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John W. Hawley

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THE OGALLALA AND GATUŇA FORMATIONS IN THE SOUTHEASTERN NEW MEXICO REGION, A PROGRESS REPORT

JOHN W. HAWLEY

New Mexico Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801

Abstract _ The Ogallala Formation in the Southern High Plains section (Great Plains province) of southeastern New Mexico includes alluvial, eolian and playa-lake deposits and pedogenic calcretes of late Miocene and early Pliocene age (about 4-12 Ma). Beneath the Llano Estacado, it forms an almost continuous cover on rocks of Mesozoic age, is locally more than 400 ft ([20 m) thick and is a major aquifer. In the Pecos Valley section of the Great Plains and along the Portales Valley through the western Llano Estacado, fine- to coarse-grained elastics of late Miocene to middle Pleistocene age locally form thick fills (>1000 ft, 300 m) in large solution-subsidence depressions. These features are aligned along segments of the ancestral Pecos and Brazos Valleys and are underlain by evaporites of Late Permian age. Some of these deposits have always been included in the Ogallala Formation; but in the lower Pecos Valley area (Roswell, NM to Pecos, TX), correlative depression and valley fills have been mapped variously as "older alluvium, quartzose conglomerate, valley-fill alluvial deposits," and as the Gatuňa Formation. Gatuňa-Ogallala chronologic and nomenclature problems have not yet been resolved in that area; however, it is clear that an ancestral "lower" Pecos fluvial system has existed since late Miocene time near the present valley position between the Roswell (artesian) and Delaware Basins. In the sediment source area west of the Great Plains, Ogallala and Gatuňa correlatives are discontinuous, commonly thin and only locally aquifers. The oldest deposits include piedmont fan alluvium, pediment veneers and valley and basin fills. They record semiarid climatic conditions, prior epeirogenic uplift and volcanism and ongoing Basin-and-Range tectonism in a broad area extending southward from the Southern Rocky Mountains through the Sacramento section of the Basin and Range province. Significant uplift of mountain fault blocks occurred along the Rio Grande rift margin in the western part of the (sediment) source region. The facies-distribution patterns of both the Ogallala and Gatuňa Formations are quite complex west of the Southern High Plains. The oldest units may form basal fills of structural basins, solution-subsidence depressions, or stream valleys, or they may be preserved as piedmont alluvium capping high divides and tablelands, with younger deposits occurring as inset valley fills. Rising western highlands not only contributed runoff and sediment to the High Plain depositional system but also had a major influence on regional climate. The occurrence of prominent zones of secondary-carbonate accumulation in paleosols of the High Plains eolian cover indicates increasingly dry and more continental conditions in late Cenozoic time. Episodic deflation of alluvial plains prograding eastward and southeastward from mountain and piedmont source areas also produced eolian sediments that are a significant component of the Ogallala Formation and overlying Plio-Pleistocene deposits of the Llano Estacado area.

INTRODUCTION

The upper Tertiary Ogallala Formation in southeastern New Mexico comprises continental elastic deposits primarily derived from erosion of emerging highlands of the Southern Rocky Mountain and eastern Basin and Range physiographic provinces (Fig. 1; Hawley, 1984, 1986). As defined by Darton (1899, 1905, 1928a, b) in the High Plains section of the Great Plains province, the formation typically occurs as a widespread apron of alluvial and eolian deposits with a calcrete-caprock zone. In addition, valley and (solution-subsidence) depression fills in lowland areas throughout the Sacramento (Basin and Range) and Pecos Valley (Great Plains) sections are partly correlative with the Ogallala, but also include upper Cenozoic deposits mapped as Gatuňa Formation (incorrectly spelled Gatuňa). This paper provides a general overview of the late Neogene history of southeastern New Mexico and adjacent parts of western Texas (Figs. 1, 2) and a progress report on the status of the Gatuňa and Ogallala lithostratigraphic units. Emphasis is on geomorphic processes active in the region during the past 10 to 15 Ma, and on landforms and deposits of late Miocene (12 to 5 Ma) and Plio-Pleistocene (5 to 0.5 Ma) age. Papers in Gustayson (1990), Gustayson et al. (1991) and Whetstone (1984) provide further information on stratigraphy and aquifer characteristics of the Ogallala Formation and other upper Cenozoic units and the geomorphic evolution of the southern Great Plains. Brief discussions by Hawley (road log minipapers, this volume) summarize late Cenozoic stratigraphy, geomorphic history and calcisol genesis and classification in the southeastern New Mexico region.

BACKGROUND

Early studies

The Ogallala Formation was first formally described and mapped in eastern New Mexico by Darton (1928a, b). Prior to 1970, however, surface geologic studies were primarily of a reconnaissance nature and involved very little large-scale mapping or detailed measurement of sections. Early stratigraphic studies were concentrated in the Llano Estacado region of the Southern High Plains in western Texas (Patton, 1923; Reed and Longnecker, 1932; Evans, 1948, 1949; Johnson and Savage, 1955; Frye and Leonard, 1959, 1964). In that region, the formation is the dominant surficial geologic unit and is as much as 700 ft (210 m) thick. The fact that upper Cenozoic deposits constitute the major aquifer system of the Llano Estacado area of the High Plains received early recognition (Baker, 1915). Starting with Theis (1932), the High Plains aquifer system, with the Ogallala Formation as its main constituent, has been described in many parts of eastern New Mexico by ground-water geologists and hydrologists of the U.S. Geological Survey, State Engineer's Office and New Mexico Tech (Hawley, 1993, Appendix A).

