

FORMATION OF THE WINK SINK,
A SALT DISSOLUTION/COLLAPSE FEATURE,
WINKLER COUNTY, TEXAS

by

Robert W. Baumgardner, Jr.

Ann D. Hoadley

Arthur G. Goldstein

Assisted by Gary Hummel, D'nese Young,
Melissa A. Sandstrom, Jennifer Forman

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Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78712

TABLE OF CONTENTS

	Page
Abstract	
Introduction	
Regional geologic setting	
Surficial geology	
Stratigraphy	
Structural geology	
Salt dissolution in the Delaware Basin	
History of salt dissolution	
Mechanisms of salt dissolution	
Brine density flow	
Downward ground-water flow	
Dissolution phenomena in the Delaware Basin	
Collapse features	
Pecos River salt load	
Development of the Wink Sink	
Mechanisms of dissolution	
Local geologic setting	
Stratigraphy and structural geology	
Gravity survey	
First-order levelling	
Hydrology of the Wink Sink	
Water level changes	
Water chemistry	
History of Hendrick well no. 10-A	

Brine production and injection

Subsidence features in western Winkler County

Sinkholes in other areas

Conclusions

Acknowledgments

References

Appendix A. Description of stratigraphic units

Appendix B. Wells cited in text

Appendix C. Changes in ground surface elevation at the Wink Sink

Figures

Fig. 1A. Oblique aerial photo of the Wink Sink.

Fig. 1B. Slab failure and splash.

Fig. 2A. South side of Wink Sink showing subsidence.

Fig. 2B. Broken pipes and Shell Oil Company tank farm.

Fig. 3A. Tangential surface fracture.

Fig. 3B. East-west tension fracture.

Fig. 4. Generalized geologic map of southern Winkler County, Texas.

Fig. 5. Structural setting of West Texas and eastern New Mexico: (A) regional tectonic element; (B) regional Bouguer gravity map.

Fig. 6. Regional east-west cross section A-A'.

Fig. 7. Local east-west cross section B-B'.

Fig. 8. Structure contour map on base of Tansill Formation.

Fig. 9. Structure contour map on top of Rustler Formation.

Fig. 10. Isopach map of Salado and Tansill Formations.

Fig. 11. Aquifer systems and salt dissolution.

Fig. 12. Schematic diagram of static fluid levels in formations in southwest Winkler County.

Fig. 13. Dissolution and collapse features in the Delaware Basin.

Fig. 14. Evidence of salt dissolution and collapse in vicinity of Wink Sink.

Fig. 15. Detailed east-west cross section C-C'.

Fig. 16. Local north-south cross section D-D'.

Fig. 17. Complete Bouguer anomaly values for gravity stations near Wink Sink.

Fig. 18. Results of first-order levelling surveys: (A) July 19-August 24, 1980; (B) August 24-October 7, 1980.

Fig. 19. Results of first-order levelling surveys: (A) October 7-December 12, 1980; (B) Summary: July 19-December 12, 1980.

Fig. 20. Total dissolved solids for water samples from wells.

Fig. 21. Hendrick well number 10-A.

Fig. 22. Water used in waterflood projects in Winkler County, Texas.

Tables

1. Stratigraphic section examined in this report.
2. Thickness of Salado Formation.
3. Formation pressure data from drill stem tests.
4. Chemical analyses of water samples from Wink Sink and nearby wells.
5. Driller's log for Hendrick well number 10-A.

ABSTRACT

The Wink Sink in Winkler County, Texas, formed on June 3, 1980. It expanded to a maximum width of 360 ft (110 m) within 24 hours. On June 5, maximum depth was 110 ft (34 m). Volume of the sinkhole is about 5.6 million ft³ (158,600 m³). Between June 3 and June 6 a large area bordering the south rim of the sink subsided about 10 ft (3 m) relative to the north side. Further subsidence of 1.456 ft (44.4 cm) occurred along the southern rim between July 19 and December 12, 1980.

Precursor to the sinkhole was probably a solution cavity that migrated upward by successive roof failures producing a collapse chimney filled with brecciated rock. Dissolution of salt in the Permian Salado Formation is inferred to have produced the solution cavity. Depth of the Salado ranges from 1,300 to 2,200 ft (396 to 670 m). Data are unavailable on the size and initial depth of the solution cavity.

Several dissolution zones exist within the Salado Formation in the region. Occurrence of dissolution in the middle of the Salado evaporite sequence may have resulted from ground-water flow along fractured anhydrite interbeds. Water may come in contact with salt by downward movement from overlying aquifers or by upward movement from underlying aquifers under artesian pressure.

The Wink Sink lies directly above the Permian Capitan Reef which contains water that is unsaturated with respect to sodium chloride. Hydraulic head of water from the reef is higher than the elevation of the Salado Formation, but lower than the head in the Triassic Santa Rosa Formation, a near-surface fresh water aquifer. Fracture or cavernous permeability occurs above, within, and below the Salado Formation, as shown by the loss of drilling fluid circulation in wells drilled near the site of the sinkhole. Consequently, a brine density

flow cycle may be operating: relatively fresh water moves upward under artesian pressure, dissolves salt, and denser brine moves downward under gravity flow in the same fracture system. Alternatively, downward flow of water from aquifers such as the Santa Rosa Formation or Quaternary sediments above the salt is also possible. A plugged and abandoned well that was located within the circumference of the sinkhole may have provided a conduit for water movement.

Composition of water in the Wink Sink is similar to water in nearby wells producing from Quaternary alluvium and from the Triassic Santa Rosa Formation.

The Hendrick No. 10-A well was drilled in 1928 at a site now within the circumference of the sinkhole. The well initially produced about 80 percent water from the Permian Tansill Formation and was plugged with cement and abandoned in 1964. The well was not used for brine disposal. Over 12 million barrels of salt water produced from the Hendrick Field were disposed of by injection into the Permian Rustler Formation during 1961. Waterflood projects in the Hendrick Field began in 1963 and are still in progress.

Sinkholes similar to the Wink Sink occur in other areas of North America. Their morphology, associated strata and mode of formation suggest that dissolution, brecciation, and surface subsidence are processes common in their formation.

INTRODUCTION

The sudden formation of the Wink Sink on June 3, 1980, attracted widespread public attention through both national and local news media. In the days following the appearance of the sinkhole there was much speculation regarding its development and the possibility that additional sinkholes might develop. This report addresses some of the questions concerning the origin of the sinkhole, based on several months of intensive investigation.

On June 3, 1980, at about 9 a.m. a Harvard Construction Company crew was inspecting a Gulf Oil Company brine pipeline on the east side of Section 41, Block B-5, Public School Lands (PSL) Survey in Winkler County, Texas. The pipeline was leaking from a collar joining two sections of 24-inch (61 cm) diameter pipe (Juan Garcia, Harvard Construction Co., personal communication, September 28, 1980). Splashing water drew the attention of one crew member to a 20-ft-wide (6 m) hole in the ground about 100 ft (30 m) west of the pipeline. Large blocks of earth were collapsing into the hole throwing water 30 ft (9 m) into the air. By noon the diameter of the hole was about 100 ft (30 m). Rapid expansion of the oblong cavity ceased by the next morning when its longest (east-west) dimension was about 360 ft (110 m) (fig. 1A).

The maximum depth of the hole on June 5 was 110 ft (34 m), and average depth was estimated at 80 ft (24 m) based on a line and plummet survey of the hole. Surface area of the sink was about 70,400 ft² (6,540 m²) and its volume was about 5.6 million ft³ (158,600 m³). This is more than twice the volume of the Cargill salt plant sinkhole near Hutchinson, Kansas, and almost three times the size of the Panning sinkhole in Barton County, Kansas (Walters, 1978).

