailed surface geologic mapping and a gravity survey were completed over Addwest Minerals' land holdings during 1990-91. This subsequent work has generated more than a dozen moderate to high-priority exploration targets in addition to the known sulfur mineralization.

All sulfur mineralization at Pokorny is hosted by the Castile Formation, in which sulfur-bearing bioepigenetic limestone has replaced anhydrite or gypsum. The Castile Formation crops out throughout the Pokorny deposit area and the underlying Lamar Limestone Member of the Bell Canyon Formation is usually present between 900 to 1000 ft beneath the surface. The Castile Formation strata dip gently 1-2° to the east. The overlying Salado Formation crops out approximately 2—3 mi east of the deposit area.

All halite interbeds in the Castile Formation at Pokorny and in the western Delaware Basin in general, have been dissolved by near surface meteoric water (Anderson et al., 1978). Following halite dissolution, the collapse of overlying anhydrite/gypsum strata forms a laterally extensive horizon of collapse breccia (Anderson et al., 1978; Smith, 1978). At Pokorny, three major zones of collapse breccia have been noted in drill cuttings and core. These three zones correspond to the halite I, halite II and halite III dissolution horizons of Dean and Anderson (1978), Anderson et al. (1978) and Smith (1978). Where not extensively altered, these halite dissolution horizons at Pokorny consist of a homolithic, clast-supported breccia, generally with i/4-to-2 in. angular-to-subangular and/or subrectangular anhydrite clasts. The clasts are encased in a fine-grained matrix of anhydrite and gypsum. In this breccia, the clasts generally make up greater than 50% of the rock volume, usually between 70 and 90%.

Locally closely spaced, northeast-striking, high-angle normal faults of small to moderate displacements (50 to 250 ft) occur at Pokorny. Presumably these structures formed as a result of late phase (middle Miocene to Holocene), northwest-orientated Basin-and-Range extension (Hentz and Henry, 1989). The intersection of these faults (which tap hydrocarbon-rich waters flushed through the Bell Canyon Formation) with halite dissolution beds are favorable sites for sulfur mineralization at Pokorny.

The Pokorny sulfur deposit is a crescent-shaped body of sulfur-bearing bioepigenetic limestone concave to the east. Both limbs of the crescent are cunently open-ended. Sulfur mineralization occurs as canary yellow, subhedral to euhedral crystals (sometimes >1 in. in di-

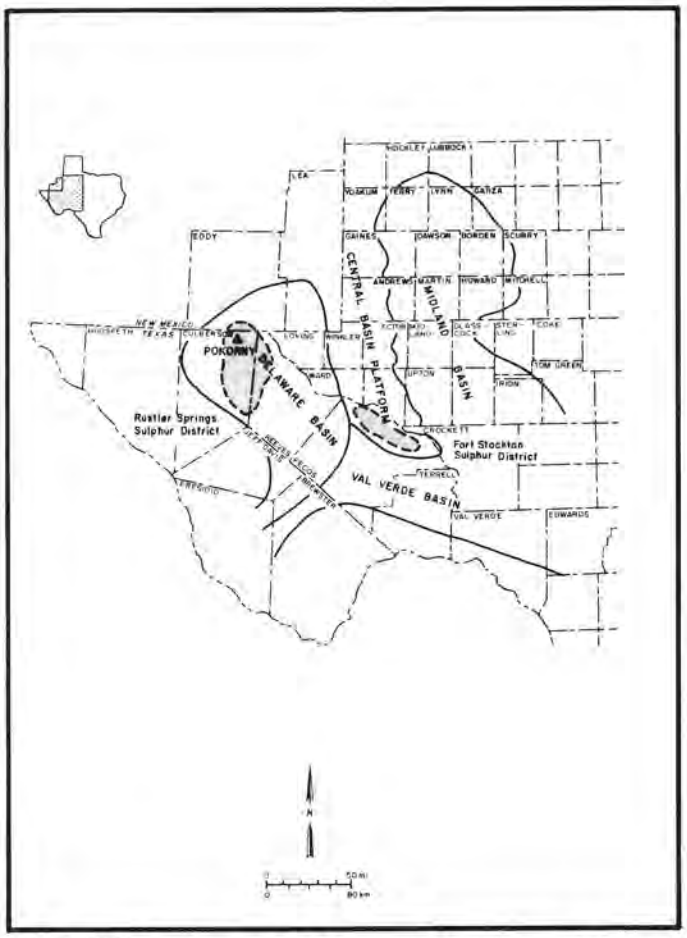

FIGURE 1.20. Location map of the Pokorny sulfur deposit within the Delaware Basin.

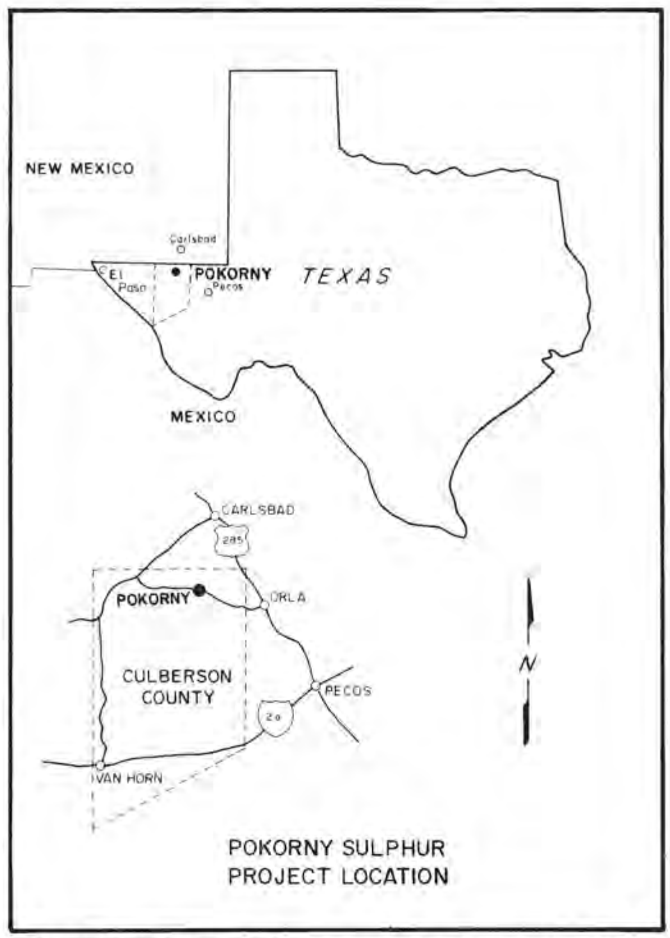

FIGURE 1.21. Geographic location map of the Pokorny sulfur deposit.

ameter) deposited in discontinuous planar voids and large vugs and as small disseminated grains (to ,/8 in. diameter) in a bioepigenetic limestone matrix. Based on drilling results, three types of sulfur-bearing bioepigenetic limestone have been noted, possibly suggesting varying intensities of anhydrite/gypsum replacement (Klemmick, 1992).

The first type of sulfur-bearing bioepigenetic limestone is termed "banded" ore. The relict banding of Castile Formation evaporites is commonly preserved in this type, with sulfur mineralization occurring on small planar voids that parallel the bedding. Sulfur mineralization occurs as small bright yellow to brown-yellow subhedral crystals disseminated within replaced anhydrite layers. Accompanying the sulfur are lesser amounts of calcite, barite and celestite. Grades in this type ore can be up to 35 wt.% elemental sulfur.

The second type of bioepigenetic limestone at Pokorny is "massive" ore. It has characteristics very similar to "banded" ore, but in addition exhibits crosscutting barite and sulfur-bearing veins along fractures that intersect relict anhydrite banding at a 30 to 40° angle, suggesting two episodes of mineralization. Generally the veins are up to 0.5 in. wide, occur in parallel sets with the veins spaced approximately 0.5 in. apart and consist of massive to bladed barite with interspersed subhedral, bright yellow sulfur crystals. The fracture-filling commonly contains greater than 75% $BaSO_4$. The fractures are nearly completely filled with mineral and have little or no remaining porosity. Sulfur grades are similar to "banded" ore (up to 35 wt.% elemental sulfur) with little contribution (3 to 5 wt.% elemental sulfur) from the crosscutting, barite-rich veins.

The third and final type of ore is "vuggy" ore. This type consists of complete bioepigenetic alteration and replacement of limestone and anhydrite. The "vuggy" ore is usually light to medium gray with large voids (up to several inches in diameter) and locally contains vugs up to several feet in diameter. No relict banding of Castile anhydrite is preserved. Yellow, fine-grained, anhedral-to-subhedral sulfur (up to 10-15 wt.% sulfur) is disseminated throughout the enclosing bioepigenetic limestone matrix with large, euhedral, canary yellow sulfur crystals (usually V2-to-2 in.) lining the large voids in the "vuggy" ore. Lesser amounts of calcite, barite and celestite accompany sulfur mineralization in the voids or vugs.

The "vuggy" ore also exhibits two episodes of mineralization. Sulfur is first deposited concurrently with the bioepigenetic limestone and is disseminated throughout the limestone matrix. Due to a reduction in rock volume from conversion of anhydrite to bioepigenetic limestone, large voids and vugs have formed. Later pulses of polysulfide-rich waters precipitated crystalline sulfur in the newly created voids. The great majority of sulfur mineralization at Pokorny occurs as "vuggy" ore and to a lesser extent, "banded" ore. "Massive," barite-rich ore accounts for only about 5% of the total sulfur in the deposit.

Three mineralized horizons, or zones (upper, middle and lower), are present at the Pokorny sulfur deposit. The upper zone is within the halite III dissolution horizon, the middle zone is within the halite I and II dissolution horizons and the lower zone occurs at or near the Castile Formation-Bell Canyon Formation contact (Fig. 1.22). Volumetrically, sulfur mineralization is concentrated in the middle and lower zones, with most mineralization in the middle zone. The upper zone, although rarely mineralized, locally contains significant concentrations of sulfur.

Continue east on FR-652. 0.2

52.1 Crossing lower Castile Draw; surface drainage is disrupted at "Sink Hole Flat" about 1.5 mi to the south. **0.2**

52.3 Castile Formation in roadcut. 1.7

54.0 To the north, the small Sunburst Field, produced from the Olds Sandstone, has cumulative production of 0.007 MMBO and 0.608 BCFG. To the south, the small Fuego Navidad Field with production from the Atoka has cumulative production of 0.00035 MBO and 601.6 MCFG. **0.9**

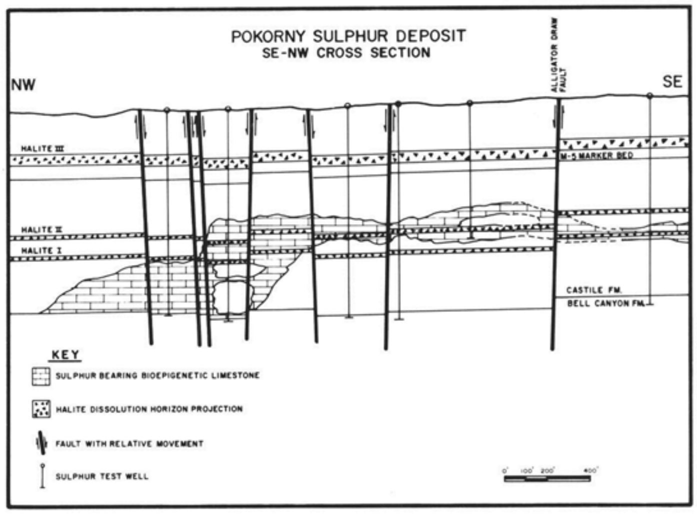

FIGURE 1.22. NW-SE orientated geologic cross section across the Pokorny sulfur deposit.

54.9 Rustler Formation outliers at 10:00 to 12:00 mark western edge of Rustler Hills cuesta (dipslope to east). "Castile Hill" is about 1 mi south of the highway at 3:00. 1.0

55.9 Change of slope and vegetation at the base of the hills to the left marks the Rustler-Salado contact. 0.7

56.6 Roadcut through the Salado Formation here overlain by the lower Rustler. The red gypsum locally indicates the Salado. 0.7

57.3 Bridge over Kimbell Draw. Gypsiferous Holocene valley fill exposed in arroyo walls. Route ahead mainly in upper Salado Formation, under thin alluvium-colluvium and just below the contact with the Rustler. **0.9**

58.2 Junction with FR-2185 and access to the Phillips Ranch sulfur deposit (Addwest Minerals) about 13 mi to the south (see minipapers by Davis and Guilinger). Continue on FR-652. **0.3**

58.5 Roadcut in Rustler collapse breccia that has subsided into the Salado Formation. **1.2**

59.7 Low-lying Screw Bean Hills, left and right ahead, are in the Rustler Formation that overlies the Salado Formation. The name is derived from tornillo mesquite (*Prosopis* sp.), whose beans are corkscrew in shape (Vines, 1960). **0.9**

60.8 The roadcut exposes southeast-dipping lower Rustler Formation. The west end of the roadcut exposes the contact between the Rustler and underlying gypsum of the Salado Formation. **0.2**

61.0 Red gypsum in the Salado Formation to left. **0.7**

61.7 Hills to left and right are eroded Rustler Formation. **1.2**

62.9 Contact of Rustler on Salado in cut to right. **0.2**

63.1 Cuts in collapse breccia to left. **0.2**

63.3 Red beds on both sides of the road for several miles are in the Salado Formation; local slumping of the Rustler is evident. **2.9**

66.2 Crossing broad erosional plain east of the Screw Bean Hills area of the Rustler Hills cuesta. The surface is cut primarily on the Rustler Formation and veneered with thin alluvium-colluvium. 1.0

67.2 Railroad tracks leading south to the Pennzoil's Culberson Sulfur mine. **Prepare for right turn. 0.3**

67.5 **Turn right (south)** on paved road toward the Culberson Sulfur mine, 11 mi ahead. **0.9**

68.4 View to the south over valley of Screw Bean Draw. Knobs of Rustler Hills cuesta are on the west side of the road. Small conical hills that dot the landscape are Rustler Formation dolomites. The railroad parallels the route on the west side toward the sulfur operation. **1.5**

69.9 Dip in road marks channel of Screw Bean Draw. View to left across valley floor shows soft, creamy thin-bedded, upper Quaternary sediments that are commonly impregnated with powdery gypsum. **2.5**

72.4 Crossing high-level geomorphic surface, early to middle Pleistocene(?), on the drainage divide between Screw Bean and Salt Draws. **0.2**

72.6 In railroad cut to the right, beyond the small radio tower, is an excellent exposure of high-level gravels composed of chert pebbles, fossiliferous carbonates and other clasts derived from the Delaware Mountain Group and the Cox, Rustler and Castile Formations. These deposits are capped with a stage IV pedogenic calcrete and overlie a broad, east-sloping erosion surface cut on the Rustler Formation. Fluvial cut-and-fill structures are locally exposed that project west to east across the railroad cut. The Castile Formation lies about 900 ft below the surface here. The Castile and Delaware Mountain Group are topographically and structurally much higher in the probable western source area and could provide a significant proportion of the clastic material observed in this exposure. **2.7**

75.3 Crossing upper valley of Salt Creek, with springs and marshes (cienega) both upstream and immediately downstream. **1.7**

77.0 Crossing Virginia Draw. Roadcut ahead in gypsiferous valley fill (late Quaternary). **1.6**

78.6 Road junction with FR-2119 on left. **Continue toward the mine on the right. 0.2**

78.8 Turn into Pennzoil office parking area at right.

STOP 4: Culberson sulfur mine. Joseph E. Crawford, resident geologist, will guide the tour through the facilities and the producing Frasch well field (Figs. 1.23, 1.24) of the Culberson mine. See Crawford and Wallace (this volume) for an extended discussion of this sulfur deposit.

The Culberson sulfur mine (Fig. 1.25) was discovered by Duval Corp., Pennzoil's former mining subsidiary, in 1967, although native sulfur was mined in the area more than 75 years ago (Fig. 1.26). The Culberson mine is in the Rustler Springs Sulfur District, which covers approximately 1200 mi2 in northeastern Culberson and northwestern Reeves Counties, Texas (Bishop and Dixon, 1968). At the mine, native sulfur is hosted in limestone breccias within the Upper Permian (Ochoan) Castile, Salado and Rustler Formations. Sulfur ore occurs in the Salado Formation at depths averaging 350 to 600 ft. Gangue materials include calcite with minor barite and celestite (Price et al., 1983). This stratabound deposit is bioepigenetic in origin (Davis and Kirkland, 1970, 1979; Ruckmick et al., 1979; Price et al., 1983). Reserves from this 1400—acre deposit are estimated to be 76 million long tons (10.

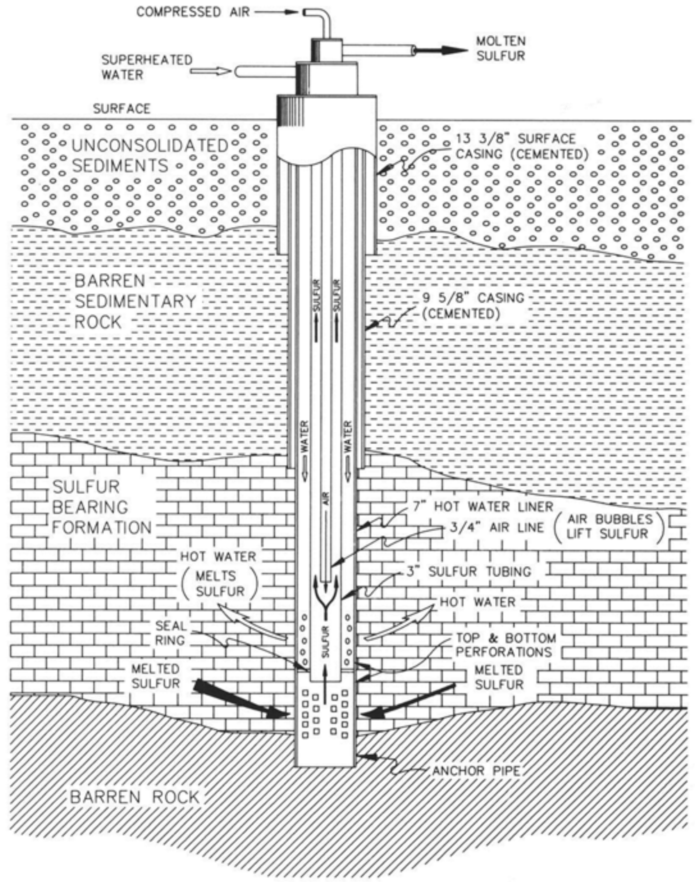

FIGURE 1.23. Diagrammatic cross section of a producing Frasch sulfur well.