The topography of the base of the Ogallala Formation beneath the Llano Estacado and the distribution patterns of underlying formations (Mesozoic and upper Paleozoic) are very important factors in any reconstruction of late Tertiary erosional surfaces and depositional events. Cronin's (1969) map compilation "showing (the) approximate altitude of the base of the Ogallala Formation" beneath the Llano Estacado area of Texas and New Mexico is certainly one of the most important contributions to the late Cenozoic history of southeastern New Mexico. Trends of master paleovalleys are clearly shown and can be tied to outcrops of Ogallala valley fills along western High Plains escarpments. Cronin's (1969) map also shows the position of a major drainage divide in the sub-Ogallala topography. Of particular interest is the buried ridge of Triassic bedrock that nearly coincides with the Mescalero Ridge escarpment at the southwestern edge of the Llano Estacado (Fig. I; Nicholson and Clebsch, 1961; Ash, 1963). As subsequently discussed, this divide separates two major fluvial systems (ancestral lower Pecos

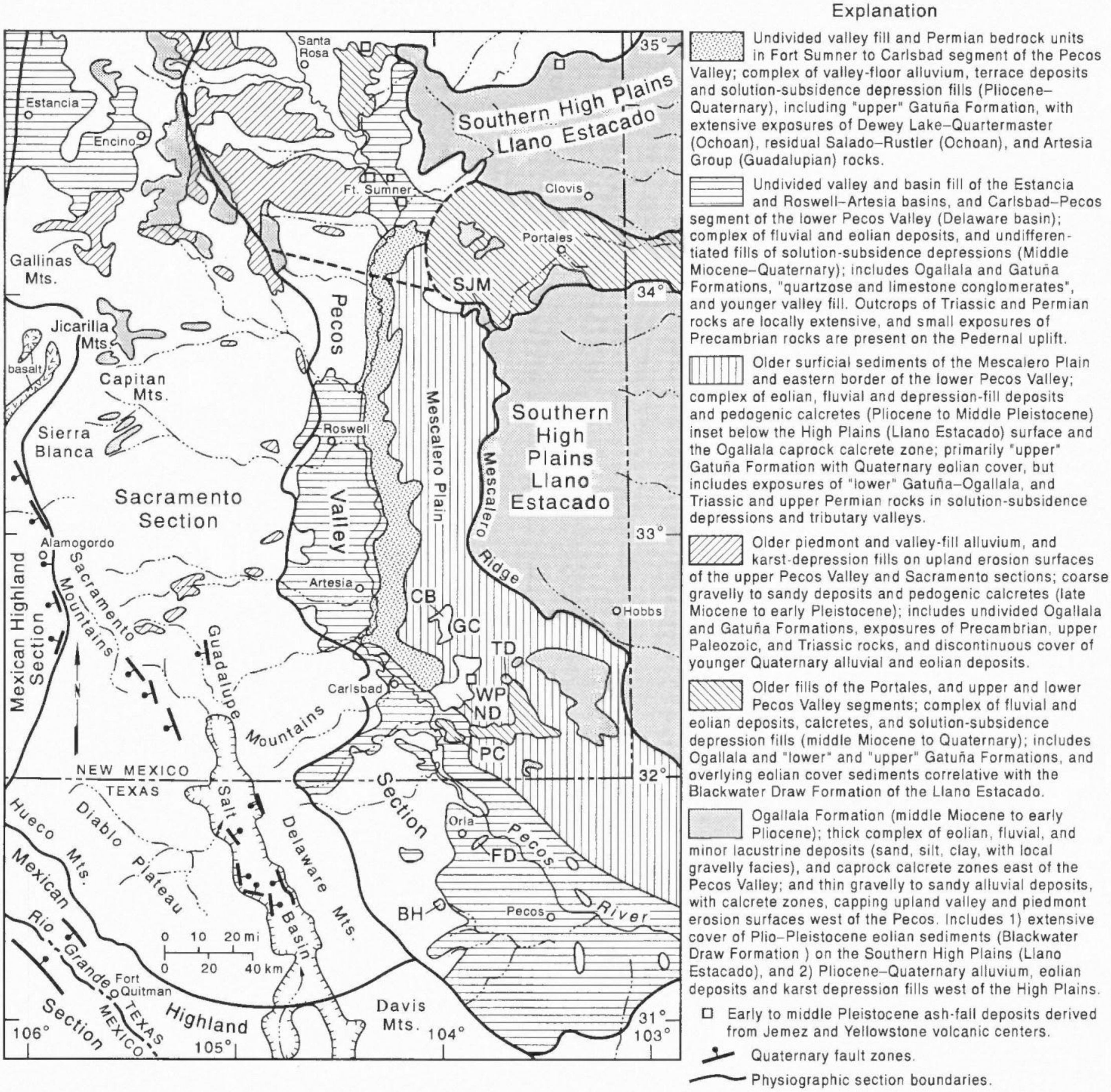

FIGURE 1. Index map of southeastern New Mexico region showing location of major physiographic subdivisions and general distribution patterns of upper Cenozoic deposits that include the Ogallala and Gatuña Formations or their correlatives. Occurrences of Plio-Pleistocene volcanic ashes and zones of known Quaternary faults are also shown. BH = Burnt Hills (TX), CB = Clayton Basin (NM), FD = Fourmile Draw (TX), GC = Gatuña Canyon (NM), ND = Nash Draw (NM), PC = Pierce Canyon (NM), TD = The Divide, SJM = San Juan Mesa (NM) and WS = WIPP site.

and upper Pecos-Brazos) that probably persisted throughout much or all of Ogallala time (Reeves, 1972; Hawley, 1984).

Early studies also dealt with the evolution of the ancestral Canadian and upper Pecos drainage systems, which are now entrenched below the High Plains surface in northeastern and in east-central New Mexico. The Portales Valley, which is cut below the Llano Estacado (Fig. 1), is the site of an abandoned reach of the upper Pecos that appears to have formed the headwaters of the ancestral Brazos River during late Miocene to early Pleistocene time. Basic elements of Portales Valley history were recognized by Baker (1915) and ancestral upper Pecos-Brazos deposits in New Mexico were first described in detail by Galloway (1956).

