Regional geology of Ochoan evaporites, northern part of Delaware Basin

By George O. Bachman

CIRCULAR 184 New Mexico Bureau of Mines & Mineral Resources 1984

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

FRONT COVER—Index map of southeastern New Mexico and western Texas showing approximate position of Capitan Limestone (reef) and area discussed in this report.

Circular 184

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Regional geology of Ochoan evaporites, northern part of Delaware Basin

by George O. Bachman

Star Rte Box 1028, Corrales, New Mexico 87048

SOCORRO 1984

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
Laurence H. Lattman, *President*

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES
Frank E. Kottlowski, *Director*
George S. Austin, *Deputy Director*

BOARD OF REGENTS

Ex Officio
Toney Anaya, *Governor of New Mexico*
Leonard DeLayo, *Superintendent of Public Instruction*

Appointed
Judy Floyd, President, 1977–1987, *Las Cruces*
William G. Abbott, Secretary-Treasurer, 1961–1985, *Hobbs*
Donald W. Morris, 1983–1989, *Los Alamos*
Robert Lee Sanchez, 1983–1989, *Albuquerque*
Steve Torres, 1967–1985, *Socorro*

BUREAU STAFF

Full Time

Orin J. Anderson, *Geologist*
Ruben Archuleta, *Technician I*
Brian W. Arkell, *Coal Geologist*
Al Baca, *Crafts Technician*
James M. Barker, *Industrial Minerals Geologist*
Robert A. Bieberman, *Senior Petrol. Geologist*
Steve Blodgett, *Associate Editor*
Nancy A. Blount, *Coal Lab Technician*
Lynn A. Brandvold, *Senior Chemist*
James C. Brannan, *Drafter*
Ron Broadhead, *Petroleum Geologist*
Brenda R. Broadwell, *Assoc. Lab Geoscientist*
Frank Campbell, *Coal Geologist*
Richard Chamberlin, *Economic Geologist*
Charles E. Chapin, *Senior Geologist*
Jeanette Chavez, *Admin. Secretary I*
Richard R. Chavez, *Assistant Head, Petroleum*
Ruben A. Crespin, *Laboratory Technician II*
Lois M. Devlin, *Director, Bus./Pub. Office*
Nanette Dynan, *Staff Secretary*
Robert W. Eveleth, *Mining Engineer*
K. Babette Faris, *X-ray Lab Manager*
Rousseau H. Flower, *Sr. Emeritus Paleontologist*
Michael J. Harris, *Metallurgist*
Zana Harvey, *Clerk-Typist*
John W. Hawley, *Senior Env. Geologist*
Carol A. Hjellming, *Editorial Secretary*
Gary D. Johnpeer, *Engineering Geologist*
Annabelle Lopez, *Staff Secretary*
David W. Love, *Environmental Geologist*
Jane A. Calvert Love, *Assistant Editor*
Wess Mauldin, *Driller*
Virginia McLemore, *Geologist*
Lynne McNeil, *Staff Secretary*
Norma J. Meeks, *Department Secretary*
David Menzie, *Manager, Inf. Ctr.*
Teresa A. Mueller, *Sci. Illustrator I*
Diane Murray, *Geologist*
Robert M. North, *Mineralogist*
Keith O'Brien, *Hydrologist*
Glenn R. Osburn, *Economic Geologist*
JoAnne Cima Osburn, *Coal Geologist*
Kathryn E. Parker, *Drafter*
Barbara R. Popp, *Biotechnologist*
Marshall A. Reiter, *Senior Geophysicist*
Jacques R. Renault, *Senior Geologist*
James M. Robertson, *Mining Geologist*
Gretchen H. Roybal, *Coal Geologist*
Deborah A. Shaw, *Assistant Editor*
William J. Stone, *Hydrogeologist*
Samuel Thompson III, *Senior Petrol. Geologist*
Judy M. Vaiza, *Executive Secretary*
Manuel J. Vasques, *Mechanic*
Robert H. Weber, *Senior Geologist*
Linda L. Wells-McCowan, *Drafter*
Donald Wolberg, *Vertebrate Paleontologist*
Michael W. Wooldridge, *Chief Sci. Illustrator*
Lisa Zangara, *Receptionist*
Jiri Zidek, *Chief Editor–Geologist*

Research Associates

Christina L. Balk, *NMT*
Russell E. Clemons, *NMSU*
William A. Cobban, *USGS*
Aureal T. Cross, *Mich. St. Univ.*
John E. Cunningham, *WNMU*
Wolfgang Elston, *UNM*
Marian Galusha, *Amer. Mus. Nat. Hist.*
Jeffrey A. Grambling, *UNM*
Joseph Hartman, *Univ. Minn.*
Alonzo D. Jacka, *Texas Tech. Univ.*
David B. Johnson, *NMT*
William E. King, *NMSU*
Edwin R. Landis, *USGS*
David V. LeMone, *UTEP*
A. Byron Leonard, *Kansas Univ.*
John R. MacMillan, *NMT*
Howard B. Nickelson, *USGS*
Lloyd C. Pray, *Univ. Wisc.*
Allan R. Sanford, *NMT*
John H. Schilling, *Nev. Bur. Mines & Geology*
William R. Seager, *NMSU*
James E. Sorauf, *SUNY Binghamton*
Richard H. Tedford, *Amer. Mus. Nat. Hist.*
Jorge C. Tovar R., *Petroleos Mexicanos*
Lee A. Woodward, *UNM*

Graduate Students

Margaret Barroll
James T. Boyle
Lee Brouillard
Steven M. Cather
Gerry W. Clarkson
Ted Eggleston
Charles Ferguson
Grant Goodyear
Adrian Hunt
Laura Kedzie
Richard P. Lozinsky
Jeffrey Minier
Stewart Smith
Stephen Turnbull

Plus about 50 undergraduate assistants

Original Printing, 1984

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Plant, May 1984

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

Contents

Figures

Tables

Abstract

The Ochoan Series (Permian) in the northern part of the Delaware Basin, southeastern New Mexico, includes in ascending order the Castile, Salado, and Rustler Formations, and the Dewey Lake Red Beds. The Castile and Salado Formations comprise a sequence of evaporites which include anhydrite, gypsum, halite, and associated potash salts. The Rustler Formation contains some halite and minor amounts of potash minerals. These evaporites were deposited within the basin formed by the Capitan barrier reef, as well as across the reef. The evaporites, as well as the Capitan *reef*, are all subject to dissolution with resulting karst features analogous to those formed in limestone regions.

An Ancestral Pecos River was the major drainage system in the western part of the Delaware Basin, New Mexico, during late Cenozoic time. That ancient river system was responsible for the formation of an extensive karst terrain along the east side of the present Pecos River in New Mexico and southward into Texas. During late Cenozoic time extensive dissolution occurred in the Salado Formation within the karst area as a result of the ground-water regime. The dissolution front was perched on the upper anhydrite member of the Castile Formation.

On the eastern side of the Delaware Basin in New Mexico, a large collapse sink—San Simon sink—overlies the Capitan reef which is a prominent aquifer system in that area. So-called "breccia pipes" are ancient sinks which collapsed into the caverns in the reef on the northern margin of the basin. These have since been partially exhumed. The San Simon sink is presumed to be a modern analog of these breccia pipes.

Introduction

Numerous studies of the Delaware Basin have been undertaken with various objectives. The earliest comprehensive studies were the result of exploration for petroleum. Drill holes penetrated Ochoan and older Permian rocks, providing control points for correlation of stratigraphic units. Potash minerals were discovered east of Carlsbad in 1925. Development of these deposits included extensive drilling programs to determine their extent and grade. As a result of this development, the details of the potash-bearing formations are well understood within the potash mining district in the north-central part of the Delaware Basin.

More recently, intensive studies have been undertaken in a limited area in the north-central part of the Delaware Basin to determine the feasibility of storing radioactive waste in underground beds of salt. These studies have provided background for the proposed construction of a Waste Isolation Pilot Plant (WIPP). Numerous drill holes have penetrated portions of the Ochoan Series, the salt-bearing rocks, during these background studies.

The present work was undertaken to summarize some of the knowledge derived from these studies and to examine the regional geology of part of the salt-bearing Ochoan Series in a northern part of the Delaware Basin. The Castile Formation, the basal unit of the Ochoan Series, underlies the WIPP site. Minute details of some aspects of the Castile have been studied in the past, but its regional stratigraphy and geologic setting have been neglected. Some concern has been expressed by critics of the WIPP site that soluble rocks in the Castile might be dissolved to provide an unstable base for the site. For these reasons, most effort during the present study concentrated on the regional setting of the Castile.

The Salado and Rustler Formations, the other salt-bearing units in the Ochoan Series, receive less attention here. They are discussed only as background for the consideration of processes of subsurface dissolution.

Methods of study included examination of surface exposures over much of the northern part of the Delaware Basin. The relationship of Ochoan rocks to adjacent deposits has been studied to evaluate the history of those rocks since their deposition. Ancient drainage systems were studied both by field observations and examinations of well logs. More than 300 wire-line logs of drill holes in the northern part of the Delaware Basin were examined. Cores were studied from drill holes in the vicinity of the proposed WIPP site as well as from other parts of the basin.

J. W. Mercer and R. P. Snyder of the U.S. Geological Survey contributed generously their time and knowledge of the Delaware Basin. J. W. Mussey of Duval Mining Corporation provided core of the Castile Formation for study. The manuscript was reviewed and constructively criticized by John W. Hawley of the New Mexico Bureau of Mines and Mineral Resources, and Lokesh Chaturvedi of the State of New Mexico Environmental Evaluation Group.

Stratigraphy

Ochoan Series

Rocks of Permian age in southeastern New Mexico and western Texas are divided, from oldest to youngest, into the Wolfcampian, Leonardian, Guadalupian, and Ochoan Series. They were deposited in marine environments in a tectonically negative area, the Delaware Basin (Fig. 1). Rocks from Wolfcampian through Guadalupian age are mostly fine-grained sandstones, siltstones, shales, and various types of limestone. During Guadalupian time, the Capitan reef was built as a massive limestone barrier which fringed the margins of the Delaware Basin. As defined by the Capitan reef, the Delaware Basin was an elongate, bowl-shaped depression. Most of early Ochoan deposition was confined to this basin. Later, during Ochoan time when the basin became filled with sediments, some beds lapped across the reef into adjacent areas.

Most of the rocks deposited during Ochoan time were evaporites such as anhydrite, halite, and potash minerals with only minor amounts of limestone, mud-stone, and siltstone. The rocks of the Ochoan Series are subdivided into (ascending) Castile Formation, Salado Formation, Rustler Formation, and Dewey Lake Red Beds. Within the Delaware Basin, the Castile Formation rests on the Bell Canyon Formation of the Guadalupian Series. The stratigraphic relations of Ochoan rocks in the northern part of the Delaware Basin are shown in Figure 2.

Castile Formation

The Castile Formation, the basal unit of the Ochoan Series, was named by Richardson (1904, p. 43) for Castile Spring in Culberson County, Texas, about 20 mi south of the New Mexico—Texas State line. For a time the Castile was divided into a "lower" and "upper" salt series. Lang (1935, pp. 265-267) separated the "upper salt series" from the Castile and named it the Salado Formation.

Later, an extensive bed of anhydrite, which rests on the Capitan Limestone in places in the subsurface, was defined as the base of the Salado Formation (Lang, 1939). This anhydrite was described in detail and named the Fletcher Anhydrite Member of the Salado Formation (Lang, 1942, pp. 75-78). This definition served to restrict the Castile to the Delaware Basin.

However, Jones (1954, p. 109; 1973, p. 10) indicated that the upper part of the Castile includes a northward-thinning tongue of anhydrite which overlaps the Capitan and Tansill Formations outside the basin. This tongue appears to include the Fletcher, which is transitional with the upper part of the Castile in the Delaware Basin. The Fletcher is readily separated from the main body of Castile anhydrite around the margin

FIGURE 1—Index map of southeastern New Mexico and western Texas showing approximate position of Capitan Limestone (reef) and area discussed in this report.