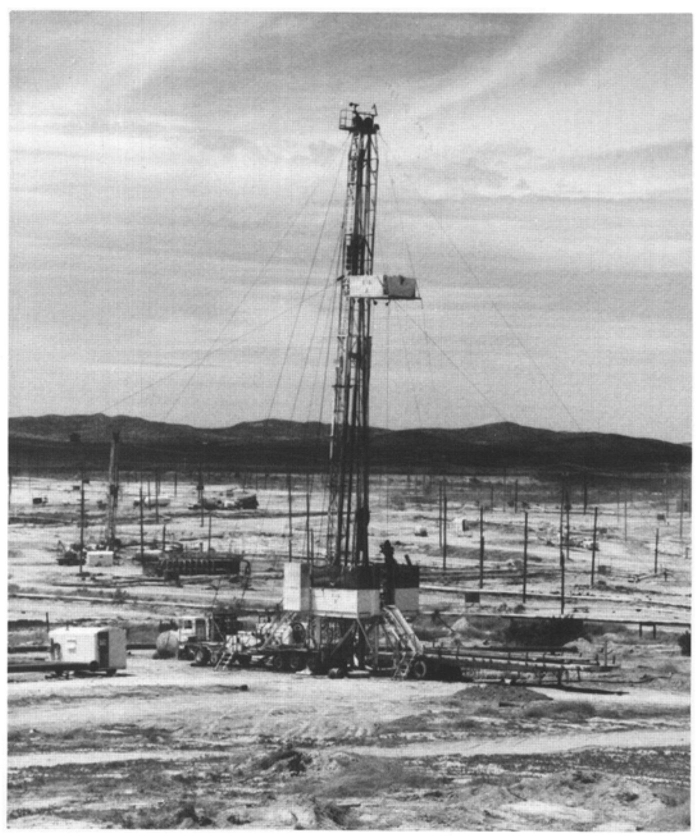

FIGURE 1.24. Production drilling rig in area of new mine development in the Culberson mine.

FIGURE 1.25. Aerial photograph of the Culberson mine facilities from the northeast. Sulfur deposit and well field in upper right.

On the west side of the mine area, a flood diversion canal (Fig. 1.27) was excavated through a hill composed of Rustler Formation and probably Salado Formation in which primary sulfate was altered to biogenic limestone (Fig. 1.28). Large native sulfur crystals locally occur within white acicular calcite and aragonite masses (Fig. 1.29). Primary depositional features are preserved in the biogenic limestone (Fig. 1.30). Immediately west, unaltered Salado is exposed in shallow excavations along the base of the Rustler Formation.

The structural position of the biogenic carbonate—Salado outcrop in relation to the main orebody to the east suggests that the orebody was displaced down to the east along a fault during or after alteration and mineralization and that this site is a small remnant of what was once a larger, more continuous body of alteration. An alternate interpretation is that the biogenic limestone exposed in the canal formed at a point structurally higher than the main orebody during mineralization and is along a preexisting fault that allowed reactants to contact pri-mary Salado sulfates.

THE GEOLOGY AND DEVELOPMENT OF THE PHILLIPS RANCH SULFUR DEPOSIT

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Addwest Minerals, Inc., 5460 Ward Road, Suite 370, Arvada, Colorado 80002

In April 1990, Addwest Minerals acquired the Phillips Ranch sulfur property. The deposit is hosted in the lower portion of the Permian

FIGURE 1.26. Panoramic view of the Michigan mine abandoned workings in the foreground and looking eastward. Native sulfur was excavated early in this century (ca. 1917) by hand methods and later by power shovels. Mining took place sporadically over a period of 50 years. Modern mine facilities are in distance.

FIGURE 1.27. View south through flood diversion canal west of Culberson operations. Breccias and biogenic limestone developed within the Salado Formation are exposed in the 50 ft. highwall.

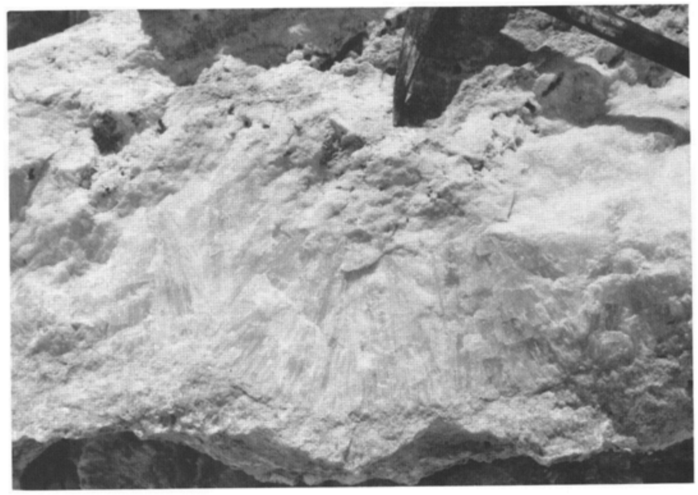

FIGURE 1.29. Radiating crystalline masses of aragonite in Salado Formation, east highwall of the canal cut, Culberson mine. Rock hammer at top of photograph for scale.

Castile anhydrite at a depth of 1400 to 1800 ft below the surface. In July 1990, Addwest successfully completed a drilling program designed to test the grade and continuity of previous favorable results that Tex-asgulf Inc. and Pennzoil Sulphur reported in their drilling programs.

The drilling of a regional gravity low by Texasgulf Inc. in the late 1960s resulted in the discovery of the Phillips Ranch sulfur deposit. Drilling by Texasgulf continued for several years until the sulfur market collapsed in the early 1970s. Texasgulf subsequently terminated their lease and activity at Phillips Ranch was nil until Pennzoil Sulphur Company acquired the property in early 1980. After extensive drilling, Pennzoil constructed a small Frasch plant on-site and began a limited pilot plant production operation that lasted from 1980 to 1982. A total of 85,267 lt of sulfur was produced before the project was shut in. Due to depressed sulfur markets, no additional work was done at Phillips Ranch and the mining lease was allowed to expire. For a second time, activity at Phillips Ranch was at a standstill until Addwest's acquisition and subsequent development that began in May 1990.

The basal clastic unit that immediately underlies the sulfur-bearing Ochoan Castile formation is the Lamar Limestone of the Guadalupian Delaware Mountain Group. The Lamar Limestone is silty to shaly, dark gray to black and locally very petroliferous. The Castile consists mainly of anhydrite with organic-rich calcite laminae. Halite beds within the Castile extended as far as Phillips Ranch but are now absent due to dissolution (Anderson et al., 1978). Locally in the Phillips Ranch area, the Castile is approximately 1300 ft thick and occurs only in the subsurface.

Sulfur-rich secondary limestone (biocalcite) occurs extensively at Phillips Ranch almost exclusively in the basal portion of the Castile. The secondary limestone is a biogenic alteration feature of the Castile and varies in thickness from 50 to 300 ft. Overlying the Castile is the Ochoan Salado Formation. The Salado is composed primarily of gypsum and massive anhydrite with minor clay and shale interbeds. Locally,

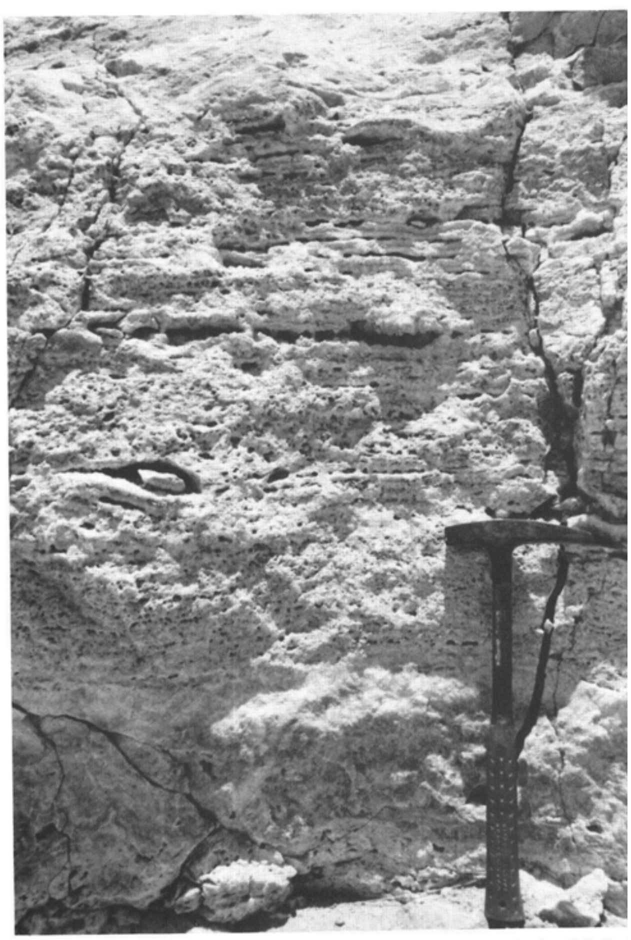

FIGURE 1.28. Fenestral porosity in the biogenic limestone in the Salado mation is exposed in the flood diversion canal cut, Culberson mine.

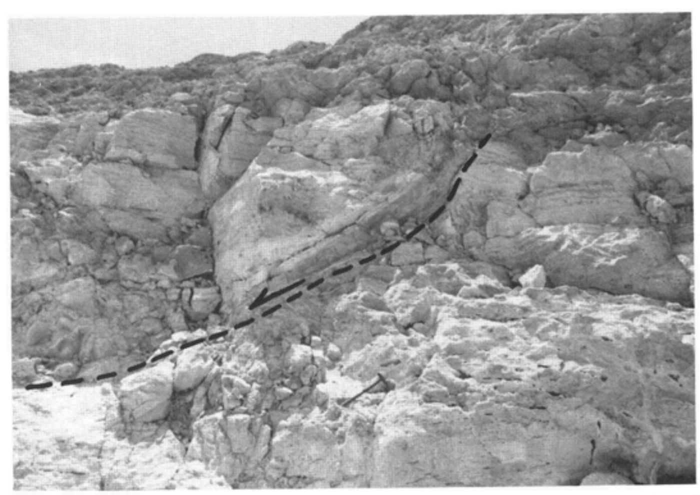

FIGURE 1.30. Soft-sediment slump feature preserved in biogenic limestone of Salado Formation; east highwall flood diversion canal, Culberson mine. Rock hammer for scale at bottom middle of photograph.

the gypsum and anhydrite are brecciated and contain solution channels and sinkholes. Due to solution collapse of halite beds plus extensive surface erosion during the Triassic-Jurassic hiatus, the Salado varies between 100 and 350 ft thick. Basal dolostone and siltstone units of the Ochoan Rustler Formation occur in scattered remnant outcrops overlying the Salado. These strata are heavily eroded and form small hills of variable relief.

Based upon drill hole data and surface mapping, the upper Ochoan Dewey Lake Formation does not appear to be preserved at Phillips Ranch. Extensive erosion during the Triassic-Jurassic hiatus might account for the absence of the Dewey Lake. Following this inferred erosion interval, the Upper Cretaceous (Comanchean) Cox Formation was deposited on the Salado and Rustler Formations, locally filling structure lows. The Cox is composed of chert-pebble conglomerates and calcareous sandstones. The Phillips Ranch deposit is located within the northeast-trending Virginia Draw graben. Based on cross section and structural interpretation, it appears that a zone of small northeast-trending grabens generally parallels the Virginia Draw graben (Figs. 1.31, 1.32). Near vertical cross-faults (Fig. 1.33) that cut the grabens are prevalent across the property. Evidence for their existence consists of (1) drill holes that intercept near vertical slickensided high angle fault surfaces in the Castile; (2) repeated sections of the Lamar and sulfur-rich secondary limestone in the ore zone; and (3) offsets of the Lamar from 30 to 90 ft as indicated from the drill data. Many of these cross faults are post-mineral. Both the graben bounding faults and the cross faults (pre- and postmineralization) are probably related to mid-Miocene Basin-and-Range extension (Hentz and Henry, 1989).

Sulfur mineralization at Phillips Ranch is in secondary limestone within the Castile Formation approximately 1400 to 1800 ft below the surface. The sulfur is bioepigenetic, having been formed by anaerobic bacterial reduction of gypsum or anhydrite and the oxidation of hydrocarbons (Ruckmick et al., 1979). Ground water, bacteria and hydrocarbons migrated from the underlying Bell Canyon aquifer along the graben faults and associated normal faults into the basal Castile. Concurrent with the water, bacteria and hydrocarbon movement, fault closure was by gypsum hydration and blockage of upward flow. Sulfur formation was initiated in the resulting trap.

The sulfur at Phillips Ranch is predominantly crystalline and occurs in a gray to brown, vuggy, brecciated, laminated to unlaminated secondary limestone. Locally, the sulfur-bearing limestone can be very oily and contain a large amount of hydrogen sulfide gas (H2S). Other minerals found in association with the sulfur deposit are barite, celestite and pyrite. The concentrations of these minerals are minor and they are only occasionally seen in drill cuttings.

Utilizing drill hole assay results from the Texasgulf, Pennzoil and Addwest drilling programs, an in-situ ore reserve estimate was compiled for Phillips Ranch by both James Askew and Associates (JAA) and Addwest personnel. The mining software package used for estimation of ore reserves was PC-MINE. Based on a statistical analysis of the drill data, a three-dimensional block model was generated that represents the sulfur deposit as a matrix of rectangular blocks. The block sizes are constant and measure 250 ft by 50 ft in plan view. Each block is 20 ft thick. The long axes of the blocks were aligned with the strike of the north and south deposits (N65°E).

JAA created a geological model of the deposit by initially plotting pierce point level plots. Using the three-dimensional geological block model and the coded secondary limestone values, a reserve model was compiled. Visual sulfur values (reported in percents—V%S) were estimated for every block previously coded as containing sulfur via the Inverse Distance Squared (IDS) method. Variograms calculated to define the spatial variability of the sulfur indicate that the grades can be estimated up to 550 ft along strike from the nearest drill hole. Vertically, the distance is restricted to 35 ft. Because of the variability between the horizontal and vertical dimensions, anisotropic weighting was talcen into consideration for calculation of reserves.

Ore reserves reported for the Phillips Ranch Deposit are classified as proven/probable and are correlated to the ranges of the variograms (550 ft). Ore host blocks not assigned a V%S value are considered to be a potential resource. Based on the developed reserve model, current drill hole data indicates that 2,613,000 It of sulfur is present within the north and south deposits. The tonnage was calculated from the average grade of 14.7 V%S over a total volume of 309,250,000 fe using a tonnage factor of 17.43 elt for solid sulfur and a mineralized total structure strike length of 14,200 ft. The tonnage quoted above includes a reduction in the reserve statement to account for the past production of 85,000 It.

The Phillips Ranch Frasch sulfur mine has the capacity to heat 4,000,000 gal of water and produce 800 It of sulfur per day. The productive ore horizon will be the basal portion of the Castile anhydrite. The Phillips Ranch mine is a fully permitted facility and once sulfur prices recover, the plant will be constructed and production will commence.

PROGRESS REPORT ON GROUND-WATER MOVEMENT WITHIN THE SULFUR-BEARING ZONES OF THE LOWER CASTILE FORMATION AT PHILLIPS RANCH DEPOSIT, CULBERSON COUNTY, TEXAS

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The purpose of this report is to discuss the nature of aquifers and ground water movement within the lower Castile Formation near the western edge of the Delaware Basin at Addwest Minerals' Phillips Ranch sulfur mine in Culberson County, Texas. Numerous generalized investigations of the artesian meteoric waters of the lower Castile have been done (Webemick, 1952; Olive, 1957; McNeal, 1965; Davis and Kirkland, 1970; Hiss, 1975; Ruckmick et al., 1979; Hill, 1990). However, studies focusing on specific aquifer characteristics are absent in the literature.

The stratigraphic section at Phillips Ranch consists of remnant outcrops of clastic-carbonate rocks of the Ochoan Rustler Formation underlain by 100 to 350 ft of gypsum and massive anhydrite of the Salado Formation. The Salado is underlain by approximately 1000 ft of banded and massive anhydrite of the Castile Formation. The lower Castile is characterized by biogenic alteration of banded anhydrite/carbonate evaporite and hydrocarbons to secondary limestone and subsequent sulfur deposition (Davis and Kirkland, 1970, 1979; Davis et al., 1970; Kirkland and Evans, 1976; Anderson et al., 1978; Smith, 1978; Ruckmick et al., 1979; Hentz and Henry, 1989; Hill, 1990; Crawford, 1990, this volume). The Castile is underlain by the black-gray silty limestones of the Lamar Member of the Guadalupian Bell Canyon Formation (Guilinger and Nestlerode, 1990; Guilinger, this volume).

The geometry of the lower Castile aquifer is controlled by the occurrence of secondary biogenic limestone. The nearly impervious anhydrite constrains the waters of the lower Castile to the configuration of the secondary limestone. The sulfur-bearing limestone masses are conical in shape and occur at the base of the Castile Formation. This zone of biogenic alteration varies in thickness from 0 to 300 ft. Absence of biogenic alteration within the basal Castile at Phillips Ranch coincides with the absence of faulting.

The horizontal extent of the lower Castile aquifer is undetermined. The outline of the aquifer is delineated within the study area by data from exploration-production well logs (Fig. 1.34). Cross sections show that two parallel, subsurface dissolution-replacement channels occur within a northeast-trending graben paralleling the Virginia Draw Graben (Fig. 1.34). These structures coincide with the occurrence of secondary limestone and hence, delineate the aquifer boundaries. These channels average approximately 300 ft in width and greater than 9850 ft in length. The area of the two structures is about 0.42 mi2 at a minimum. The shape of the aquifer resembles two concave-downward parallel troughs. Cores from the lower Castile exhibit dual-porosity; matrix porosity averages 25% and cavernous porosity is observed occasionally.

Ground-water movement within the lower Castile aquifer was investigated by slug-test analysis and static water-level measurements within abandoned sulfur and water production (bleed) wells. Data from

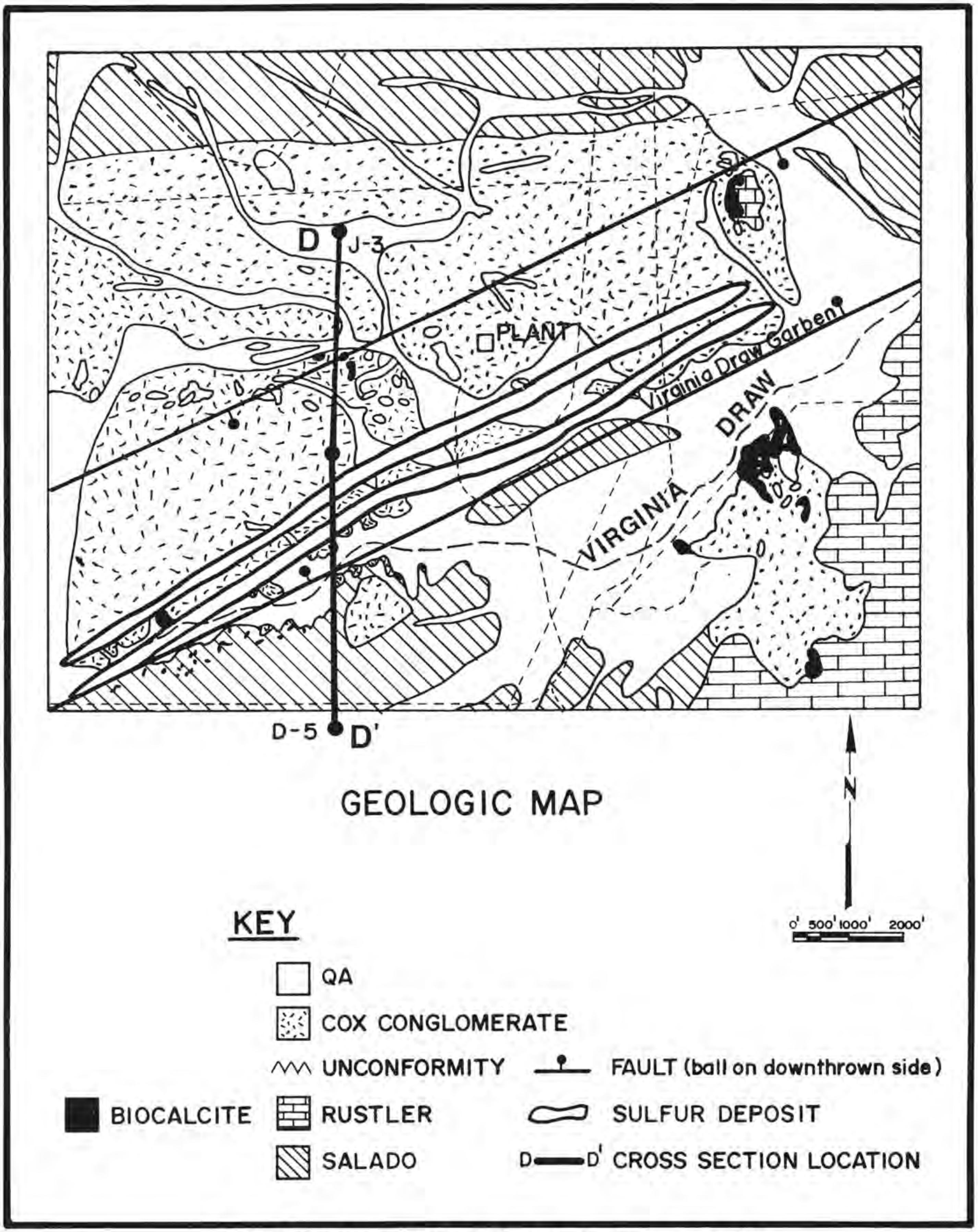

FIGURE 1.31. Geologic map of the Phillips Ranch sulfur deposit with cross section D-D.