Lee (1925) was probably the first to recognize the major role that the dissolution of Permian evaporites had played in late Cenozoic landscape evolution of the Pecos Valley region and Adams (1944) documented widespread dissolution of Ochoan evaporites in the Delaware basin. Maley and Huffington (1953) mapped fills of late Cenozoic age that are particularly thick in solution-subsidence depressions adjacent to the Capitan reef trend and ancestral Pecos drainage lines. These deposits are as much as 1900 ft (580 m) thick in the Texas part of the

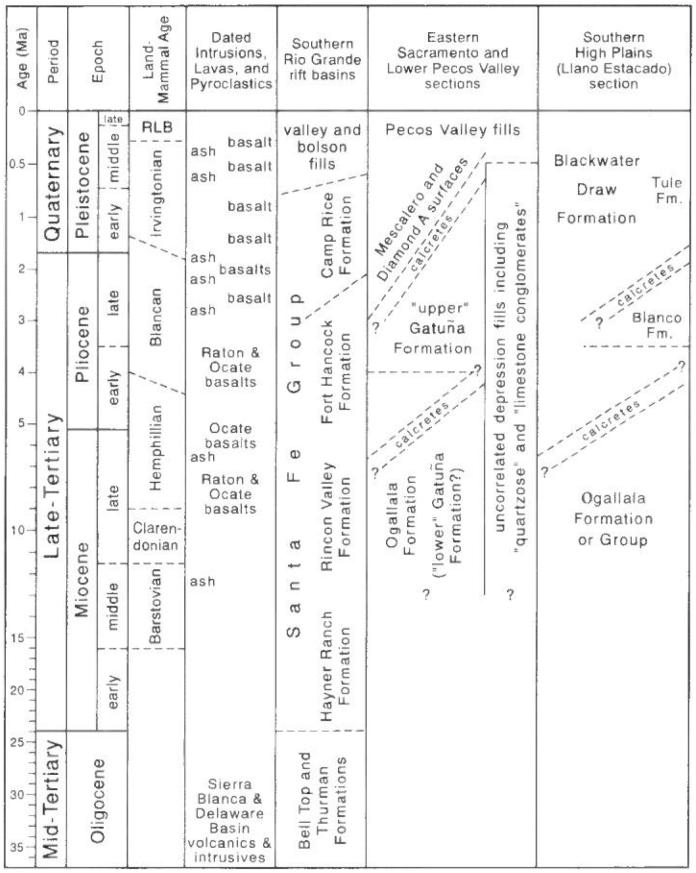

FIGURE 2. Provisional correlation of upper Cenozoic stratigraphic units in the southeastern New Mexico–western Texas region.

basin and about 1100 ft (360 m) thick in southeastern Eddy County, New Mexico (Bachman, 1984). Nicholson and Clebsch (1961) described similar but smaller-scale features (including the active San Simon Sink) in Lea County, New Mexico; and "solution-subsidence troughs" in the Gypsum Plain area of the Black and Delaware River basins west of the Pecos were mapped by Olive (1957).

Leonard and Frye (1962) made a limited field investigation of erosion surfaces, surficial deposits and associated molluscan faunas in the Texas part of the region. They described an ancestral (Pecos) river valley of Ogallala age between the Delaware Mountains on the west and the High Plains and Edwards Plateau sections on the east. Leonard and Frye (1962, p. 11), also presented geomorphic evidence for the existence of an integrated lower Pecos–Rio Grande system, "at least since mid-Tertiary time," downstream from Pecos and Reeves Counties, Texas. They did not, however, recognize the great significance of the solution-subsidence process in the geomorphic evolution of the area .

Darton (1928a, b) also noted that the Ogallala is present as discontinuous and relatively thin deposits capping erosion surfaces in the Sacramento section of the Basin and Range province. The Sacramento section includes a large part of central and south-central New Mexico (Fig. 1) and served as the major source area for Ogallala and younger deposits in the Pecos Valley and adjacent parts of the High Plains. This upland region is flanked on the north by the southern end of the Sangre de Cristo Range and extends southward through mountains of the Gallinas-Jicarilla-Capitan–Sierra Blanca area that are primarily formed on igneous-intrusive and volcanic rocks of middle Tertiary age. East-tilted fault block ranges, including the Sacramento, Guadalupe and Delaware Mountains, make up much of the southeastern part of the section. Northwestern mountain source areas for Ogallala sediments included precursors to the present Manzano, Sandia, Ortiz–San Pedro and southernmost Sangre de Cristo uplifts. The surface drainage in this area now discharges into the closed Estancia basin, Rio Grande or upper Pecos (Allen and Hawley, 1991).

Much of the valley and (solution-subsidence) depression fill in the lower Pecos area is ultimately derived from the Guadalupe, Delaware and Apache Mountains, which form the southeastern border of the Sacramento section (King, 1948, 1949; Hayes, 1964). A synthesis of the geology of the Texas part of the Guadalupe-Delaware-Apache range and adjacent basin areas has been published by the Bureau of Economic Geology (1968). King (1948) and Hayes (1964), respectively, described the Texas and New Mexico portions of the Guadalupe Mountains in detail. While these highlands have long been recognized as source areas for upper Neogene alluvial deposits (e.g., Sellards et al., 1932, p. 770), neither King nor Hayes (p. 54) found deposits of Ogallala age on highland erosion surfaces of the area.

The first major study of the Ogallala west of the southern High Plains was by Bretz and Horberg (1949a). They also investigated the origin of caliche caprock (primarily a pedogenic calcrete) and the geomorphic evolution of the Pecos Valley and adjacent parts of the Sacramento section (Bretz and Horberg, 1949b; Horberg, 1949). They made special note of carbonate-cemented gravelly fills of the ancestral Pecos Valley that had previously been designated the "quartzose conglomerate" by Meinzer et al. (1926) and Fiedler and Nye (1933) in studies of the Carlsbad Irrigation District and the Roswell artesian basin (Cox, 1967). Bretz and Horberg suggested that these deposits were a basal member of the Ogallala and not post-Ogallala valley fills; and they proposed that hundreds of feet of the formation once deeply filled the Pecos lowland to the level of an upland erosion surface, "the Sacramento Plain," which was graded from the Sacramento Mountain highlands to the Llano Estacado. According to their model, subsequent cycles of Pleistocene erosion (Diamond A—Mescalero, Blackdom, Orchard Park, Lakewood surfaces of Nye, 1933) resulted in removal of much of this ancient valley fill (Bretz and Horberg, I 949a, p. 488; Horberg, 1949, fig. 1).