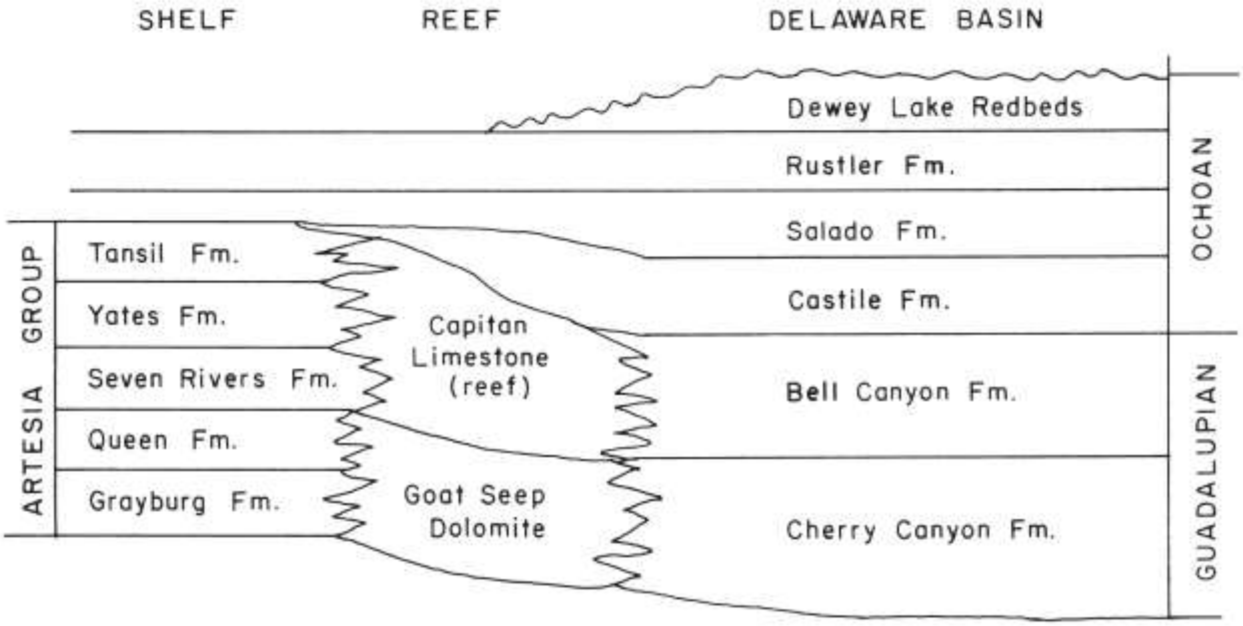

FIGURE 2—Diagram showing nomenclature and stratigraphic relations of Guadalupian and Ochoan rocks in northwestern part of the Delaware Basin.

of the basin, where it rests on the Capitan or Tansill Formations; but within the basin it merges with, and is indistinguishable from, a sequence of thick anhydrite in the upper part of the Castile.

Anhydrite is the dominant rock type in the Castile Formation. Halite is present as several massive beds in the formation in the subsurface, but is much less prominent than the halite in the overlying Salado Formation. Limestone interlaminated in anhydrite, thin beds of limestone, and minor amounts of dolomite and magnesite are also constituents of the Castile. Where the Castile Formation is exposed along the western side of the Delaware Basin, the halite beds have been either removed by dissolution or were never deposited in that area; and the anhydrite has been altered to gypsum. At these surface exposures the gypsum may be either massive or thinly laminated.

Interlaminated anhydrite and limestone are distinctive lithologic features in the Castile Formation. Attempts to explain these laminae have occupied numerous investigators. Udden (1924) suggested that these laminae represent annual cycles of sedimentation. Adams (1944, pp. 1604-1606) described the laminae in detail. He recognized that typical laminae consist of alternating bands of calcite and anhydrite. Bituminous material stains the carbonate deep brown. Where the calcite is absent, "brown organic bands are present along the bedding planes of the anhydrite. The bituminous material, however, is nowhere mixed with the white anhydrite as it is with calcite" (Adams, 1944, p. 1604).

Adams observed that there are almost unlimited variations in the character of the laminae. He described the gross features as follows:

> Where evenly developed, the laminae resemble chemical varves with the anhydrite layers two or three times as thick as the calcite . . . Individual carbonate partings range from scattered calcite crystals on the anhydrite bedding planes to beds of thinly laminated limestone several feet thick. The limestones are not dolomitic. The average thickness of the calcite laminae appears to be about 1/20 inch. Thin sections show that the thinnest laminae are made up of one layer of coarsely crystalline calcite, and that the thicker beds are coarsely granular limestone.
>
> Irregularly distributed through the normal banded zones are beds of unlaminated anhydrite, ranging from 1/2 inch to several feet in thickness, and separated by banded zones that vary even more widely. There is a tendency for secondary calcite crystals to develop in fractures and to wavy ghost-like bands or even sprinkled about at irregular intervals, through these thicker anhydrites. The secondary calcite is almost everywhere lighter-colored than that of the normal laminae. (Adams, 1944, p. 1604.)
>
> In addition to the primary variations in the calcite-banded anhydrite of the Castile Formation, there are many secondary irregularities. Calcite laminae disappear in nodular masses of anhydrite. Concretionary anhydrite lenses grow between the partings and disrupt them. Bands of crinkled laminae appear to writhe about between flat beds, and in some transverse zones all evidence of bedding is lost. More important still is the faulting, fracturing, and slipping that characterize most of the cores and outcrops. Since most of the variations occur both at the surface and at depths of thousands of feet, it is assumed that most of them were produced by early diagenetic processes. (Adams, 1944, p. 1606.)

Anderson et al. (1972) studied the petrology and depositional history of the Castile Formation in great detail. They counted and measured approximately 260,000 couplets of calcite-laminated anhydrite in the core of one drill hole in Culberson County, Texas. They correlated individual laminae in this core with those in a core from a drill hole in Winkler County about 56 mi to the east. In other studies they have correlated individual laminae for distances as great as 70 mi (Anderson et al., 1978).

Although anhydrite and gypsum in the Castile Formation are usually thinly laminated, massive beds of these rock types are present in places in the upper part of the formation. Adams (1944, p. 1605) observed that the banded anhydrite is absent in the upper 800 ft of the Castile in the northeast part of the Delaware Basin. Along the western edge of the basin in New Mexico, many surface exposures of the Castile include beds of massive white gypsum (Hayes, 1964). Elsewhere in the subsurface, laminated anhydrite may grade upward into massive anhydrite (Adams, 1944, p. 1605; Jones, 1954, p. 109; 1973, p. 9). These massive beds are correlative with other beds of known Castile age in the subsurface and cannot be correlated with any unit within the overlying Salado Formation.

Near all the margins of the Capitan reef in New Mexico the Castile Formation consists entirely of anhydrite or gypsum, with the exception of one or more thin beds of limestone along the western margin. Away from the margins of the basin one or more beds, or lenses, of halite are interbedded with the anhydrite. The number of halite beds increases towards the center of the basin, where as many as five discrete sequences of halite are present. Locally, halite interfingers with thin beds of anhydrite to form complex strati-graphic units.

Informal members of the Castile Formation have been described and designated by Roman numerals (Anderson et al., 1972) as (ascending) Basal Limestone, Anhydrite I, Halite I, Anhydrite II, Halite II, Anhydrite III, Halite III, and Anhydrite IV. The Basal Limestone is too thin to be recognized in well logs and is not discussed in this report. An additional set of halite beds was recognized locally within Anhydrite IV during the present work. These are designated Halite V.

Where halite beds are present in the Castile below Anhydrite III, the members are remarkably uniform in thickness and stratigraphic expression. This indicates that from the outset of Castile deposition through the deposition of Halite II the basin was stable over much of its area. Halite I consists of almost pure halite. Halite II usually contains five anhydrite interbeds which are correlative over almost the entire basin wherever Halite II is represented.

During deposition of Anhydrite III, the Delaware Basin became mildly unstable with some local differential subsidence. This is reflected in logs of drill holes in southern Lea County, New Mexico, where within a distance of 9 mi there is progressive thickening of each stratigraphic unit above Halite II. In a drill hole in sec. 18, T. 26 S., R. 34 E., the interval from the base of Anhydrite III to the top of the Castile is 100 ft thicker than the same interval in a drill hole to the west, in sec. 15, T. 26 S., R. 32 E. The thickening would be less remarkable if it would not be accompanied by an increase in halite content. This has resulted in complex facies changes within a relatively short distance. These facies changes are also indicated in the logs of drill holes in the same area along a north—south line (Fig. 6 in pocket).

It is generally agreed that during Castile time the Delaware Basin was a steep-sided, closed marine basin confined by the Capitan barrier reef except for a low passage to the southwest. The basin was connected to the open sea by a channel through which water entered the basin to replace water lost by evaporation. Water from the open sea entered the basin as a surface layer which extended down to wave base. The laminations in the anhydrite are assumed to represent annual layers which resulted from evaporation of sea water and precipitation of sulphate salts. Calcium sulphate was deposited as anhydrite below the wave base (King, 1947).

Dean and Anderson (1982) summarize the characteristics of Castile lithology and discuss its depositional environment. They agree with earlier workers that the Delaware Basin was a deep, starved basin which filled rapidly with evaporites. They note that there is no evidence of shallow water deposition and that water in the Delaware Basin was deep enough to preserve the delicate details of individual laminae. They suggest that the initial depth of the basin "was at least several hundred meters" (Dean and Anderson, 1982, pp. 330-331). Of particular interest is their observation that with the continuous filling of the basin with evaporites "the factors which affect salinity . . . were affecting a progressively shallower basin and hence a smaller volume of water. The smaller the volume of water being affected, the less buffered the evaporative system is and therefore the greater the possibility for larger variations in salinity" (Dean and Anderson, 1982, p. 331). Variations in salinity are indicated in the central part of the basin by intricate interbedding of anhydrite and halite in the upper part of the Castile (Figs. 5 and 6 in pocket).

There is little indication of a well-defined axis of deposition in the northern part of the Delaware Basin during much of Castile time. The Castile averages from about 1,500 to 1,700 ft in thickness in the subsurface, where the only complete stratigraphic sections are found. Locally, the Castile is more than 2,100 ft thick in north-central Loving County, Texas (Fig. 3). Distribution of these variations in thickness appears to be random. During the deposition of Halite III there may have been a northwesterly trending depositional axis (Fig. 4) which shifted to the south and changed its trend to northerly as the basin filled during the deposition of Halite IV.

Castile—Salado contact

The interpretation of the Castile—Salado contact is basic to an interpretation of the history of dissolution; consequently, this contact was studied in detail. As generally accepted, the contact between the Castile and the overlying Salado Formations is between massive beds of anhydrite in the Castile and a sequence dominated by halite, potash minerals, and thin beds of anhydrite in the Salado. Adams (1944, p. 1608) and other workers have described an "angular unconformity" between the Castile and the Salado in the north and east parts of the Delaware Basin. Jones (1954, p. 108; 1972, p. 39; 1973, p. 10) indicated that the contact between the Castile and Salado is gradational and interfingering.