Blocks up to 30 ft (9 m) long continued to fall into the hole at irregular intervals for several weeks (fig. 1B). Annular cracks that surround the hole extend up to 290 ft (88 m) from the southern edge. A large area bordering the south rim of the sinkhole subsided about 10 ft (3 m) relative to the north side, within the first three days of movement (fig. 2A). This small graben-like depression is bounded on the east and west by fissures up to 60 ft (18 m) long that are tangent to the hole (fig. 3A). Subsidence has been accompanied by faulting and lateral movement of the depressed block, as shown by abundant tension fractures (fig. 3B).

Development of the sinkhole had little impact on oil field operations. Workmen cut and re-routed a 6-in (15-cm) diameter Shell Oil Company pipeline that carried crude oil to storage tanks 1,000 ft (305 m) northeast of the sinkhole (fig. 2B). The brine pipeline being inspected by the maintenance crew was broken by the expanding hole (fig. 2A). As a result, the oil wells producing the brine had to be shut down.

Workers for Petro-Lewis Company, an independent oil company, were attempting to circulate cement behind the liner in Hendrick Well No. 3-A, a producing oil well about 500 ft (152 m) south of the sinkhole when the sinkhole began to form. They plugged and abandoned the well on June 5 because of the proximity of tension fractures to the well (Mike Handren, Petro-Lewis Company, personal communication, August 14, 1980).

REGIONAL GEOLOGIC SETTING

Surficial Geology

The Wink Sink formed 2.5 mi (4.0 km) northeast of Wink, southwestern Winkler County, Texas (fig. 4). Winkler County is covered principally by Quaternary deposits that obscure bedrock formations. Along Concho Bluff in the northeastern corner of the county, Cretaceous strata are exposed.

Surface drainage is poorly developed in Winkler County because surface sediments are highly permeable and rainfall is infrequent and usually localized. Mean annual precipitation is about 12 in (30 cm), and the annual net lake surface evaporation rate is over 70 in (178 cm) (Arbingast and others, 1976). Most precipitation collects in playas and other internally drained depressions. The Wink Sink is located on a line described by a group of these surface depressions that extends from west of Kermit to east of Wink (fig. 4).

Stratigraphy

The Delaware Basin of southeast New Mexico and West Texas is the western part of the Permian Basin Province (fig. 5A). It is separated from the Midland Basin to the east by the Central Basin Platform, a north-south oriented structural high. The Delaware Basin is filled primarily with sedimentary rocks of Permian age. Uppermost Permian strata comprise the Ochoa Series (table 1). This series is composed of four formations. The lower two formations, the Castile and Salado, contain most of the evaporite deposits in the Delaware Basin. The upper two formations, the Rustler and the Dewey Lake, are composed mainly of red beds, some gypsum and anhydrite, and minor amounts of salt (Johnson and Gonzales, 1978).

The Castile and the Salado Formations were deposited on very uniform stable surfaces, as evidenced by the lateral continuity of individual laminae which can be traced over distances of several miles (Anderson and Kirkland, 1966; Hills, 1968; Anderson and others, 1972). The Castile Formation consists of anhydrite and halite and is as much as 1,650 ft (503 m) thick. It was deposited entirely within the Delaware Basin, bounded by the Capitan Reef, which essentially surrounds the basin (Anderson and Kirkland, 1980) (figs. 5A, 6, 11). The Castile contains more anhydrite than the overlying Salado Formation, which contains potash deposits (Johnson and Gonzales, 1978).

The Salado Formation was deposited over a larger area than the underlying Castile, extending far beyond the Capitan Reef which defines the margin of the Delaware Basin. On the north and east sides of the basin (fig. 6), it overlies the Capitan strata, but salt in the Salado Formation has been removed by dissolution from most of the area west of the Pecos River (fig. 13) (Maley and Huffington, 1953). Where dissolution has not occurred, the Salado consists

primarily of halite with some anhydrite interlayers. Depth to salt increases from about 165 ft (50 m) on the west side of the Delaware Basin to 2,540 ft (747 m) farther east. The formation has a maximum thickness of 1,950 ft (595 m) in the Delaware Basin; salt thickness reaches 1,650 ft (503 m) locally (Johnson and Gonzales, 1978). In the study area a maximum of 945 ft (288 m) of salt has been observed (table 2).

The Rustler Formation also contains salt. Individual salt beds are 6 to 33 ft (2 to 10 m) thick and constitute about 40 percent of the formation where dissolution has not occurred (Johnson and Gonzales, 1978).

The uppermost Permian formation, the Dewey Lake, contains no salt. It is composed primarily of red siltstone and some gypsum, anhydrite and red shale (White, 1971) (figs. 6, 7).

The Tecovas Formation of Triassic age unconformably overlies the Permian Dewey Lake Formation. In this report the base of the Tecovas is defined as the contact between claystone of the Tecovas and siltstone of the Dewey Lake (Appendix A).

Above the Tecovas Formation is the Triassic Santa Rosa Sandstone, composed of medium- to coarse-grained sandstone (White, 1971). The Santa Rosa-Tecovas contact is at the contact between clean Santa Rosa sands and underlying fine-grained claystone of the Tecovas (Appendix A). The contact of the Santa Rosa and overlying undifferentiated Triassic or Cenozoic strata is defined here as the first clay- or siltstone or porosity "break." Position of the upper and lower Santa Rosa contacts is approximate, as indicated by the dashed lines on figures 7, 15, and 16. In the area covered by this study Triassic strata overlying the Santa Rosa Sandstone are not readily separable from Cenozoic sediments. Consequently, post-Santa Rosa deposits are not differentiated on cross sections (figs. 6, 7, 15, 16). Where post-Santa Rosa Triassic sediments have

been recognized, they are conformable with the underlying Santa Rosa Sandstone (White, 1971).

Structural Geology

The structural setting of the region is illustrated by a structure contour map on the base of the lowermost dolomite within the Tansill Formation (fig. 8), which is predominantly dolomitic near the Capitan Reef (White, 1971). The Tansill Formation probably does not extend basinward beyond the top of the Capitan Reef (fig. 6). However, the dolomite used for constructing figure 8 can be traced throughout the study area (Appendix A). In the vicinity of the sinkhole the Tansill overlies the Yates Formation, but westward the Yates pinches out and the Tansill Formation directly overlies limestones of the Capitan Reef (fig. 6).

The Wink sinkhole is located above a closed structural high (fig. 8). Basal Tansill strata dip 25 ft/mi (4.7 m/km) east of the sinkhole and 500 ft/mi (95 m/km) to the west. The steeper westward dip probably reflects the steeply sloping face of the underlying Capitan Reef and is probably not related to salt dissolution.

Structural configuration on top of the Rustler Formation resembles that of the Tansill except that no structural high exists beneath the Wink Sink, but a broad closed high occurs 2 mi (3.2 km) to the east (fig. 9). East of the high the formation dips eastward at about 75 ft/mi (14 m/km), about three times greater than the eastward dip at the base of the Tansill. West of the high the Rustler dips 200 ft/mi (38 m/km) to the position of the Wink Sink and then increases dip to 500 ft/mi (95 m/km).

The westward dip exhibited by the Rustler Formation is greater than its eastward dip as a result of salt dissolution in the underlying Salado Formation. As the salt was removed, overlying formations collapsed to fill available space.

Because the thickness of the Rustler does not increase into the dissolution trough (fig. 6), the trough formed after Rustler deposition.

This explanation for the structure displayed by the Rustler Formation is demonstrated by an isopach map of the Salado and Tansill Formations (fig. 10). The isopach map documents a decrease of over 800 ft (244 m) in thickness from the thickest point shown on the map to the thinnest point in the dissolution trough on the west. These thickness variations result from salt dissolution because neither the Tansill nor the anhydrite beds in the Salado vary more than 50 ft (15 m) in thickness (fig. 7).

Furthermore, the remarkable congruence between the isopach configuration of the Salado and Tansill Formations (fig. 10) and the structural configuration on top of the Rustler Formation (fig. 9), including isolated highs and reentrants, suggests that dissolution in the Salado strongly controls the structure of the Rustler. The Rustler appears to be draped over the underlying formation.

