Geology of the WCS – Flying "W" Ranch, Andrews County, Texas

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Submitted to

Andrews Industrial Foundation

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April, 2000

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1. Introduction

The general geological setting of the WCS - Flying "W" Ranch area in western Andrews County, Texas, has been previously described in permit applications (e.g., AM Environmental, 1993) and unpublished reports (Lehman, 1996a; 1996b). These reports provide an adequate overview of the regional geological setting and a detailed description of the site-specific conditions at the WCS facility. For example, Figure 1 shows the local topography of the "red bed" surface as was determined by the thorough geotechnical investigation done during the design of the WCS facility (AME, 1993). An exploratory drilling program conducted from March through June 1999 has greatly expanded the database on subsurface geologic conditions and groundwater in this area. In this report, some pertinent general information from the earlier documents is repeated, but attention is focussed instead on new detailed information that has resulted from the recent drilling program.

Thirty-five air-rotary boreholes were completed as piezometers on the WCS - Flying "W" Ranch (Figure 2). Three of the boreholes (#22, 23, and 24) were offset and drilled to greater depth (#22B, 23B, 24B). One borehole (#4) partially collapsed and remains problematic. Detailed geologic logs for each of the 35 boreholes are included as an appendix to this report. This report provides the following:

[1] further delineation of the "Red Bed Ridge" beneath the ranch property,

[2] description of each of the geologic units penetrated in the boreholes,

[3] discussion of the relationship between the occurrence of groundwater and subsurface geologic conditions, and

[4] methods used to discriminate deposits of the Ogallala and Antlers Formations.

Several figures are included to document the subsurface geology and groundwater distribution, and are discussed where appropriate in the report. Figure 2 shows the locations of five lithologic cross-sections that are provided as Figures 3 through 7. Figures 8 through 10 map the elevation of the "red beds," the thickness of the Antlers sand, and the areal distribution of saturated thickness.

2. Nature and Origin of the Buried Triassic "Red Bed Ridge"

2.1 General Information

The WCS-Flying "W" Ranch straddles a prominent buried ridge developed on the upper surface of the Triassic Dockum Group "red beds." This feature is referred to informally as the "Red Bed Ridge." Previous reports (e.g., Lehman, 1996a) have described this feature, but the recent drilling program provides additional information on its nature and extent (Figure 8).

The crest of the buried "Red Bed Ridge" is a mile or so in width and extends for at least 100 miles from northern Lea County, New Mexico, through western Andrews County and into Winkler and Ector Counties, Texas. The modern surface topography roughly coincides with the trace of this buried ridge, but is in general more subdued. In Lea County, the buried ridge runs parallel to and less than a mile northeast or southwest of the Mescalero Escarpment (Nicholson and Clebsch, 1961; Ash, 1963; Cronin, 1969), and similarly in Winkler and Ector counties the buried ridge coincides roughly with the western escarpment of the High Plains. The ridge is at least in part a product of structural deformation, as underlying Triassic strata have subsided in response to dissolution of Permian salt beds to the south and west of the ridge, underlying the Monument Draw Trough, San Simon Swale, and Pecos River Valley (Maley and Huffington, 1953; Nicholson and Clebsch, 1961; Anderson, 1980; Baumgardner et al., 1982; Gustavson and Finley, 1985). The ridge also roughly parallels the western margin of the buried Central Basin Platform in underlying Permian strata. However, the ridge is also in part a product of post-Triassic erosion, which has removed part of the Triassic section both northeast and southwest of the ridge. Cretaceous strata are absent southwest of the ridge. To the north and east of the "Red Bed Ridge", the High Plains surface is relatively undisturbed, and underlying Cretaceous and Tertiary strata are gently inclined to the southeast. In contrast, to the south and west of the ridge, dissolution of underlying Permian salt beds has resulted in deformation of the Triassic and Tertiary strata, and the High Plains surface has been locally disrupted by subsidence.

Several authors have commented on the nature and importance of this buried ridge, but it has not received widespread attention. Hawley (1984, pp. 161-162) regarded this as the position of a major drainage divide in the sub-Ogallala topography, and that this divide separated two major fluvial systems throughout Late Cenozoic time. Deposits of the Ogallala Formation lie to the north and east of the buried ridge, while deposits of the ancestral Pecos River (variously mapped as "Cenozoic Basin Fill," Gatuña Formation, or Ogallala Formation) lie to the south and west of this ridge (Reeves, 1972; Kelley, 1980; Hawley, 1984, 1993). Hawley (1993) suggested that use of the name "Ogallala Formation" could be restricted to deposits northeast of this divide, while the name "Gatuña Formation" could be used for equivalent deposits to the southwest. Little or no sediment accumulated on the summit of the buried "Red Bed Ridge", where instead, the "Caprock" Caliche developed directly on the exposed surface of underlying Triassic or Cretaceous strata, or on a thin veneer of eolian sediment. Reeves (1972) indicated that basal Ogallala gravels are present, at least locally on the crest of the ridge, suggesting that it may not have been an effective drainage divide during the later phases of Ogallala deposition. It is apparent that the buried ridge marks the position of a persistent ancient drainage divide between the ancestral Pecos River (to the southwest) and the Brazos and Colorado Rivers (to the northeast). It also roughly coincides with the modern drainage divide.

2.2 WCS - Flying "W" Ranch

The recent drilling program defined the extent of the "Red Bed Ridge" on the ranch area in greater detail than known previously, and provided further evidence for the origin of this feature. Cretaceous strata overlie the summit of the ridge along its length. AM Environmental (1993) had previously reported over 50 boreholes and well logs within the WCS site (Figure 1), and these data points were considered in the construction of the "red bed"-related maps within Andrews County in this report. Weaver Boos & Gordon, Inc. (1997) also provided data at 11 boreholes west of the state line and west of the WCS site. The "Red Bed Ridge" enters the northwest corner of the ranch and extends to the WCS landfill area and southeastward to Windmill Hill (Figure 3). From there, the ridge branches southward to the vicinity of well #30 and eastward to the vicinity of well #26. The southern branch likely terminates south of the ranch boundary, while the eastern branch probably tracks the continuation of the ridge to the south and east. Along the length of the ridge, the "Caprock" Caliche is exposed at or near the land surface, and so generally corresponds to the mapped distribution of the Kimbrough soils or Blakeney and Conger soil association (Figure 2; Conner et al., 1974). Additional drilling is necessary to establish the continued course of the "Red Bed Ridge" to the east; however, it likely continues roughly south and east along the route of State Highway 176 where the Kimbrough and Blakeney-Conger soils are present.

The presence of the "Caprock" Caliche over the entire area, both north and south of the "Red Bed Ridge" suggests that the ridge is not the buried erosional edge of the Caprock Escarpment, one of several possible interpretations of this feature. The ridge was present prior to formation of the "Caprock" Caliche and subsequent erosional retreat of the escarpment of the High Plains. Nevertheless, the absence of Cretaceous strata southwest of the ridge indicates that at least part of the relief on this feature is a result of erosion.

On the WCS - Flying "W" Ranch, and along most of the length of the "Red Bed Ridge", the southwestern flank of the ridge is more steeply inclined than the northeastern flank. The decline in elevation of the basal sand interval of the Antlers Formation southwest of the ridge (e.g., Figure 4, well #15) suggests that some of the relief on the "Red Bed Ridge" is owing to post-Cretaceous/pre-Late Tertiary structural deformation. However, the irregular southern boundary of the ridge indicates that relief is likely not due to faulting, and may more likely reflect a gentle fold.

3. Subsurface Geology

In this following section, each of the geologic units documented in the WCS - Flying "W" Ranch drilling program is described. The formations are given in ascending order (from oldest to youngest). General information on the distribution and characteristics of each unit is provided, followed by information specific to conditions observed in the WCS - Flying "W" Ranch area.

3.1 Chinle Formation (= Cooper Canyon Formation, Dockum Group: Triassic)

3.1.2 General Information

The distribution and regional characteristics of the Triassic Dockum Group were recently reviewed by Lehman (1994a, 1994b). The Dockum Group consists of five formations; in ascending order these are the Santa Rosa, Tecovas, Trujillo, Cooper Canyon, and Redonda Formations. These strata attain their maximum total thickness in excess of 1800 ft in the subsurface of Yoakum County, and are over 1000 ft thick in western Andrews County. The uppermost unit in the Dockum Group was traditionally (but incorrectly) referred to as part of the Chinle Formation in the southern part of the High Plains region. More recently these strata have been identified as the Cooper Canyon Formation (Lehman, 1994; Lehman et al., 1992). These

1989) and Nativ and Gutierrez (1988). The entire local Cretaceous stratigraphic section consists of six formations; in ascending order these are the Antlers, Walnut, Comanche Peak, Edwards, Kiamichi, and Duck Creek Formations. In the Southern High Plains area, Cretaceous strata attain their greatest preserved thickness in the vicinity of Yoakum County where they exceed 220 ft in total thickness. Southward from Yoakum County, the Cretaceous section thins and is absent in some areas of Gaines and Andrews Counties, primarily due to erosion prior to deposition of the Ogallala Formation. In southern Andrews County, and areas further south, Cretaceous strata are thicker and widely exposed.

Only the basal Cretaceous unit, the Antlers Formation, is present in the WCS-Flying "W" Ranch area; although a small outcrop identified as Fort Terrett Formation (equivalent to the Comanche Peak Limestone) is mapped immediately west of the ranch in Section 29 T.21S. (Hobbs Sheet, 1976), and a thick bed of Cretaceous limestone is also exposed on the ranch in the floor of a gravel pit in the west-central part of Section 8 (Block A-39; see Figure 9). This material is also likely a part of the Fort Terrett (= Comanche Peak) limestone. The "basal sand" of the Cretaceous section in the High Plains region is identified as the Antlers Formation, but in older literature is also referred to as the Antlers Sandstone, Trinity Sandstone, or Paluxy Sandstone (see Fisher and Rodda, 1967). It is also referred to informally variously as the "Antlers Sand" or "Trinity Sand." This unit consists of weakly cemented fine to medium-grained quartz sandstone and chert-pebble conglomerate. The Antlers Formation varies regionally from 10 ft to 80 ft in thickness (Nativ and Gutierrez, 1988). The thick areas comprise several linear belts trending approximately southeastwardly across the High Plains, where the Antlers Formation fills erosional channels incised into the underlying "red beds" of the Dockum Group (Fallin, 1989).