The present study generally confirms the conclusions outlined by Jones. There is no evidence in the northern part of the Delaware Basin of a disruption of deposition at the end of Castile time, nor of dissolution between the two formations. The only places where a hiatus is found between the Castile and Salado Formations is where dissolution of salt in the Salado has occurred subsequent to deposition. In the

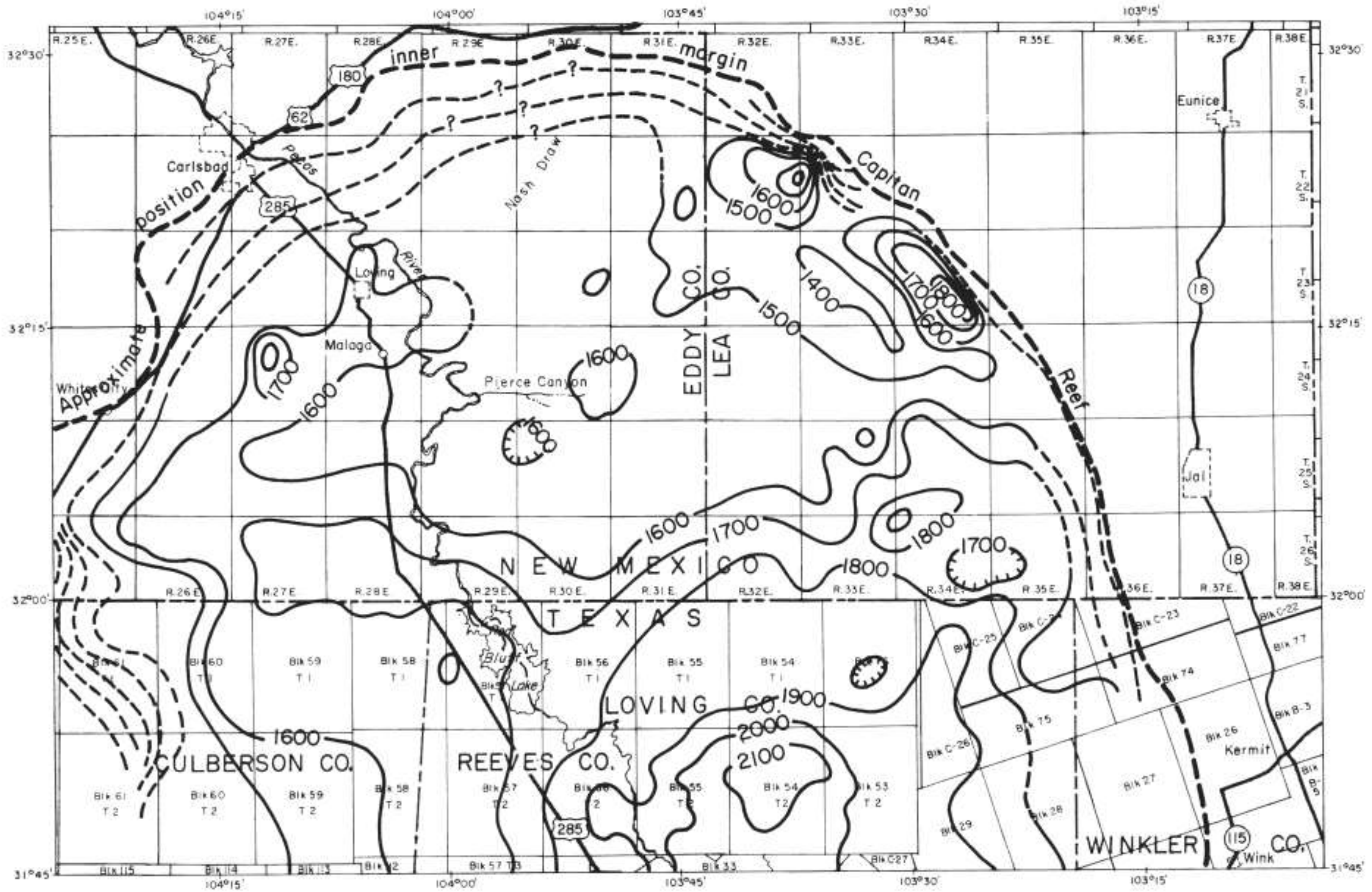

FIGURE 3—Isopach map of Castile Formation.

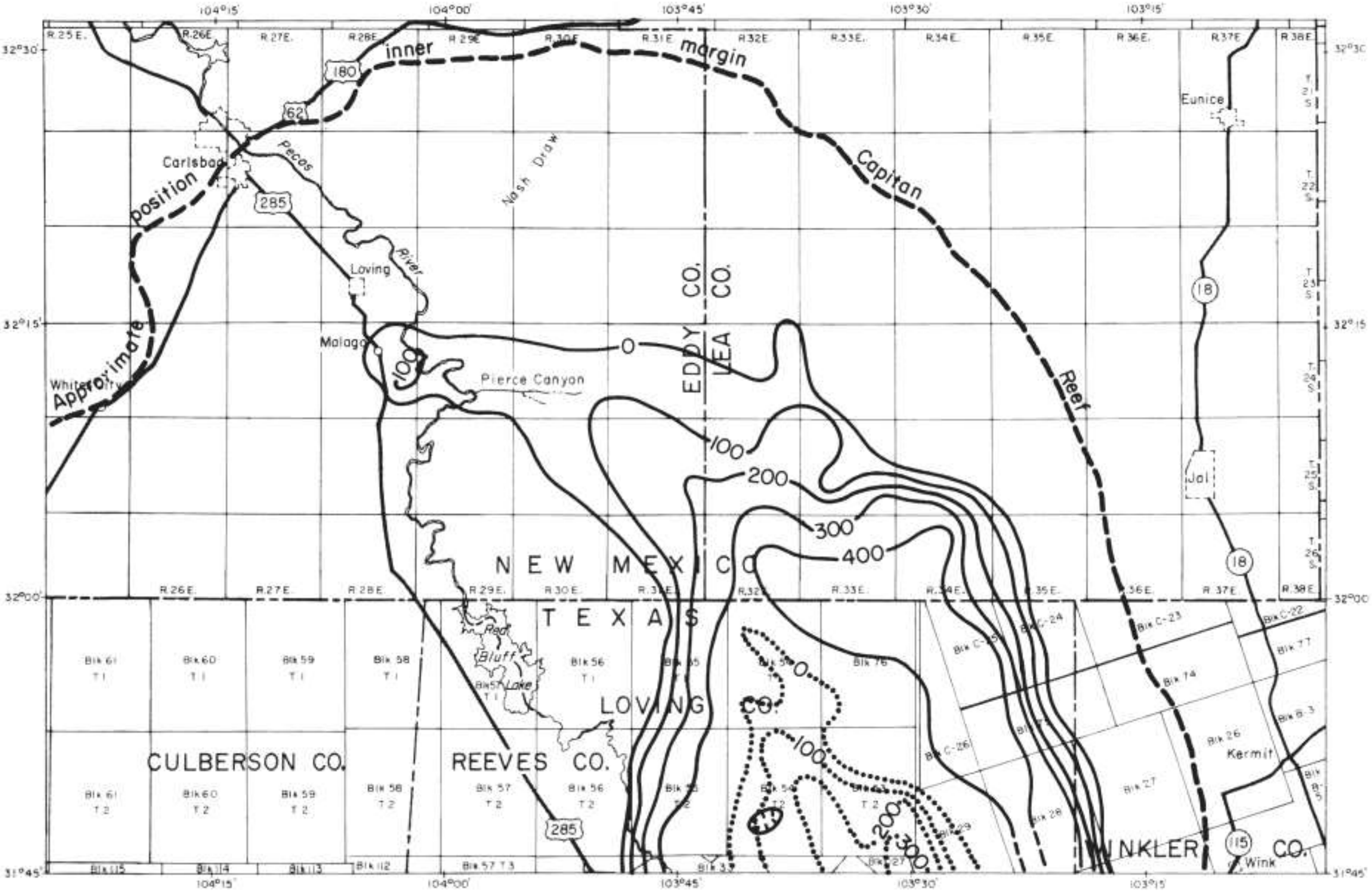

FIGURE 4—Isopach map of Halite III (anhydrite interbeds included) and Halite IV. Isopach lines of Halite IV shown as dotted line.

deepest part of the basin in southeastern Lea County, New Mexico, and northeastern Loving County, Texas, halite beds make up a prominent part of the upper Castile. There the basal anhydrite beds in the Salado (including the Cowden Member) merge by interfingering with massive anhydrite of the upper Castile (Figs. 5 and 6 in pocket). Kroenlein (1939) was aware of this stratigraphic relationship. This interpretation is only slightly different from that of Jones (1954, p. 108), who has drawn the Salado—Castile contact in the south part of the present study area on a bed of anhydrite somewhat lower in the stratigraphic section than drawn in this report. In spite of this difference in nomenclature, the interpretation of depositional history resulting from this study is similar to that implied by Jones.

In most places the contact between the two formations is sharp. Problems of nomenclature occur only in the area of interfingering lithologies. The determination of formation boundaries presented here was made only after correlation of distinctive marker beds throughout the Salado and Castile Formations, from the potash district in the northern part of the basin through numerous closely spaced drill holes to the southern part of the study area. The present interpretation of stratigraphic relations conforms to the model of deposition proposed by Dean and Anderson (1982). They suggested that filling of the basin indicates a smaller volume of water for evaporation and larger variation in salinity. This condition could explain the fluctuations in anhydrite—halite deposition at the close of Castile time, and the transition to dominant halite deposition in Salado time.

In the southern part of Eddy County, New Mexico, and southward into Texas, the boundary between the Castile and the overlying Salado is marked by solution breccias and residue of the Salado which rest on the anhydrite of the Castile. At places anhydrite beds in the Salado collapsed onto Castile anhydrite, where they became indistinguishable from one another. In these areas the base of the Salado is indicated on wireline logs by a marked change in the traces of sonic transit time and gamma rays. Castile traces are characteristically uniform, with only minor fluctuations. Solution breccias, collapsed beds, and residue in the Salado are marked by broad fluctuations in the log traces (Fig. 7). These brecciated beds indicate a discontinuity between the two formations, which developed by dissolution long after they were deposited.

Salado Formation

The so-called "upper" salt series of early workers was named the Salado Formation by Lang (1935) for Salado Wash in Loving County, Texas. His type locality was in a drill hole, the "Means well" (SE corner sec. 23, blk. C-26, P. S. L., Loving County, Texas). The Salado Formation includes halite, minor beds of anhydrite, and commercial deposits of potash minerals. Owing both to commercial interest and background studies for construction of the WIPP site, the Salado has been studied intensively in the northern part of the Delaware Basin.

In the potash district in Eddy County, New Mexico, numerous so-called "marker beds" have been recognized in the Salado Formation (Jones et al., 1960; Jones, 1978; Sandia Report, 1982a, b). These distinctive beds include potash-ore horizons and thin beds of siltstone or anhydrite. They are persistent within the potash district, and some are recognized over much of the Delaware Basin in New Mexico and southward into Texas.

Marker beds are designated by informal names or by a numbering system. Only those prominent marker beds useful to the discussion of dissolution in the present report are treated here. They are listed in Table 1. The intervals between marker beds on this list include halite and potash minerals. Approximate thicknesses of marker beds, intervals between marker beds, and lithologic descriptions are from Sandia Reports (1979, 1982a, b, 1983) and wire-line logs of Patoil, Wright Federal, No. 1 (sec. 27, T. 23 S., R. 32 E.). The Cowden Anhydrite (see Table 1) is about 180 ft above the base of the Salado Formation in the northern part of the Delaware Basin. It merges with massive anhydrite of the Castile Formation in southwestern Lea County, New Mexico, and northeastern Loving County, Texas.

In the subsurface, the Salado Formation ranges from about 1,200 to 2,300 ft in thickness. Much of this variation in thickness is the result of removal of rock salt by dissolution. Surface exposures of the Salado Formation consist only of brecciated gypsum embedded in clay, which is mostly a residuum from the dissolution of salts (Fig. 8).

Rustler Formation

The Rustler Formation was named by Richardson (1904, p. 44) for exposures in the Rustler Hills, Culberson County, Texas, about 20 mi south of the New Mexico—Texas State line. In that area only the lower part of the formation is exposed. In many areas of southeastern New Mexico much of the Rustler has been removed by dissolution and erosion, and complete stratigraphic sections are found only in drill holes. At many places the salts in the Rustler have been removed by dissolution even in the subsurface.