If solution cavities had developed in the Salado and migrated upward through the Rustler, closed depressions should occur at the top of the Rustler. Features of this kind are not apparent in figure 9, but the distance between most data points is too great to detect a feature less than 360 ft (110 m) in diameter, the approximate size of the Wink Sink.

SALT DISSOLUTION IN THE DELAWARE BASIN

History of Salt Dissolution

The chronology and geographic distribution of salt dissolution in the Delaware Basin were and are controlled by local hydrologic conditions and the geology of the basin. The timing and style of dissolution differ for the western and eastern parts of the basin.

In the western part of the basin, Salado salt deposits were dissolved when the Delaware Basin was tilted eastward between the end of Salado deposition and the beginning of Rustler deposition (Adams, 1944), and again in the late Tertiary (Maley and Huffington, 1953; Bodenlos, 1978). Structural tilting elevated strata on the western side of the basin, and as a result, salt beds were dissolved by ground and surface water coming into contact with the shallow or exposed salt beds (Mercer and Hiss, 1978).

In the eastern Delaware Basin, Salado salt dissolution and related subsidence began during the Permian (fig. 6) and probably continues today. The Permian Dewey Lake Formation is about 140 ft (43 m) thicker in the dissolution trough, indicating that its deposition coincided with or post-dated a period of subsidence. Triassic and Cenozoic sediments are up to 1,100 ft (335 m) thicker in the trough (fig. 6), illustrating that dissolution and subsidence were active during the Triassic and Cenozoic.

Source of the waters that dissolved the Salado salt has been a subject of several geologic studies of the area. Maley and Huffington (1953) mapped the dissolution trough (fig. 6), and they ascribed the anomalous occurrence of 1,500 ft (457 m) of Triassic and Cenozoic alluvial deposits to dissolution of salt above the Capitan Reef aquifer. A correlation between salt dissolution and the Capitan Reef was earlier recognized by Adams (1944), who suggested that faults in the Rustler, caused by dissolution, subsidence, or warping of the underlying Capitan Reef, had facilitated movement of ground water down through the Rustler and into contact with Salado salts. Hills (1970) similarly concluded that dissolution may have been caused by ground water moving along joints and faults opened by movement along a north-south trending fault zone on the west side of the Central Basin Platform (fig. 5A).

Mercer and Hiss (1978), on the other hand, concluded that the Capitan Reef and shelf-aquifer systems were the source of the waters that dissolved Salado

salt and formed the collapse features on the northeast side of the Delaware Basin (figs. 11, 13). This hypothesis requires, of course, that the source of water be below the Salado salt. This mechanism was proposed by Parker (1967) to explain salt dissolution in the Williston Basin in North Dakota and in the Powder River Basin in Wyoming and more recently has been used by Anderson and Kirkland (1980) to explain dissolution in the Delaware Basin.

Mechanisms of Salt Dissolution

Brine Density Flow

A brine density flow mechanism to explain dissolution by upward movement of unsaturated ground water in the Delaware Basin was recently described by Anderson and Kirkland (1980) (fig. 11). They report that the mechanism is a cycle with two components: (1) an underlying artesian source of relatively fresh water and (2) a permeable fracture zone between the underlying water source and salt strata that normally are isolated from shallow ground water.

Artesian pressure in the Capitan Reef aquifer is at least partly maintained by recharge from the Delaware Mountain Group (fig. 11). Water in the Delaware Mountain Group moves across the Delaware Basin from west to east (McNeal, 1965). Salinity of the water in the Brushy Canyon, Cherry Canyon and Bell Canyon Formations increases from less than 5,000 mg/l on the west to more than 200,000 mg/l on the east (Hiss, 1975).

Where the brine density flow cycle operates, relatively fresh water is forced upward under artesian conditions into contact with salt strata where the salt is dissolved. Brine produced by dissolution is more dense than the fresher water; hence, the brine moves downward under gravity flow and forces fresher water to move upward to replace the brine, thereby perpetuating the cycle. Both downward and upward flow may occur simultaneously in the fracture system because of differences in fluid density.

Evidence of this phenomenon has been documented in southeastern Eddy County, New Mexico (Anderson and others, 1978). Dissolution zones were found in the upper part of the Castile Formation and lower part of the Salado Formation, but overlying salt beds in the upper and middle Salado were not dissolved.

A similar pattern of dissolution exists in western Winkler County, Texas. Salt dissolution zones occur at several levels within the Salado Formation and appear to be associated with anhydrite interbeds (figs. 7, 15, 16). The mechanism for dissolution in the middle of an evaporite sequence has not been fully explained, but Anderson and his co-workers (1978) suggest that permeable beds within the evaporite sequence could permit ground water to migrate into contact with and dissolve salt beds. Anhydrite beds shown in figures 7, 15, and 16 may be permeable pathways due to fracturing or partings between thin dolomite and carbonate beds within the anhydrite. Fractures in the Salado Formation may have been caused by warping of these younger strata over the underlying Capitan Reef (Adams, 1944), by deeper solution and collapse, or by minor faulting. Keller (1980) reports that microseismic events in the southwestern Winkler county-northern Ward County area are common.

Downward Ground-Water Flow

If permeable zones above and below the salt are interconnected, then the brine density flow mechanism is less feasible. Salt dissolution by the brine density cycle functions only if salt strata are isolated from shallower aquifers that have hydrostatic heads higher than the underlying artesian aquifer (G. Fogg, Bureau of Economic Geology, personal communication, 1981). Results of drill stem tests from wells in the vicinity of the Wink Sink show that in 1975, the hydraulic head in the Santa Rosa Formation was higher than that in the Tansill, Yates or Capitan (fig. 12). If the Santa Rosa were connected via permeable zones with the aquifers underneath the Salado Formation, downward flow

into the deeper aquifers would result, the reverse of the brine density flow model.

Furthermore, Garza and Wesselman (1959) report that in Winkler County, wells drilled into the Rustler Formation for waterflood projects yielded artesian water. Three wells completed in the Rustler north and northwest of Kermit between 1954 and 1957 had static water levels that were higher than those in the Yates and Tansill Formations in 1975 (Garza and Wesselman, 1959; table 7, plates 1 and 3). No hydrologic data were available from wells completed in the Rustler near the location of the Wink Sink during that period (1954-1957).

Two factors, however, may impede downward movement of water from these two formations. First, the Dewey Lake Formation, which lies between the Santa Rosa and the Salado Formations, is a relatively impermeable red bed sequence and acts as a barrier to water movement except where it is fractured, or perhaps, penetrated by wells. Second, permeability and water yields of the Rustler are highly variable, owing to the sporadic occurrence of cavernous porosity. Therefore, downward flow into the Salado Formation from the Santa Rosa and Rustler Formations may occur only locally. At the same time, brine density flow may be occurring in isolated lower parts of the Salado Formation that are not hydraulically connected with the overlying aquifers.

Dissolution Phenomena in the Delaware Basin

Collapse Features

The proximity of several dissolution/collapse features to the Capitan Reef trend suggests that the reef plays an important role in their development (fig. 13). The Clayton Basin in eastern Eddy County, New Mexico, has subsided more than 100 ft (30 m) since the middle Pleistocene (Bachman, 1976). Nash Draw is an unfilled solution trough which is actively developing (Adams, 1944).

According to Bachman (1976), parts of the draw have subsided as much as 180 ft (55 m) since middle Pleistocene.

Perhaps the best-known solution features in the Delaware Basin are the San Simon Swale and San Simon Sink in Lea County, New Mexico (fig. 13). The swale is a 100 mi² (260 km²) elongate depression, trending northwest-southeast on the northeastern edge of the basin. The swale overlies and is parallel to the inner margin of the Capitan Reef. According to Nicholson and Clebsch (1961, p. 14) the swale "probably originated as the result of a deep-seated collapse."