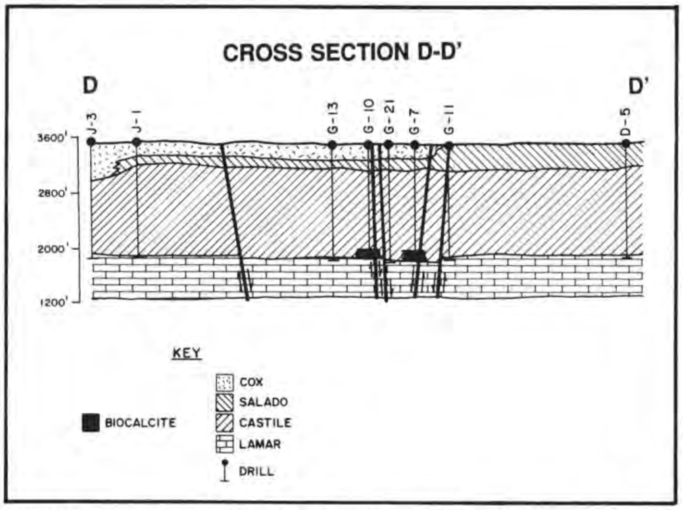

FIGURE 1.32. Cross section D-D through the Phillips Ranch sulfur deposit.

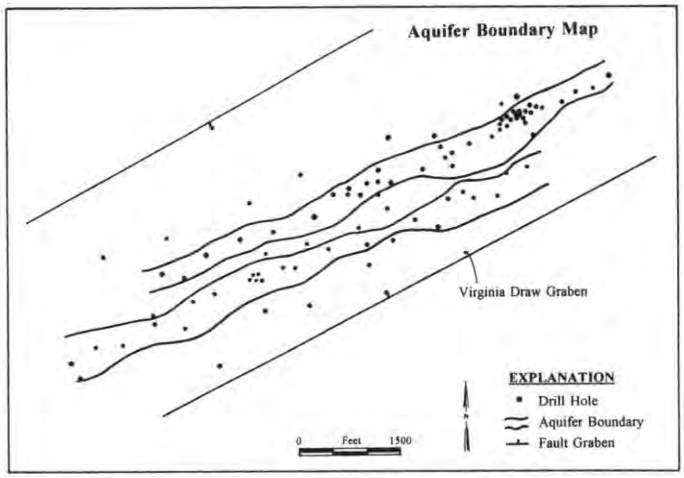

FIGURE 1.34. Castile aquifer boundary at Phillips Ranch Area.

four open-hole-completed and fully penetrating water-production wells were used for interpretation. The water-production wells most closely represent unmined, undisturbed aquifer conditions. Two water-production wells are located within each of the two dissolution-replacement structures. If we assume that the two structures are hydraulically connected, the direction of ground-water flow is toward the northeast, parallel to the structural trend of the graben and roughly down regional dip of the underlying Lamar Limestone. The potentiometric surface of the lower Castile aquifer ranges in elevation from 3353 to 3362 ft. The elevation of the top of the saturated zone within the lower Castile ranges from 1791 to 1875 ft. Pressure potentials range from 1478 to 1571 ft, indicating confined aquifer conditions. The hydraulic gradient within the northern structure between the two water-production wells is 0.004, or 1.11 head difference over 300 ft. The southern structure exhibits a hydraulic gradient of 0.001, or 0.49 head difference over 425 ft.

The discharge area(s) for the lower Castile aquifer in the vicinity of Phillips Ranch is yet to be identified. The only surface elevation that approaches the potentiometric surface near Phillips Ranch is near the confluence of Virginia Draw and Cedar Pasture Draw. I hypothesize that some component of discharge for the lower Castile aquifer at Phillips Ranch is located in a marshy area of Virginia Draw, down canyon of this confluence.

Recharge for the lower Castile aquifer may be from the western part of the Delaware Basin where the Upper Bell Canyon Formation and the basal Castile Formation crop out (Olive, 1957). Olive (1957) noted that recharge water entering at the Castile—Bell Canyon contact from

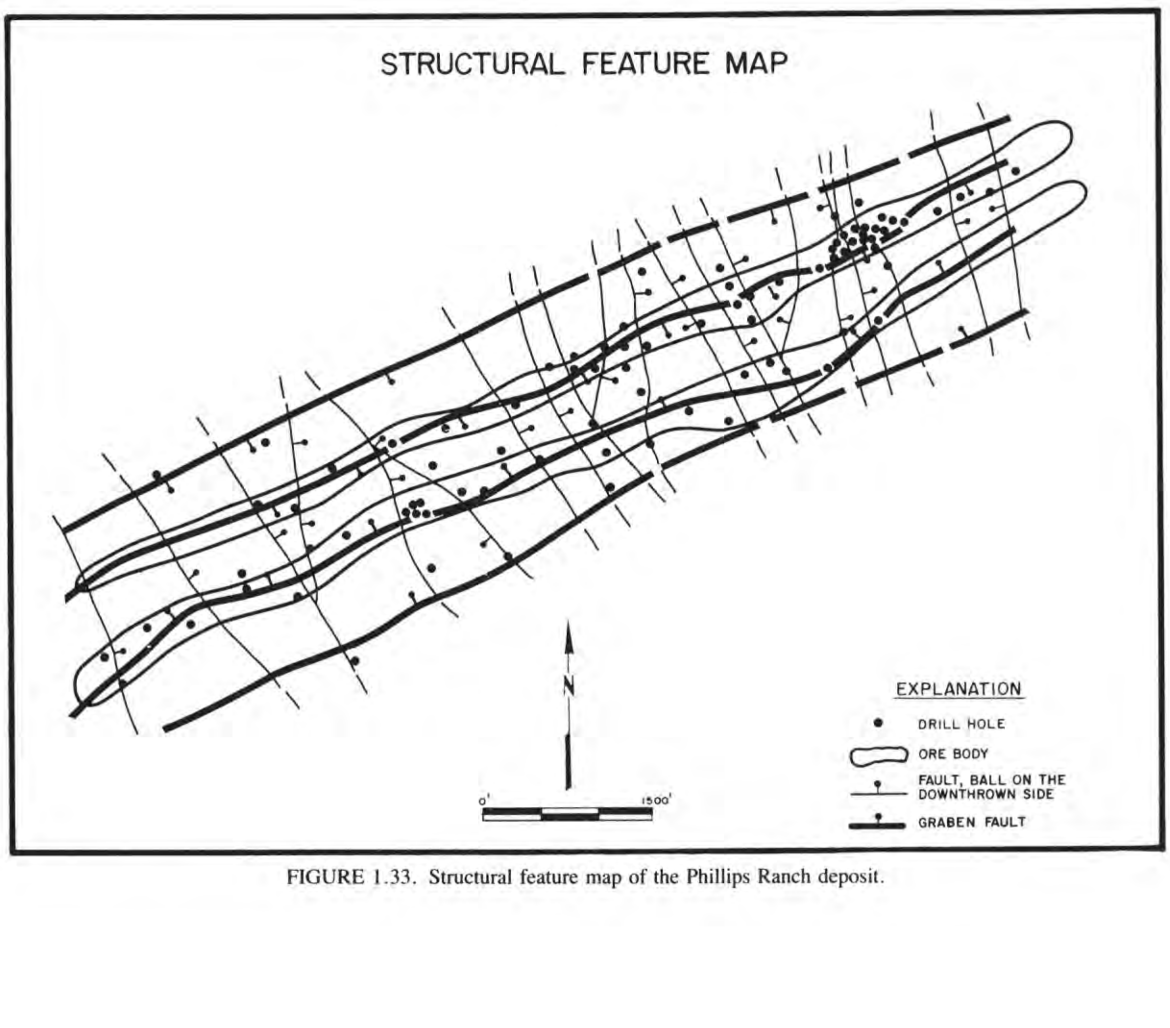

FIGURE 1.33. Structural feature map of the Phillips Ranch deposit.

the outcrop area in the reef escarpment and northern Delaware Mountains were the water flows parallel to dip and which rise along fractures or faults into the Castile Formation.

Three types of slug test responses were observed at Phillips Ranch (Fig. 1.35): (1) underdamped (oscillatory about the equilibrium position with the amplitude lessening, or damping, for successive periods); (2) overdamped (a slow return back to the equilibrium position, approximately exponential and with no oscillations); and (3) critically damped (returns to equilibrium in a short amount of time and a condition between overdamped and underdamped where the damping coefficient is considered to equal one) (Bredehoeft et al., 1966). The underdamped case was observed in all four of the water-production wells. All three types of slug test responses were observed in the sulfur-production wells.

The slug test responses observed at Phillips Ranch appear to be affected by inertia in the aquifer-well system. The effects of well inertia upon slug test responses have been studied by numerous investigators (Bredehoeft et al., 1966; van der Kamp, 1976; Kabala, 1985; Kipp, 1985), whereby the aquifer-well system is analogous to a mass-spring. The mass is equivalent to the length of the water column in the well and the spring to the aquifer compressibility. Aquifer-well conditions under which oscillations can be expected from slug test responses tend to be associated with high transmissivities and long water column lengths (Bredehoeft et al., 1966; Kipp, 1985; Kabala, 1986). Multiple sets of oscillations with distinctly different angular frequencies are observed within a single slug test at Phillips Ranch. Several slug tests were conducted in each well and measured damping constants and angular frequencies were reproducible between tests. Contour data, cross section analysis, static water-level measurements and slug test responses suggest that a hydrologic connection between the two subsurface dissolution-replacement channels exists. Preliminary results suggest high transmissivities within the lower Castile aquifer.

Gratitude is expressed to Charlie Williams, Executive Vice President of Addwest Minerals, for granting permission to publish this report and for providing support for this project. I thank James R. Guilinger of Addwest Minerals for supporting this project. Review of this report and helpful comments by Jane Cramer and Danny Katzman are greatly appreciated. A special thanks is expressed to Danny Katzman for drafting the figures.

Turn left at junction with FR-2119 at Pennzoil property entrance and retrace route on company road to FR-652. **11.2**

90.0 Junction of company road and FR-652. **Turn right (east)** toward Orla. To the north are the large Geraldine and West Geraldine oil fields; to the northeast are the Ford and West Ford Fields. All are Delaware sandstone oil fields found by Midland independent geologist Ford Chapman. Geraldine was his wife. The Geraldine field, with production from the Delaware at 3400 ft and 4000 ft and from the Ford zone, has cumulative production of 1824 MMBO and 5295 BCFG; 0.18 MMBO and 233.7 BCFG; and 27.7 MMBO and 48,303 BCFG, respectively. The West Geraldine, with production from the Delaware at 2435 ft, has cumulative production of 0.36 MMBO and 276.8 BCFG. The Ford field, with Delaware production from a higher elevation and also from 4000 ft, has a cumulative production of 0.026 MMBO and 5.8 BCFG and 3.23 MMBO and 6684 BCFG, respectively. The West Ford field, with Delaware production from 2500 ft and 4100 ft, has cumulative production of 0.03 MMBO and 5.49 BCFG, and 2.871 MMBO and 7034 BCFG, respectively. **1.5**

91.5 Oilwell pad to left on Rustler Formation. This is the Screw Bean oil field that has produced small amounts of oil from both the Bell Canyon and Castile Formations at depths of 984 to 2400 ft. The Delaware production

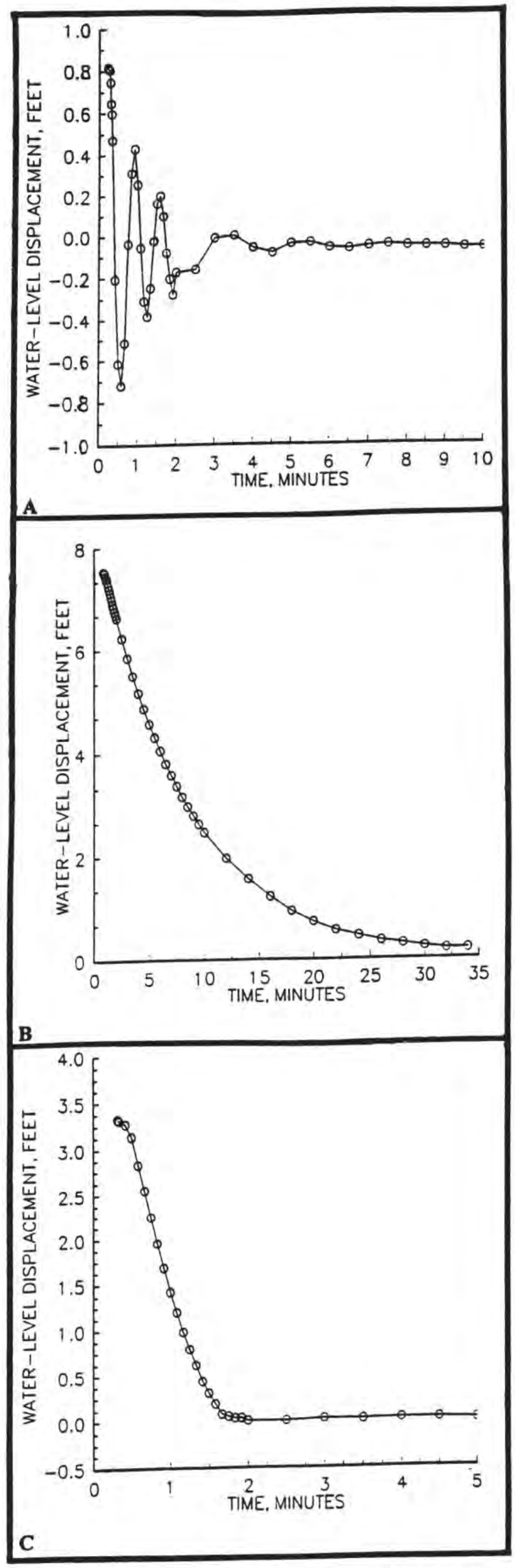

FIGURE 1.35. Slug test responses: (A) underdamped case, (B) overdamped and (C) critically damped.

of the Screw Bean have been a cumulative 0.87 MMBO and 890.3 BCFG. Cumulative production from the 1000 Sandstone is 0.125 MMBO and 5.9 BCFG. The Northeast Screw Bean field, with Delaware Production, has cumulative production of 1.2 MMBO and 2075.7 BCFG. 1.1

92.6 Valley of Salt Creek, a perennial tributary of the Pecos River, ahead. 1.0

93.6 Bridge over Salt Creek, with Rustler dolomite exposed in west abutment. About 30 ft of upper Pleistocene valley fill is exposed in channel walls. This sandy alluvium, with lenses of pebbles and small cobbles, is capped with a well-developed gypsic soil horizon including discon-tinuous gyperete zones. 1.0

94.6 Entering area covered by the Pecos Sheet of the Geologic Atlas of Texas (Bureau of Economic Geology, 1976b). High-level gravels mapped between here and mile 98.3 as unit "Qoa" are remnants of ancestral Pecos River deposits that may be late Tertiary to early Pleistocene in age. They fill broad channels cut in the Rustler Formation and locally form the upper part of thick, deformed fills of large solution-subsidence depression. Highest-level remnants are about 300 ft above the Pecos River in the Orla area. **0.9**

95.5 Twin windmills on the left at 9:00. **1.6**

97.1 **OPTIONAL STOP.** Park at microwave transmission tower on the left. This is part of the Chapman Field, named after Midland oilman Ford Chapman, who pioneered development of many Delaware Sandstone fields. Oil and gas production from the Bell Canyon and Cherry Canyon reservoirs is 1.65 MMBO and 302.9 BCFG and 0.05 MMBO and 342.6 BCFG, respectively.

UPPER NEOGENE VALLEY AND DEPRESSION FILLS OF THE ORLA, TEXAS AREA

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The roadcut to the right exposes beds at the northern edge of the largest remnant of high-level gravels in the Orla area (3030 ft elevation; here about 300 ft above Pecos Valley floor). Rounded pebbles are mostly carbonates with some cobbles (up to 8 in.) also present. Subordinate clast lithologies include "Cox" sandstone, chert, quartzite, quartz, granite, gneiss and intermediate volcanics. These high-level deposits are here correlated with upper Miocene and Pliocene fluvial sediments of the ancestral Pecos system (Hawley, this volume). Thick older fills of solution-subsidence depressions are also exposed in nearby areas and include readily accessible outcrops along the tour route at mile 103.8, mile 128.1 and Stop 6. Powers and Holt's paper (this volume) on the Gatufia Formation describes these deposits in more detail.

One of the best exposures of subsidence-depression fill is adjacent to the valley of Fourmile Draw, 9.5 mi southeast of this stop. The Fourmile Draw section, which crops out in roadcuts along US-285 8.2 mi southeast of Orla, is mapped as Gatufia Formation (Pleistocene) by the Texas Bureau of Economic Geology (1976b). It is at least 400 ft thick and significantly deformed, with maximum dips of 30 to 45° in beds that slope toward the valley axis. Fluvial channel sandstones and siliceous-pebble conglomerate layers are interbedded with mudstones and finer sandstones deposited in a variety of environments, including fluvial, ponded and eolian. Gypsum and selenite zones are also present.

The lithologic character of these partly indurated rocks compares most closely with members of the Ogallala Formation, whose nearest mapped exposures are on High Plains remnants (elev. 3300 ft; Bureau of Economic Geology, 1976a) about 25 mi northeast of and 500 ft above the Fourmile Draw locality. Preliminary radiometric dating of volcanic ash in a core sample collected during recent drilling of another depression fill in the Orla area indicates that older parts of these deposits may date from the early part of the late Miocene (Powers and Holt, this volume). Sediments of this age are slightly older than the oldest known Ogallala beds in the region (about 12 Ma; Gustayson, 1990).