The Rustler Formation may be divided into five lithologic units. These include, in ascending order, an unnamed sequence of reddish-brown siltstone with interbeds of gypsum or anhydrite and halite, the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member. The Culebra and Magenta Members were named by W. B. Lang (Adams, 1944). The Tamarisk and Forty-niner Members were named by Vine (1963).

The Rustler ranges in thickness from a thin dissolution breccia at places on the surface to more than 550 ft in the subsurface in southwestern Lea County. Over much of the study area it averages 300-350 ft in thickness. Much of the variation in thickness is the result of the dissolution of salts. The basal unnamed member, as well as the Tamarisk and Forty-niner Members, include halite with some associated potash minerals in undisturbed sequences in the subsurface. At places where the salts have been dissolved, a "collapse breccia" occupies their stratigraphic position. At these places the anhydrite is usually altered to gypsum.

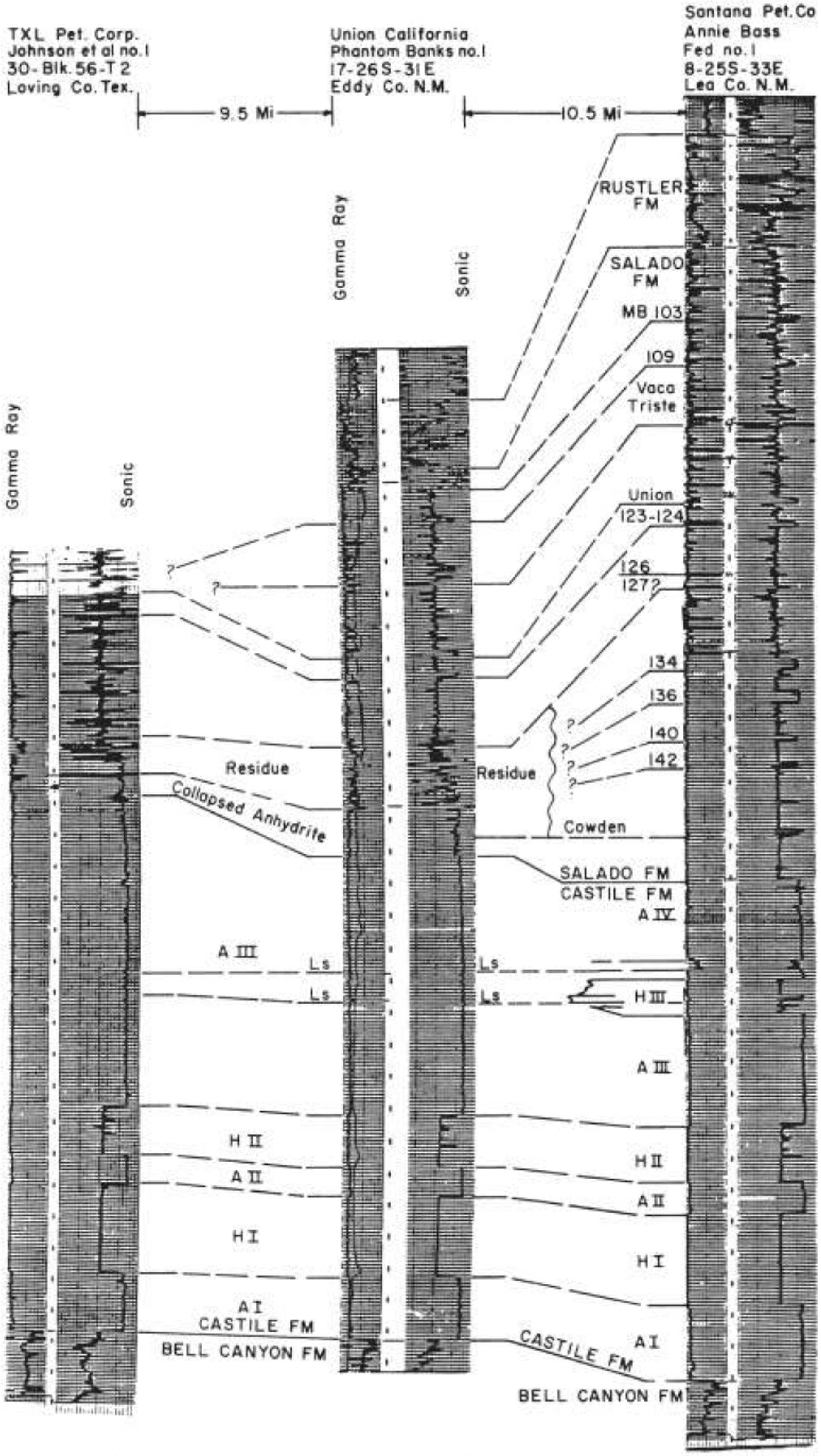

FIGURE 7—Correlation of marker beds. The log of the Santana well in Lea County, New Mexico, illustrates a relatively normal stratigraphic section of evaporites in the Castile and Salado Formations. The log of the Union well in Eddy County, New Mexico, illustrates dissolution of halite beds in the Salado Formation from the approximate horizon of marker bed 127 to the top of the Castile Formation. Minor dissolution has occurred in the upper part of the Salado. This well is near the eastern margin of the Ancestral Pecos drainage system. The log of the TXL well in Loving County, Texas, indicates that pervasive dissolution has occurred in both the lower and upper parts of the Salado Formation. This well was drilled near the center of the Ancestral Pecos drainage system. There is no evidence of dissolution in any part of the Castile Formation in any of these drill holes. Halite III is absent in the TXL and Union wells due to non-deposition.

TABLE 1—The more prominent marker beds in the Salado Formation, potash district in Eddy County, New Mexico.

	Thickness	Lithology
Top of Salado Fm.		
180-ft interval		
MB 103	20 ft	Anhydrite
120-ft interval		
MB 109	20 (+) ft	Anhydrite, finely crystalline, interbedded thin stringers of halite, polyhalite, and mudstone.
200-ft interval		
Vaca Triste (of Adams, 1944)	10 ft	Siltstone and silty mudstone, brownish, interbedded with halite.
210-ft interval		
Union Anhydrite	15–20 ft	Anhydrite, finely crystalline, with stringers of halite.
70–90-ft interval		
MB 123	5–10 ft	Halite and polyhalite. Distinctive sequence overlying MB 124.
MB 124	5–10 ft	Anhydrite, finely crystalline, laminated. May have stringers of mudstone.
390-ft interval		
MB 134	10–15 ft	Anhydrite, gray, dense.
70-ft interval		
MB 136	10–15 ft	Anhydrite, light gray, dense. May have interbeds of halite or polyhalite.
200-ft interval		
MB 142	15 ft	Anhydrite with interbeds of halite and stringers of mudstone.
150-ft interval		
Cowden Anhydrite	ca 20 ft	Anhydrite, finely crystalline, laminated, may have thin interbeds or stringers of magnesite and mudstone. Divided into two units by intervening halite in southeastern Eddy County, New Mexico.

Both the Culebra and Magenta Members are distinctive stratigraphic markers useful in estimating the amount of dissolution which has occurred in the halite-bearing members. The Culebra is a brownish-gray, thinly bedded, finely crystalline dolomite. Many layers are marked by distinctive brownish vugs that range from 2 to 10 mm in diameter. The Culebra averages 25-30 ft in thickness.

The Magenta Dolomite Member is a thinly laminated dolomite with couplets of anhydrite or gypsum. The laminae are generally less than 10 mm thick. At surface exposures the laminae are undulatory—probably because of the expansion of gypsum during its hydration from anhydrite. The dolomite laminae are light reddish-brown and the anhydrite or gypsum is gray. The Magenta ranges from 20 to 30 ft in thickness.

Dewey Lake Red Beds

The Dewey Lake Red Beds are the uppermost formation in the Ochoan Series. They were named by Page and Adams (1940, pp. 62-63) based on a subsurface stratigraphic section in Glasscock County, western Texas. This formation has been called the Pierce Canyon Redbeds (Lang, 1935, p. 264) for exposures in the vicinity of Pierce Canyon southeast of Loving, New Mexico. However, owing to the poor definition of the Pierce Canyon and the wider acceptance of the term Dewey Lake among geologists, the U.S. Geological Survey has abandoned the Pierce Canyon and extended the term Dewey Lake to New Mexico for this stratigraphic interval.

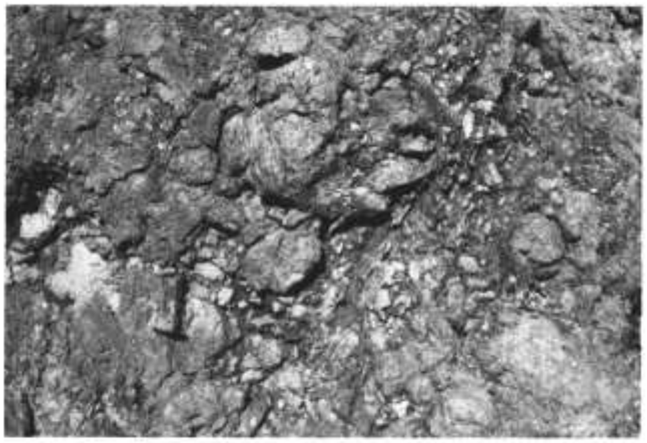

FIGURE 8—Collapse breccia in Salado Formation. Breccia includes gypsum, siltstone, and reddish clay.

The Dewey Lake Red Beds rest conformably on the Rustler Formation and consist mainly of alternating thin, even beds of moderately reddish-brown to moderately reddish-orange siltstone and fine-grained sandstone. There are occasional small-scale laminations and ripple marks. Many beds are mottled by greenish-gray reduction spots. Well-sorted quartz grains constitute most of the rock. Cement is usually selenite or clay.

Beds of Triassic age rest unconformably on, and overlap, the Dewey Lake Red Beds; and the thickness and regional distribution of the Dewey Lake is related directly to erosion before Triassic time. The Dewey Lake is thickest in eastern Eddy and western Lea Counties, where it is as much as 560 ft thick. It thins towards the west and is absent in some exposures where Triassic rocks lap across the westernmost line of outcrop.

Mesozoic rocks overlying the Ochoan Series

To understand the post-depositional history of the Ochoan Series, it is necessary to consider the distribution of overlying strata. These strata include Triassic, Cretaceous, and Cenozoic rocks.

Rocks of Triassic age

Rocks of Triassic age are exposed along the northeastern rim of Nash Draw and in isolated collapse-sink deposits in the Pecos Valley. These exposures are erosional remnants of deposits which formerly extended continuously northward into east-central New Mexico. Triassic rocks are dark reddish-brown, cross-laminated, poorly sorted conglomeratic sandstones with interbeds of dark reddish-brown sandy shale. They were deposited in a fluvial—deltaic—lacustrine system whose depositional edge coincides approximately with the western edge of the Delaware Basin (McGowen et al., 1977). The position of this depositional edge overlying the Ochoan Series indicates that evaporites were exposed, or near the surface, and available for dissolution during Triassic time.

Rocks of Cretaceous age

In regions where complete stratigraphic sections are preserved, rocks of Jurassic age overlie Triassic strata. However, rocks of Jurassic age have not been preserved, and regional stratigraphic relations indicate that they were never deposited in southeastern New Mexico.

Rocks of Early Cretaceous age (Washita) are preserved at a few localities in the Pecos Valley as collapse-sink deposits. These rocks consist of marine, fossiliferous sandy limestones. At one locality, 5 mi northeast of Carlsbad, Cretaceous rocks are mingled with collapse blocks of Culebra Dolomite and Triassic conglomerate. At two localities, 6 mi and 7.8 mi southwest of Whites City, Cretaceous rocks have collapsed on gypsum of the Castile Formation, and are associated with isolated blocks of Culebra Dolomite. Triassic rock debris has not been observed at these localities. The absence of Triassic rocks suggests that Triassic sediments either were not deposited in this area, or were removed by erosion before Cretaceous time.

