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Distribution:
J Pohle

(Return to WM, 623-SS)

July 16, 1986

'86 JUL 22 A11:33

009/NWC/PM
RS-NMS-85-009
Communication No. 76

U.S. Nuclear Regulatory Commission
Division of Waste Management
Geotechnical Branch
MS-623-SS
Washington, DC 20555

Attention: **Mr. Jeff Pohle, Project Officer**
Technical Assistance in Hydrogeology - Project B (RS-NMS-85-009)

Re: **Trip Report: NWC/DBS - Palo Duro Basin**

Dear Mr. Pohle:

This cover letter transmits to the NRC staff the Nuclear Waste Consultants' (NWC) Trip Report for the joint NWC/Daniel B. Stephens and Associates (DBS) field trip through the Palo Duro Basin. The three-day field trip was attended by managers and staff of DBS and by Mssrs. Adrian Brown and Mark Logsdon of NWC under Subtask 3.5 (DBS) and general project management functions (NWC) of Contract No. RS-NMS-85-009. As discussed with the NRC Project Officer and the Palo Duro Site Lead, no contacts were made with DOE or State of Texas: the trip was entirely for the purposes of the DBS/NWC team in preparing its Subtask 3.5 work. The field trip was designed by DBS as a step in evaluating conceptual models for the Palo Duro Basin Site, a matter which we consider difficult if not impossible to perform without direct knowledge of the geology and critical field aspects of the hydrogeology of a site.

The trip report includes copies of the field trip logs and papers that were used by the team as the background for field observations and team discussions. Because of the substantial bulk of these materials, I am transmitting only one copy to the NRC for document control purposes. Additional copies of all field trip materials are on file with NWC, should it be necessary for the NRC to reconstruct the attachments at any time in the future.

Contrary to some expectations, there was a substantial amount of geologic and hydrogeologic information available for the team to see, discuss and argue about during the field trip. Examples cited in the trip report include the nature, facies relations and hydrogeologic importance of Permian and PreCambrian sediments that are considered to underlie the potential repository strata and of the Triassic and Quaternary units (Dockum and Ogallala) that overlie the repository strata. Outstanding exposures of these units were observed in a variety of places in New Mexico and Texas. In addition to the field work during the days, the entire team spent a great deal of time in the evenings discussing the hydrogeology of the Palo Duro Basin and developing plans for the Subtask 3.5 evaluations.

3219

Nuclear Waste Consultants considers that the field trip was a very important part of the DBS preparations for evaluating conceptual models of Palo Duro Basin. In addition, the trip provided NWC with a unique opportunity to follow the development of the DBS technical positions and to provide both technical and managerial input into the upcoming Subtask 3.5 process. The trip confirms our view that site visits are an indispensible part of a hydrogeologic evaluation. We recommend that the NRC Staff consider developing plans at an early time to have a site vist for the NNWSI team, perhaps as an Appendix 7 visit.

If you have any questions concerning this report or related matters, please contact me immediately.

Respectfully submitted,
NUCLEAR WASTE CONSULTANTS, INC.

Mark J. Logsdon

Mark J. Logsdon, Project Manager

Att: Trip Report: NWC/DBS Field Trip to Palo Duro Basin

cc: US NRC - Director, NMSS (ATTN: PSB)
DWM (ATTN: Division Director) - 2
Mary Little, Contract Administrator
WMGT (ATTN: Branch Chief)

bc: M. Galloway, TTI
L. Davis, WWL
R. Knowlton, DBS

See D1021 7/16/86
TO: J. Pohle
communication NO. 76

TRIP REPORT - NWC/DBS FIELD TRIP TO PALO DURO BASIN, TEXAS
JULY 1-3, 1986
ALBUQUERQUE, NM - AMARILLO, TX

1.0 INTRODUCTION

Members of the NWC Salt Team from Daniel B. Stephens and Associates (DBS) and managers of Nuclear Waste Consultants (NWC) participated in a hydrogeologic field trip across the Palo Duro Basin and adjacent area, from Albuquerque, NM to the area of Amarillo, TX, July 1-3, 1986. Participants in the field trip included:

DBS: D. Stephens; F. Phillips; J. Yeh; R. Knowlton; J. Minier; W. Cox; J. Havelinas

NWC: A. Brown; M. Logsdon.

Transportaion for the field trip was by van, so that the entire team could discuss the geology and hydrology as we progressed from the purported recharge areas of eastern New Mexico across the basin to potential regional discharge areas along the Canadian and Red River drainages. Headquarters for the trip were in Amarillo, central to excellent exposures of the Permian to Quaternary units of Palo Duro and Caprock Canyons and the Canadian Breaks.

The trip was organized by DBS to provide actual field exposure of the team to the hydrogeology of the Palo Duro Basin area. Matters to be addressed during the field trip and its subsequent evaluation included:

- o Stratigraphy and hydrostratigraphy
- o Major structural features of the basin and adjacent highlands
- o Hydrogeology of potential recharge areas in New Mexico and potential discharge areas in Texas
- o Field evidence that could be used to support alternative conceptualizations of the hydrogeology of the basin and the site.

2.0 CHRONOLOGY OF THE FIELD TRIP

The DBS team developed and provided to all the participants a set of road logs with supporting material drawn from the geologic and hydrologic literature of the Palo Duro Basin and adjacent areas. The road logs are attached to this Trip Report as Attachments I and II. Day one was spent driving from Albuquerque to Amarillo, with numerous stops to observe exposures of rocks that underlie the proposed repository and to consider hydrogeologic processes in the recharge region for the Palo Duro Basin. Day two concentrated on the geology and hydrogeology of the units exposed in Palo Duro and Caprock Canyons State Parks, east of the proposed site. Day three included field work in the Canadian Breaks, a brief stop along the road near the site proposed for the repository, and further field observations and discussions while moving down-section from the site back to Albuquerque. All of these matters are dealt with in the road logs and technical papers that are parts of Attachments I and II.

In addition to the daytime field work, the team worked evenings to review the days' efforts and to develop detailed plans for Subtask 3.5 reports that reflect the information gathered from the discussions and field observations of the trip.

The subsequent discussion points of Section 3.0 highlight selected matters of particular discussion during the field trip. Additional discussion of these and other matters of concern will be presented in the DBS Subtask 3.5 reports and their semi-annual updates.

3.0 TOPICS OF SPECIAL DISCUSSIONS

The following list includes matters of particular discussion and debate by the field-trip team over the three days of the trip.

- NATURE OF THE BASEMENT ROCKS AND THE SEDIMENTARY SECTION UNDERLYING THE PROPOSED REPOSITORY. The field trip included stops at numerous outcrops of PreCambrian, Pennsylvanian and lower Permian rocks in eastern New Mexico. The focus of discussion at each stop was on how the exposed materials might be related through sedimentary facies analysis to time-synchronous materials deeper in the basin and how one could use that knowledge of sedimentary basins to supplement the drillhole data from the site area. Emphasis at all times was on how the materials would likely behave hydrologically, including such detailed matters as the basis on which one could estimate correlation lengths, if a stochastic analysis were to be conducted.

- NATURE OF RECHARGE PROCESSES IN EASTERN NEW MEXICO. Since it is generally considered that recharge to the deeper portions of the Palo Duro Basin occurs along the basement uplifts in eastern New Mexico, the field trip included several stops to examine the geology and hydrogeology of the PreCambrian-Permian relationships along the Sandia and Pedernal Uplifts, of the playa deposits in the Estancia and adjacent basins, and of the karstic terrain in the Permian rocks near Santa Rosa, NM. In addition, because of the importance of the Pecos River to recharge-discharge relationships in the shallower parts of the basin in New Mexico, the team included a significant stop at the Pecos River in Santa Rosa to discuss the hydrogeologic relationships of the major through-flowing river.

- NATURE OF INFILTRATION AND RECHARGE TO THE TRIASSIC AND QUATERNARY SEQUENCE IN THE SITE AREA. The team spent several hours at Palo Duro Canyon State Park, observing exposures of the upper Permian to Quaternary section that is so well exposed there. One of the major topics for discussion (and debate) was the nature of the Ogallala Formation, particularly the likelihood that the caliche formation might be used to calibrate an effective, long-term infiltration value. In addition to the caliche debate, the team discussed current and recent efforts to evaluate net recharge to the Ogallala using chloride balance and artificial recharge studies.

- NATURE OF STRUCTURAL DEFORMATION AND SALINE DISCHARGE: IMPLICATIONS FOR SALT DISSOLUTION AND GROUNDWATER FLOW. The team made numerous stops to observe and discuss structural elements in the Lake Theo - Eagle Point area of Caprock Canyons State Park and in the Canadian Breaks; sinkholes, dolines, and surface fractures along the Prairie Dog Town Fork of the Red River in Briscoe and Hall Counties; and zones of saline discharge to the rivers and streams, such as Estelline Spring. The focus of discussion throughout was on the implications of the dissolution and discharge information for flow system analysis.

4.0 CONCLUSIONS

While it is true that there is little to see (except attractive farm land) at the proposed Deaf Smith County site (in the sense of the proposed 50,000 or so acre "controlled area"), there is a great deal of useful information concerning the geologic framework and selected aspects of the regional hydrogeology that can be gleaned only from first-hand observations in the Palo Duro Basin. Valuable observations and discussions covered matters ranging from scales at which processes such as regional recharge-discharge relationships might be significant to the implications for modeling of facies changes within the Permian sedimentary rocks. NWC and DBS consider that the opportunity of the team to observe key features of the basin and to be able to debate their significance within a knowledgeable group all operating from the same information base is an invaluable step in formulating technically informed positions and plans. The ability of the DBS team to evaluate alternative conceptual models of the Palo Duro Basin and to formulate defensible models of its likely behavior has been significantly advanced, and we consider that the team will be much better able to review and independently evaluate data and analyses performed by DOE, TBEG and other groups than they would have been without such a field trip.

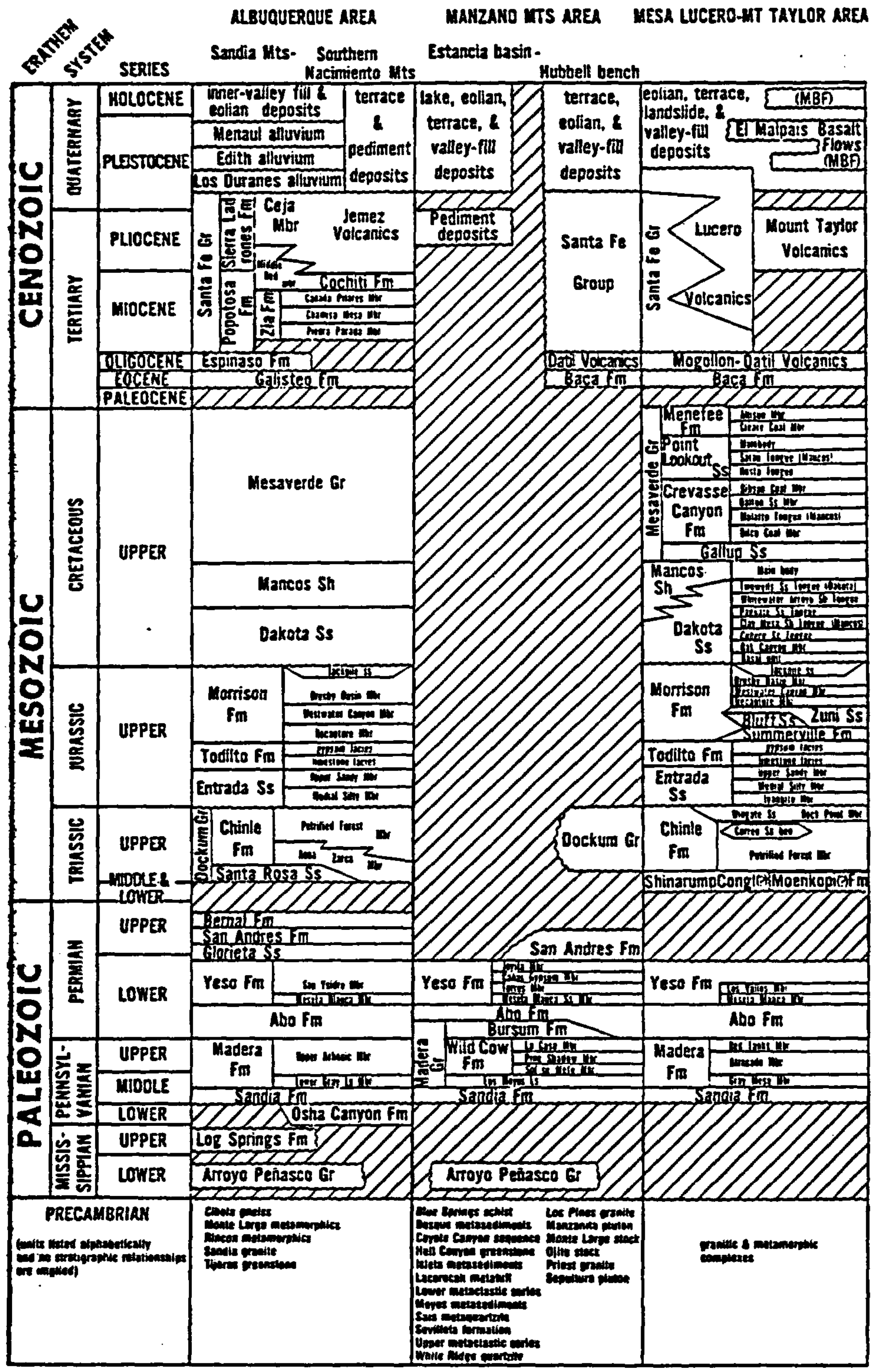
Logsdon
7/1/86

1st Day

ALBUQUERQUE - TIJERAS		pp. 1-12	Mile
Stop 1	Precambrian Metamorphic Terzanes	4	11.1
Stop 2	Lower Permian Abo Fm	7	12.8
Stop 3	Pennsylvanian Madera	10	8.0
TIJERAS - CLINES CORNERS		pp. 13-16	
	Estancia basin to south		
CLINES CORNERS - VAUGHN		pp. 17-24	
Stop 4	Precambrian, Yeso	18	73.6
Stop 5	Playa	19	94.2
Stop 6	Ogallala	22	113.3
VAUGHN - SANTA ROSA		pp. 25-34	
Stop 7	San Andres	27	115.7
Stop 8	Grayburg Queen	27-28	128.9, 129.4
	Santa Rosa	30	11.7, 12.2
SANTA ROSA - AMARILLO		pp. 35-44	
Stop 9	Chinle Sh.	36	12.3
Stop 10	Deaf Smith Site		

STRATIGRAPHIC NOMENCLATURE CHART

G. Saucier, S. G. Wells, and B. S. Kues



Stratigraphic nomenclature chart for the Albuquerque Country II field conference. Precise correlations are not implied; rather, stratigraphic and relative ages are generalized. In the Albuquerque-area column, left part of column applies to Sandia Mountains and south and central Albuquerque basin, and right column applies to northwestern Albuquerque basin and southern Nacimiento uplift. In the Manzano Mountains-area column, left part of column from Upper Permian to Holocene applies to the Estancia basin, and right part of column from Upper Permian to Holocene applies to Hubbell bench area; Lower Permian to Precambrian stratigraphy applies to Manzano Mountains. In the Mesa Lucero-Mount Taylor column, Lower Permian through Precambrian exposed in the Mesa Lucero area only. Contributors to this chart include: D. Baars, B. Black, J. Callender, W. Cavin, J. Hawley, R. Ingersoll, K. Manley, C. Maxwell, and L. Woodward.

STRATIGRAPHIC TABLE

Era	Period	Epoch	Group / Formation	Unit	Equivalent units	Equivalent units
Cenozoic		Holocene	Valley alluvium, lake beds, aeolian sand, caliche, low river terraces such as Lakewood and equivalents along the Pecos and Canadian drainage systems, local alluvial fans.			
Cenozoic		Pleistocene	Sand and gravel of Portales Valley, Tucumcari basin, and High Plains: pediment and terrace gravel of the Pecos and Canadian drainage systems. Gatuna Formation(?)			
Cenozoic	Tertiary	Pliocene	Ogallala Formation		Bridwell Formation Couch Formation	
Cenozoic	Tertiary	Miocene				
Cenozoic	Tertiary	Oligocene				
Cenozoic	Tertiary	Eocene				
Cenozoic	Tertiary	Paleocene				
Mesozoic	Cretaceous		Carlile Shale			
Mesozoic	Cretaceous		Graneros Shale			
Mesozoic	Cretaceous		Dakota Sandstone			
Mesozoic	Cretaceous		Purgatoire Group	Pajarito Shale		
Mesozoic	Cretaceous		Purgatoire Group	Mesa Rica Sandstone . Purgatoire Formation . Cheyenne Formation		
Mesozoic	Cretaceous		Purgatoire Group	Tucumcari Shale		
Mesozoic	Jurassic		Morrison Formation			
Mesozoic	Jurassic		Todilto Limestone . Wanakah Formation . Bell Ranch Formation			
Mesozoic	Jurassic		Exeter Sandstone . Entrada Sandstone			
Mesozoic	Triassic		Redonda Formation . Naranjo Formation			
Mesozoic	Triassic		Chinle Formation	Upper shale member	Trujillo Formation	
Mesozoic	Triassic		Chinle Formation	Cuervo Sandstone Member	Trujillo Formation	
Mesozoic	Triassic		Chinle Formation	Lower shale member	Tecovas Formation	
Mesozoic	Triassic			Santa Rosa Sandstone	Tecovas Formation	
Paleozoic	Permian		Artesia Group	Tansill Formation		Quartermaster Formation (Alibates Dolomite Lentil)
Paleozoic	Permian		Artesia Group	Yates Formation		Quartermaster Formation (Alibates Dolomite Lentil)
Paleozoic	Permian		Artesia Group	Seven Rivers Formation		Quartermaster Formation (Alibates Dolomite Lentil)
Paleozoic	Permian		Artesia Group	Queen Formation		Quartermaster Formation (Alibates Dolomite Lentil)
Paleozoic	Permian		Artesia Group	Grayburg Formation	Bernal Formation	Quartermaster Formation (Alibates Dolomite Lentil)
Paleozoic	Permian		San Andres Formation	Fourmile Draw Member		
Paleozoic	Permian		San Andres Formation	Bonney Canyon Member		
Paleozoic	Permian		San Andres Formation	Glorieta Sandstone Member . Rio Bonito Member		
Paleozoic	Permian		Yeso Formation			
Paleozoic	Permian		Abo Formation			
Paleozoic	Pennsylvanian		Magdalena Group, Madera Fm.	Upper arkosic member	Alamitos Formation	Sangre de Cristo Formation
Paleozoic	Pennsylvanian		Magdalena Group, Madera Fm.	Lower gray limestone member	La Pasada Formation	
Paleozoic	Pennsylvanian		Magdalena Group	Sandia Formation	La Pasada Formation	
Paleozoic	Mississippian		Tererro Formation	Cowles Member Manuelitas Member Macho Member		
Paleozoic	Devonian		Espiritu Santo Formation	Del Padre Member		
Paleozoic	Silurian					
Paleozoic	Ordovician		Ellenburger Formation?			
Paleozoic	Cambrian					
Precambrian			Granite, gneiss, schist, quartzite, metavolcanics			

to Capilla Peak gives an overview of the western slope of the mountains, a close view of the Precambrian metamorphic terrane and overlying Pennsylvanian rocks at the crest of the range, and a glimpse of the Laramide reverse faults separating the western and eastern structural zones. An optional stop is at the Quarai Ruins Unit of the Salinas National Monument. The final part, from Mountainair to Abo Canyon, emphasizes Pennsylvanian and Permian stratigraphy at the southern end of the Manzanos and along the upper valley of Abo Arroyo. The bedrock section observed includes the Madera Gr and the Bursum, Abo, and Yeso Fms.

Road-log segment I-C includes a tour through upper Paleozoic stratigraphy and Precambrian metamorphic units along U.S. 60 in the Abo Pass–Blue Springs area (Stop 4). The tour route leaves competent rocks, crosses into the Albuquerque basin, goes northwest to Belen, and then northward to Albuquerque. Features of the Albuquerque basin which are emphasized include Quaternary landforms, basin-fill stratigraphy, ground-water hydrology, and Miocene-to-Pliocene volcanics; oil tests are also discussed.

Road-log segment I-D is a trip to Hubbell bench and the front of the Manzano Mountains (Cañon del Trigo) from Rio Grande Estates. Riverine and piedmont landforms and fill-stratigraphy of the Albuquerque basin are emphasized on the way to J. F. Kennedy campground in Cañon del Trigo. Stop 5, at the Hubbell Springs fault, shows pedimented and deformed Paleozoic, Mesozoic, and Tertiary units exposed in the Hubbell bench. Stop 6 provides an overlook of the Hubbell bench and Albuquerque basin, together with a walking tour through Precambrian rocks in lower Cañon del Trigo.

ROAD-LOG SEGMENT I-A: ALBUQUERQUE TO TIJERAS CANYON

J. R. CONNOLLY, L. A. WOODWARD, and J. W. HAWLEY

Welcome to Albuquerque (1980 population: 331,767). In 1706 New Mexico's colonial governor, Don Francisco Cuervo y Valdez, founded a villa here that he named San Francisco de Alburquerque in honor of Don Francisco, Duque de Alburquerque and Viceroy of New Spain. When the governor placed the new villa under the patronage of San Francisco, he selected the name of his own patron saint and that of the viceroy. The viceroy, however, fearing the displeasure of King Philip V of Spain (who had not authorized the villa) decided to rename it San Felipe de Alburquerque, honoring the patron saint of the monarch. In the 19th century, English-speaking people dropped the "r" in the second syllable. The city is the commercial hub of the state and the site of the University of New Mexico, founded in 1889 (Pearce, 1965).

Mileage

0.0 Carlisle Boulevard I-40 overpass. **Take I-40 East on-ramp. 0.1**

0.1 MP (Milepost) 161. **Merge with Coronado Freeway and move to left lane. 0.8**

0.9 Passing under San Mateo Blvd. Route ascends piedmont slope west of the Sandia Mountains along the topographic low between the large fan of Tijeras Creek (to the south) and coalescent fan surfaces extending from Embudo and Embudito canyons in the southern Sandia Mountains. Arroyo del Embudo follows the axis of this interfan valley and now occupies the concrete-lined channel between the east- and westbound freeway lanes. This canal is part of an extensive system of flood-control structures that help handle severe rainstorm-runoff problems in northeastern Albuquerque. Piedmont-slope gradients range from 10 to 57 m/km. From here to the mountain front, boulder alluvial and mudflow deposits are common in piedmont sediments of both Holocene and Pleistocene age.

Basin fill in this area is hundreds of meters thick, with the bulk of the deposits belonging to the Lower Miocene to middle Pleistocene Santa Fe Gr. Post–Santa Fe piedmont-slope alluvium probably does not exceed 30 m in thickness. The upper Santa Fe Gr constitutes the major aquifer utilized for the urban-water supply. Wells near the freeway between San Mateo and the mountain front are from 300-400 m deep and produce from a saturated zone 100-170 m below the piedmont surface. The water-table elevation in the basin fill approximates the level of the Rio Grande floodplain, rising sharply near the mountain front (Bjorklund and Maxwell, 1961) (see Kelly, this guidebook).

Further details appear in road-log segment III-S of Day 3 and in Kelley's (1974) *Scenic Trips to the Geologic Past*, n. 9. **2.6**

3.5 Passing under Eubank Blvd. The bold escarpment of the Sandia Mountains forms the skyline to the left. Antennae of Albuquerque radio and TV stations are on the crest (elev. 10,678 ft; 3,255 m). The scar to the right of the crest was produced by blasting the rim of the escarpment when the Sandia tram was built. The upper tramway terminal and restaurant (Day 3, Stop 2) is directly above the scar. The slopes of the Sandia front are formed on Precambrian intrusive rocks capped with a layered sequence of Mississippian and Pennsylvanian sedimentary rocks. Straight ahead on the southern side of Tijeras Canyon in the Manzanita Mountains, the upper Paleozoic sedimentary sequence overlies a complex Precambrian metamorphic and igneous terrane. **1.6**

5.1 **MP 166. Move to right lane and prepare to exit at Tramway Blvd. 0.8**

5.9 **Take Tramway Blvd exit (no. 167). Keep right. 0.2**

6.1 Traffic light. **Turn right (south) on Tramway Blvd; cross Central Ave, and curve left on frontage road (U.S. 66).** Motor hotel on right. **0.3**

6.4 Stop sign. **Continue east on U.S. 66.** Four Hills Road to right descends Tijeras Arroyo valley by following a tributary stream that flows along the north-south-trending frontal fault of the Sandia uplift. Older alluvium (upper Santa Fe Gr) of the Tijeras Creek fan is down-faulted against Sandia granite (Precambrian, ~1.4 b.y.; see **Brookins, Brookins and Majumdar, and Affholter and Lambert, this guidebook**). The tour route from here east includes parts of Tijeras quadrangle mapped by Kelley and Northrop (1975) and Myers and McKay (1976). **0.2**

6.6 Route is on pediment cut on Sandia granite, with a discontinuous veneer of Quaternary alluvium and colluvium deposited in the apex area of the Tijeras Creek fan. **0.4**

7.0 Break in slope (piedmont angle) at 9:00-10:00 between mountain front and piedmont erosion surfaces on Sandia granite. Route enters Tijeras Canyon. Outcrops for next 3 mi are dominated by residual corestone features formed by weathering and erosion of jointed blocks of granite. Note the gradual change from more weathered rounded residual masses to blocky fresher granite. **0.6**

7.6 Lamprophyre dike cuts Sandia granite in road cut to left. Woodward (1970) described the petrography of the dikes and presented chemical analyses of a typical hornblende spessartite variety. Shomaker (1965) assigns a Tertiary age to these intrusives which cut across Precambrian aplite dikes and extend as a swarm in an area of Sandia granite about 19 km long and 3 km wide. **0.2**

7.8 Carnuel interchange. Cross I-40 and **continue east on U.S. 66. 0.2**

8.0 Village of Carnuel and Tijeras Creek to right. *A farming community named San Miguel de Carnuel (pronounced Carn-way) was established in this area by Spanish settlers in the 18th century. By the 1760's, Apache raids had become such a threat that the settlers asked the Spanish government for soldiers. They received a mandate to fortify a new, consolidated townsite and a formal land title for 19 families. Work by the Center for Archeological Studies indicates that the new village was built immediately west of the old settlement and consisted of at least eight separate structures, positioned on three sides of a plaza with the west side reserved for eventual construction of a church. An adobe wall was built around the perimeter. Apache pressure continued until October 1770, when raiders breached the wall, forcing the residents to flee to the villa of San Felipe de Alburquerque 12 mi (19 km) to the west. The plundered village was dismantled by May 1771, and left in ruins. The present village of Carnuel began after February and March of 1819, when the Governor of New Mexico and alcalde of Albuquerque gave land in Tijeras Canyon, including Carnuel, to 77 landless people from Albuquerque. The earlier ruin of Carnuel was all but forgotten until 1974 when archaeologist Albert Ward obtained the permission of landowners to excavate the site. On May 4, 1977, Carnuel was entered in the National Register of Historic Sites. Plans call for excavation and partial restoration of this historic community (Pearce, 1965; Ward, 1976).*

From the Carnuel exit to Deadman's curve (2.5 mi) are exposures of Sandia granite, easily recognizable from a distance by its spheroidal weathering pattern. The "granite" in this area is generally quartz monzonite to granodiorite, and it contains large pinkish porphyroblasts of microcline. The microcline is largely metasomatic in origin and presumably crystallized as potassium-rich solutions were expelled from the crystallizing magma. The border zones of granite area locally foliated, and this, combined with the metasomatic halo of microcline porphyroblasts extending into the metasedimentary Cibola gneiss, has created a gradational contact between granite and gneiss (see **Connolly, this guidebook**). **1.0**

9.0 Sandia granite in large roadcut to left. **0.3**

9.3 Turnoff to right across Tijeras Arroyo leads to mines in southern part of Tijeras greenstone terrane. This area has a long history of base and precious metal mining from Precambrian host rocks (see **Fulp and others, this guidebook**). Pinkish hill across creek at 9:00 is Cibola gneiss. Sandia Mountain crest to left is capped by limestone, shale, and sandstone of the Sandia Fm and Madera Gr. The Pennsylvanian sequence in this area is underlain by local, thin patches of crinoidal limestone of the Mississippian Arroyo Peñasco Gr (Armstrong, 1967; Armstrong and Mamet, 1974, 1979; Armstrong and others, 1979; Szabo, 1953) and Precambrian igneous and metamorphic rocks. Notice the weathered (corestone) granite slope giving way to the bold, craggy outcrops high on the ridge. Trees here (elev. 6,000 ft; 1,829 m) are mostly juniper of the upper Sonoran life zone; native mountain cottonwoods grown along Tijeras Creek. **0.5**

9.8 Beginning of gradational contact between Sandia granite and Cibola gneiss. This contact is mapped as orthogneiss on the geologic map (p€ co of fig. 2 in **Connolly, this guidebook**). **0.2**

10.0 Lamprophyre dike in granite gneiss to left. **0.1**

10.1 Cibola gneiss exposures on left. Between this point and Deadman's curve, gray quartzite in the gneiss terrane crosses under the highway and is exposed on steep southwest-facing talus slope and on the south wall of the arroyo. **0.4**

10.5 I-40 overpass at Deadman's curve. The Tijeras fault crosses under the highway in this area, and for the next 1.5 mi, I-40, old U.S. 66, and Tijeras Arroyo are subparallel to the northeast-striking Tijeras fault. Before highway realignment in the mid-

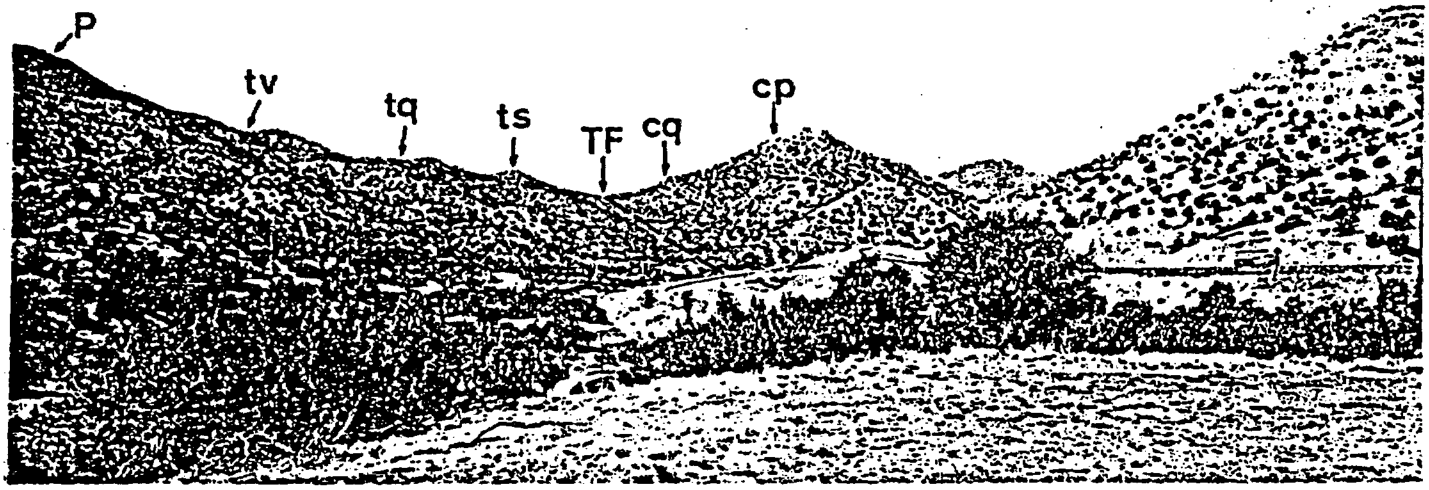


Figure I-A11.1a. Panorama of Precambrian terranes in Tijeras Canyon looking southwest from Stop 1. From left is Tijeras greenstone, the Tijeras fault, and Cibola gneiss. See text under Stop 1 for complete explanation of symbols.

1970's, Deadman's curve was a very sharp bend and was particularly hazardous during winter storms. **0.2**

10.7 Terrace gravel and fan deposits to right cap metamorphic rocks in cut above Tijeras Creek. **SLOW, prepare for sharp right turn ahead at tour stop. 0.3**

11.0 Turn right onto graded turnout area and park on crest of low ridge. **0.1**

11.1 **STOP 1.** Precambrian metamorphic terranes of Tijeras Canyon.

This stop is a turnoff to the site of an old Atomic Energy Commission radio tower and gives an excellent view of the Precambrian terranes as well as some of the Quaternary terrace gravels exposed along Tijeras Arroyo. View to the southwest (fig. I-A11.1a) shows panorama of Precambrian terranes: from left (southeast)—steep rim of southeast-tilted late Paleozoic strata (P), metavolcanic part of Tijeras greenstone (tv), metasedimentary part of Tijeras greenstone (ts) with quartzite lenses (tq), northeast-striking Tijeras fault (TF), and meta-arkosic Cibola gneiss (cp) with resistant ridge of quartzite (cq). Foliation and layering in both gneiss and greenstone strike generally northeast, with dips to the southeast in the greenstone and to the northwest in the gneiss.

The area is underlain by metasedimentary phyllite, quartzite, and metavolcanics of the Tijeras greenstone, and good exposures of highly deformed spotted phyllite may be seen about 985 ft (300 m) to the northeast along the gas pipeline service route. A drainage tunnel under I-40 about 560 ft (170 m) to the northeast from the pipeline route provides access to the Cibola gneiss terrane. A Tertiary, green lamprophyre dike with an altered chilled margin intrudes Cibola gneiss in a roadcut on I-40 to the northwest, and an excellent view of the Tijeras fault is visible in I-40 roadcuts about 0.6 mi (0.7 km) to the northeast.

Tijeras greenstone and Cibola gneiss are complexly deformed and metamorphosed Proterozoic terranes of contrasting lithology. Cibola gneiss is primarily meta-arkose with a prominent ridge of isoclinally folded quartzite, implying isoclinal folding has occurred throughout the terrane. Tijeras greenstone contain pelitic metasediments and quartzite in addition to the tholeiitic metavolcanics which dominate the terrane; isoclinal folding has also occurred in the greenstone. Syntectonic metamorphic grade in both terranes is low-pressure amphibolite facies, but the internal structural geometries in the two terranes are distinctly different (see **Connolly, this guidebook**).

The northeast-striking, subvertical Tijeras fault is buried beneath road fill in this area. Documented fault movement postdates folding and amphibolite-facies metamorphism in gneiss and greenstone, and the presence of numerous en-echelon granitic and pegmatitic dikes adjacent to the fault, in the greenstone southwest of Deadman's curve, suggests left-slip contemporaneous with granitic intrusion. The contrast in structure and lithology between the juxtaposed metamorphic terranes suggests considerable slip, probably at least several kilometers, has occurred on the Tijeras fault. There have been at least four episodes of movement along the fault, including left slip during the Precambrian, either dip-slip or strike-slip movement during middle and late Paleozoic time to form a north-facing scarp and related structure, late Cenozoic dip slip with subordinate left slip, and normal slippage (north-side down) during late Quaternary time (Lisenbee and others, 1979).

Return to vehicles and continue east on U.S. 66. 0.5

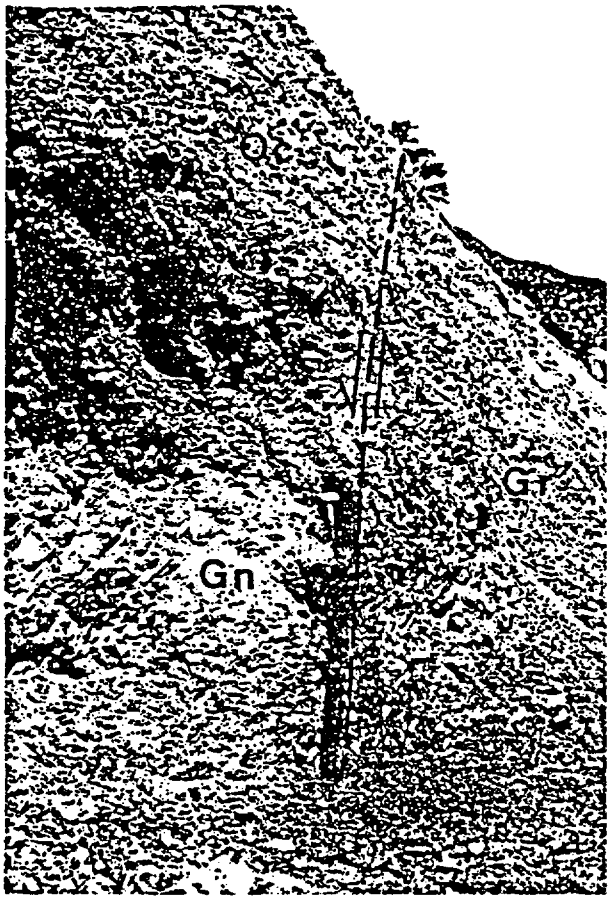


Figure I-A11.1b. Close-up view of Tijeras fault in roadcut on I-40. Highly fractured gneiss (Gn) and colluvium derived from gneiss (Qc) are juxtaposed with sheared and fractured phyllitic greenstone (Gr). Arrows show probable sense of most recent movement only, which has juxtaposed greenstone and colluvium.

QUATERNARY GEOLOGY AND GEOMORPHOLOGY OF TIJERAS CANYON, NEW MEXICO

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INTRODUCTION

Tijeras Creek drains a large portion of the southeastern Sandia and Manzanita mountains through Tijeras Canyon. The canyon parallels the southwestward trend of the Tijeras fault between the village of Tijeras and Deadman's curve on U.S. 66. West of Deadman's curve the canyon trends westerly. The influence of bedrock lithology on the canyon's morphology is evident near the village of Tijeras where the canyon is developed in less resistant upper Paleozoic sedimentary rocks in the headwaters and is developed in more resistant Precambrian metamorphics in the section between Tijeras and Deadman's curve; thus, the canyon is narrow in the metamorphics and is wider in the sedimentary rocks. Downstream from Deadman's curve, the increase in the canyon width is due to pedimentation of the Sandia granite. The purpose of this summary is to discuss the landforms and surficial deposits of Tijeras Canyon in the metamorphic rocks near Deadman's curve and in the Sandia granite near Carnuel and to show how bedrock lithology influences the formation and perservation of Quaternary deposits.

Stratigraphy and soils of Quaternary deposits indicate that multiple erosional and depositional events occurred at both study sites; however, a canyon-wide sequence of fluvial activity has not yet been recognized. Quaternary deposits in the canyon include both axial facies characterized by rounded gravels of mixed lithologies derived from the canyon headwaters and tributary facies containing abundant angular clasts of local provenance (e.g., valley-side slopes). Soils in both areas have formed on fluvial, alluvial fan, and pediment deposits. A paucity of colluvium and associated soils is typical of granite terrane; whereas, colluvium and soils occur in the metamorphic terrane. For example, a complex soil developed on the colluvium mantling the Cibola gneiss has a Btca horizon in excess of 2 m thick.

LANDFORMS AND DEPOSITS IN METAMORPHIC TERRANE

The stratigraphy and geomorphic history of the Deadman's curve area is complex due to bedrock and structural control (hence, steepness and narrowness of the canyon) and contributions of debris from adjacent mountain slopes. Bedrock consists of Precambrian greenstone and quartzite. Stratigraphic interpretations of the Quaternary deposits are complicated by the interfingering of axial fluvial facies with alluvial fan and colluvial facies. However, stratigraphic relationships have allowed the recognition of two axial facies deposits (Qa_1 and Qa_2), three alluvial fan deposits ($Qf_{1a,b}$, Qf_2, Qf_3), modern channel and side-slope alluvium (Qa_3), and colluvial deposits (Qc). Figure I-A11.1c is a Quaternary geologic map of the area and Figure I-A11.1d is a diagrammatic cross section which shows the stratigraphic relationships seen in the arroyo walls near Deadman's curve. Qa_1 consists of rounded gneissic, granitic, and sedimentary cobbles and boulders which are imbricated. Upward-fining sequences occur with interspersed channel facies of coarse

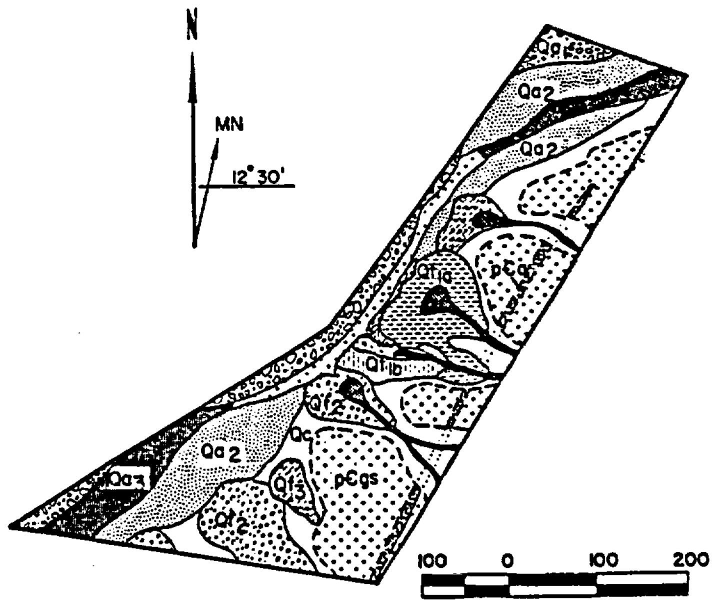

Figure I-A11.1c. Quaternary geologic map of the Deadman's curve area. Symbols: P€g = Precambrian granite; p€gs = Precambrian greenstone; p€q = Precambrian quartzite; Qa_1 and Qa_2 = Quaternary axial facies deposits, $Qf_{1a,b}$, $Qf_{2,3}$ = Quaternary alluvial fan deposits; Qa_3 = Quaternary channel and side-slope alluvium; Qc = Quaternary colluvial deposits.

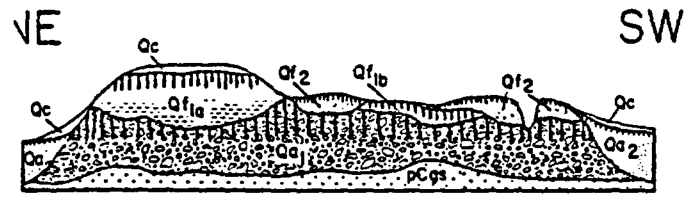

Figure I-A11.1d. Diagrammatic cross section of the Deadman's curve area showing the stratigraphic relationships exposed in arroyo walls. Symbols are explained in Figure I-A11.1c. Vertical lines represent soil development. Longest, heaviest-weight lines represent strongest soil development; short, light-weight lines represent weakly developed soils.

gravels, cobbles, and small boulders. Granitic boulders in Qa_1 are at an advanced stage of weathering and are almost completely grussified; whereas, gneissic boulders are less weathered. Qa_1 rests on greenstone bedrock and interfingers with angular side-slope colluvium in its upper parts. Qf_{1a} and Qf_{1b} rest on and are inset into Qa_1, and they consist of angular clasts of greenstone in upward-coarsening sequences. Topographic and soil relationships suggest that Qf_{1a} is older than Qf_{1b}, but erosion of the soil on Qf_{1a} obscures relative-age relationships. Qf_2 is inset into both Qf_{1a} and Qf_{1b} and is distinguished by its darker color and less well-developed soil. Qa_2 is a very fine-grained fill resting on bedrock and, in places, on Qa_1. Qa_2 is preserved as a fill terrace below the Qf_{1-2} terrace level. Bedrock has been incised more than 2 m below the base of Qa_1 deposits. A high-level strath terrace is conspicuous about 40 m above the stream level.

Soils are developed on all units with most pronounced development on Qa_1 and $Qf_{1a,b}$ deposits. Soils are complex due to erosion and intermittent interruption of pedogenesis by burial from side-slope debris and alluvial-fan deposition. Soils developed on Qf_{1b} are well-exposed and may represent polygenetic soil development. The upper soil of Qf_{1b} has a 1-m-thick Btca horizon with stage II calcium carbonate development in the Cca horizon. A buried soil occurs beneath this and is characterized by a 1-m-thick truncated Bt-Btca horizon with stage III $CaCO_3$ morphology. The carbonate morphology of this soil suggests an age of mid to late Pleistocene. Soils are developed below this in Qa_1 deposits but have not been described. A 1-m-thick Cca horizon (stage III) is all that remains of the soil on Qf_{1a}. The Qa_2 deposits exhibit minimal horizonation and a maximum of stage I $CaCO_3$ development. These are slightly less developed than Qf_2 soils, suggesting that Qa_2 was deposited soon after Qf_2 deposition or else that the difference in parent material accounts for the small difference in soil development on two deposits of different age.

Based on stratigraphy, soil development, and soil-stratigraphic relationships, the following geomorphic history is suggested for the metamorphic terrane of the Deadman's curve area: (1) deposition of Qa_1 in a predominantly bedrock valley followed by stability and soil formation; (2) erosion of upper Qa_1, truncation of Qa_1 soils, fan deposition (Qf_{1a}), and soil formation; (3) erosion of Qf_{1a} prior to Qf_{1b} deposition, followed by stability and soil development; (4) Qf_2 deposition; (5) downcutting of Tijeras Creek to bedrock, followed by backfilling of Qa_2 (possibly latest Pleistocene and early-mid Holocene, respectively); and (6) mid-late Holocene incision to bedrock level.

LANDFORMS AND DEPOSITS IN GRANITIC TERRANE

Major geomorphic features in the Sandia granite of Tijeras Canyon include corestones and pediments; other minor features are alluvial fans (composed of grus), strath and fill terraces, and incised arroyos. Corestone, spheroidally weathered granite blocks, are well-developed on the bedrock slopes in Tijeras Canyon. These features form by physical and chemical weathering along the fractures in the granite with the major weathering products being rinds on the corestones and grus. Weathering rinds are form 1 to 15 cm thick and form concentric sheets around the subrounded, fresh rock. The rinds commonly can be divided into two parts: (1) an inner section of semi-consolidated aggregates of mineral grains with altered biotite (red-brown color as opposed to black in fresh sample) and (2) an outer portion of mineral grains in an oxidized, clayey matrix (little biotite present). A comparison of oxide composition of weathered grus and unweathered granite is given in Table I-A11.1a; SiO_2 is increased by an adjusted 3.55% reflecting quartz stability (Al_2O_3 is held constant). The ferric-iron content is greater in the grus reflecting the alteration of biotite. Additionally, K_2O is decreased in the grus relative to the granite, suggesting a loss of potassium during weathering of potash feldspar.

Many corestones are surrounded by grus that has been transported around the bedrock as opposed to forming in situ. Evidence of past burial on corestones can be seen as at least two reddish pink oxidation surfaces (coatings) that occur above the present ground surface. The elevation of these oxidized surfaces can be projected to the elevation of fill remnants preserved along the flanks of the bedrock hillslopes. These relationships suggest a widespread period of corestone formation, erosion of the in-situ grus, later filling with transported grus, renewed corestone weathering, and removal of this fill and weathered granite during latest erosional period. This complex relationship of weathering and episodic erosion and deposition may be one of the main processes of pedimentation in Tijeras Canyon.

Pediments developed on granite have been incised, and remnants of the bedrock surfaces are conspicuous for at least 4 km down lower Tijeras Canyon. Terraces are inset into the pediments along the canyon. Near Carnuel the pediment is overlain by remnants of a grus mantle which exhibits a well-developed soil. This soil is preserved beneath an alluvial fan that covered the pediment prior to incision of the modern tributaries to Tijeras Creek. The soil has a 15-cm-thick argillic B horizon and a calcic horizon with stage II-III morphology; completely grussified granitic clasts are present in the C horizon. Calcic-horizon morphology suggests an age of late Pleistocene or older.

Landscape-stratigraphic relationships in the Carnuel area suggest the following geomorphic history: (1) pedimentation and concurrent soil formation; (2) pediment incision by Tijeras Creek and its tributaries; (3) ~10 m of canyon alluviation and alluvial-fan formation at the range margins and near Tijeras Creek; and, most recently, (4) incision through valley fill to the present bedrock channel (see fig. I-A11.1e).

Based on soil development, pedogenic $CaCO_3$ morphology, and the occurrence of grussified cobbles and boulders in Qa_1 deposits, it is

Table I-A11.1a. Chemical constituents in fresh and weathered Sandia granite, Tijeras Canyon; analysis by UNM Geology Department Staff Chemist, J. Husler.

Constituent	Fresh (%)	Weathered (%)
SiO_2	65.71	66.29
Al_2O_3	14.47	13.85
Fe_2O_3	2.19	4.06
FeO	3.01	1.08
MgO	1.41	1.23
CaO	3.09	3.21
Na_2O	3.03	3.11
K_2O	4.49	3.42
H_2O	1.12	2.38
Others*	1.47	1.36
Total	99.99	99.99

*Others include: TiO_2, P_2O_5, MnO, SrO.

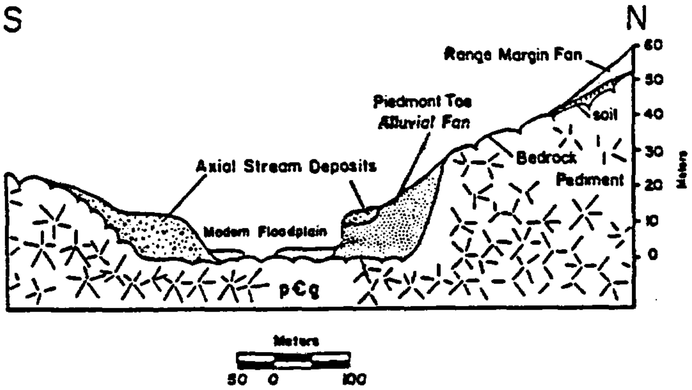

Figure I-A11.1e. Generalized cross section of Quaternary deposits of Tijeras Canyon near Carnuel; p€g = Precambrian granite.

apparent that Quaternary deposits in the metamorphic terrane near Deadman's curve are older than those near Carnuel. This may be due to lithologic controls which favor the preservation of older alluvial deposits in the resistant metamorphics; whereas, the destruction and removal of older deposits has occurred in the granitic terrane due to the ease of granite weathering and erosion of grus. Before an accurate correlation of Quaternary depositional and erosional units and events can be made, additional investigations are needed throughout the Tijeras Canyon area.

11.6 Seven Springs to right. From this area to the mouth of Tijeras Canyon, both alluvium and fractured Precambrian rocks serve as aquifers (Titus, 1980). Alluvium in the inner valley locally is more than 30 m thick. Most wells are from 8-46 m deep and yield up to 190 l/min. Chemical quality is good, except for excessive nitrate in some wells. To the east, limestones of the Madera Gr form the principal aquifer, particularly where small solution channels are present in zones of fracturing or above shale interbeds (see Jenkins, this guidebook). Most wells are less than 91 m deep and produce small amounts of water (average for 46 wells of 45 l/min, or 12 gpm). However, 335-m-deep artesian wells produce from the Madera Gr at the Ideal Cement plant at Tijeras, about 1.5 mi (2.4 km) to the east. Northeast of Tijeras is a small area on and adjacent to the Tijeras anticline, where ground water is produced from Permian and Mesozoic carbonate and clastic rocks. Again, most wells yield less than 38 l/min, but quality is generally poor with excessive sulfate and dissolved solids (Titus, 1980). **0.4**

12.0 Good exposures of highly deformed metavolcanics of Tijeras greenstone in roadcut to right under boulder gravels. **0.8**

12.8 Village of Tijeras ahead was founded in 1856. However, Tijeras Canyon has been a major thoroughfare since prehistoric times. The complex of canyons crossing the mountains here resemble open scissors, the translation of "tijeras." Road cuts are in reddish-brown mudstone of the Lower Permian Abo Fm, which overlies the Madera Gr in this area. **0.3**

13.1 Stop sign at junction with N.M. 14. Road-log segment I-B to Abo Canyon, via Estancia and Manzano, begins to right. **Turn left under I-40. 0.2**

13.3 I-40 westbound, **approach ramp to left. Continue straight** on winding subdivision road (U.S. Forest Service road 519) up southeast slope of Sandia Mountains. Red-bed sandstone and mudstone of Abo Fm in roadcut to left. **0.5**

13.8 Park in cul-de-sac at upper end of subdivision road and take U.S. Forest Service trail 130 to Hondo Canyon area. **0.1**

13.9 **OPTIONAL STOP.** Stratigraphy and structure near Hobbies, southern Sandia Mountains.

This stop (fig. I-A13.9) provides an excellent overview of the area to the east and northeast of the Sandia Mountains as well as a stratigraphic section ranging from the Madera Gr (Pennsylvanian) to the Mancos Shale (Cretaceous). A short

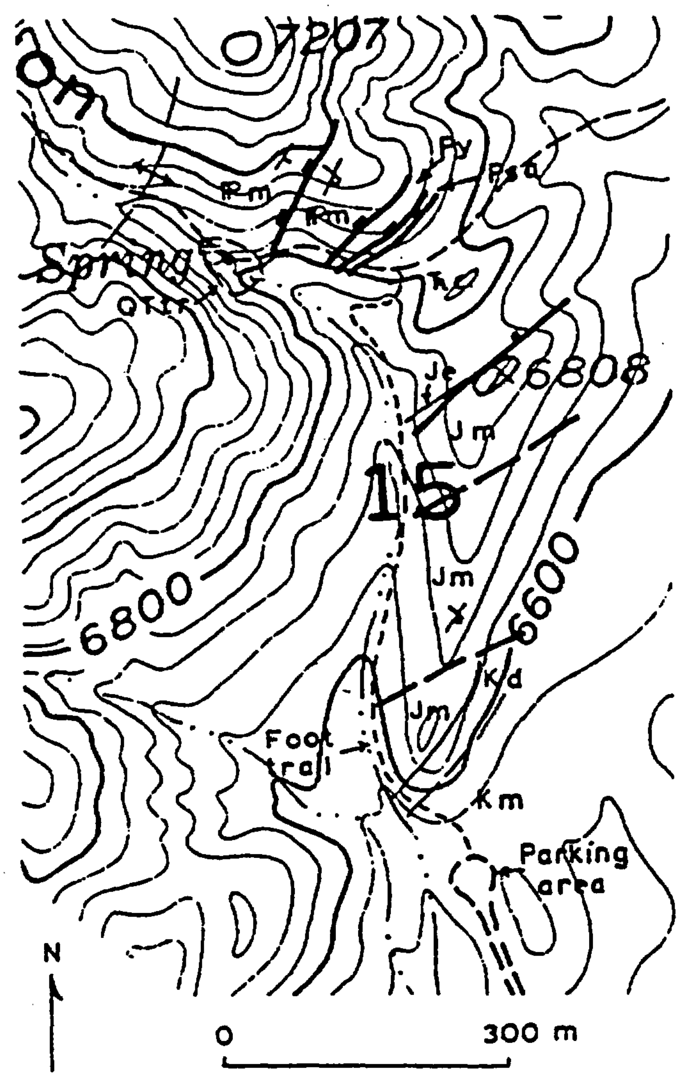

Figure I-A13.9. Geologic map of segment of Forest Service Trail 130, near Hobbies, by L. A. Woodward.

walk along the U.S. Forest Service trail (see map) leads through an inverted stratigraphic section that is bounded on the west by a reverse fault which brings upright Madera Gr above overturned to vertical Madera Gr.

The most convenient way to see this section is to walk to the travertine deposit (QTtr) at the spring about 1,970 ft (600 m) up the trail and then return along the northerly trending ridge just east of the trail. The following description of the rock units and the structure begins at the travertine deposit and ends at the parking area. To the northwest of the travertine (QTtr), limestone beds of the Madera Gr (IPm) are right-side-up along the eastern limb of an open, upright anticline. The spring is located along a steep reverse fault with inverted Madera limestone beds to the east.

Orange-tan, fine-grained sandstone of the Permian Yeso Fm (Py) is present as a fault slice east of and structurally below the Madera. Several hundred meters of Abo Fm and part of the Yeso have been tectonically cut out along the fault separating the Madera from the Yeso. East of the Yeso, there is yellowish-tan limestone of the Permian San Andres Fm (Psa); the Permian Glorieta Sandstone and Bernal Fm as well as the Triassic Santa Rosa Sandstone are tectonically eliminated here.

The low saddle to the north is underlain by Triassic Chinle Fm (Trc), a unit composed of several hundred meters of reddish to purplish shale with subordinate interbedded red to brown sandstone and brown limestone-pebble conglomerate. East of the Chinle outcrop, a high-angle normal fault down to the west has cut out most of the Jurassic Entrada Sandstone (Je) and Todilto Fm; a small wedge of Entrada is present on the west side of the ridge.