Maximum thickness of Neogene subsidence-depression fill in the Toyah basin between here and Pecos, Texas, is about 1900 ft (Maley and Huffington, 1953). Bachman (1984, fig. 13) described as much as 1000 ft of "Gatufia" in a large depression that straddles the state line to the north (east of Stop 5). Basal parts of such deposits could be at least as old as late Miocene (5-12 Ma), because fills of comparable thickness in actively subsiding structural basins of the southern Rio Grande rift invariably range that far back in age (Seager et al., 1987; Hawley and Lozinsky, 1992). Previous work by Leonard and Frye (1962), Reeves (1972) and Kelley (1980) in the lower Pecos Valley area supports this age interpretation (Hawley, this volume). **1.2**

98.3 Gravel-capped hills to left. **0.9**

99.2 Entering Orla, Texas. Orla is significant in Texas' history, particularly during the Westward Movement. Sign at the intersection: "Gateway to Red Bluff Lake, Guadalupe Mountains, Carlsbad Caverns recreation areas. Established 1890 on Pecos Valley Railroad. Developed during land promotions. Had school, general stores, hotel, livery stable. In 1931, remaining merchant and Postmaster Hal Olds moved V4 mile west to new highway." In a report on the geology of the Fort Stockton quadrangle, Adkins (1927) mentioned records noting elephant tusks of probable Pleistocene age found along the railroad bed 2 mi northwest of Orla and 12 mi west of Orla (Salt Creek Valley?) near the Culberson County line. The Sabre Delaware Sand Field discovered in 1958 is west of Orla. Production is from the Delaware and Cherry Canyon zones. Cumulative production is 5.541 MMBO and 5302.9 BCFG and 0.066 **MMBO** and 412.2 BCFG, respectively. **0.3**

99.5 Junction with US-285. Turn left (northwest) onto US-285. Production east of US-285 is in the Olds Field from the Delaware. Cumulative production is 1.267 MMBO and 1786.6 BCFG. **1.7**

101.2 Oil field pumpjacks in the Chapman Field on left and right. 1.0

102.2 Road on right to Red Bluff (3 mi northeast). **Red Bluff Dam** (Historic Marker) reads: Constructed for irrigation and electrical power purposes during 1934-36, dam is located on Pecos River 8 miles south of Texas-New Mexico stateline. It impounds an 11,700-acre lake occupying parts of Reeves and Loving Counties, Texas and Eddy County, New Mexico. Floods first filled the reservoir in June 1937. Capacity is 310,000 acre-feet of water. Main embankment-9230 feet long-rises 105 feet above stream bed at highest point. Dam has top width of 25 feet. These waters irrigate about 140,000 acres, which extend for 100 miles along the Pecos River (1972).

Small caves in the Rustler Formation exposed along the eastern shoreline contain beautiful alabaster gypsum. **1.6**

103.8 Bridge over Salt Creek. Subsidence-depression fill mapped as "Gatuiia Formation" (Texas Bureau of Economic Geology, 1976b) includes two distinct units that are well exposed along the stream channel upstream from the abandoned railroad bridge to the east of the highway. The lower unit is a tilted sand and clay sequence with thin, sparsely pebbly sandstone beds at least 200 ft thick in an upstream-dipping section west of the highway. The upper unit, 20-30 ft of coarse conglomerate with sandstone interbeds, crops out in the south bank between the bridges. Upper Pleistocene valley fill, exposed to the west in the 30-ft-thick terrace north of the creek, is unconformable on the tilted "Gatuna" section. Terrace deposits include sand and gravel that grade upward into a strong gypsic soil profile similar to the one noted in the upper Salt Creek section at mile 93.6. A still lower (about 10 ft) Holocene terrace is composed of loamy to sandy material with a dark, organic surface soil. **1.2**

105.0 The Sullivan and Kennedy-Faulkner fields are west of the highway. Cumulative production (Delaware) of the Sullivan is 1.76 MMBO and 2951.9 BCFG. Cumulative production (Delaware) of the Kennedy-Faulkner is 0.040 MMBO and 89.2 BCFG. The South Kennedy-Faulkner has cumulative Delaware production of 0.02 MMBO and 48.5 BCFG. **1.9**

106.9 Oil wells of the Orla field are on both sides of the highway. Production is from the Bell Canyon at 3410 ft. Rustler Formation is exposed in low hills to left. **0.9**

107.8 Microwave towers on west side of the road. **1.3**

109.1 Road on right leads to Red Bluff Lake at Robinson Arms Landing, 3 mi distant. **Red Bluff Lake Recre,ation Area** (Historic Marker) reads: Pope's Crossing, used by immigrants and the southern (Butterfield) overland mail which linked St. Louis and San Francisco with a semi-weekly mail 1858-1861. Headquarters in 1855 of Capt. John Pope, supervisor of the drilling of the first well west of the 981/2 meridian. They struck water at 244 feet but sank to 1140 feet hoping to strike artesian flow. The well caved before its value could be determined. This $100,000 experiment paved the way to deep well drilling in the Great Plains.

This project was called "Pope's Folly" and "a plundering of the Treasury by Army officers" in the U.S. Congress. Pope's crossing now lies at the bottom of Red Bluff Reservoir. A synopsis of Pope's three waste wells is given in "Historic Guadalupe Pass" (J. W. Adams, 1988). The following quotes are from A. B. Gray's report on a "survey of a route on the 32nd Parallel for the Texas Western Railroad, 1854" as edited by L. R. Bailey (1963, p. 23):

"From the Pecos river to El Paso, on the Rio Grande-161 miles [February 1854]

The latitude of the proposed crossing of the Pecos is 31 deg. 45 min. This river though tortuous in places, may possibly be made a channel to convey rafts of timber for railroad purposes, if needed. It heads far north, in the neighborhood of Santa Fe, New Mexico and where the parallel of 31 deg. 45 min. intersects it, is a bold, running stream, sixty-five feet wide, pursuing a S.E. course until it joins the Rio Grande, 400 miles below El Paso. Its valley is from one to three miles in width and might be made highly productive, having a rich and fertile soil. There is no timber about it near the line of the proposed route, except for firewood. Above the 32d parallel, there are numerous rapids over a rocky bottom. It has firm banks and can be easily bridged. We forded it with *cargas* on the mules, without difficulty." **2.7**

111.8 Oil wells on both sides of the road are on the north end of the Geraldine field. **1.8**

113.6 Leave Texas, enter New Mexico (Milepost 0). State Line services on the right. Local time is now Mountain Standard time. Road crosses alluvium that overlies the Rustler Formation. We just nicked the northeast corner of Culberson County. 0.1

113.7 Culebra Dolomite (lower Rustler) on right. **0.2**

113.9 Railroad crossing (Culberson Mine spur). More Culebra exposed ahead on the left. **0.3**

114.2 Older gravel unit caps reddish brown silty sand in cut to right; crossing domal karst plain on Rustler-Salado section. **0.6**

114.8 Domal karst structure is in roadcut to right; note reddish Salado-basal Rustler residual material below Culebra Dolomite. Bachman (1980) described the karst domes between here and Malaga (including Stops 5 and 6). Differential solution of evaporites in karst domes in the upper Salado-basal Rustler zone has left nearly intact bodies of Culebra Dolomite as cores of mounds and ridges in this part of the lower Pecos, Delaware and Black River valley systems. **0.8**

115.6 Milepost 2. Approaching bridge over Delaware River. Younger (Holocene) terrace fill of gypsiferous sand and gravel rests on poorly exposed older alluvium that includes sand with a few, fine-pebbly zones and gypsite layers near stream level. **0.2**

115.8 Road ahead crosses a stepped sequence of middle Pleistocene terraces of the Delaware River. Gravelly terrace fills are locally capped with well-developed calcisols but not by well-developed calcretes. **1.3**

117.1 Crossing high-level surface on divide between the lower Delaware River and Red Bluff Draw drainage basins, graded to an ancestral Pecos base level about 90 ft above the present valley floor. **0.2**

117.3 **Turn right (east) onto Whitehorse Road** (Eddy County 725). Route descends to inner Pecos Valley through Rustler-Salado domal karst area, with local remnants of higher fluvial-terrace deposits. 1.0

118.3 Gas well to left. **1.2**

119.5 Highest river terrace remnants in this area are about 90 ft above the Pecos channel (2835-2840 ft). **0.3**

119.8 Railroad crossing. Road drops to lower terrace surface. **0.3**

120.1 Cattle guard. Pump station on left. **0.3**

120.4 Cattle guard. Continue east on unpaved Eddy County 725; roadcuts ahead in Pleistocene terrace deposits about 60 ft above the river. **0.4**

120.8 Road forks. Continue straight ahead on truck route. An alternate "car" route turns right. It allows access to the east side of the Pecos via the pipeline bridge when the river is at flood stage. **0.3**

121.1 Crossing Pecos River over low-flow culvert or high-flow concrete apron.Cars **should use alternate route during high water. 0.1**

121.2 Stop 5B site at cut in Culebra Dolomite to left; continue east through lower Rustler Breaks (or Bluffs). **0.2**

121.4 Cattle guard at junction with alternate "car" route. **Turn around** and park along road.

STOP 5: Rustler Breaks east of Pecos River. This stop provides an overview of the Rustler Breaks (or Bluffs) area of the Pecos Valley about 2 mi upstream from the head of Red Bluff Reservoir. The bluff line on the eastern horizon is formed by conglomerates and sandstones of the Gatufia Formation with locally well-developed calcrete caprock zones. The pipeline road (Eddy County-725) provides the only easy access to the southern Mescalero plains, beyond the Breaks, where the Gatufia as defined by Bachman (1984) attains a maximum thicicness of 1000 to 1100 ft in a solution-subsidence depression aligned along the course of the ancestral (late Tertiary) Pecos River. This stop is also at the site of "Rock House" (Malaga 15—minute topographic map) designated by Bretz and Horberg (1949b, pl. 1) as a "type area" for a brecciated, dense (pisolitic) "caprock" caliche fabric that is characteristic of Stage VI pedogenic calcretes (Hawley minipaper). The exact Bretz and Horberg sample site has never been relocated; but calcretes exhibiting "rock-house structure" are locally preserved on surfaces capping remnants of the Gatufia Formation mapped by Kelley (1971), Reeves (in Bureau of Economic Geology, 1976a) and Baclunan (1976, 1980, 1984) between this stop and Pierce Canyon (Stop 6).

Geologic mapping to date has been at small scale and at reconnaissance level of detail, so stratigraphic and geomorphic problems still need to be resolved. Articles by Hawley and by Powers and Holt on the Gatufia and Ogallala Formations (this volume), the following note (Stop 5A) and additional comments at Stops 6 and 7 make this point very clear. After Stop 5A retrace route to the base of the Rustler Breaks (Stop 5B) to examine exposures of the Culebra Dolomite and solution-subsidence features that involve at least the upper Salado—lower Rustler sequence. 0.2

STOP 5A. Docluun versus Gatutia east of Red Bluff Reservoir, Eddy County, New Mexico. The Hobbs Sheet of the Geologic Atlas of Texas (Bureau of Economic Geology, 1976a) shows significant outcrops of the Upper Triassic Dockum Formation east of Red Bluff Reservoir in Brushy Draw and along the eastern side of the Pecos River in southeastern Eddy County, New Mexico (SE'/4 sec. 12, T26S, R29E). However, recent examination reveals all these outcrops to be conglomerates, sedimentary breccias and calcretes of the upper Cenozoic Gatufia Formation that, as mapped by Bachman (1984, figs. 12 and 13), can be as thick as 1000 ft. A good example is provided by the bluff in the N1/2 secs. 34 and 35, T26S, R29E (about 4.5 mi southeast of this stop), where coarse, clast-supported gravels and sandstones of the Gatufia (not Dockum) Formation are unconformable on Upper Permian red beds. The fact that the light-colored beds are erosion resistant and overlie the red beds produced the mapping error, because from a distance basal Upper Triassic strata (Santa Rosa For-mation) have the same stratigraphic position and topo-graphic expression. But, on close examination, the micaceous, well-indurated litharenites and pebble con-glomerates of the Triassic strata are readily distinguished from the less-well consolidated sediments and calcretes of the upper Cenozoic strata. The Permian red beds are here referred to as the Quartermaster Formation (Gould, 1902; Lucas and Anderson, this volume) rather than being designated the Dewey Lake Formation or "Red Beds" (Page and Adams, 1940; Bureau of Economic Geology, 1976a). Quartermaster—Dewey Lake, Dockum—Santa Rosa and Gatufia-Ogallala discussions continue at Stops 6 and 7.

STOP 5B: **Domal karst features in the lower Rustler Breaks.** The Culebra Dolomite Member of the Rustler Formation is well exposed between this point and the pipeline bridges about 300 yds downstream. It is incorrectly shown as upper Rustler (Magenta?) by Kelley (1971, pl. 4). This well-bedded, vuggy dolomicrite is here preserved as small domal bodies flanked by masses of disturbed overlying red beds with large "floating" blocks of gypsum. Upper Rustler members, -including the Tamarisk (gypsum after anhydrite) unit and possibly older valley fill (here mapped as Gatufia by Kelley, 1971) are involved in these subsidence structures that flank domal cores of Culebra.

POST-TECTONIC REHEATING OF PORTIONS OF THE PERMIAN BASIN AS EXPRESSED BY ISO-REFLECTANCE LINES ON REGIONAL STRUCTURAL SECTIONS

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The Delaware Basin is separated from the Midland Basin to the east by the Central Basin Platform and the three together constitute the Permian Basin (Fig. 1.36). The Central Basin Platform is an uplift delineated by north-trending normal faults. In the Mississippian, these faults disrupted the precursor Tobosa basin and culminated in the separation of distinct depocenters (Fig. 1.37) in the Delaware and Midland Basins (Adams, 1965; Hills, 1984). We measured vitrinite reflectance on sedimentary organic matter concentrated from drill cuttings from over 40 wells in the Permian Basin and compiled similar data from another 10 wells from the literature and unpublished sources. The mean

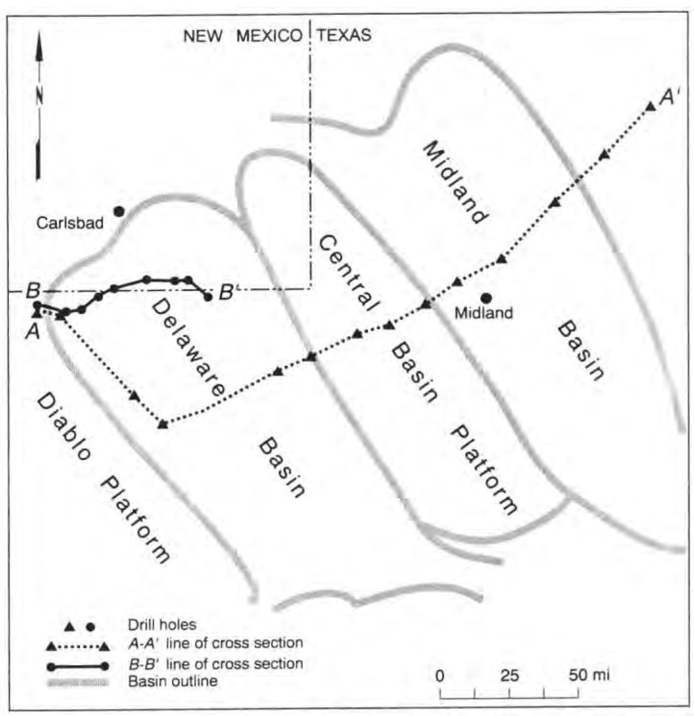

FIGURE 1.36. Map of the Permian Basin showing structural provinces and lines of structural sections A-A' and B-B'. Modified from Hills (1984) and the Texas Water Development Board (1972).

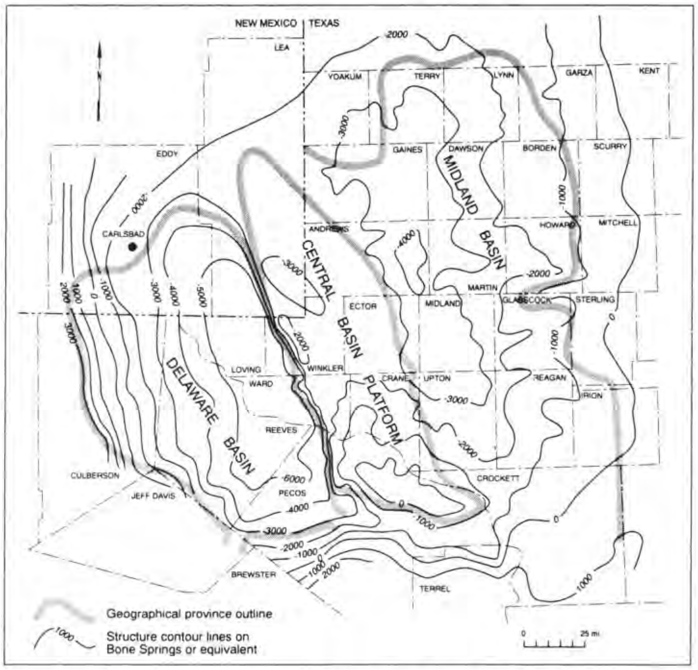

FIGURE 1.37. Structure contour at the top of the Bone Spring Limestone or its equivalents. Datum is mean sea level and the contour values are in feet. Elevation of Bone Spring Limestone top from Texas Water Development Board (1972), Brooks (1964) and Vertrees (1963). Contours based in part on Texas Water Development Board (1972, map fig. 51). Note that the Delaware Basin boundary with the Central Basin Platform is complexly block faulted and is not exactly depicted at this borehold spacing.

random vitrinite reflectance measurements (Rm) were made by the methods used in Barker and Pawlewicz (1987). The timing of petroleum generation is inferred from the iso-Rm lines at 0.6%, 0.9%, 1.2-1.3% and 2.0% Rm which generally correspond to the onset of oil, peak oil, end of oil generation and onset of dry gas generation, respectively (Tissot and Welte, 1984).

Post-Mississippian tilting produced greater subsidence and a thicker, mostly uneroded, sedimentary section in the eastern portion of the Delaware Basin (Fig. 1.38). Continued tilting prior to Cretaceous time caused uplift and erosion that exposed the Upper Permian section and decreased temperatures in the western part of the basin. Later, above-average basinal paleogeothermal gradients in the western Delaware Basin, associated with numerous igneous intrusions (Stipp, 1960; Calzia and Hiss, 1978) and increased heat-flow related to the development of the Basin and Range Province (Barker and Pawlewicz, 1987), have caused local heating and thermally matured rocks as young as Late Permian. Dating of igneous intrusions in the western half of the Delaware Basin suggest they were emplaced 40 to 30 Ma (Henry and Price, 1985) and were followed by Miocene to Holocene (23 to 0 Ma) Basin-and-Range-type block faulting and associated high heat flow (Horak, 1975; Henry, 1979). 1so-Rm lines that sharply cut across formation contacts in the westem Delaware Basin rather than roughly subparallel them like those observed in the eastern Delaware Basin (Fig. 1.39), confirm that this local reheating is post-tectonic (Stach et al., 1982). The post-tectonic heating occurred after eastward tilting and erosion had reduced burial depth in the western Delaware Basin. In an extreme case directly related to an igneous intrusion, renewed heating at the Magnolia Cowden 1 borehole caused Rm to vary from 0.6% at 60 m near the top of the Guadalupian (Late Permian) to 2.8% in Devonian rocks at 2900 m (Fig. 1.39).