Cenozoic rocks

Ogallala Formation

The Ogallala Formation (Miocene—Pliocene) consists largely of well sorted, yellowish-brown to light reddish-brown, wind-blown sand. Poorly sorted stream deposits and carbonate pans are locally present. The Ogallala is capped by the "caliche caprock," which was deposited by soil-forming processes. Ogallala sediments were derived from the west and deposited on an irregular erosional surface as a series of complex overlapping and coalescing alluvial fans. The Ogallala Formation is well represented on the northeast side of the Delaware Basin, but it is absent west of San Simon Swale except for thin exposures at the Divide.

Gatuna Formation

The Gatuna Formation (early? to middle Pleistocene) consists mainly of pale reddish-brown sand and sandy clay. Locally it contains yellowish sand and lenticular bodies of river gravels. The widespread reddish-brown sediments are presumed to have been deposited on a flood plain. A bed of volcanic ash is present near the top of the formation on the east side of Nash Draw. This ash has been identified as Lava Creek Ash (Izett and Wilcox, 1982), which is about 600,000 years old.

Soils

Two soils of Pleistocene age have been identified in the western part of the Delaware Basin. These are the Mescalero caliche and the Berino soil.

The Mescalero caliche is an informal stratigraphic unit named for the Mescalero Plain, a broad geomorphic surface which lies east of the Pecos River and west of the High Plains in southeastern New Mexico. It was deposited by soil-forming processes and consists of earthy, nodular to well-cemented calcareous caprock. It accumulated on a relatively stable land surface and has provided a useful datum for timing some Pleistocene and Recent events. By measuring uranium series disequilibrium, it has been determined that the Mescalero caliche began to accumulate about 510,000 years ago and the upper crust formed about 410,000 years ago (J. N. Rosholt, written comm. 1979).

The Berino soil is an informal stratigraphic unit which consists of dark red, sandy, argillic paleosol. It overlies the Mescalero at some places. The Berino is non-calcareous. The uranium-series disequilibrium technique indicates that the Berino began to form about 350,000 (± 60,000) years ago (J. N. Rosholt, written comm. 1979).

Dissolution of evaporites

Dissolution of evaporites in the Ochoan Series in southeastern New Mexico has been discussed by many geologists. One of the earliest attempts to place the events of evaporite deposition in geologic time was by Adams (1944, pp. 1622-1624), who described salt dissolution in the Delaware Basin and concluded that it occurred during geologic time as follows:

1. Dissolution occurred first during Permian time, when the upper salt series of the Castile (Adams' "third group") was partially dissolved during the break between Castile and Salado deposition.
2. At the close of Salado and the beginning of Rustler deposition the west edge of the Delaware Basin was uplifted and truncated. Subsequent erosion left a series of solution valleys in the potash district southeast of Carlsbad. These valleys were covered and filled by Rustler sediments.
3. During Triassic time Salado salts were removed along the east edge of the Delaware Basin from the Pecos River northward into New Mexico. "The so-

lution trough developed at this time is 800 or 900 feet deep and is filled by an over-thickened section of Triassic" (Adams, 1944, p. 1623).

4. Post-Triassic—pre-Cretaceous salt solution is not indicated in the Delaware Basin.
5. The main period of solution in the Delaware Basin took place during the Tertiary. "The main trough is roughly bordered on the east by the Pecos River, and extends from Carlsbad, New Mexico, to Toyah Lake in Texas" (Adams, 1944, pp. 1623-1624). At one place in Reeves County, Texas, this trough is more than 1,300 ft deep. Adams suggested that the sinking trough was filled with sediments as fast as it formed.

Of these episodes of dissolution only those assigned to Triassic and Cenozoic were recognized during the present work.

Maley and Huffington (1953) described three extensive accumulations of Cenozoic fill in the Delaware Basin. The fill has a maximum thickness of approximately 1,900 ft. Localization of the fill deposits is attributed to the formation of depositional basins by evaporite dissolution. They constructed an isopach map of the total amount of salt present in the combined Castile and Salado Formations. This map indicates that the fill is generally thickest in areas where salt deposits are thin or absent. They attributed the localization of solution to tilting of the Delaware Basin, chiefly during late Tertiary time, with the consequent removal of salt by solution. Further, they suggested that the local basins were formed initially by local concentration of runoff and downward percolation of water which gradually dissolved the underlying salts. Maley and Huffington (1953, p. 543) did not believe that the areas of deep fill represent the former course of the Pecos River because "according to this concept, the thickness of fill should represent the depth of the former stream valley." They failed to recognize that subsurface dissolution may cause collapse and fill at the surface until the depth of fill is below the local base level of erosion.

Anderson et al. (1972, p. 81; 1978, pp. 47-52; 1980, pp. 66-69) discussed dissolution of halite and described "dissolution breccia" in the Castile—Salado sequence in the western part of the Delaware Basin. Their conclusions are listed as follows (Anderson et al., 1978, p. 52):

1. Every salt bed recognized on accoustical logs in the eastern side of the Delaware Basin has an equivalent bed of dissolution breccia in the western side of the basin, indicating that all of the western salt-bed margins are dissolutional rather than depositional.
2. The dissolution of salt beds proceeded downdip from the western edge of the basin, with the preferred dissolution horizons occurring between the Halite III salt of the Castile Formation and the 136 marker bed of the Salado Formation.
3. Downdip dissolution within the body of evaporites undercut the overlying salt beds for distances in excess of 20 mi, and more extensive dissolution at these same horizons in localized areas resulted in large scale collapse and dissolution features such as Big Sinks depression.

Anderson and Kirkland (1980, pp. 66-69) described a theoretical process of "brine density flow" which they believe had been responsible for the dissolution of salt deposits in the Delaware Basin. According to their definition, "gravity flow of brine occurs when fresh water contacts the salt body and becomes more dense by dissolution of salt. The differential density between the brine and fresh water causes movement of brine downward along separate and distinct pathways, but in the same fracture system or permeable zone as the rising fresh water. The descending brine ultimately flows through the aquifer to a point of natural discharge and, because the system is under artesian pressure, the brine flow is continuously replaced by fresher water. Sustained flow results in the enlargement of dissolution chambers or an advancing front of dissolution. Subsequent collapse of competent beds causes brecciation." (Anderson and Kirtland, 1980, p. 66.)

Anderson (1981) adapted the concept of brine density flow to large scale depressions within the Delaware Basin as well as to the deep depressions along the margin of the eastern reef. He assumed that there is communication between the lower Salado Formation, where a dissolution horizon is recognized, and the underlying Delaware Mountain Group (Bell Canyon) aquifer. Fracture permeability could have developed within the basin through the dissolution and collapse of lower Castile salt and subsequent stoping to the stratigraphic level of the lower Salado (Anderson, 1981, p. 143). However, there is no evidence in the northern part of the Delaware Basin that the lower Castile salt has been dissolved.

Lambert (1983, p. 83) indicates another discrepancy in Anderson's model. He reasons that the solute relationships in the small amount of Bell Canyon waters could not have arisen from simple evaporite dissolution. Bell Canyon waters have consistent Na/Cl ratios which range from 0.46 to 0.56, whereas the Na/Cl ratio of brines resulting from dissolution of salt is about 0.64 (Johnson, 1981).

Understanding of dissolution in the Ochoan Series is dependent on an understanding of regional stratigraphic and geologic history, as well as on drill-hole data. The writer has previously outlined a history of dissolution in the Delaware Basin in New Mexico (Bachman, 1980, pp. 81-85). That outline was based on extensive field work and study of the literature. It is summarized here as follows:

Erosion and dissolution occur while land masses are above sea level. The region of southeastern New Mexico was uplifted at the close of Permian time. It was above sea level throughout Triassic and Jurassic times. During the Early Cretaceous the region was again below sea level. Isolated occurrences along the Pecos Valley in New Mexico of rocks containing Early Cretaceous marine fossils provide evidence for that incursion of the sea. At the close of Cretaceous time the entire region was lifted above the sea level again. In summary, the region has been above sea level for a minimum of 154 million years, and below sea level for less than 71 million years since the end of the Permian.

Erosion and dissolution were active processes along the western margin of the Delaware Basin during Triassic time. Streams flowed easterly across the basin from a highland in the vicinity of the present Sacramento Mountains. The depositional wedge-edge of Triassic rocks was along a line trending northeasterly in the vicinity of the modern Pecos River.

Triassic stream deposits indicate that a water table was present in strata immediately overlying the Ochoan Series. Field relations of Triassic and Permian rocks about five miles northeast of Carlsbad and along the east side of the Pecos River near Red Bluff Reservoir indicate that the upper part of the Rustler Formation, including the Magenta Dolomite, was removed before or during Triassic deposition. Elsewhere in the Delaware Basin, Adams (1929, p. 1050) believed that as much as 400 ft of Upper Permian beds may have been removed from the basin during Permian time.

Jurassic deposits are not present in the Delaware Basin, but geologic relations in regions to the north and south of the basin indicate that southeastern New Mexico continued to be above sea level as an area of non-deposition throughout Jurassic time. It may be assumed that erosion and dissolution were active processes during that time.

Although Jurassic rocks are not represented in the Delaware Basin, and deposits which contain marine Cretaceous fossils did not collapse until long after the rocks had lithified, the association of other rock types with the Cretaceous deposits indicates the depth of erosion before Cretaceous time. These rock associations indicate the following stratigraphic relations along the western edge of the Delaware Basin in New Mexico:

1. Rocks above the Culebra Dolomite were partially removed in the vicinity of the modern Pecos River before Cretaceous time.
2. The Salado Formation was removed completely in a belt along the western margin of the basin in New Mexico before Cretaceous time, allowing the Culebra Formation to rest on the Castile Formation. Much of this removal was by dissolution.

The above observations are outlined to indicate that some dissolution of Ochoan evaporites occurred during long periods of the geologic past. The quantitative results of that dissolution are conjectural. The most obvious evidence for dissolution consists of features and deposits visible in the present Pecos Valley. These features were formed during Cenozoic time. Some dissolution of evaporites in the Ochoan Series continues today. The processes by which this dissolution takes place are here considered to be analogous to the formation of karst terrain in limestone regions.

Karst processes in evaporites

Most studies of karst terrain, the study of landforms which develop in soluble rocks, have been conducted in limestone regions. These regions include areas in Great Britain, Central Europe, Yugoslavia, Kentucky, and many other parts of the world. Caves, underground rivers, and springs characterize these regions. Evaluation of public water supplies has been an incentive to the study of these features and the processes which formed them. Consequently, karst in limestone terrains has been described extensively in the literature.

Limestone is composed mainly of calcium carbonate and is soluble in acids. Atmospheric water normally carries varying amounts of carbon dioxide which forms a weak carbonic acid in solution. Thus, in combination with geologic time, atmospheric water dissolves limestone to etch out the distinctive features of karst landscape.

Karst features form as readily in evaporites as in limestone, but ground water in contact with evaporites is usually of poor quality. Consequently, there has been little interest in the study of karst or subterranean water systems in those regions, and relatively few papers on karst processes in evaporites have been published. Those areas where such processes are recognized include Italy, France, Germany, Oklahoma, Texas, and New Mexico (Herak and Stringfield, eds., 1972). The rising interest in beds of salt as potential isolation bodies for the storage of nuclear waste provides a new incentive for the study of karst in evaporites.

Acidic solutions are not a prerequisite to the solubility of halite and associated salts. These rocks are extremely soluble in fresh water. The only requirement for their dissolution is unsaturated water which flows across the rocks through an open, circulating system. The continuation of this process through geologic time leaves behind a relatively insoluble residue of collapsed breccia and clay. Even limited supplies of unsaturated water through geologic time are sufficient to create huge areas of complex solution breccias and karst features. The writer has examined brecciated karst areas in evaporites over hundreds of square miles in the desert of central Saudi Arabia, where the annual rainfall averages less than two inches.