To the east, the ridge is underlain by yellowish to buff sandstone and variegated mudstone of the Jurassic Morrison Fm (Jm). Overturned crossbeds are well displayed at the southern knob of the ridge near the stratigraphic top of the Morrison.

Sandstone of the Cretaceous Dakota Fm (Kd) stratigraphically overlies the Morrison which forms the crest of the ridge. An interval of black carbonaceous shale occurs between the Dakota sandstones here. Black to dark-gray Cretaceous Mancos Shale (Km) stratigraphically overlies the Dakota and forms the low saddle near the parking area. Reddish pediment deposits unconformably cover the Mancos on the small hill east of the parking area.

Return to I-40. **0.5**

14.4 Stop sign at I-40 on-ramp. **End of road-log segment I-A.** Road-log segment I-B to Abo Pass via Estancia, Manzano, and Mountainair starts at N.M. 14–U.S. 66 junction just south of freeway.

ROAD-LOG SEGMENT I-B: TIJERAS CANYON TO ABO CANYON VIA ESTANCIA AND MANZANO

J. W. HAWLEY, R. W. FOSTER, R. BROADHEAD, and D. W. LOVE

Mileage

0.0 **Head south on N.M. 14** from U.S. 66 toward Tijeras Creek bridge. Pennsylvanian and lower Permian units along the northern part of the route (mi 0.0-21.5). Descriptions of these units are found in Zidek (1975), Myers and McKay (1976), and Myers (this guidebook). In the Manzanita Mountains, rocks previously considered as the Madera Limestone have been placed in the Madera Gr by Myers (1973). In this area, he divided the Madera Gr into two formations: the basal Los Moyos Limestone (Desmoinesian–early Missourian) and the upper Wild Cow Fm (Missourian-Virgilian, and possible also earliest Wolfcampian). Myers' dating is based on fusilinid evidence. Major stratigraphic divisions appear in Table I-B0.0. **0.1**

Table I-B0.0

Abo Fm
Wild Cow Fm—Madera Gr La Casa Mbr (Unit D) Pine Shadow Mbr (Unit C) Sol se Mete Mbr (Unit B)
Los Moyos Limestone—Madera Gr
Sandia Fm

0.1 Faulted sandstone of the Abo Fm caps ridges at 9:00. **0.1**

0.2 Bridge over Cedro Creek. Ideal Basic Industries cement plant at 2:00, with quarries in the Wild Cow Fm. Quarry capacity (limestone, shale) is 3,600 metric tons (4,000 tons/day), and Portland Cement clinker capacity is 1,452 metric tons (1,600 tons/day, or ~500,000 tons/yr). **0.2**

0.4 Contact between Abo Fm and La Casa Mbr of the Wild Cow Fm in east wall of valley at 9:00. Sandstone, mudstone, and limestone of La Casa Mbr in roadcut to right. Tijeras Pueblo site on low terrace to left. **0.1**

PREHISTORIC ARCHAEOLOGY IN TIJERAS CANYON

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RECENT RESEARCH

Tijeras Canyon was the scene of intensive archaeological investigation between 1971 and 1976. The University of New Mexico's summer field school in archaeology conducted in inventory survey, recording archaeological sites in 25 sections of the Tijeras Canyon–South Sandia area (Blevins and Joiner, 1977) and excavated Tijeras Pueblo, a large 14th-century village (Cordell, 1977, 1980). Beginning in 1972, the Laboratory of Anthropology of the Museum of New Mexico carried out archaeological survey and excavation in conjunction with the expansion of I-40 and North N.M. 14 (Farwell, 1977; Oakes, 1978; Snow, 1976; Wiseman, 1980). The Laboratory's work was completed in 1975. The combined research of both institutions recorded 150 archaeological sites and provided a record of prehistoric occupation of the canyon from about A.D. 700 to the 1600s. Complementary archival and ethnohistoric work (Swadesh, 1977; Quintana and Kayser, 1980) document the Hispanic settlement of the canyon from 1763. This review is concerned with the prehistoric period. The research focus of the University and Laboratory work was on defining prehistoric settlement and resource use in the canyon setting (Cordell, 1980).

SETTLEMENT CHRONOLOGY

There is only slight evidence of use of Tijeras Canyon during the Preceramic Period (10,000 B.C. to A.D. 600). Projectile points dating to this period have been collected, but only one late Preceramic site recorded (Snow, 1972). It is likely that alluvial sediments obscure remains of this antiquity (Cordell, 1977, 1980). During the Rio Grande Developmental Period of A.D. 600 to 1200 (Wendorf and Reed, 1955), a number of small, probably seasonally occupied communities were located in the canyon. These sites are at low elevation settings on or adjacent to alluvial land. The Dinosaur Rock site, the one excavated site falling within this time period, is larger than most and may have been lived in year round. The site consisted of six rectangular rooms, with well-made floors, and three jacal (mud and twig) structures south of the rooms. The rooms lacked hearths and cultural debris and may have been used for storage. The jacal structures each contained a hearth, faunal remains, corn, and other food debris. The Dinosaur Rock site probably dates to about A.D. 700 (Oakes, 1978).

During the Coalition Period (A.D. 1200 to 1325), the number of sites in the canyon doubled, and sites were distributed over a wider range of local environmental zones than they have been previously. One small site near Deadman's curve, occupied between about A.D. 1250 and 1350, was excavated by the Laboratory of Anthropology (Wiseman, 1980). The site consisted of three nearly rectangular pit houses and about eleven rectangular surface rooms and associated jacal structures. Tijeras Pueblo was founded in about A.D. 1310 and shortly became the largest village in the canyon (Cordell, 1977, 1980).

By about A.D. 1325, many of the small habitation sites in the canyon were abandoned, and population aggregated at Tijeras Pueblo and at San Antonio. The full extent of San Antonio is not known, because the site was only partially excavated. Tijeras Pueblo comprised about 200 rooms arranged in a loose circle, open to the north. A very large, circular, masonry-walled kiva, nearly 21 m in diameter, was built in the center fo the community. In addition to these two sites, numerous limited activity sites (such as chipping stations, hunting camps, and seed gathering areas) were dispersed throughout the canyon. During the late 1300s Tijeras Pueblo was partially abandoned, and a new, smaller, U-shaped pueblo was built over part of the site. The circular kiva was abandoned, and a smaller, rectangular, adobe-walled kiva constructed. The new pueblo contained about 100 rooms. By A.D. 1425, Tijeras Pueblo was completely abandoned, but San Antonio was occupied, at least intermittently, until about 1600. Very few sites dating to the 16th and 17th centuries were found in the canyon, and those that were found are primarily small sherd and lithic scatters indicating areas of limited activity rather than year round occupation (Cordell, 1980).

EXPLAINING SETTLEMENT CHANGES

The local environment of Tijeras Canyon is not very secure for agricultural communities. It is significant that the Hispanic settlements combined farming and ranching but were required to supplement their economic base through timber cutting and wage work (Quintanta and Kayser, 1980). Variability in growing season length, and especially in rainfall, has always made farming risky. Paleoclimatic information, obtained from tree-ring studies, shows that rainfall conditions in the canyon from about A.D. 600 to 1300 were similar to those of today. Small numbers of people, probably originating in the Albuquerque area, settled in the canyon to farm, gather wild foods, and hunt. This initial settlement may have been prompted by shortages of good quality, easily worked agricultural land along the Rio Grande. The two large villages, Tijeras Pueblo and San Antonio, were founded when rainfall conditions in the canyon were optimal. Several lines of evidence suggest that agriculture was the major source of food at this time. Studies of faunal remains show an emphasis on small game, especially animals that could be hunted without conflicting with the agricultural cycle and that are themselves agricultural pests. Second, studies of the burial population (Ferguson, 1980) indicate a fairly high incidence of disease related to protein deficiencies that accompany diets made up largely of corn and other plant foods.

The tree-ring-derived rainfall patterns indicate that at the end of the 1300s and the beginning of the 1400s, optimal conditions were no longer present. In fact, rainfall deficits were rather more severe than they are in the canyon today. Had the prehistoric Pueblos been able to intensify agricultural production, by practicing irrigation for example, these problems might have been mitigated. However, the springs which are the most reliable perennial sources of water in the canyon are not adjacent to arable land. The only solution available to the prehistoric population was abandonment of the agricultural villages (Anderson and Oakes, 1980; Cordell, 1980).

0.5 U.S. Forest Service Tijeras Ranger Station to left. Basal arkosic sandstone and conglomerate of La Casa Mbr on resistant gray calcarenite of the Pine Shadow Mbr in roadcut. In this area, beds of Pine Shadow Mbr contain a marine faunal assemblage which includes *Triticites* sp., *Bellerophon* sp., openly coiled cephalopods, and numerous species of brachiopods. **0.2**

0.7 Cross southwest-striking fault (down to north) in Wild Cow Fm. Lower calcarenite of Pine Shadow Mbr is down-faulted against Sol se Mete Mbr. Roadcuts for the next mile are in ledge-forming, locally cherty, light-gray calcarenite and interbedded gray shale and lenticular sandstone of the Sol se Mete Mbr. Small faults and flexures are common. **0.5**

1.2 MP 117. Cedro Peak (7,767 ft; 2,367 m) at 10:00. The peak is capped with about 189 m of the Wild Cow Fm (21 m La Casa Mbr/110 m Pine Shadow Mbr/58 m Sol se Mete Mbr), which is underlain by 207 m of Los Moyos Limestone, and about 34 m of the Sandia Fm. The latter unit, comprising sandy and shaly limestone over basal arkosic sandstone and conglomerate, is unconformable on Precambrian schist. **0.5**

1.7 Small turnout to right. Route crosses contact between basal sandstone of the Wild Cow–Sol se Mete Mbr and cliff-forming gray calcarenite of the underlying Los Moyos Limestone. Narrow and winding part of Cedro Canyon for the next 4.5 mi is cut in the Los Moyos unit. **0.3**

2.0 Southeast-trending side canyon at 9:00 crosses small inlier of Precambrian schist at the western base of Cedro Peak. **0.1**

2.1 Faulted and tilted Los Moyos Limestone, the basal unit of the Madera Gr of Myers (1973), exposed in roadcuts ahead. **0.5**

2.6 Meadow to right along Tunnel Canyon was site of Stop 1, Day 2 of NMGS Third Field Conference in 1952. **0.1**

2.7 Fault at 9:00 displaces strata of Los Moyos Limestone (ENE trend, down to south). **0.3**

3.0 Road and canyon are parallel to west-dipping beds of Los Moyos Limestone. Small faults, mostly downthrown to the east, are present in and east of the canyon. **0.4**

3.4 Culvert. Crossing Cedro Creek; canyon makes sharp bend to the east. **0.2**

3.6 High roadcuts in Los Moyos Limestone ahead. **0.6**

4.2 Black shale partings in Los Moyos Limestone ahead. **0.2**

4.4 North-trending andesite porphyry dike in Los Moyos Limestone to left. **0.1**

4.5 Small faults in Los Moyos Limestone are downthrown to the east. **0.3**

4.8 Los Moyos Limestone in south canyon wall (3:00) comprises cliff-forming gray calcarenite overlain by ledge-forming limestone and black shale. Sol se Mete Mbr (Wild Cow) forms the crest of the ridge to the south. **0.3**

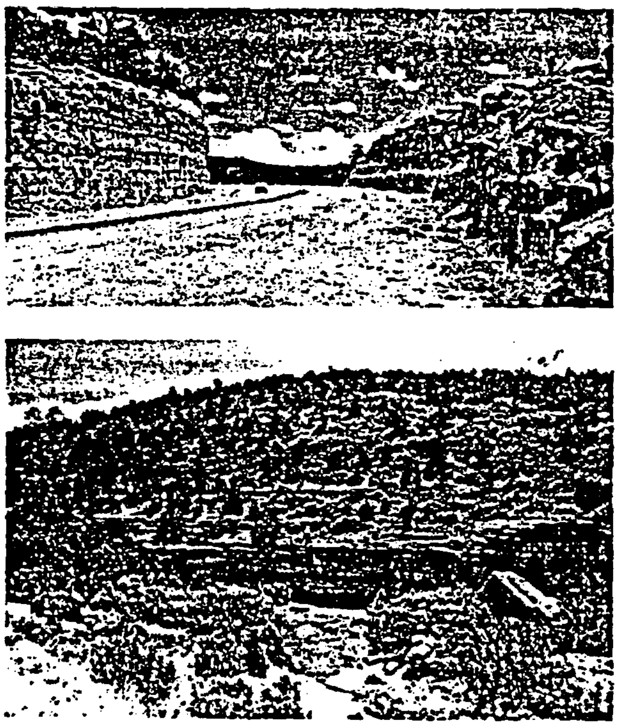

Figure I-B4.8. Roadcut (upper) and canyon-wall (lower) exposures of Los Moyos Limestone (Madera Gr) near mi 4.8 in Cedro Canyon.

5.1 MP 113. U.S. Forest Service road to left leads up Sabino Canyon to Cedro Peak Lookout. **0.4**

5.5 Basal sandstone and shale of Wild Cow Fm on Los Moyos Limestone in cut to left. **0.2**

5.7 Cedro at 3:00. Approaching southeast end of Cedro Canyon; route on upper part of Los Moyos Limestone. **0.2**

5.9 Cedro road to right. Fault (down to north) displaces Los Moyos Limestone beds and nodular limey shale in roadcut to left. **0.4**

6.3 Contact in cuts to left of basal yellowish-gray to grayish-orange siltstone, shale, and sandstone of the Sol se Mete Mbr on Los Moyos Limestone. **0.7**

7.0 Pine Flat picnic area to left. Cross rolling upland south of Cedro Canyon. **0.4**

7.4 Approximate contact of basal, pale-orange sandstone of the Pine Shadow Mbr on light-olive-gray calcarenite of the upper Sol se Mete Mbr. **0.2**

7.6 Deadman picnic area to left. **0.2**

7.8 **Turn right and continue southwest on graded road to quarry in Pine Shadow Mbr. 0.2**

8.0 **OPTIONAL STOP.** Pine Shadow Mbr, Wild Cow Fm, Madera Gr at Kinney brick quarry.

This stop offers an excellent view of Tijeras Canyon and the eastern slope of the Sandia Mountains (fig. I-B8.0). The ridge crests in this area are capped with the La Casa Mbr of the Wild Cow Fm, here a gray calcarenite with local chert nodules, that grades downward through gray shale with redbeds to basal arkose and conglomeratic sandstone. The valley-side slopes, including the quarry area, are underlain by the Pine Shadow Mbr, also characterized by an upper calcarenite to shale-siltstone to basal conglomeratic arkose sequence. The gray to yellowish-brown silty shale and siltstone exposed in the quarry contain pec-

Figure I-B8.0. Exposure of Pine Shadow Mbr, Wild Cow Fm (Madera Gr) at Kinney Brick quarry. View to north toward dipslope of Sandia Mountains; with Cedro Peak in upper center.

tens, ferns, and remains of a Virgilian fish fauna, part of which has been described by Zidek (1975). The fauna includes representatives of all the higher taxa of fish known from the Late Paleozoic. Original collections (1963-64) were made by David H. Dunkle of the U.S. National Museum. His specimens (mostly disarticulated) are preserved in a thinly-laminated, yellowish-brown, argillaceous limey shale. In 1967, Sergius H. Mamay of the U.S. Geological Survey recovered fish remains in good to excellent state of preservation from a carbonaceous shale unit. Mamay also collected Virgilian megaflora from this locality (see **Ash and Tidwell, this guidebook**); and D. S. Berman (1973) described an amphibian from this area. Berman concluded that depositon was in near-shore, probably lagoonal waters, with terrestrial organisms being carried to the site by silt-laden stream discharge (Zidek, 1975) **See Kues, this guidebook. 0.4**

8.4 Roadcut in upper Pine Shadow Mbr to right. **0.2**

8.6 MP 110. Contact of La Casa Mbr on Pine Shadow Mbr in roadcut and hill slope to right. For about the next 10 mi, route is in Escabosa quadrangle mapped by Myers (1969). **0.2**

8.8 Limestone and shale beds of the Wild Cow Fm–La Casa Mbr in roadcut. **0.4**

9.2 Oak Flat picnic area to left. Leaving Cibola National Forest. Highway is on covered interval of the Wild Cow Fm of the Madera Gr. A north-trending fault cuts the formation just east of the road at the Forest boundary, with La Casa Mbr on the western, downthrown block and Pine Shadow Mbr to the east.

This is the topographic divide (elev. 7,560 ft; 2,304 m) between Hell Canyon and Cedro–Tijeras Canyon drainages on the Rio Grande slope of the Manzanita Mountains. However, in terms of structure, this is the eastern (dip) slope of the Manzanita Mountains. The high peaks visible on the southwestern horizon are in the northern Manzano Mountains. The twin peaks at 1:00 are Guadalupe (N) and Mosca (S), and beyond is Capilla Peak. Guadalupe and Mosca peaks are capped by about 150 m of Los Moyos Limestone which is underlain by about 75 m of the Sandia Fm, then by unconformably underlying Precambrian granite of the Ojito stock (Reiche, 1949). Capilla Peak is also capped by the Los Moyos–Sandia sequence, locally underlain by a thin basal Mississippian unit, which in turn rests on Sevilleta metarhyolite of Reiche (1949).

The Manzanita-Manzano uplift is the middle segment of the block-faulted Sandia–Manzano–Los Pinos range, which forms the eastern boundary of the Rio Grande rift in this part of New Mexico. The east-tilted Manzanita-Manzano segment, with complex internal structure, consists primarily of gently-dipping Pennsylvanian to Permian strata on a relatively planar erosion surface on Precambrian rocks. The block-faulted range is late Cenozoic in age. Prior deformation included intense deformation during the Precambrian and high-angle thrusting in Late Cretaceous to early Tertiary time, resulting in complex metamorphic terranes exposed on the scarp face of the mountain block. **0.4**

9.6 Picnic area to left. **0.3**

9.9 Road curves to left. Limestone and shale beds of the Pine Shadow Mbr in roadcut; fault to left is downthrown to the northwest. **0.2**

10.1 Intersection with Kuhn Rd at Ponderosa Pine. Crossing drainage divide between Rio Grande (through flowing) and Estancia (interior) basins (elev. 7,531 ft; 2,295 m). **Park to left on east side of fire station for optional stop. 0.1**

10.2 **OPTIONAL STOP.** Eastern slope of Manzanita Mountains.

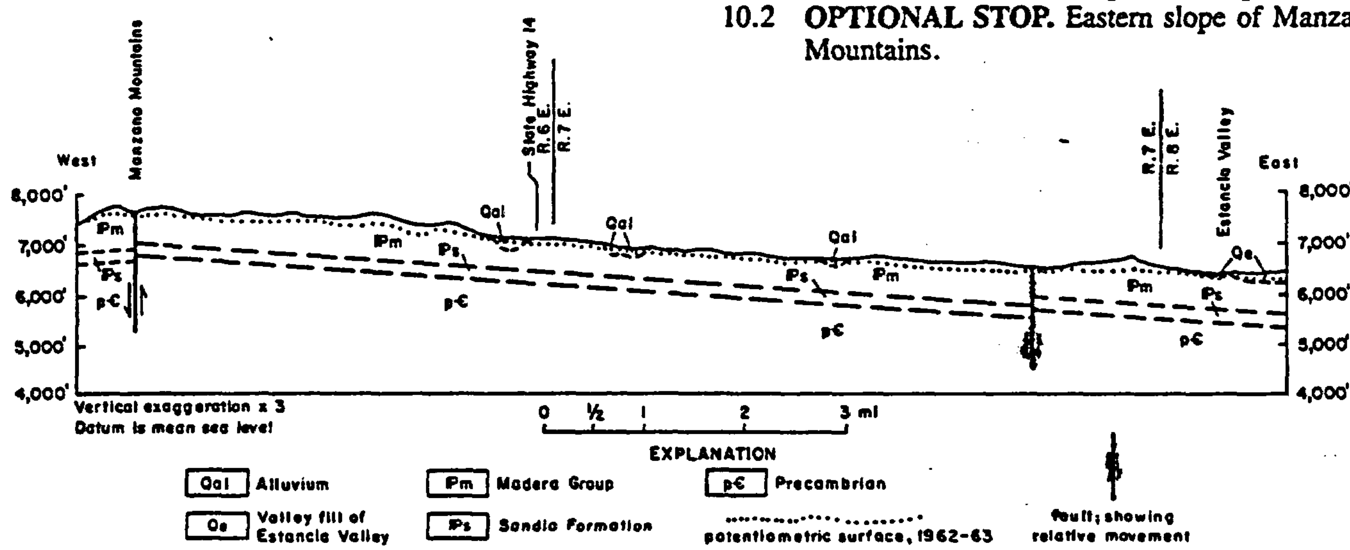

Figure I-B10.2. Hydrogeologic section from crest of northern Manzano Mountains to central Estancia valley (T8N); from Titus (1980, fig. 14).

Estancia valley from 11:00 to 12:30 beyond wooded area. Pedernal Peak (elev. 7,580 ft; 2,310 m), highest point of the Pedernal Hills, is on horizon at 11:30. These hills are an exhumed positive element of the late Paleozoic Pedernal uplift. Higher areas are underlain primarily by Precambrian quartzite, with Permian Yeso Fm overlapping a complex Precambrian terrane of low to moderate relief on the flanks of the uplift (Gonzalez and Woodward, 1972). See **Armstrong and Holcombe, this guidebook.**

According to Titus (1980), the Madera Gr, here with maximum thickness of about 396 m, is the principal aquifer on the Manzano backslope (fig. I-B10.2, n. 14 of Titus). See **Jenkins, this guidebook.** Several hundred wells have been drilled in the Madera; most are less than 91 m deep. Solution-enlarged channels in limestones, localized along fractures and bedding planes, provide the porosity and permeability in most areas, with well yields averaging about 45 l/min (12 gpm). Calcium bicarbonate commonly dominates the water chemistry. Extreme well yields (locally exceeding 3,785 l/min; 1,000 gpm) associated with very high permeability and anomalous amounts of dissolved carbon dioxide occur in the Madera between Chilili and Witt. This is an area of former commercial production of carbon dioxide from the lower Madera–Los Moyos Limestone (see Day I, Stop 2, mi 26.4).

The route from here to Mountainair is on the dipslope of the Manzano-Manzanita uplift and adjacent parts of the Estancia structural basin. The route closely follows the eastern margin of the Mexican Highland section of the Basin and Range physiographic province, just west of the Sacramento section. The latter unit, in a structural as well as physiographic sense, marks the transition between the Great Plains and the Basin and Range provinces. Although now disrupted by structural deformation, solution subsidence, and eolian processes, Estancia valley drainages should be considered as part of the Pecos slope watershed (Kelley, 1972; Titus, 1973). Older basin fill, on high divides as well as in the subsurface, was part of the High Plains–Pecos Valley alluvial system that developed in late Neogene time (less than 15 m.y. ago). These deposits include correlatives of the Ogallala, Blanco, Gatuna, and Tule Fms (Frye and others, 1982; Hawley and others, 1976).

Continue east on N.M. 14 across dipslope formed on Pine Shadow Mbr of the Wild Cow Fm. **1.3**

11.5 Upper Quaternary alluvium in valley of Arroyo Yrissari to right. Ridge side from 10:00 to 11:00 is underlain by limestone and shale beds of Pine Shadow Mbr. **0.4**

11.9 Enter Yrisarri. Approximate contact of Pine Shadow Mbr and Sol se Mete Mbr is in lower hillslope behind Ponderosa Saloon. *This former community was established by Spanish loyalist Don Pablo Yrisarri when he was driven out of Vera Cruz by Mexican patriots. He later moved to the Rio Grande Valley and married twice into families of the Albuquerque district in 1811 and 1822 (Pearce, 1965).* **Prepare for right turn. 0.5**

12.4 Intersection with N.M. 222. **Turn right and continue south on N.M. 14** across Arroyo Yrissari. Route for next 4.3 mi crosses high rolling terrain, with ridges and valleys underlain by Sol se Mete Mbr of the Wild Cow Fm. **1.9**

14.3 Shale and nodular beds of the Sol se Mete Mbr in roadcut. **0.5**

14.8 **Slow.** Approaching Escabosa. Shale and siltstone of the Sol se Mete Mbr in roadcut to right. **0.4**

15.2 Passing through farming community of Escabosa. The name is a corruption of Spanish *escobosa*, "broom grass." **0.4**

15.6 Culvert over Cañada de Escabosa. **0.3**

15.9 Sol se Mete limestone in roadcut. **0.8**

16.7 Limestone quarry to left is on private property (Chilili Grant). Upper limestone and shale beds of the Sol se Mete Mbr exposed in the quarry contain a rich marine faunal assemblage (including productid and spiriferid brachiopods and *Triticites*). Ridge ahead is capped with basal arkosic sandstone of the Pine Shadow Mbr. This was Stop 2, Day 2 of the NMGS Third Field Conference in 1952. **0.3**

17.0 Estancia valley at 12:00. Pine Shadow Mbr arkosic sandstone over shale in roadcuts ahead. **0.5**

17.5 Yellowish-brown and red shale and gray limestone beds of Sol se Mete Mbr in roadcut. **0.6**

18.1 Sol se Mete Mbr in roadcut. **0.1**

18.2 Pedernal Peak on horizon at 12:00. **0.2**

18.4 Boundary between Escabosa and Estancia quadrangles. **0.3**

18.7 MP 100. **0.6**

19.3 **Slow. Approaching Chilili.** Sol se Mete limestone in road cut. **0.3**

19.6 Enter Chilili. *This is one of the oldest place names in New Mexico, since the site was visited by Chamuscodo in 1581 and probably is referred to by Oñate in 1598 as* Chin Alle. *Fray Alonso de Benavides mentions it in 1630 as the first pueblo of the Tompiro Indian group and refers to missionary activity begun by the Franciscans in about 1613. The pueblo was abandoned between 1669 and 1676 because of Apache raids. Chilili is on L'Atlas Curieux of 1700. Ruins of the Indian pueblo lie on the west side of Arroyo de Chilili. The present village, east of the arroyo, was established as part of the Chilili Grant by Santiago Padilla and six others for themselves and twenty more heads of*

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QUATERNARY HISTORY OF THE ESTANCIA VALLEY, CENTRAL NEW MEXICO

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INTRODUCTION

The Estancia valley lies within a closed physiographic and structural basin near the geographic center of the state of New Mexico (fig. 1). This arid valley presently has a deficit water budget of 122 cm annually which precludes the existence of natural perennial-water bodies. Geomorphic, sedimentologic, and paleontologic evidence, however, indicates that major climatic oscillations occurred during the Quaternary.

The geologic history of the Estancia valley has been synthesized over a period of almost 80 years following Keyes' (1903) observation that the valley contained ". . . evidences of the existence of old lakes." Keyes and other researchers in the valley believed that the pluvial system, while of considerable areal extent and water depth, did not overflow into adjacent basins. Consequently, it was assumed that the lake system never evolved into a fresh-water body.

The highest elevations (over 3,050 m; 10,000 ft) within the Estancia valley occur along the western rim of the watershed; whereas, the lowest elevations (1,842 m; 6,045 ft) are found along the central topographic axis. Along the valley axis a series of wind-excavated playas, arranged in an elliptical pattern, are incised into the valley floor (fig. 1). The deflation basins are cut into lacustrine sediment exposing a complex stratigraphic sequence of up to 10.5 m in thickness. In the southeastern corner of the basin a broad, gently-sloping saddle, termed the topographic sill, separates the Estancia valley from the Pinos Wells basin. Presently, the topographic sill has a minimum elevation of 1,929 m (6,330 ft), rendering a total topographic closure of 87 m.

GEOMORPHIC EVIDENCE

Geomorphic evidence of a pluvial system within the Estancia valley has been recognized since the turn of the century (Keyes, 1903). Meinzer (1911) describes a geomorphic complex of well-preserved wave-cut cliffs, terraces, beaches, spits, and bars. Many of these features are obvious on aerial photographs. Significantly, the highest shoreline features described by Meinzer occur 30 m below the present topographic sill. Meinzer's observations led later researchers (Leopold, 1951; Harbour, 1958) to conclude that the pluvial lake had no outlet and, therefore, was saline. Bachhuber (1971) refers to this geomorphic complex as "younger shoreline features."

More recent work in the basin (Lyons, 1969; Titus, 1969) suggests that the pluvial system was much deeper and greater in areal extent than originally proposed. Titus, in particular, reports suspected shoreline features at an elevation of 1,939 m (6,360 ft), 10 m above the topographic sill. The features described by Titus are highly dissected, and the widely-scattered remnants can be interpreted as resulting from other geomorphic processes. Because of their questionable origin these features and others termed "older shoreline features" by Bachhuber (1971) are not conclusive evidence of a higher lake stand. Nonetheless, they do suggest the possibility of a lake level at one time being above the topographic sill.

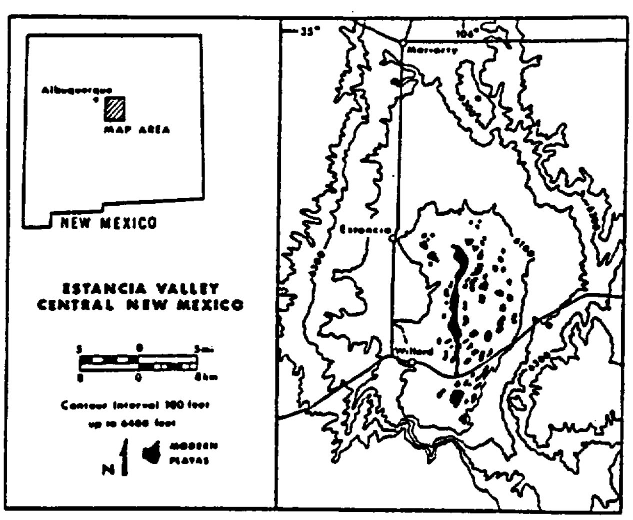

Figure 1. Index map of the Estancia valley in central New Mexico.

SEDIMENTOLOGIC EVIDENCE

A maximum of 10.5 m of stratigraphic section (fig. 2) is exposed along the flanks of the more centrally located deflation basins. This section contains a number of distinct sedimentologic and biostratigraphic units which indicate that the Estancia valley had not one but a series of pluvial lakes.

The lower portion of the exposed section consists of interbedded clay, silt, and gyparenite, capped by massive-bedded flint-gray clay. This sediment represents various stages of the development of late Lake Estancia, the highest lake stand within the basin. The late Lake Estancia sediment is subdivided into four units, or phases: (1) a pre-pluvial phase which consists of thin- to thick-bedded gyparenite, silt, and silty clay, some of which appears to be of turbidite origin; (2) a pluvial maximum phase characterized by a dominance of flint-gray clay; (3) a partial drawdown phase consisting of interbedded gyparenite, silt, and clay; and (4) a final high-water phase characterized by massive-bedded flint-gray clay. In general, the late Lake Estancia sediment represents maximum glacio-pluvial conditions.

The late Lake Estancia sediment is overlain conformably and unconformably by red to brown, finely-intercalated silt, clay, and gyparenite. This unit, referred to as the Estancia playa complex, is easily delineated from the underlying and overlying sediment by color alone. The Estancia playa complex represents an inter-pluvial period which led to the desiccation of late Lake Estancia. Following intermittent flooding of the basin, the sediment of the interval accumulated in a playa-like environment.

The sediment of the Estancia playa complex is transitional with a flint-gray clay of the Lake Willard unit. The change in sediment character indicates that basin flooding and the ephemeral lakes, characteristic of the preceding inter-pluvial stage, became more persistent and eventually evolved into the Lake Willard pluvial stand. Although water level probably fluctuated drastically during early and late developmental stages, Lake Willard at its maximum stand occupied much of the Estancia valley.

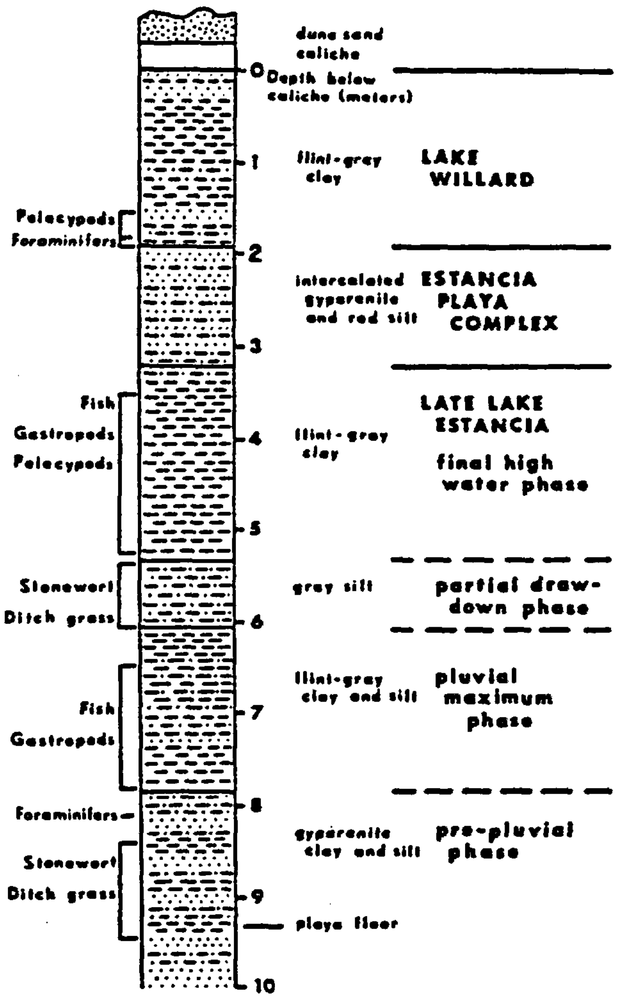

Figure 2. Stratigraphic and biostratigraphic column of pluvial and inter-pluvial sediment of the Estancia valley.

The Lake Willard sediment is capped by a 0.5-m-thick caliche (Willard soil) which marks the desiccation of the last major pluvial stand within the Estancia valley. Based on correlations with other areas, the Willard soil is believed to have formed during the Altithermal. During this time, in addition to the development of caliche, an early sequence of shallow deflation basins (cut into the Willard soil and underlying lacustrine sediment) and sand dunes was being formed. Subsequently, with a return to more mesic conditions, the valley floor was flooded again during a sub-pluvial episode. The sub-pluvial episode (Lake Meinzer) resulted in the filling of the shallow deflation basins with intercalated clay and coarse clastics, modifications of the sand dunes by wave erosion, and the development of the lowest elevational shoreline features found within the valley. The chronology of Lake Meinzer is unknown, except the lake must postdate the Altithermal. The short sub-pluvial episode, evidenced by Lake Meinzer, was followed by a return to post-pluvial dry climate. The present deflation basins and associated sand dunes began to form following the desiccation of Lake Meinzer. The process has been intermittent up to today.

PALEONTOLOGIC EVIDENCE

Fossil evidence within the Quaternary lacustrine sediment of the Estancia valley is abundant. The pluvial and inter-pluvial sediment records the occurrence of pollen (50 taxa), seeds (4 taxa), other plant parts, algae (3 taxa and 37 species of diatoms), foraminifers (2 species), ostracods (8 species), insects (3 taxa), mollusks (5 species), fish, and salamander (Bachhuber, 1971). The identification of the highly varied floral and faunal elements and recognition of their paleoecologic requirements permit a reconstruction of paleoenvironmental conditions. Although virtually all of the organisms have some paleoecologic significance (e.g., pollen and diatoms appear to be very sensitive indicators of changing conditions), only the most diagnostic ones are mentioned in this report.

The four developmental phases recognized in the late Lake Estancia sedimentologic sequence have distinctly different fossil assemblages. The pre-pluvial phase is characterized by the occurrence of stonewort (*Chara canescens*) and ditch grass (*Ruppia maritima*). These aquatic plants grow in brackish, shallow-water environments, and their occurrence in the late Lake Estancia basin appears to represent a life population. In addition, the upper portion of the pre-pluvial sediment contains marine foraminifers (Bachhuber and McClellan, 1977). The salinity and thermal requirements of the foraminifers, which are extant species, along with the other fossils suggest that the pre-pluvial phase was a period of low water level, had a salinity corresponding to that of marine conditions, and had a water temperature of about 10°C during the warmest months of the year.

The sediment of the pluvial maximum phase of late Lake Estancia records the first occurrence of mollusks and the arrival of fish into the lake basin. The sparse assemblage of gastropods and pelecypods is not diagnostic by itself, but the occurrence of cutthroat trout (*Salmo clarki*) in association with the mollusks indicates the high likelihood of freshwater conditions. More significantly, the occurrence of trout in the Estancia valley pluvial system is evidence that, at least on one occasion, the lake system had a drainage outlet.

The sediment of the partial drawdown phase does not contain the faunal elements found in the preceding pluvial maximum phase. Instead, stonewort and ditch grass return as the dominant megafossil types. The disappearance of fish and mollusks and their replacement by brackish-water aquatic plants signify that lake level was lowered below the topographic sill and through time the lake became more saline.

The flint-gray clay of the final high-water phase is characterized by the reappearance of mollusks and cutthroat-trout fossils. The unit also records the first and last appearance of *Cytherissa lacustris*, an ostracod presently found in large, cold-water, glacial lakes of Scotland, Norway, Sweden, and Siberia (Moore, 1961). The fossils of the final high-water phase show that late Lake Estancia water levels rose, perhaps to an overflow stage, with an accompanying lowering of salinity.

In contrast to the sediment of late Lake Estancia, the inter-pluvial Estancia playa complex sediment has a low density and diversity of fossils. Other than pollen the only fossils recorded are an alga (*Botryococcus*) and one species of ostracod (*Limnocythere staplini*). Both of these organisms are thought to be saline tolerant. Their sporadic occurrence in the Estancia playa complex sediment apparently represents periodic blooms following heavy rains and flooding of the basin floor. Upon desiccation of the ephemeral ponds the organisms were eliminated, only to reappear during the next rainy season.

The flint-gray clay of the Lake Willard pluvial episode is depositionally transitional with the gyparenite and silt of the Estancia playa complex. Similar to that of the late Lake Estancia sequence, the Lake Willard sediment and enclosed fossils illustrate a developmental phase as the lake expanded. The lower-most sediment, in littoral and profundal facies, contains the same foraminifers as found in the late Lake Estancia pre-pluvial phase. This indicates that an initial phase of lake development consisted of a persistent, shallow, saline-water body. As climatic conditions continued to change, Lake Willard water level rose. Geomorphic evidence indicates that the lake did not reach an overflow stage, but the occurrence higher in the section of a pelecypod (*Pisidium*) and an alga (*Pediastrum*) attest that salinity was greatly reduced from that of the earlier infilling stage.

Following the highest water-level stage, a return to inter-pluvial climatic conditions resulted in the shrinkage of Lake Willard and the formation of recessional strandlines. Fossil evidence which could support a gradual lowering of water level and accompanying increase in salinity is not found. That desiccation did occur, however, is evidenced by the Willard soil.

PALEOLIMNOLOGY

The various pluvial and inter-pluvial phases, recorded in the stratigraphic section of Quaternary fill in the Estancia valley, are delineated by sedimentologic, geomorphic, and paleontologic evidence. The exposed stratigraphic section records two major pluvial episodes and a sub-pluvial episode, each of which was followed by inter-pluvial conditions. The abundance and character of plant and animal fossils provide a unique opportunity for a limnological reconstruction of the pluvial episodes. By inference, a climatological framework can also be established for Quaternary events.

Late Lake Estancia

Late Lake Estancia was characterized by four distinct developmental phases, each of which was related to climatic oscillations. Since only a few radiocarbon dates are available from the Estancia valley sediment, the chronology and duration of the individual phases is somewhat speculative. It is clear, however, that late Lake Estancia is correlative with the Wisconsin glacio-pluvial maximum estimated to have occurred between 18,000 to 10,500 years B.P.

Pre-pluvial phase

The pre-pluvial phase was a period of initial flooding of the Estancia basin floor. Interbedded clay lamina associated with gyparenite units indicate that this phase of lake development was characterized by rather rapid fluctuations in lake level. The occurrence of an abundance of aquatic plants, in a life population, indicates that water depth was on the order of 1 to 8 m. The aquatic plants and the existence of marine foraminifers near the top of the pre-pluvial section document a paleosalinity range of 25 to 35 parts per thousand. In addition, the thermal tolerance of the foraminifers, which at present have a holarctic distribution, suggests a water temperature during the warmest month of approximately 10°C (Bachhuber and McClellan, 1977). The shallow-water nature of the emerging lake and high seasonal wind would have precluded thermal stratification; therefore, it is probable that atmospheric temperature was also 10°C or about 10°C below that of the present. A lowering of temperature of this magnitude would have assured the growth of the lake even without a significant increase in precipitation.

Pluvial maximum phase

With greatly reduced temperatures, late Lake Estancia expanded. The occurrence of cutthroat-trout fossils in the sedimentologic record is conclusive evidence that the lake expanded to an overflow stage. Drainage flowed eastward across the topographic sill and entered the Pinos Wells basin, the Encino basin, Pintada Canyon, and eventually into the Pecos River drainage system (fig. 3). This is presumably the water route by which fish were introduced into the Estancia basin. At the time of overflow the lake was oligotrophic. This implies among other things that cold, fresh-water conditions existed. Late Lake Estancia had a minimum depth of 90 m and covered an area of 2,340 km^2. The total lake pool including the flooded Pinos Wells and Encino basins encompassed 2,860 km^2.

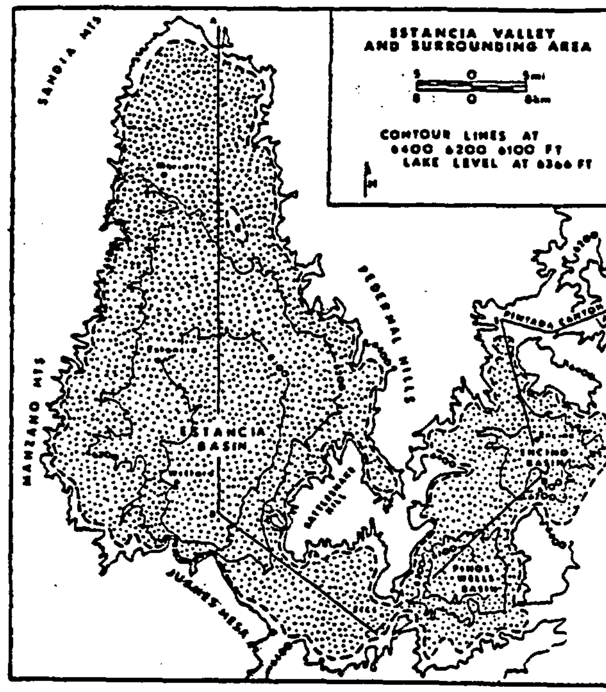

Figure 3. Inferred areal extent of late Lake Estancia during the pluvial maximum phase indicating overflow into Pintada Canyon.

Partial drawdown phase

The partial drawdown phase represents a period of rapid water-level lowering. A reduction of water level from that of the pluvial maximum phase is evidenced by an increase in coarse-clastic deposition, the reoccurrence of certain aquatic plants and, indirectly, by the disappearance of the fresh-water aquatic fauna. The aquatic-plant fossils are found near the axis and deepest water portion of the basin, but the assemblage does not represent a life population. Instead, the plant material was carried into the profundal zone, perhaps by turbidity currents. This suggests that minimum water depth was somewhat greater than that of the pre-pluvial phase. It is likely that water quality was brackish to saline and air temperatures were higher than in the preceding developmental phases. A radiocarbon date of 12,400 ± 450 years B.P. derived from *Ruppia achenes* places the partial drawdown phase in the late Wisconsin.

Final high-water phase

The final high-water phase of late Lake Estancia was characterized by the repopulation of the lake by cutthroat trout and other freshwater species. Lake level rose and water quality improved significantly. Lake overflow, however, during the final high-water phase cannot be demonstrated, and it is not a prerequisite for the reestablishment of trout. It is conceivable that during the partial drawdown phase, as salinity increased, trout dispersed into perennial streams draining from the western highlands. This stream population was then free to disperse from the streams into the lake basin as water level rose and salinity decreased. It is inferred that, with or without overflow, lake morphometry would have been similar to that of the pluvial maximum phase. If the lake overflowed, the "older shoreline features" could have formed at this time. Conversely, if the lake did not overflow, the geomorphically old shoreline features would have formed during the pluvial maximum phase. A radiocarbon date on fish bones of 11,740 ± 900 years B.P. places the final high-water phase near the close of the late Wisconsin.

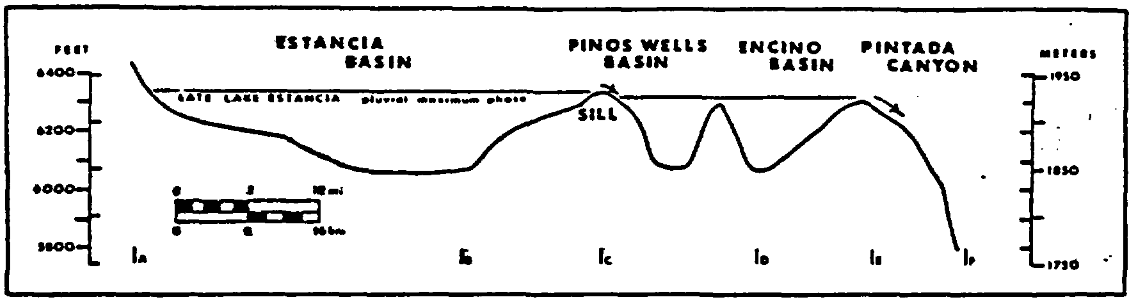

Figure 4. Long-profile through the Estancia basin to Pintada Canyon (A to F, fig. 3) indicating lake level during the pluvial maximum phase of late Lake Estancia.

Estancia Playa Complex

The sediment of the Estancia playa complex marks the advent of full inter-pluvial conditions. The desiccation of late Lake Estancia was probably a gradual process, but eventually the whole lake floor was exposed subaerially. The intercalated nature of gyparenite, red clay, and silt indicates that alluviation alternated with shallow-water deposition. During periods of seasonal rainfall the basin floor was flooded. Initially water quality of the emphemeral ponds was conducive to ostracodal and algal blooms. Upon evaporation, however, hypersaline conditions and eventually desiccation caused their elimination. Reappearance of the organism followed the next episode of basin flooding. No radiocarbon dates are available from the Estancia playa complex sediment. Based on correlation with other areas, it is believed that the interval began at about 10,500 years B.P. and closed at about 8,500 years B.P.

Lake Willard

A return to pluvial conditions resulted in the growth and expansion of Lake Willard. Sedimentologic aspects suggest that an early phase of lake development was characterized by widely fluctuating water level and salinity. The occurrence of Foraminifera in the lowest portion of the section has the same paleoecologic implications as that of the pre-pluvial phase of late Lake Estancia. The most critical of these was greatly depressed water and atmospheric temperatures. As water level rose, salinity decreased and the foraminifers were replaced by a fresh-water pelecypod. At this time the highest "younger shoreline feature" was formed. Since it is 30 m below the topographic sill, Lake Willard did not reach an overflow stage. The highest, geomorphically young strandline in the Estancia basin shows that during maximum expansion Lake Willard covered 1,170 km². The maximum water depth was approximately 46 m. From this point water level was gradually reduced with the resultant formation of recessional strandlines.

No radiocarbon dates have been obtained directly from the Lake Willard stratigraphic sequence. Nonetheless, two mammoth-tusk dates (Lyons, 1969) from what is believed to be associated marginal sediment range from 7,950±300 years B.P. to 6,000±200 years B.P. These dates represent a fairly accurate chronology of Lake Willard.

Later Events

The desiccation of Lake Willard brought to a close full glacio-pluvial conditions in the Estancia valley. The valley floor was subaerially exposed, and caliche development occurred throughout the area. During the time of formation of the Willard soil at least two large deflation basins were carved to a depth of 7 m into the lacustrine sediment. Wind-blown material also accumulated in a series of small sand dunes.

After calichification, deflation, and deposition of the small dunes, the Estancia valley was influenced again by a more mesic climatic oscillation. The valley floor was flooded with the resulting growth of Lake Meinzer. No paleontologic evidence of this particular sub-pluvial episode has been found, but geomorphic evidence indicates that Lake Meinzer rose and formed a beach complex that nearly rings the central portion of the basin. The previously formed deflation basins were filled with sediment and wave action modified and cemented the series of small dunes. At its highest stand Lake Meinzer would have been 20 m deep, covering an area of 520 km².

The present major topographic surfaces and geomorphic features were formed after desiccation of Lake Meinzer. The complex of deflation basins and associated parabolic dunes and sand sheets is the result of the modern arid climate.

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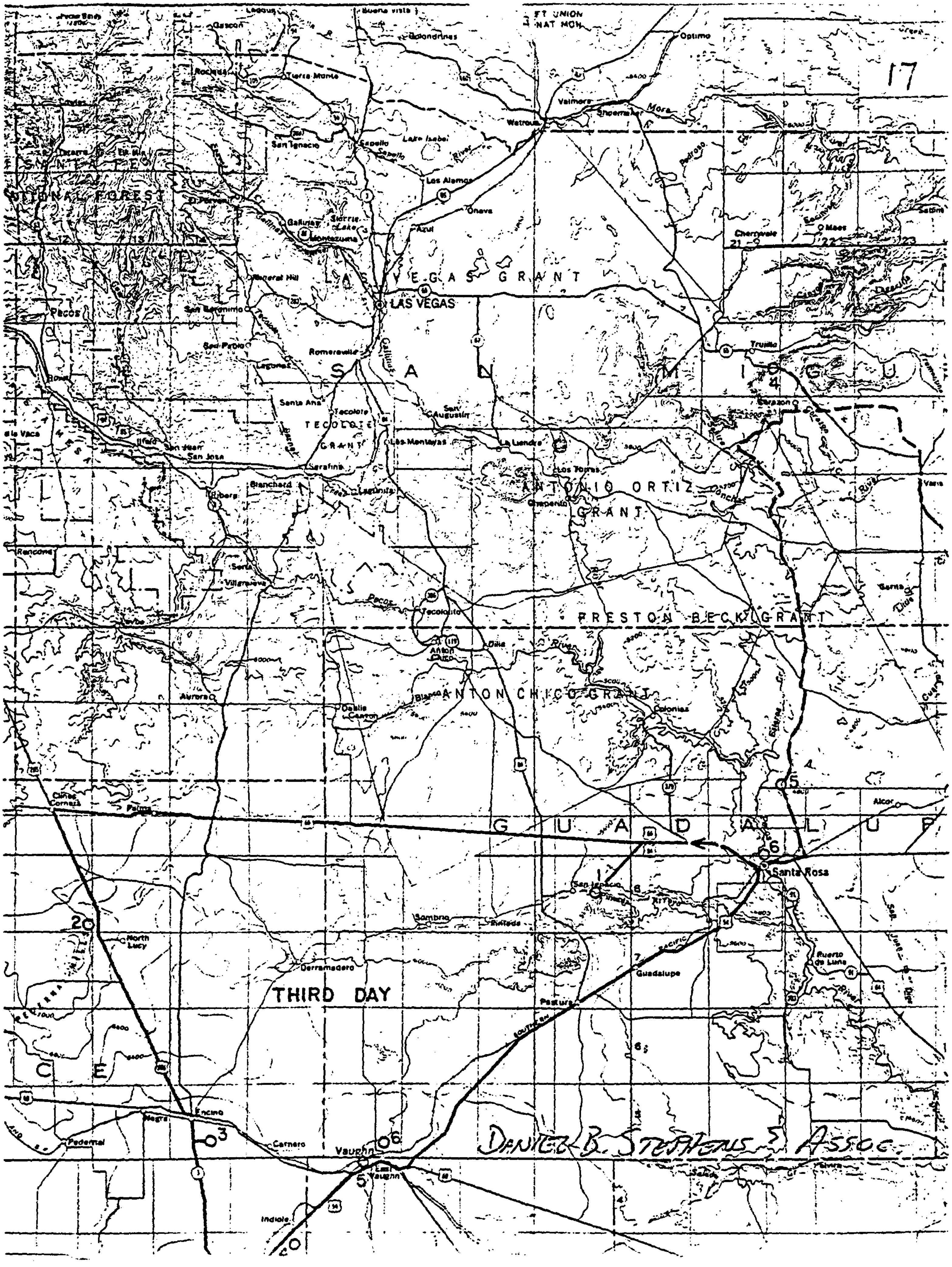
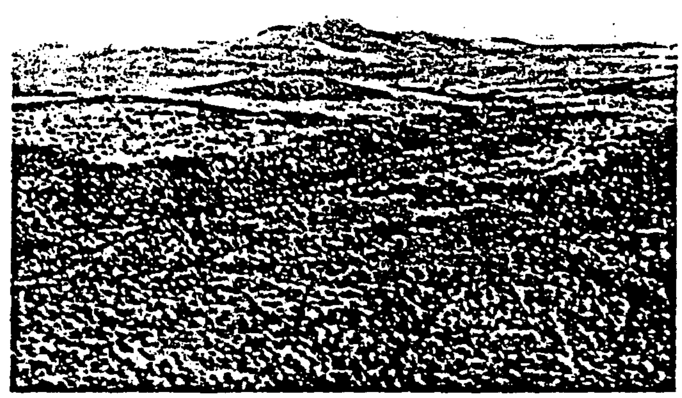

17
FT UNION NAT MON
Optimo
Golondrinas
Gascon
Rociada
Tierra Monte
Valmora
Watrous
Shoemaker
Mora
San Ignacio
Sapello
Lake Isabel
Las Alamos
Onava
Azul
Gallinas
Montezuma
Cherryvale
Maes
SANTA FE
NATIONAL FOREST
Mineral Hill
LAS VEGAS GRANT
LAS VEGAS
San Geronimo
Pecos
San Pablo
Romeroville
Trujillo
SAN MIGUEL
Lagunas
Santa Ana
Tecolote
TECOLOTE GRANT
San Augustin
Conchas
La Liendre
Los Montoyas
San Juan
San Jose
Serafina
Los Torres
ANTONIO ORTIZ GRANT
Chaperito
Blanchard
Lagunita
Ribera
Rencona
Sena
Villanueva
Pecos
Tecolotito
PRESTON BECK GRANT
Anton Chico
Dilia
ANTON CHICO GRANT
Aurora
Dahlia
Colonias
Clines Corners
Palma
GUADALUPE
Alcor
Santa Rosa
San Ignacio
Sombrio
Puerto de Luna
North Lucy
Derramadero
Guadalupe
THIRD DAY
Pastura
Encino
Negra
Pedernal
Carnero
Vaughn
East Vaughn
Indiole
Daniel B. Stephens & Assoc.

42.4 Overpass, *straight ahead;* road ahead rises from the younger pediment onto what may be an Ogallala level and pediment.
1.7
44.1 Base of Ogallala; gravel and caliche.
0.2
44.3 Ogallala surface. Mesas ahead are capped by Glorieta Sandstone.
2.7
47.0 Exit to roadside business; *straight ahead.* Beneath the pediment, somewhere between here and the mesas ahead, the Santa Rosa is plicated because it must be projected to a level above the mesas.
0.5
47.5 Overpass.
2.9
50.4 Sandstone beds on right of road are Glorieta.
0.6
51.0 Overpass to state road 3.
0.6
51.6 Glorieta-capped mesa on left.
2.0
53.6 Roadcut on left exposes contact between Glorieta Sandstone above and red and tan siltstone and gypsum of the Yeso Formation below. Contact is at base of blocky medium-bedded sandstone.
0.3
53.9 Incompetent folds in the Yeso in roadcut on left.
1.5
55.4 Overpass.
0.7
56.1 Road ascends Glorieta-capped mesa.
0.4
56.5 Overpass.
0.9
57.4 Pedernal Peak (Precambrian) at 9:30 rises out of surrounding Permian beds.
1.4
58.8 Road crosses Glorieta-San Andres contact; mesa here has patchy outliers of San Andres limestone on Glorieta.
2.0
60.8 Exit to rest area, *straight ahead.*
1.0
61.8 Road is back on Glorieta.
1.2
63.0 Clines Corners and U.S. 285 exit. *Turn right.*
0.3
63.3 Stop sign. *Turn left* and across overpass toward Vaughn.
0.6
63.9 Note red Bernal sandstone on right. It overlies San Andres in a local patch.
1.6
65.5 San Andres in cut on left. Pedernal Peak at 1:00 is Precambrian quartzite rising through burying Yeso beds.
2.0
67.5 Glorieta along road.
0.8
68.3 Solution swale to left; probably collapse occurs in Yeso here about 100-200 ft beneath the surface.
0.7
69.0 Precambrian hills around Pedernal Peak 1:00 to 2:30. Road crosses down onto Yeso Formation.
1.2
70.2 Note reddish Yeso beds along arroyo rim between here and Pedernal Peak.
0.3
70.5 Yeso in cuts on left.
2.0
72.5 Pediment material here is probably Ogallala.
1.1
73.6 STOP 2. LUNCH Walk to south flank of hill to see Yeso contact. Small quartzite hill at 3:00 is completely surrounded by Yeso. Here

Contact between Glorieta (about at right power pole) and Yeso in lower slope of roadcut at mile 53.6



Air view west of Precambrian hills and knolls protruding through burying flat-lying Yeso beds of foreground canyons. Pedernal Peak top center. Photo taken about over mile 74.7.

and elsewhere around the hills the Yeso near the Precambrian contains angular fragments washed from the basement rocks. They are scarce, but locally abundant in thin sandstone beds. Locally the red mudstone and fine-grained sandstone is more micaceous or arkosic. Some limestone beds, but no gypsum is seen near the Precambrian. Curiously, however, swales resembling solution collapse features occur near the Precambrian farther south.