Lang (1938, p. 84-85) introduced "Gatuňa formation" as the formal name for "an assemblage of rocks of various kinds that were laid down in the (lower) Pecos Valley in post–High Plains time and apparently after the completion of the maximum cycle of erosion of this valley. The deposits are of terrestrial origin and with them began the process of refilling of this valley." Lang designated a type area in "Gatuňa" Canyon at the eastern edge of Clayton Basin (sec. 35, T195, R30E) but he did not describe a type section. Gatuňa (Sp. Ufia de Gato) is a common name for *Acacia greggii* or catclaw acacia (Vines, 1960, p. 498-499). The formation was first mapped in detail by Vine (1963) in Nash Draw Quadrangle. He described Gatuňa reference sections at Pierce Canyon southwest of Nash Draw (secs. 22 and 23, T24S, R29E) and recognized that the unit "might actually represent rocks equivalent in part to the Ogallala" (Vine, 1963, p. 31) Vine (1960) also described post-Gatuňa solution-collapse features that involve the Permo-Triassic and upper Cenozoic section above the buried Capitan reef trend about 12 mi northeast of Carlsbad.

Thick fills of Late Cenozoic age, which correlate with both the Ogallala and Gatuňa Formations, are definitely present in adjacent parts of the Salt (structural) Basin west of the Guadalupe-Delaware range. In the Pecos Valley section, however, much of this material has been let down into solution-subsidence depressions and only scattered (high-level) gravel remnants are exposed at the surface. On quadrangle reaps by Hayes (1957, 1964) and Motts (1962), these deposits are included in "older alluvial" units of Pleistocene age. Upper Miocene to middle Pleistocene valley and depression fills are also mapped on the Geologic Atlas of Texas—Hobbs and Pecos Sheets (Bureau of Economic Geology, 1976a, b) as Gatuňa Formation of Pleistocene age. Brand and DeFord (1962) described "Gatuňa" gravels in the Burnt Hills area of western Reeves County, Texas (Fig. 1). The Burnt Hills deposits, which may be as old as late Miocene, are shown as "Bolson deposits (QTb)" on the Van Horn–El Paso (atlas) Sheet by the Bureau of Economic Geology (1968).

Studies since 1970

General geologic mapping at scales from 1:180,000 to 1:250,000 has been completed in southeastern New Mexico and adjacent parts of western Texas (Kelley, 1971, 1972; Bureau of Economic Geology, 1968, 1974, 1976a, b, 1978). There is a strong emphasis on late Cenozoic geology in many of these field studies. Mapping in New Mexico by the Texas Bureau of Economic Geology was for their Geologic Atlas project, with much of the field work being done by C. C. Reeves, Jr. The New Mexico State Highway Department (Lovelace et al., 1972) also published an atlas of 30—minute quadrangle maps on surficial geology and aggregate resources of southeastern New Mexico. The accompanying report includes an excellent review paper on the origin and distribution of caprock caliche deposits in southeastern New Mexico. General stratigraphic and structural information relating to units discussed here is also shown on the New Mexico Geological Society (1982) state highway geologic map (scale 1:1,000,000). Syntheses on the regional tectonic setting have been prepared by Woodward et al. (1978) and Henry and Price (1985).

Reviews of late Cenozoic stratigraphy and geomorphology of the region have been written by Reeves (1972), Bachman (1976, 1980), Hawley et al. (1976), Kelley (1980), Frye et al. (1982), Gustayson (1990) and Gustayson et al. (1991). Reports by Seni (1980) and Knowles et al. (1984) are two of a series of state and federal publications on the High Plains regional aquifer system (Weeks and Gutentag, 1981). They include maps of basal Ogallala topography and lithofacies distribution. Seni's (1980) report covers only the Texas part of the Llano Estacado, but he does present a hypothetical model of Ogallala depositional environments in eastern New Mexico. Maps in Knowles et al. (1984), which include the New Mexico High Plains and were compiled in part by C. C. Reeves and students at Texas Tech University, illustrate distribution patterns of major paleovalleys and lithofacies units. A very speculative model of the geomorphic evolution of the entire Pecos River basin developed by Thomas (1972), however, has not stood up under close geological scrutiny.

Much of the published work on the late Cenozoic stratigraphy of southeastern New Mexico was done by John Frye, Byron Leonard and Herbert Glass between 1970 and 1982. Brief descriptions of representative stratigraphic sections were made at hundreds of sites and samples were collected for paleontological and mineralogical analyses and carbon-14 dating. Ogallala reference sections were described by Frye et al. (1974, 1982), Leonard and Frye (1975) and Leonard et al. (1975). In many areas studied by Frye and associates, the Ogallala Formation appears to have a distinctly zoned suite of clay minerals, including smectites (montmorillonites), palygorskite (attapulgite) and sepiolite. Frye, Leonard and Glass used clay-mineral zonation combined with other properties such as pisolitic calcrete-caprock morphology and limited paleontological information to identify Ogallala deposits throughout the region.