3.2.2 WCS - Flying "W" Ranch

No outcrops of the Antlers Formation are found in the WCS - Flying "W" Ranch area, but these deposits are exposed in the walls of the excavation at the WCS facility, and are present within a few feet of the land surface in that vicinity. The Antlers Formation is present only in the northwest and central part of the ranch area where it forms a buried erosional remnant along the crest of the "Red Bed Ridge" (Figure 9). The top of the Antlers Formation is encountered in borings at depths between 5 and 80 ft below ground surface. The subcrop of the buried Antlers

Formation is expressed at the land surface, and corresponds roughly with the area bounded by a subtle increase in slope at a topographic elevation of about 3450 to 3485 ft.

In the WCS - Flying "W" Ranch area, the Antlers Formation attains a maximum thickness of about 70 ft and consists of three stratigraphic units; in ascending order these are [1] a lower coarse-grained gravelly sand, yellowish brown in color (10 YR 7/2 to 7/6), between 10 and 30 ft thick with distinctive multicolored chert gravel, [2] a very fine to fine-grained white (10 YR 8/2) quartzose sand, consisting of nearly pure quartzarenite, 10 to 30 ft thick, and [3] an upper interval of multicolored shale and mudstone, 5 to 45 ft thick. Where the upper shale interval is thickest, it exhibits a stratigraphic sequence with white siltstone (10 YR 8/2) at the base, grading upward to dark red or purple mudstone (10 R 4/4 or 5 YR 8/4 to 6/4), gray (5 Y 7/2) shale, and an upper layer of yellow (10 YR 7/6) calcareous shale or argillaceous limestone. The limestone layer at the top of this interval may actually be the base of the Fort Terrett (= Comanche Peak) limestone. It is exposed at the land surface in the floor of a gravel pit in Section 8 (Block A-39).

The upper shale interval (unit 3, above) is present only where the Antlers Formation exceeds 40 ft in thickness, in the northwestern corner of the WCS - Flying "W" Ranch area and in the central area surrounding Windmill Hill (see Figures 5, 7, and 9). Elsewhere in the area, the Antlers Formation has been thinned or entirely removed by post-Cretaceous erosion, and younger strata rest on the lower sandy strata of the Antlers or on the underlying Dockum Group "red beds". Only the lowermost part of the Antlers Formation (unit 1, above) is present within the WCS Facility boundaries and exposed in the walls of the excavation there.

Groundwater in the WCS - Flying "W" Ranch area is found almost exclusively in the lower sandy part of the Antlers Formation.

3.3 Ogallala Formation (Late Tertiary: Miocene)

3.3.1 General Information

The regional distribution and characteristics of the Ogallala Formation and the Ogallala aquifer are well known (Cronin, 1961; 1969), and have been documented in numerous reports (recently reviewed by Gustavson, 1990; Gustavson et al., 1991). Regionally, the Ogallala Formation thins southward across the High Plains, and so is relatively thin in Andrews County, which lies near the southwestern border of the High Plains. In the southern part of its distribution, the Ogallala Formation does not exceed 100 to 200 ft in thickness (Seni, 1980). On a local scale, the thickness of the Ogallala Formation also varies from relatively thick sections (typically exceeding 100 ft) dominated by gravel and coarse sand, to relatively thin sections (typically less than 100 ft) dominated by finer sand and silt. The thick sections represent fluvial paleo-valley fill deposits that trend southeastwardly across the High Plains. These paleo-valley deposits are marked by higher net thickness of sand and gravel, and a high percentage of sand and gravel (Seni, 1980). Such areas generally correspond to the greatest saturated thickness in the Ogallala aquifer. The broad areas where the Ogallala Formation is relatively thin or absent represent "interfluve" or upland regions between the paleo-valley axes, where fine-grained eolian sediments predominate. The Ogallala Formation is thin or absent over the top of remnant Cretaceous bedrock "highs" on interfluves (e.g., Reeves, 1972), and may never have been deposited in these areas. Where present in interfluve regions, the Ogallala has a low net sand and gravel thickness and low percentage of sand and gravel. The interfluve areas correspond to regions with lower saturated thickness in the Ogallala aquifer (e.g. Peckham and Ashworth, 1993; Nativ and Smith, 1987).

In northern Andrews County, northeast of the "Red Bed Ridge," the Ogallala Formation is relatively thick and consists of fluvial sand and gravel deposits filling the southernmost of the paleo-valleys, which roughly coincides with the present course of Monument Draw in northern Andrews and southern Gaines Counties. The Ogallala Formation is absent from central Andrews County and areas southward where Cretaceous strata are present at or near the land surface in most areas. The "Red Bed Ridge," including the WCS - Flying "W" Ranch area, is an interfluve region.

3.3.2 WCS - Flying "W" Ranch

The Ogallala Formation is not exposed in the WCS - Flying "W" Ranch area, but is present in the subsurface along the north and east sides of the ranch boundary at a depth of 45 to 105 ft below ground surface. In this area, the Ogallala Formation varies from 5 to 40 ft in thickness and rests on Dockum Group "red beds" or locally on the Antlers Formation (see Figures 4, 5, and 6). These deposits consist of yellowish brown (10 YR 8/4) fine to medium-grained sand with granule-pebble gravel. Where the Ogallala deposits are greater than 20 ft thick, an upper interval of very fine to fine-grained sand, slightly pink in color (5 YR 7/4) is present.

Groundwater was found in only three borings that penetrated the Ogallala Formation along the eastern border of the ranch area.

3.4 ?Gatuña Formation ("Cenozoic Basin Fill": Late Tertiary - ?Quaternary)

3.4.1 General Information

Southwest of the "Red Bed Ridge," deposits in part equivalent in age to the Ogallala Formation are present, but these have typically been identified informally as the "Cenozoic Basin Fill" (Maley and Huffington, 1953) or "Cenozoic Pecos Alluvium" (Ashworth and Flores, 1991). They are at least in part equivalent to the Gatuña Formation (Kelley, 1980). Some of these deposits have been mapped as Ogallala Formation (Nicholson and Clebsch, 1961; shown as "To" on the Geologic Atlas of Texas, Hobbs Sheet, 1976), but may more logically be included with the Gatuña Formation, as suggested by Hawley (1993). In the WCS - Flying "W" Ranch area, these deposits predate formation of the overlying "Caprock" Caliche, and therefore are equivalent in age to the Ogallala Formation. Nevertheless, they differ lithologically from sediments of the Ogallala. These deposits will be referred to here as the ?Gatuña Formation, using the question mark to indicate this uncertainty in formation assignment.

The alluvial fill of the Lower Pecos Valley (including the Gatuña Formation) is at least 13 million years old (as old as the basal sediments of the Ogallala Formation; Powers and Holt, 1993; Hawley, 1993), and so downcutting and widening of at least the lower part of the Pecos River Valley must have occurred before or during deposition of the Ogallala Formation. The youngest part of the Gatuña Formation is no older than 600,000 years.

The Pecos River Valley subsided in response to subsurface salt dissolution. A peripheral zone of subsurface (Permian) salt dissolution surrounds the High Plains, with its inner boundary generally coincident with the present escarpment of the High Plains (Gustavson and Simpkins, 1989). This peripheral belt of subsurface salt dissolution underlies the Pecos River Valley. A curvilinear belt of subsurface salt dissolution also coincides with the buried Permian Capitan Reef trend surrounding the Delaware Basin. Salt dissolution has occurred over the buried summit of the artesian reef aquifer (Anderson, 1980; Baumgardner et al., 1982; Reeves, *in* Gustavson et al., 1991). Extensive salt dissolution over the Capitan Reef trend resulted in subsidence of the Monument Draw Trough in Winkler and Ward counties, Texas and in the

Delaware Basin beneath the Pecos River Valley (Maley and Huffington, 1953). Subsidence over the reef trend resulted in a depression now filled with "Cenozoic Basin Fill," referred to locally as the Monument Draw Trough. This belt lies 15 to 20 mi west-southwest of the WCS - Flying "W" Ranch.

3.4.2 WCS - Flying "W" Ranch

The ?Gatuña Formation is exposed on the ranch only in a small area at Baker Spring (Figure 2; Section 28, T.21S.). Approximately 15 to 20 ft of coarse, red, cross-bedded gravelly sand, with scattered large boulders of sandstone and limestone, is exposed along the steep bluff on the north and east side of Baker Spring, overlain by the "Caprock" Caliche. The base of the ?Gatuña Formation is not exposed at this location, but must lie at shallow depth because the Dockum Group "red beds" crop out several hundred feet to the south. The ?Gatuña Formation is present extensively in the subsurface along the southern and southwestern boundary of the ranch area at depths from 45 to 115 ft below ground surface (see Figures 3, 4, 5, and 6). The ?Gatuña deposits are very thin in this area, from 5 to 15 ft, and consist of fine to medium-grained sand and sandstone with granule-pebble gravel. These sediments have a distinctive red coloration (10 R 6/4 to 5 YR 4/6-6/6). Deposits of the ?Gatuña Formation rest on Dockum Group "red beds" everywhere on the WCS - Flying "W" Ranch.

No groundwater was found in the boreholes in the ?Gatuña Formation, although groundwater appears to be discharging from these deposits at Baker Spring (see Figures 3 and 7).

3.5 "Caprock" Caliche (Late Tertiary - ?Quaternary)

3.5.1 General Information

Overlying all pre-Quaternary strata in the High Plains region is a thick bed of hard caliche. This dense layer of pedogenic limestone is often referred to informally as the "Caprock" Caliche in the Southern High Plains region where it overlies the Ogallala Formation. It is usually mapped as part of the Ogallala Formation. However, the term "Caprock" Caliche has not been accepted as a formally recognized stratigraphic unit, because in many areas it consists of several superimposed caliche beds that formed at different times, and includes caliche that formed earlier during deposition of the Ogallala Formation, as well as in more recent times, long after the end of Ogallala deposition (Gustavson et al., 1991). Caliche developed on the surface of older

Cretaceous rocks is mapped simply as "caliche" (shown as "Qcc" on the Geologic Atlas of Texas, Hobbs Sheet, 1976), and not as part of the Ogallala Formation although it is identical in composition and morphology to the "Caprock" Caliche and likely formed at the same time. The term "Caprock" Caliche is used here in quotation marks to reflect this informal status and uncertain correlation.

In areas such as western and southern Andrews County, where the Ogallala Formation is absent or very thin, the "Caprock" is highly brecciated, pisolitic, and silicified; and it formed directly on the eroded surface of older (Cretaceous) strata. Many of the exposures mapped as Ogallala Formation in Andrews County (shown as "To" on the Geologic Atlas of Texas, Hobbs Sheet, 1976) consist in reality only of "Caprock" Caliche developed on top of older Cretaceous strata. In many cases, no actual deposits of the Ogallala Formation are present. In southern Andrews County, and areas farther south, caliche developed on the surface of older Cretaceous rocks is mapped simply as "caliche" (shown as "Qcc" on the Geologic Atlas of Texas, Hobbs Sheet, 1976), and not as part of the Ogallala Formation.