0.2

73.8 Begin descent of Red Hill; good Yeso outcrops; Duran Mesa (Glorieta Sandstone) on skyline at 12:00.

0.9

74.7 North Lucy at 9:00; Yeso cliffs beyond the settlement.

3.3

78.0 Side roads right and left; *straight ahead.* Road ahead to Encino runs on Yeso, capped locally by pediment gravel and caliche.

2.0

80.0 Mesa on skyline 9:00 to 10:00 is capped by Glorieta and the contact with the Yeso is in the slope.

1.3

81.3 At 9:30, about along the fence line in the distance, is a low divide between eastward-flowing Pintada Canyon drainage through the defile at 9:00 and south-flowing drainage into the interior Encino basin drainage to the south. The elevation at this divide is about 6,300 ft and some geologists have maintained that a maximum filling of the Encino basin from old Lake Encino spilled across this divide into Pintada Creek. However, the divide east of Encino (Llano Summit) on the road to Vaughn is about 40 ft lower than here.

3.4

84.7 Milepost 228. Slow for view (look back) of cute dome in arroyo on right. It is a circular flowage or piercement-type dome in the evaporitic and incompetent Yeso.

1.3

86.0 Encino at 11:30; Duran Mesa 12:30; Chameleon Hill (Precambrian inlier) at 12:15. Laccolithic Gallinas Mountains at 2:00 (Kelley, N. Mex. Bur.ines Bull. 98, p. 34, map 1, 1972)

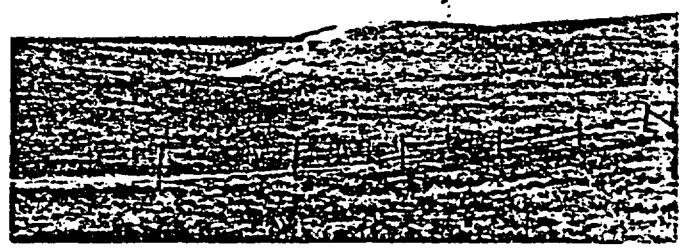
3.2

89.2 Fork, *take left,* U.S. 285.

0.4

89.6 Stop sign. Junction U.S. 60, *continue* to Encino.

0.5



Flowage dome in Yeso at mile 84.7

90.1 Junction state road 3. *Turn right* and cross Santa Fe tracks.

1.1

91.2 Road ascends across one of the high shorelines of old Lake Encino.

0.4

91.6 View of Encino Lake bottom and blowout playa lake which was deflated from the floor of the lake after dessication. White bank along the far bluffs 9:00 marks a high shore line.

0.6

92.2 Cattle guard. *Turn hard left.*

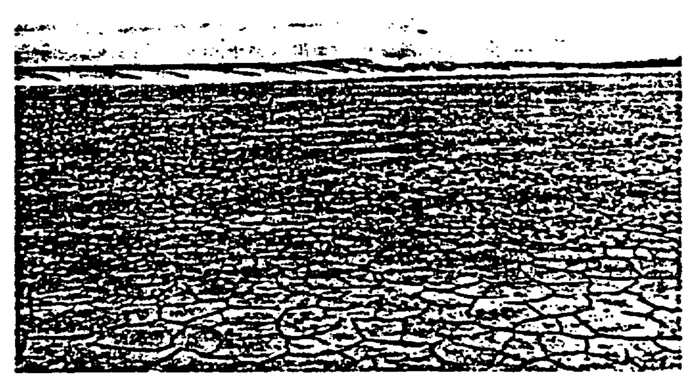
0.4

92.6 *Turn left* before cattle guard into Encino dump and follow around fence and onto the playa lake, and away you go to the far end.

1.6

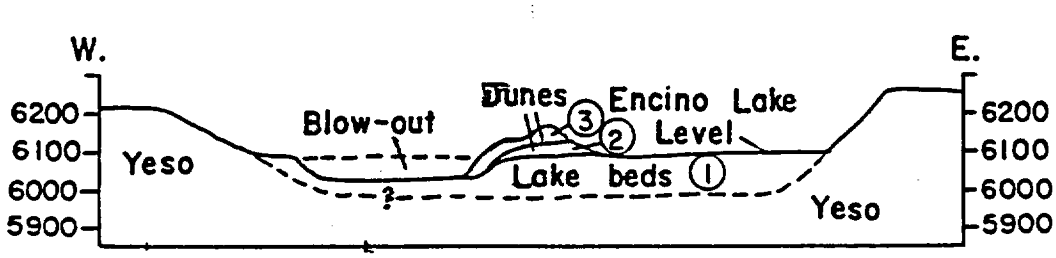
94.2 STOP 3. East end of Encino playa. Examination of old lake beds and overlying aeolian blow-out sand dunes which form on the lee sides of such lakes. The origin of this lake and its relationships to the Pinos Wells and Estancia lakes will be discussed.

The Encino playa is a deflation depression probably formed in Holocene time after, or near, the end of the dessication of old Encino Lake. The accompanying map of Quaternary lakes in Torrance County shows a possible chain of drainage from large old Lake



View southeast across mud-cracked floor of Encino playa. Note Holocene gulleys cut through arrested blow-out sand dunes along the east side.


U.S. 285
N
U.S. 60
AT & SF
N.M. 3
6,175 ft highest shoreline
W
E
6050
Stop 3
High Shorelines
1 Mile


W.
E.
6200
6100
6000
5900
Yeso
Blow-out
Dunes
Encino Lake Level
3
2
Lake beds
1
Yeso
6200
6100
6000
5900

Estancia through Pinos Wells, Encino, and easterly into the Vaughn sag. The highest recognized levels and sill elevations for outlet are shown. All three old lake floors have deflation holes scoured out of the bottoms some time after disappearance of the permanent water bodies. The old Estancia Lake has some 60 of these, Pinos Wells 2, and Encino 1. Presently most precipitation flowing into the three lake depressions ends up in the deflation or blow-out playas as at the Encino.

Meinzer (U.S.G.S., Water-Supply Paper 275, 1911) long ago noted that a thickness of some 20 feet of laminated lake beds was exposed in the sides of the playa. Inasmuch as the old lake floor is only 25 to 30 feet above the blow-out playa floor, additional lake bed thickness cannot be measured at the surface. Until drilling is done on the playa floor the full thickness of the lake beds will be unknown. In Estancia basin alluvial sand and gravel underlies the lake beds, but at Encino either alluvials or Yeso may be below.

More than 100 feet of relief exists from the floor to the top of the rim along the east side of the playa. Because only the section up to the level of the surrounding old lake floor can be lake beds, the overlying materials must be of different origin. The section consists of three parts, 1) the laminated clay, silt, sand, and limestone at the base, 2) thick-bedded silt, clay and sand some 30 to 45 feet thick, and 3) dune sand some 50 to 60 feet thick consisting largely of gypsum. The silt and sand overlying the lake beds may represent the first energetic deflation product derived from the lake beds. After the playa became large enough or aeolian energy subsided, gypsum and other evaporite crusts preciptated on the floor to be skimmed by wind into the gypsum sand dunes. Thus, the sand dunes are a feature developed in the playa. Presently this process appears to be somewhat arrested; also there is much alluviation of the floor and gulleying of the dunes on the east side.

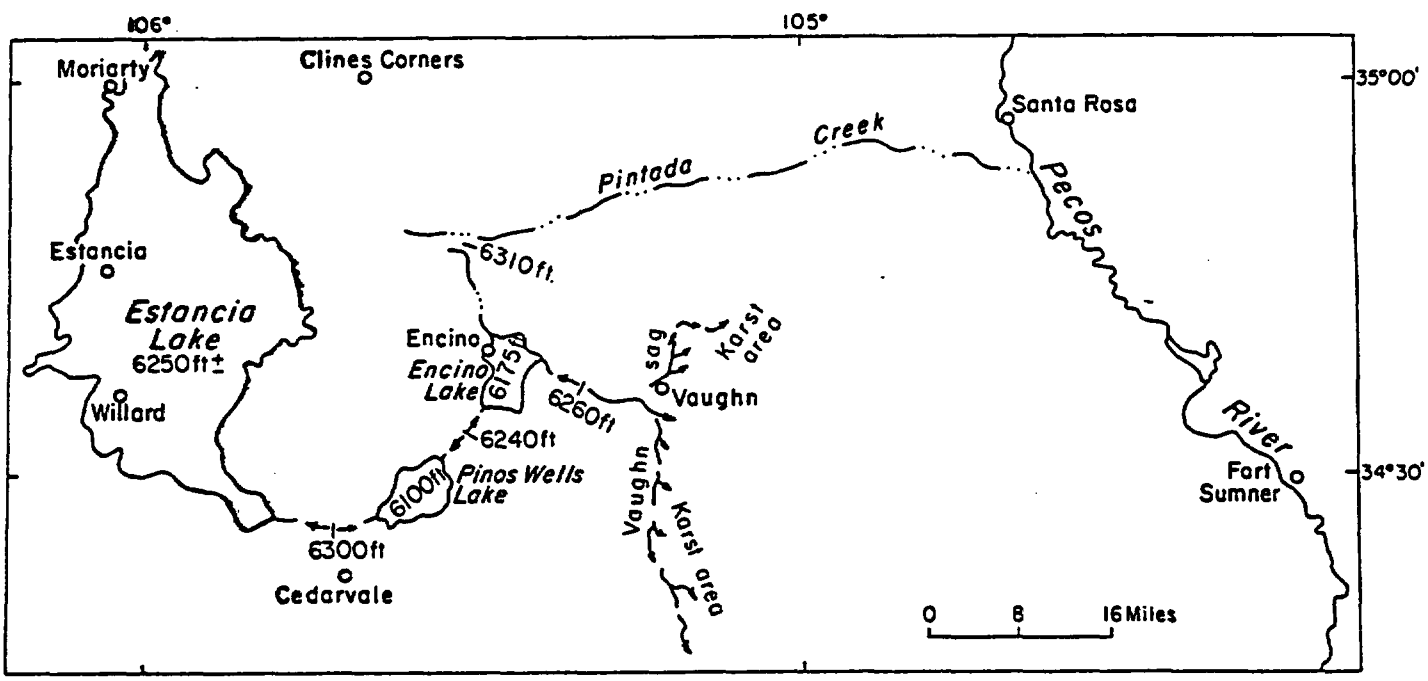
The origin of the basins is significant. Doubtless the Estancia basin is tectonic. Tectonic downwarp is not evident for the Pinos Wells and Encino basins, however, and it is generally assumed that they are large solution collapse swales. On the other hand, the depth, regularity, and magnitude of the depression appear to stretch the original volume of gypsum thought to be in the Yeso. Perhaps after considering the magnitude of the playa hole at Encino, deflation as an origin for the entire basin is a good possibility with, of course, accompanying solution in the underlying Yeso Formation.

Retrace route to state road 3.

1.6

95.8 State road 3. *Turn left* toward Duran. Yeso tan-brown sandstone and light-gray limestone in bluffs to west.

0.3



Quaternary lakes drainage system—If Encino Lake ever filled to its 6,260-ft sill, Encino Lake and Pinos Wells Lake would have formed one lake (Kelley, p. 48, fig. 8, 1972).

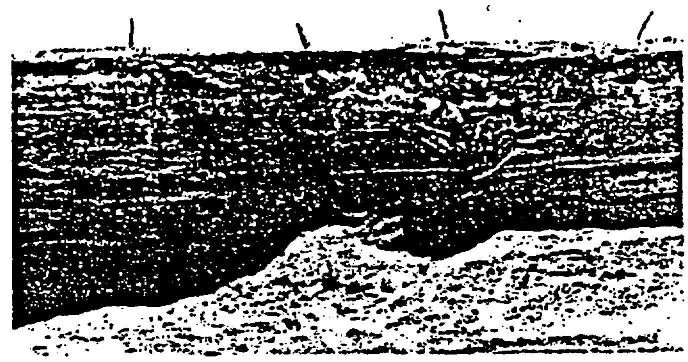
96.1 Road descends on Encino Lake floor.
2.7
98.8 Road rises from lake floor at turn to right. Yeso in bluffs consists of tan-brown sandstone and local white gypsum beds.
0.6
99.4 About the position of a high lake level. Note diabase boulders along side of road; they are float from a sill near the top of the hill ahead.
0.4
99.8 Sill in roadcuts. There are 3 or 4 sills or groups of sills in this part of the Yeso, up to about the base of the high Duran Mesa. The highest one at the mesa is as much as 75 ft thick. The other sills have been mapped (Kelley, NMBM Bull 98, p. 35, 1972) and are mostly in units 20 to 30 ft thick. Where exposures are good one unit may be seen to consist of up to 10 thin sills, 1 inch to 5 or 10 feet thick.
2.1
101.9 Note diabase in roadcut on right; gray beds overlying the sill are Quaternary sand and caliche here. Solution swale on left. Duran Mesa ahead is made up of Glorieta Sandstone, here about 270 feet thick. A thin rind of limestone of Bonney Canyon Member (San Andres Formation) locally caps the mesa, and the underlying Yeso top is just about at the base of the mesa.
2.2
104.1 Bear left with the road.
0.1
104.2 Yeso gypsum and limestone seen in cuts next 0.3 mile.
0.4
104.6 Crossing diabase sill; note float.
0.5
105.1 Sill again, overlain by purplish Yeso; butte at 11:00 is capped by Glorieta.
0.7
105.8 Highly weathered sill again showing in left cut float; note outcrop 200 feet to east.
1.0
106.8 Road here in sand dunes derived from Glorieta; gravel along road added and is mostly crushed San Andres Limestone.
2.0
108.8 Stop sign. Southern Pacific Railway tracks; cross and stop at U.S. 54. *Turn left.* This is Duran, a ranching community established in 1900 by Spanish families named Duran. The Southern Pacific Railway early considered the town for shops and a roundhouse but finally decided in favor of Alamogordo. At the time there were many construction workers, and plans called for substantial building, as witness the number of fine stone structures still standing. The stone was quarried from Glorieta Sandstone in the mesa southwest of Duran.
2.5
111.3 Milepost 193. Roadcuts are in a diorite sill in upper part of the Yeso. This may be the same sill as on the west face of Duran Mesa. The peculiar nodular weathering appears to be related to a primary orbule-like structure. Chloritic veneers and some textural variation coincides with the subrounded balls.
2.0
113.3 STOP 4. Road cuts at Milepost 195. Examination of Ogallala gravel which in part consists of Glorieta sandstone, diabase sill rock and reworked caliche. Bedrock at the base of the cut is Yeso limestone and gypsum. Correlation of this deposit at this high level is suggested by Kelley, (N. Mex. Bur. Mines & Min. Res. Bull. 98, map 1, 1972).
0.9
114.2 Road crosses about here onto partly covered base of the Glorieta.
0.8
115.0 Roadcuts in Bonney Canyon limestone.
0.5
115.5 Guadalupe-Torrance County line.
0.3
115.8 Road crosses out of Bonney Canyon into Ogallala and caliche. Below the Ogallala the bedrock is the evaporitic Fourmile Draw Member of the San Andres Formation.
1.5
117.3 Milepost 199. Skyline 12:30 to 4:00 is the Vaughn fault scarp. From about here to the fault there is an eastward-tilted wedge of Ogallala gravel 100 to 300 feet thick filling the Vaughn sag.
3.3
120.6 U.S. 60 and 285 join U.S. 54. *Straight ahead.* Note at 10:45 that the Southern Pacific, which we have been following, passes under the Santa Fe from Encino (S. P. was here first!).
2.2
122.8 *Turn left* on dirt road at roadside park across from Conoco service station.
0.1
122.9 Cross street, *straight ahead.*
0.1
123.0 Cross street, *straight ahead.* At 12:00-1:00 beyond railroad tracks the hills are Fourmile Draw limestone and gypsum dissolved and collapsed into a karst topography which we will loop through after visiting gravel pit.
0.1

123.1 *Turn left* and through fence into gravel pit.
0.1

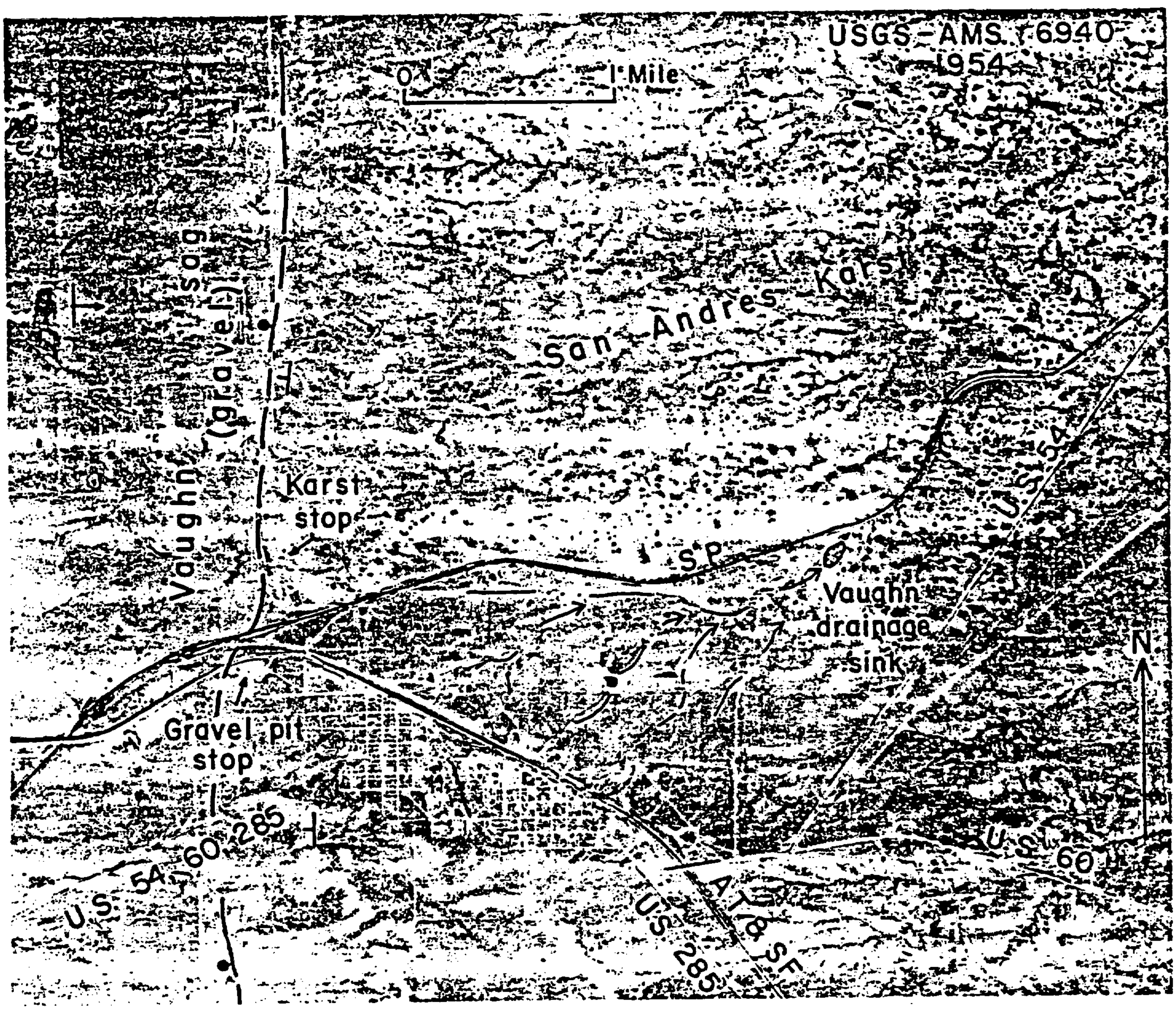
123.2 Gate into gravel pit, *bear right.*
0.2

123.4 STOP 5. Gravel pit. The gravel here contains numerous Precambrian fragments as well as those from nearby Permian and Triassic rocks. Near the northern edge of the pit a small patch of Santa Rosa underlies the gravel having been dropped and preserved in a sinkhole. The southern limit of this gravel is covered, but south of U.S. 60 there is a considerable area of Tertiary sandstone and mudstone that may be earlier Ogallala.
0.2

123.6 Exit gravel yard and *turn left.*
0.2



Probable Ogallala gravel in gravel pit at Stop 5. Note pre-present surface solution collapse or cut and fill in the gravel.



123.8 Stop sign. Santa Fe Railroad double tracks, *straight ahead.*
0.1
123.9 *Turn right.*
0.5
124.4 Cross Southern Pacific tracks. Fourmile Draw Member in bluffs ahead. Sinkhole shows limestone and gypsum.
0.2
124.6 Red sandstone in blade cuts on road are in Grayburg-Queen Formation (Artesia Group) here collapsed into Fourmile Draw.
0.1
124.7 Fourmile Draw limestone in bluffs.
0.2
124.9 Vaughn City dump, again in holes.
0.1
125.0 *Turn right* on obscure side road into karst area. Surface irregularities here in limestone and gypsum are natural—not excavations.
0.2
125.2 STOP 6. Examination of Fourmile Draw limestone and karst topography. Overview of Vaughn sag and discussion of regional relations and origin.

The Vaughn sag is a long north-south downwarp, some 30 miles in length. It is formed here by a fault downthrown on the west several hundred feet and elsewhere by a buckle fold facing west. Considerable gravel, probably Ogallala, is downthrown into the sag. Barracading of stream flow from the west at the upthrown side has accentuated solution, collapse, and karst development in the Fourmile Draw Member seen here. Continue on road through karst and loop back to the road.
0.3
125.5 Fork, *take left.*
0.2
125.7 Rejoin road, *turn left* and retrace route to Vaughn. END OF THIRD DAY.

92.3 The surface from here to Vaughn is broken by numerous karst features, mainly playa depressions, creating an undulating landscape. The karst features are developed in Permian gypsum and limestone units, particularly (in this area) the Grayburg–Queen and San Andres Formations. **0.8**

93.1 Caliche in roadcuts. **0.1**

93.2 Mile marker 290. **0.4**

93.6 Grayburg–Queen Formation in roadcut on left. **0.6**

94.2 Abandoned ranch site on left. **0.3**

94.5 Litter cans, both sides. Caliche horizon in roadcuts for next 1 mi, several playas along highway here. **0.9**

95.4 **De Baca–Guadalupe County line; entering Guadalupe County. 0.7**

96.1 Large playa to right. **0.6**

96.7 Highway descends gently into a wide depression; Grayburg–Queen Formation overlain by Pleistocene deposits exposed to right. **0.5**

97.2 Caliche deposits by road on left. **1.2**

98.4 Stock tank on right. **0.2**

98.6 Guadalupe County Road 3H on left. **3.0**

101.6 Outcrops of Grayburg–Queen or San Andres Formation exposed on right about 4 mi in the distance. **1.5**

103.1 Mile marker 280. **1.6**

104.7 Pediment caliche exposed in roadcuts. **1.4**

106.1 Karst depression on right; low roadcuts in Fourmile Draw Member of San Andres Formation. This is the uppermost member of the San Andres here, and consists predominantly of interbedded dolomite and gypsum with lesser amounts of reddish mudstone. The regional stratigraphic distribution of Permian units in this area is shown in Fig. 3.19. Kelley (1972a) reported that karst topography and much caliche characterize the surficial exposures of the Fourmile Draw Member; sinkholes are exceedingly abundant. The member is widely exposed north and east of Vaughn. **0.3**

106.4 Highway descends sharply into karst depression. **0.4**

106.8 Gray to white gypsum of the Fourmile Draw Member exposed along road at right. **0.6**

107.4 Mesa Leon, capped by Santa Rosa Formation, in distance to right at 2:00. **0.2**

107.6 Litter can on right. **0.7**

108.3 Fourmile Draw Member exposed in arroyo to right. **0.6**

108.9 Gypsum of Fourmile Draw Member exposed in low roadcut on right. The highway is traversing a hummocky karst surface with slightly eroded San Andres exposures. **0.2**

109.1 Reddish-orange Quaternary deposits with caliche in roadcuts. **1.0**

110.1 Medium-gray to white Fourmile Draw Member crops out in sides of wide, low arroyo on right. **0.5**

110.6 Highway rises over rather sharply reliefed karst. **0.3**

110.9 Caliche rubble in low roadcut. **0.5**

/111.4 **Junction of US-60 and US-54 north to Santa Rosa. Vaughn is about a mile ahead on US-60, but turn right on US-54. 0.5**

111.9 Minor grayish-green gypsiferous sandstone (Grayburg–Queen Formation?) covered by reddish Quaternary deposits and caliche in roadcuts. **0.4**

112.3 Sinkholes and other karst features are well developed along the next 17 mi, often with limestone and gypsum units of the Fourmile Draw Member of the San Andres Formation exposed as ledges around the margins of sinkholes (Fig. 3.20). **0.4**

112.7 Small sinkhole to left. **0.1**

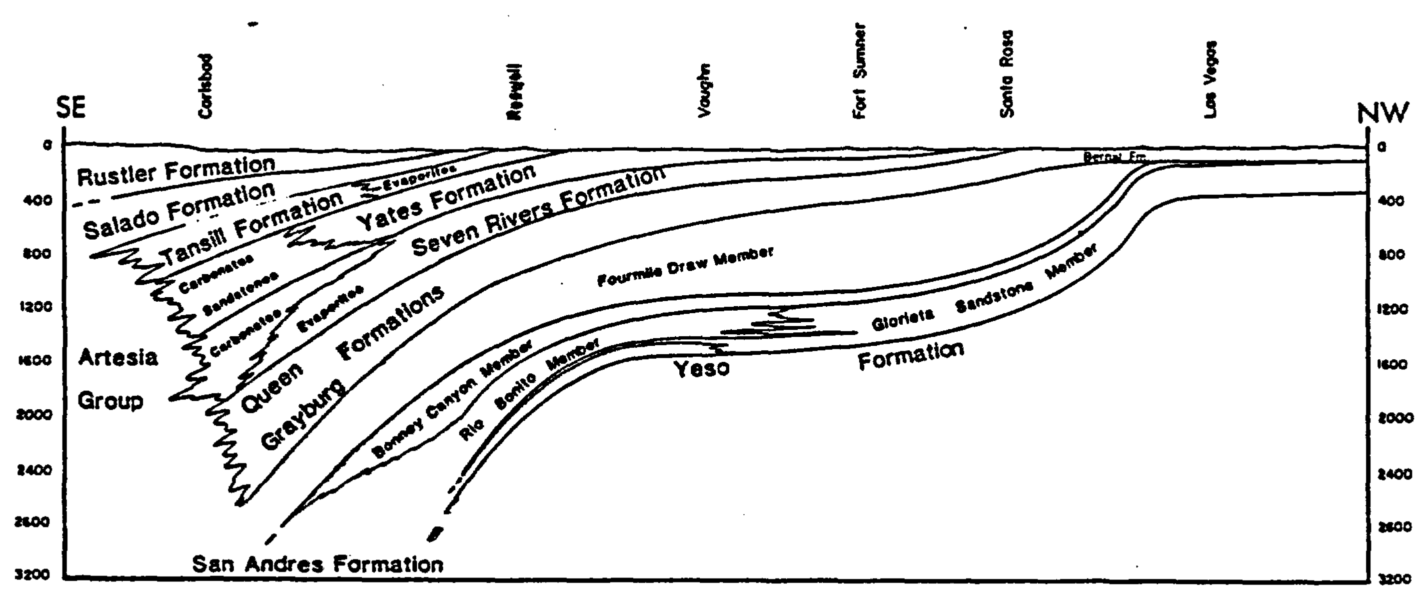


FIGURE 3.19. Regional-stratigraphic diagram of Permian formations from Carlsbad to Las Vegas (after Kelley, 1972b).

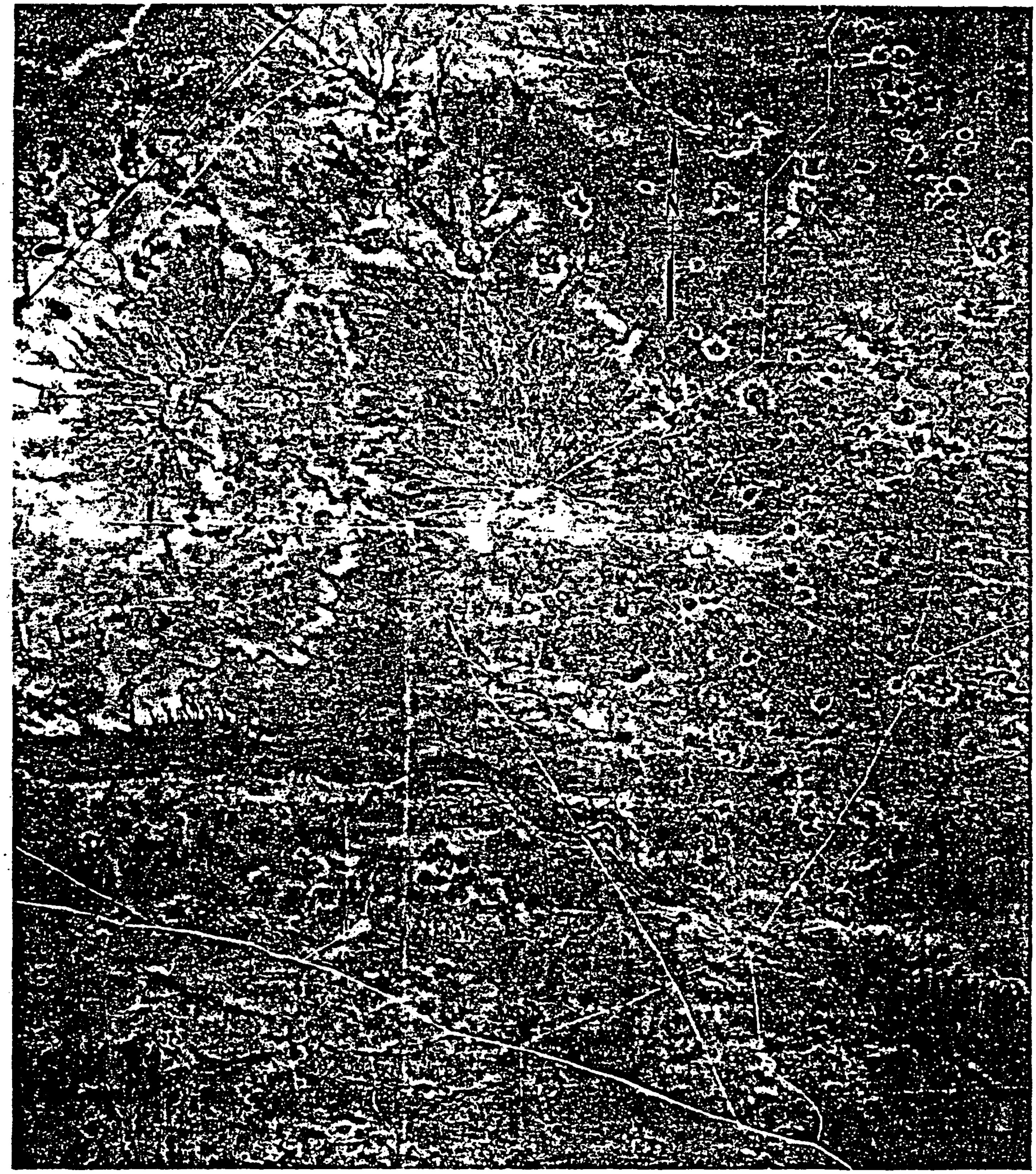


FIGURE 3.20. Aerial photo showing karst relief with abundant sinkholes about 8 mi north of Vaughn. Scale 1:33,736.

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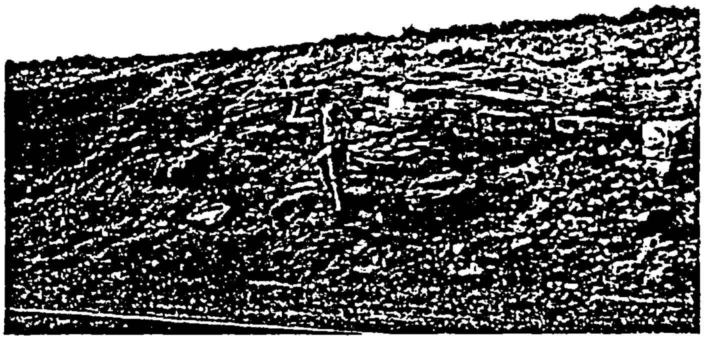

FIGURE 3.21. Limestone and gypsum of Fourmile Draw Member of San Andres Formation at Stop 3.

FIGURE 3.22. Sinkhole in Fourmile Draw Member at Stop 3.

112.8 Fairly extensive exposures of Fourmile Draw Member of San Andres around depression to right. **0.3**

113.1 Fourmile Draw Member exposed around sinkholes to right for next 0.3 mi. **0.4**

113.5 Fourmile Draw Member in roadcut on left and sinkhole beyond. **0.2**

113.7 Fourmile Draw Member along road to right as highway crosses a sinkhole. **0.4**

114.1 Deep, well-developed sinkhole on right, with exposures of the Fourmile Draw Member. **0.1**

114.2 Fourmile Draw Member in low roadcuts. **0.4**

114.6 Large piles of calcareous debris along railroad tracks to left. **0.3**

114.9 Low Fourmile Draw exposures in roadcuts and in sinkholes for next 0.4 mi. **0.8**

115.7 **STOP 3.** Good, long roadcut through the Fourmile Draw Member of the San Andres (Fig. 3.21), with a well-developed large sinkhole on right just beyond the roadcut (Fig. 3.22). The section here consists of a medium-gray, massive limestone/dolomite unit overlying a dark-gray, incompetent gypsum unit with undulating bedding. **0.7**

116.4 Highway is on caliche-rich gravel above the Grayburg–Queen Formations. **0.6**

117.0 Small metal shed on right. **1.3**

118.3 Unpaved roads on left and right. **0.1**

118.4 Holocene soil in roadcut on left. **0.3**

118.7 Pediment soil, gravel and caliche in roadcuts. **0.6**

119.3 Highway descends sharply into a large depression, San Pablo Draw. **0.4**

119.7 Highway ascending from San Pablo Draw; high-level, late Pliocene–Pleistocene gravel and caliche in roadcuts. **0.3**

120.0 Highway descends gently; small sinkhole to right at 2:00. **0.3**

120.3 Mile marker 215. **0.4**

120.7 Small metal shed to right; high-terrace gravel overlain by caliche in roadcuts. **0.9**

121.6 Large sinkhole to left. **0.1**

121.7 Caliche in low roadcuts. **0.4**

122.1 Sinkhole to left. **1.1**

123.2 Grayburg–Queen(?) below caliche rubble in low roadcuts for next 0.3 mi. Mesa Aragon, with Permian Grayburg–Queen and Triassic Santa Rosa Formation exposed on sides, is visible to left at 10:00–11:00. **0.4**

123.6 Brownish-red, gypsiferous, fine-grained sandstone overlying grayish-green siltstone of Grayburg–Queen Formations in low roadcuts. The Permian units are capped by caliche with clasts of reddish-brown sandstone in it. **0.4**

124.0 Highway crosses a shallow depression; Grayburg–Queen(?) poorly exposed to left. **0.1**

124.1 Caliche in roadcuts. **0.4**

124.5 Road to small metal shed on right. **0.5**

125.0 Sinkholes to right at 2:00; low San Andres limestone exposures, next 0.4 mi. **0.3**

125.3 Mile marker 220. **0.4**

125.7 Small sinkhole on right, with a little San Andres along sides. **0.5**

126.2 Two windmills on right away from highway. **1.8**

128.0 Limestone debris piled along railroad on left. The highway is now on the northeast side of Guadalupe Mesa, a northern extension of Buchanan Mesa. The Guadalupe Mesa surface is capped with early Pleistocene caliche-rich sediments and is 100 to 200 ft below an older surface consisting of Ogallala deposits. This upper surface is limited to the tops of several smaller mesas in this area, such as Mesa Aragon and Mesa Leon (Kelley, 1972a, p. 29). **0.4**

128.4 Small metal shed to right. **0.4**

128.8 Small ledge of gray San Andres limestone exposed to right along sides of small depression. **0.1**

128.9 Red sandstone of Grayburg–Queen Formations,

FIGURE 3.23. Roadcut in Grayburg–Queen Formations at mile 139.5.

FIGURE 3.24. Sandstone of Santa Rosa Formation overlying Grayburg–Queen mudstone in roadcut at mile 141.9.

overlain by white, solution-pitted limestone and caliche rubble in roadcuts. **0.5**

129.4 Grayburg–Queen Formations in roadcuts. According to Kelley (1972a), the Grayburg and Queen Formations (undivided) are equivalent to the unit known as Bernal farther north. He suggested that Bernal be used north of the latitude of Santa Rosa and west of the longitude of Vaughn (Fig. 3.19). **0.4**

129.8 Guadalupe County Road 3J to right; road to the town of Pastura to left just beyond. Pastura (population 25; elevation 5285 ft) once supported an outlet of the Charles Ilfeld Company, which dealt in cattle, sheep and wholesale and retail goods in stores throughout New Mexico. When Charles B. Eddy's El Paso & Rock Island Railroad built northward from Carrizozo to Santa Rosa in 1902, Pastura became a station and served as a shipping point for the large Ilfeld holdings at the Pintada Ranch, northwest of Pintada Arroyo and about 8 mi northwest of Pastura. Since 1940, when the town had a population of more than 200, Pastura has dwindled to become a small farming and ranching community. **0.7**

130.5 Junction of US-54 with NM-219; **turn left onto NM-219.** Supplemental Road Log 9 (see p. 95) continues on NM-54 to Santa Rosa. **0.3**

130.8 Road crosses Southern Pacific railroad tracks. East end of Mesa Aragon (=Argonne Mesa on USGS 7.5-minute quad) ahead at 12:00. Mesa Aragon is developed in the Grayburg–Queen (=Bernal) Formation, which is overlain by the Santa Rosa Formation. **0.3**

131.1 Guadalupe County Road 4PP to left. Slight roadcuts through calichified alluvium for next 2 mi. **2.7**

133.8 Road crosses bridge over wash leading from Kipping Canyon to west; begin ascent across east side of Mesa Aragon. Santa Rosa Formation on ridge crest to left at 10:00. **0.7**

134.5 Gray to brown sandstone of Santa Rosa Formation in roadcuts. **1.6**

136.1 Grayish-green mudstone and thin sandstone of Santa Rosa Formation in roadcuts. **0.3**

136.4 Road crosses crest of ridge; Pintada Canyon ahead at 12:00, with Santa Fe Mountains in far distance on horizon. Santa Rosa sandstone and conglomerate along road. **0.3**

136.7 Good view of Pintada Canyon ahead; road passes contact between Grayburg–Queen and Santa Rosa Formations as it descends towards Cañada Bonita, a major tributary of Pintada Arroyo. **0.6**

137.3 Grayburg–Queen exposed in roadcuts on left and right. **0.5**

137.8 Road crosses bridge over Cañada Bonita. **0.7**

138.5 Grayburg–Queen Formations in roadcut on right. **0.3**

138.8 Santa Rosa Formation visible capping a small outlier of Mesa Aragon on left. **0.7**

139.5 Gypsum and dolomite of lower part of Grayburg–Queen Formations exposed on right (Fig. 3.23). Kelley (1972a) commented on the difficulties in placing the boundary between the lower Grayburg–Queen and upper part of the Fourmile Draw Member of the San Andres Formation, due to similar lithologies in both units. **0.5**

140.0 Road crosses bridge over Pintada Arroyo and begins ascent through Grayburg–Queen. **0.3**

140.3 Guadalupe County Road 4CC to left. **1.6**

141.9 Good roadcut on right shows reddish-brown Santa Rosa Formation overlying a mudstone sequence of similar color, probably the Grayburg–Queen (Fig. 3.24). The relationships of these two units along Pintada Arroyo were described by Kelley (1972a, p. 21). **1.3**

143.2 Road reaches crest of low ridge; Canadian Plateau is visible in the far distance at 11:00 to 1:00. The road now is on the high Pleistocene surface. **0.8**

144.0 Early Pleistocene alluvial and eolian deposits in roadcut, with Santa Rosa Formation bedrock at base. **1.7**

145.7 **I-40 overpass. Supplemental Road Log 10 from "Vegas Junction" west to Clines Corners along I-40 begins here.**

End of road log for Third Day.

12.0 **Enter Colonias (population 40; elevation 4910 ft),** a small settlement with numerous crumbling adobe and sandstone-slab buildings, situated in the valley of the Pecos River. The town was settled in the 1830's and thus predates both Puerto de Luna and Santa Rosa. The early inhabitants subsisted on buffalo-hunting, farming and ranching. Because of its exposed position and the absence for long periods of time of many of its men, the original settlement was built with no windows facing outward, around a courtyard that protected the livestock and water supply. Around the turn of the century, about 300 people lived in the vicinity, and raising livestock was the principal industry. When the Pecos River changed course in the 1930's, the farmers were deprived of irrigation water and many departed. **0.3**

12.3 **Turn right and stop at the old, yellow San Jose Church across the road from Colonias park.** The church has large cracks in its walls and the cemetery is overgrown with weeds (Fig. S-8.1). Note that many of the gravestones are carved in red Permian and Triassic sandstones, doubtless from the surrounding area. The high bluffs overlooking the town on the northeast side of the Pecos display the Bernal and Santa Rosa Formations.

FIGURE S-8.1. San Jose Church and cemetery in Colonias, with carved sandstone gravestones.

End of Supplemental Road Log 8.

SUPPLEMENTAL ROAD LOG 9, FROM PASTURA TO SANTA ROSA

BARRY S. KUES

Mileage

0.0 **Junction of US-54 with NM-219; continue straight (northeast) on US-54.** The Third-Day Road Log turns left on NM-219 at this point and progresses north to Vegas Junction on I-40. **0.7**

0.7 Light-pinkish-gray Pleistocene deposits with caliche rubble (Guadalupe Mesa surface) in roadcuts for next 0.4 mi. **0.4**

1.1 Windmill on left. **0.6**

1.7 Small metal shed on right. **0.9**

2.6 Calichified Pleistocene deposits in roadcuts for next 0.4 mi. **0.3**

2.9 Shallow karst depression to right. **1.4**

4.3 Windmill and Guadalupe County Road 4M to left, at former site of the town of Guadalupe (post office, 1900–1941). About 2 mi to the north, visible at 10:00, are low mesas composed of the Santa Rosa Formation. The discovery of copper mineralization in the upper part of the Santa Rosa here led to the opening of the Guadalupe (or Stauber) mine in 1925, which was operated intermittently through the 1950's. The mine produced a total of about 5000 tons of copper through 1954, from ore having an average grade of about 5% (Anderson, 1957). High-grade concentrations of copper occurred locally in large fossilized logs. A detailed summary of the geology and ore deposits of the mine was provided by Harley (1940). **0.6**

4.9 Mile marker 230. **0.7**

5.6 Small metal shed on right. **0.7**

6.3 Windmill and abandoned stone building on right. **0.3**

6.6 Light-reddish-brown to white, caliche-rich Pleistocene sediments in roadcuts for next 0.4 mi. **1.1**

7.7 Caliche in roadcuts. **0.6**

8.3 Windmill on right away from highway. **1.0**

9.3 Small metal shed on right. **0.6**

9.9 Highway crosses crest of low ridge and begins descent. **0.2**

10.1 Road to H Ranch on right. **0.2**

10.3 Windmill on left along small creek; note dark-gray outcrops of Santa Rosa Formation behind it along bottom of creek. **0.9**

11.2 Green house on ridge to right; large, light-cream-

colored blocks of Santa Rosa Formation piled up along road to left. The ridge to the right is composed of Santa Rosa Formation and marks the southern edge of the Santa Rosa sink. **0.5**
11.7 Highway crosses crest of a ridge; Santa Rosa Formation in roadcuts for next 1 mi. Bluffs along Pecos River visible on horizon at 1:30. **0.5**
12.2 Gray to tan sandstone of the Santa Rosa Formation exposed as ledges along ridge to left and right. **1.0**
13.2 Small metal building on right; stock dam on left. **0.2**
13.4 Light, reddish-orange, older Quaternary gravels in roadcuts for next 1 mi. **0.3**
13.7 Highway crosses Pintada Arroyo; note two terraces along its sides. Highway begins ascent out of Pintada Arroyo valley up a low ridge ahead. **0.7**
14.4 Light, reddish-orange, older Quaternary alluvial sediments in roadcuts. **0.1**
14.5 Santa Rosa Formation in roadcuts. **0.2**
14.7 Windmill on left. **0.3**
15.0 Highway nears crest of a ridge; light-reddish-brown alluvial sand and overlying soil in roadcuts. **0.1**
15.1 Town of Santa Rosa comes into view ahead at 12:00; highway descends towards it. **0.5**
15.6 Dark- to light-red alluvium in roadcuts. **0.4**
16.0 Highway passes through an area of hills formed as a result of erosion of the 250- to 400-ft-thick Quaternary sand and gravel in the Santa Rosa sink. Exposures of this light-red to brick-red sediment are present along the sides of these hills in places and in roadcuts for next 0.6 mi. **0.5**
16.5 Highway crosses bridge over a small creek, a tributary to the Pecos River, about 0.7 mi to the east. **0.1**
16.6 Windmill to left on north side of creek. **0.8**
17.4 **Santa Rosa city limits. 0.3**
17.7 **Junction of US-54 with I-40 business loop through Santa Rosa.**

End of Supplemental Road Log 9.

SUPPLEMENTAL ROAD LOG 10, FROM VEGAS JUNCTION TO CLINES CORNERS

BARRY S. KUES, SPENCER G. LUCAS and JOHN W. HAWLEY

Mileage

0.0 **Exit 256, "Vegas Junction" to US-84 north of Las Vegas; continue westward on I-40 from end point of Third-Day Road Log. 0.2**
0.2 Overpass. **0.3**
0.5 Windmill to left away from highway. Highway is on high-level alluvium and eolian deposits, with significant amounts of caliche that have been correlated with the Ogallala Formation by Frye et al. (1982). View to right is across an expanse of flat to slightly undulating grassland having sparse yucca and cholla. **1.4**
1.9 Highway crosses small ditch to right. **0.2**
2.1 Light-red Quaternary alluvium and eolian deposits in low roadcut on right. **0.6**
2.7 Low ridges to left, about a mile in the distance, show limited ledges of tan Santa Rosa Formation. **0.7**
3.4 Light-gray to brown deposits of nonindurated caliche fragments are exposed intermittently in low roadcuts for next 1 mi. **1.1**
4.5 Overpass. **0.4**
4.9 Ranch and windmill to left, with low exposures of Santa Rosa Formation cropping out around a low hill. **0.1**
5.0 Exit 252 to rest area along shallow Cañon de Baca. **0.1**
5.1 Beginning of a long roadcut, which extends for next 0.3 mi. Strata exposed here, and along Cañon de Baca to right, are units of the Santa Rosa Formation. The basal bed is a maroon-red shale, overlain by a lensoid, 8-ft bed of massive, gray, poorly rounded and poorly sorted conglomerate composed of clasts of chert, limestone and sandstone up to about 6 in. in diameter (Fig. S-10.1). The upper units are light-orangish-brown to grayish-brown, coarse-grained sandstone. Stratigraphically, this sequence is in the lower quarter of the Santa Rosa Formation. **0.9**
6.0 Light-reddish-brown to cream-colored, high-level gravel with thin caliche caprock (a possible Ogallala remnant) is exposed almost continuously in low roadcuts for next 2 mi. **2.6**
8.6 Highway ascends a low ridge; caliche-rich deposits exposed in roadcuts for next 0.4 mi. **0.5**
9.1 Highway descends grade; two small buttes held up by the Santa Rosa Formation are visible to the left at 11:00; note also a playa to the left. **1.1**
10.2 Reddish-brown Quaternary deposits above poorly

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GEOLOGY OF THE SANTA ROSA AREA

by

VINCENT C. KELLEY
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PHYSICAL SETTING

Santa Rosa is situated on the Pecos River and is the seat of government for Guadalupe County. Interstate Route 40 and U.S. Highway 66 junction at Santa Rosa with U.S. 54 leading to Vaughn and U.S. 84 to Fort Sumner. Established in 1865 it became the rail center with the coming of the Rock Island and El Paso Northwestern in 1901. After the railroad building period the town became a general trading center and finally the county seat. With the development of the transcontinental highways the town gradually became a tourist attraction, and its full recreational potential is probably just beginning. It has one of the most unusual physiographic and geologic settings of any city in New Mexico.

The physiography is a huge sink caused by underground water dissolving spongy holes and caverns in limestone and other soluble rocks to the extent that the surface has gradually subsided in a large roughly circular area. The Santa Rosa sink is about 6 miles in diameter and up to 400 feet deep. An inward-sloping drape of sandstone beds surrounds the sink. Santa Rosa is at the northeast edge of the sink floor and spreads onto the adjacent rim along U.S. 66. The sink appears to have grown by expanding outward as is suggested by the several convex outward bights separated by inward "points" or noses of uncollapsed boundaries (Fig. 1).

Good views of the sink are seen coming east on I-40 about 3 miles west of town and in coming north on U.S. 54 about 6 miles southwest of town. The Pecos River enters the sink through a narrow gorge about 1 mile north of the center of town and flows across the eastern floor of the sink to an exit through the southern drape wall of the sink.

Collapse of the sink probably began in early Pleistocene or several hundred million years ago and may be going on locally and sporadically at present. From the beginning, the Pecos and its tributaries brought gravel and sand into the sink and this material appears to have accumulated to as much as 250 to 400 feet in thickness. Subsequently regional uplift caused the Pecos River to incise its course into the canyon that is so prominent north and south of the sink around Santa Rosa. During the canyon cutting much of the gravel within the sink has been eroded. However, large hills of the dissected gravel lie south and southwest of town. Except for small bluffs at river level and in a few places around the town the floor of the large sink is sand and gravel and this material contrasts with the hard strong sandstone that armors the sides and rim of the sink.

In addition to the peripheral drape of sandstone beds into the sink there are numerous sharply collapsed sink holes and some smoothly sloped swales without broken walls that have sagged into underlying caverns. These range from about 50 to 1,500 feet in diameter. About 190 of these occur in and marginal to the large sink and with few exceptions are concentrated along the northern and western sides. Those near the Pecos River if low enough have permanent water in them. There are 16 such small natural lakes near Santa Rosa.

WATER RESOURCES

Thanks to the Pecos River Santa Rosa is blessed with more potential water of nonminable type than most southwestern cities of its size. Even though Santa Rosa is referred to as "The City of Lakes," until 1926 drinking water was brought in by railroad tank car and sold at 50 cents per barrel (Larsen, 1969). However, the Rock Island Railway (Southern Pacific) had developed three surface water reservoirs, Tres Lagunas, near the head of El Rito Creek 2 to 3 miles east of town. In 1954 the Railway gave these and their filtering and pumping plant to the City. In 1956 the City took over the public water system from Southwestern Public Service Company which pumped water from the Pecos River. Recently (1966) the City established a well field 12 miles to the northwest on the road to Colonias. Three wells have been drilled and, presently, two of these supply the needs. The wells have been drilled to about 600 feet. Water was encountered first at about 420 feet but after completion the water rose about 360 feet. Pumping potential is reported to be 1,000 gpm. Withdrawals are considerably lower and ample water appears assured for considerable growth.

MINERAL RESOURCES

Gravel is the only local mineral resource that is currently important to the urbanization of Santa Rosa. Ample supplies exist in and near the city. Additional good gravel deposits are widespread on the pediments a few miles away. The Santa Rosa sandstone is, of course, abundant and could be used for both ornamental and dimension building stone. A considerable number of stone houses in the older part of town have been built of Santa Rosa sandstone. Additionally some of the more indurated Permian sandstone which occurs south of town along the Pecos Canyon could be used. However, the stone quarry operations appear to have given way competitively to fabricated building blocks.

In the 1930's the natural asphalt occurring in the Santa Rosa Sandstone 6 miles to the north was used to pave roads in the city. This source is no longer competitive which manufactured petroleum asphalt.

BEDROCK AND FOUNDATIONS

Buildings, roads, and highways have been constructed on all the outcropping rocks in the Santa Rosa area. Types of foundation material include sandstone and shale, sand and gravel, river terrace gravel, some lacustrine or swamp clays and silts, and dune sand. Sand and gravel of the sink appear stable and are easily excavated for burial of pipes or other installations such as septic tanks. The river terrace gravel benches as along

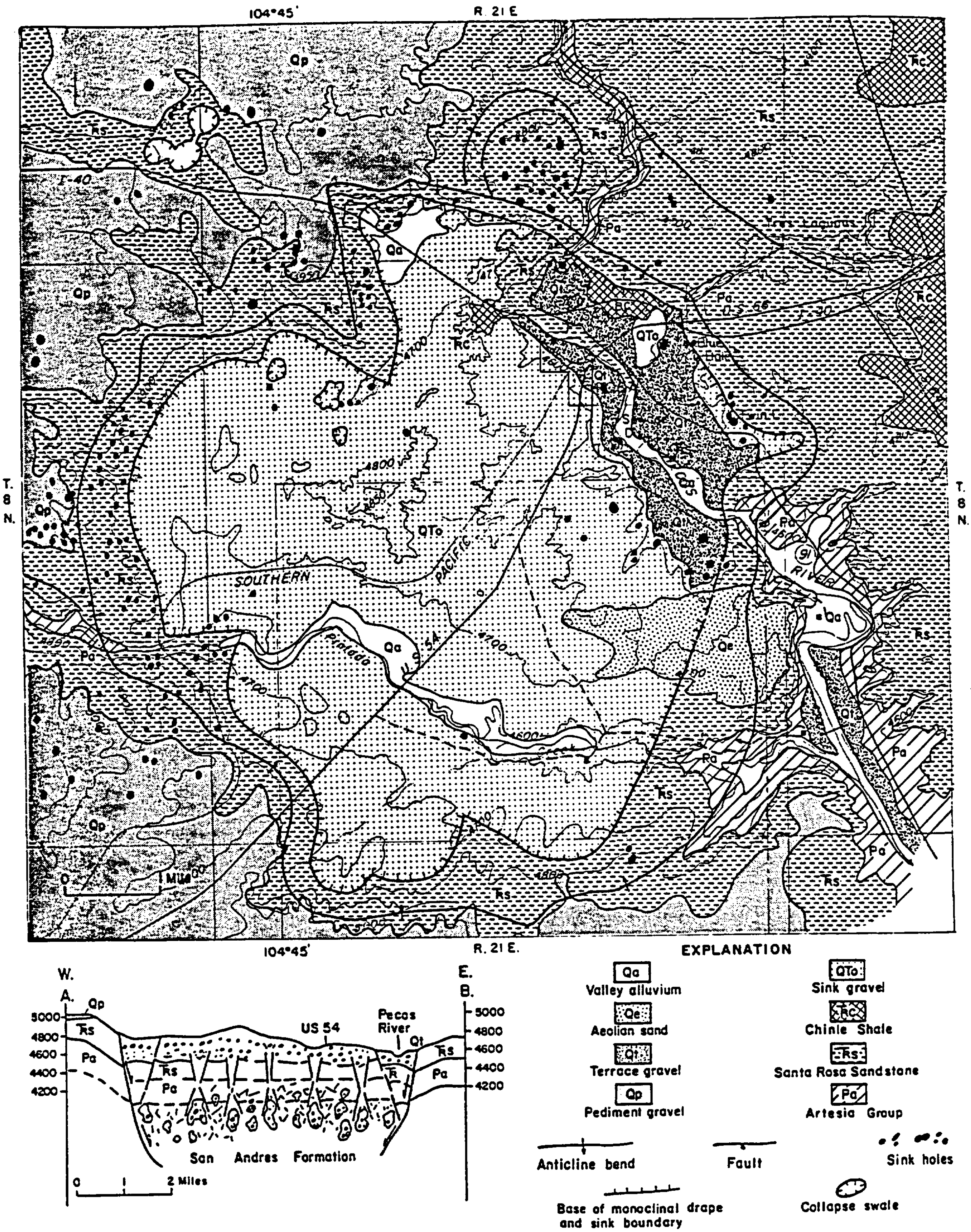


Figure 1. Geologic map of Santa Rosa and the Santa Rosa sink.