The lowest part of the swale is the San Simon Sink. It covers an area of a half square mile (1.30 km²). The sink is about 130 ft (40 m) deep and is filled with at least 400 ft (120 m) of alluvium deposited above the surface of Triassic red beds. The most recent subsidence at the sink occurred about 50 years ago (Nicholson and Clebsch, 1961).

Several workers studied the relationship between evaporite dissolution and ephemeral streams. Morgan (1942) believes that evaporite dissolution influenced the effectiveness and location of ephemeral stream channels in the Pecos River basin. Maley and Huffington (1953) suggest the opposite, that ephemeral surface drainage affected subsurface evaporites. They conclude that dissolution was probably enhanced along stream courses by percolation of fresh water into underlying sediments.

Monument Draw (fig. 13) which extends from central Lea County, New Mexico, to the Pecos River in Ward County, Texas, has been cited as an example of surface drainage which has been affected by evaporite dissolution (Nicholson and Clebsch, 1961). In southern Lea County the north-south trend of the draw defines an acute angle to regional northwest-southeast dip, suggesting that its orientation is a result of "stream capture" by surface lowering along a trend parallel to the subsurface Capitan Reef. In northern Winkler County, the draw

veers 90 degrees to the southwest, passing above the Capitan Reef, then abruptly changes direction again, and passes 3.1 mi (5 km) west of the Wink Sink parallel with the trend of the inner margin of Capitan Reef (figs. 4 and 13). These angular bends in the draw may be controlled by subsurface faults or linear dissolution zones.

Pecos River Salt Load

The Pecos River is a discharge zone for saline springs in the Delaware Basin. The largest concentration of springs is at Malaga Bend in southeastern Eddy County, New Mexico (fig. 13). Historically, brine discharging at that location from the Rustler Formation increased the load of total dissolved solids in the Pecos River by at least 340 tons per day (U.S. Geological Survey, 1941). Recharge in the outcrop zone near Clayton Basin maintained a hydraulic head that forced the brine (concentration = 125,000-155,000 ppm) upward to discharge points along the river. Presumably, the salt was derived from dissolution of the Salado underlying the Rustler.

Farther downstream, between Orla and Grandfalls, Texas (fig. 13), the salt content of the Pecos River water is increased by evaporation, transpiration of water by phreatophytes along the river channel, saline ground-water discharge and contamination from oil wells (Pecos River Commission, 1955; Grozier and others, 1966). Samples obtained May 10-12, 1965, exhibited chloride concentrations of 7,710 ppm at Orla and 16,300 ppm at Grandfalls. This large increase probably was due, at least in part, to brine pollution from oil fields upstream from Grandfalls (Grozier and others, 1966). The Patton Oil Field straddles the Pecos River just upstream from Grandfalls. Source of salt from natural seeps was not determined.

Downstream from Grandfalls the quality of the river water gradually improves as fresher water from Cretaceous aquifers dilutes the river water. Near

Imperial, Texas, 13 river miles (21 km) downstream from Grandfalls, chloride concentration on May 10-12, 1965, was 7,220 ppm (Grozier and others, 1966).

Based on the number and size of dissolution features, it is evident that large volumes of salt have been removed from the Delaware Basin. Morgan (1942) estimates that the amount of salt removed from the Salado Formation in eastern Eddy County, New Mexico, amounts to 56 percent of all sediment and solute removed from the area during early and mid-Pleistocene. He also concludes that if present rates of discharge from aquifers in contact with the Salado continue unchanged during the next million years, the ground surface will be lowered 56 ft (17 m) over an area of 1,500 mi² (3,900 km²). Anderson and Kirkland (1980) predict that over a period of 30,000 years, sufficient salt could be removed from the Delaware Basin in New Mexico alone to form 100 dissolution chambers each with a volume of 35 million ft³ (990,000 m³) or about six times larger than the Wink Sink.

DEVELOPMENT OF THE WINK SINK

Mechanisms of Dissolution

How water comes in contact with a salt body is not well understood. Anderson and Kirkland (1980) report that dissolution may occur in zones that are well-removed from recharge areas of the dissolving waters. If this is true in the case of the Wink Sink, it may be impossible to pinpoint the source of the water which produced the dissolution chamber. Available data indicate that dissolution may have occurred by upward or downward movement of water, and that water movement may have been influenced by the presence of an abandoned 52-year-old borehole.

The two components of a brine density flow cycle are extant in the vicinity of the Winkler County sinkhole. First, drill stem test data from two oil wells within 1,500 ft (457 m) of the sink (table 3) indicate that hydraulic heads in the Yates and Tansill Formations and the Capitan Reef are at least as high as the Salado Formation (fig. 12). Historically, the head in the Capitan was higher than its present level, but withdrawal of water for water flood projects has lowered the head in the aquifer (Hiss, 1971).

Water in the Yates Formation and in the Capitan Reef is relatively fresh. Chloride ion concentrations have been reported for water samples taken near the sinkhole (Hiss, 1975). They range from 4,300 to 35,000 mg/l for water from the Yates and from 1,300 to 3,600 mg/l for water from the Capitan. None of these concentrations approaches saturation with respect to salt: 311,300 mg/l or 226,000 ppm (Walters, 1978). Thus, artesian pressure and relatively fresh water provide the first component of a brine density flow system.

Second, presence of permeable fracture or cavernous zones is indicated by the loss of fluid during well drilling. This occurred in four different wells drilled in 1927 and 1928 between depths of 956 and 2,293 ft (291-699 m) (fig. 14). Circulation was lost in (1) sand and red beds in the Dewey Lake Formation (well 8); (2) salt in the Salado Formation (well 121, hole no. 1 and well 135); and (3) dolomite in the Tansill Formation (well 121, hole no. 2). These lost circulation zones are highly permeable pathways for the movement of fluids within, above, and below the Salado Formation.

According to Anderson and Kirkland (1980), brine density flow presently is active in the Delaware Basin and has produced a "dissolution wedge" along the inner-reef margin on the eastern side of the basin (fig. 11). Most of this wedge lies west of the Wink Sink, which is directly above the reef (fig. 13). On the other hand, because the hydraulic head in the Triassic Santa Rosa Formation is higher than the head in any of the deeper aquifers (fig. 12), water

would flow from the Santa Rosa downward into any of the Permian aquifers if connected by a permeable zone. Potential for downward movement of relatively fresh water may be enhanced by the presence of abandoned oil and gas wells which can serve as vertical pathways. Development of the Wink Sink may have been enhanced by an abandoned 52-year-old oil well, the Hendrick No. 10-A, which was drilled at a point within the circumference of the sinkhole. The history of the well is discussed on page 25.

Local Geologic Setting

Stratigraphy and Structural Geology

In the vicinity of the Wink Sink, maximum thickness of Salado salt is about 700 ft (213 m) less than reported by Johnson and Gonzales for the Delaware Basin (1978) (table 2). As illustrated by figure 7, locally salt beds thin from east to west as a result of salt dissolution. Salt thickness decreases from 945 ft (288 m) 1.2 mi (1.9 km) east of the sinkhole in well 67 to 42 ft (13 m) 2.5 mi (4 km) west of the sinkhole in well 140 (table 2). The eastern flank of a north-northwest to south-southeast trending solution trough (fig. 6) extends about 20 mi (32 km) north and 40 mi (64 km) south of cross section B-B' (fig. 7).

Dissolution of salt by ground water has occurred at several levels in the Salado Formation. This is readily documented by tracing anhydrite beds laterally and noting the progressive decrease in thickness of intercalated salt beds (figs. 7, 15). For example, three anhydrite beds in the upper 350 ft (107 m) of the Salado can be traced between wells 66 and 139 (fig. 7), a distance of about 3.5 mi (5.6 km). Salt between the three anhydrite beds thins westward from 180 ft (55 m) to 90 ft (27 m). Between wells 87 and 81, thinning is very abrupt: 105 ft (32 m) of salt in well 87 thins to 70 ft (21 m) in well 81, a distance of 2,050 ft (625 m). Two salt layers between wells 87 and 81 thin

eastward, opposite of westward thinning associated with the dissolution trough (fig. 6), illustrating that dissolution can be very localized.