The "Caprock" Caliche formed on the High Plains surface after deposition of the Ogallala Formation (Late Miocene) and at least in part prior to deposition of the Blanco Formation (Late Pliocene). It is likely that formation of the "Caprock" began when the High Plains surface was isolated by erosional incision of the Pecos, Canadian, Brazos, and Colorado rivers (Osterkamp and Wood, 1984).

3.5.2 WCS - Flying "W" Ranch

The "Caprock" Caliche is present over the entire ranch area, and the upper surface of the "Caprock" is exposed at the land surface in many places along crest of the "Red Bed Ridge" where erosion has removed the overlying cover of Quaternary windblown sediment (see Figure 2). Where the "Caprock" is present near the land surface, the thin Kimbrough soil, or Blakeney and Conger soil association, is developed (Conner et al., 1974). A complete section of the "Caprock" is exposed along the north and east sides of Baker Spring, and in several gravel pits (Figure 2; southeast Section 3 and west-central Section 8, Block A-39). The top of the "Caprock" typically lies at a depth of 25 to 50 ft, but is found at nearly 100 ft in the southwest corner of the ranch. The "Caprock" formed on the upper surface of the Antlers, Ogallala, and

?Gatuña Formations and engulfs materials of these formations, particularly in its lower part. It evidently formed on a land surface with substantial topographic relief (see Figures 3 through 7)

The "Caprock" Caliche consists of hard, laminated, and pisolitic caliche with included chert pebbles. It is typically 5 to 10 ft thick, but up to 20 ft thick in a few places. Where the "Caprock" is thick, it has been partially replaced with nodules and layers of opal. It has a dense brown (5 YR 6/4) laminated, pisolitic, and partly silicified upper layer that grades downward into softer lighter colored (5 YR 8/4) caliche. Where it is exposed at the land surface, the "Caprock" has degraded to form a broken rubble with fissure fillings and clasts of dark brown sand. Clasts of degraded caliche form a mantle of colluvium on slopes. In places, this degraded caliche rubble is mapped as "other Quaternary deposits" (Qao) on the Geologic Atlas of Texas Hobbs Sheet (1976).

The "Caprock" Caliche can be distinguished from younger caliche deposits in overlying Quaternary strata (e.g., Blackwater Draw Formation) which are lighter in color, softer, lower in density (owing to higher porosity), include abundant sand, and are not laminated or pisolitic.

The "Caprock" typically lies within the unsaturated zone. Groundwater was found within the "Caprock" Caliche at one location (well #2).

3.6 Blackwater Draw Formation (Quaternary: Pleistocene)

3.6.1 General Information

The regional distribution and characteristics of the Blackwater Draw Formation were reviewed by Reeves (1976) and Holliday (1989). These deposits were formerly referred to as the "windblown cover sand" and are so designated on the Geologic Atlas of Texas (shown as "Qcs" on the Hobbs Sheet, 1976).

The Blackwater Draw Formation is eolian in origin, and forms an extensive mantle over the surface of the High Plains, diminishing in grain size from predominantly sand on the southwestern side of the High Plains to clay on the northeast. Alluvial sediments of the Pecos River Valley served as the source area for windblown sediment transported to the northeast onto the High Plains surface (Holliday, 1989). Modern effective sand-transporting winds blow from the west-southwest (Machenberg, 1984, 1986); grain-size trends and orientation of Pleistocene vegetated dune ridges indicate that this has been the case for most of Quaternary time. Over the past 2 million years, most of the High Plains surface experienced periods of wind erosion and deposition, alternating with periods of stabilization of the surface by vegetation, resulting in soil formation and accumulation of the Blackwater Draw Formation (Holliday, 1989). Radiometric age determinations on ash beds, and interbedded playa deposits demonstrate that deposition of the Blackwater Draw Formation began prior to 1.4 million years ago and continued until at least 100,000 to 50,000 years ago (Gustavson et al., 1991). Interbedding of the Blackwater Draw Formation with radiocarbon-dated playa basin deposits suggests that deposition continued at least locally up to 3000 years ago (Gustavson et al., 1991; Holliday, et al., 1996).

3.6.2 WCS - Flying "W" Ranch

The Blackwater Draw Formation is present at or near the land surface over much of the ranch area, but is absent along the crest of the "Red Bed Ridge", and is buried under younger windblown sand in the northern and southern parts of the ranch (Figure 2). Where these deposits are present at the land surface, the Triomas and Wickett soil association has developed (Conner et al., 1974). A typical section of the upper part of the Blackwater Draw Formation is exposed in the gravel pit along the common southern borders of Sections 16 and 17 (Figure 2; Block A-29). Sediments of the Blackwater Draw Formation are up to 60 ft thick on the north side of area, and as much as 100 ft thick on the south, substantially thicker than previously reported (typically less than 10 ft according to the Geologic Atlas of Texas, Hobbs Sheet, 1976). The upper 5 to 15 ft of these sediments consists of reddish brown (10 R 5/6 to 5 YR 5/6 or 6/6) clayey fine to very fine sand with nodules of soft sandy caliche. Locally, the upper 5 ft is very clayey and contains a dark brown (10 YR 5/2 to 5 YR 6/6) organic surface horizon. Sand grains have iron oxide and clay coatings which give the sediment its distinctive dark red coloration. These grain coatings are a result of soil formation (Holliday, 1989). The lower part of the Blackwater Draw Formation was less affected by soil development (i.e., iron and clay illuviation), and is lighter in color (typically 5 YR 7/4 to 8/4) with many layers of soft sandy caliche. The lower 10 to 20 ft contains some coarse to very coarse sand as well as layers of granule-small pebble gravel, and may be partly alluvial rather than eolian in origin.

The Blackwater Draw Formation typically lies within the unsaturated zone. No groundwater was found in these deposits.

3.7 Playa Deposits (Quaternary: Holocene)

3.7.1 General Information

The origin and history of playa basins on the High Plains has been a subject of study and debate for nearly a century (reviewed by Reeves, in Gustavson, 1990 and Gustavson et al., 1991; Holliday et al., 1996). Playa basins range in size from 30 ft to 1.5 miles in diameter, though most are less than half a mile in diameter, and exhibit up to 30 ft of topographic relief. The basins originated 30,000 to 10,000 years ago, although some may be older, and have partially or completely filled with up to 3 to 30 ft of sediment since that time (Holliday et al., 1996). The basins formed within the eolian "cover sands" of the High Plains (Blackwater Draw Formation) primarily by wind erosion, and hence are larger and more numerous where the "cover sands" are thicker (Holliday et al., 1996). The basins typically hold water temporarily only after extended periods of rainfall, and focussed infiltration of water through the floors of the playas may cause dissolution of shallow soil caliche layers beneath the basin, resulting in subsidence and gradual enlargement of the basins over time (Osterkamp and Wood, 1987; Wood and Osterkamp, 1987). However, Holliday et al. (1996) argued that dissolution-induced subsidence is not generally responsible for the origin of playa basins. Formerly, buffalo (and more recently, cattle) may also have played a role in enlarging the original depressions by transporting mud or dust out of the basins on their hooves and hides. Playa basins are apparently a surficial phenomenon, and do not reflect deep-seated subsidence or salt dissolution.

3.7.2 WCS - Flying "W" Ranch

Playa deposits are found only in one area, south of the WCS facility boundary (Figure 2; vicinity of borehole #19). The deposits consist of 10 ft of dark brown clayey fine sand, underlain by 5 ft of color mottled yellow and brown ("gleyed") clayey fine sand. The deposits occupy a subcircular depression in the land surface, approximately 2000 ft in diameter. This playa basin is not active, since it is not known to accumulate surface runoff, and the deposits appear to be undergoing erosion. An arcuate dune deposit (shown as "Qsd" on the Geologic Atlas, Hobbs Sheet; 1976) bounds the northeastern margin of the depression (see Figures 2 and 4). There are no mapped occurrences of Lipan clay soils (as are typically developed in the bottoms of modern playas in this region) on the ranch area (Conner et al., 1974).

No groundwater was found in playa deposits on the WCS - Flying "W" Ranch.

3.8 Windblown Sand (Quaternary: Holocene)

3.8.1 General Information

Recent deposits of eolian dunes, now mostly stabilized by vegetation, are mapped as "windblown sand sheets, dunes, and dune ridges undivided" (Qsu) on the Geologic Atlas of Texas (Hobbs Sheet, 1976). These are probably equivalent in part to those referred to as the Monahans Formation to the southwest in the Pecos River valley (Green, 1961; Machenberg, 1984). These surficial eolian deposits are younger than the Blackwater Draw Formation that they overlie in many areas, and are typically 5 to 10 ft in thickness. In places these deposits are undergoing active transport as modern dunes, but in most areas they are at least partially stabilized by vegetation.

3.8.2 WCS - Flying "W" Ranch

Windblown sand deposits are present extensively in the north, northeast, and southwest part of the area. Their distribution generally corresponds with the Jalmar and Penwell soil association (Conner et al., 1974). Windblown sand deposits are up to 35 ft thick, and consist of light yellowish brown (5 YR 5/4 to 7.5 YR 6/4) clean, very well sorted sand. In most areas, they form a thin irregular veneer, 5 to 15 ft thick, over the land surface, with the thickest accumulations in northwest-southeast trending vegetated linear dune ridges. These deposits are distinguished from similar sands in the Blackwater Draw Formation by their pale coloration (locally very pale; e.g. 10 YR 8/4), absence of iron oxide grain coatings, and absence of caliche nodules.

Deposits of windblown sand typically lie within the unsaturated zone. No groundwater was found in these deposits on the WCS - Flying "W" Ranch.

4. Geological Control on Groundwater Hydrology

4.1 General Information

Three regional aquifers converge in central Andrews County. The "Ogallala aquifer" extends southward across the Southern High Plains into the northern part of Andrews County (e.g., Cronin, 1969). The "Edwards-Trinity (Plateau) aquifer" extends northward from the Edwards Plateau into southeastern Andrews County (e.g., Ashworth et al., 1991). The "Cenozoic Pecos Alluvium aquifer" extends northward from the Pecos River Valley into southwestern Andrews County (e.g., Ashworth and Flores, 1991). The boundaries between these aquifers are as yet poorly defined in Andrews County. Cretaceous strata on the High Plains, such as documented here on the WCS - Flying "W" Ranch area, are thought to be in hydraulic continuity with the Ogallala Formation; and they are included together as part of the "High Plains aquifer" in many studies (e.g., Knowles et al., 1984; Peckham and Ashworth, 1993) although the nature of cross-formational flow between these units is not well established. In such regional studies, the WCS - Flying "W" Ranch area has been generally included within the distribution of the Ogallala (High Plains) aquifer.