Anhydrite alters by hydration to gypsum when exposed to surface or vadose water. This process results in expansion of about 35% by volume, which may close some fractures and prevent the passage of water (Jakucs, 1977, pp. 79-80). However, it also results in buckling of rocks at the surface, which may open other passages. Buckling and tension are responsible for fracturing and jointing gypsum to open passages across bedding planes. Joint sets are commonly observed in surface exposures of gypsum. These systems of open fractures provide paths for surface water to dissolve evaporites at depth. Collapse sinks develop along these fractures and act as sumps for surface water (Fig. 9).

Without fractures the permeability of either anhydrite or gypsum is negligible. For example, salt interbedded in anhydrite in the subsurface Castile Formation is well protected from dissolution by the anhydrite. Contrary to the statement of Anderson et al. (1978, p. 52) that "every salt bed recognized on acoustical logs in the eastern side of the Delaware Basin has an equivalent bed of dissolution breccia in the western side of the basin . . . ," there is no evidence in the present study area that subsurface beds of salt present in the Castile, as that formation is here recognized, have been subjected to dissolution since they were deposited.

The karst cycle begins with surface drainage. At maturity there is maximum underground drainage in

FIGURE 9—View across collapse sink in Rustler gypsum, Nash Draw, eastern Eddy County, New Mexico, showing joint control.

caverns, sink holes, and blind valleys. At times during the cycle dissolution fronts move laterally as perched ground-water tables in these subterranean systems. The cycle of dissolution is completed when all soluble rocks are removed and drainage returns to the surface. The only indications of past karst processes may be remnants of insoluble residues, brecciation, and disruption of intervals in the soluble portion of the stratigraphic column. The results of this cycle can be observed in some ancient deposits in southeastern New Mexico.

The Ancestral Pecos River

Few studies of paleokarst have been undertaken and most of these have been limited to discussions of cave fillings in carbonate rocks such as those which mark unconformities at some stratigraphic horizons. Only recently the study of paleokarst has attracted the attention of geologists involved in problems of nuclear waste disposal. Studies in western Texas have linked regional dissolution of salt to Miocene—Pliocene (Ogallala) stream systems (Gustayson et al., 1980). These ancient stream systems were responsible for dissolving evaporites to form collapse sinks which were later filled with sediments.

A similar ancient river system, the Ancestral Pecos River, was responsible for the dissolution of large amounts of evaporites and the formation of collapse features in southeastern New Mexico. During Pleistocene, and probably later Tertiary, the Ancestral Pecos River occupied channels to the east of its present course (Fig. 10). It flowed southeasterly across the area now cut by Pierce Canyon, where it left channel deposits. It flowed across the area of Poker Lake and built terraces along the New Mexico—Texas State line as far east as Phantom Banks. Some of the collapse features south of Pierce Canyon depicted on a structural map of the Rustler Formation (Hiss, 1976) resulted from dissolution in this stream system.

The Ancestral Pecos was a high-energy stream capable of carrying pebble and cobble debris as large as 2^3/4 inches in diameter far from its source. Igneous-rock types (porphyry) completely foreign to the Delaware Basin are present in channel and terrace deposits in both Pierce Canyon and in the vicinity of Phantom Banks. These rock types were traced by the writer up the Pecos and Hondo drainages to their source in the Capitan and Sierra Blanca Mountains about 100 mi northwest of Carlsbad.

Thus, during some of its history the Ancestral Pecos drainage system was far different from the modern river. Today the Pecos River is sluggish, at places it flows underground, and its erosive action is largely corrosional. The load it carries is mostly solutes derived from the dissolution of evaporites. Sediments, except for flocculents, settle into sinks and other dissolution cavities in the river bed and probably are not being transported out of the evaporite karst area.

The Ancestral Pecos River was an extant drainage system during middle Pleistocene, at least 600,000 y.B.P. This age is indicated in Pierce Canyon and adjacent areas, where ancestral-river gravels are interbedded with sediments in the Pleistocene Gatuna Formation. In Pierce Canyon the uppermost ancestral-river gravels are at the top of the Gatuna, which indicates only that middle Pleistocene is a minimum age for these gravels. The maximum age of the Gatuna Formation is not known, and it is probable that the ancestral Pecos system was initiated in late Tertiary time, when erosion of the eastern slope of the Sacramento—Sierra Blanca—Capitan uplift began.

Although the Ancestral Pecos River had a tremendous carrying power, it also began a new episode of dissolution of evaporites. At first it was a through-flowing river. Then, at least as early as by middle Pleistocene, it formed a karst plain southeasterly from the latitude of Malaga. In Pierce Canyon a lenticular channel gravel 780 ft across and 78 ft thick collapsed into a sink (Figs. 11, 12). The Magenta Dolomite is also collapsed into a chaotic structure in the upper reaches of Pierce Canyon. At the mouth of Pierce Canyon, near the channel of the modern Pecos River, the rim of an extensive sediment-filled collapse sink is defined by steeply dipping beds in the Gatuna Formation. Dissolution on the karst plain initiated Poker Lake as a collapse sink.

Some filled sinks described by Maley and Huffing-ton (1953) were created by the Ancestral Pecos River. They stated that "the thickness of fill should represent the depth of the former stream valley" (Maley and Huffington, 1953, p. 543). This observation would be

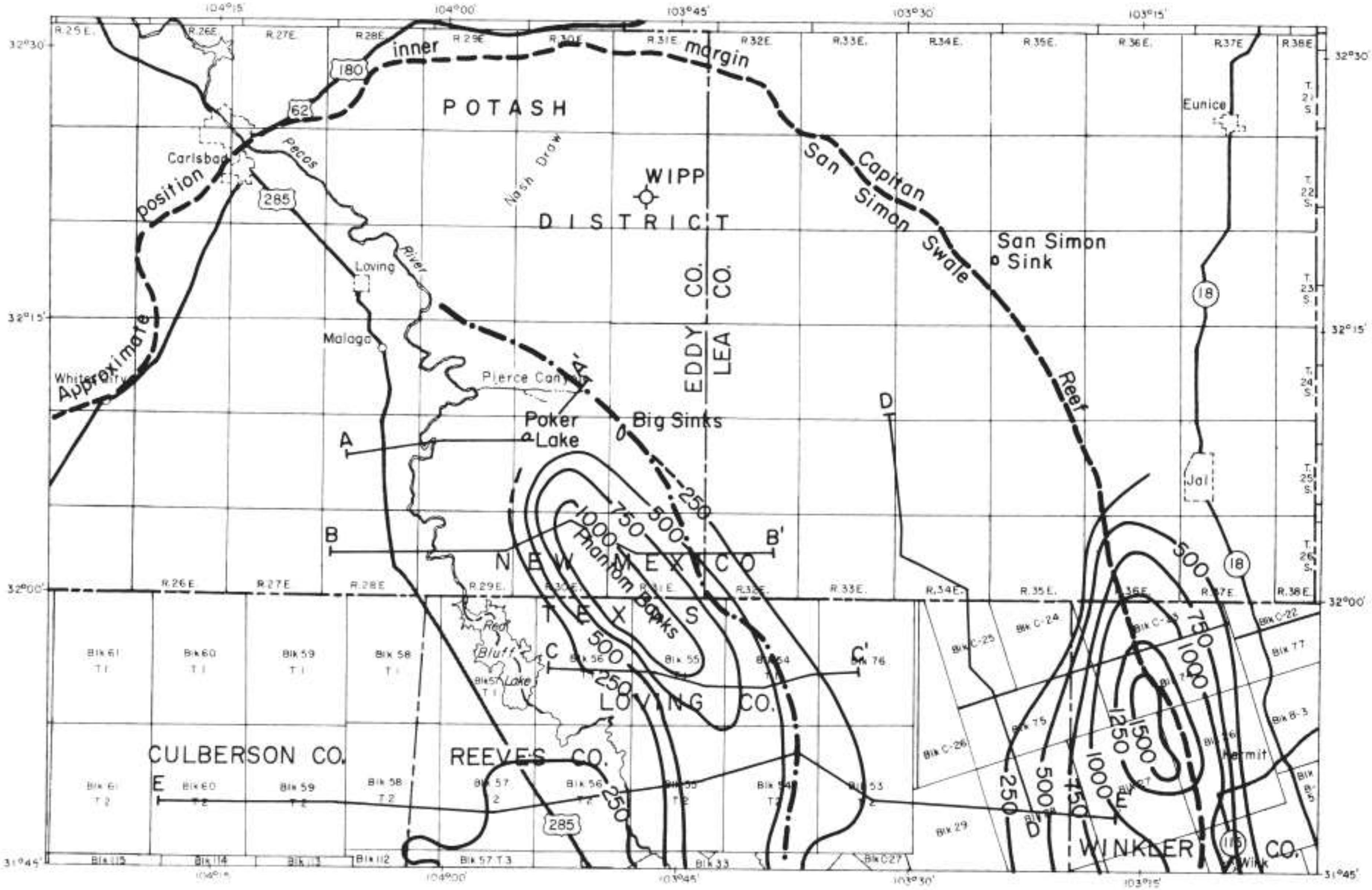

FIGURE 10—Index map showing position of Ancestral Pecos River and isopachs of Cenozoic fill. Cenozoic isopachs generalized from Maley and Huffington (1953); —— · —— · —— indicates eastern margin of Ancestral Pecos drainage system.

FIGURE 11—Collapsed channel gravel in upper part of Gatuna Formation in Pierce Canyon, Eddy County, New Mexico. Channel is 780 ft across and 78 ft thick. The Mescalero caliche engulfs the upper bed of the channel.

relevant if the valley had been cut entirely by erosion. However, karst valleys may dissolve their course far below the level of surface drainage. Repeated episodes of dissolution and collapse followed by filling of the collapsed feature are capable of creating deep, sediment-filled sumps beneath, and adjacent to, the river bed.

Salt has been dissolved from the basal part of the Salado Formation in a belt to the east of the Pecos River and southward from the latitude of Malaga and Pierce Canyon. This belt coincides with the course of the Ancestral Pecos River (Fig. 10, Fig. 13 in pocket). Along this belt dissolution has removed beds in the stratigraphic section to varying horizons within the formation. Residue, breccia, and collapsed beds of anhydrite are the only remnants of the dissolution process. At most places dissolution has occurred from the top of the Castile to the 137 marker bed in the Salado and at the base of the Rustler Formation. Salt beds with their intervening anhydrite marker beds are recognized and well preserved in the Salado Formation above the 137 horizon (Fig. 7). However, at places along this belt salt beds throughout the Salado have been dissolved (Fig. 13 in pocket). The remaining beds are a jumble of residue and breccia with marker anhydrite beds collapsed into an indistinguishable mass.

The selective dissolution in the Salado between the 137 marker bed and the uppermost anhydrite in the Castile Formation indicates that this interval has been available to a through-flowing system of underground water, which was perched on the Castile anhydrite. This dissolution front undercut beds in the Salado immediately overlying the Castile. An analogous hydrologic situation is present in the northern part of the Delaware Basin, in the vicinity of the WIPP site. There a hydrologic system—the so-called "brine aquifer"—is present at the contact between Salado salt and the overlying Rustler Formation (Mercer, 1983, p. 47). Brine is perched on a thin, clayey residue at the top of the Salado Formation. It flows laterally at various rates. This aquifer has been studied intensively for many years, first because it transports contaminating brine to the Pecos River, and secondly because it is part of the hydrologic investigation of the WIPP site (Mercer and Orr, 1977; Mercer, 1983).

The "brine aquifer" has been monitored in three drill holes (designated H-1, H-2c, H-3; Mercer and Orr, 1977, pp. 56-70) in the immediate vicinity of the WIPP site. Water gains access to the system through fractures in recharge areas as far north as Bear Grass Draw (T. 18 S., R. 30 E.) about 30 mi north of Malaga Bend, and probably in Clayton Basin and Nash Draw (Mercer, 1983, pp. 49-53) where it flows across salt beds before reaching the observation wells. By the time it reaches these observation wells, it is near saturation and dissolution is minimal. In the vicinity of the WIPP site, brine in this aquifer flows westerly from the site and towards Nash Draw (Mercer and Gonzales, 1981, p. 128; Mercer, 1983, p. 51).