The report by Frye et al. (1982) on the western extent of the Ogallala Formation in New Mexico summarizes their interpretations of late Cenozoic stratigraphy and structural deformation in the western Great Plains and adjacent parts of the Basin and Range province in central New Mexico (Figs. 1, 2). They concluded that significant tectonic deformation occurred in the Pecos Valley area after Ogallala deposition. Current research (next section), however, suggests that the major structural displacements in eastern New Mexico had taken place by early Pliocene time and that Plio-Pleistocene deformation in the Pecos and Canadian Valley region is primarily due to widespread solution subsidence (Bachman, 1980, 1984; Gustayson and Budnick, 1985; Gustayson and Finley, 1985; Gustayson, 1986).

The northern Delaware basin area, including parts of the lower Pecos Valley, is the site of ongoing geologic and hydrologic research for the Waste Isolation Pilot Plant (WIPP), a federal facility for disposal of radioactive wastes that are being generated by the Department of Defense. A salt bed in the Upper Permian (Ochoan) Salado Formation serves as the subsurface waste-repository unit. Of particular importance to Ogallala studies is WIPP site-characterization research that deals with the local and regional hydrogeologic setting (Lappin, 1988; Powers et al., 1990; Reith and Fischer, 1992; Chaturvedi, Corbet and Wallace, and Powers and Holt, this volume). While there are contrasting views of how the salt dissolution process occurs, all workers recognize the significant impact of dissolutional processes on late Cenozoic geomorphic history of the WIPP site area (Anderson, 1981, 1982; Bachman, 1980, 1981, 1984; Snyder and Gard, 1982). Detailed field studies by Bachman (1980, 1981) clearly support earlier observations on extensive solution collapse and basin filling made by Lee (1925), Adams (1944), Bretz and Horberg (1949a), Horberg (1949), Maley and Huffington (1953), Nicholson and Clebsch (1961) and Vine (1960, 1963).

The Gatuňa Formation and correlative deposits (e.g., "quartzose conglomerate") in the lower Pecos Valley have also been the subject of recent investigations, several related to the Waste Isolation Pilot Project. As is subsequently discussed, there is still no consensus on the age of the Gatuňa and its relationship to the Ogallala Formation of the Llano Estacado region (Kelley, 1971, 1980; Reeves, 1972; Bachman, 1976, 1980, 1981, 1984; Hawley, 1984; Powers and Martin, 1990; Powers and Holt, this volume).

CURRENT INTERPRETATIONS OF LATE NEOGENE HISTORY AND STRATIGRAPHY

Regional structural setting

The regional structural setting, in terms of both source highlands and sites of deposition, is a major factor that must be considered in any discussion of Late Cenozoic history (Hawley, 1978; Henry and Price, 1985; Eaton, 1987). Details on relative rates of uplift over the past 10-15 Ma are lacking, but current research in the Rio Grande rift shows that the major basin-range structural and topographic elements had formed by early Pliocene time (approximately 4 Ma; Riecker, 1979; Seager et al., 1984; Chapin, 1988). Information on inferred vertical crustal movements during the past 10 million years has been compiled by Gable and Hatton (1983). Their interpretations of the recent tectonic history of the Southern Rocky Mountain—Rio Grande rift region are primarily based on studies of Tertiary paleobotany by Axelrod and Bailey (1976). The latter workers suggested that relatively low mountain and basin altitudes and "mild-largely frostless" climates prevailed in north-central New Mexico in middle Tertiary through Barstovian time (middle Miocene; about 12-15 Ma, Tedford, 1981). Regional epeirogenic uplift started in middle to late Miocene time according to the Axelrod and Bailey model. Their interpretation is currently being challenged, however, because recent paleobotonical research indicates that much, if not all of the broad epeirogenic uplift of the southern Rocky Mountain region had already occurred by early Oligocene time (C. E. Chapin, personal comm. July 1992; Gregory and Chase, 1992).

Differential uplift and subsidence of Basin-and-Range and Rocky Mountain—Front Range blocks had a major impact on the Ogallala sediment source area, particularly during the late Miocene (O'Neill, 1988; S. Kelley et al., 1992). Uplift and east tilting of crustal blocks that form the major ranges of the southeastern Sacramento Section (Sacramento, Guadalupe, Delaware) has continued through late Quaternary time. Late Quaternary faults are well documented in the Salt and Tularosa Basins west, respectively, of the Guadalupe-Delaware and Sacramento uplifts (V. Kelley, 1971; Goetz, 1980; Seager, 1980; Pray, 1988). Kelley (1971) also proposed that Quaternary faults occur at the base of the Reef and Cueva Escarpments between Whites City and Carlsbad (Guadalupe Mountain—Delaware Basin boundary). Hayes and Bachman (1979, p. 1), however, "examined the evidence for those faults in the field and conclude(d) that the faults are nonexistent and that Kelley's conclusions were based on misinterpretation of exposures of fan gravel, jointing and shrub alignment." The Reef (and Cueva) Escarpment is basically an exhumed landform produced by partial removal of the evaporite-dominated sequence of Ochoan rocks that once filled the Delaware Basin and overtopped the Guadalupian rocks of the Reef and Northwestern Shelf area.

Rising western mountain masses resulting from Rio Grande rift and southern Basin-and-Range tectonism had a significant effect on climate, vegetative cover and geomorphic processes in the southern Great Plains region; and highlands of central and north-central New Mexico contributed much runoff and sediment to the Ogallala and Gatuňa depositional systems. Details of this changing climate-process system are not well documented, but the occurrences of well-developed pedogenic calcretes and other types of secondary carbonate accumulations in Ogallala and post-Ogallala deposits indicate increasingly arid and continental climatic conditions during Mio-Pliocene time (Hawley, 1984; Machette, 1985; Hawley, first day minipaper, this volume).

Future studies must give more consideration to the syntectonic character of the Ogallala depositional system. Workers in the High Plains (aquifer) area have routinely dealt with layer-cake stratigraphy in a predominantly aggradational environment. However, along the western margin of the Llano Estacado and certainly farther west across the Pecos and upper Canadian valleys, the process of regional uplift and local faulting and folding must have been active at least episodically during Ogallala deposition. Therefore, in many parts of southeastern New Mexico, the geomorphic position of older to younger members may often be reversed from the stacked sequence of beds observed in the Texas High Plains. The oldest (and perhaps coarsest) Ogallala deposits are more likely to occur as piedmont alluvial veneers capping highest divides and tablelands of the present landscape, whereas younger members would form higher terraces in stepped sequences of inset valley fills.