However, the WCS - Flying "W" Ranch area straddles the "Red Bed Ridge," which exerts control on local and regional groundwater flow. The "Red Bed Ridge" probably acts as a regional groundwater divide, separating the Ogallala (High Plains) aquifer to the northeast from the "Cenozoic Basin Fill" aquifer (or the "Cenozoic Pecos Alluvium" aquifer of Ashworth and Flores, 1991) to the southwest. Groundwater flow in the Cenozoic Basin Fill aquifer is to the south-southwest, while flow in the High Plains aquifer is to the east-southeast (Nicholson and Clebsch, 1961). The Triassic bedrock "high" beneath the overlying Cenozoic deposits interrupts the groundwater table in many areas along its length. In northern Lea County, the crest of the "Red Bed Ridge" lies above the water table in the Ogallala Formation to the northeast (Ash, 1963; see his sheet 1, cross-section A-A'). Similarly, in central Lea County, Nicholson and Clebsch (1961, their Plate 2) illustrated several areas where the water table in Cenozoic deposits is interrupted by bedrock highs on the Triassic "Red Bed Ridge". In western Andrews County, the crest of the "Red Bed Ridge" coincides with the belt of 0 to less than 20' saturated thickness in the High Plains aquifer (Knowles et al., 1984).

4.2 WCS - Flying "W" Ranch

Groundwater is not present continuously beneath the WCS - Flying "W" Ranch, but was encountered in 17 of 35 boreholes completed (see Figure 10). Over 60 previous boreholes and well logs, all of which located the "red bed" surface contact without finding water, were reported by AM Environmental (1993) on the WCS site and Weaver Boos & Gordon, Inc. (1997) to the west of the state line, and these data points were also considered in construction of Figure 10. Groundwater occurs in two discrete areas, one in the northwestern corner of the ranch, and the other in the central area surrounding Windmill Hill. In both cases the groundwater occurs almost exclusively (14 of 17 wells) within the basal sand unit of the Antlers Formation, and the limits of observed groundwater (Figure 10) clearly correspond with the subcrop of the Antlers Formation (Figure 9). The two groundwater-bearing areas are not connected, although the complete lateral extent of both areas is yet to be established. The saturated thickness is typically less than 10 ft in each area. The maximum saturated thickness observed is 25 ft in the northwestern area (Figure 10). Both areas are overlain by the upper shale interval of the Antlers Formation (unit 3, above) which could conceivably act as a confining layer (see Figures 3 and 5). However, in most wells the sand interval in the Antlers Formation is not entirely saturated. Water table elevations suggest that groundwater here likely reflects local recharge and not regional lateral flow within the "High Plains aquifer." The many closed surface depressions along the crest of the "Red Bed Ridge" could act as local recharge points (Figure 5). These depressions are not playa basins, but have formed where the "Caprock" Caliche is at or near the land surface (e.g., see areas mapped as Kimbrough soils; Conner et al., 1974) and are known to hold surface runoff after extended periods of rainfall. One artificially deepened depression southeast of Windmill Hill (southeast Section 4, Block A-39) retains a significant amount of surface runoff. High water table elevations beneath the central area suggest that recharge may occur in the area southeast of Windmill Hill (Figure 5, see Figure 10; sections 3 and 8, Block A-39).

These local "pockets" of groundwater do not appear to contribute groundwater southward to the "Cenozoic Pecos Alluvium" (=Gatuña) Aquifer. No groundwater was encountered along the southern border of the WCS - Flying "W" Ranch. The Gatuña Formation was fully penetrated in at least ten borings and no groundwater was found, although water appears to discharge from the Gatuña Formation at Baker Spring. Similarly, in light of the declining water table elevation and declining saturated thickness along the north and east boundaries of the ranch area, the local groundwater "pockets" may also not contribute groundwater northward or eastward to the Ogallala Aquifer.

The absence of groundwater at lower elevations to the south, steep decline in the water table elevation, and low saturated thickness to the north and east together suggest that some barrier to lateral flow of groundwater may exist. The nature of such a barrier is unknown. Alternatively, it is possible that local groundwater flows laterally to the southeast beneath Windmill Hill and discharges at the land surface where the elevation falls below the level of the local water table at incised drainages immediately east of Sections 2 and 9 (Block A-39; see Figure 10, Figures 6 and 7). The incised drainage in the southeast corner of Section 2 flows intermittently eastward to an unnamed saline lake basin about 1 mile east of the WCS - Flying "W" Ranch. Saline lake basins are known to be sites of groundwater discharge on the High Plains (e.g., Wood et al., 1992). However, the incised surface drainage here is not known to be an area of spring discharge, but is dammed at points along its length, where it retains surface runoff. Further exploratory drilling to the north and east of the WCS - Flying "W" Ranch is necessary to firmly establish the limits of groundwater in these areas.

Similarly, it is not clear why the two areas where local groundwater occurs are not connected. The basal sand interval of the Antlers Formation is present continuously between the two areas (Figure 9), and elevations on the land surface, water table, and "red bed" surface suggest that lateral southeastward flow of groundwater could occur between the two areas (Figure 7). No barrier to lateral flow is apparent. Groundwater flowing southeastward from the northwestern area may be intercepted in the subsurface by a southwesterly-directed drainage (Section 16, Block A-29) to discharge at the land surface at Baker Spring (Figure 3). The lack of groundwater in boreholes both north and south of Baker Spring drilled by Weaver Boos & Gordon, Inc. (1997) in Lea County indicate it is also possible that groundwater may flow to Baker Spring from the west or northwest. This uncertainty might be resolved by installation of an additional borehole between well location #16 and the WCS facility (i.e., in the northwest corner of section 25, Block A-29) or west of Baker Spring in Lea County.

5. Discrimination of Ogallala and Antlers Deposits

5.1 General Information

Because of uncertainties regarding the nature of cross-formational flow of groundwater between Cretaceous strata and the Ogallala Formation, it is useful to discriminate these deposits in the subsurface where possible. In recent reports, Cretaceous strata are often not separated from the Ogallala Formation, and these are collectively included in the "High Plains aquifer" (e.g., Knowles et al., 1984; Ashworth et al., 1991; Peckham and Ashworth, 1993). Nevertheless, it may be important to distinguish these strata for regulatory considerations (e.g., Dutton, 1999).

Determining exactly where the Ogallala Formation pinches out in Andrews County is problematic. Existing compilations of water well driller's logs in the area are not very useful in discriminating whether or not the Ogallala Formation is actually present, because in well cuttings the hard caliche layers (such as the "Caprock" Caliche) are difficult for water well drillers to distinguish from Cretaceous limestone beds (such as in the Comanche Peak and Edwards Limestone), and the sand and gravel in the Ogallala Formation is difficult to distinguish from that in the Antlers Formation. The top of the underlying Dockum Group "red beds" is often readily identified in cuttings by water well drillers, and so this interface is often reliably picked on logs.

In well cuttings it is often difficult to distinguish the Antlers Formation from the Ogallala Formation, because both units consist predominantly of poorly cemented sand and gravel. Sands in the Antlers Formation are fine to medium-grained, white to yellow, and highly quartzose, with brightly colored chert pebble gravel, dominantly comprised of pink, red, and black chert, and white quartzite. Sand in the Ogallala Formation is fine to medium-grained and sublithic, with pebble gravel containing clasts of igneous and metamorphic rocks (quartzite, granite, rhyolite, and gneiss), sedimentary rocks (limestone and sandstone), and abraded Cretaceous *Gryphaea* shells (e.g., reviewed by Reeves, 1984).

5.2 WCS - Flying "W" Ranch

The excellent exposure in the walls of the excavation at the WCS facility leaves little doubt that this unit is the Antlers Formation, and not the Ogallala Formation. It is identical in composition to the same unit exposed to the east at Shafter and Whalen Lakes. Similarly, in the surrounding subsurface where the upper shale interval (unit 3, described above) is present at the top of the Antlers Formation, these deposits are readily identified because similar strata are not known to occur in the Ogallala Formation. Nevertheless, in many areas it remains difficult to discriminate the Antlers and Ogallala solely on the basis of well cuttings.

In an effort to systematically discriminate deposits of the Ogallala and Antlers Formations, samples of each unit were obtained from locations where their identification was certain. Two samples of gravel from the base of the Antlers Formation were obtained from definitively mapped exposures (SHA-5 from the western side of Shafter Lake in central Andrews County; FLU-1 from a roadcut on FM 1269 north of Fluvanna in Scurry County). Two samples of gravel were obtained from water wells drilled to the base of the Ogallala Formation (AND-1 and AND-2 from two wells in the Monument Draw paleo-valley adjacent to US Hwy 385 in northcentral Andrews County). These were compared with a sample of gravel (WCS-1) collected from the landfill excavation at the WCS facility. Approximately 1 kg samples were washed, disaggregated, and sieved to separate all pebbles larger than 8 mm (U.S. Standard #4 mesh sieve) for identification. All pebbles were identified as to lithology and counted (n = 247 to 2691) to determine their relative abundance in each sample. The results of this analysis are given in Figure 11.

Samples of the Antlers gravel are distinctive in consisting entirely of clasts of multicolored chert, hydrothermal "vein" quartz, and a few highly indurated dark brown sandstone (possibly quartzite) clasts (pebble types 1 - 8 in Figure 11). Samples of Ogallala gravel also contain these clast types, though in lower relative abundance, because the Ogallala gravel is derived in part from erosion and reworking of the Antlers deposits. Importantly however, samples of Ogallala gravel also contain high percentages of limestone clasts, reworked Cretaceous mollusc shells (e.g., *Gryphaea*), friable yellow, pink, and black sandstone clasts, and porphyritic igneous rock clasts (pebble types 9 - 12 on Figure 11). These are entirely absent in samples of gravel from the Antlers Formation.

Careful inspection of washed cuttings from borings will reveal at least a few of these distinctive clast types if present, and so it is not necessary to sieve, count, and identify all pebbles to obtain an accurate stratigraphic determination. Ogallala sand also typically has a high percentage of lithic grains compared to Antlers sand, which is virtually pure quartzarenite. These criteria were used to distinguish the two deposits over the WCS - Flying "W" Ranch area.