A thermal maturation gradient of 0.5% Rm/km (Fig. 1.40) from the western edge of the Delaware Basin suggests a larger area of reheating than documented in the structure sections. This area was much wanner than the central and eastern portions of the Permian Basin which has a 0.3% Rm/km gradient (Fig. 1.41). Maximum temperatures computed from Rm-depth relationships (Barker, 1993) infer that average paleogeothermal gradients reached nearly 40°C/km (2.2°F/100 ft) in the western Delaware Basin and about 30°C/km in the rest of the Permian Basin. The Rm data and burial history reconstruction indicate that oil and gas was generated during near maximum burial in the Permian (Horak, 1985; Barker and Pawlewicz, 1987; among others). Reheating in the Tertiary thermally matured rocks as young as Guadalupian in the western Delaware Basin, resulting in a second episode of oil and gas generation. By this time, the Permian reservoir rocks and Ochoan evaporite seals were partially to completely eroded, resulting in poor conditions for trapping during the later pulse of oil and gas generation. This lost oil and gas may have influenced the formation of large sulfur deposits in the area.

The iso-Rm lines on the structural sections across the Central Basin Platform also suggest increased temperatures at shallow depth (Fig. 1.38). Mazzullo (1986) attributed the reheating to a Late Mesozoic to Tertiary discharge of deep basinal fluids along the Central Basin Platform. On the Central Basin Platform, traps were not disrupted as in the western Delaware Basin. This reheating added another pulse of petroleum to existing resources and potentially filled traps that formed after the Paleozoic. The obvious inference is that important sites of oil and gas generation in the Permian Basin were in the band of deeply buried source rocks along either side of the Central Basin Platform (Figs. 1.37, 1.38). The data suggest initial heating generated oil and gas by burial during the Permian and by later reheating in the Late Mesozoic and Tertiary due to increased temperatures at shallow depths.

Return to US-285 on Eddy County-725. 3.9

125.5 Intersection with US-285. **Turn right (north). 0.2**

125.7 Milepost 4. Route for the next mile is on high-level terrace fill that caps the divide between the lower Delaware River and Red Bluff Draw drainage systems. Deposits have been mapped as "pediment gravel" by Kelley (1971) and the surface was included in the "Orchard Park plain" by Horberg (1949). The surface appears to represent an early stage of middle Pleistocene, post-Gatufia Pecos Valley development. **1.3**

127.0 High terrace remnant to right; undulating karst surface ahead dotted with domal remnants of the Culebra Dolomite. 1.1

128.1 Roadcuts in the north-dipping (up to 50°) reddish sandstone of the (lower) Gatufia Formation to the left and right. The dips flatten out to the north and gravelly layers become dominant. Pebble to small cobble-size clasts are for the most part locally derived (Guadalupe Mountain area), but a small percentage of intermediate igneous types (mostly porphyries) indicate a contribution from the Sierra Blanca-Capitan-Jicarilla area of south-central New Mexico. The lower sands exposed in the banks along Red Bluff Draw are gypsiferous. 0.1

128.2 Crossing Red Bluff Draw. **0.5**

128.7 Solution-pitted surface of deformed Culebra Dolomite beds in ditch to right. **0.8**

129.5 Crossing another high, gravel-capped surface, with projecting knobs of Culebra Dolomite. **2.5**

132.0 Bridge over Salt Draw. **0.5**

132.5 The Gatufia Formation of Kelley (1971) is exposed in a roadcut to right. Gravelly calcrete overlies deformed reddish sand and soft sandy mudstones. 0.2

132.7 Route traverses the high-level surface, here mapped as post-Gatuiia, "pediment gravel" by Kelley (1971). 1.0

133.7 Milepost 12. Active sink holes in post-Rustler (Gatuiia?) gypsite and underlying Rustler evaporites to right and left. **1.5**

135.2 Willow Lake Recreation area at 9:00. **0.5**

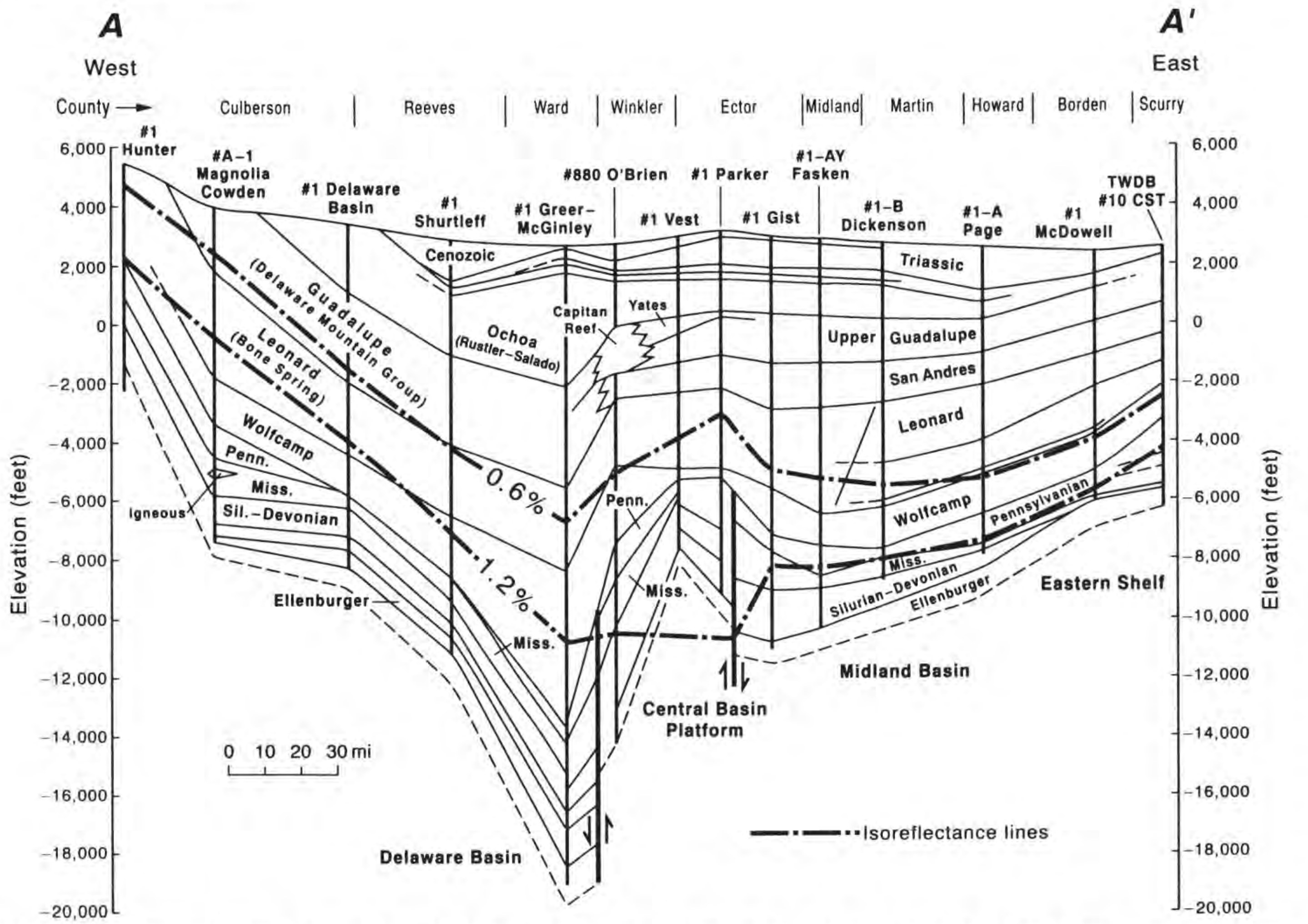

FIGURE 1.38. West to east subsurface cross section A-A', Permian Basin. Location shown in Fig. 1.36. Based on the Texas Water Development Board (1972) cross section A-A', with additional data on igneous intrusions from Calzia and Hiss (1978) and formation tops for Richardson and Bass Kyle 1 from Vertrees (1963). Vitrinite reflectance points 0.6% and 1.2% Rm interpolated from data in Barker and Pawlewicz (1987) and unpublished data. Rm interpolated from data in Barker and Pawlewicz (1987) and unpublished data.

135.7 Milepost 14. Roadcut in Rustler Formation ahead on left. **Prepare to turn right. 0.2**

135.9 **Turn right** (east) on Pulley Road (Eddy County-721). **0.5**

136.4 Railroad crossing. **0.7**

137.1 Sharp turn to left (north) and cattle guard. **1.4**

138.5 **Turn right (east)** onto McDonald Road (Eddy County-746). **0.2**

138.7 End of pavement; road curves to the southeast. Pecos valley floor to left. **0.9**

139.6 Lower Rustler and upper Salado are exposed in karst domes similar to the features observed between mile 114.8 and Stop 5B. **0.3**

139.9 View of Queen Lake (about 1 mi to south) through gap in hills to right. The karst dome and mound structures of this area were originally mapped by Reddy (1961) and subsequently described by Bachman (1980). **0.7**

140.6 Eddy County-788 to left leads to the Malaga Bend (tight meander) of the Pecos River. Continue southeast on County 746. **0.4**

141.0 Salt lake to right was the experimental disposal site for an earlier salinity alleviation project that was supposed to significantly improve the quality of the Pecos downstream from Malaga Bend. However, brine pumpage from the Nash Draw area and disposal here had no apparent affect on the quality of ground-water contributions to the Malaga Bend reach of the Pecos, so the project was abandoned. Hopper crystals of halite can still be collected here; but be careful not to break through the fragile salt crust and become part of the future geologic record. **1.5**

142.5 The road drops to a low terrace level (late Pleistocene). **0.5**

143.0 Sharp curve to the left (north). **0.2**

143.2 Ford across the Rio Pecos floodway at Pierce Canyon Crossing. 0.1

143.3 Bridge over the Rio Pecos conveyance channel (weight limit: 20 st). **0.15**

143.45 Fork in the road, ranch and ENRON well to right; **stay left on McDonald Road.** The well is part of the Owen Mesa pool (discovered in 1983), which is in NW'/4 SE1/4 sec. 26, T24S, R29E. Owen Mesa (Atoka) production is from a depth of 12,725 ft with a cumulative 0.01 MMBO and 9.0 BCFG. **0.15**

143.6 Irrigation ditch. **0.6**

144.2 Curve to right on "terrace" surface capped by gravelly

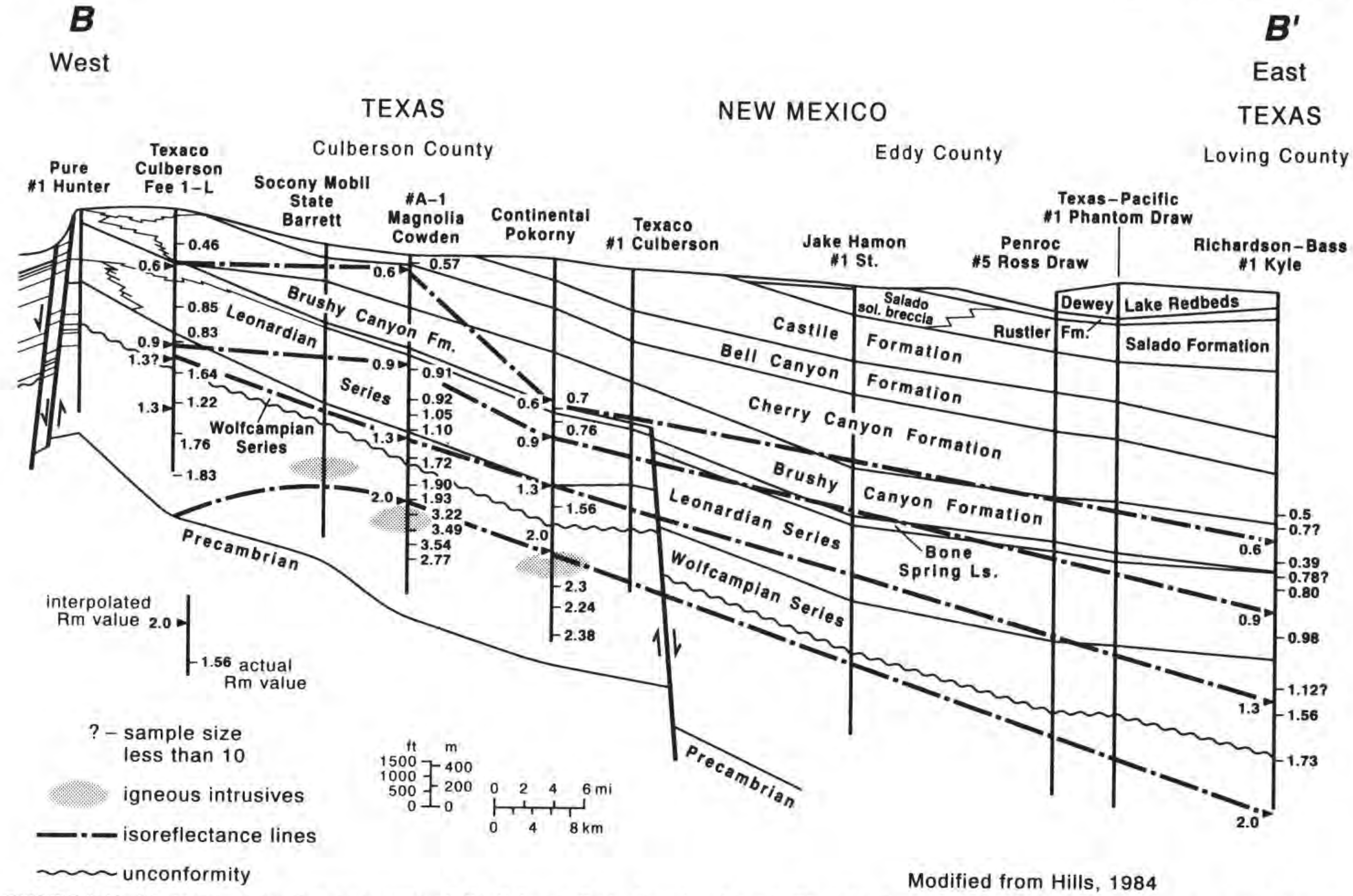

FIGURE 1.39. West to east subsurface cross section B-B', Delaware Basin. Location shown in Fig. 1.36. Based on Hills (1984) cross section A-A', with additional data on igneous intrusions from Calzia and Hiss (1978) and formation tops for Richardson and Bass Kyle 1 from Vertrees (1963). Vitrinite reflectance points 0.6%, 0.9%, 1.3% and 2.0% Rm interpolated in each well on the cross section or nearby wells from data in Barker and Pawlewicz (1987) and our unpublished data.

calcrete (stage V) with siliceous pebbles (Gatuña Formation). This deposit forms the upper part of an extensive solution-subsidence depression fill. Caliche pit to right. **0.1**

144.3 Cattle guard. **0.5**

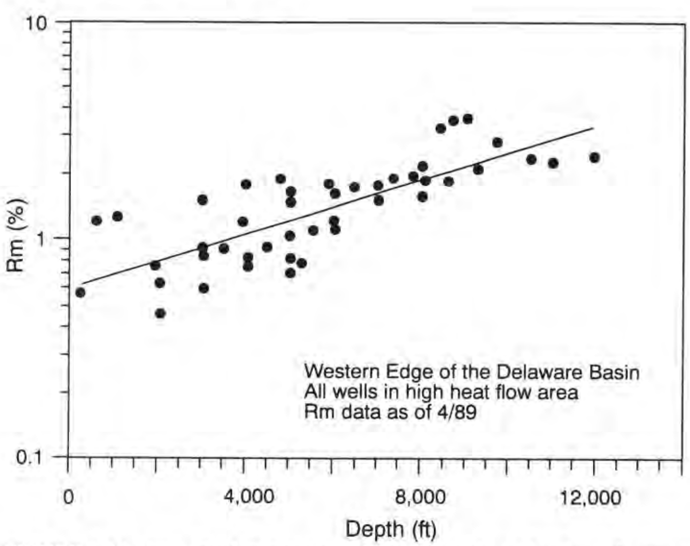

FIGURE 1.40. Mean random vitrinite reflectance (Rm) as a function of present depth using only wells from apparent high heat flow area in the western Delaware Basin.

144.8 Road curves to left; turn around and park facing west. **0.1**

144.9 **STOP 6: Pierce Canyon.** Cross fence and take trail along scarp to right; walk east about 300 yds to Pierce Canyon overlook (Fig. 1.42). This site provides a good vantage point for reviewing three significant aspects of Carlsbad area geology: (1) development of lithostratigraphic concepts and terminology for Permo-Triassic rocks; (2) field evidence for large-scale solution subsidence during the late Cenozoic; and (3) geomorphic evolution of the lower Pecos fluvial system.

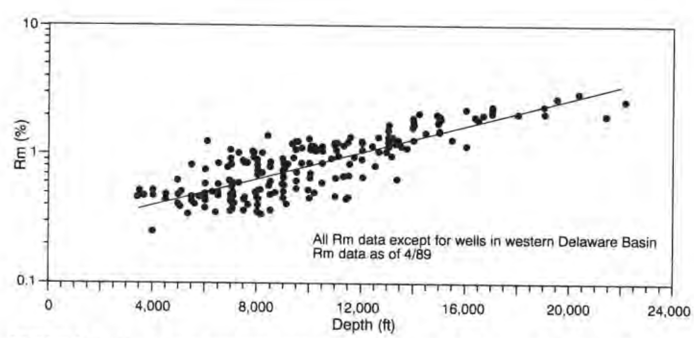

FIGURE 1.41. Mean random vitrinite reflectance (Rm) as a function of present depth, all Permian Basin wells except for the western Delaware Basin.

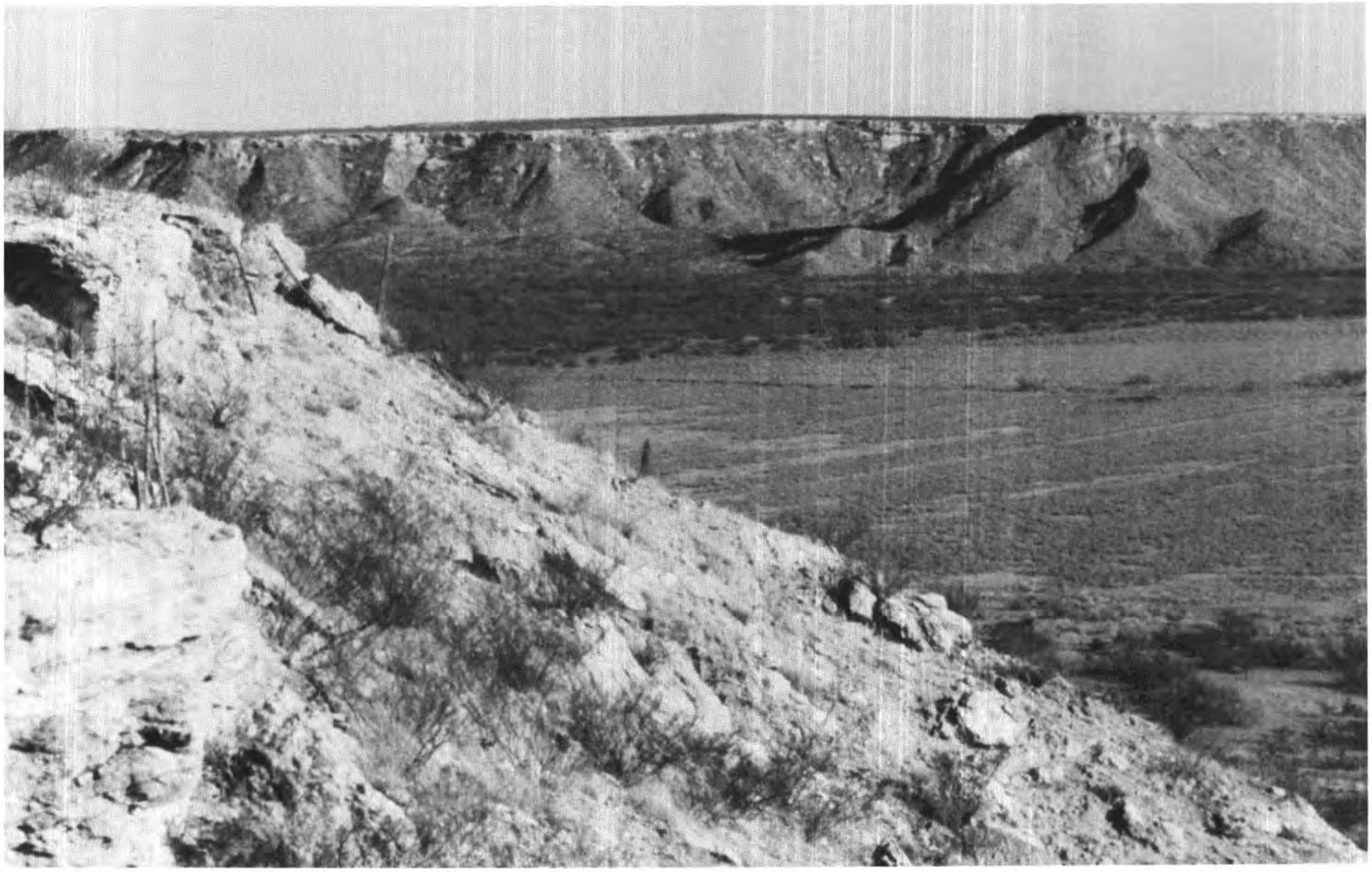

FIGURE 1.42. Mouth of Pierce Canyon from Stop 6. Note level of petrocalcic soil above Gatuña on north side of canyon is 50 to 75 ft lower than much thicker and older petrocalcic soil capping tilted Gatuña/Ogallala on south rim of canyon.