Although salt beds in the Rustler Formation have been dissolved in Nash Draw, resulting in chaotic stratigraphy to the west of the WIPP site (Mercer, 1983, p. 45, fig. 5), "east of Nash Draw where the Rustler Formation is covered and protected by the Dewey Lake Red Beds and younger rocks, structures are less chaotic and the Rustler attains a more regular character" (Mercer, 1983, p. 45). In the three observation wells at the WIPP site, salt is intact in the Rustler Formation overlying the brine aquifer. However, it is apparent that dissolution of adjacent salt beds would occur if a steady supply of unsaturated water was introduced into the system. The brine aquifer is an example of a hydrologic system which has undercut a formation.

The relative impermeability of an anhydrite explains the persistent zone of dissolution in the lower part of the Salado Formation in the belt east of the Pecos River. During Pleistocene time, when water was more plentiful, it penetrated fractures along the western side of the Delaware Basin and upstream along the Pecos River. The water percolated downward to the impermeable anhydrite at the top of the

FIGURE 12—Close-up view of gravel in channel deposit shown in Figure 11. Gravel is cemented by lime carbonate.

Castile Formation, where it was perched and could only move laterally. The halite beds in the Salado became vulnerable to dissolution. Perched water tables are common in karst regions, and it is not necessary to explain this dissolution by the rather complex "brine density flow" mechanism proposed by Anderson and Kirkland (1980).

The Castile anhydrite has been an effective barrier to dissolution. At places where Halite III is present beneath the dissolution zone in the Salado, it has remained untouched by dissolution. The more deeply buried Halites I and II are likewise intact. Contrary to the conclusion of Anderson et al. (1978, p. 52), based on the situation farther south in Texas, that "all western salt-bed margins are dissolutional rather than depositional," Castile salt-bed margins in the western part of the basin in New Mexico are depositional. To the north, in the vicinity of the WIPP site, close examination of cores indicates that there is no solution breccia in the Castile anhydrite in the projected interval of Halite III. It can only be concluded that Halite III was never deposited in that area.

Since Pleistocene time, the Pecos River has migrated to the west of its ancient course. It is now entrenched in a series of karst features which include collapse sinks and caves. At places in Eddy County the river flows primarily underground.

Although the Mescalero caliche did not form on an absolute plane, a comparison was made of elevations on the Mescalero at places where it has engulfed ancestral stream deposits. For example, the elevation of ancient river deposits near Carlsbad is 3,170 ft, whereas at Pierce Canyon their elevation is 3,050 ft. This indicates a gradient of about 5.2 ft per mile between Carlsbad and Pierce Canyon, which corresponds to the gradient of the modern river. However, the elevation of terrace and overbank deposits at Phantom Banks is 3,180 ft, 10 ft higher than at Carlsbad and 130 ft higher than at Pierce Canyon. This suggests that the area in the vicinity of Pierce Canyon and as far north as Carlsbad has subsided since modern entrenchment of the river. Some areas in the vicinity of Pierce Canyon may remain undermined and continue to subside. In fact, some features along the Pecos River which superficially resemble oxbows (cutoff meanders) are actually controlled by relatively recent collapse of the surface. However, the modern entrenchment of the Pecos River insures that dissolution on the scale of that in the vicinity of Pierce Canyon during the Pleistocene has ceased.

Dissolution along the eastern margin of the Delaware Basin

The Capitan reef is a major aquifer around the margin of the Delaware Basin, and has been influential in the process of dissolution along the eastern margin of the basin. An area of thick Cenozoic fill has been outlined near the New Mexico—Texas State line on the east side of the basin (Maley and Huffington, 1953, pl. 1). However, the major portion of this fill is to the south, in Winkler County, Texas, where salt has been dissolved from the Salado Formation directly above the reef. Salt was probably never deposited there in the Castile Formation. Drill holes adjacent to the reef in Lea County, New Mexico, do not indicate that dissolution has altered the stratigraphic section either above, or adjacent to, the reef.

Farther north in Lea County, New Mexico, the San Simon sink is a prominent collapse feature that overlies the reef. This sink has been drilled as part of the background studies for the WIPP site. Unfortunately, it was drilled only to a depth of about 800 ft. Cenozoic sand and clay comprise the upper 545 ft and rest on collapsed Triassic red beds. As the roots of this collapse sink were not penetrated, it is impossible to interpret the mechanism by which the sink formed, or the horizon in the subsurface which has been dissolved to allow the sink to collapse.

The San Simon sink is extremely restricted geographically. Exploratory drill holes for oil and gas in surrounding areas (including the large San Simon Swale depression) show no dissolution of underlying evaporites and indicate only limited areas of Cenozoic fill. For these reasons the San Simon sink cannot be compared with the broad area of dissolution along the east side of the Pecos River south of Pierce Canyon. It is more readily compared with the breccia pipes which overlie the Capitan reef on the northern margin of the Delaware Basin (Bachman, 1980, pp. 61-73; Snyder and Gard, 1982). These features are also restricted to relatively small chimneys, which may have collapsed into a cavern in the Capitan reef itself (Snyder and Gard, 1982, p.62). They represent the core of a feature reminiscent of the present-day San Simon sink. The San Simon sink itself is presumed to be an actively collapsing breccia pipe. The thick Cenozoic fill along the eastern margin of the Delaware Basin in Texas may represent localities where the karst process of breccia chimney formation has been carried to maturity.

Conclusions

Since the end of Permian (Ochoan) time, evaporites in the Delaware Basin in New Mexico have had many exposures to atmospheric waters which have dissolved some of the more soluble portions of these rocks. However, major dissolution has been restricted to areas where river systems have initiated karst systems, or to limited areas which overlie the Capitan reef aquifer. There is no evidence for deep dissolution in the Castile Formation in the central part of the basin.

An Ancestral Pecos River system developed during Cenozoic time along the western side of the Delaware Basin. This ancient river system was responsible for the development of an extensive karst terrain along the east side of the Pecos River in southeastern Eddy County, New Mexico, and southward into Loving County, Texas. At that time salt beds of the Salado Formation were dissolved and removed completely at some places. At other places the dissolution was selective, restricted mostly to the basal part of the Salado Formation. All the dissolution in the ancient Pecos River system was the result of a dissolution front perched on the upper anhydrite in the Castile Formation during Cenozoic time. Salt beds in the Castile Formation in the northern part of the Delaware Basin have not been subject to the dissolution process. Dissolution on the east side of the Delaware Basin in New Mexico has been limited to pipe-like collapse sinks which overlie the Capitan aquifer.

Anderson (1982) regards the Waste Isolation Pilot Plant site as an area predisposed to deep-seated dissolution. He concludes that salt is missing "from the horizon of the repository, at localities not too distant from the site, and by a largely unknown dissolution process." The present work indicates that dissolution along the western margin of the Delaware Basin was by karst processes which were active during late Tertiary or Pleistocene time under hydrologic conditions radically different from those existing today. The so-called "deep dissolution" was nothing more than an advanced state of solution and fill (Lee, 1925; Bachman, 1980). The Tertiary and Pleistocene hydrologic conditions no longer exist except along the present Pecos channel, and the probability of further dissolution in the proximity of the repository horizon is remote.

References

Adams, J. E., 1929, Triassic of west Texas: American Association of Petroleum Geologists, Bulletin, vol. 13, no. 8, pp. 1045-1055.

, 1944, Upper Permian Ochoan Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bulletin, vol. 28, pp. 1596-1625.

Anderson, R. Y., 1981, Deep-seated salt dissolution in the Delaware Basin, Texas and New Mexico; pp. 133-145 *in* Wells, S. G., and Lambert, W. (eds.), Environmental geology and hydrology in New Mexico: New Mexico Geological Society, Special Publication no. 10.

1982, Deformation-dissolution potential of bedded salt, Waste Isolation Pilot Plant Site, Delaware Basin, New Mexico: Fifth International Symposium on the Scientific Basis of Radioactive Waste Management, Berlin (West) Germany, 10 pp.

, and Kirtland, D. W., 1980, Dissolution of salt deposits by brine density flow: Geology, vol. 8, no. 2, pp. 66-69.

, Kietzke, K. K., and Rhodes, D. J., 1978, Development of dissolution breccias, northern Delaware Basin, New Mexico and Texas; pp. 47-52 *in* Austin, G. S. (compiler), Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources, Circular 159.

, Dean, W. E., Jr., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved sequence, west Texas and New Mexico: Geological Society of America, Bulletin, vol. 83, pp. 59-86.

Bachman, G. 0., 1980, Regional geology and Cenozoic history of Pecos region, southeastern New Mexico: U.S. Geological Survey, Open-file Report 80-1099, 116 pp.

Dean, W. E., and Anderson, R. Y., 1982, Continuous subaqueous deposition of the Permian Castile evaporites, Delaware Basin, Texas and New Mexico; pp. 324-353 *in* Handford, C. R., Loucks, R. G., and Davies, G. R. (eds.), Core workshop no. 3: Society of Economic Paleontologists and Mineralogists, Calgary, Alberta, Canada.

Gustayson, T. C., Finley, R. J., and McGillis, K. A., 1980, Regional dissolution of Permian salt in the Anadarko, Dalhart, and Palo Duro Basins of the Texas Panhandle: University of Texas (Austin), Bureau of Economic Geology, Report of Investigations no. 106, 40 pp.

Herak, M., and Stringfield, V. T. (eds.), 1972, Karst. Important karst regions of the Northern Hemisphere: Elsevier Publishing Co., Amsterdam, London, New York, 551 pp.

Hiss, W. L., 1976, Structure of the Permian Ochoan Rustler Formation, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources, Resource Map 7.

Izett, G. A., and Wilcox, R. E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: U.S. Geological Survey, Miscellaneous Investigations Series, Map 1-1325 (1:4,000,000).

Jakucs, L., 1977, Morphogenetics of karst regions: Wiley (Halstead Press), New York, 284 pp.

Johnson, K. S., 1981, Dissolution of salt on the east flank of the Permian Basin in the southwestern USA: Journal of Hydrology, vol. 54, pp. 75-93.

Jones, C. L., 1954, The occurrence and distribution of potassium minerals in southeastern New Mexico: New Mexico Geological Society Guidebook, Southeastern New Mexico, 5th Field Conference, pp. 107-112.

, 1972, *in* Brokaw, A. L., Jones, C. L., Cooley, M. E., and Hays, W. H., Geology and hydrology of the Carlsbad potash area, Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Report 4339-1, 86 pp.

, 1978, Test drilling for potash resources, Waste Isolation Pilot Plant Site, Eddy County, New Mexico: U.S. Geological Survey Open-file Report 78-592, 2 vols., 431 pp.

, Bowles, C. G., and Disbrow, A. E., 1960, Generalized columnar section and radioactivity log, Carlsbad Potash District, New Mexico: U.S. Geological Survey, Open-file Report.

King, R. H., 1947, Sedimentation in Permian Castile Sea: American Association of Petroleum Geologists, Bulletin, vol. 31, pp. 470-477.

Kroenlein, G. E., 1939, Salt, potash, and anhydrite in Castile Formation of southeastern New Mexico: American Association of Petroleum Geologists, Bulletin, vol. 23, pp. 1682-1693.

Lambert, S. J., 1983, Dissolution of evaporites in and around the Delaware Basin, southeastern New Mexico and west Texas: Sandia Report SAND 82-0461, 96 pp.

Lang, W. B., 1935, Upper Permian formations of Delaware Basin of Texas and New Mexico: American Association of Petroleum Geologists, Bulletin, vol. 19, pp. 262-270.

, 1939, Salado Formation of Permian Basin: American Association of Petroleum Geologists, Bulletin, vol. 23, pp. 1569-1572.