El Rito Creek east of the Pecos and south of Bass Lake are boggy and present drainage problems for some foundations. In such places the terraces may be underlain by impervious Triassic shale.

The indurated Santa Rosa sandstone presents excavation problems in the eastern and northern parts of town. For additional bridges across the river, foundations near town might be in Santa Rosa, however, local areas of broken rock, mud, and gravel, which have collapsed into the more stable sandstone, could pose some foundation support problems. The greatest foundation and stability problem lies in the possibility of local sagging or collapse. Future building of any massive structures should be preceded by careful geologic examination and possible drilling to ascertain the existence or likelihood of weak cavernous ground below the surface.

GEOLOGIC HAZARDS

Urban geologic hazards may include landsliding, mudflows, flooding, earthquakes, volcanic eruptions, subsidence. Some cities, as in California and other mountainous parts of the world, exist with several or all these hazards. For Santa Rosa, only subsidence is a hazard as evidenced by the numerous sinks some of which show marks of recency. The likelihood of damage or destruction because of this natural hazard is rather small. There is little that can be done to avoid the possibility except for careful geologic and engineering examination of all future sites of large construction projects. No landslides exist in the area and none is likely; little or no mud is present; and the region is one of no volcanic history. Earthquakes that have occurred in this part of the state are discussed elsewhere in this guidebook. Although the possibility of earthquake effects at Santa Rosa is quite minor, should one occur it could trigger sinking and local modification of lake levels.

The Pecos River is entrenched in its channel some 20 to 50 feet through the city so that even very large storms on the river would not flood the city. The surrounding slopes and gradients of arroyos and creeks are such as to pose little flooding hazard. The following peaks, recorded by the U.S. Weather Bureau, are indicative of the potential: June 9, 1903, 21.1 ft; September 30, 1904, 24.7 ft; and June 2, 1937, 25.7 ft. However, the main part of town is 40 to 60 ft. above the river.

The city has been using a sink hole on the hill about one-half mile north of town as a dump and this could result in some pollution to domestic wells near town that may not be tied into the city system. It is reported that dumping in this sink is to be discontinued.

REFERENCE

Larsen, K. W., 1969, Comprehensive plan, a guide to growth for Santa Rosa, 1969-1988, Kenneth W. Larsen and Associates, Albuquerque, N.M., 96 p.

SECOND-DAY ROAD LOG
FROM SANTA ROSA TO NEWKIRK, VARIADERO, TRUJILLO, LAS VEGAS, TECOLOTITO, ANTON CHICO, DILIA AND BACK TO SANTA ROSA

SPENCER G. LUCAS, BARRY S. KUES, GARY WEADOCK, KENNETH K. KIETZKE, JOHN W. HAWLEY, ADRIAN P. HUNT and NIALL J. MATEER

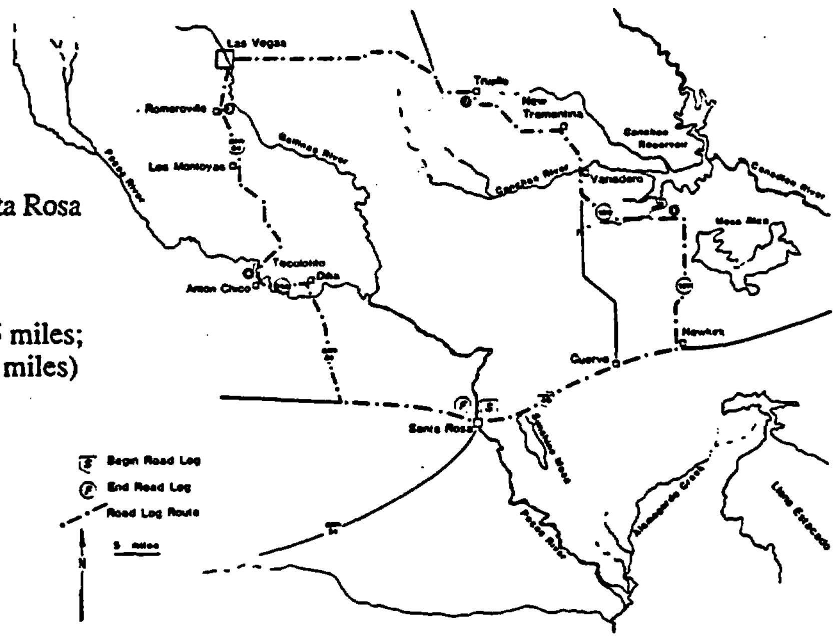
FRIDAY, SEPTEMBER 27, 1985

Assembly Point: Parking lot of Club Cafe in Santa Rosa

Departure Time: 7:30 a.m.

Distance: 180.8 miles (Segment 1: 109.5 miles; Segment 2: 71.3 miles)

Stops: 4



SUMMARY

The second day's tour of the canyons and plateaus north of Santa Rosa emphasizes: (1) the Chinle Formation, especially the Cuervo Member; (2) Jurassic and Cretaceous stratigraphy along the Las Vegas plateau and southeastern flank of the Sangre de Cristo Mountains and (3) Permo-Triassic stratigraphy.

We first proceed northeastward from Santa Rosa through a Triassic terrane developed on low mesas and in tributaries of the Canadian River. North of Newkirk, Mesa Rica is visible east and northeast of our route. This mesa, capped by the Mesa Rica Sandstone, has slopes composed mostly of Jurassic strata above a plain of Triassic bedrock. At Stop 1, we will examine Kelley's (1972a) type section of the Cuervo Member of the Chinle Formation. We then travel north and west to climb the edge of the Las Vegas plateau at "Trujillo Hill." Stop 2, at "Trujillo Hill," presents an excellent opportunity to inspect the Jurassic (Entrada–?Bell Ranch–Morrison) and overlying Cretaceous (Dakota) section. The subsequent route west to Las Vegas traverses a plateau defended by the Dakota Sandstone and covered with low outcrops of the Graneros Shale and Greenhorn Limestone. From Las Vegas, we begin Segment 2 of today's tour and proceed southward along I-25 to Romeroville gap. Here, at Stop 3, the Jurassic and Cretaceous section can be inspected again and compared with the equivalent section at Trujillo Hill (note, for example, the Todilto Formation at Romeroville gap; it is not present at Trujillo Hill). The highway from Romeroville southeastward follows the Anton Chico monocline (Kelley, 1972c) through Triassic and Jurassic bedrock. Near Anton Chico, at Stop 4, we examine the Permian section typical of north-central New Mexico: San Andres (including Glorieta Sandstone) and Bernal Formations. Tomorrow's tour will allow you to contrast the Bernal with its equivalents to the southeast, the Grayburg and Queen Formations of the Artesia Group. After Stop 4, we continue southward through the Bernal and overlying Triassic Santa Rosa Formation and then cross the Pecos River just south of Dilia. From here to I-40 the route crosses an extensive Quaternary surface.

At the intersection of US-84 and I-40 we turn east to return to Santa Rosa, entering the Santa Rosa sink a few miles before the end of this day's tour.

SECOND-DAY ROAD LOG, SEGMENT 1, FROM SANTA ROSA TO LAS VEGAS

Mileage

0.0 Through underpass beneath I-40 on US-84 in eastern part of Santa Rosa; **turn left onto entrance ramp leading to I-40 east. 0.3**

0.3 Tres Lagunas ("three lakes") visible at 8:00 just after entering I-40. These lakes are surface-water reservoirs near the head of El Rito Creek developed by the Chicago, Rock Island and Pacific Railway, which gave them, and their filtering and pumping plants, to the city of Santa Rosa in 1954. **0.3**

0.6 Sunshine Mesa to right at 1:00 to 2:00; low ridge about 0.5 mi to left held up by Santa Rosa Formation. **0.2**

0.8 Highway crosses small creek bed, the head of El Rito Creek; railroad trestle over creek to left. **0.2**

1.0 Stock pond to right. **0.4**

1.4 Sunshine Mesa to right (elevation about 200 ft above interstate). Highway is traversing the lower shale member of the Chinle; most of Sunshine Mesa is developed in the overlying Cuervo Member. The mesa is capped by Quaternary caliche deposits, which are mined in several gravel pits on the summit of the mesa. Low exposures of Cuervo Member to left of highway. **1.2**

2.6 PNM powerline crosses highway. Good view of northeast end of Sunshine Mesa to right; slump blocks of Cuervo Member litter slopes of mesa. **0.7**

3.3 Stock dam on right. **0.4**

3.7 Ruins of a stone building on right. **0.5**

4.2 Low ridge on left formed by a sandstone in the lower shale member of the Chinle. **0.7**

4.9 Stock dam on right. **0.3**

5.2 Low exposures of lower shale member of Chinle in railroad cut to left. **1.2**

6.4 Los Tanos railroad siding to left, with a small abandoned house in the distance. The community of Los Tanos once existed here; 400 people lived in the neighborhood, and a post office existed from 1907 to 1925. **0.8**

7.2 Exit 284 leads to an abandoned gas station and a western-style tourist "ghost town" on right. **0.7**

7.9 Overpass; windmill at 9:30 and on right and left in distance. **0.5**

8.4 Soils and calcrete rubble in roadcuts. **0.3**

8.7 Cuervo Hill, a large, isolated, conical mound, comes into view on left about 9 mi north of I-40. **0.9**

9.6 Windmill and buildings on right. **0.5**

10.1 Radio transmission tower on right. **0.2**

10.3 Mesa Cuervo comes into view at 11:00 to 1:00 ahead as highway ascends gentle ridge; small isolated peak to left at 10:00 is Cuervito Peak (elevation about 100 ft above the surrounding plain) in the upper shale member of the Chinle. **0.2**

10.5 Mesita Contadero, a low elongate structure, is visible to the right at 1:30. **0.4**

10.9 Brick-red sandstone of upper shale member of the Chinle exposed in roadcuts to right. **0.9**

11.8 Mesita Contadero at right beyond abandoned stone ranch house. The mesa is developed primarily in the upper shale member of the Chinle and is capped by the Ogallala Formation. **0.5**

12.3 Roadcuts in brick-red shale and crossbedded sandstone of the upper shale member of the Chinle. To the left is a good panorama on the horizon, including Cuervo Hill (elevation 5366 ft) at about 8:30, and beyond it, in a west-to-east line, are Mesa Cherisco, Mesa Pino and West Mesa. Cuervo Hill (Fig. 2.1) is an isolated western outlier of the Llano Estacado composed of many of the same units that are present farther to the east on Mesa Rica and Luciano Mesa. The upper shale member of the Chinle is present at its base, overlain by a 138-ft-thick section of the Redonda Member of the Chinle (described by Kelley, 1972c), with the Jurassic Entrada and Morrison Formations above, and a 14-ft cap of "Purgatoire Formation" (Gorman and Robeck, 1946). During the course of road-log preparation, one of us (BSK) laboriously ascended this misnamed "hill" to examine the "Purgatoire." The Tucumcari Shale, present above the Morrison to the east, is absent here, but about 15 ft of basal Mesa Rica Sandstone was observed. It contains a rather poorly preserved marine Early Cretaceous mollusc fauna dominated by *Scabrotrigonia*, and numerous trace fossils. I-40 begins descent into valley of Cuervito Creek. **0.5**

12.8 Cuervito Peak (Fig. 2.2) prominent to left, about a mile north of the highway; displays shale and thin sandstone of the upper shale member of the Chinle. **0.2**

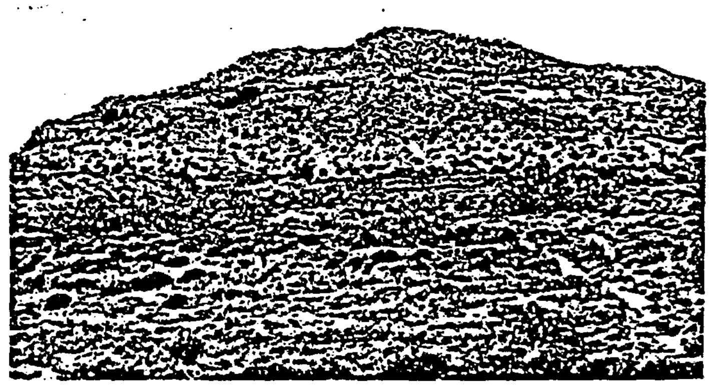


FIGURE 2.1. View of Cuervo Hill from a point about 0.5 mi south of the peak (8 mi north of I-40).

FIGURE 2.2. Cuervito Peak, north of I-40 at about mile 13, with Cuervo Hill in far background.

13.0 Light-greenish-gray to greenish-tan, locally conglomeratic sandstone of the Cuervo Member of the Chinle in roadcuts. **0.1**
13.1 Highway crosses Cuervito Creek. The creek has cut down from the upper shale member surface to the underlying greenish sandstone of the Cuervo Member. **0.2**
13.3 Greenish sandstone of Cuervo Member exposed in roadcuts. **0.4**
13.7 Reddish shale and sandstone of lower part of upper shale member of the Chinle in roadcuts. **0.4**
14.1 Cuervo Mesa ahead to right at 1:00 to 2:00. **0.2**
14.3 Grayish-green shale and sandstone of Cuervo Member of the Chinle in roadcuts. **0.2**
14.5 Exit 291 to Cuervo. **0.2**
14.7 Overpass; **town of Cuervo** (population 100; elevation 4880 ft) along both sides of I-40. Cuervo (Spanish for crow) was established about 1902 as a station on the Chicago, Rock Island and El Paso Railway, which had built westward to Santa Rosa the previous year. The town enjoyed its greatest prosperity around 1910, during a land boom that opened the area to cattle and sheep ranching. At that time, it had a population of about 300, with two schools, two hotels and a newspaper called the Cuervo Clipper. An abandoned school house and an attractive Catholic Church, built during World War I out of red-sandstone blocks, are visible on the southern side of I-40, along with most of the residences. The "business district" is on the north side. **0.8**
15.5 Cuervo Mesa rises about 500 ft above highway level to right. It is predominantly in the upper shale member of the Chinle, with a thin cap of Ogallala. Some local slump and landslide debris are present along the base of the northern side of the mesa, and gravel pits are visible along the rim. **1.4**
16.9 Cuervo Mesa close to highway on right. **0.2**
17.1 Brick-red shale and sandstone of the upper shale member of the Chinle exposed in roadcut on right. **0.7**
17.8 Highway crosses shallow arroyo; note red soil on Chinle in arroyo banks. **0.5**
18.3 Highway begins descent from crest of gentle ridge. Panorama ahead with Mesa del Gato to left at 11:00, Luciano Mesa to right at 1:00, and Palomas Mesa in far distance at 12:30. **0.4**
18.7 Sandstone of Cuervo Member of Chinle overlain by soil in washes to right, next 0.8 mi. **1.0**
19.7 Mesa del Gato to left at 10:30 to 11:30. This mesa (240 ft above road level) represents an outlier of the upper shale member of the Chinle above the Cuervo Member. A well-developed reddish-brown sandstone in the upper part of the upper shale member, caps the mesa. According to Kelley (1972c, p. 88), this sandstone unit is widespread and can be traced from west of Cuervo to the Canadian River north of Tucumcari. **1.1**
20.8 Shallow, elongate depression visible to right about 0.3 mi from highway is a small tributary of Pajarito Creek to the south. Red soil from upper shale member of Chinle covers this area. **0.5**
21.3 South end of Mesa del Gato to left, with a small outlier close to highway at 11:00 (Fig. 2.3). Good view of stratigraphy of upper shale member of Chinle. **0.9**
22.2 Ruins of ranch house on right. The highway is at about the contact between the Cuervo Member and upper shale member of Chinle. **0.4**
22.6 Chinle exposed in borrow pit at right. **0.2**
22.8 Low ridge in upper shale member of Chinle marks northern bank of main channel of Pajarito Creek. **0.6**
23.4 **Exit 300 to NM-129 and Newkirk; exit I-40 here. 0.2**
23.6 Stop sign at end of exit ramp; **turn left and proceed north across I-40. 0.2**
23.8 Cattleguard; Newkirk along road to right. Newkirk (population 60; elevation 4560 ft) was originally named Conant, after an early rancher in the area, and was established as a station on the Chicago, Rock Island and El Paso Railroad in 1901. By 1910 the area had about 450 people, and the town was a center for extensive farming and stock-raising activities. In the late 1930's, NM-129 was constructed to the site of Conchas Dam, and, as

FIGURE 2.3 Outlier at north end of Mesa del Gato, just north of I-40 at mile 21.8; view from southeast.

ROAD LOG OF TUCUMCARI, CANADIAN ESCARPMENT AND SANTA ROSA COUNTRY

by

VINCENT C. KELLEY and ROBERT W. KELLEY

SECOND DAY: Tucumcari, Friday, September 29, 1972

ASSEMBLY POINT: New Mexico State Police parking lot at west edge of town, 0.5 mile west of Pow Wow Motel.

DEPARTURE TIME: 7:30 a.m.

DISTANCE: 161.8 miles

NUMBER OF STOPS: 6

SUMMARY

This trip includes a considerable variety of stratigraphic and geomorphic features characteristic of central-eastern New Mexico. It begins with a particularly striking road cut in the Morrison Formation. Here some of the engineering geology problems will be described. The route up Luciana Mesa presents a good view of the Redonda Formation and a fine opportunity to examine the Exeter Sandstone. The Triassic, however, is the emphasis of this day, and from Montoya to Trujillo all the units of the Dockum Group of New Mexico are seen. The three members of the Chinle Formation and especially the middle unit, Cuervo Sandstone Member, are well displayed. The route ascends the Canadian Escarpment, one of the distinctive large physiographic features of the state. For many, the highlight of the trip may be the Santa Rosa asphalt quarry. The trip ends with an overview of the large Santa Rosa collapse sink from the type locality of the Santa Rosa Sandstone.

0.0 Stop sign, *Turn left* (west) on to U.S. 66.
0.1

0.1 Fork with U.S. 54 on right; *straight ahead.* 0.6
0.6

0.7 At 9:00 sign of Tucumcari Irrigation Project; ditch brings water from Conchas dam.
0.3

1.0 Hills 9:00 to 10:00 are Morrison capped by Tucumcari Shale and Mesa Rica Sandstone; similar exposures 2:00 to 3:00 on skyline.
1.2

2.2 U.S. 66 curves left into I-40 to Santa Rosa.
0.3

2.5 Bear right to Albuquerque on I-40.
0.4

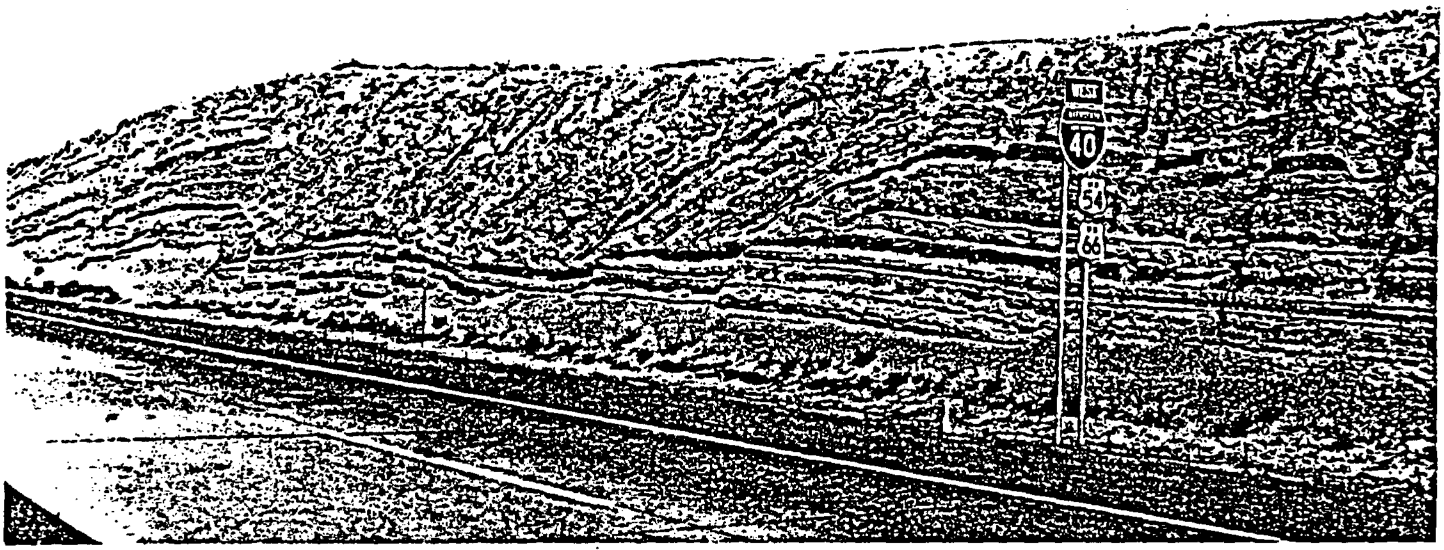
2.9 STOP 1. Park on unused I-40 eastbound lane.
The roadcut exposures are all in Morrison variegated claystone, mudstone and sandstone. Numerous small faults, landslide blocks and collapse structures are shown in striking manner. Additionally there are several primary sedimentary features such as lateral lithologic changes, crossbedding, and lenticularity. The structures are partly surficial but others including small reverse faults, and possible bedding surface slipping may be related to basin epeirogenic movements and to differential burying and unloading stresses. Excavation encountered bentonitic clays in the western end of the cut requiring removal and backfill with a select borrow material to insure subgrade stability of the highway. Quaternary clay, silt, sand, and gravel overlie the Morrison unconformably in the western part of the north cut. Several features exposed in this cut illustrate the importance of geology to highway construction. The landslide block exposed in the accompanying photo is one. Others are explained by Arlon Lovelace in the caption to the photo.
1.0

3.9 Tucumcari Metropolitan Park well field (on both sides of road). This is a structural depression in which both Exeter Sandstone and Morrison Formation attain their greatest thickness in region, suggesting subsidence was in progress during the time of their deposition.
0.8

4.7 Hills and mesas to left and right backgrounds are capped by Cretaceous Tucumcari Shale and Mesa Rica Sandstone. Southern Pacific railroad follows highway on right.
1.5

6.2 Cut in knob on right is in Morrison red and gray mudstone capped by Morrison sandstone; also in mesas on left.
1.4

7.6 Low cuts in Morrison.
0.4



This is a typical example of an ancient rotational type landslide within the Morrison Formation. Most of the surface features of the slide have been beveled off by weathering since it occurred but recent excavation during the construction of Interstate 40 has exposed many classic features that we do not offten get to observe. The east end of this highway cut is located through the center of the slide and the main surface of rupture is exposed about 5 to 6 feet above the ditch section immediately west of the I-40 sign on the north side of the road. The foot of the slide is immediately above the I-40 sign and the toe or an auxiliary slide is at the east end of the cut. A large part of this slide has been removed by excavation but a small segment representing the right flank of the slide can be observed in the cut to the south. Fortunately the direction of movement parallels the highway and excavation did not trigger any additional movement.

A more serious problem during construction was associated with the poor subgrade soils on which the road surface was to be placed. As highway excavation in this cut section approached finished subgrade, it became obvious that a serious subgrade failure was inevitable if remedial action was not taken. This failure would have resulted from heave of the expansive shales and clays that are exposed in the lower part of this cut.

Several corrective measures were considered and it was declared that an asphalt membrane would reduce expansion and hold the moisture fluctuation to a minimum. This idea is not new. Colorado Department of Highways used it on a research and experimental project on Interstate Highway 70 in Western Colorado and later on a construction project on U.S. 40 in extreme northwest Colorado to control similar problems in Cretaceous shales. Even before Colorado used this method membranes were constructed from various types of asphalts and other materials.

In most cut sections of this type material, the plans call for the top one foot of the subgrade to be scarified and recompacted to 95 percent of AASHO T99 with the moisture content to be not lower than two percentage points below optimum. Like Colorado, New Mexico decided not to scarify and recompact. It has been found that there is no need for special preparation of the bases of cuts before the membrane is placed and the subgrade will remain in equilibrium and actually be more stable when left undisturbed.

Prior to application of the asphalt membrane the subgrade was bladed to grade and all irregularities were eliminated by use of a flat-wheeled roller. The base of this entire cut section was covered with a membrane constructed from 50-60 penetration catalytically blown asphalt cement. The placement rate was about 1.15 gallons per square yard and the thickness of the membrane is about 3/16 inch. Application temperature of the asphalt was between 350° to 400° F.

Six inches of a well-graded cushion material (c usher fines) were placed on top of the membrane to protect it from puncture under each lane and shoulder section of the highway and twelve inches of soil were placed on the membrane in the median and ditch sections. The basic design of the surfacing called for 4" of cement treated subbase and 9" of Portland Cement Concrete pavement on the driving lanes; 5½" base course, 3" plant mix asphalt treated base course and 5/8" plant mix seal coat on the shoulder or parking lanes.

Since ground water was not a problem here the main purpose of the membrane is to prevent moisture from entering or escaping at the surface. So far the highway department seems to have accomplished that purpose. It may be asked, "what happens when this material is placed in a fill section?" It seems that if the moisture and density is properly controlled that the problems are minimized. The particular fill sections, both east and west of this cut section, are composed of this material. The project engineer kept the moisture content about 2 percentage points above optimum using AASHO T99 for moisture and AASHO T180 for density. The pavement shows no distress to date or since completion of construction on August 13, 1971.

To compare this method of correction with a more conventional method, observe a shallow cut section opposite the large metal water tank to the west. You will note a small heave in the pavement at this location. The expansive shales and clays were subgraded, removed and replaced with granular materials.

The basis of this information was taken from the New Mexico State Highway Department files, Project 1-040-6(6)326, construction completed August 13, 1971 and the Project Engineer Jack Newbill, Tucumcari, New Mexico.

8.0 Roadcut on left exposes Tucumcari Shale capped by Mesa Rica. A biostrom of *gryphea* and related forms commonly found in the Tucumcari Shale extends along the base of the cut, at road level. Best collecting sites are at west end of cut, and on undisturbed hillslope just beyond east end of cut. Dr. Charles Mankin recently collected a sample of dark-gray mottled fine sandstone from the top of the Tucumcari Shale at this roadcut which was studied by L. R. Wilson who reported as follows: "Palynomorphs abundant, 50 to 60 species of acritarchs, foraminifera test linings of meglaspheric stages, moss, fern, and lycopod spores are most abundant fossils, several species of conifer pollen, and one species of angiosperm pollen.

"The fern spores are mostly of tropical and subtropical tree fern genera and the conifers are from higher ground but also subtropical types.

"The palynomorph assemblage is distinct from any yet described but has numerous species in common with the Lytle Sandstone of Colorado (Cretaceous-Dakota ?), the Amadi shale (Cretaceous-Dakota) of Oklahoma and the "Walnut" shaly member of the Goodland Limestone (Cretaceous-Comanche Series-Albian) of Oklahoma. The abundance of the spore genus *Camarazonosporites* and other palynomorphs strongly suggest a Cenomanian age for the Tucumcari Shale.

"The abundance of acritarchs and foraminifera test linings indicate that the aquatic conditions were marine and shallow. The plant palynomorphs further indicate by the abundance of strand species that the depositional location was near shore (less than 1,000 meters). The lithology (fine grained carbonaceous sandstone) further supports the above statements."

0.3

8.3 Bridge over Blanco Creek.

0.4

8.7 Roadcuts in Mesa Rica; basal contact with Tucumcari Shale locally visible in cuts at road level.

1.1

9.8 Exit to Palomas, *straight ahead.*

1.3

11.1 Overpass.

0.4

11.5 Mesa Rica on skyline, 12:00 to 2:30. Road is in Morrison and alluvium.

0.5

12.0 Morrison variegated mudstone in roadcuts on right.

0.8

12.8 Morrison sandstone in roadcut on left with slide blocks above. On west end of roadcut note thin redbeds near base of Morrison, and underlying white Exeter Sandstone.

0.4

13.2 Probable Redonda sandstone beds in low cuts on left.

0.9

14.1 Low, red outcrops in valley on right are Redonda.

0.2

14.3 Road underpass and road over railroad; elevation: about 4,260 ft.

2.0

16.3 Road underpass. Montoya Mesa at 9:30 to 10:30 is capped by Ogallala (Pliocene) and Pleistocene caliche. Tailings along crest are from highway material pits for aggregate used in construction of I-40. Reddish-brown, thin-bedded mudstone and sandstone in lower half of mesa are Chinle shale. Orange-brown sandstone ledges of Redonda Formation, here about 150 ft thick, overly the Chinle and are superseded by the white Exeter Sandstone (Jurassic) (see also the near mesa, 8:30-9:00). Slope above consists of Morrison and a thin band of Tucumcari Shale. Mesa Rica was removed by pre-Ogallala erosional truncation. Luciana Mesa is at 10:30 to 11:00.

3.7

20.0 Exit to Montoya. *Turn right.*

0.3

20.3 Stop sign at intersection with frontage road; *Turn left* and cross overpass.

0.3

20.6 Intersection, *Turn left* and proceed south on county road.

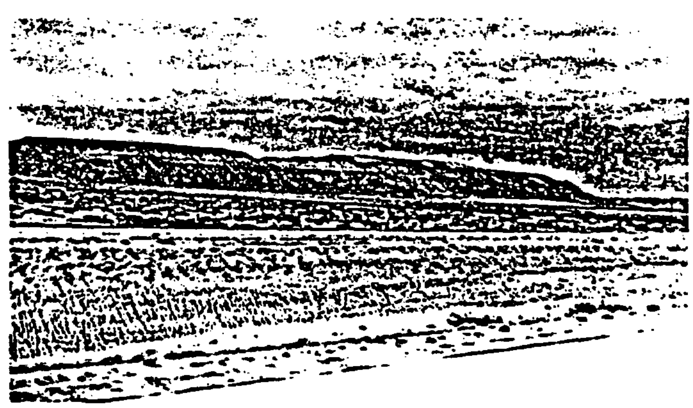
1.5

22.1 Low sandstone benches on left are Chinle.

2.5

24.6 Gate, *straight ahead.* Mesa at 11:00 is capped by Morrison. The smooth white, massive sandstone unit is Exeter Sandstone. All beds below including the white and brown cliff and the

Mesa Rica Sandstone in north cut at mile 8.7. Top of Tucumcari shows in crest of anticline at road level.



Montoya Mesa from mile 16.3

well-bedded, tan-brown sandstone and siltstone of the slope, nearly to the bottom of the outcrop, are Redonda.

1.1

25.7 Road crosses arroyo and begins ascent of Luciana Mesa.

0.5

26.2 Contact between the Upper shale member of the Chinle and the Redonda Formation; road follows contact around the small canyon to just above the rock-cribbed road foundation.

0.5

26.7 Buff sandstone up hill on left is in the upper part of the Redonda. Across the valley to the west the base of the Redonda Formation is at the base of the pyramid-shaped butte.

0.1

26.8 Morrison landslide slope on left.

0.2

27.0 Redonda finally comes out again from the Morrison slides.

0.2

27.2 Contact of Redonda and Exeter Sandstone.

0.1

27.3 STOP 2. Crossbedded Exeter in cuts, and as road pavement. Stratigraphy and lithologies of the Chinle, Redonda, and Exeter are described and discussed as they are seen here in Luciana Mesa. The valley to the north is floored by Chinle shale and Mesa Rica on the skyline across the valley has much the same stratigraphic section as at this stop. Mesa Rica is the type locality for the formation.

0.4

27.7 Flats here are in Morrison much covered by landslide.

0.3

28.0 Good ledges of Mesa Rica on ridges above road.

0.3

28.3 Morrison in roadcuts.

0.1

Exeter Sandstone on Redonda at mile 27.2

28.4 Small Tucumcari Shale exposure in roadcuts on right; Mesa Rica base just above.

0.1

28.5 Road tops Mesa Rica; gray and lavender mudstone and thin buff sandstone of Pajarito ahead on right. View of city of Tucumcari and Tucumcari Mountain at 10:00 to 10:30.

0.1

28.6 Road tops Luciana Mesa, here surfaced by caliche.

0.1

28.7 Old rut road forks right; follow and loop left back on county road. Retrace route to Montoya.

8.1

36.8 Stop sign at frontage road; *Turn right* and cross I-40 on overpass.

0.4

37.2 I-40 access, *Turn right* and proceed west on I-40.

3.5

40.7 Guadalupe County line. Small mesa on left is held up by the prominent red-brown middle sandstone unit of the Upper shale member of the Chinle.

3.2

North side of Luciana Mesa seen from about mile 26.2. Upper Chinle in foreground; pyramid butte is Redonda Formation also up mesa on left to white Morrison sandstones.

Exeter Sandstone near Stop 2

43.9 Overpass.
0.4

44.3 Cuervo Sandstone Member of Chinle Shale in roadcuts here, and for several miles ahead, in outcrops and other cuts on both sides of the road.
2.1

46.4 The sandstone of Newkirk caps low mesas to right of road.
0.7

47.1 Roadside area. Last outcrops of Cuervo about here as road stratigraphically ascends into the upper shale member of Chinle.
1.6

48.7 Exit to Newkirk at state road 129. *Turn right.*
0.2

48.9 Stop sign. *Turn right* on State 129.
0.2

49.1 Railroad crossing, *straight ahead.* The sandstone unit of Newkirk at 12:00 capping mesa.
3.7

52.8 Diamond-Shamrock petroleum pipeline.
0.3

53.1 Road rises onto Cuervo Sandstone Member and rides near its top for many miles.
2.5

55.6 West end of Mesa Rica on skyline ahead. Sandstone near top is Mesa Rica.
1.4

57.0 Canyons and mesas at 11:00 are along Cuervo Creek, the type locality. Mesas of distant skyline are part of the Canadian Escarpment.
2.8

59.8 Side road right to U.S. government installations on top of Mesa Rica (gate is locked).
0.1

59.9 San Miguel County line.
1.1

61.0 Exeter Sandstone in landslide at 3:00. Mesa Rica is well developed here along the rim.
0.8

61.8 Cuervo Sandstone in roadcuts.
0.6

62.4 Cuervo in curved cuts. Redonda beds below Exeter at 3:00 in mesa.
2.1

64.5 Red sandstone of upper shale member of Chinle in roadcut; Redonda and Exeter in mesa at 3:00.
0.7

65.2 Cuervo sandstone in cuts.
1.0

66.2 Stop sign. Junction State Road 104. *Turn left.*
1.0

67.2 Cuervo typical greenish-gray and reddish-brown mudstone in roadcut on right.
2.5

69.7 STOP 3. Cuervo Sandstone Member type section in long roadcut ahead.

The Cuervo Sandstone Member exposed at this stop, and in the new and old roadcuts and along Cuervo Creek, have been designated the type locality (Kelley, 1972, p. 26 and elsewhere in this guidebook). Good details of the lithology and bedding may be seen in the big cut.

One might suppose that the Cuervo base should be at the top of the red-brown mudstone seen near the lower end of the cut. However, examination of wider relationships along Cuervo Creek and in the surrounding mesas indicates the base is better chosen below the next lower sandstone farther down the road and north along the canyon. Across the valley to the northwest this lower sandstone unit in the Cuervo may be seen below the reddish-brown mudstone (slope forming) that is exposed at the stop.
0.3

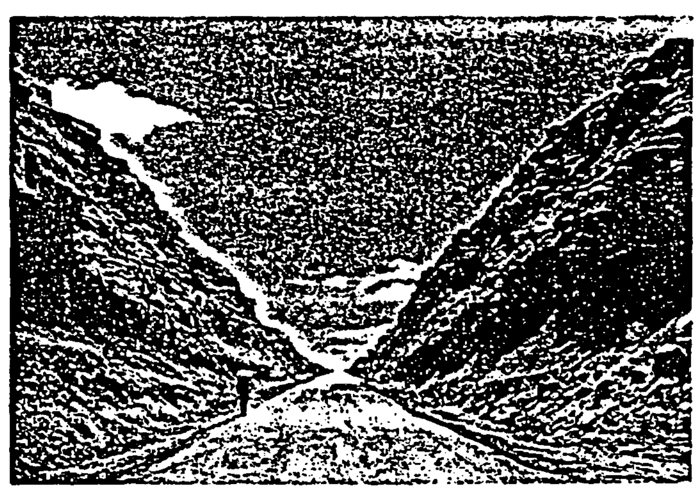
70.0 Base of Cuervo. Red-brown mudstone above this sandstone is included in the member. Cuervo caps mesas all along the canyon of Cuervo Creek.
0.4

70.4 Sandstone here is in the Lower shale member of Chinle.
0.4

70.8 Cuervo Creek bridge.
1.7

72.5 Pino Creek bridge. Far up the valley is Pino Mesa, an outlier of Cuervo. The floor of Pino Canyon here is in the Lower shale member, and the Santa Rosa top here is only about 100 ft. below the surface.
1.7

74.2 Tri-ledged Cuervo section (Kelley, this guide-



Cuervo Sandstone Member in road cut at mile 69.7

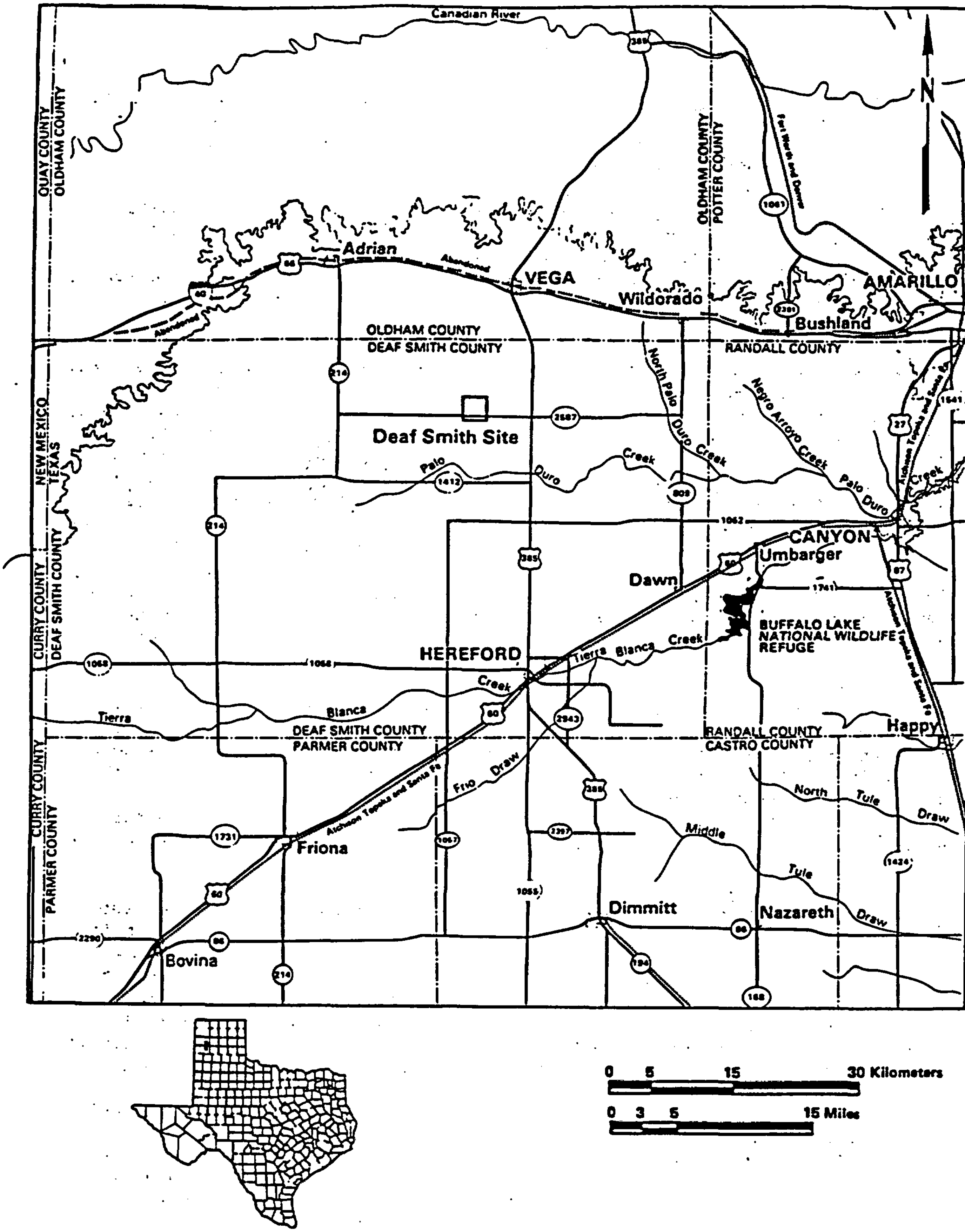
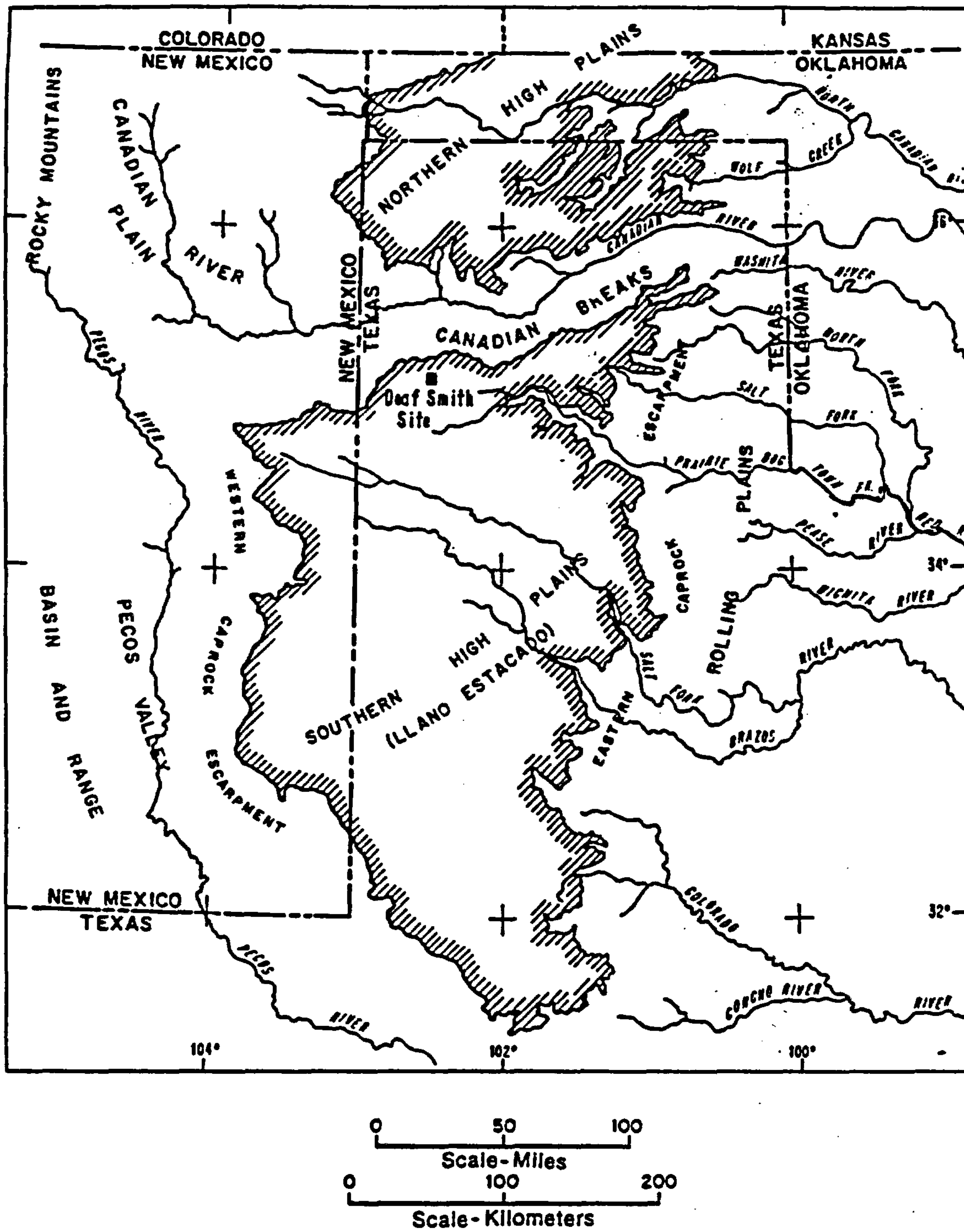


Figure 2. Deaf Smith site, Texas.

44



Explanation

Boundary of High Plains Surface

Source: SWEC, 1983, DOE/CH/10140-1.

Major Physiographic Elements of the Texas Panhandle Region

Figure 3-5

Logsdon
7/2/84

2nd Day

HYDROSTRATIGRAPHIC COLUMN and POTENTIOMETRIC SURFACES pp. 1-6

Stop 1 Palo Duro Canyon 7-32
Ogallala
Trujillo } Triassic Dockum Group
Tecovas
Quartermaster Permian

Stop 2 Caprock Canyon 33-63
Brine springs, sinkholes, surface fracture, collapse brecias, folding, veining, and faulting associated with salt dissolution and collapse

Stop 3 Canadian River
Triassic and Permian exposed north of Amarillo.

ERA	SYSTEM	SERIES	GROUP	FORMATION	HYDROSTRATIGRAPHIC UNIT (HSU)
CENOZOIC	QUATERNARY			RECENT FLUVIAL AEOLIAN AND LACUSTRINE DEPOSITS	FRESHWATER FLOW SYSTEM *HSU A*
CENOZOIC	TERTIARY			OGALLALA AND LACUSTRINE DEPOSITS	
MESOZOIC	CRETACEOUS	COMANCHE	WASHITA		
			FREDRICKSBURG		
			TRINITY		
	TRIASSIC		DOCKUM	TRUJILLO (Santa Rosa)	
				TECOVAS	
PALEOZOIC	PERMIAN	OCHOA		DEWEY LAKE (Quartermaster)	SHALE AND EVAPORITE AQUITARD *HSU B*
				ALIBATES	
				SALADO-TANSILL	
		GUADALUPE	ARTESIA (WHITEHORSE)	YATES	
				SEVEN RIVERS	
				QUEEN-GRAYBURG	
			PEASE RIVER	SAN ANDRES (BLAINE)	
		LEONARD		GLORIETA	
			CLEAR FORK	UPPER CLEAR FORK	
				TUBB	
				LOWER CLEAR FORK	
				RED CAVE	
			WICHITA		
		WOLFCAMP			DEEP-BASIN FLOW SYSTEM *HSU C*
	PENNSYLVANIAN	VIRGIL	CISCO		
		MISSOURI	CANYON		
		DES MOINES	STRAWN		
		ATOKA	BEND		
		MORROW			
	MISSISSIPPIAN	CHESTER			
		MERAMEC			
		OSAGE			
	ORDOVICIAN	CANADIAN	ELLENBURGER		
	CAMBRIAN		UNNAMED SANDSTONE		
	PRECAMBRIAN				

Explanation

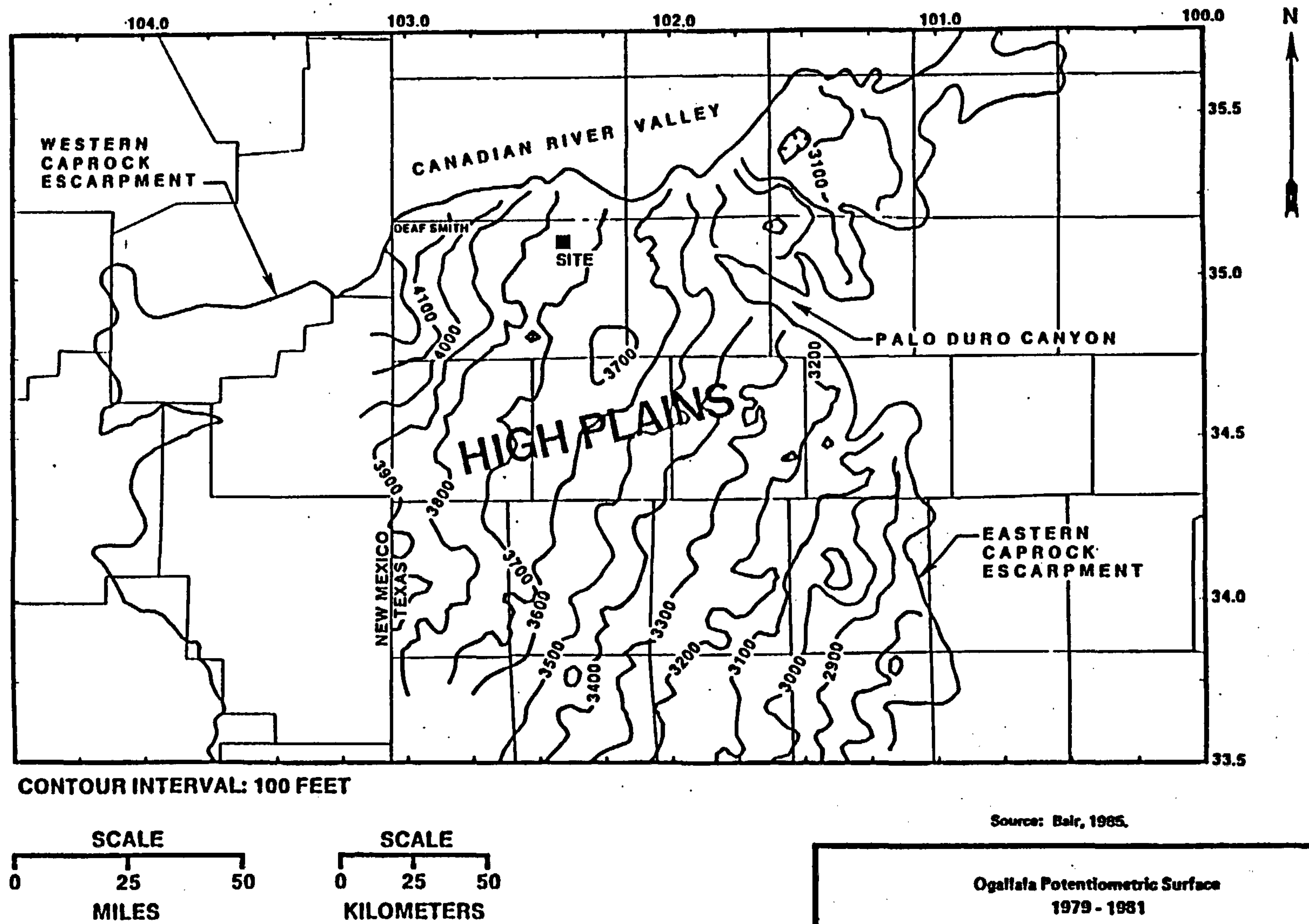
——— Unconformity

- - - - - Boundary in Dispute

Source: Bair et al., 1985, BMI/ONWI-566.

Generalized Hydrostratigraphic Column for the Palo Duro Basin

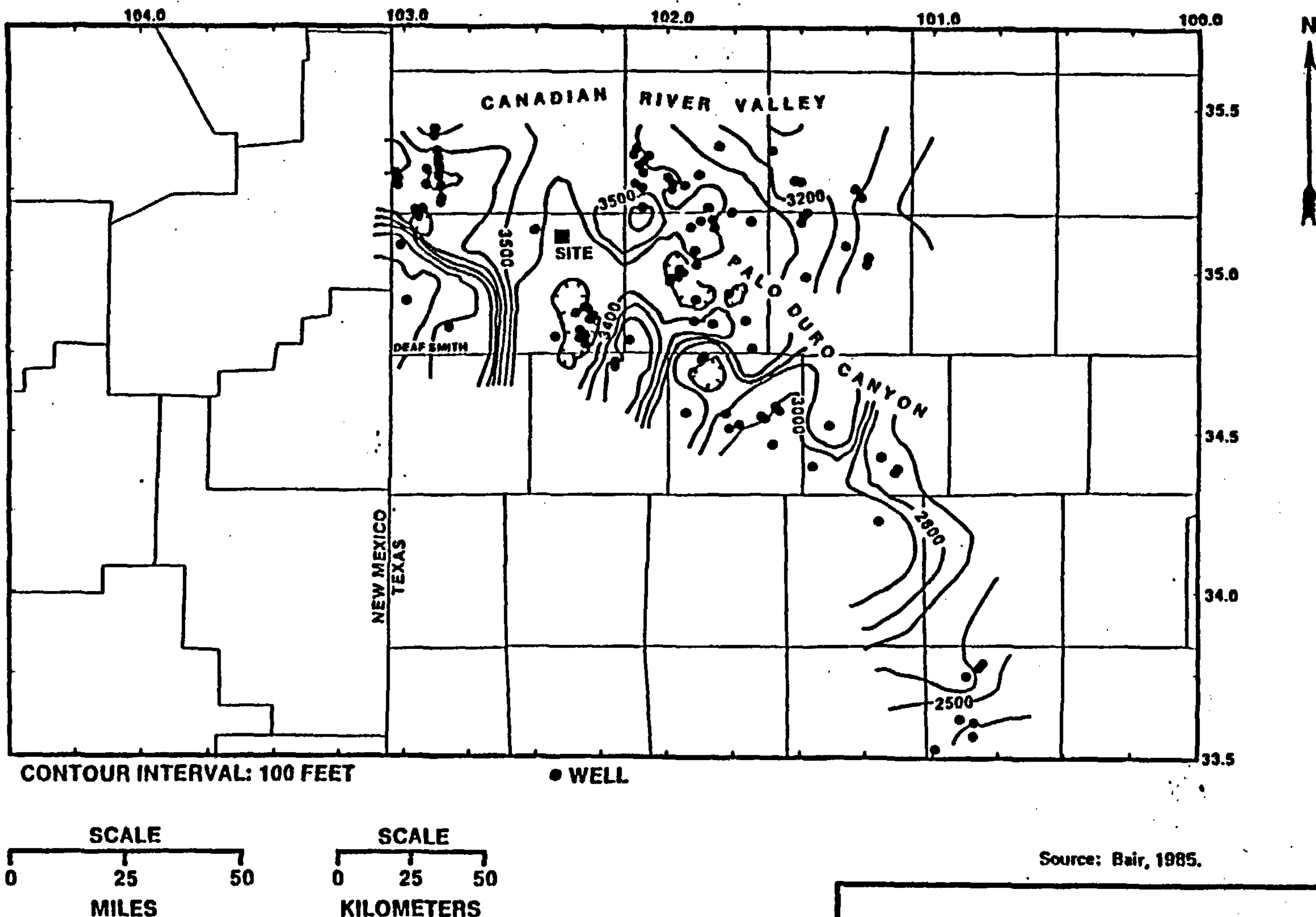
Figure 3-56



Source: Bair, 1985.