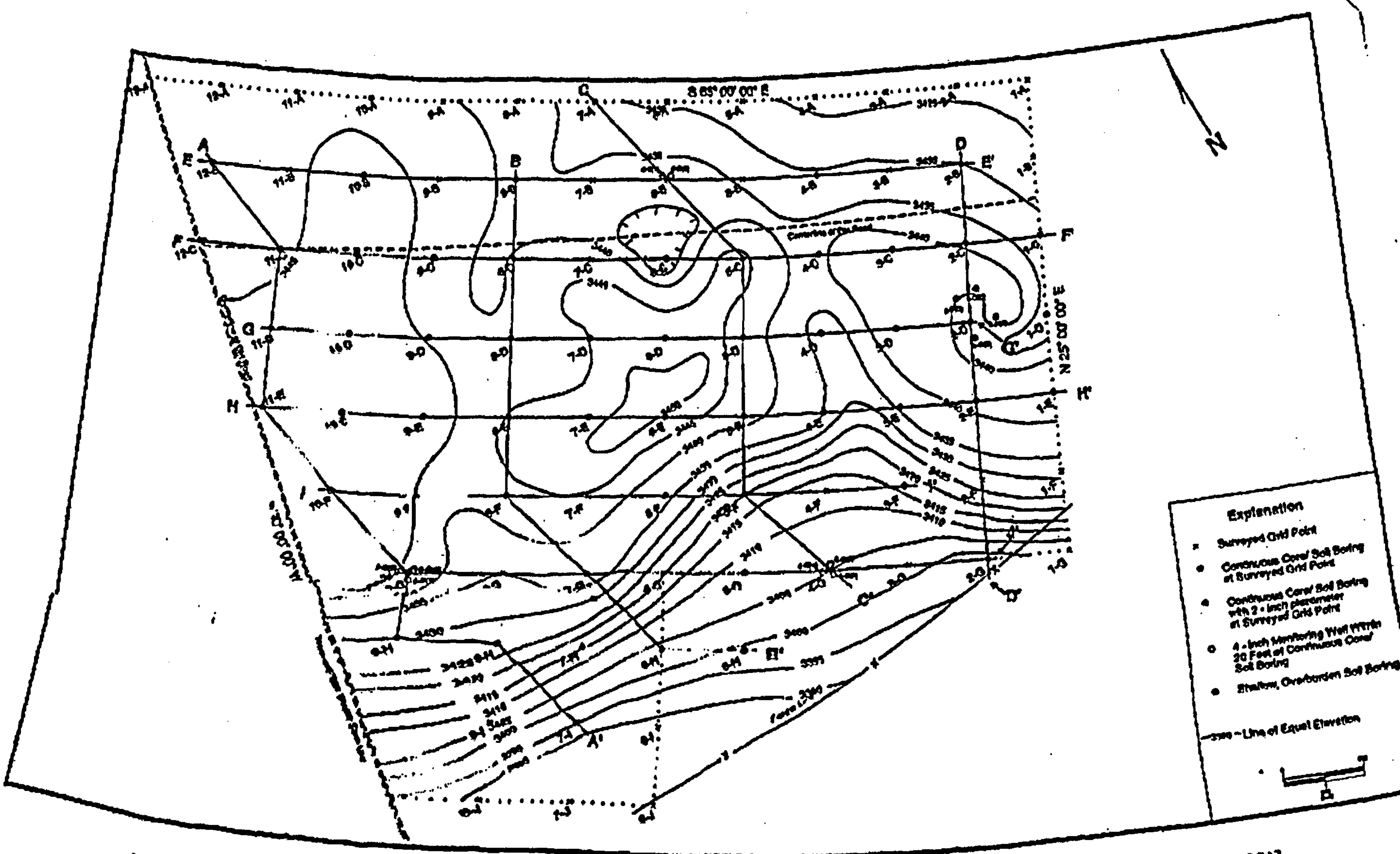

Figure 1. Contour Map of the Dockum ("red beds") Group Surface Beneath the WCS Site [Source: AME (1993)]

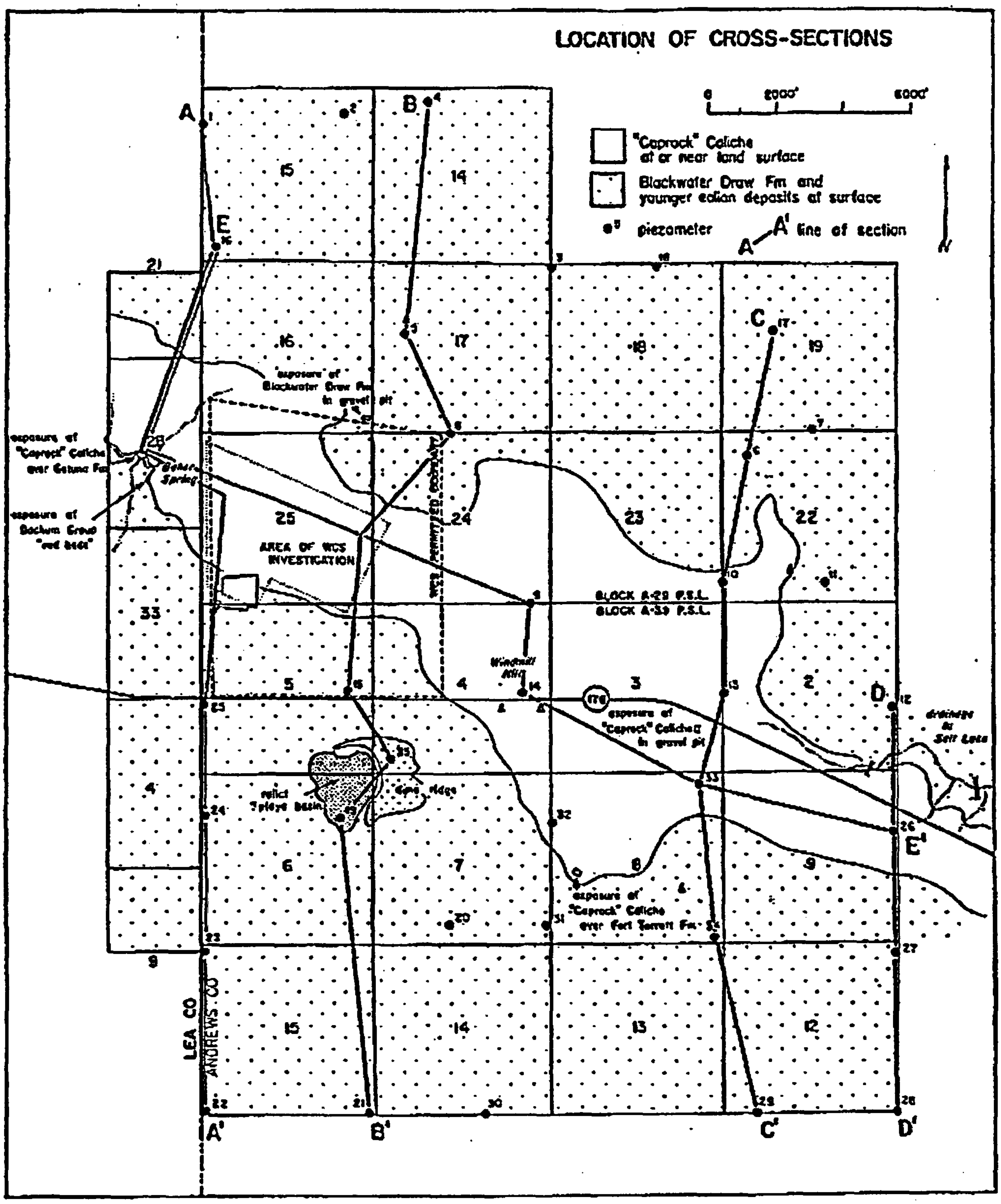

Figure 2. WCS – Flying "W" Diamond Ranch Site Map

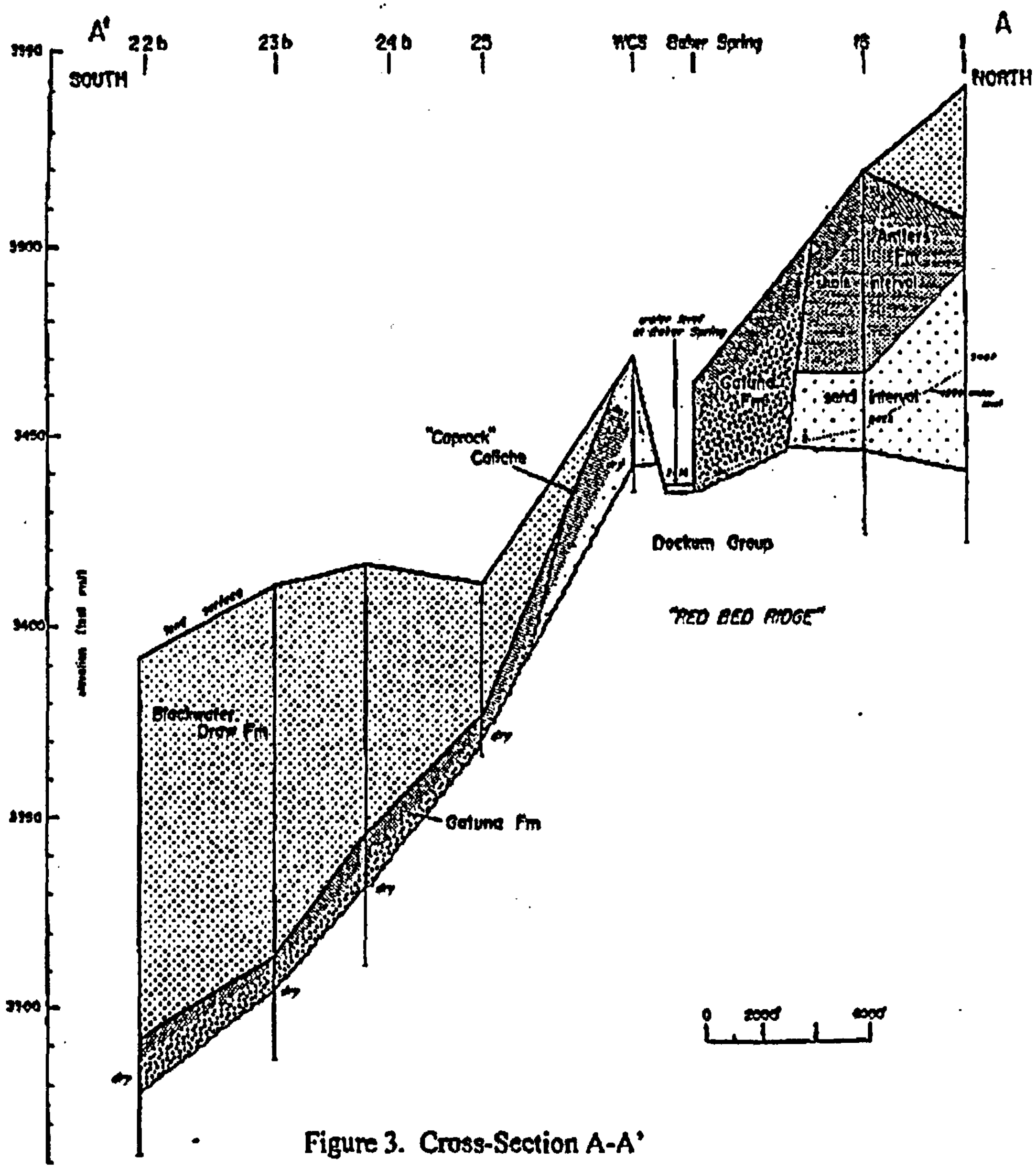

Figure 3. Cross-Section A-A'