Such abrupt variations in salt thickness most likely result from salt dissolution rather than from facies changes imposed during deposition of the salt. Anderson and others (1972) reported that horizontal laminae in the Castile and Salado Formations can be correlated for 70 mi (113 km).

In the vicinity of the sink cross section D-D' (fig. 16) is approximately parallel to the axis of the dissolution trough. The same three anhydrite beds observed on cross sections B-B' and C-C' (figs. 7, 15) occur in the upper 380 ft (116 m) of the Salado Formation, and dissolution zones are associated with all three beds. Net salt decreases southward from 600 ft (183 m) in well 10 to 415 ft (126 m) in well 109 and to 710 ft (216 m) in well 269 (table 2). No progressive change in salt thickness is recognized parallel to the dissolution trough, but cross section D-D' reveals that dissolution zones extend beneath the Wink Sink.

Analysis of geophysical logs near the sinkhole indicates that dissolution of Salado salts has occurred. These logs and maps derived from log data, however, provide no evidence that permits prediction of where a sinkhole may form.

Evolution from solution cavity to collapse chimney to sinkhole may take a considerable amount of time. The development probably involves (1) roof collapse followed by (2) gradual dissolution of the soluble part of the breccia followed by (3) roof collapse until a cavity becomes large enough to migrate to the surface. On the other hand, rapid development of a chimney could occur by coalescence of several solution cavities at different levels in the evaporite formation. Figures 7 and 15 illustrate superposed dissolution zones in the Salado Formation beneath the Wink Sink. These may have been precursors to the sinkhole, and thus may have controlled the general location where ground-collapse occurred.

Gravity Survey

In an attempt to define the collapse zone below the sinkhole, a gravity survey was conducted at the site of the sink on July 9-10, 1980 (fig. 17). Purpose of the survey was to detect density differences between the zone of collapse below the sinkhole and undisturbed strata surrounding it. A La Coste-Romberg gravity meter accurate to 0.01 mgal was used. All gravity stations were surveyed and located horizontally and vertically to within 0.001 ft (0.3 mm) and except for stations 42-47 all are marked by a concrete monument in which a nail is imbedded.

A complete Bouguer anomaly was calculated for each station using a Bouguer density (ρ) of 2.0 g/cm³. Data for three profiles are shown in figure 17; two profiles cross directly over the sinkhole (A, B) and one lies approximately 500 ft (152 m) south of the sink (C). All three profiles show a smooth gradient without significant perturbation in the vicinity of the sinkhole. The gradient is probably related to the major positive gravity anomaly associated with the Central Basin Platform east of the sinkhole (fig. 5B). The two southwest-northeast profiles increase eastward displaying similar slopes, whereas the southeast-northwest profile decreases northward, cutting the regional gravity gradient at a slight angle. Absence of a gravity anomaly near the Wink Sink concurs with Weart's (1980) observation that collapse features in southeastern New Mexico failed to exhibit significant density contrast.

Absence of a detectable gravity anomaly related to the sinkhole is not inconsistent with expected subsurface geology. Two phenomena might yield horizontal density contrasts which could be detected with the gravity technique: (1) brecciation above a zone of collapse yielding a negative density contrast and (2) collapse of overlying sedimentary rocks ($\rho = 2.55 \text{ gm/cm}^3$) into a void in the Salado Formation ($\rho = 2.40 \text{ gm/cm}^3$) yielding a positive density con-

trast. A zone of collapse in the Salado Formation exactly the size of the sinkhole would give rise to a positive gravity anomaly of only 0.04 mgal (calculation made using vertical cylinder model, Dobrin, 1960). A zone of collapse and brecciation above the Salado would be expected to yield a negative anomaly of similar magnitude. Thus, the two phenomena could produce density contrasts that cancel, resulting in no anomaly. In addition, noise introduced by inaccuracies in determining Bouguer density, elevation and latitude of gravity stations could approximate 0.0446 mgal (Speed, 1970), making detection of a 0.04 mgal anomaly impossible. Gravity data indicate that no significant void space remains below the sinkhole, a conclusion corroborated by first-order levelling surveys showing that subsidence around the sinkhole is decreasing with time.

First-Order Levelling Survey

Professional surveyors conducted first-order levelling surveys at the Wink sinkhole to monitor movement of the ground surface. An AGA brand Geodimeter was used to measure to 0.001 ft (0.3 mm); survey monuments were nails set in concrete. Each survey documented changes in elevation relative to a concrete monument outside the area affected by sinkhole development (figs. 18, 19). Horizontal distances between monuments were established relative to two stable points 450 and 600 ft (137 and 183 m) beyond the boundary of the subsided area. Latitude and longitude of the two horizontal control points were taken from the Wink North quadrangle map (U.S. Geological Survey, 1970), and the bearings of the survey monuments established by the surveyors are based on this control.

Results of surveys of July 19, August 24, October 7, and December 12, 1980, show that the south side of the sinkhole settled more than other areas bordering the sinkhole (figs. 18, 19). Maximum total subsidence between July 19 and December 12 was 1.456 ft (44.4 cm) (fig. 19B) (Appendix C).

Results of the December 12 survey (fig. 19A) differ from those of the earlier surveys (fig. 18A, B) in three ways: (1) areal extent of ground movement was about 75 percent less; (2) no upward movement was observed; and (3) all subsidence was nearly concentric to the sinkhole. Ground surface more than 200 ft (61 m) away from the edge of the sinkhole was stable between October and December.

Between July and December the horizontal distance between monuments changed only for the six nearest the sinkhole: 1, 2, 8, 9, 15, 23 (see numbers, fig. 18A). Monuments on the north and east sides of the sinkhole moved toward the hole as much as 0.428 ft (13.0 cm) (monument 16). Those on the south and west sides moved away from the hole as much as 0.503 ft (15.3 cm) (monument 8).

Results suggest that earth movement on the south and west sides of the sinkhole was not caused directly by the sinkhole, but that it resulted from (1) subsidence into minor residual void space below the sinking area and/or (2) compaction of the fractured, subsided area and closing of ground cracks that opened prior to the July 19 survey. Movement was dominated by rotational slippage along curved surfaces inclined toward the sinkhole; pressure ridges up to 1.31 ft (40 cm) high south of the sink indicate that horizontal compression is occurring.

By contrast, earth movement on the north and east sides of the sinkhole was dominated by planar movement. This type of slope failure has been described by Embleton and Thornes (1979) as slab failure. Steeply inclined tension fractures separate blocks from the surrounding undisturbed material. The blocks are thin relative to height and tilt toward the hole. Failure occurs by toppling as blocks slide or break along a plane inclined toward the hole.

Subsidence was accompanied by cracking of the ground surface (fig. 3) as subsiding areas closer to the hole separated from peripheral areas. Cracks are

most abundant south of the sinkhole, but occur on all sides of the sink and cover an area 740 ft (225 m) in diameter. Separation along the cracks measures as much as 6 in (15 cm), although soil slumping from edges of the cracks increases the apparent width to as much as 24 in (61 cm) (fig. 3B).

Tension fractures concentric with the sinkhole have widened more than tension fractures tangent to the sinkhole, such as shown in figure 3A, southeast of the sink. This crack did not widen between June 27 and November 18, 1980, while one monitored concentric crack increased from a width of 3.5 in (9 cm) to 5.6 in (14 cm) during the same period.