Except for Frye et al. (1982) and Hawley (1984), most geologists have assumed that only the highest erosion surfaces west of the Llano Estacado are capped by Ogallala deposits and have lumped all inset fills with post-Ogallala units (Kelley, 1971, 1972; Bachman, 1976; Hawley et al., 1976). Following the alternative (syntectonic) interpretation, the older inset fills of the western Portales Valley and areas to the west (Fig. I) may grade to upper beds of the Ogallala sequence on the Texas High Plains. If this is the case, then the highest-level (mesa-capping) gravels in the area (e.g., San Juan Mesa—Fig. 1) may correlate with basal Ogallala channel deposits in subsurface sections beneath the Llano Estacado farther to the east. Such structural interpretations are obviously complicated by the fact that salt dissolution (local and regional scale) has been going on concurrently with the tectonic deformation (Hawley et al., 1976; Hawley, 1984; Gustayson and Budnick, 1985; Gustayson and Finley, 1985; Gustayson, 1986).

Regional stratigraphic relationships

Gustayson and Winkler (1988) and Winkler (1990) recently demonstrated that the Ogallala Formation of the Texas High Plains (Llano Estacado) is not a series of coalescent alluvial fans as proposed by Seni (1980) and many earlier workers (e.g., Sellards et al., 1932, p. 770). It is instead a complex sequence of alluvial valley fills and eolian sand sheets with lesser amounts of lake and playa facies. In addition, Seni's (coalescent-fan) model of Ogallala deposition does not allow for persistence of a major fluvial system in the present lower Pecos Valley area since middle Miocene time (refer to Seni, 1980, fig. 12C, D). Large scale solution-subsidence associated with contemporaneous dissolution of Permian evaporites in the Pecos Valley section during this interval was the major factor complicating interpretations of the region's geomorphic history.

There is little direct evidence of the age of Ogallala deposits in New Mexico, except for K-Ar dating of interbedded and overlapping lava flows in the Raton section (4.1-8.3 Ma old; O'Neill, 1988). Bio stratigraphic and tephrochronologic information is available for correlative Ogallala and Santa Fe Group sections in adjacent parts of the Texas High Plains (Fig. 2; Lindsay et al., 1976; Izett, 1981; Schultz, 1990; Winkler 1987, 1990) and the Rio Grande rift in central New Mexico (Hawley, 1978; Tedford, 1981; Seager et al., 1984; Chapin, 1988). The biostratigraphic studies in the Texas Panhandle, with supporting dates from tephrochronology, provide approximate limits on the age range of the Ogallala Formation (Schultz, 1972, 1990; Winkler, 1990; Gustayson et al., 1991). Vertebrate fossils of Clarendonian provincial age (late Miocene) in basal Ogallala deposits indicate that they are at least 10 to 12 Ma old (Tedford et al., 1987). Fossils of Hemphillian (latest Miocene to earliest Pliocene) age and dated volcanic ash in the upper Ogallala show that uppermost beds, including at least part of the caprock zone, can be as young as 4 to 5 Ma.

In the Llano Estacado region, the Ogallala can be no younger than the overlying Blanco Formation and correlative units of Blancan provincial age, which may be as old as 3.5 Ma (Evans, 1948; Lindsay et al., 1976; Tedford et al., 1987). The pedogenic calcrete, with complex pisolitic and laminar structures (stage VI morphology, Hawley, first day minipaper, this volume) that forms the caprock zone is overlain by a complex sequence of eolian, playa-lake and local-alluvial deposits with lenses of volcanic ash. The tephra units in this sequence are mainly derived from calderas in the Jemez Mountains of New Mexico and the Yellowstone Park area. They range in age from about 2.3 to 0.6 Ma (Izett, 1981; Izett et al., 1972, 1981; Izett and Wilcox, 1982; Sarna-Wojcicki and Davis, 1991). Reworked clasts of Ogallala calcrete also occur in basal gravels of the Blanco Formation on the Llano Estacado and the "upper" Gatuňa Formation in the lower Pecos Valley (Evans, 1948; Bachman, 1976). A volcanic ash bed of middle to late Miocene age (preliminary radiometric date) has also been reported in the fill of a solution-subsidence depression in the lower Pecos Valley near Orla, Texas (37 mi northwest of Pecos, Fig. I; Hawley, first day minipaper; Powers and Holt, this volume). This fill has previously been correlated with the Gatuňa Formation.

The oldest Ogallala described in uplands of the Sacramento section includes pediment veneers and fills of valleys in mountains and high plateaus (Kelley, 1971, 1972; Lovelace et al., 1972; Segerstrom and Ryberg, 1974; Frye et al., 1982). These deposits in part record local Basin-and-Range tectonism; however, much of the area's local relief is probably residual from volcanic highlands that developed in Oligocene time and preceding (Laramide) uplift. As topographic relief increased, dissection of earlier-stage piedmont deposits and highland-valley fills contributed to downslope progradation of local alluvial aprons. This process ultimately resulted in construction of extensive alluvial plains in lowlands of the northern Sacramento section and deposition of fluvial, eolian and lacustrine deposits in adjacent parts of the Great Plains province (Pecos Valley and High Plains sections).