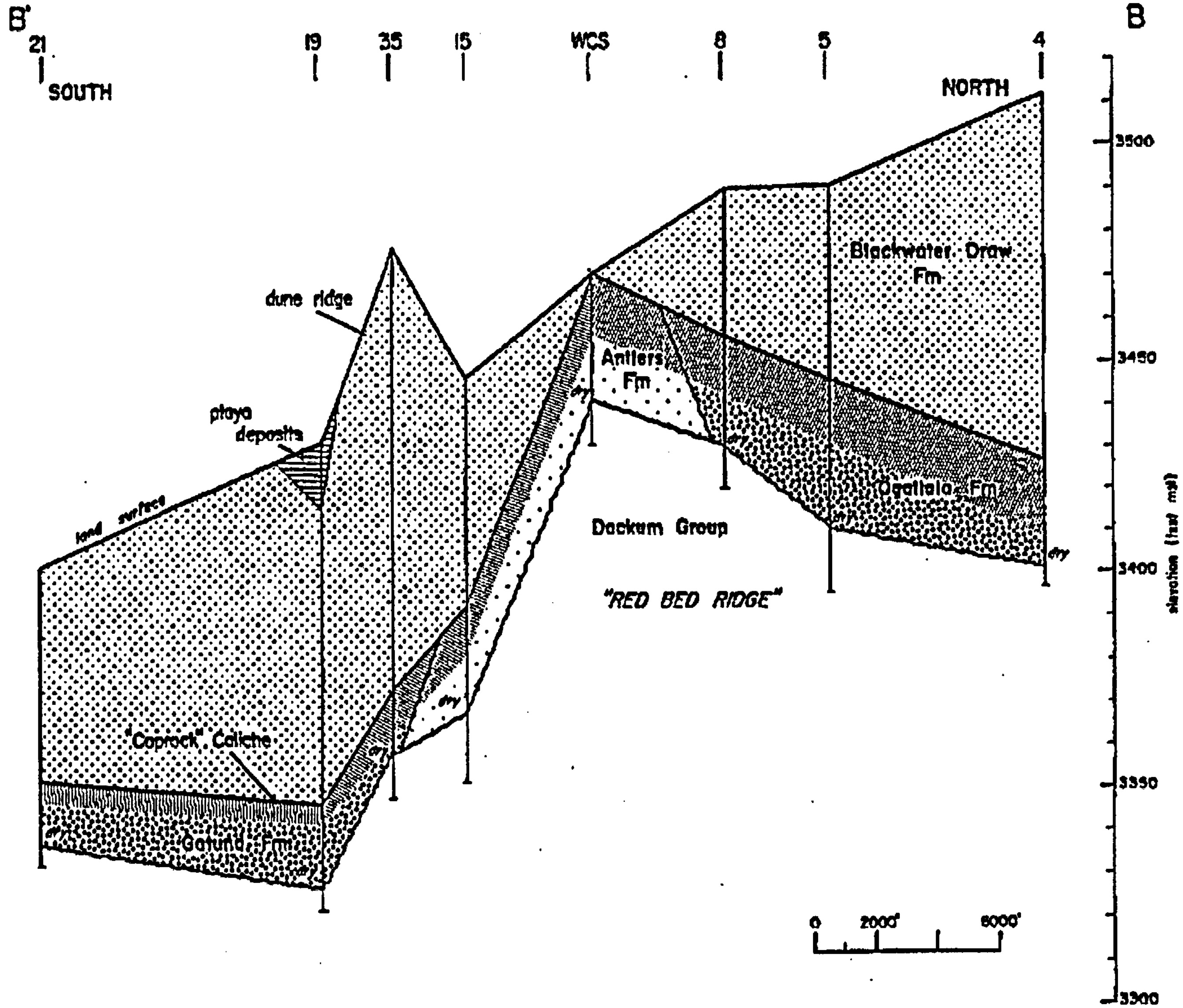

Figure 4. Cross-Section B-B'

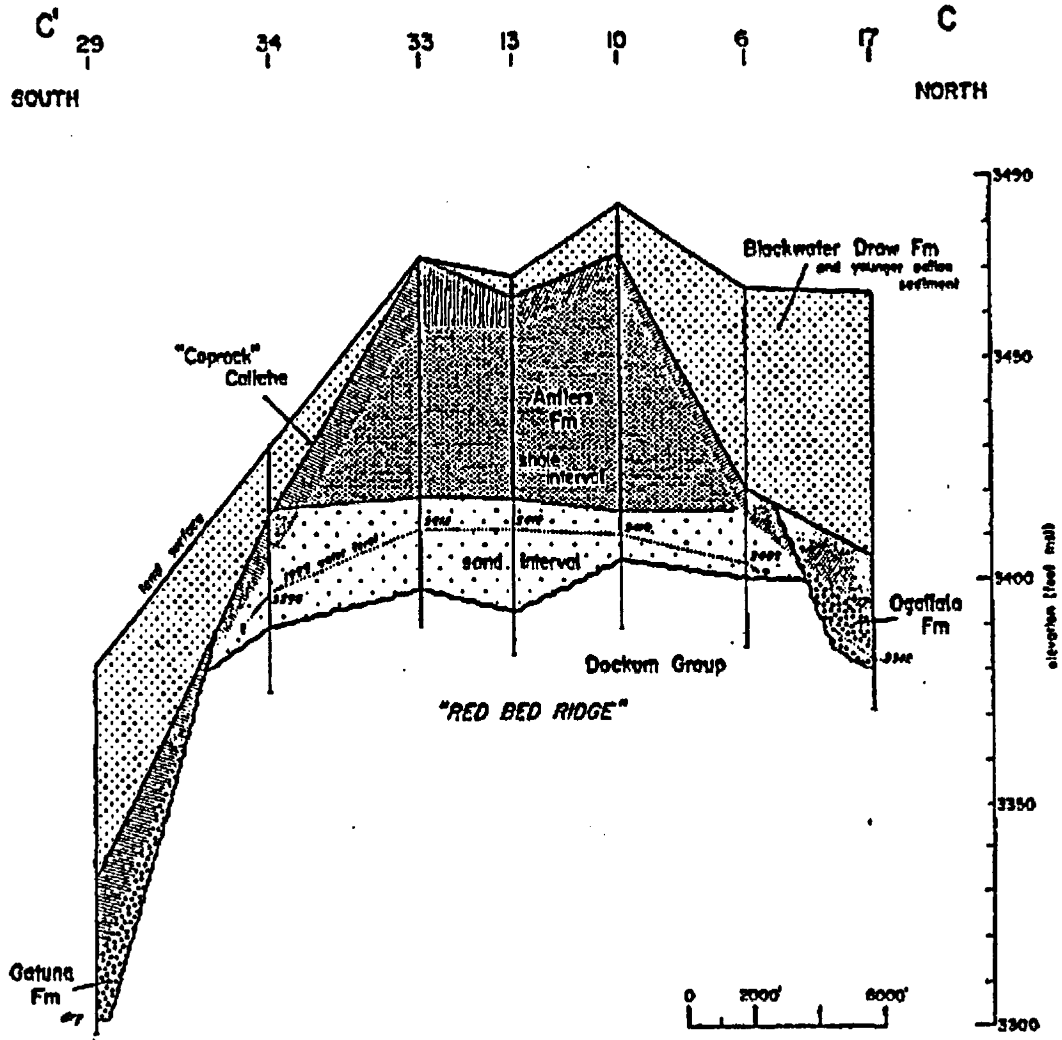

Figure 5. Cross-Section C-C'