CENOZOIC CONFUSION, CONTROVERSY AND COLLAPSE AT PIERCE CANYON

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Lang (1935) coined the term "Pierce Canyon Formation" for Upper Permian red beds in southeastern New Mexico above the Rustler Formation and below Upper Triassic strata of the Santa Rosa Formation. Clearly, Lang's concept of the Pierce Canyon is the same as the Quartermaster Formation of Gould (1902) or the Dewey Lake Formation of Page and Adams (1940), although he originally thought the Pierce Canyon strata might be of Triassic age (see Lucas and Anderson, this volume). Vine (1963) recognized the unfortunate choice of the name "Pierce Canyon" in his report on the geology of Nash Draw Quadrangle, because neither upper Ochoan (post-Rustler) nor upper Triassic "red beds" are represented at this locality. He did, however, continue to use the term in an informal lithostratigraphic sense to identify an undifferentiated mapping unit comprising the upper Permian and Triassic red beds of the area. In 1963, the U.S. Geological Survey formally designate(' "Dewey Lake" as the proper name for the uppermost Ochoan in the southeastern New Mexico region; and "Pierce Canyon" has since been abandoned (last being used by Miller, 1966). Lucas and Anderson (this volume) consider that "Quartermaster" takes precedence over "Dewey Lake" because the former name (Gould, 1902) was introduced long before the latter term, even though neither unit has a type area near Carlsbad (the type Quartermaster is in Oklahoma and the type Dewey Lake is near Midland, Texas).

Multiple late Neogene episodes of solution subsidence, erosion, soil formation and warping of depression fills are indicated by excellent exposures of the "Gatufia Formation" in Pierce Canyon. With the exception of recent studies by Powers and Holt (this volume), the unit has never been described in detail. Vine (1963, p. B28-29) briefly described three (reference) sections along the north side of Pierce Canyon near this stop (secs. 22 and 23, T24S, R29E) to define better the Gatufia Formation, because no sections had ever been measured at Lang's (1938) type area about 30 mi north in "Gatuna" Canyon. Bachman (1976) described a "reference" section in that area, about 6 mi north of Stop 7 at the east edge of Clayton basin below Nimenim Ridge.

Vine's second section (SE, /4 sec. 22) is at this stop. A tilted block of gray, wavy-bedded dolomite of the Magenta Member of the Rustler Formation (Fig. 1.43) is iminediately below the base of his section. He interpreted the block (at least 100 by 200 ft) to be "incorporated" within a thicker Gatufia sequence. A general description (modified from Vine, 1963, p. B29) of the 80-ft section from the "canyon" rim to the Magenta block follows:

Pedogenic calcrete (indurated), stage IV to V (Hawley, minipaper, this road log), markedly decreasing in degree of carbonate accumulation and cementation 3 to 6 ft below the surface.

Uncemented to weakly indurated pebbly orange laminated and crossbedded sand 13-17 ft thick. Weakly cemented fractures and small faults within the unit. Grades upward into calcisol.

Local angular unconformity.

Tilted, faulted and fractured sandstone, pale-red to moderate reddish-orange, medium-grained; locally contains granules, pebbles and clay layers; 23-27 ft thick.

Tilted, fractured and faulted conglomerate, grayish-pink to pale red, crossbedded; contains variously colored rounded siliceous pebbles and rounded to angular siltstone pebbles; 22 ft thick.

Tilted, fractured and faulted siltstone and claystone, moderate reddish-orange and pale-red conglomerate containing rounded quartz

FIGURE 1.43. Vine's (1963) section of Gatuña Formation over Rustler Formation along the north side of Pierce Canyon at Stop 6.

and chert pebbles and angular fragments of pink dolomite apparently derived from the Magenta member of the Rustler Formation; 10 ft thick. Thin basal zone covered by alluvium.

Block of Magenta Member dolomite.

The south wall of Pierce Canyon is 50 to 75 ft higher topographically than the north side. Similar tilted Gatufia beds are exposed beneath the capping caliche and are at least 100 ft thick at a point directly across the canyon (SE1/4 sec. 26) and may be as much as 300 ft thick in the Pierce Canyon area (Reeves, 1972). The tilted Gatufia beds are truncated by an angular unconformity that is overlain by a 20 to 30 ft layer of coarse gravelly, crossbedded sand. In addition to locally derived car-bonate types, the (small) cobbles and pebbles include a broad range of resistant clasts, including quartz, chert, quartzite, granite, intermediate porphyries, schists, gneisses and metarhyolites. One-half mile farther east (NE1/4 sec. 26), the upper gravelly unit thickens to major fluvial channel deposit of the ancestral Pecos described by Bachman (1984, p. 17-20), that is almost 800 ft wide, 80 ft thick and filled with pebble to cobble conglomerate and interbedded pebbly sandstone. The capping (stage V-VI) calcrete zone is only slightly tilted, but the underlying channel fill has collapsed into a major solution-subsidence feature and is strongly tilted. Bachman (1984) considered sections on both sides of the canyon to be representative of Gatufia Formation of "early? to middle Pleistocene (post-Ogallala) age." He did, however, recognize that in Pierce Canyon:

> . . . the uppermost ancestral-river gravels are at the top of the Gatufia, which indicates only that middle Pleistocene is a minimum age for these gravels. The maximum age of the Gatufia Formation is not known and it is probable that the ancestral Pecos system was initiated in late Tertiary time, when erosion of the eastern slope of the Sacramento-Sierra Blanca-Capitan uplift began (Bachman, 1984, p. 17).

The pedogenic calcrete at the top of the section is 10.15 ft thick and has stage VI morphology with local pisolitic zones and bands of secondary chalcedony. Clearly, this soil represents a much longer interval of pedogenesis (several million years) than the soil on the north side of the canyon (probably formed since early Pleistocene). The contrast in soils, clast types and induration within the deposits above the uppermost angular unconformities at these two sections imply that the "terrace" on the north side of Pierce Canyon was the site of cut-and-fill activity long after the south-rim surface had been abandoned. Hawley (this volume) suggests that all described deposits, except the upper sand and calcrete unit (about 20 ft thick) at this stop, are correlative with the upper Miocene-lower Pliocene Ogallala Formation of the southern High Plains region. Deformation of Quaternary geomorphic surfaces along and beyond the Pierce Canyon, particularly toward the Pecos River, indicate that subsidence is continuing. If the Ogallala correlation is correct, the major deformation features observed at this stop had already developed by late Miocene and prior to formation of the stage V-VI pedogenic calcrete on the south canyon rim.

Return to vehicles. Retrace route on McDonald Road to paved section of Eddy County-746 east of Malaga. An alternative route has also been logged to the Nash Draw area via Poker Lake, Los Medafios, the WIPP site and Laguna Grande de la Sol (Salt Lake) in Nash Draw. **6.1**

151.0 Pavement begins on McDonald Road (Eddy County-746). **0.2**

151.2 Intersection of Pulley Road (Eddy County-721) and McDonald Road (Eddy County-746). Continue ahead on McDonald Road. 1.1

152.3 **Turn left (west)** on Duarte Road (Eddy County-720) toward Malaga. **1.2**

153.5 **Turn right (north)** on US-285 toward Loving. **0.4**

153.9 Historical note about Espejo Trail reads: "Don Antoilio de Espejo, leader of the third expedition to explore New Mexico, passed near here on his return to Mexico City in 1583. After learning of the martyrdom of two Franciscan friars from an early expedition, he explored the Pueblo country and then followed the Pecos River valley south." **0.3**

154.2 Milepost 17. Crossing inner valley of Black River (mile 154.3). Railroad bridge at right. Low bluffs along river are held up by beds of well-indurated pebble conglomerate and conglomeratic sandstone that overlie a weakly cemented zone of sand and pebbly sand. This is the "quartzose conglomerate" unit of Bretz and Horberg (1949a), which they correlated with basal Ogallala. **0.8**

155.0 Small irrigation canal to left. Guadalupe escarpment and El Capitan are visible in the far distance to the west (9:00-10:00). **0.9**

155.9 Quarry to right along with oilwells of the Loving East (discovered in 1987) and the Culebra Bluff South (1979) pools in secs. 33 and 34, T23S, R28E. Loving East (Delaware) production has a cumulative total 2.8 MMBO and 7.7 billion BCFG. Culebra Bluff South (Atoka) production is from a depth of 11,550 ft with a cumulative 0.08 MMBO and 50.9 billion BCFG. Crossing bedrock spur (Rustler) with discontinuous cover of older gravels and gravelly calcrete (Gatufia?). **1.3**

157.2 Milepost 20. Drop to Orchard Park plain of Horberg (1949), the main geomorphic surface "complex" in the Carlsbad area. **0.4**

157.6 Loving, elevation 3050 ft. Loving's Bend was named for Oliver Loving, partner in the Goodnight-Loving cattle concern, who was fatally wounded in a running fight with a band of Comanche Indians here in July 1867. Despite his wounds, Loving and "One-arm Bill Wilson" stood off the attack for three days and nights. Loving died in Ft. Sumner the following September 25. 0.1

157.7 Intersection of US-285 and Eddy County-712. **Jog right and continue straight ahead (north)** on Eddy County-712. 0.1

157.8 Railroad crossings. Route is now on the lowest member of the stepped-sequence of geomorphic surfaces bordering the Pecos River floodplain. Horberg (1949) correlated this surface with the Lakewood terrace mapped by Fiedler and Nye (1933) in the Roswell basin. **1.3**

159.1 **Turn right (east)** on NM-31 (Potash Mines Road). **0.3**

159.4 Rise to "terrace" correlated with the Orchard Park plain by Horberg (1949). The surface is here about 70 ft above the Pecos channel. Borrow pit on right in gravelly (stage V) pedogenic calcrete over "quartzose conglomerate." **0.6**

160.0 Milepost 2. **0.9**

160.9 Railroad crossing on Lalcewood terrace of Horberg (1949), here about 30 ft above the Pecos channel. Highway ahead rises to another remnant of the "Orchard Park plain." **0.4**

161.3 Approaching inner valley of Pecos River (modern floodplain; and lowest Lakewood level of Horberg, 1949). Low bluff to right exposes about 40 ft of older valley fill comprising an upper pedogenic calcrete (stage IV to V) transitional downward into an "upper" conglomeratic zone, a poorly indurated middle sandstone to silty sand unit and a basal ledge-forming siliceous pebble conglomerate and conglomeratic sandstone that crops out just above river level. This is a typical "quartzose conglomerate" section as defined by Bretz and Horberg (1949a) and Horberg (1949), and originally defined in the Carlsbad-Roswell area by Meinzer et al. (1926) and Fiedler and Nye (1933). The upper conglomerate and capping calcrete zone forms a prominent low bluff south of the bridge and includes abundant carbonate clasts from the local (Guadalupe Mountain) source as well as a significant amount of siliceous pebbles (primarily quartzite, quartz, jasper and chert). The dominant (non-carbonate) component in the basal conglomeratic unit also includes minor amounts of silicic to intermediate igneous clasts (granite, gneiss and porphyry) and sandstone. 0.1

161.4 Bridge over Pecos River. Culebra Dolomite is well exposed in Culebra Bluff (10:00) on the east side of the river about 1 mi to the north. **0.3**

161.7 Railroad crossing. Poorly maintained road to left leads to Culebra Bluff, the "best outcrops of Culebra Dolomite," and Stop 2-4 of Powers and Martin (1990, p. 13). The Culebra Dolomite in the Nash Draw area is a dolomicrite with zones of abundant vugs and moderately well-developed bedding. In the WIPP shafts, it is underlain by a sticky clay with some laminae. At the top of the Culebra in the shafts, about 1 ft or more of waxy yellow clay and carbonate with laminae from an algal deposit is present. Some vugs formed from the displacive growth of sulfate. From here to the east, vugs are progressively filled with silt, gypsum and anhydrite. The vug filling is related to the transmissivity and chemistry of the Culebra. Fractures connect vugs and dominate much of the hydrogeology of the Culebra. Examination of the exposure here reveals important porosity variations and sedimentary collapse features (Powers and Martin, 1990). **1.3**

163.0 Milepost 5. New Mexico Salt and Minerals Corporation on the right. Entering "Carlsbad Potash Enclave"; see Olsen minipaper (this road log, below) and Barker and Austin (this volume). **1.2**

164.2 Salt Lake (Laguna Grande de la Sal) on the right. Lake elevation (approximately 2950 ft) is about the same as the adjacent reach of the Pecos River channel across low divide to the west. This is the only natural and permanent body of water in Nash Draw, but its salt content has been augmented by brines from the tailings piles of potash refinery operations. On the lakeshore are evaporation pans and other salt harvesting facilities of the New Mexico Salt and Minerals Corporation. **0.5**

164.7 Bluffs to left are calcrete-capped Gatufia Formation on Rustler Formation. **0.8**

165.5 Junction with Jal Highway (NM-128) to east. **Continue straight ahead** on US-31.

OPTIONAL STOP: 0.8 mi east on NM-128 at the north edge of Salt Lake and on the alternate (WIPP site-Nash Draw) route from Pierce Canyon (Stop 6). **0.3**

165.8 Milepost 8. Ascending Quahada Ridge, a western outlier of the Mescalero plain, which is capped by Gatufia Formation. **1.3**

167.1 Crossing railroad. Potash ore is shipped along this line from the Western Ag-Minerals Nash Draw mine about 10 mi due east to their mill about 10 mi to the north by a very circuitous route. 2.4

169.5 Roadcut to left exposes reddish Rustler sandstone and sandy mudstone with a thin rubbly caliche or caliche-rubble cap. **1.3**

170.8 Milepost 13. Eddy County-801 to right leads to the IMC Fertilizer potash mill. The Dewey Lake Formation and the Tamarisk, Magenta Dolomite and Forty-Niner Members of the Rustler Formation crop out in the west wall of the Nash Draw depression about 0.5 mi to the south-southeast (Bachman, 1981). **0.6**

171.4 IMC Fertilizer, Inc., plant to right (Eddy County-800). **0.8**

172.2 United Salt Corporation collecting plant on the right. Igneous intrusives have been encountered in drill holes to the southwest and IMC Fertilizer potash mine workings about 1 mi west and 1 mi north of this point (Jones and Madsden, 1959; Calzia and Hiss, 1978). Their trend parallels that of the lamprophyre dikes discussed at mile 25.7 (near Stop 1B). The intrusive zone is also encountered underground in the New Mexico Potash Corporation mine 10 mi to the northeast (Jones, 1973) and in drill holes farther northeast to an area about 25 mi southwest of Lovington. **0.5**

172.7 Cimarron Road (Eddy County-796) to right provides access to central Nash Draw and Livingston Ridge area mapped by Bachman (1981). This is another segment of the 1990 GSA tour route logged by Powers and Martin (1990, p. 14-15). **Continue north on NM-31.** Roadcuts ahead are in Gatufia calcrete (stages IV and V) with scattered pebbles and a basal calcareous to gypsiferous silty sand zone that is unconformable on soft, light reddish Rustler siltstone and gypsum. Small secondary silica (chalcedony to opaline) masses occur in the Gatufia and large dissolution features with complexly jointed carbonate and gypsum veins are present in the underlying Rustler gypsum zone. 1.1

173.8 Milepost 16. On eastern edge of Quahada Ridge; Gatufia Formation with veneer of eolian sand for the next 1.8 mi. **2.2**

176.0 Maroon Cliffs at 2:00-3:00 border Nash Draw on the north and separate it from the Mescalero plain. Triassic Santa Rosa Formation and the Dewey Lake (Quartermaster) Formation are both exposed in this area. Vine (1963), the Geologic Map of New Mexico (Dane and Bachman, 1965) and the Hobbs Sheet of the Geologic Atlas of Texas (Bureau of Economic Geology, 1976a) show much more extensive Upper Triassic outcrops in the Maroon Cliffs area than actually are present. Most of the light-colored, resistant strata that cap the cliffs and nearby hills are either calcretes and sedimentary deposits of the Gatutia Formation or sandstones in the upper part of the Dewey Lake—Quartermaster. Indeed, the only two locations in the Nash Draw—Maroon Cliffs area where the Upper Triassic strata crop out are near the radio tower in sec. 36, T20S, R31E (Fig. 1.44) and at and around the area of Stop 7 (sec. 1, T21S, R29E). **0.4**

176.4 Large sink with playa to left. 1.0

177.4 Mississippi Chemical Potash mine and mill to right. **0.8**

178.2 The bunkers in the hillside on the right are in Dewey Lake (Quartermaster) Formation. **2.3**

180.5 **Stop sign. Turn right** on US-62/180. Western Ag—Minerals Saunders Mill is at 10:00. Move to the left lane and prepare for left turn. **1.5**

182.0 Hill "B" to left (Bachman, 1980) and Stop 6 area. The Barber pool in secs. 28, 32 and 33, T20S, R3OE on the left (north) was discovered in 1937. The Dos Hermanos pool in the same general area was discovered in 1955. Barber (Yates) production is from a depth of 1500 ft with a cumulative total 1.9 MMBO. Dos Hermanos (Yates and Seven Rivers) production is from a depth of 1640 ft with a cumulative 1.5 MMBO and 0.004 BCFG. Dos Hermanos (Morrow) production is from a depth of 12,300 ft with a cumulative 0.08 MMBO and 12.7 BCFG. **0.5**

182.5 Milepost 55. Prepare for left turn ahead. **0.2**

182.7 **Turn left at crossover** at Western Ag—Minerals plant entrance and **left again** onto west-bound lanes of US-61/180. Stay in right lane going west. **0.5**

183.2 Pull off to the right and park at the side of the road opposite the hill north of the highway. 0.1

183.3 **STOP 7: "Hill B" breccia pipe and Permian-Triassic boundary.** Two large domal structures ("Hills A and B," Fig. 1.44) with brecciated cores are present at this site. Their diameters are in the 1000 to 1500 ft range and they rise as much as 100 ft above surrounding low-lands. Partial breeching of these structures has exposed a disturbed section of Upper Triassic over Upper Ochoan rocks. Capping beds of the Gatufia Formation and as-sociated "Mescalero caliche" are also deformed. Com-ments on units straddling the Permian-Triassic boundary follow introductory discussions on the origin of the brec-cia pipes and related domal landforms.