Ogallala Potentiometric Surface
1979 - 1981

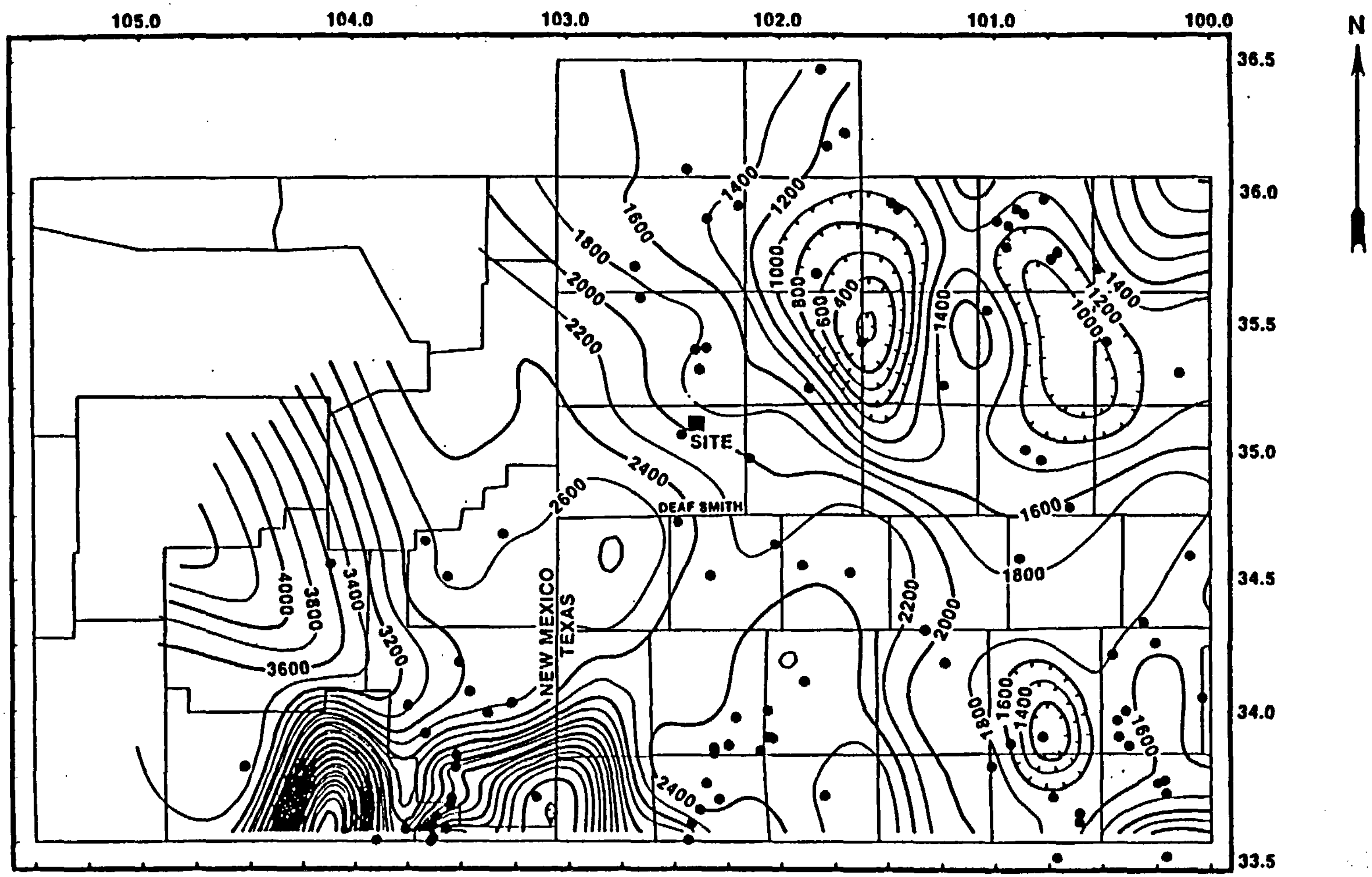
Figure 3-57



Source: Bair, 1985.

Approximate Dockum Potentiometric Surface

Figure 3-58



CONTOUR INTERVAL: 200 FEET

• DST WELL

SCALE

0 25 50

MILES

SCALE

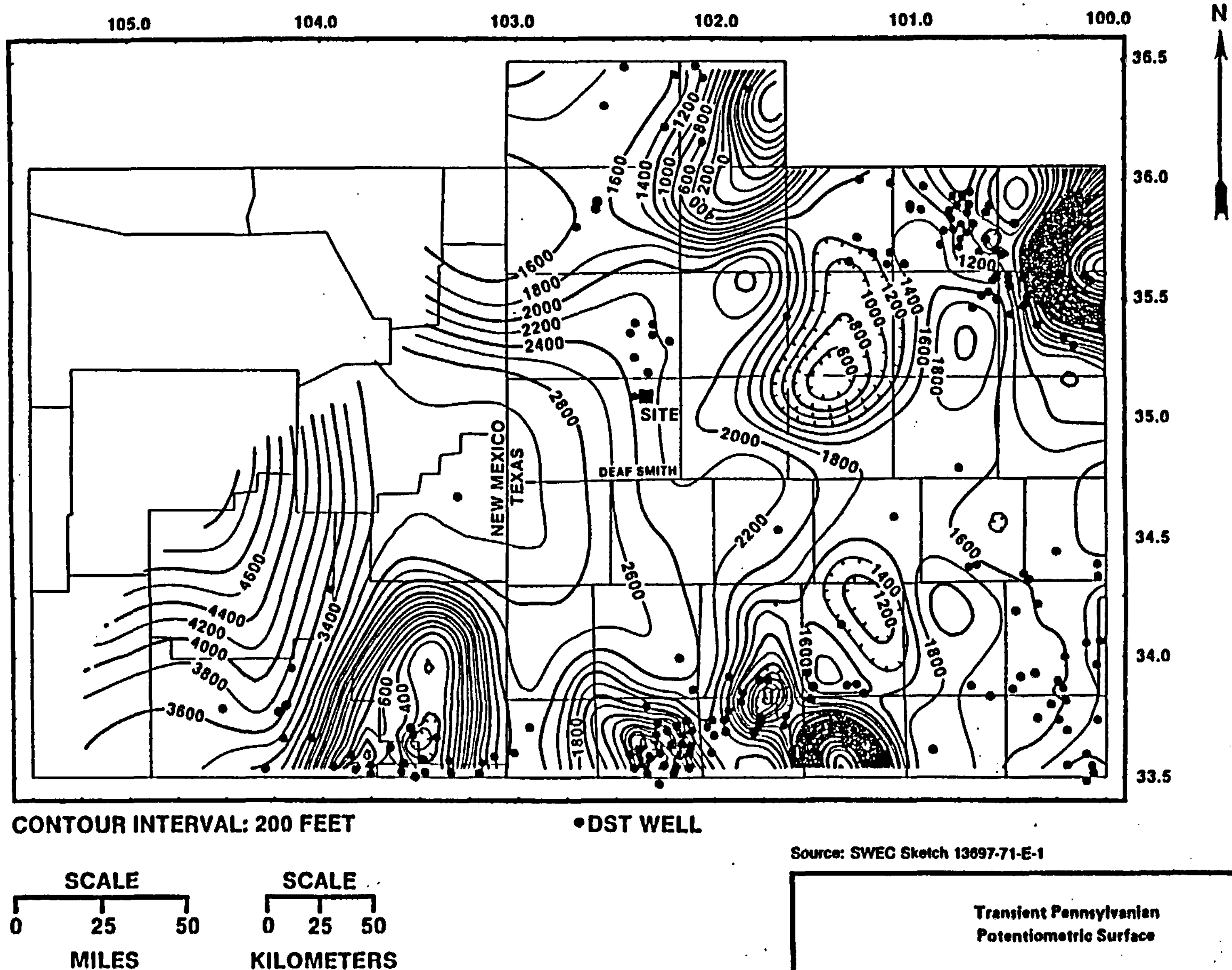
0 25 50

KILOMETERS

Source: SWEC Sketch 13697-71-D-1

Transient Wolfcamp Potentiometric Surface

Figure 3-63



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Transient Pennsylvanian Potentiometric Surface

Figure 3-64

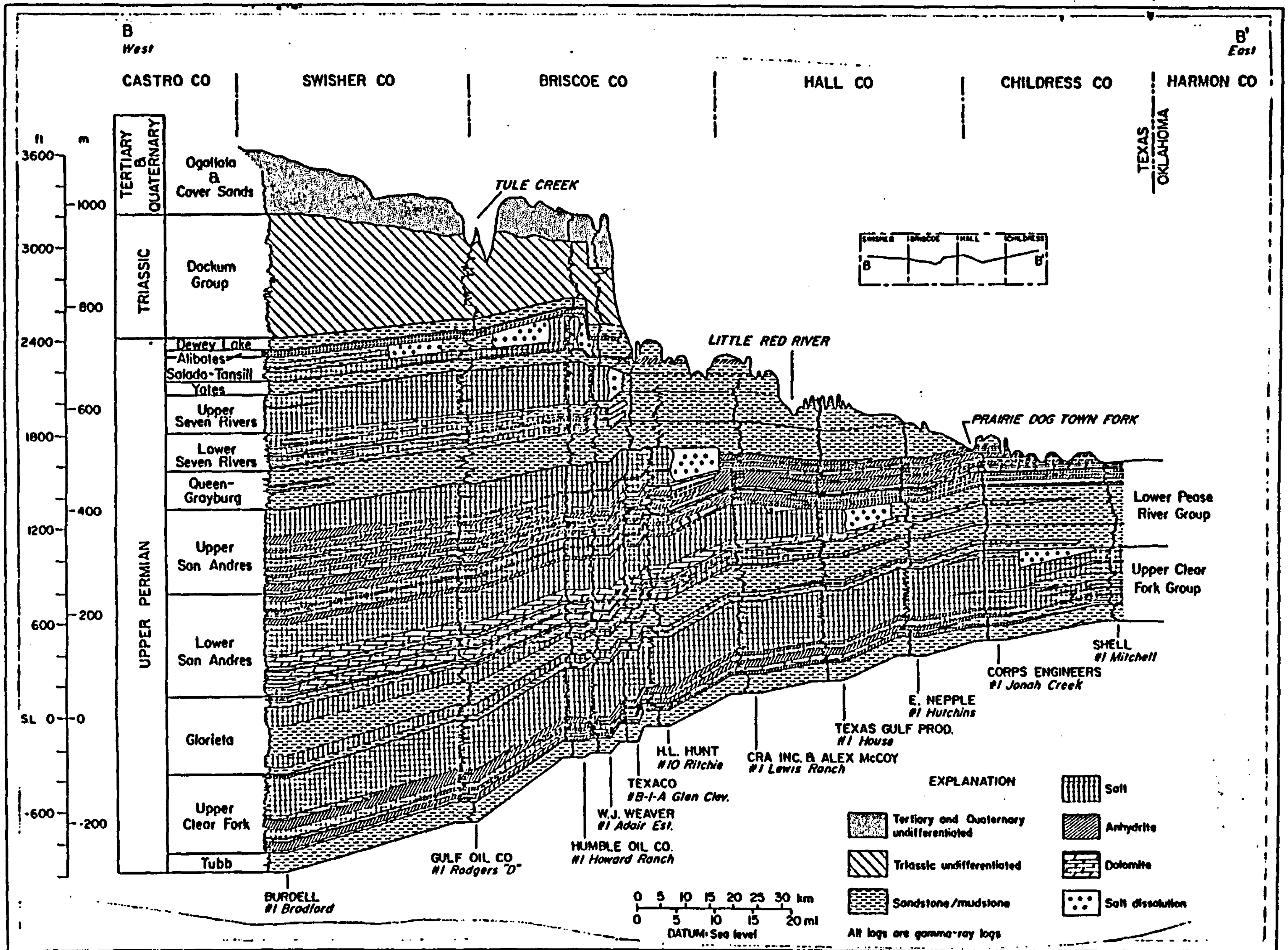

FIGURE 2. Stratigraphic cross section showing Upper Permian, Triassic, Tertiary, and Quaternary strata. Salt dissolution is illustrated between wells where some or all of the salt section is missing and where structural collapse of strata has occurred.

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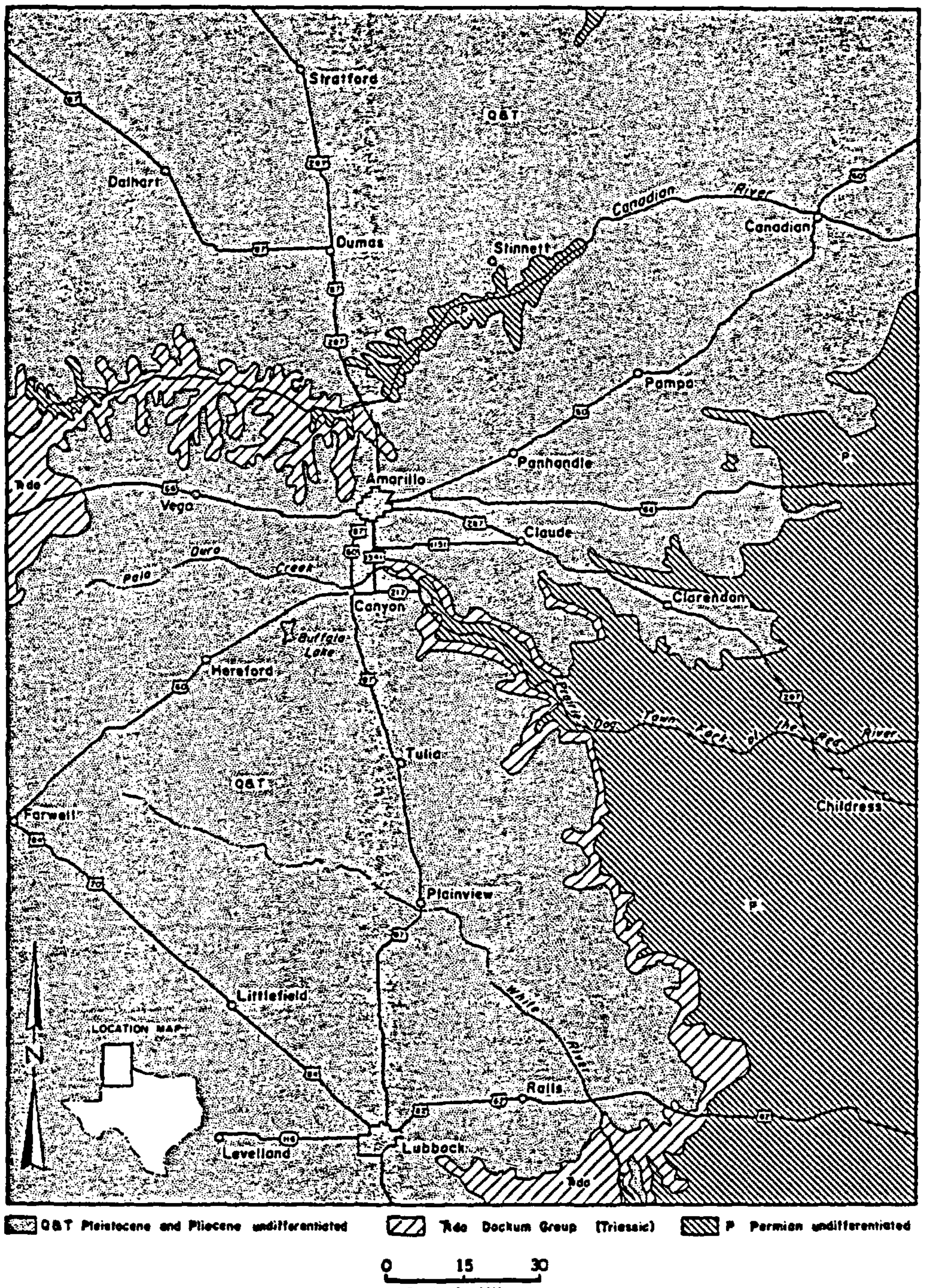

FIG. 5. Generalized geologic map of the Texas Panhandle showing location of Palo Duro Canyon.

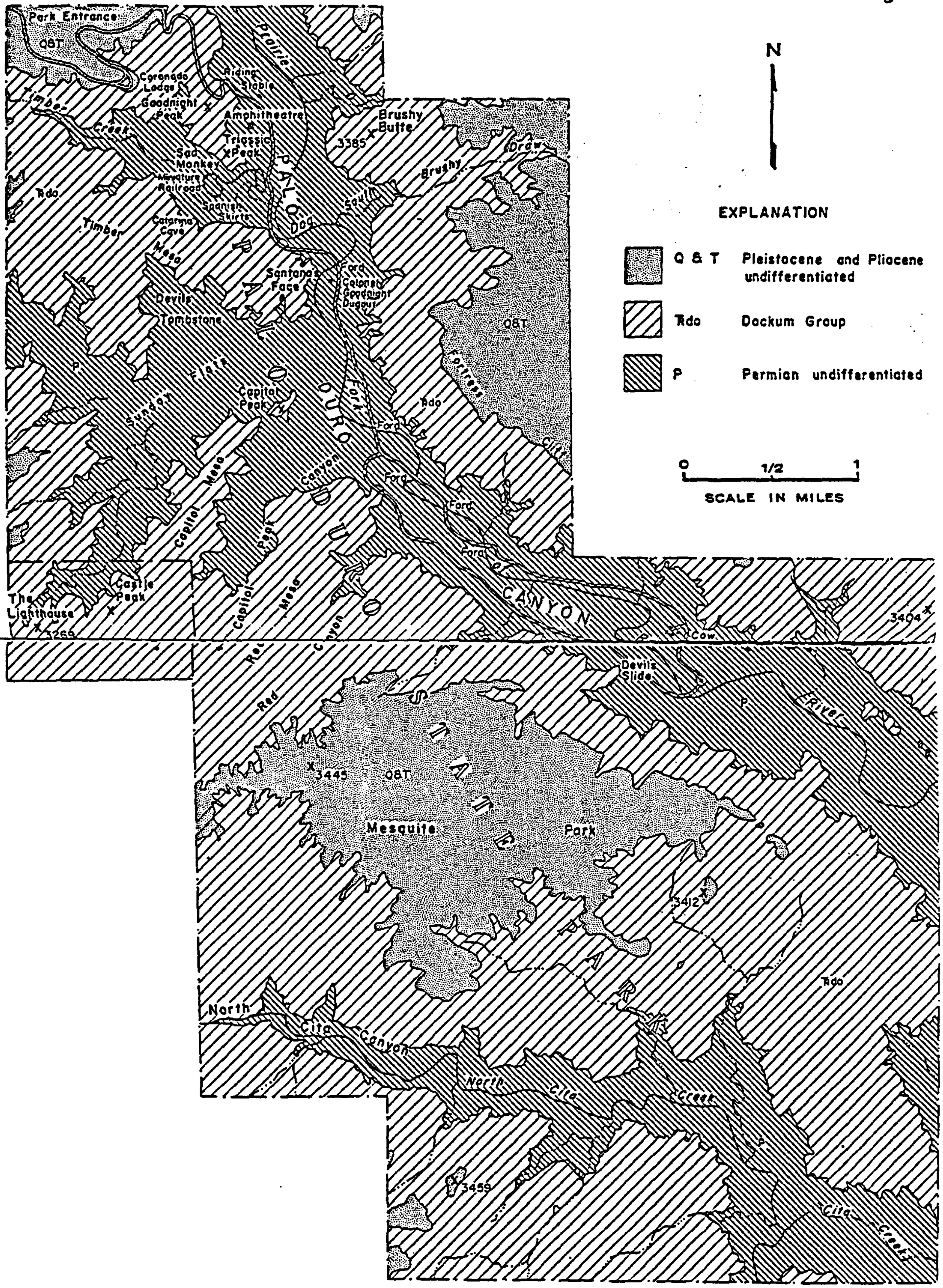

FIG. 7. Generalized geologic map of Palo Duro Canyon State Park.

simplified geologic map is presented in figure 7; this shows the distribution of the major rock types in the canyon. The reader will find it helpful to refer to this map when reading the descriptions of the various formations.

Quartermaster Formation.—The oldest formation exposed in the canyon is the Quartermaster Formation of Permian age (*see* fig. 6) which is named from exposures along the banks of Quartermaster Creek in Roger Mills County, Oklahoma. One of the more colorful formations in the park, the Quartermaster is composed primarily of brick-red to vermilion shales which are interbedded with lenses of gray shales, clays, mudstones, and sandstones. Averaging about 60 feet thick where exposed in the park, the Quartermaster forms the floor and lower walls of the canyon.

The rocks of this formation are easily examined at many places throughout the canyon and in them can be seen a number of interesting geologic phenomena. Probably the most noticeable of these features are the shining white veins of *gypsum* that lace the face of the red shale outcrops (fig. 8). A soft, transparent to translucent mineral that can be scratched by a fingernail, gypsum is hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$). Three varieties of gypsum are found in the canyon: (1) *satin spar,* a fibrous variety with a silky sheen; (2) *selenite,* a colorless, transparent variety which commonly occurs in sheet-like masses; and (3) a fine-grained massive variety called *alabaster*. Satin spar is the most common variety of gypsum present and it commonly occurs in thin bands interbedded with the mudstones and sandstones. It is much more noticeable in the shales, however, for it is typically seen in narrow veins which criss-cross the surface of the outcrop and intersect the bedding planes at various angles. Although normally white, some of the satin spar has a soft pink or bluish hue due to the presence of impurities in the mineral.

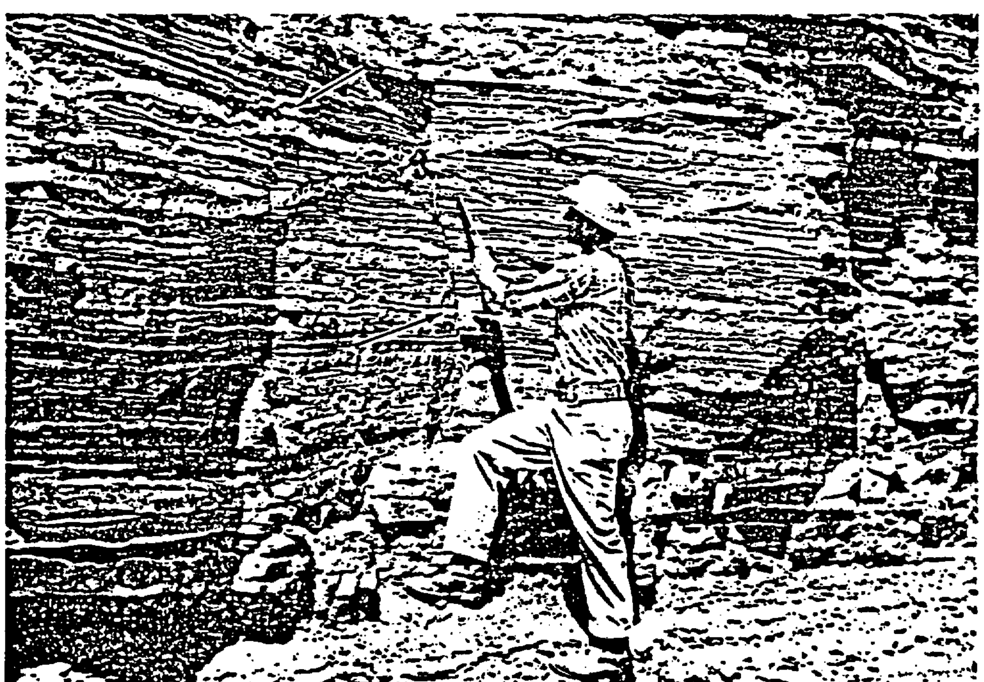

FIG. 8. Veins of selenite gypsum (top arrow) in Quartermaster Formation. Notice diagonal joint to left of geologist's hand (lower arrow).

The presence of gypsum in the Quartermaster red beds is of special significance to the geologist, for it provides valuable information about the geologic history of the Palo Duro area. It is known, for example, that when a landlocked body of sea water in an arid climate becomes separated from the ocean, one of the most common salts to precipitate is hydrous calcium sulfate, or gypsum. Gypsum may also be precipitated when a lake without an outlet evaporates in an arid climate. Geologic evidence suggests that the sediments which gave rise to the rocks of the Quartermaster Formation were deposited in a landlocked arm of the sea during the latter part of the Permian Period. As evaporation continued and the sea water was reduced to approximately one-third of its original volume, gypsum was precipitated. There must have been periodic influxes of silt- and mud-bearing waters entering the ancient Permian sea, for layers of shale and mudstone are interbedded with the gypsum.

It is believed that much of the satin spar and selenite gypsum was originally *anhydrite* ($CaSO_4$). Unlike gypsum, anhydrite does not contain water, but it can be changed to gypsum in the presence of moisture. There are two lines of evidence that indicate an anhydrite origin for the Quartermaster gypsum. First, microscopic examination of gypsum samples reveals the presence of residual anhydrite crystals embedded in the gypsum. Second, many of the gypsum beds have been squeezed into rather gentle *folds*. These consist of small *anticlines*, upfolds or arches, and *synclines*, downfolds or troughs (fig. 9). It has been suggested that this folding took place as the anhydrite underwent *hydration*, or took on water. As hydration occurred and the anhydrite was converted to gypsum, the gypsum expanded, thereby exerting both lateral and vertical pressure on the beds around it. This produced the crumpled, wave-like folding so characteristic of certain of the gypsum beds. However,

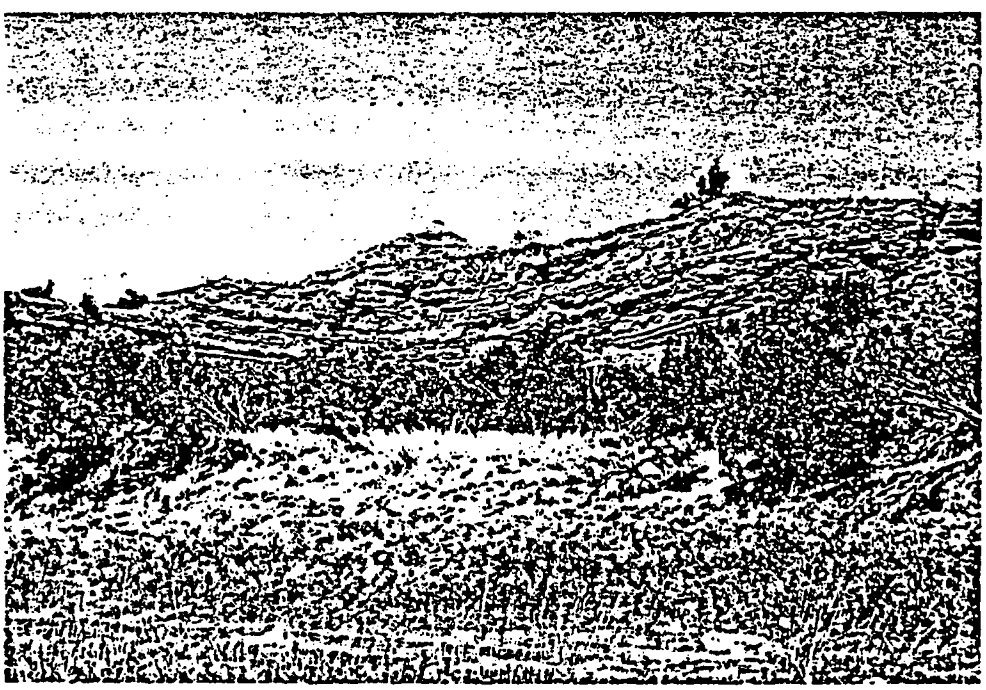

Fig. 9. Sagging beds of Quartermaster Formation have produced this gentle syncline, or downfolding, in the rocks. The "dome" on Capitol Peak can be seen in the background.

there is not complete agreement that the folding in the gypsum is due to the hydration of anhydrite. Certain geologists attribute this deformation to slumping caused by solution cavities, for gypsum is relatively easily dissolved in water. As the gypsum was dissolved and carried away in solution, the removal of the supporting layers of gypsum permitted slumping and consequent deformation in the overlying shales and mudstones. Although some geologists believe that the folds were caused by expansion due to the hydration of anhydrite and others support deformation related to the removal of soluble gypsum, there is general agreement that the folding is local and not related to regional or widespread deformation.

Not all of the red Quartermaster shales are uniformly colored. Some of them contain gray-green, circular spots called *reduction halos* (fig. 10). These spots, which in places give the red shales a distinctive polka-dot appearance, have been produced as the result of chemical change of certain minerals within the shale.

As noted earlier, sediments are usually laid down in horizontal layers. However, in certain environments, sediments may be deposited in such a way that the layers are inclined at angle to horizontal (fig. 11). This structure, called *cross-bedding* or *cross-stratification*, is found in certain sandstones and other coarse-grained or fragmental sedimentary rocks. Cross-bedding typically consists of rather distinct inclined layers separated by *bedding planes* (the surface of demarcation between two individual rock layers). Bedding of this type commonly occurs in sedimentary rocks formed in rivers, deltas, and along the margins of lakes or oceans. The cross-bedding in the Quartermaster and certain of the Triassic formations is believed to have been developed under similar conditions. Although cross-bedding is also common in certain rocks of *eolian* origin (deposited by wind) none of the cross-bedding in the canyon's rocks is due to the action of wind.

In addition, some of the Quartermaster strata have *ripple marks* on their surfaces. These features are common in certain sedimentary rocks and were formed when the surface of a bed of sediment was agitated by waves or currents. The size, shape, and cross section of the ripple marks can be used to tell whether the marks were produced by waves or currents. The ripple marks in the Quartermaster appear to have been formed by the action of waves on a shallow sea floor.

A number of interesting geologic features in the canyon have been formed in part in the Quartermaster Formation. These include the multi-hued Spanish Skirts (fig. 26), the Devil's Slide (fig. 35), Capitol Peak (fig. 32), and Catarina Cave (fig. 27). The latter is a rather unusual cave in that it has developed in a large mass of landslide debris divided by projecting bedrock of the Spanish Skirts. The cave has been formed by *suffosian*, a process whereby water enters the landslide debris on the upper slopes and follows buried channels in the landslide removing rock debris as it passes through. The flood water exits at the base of the landslide by means of Catarina Cave. The plan of the cave closely resembles the drainage patterns of surface gullies.

Tecovas Formation.—Rocks of the Triassic System (fig. 6) are well represented in Palo Duro Canyon and consist of the *Tecovas* and *Trujillo* Formations. These formations are part of the Dockum Group of Late Triassic age.

Having a total thickness of about 200 feet, the Tecovas (which is named from exposures found on Tecovas Creek in Potter County, Texas) consists largely of multicolored shales. Also present are thin layers of soft sandstone, which are disseminated throughout the shales, and a more prominent bed of white sandstone, which marks the middle of the formation. The Tecovas shales overlie the Quartermaster Formation, and the lower zone of lavender, gray, and white shales forms a relatively smooth slope that is easily distinguished from the steeper slopes of gul-

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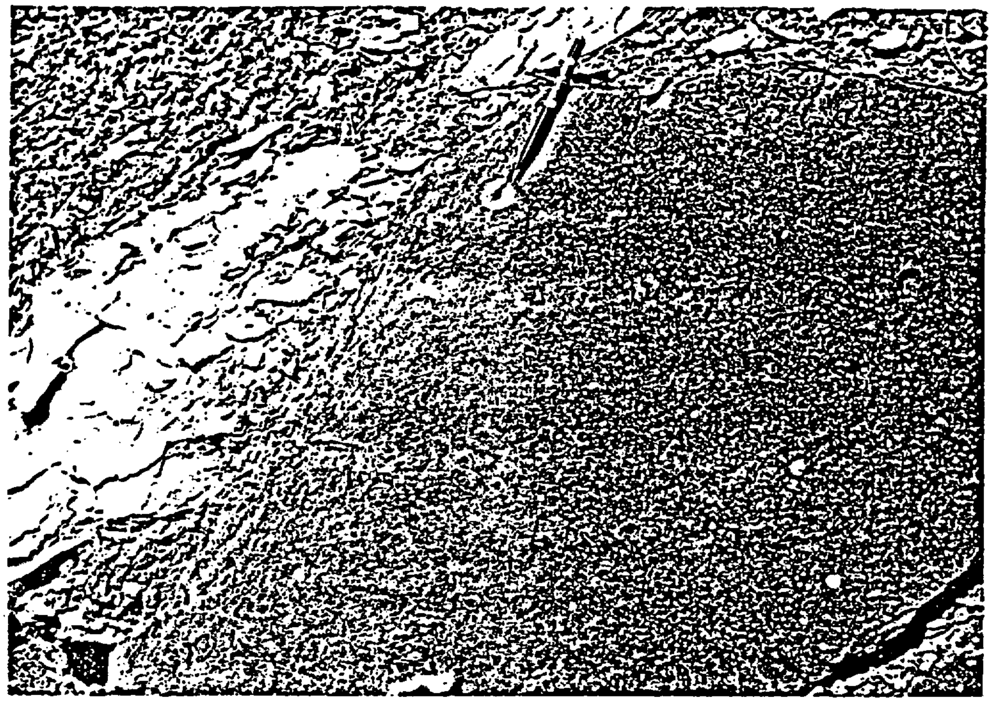

Fig. 10. Chemical reactions in certain of the red Quartermaster shales have produced reduction halos (p. 19) which give the rocks a polka-dot appearance.

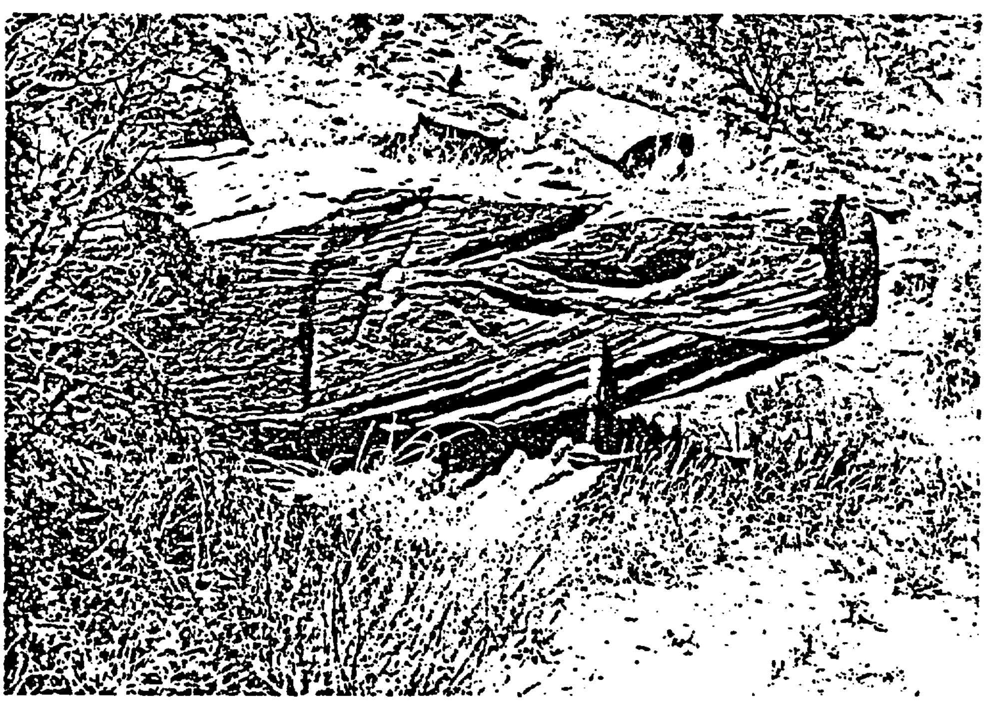

Fig. 11. This boulder, located near the foot of Triassic Peak along the Sad Monkey Railroad track, exhibits the cross-bedding typical of the Trujillo sandstones.

lied red-and-white-banded shales beneath them (fig. 12).

But the contact zone between the Tecovas and Quartermaster shales involves more than a mere change in color. Here is one of the missing "chapters" in the geologic history of the canyon, for part of the Late Permian record and all of the record of Early and Middle Triassic time are missing from the geologic column. Such gaps in the column are represented by *unconformities* in the rocks. Here the unconformity is an ancient erosional surface between the Tecovas Formation of Late Triassic age and the Late Permian Quartermaster Formation, and there are many millions of years of earth history represented in this missing "chapter" in the geologic story of Palo Duro Canyon. During this vast span of time, thousands of feet of sediments were probably deposited, converted into rock, and then later removed by erosion.

Near the middle of the Tecovas Formation there is a bed of white, crumbly (friable) sandstone. Averaging about 15 feet in thickness, this sandstone contains many *joints* (small crack-like fractures) along which no appreciable movement has taken place (fig. 8). There are two distinct sets of these joints which intersect each other at right angles. The distinctive joint patterns, the color, and the friability of this sandstone clearly differentiate it from the harder, darker, and more coarse-grained sandstones of the overlying Trujillo Formation (p. 22).

The upper part of the Tecovas consists of a layer of orange shale which overlies the middle sandstone unit and is in contact with the lower part of the Trujillo Formation.

The fossils which have been found in the Tecovas Formation suggest that these rocks were derived from sediments deposited in swamps and streams. Unlike the *marine*

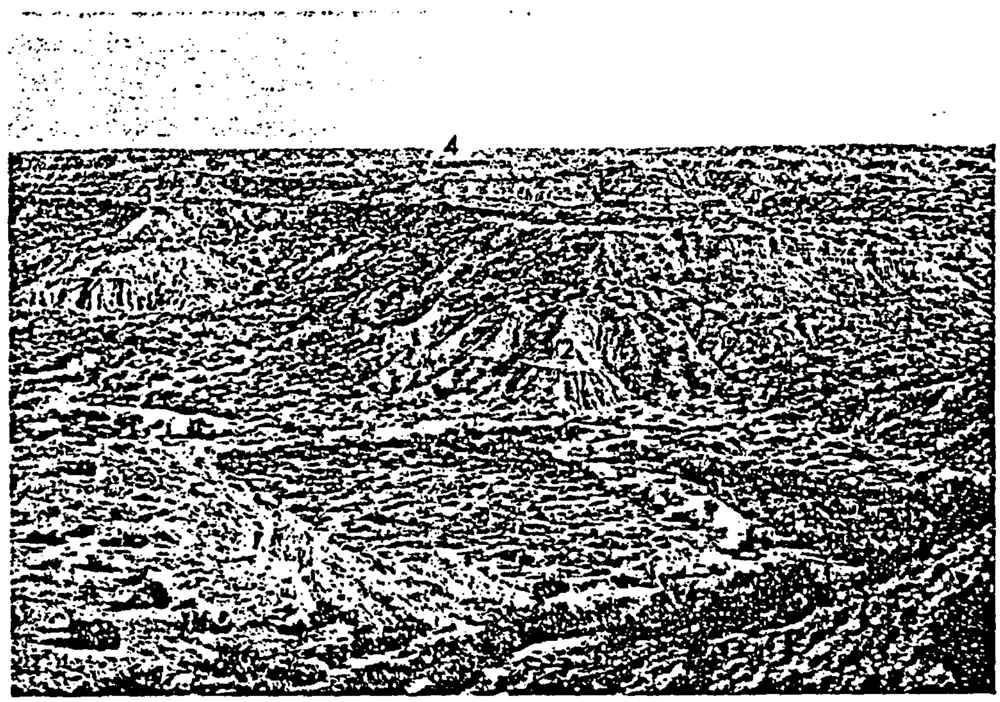

FIG. 12. Taken from the northwest rim near Coronado Lodge, this photograph shows the four major rock units exposed in the park: (1) The Quartermaster Formation which forms the lower wall and canyon floor; (2) Tecovas Formation; (3) Trujillo Formation which caps the mesas; and (4) Ogallala Formation.

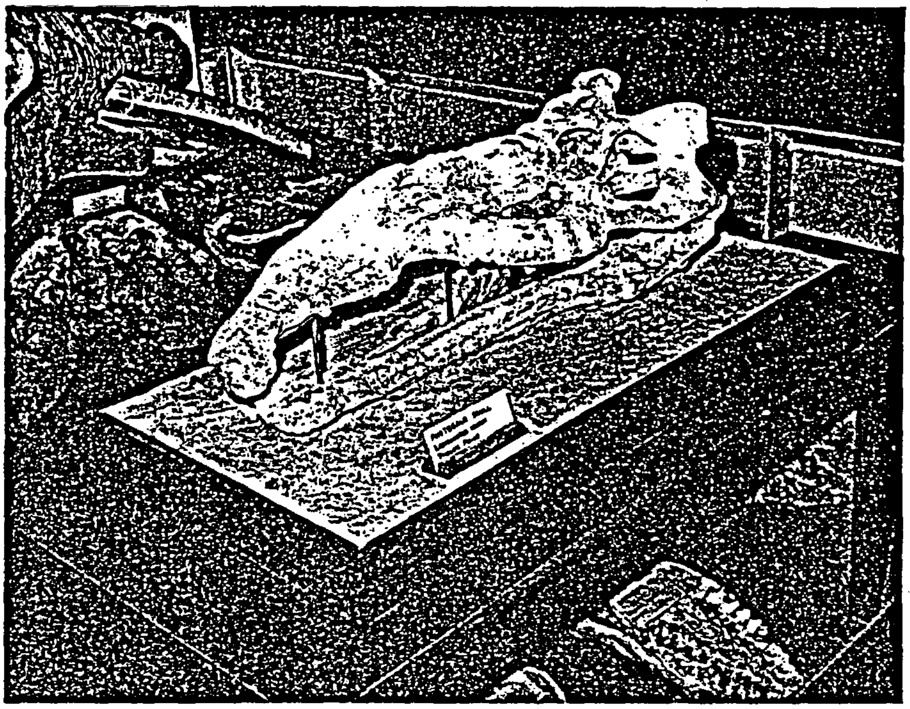

FIG. 13. The skull of this crocodile-like creature called a phytosaur is typical of the reptiles that inhabited the Palo Duro area during the Triassic Period. (Photograph courtesy Panhandle-Plains Historical Museum.)

deposits of the Quartermaster, the rocks of the Tecovas were formed from *continental* deposits laid down on the land. Fossils found in the canyon include the bones and teeth of the extinct semi-aquatic reptiles known as *phytosaurs* (fig. 13) and bone and skull fragments of a primitive amphibian called *Buettneria* (fig. 14). *Coprolites* (the fossilized excrement of animals), pieces of petrified wood, and the teeth and bones of lungfish have also been reported from the Tecovas.

A number of minerals including *hematite*, an iron mineral, and *psilomelane*, a barium-magnesium oxide, occur in the Tecovas. Hematite is an ore of iron and psilomelane a manganese ore, though neither of these is present in commercial quantities in the canyon.

The Tecovas also contains a number of *concretions* which range from a fraction of an inch to as much as 6 inches in diameter. These spherical masses are generally harder than the fine-grained shaly sands in which they are found and were thus left behind when the surrounding rock was eroded away. Some of these concretions are marked by cracks or veins filled with the mineral *calcite*. Concretions bearing this type of structure are called *septaria*, or *septarian concretions*.

Geodes are also found in the Tecovas Formation. These are rounded concretionary rocks with a hollow interior that is frequently lined with mineral crystals. Well-formed crystals of clear calcite have been found in many of the geodes from the Tecovas.

Among park landmarks that are characterized by the multi-hued Tecovas strata are the middle portion of Triassic Peak (fig. 25), the upper part of the Spanish Skirts (fig. 26), Capitol Peak (fig. 32), and the Devil's Slide (fig. 33).

Trujillo Formation.—Named from rock exposures on Trujillo Creek in Oldham

County, Texas, the Trujillo is easy to distinguish from the underlying Tecovas Formation. The contact is quite distinct and lies between the top of the orange Tecovas shale and the base of the massive-bedded, cliff-forming Trujillo sandstone (fig. 25). Although generally fine grained and thickly bedded, there are local concentrations of pebble-sized rock fragments in the Trujillo. The weathered surface of the lower sandstone is stained red or dark brown by iron oxides. However, a fresh, unweathered surface is typically gray or greenish gray in color, and careful examination of the unweathered rock reveals the presence of tiny flakes of mica.

The basal Trujillo sandstone is one of the most conspicuous rock units in the canyon and forms many of the prominent benches and mesas so typical of the Palo Duro landscape. In places the sandstone is cross-bedded (p. 20) and contains channel deposits of coarse sand which suggest that the sediments from which it was derived were deposited in ancient stream beds.

Red, maroon, and gray shales overlie the basal sandstone member of the Trujillo, and these shales are overlain by cross-bedded, coarse-grained sandstone. Another interval of varicolored shales separates the middle sandstone bed from the upper sandstone member. The middle sandstone unit is a conspicuous ledge- or cliff-forming rock and is medium to coarse grained and commonly cross-bedded. In most localities, the upper sandstone is overlain by a section of red and green shales which mark the uppermost limits of the Trujillo Formation. In places, however, this shale section has been removed by erosion and rocks of Tertiary age directly overlie the sandstone.

Although fossils are not common, the remains of *Buettneria* (fig. 13), leaf imprints, pieces of mineralized wood, and the scattered teeth and bone fragments of reptiles and amphibians have been found. Phytosaur remains, especially teeth, have also been collected from the Trujillo sandstones.

The Indians who formerly inhabited the Palo Duro area (p. 3) put the rocks of the canyon to a number of uses. This appears to be especially true of the rather coarse-grained Trujillo sandstones, which were commonly used for constructing primitive rock shelters. The abrasive surface of the sandstone was especially well suited for grinding grain, and mortar holes have been found in a number of places. One of these (fig. 15) can be seen along the tracks of the Sad Monkey Railroad (p. 35) near the foot of Triassic Peak. The Indians also used the clays of the Quartermaster, Tecovas, and Trujillo Formations to make pottery, and iron and copper minerals such as hematite and malachite were used to make red and green pigments for decoration and war paint.

The Trujillo shales and sandstones can be seen in a number of Palo Duro's more spectacular geological oddities. These erosional remnants are best developed where blocks of erosion-resistant sandstone protect underlying pedestals of softer shale (fig. 15). This type of differential weathering (p. 31) has produced a number of interesting and unusually shaped pedestal rocks or "hoodoos" (figs. 16 and 20). The most spectacular erosional remnant—and one that has come to be the "trademark" of Palo Duro Canyon—is the Lighthouse (fig. 31). The great jumble of boulders called the Rock Garden (fig. 34) is also composed largely of massive blocks of dislodged Trujillo sandstone. These boulders accumulated on the canyon floor as a result of landslides. In addition, the rock profile known as Santana's Face (fig. 28) is a naturally sculptured profile in the Trujillo sandstone that forms the cap of Timber Mesa.

Ogallala Formation.—The Ogallala Formation is named from exposures around Ogallala in Keith County, Nebraska. There is a major unconformity between the Trujillo Formation of the Triassic and the overlying Ogallala Formation of Pliocene (Late Tertiary) age. Missing here is the geologic evidence for what may have been some of the more exciting chapters in the canyon's history. There is no record, for example, of the Jurassic and Cretaceous Periods which together encompass almost

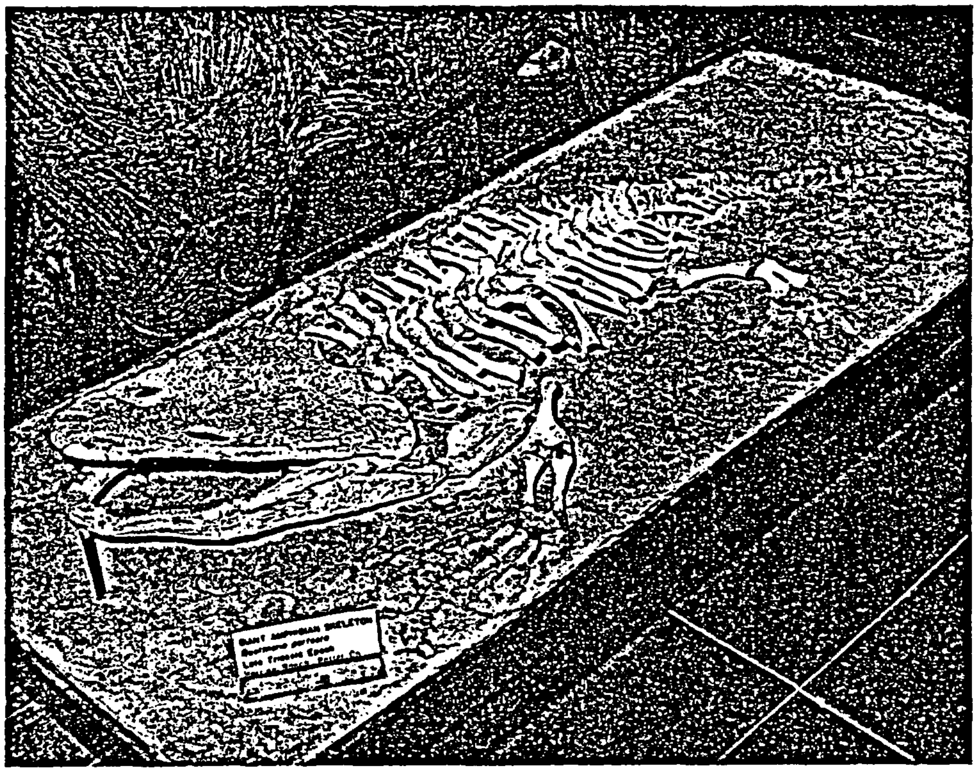

FIG. 14. The skeleton of *Buettneria*, a large amphibian, found in Upper Triassic strata in the canyon. (Photograph courtesy Panhandle-Plains Historical Museum.)

120 million years of earth history. Also missing is any evidence of what transpired during more than 90 percent of the Tertiary Period, for no rocks of Paleocene, Eocene, Oligocene, or Miocene age are exposed in the canyon. Together these four epochs comprise approximately 47 million years of earth history. It is impossible, of course, to determine how many geologic formations may have been formed and later eroded during the 167 million years represented by this unconformity. However, our knowledge of present-day deposition and erosion suggests that the missing geologic record undoubtedly represents many thousands of feet of rock.

The lower portion of the Ogallala Formation is composed of a reddish-brown, fine- to medium-grained sandstone that contrasts sharply with the underlying red and green shales that are exposed in the top of the Trujillo Formation. Much of this sandy rock is characterized by pebbles consisting of a variety of igneous, sedimentary, and metamorphic rocks. Because it consists of rock and mineral fragments of varied composition and size, this kind of sedimentary rock is called a *conglomerate*. The type of rock fragments found in basal Ogallala conglomerates suggests that they were transported to the Panhandle-Plains area by streams flowing southeastward from the Rocky Mountains. As these streams deposited their loads, they left behind a wide spread blanket of sand, gravel, and mud which formed an extensive alluvial plain that extended from western Nebraska to northwest Texas. Although it is less than 100 feet thick in Palo Duro Canyon, in places this great mantle of *fluvial* (stream-deposited) sediments is as much as 900 feet thick.

Most of the Ogallala Formation consists of a mixture of diverse rock types such as

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Fig. 15. The depression in this boulder is a mortar hole believed to have been used by the Indians for grinding corn.

Fig. 16. This pedestal rock, located near the Lighthouse, is capped by a slab of weather-resistant Trujillo sandstone.

conglomerate, sandstone, siltstone, clay and marl. But the upper part of the formation is characterized by thick *caliche* deposits. A dull, earthy calcite deposit, caliche typically forms in areas of scant rainfall. It is believed to originate when ground moisture, containing dissolved calcium bicarbonate, moves to the surface where the moisture steadily evaporates leaving a calcium carbonate crust on or near the surface (fig. 17).

Caliche, which derives its name from the Latin *calix* meaning "lime," may be firm and compact or loose and powdery. It is also commonly found mixed with other materials such as clay, sand, or gravel. Caliche commonly occurs in the Trans-Pecos, southwestern Gulf Coastal Plain, and the High Plains area of Texas (*see* fig. 5, p. 8). In the latter area it typically makes up the "caprock." Caliche is commonly quarried in these parts of Texas where it is used as road material and as an aggregate.

Good exposures of Ogallala caliche can be seen on the surface around the overlook at Coronado Lodge on the northwest rim of the canyon (fig. 17). Ogallala strata also crop out along the upper reaches of Park Road 5 as it starts to descend into the canyon. But probably the most spectacular exposures of the Ogallala are exposed in the precipitous face of the Fortress Cliff (fig. 33) which forms part of the eastern rim of the canyon.

Also located within the Ogallala Formation is a very important *aquifer*—a porous, water-bearing rock formation. This fine- to coarse-grained sandstone is very porous and permeable and is the most important single water-producing formation in the Panhandle-Plains area.

Opal and chert are locally abundant in the Ogallala conglomerates. The opal, which is found in small cavities in the conglomerate is not of the gem variety but it does *fluoresce*. Minerals that exhibit *fluorescence* emit visible colors when exposed to ultraviolet light. For this reason, the Ogallala opal is sought after by rock and

FIG. 17. The white surface in the right foreground consists of caliche (p. 26) in the Ogallala Formation. Coronado Lodge can be seen in the right background.

mineral collectors. The chert, a flint-like variety of quartz, occurs as nodules in the conglomerate and in a well-developed layer near the base of the formation. Both of these *siliceous* (silica-bearing) rocks were apparently prized by the Indians, who used them to fashion knives, scrapers, projectile points, and other artifacts. The Indians also learned that flat slabs of caliche were ideal for lining fireplaces and to construct primitive rock shelters.

A number of Pliocene vertebrates have been found in the Palo Duro area. Known as the "Age of Mammals," the Tertiary Period was characterized by mammals as diverse as were the reptiles of the Mesozoic Era. Among these unusual creatures were such now-extinct species as the saber-tooth cat and the elephant-like shovel-jawed mastodon (fig. 18). The remains of these as well as bones of giraffe-like camels, pony-sized horses, and sloths have been found in the vicinity of the canyon. The grassy plains of Pliocene time were also inhabited by large tortoises which reached lengths of up to 3 feet (fig. 19). Dioramas showing how these animals might have looked, as well as their actual remains, are on display in the Hall of Pre-History in the lower floor of the Panhandle-Plains Historical Museum in Canyon, 13 miles west of the park (p. 35).

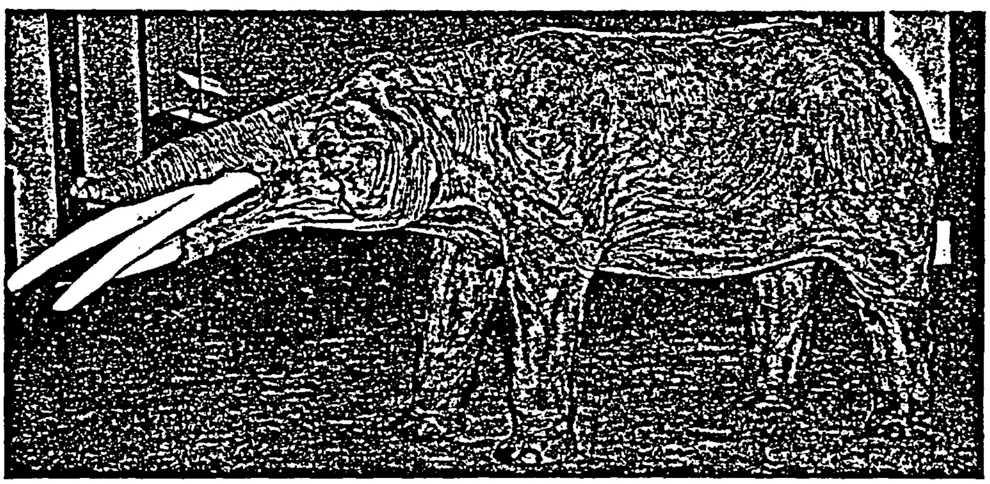

FIG. 18. This life-size model of a shovel-jawed mastodon is typical of the now-extinct, elephant-like creatures that lived in this area during the Pliocene Epoch. (Photograph courtesy Panhandle-Plains Historical Museum.)

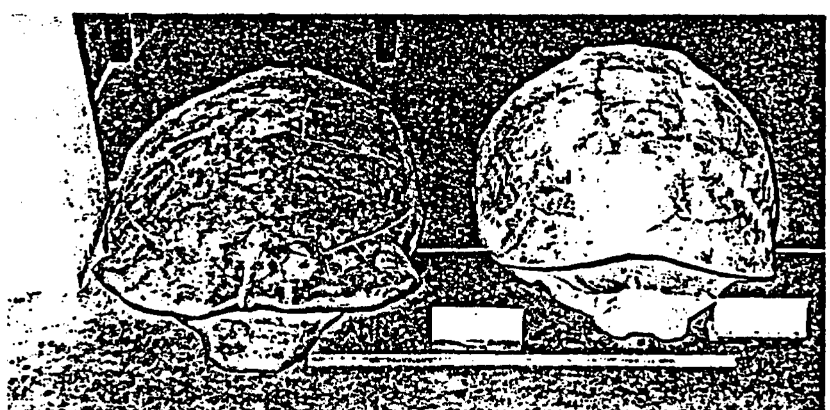

FIG. 19. The carpaces of giant tortoises as much as 3 feet long have been collected from Pliocene rocks in the Palo Duro area. (Photograph courtesy Panhandle-Plains Historical Museum.)

Rocks of the Pleistocene.—The youngest rocks in Palo Duro Canyon State Park were formed during the Pleistocene Epoch of the Quaternary Period of the Cenozoic Era (*see* geologic time scale, p. 11). Pleistocene rocks are rather widespread in much of the Panhandle-Plains area and they are mostly composed of sediments which were deposited in stream valleys, in lakes or ponds, or by the wind. Most of the Pleistocene strata in the park area consist of loose deposits of silt and sand which were deposited by wind action. Known locally as "blow sand," this reddish-brown, silty sand overlies the Ogallala caliche at most points along the canyon's rim.

WHAT TO DO AND SEE AT PALO DURO CANYON STATE PARK

The visitor to Palo Duro Canyon can choose from a number of recreational and educational activities. Moreover, regardless of whether one visits for a few hours to picnic along the banks of the river, or spends a week at one of the well-kept campgrounds, the visit will probably be both pleasant and rewarding. In the pages that follow there is a brief description of certain of the park landmarks and some of the more popular attractions within the canyon. The numbers in parentheses refer to numbers which designate these places on the map of Palo Duro Canyon (fig. 2, pp. 4–5). Hopefully, this information will help one to plan his visit to the canyon and thereby make his stay more enjoyable and worthwhile.