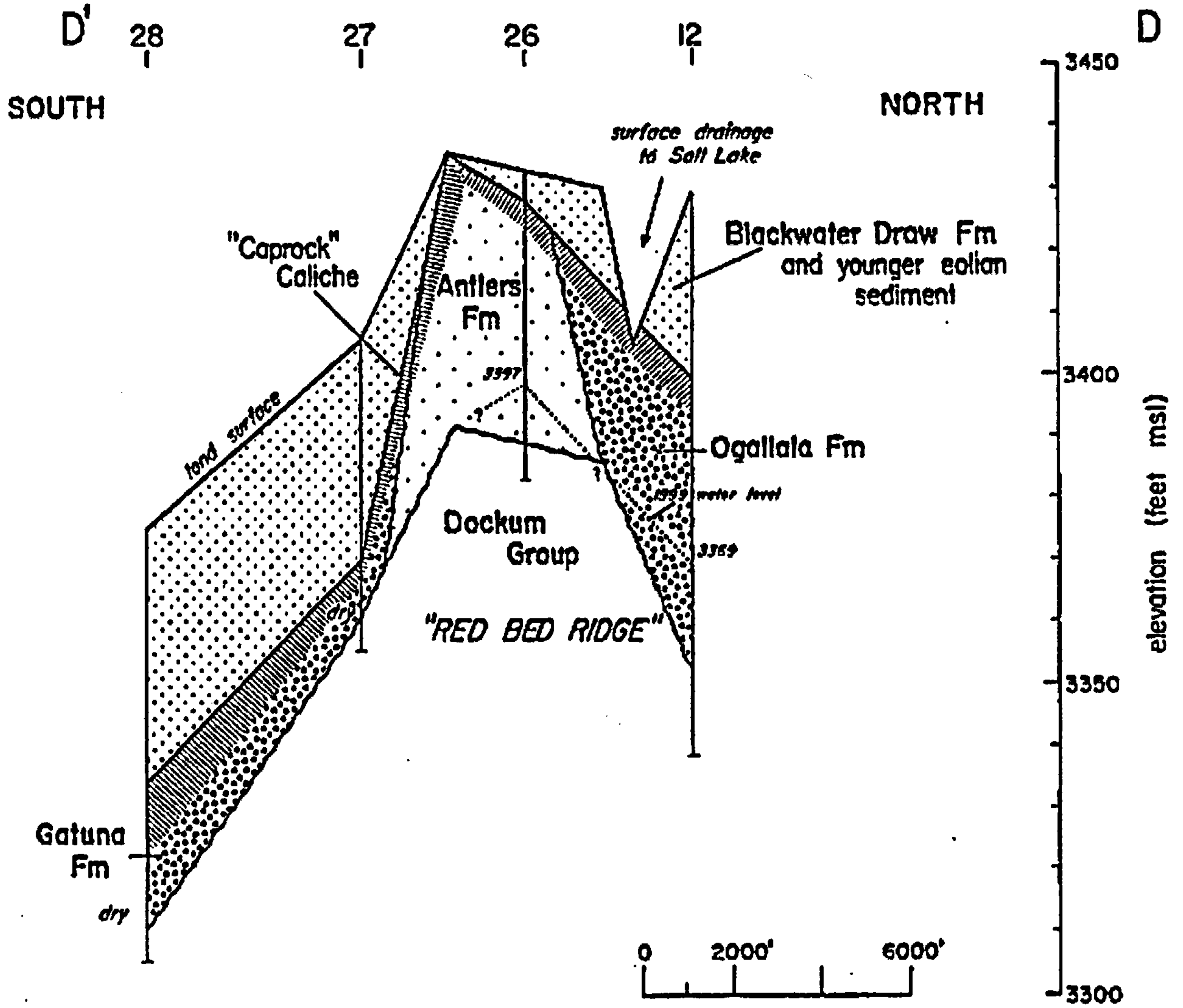

Figure 6. Cross-Section D-D'

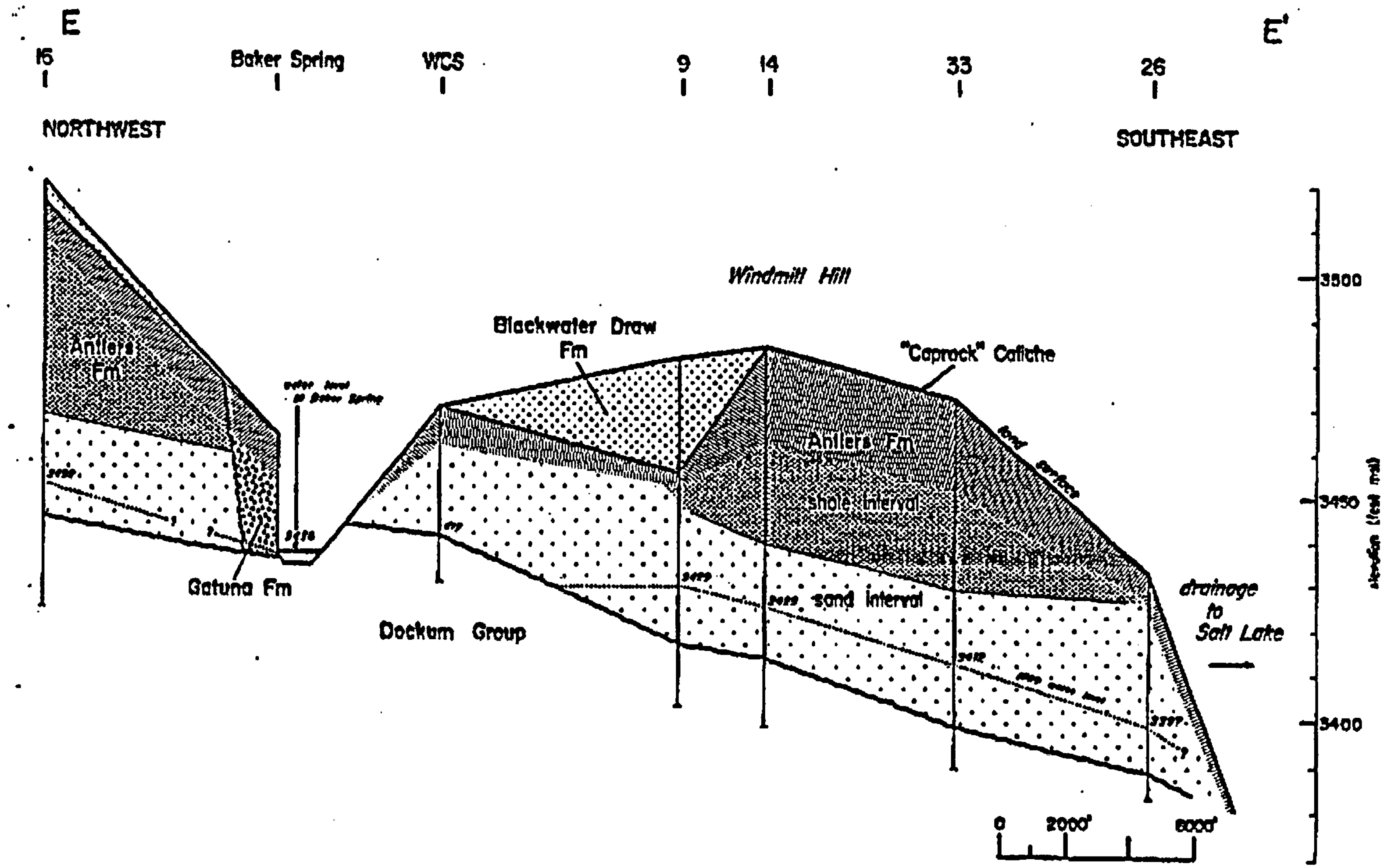

Figure 7. Cross-Section E-E'