Kelley (1980) also suggested that the Gatuňa forms an extensive, but thin and discontinuous upland cover west of the Pecos Valley. Frye et al. (1982), on the other hand, included most of Kelley's (1980) Gatuňa in the Ogallala Formation. Discontinuous veneers of siliceous pebbles also occur on the summit of Guadalupe Ridge in Carlsbad Caverns National Park. These residual deposits were originally described as Ogallala by Bretz and Horberg (1949a), and other workers have suggested that the veneers are either Ogallala or Gatuňa remnants (Thomas, 1972; McKnight, 1986; Hill, 1987, p. 16-17). As already noted, King (1948, 1949) and Hayes (1964) found no evidence of Ogallala deposits in the Guadalupe-Delaware Mountain area. Ongoing studies (Hill, Crawford, Hawley and Cather) indicate that the Guadalupe Ridge veneers are derived from erosion of Cretaceous conglomeratic sandstones (Cox?) that originally capped an erosion surface on the Guadalupian reef-shelf depositional sequence. Hayes (1964, p. 37-38) described fissure-tilling remnants of these sandstones at several sites on Guadalupe Ridge and correlated them with "Washita age" (early Cretaceous) rocks that had already been recognized in nearby areas. This interpretation is also supported by recent published observations on "sand-filled fractures" within the Capitan Limestone by Melim (1991, p. 42-45).

Drainage from the Sacramento section contributed to the two major fluvial systems south of the Canadian River (Figs. 1, 2), one northeast of the Mescalero Ridge divide that crossed the Llano Estacado through the ancestral Portales Valley (upper Pecos–Brazos system) and one to the southwest through the Roswell and Delaware basins (lower Pecos). Subsurface information in cited reports, geologic mapping in the Pecos Valley (Kelley, 1971, 1980; Reeves, 1972, p. 110) and current investigations by the author and Powers (this volume) clearly support the premise that both of these fluvial systems existed throughout much, if not all of Ogallala time. Buried topography on Triassic bedrock (Nicholson and Clebsch, 1961; Ash, 1963) and surface topography of Ogallala caprock along the Mescalero Ridge and in outliers to the southwest show that the ridge area has persisted as a major drainage divide throughout late Cenozoic time (Hawley, 1984).

Eolian activity made a very significant contribution to Ogallala deposition, particularly in the High Plains area of east-central and southeastern New Mexico. The prevalence of eolian sediments (rather than fluvial) in Ogallala sections exposed along the Mescalero Ridge escarpment was first documented by Reeves (1972). It seems reasonable to assume that deflation of the vast alluvial plains prograding southeastward into the ancestral lower Pecos Valley system from highlands of the Sacramento section produced a significant amount of eolian material, especially in the western Llano Estacado area. Gustayson and Winkler (1988) and Gustayson (1990) noted similar eolian facies in Ogallala sections beneath the northeastern Llano Estacado that are downwind from the ancestral upper Pecos-Portales-Brazos Valley system. A trend toward drier climates in late Miocene-early Pliocene (Clarendonian and Hemphillian) time appears to have contributed to the effectiveness of eolian processes.

Deposits of the lower Pecos Valley and Delaware Basin in southeastern New Mexico and western Texas

Much work remains to be done on the gravelly to fine-grained deposits of late Cenozoic age that comprise the older valley fill sequence in the lower Pecos Valley section (Kelley, 1971, 1980; Reeves, 1972; Hawley et al., 1976; Bachman, 1976, 1980, 1981, 1984; Hawley, 1984; Powers and Holt, this volume). This very complex and locally thick sequence is primarily derived from source areas extending westward to highlands of the southern Sacramento section (Gallinas to Delaware Mountains). It includes the "quartzose conglomerate" (Meinzer et al., 1926; Fiedler and Nye, 1933; Bretz and Horberg, 1949a; Horberg, 1949; Cox, 1967), alluvial aquifers of the Roswell and Carlsbad ground-water basins (Hendrickson and Jones, 1952; Motts, 1962; Welder, 1983) and the Gatuňa Formation. The latter unit is described in detail by Powers and Holt (this volume) and discussed at several First Day stops. Bachman's (1976, 1980, 1981, 1984) studies show that at least the upper part of the Gatuňa forms an extensive valley and subsidence-basin fill of Pliocene to middle Pleistocene age. As has already been noted, no mapping or section description was originally done by Lang (1938) at the formation's type locality in Gatuňa Canyon (sec. 35, T195, R30E). The youngest part of the Gatuňa contains mid-Pleistocene (Lava Creek-B) ash derived from the last major eruption of the Yellowstone volcanic center about 0.6 Ma (Bachman, 1980, 1981; Izett and Wilcox 1982). The formation's "reference section" described in the Gatuňa Canyon type area by Bachman (1976) contains pisolitic caliche clasts clearly derived from erosion of Ogallala caprock-caliche now exposed in the western (Mescalero Ridge) escarpment of the Llano Estacado.

Kelley (1971, 1980), Reeves (1972) and Hawley (1984) considered that at least the lower part of the Pecos Valley fill, including much of the "quartzose conglomerate" and Gatuňa Formation, is an Ogallala-age deposit. The latter interpretation is in agreement with early observations by Bretz and Horberg (1949a; Horberg, 1949) and current work by Powers and Holt (this volume). As noted above, Bretz and Horberg also suggested that the early stage river valley was originally filled with great thicknesses of upper Tertiary sediments (which have since been removed by stream erosion). This hypothesis does not appear to be warranted, however, since there is no clear-cut geomorphic or strati-graphic evidence "that the Ogallala once ... covered all but the highest portions of the Sacramento and Guadalupe Ranges" (Bretz and Horberg, 1949a, p. 488; Horberg, 1949, fig. I; Hill, 1987, p. 91-92).