Park Entrance (1).—The first stop in the park is the gate at the ranger station (fig. 21). Here one pays a modest admission fee and receives literature and information about the park. The park is open every day of the year, but the entrance gates close at sundown.

Coronado Lodge and Observation Point (2).—The overlook at Coronado Lodge (fig. 22), located about half a mile from the Park Entrance, is a good place to start one's visit. Situated on a ledge of Ogallala caliche (p. 26), the Lodge is an attractive, rustic structure constructed of blocks of Trujillo sandstone (p. 22). Its picture windows and outdoor overlook provide a matchless view of the canyon and make it possible to become oriented for the descent to the canyon floor. Large, coin-operated telescopes permit close-up views of distant parts of the canyon, and there are museum cases containing objects of historical and geological interest from the Palo Duro area. If possible one should visit the Coronado Observation Point more than once during the visit, preferably at different times of the day. Because of shifting clouds and changing lighting conditions, the canyon presents a continually changing panorama from sunrise to sunset. Open year-round, the Lodge offers a complete line of souvenirs, film, and camping supplies. There is also a snack bar where coffee, sandwiches, and cold drinks can be purchased.

The Scenic Drive (1–16).—After viewing the canyon from Coronado Lodge, one should take the scenic drive on Park Road 5. This paved, all-weather road descends the northwest rim of the canyon and continues on to the turnaround at Cow Camp, a distance of about 8 miles. Although the present scenic drive was completed in 1951, the path that it follows is essentially that which was laid out by Colonel Charles Goodnight when he established Palo Duro ranch in 1876. The road descends to the canyon floor in a series of well-engineered turns, but because it drops some 800 feet in little more than a mile it is wise to use second or low gear on the descent. One should also observe the posted speed limits (10 to 20 miles per hour) and keep to the right side of the road at all times.

In the 800-foot drop from rim to floor, the complete geologic section of the canyon is traversed, as one passes from the Pleistocene sands through the Ogallala, Trujillo, and Tecovas Formations, before reaching the Quartermaster Formation which is exposed in the canyon floor. Each of these geologic formations is discussed elsewhere in this publication (pp. 16–28).

Pioneer Amphitheatre (3).—Upon reaching the canyon floor, Park Road 5 flattens out and from this point it is but a short distance to the Pioneer Amphitheatre, one of the canyon's newest and most popular attractions. Here, located at the foot of a colorful 600-foot cliff, is a remarkable 1500-seat outdoor theatre of latest design (fig. 23). Each evening during a ten-week summer season, a symphonic drama portraying the history of the Texas Panhandle is presented in the amphitheatre. Information about these produc-

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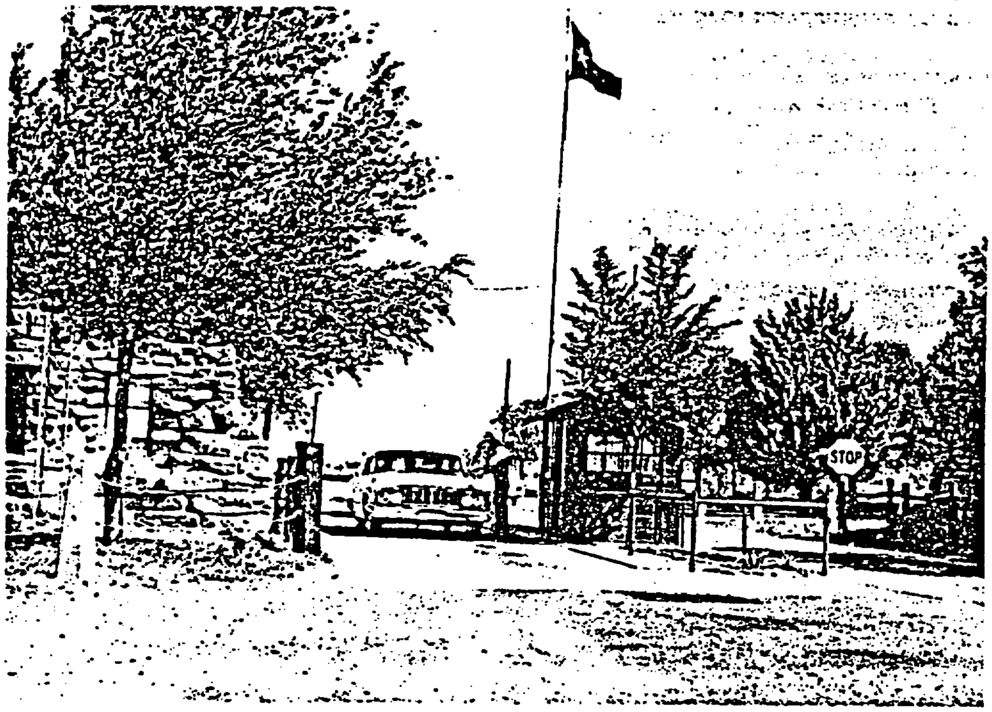

FIG. 21. The entrance gate to Palo Duro Canyon State Park.

FIG. 22. Coronado Lodge on the canyon's northwest rim affords panoramic views of the canyon.

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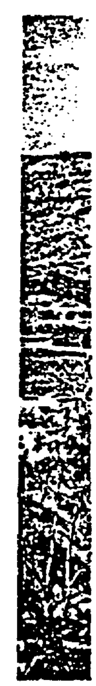

FIG. 2
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tions can be obtained at the Park Entrance, Coronado Lodge, and other points within the park.

Sad Monkey Train Ride (4).—The Sad Monkey Railroad begins—and ends—at Sad Monkey, Texas, a small "community" that lies at the foot of Triassic Peak (fig. 24). Unlike most miniature railroads, the Sad Monkey Special is not a "kiddie" ride. Instead, this 2-mile journey provides an opportunity to get away from the road for a closer look at the geologic formations exposed along the track. There are especially good views of the Spanish Skirts (fig. 26), Catarina Cave (fig. 27), and Triassic Peak (fig. 25). These, and other features of geologic interest, are pointed out by an experienced lecturer who also presents a brief review of the geologic history of the area.

Triassic Peak (5).—Long used by Indians and ranchers as a Palo Duro landmark, the canyon visitor will find Triassic Peak to be equally useful as a geologic landmark. When viewed from the Sad Monkey Railroad Terminal, the south face of Triassic Peak clearly reveals three of the four major geologic formations of the canyon (fig. 25).

The lower one-third of the peak consists of deeply furrowed, red and white banded shales of the Quartermaster Formation (p. 17). Overlying the Permian red beds are the brightly colored, multi-hued Tecovas shales of Triassic age (p. 19). The composition of the Tecovas is such that the lower shales tend to weather into relatively gentle slopes with rather smooth surfaces. Triassic Peak is capped by a weather-resistant layer of Trujillo sandstone, and this durable cliff-forming sandstone has served as a protective covering to impede the erosion of the softer rocks of the Tecovas and Quartermaster Formations. Although it has withstood the ravages of time exceedingly well, the large blocks of Trujillo sandstone which litter the flanks and foot of Triassic Peak clearly indicate

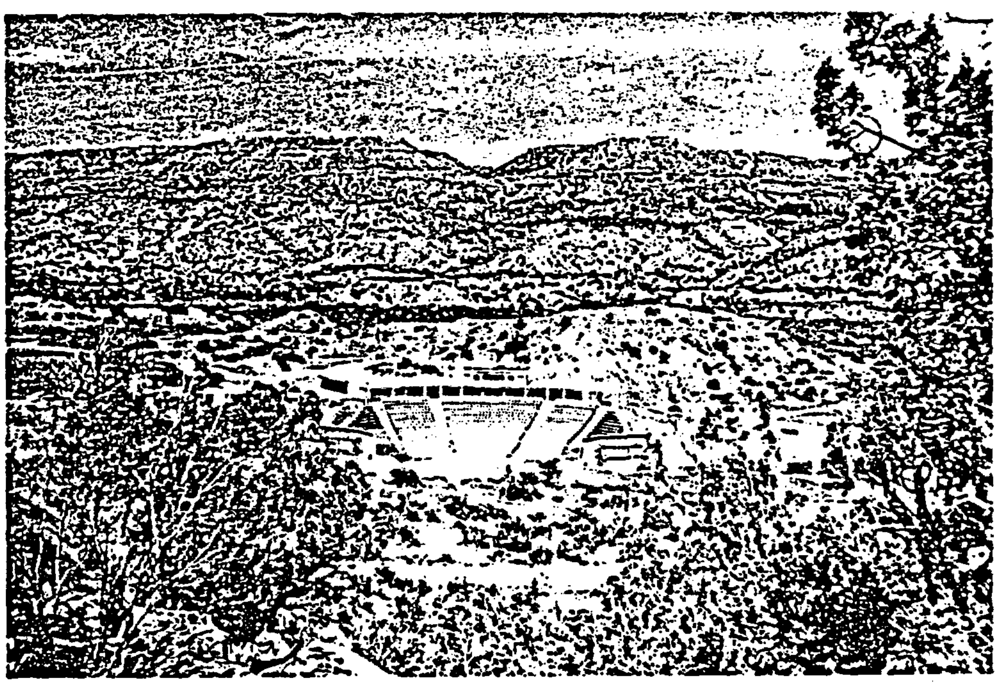

FIG. 23. Located on the canyon floor, Pioneer Amphitheatre is a modern outdoor theatre where symphonic dramas are presented each summer. (Courtesy Mrs. Ples Harper, Texas Panhandle Heritage Foundation, Inc.; photograph by Ron Horn.)

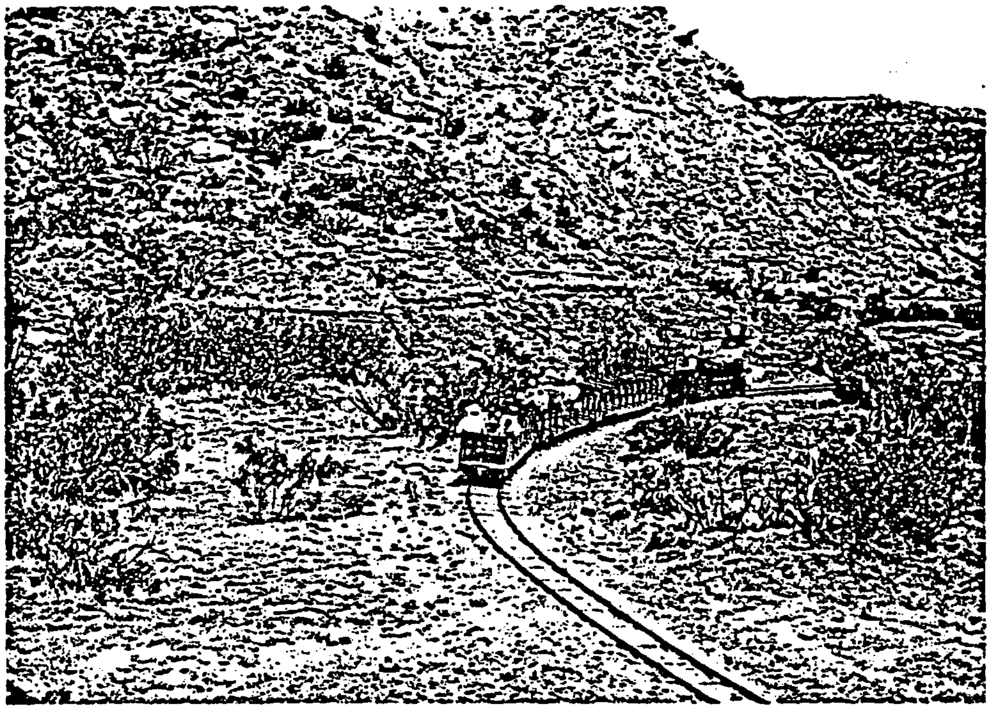

Fig. 24. A trip on the Sad Monkey Railroad is a good place to learn more about the canyon's geology and get a closer look at the rocks.

Fig. 25. Excellent exposures of the Quartermaster Formation of Permian age (1) and the Triassic Tecovas (2) and Trujillo (3) Formations can be seen in the south face of Triassic Peak. The feature known as the Sad Monkey is indicated by the arrow.

that weathering and mass-wasting have exacted their toll in the geologic past.

Sad Monkey, Texas derives its name from the prominent mass of Trujillo sandstone at the southern extremity of Triassic Peak. When viewed in the proper perspective—and with the proper amount of imagination—this massive block of sandstone bears a striking resemblance to an aged and saddened monkey.

Spanish Skirts (6).—Few of the canyon's features are as well-named as the gaudy Spanish Skirts (fig. 26). The lower part of this multi-colored bluff consists of alternating layers of red and white Quartermaster shale, capped by the colorful maroon and lavender Tecovas shales. Located on the north flank of Timber Mesa, the Spanish Skirts and nearby Catarina Cave can be reached by an easy half-mile path. The trail begins on the west side of Park Road 5, just beyond the Timber Creek bridge located several hundred feet from the Sad Monkey Station.

Catarina Cave (7).—A short distance west of the Spanish Skirts lies Catarina Cave. This depression has been washed out of the relatively soluble Permian shales (fig. 27).

Santana's Face (8).—Like Triassic Peak, Timber Mesa is capped by a thick layer of massively bedded Trujillo sandstone. On the eastern tip of the mesa the sandstone has been eroded in such a fashion that it resembles the profile of an Indian (fig. 28). This feature, called Santana's Face, is best seen from the park road shortly after leaving Sad Monkey Station.

The Sky Ride (9).—The Sky Ride, located near the first water crossing on Park Road 5, transports visitors from the canyon floor to the top of Timber Mesa (fig. 28). The 300-foot ascent is made in ski-lift

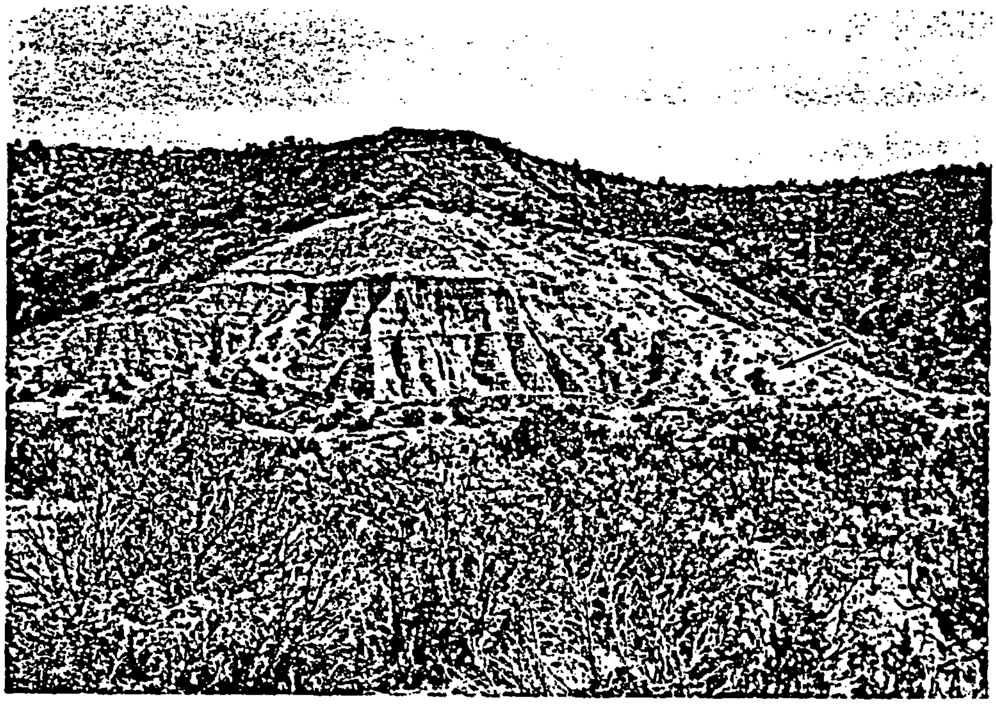

Fig. 26. The gaudy Spanish Skirts are a colorful expanse of Quartermaster and Tecovas strata exposed on the north flank of Timber Mesa. Note the contrast in weathering in the lower, gullied Quartermaster Formation and the smooth slopes of the Tecovas shales above it. Catarina Cave (arrow) is at the right.

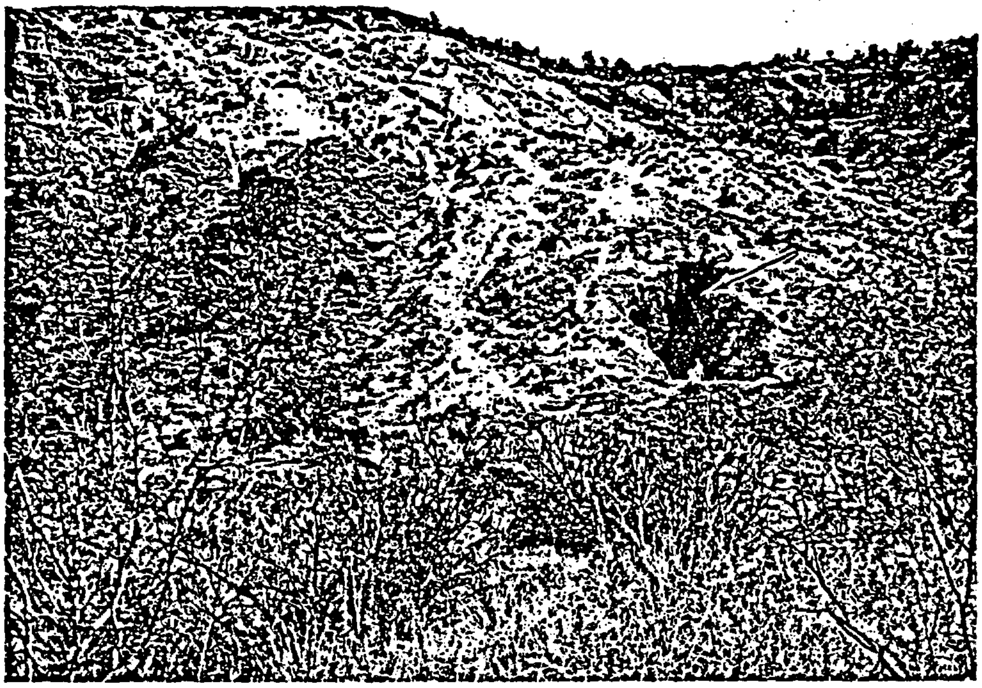

Fig. 27. Catarina Cave (arrow) is easily reached by a half-mile trail from Park Road 5.

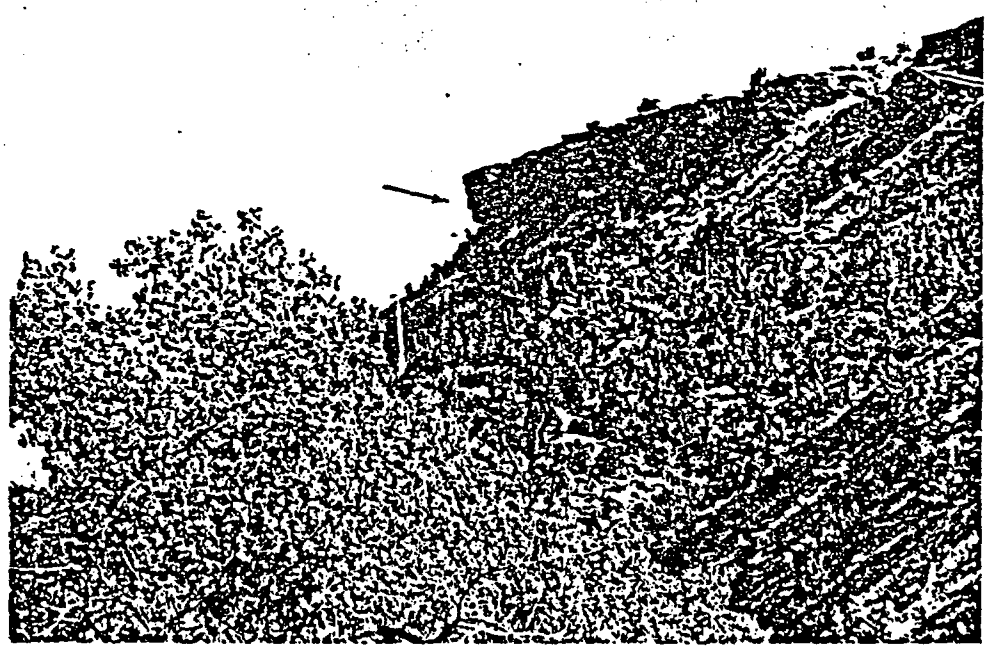

Fig. 28. Santana's Face (left arrow) has been sculptured from the Trujillo sandstone cap of Timber Mesa. The cable for the Sky Ride (p. 37) passes through the notch indicated by arrow at right.

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Fig.
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chairs that are comfortable and safe. The observation area atop the mesa offers an unusually fine view of most parts of the canyon.

The First Water Crossing (10).—As it winds through the canyon, the park road crosses the Prairie Dog Town Fork of the Red River seven times in a distance of about 4 miles. These fords, or water crossings as they are called locally, are paved and are normally safe to pass through. They should, however, be avoided during times of heavy rains and flash flooding. Because of stream erosion, especially fine exposures of the Quartermaster Formation are revealed in the stream banks near several of the crossings.

The first of these crossings (fig. 29) is about 1 mile from the Sad Monkey Station and is one of the more popular picnic areas in the park. This area was also popular with earlier residents of the park, for it is believed to have been the campgrounds of both the Kiowa and Comanche Indians.

Colonel Charles Goodnight's Dugout (11).—As mentioned earlier (p. 6) Colonel Charles Goodnight entered the canyon in 1876 with more than 16,000 head of cattle. Although he later established more comfortable quarters, Col. Goodnight first lived in a primitive dugout similar to the one shown in figure 30. A replica of this early shelter has been constructed of mud, stone, and logs and can be seen on the west side of the park road just beyond the first water crossing (*see* fig. 29).

The Lighthouse (12).—The unpaved road to the Lighthouse enters Park Road 5 about two-tenths of a mile beyond the first water crossing. Although considered by many to be the canyon's best-known landmark, the Lighthouse is actually not within park boundaries. It is located in Little Sunday Canyon about 3 miles west of the road and is not easily accessible to the average visitor. Like many of the park's natural attractions, the Lighthouse is an erosional remnant of colorful Trujillo

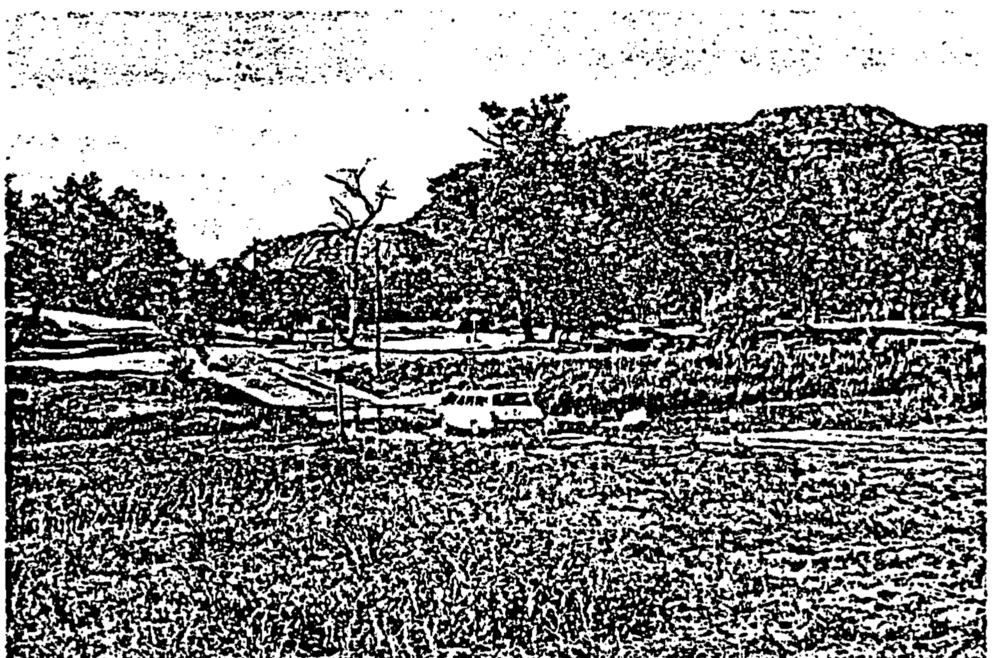

FIG. 29. Now a popular picnic spot, the wooded arear near the first water crossing through the Prairie Dog Town Fork of the Red River was a favorite Indian campground.

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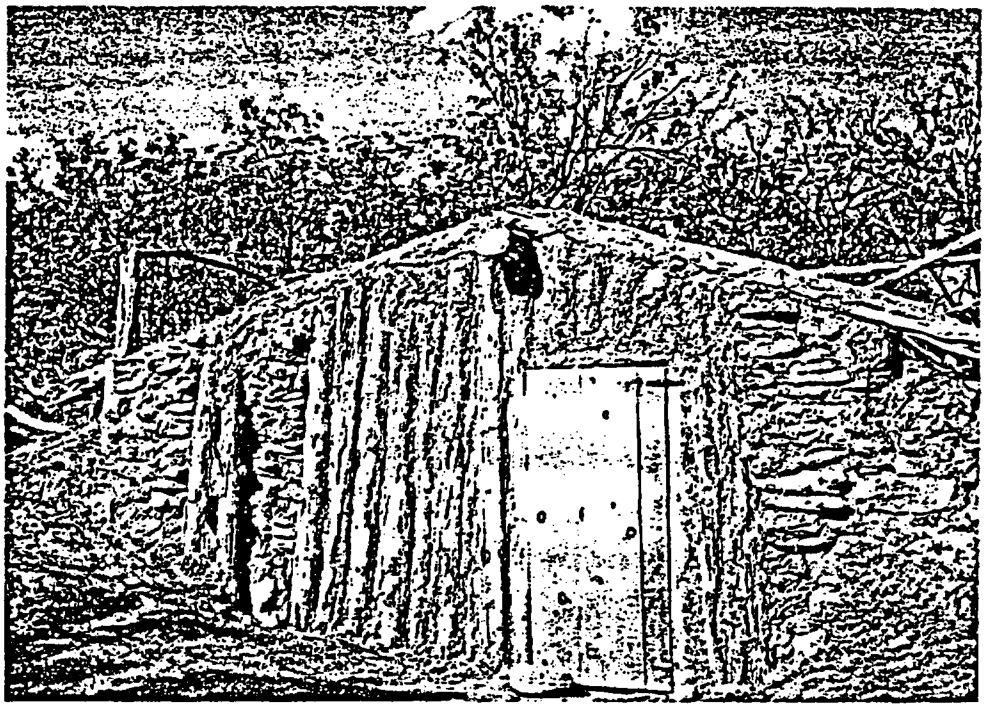

FIG. 30. When Colonel Charles Goodnight settled in the canyon in 1876 he lived in a primitive dugout similar to the one shown here.

shales and sandstones (fig. 31). A similar pedestal rock, the Devil's Tombstone, can be reached by means of a trail which leaves the Lighthouse road and enters Sunday Canyon.

Capitol Peak (13).—Capitol Peak (figs. 20 and 32) is a rather imposing geologic feature that can be seen from a number of points along Park Road 5. There are especially good views in the vicinity of the second water crossing if one will look to the west of the road. Just beyond the crossing an unimproved road leads to the foot of Capitol Peak. The lower part of this feature is composed of Quartermaster shales of Permian age and the upper section consists largely of Triassic Tecovas shales. When viewed from the proper angle, the silhouette of Capitol Peak is thought to resemble the prostrate form of a human (fig. 32). For this reason it has also been called the Sleeping Indian.

Fortress Cliff (14).—The Ogallala Formation of Pliocene age (p. 23) forms the upper rim of the canyon and is well exposed in impressive Fortress Cliff (fig. 33). Although this precipitous cliff dominates the eastern rim of the canyon along most of the scenic drive, especially good views are afforded between the second and third water crossings.

The Rock Garden (15).—Shortly after fording the river at the fifth water crossing, there is a jumbled pile of boulders on the west side of the road (fig. 34). This accumulation of Trujillo sandstone blocks has been named the Rock Garden. Many boulders such as these have accumulated on the floor of the canyon in ages past. However, most of these have been destroyed by weathering and their fragments removed by the canyon's streams.

The Devil's Slide (16).—The Devil's Slide can be reached by an unimproved road that leads southwest from the scenic drive for a distance of about half a mile. Composed of upper Quartermaster and lower Tecovas shales, the surface of this

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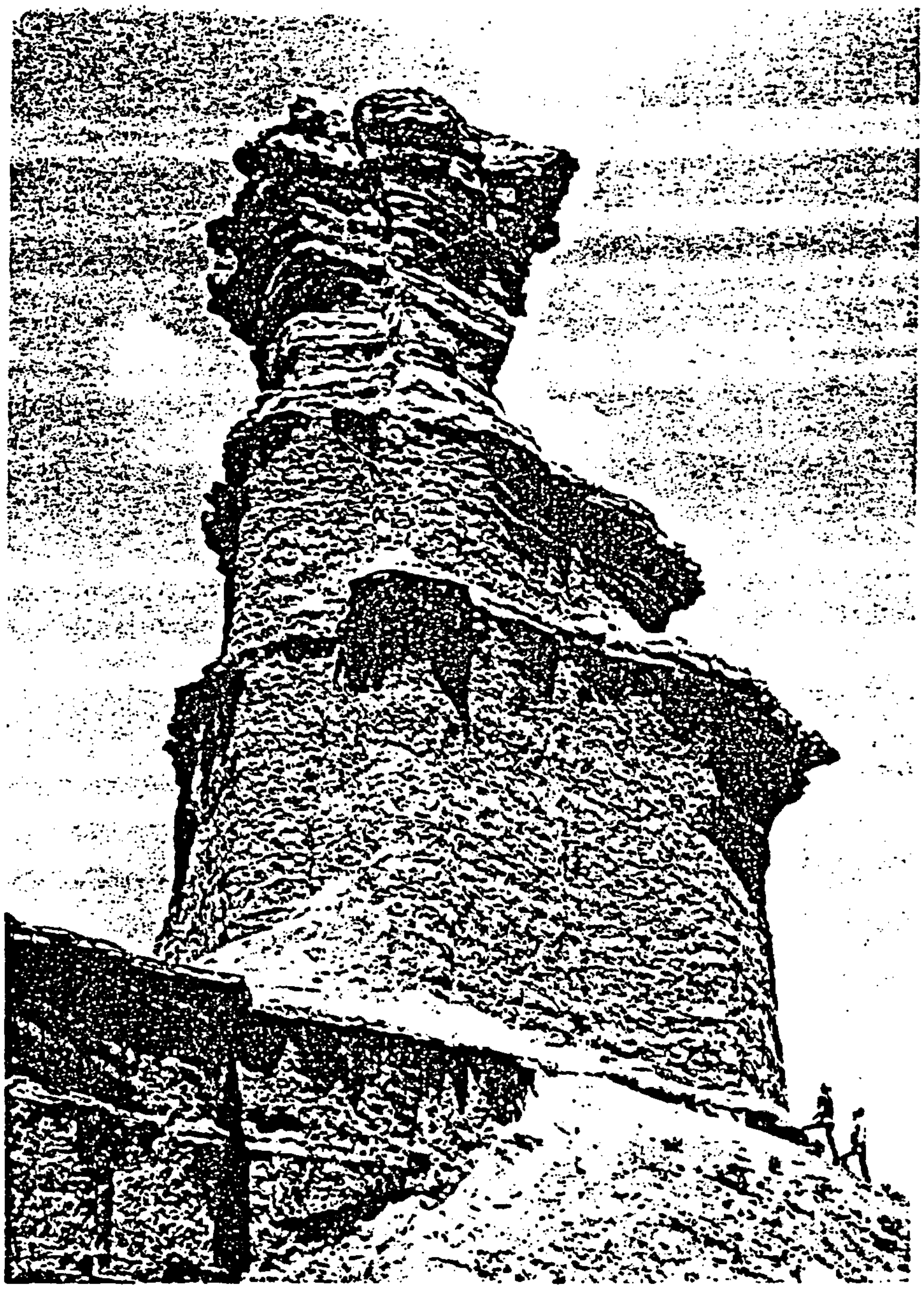

FIG. 31. The Lighthouse, an erosional remnant and the "trademark" of Palo Duro Canyon, exhibits well the geologic phenomenon of differential erosion (p. 31).

eroded spur is laced with many trails and "slides" that have been made by previous visitors (fig. 35).

The Turnaround (17).—A loop marks the end of Park Road 5 and the conclusion of the scenic drive. Located in this area are a number of fine camping areas, picnic grounds, the old stone cottages called the "Cow Cabins," and rest rooms with shower facilities (fig. 36).

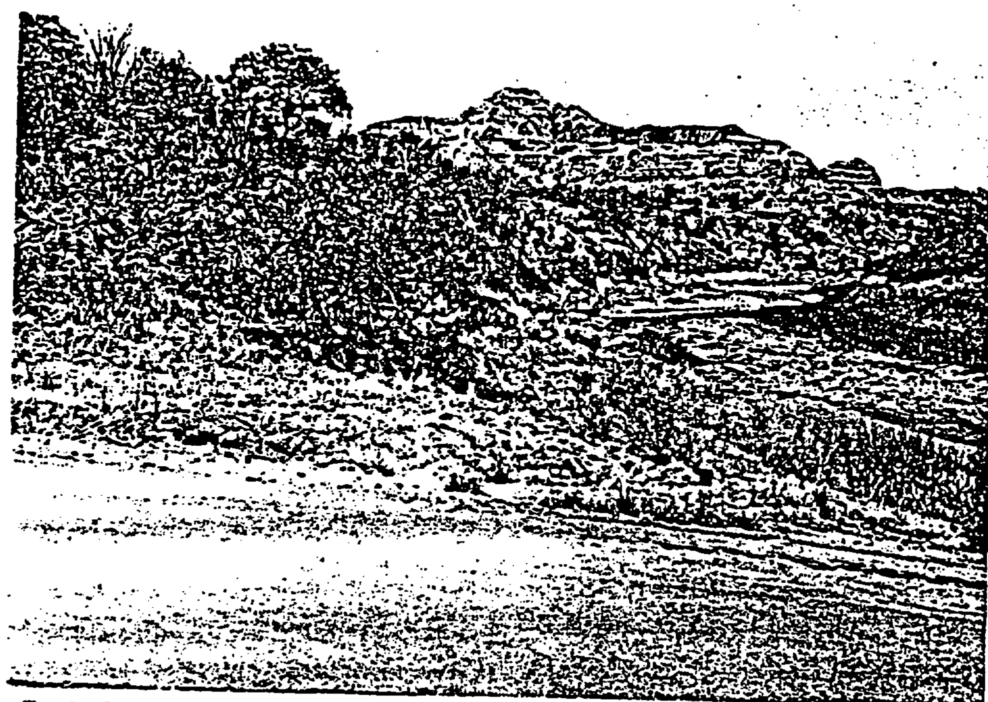

FIG. 32. The "dome" on Capitol Peak is a well-known canyon landmark. Composed of the Tecovas and Quartermaster Formations, the profile of Capitol Peak is referred to as the Sleeping Indian. (The "Indian's" head can be seen in the right background.)

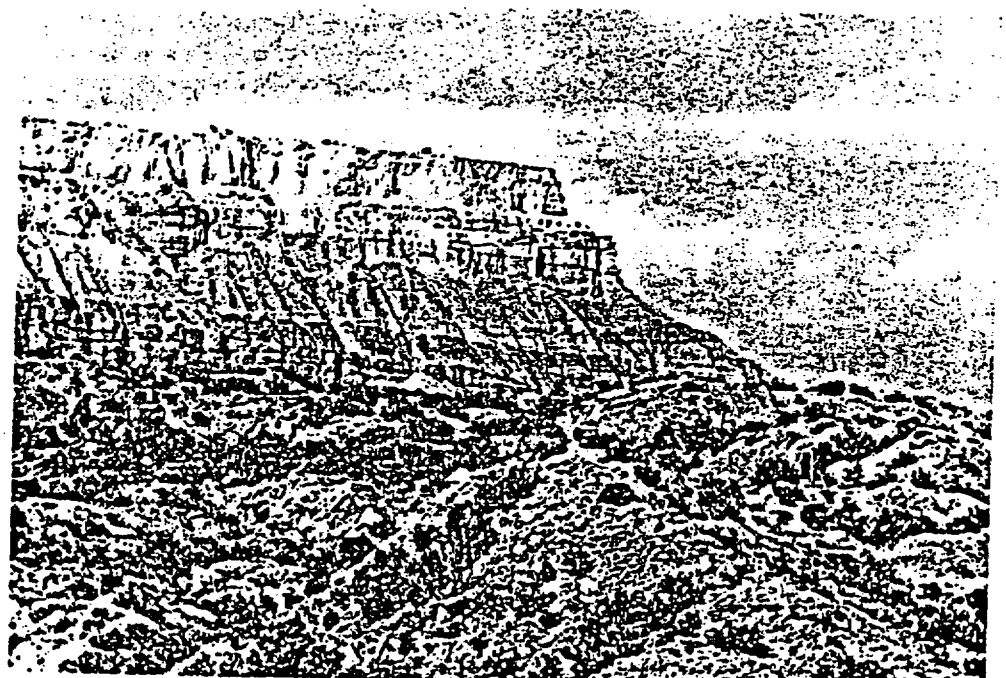

FIG. 33. Fortress Cliff is a prominent feature on the eastern rim of the canyon. Seen here are the precipitous cliffs developed in the Ogallala caliche (p. 26) and the sandstones and shales of the Trujillo Formation.

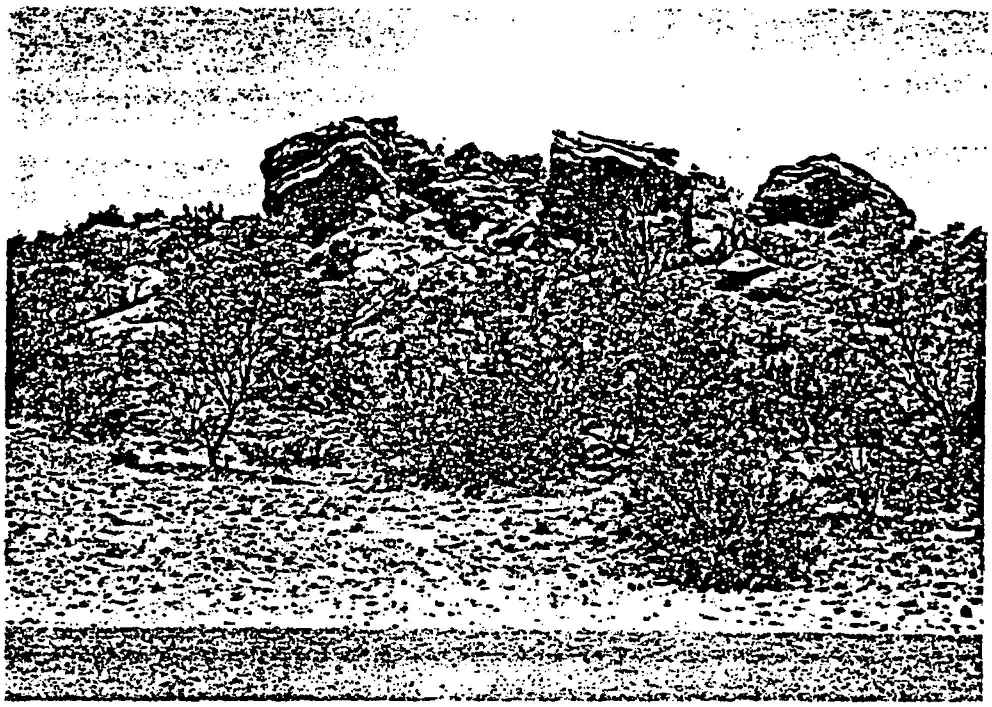

FIG. 34. The Rock Garden is a jumbled mass of Trujillo sandstone boulders that mark the site of an ancient landslide.

Hiking.—There are a number of established trails for the visitor who is interested in hiking. The more popular trails include those to the Spanish Skirts and Catarina Cave (p. 37), the Devil's Tombstone, the Lighthouse (p. 39), and the Devil's Slide (p. 40). Park rangers will be glad to provide more complete information about these and other trails within the canyon.

Horseback riding.—Saddle horses can be rented at the stables located east of the road near the Pioneer Amphitheatre. There are a number of trail rides that can be taken on well-trained horses accustomed to the rugged terrain of the canyon. Additional information may be obtained from the attendants at the stable.

Camping and picnicking.—An ample number of well-developed camping and picnic areas are scattered throughout the canyon. Most are located adjacent to or a short distance from Park Road 5; they are equipped with outdoor fireplaces and tables. Running water, rest rooms, and showers are provided in certain areas. Campsites are available on a first-come first-served basis, and there is a 10-day limit on overnight camping. Detailed information on camping regulations and camping areas is available from a park ranger or at the Entrance Station.

Photography.—Palo Duro Canyon offers many opportunities for both amateur and professional photography. The multi-colored rock formations, erosional land-forms, and plants and animals offer limitless possibilities to the creative and imaginative photographer. Color shots are especially effective, but a haze filter will be helpful when photographing distant objects. Morning and afternoon are the best times for picture taking as the mid-day sun is "flat" and lends little perspective to the canyon scene.

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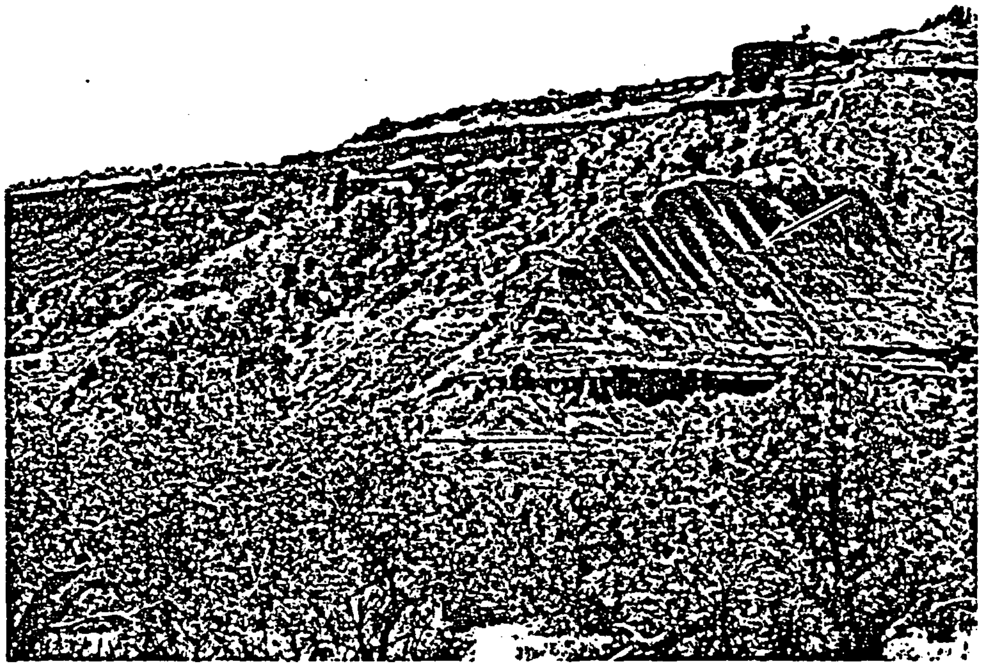

FIG. 35. The Devil's Slide in the south end of the park is an eroded spur of Tecovas shales. Some of the "slides" made by visitors are indicated by the arrow.

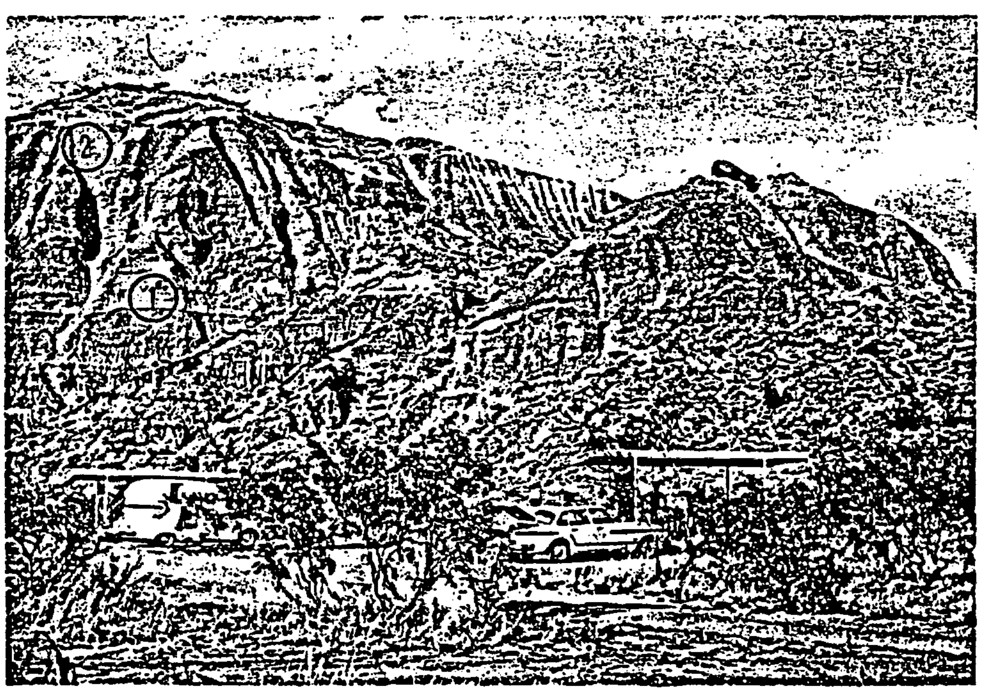

FIG. 36. Outcrops of the Quartermaster (1) and Tecovas (2) Formations provide a geological backdrop for this campsite near the turnaround at the end of Park Road 5.

INTRODUCTION

This field guide summarizes recent interpretations of geomorphic processes and Quaternary stratigraphy in parts of the Rolling Plains and Southern High Plains of the Texas Panhandle. Field Stops, primarily in Hall and Briscoe Counties, were selected as examples of geologic phenomena that are widespread in the Texas Panhandle (*fig.* 1). Particular attention is paid to the dissolution of evaporites, primarily salt, and collapse of overlying strata as processes that have significantly affected landscape development and Quaternary stratigraphy in this area (Stops 1 through 4, 6, 7, 11, 14, and 16). The stratigraphy, depositional environments, paleontology, archeology, and paleoclimatic history of a newly recognized, unnamed Quaternary formation are presented (Stops 10 through 15). The deposition and incision of unpaired terraces along the Little Red River are described, as are recent hillslope erosion rates and certain effects of eolian processes (Stops 5, 8, and 9). Archeological resources of the Lake Mackenzie area (Stop 17) and vertebrate remains from the Tule Formation (Stop 18) are also described.

Keywords: salt dissolution, collapse features, structure, Quaternary stratigraphy, radiocarbon dates, erosion rates, eolian processes, vertebrate biostratigraphy, archeology

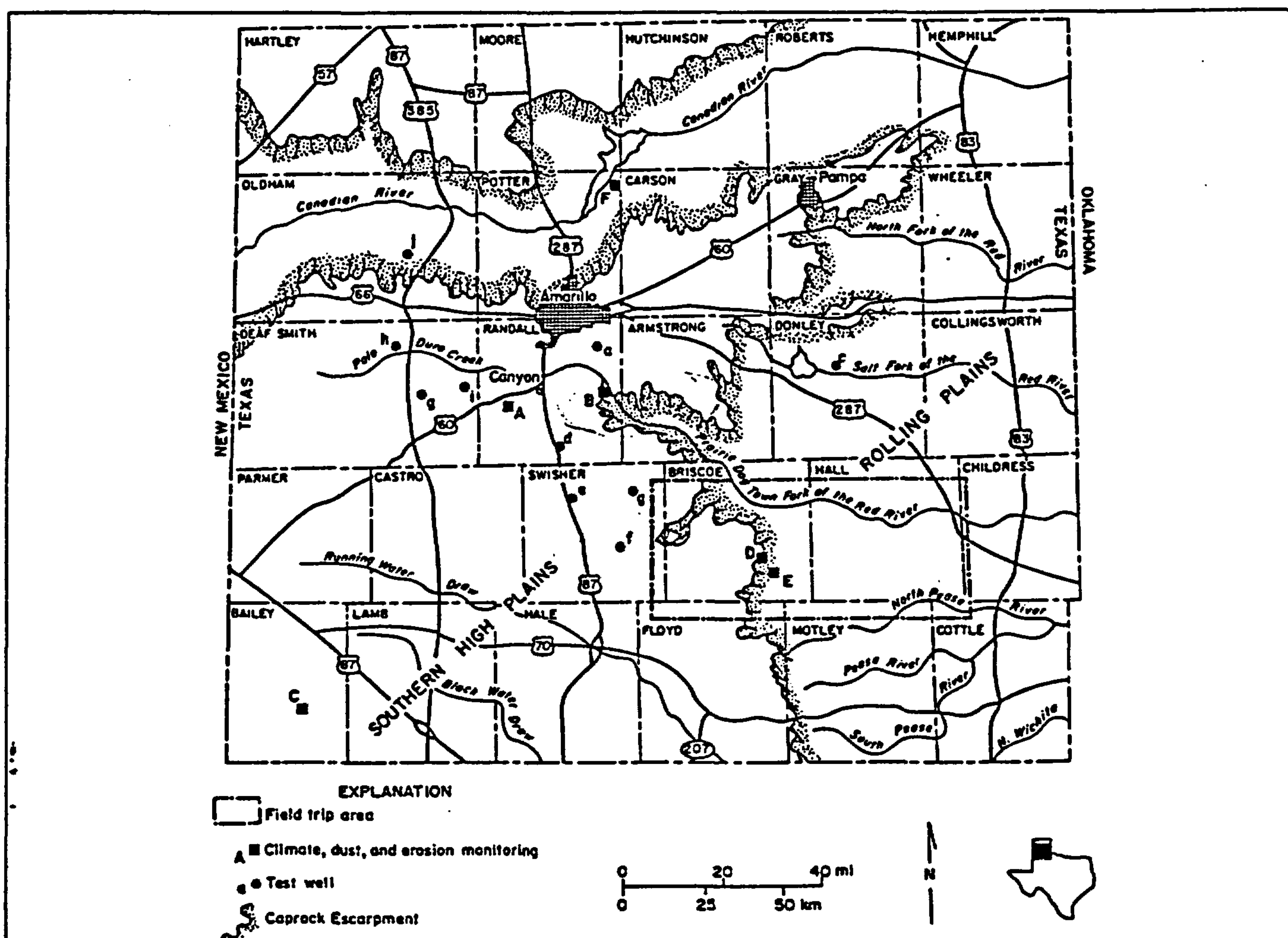

FIGURE 1. Map showing the area covered by the field trip in Briscoe and Hall Counties. Climate-monitoring stations and Department of Energy stratigraphic and hydrologic test wells are indicated by symbols. Test wells are (a) DOE/Gruy Federal Rex White No. 1; (b) DOE/Gruy Federal Grabbe No. 1; (c) Stone and Webster Engineering Corp. (SWEC) Sawyer No. 1, (d) SWEC Holtzclaw No. 1; (e) SWEC Harman No. 1; (f) SWEC Grabbe No. 1; (g) SWEC Detten No. 1; (h) SWEC J. Friemel No. 1; (i) SWEC G. Friemel No. 1; and (j) SWEC Mansfield No. 1. Monitoring stations are at (A) Buffalo Lake National Wildlife Refuge; (B) Palo Duro Canyon State Park; (C) Muleshoe National Wildlife Refuge; (D) and (E) Caprock Canyons State Park; and (F) Lake Meredith National Recreation Area.

REGIONAL GEOLOGIC SETTING

In late Paleozoic time, rocks of the Wichita igneous province and the Red River mobile terrane were faulted and uplifted to form the Wichita Mountains - Amarillo Uplift trend and the Matador and Cimarron Arches (Birsa, 1977). These are the major positive tectonic elements bounding the Palo Duro, Dalhart, and Anadarko Basins within the Texas Panhandle. Tectonic movement along the Amarillo Uplift, Matador Arch, and Cimarron Arch during the Pennsylvanian and Early Permian controlled sedimentation and facies distribution within the basins (Dutton and others, 1979). Continued minor movement may have occurred throughout the basins in Tertiary time and possibly as late as Quaternary time (Budnik, 1983).

Substantial parts of the Texas and Oklahoma Panhandles and central-eastern New Mexico have undergone nontectonic vertical displacements of as much as 180 m (600 ft), owing to dissolution of bedded Permian salts within approximately 400 m (1,300 ft) of the surface (Gustavson, 1979; Gustavson and others, 1980a, b) (fig. 2). Regional dissolution and resulting subsidence have occurred since the Late Cretaceous. Collapse owing to salt dissolution is probably active today along the western, northern, and eastern escarpments of the Southern High Plains (Simpkins and others, 1981; Gustavson and others, 1982).

During Mississippian time, marine carbonates were deposited across the Panhandle. Deposition of terrigenous clastic sediments, informally called granite wash, was prevalent during the Pennsylvanian and Early Permian. Granite wash was derived from and deposited near the principal uplifts (Handford and Dutton, 1980). Sedimentation during the Late Pennsylvanian and Early Permian was dominated by shelf carbonates, the deeper parts of the basin being filled by fine-grained clastic sediments. Salt, anhydrite, dolomite, limestone, and red beds compose Upper Permian strata in the Palo Duro and surrounding basins (Presley, 1979a, 1979b; 1980a, 1980b) (fig. 2). These rock types were deposited in a range of subtidal to supratidal environments.

The Triassic Dockum Group consists of fluvial, deltaic, and lacustrine facies that accumulated in a large fluvial-lacustrine basin south of the Amarillo Uplift (McGowen and others, 1979). Dockum Group strata are overlain unconformably by the Upper Jurassic Exeter Sandstone in certain areas and by Lower Cretaceous strata, including the Kiamichi Formation, Dakota Group sandstones and conglomerates, and Kiowa Shale, in other areas. After a period of extensive erosion, the Miocene-Pliocene Ogallala Formation was deposited in northwestern Texas, western Oklahoma, and eastern New Mexico. Lower Ogallala sediments are primarily fluvial deposits and, to a lesser extent, lacustrine sediments deposited in a wet-alluvial-fan environment (Seni, 1980). Upper Ogallala strata are in large part eolian. The upper contact of the Ogallala Formation is extensively calichified, forming the Caprock caliche.

The Quaternary Blackwater Draw Formation forms an eolian mantle beneath most of the Southern High Plains. Pleistocene lacustrine deposits, including the Tule Formation (Stops 16 and 18), are interbedded with eolian sediments of the Blackwater Draw Formation (Gustavson and Holliday, 1985).

QUATERNARY STRATIGRAPHY OF THE WESTERN ROLLING PLAINS

Previous Work

Several investigators have described the Pleistocene geology of the area east of the High Plains, including Gould (1906), Frye and others (1948), Frye and Leonard (1957, 1963), Van Siclen (1957), and Dalquest (1964a, b). Van Siclen (1957) investigated Quaternary deposits on the Rolling Plains south of Garza County. These strata may be genetically similar and time-equivalent in part to those in the present study area, but relations between the Quaternary sequences in the two areas have not yet been established.