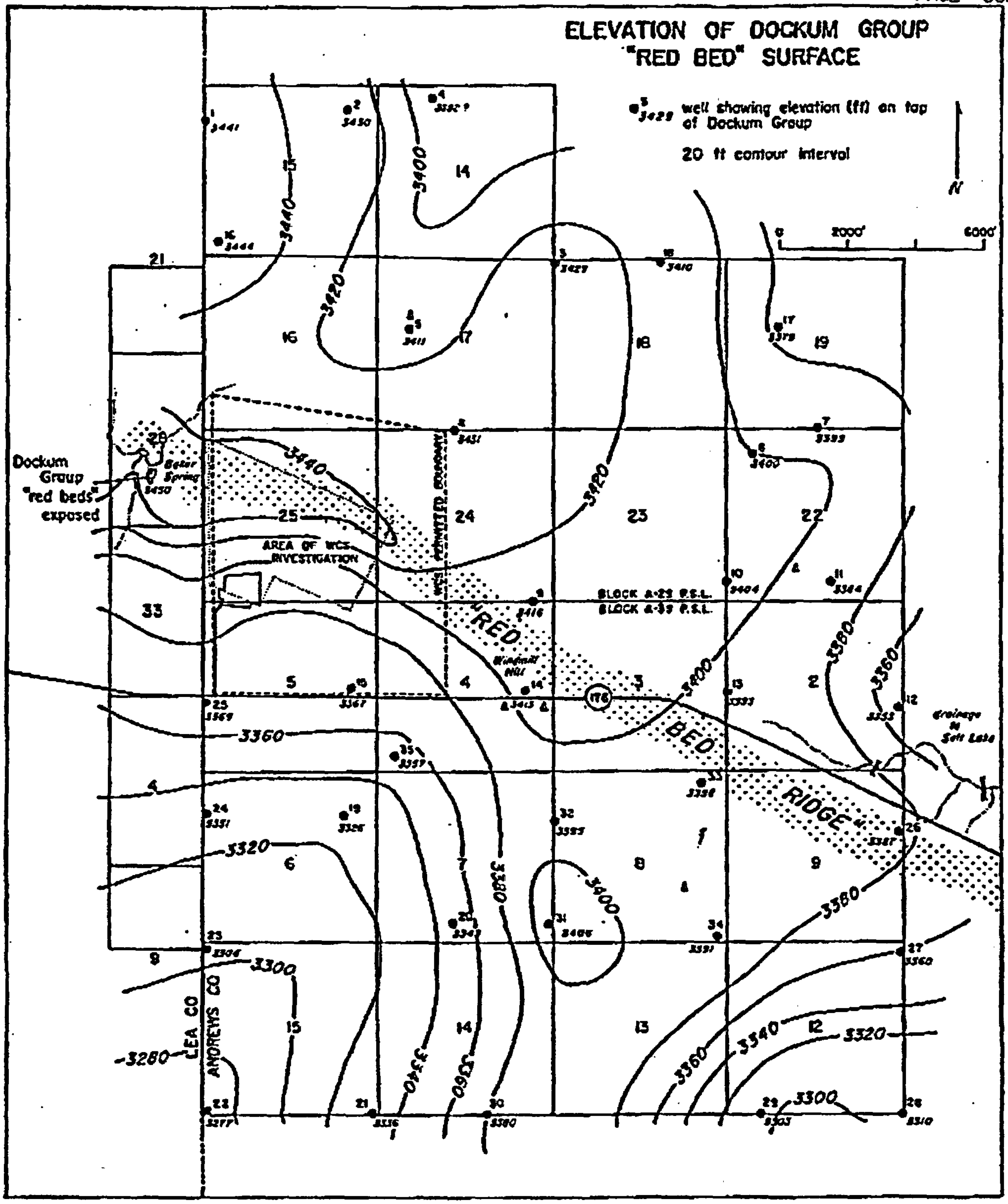

Figure 8. Elevation of Dockum Group "Red Bed" Surface

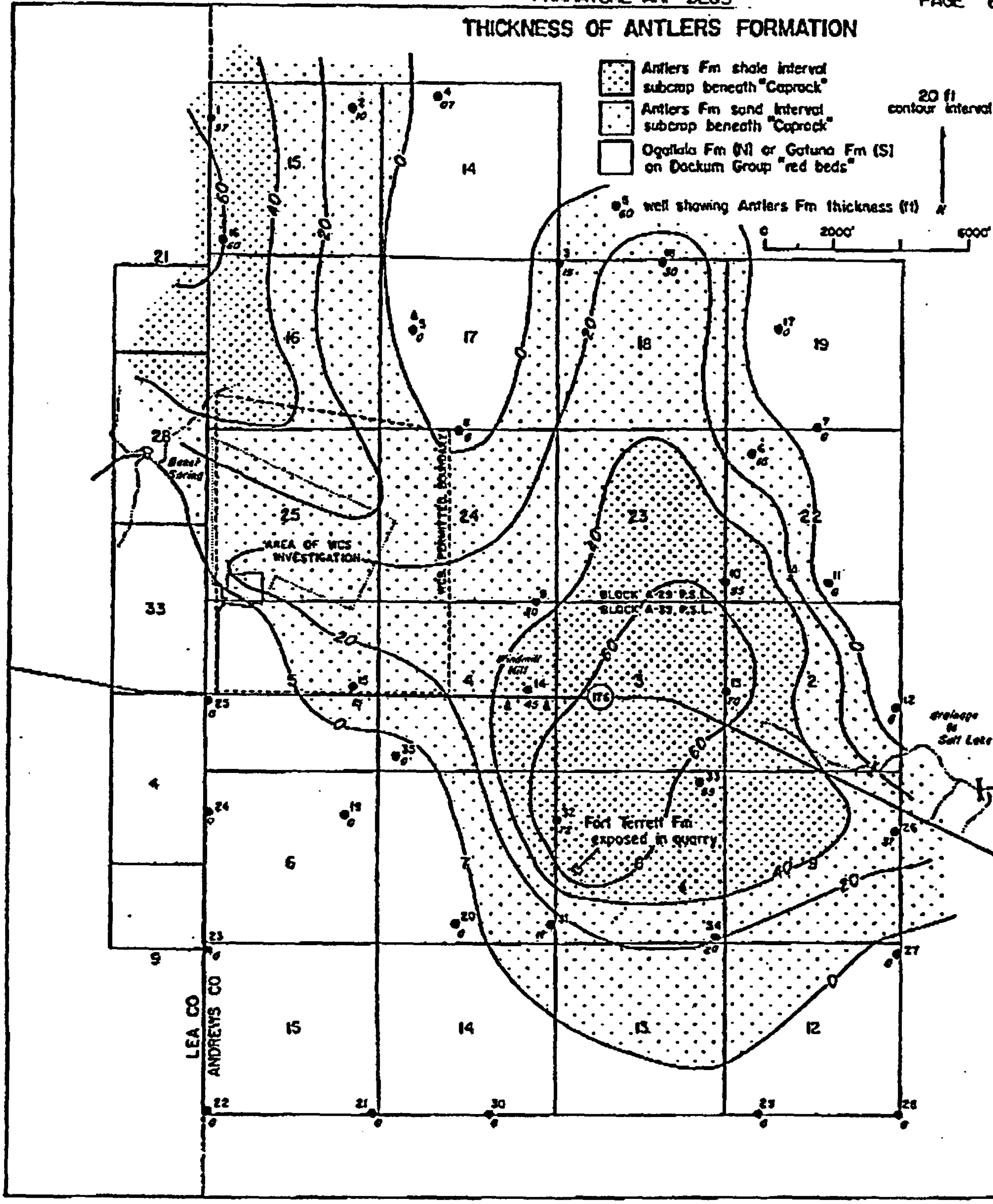

Figure 9. Thickness of Antlers Formation

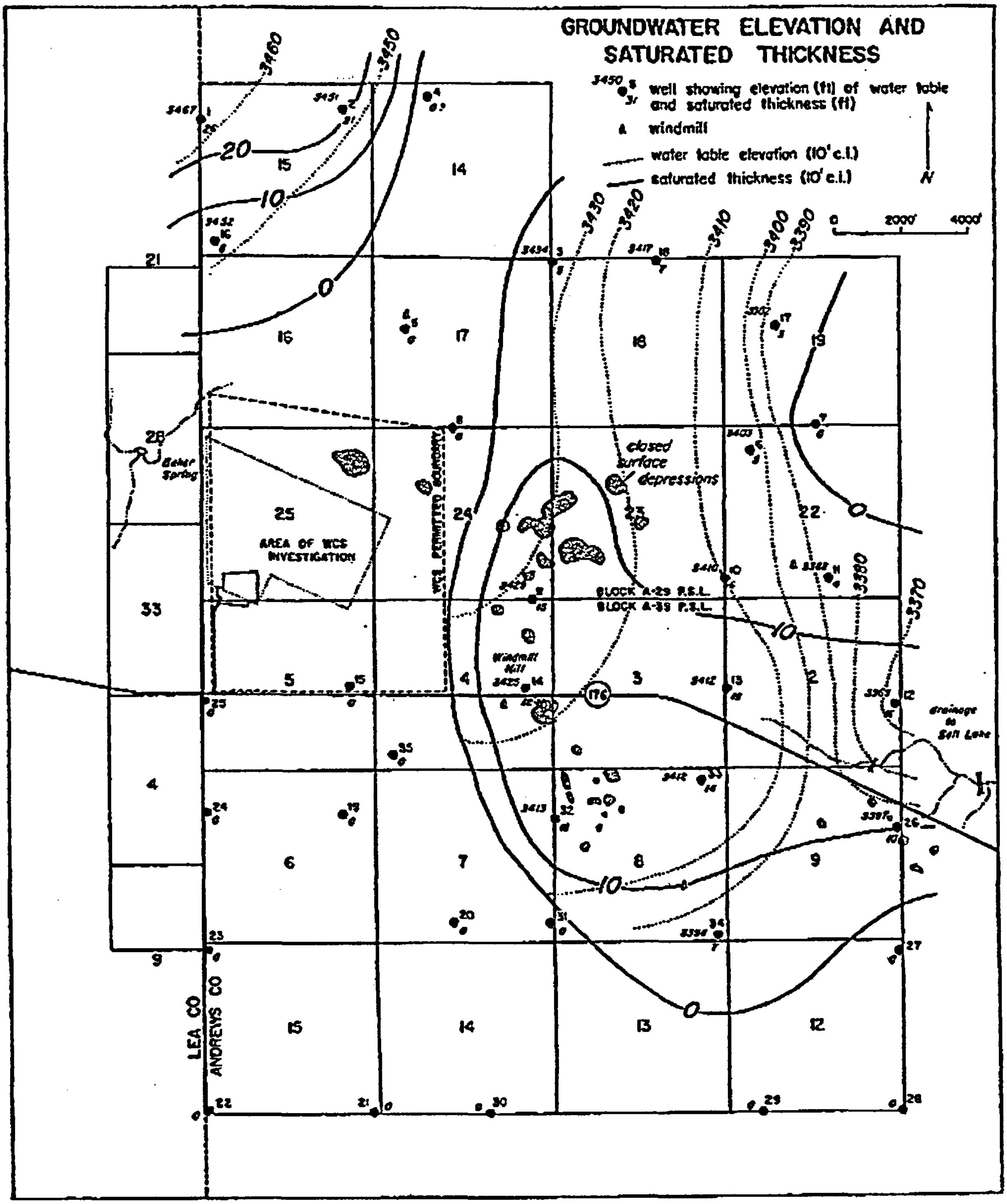

Figure 10. Groundwater Elevation and Saturated Thickness

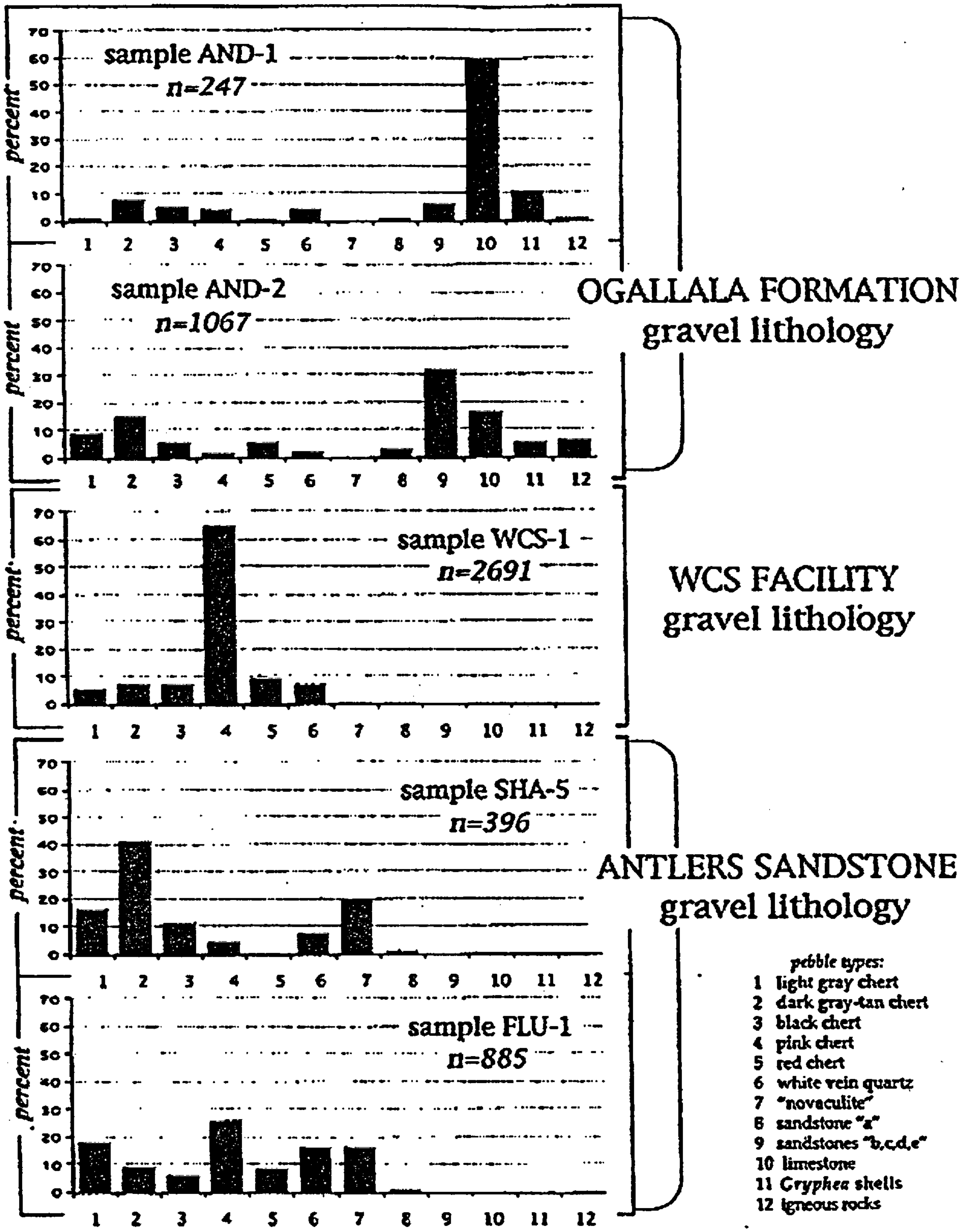

Figure 11. Comparison of Gravel Characteristics in Ogallala and Antlers Formations

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