The levelling surveys revealed an unexpected phenomenon: upward movement outside the subsiding area surrounding the sinkhole (fig. 18B). Maximum upward movement of 0.223 ft (6.80 cm) occurred at monument 21 between August 24 and October 7 (Appendix C). During the same period 17 of the 39 monuments moved upward on all sides of the sinkhole (fig. 18B). One might suspect that the benchmark from which the other elevations are established had moved downward, giving the false impression that other monuments had moved upward. However, several monuments displayed no movement relative to the benchmark, making that explanation implausible.

Hydrology of the Wink Sink

Water Level Changes

When the sinkhole began to form on June 3, 1980, the top of the water surface was about 33 ft (10 m) below the ground surface on the northwest side of the sinkhole. By June 6 the water surface was 3 ft (0.9 m) lower. Three weeks later on June 27 the water level had stabilized at about 66 ft (20.1 m) below the ground surface. On July 10 and November 18 the water level was still about 66 ft (20.1 m) lower than the ground surface on the northwest side of the sink-

hole. Reference is made to the northwest side of the sinkhole because it is the most stable.

Ground water was elevated above the water table as the roof of the solution cavity collapsed and displaced the water. The rapid drop of the water level in the sinkhole was probably caused by lateral movement of water out of the cavity into the pore spaces in the surrounding unsaturated zone above the water table. This lateral movement of water may have been the last step in the formation of the sinkhole. While the cavity migrated upward through saturated or impermeable strata, the weight of the roof was partially supported by water in the cavity. But when the ceiling of the cavity emerged above the water table, this support was lost and the roof collapsed into the cavity, breaching the surface and displacing water upward above the local water table.

Water Chemistry

A water sample taken from the Wink Sink on June 7, 1980 was analyzed for major chemical constituents by Martin Water Laboratories, Inc., of Monahans, Texas. These results, along with results of chemical analyses of water from three nearby wells are shown in table 4. Because water samples were not collected from wells during this study (June 3-December, 1980), review of water chemistry is limited to the composition of the last samples collected by the Texas Department of Water Resources before the sink formed. Results of analyses of water from three wells north of the sinkhole (fig. 20) are shown because the water table in the alluvium tapped by the wells slopes southward in the vicinity of the sinkhole from a potentiometric mound west of Kermit (Couch, 1969). Thus, water in the Quaternary alluvium aquifer moves from north to south, and previous water samples taken from wells north of the sinkhole should resemble water taken from the sinkhole unless it was contaminated by waters contributed to the sinkhole from deeper aquifers.

Water from the sinkhole is higher in sodium, chloride, bicarbonate, and total dissolved solids (TDS) than the three water samples from the nearby water wells (table 4). But, the difference in TDS among these samples from or near the sinkhole is much less than the difference in TDS between these samples and most other nearby wells (fig. 20). The three wells immediately north of the sinkhole (table 4) are near the center of an area of high TDS values, probably resulting from ground-water contamination by oil field brines from unlined surface pits (Garza and Wesselman, 1959).

Water in the sinkhole is probably a mixture of local shallow ground water, as well as water from deeper aquifers. It is possible that some brine was transported upward from the solution cavity in the Salado Formation. In order to identify the source(s) of water in the sinkhole, more detailed chemical analysis, including trace element analysis, will be required. Water samples from aquifers below and above the Salado Formation, from the Salado Formation, and from oil wells producing brines should be analyzed.

HISTORY OF HENDRICK WELL NO. 10-A

Located within the circumference of the Winkler County sinkhole is a plugged and abandoned oil well, Hendrick Well No. 10-A (inset, fig. 21) (Texas Railroad Commission, 1928). The sink did not form around this borehole, but first appeared to one side of it. As the sinkhole expanded laterally by slumping and caving of the sides, the surface casing was apparently incorporated in the slump material. No eyewitnesses reported seeing the surface casing of the well as the sinkhole expanded.

Republic Production Company began drilling Hendrick Well No. 10-A on June 29, 1928, and completed it October 25 of the same year. The driller's logs document drilling procedures (Texas Railroad Commission, 1928) (table 5). It

was drilled with rotary tools to the top of the "brown lime of the Tansill Formation" at a depth of 2,193 ft (668 m) and cable tools were employed thereafter. Surface casing of 15 1/2-inch (39 cm) diameter was set at a depth of 400 ft (122 m) and cemented with 300 sacks of cement (fig. 21). Ten-inch (25.4 cm) casing was set at a depth of 2,196 ft (669 m) and cemented with 800 sacks of cement. Finally, casing of a diameter of 8 1/4-inch (21 cm) was set at a depth of 2,440 ft (744 m) but was not cemented. The well was completed in the Yates Formation at a depth of 2,552 ft (778 m). No casing was set below 2,440 ft.

At a depth of 2,300 ft (700 m) the hole was straightened by exploding 160 quarts (151 liters) of nitroglycerine in the borehole, a common practice during that era of oil well drilling. When the borehole deviated too much from the vertical, explosives were used to fracture the rock to allow the hole to be re-aligned. Explosions could have fractured the cement lining the borehole, creating avenues for water movement.

Republic Production Company deepened the well to 2,570 ft (783 m) in January, 1930, and filed an application to deepen to 3,100 ft (945 m) in December, 1931 (Texas Railroad Commission, 1930, 1931). However, no drilling log on file at the Texas Railroad Commission indicates that the well was drilled deeper than 2,570 ft depth (table 5).

When Bradberry and Sasser Company plugged the well in 1951, the well was sealed with cement from 2,570 to 2,150 ft (783 to 655 m). The wellbore was filled with mud and plugged again from 400 to 370 ft (122 to 113 m) with 25 sacks of cement; however, this plug was later removed. Fifteen sacks of cement were used to plug the well at the surface (Texas Railroad Commission, 1930). The well was then abandoned for 13 years.

In 1964, Mallard Petroleum Company attempted to deepen the well. Records show that the drillers were unable to reenter the hole "because of junk" in the

borehole (Texas Railroad Commission, 1964). The well was plugged March 2, 1964, with 50 sacks of cement at 1,100 ft (335 m), with 40 sacks at 1,060 ft (323 m) (within the Rustler anhydrite) and with 10 sacks at the surface (fig. 21). Over 600 ft (183 m) of 10-inch diameter pipe were removed, leaving an unlined borehole, presumably filled with mud, between 1,062 and 400 ft depth (324 to 122 m) or from below the top of the Rustler Formation to below the bottom of the Santa Rosa Formation.

No geophysical log is available for this well, but a driller's log filed by Republic Production Company describes the strata encountered in the well (Texas Railroad Commission, 1928, 1930). This description (table 5) is very general and should be compared with the stratigraphy shown in figure 21, which is based on gamma ray logs from wells 113 and 163 (fig. 16, Appendix B).

The driller recorded depths to two distinct lithologic boundaries that are similar to depths recorded by gamma ray logs. The first anhydrite was encountered in Well No. 10-A at a depth of 1,050 ft (320 m), and the top of a "lime" formation was recorded at 2,193 ft (668 m) depth (table 5). On figure 21, depth to the first anhydrite (Rustler Formation) is 1,050 ft (320 m) and depth to the first dolomite in the Tansill Formation is 2,200 ft (670 m). Because these depths recorded by both methods are very similar, we are confident that the driller correctly noted where the 10-inch (25.4 cm) casing was set and that the borehole was lined with casing through the entire Salado Formation.

The driller did not record a loss of drilling fluids, but four dissolution zones are present in the Salado below the Wink Sink (figs. 16, 21). These zones could have formed before or after Well No. 10-A was drilled as a result of ground-water movement unrelated to the presence of the borehole.

On the other hand, the abandoned well may have been an important factor in the development of the dissolution zones and the sinkhole. Initial production

from the well was estimated to be 5,000 barrels per day of which 80 percent was water (Texas Railroad Commission, 1928). Pumping large amounts of saline water from this well may have enhanced corrosion of the pipe which lined the borehole. Water from the Yates Formation in the vicinity of the well has chloride-ion concentrations ranging from 4,300 to 21,000 mg/l (Hiss, 1975).