Gould (1906), Frye and Leonard (1957, 1963), and Dalquest (1964a) were the first to discuss the Quaternary strata in the westernmost Rolling Plains, describing the paleofaunas but interpreting the deposits as fluvial terraces. These authors recognized neither the enormous, nearly continuous extent of the deposits nor their complex origin. The age of the sequence was also in question. Frye and others (1948, p. 522) reported that the Pleistocene Meade Formation in central and southwestern Kansas "fill[s] deep valleys cut below the Ogallala surface or fill[s] solution-subsidence or downfaulted areas." Subsidence features are common in the western Rolling Plains of Texas (Gustavson and others, 1982); active and formerly active (filled) examples can be seen at Stops 1, 2, 3, 11, and 14, where subsidence has localized and even accelerated deposition. The resulting sedimentary sequences are much younger than the Kansan-age Meade Formation, although deposits roughly

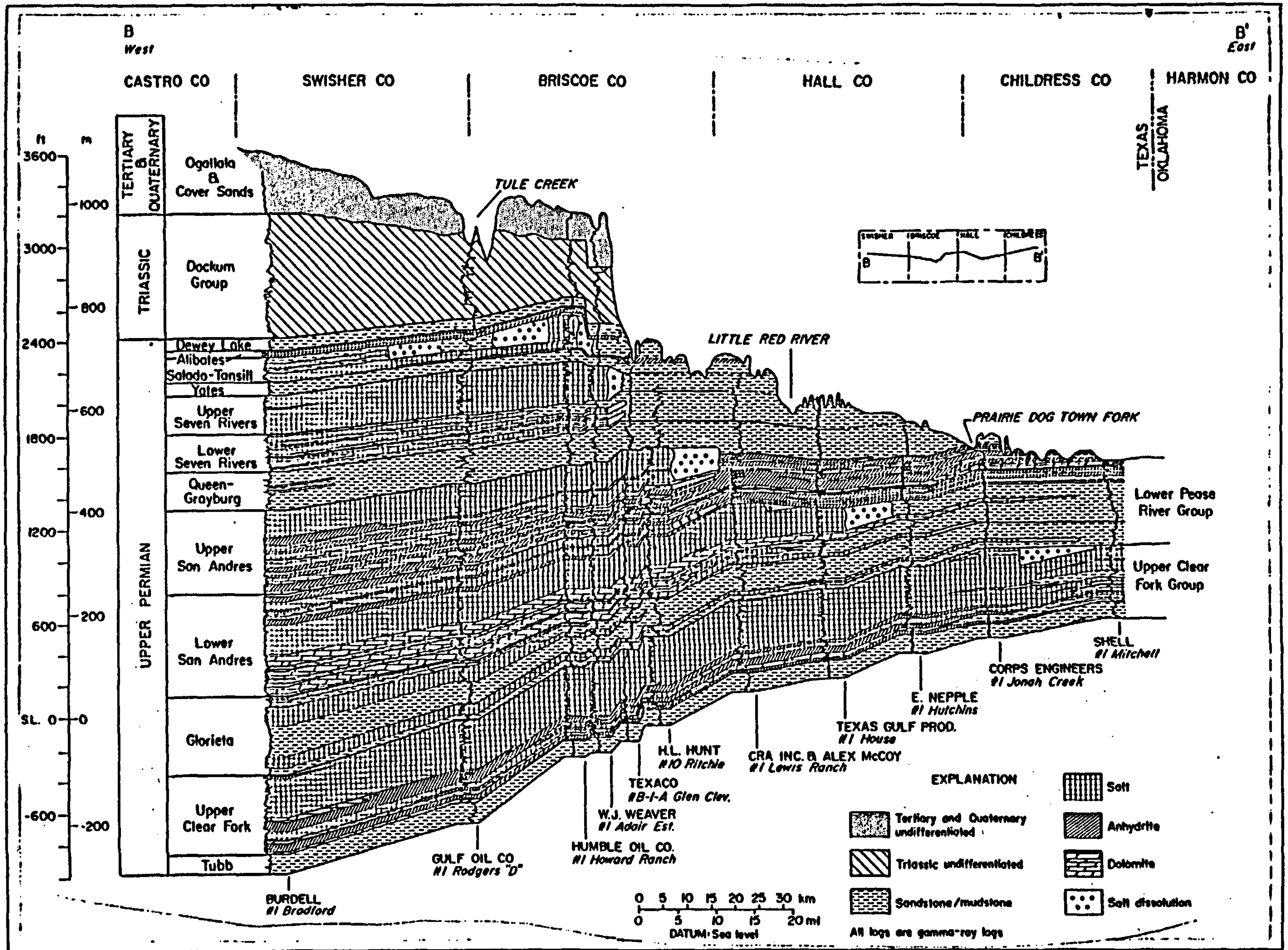

FIGURE 2. Stratigraphic cross section showing Upper Permian, Triassic, Tertiary, and Quaternary strata. Salt dissolution is illustrated between wells where some or all of the salt section is missing and where structural collapse of strata has occurred.

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equivalent to the Meade have been found farther east. Dalquest (1964b) described the paleofauna of a Pleistocene terrace in northwestern Childress County, east of Hall County, and on the basis of the presence of mammoth remains and the absence of *Bison* material, he concluded that the deposit was Kansan or Yarmouthian in age. Geomorphic evidence demonstrates clearly that although this high-terrace remnant is considerably older than the strata exposed farther west (Stops 10 through 15), its origin may be similar. Caran and Baumgardner (appendix, this volume) summarized and evaluated more than 50 radiocarbon dates from deposits in the study area. These dates indicate that the alluvial sequence probably is diachronous but no older than Wisconsinan and Holocene.

Current Work

Previously unrecognized Quaternary alluvial deposits extend eastward as much as 50 km (31 mi) from the base of the Eastern Caprock Escarpment, from Briscoe and Hall Counties southward to Garza County, Texas (fig. 3). The deposits thin to the east, wedge out against the escarpment on the west, and are truncated on the north by the headwaters of the Little Red River in southeastern Briscoe County. Originally these sediments may have covered an area of 7,800 km^2 (3,000 mi^2) or more between the valleys of the Little Red River and the Double Mountain Fork of the Brazos River south of Post, Texas. The areal extent of this alluvial complex has been reduced by erosion, so that at present only 1,660 km^2 (640 mi^2) may remain. Similar deposits are found farther east, and to the north as well, in the valley of the Prairie Dog Town Fork of the Red River, but their relation to the Quaternary sequence in the present study area has not been demonstrated.

Driller's logs from more than 300 water wells in Briscoe, Floyd, Hall, and Motley Counties were studied to determine the lateral boundaries and thickness of this sedimentary sequence. Logs from wells south of Motley County were also reviewed, but the extent of deposits in this area was mapped solely on the basis of limited field reconnaissance. Over much of the region, the maximum thickness of Quaternary strata is about 40 m (130 ft), but the deposit thickens to more than 73 m (240 ft) locally. The thickest deposits lie within closed basins or deep troughs on the Permian or Triassic subcrop. In these areas, dissolution of Permian evaporites at depths of 150 m (500 ft) or more apparently resulted in karstic subsidence contemporaneous with deposition of the Quaternary sediments.

Representative sections (Stops 11 through 15) through the Quaternary deposits denote an upward-fining sequence from fluvial sand and gravel at the basal contact on underlying Triassic and Permian red beds, to eolian sand and silt at the surface, with interposed lenses of lacustrine clay. The basal, coarse-grained sediments probably were deposited by alluvial fans spreading eastward from the retreating Caprock Escarpment. At a few sites this coarse-clastic component contains Rancholabrean faunal remains, indicating that these deposits are less (probably much less) than 600,000 yr old (Kurten and Anderson, 1980, p. 5) and more than 5,000 yr old (Johnson and others, 1982, p. 131).

Overlying these basal gravels, near the middle of the alluvial sequence, is a zone of fossiliferous, argillaceous strata. The fine silt and clay composing these deposits accumulated in closed basins that were the sites of ponds and small lakes. These perennial water bodies provided suitable habitats for aquatic gastropods, pelecypods, and ostracodes, including several species no longer indigenous to the area (Stops 11, 12, and 14). A few microvertebrates and the benthic alga *Chara* also are represented at some sites, as are allochthonous remains of terrestrial mollusks and large vertebrates (Stops 10 and 12).

Accumulation of these pond deposits was enhanced, in some places, by subsidence. Locally the Quaternary section includes thick sequences of lacustrine sediment and paleosols filling closed structural depressions. Some of these deposits are tilted and faulted, indicating that subsidence has occurred episodically since the late Pleistocene (Stops 11 and 14). At Stop 14 the lacustrine deposits are more than 9 m (30 ft) thick. Work by Gustavson and others (1981b) demonstrated that subsidence was active historically in Hall and Briscoe Counties, producing sinkholes (Stops 1 and 2) and subsidence basins (Stops 2 and 3). These features formed as a result of dissolution of Permian evaporites 150 to 240 m (500 to 800 ft) below the surface, or 120 to 180 m (400 to 600 ft) beneath the Quaternary deposits (Gustavson and others, 1982; McGookey and others, 1985).

A similar pattern of karstic subsidence apparently produced comparable features throughout late Pleistocene and Holocene time. During much of this interval, subsidence may have been more widespread than it is today because of the wetter climate and possibly higher rates of infiltration and movement of ground water (Caran and McGookey, 1983). The moist climate of the late Pleistocene turned sinkholes and subsidence basins into pluvial ponds and lakes, the largest of which probably received phreatic discharge as well. Although subsidence has continued to the present, most of

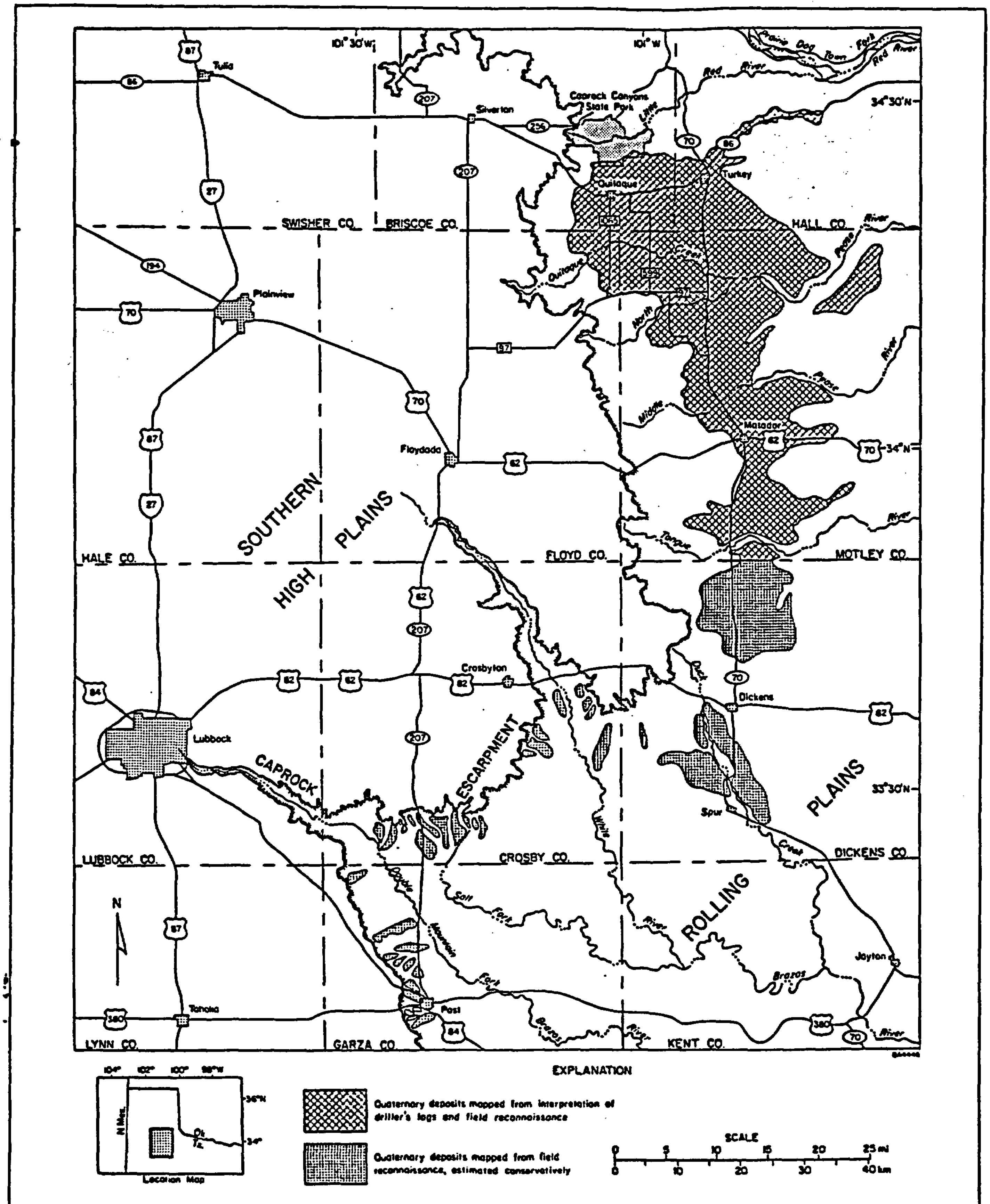

FIGURE 3. Map showing distribution of Quaternary alluvial deposits at the base of the Eastern Caprock Escarpment. These deposits cover 1,660 km² (640 mi²) or more between the Little Red River on the north and the Caprock Escarpment near Post, Texas.

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the limnic deposits occupy a stratigraphically consistent position in the middle of the Quaternary section, corresponding to a period of greater available moisture. Later, the climate became increasingly arid; as a result, eolian and less common fluvial deposits, often pedogenically modified, compose the upper part of the section (Stops 13 and 15).

Structural deformation influenced the deposition of Quaternary sediment near the Caprock Escarpment and probably altered the near-surface ground-water regime in those sediments (Stops 11 and 14). Karstic subsidence and normal faulting created permeable pathways for infiltrating ground water. Under slightly different circumstances this type of structural disturbance could lower local base levels along streams and enhance or initiate incision. Over an extended period these processes could affect the retreat rate of the Caprock Escarpment.

GEOMORPHIC PROCESSES

Salt Dissolution and Collapse

Regional salt dissolution and the subsequent collapse of overlying strata affected substantial parts of the Texas and Oklahoma Panhandles (Stops 1 through 4, 6, 7) (Gustavson and others, 1980, 1982; Johnson, 1981). Seven salt-bearing units are within the Permian System of the Texas Panhandle and eastern New Mexico. With the probable exception of the lower Clear Fork Formation, all the younger salt-bearing units are locally undergoing dissolution.

Several lines of evidence support the conclusion that zones of salt dissolution underlie parts of the Southern High Plains, the Rolling Plains, and the Canadian River Breaks (Gustavson and others, 1980a, b; 1982).

(1) The major streams draining the region surrounding the Southern High Plains carry high-solute loads, indicating that dissolution is active. For example, the Prairie Dog Town Fork of the Red River carries a mean annual solute load of 1,003.4 x 10^3 tons (912 x 10^3 metric tons) of dissolved solids per year, including 425.3 x 10^3 tons (387 x 10^3 metric tons) of chloride per year (U.S. Geological Survey, 1969-1977). Brine springs, salt springs, and salt pans appear along this and other stream valleys (Stop 1).

(2) The abrupt loss of salt sequences between relatively closely spaced oil and gas exploration wells indicates salt dissolution and not facies change. Structural collapse of overlying strata is evident in the wells where salt is missing (fig. 2).

(3) Brecciated zones, fractures with slickensides, extension fractures filled with gypsum, and insoluble residues composed of mud, anhydrite, or dolomite overlie the uppermost salts in cores from the DOE/Gruy Federal No. 1 Rex H. White well in Randall County, the DOE/Gruy Federal No. 1 D. N. Grabbe well and the Stone and Webster Engineering Corp. No. 1 Zeeck and No. 1 Harman wells in Swisher County, the Stone and Webster Engineering Corp. No. 1 Sawyer well in Donley County, the Stone and Webster Engineering Corp. No. 1 G. Friemel, No. 1 J. Friemel, and No. 1 Detten wells in Deaf Smith County, and the Stone and Webster Engineering Corp. No. 1 Mansfield well in Oldham County (fig. 1).

(4) Numerous sinkholes and closed depressions (dolines) have formed recently in the Rolling Plains and are interpreted to be the result of dissolution and subsidence (Stops 1 through 3) (Gustavson and others, 1982).

(5) Permian outcrops east of the Caprock Escarpment (Stops 4, 6, and 7) display folds, extension-fracture systems, breccia beds, and remnants of caverns.

Rates of salt dissolution have been calculated in drainage basins on the Rolling Plains. Swenson (1974) found that in the drainage basin of Croton Creek, a small subbasin of the Salt Fork of the Brazos River, the vertical dissolution rate was 0.15 mm (0.006 inch)/yr for the entire subbasin. Gustavson and others (1980b) calculated both vertical and horizontal dissolution rates in most of the drainage basins in the Rolling Plains in the Texas Panhandle. For example, the mean horizontal dissolution rate of salts underlying the Prairie Dog Town Fork of the Red River is 2.6 cm (1 inch)/yr based on 5 yr of data. A vertical dissolution rate of 0.054 cm (0.02 inch)/yr was calculated by using the same data base.

Retreat of the Caprock Escarpment

Estimates of the retreat rate of the Caprock Escarpment and the denudation rate on the Rolling Plains have been made using several methods (Gustavson and others, 1981). On the basis of projections of the easterly extent of the High Plains at the end of deposition of the Ogallala Formation (Miocene-Pliocene) and the Seymour Formation (late Pleistocene), we calculate that retreat rates range from 110 to 180 m/1,000 yr (360 to 590 ft/1,000 yr). Based on an analysis of incision rates of the Little Red River, retreat rates were found to be from 115 to 139 m/1,000 yr (375 to 458 ft/1,000 yr).

Although estimates of rates of scarp retreat are available, the mechanisms by which this process occurs are poorly understood. Gustavson (1983), however, suggested that spring sapping has been influential in escarpment retreat but that this process is no longer important because spring discharge has almost ceased along the escarpment owing to depletion of the Ogallala aquifer. Recent observations of landslides and rock falls after heavy rainfall (15 to 22 cm [6 to 9 inches]) on October 18 to October 21, 1983, indicate that mass movements greatly affect escarpment retreat.

Denudation of the Rolling Plains

Denudation rates have been estimated in 19 drainage basins within the Rolling Plains (Gustavson and others, 1981). These estimates, which range from 9 to 297 cm/1,000 yr (4 to 118 inches/1,000 yr), were based on reservoir sedimentation rates (Maner, 1958), sheet-erosion rates (U.S. Department of Agriculture, 1977), suspended-sediment-load analyses, and morphometric analyses of river basins. Erosion rates on the Rolling Plains are quite high, and will remain high under current land use practices and climatic conditions (Schumm, 1965; Gustavson and others, 1981a).

Analyses of local erosion rates in the Rolling Plains continue and have shown that erosion along selected high-relief areas of the Caprock Escarpment in a 3-yr period averaged 0.40 cm/yr (0.15 inch/yr) (Stop 8), whereas deposition on a terrace of the Little Red River averaged 0.21 cm/yr (0.08 inch/yr). Recent observations of dustfalls between March 1983 and January 1984 documented a cumulative eolian influx of 34.9 g/m^2 (0.152 t/ac), which is roughly equivalent to a sedimentation rate of 0.02 mm/yr (0.001 inch/yr). On the other hand, wind erosion is locally intense, as indicated by cultivated fields that have lost as much as 0.8 m (2.6 ft) of soil since the 1920's (Stop 9).

CULTURAL BACKGROUND

Archeologists have recognized four distinct cultural stages in the Texas Panhandle and the adjacent states (table 1): Paleo-Indian, Archaic, Neo-Indian, and Historic.

Paleo-Indian Stage

This stage is represented by sites that were occupied by a nomadic, big-game-hunting culture during the late Pleistocene. Although new data are changing the assigned relative ages of this culture, most archeologists accept the dates of 10,000 to 5000 B.C. The remains of mammoth and large-horned bison associated with projectile points were found at the most common Paleo-Indian sites in the Texas Panhandle.

TABLE 1. Chronologic chart of human occupation in the Texas Panhandle.

Historic	
A.D. 1810 - A.D. 1913	Anglo-American exploration and settlement
A.D. 1540 - A.D. 1810	Early exploration, mainly Spanish
Prehistoric	
A.D. 1 - A.D. 1540	Neo-Indian
5000 B.C. - A.D. 1	Archaic
8000 B.C. - 5000 B.C.	Late Paleo-Indian
9000 B.C. - 8000 B.C.	Folsom
10,000 B.C. - 9000 B.C.	Clovis
Pre-10,000 B.C.	Pre-Clovis?

The Miami Site, well known among anthropologists, was excavated in 1938 by E. H. Sellards. This site contained bones of an extinct mammoth associated with Clovis points. A second Paleo-Indian site in Lipscomb County contained many large bison skeletons and associated Folsom points. Excavated by C. B. Schultz of the University of Nebraska in 1943, this site also contained additional points that were collected from the surface by personnel of the Panhandle-Plains Historical Museum.

Archaic Stage

The Archaic Stage in the Texas Panhandle is transitional from a big-game-hunting culture to a lifestyle of hunting and gathering. Only the middle and late periods of this stage have been recognized, and they have not been reported in the literature. These sites are large to small open camps in the bottoms of the stream-fed canyons and below pour-offs on tributaries where natural water pools are formed. Some sites contain mortar holes; the sites with holes may be permanent camps and those without may be hunting camps. Dates of the Archaic in the Texas Panhandle range from 6000 B.C. to perhaps as late as A.D. 500.

STOP 1: Estelline Spring: brine springs, salt seeps, and sinkholes

T. C. Gustavson

Brine springs and salt seeps discharge as much as 1.10 x 10^5 tons (1.0 x 10^5 metric tons) of chloride per year into the Prairie Dog Town Fork of the Red River near Estelline, Texas.

Estelline Spring issued from a large sinkhole in the valley of the Prairie Dog Town Fork of the Red River, approximately 3 km (2 mi) east of Estelline, Texas. Formerly one of the largest brine springs in the region, Estelline Spring discharged brine at an average rate of 0.11 m^3/s (4 ft^3/s), which is approximately equivalent to a daily discharge of 300 tons (273 metric tons) of chloride (U.S. Army Corps of Engineers, 1980) and its average salinity was 25,000 ppm. The spring no longer flows and is now contained in an impoundment structure, which is part of the U.S. Army Corps of Engineers' efforts to reduce natural pollution of fresh water in this region (fig. 4). At least four other sinkholes occur within a few hundred meters of Estelline Spring. None of these smaller sinkholes discharge brine at the surface; however, all of these sinkholes contain brines. Salt seeps and salt flats occur on the floodplain near Estelline Spring and adjacent sinkholes. This part of the floodplain of the Prairie Dog Town Fork of the Red River is characterized by a lack of vegetation and by intermittent thin salt crusts composed of halite and gypsum (fig. 4). For detailed descriptions of the geology, hydrology, and water chemistry of areas in the Rolling Plains of Texas where large volumes of brine are being discharged, see U.S. Army Corps of Engineers (1980) and unpublished reports to the U.S. Army Corps of Engineers by Engineering Enterprises, Inc. (1974) and NSF/National Soil Services, Inc. (1979).

Sinkholes, brine springs, salt seeps, and salt pans are the surface manifestations of the subsurface process of dissolution. Brine springs such as Estelline Spring confirm that Upper Permian bedded salts underlying the Rolling Plains of the Texas Panhandle are actively undergoing dissolution. Widespread brine springs, salt seeps, and salt pans along streams draining the Rolling Plains and the high chloride contents of the streams attest that the process is regional rather than local.

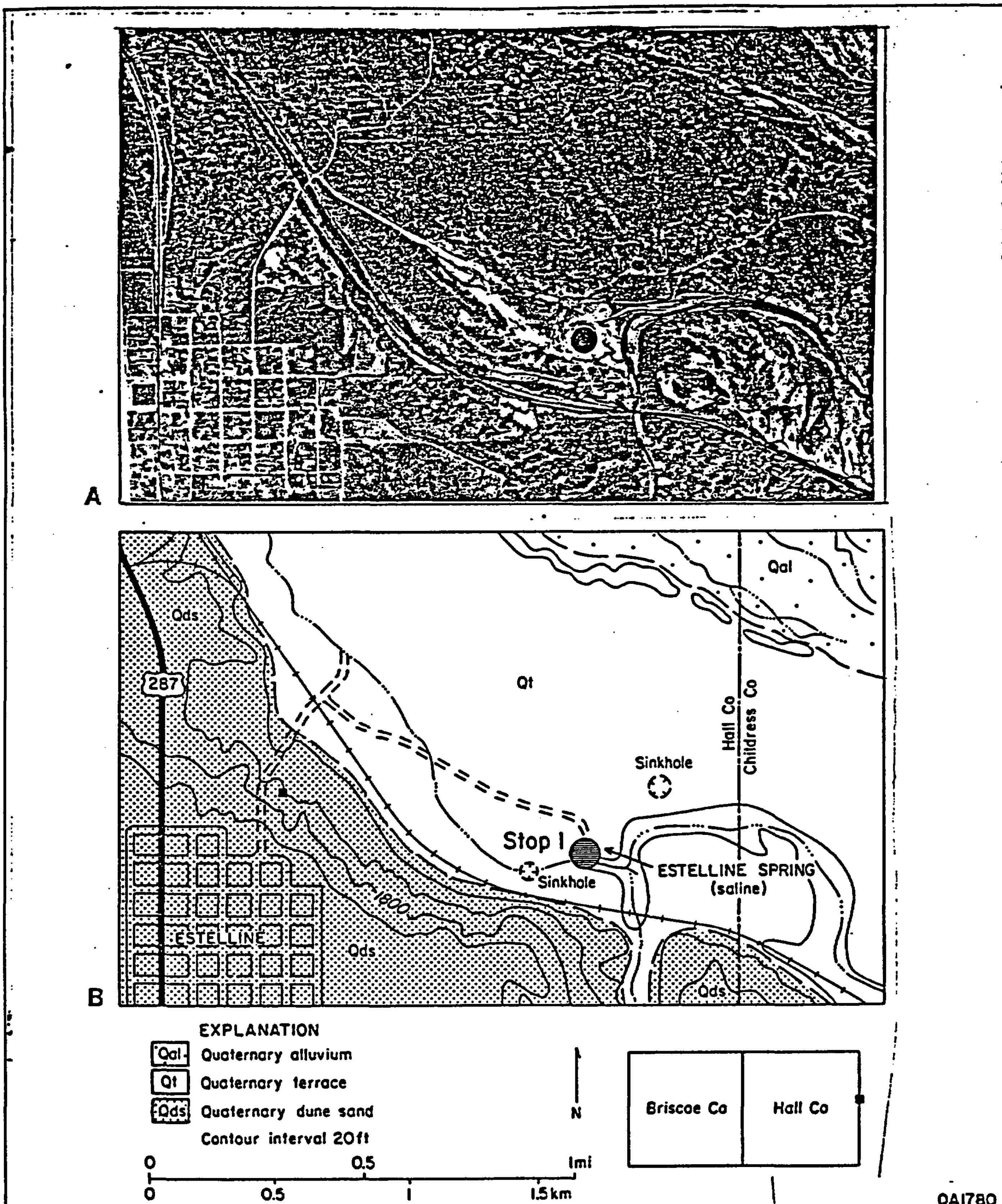

FIGURE 4. A. Vertical aerial photograph (U.S. Soil Conservation Service photograph CRO-2EE-207, Hall County, 1-9-64, scale 1:20,000) showing Estelline Spring, several adjacent sinkholes, and salt flats (areas of high reflectivity northwest and southeast of Estelline Spring). All of these features occur on the lower terrace of the Prairie Dog Town Fork of the Red River. B. Corresponding topographic map. Topography derived from Estelline Quadrangle, U.S. Geological Survey 15-minute quadrangle map series.

STOP 2: Sinkholes

T. C. Gustavson

Sinkholes are common features in the Rolling Plains of the Texas Panhandle. More than 200 sinkholes occur in Hall County.

Collapse sinkholes observed in the Rolling Plains of the Texas Panhandle are characteristically circular to oval in plan view and, when recently formed, have steep sides leading to a central collapsed area (fig. 5). In older sinkholes, the sides are generally degraded, especially if the sinkhole is filled with water. These features are up to 100 m (330 ft) wide and 30 m (100 ft) deep. More than 200 collapse sinkholes were observed in Hall County (fig. 6), and between 1940 and 1972 at least 36 new sinkholes formed in a small (310 km^2 [120 mi^2]) area within the county (Gustavson and others, 1982). Simpkins and others (1981) reported similar features throughout the Rolling Plains between Kent County on the south and the Canadian River on the north.

The largest sinkhole in Hall County occurs 0.8 km (0.5 mi) west of Texas Highways 70 and 256 and 2.4 km (1.5 mi) north of the Prairie Dog Town Fork of the Red River (fig. 7). This large sink, developed in Permian strata, is the southernmost in a series of large sinks that occurs along the divide between Mulberry Creek and Battle Creek in northwestern Hall County and northeastern Briscoe County. The other sinks, all of which occur in Briscoe County, are Sink Lake, consisting of two sinkholes, and Timber Lake.

Sinkholes in the Rolling Plains apparently resulted from dissolution of Permian evaporites and collapse of overlying strata. High chloride and sulfate loads in the streams that drain the Rolling Plains indicate that dissolution of salt and gypsum is now active. Salt dissolution is mostly a subsurface process, whereas gypsum dissolution is a surface or near-surface process. Surface exposures of 2- to 3-m-thick gypsum beds, commonly found throughout the Rolling Plains, show evidence of minor solutioning along joints and as karren. Examination of geophysical logs shows no significant evidence of thinning of gypsum beds in the subsurface that can be attributed to dissolution. Salt beds, on the other hand, are never exposed at the surface and show substantial evidence of thinning in the subsurface as a result of dissolution. Small sinkholes may have resulted from dissolution of thin, near-surface gypsum beds, but most sinkholes probably resulted from dissolution of deep, thick salt beds.

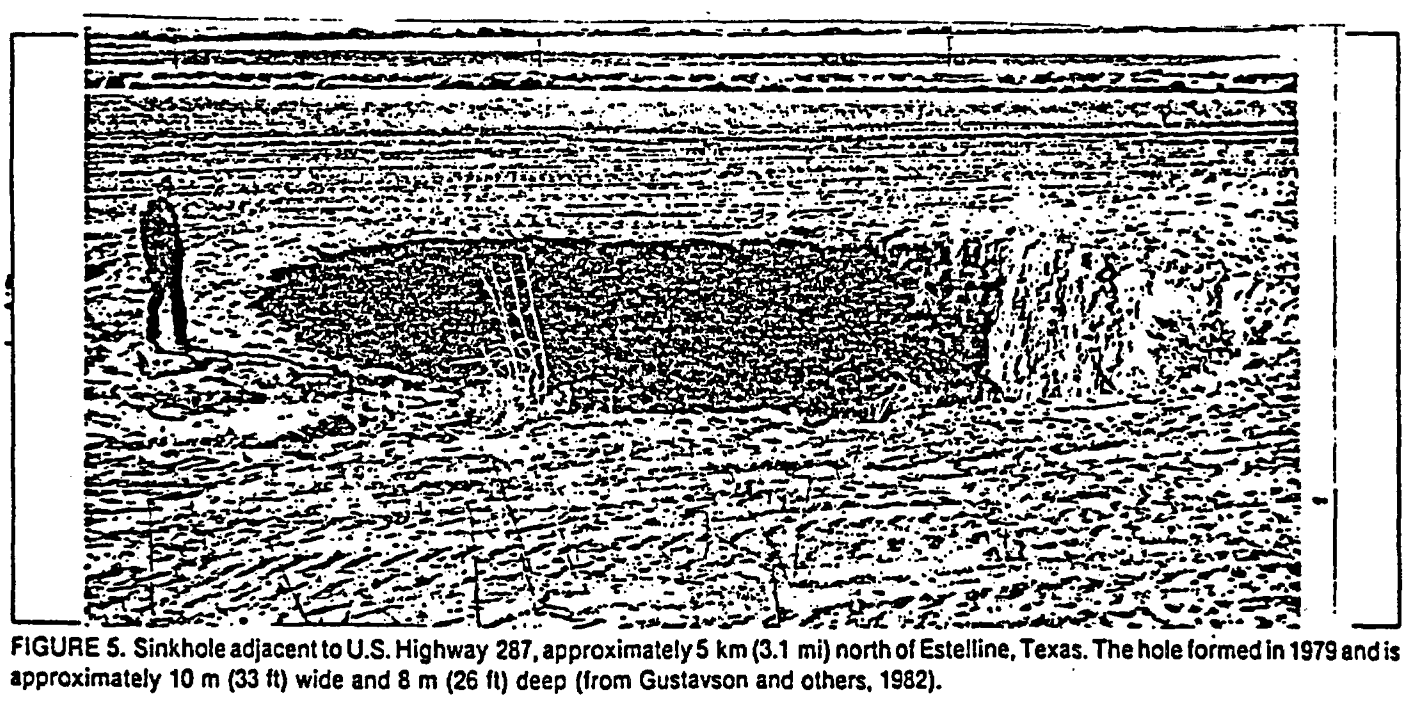

FIGURE 5. Sinkhole adjacent to U.S. Highway 287, approximately 5 km (3.1 mi) north of Estelline, Texas. The hole formed in 1979 and is approximately 10 m (33 ft) wide and 8 m (26 ft) deep (from Gustavson and others, 1982).

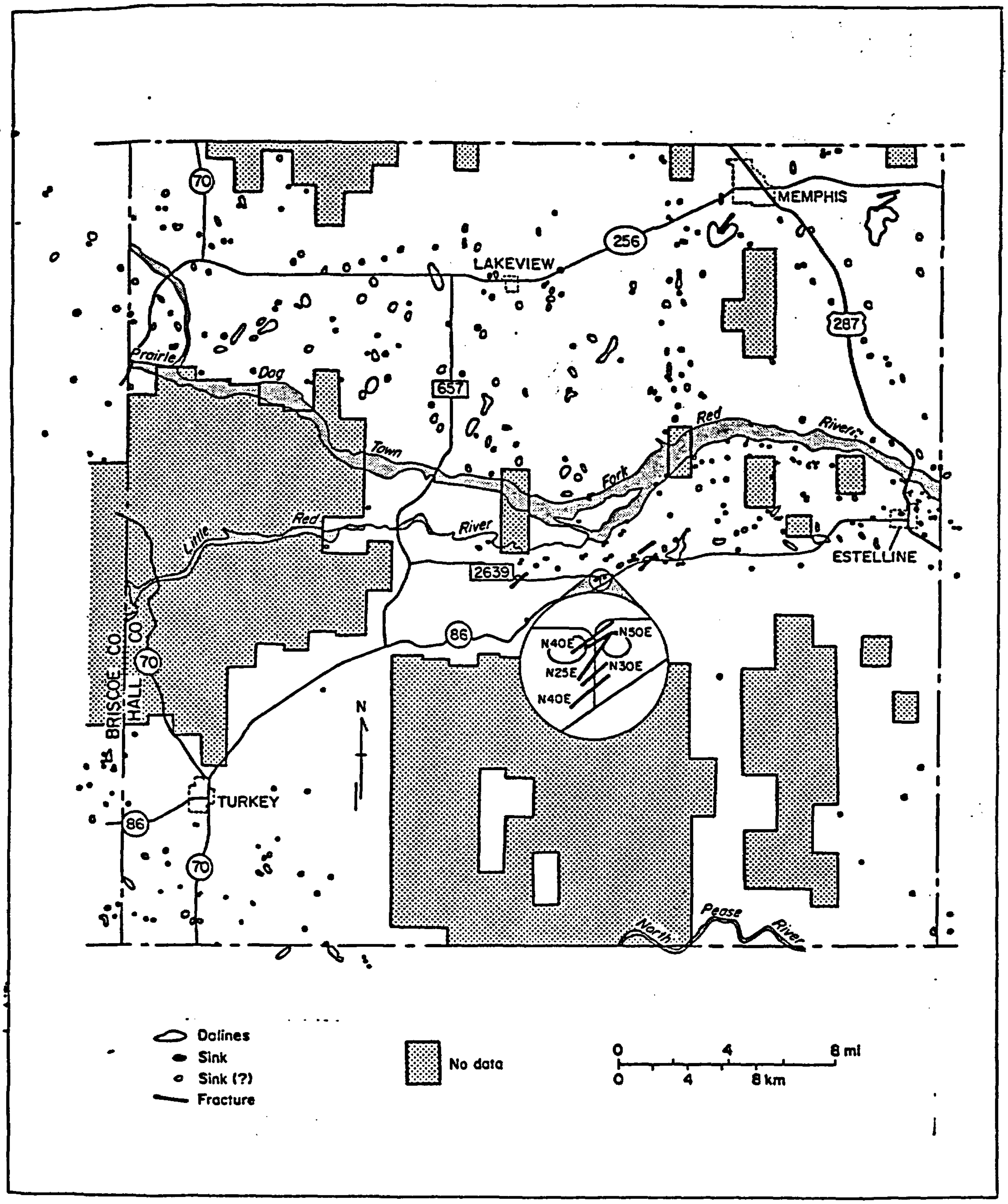

FIGURE 6. Location of sinkholes, dolines, and fractures in Hall and eastern Briscoe Counties, Texas. Dolines are drawn to scale; sinkholes that are much smaller are not to scale. Areas of no data are those for which low-level color aerial photographs were unavailable. These areas are relatively highly dissected, and closed depressions are not recognizable here (from Gustavson and others, 1982).

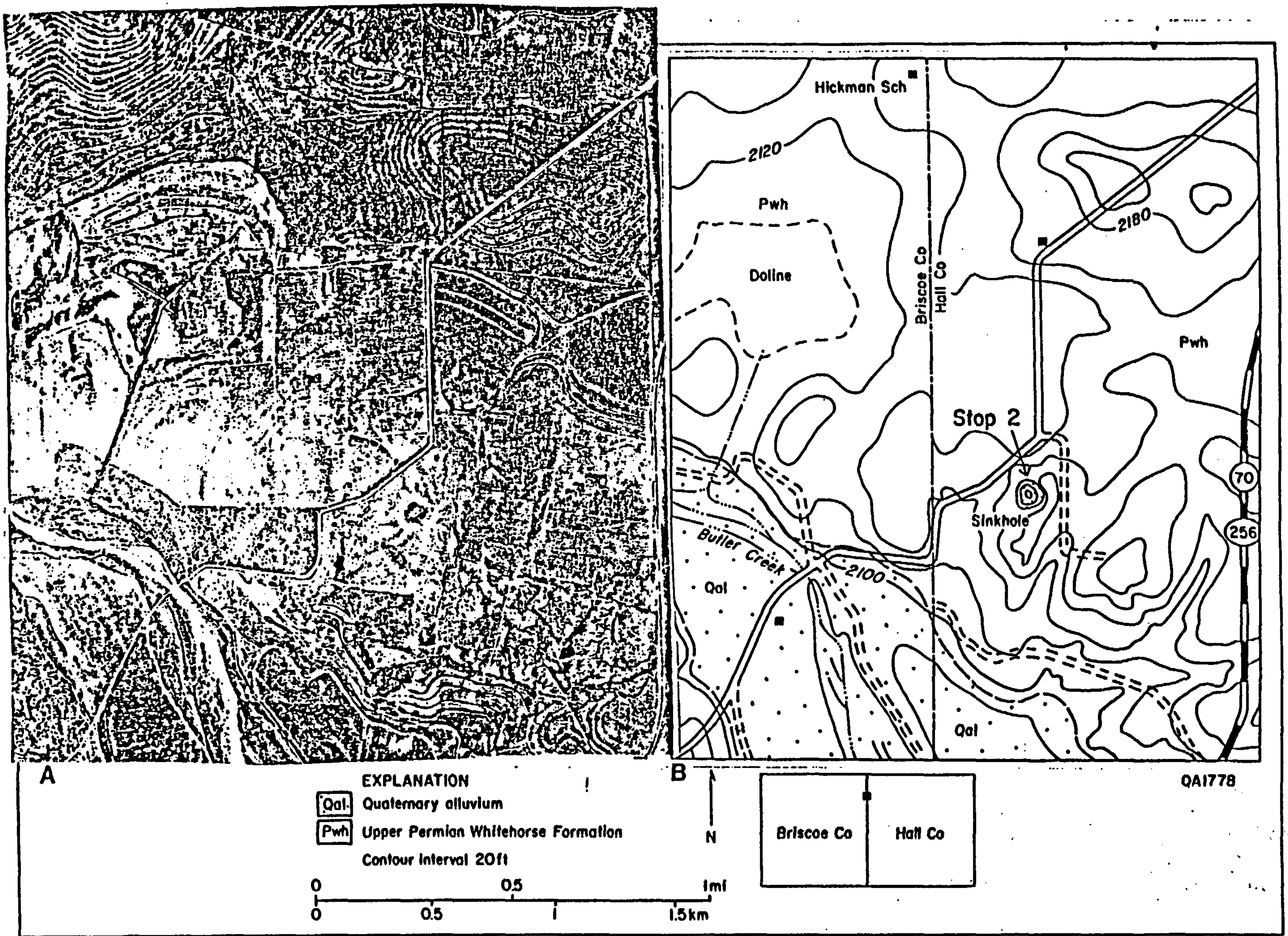

FIGURE 7. A. Vertical aerial photograph (U.S. Soil Conservation Service photograph CRT-4MM-79, Hall County, 2-7-72, scale 1:20,000) showing a large sinkhole. The sinkhole, exposed in Permian bedrock, is approximately 100 m (330 ft) wide and 30 m (100 ft) deep. This is the largest sinkhole in Hall County, Texas, and the surrounding area. B. Corresponding topographic map. Topography derived from Brice Quadrangle, U.S. Geological Survey 15-minute quadrangle map series.

STOP 3: Surface fractures and dolines

T. C. Gustavson

A system of fractures associated with a series of dolines has repeatedly opened in central Hall County since 1979.

SURFACE FRACTURES

Surface fractures appear in several areas of Hall County, Texas (Gustavson and others, 1982). Of these the best exposed and most active fracture system occurs in fields adjacent to Farm-to-Market Road (FM) 2639 in central Hall County approximately 125 m (413 ft) north of the intersection of FM 2639 and Texas Highway 86 (fig. 8). Open fractures were first observed here in May 1979 and most recently in November 1983. C. M. Wooten (personal communication, 1983), who owns the land west of FM 2639, said that the fractures open after heavy rains and that the fracture system can be followed for as much as 0.8 km (0.5 mi) on either side of FM 2639. Recently observed fractures may be as wide as 50 cm (1.6 ft) and as long as 150 m (500 ft) (fig. 9). True fracture depths are unknown. In May 1979 a fracture opened across FM 2639 that had a vertical offset of 4 cm (1.5 inches) down to the north.

Associated with the recently opened fractures along this part of FM 2639 is evidence of several older fractures, preserved only as diagonal cracks and patches across the pavement of FM 2639 in 1979. More recent patching of the highway has obscured some of the earlier diagonal patches and cracks. Orientations of all fractures along this section of FM 2639 range from N25E to N50E (fig. 6).

A second system of open fractures occurs in the field south of FM 2639 approximately 5.2 km (3.25 mi) from the intersection of FM 2639 and Texas Highway 86. This system was first observed in May 1979 and most recently in April 1983. This fracture was oriented N45E.

Fractures are generally filled by landowners shortly after they form. If left open they tend to fill by slumping and alluviation after light rains.

DOLINES

Approximately 200 dolines (closed depressions), a variety of sinkhole, have been identified in Hall County (Gustavson and others, 1982) (fig. 8). These are broad, shallow, internally drained basins that are usually oblong in plan view and that are up to 3.5 km (2.2 mi) long and 10 to 15 m (30 to 45 ft) deep. At least two dolines are thought to have formed in Hall County since 1950. Three dolines occur near FM 2639 (fig. 8); the largest depression is crossed by FM 2639 approximately 0.5 km (0.3 mi) north of the intersection of FM 2639 with Texas Highway 86. This depression is 0.6 km (0.4 mi) long and several meters deep. All three depressions are elongate subparallel to the orientations of the fracture systems that cross FM 2639.

FORMATION OF SURFACE FRACTURES AND DOLINES

Surface fractures and dolines in Hall County as well as those near FM 2639 were interpreted by Gustavson and others (1982) to have resulted from collapse after subsurface dissolution of Upper Permian bedded salts. The fracture system crossing FM 2639 probably marks an area of extension related to subsidence to the north near the dolines. Although at least two dolines are thought to have formed in Hall County since 1950, it is not known if the depressions in this area are still undergoing subsidence. The recurrence of surface fractures may indicate ongoing subsidence. However, it is also possible that the fractures formed some time ago and are now being intermittently reopened near the surface as episodic rainfalls wash alluvium deeper into the fracture system.

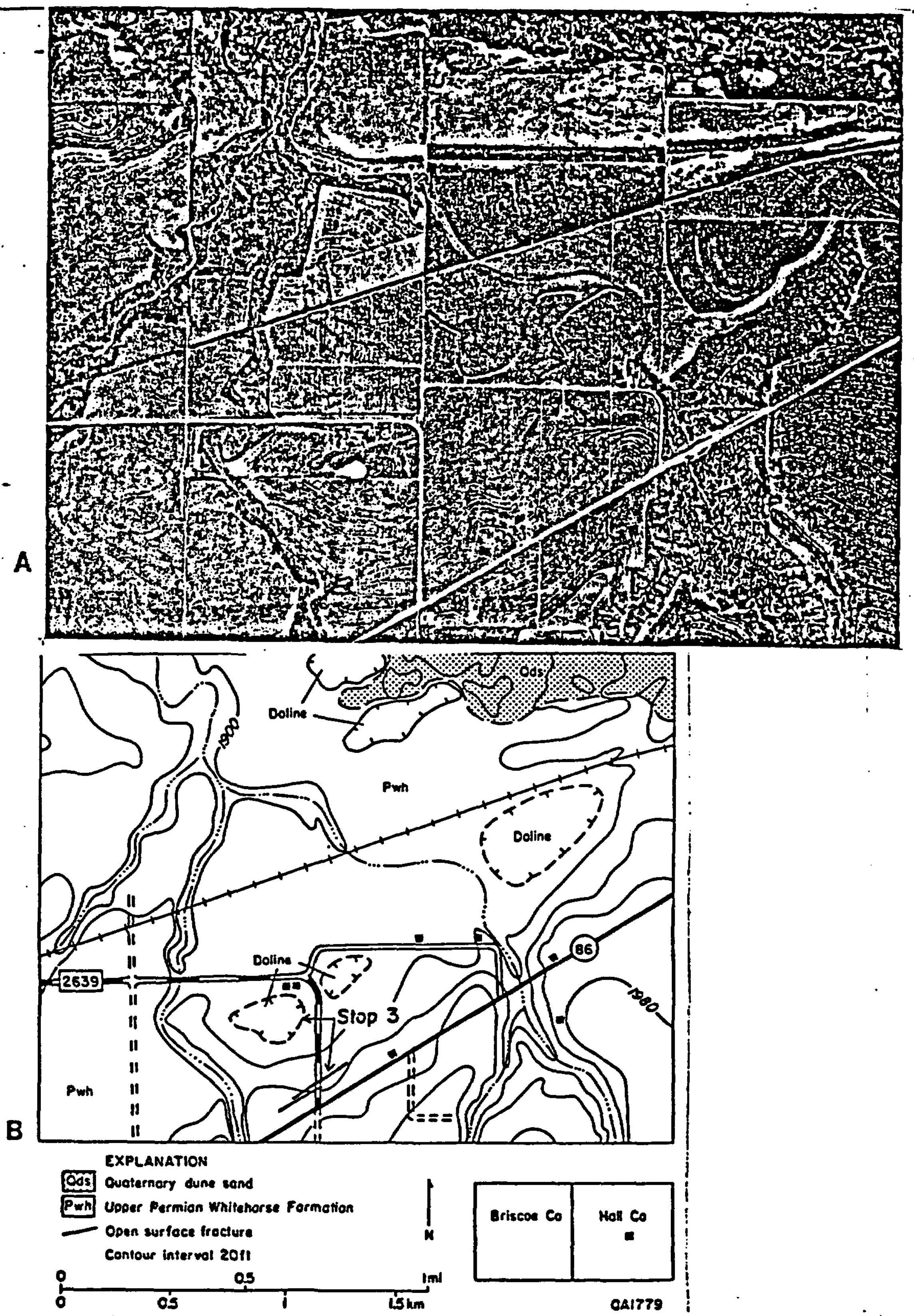

FIGURE 8. A. Vertical aerial photograph (U.S. Soil Conservation Service photograph CRT-3EE-192, Hall County, 1-10-64, scale 1:20,000) illustrating terrane with dolines and fractures. B. Corresponding topographic map. Topography derived from Memphis Quadrangle, U.S. Geological Survey 15-minute quadrangle map series. Dolines and fractures are shown on the topographic map.

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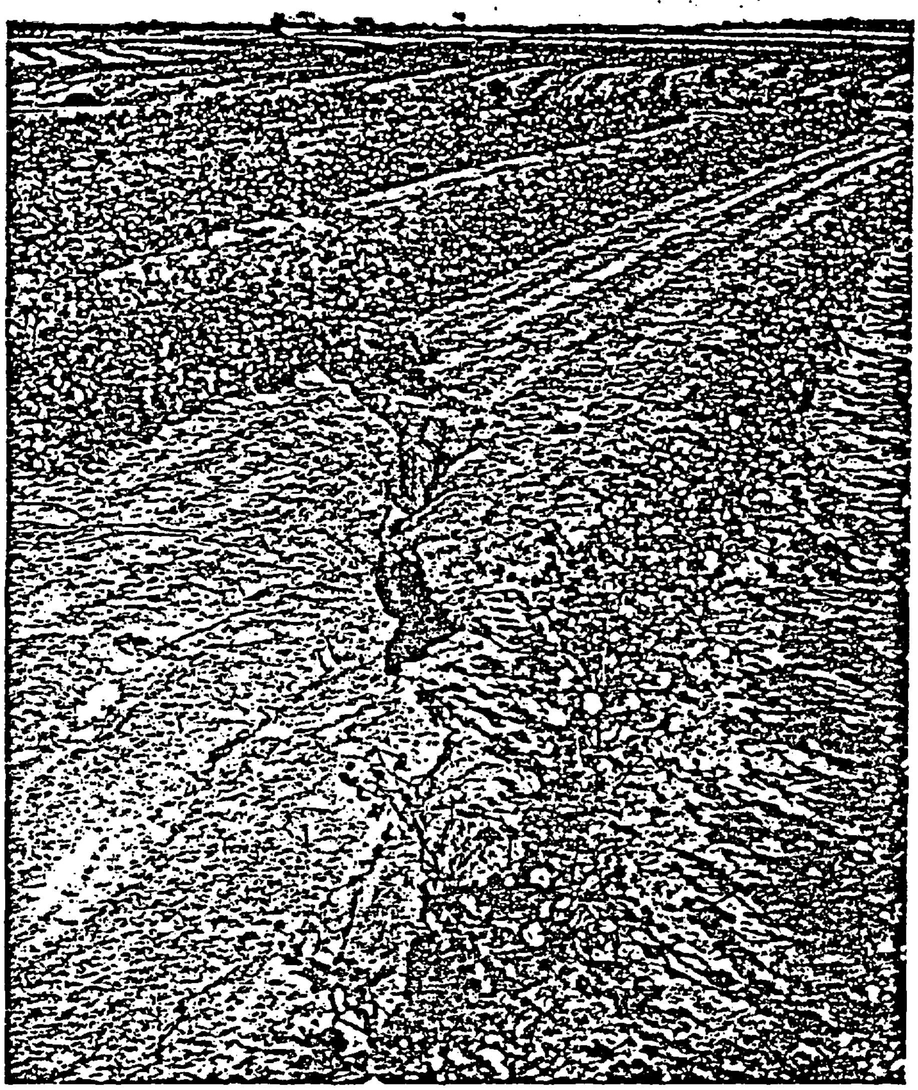

FIGURE 9. Open fracture in field west of FM 2639, 125 m (410 ft) north of Texas Highway 86, Hall County. This fracture opened following heavy rains (28 cm, or 11 inches) on October 18-20, 1983. This fracture is up to 50 cm (1.6 ft) wide and approximately 150 m (500 ft) long.

STOP 4: Remnants of dissolution caverns

T. C. Gustavson

Gypsum collapse breccias, remnants of caverns, and coarse selenite mineralization indicate the former presence of large caverns in the Upper Permian Whitehorse Formation.

Evidence of the former presence of a large cavern or system of caverns is exposed in Upper Permian strata along the banks of the Little Red River in Caprock Canyons State Park north of Quitaque, Texas (figs. 3 and 10). To reach these outcrops, follow the main park road from the park headquarters 4.4 km (2.75 mi) northwest to the horse unloading area. Follow on foot the unimproved dirt road that leads from the horse unloading area to the north for approximately 1.2 km (0.75 mi), to the confluence of the North and South Prongs of the Little Red River. At the Little Red River, turn east and follow the dirt road along the valley of the Little Red River for approximately 0.4 km (0.25 mi). Gypsum breccia and selenite mineralization are exposed in the cutbank on the north side of the stream.

A coarse breccia of gypsum clasts in mudstone or gypsum matrix is exposed in the middle of a 2 to 3 m (7 to 10 ft) thick gypsum bed (fig. 11). The gypsum breccia bed is approximately 100 m (330 ft) long and up to 1 m (3.3 ft) thick. It extends the length of exposure to where the gypsum beds dip below the streambed. Clasts of the breccia have been rotated, indicating that the breccia was formed by gypsum or anhydrite blocks that fell into an open space or cavern. These gypsum beds occur within the Upper Permian Whitehorse Formation and are probably correlative with the Salado-Tansill Formation in the subsurface.

Locally, coarse gypsum (var. selenite) crystals are associated with the gypsum bed. In certain areas the gypsum crystals are intergrown and have completely filled the original cavity. Pods of coarsely crystalline gypsum are several tens of centimeters thick and as much as several tens of meters long. In other areas of the outcrop, selenite crystals occur in open cavities that are now partly filled with silt and fine sand. WARNING! COLLECTING MINERAL SPECIMENS IN A TEXAS STATE PARK IS NOT ALLOWED WITHOUT A COLLECTING PERMIT. Examples of selenite crystals within the park are limited to this area. Please leave these for others to view.

Selenite crystals apparently grew in areas of the cavity not filled with gypsum breccia. Areas where fully terminated selenite crystals occur are apparently remnants of the original cavity. The sands and silts that partly fill these areas are not cemented and were apparently deposited sometime after the selenite crystals completed their growth.

The size of the original cavern or system of caverns is not known, but the cavern apparently extended at least 0.5 km (0.3 mi) west of this outcrop. Original height of the cavern is also unknown, but it probably exceeded 1 m (3.3 ft) because the breccia bed is approximately 1 m (3.3 ft) thick. This former cavern may have formed by dissolution of (1) the gypsum bed that bounds the breccia bed, (2) the underlying salt beds, followed by partial collapse of the gypsum bed along mudstone interbeds, or (3) the bedded salt that was originally present within the gypsum beds.

Dissolution of gypsum as seen elsewhere in Caprock Canyons State Park tends to occur along joints and to a lesser extent along bedding planes. Gypsum dissolution tends to produce irregular surfaces on joints and bedding planes. Where large blocks of gypsum are exposed, karren and rillenstein form on the surfaces. No evidence of these forms of dissolution appears in the gypsum beds that bound the gypsum breccia, nor is there extensive dissolution of the gypsum clasts that compose the breccia; these absences probably preclude dissolution of the gypsum beds as a mechanism for formation of the original cavern.

The second possibility is that these caverns resulted from differential subsidence of strata after dissolution of underlying bedded salts. As dissolution took place, overlying strata subsided, but for unknown reasons the upper half of the gypsum bed exposed here did not collapse completely, creating a space between it and the underlying gypsum bed. It seems unlikely that the original thick gypsum would split longitudinally because no friable interbeds or bedding-plane fractures appear in outcrop.

The former cavern exposed in this outcrop most likely resulted from the dissolution of salt that originally separated the two gypsum beds. This hypothesis is consistent with other evidence in this region of dissolution and subsidence, including brine springs (Stop 1), sinkholes (Stop 2), surface fractures and dolines (Stop 3), and loss of salt in the Salado Formation (fig. 2).