, 1942, Basal beds of Salado Formation in Fletcher potash core test, near Carlsbad, New Mexico: American Association of Petroleum Geologists, Bulletin, vol. 26, pp. 63-79.

Lee, W. T., 1925, Erosion by solution and fill: U.S. Geological Survey, Bulletin 760-D, pp. 107-121.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1977, Depositional systems, uranium and postulated ground-water history of Triassic Dockum Group, Texas Panhandle-eastern New Mexico: University of Texas (Austin), Bureau of Economic Geology, Report for U.S. Geological Survey, 104 pp.

Maley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporite solution in the Delaware Basin, Texas and New Mexico: Geological Society of America, Bulletin, vol. 64, pp. 539-546.

Mercer, J. W., 1983, Geohydrology of the proposed Waste Isolation Pilot Plant, Los Medanos area, southeastern New Mexico: U.S. Geological Survey, Water-resources Investigations Report 834016, 113 pp.

, and Gonzalez, D. D., 1981, Geohydrology of the proposed Waste Isolation Pilot Plant site in southeastern New Mexico: New Mexico Geological Society, Special Publication no. 10, pp. 123-131.

, and Orr, B. R., 1979, Interim data report on the geohydrology of the proposed Waste Isolation Pilot Plant site, southeastern New Mexico: U.S. Geological Survey, Water-resources Investigations 79-98, 178 pp.

Page, L. R., and Adams, J. E., 1940, Stratigraphy, eastern Midland Basin, Texas: American Association of Petroleum Geologists, Bulletin, vol. 24, no. 1, pp. 52-64.

Richardson, G. B., 1904, Report of a reconnaissance of Trans-Pecos Texas north of the Texas and Pacific Railway: Texas University Bulletin 23, 119 pp.

Sandia Report, 1979, Basic data report for drillhole WIPP 13 (Waste Isolation Pilot Plant-WIPP): Sandia Laboratories and U.S. Geological Survey, SAND 79-0273, 16 pp.

, 1982a, Basic data report for drillhole AEC 7 (Waste Isolation Pilot Plant-WIPP): Sandia National Laboratories, SAND 79-0268, 95 pp.

, 1982b, Basic data report for deepening of drillhole WIPP 13 (Waste Isolation Pilot Plant-WIPP): Sandia National Laboratories, SAND 82-1880, 54 pp.

,1983, Basic data report for drillhole ERDA 9 (Waste Isolation Pilot Plant-VVIPP): Sandia National Laboratories, SAND 79-0270, 52 pp.

Snyder, R. P., and Gard, L. M., Jr., 1982, Evaluation of breccia pipes in southeastern New Mexico and their relation to the Waste Isolation Pilot Plant (WIPP) site. With a section on drill-stem tests by J. W. Mercer: U.S. Geological Survey, Open-file Report 82-968, 73 pp.

Udden, J. A., 1924, Laminated anhydrite in Texas: Geological Society of America, Bulletin, vol. 35, pp. 347-354.

Vine, J. D., 1963, Surface geology of the Nash Draw quadrangle, Eddy County, New Mexico: U.S. Geological Survey, Bulletin 1141B, 46 pp.

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

Editor: Jiri Zidek
Drafters: Russell J. Wood, Teresa A. Mueller

Type face: Palatino

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Saddlestitched with softbound cover

Paper: Cover on 12-pt. Kivar
Text on 70-lb White Matte

Ink: Cover—PMS 320
Text—Black

Quantity: 1,000

Contents of pocket

FIGURE 5—N—S cross section showing local interfingering of anhydrite—halite facies in Castile Formation and interfingering of Salado Halite facies with Castile Anhydrite.

FIGURE 6—E—W cross section showing lenticular bodies of halite in upper part of Castile Formation.

FIGURE 13—Stratigraphic cross sections showing relationship of dissolution to course of Ancestral Pecos River.

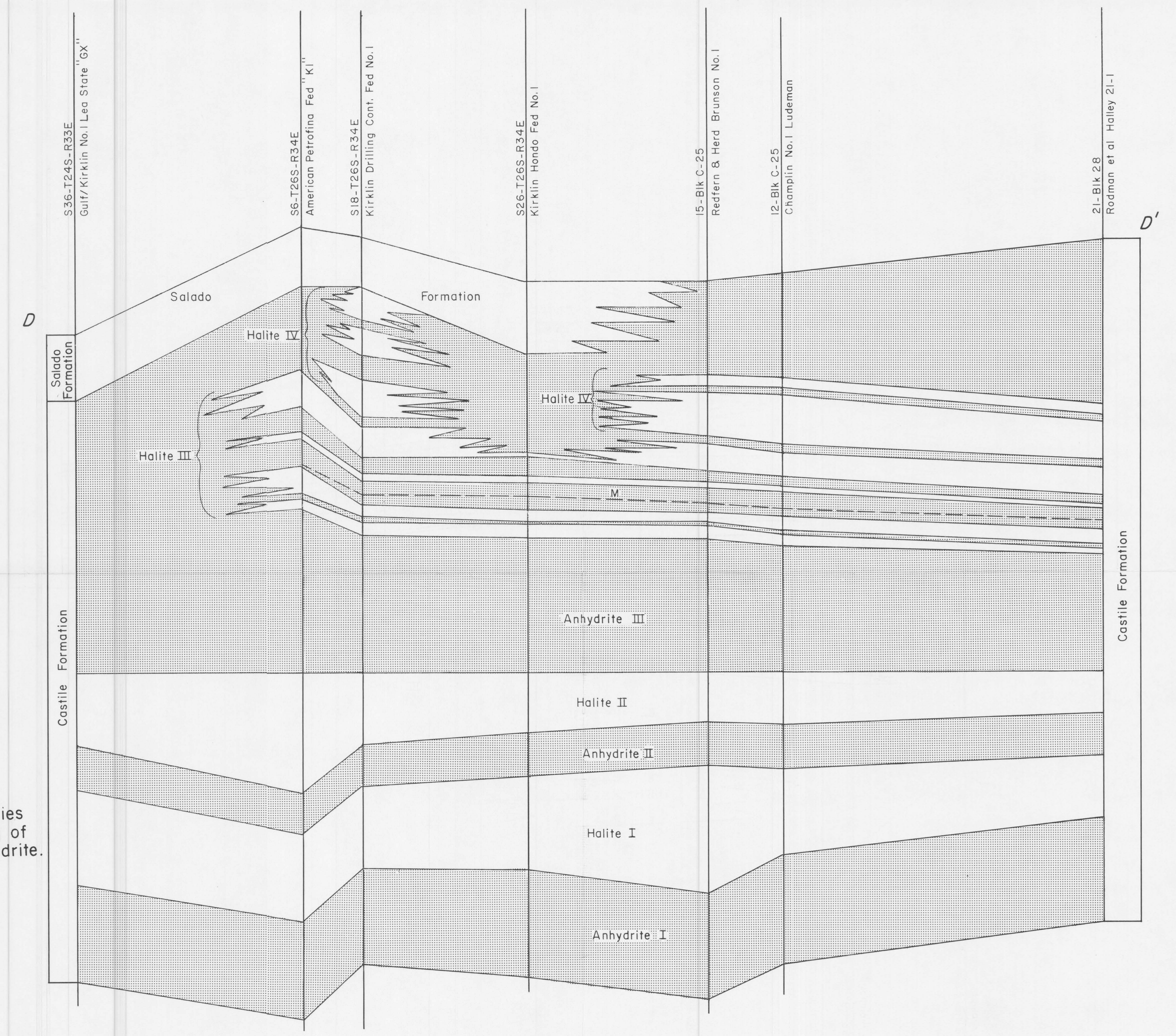

Figure 5
N-S Cross section showing local interfingering of Anhydrite-Halite facies in Castile Formation and interfingering of Salado Halite facies with Castile Anhydrite.

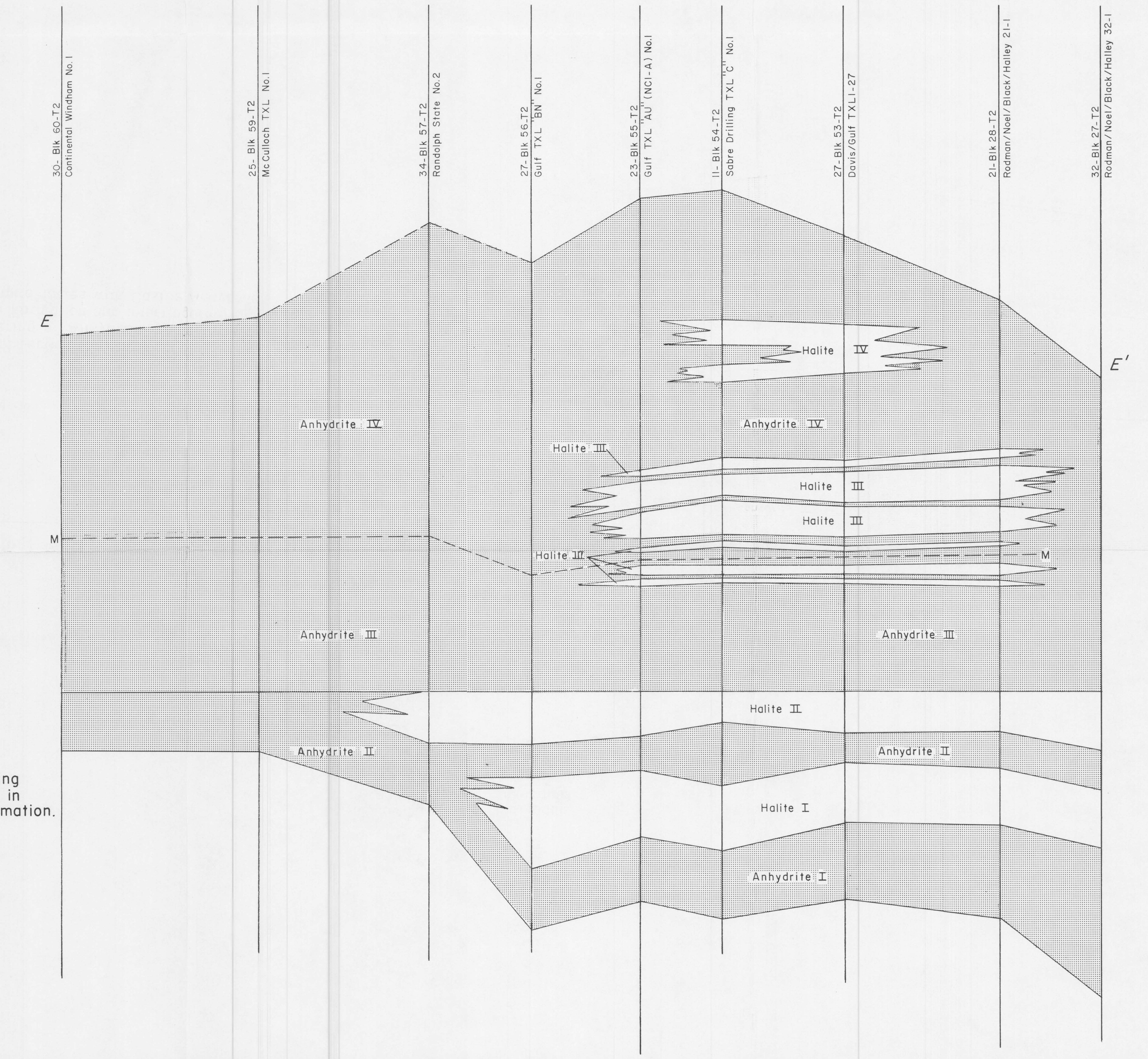

Figure 6
E-W Cross section showing lenticular bodies of Halite in upper part of Castile Formation.

Figure 13— Stratigraphic cross sections showing relationship of dissolution to course of Ancestral Pecos River.

Bachman OCHOAN EVAPORITES New Mexico Bureau of Mines & Mineral Resources Circular 184