Leaks are present in the casing of a nearby well of similar age. Casing in Hendrick Well No. 3-A, 660 ft (200 m) south of Hendrick Well No. 10-A, was installed in 1928. Initial production from that well was about 5,000 barrels per day, of which 90 percent was water (Texas Railroad Commission, 1928). An attempt to circulate cement behind the casing in Well No. 3-A failed in early June, 1980 (prior to the formation of the Wink Sink) because of leaks in the casing (Mike Handren, Petro-Lewis Co., personal communication, August 14, 1980). Presumably, these leaks were caused by corrosion. The similar production histories and ages of both wells suggest that the casing in Well No. 10-A also may have been perforated by corrosion.

Perforations in the casing and fractures in the cement lining the borehole may have been pathways for movement of water either up or down the borehole. In the vicinity of the sinkhole the base of the Santa Rosa Formation, a fresh-water aquifer, is at a depth of about 400 ft (122 m) (fig. 16). A poor cement job at the base of the surface casing at 400 ft (122 m) depth (fig. 21) could have allowed fresh water to leak down the borehole outside the casing. In addition, the absence of cement plugs or a cement lining below a depth of 2,196 ft (669 m) in Well No. 10-A during the 23-year period from 1928 to 1951 may have allowed water under artesian pressure to move upward to near the base of the Salado Formation. Use of nitroglycerine to fracture the Tansill dolomite at a depth of 2,300 ft (701 m) could have increased permeability locally, thereby enhancing water movement along the borehole from the Capitan, Tansill or Yates into the base of the Salado.

Because the hydraulic head of the Santa Rosa is higher than that of the Capitan, Yates or Tansill Formations (fig. 12), water would flow from the Santa Rosa into any of the other three formations, if they were connected by a suitably permeable pathway. A borehole acting as such a pathway could contribute to salt dissolution if the casing were perforated in the salt section.

BRINE PRODUCTION AND INJECTION

The first oil well in the Hendrick Field was drilled in February, 1926, in Section 42, Block B-5 of the Public School Land Survey (Ackers and others, 1930). Production from the field was intense and resulted in rapid depletion of the oil reservoir (Myres, 1977). From the beginning, some oil wells pumped as much as 90 percent water, and this amount increased as time passed (Texas Railroad Commission, 1928).

Beginning in 1952, oil producers in Winkler County began to inject produced water into the production horizons in waterflood projects (fig. 22). Prior to 1952, waterflood projects in Winkler County used fresh water obtained from Cenozoic and Santa Rosa aquifers, and the saline produced waters were pumped into surface pits or natural drainage courses (Texas Water Commission, 1963). Waterflooding began in the Hendrick Field in 1963 and is in operation today (Texas Railroad Commission, 1968, 1980). The brine pipeline that was ruptured by collapse on the east side of the sinkhole carried water to a pumping station south of the sinkhole (John Fogle, Gulf Production Co., personal communication, September 12, 1980). From there the brine was pumped to the Keystone Field northeast of Kermit, Texas, for use in a waterflood project.

Waterflooding should not be confused with salt water disposal by injection. Waterflooding is a means of secondary recovery in which water is injected into the producing horizon to improve recovery from the hydrocarbon reservoir. Salt

water disposal involves injection of water into any suitable permeable subsurface zone, normally one which already contains saline water. Disposal involves environmental protection and is not intended to enhance hydrocarbon production.

In 1961, the Texas Railroad Commission conducted a state-wide survey of brine production and injection (Texas Water Commission, 1963). Waterflooding and salt water disposal were considered together as injection. According to that study over 12 million barrels of salt water were injected in the Hendrick Field in 1961. Over half of that amount was injected as a waterflood project into a single well about 1.7 mi (2.7 km) north of the site of the Wink Sink. That well (T. G. Hendrick Well No. 22-W, Block 26, Section 45, PSL Survey) was continuously listed as an injection well from 1967 to 1979 (Texas Railroad Commission, 1967-1979).

Applications on file with the Texas Department of Water Resources record the intervals to be used for proposed salt water disposal wells. Until 1963, disposal into the Rustler Formation was allowed. Since then, no application has been approved that proposed to dispose of salt water in the Rustler Formation. Disposal into the Yates and Seven Rivers Formations is by gravity flow, but disposal into the Capitan Reef below a depth of 2,565 ft (782 m) required pressure of 100 psi (7.03 kg/cm²) in 1964 (Texas Department of Water Resources, 1964).

No records are kept of the amount of water disposed by injection wells. Consequently, there is no way to determine how much water has been injected near the sinkhole. No permit was ever filed for Hendrick Well No. 10-A to be used as an injection well.

SUBSIDENCE FEATURES IN WESTERN WINKLER COUNTY

Two vintages of aerial photographs of western Winkler County were examined to detect subsidence features that formed between 1954 and 1968. None were

found. However, two closed depressions were mapped that appear to be older degraded sinkholes on 1954 and 1968 vintage aerial photographs (fig. 14). Both features appear as roughly circular depressions about 15 ft (4.6 m) deep on U.S. Geological Survey topographic maps of the area. One depression is 5.6 mi (9.0 km) north of the Wink Sink; the other is 3.0 mi (4.8 km) southeast of the sink.

The diameter of both depressions, as measured on the aerial photographs, is about 930 ft (283 m) or about 2-1/2 times larger than the Wink Sink. However, the distance between the peripheral tension fractures surrounding the Wink Sink is about 740 ft (225 m). Larger depressions up to 3,500 ft (1,070 m) in diameter are also common features of the landscape in western Winkler County in the vicinity of the Wink Sink and west of Monument Draw where numerous playa deposits previously have been mapped (fig. 4).

The two small depressions on figure 14 and the Wink Sink lie above the subsurface trend of the Permian Capitan Reef, as do a number of wet-weather ponds and depressions. Some of these internally-drained depressions, such as one just south of Highway 302 (fig. 14) were formerly used for disposal of oil field brines. It is likely that these features, like the Wink Sink, are the result of surface subsidence. Their orientation and location relative to the Capitan Reef suggest that the reef may have influenced their formation in the same manner that it apparently affected the dissolution preceding the appearance of the Wink Sink.

The two small depressions shown in figure 14 are probably relict sinks and the Wink Sink may resemble their appearance in several thousand years. The depressions exhibit flat or slightly concave bottoms and gently sloping sides. Caliche zones sometimes crop out on the upper slopes where runoff has eroded the soil. Caliche pebbles up to 1.0 in (2.5 cm) in diameter are found on the

sloping sides of the depressions, but not on the bottoms. No vertical scarps exist at the margin of the depressions; rather, the slope of the sides of the depressions diminishes gradually over a few tens of feet until it is the same as the surrounding terrain. Bottoms of depressions have a thick grass cover, unlike the surrounding area where grass is sparse or absent.

SINKHOLES IN OTHER AREAS

Sinkholes resulting from salt dissolution have been reported in a number of places in North America including Indiana (Hall, 1976), Kansas (Walters, 1978), Michigan (Landes, 1959), Montana, North Dakota, Wyoming (Parker, 1967), South Dakota (Bowles and Braddock, 1963; Laury, 1980), Texas (Fogg and Kreitler, 1980), and Saskatchewan (De Mille and others, 1964). Sinkholes very similar to the Wink Sink have been described in Saskatchewan by Gendziwill and Hajnal (1971) and in Utah by Huntoon and Richter (1979).

In Saskatchewan, a seismic reflection survey defined the shape of a collapse chimney below an 800-ft-wide (244 m) circular depression known as Crater Lake (Gendziwill and Hajnal, 1971). The geophysical data showed that the chimney originated in the Prairie Evaporite (salt) Formation at a depth of 3,000 ft (915 m). Precursor to the chimney was a solution cavity 125 ft (38 m) deep and 800 ft (244 m) in diameter. The collapse chimney is about 350 ft (107 m) in diameter. When it formed, the ground surface dropped about 240 ft (73 m). The Wink Sink may have originated in the same fashion but at a shallower depth.