My current work shows that pedogenic calcrete, with the typical stage VI morphology of the Ogallala caprock (latest Miocene to early Pliocene age), caps the south rim of Pierce Canyon about 7 mi southwest of Malaga in the NV2 sec. 26, T24S, R29E. The calcrete zone is as much as 10 ft (3 m) thick and grades downward through pebbly sandstones into conglomeratic fluvial deposits (ancestral Pecos channel). Underlying red beds, as much as 300 ft thick, are well exposed between Pierce and Cedar Canyons east of the Pecos River in secs. 25, 26, 35 and 36, T24S, R29E. The entire sequence, which has always been correlated with the Gatuňa Formation (Vine, 1963; Reeves, 1972; Bachman, 1976, 1980; Kelley, 1980), fills a large solution-subsidence depression. Much of the section below the caprock and upper sandstone zone is highly deformed and tilted blocks of the Magenta Dolomite (upper Permian Rustler Formation) are locally exposed on the canyon floor. See Bachman (1980, 1984), detailed section descriptions by Powers and Holt (this volume) and discussion at First Day Stop 6.

The three reference sections of the Gatuňa Formation described by Vine (1963, p. B28-29) are on the north wall of Pierce Canyon in secs. 22 and 23, T24S, R29E. The top of these exposures, however, is about 70 ft (21 m) lower than the south canyon rim and they are capped with a less well developed pedogenic calcrete (stage V morphology) that is typical of early to middle Pleistocene geomorphic surfaces of the area (e.g., "Mescalero caliche" of Bachman, 1976, 1980). Current work indicates that there is a major unconformity in Vine's (1963) Gatuňa sections, with the upper part being about the same age as the reference section described by Bachman (1976) at the formation's type locality at Gatuňa Canyon (Fig. 1). The lower (deformed) "redbed" unit is correlative with the much older (late Miocene) depression fill that is better exposed on the south side of Pierce Canyon.

Reeves (1972, p. 110) suggested that "the Gatuňa Formation represents an ancient Pecos Valley fill contemporary with the post-basal gravel part of the Ogallala Formation on the Llano Estacado." The south-wall section in lower Pierce Canyon clearly supports this hypothesis; however, Vine's (north-wall) sections demonstrate that the upper Gatuňa Formation *as mapped* can be as young as middle Pleistocene (Bachman, 1976, 1980, 1981). If all the Pierce-Cedar Canyon deposits are included in the Gatuňa Formation (as has been done by most workers starting with Vine, 1963), then the definition of this lithostratigraphic unit should be changed to allow correlation of much of the depression fill with the Ogallala Formation.

Much of the ongoing confusion in stratigraphic nomenclature simply relates to lack of detailed mapping and subsurface control with respect to upper Cenozoic units in this region. One solution to the nomenclature problem would be to restrict the Ogallala Formation in southern New Mexico and western Texas to the Llano Estacado area. The Gatuňa Formation (or Group) could be then used to designate a separate lithostratigraphic subdivision of middle (?) Miocene to middle Pleistocene age that comprises valley and (solution-subsidence) depression fills in the lower Pecos Valley and adjacent parts of the Sacramento sections. Such a broad redefinition agrees with the earlier observations by Bretz and Horberg (1949), Reeves (1972) and Kelley (1980). A Plio-Pleistocene "upper" subdivision of the Gatuňa would also have to be recognized. This unit would coincide with the original concept of a post-Ogallala Gatuňa Formation (Lang, 1938; Vine, 1963; Bachman, 1976, 1980, 981) that is already well established in the Clayton Basin and Nash Draw areas. An equally valid alternative would be to follow Bachman (1976) in restricting the Gatuňa to post-Ogallala deposits of Plio-Pleistocene age in the lower Pecos Valley area. Ancestral valley and depression fills of late Miocene to early Pliocene age (>4 Ma) should then either be recognized as a member of the Ogallala Formation or be assigned a new lithostratigraphic name.

CONCLUDING REMARKS

The emphasis of this progress report is on the geology and late Neogene geomorphic history of eastern New Mexico, with special attention given to deposits of late Miocene to middle Pleistocene age (approximately 12 to 0.5 Ma) that include the Ogallala and Gatuňa Formations. The latter units have been a formally recognized in New Mexico for more than 50 years and the list of workers involved in their study almost reads like a Who's Who of North American geology. These formations and correlative valley and depression fills are still inadequately mapped, however, particularly in the subsurface; and many important chronostratigraphic, lithofacies and structural problems remain to be solved.

The age of dominantly fine- to medium-grained fills in the large solution-subsidence depressions of the northern Delaware Basin (originally described by Maley and Buffington, 1953), as well as thinner conglomeratic deposits in the Roswell to Carlsbad segments of the Pecos Valley (Fiedler and Nye, 1933; Horberg, 1949; Cox, 1967), is still poorly documented. The maximum thickness of these upper Tertiary deposits ranges from 1000 to 1900 ft (300-580 m) in the Carlsbad, New Mexico to Pecos, Texas area. It now appears that much of this depression and valley fill is of late Miocene age, but it has been previously correlated with a Plio-Pleistocene Gatuňa Formation by many workers. Similar (Ogallala) deposits of Hemphillian and Clarendonian age (5-12 Ma) occur in the Canadian Valley-northern Llano Estacado area of the Texas Panhandle (Gustayson and Finley, 1985; Gustayson, 1990; Winkler, 1990).

An important (and certainly the most controversial) conclusion in this report is that, for at least the past 10-12 Ma, an ancestral "lower" Pecos fluvial system followed a course through southeastern New Mexico and western Texas that is very close to the present Roswell-Carlsbad-Pecos valley trend. Deposits of this system (e.g., Ogallala, Gatuňa and "quartzose conglomerate") have progressively and differentially subsided as dissolution of evaporites of Leonardian to Ochoan age (Yeso to Rustler Formations) occurred in various parts of the region. Implications relating to WIPP site integrity are very clear. Rates of dissolution in the "lower" Pecos Valley of New Mexico are significantly slower than those of models that limit most of valley and solution-subsidence depression formation to post-Ogallala time (past 4 Ma).

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For many years these tombstones marked the graves of Andrew Boyle and John Beckwith at the mouth of Pierce Canyon, where they and John Jones were killed in a series of 1879–1880 gun battles. Photographer unknown, c. 1926. Courtesy of Southeastern New Mexico Historical Society of Carlsbad.