Recent domal structures in southeastern New Mexico, including the "Hills A and B" in this area, were originally described by Vine (1960). About l 1 mi west of this site (secs. 25 and 26, T20S, R28E), Kelley (1971, p. 31, pl. 4) mapped an even larger collapse structure, with "a core of much-disturbed Gatutia in a . . . sink and dome structure of the type described by Vine (1960)." These deep-rooted features, as well as the historically active San Simon Sink (Nicholson and Clebsch, 1961), all overlie the buried margin of the cavernous Capitan (reef) aquifer system (Hiss, 1975a, 1975b, 1976a, 1980; Wallace, this volume).

Core drilling and geophysical studies in this area demonstrate that the domal landforms are simply the surface expression of relatively shallow solution-subsidence (in the upper Salado—lower Rustler) and resultant draping of a clastic cover (here the Gatuiia—Santa Rosa—Dewey Lake [Quartermaster] sequence), over and around an older (deep-seated) breccia-pipe plug that is presumably rooted in cavernous Capitan Limestone.

The area of this stop has been mapped in detail by Bachman (1980, scale 1:2400). Snyder and Gard (1982) evaluated these and other breccia pipes in terms of their relationship to the WIPP project. In these reports, the partly breeched domal structure at this stop is designated "Hill B." The more completely dissected feature, 1000 ft to the north and traversed by a railroad cut, is "Hill A." Bachman (1987, p. 121-123) summarized recent detailed research on the latter breccia pipe: "Hill A is about 18.5 mi northeast of Carlsbad, New Mexico (SW '/4 sec. 35, T20S, R30E). It is a low breached dome, about 1200 ft in diameter and rises about 40 to 50 ft above the surrounding terrain. The center of the hill has been eroded to a shallow basin by an arroyo system cutting headward from the west."

Permian (Dewey Lake) red beds are exposed in up-turned beds and form a wall rock around the periphery of the dome. Triassic beds of the Dockum Group rest on the Permian wall rock at places. Inside the dome a peripheral ring fault cuts the wall rock. A breccia consisting of blocks of Triassic clay, sandstone and conglomerate fills the core inside the ring fault. It is apparent from surface exposures that the breccia has collapsed into the core of the dome.

Snyder and Gard (1982, p. 21) made the following observations. "A hole has been drilled in the center of Hill A to a depth of 1981 ft. Brecciated and steeply dipping rocks were encountered throughout the drilling. The breccia is a chaotic mixture of Triassic rocks, Dewey Lake Red Beds, Rustler Formation and residues of the Salado Formation. A thick bed of steeply dipping anhydrite was encountered at the 1903 ft level. It has been identified as the basal member of the Salado Formation. . . . It is evident that the breccia cores of these domal structures collapsed into a large underground cavity. As the domes overlie the Capitan reef and its associated facies, it may be assumed that large limestone caves could have been present in the subsurface beneath the area of the domes. . . . Although the collapse of breccia pipes may have occurred during unusual hydrologic conditions, a modern analog of breccia pipes may be present in southeastern New Mexico. San Simon Sink in Lea County is an active collapse sink which may have its roots in the phreatic zone of the underlying Capitan Limestone. . . ."

The "Hill B" breccia pipe is one of few outcrops in the Maroon Cliffs area, indeed in southeastern New Mexico, where Upper Triassic strata are preserved and the Permian-Triassic boundary can be observed on outcrop (Fig. 1.44). Here, the uppermost strata of the Upper Permian Quartermaster (Dewey Lake) Formation (Gould, 1902; Page and Adams, 1940) are reddish brown siltstones and very fine-grained sandstones overlain by greenish gray and grayish red conglomerate, sandstone and mudstone of the Upper Triassic Santa Rosa Formation (Lucas and Anderson, this volume). Particularly impressive are the rip-up clasts of Quartermaster in the

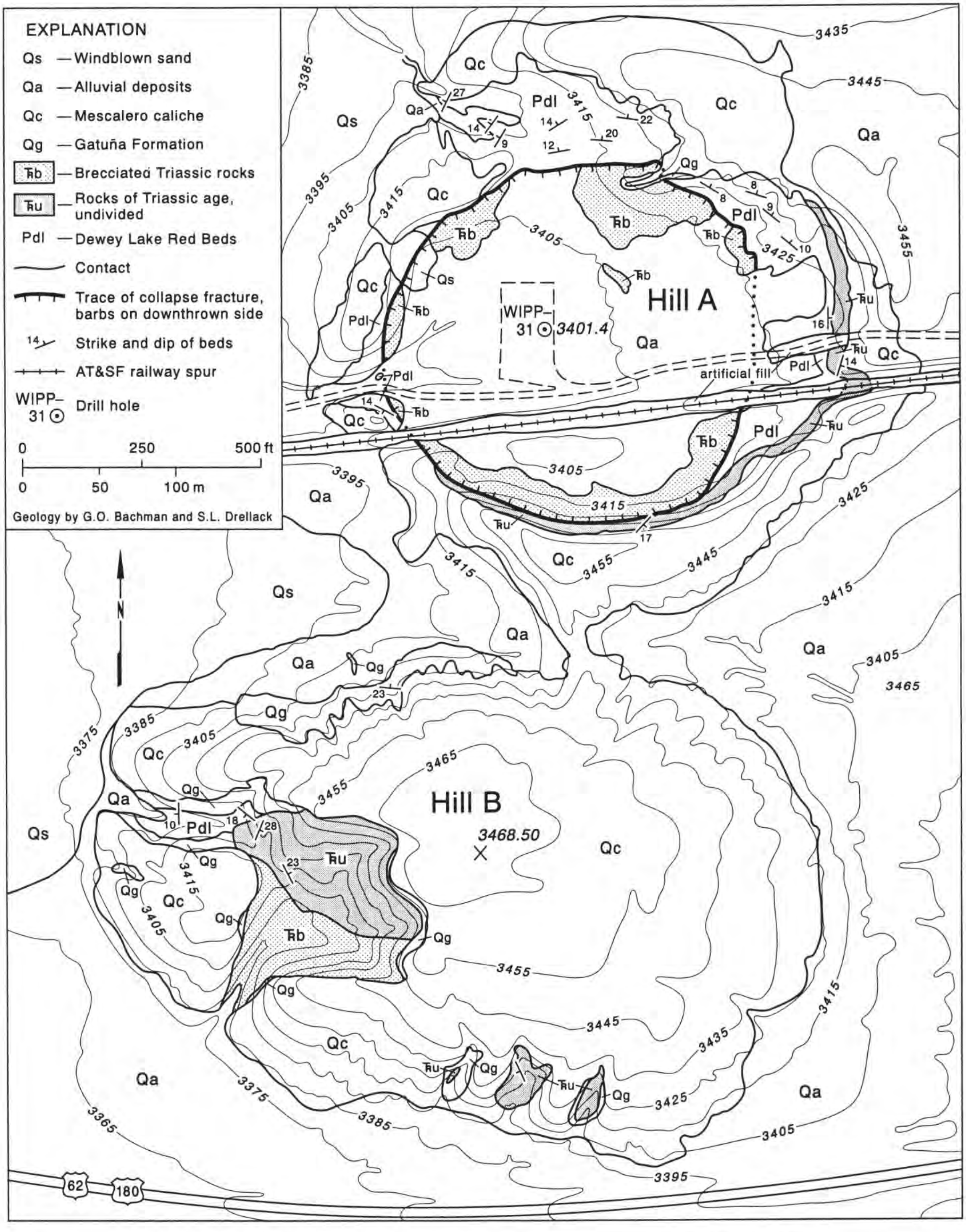

FIGURE 1.44. Geologic map of "Hills A and B," Stop 7 area, adapted from Snyder and Gard (1982, pl. 1)

basal conglomerates of the Santa Rosa Formation. Fossil bone fragments and coprolites are found in some of the Santa Rosa conglomerates well above the Permo-Triassic contact (Fig. 1.45).

The contrast between Permian and Triassic lithologies and bedforms is striking. Permian strata are finer grained, more evenly bedded or massive and much more mature mineralogically and texturally than the Upper Triassic strata. Furthermore, the color contrast between reddish brown to orange Permian strata and overlying greenish gray and grayish red Triassic strata is hard to miss.

Despite this, there has been much confusion in the Maroon Cliffs area about the placement of the Permian-Triassic contact (mapping boundary). This can be seen well by walking a couple of hundred yards northeast from this outcrop to the railroad cut over the top of the hill. Vine (1963, fig. 9) illustrated this outcrop (in the SW1/4 SE'/4 sec. 35, T20S, R30E) and placed the Permian-Triassic contact at the base of the prominent sandstones in the deepest part of the cut. But, close examination reveals that the lower 3.1 m of these sandstones are of Quartermaster lithology and are overlain by a 1.1-m-thick conglomerate that marks the base of the Triassic. Clasts in this conglomerate are 4-5 in. cobbles of Quartermaster sandstone. The Santa Rosa Formation in this area is in turn overlain by downwarped deposits of the Gatufia Formation and a capping pedogenic calcrete unit, the "middle Pleistocene Mescalero caliche" of Bachman (1980).

A TOTAL DISSOLVED SOLIDS MAP FOR THE NORTHERN PORTION OF THE CAPITAN AQUIFER

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The Capitan reef contains both fresh and saline waters. Its unique environment and arc-like shape have led to a condition in which ground water quality varies greatly with location, both vertically and areally. The purpose of this study was to define the limits of fresh and saline waters within a region of the Capitan reef. This region roughly comprises the Capitan reef north of the New Mexico border, east of the Pecos River and west of R35E. For purposes associated with this paper, "fresh" water is defined as water having total dissolved solids (TDS) concentrations less than 10,000 ppm.

Hiss (1973, 1975c, 1980) conducted some of the most comprehensive surveys to date on Capitan reef hydrogeology. In those studies he postulated the overall flow regime, tabulated information on the stratigraphy, water levels and water quality and inferred future flow regimes due to (then) current conditions. Hiss had prepared a map of chloride ion distributions (1975c) but not of TDS. He had tabulated TDS for 10 Capitan observation wells and chloride (as well as all of the other major cations and anions) in a 1973 study. The chloride map added over 15 additional data points to the ten of the previous study. A more reliable TDS map could be developed if these 15 chloride points were included.

For TDS to be backed out of chloride concentrations, a justifiable relationship must be determined. In most saline waters, chloride ions constitute roughly half of the total TDS. However, this relationship is dependant upon the relative concentrations of other constituents and these relative concentrations could vary widely from sample to sample.

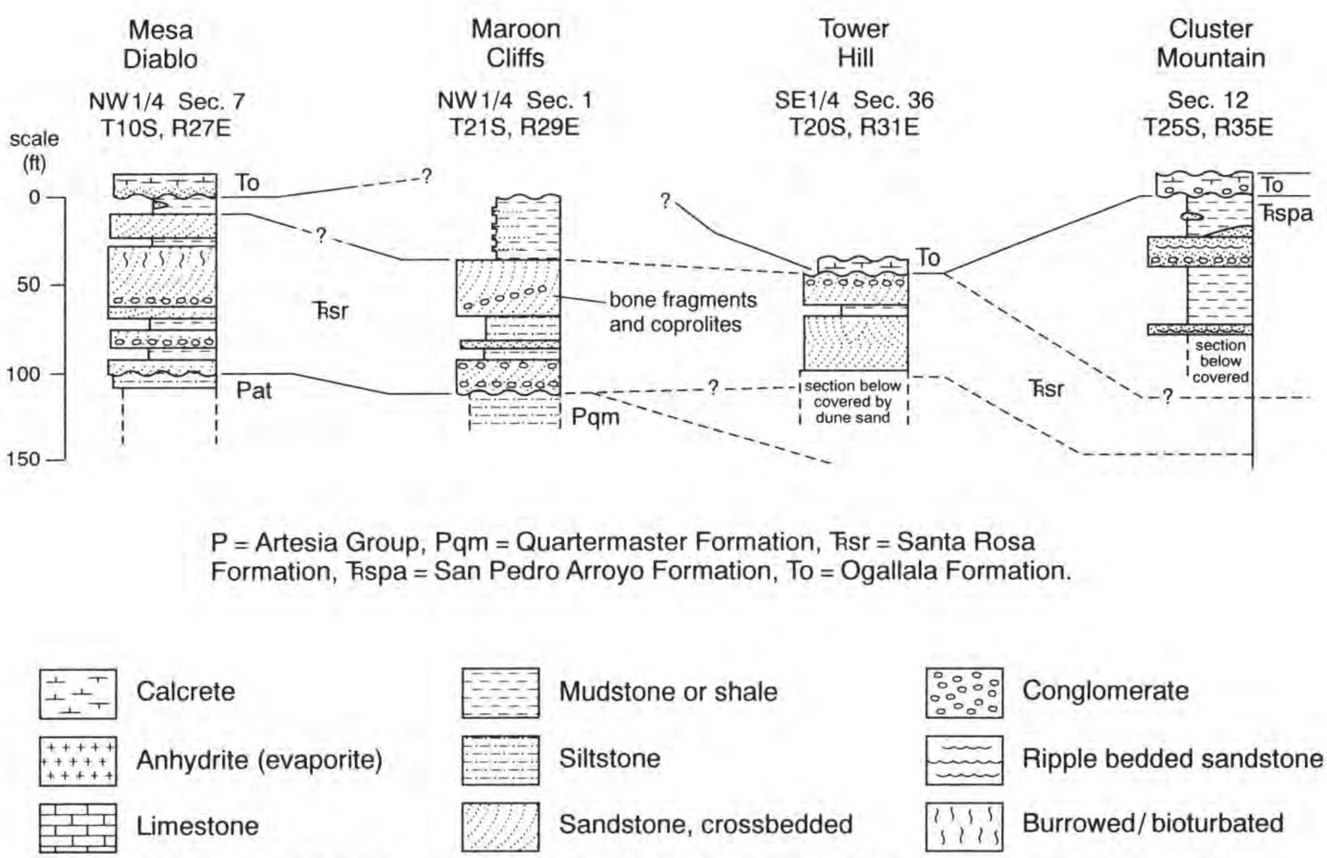

FIGURE 1.45. Correlation of surface sections in Chaves, Eddy and Lea Counties, New Mexico (after Anderson and Lucas, 1992).

Therefore, the first step of this study was to determine how severely Capitan water samples varied chemically within the study area. If the water samples did not vary greatly, the next step was to back-calculate TDS from the chloride values. The final step was to plot these values on a map of the Capitan and to contour the distribution of TDS.

Hiss (1973, table 2) and selected data from Richey et al. (1985) were used to develop a Piper trilinear diagram for the area. This diagram is a useful tool for the comparison of different water samples based on relative concentrations of major ions. The diagram is useful even when TDS varies greatly, because it is only concerned with relative concentrations in equivalents per million (epm). Once data points are mapped onto the diagram, patterns and/or clusters of water samples with similar chemistry can be discerned and inferences can be made on the overall hydrogeological system.

Fig. 1.46 is the trilinear diagram resulting from this exercise. The locations of the points plotted on the trilinear diagram can be found in the Hiss papers. A few non-Capitan points within the same region were also plotted for comparison. Based on the diagram, water within the Capitan appears to be "well mixed." In other words, the ion ratios are similar throughout the Capitan. This is especially interesting because water samples were not only taken at different locations, but also at different times and depths. This also supports the approach of back-calculating TDS from chloride concentrations, because chloride has essentially the same proportion to TDS for all of the samples. The net result is that chlorides constitute an average 50% of the TDS for the Capitan waters. Therefore, all that is required is to double the chloride values from Hiss (1975) to obtain TDS.

The TDS map (Fig. 1.47) indicates that most of the waters in the Capitan reef, from the Pecos River area arcing eastward to R35E, have a TDS concentration higher than 20,000 ppm. A transition zone, from relatively fresh water (approx. 1000 to 2000 ppm) to relatively saline water (20,000 ppm), extends roughly 6 mi eastward/northeastward from the Pecos. A zone of relatively high TDS waters (greater than 100,000 ppm) exists near the northernmost extension of the shelfward portion of the Capitan. This area covers parts of T19S, R3OE and T19S, R31E. A zone of waters having TDS concentrations below 10,000 ppm exists within the Capitan to the east and south of R35E. Although not shown on the map, additional areas of extremely high TDS exist in this region. An additional point is that, although a significant quantity of water in this locale is technically "fresh," it is unpotable due to high concentrations of hydrogen sulfide.

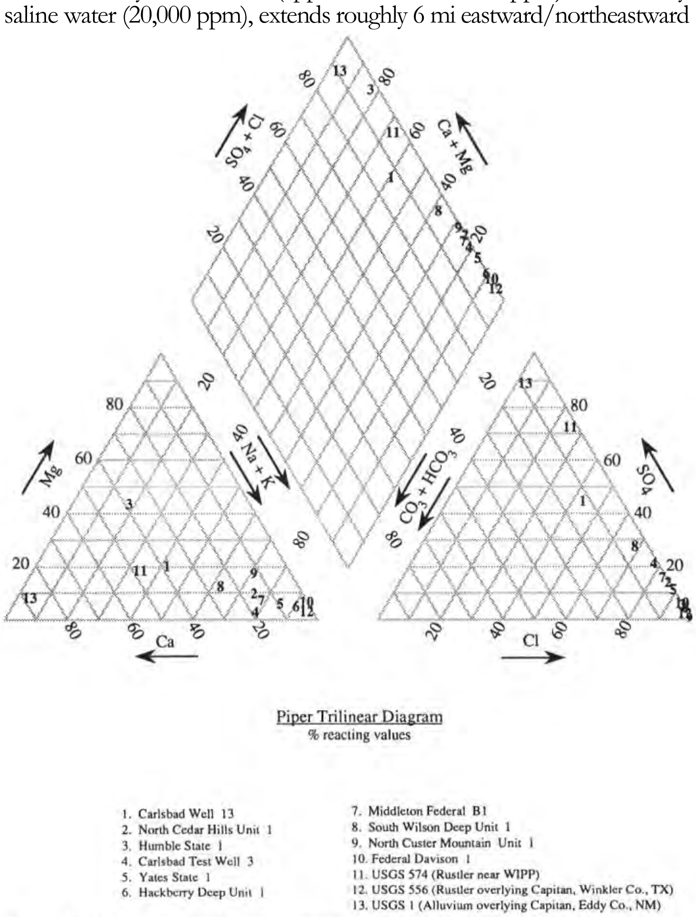

FIGURE 1.46. Piper trilinear diagram of water samples from a northern portion of the Capitan aquifer.