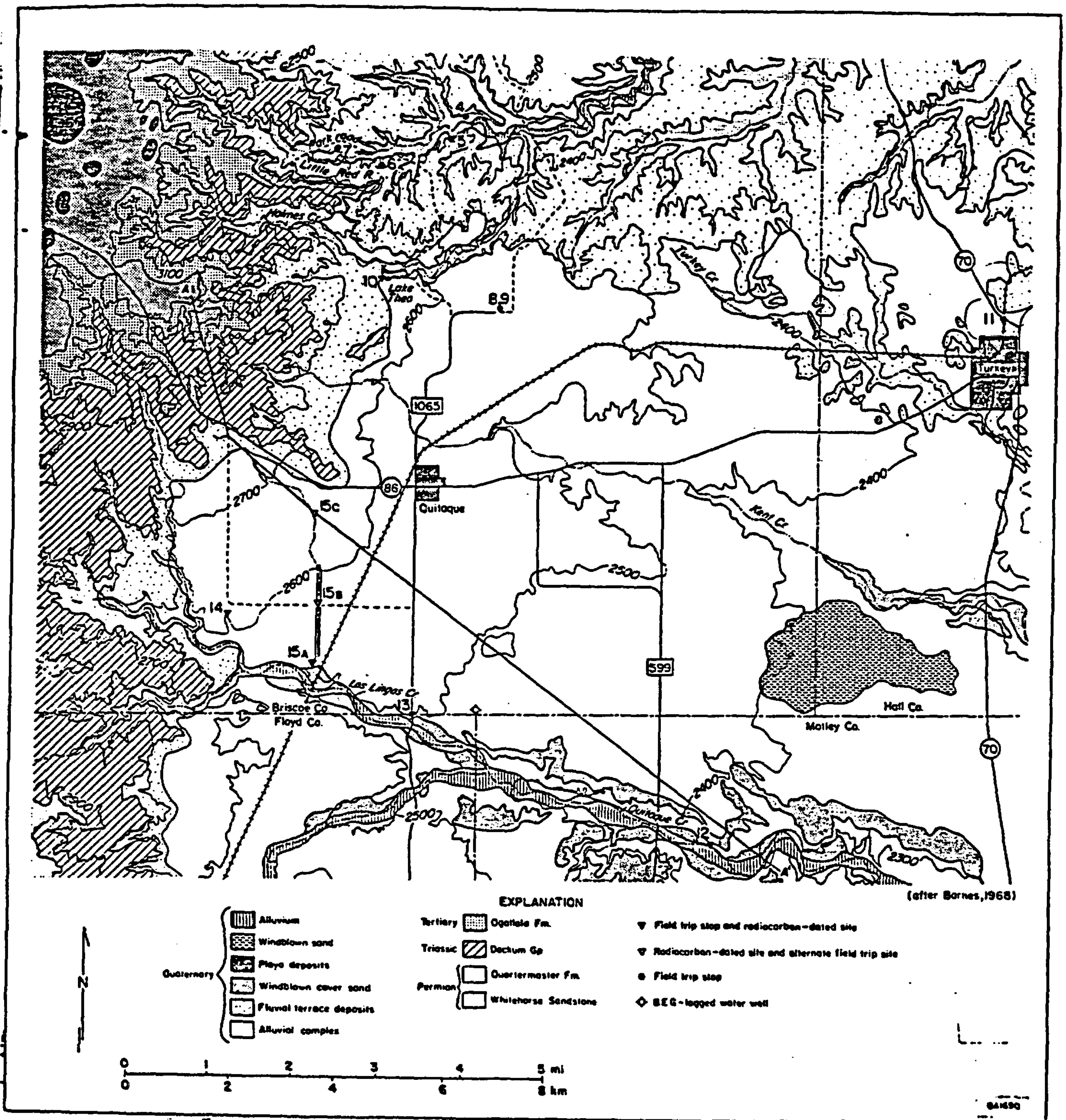

FIGURE 10. Geologic map of Caprock Canyons State Park and vicinity showing locations of field trip Stops 4 through 15. Cross section A-A' shown in figure 42.

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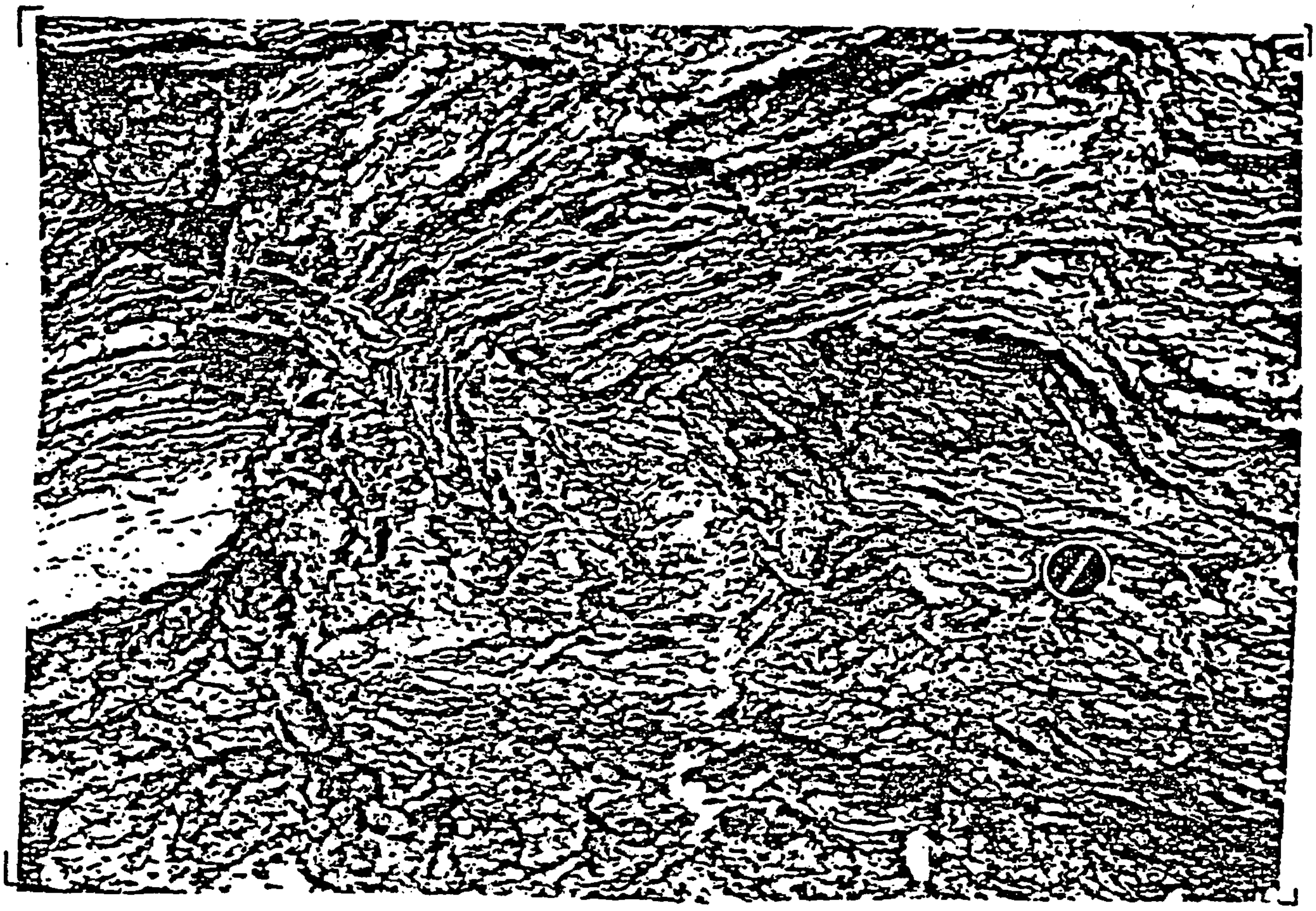

FIGURE 11. Breccia composed of coarse, angular blocks of laminated gypsum in a gypsum matrix. See lens cap for scale.

STOP 5: Terraces of the Upper Little Red River

R. W. Baumgardner, Jr.

Unpaired alluvial terraces occur along the banks of the Little Red River and its tributaries in Caprock Canyons State Park. In one locality, 7.1 m (23.3 ft) of overbank deposition and 9.6 m (31 ft) of stream downcutting have occurred during the last 2,140 ± 110 yr.

In Caprock Canyons State Park, remnants of fluvial terraces can be observed along the channels of tributaries of the Little Red River (fig. 12). In the upper 14 km (8.7 mi) of the Little Red River, heights of terraces above the river range from 1.6 to 15.0 m (5 to 49 ft). Because the terraces are unpaired (at unequal heights on opposite sides of the stream at any location), they probably formed during one period of downcutting accompanied by lateral migration of the stream. Together with terrace stratigraphy exposed in meanderbends, this mode of terrace development suggests that all but the highest terrace at any location formed by lateral erosion by the river. Such terraces are termed erosional (Ritter, 1978). Radiocarbon dating of organic material from terrace deposits provides a basis for estimating rates of scarp retreat and rates of deposition and erosion in stream channels.

Part of the fluvial history of the Little Red River is documented by the sediments exposed in a 10.1-m-high (33-ft) cutbank in a terrace deposit (figs. 13 through 16). The stratigraphy of the deposit is described from base to top. A layer of dark-reddish-brown silty clay near the base of the cutbank is interpreted as a paleosol (fig. 13, lowest arrow; fig. 14A, Unit 10). (NOTE: Stratigraphic units here and at Stops 11 through 15 are numbered independently.) A smooth, abrupt contact separates Unit 10 from Unit 9; Unit 10 is distinguished easily from the sediments that overlie it by its darker color, more prominent weathering profile, and lack of internal structures. Two radiocarbon dates have been obtained from Unit 10 (fig. 14A), 1,640 ± 70 yr B.P. and 2,140 ± 110 yr B.P. The younger date may be a result of natural contamination by younger organic material.

The alluvium overlying Unit 10 can be divided into three groups, each of which contains a zone of organic accumulation and is separated from the others by an abrupt, irregular boundary (fig. 14A). Units 8 and 9 compose Group C. This group is composed of horizontally bedded layers of silty very fine sand and silty clay up to 10 cm (4 inches) thick (fig. 14A). Unit 9 is characterized by prominent horizontal laminae, desiccation cracks and small scours (up to 2 cm [0.8 inch] wide) in its clay layers, and a 50-cm-thick (20-inch) bed of festoon crossbedded silty sand. Grain size in Unit 9 is much the same as in overlying units, but it is separated from overlying and underlying units by smooth, abrupt boundaries. Unit 8 has faint horizontal bedding and fines upward. Finely divided organic matter concentrated at the top of Unit 8 was sampled for radiocarbon dating and yielded a date of 1,495 ± 180 yr B.P. (fig. 14A).

Group B is separated from Group C by an abrupt, irregular boundary between Units 7 and 8 (fig. 14A). Grain size in both groups is similar, ranging from silty, very fine sand to silty clay. Each of the three units composing Group B fines upward internally, but horizontal bedding is well developed only in Unit 7. Oxidized organic matter in a 1-cm-thick (0.4-inch) layer is found at the base of Unit 6 (fig. 14A). On the basis of a visual field determination, organic humate content was judged too low to be dateable by standard radiocarbon analysis.

An abrupt, irregular boundary at the base of Unit 4 separates Groups A and B. Group A, being predominantly silty, very fine sand, is slightly coarser grained than Group B. Of the four units in Group A only Units 2 and 3 have discernible horizontal bedding on a fresh surface. However, Units 2 through 4 weather to form stepped slopes. Apparently, intervals of slightly higher clay content are somewhat more resistant. Unit 1 exhibits no sedimentary structures. This layer of silty, very fine sand is interpreted as a pedogenically modified eolian deposit. Oxidized roots and disseminated organic matter at the base of Unit 3 were radiocarbon dated as 1,465 ± 130 yr old (fig. 14A).

Radiocarbon dates from Units 3 and 8 overlap at the 1σ (68-percent confidence) level. Because both samples had low organic contents (0.08 and 0.13 percent, respectively), they were not treated with NaOH to separate dateable fractions of the organic matter (J. Stipp, personal communication, 1984). As a result, both dates may be too young. Because the two units are separated vertically by 2 m (6.6 ft) of sediment, these ages must be interpreted with caution.

The stratigraphy of these deposits and their positions relative to preserved channel deposits and to the present-day channel indicate that Units 2 through 10 are overbank deposits of the Little Red

STOP 6: Eagles Point Overlook: folding of Permian strata associated with salt dissolution and collapse

E. W. Collins, A. G. Goldstein, and T. C. Gustavson

Folding of Permian strata at Caprock Canyons State Park is characterized by synclinal depressions that have been caused by collapse of strata overlying a zone of salt dissolution.

Caprock Canyons State Park straddles the Caprock Escarpment, which has vertical relief of up to 200 m (660 ft) (fig. 10). Rock units exposed in the park near Eagles Point overlook (fig. 12) include interbedded shale, siltstone, sandstone, and gypsum of the upper Permian Whitehorse Sandstone and Cloud Chief Gypsum of the Whitehorse Group. Overlying the Whitehorse Group are massive, thickly bedded sandstones and shales of the Permian Quartermaster Formation. Permian strata are unconformably overlain by sandstones, shales, and conglomerates of the Triassic Dockum Group. Tertiary Ogallala sediments and caliche cap the Triassic rocks. The park is located over an area of regional salt dissolution (Gustavson and others, 1980b). In the park, relatively undeformed strata, exposed at Eagles Point, are underlain by greatly deformed strata, exposed in stream cuts 250 m (820 ft) north of Eagles Point, that exhibit a suite of structures that are related to dissolution collapse (fig. 18), including nonsystematic fractures, small-amplitude synclines, normal and reverse faults, and gypsum veins (Goldstein and Collins, 1984).

Chaotic folding in the zone of deformed strata commonly causes the beds to dip 10 to 20 degrees. Detailed structural mapping has defined synclines that vary in shape from elongate to circular (fig. 19). These synclinal depressions are up to 1.6 km (1.0 mi) long and are composed of conical synclines and anticlines that gently plunge up to 10 degrees toward the center of the depression (fig. 20). The amplitude of these folds is normally less than 10 to 15 m (30 to 50 ft). Rim anticlines may also occur around the periphery of the synclinal depressions. Smaller folds also exist and, although they may be associated with the development of the larger

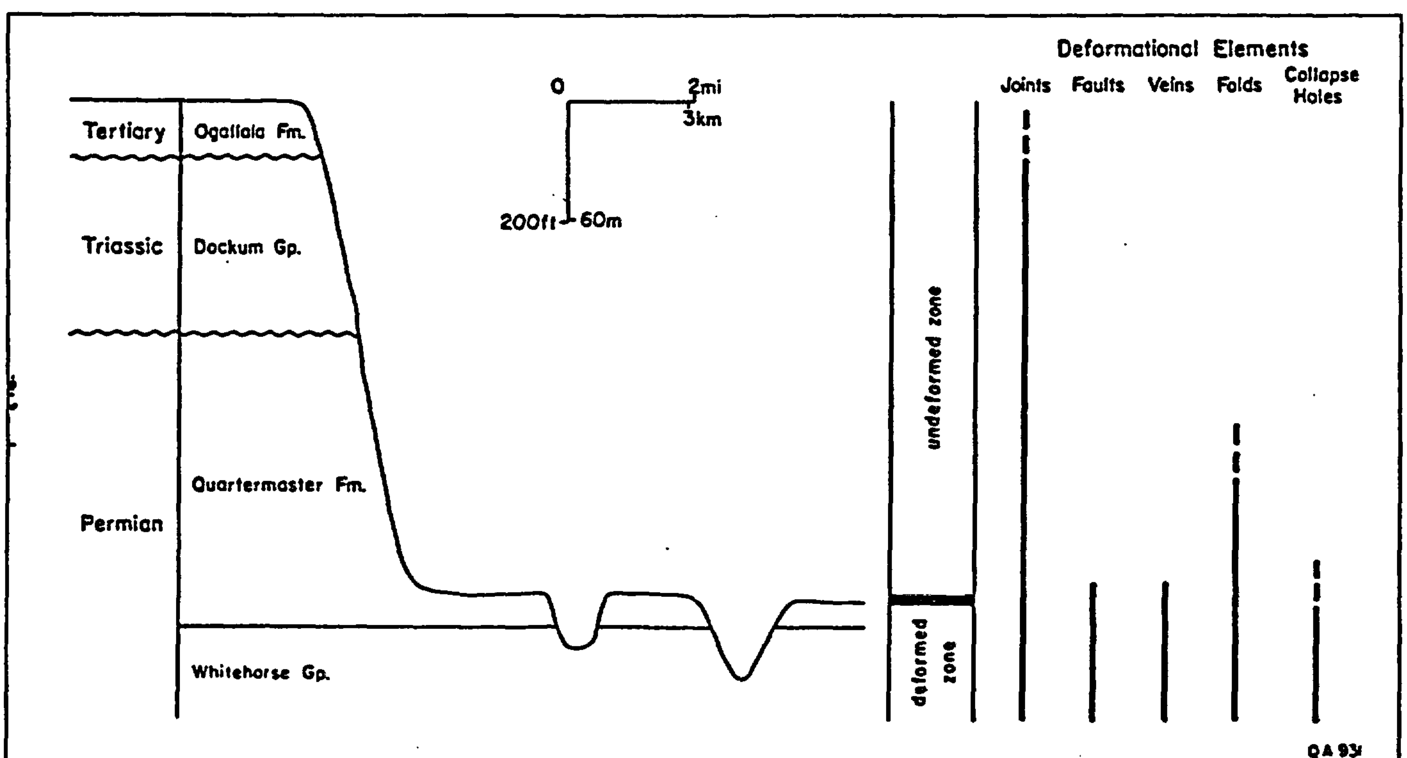

FIGURE 18. Stratigraphy and deformational elements at Caprock Canyons State Park.

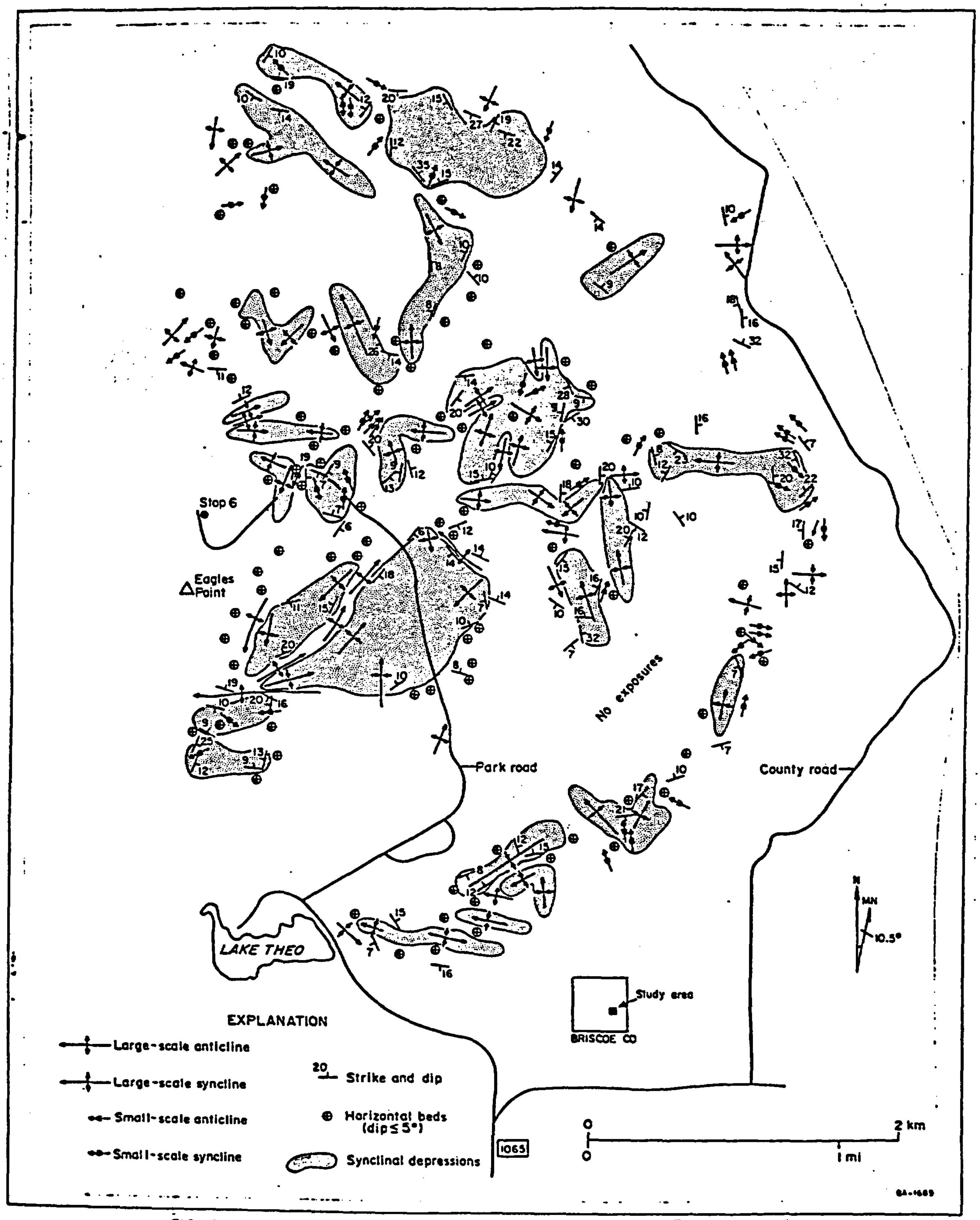

FIGURE 19. Map of structural elements of an area within Caprock Canyons State Park.

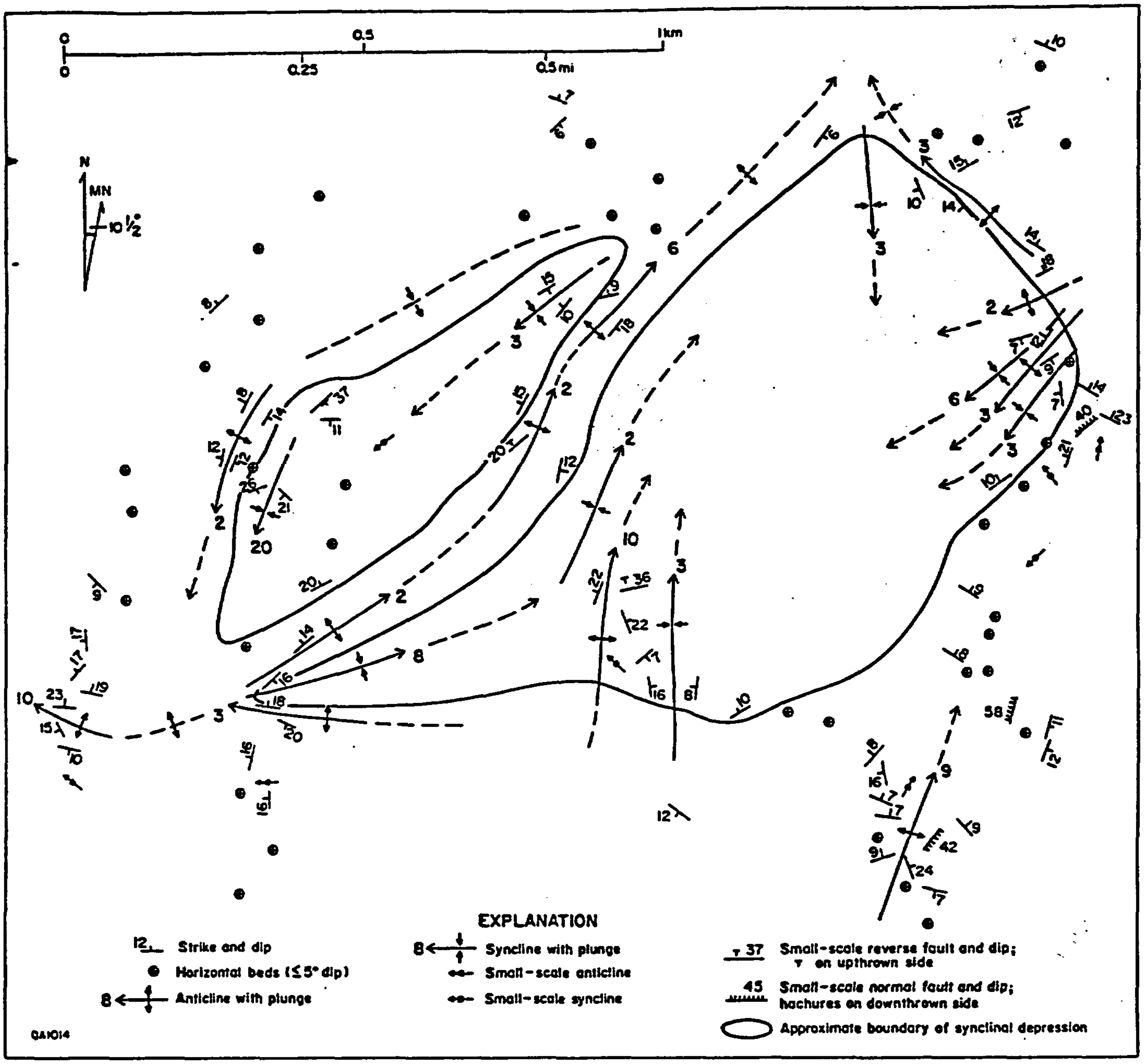

FIGURE 20. Detailed map of structural elements of individual synclinal depressions.

synclinal depressions, some of the smaller folds are probably due to expansion associated with the conversion of anhydrite to gypsum.

Dissolution of salt and collapse under the influence of gravity is the process most likely to explain the folding observed in this area. The division between the greatly deformed strata and overlying undeformed strata is probably a function of bed thickness and vertical distance from dissolution. Beds in the greatly deformed strata zone are almost always 1 m (3 ft) to 10 cm (4 inches) thick, whereas the overlying undeformed strata beds are 2 to 10 m (6 to 35 ft) thick. Thicker beds have a higher flexural rigidity. The relatively undeformed strata are also a greater vertical distance from dissolution and probably exhibit broader, gentler folding over zones of enhanced dissolution.

STOP 7: Veining and faulting associated with salt dissolution and collapse

E. W. Collins, A. G. Goldstein, and T. C. Gustavson

Brittle deformation in Permian strata includes gypsum veining and small-scale faulting showing normal and reverse motions.

In Caprock Canyons State Park, incision of the North and South Prongs of the Little Red River and their tributaries provides excellent exposures of Upper Permian strata. Veining and small-scale faulting are common within the greatly deformed zone of thinly bedded Permian strata (fig. 18). These features are exposed in the cutbanks along the South Prong of the Little Red River near the Little Red River day-use area, 0.3 km (0.2 mi) north of the Little Red River (fig. 12).

Three types of gypsum veins are present: vertical veins, veins parallel to bedding, and veins cutting the bedding at 30 to 60 degrees. The veins are composed of fibrous gypsum bisected by a medial scar (Goldstein, 1982). They are thought to be of the antitaxial type of crack-seal veins (Ramsay and Huber, 1983; Machel, 1985). The medial scar probably marks the site of earliest mineralization; new material was added at the vein-wall rock contact. The mineral fibers indicate the direction of maximum principal extension at the time they were added to the vein. The gypsum fibers in the vertical veins are horizontal, indicating that these veins formed by horizontal extension. These veins probably fill preexisting joints. Mineral fibers of the inclined and horizontal veins are vertical, suggesting that mineralization occurred during vertical extension.

Small-scale normal and reverse faults are common within the zone of deformed strata and are also gypsum filled. Fault displacements are usually less than 0.5 m (1.6 ft). Normal faults are oriented in many directions (fig. 21A), and dominantly dip north, south, east, and west. No relative age data are available for these sets. These orientations indicate either a north-south horizontal maximum principal extension followed by an east-west extension or vice versa. Reverse faults (fig. 21B) show a similar pattern. These orientations are similar to, or coincident with, normal fault orientations. The reverse faults are not as common as normal faults. Orientations of inclined veins (fig. 21C) coincide with fault orientations, suggesting that they are filled faults. Nearly all veins within fault planes display undeformed crystals adjacent to the vein-wall rock contact, indicating that fault movement predated mineralization.

The geometry of vein intersections also indicates that faulting predated mineralization (Goldstein, 1982). The mineral fibers of adjacent horizontal and inclined veins merge without a break. Some veins have sigmoidal fibers, indicating that simple shear occurred during vein growth. For the most part, however, vein fibers are straight and do not deviate from vertical by more than approximately 10 degrees in the horizontal and inclined veins, indicating that these veins formed through vertical extension. Where the veins intersect, vertical veins are everywhere cut by inclined veins and nearly everywhere cut by the horizontal veins.

A close association exists between the systematic joints, veins, and synclinal depressions that occur throughout this area. The major trends of the depression axes are 005°, 025°, 055°, 080°, and 275°, similar to the vertical veins and systematic joint sets (fig. 22). These structural elements also show a weak northwest trend. Within a specific depression, the most significant trend of the vertical veins is the same as the trend of the depression axis. Even though the inclined veins strike in all directions, the dominant strike direction is the same as the orientation of the closed depressions (fig. 23). Strikes of the small-scale faults exhibit a similar relationship, although the faults are less common than the other structures.

Dissolution of salt and subsequent collapse are the processes most likely to explain the deformation in this area. Systematic joints that predated dissolution and collapse probably created pathways for fluid migration and enhanced salt dissolution. Collapse of strata occurred within zones of enhanced dissolution and developed synclinal depressions and nonsystematic fractures.

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STOP 8: Rates of hillslope erosion at six study areas on the High Plains and Rolling Plains of the Texas Panhandle

W. W. Simpkins

Erosion pin data from six erosion-monitoring study areas indicate that net erosion is favored over net deposition in four of the study areas. Headcut retreat rates, calculated from rebar measurements, are generally higher than hillslope erosion rates, but both rates compare favorably with published rates for the region.

Erosion and deposition rates, precipitation amounts, and air temperatures have been measured since 1978 at six stations in the Texas Panhandle (fig. 1). Erosion and deposition on hillslopes have been measured using the erosion pin method (figs. 24 and 25) similar to that by Leopold and others (1966). Headward retreat of stream channels has been measured with reinforcing rods (rebars) emplaced perpendicularly in vertical headcuts. Erosion pins and rebars are deployed on outcrops of Upper Permian siltstones, Triassic Dockum Group mudstones, and Tertiary Ogallala Formation sandstones, alluvial sediment, and poorly developed soils on these parent materials. Three years of data are available for each study area, and this paper is a summary of the findings from those data.

Monitoring erosion and deposition with erosion pins is not without its inherent problems, many of which are outlined in a paper by Haigh (1977). This investigation encountered similar problems, especially (1) processes accentuated by the presence of the pins, (2) processes such as soil heave that are not measurable using the pins, and (3) the effects of local microtopography and micro-environment on the placement of pins. Bias was purposely introduced by choosing study areas that appeared to be actively eroding or depositing sediment. Some variability was introduced initially, because erosion pin fields were laid out both in groups of three to four parallel to slope contours and randomly along tributary canyons. Each pin field was unique, and a system of replicate plots (Bovis, 1982) to check system variability was not used.

Erosion estimates of these same pin and rebar fields were previously reported by Finley and Howard (1981), Simpkins and others (1982), and Simpkins and Gustavson (1984). These authors also investigated the controls on erosion and deposition, but found low correlation coefficients (r) between predictor (independent) variables (rainfall, slope angle, and vegetative cover percent) and amounts of erosion and deposition. Low coefficients of determination (r^2) also indicate that much of the variation in amounts of erosion and deposition is not accounted for by the independent variables. Apparently the erosion pin technique works best on unvegetated, steep slopes of easily erodible material (fig. 24).

Analyses of 3,770 erosion pin measurements taken at approximately 6-mo intervals indicate that net erosion is more common than net deposition (table 3). The net differences over all sites are normally distributed about a mean of -0.14 cm (0.006 inch). Net erosion is favored at Caprock Canyons State Park West, Lake Meredith National Recreation Area, Muleshoe National Wildlife Refuge, and Palo Duro Canyon State Park West (fig. 1 and table 3). Net deposition is favored at Buffalo Lake National Wildlife Refuge and Caprock Canyons State Park East (fig. 1 and table 3) and indicates short-term sediment storage there.

Data taken over longer (3-yr) periods are more useful for projecting long-term rates, as 6-mo values are partly controlled by the immediate micro-environment. Annual erosion rates based on a 3-yr record are given in table 4. These data are normally distributed, as were those for 6-mo intervals (table 3). Similar trends of erosion and deposition between stations are also evident. Hillslope retreat and headward retreat of streams are calculated from periodic measurements of rebars. Data are limited because of the smaller number of rebars deployed (26) compared with erosion pins (393). Annual rates calculated from 2 to 4 yr of data are given in table 5. Retreat rates are generally higher than denudation rates (table 4), especially retreat rates in alluvial sediment (72.4 cm/yr [28.5 inches/yr]).

Retreat rates can be compared with denudation rates if it is assumed that retreat rates represent a strictly horizontal component and denudation rates represent a strictly vertical component (assuming erosion pins are emplaced and measured vertically and are not positioned normal to the slope). Using the tangent of the slope angle on which the erosion pin is deployed, we calculated that retreat rates (converted from denudation rates) range from 0.03 to 2.1 cm/yr (0.01 to 0.8 inch/yr)—a figure comparable to the smaller retreat rate values. Anomalously high retreat rates, such as those for

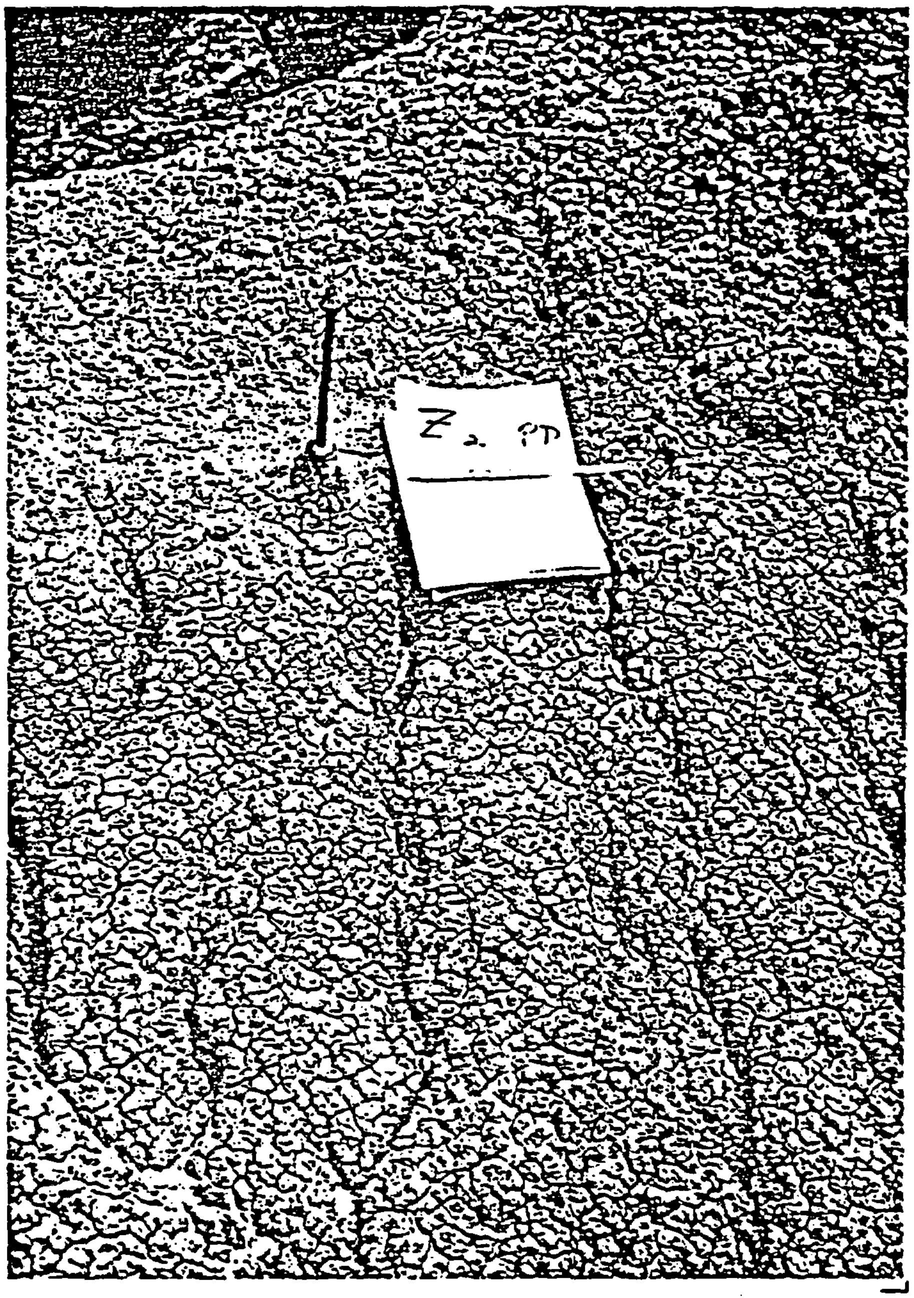

FIGURE 24. Network of rills on Triassic lacustrine sediments at Palo Duro Canyon State Park. Erosion pins in these settings are generally effective in measuring hillslope erosion from sheet and rill wash, although placement of the pin in relation to rills affects whether erosion or deposition is recorded. Note hoodoo developed under the washer owing to rainsplash processes and "popcorn crust" weathered sediment.

alluvium, suggest that processes like slumping are operating in addition to sheetwash.

Table 5 is a comparison of denudation and retreat rates from this study and those from past studies. Overall, rates of erosion and deposition are relatively rapid but are not totally unexpected given the prevailing climate and vegetation of the region. Gustavson and others (1981) suggested that these rates are probably near the maximum that could occur under the present climate.

The rates given here are useful in establishing baseline data on present-day geomorphic systems. Variation of erosion rates among stations and among sediments (soils) within a station may provide insight as to the geomorphic past and future of the region. The key to significant erosion regionally is the Caprock Escarpment, where erosionally resistant caliche and sandstone unit(s) limit the headward extension of streams abutting the High Plains surface. In both Palo Duro Canyon State Park and Caprock Canyons State Park, measurements indicate that the highest erosion rates occur on the Permian and Triassic units just east of the escarpment (table 4). In the Buffalo Lake National Wildlife Refuge and Lake Meredith National Recreation Area, it appears that alluvial sediments are excavated faster than the bedrock slopes are retreating (tables 4 through 6). Assuming that the Caprock Escarpment exhibits parallel retreat over time, a model of its retreat is suggested:

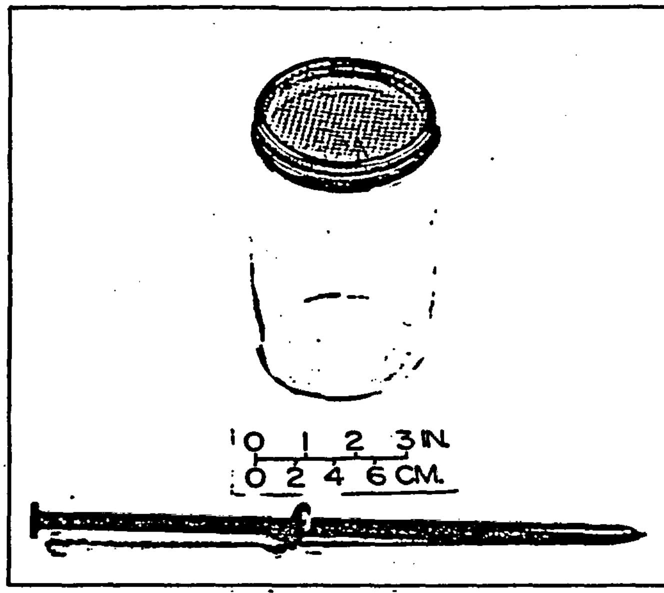

FIGURE 25. Erosion pin and washer used for measuring erosion or deposition and dust trap for collecting eolian sediment.

TABLE 3. Statistics calculated for measured erosional and depositional differences during 6-mo intervals. Means calculated on the entire normal distribution to demonstrate preference for erosion or deposition.

Station	$\bar{X}$ (cm)	S.D.	N	Maximum erosion (cm/yr)	Maximum deposition (cm/yr)
All Stations	-0.14	1.17	3,279		
Buffalo Lake National Wildlife Refuge	+0.08	0.96	416	-10.0	+7.2
Caprock Canyons State Park (West)	-0.19	0.86	646	-8.5	+5.8
Caprock Canyons State Park (East)	+0.04	0.43	152	-4.8	+2.3
Lake Meredith National Recreation Area	-0.11	0.56	886	-3.1	+5.5
Muleshoe National Wildlife Refuge	-0.16	2.78	566	-14.5	+8.2
Palo Duro Canyon State Park	-0.28	1.12	613	-6.7	+5.3

TABLE 4. Statistics calculated for erosional rates based on 3-yr data records.

Station	Rates (cm/yr) $\overline{X}$	S.	N	Maximum erosion (cm/yr)	Maximum deposition (cm/yr)
Buffalo Lake National Wildlife Refuge	+0.20	0.88	51	-2.4	+2.9
Caprock Canyons State Park (West)	-0.40	0.77	90	-2.8	+1.4
Caprock Canyons State Park (East)	+0.21	0.44	22	-0.2	+1.8
Lake Meredith National Recreation Area	-0.28	0.61	103	-2.1	+1.2
Muleshoe National Wildlife Refuge	-0.13	0.52	55	-1.9	+1.1
Palo Duro Canyon State Park	-0.61	0.74	72	-2.5	+1.4
All stations	-0.26	0.74	393	-2.8	+2.9

Table 5. Annual stream headcut or hillslope retreat rates based on 2- to 4-yr data records.

Station	Retreat rate (cm/yr) (inches/yr) Minimum		Maximum	
Buffalo Lake National Wildlife Refuge				
Alluvium	7.6	(2.3)	72.4	(28.5)
Calichified Ogallala and Blackwater Draw Formation	0.2	(0.08)	13.5	(5.3)
Caprock Canyons State Park (West)				
Calichified Ogallala and alluvium	0.8	(0.3)	1.7	(0.7)
Lake Meredith National Recreation Area				
Alluvium	6.7	(2.6)	34.0	(13.4)
Permian bedrock and alluvium	1.7	(0.7)	14.4	(5.7)

1. Permian and Triassic strata erode into badlands topography at the toes of slopes. Alluvium stored by previous events is excavated and carried out of the system. Some local storage of new slopewash sediment occurs.
2. Slope profile oversteepens because of removal of sediment at the toe of the slope. Caprock caliche and strongly cemented sandstones become unstable and are moved downslope as rockfalls.
3. Now-exhumed, less indurated Permian and Triassic sediments begin to erode by sheetwash or mass wasting. Adjustment to a new slope profile or gradient relative to the new Caprock Escarpment position begins.
4. New slope profile becomes established. Permian and Triassic units continue to erode, and Step 1 begins again.

This model suggests that during the short term, parts of the Caprock Escarpment are actually eroding at different rates, but together are continuously adjusting to a new slope profile. During the long term, the denudation and retreat rates on different parts of the slope are roughly equivalent, and the appearance and concept of parallel slope retreat are maintained.

TABLE 6. Comparison of hillslope erosion and retreat rates given in this report with those cited in Gustavson and others (1981a).

Denudation (vertical component):		
Little Red River*:	0.47 mm/yr	0.02 inch/yr
Reservoir sedimentation*:	0.61 to 2.97 mm/yr	0.03 to 0.12 inch/yr
Universal soil loss equation*:	0.57 to 2.23 mm/yr	0.02 to 0.09 inch/yr
Prairie Dog Town Fork*:	0.13 to 1.27 mm/yr	0.01 to 0.05 inch/yr
This report: (3 yr of data)		
$\overline{X}$ (total):	0.26 cm/yr	0.1 inch/yr
Range:	0 to -2.9 cm/yr	0 to -1.14 inch/yr
Retreat (horizontal component):		
Rate from age of Ogallala*:	11 cm/yr	4.3 inches/yr
Rate from age of Seymour gravel*:	18 cm/yr	7.1 inches/yr
Rate from Little Red River*:	11.5 to 13.9 cm/yr	4.5 to 5.5 inches/yr
This report (2 to 4 yr of data):		
Alluvium:	6.7 to 72.4 c./yr	2.6 to 28 inches/yr
Calichified Ogallala Formation and alluvium:	0.8 to 1.7 cm/yr	0.3 to 0.7 inches/yr

*Gustavson and others (1981a)

STOP 9: Eolian deflation and deposition, Texas Panhandle

M. D. Machenberg

Wind has substantially modified the landscape of the Texas Panhandle within historical time. Agricultural practices have locally accelerated natural rates of eolian erosion and deposition.

Deflation and eolian deposition were major geomorphic processes affecting the Southern High Plains and Rolling Plains throughout Pleistocene and Holocene time. Human activities have increased the effectiveness of wind action by disrupting the natural vegetative cover; agriculture, particularly dry-land cultivation, has been the principal form of land use in the Rolling Plains since the early 1900's. The field at this stop is approximately 5.5 km (3.5 mi) northeast of Quitaque, Texas, on FM 1065 (fig. 10) and has been deflated approximately 0.8 m (2.6 ft) since it was cleared and cultivated in the 1920's (C. D. Tunnell, personal communication, 1983). Furrows in the fields are oriented N-S, roughly parallel to the prevailing wind erosion direction (fig. 26). Strong storm winds from the north during the winter and early spring as well as prevailing southerly winds during the rest of the year remove soil aggregates and redeposit them into a broad sheet of eolian sediment. Deflation is most rapid in the spring because of (1) previous dry conditions, (2) soil expansion caused by frost heaving, and (3) mechanical disturbances associated with plowing.

In addition to plowed fields, other sources of eolian sediment include desiccated playa bottoms, sand dunes, floodplain deposits, overgrazed rangeland, construction sites, and unpaved roads. Consequently, the western part of the Texas Panhandle and adjacent New Mexico was identified as the dustiest region in the contiguous United States (Orgill and Sehmel, 1976). To assess the contribution of eolian dust deposition to the renewal of the High Plains surface, six dust collectors (fig. 25) were installed at previously established erosion- and weather-monitoring stations throughout the Panhandle (fig. 1). The contents of each dust trap are analyzed monthly. After the weight of

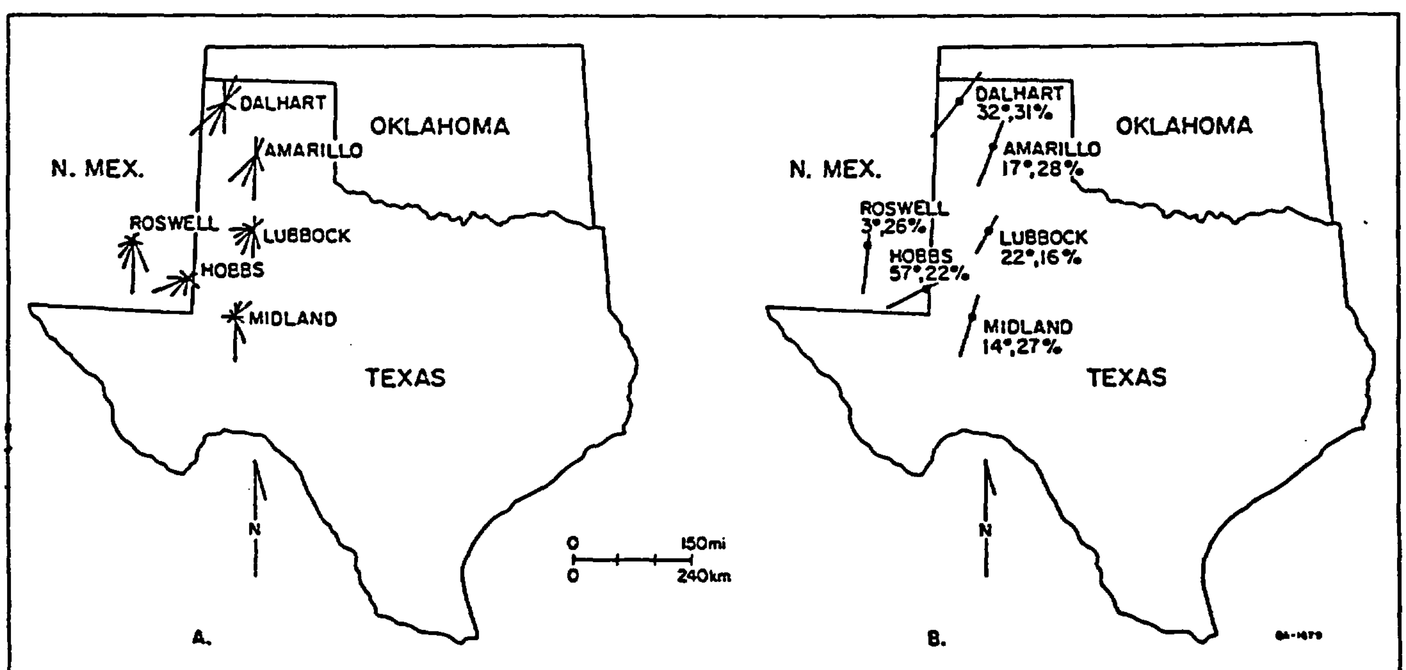

FIGURE 26. A. Wind-erosion rose diagrams, Southern High Plains. The percent of erosion and the wind-erosion direction are indicated by the length and orientation of each line in the rose. The wind blows toward the center of the rose. B. Prevailing wind-erosion directions in the Southern High Plains region, showing degrees deviation from north-south and percent erosion that occurs along that direction. The dot on each line indicates a geographic location and also divides the relative amount of erosion occurring from opposite directions. (Modified from Chepil and others [1964].)

STOP 11: Fort Worth and Denver Railroad cut

R. W. Baumgardner, Jr., and S. C. Caran

This site exemplifies the close relation between structural disturbance of Permian rocks, paleoclimate, and Quaternary deposition. Up to 8 m (26 ft) of the Quaternary section is exposed in the railroad cut. The site provides evidence of subsidence, pond development, stream incision, calichification of sandy gravel deposits, soil formation, and eolian deposition. A diverse fauna of ostracodes and mollusks is preserved in clay-rich pond deposits.

This stop consists of three parts. All are approximately 18 km (11 mi) east of the foot of the Caprock Escarpment. The stops are located in the Fort Worth and Denver Railroad cut, 0.5 km (0.3 mi) northwest of the intersection of State Highways 86 and 70 north of Turkey, Texas (fig. 10). See inset (fig. 30) for location of each stop. The three measured sections described here include paleosols that have provided radiocarbon dates ranging from 12,810 to 830 yr B.P. In this area the Quaternary sedimentary sequence is relatively thin because it was deposited over local high points on the underlying Permian rocks, and because of modern and earlier erosion. Quaternary sediments are completely absent less than 4.8 km (3 mi) to the north and east, having been removed by headward erosion along tributaries of the Little Red and North Pease Rivers (fig. 3).

STOP 11A

A 30-m-long (100-ft) section of the east wall of the railroad cut was selected for detailed description of the exposed sediments (fig. 29). The measured section (fig. 30) is located about 25 m (80 ft) south of the highway bridge over the railroad (fig. 30, inset). This part of the exposure comprises three discrete sequences of upward-fining strata, but only the upper part of the lowest sequence (Unit 3) is exposed. The middle and upper sequences decrease in grain size from gravel layers at their base to clay or sandy silt above (fig. 30). (*Note*: Stratigraphic units at different stops are numbered independently. Use of the same numbers at two or more stops does not imply correlation.)

The exposed thickness of Quaternary sediments at this measured section is about 5.6 m (18 ft). On the basis of lateral projection from the nearest outcrop of Permian rocks, approximately 1.0 km (0.6 mi) north of this site, we estimate that the total thickness of Quaternary sediments here may be 9 m (30 ft) or more. The following description begins at the base of the exposure and proceeds upward.

Unit 3B, a sandy silt, is conformably overlain by Unit 3A, a sandy silty clay. Calcium carbonate is present throughout the unit as concretions and ill-defined foci about 5 cm (2 inches) in diameter. Soil structure is weakly prismatic.

Unit 2D unconformably overlies Unit 3A on an abrupt, irregular contact. Unit 2D is a very poorly sorted, clayey, sandy gravel partly cemented by calcium carbonate. No primary sedimentary structures are preserved.

Unit 2C overlies 2D on an abrupt, irregular contact. Unit 2C is composed of fine to medium sandy clay, and is the lowermost fossiliferous stratum exposed at this site. Angular, blocky scil structure has obscured primary sedimentary features.

Units 2B and 2A are successively finer grained than 2C, and both contain abundant fossil shells of mollusks and ostracodes. Soil structure in Unit 2B is very weak, unlike that of Unit 2A, which is well-developed and microprismatic. Discrete and horizontally linked nodules of calcium carbonate are common in some laminae, but these laminae are separated by layers of clay without nodules. These features probably reflect relict bedding although the lamination is inconspicuous. In addition to its abundant mollusk shells, Unit 2A contains fine (1 mm [0.04 inch]) particles of carbonized plant material.

Both Units 2C and 2A were sampled for age dating by radiocarbon analysis of organic humates. The samples, which weighed about 4.5 kg (10 lb) each, did not contain sufficient organic matter for analysis (S. Valastro, personal communication, 1983). Frye and Leonard (1963, p. 34, fig. 2) postulated that the fossiliferous sediments exposed in the railroad cut (presumably Units 2A and 2B) were of Kansan age, overlain by Illinoisan cover sands (Units 1A and 1B). Frye and Leonard (1963) based their age determination on biostratigraphic correlation of the molluscan fauna (24 species) represented in these argillaceous strata. However,

STOP 16: A possible origin of the Tule Basin

T. C. Gustavson

The basin that contains the lacustrine Tule Formation in the vicinity of Lake Mackenzie may have resulted from the combined effects of subsidence due to dissolution of Permian salts and surface erosion during the late Pliocene and early Quaternary.

The Tule Formation (Pleistocene) is exposed around the margin of Mackenzie Reservoir at the boundary of Swisher and Briscoe Counties (figs. 43A and 43B). Access to Mackenzie Reservoir is via Texas Highway 207, approximately 15.5 km (9 mi) northwest of Silverton, Texas. Turn west from 207 at the reservoir entrance and follow the access road along the north side of the lake for 1.3 km (0.8 mi). Keep to the right. In the base of the first deep arroyo crossed by the access road, the cream to tan Tule Formation unconformably overlies the red-brown fine-grained sandstones of the Triassic Dockum Group.

Stratigraphy of the Tule Formation was discussed by Evans and Meade (1945), Frye and Leonard (1957), Reeves (1970), Kumanchan (1972), and Schultz (Stop 18, this volume). Tule Formation sediments have generally been interpreted as lacustrine deposits, although Frye and Leonard (1957) thought them to be fluvial. The presence of thin limestone and dolomite beds and laminated mudstones suggests strongly that the Tule Formation is lacustrine.

Most recently, Schultz (1977 and Stop 18, this volume) reviewed evidence of the age of these beds. On the basis of vertebrate remains and the presence of Lava Creek B Ash (Pearlette Type "O") and the Cerro Toledo-X Ash (Izett, 1977; Izett and Wilcox, 1982), Schultz suggested that the Tule Beds span most of the Irvingtonian Mammal Age (middle Pleistocene). Earlier Evans and Meade (1945) referred to these beds as middle Pleistocene, and Frye and Leonard (1957) considered them as Kansan in age. The presence of an Irvingtonian fauna within the Tule Formation indicates that the basin that it fills must have formed by the early Pleistocene.

Several possible origins of this basin have been proposed. Baker (1915) and Patton (1935) attributed the origin of the larger partly filled basins on the High Plains to subsidence due to dissolution of Upper Permian bedded salts. Evans and Meade (1945) suggested that solution and deflation were both important in developing lacustrine basins on the High Plains, deflation being the primary process. Frye and Leonard (1957) stated that the Tule Basin was a stream valley and not a deflation basin as suggested by Evans and Meade (1945). Later Reeves (1970) stated that the position of the Tule Basin, along with other large basins on the High Plains, was controlled by intersecting sets of regmatic shear fractures. Gustavson and Finley (in press) indicate that the location of the Tule Basin resulted from subsidence due to dissolution of Permian salts, but that this subsidence probably accounts for only a small part of the depth of the basin.

Dissolution of Permian bedded salts beneath the Tule Basin is suggested in figure 44, which shows that the Salado Formation salts thin by approximately 30 m (100 ft) between the Humble Oil Co. No. 1 Howard Ranch in central Briscoe County and the Gulf Oil Co. No. 1 Rodgers "D" well near Tule Creek. Overlying and underlying nonsalt beds do not change in thickness or lithology, which suggests that neither Permian structural nor facies changes can account for the changes in salt thickness. Differences in regional dip between beds overlying and underlying the Salado Formation salts west of the Humble well indicate that subsidence has occurred.

Core through the Salado Formation in the Stone and Webster Engineering Corp. No. 1 Zeeck and the DOE/Gruy Federal No. 1 Grabbe wells, which lie several kilometers west and northwest, respectively, of the Tule Basin, both contain insoluble residues and gypsum-filled extension fractures resulting from dissolution of Salado Formation salts. The net-salt map of the Salado Formation salts in the vicinity of the Tule Basin shows that Salado salts thin from 45 m (150 ft) in central Briscoe County to less than 15 m (50 ft) beneath the Tule Basin (fig. 44).

If dissolution of salt has in fact occurred, then the structure of overlying units should reflect subsidence. Elevation of the Alibates Formation decreases from approximately 795 m (2,625 ft) above sea level in central Briscoe County to about 758 m (2,500 ft) beneath the Tule Basin, nearly paralleling the changes in Salado salt thickness (fig. 45). A structure-contour map of the middle Tertiary erosion surface at the base of the Ogallala Formation shows a paleotopographic trough similar to and overlying the structural trough on the Alibates Formation (fig. 46). The vertical juxtaposition of (1) thin salt in the Salado Formation,