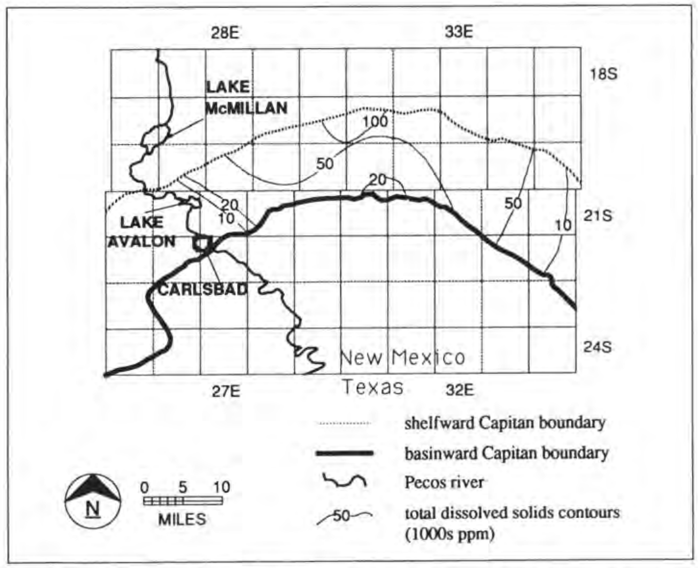

FIGURE 1.47. TDS contours for a northern portion of the Capitan aquifer.

This paper has presented a simple water quality analysis of Capitan waters, leading to a map of total dissolved solids for a northern section of the aquifer. This map is useful for many purposes, including the investigation of ground-water flow patterns in the Capital' reef.

FEDERAL MANAGEMENT OF THE POTASH AREA IN SOUTHEASTERN NEW MEXICO

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The Bureau of Land Management (BLM) manages a unique potash deposit near Carlsbad, New Mexico, This deposit contains, in part, the only known commercial accumulation of langbeinite in the world. At present, approximately 85% of domestic potash production comes from this potash area, where 90% of current production is on federal lands. Here, oil and gas and potash exist under the same lands. Simultaneously exploiting petroleum and potash at the same location would create unacceptable safety risks for underground mining and would create petroleum production difficulties. The U.S. Geological Survey and later BLM, created a series of Secretarial Potash Orders to address multiple mineral development.

Mineral development conflicts between the petroleum and potash industries began before February 6, 1939, when the first Secretarial Order was issued banning oil and gas leasing in the Potash Area. The Potash Area initially contained 42,285 acres. The subsequent Order of October 16, 1951, revoked the first Order, changed the regulations and delineated a regulated area of 298,345 acres. Subsequent Orders issued on May 11, 1965, November 5, 1975, and October 28, 1986, redefined regulations and incrementally increased the size of the Potash Area to its present 497,002 acres.

Representatives of the oil and gas and potash industries signed the "Statement of Agreement between the Potash and Oil and Gas Industries on Concurrent Operations in the Potash Area" on November 23, 1987. The State of New Mexico adopted the Statement as Oil Conservation

Division Order No. R-111-P. Subsequently, BLM created a new proposed version of its order. However, this version will not become official until published in the Federal Register.

Several special land units are in use in the Potash Area (Fig. 1.48). The largest of these is the Potash Area itself. It includes all lands designated by the Secretarial Order where the Order is applicable. The Potash Area is delineated by section or larger land divisions. The next largest unit within the Potash Area is the nown Potash Leasing Area (KPLA). The KPLA encompasses the known potash resources and some adjacent barren areas. The KPLA essentially comprises the cored portions of the Potash Area and is delineated by quarter quarter section, lot, or larger land divisions. The State of New Mexico, through the R-111-P Order, attempts to miffor the BLM KPLA with the State equivalent of that KPLA. Sixteen sections of the KPLA within the Waste Isolation Pilot Project are now withdrawn from mineral entry, secs. 15 through 22 and 27 through 34, T22S, R31E.

The Potash enclave lies within the KPLA anci comprises measured potash ore reserves. Its boundaries are interpretively determined by BLM from potash coreholes. To qualify as enclave, lands must contain at least the equivalent of 4 ft of 10% wt.% sylvite or 4 ft of 4% wt.% langbeinite in three or more coreholes spaced up to 1.5 mi apart. Other potash ores, including carnallite, leonite and polyhalite, occur in the Secretarial Area, but chiefly due to economics, are not classed as ore. Life of Mine Reserves (LMRs) are measured potash reserves determined by each operator to encompass all potash ore anticipated to be mined by that operator, or his successors. The BLM reviews LMRs prior to accepting them and may reject any LMR that appears to be unreasonable. The State of New Mexico has designated its own Known Potash Leasing Area in Order No. R-111-P as an administrative land unit for regulation of potash on state lands. The boundaries of this unit do not necessarily coincide with any BLM land unit. The State uses the LMR system on state lands within the potash area.

At irregular intervals, BLM updates and republishes a potash resource map of the KPLA. The map shows areas of measured and indicated potash reserves, inferred potash resources, barren or minor potash mineralized areas and first and second mined areas. The accompanying map (Fig. 1.48) is a simplified version combining first and second mined areas. Indicated and inferred classifications are based on direct or indirect geologic evidence from sparsely distributed data points. Ten ore zones are in the enclave. However, the resource map composites all zones into a single zone to assure company data confidentiality.

A long-standing policy iterated in all Orders since 1975 denies approval of most applications for permits to drill oil and gas tests from surface locations within the established potash enclave. Such a policy

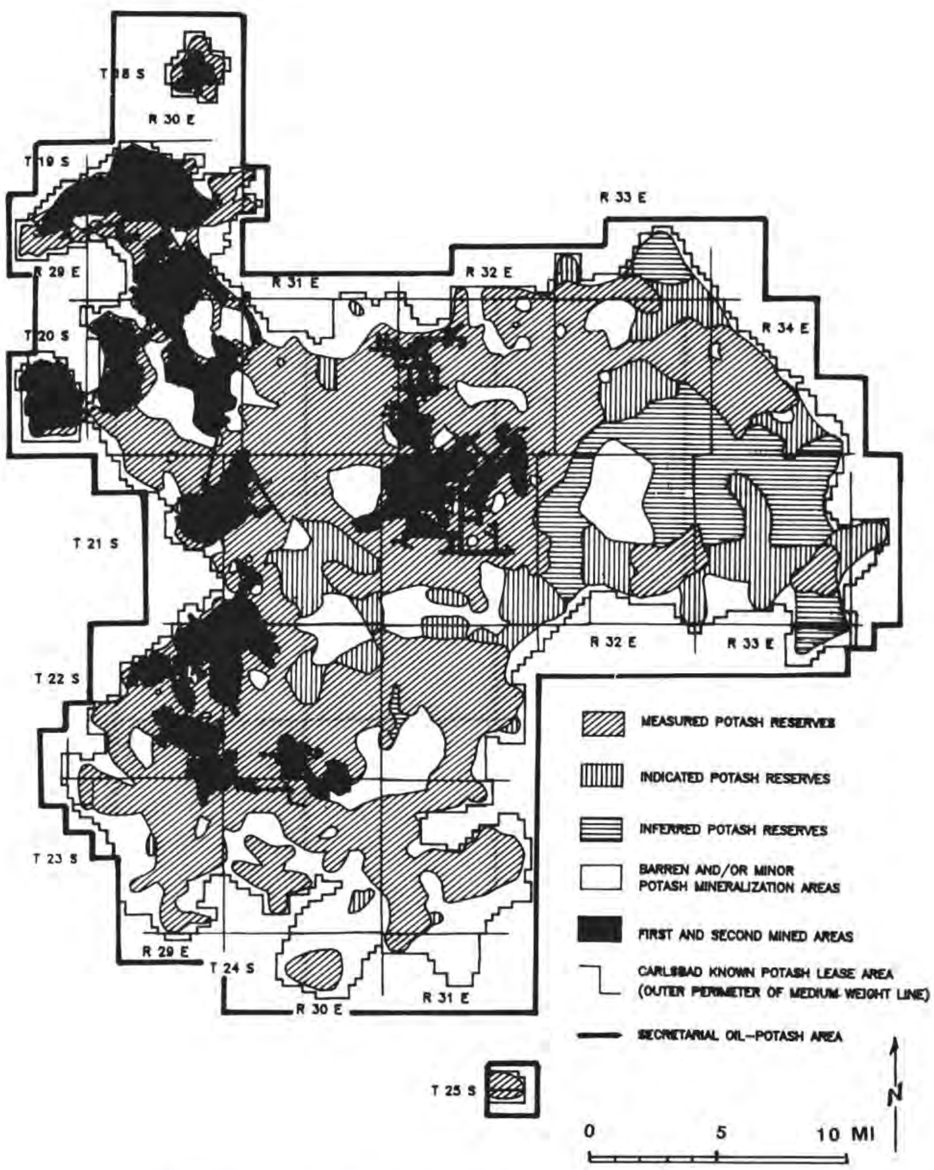


FIGURE 1.48. Potash resource map of the Carlsbad Mining District.

aids in development of economic potash reserves. The 1975 Order instituted the concept of allowing drilling islands within the enclave, when the target formation in a remote interior lease cannot be reached by a well directionally drilled from an exterior location. This allows some development of petroleum on oil and gas leases. The proposed Order (Department of the Interior, unpubl. 1993) eliminates the drilling island concept and formally institutes the LMR designation in place of enclave designation. Portions of the old enclave designation would fall outside of the LMR areas and their buffer zones. The BLM has greater latitude under the proposed Order to allow drilling in those potash reserve areas outside the LMR where ore is not likely to be mined. The current 1986 Order and the proposed Order permit drilling when that drilling will not constitute a hazard to mining, interfere with current potash operations, interfere with future mining and recovery of potash deposits, or result in undue waste of potash deposits. The BLM disallows oil and gas drilling in LMRs and LMR buffer zones.

Subsidence and subsidence-generated faults above second mined areas generally extend away from those disturbed areas at about 45°. Such subsidence can cause shearing of well casings. Shearing results in loss of the well and migration of hydrocarbons into the disturbed ground. Any significant accumulation of hydrocarbons in a potash mine measured by the U.S. Mine Safety and Health Administration results in that mine and any interconnected mine, changing to permissible (gassy) mine equipment. It is not known if fracturing parallel to the angle of failure occurs in adjacent, otherwise undisturbed strata, or its frequency if present. It has not been determined if such faulting would significantly augment gas migration.

Most unmined economic potash is between 1000 and 2000 ft deep. To comply with the Order, BLM denies applications to drill (APD) wills drilled to the base of the Delaware Group within 0.25 mi of minable measured ore or existing operating mines. The BLM denies APDs for deeper gas wells when the location is within 0.5 mi of existing operating mines or LMRs. Because these wells will penetrate target formations that lie below the Delaware Group, they may produce high-pressure gas. Therefore, BLM allows for an extra margin of safety, to avoid gas leakage into mine workings in a casing or cementing failure. These safety factors are based on the subsidence model previously described. The new Order codifies distances from LMR ore used by BLM in approval or denial of APDs. The BLM also protects unleased potash reserves in the APD review process.

Second mining, or mining support pillars, are disallowed in a horizontal direction equal to the depth of ore. This protects the integrity of existing wells, pipelines and highways or other surface structures. Casing and drilling requirements for wells drilled in the Potash Area exceed requirements for wells drilled outside of the Area. BLM requires three strings of casing in wells from the surface to strata beneath the potash producing zone.

I thank Tony Herrell of the BLM Carlsbad Resource Area for providing helpful comments and Janet Graham of the BLM Roswell District Office for updating the draft of the potash map for this paper.

Continue west on US-62/180. 0.4

183.7 Route ahead crosses undulating upland erosion surface cut on thin deposits of the Gatufia Formation with a veneer of younger eolian sands. This sequence here overlies upper Ochoan red beds. 1.1

184.8 Road to potash mines (NM-31) to left. Continue west on US-62/180. Barber oil and gas field to north discovered in 1937. **0.2**

185.0 Crossing saddle between Quahada (south) and Mimosa (north) Ridges that are locally capped by thick, sandy Gatufia deposits. 1.0

186.0 Railroad cut to right exposes stage IV to V pedogenic calcrete on sandy Gatufia. 1.1

187.1 Road to potash mines (NM-360) to right. This is the route to Lang's (1938) Gatufia "type" area in "Gatuna" Canyon at east edge of the Clayton basin along Nimenim Ridge (10 mi north). Bachman (1976) described a 55-ft "reference section" of the formation at that locality (SW'/4 SW1/4 sec. 36, T19S, R30E). See Powers and Holt (this volume). Continue west on US-62/180. **0.4**

187.5 Abandoned Eddy Mine of National Potash at 2:00. The only potash ore zone in this mine was the lowest (1st zone) and the mining depth was about 600 ft. **3.4**

190.9 Milepost 47. Route on gradual descent into the Carlsbad segment of the Pecos Valley. Sandy deposits of the Gatuft Formation poorly exposed in roadcuts to left for the next mile. New Carlsbad landfill site described by Powers and Magee (this volume) is about 1 mi to the south on Quahada Ridge. **4.7**

195.6 Carlsbad City Limits. The abandoned Beeker processing plant is on the right. **1.3**

196.9 Milepost 41. Crossing Lone Tree Draw. For the next 4.7 mi, we will be passing through the Esperanza (discovered in 1969), La Huerta South, Carlsbad East (1975), Tansill Dam (1991) and Carlsbad South (1969) pools in secs. 25-28, 33-35, T21S, R27E and secs. 2-5, T22S, R27E. Esperanza (Delaware) production has a cumulative total 1.0 MMBO and 0.2 BCFG. La Huerta South (Strawn) production has a cumulative 0.004 MMBO and 0.5 BCFG. Carlsbad East (Wolfcamp) production is from a depth of 9540 ft with a cumulative 0.7 MMBO and 12.5 BCFG. No information is available for the Tansill Dam (Atoka) pool. Carlsbad East (Morrow) production is from a depth of 11,200 ft with a cumulative 0.08 MMBO and 235.4 BCFG. **2.0**

198.9 Milepost 39. Former city landfill to right with deep trenches excavated in disturbed zone (solution-subsidence) of the upper Rustler. **0.7**

199.6 Stage IV-V pedogenic calcrete in cut to right grades downward into gravelly Gatufia sediments. Clasts mainly derived from Rustler dolomites, but a trace of siliceous pebbles is present. **1.7**

201.3 Entering Hagerman Heights area of Carlsbad; historic marker to right: "Carlsbad, founded 1888, elevation 3100 ft. Originally named Eddy after a pioneer cattle ranching family and renamed Carlsbad in 1899 after the famous European resort. The expedition of Gaspar Castan() de Soza passed through here in 1590 and noted mineral springs in the area." See minipaper by Howard (Day 3 road log). **0.3**

201.6 Muscatel Avenue to right leads to Presidents Park Amusement Village and public campground on east shore of Lake Carlsbad. Both carbonate-clast and siliceous-clast dominated "quartzose conglomerates" are exposed in Pecos River bluffs to south (Horberg, 1949). Col-lapsed masses of Culebra Dolomite also locally crop out near river level. **0.4**

202.0 Cross Pecos River on Bataan Memorial Bridge and enter downtown Carlsbad via Greene Street. Riverside park and Lake Carlsbad Recreation Area across bridge to right. Many members of the New Mexico National Guard spoke Spanish so when the guard was called into service before the outbreak of World War II, they were sent to the Philippines. When the Philippines fell to the Japanese, they were captured and endured the Bataan death march. **0.2**

202.2 Approaching junction with US-285; **prepare for left turn.** Route passes WIPP Project Administrative Center and Carlsbad Chamber of Commerce on left. 0.1

202.3 **Turn left (south) on Canal Street (US-285/62/180). 0.8**

203.1 Culebra Dolomite crops out in lower Dark Canyon Draw to right. **0.8**

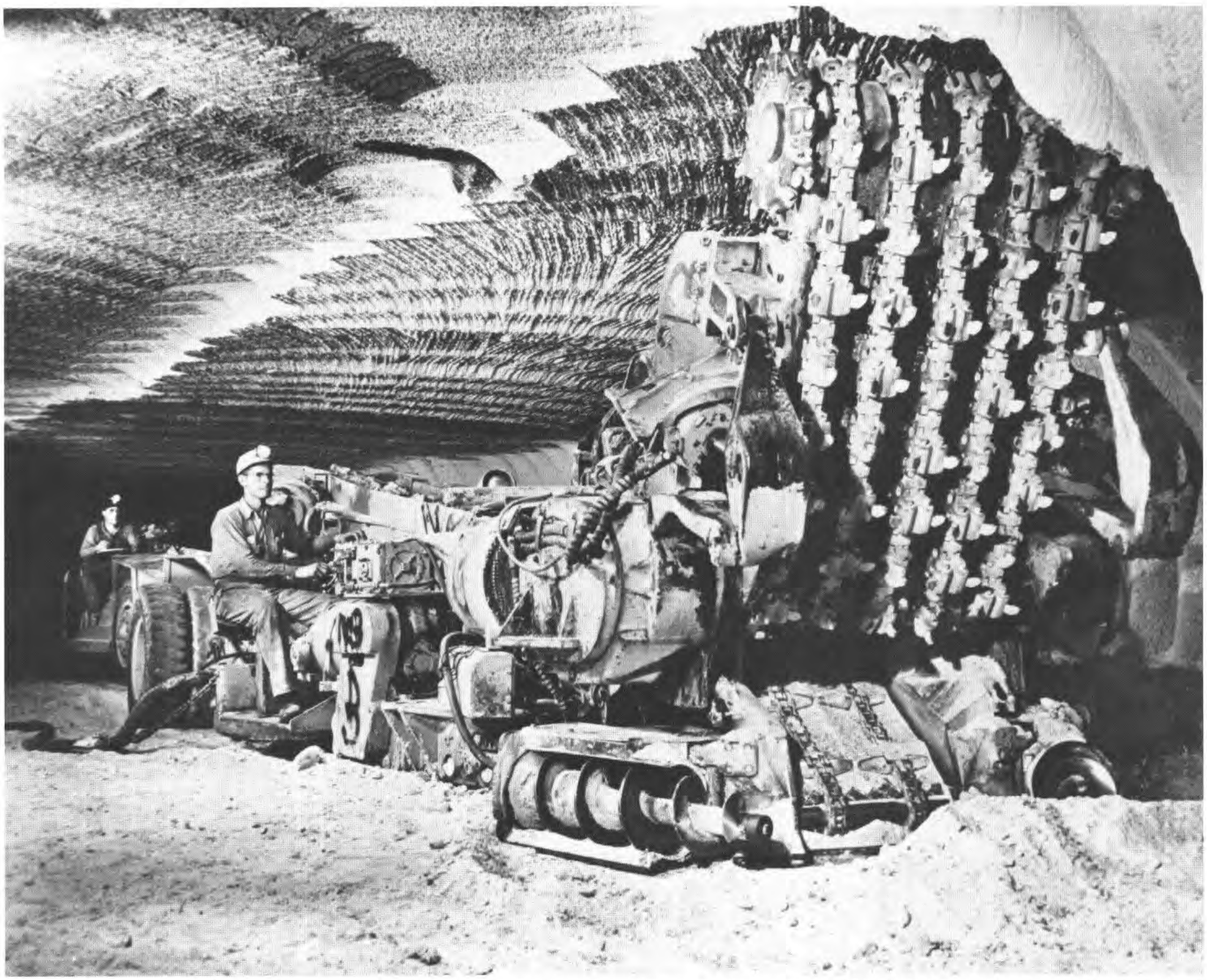
203.9 Milepost 34. Approaching junction; stay in right lane.. **0.4**

204.3 Bear right and follow US-62/180 toward Carlsbad Caverns. US-285 turns southeast toward Loving. **0.6**

204.9 National Park Service headquarters on the right. **0.8**

205.8 **Turn left (southeast)** into parking lot of the Carlsbad Civic Center.

End of First-Day Road Log.



By the end of World War II, the potash industry had begun to develop its own continuous mining equipment. This photo shows operations in the International Minerals of Chemical Corporation mine. Photograph by Robert Nymeyer, c. 1968. Courtesy of Southeastern New Mexico Historical Society of Carlsbad.