Huntoon and Richter (1979) described collapse chimneys in Utah that probably originated as cavities as a result of salt dissolution in the Paradox and Honaker Trail Formations. The cavities propagated upward by roof collapse, and their continued growth was maintained by dissolution of carbonate breccia from overlying formations. These combined processes produced chimneys that extend

upward 2,000 ft (610 m) into formations above the salt. Displacement of distinctive rock fragments from the original stratigraphic position indicates that minimum downward movement within the chimneys was about 100 ft (30 m). This compares closely with the 110 ft (33 m) depth of the Wink Sink.

CONCLUSIONS

Evaporites have been dissolving in the Delaware Basin for millions of years. Formation of the Wink Sink in June, 1980, is the most recent example of surface collapse and subsidence caused by salt dissolution. Coincidence of several surface subsidence features with the trend of the Permian Capitan Reef suggests that the reef has enhanced dissolution of the adjacent and overlying salt.

The Capitan Reef may have affected dissolution in two ways. First, differential compaction of sediments overlying the reef or faults parallel to the reef may have fractured the evaporite section, providing avenues for downward groundwater movement. Second, water under artesian pressure in the reef may have moved upward into salt beds.

Although the Wink Sink may be the result of natural processes, oil field operations in the area may be related to its formation. An abandoned oil well at the site of the sinkhole may have provided a conduit for water to come into contact with the Salado salt. Water may have moved downward from the Triassic Santa Rosa Formation or Permian Rustler Formation or up from the Capitan Reef into the Salado Formation. Corrosion of casing in the borehole or failure of cement plugs and lining could have facilitated vertical movement of groundwater. Use of explosives to fracture rock in the Tansill Formation also may have enhanced permeability locally or fractured the cement lining farther up the borehole.

Between July 19 and December 12, 1980, the ground surface surrounding the Wink Sink subsided as much as 1.456 ft (44.4 cm). The area affected by subsidence decreased markedly between July and December as areas farther from the sinkhole became stable. Future subsidence appears likely only within about 200 ft (61 m) of the edge of the sinkhole as it appeared in November, 1980.

Effects of brine injection and waterflooding on the formation of the sinkhole have not been firmly established. Hendrick Well No. 10-A, located within the sinkhole, was never used as an injection well, although nearby wells were used for injection. Injecting produced waters into the formations above and below the Salado may have altered hydrologic conditions and caused complex movement of ground water into the Salado evaporite section.

Size of the sinkhole and the depth to the salt beds in the Salado Formation are similar to other sinkholes in North America.

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FIGURE CAPTIONS

Figure 1A. Wink Sink, June 5, 1980. Oblique aerial photograph; north is to upper right. Depth to water surface is about 30 ft (9 m). Annular tension cracks surround the hole. A tangential crack (arrow) on the southeast side of the hole marks the eastern boundary of a zone of continued subsidence. All photographs, except where noted, are by Robert W. Baumgardner, Jr.

Figure 1B. Slab failure with block collapsing into the sinkhole, June 3, 1980. Photograph by John Weaver and courtesy of Winkler County News.

Figure 2A. South side of the Wink Sink, June 5, 1980. View to southeast. Area to the right (west) of brine pipeline (arrow) has subsided about 10 ft (3 m) producing a noticeable "sag."

Figure 2B. Wink sinkhole, June 5, 1980. View to east. Pipeline in foreground was not in use when sinkhole formed. Oil pipeline on far side of sink was in use and had to be rerouted after being broken. Oil storage tanks in background are operated by Shell Oil Company.

Figure 3A. Tangential surface fracture, east side of the subsided area, July 10, 1980. View is to north. Vertical displacement next to fieldbook is about 18 in (46 cm). This is the same crack marked by the arrow in figure 1A.

Figure 3B. East-west tension fracture, south side of Wink Sink, November 18, 1980. View is to east. Maximum width of crack (24 in or 61 cm) is a result of slumping. Block on left has moved only 6 in (15 cm) to the left (north),

relative to block on the right, as shown by width of crack adjacent to field-book.

Figure 4. Generalized geologic map of southern Winkler County, Texas. The Wink Sink formed between Kermit and Wink in an area covered by windblown sand. The sinkhole lies along a line coincident with a group of NW-SE trending wet-weather lakes. Adapted from Barnes, 1976.

Figure 5. Structural setting of West Texas and eastern New Mexico. A. Regional tectonic element. Note fault zone coincident with western margin of the Central Basin Platform. Adapted from Hills, 1970, and Keller and others, 1980. B. Regional Bouguer gravity map. Contour values are negative. Note gravity high associated with Central Basin Platform; in western Winkler County, the regional gravity anomaly increases from west to east. Adapted from Woollard and Joesting, 1964.

Figure 6. Regional east-west cross section A-A' on the eastern edge of the Delaware Basin. Western flank of Central Basin Platform is marked by the Capitan Reef. Dissolution trough above Capitan Reef is result of salt dissolution in Salado and Castile Formations. Well numbers on all cross sections refer to Appendix B. Study area on inset map (stippled) refers to figs. 8-10.

Figure 7. Local east-west cross section B-B' showing salt dissolution zones in Salado Formation. Westward decrease in elevation of Permian and Triassic strata above the Salado is caused by dissolution and collapse in the salt-bearing section. Upper and lower contacts of Triassic Santa Rosa Sandstone are approximate. Line of section shown on figs. 8-10.

Figure 8. Structure contour map on base of Tansill Formation. Wink Sink is located above a structural high that trends NW-SE. Base of Tansill dips westward at 500 ft/mi (95 m/km) and eastward at 25 ft/mi (4.7 m/km). For location of map, see figure 4 and figure 6 (inset). Line B-B' refers to cross section, figure 7.

Figure 9. Structure contour map on top of Rustler Formation. Top of the Rustler dips westward at 200 to 500 ft/mi (38 to 95 m/km) and eastward at 75 ft/mi (14 m/km) from NW-SE trending structural high 2 mi (3.2 km) east of Wink Sink. For location of map, see figure 4 and figure 6 (inset). Line B-B' refers to cross section, figure 7.

Figure 10. Isopach map of the Salado and Tansill Formations. Variations in thickness are largely due to salt dissolution. For location of map, see figure 4 and figure 6 (inset). Line B-B' refers to cross section, figure 7.

Figure 11. Aquifer systems and salt dissolution, Delaware Basin. Water movement shown by arrows. Western dissolution zone (1) is result of tilting of Delaware Basin and subsequent dissolution of salt by downward-percolating ground water moving through formations (2) above the Delaware Mountain Group (3). Brine density flow model requires that eastern dissolution zone (4) was produced by water from Capitan Reef aquifer (5) that moved upward and laterally into Salado (6) and Castile Formations (7) under artesian pressure. Position of potentiometric surface is generalized. Salt dissolution leads to formation of collapse structures (8) that follow trend of inner margin of Capitan Reef. Post-Salado formations (9) east of the Capitan Reef probably affect dissolution only locally. Adapted from Anderson and Kirkland, 1980, figure 4.

Figure 12. Schematic diagram of static fluid levels in formations in southwest Winkler County, Texas. All tests in well 123 were made in same borehole, at different depths. Pure water (TDS = 0 ppm) would rise higher than Salado Formation. Water saturated with respect to sodium chloride (TDS = 226,000 ppm) would rise at least to Salado Formation. Actual salinities are between these two extremes. Depths of test intervals shown in table 3. Because hydraulic head in Santa Rosa Formation is higher than in other formations tested, water would flow from Santa Rosa to other formations, if a permeable pathway were available. For location of wells, see figure 14.

Figure 13. Dissolution and collapse features and isopach map of Cenozoic sediments, Delaware Basin. Cenozoic sediments more than 500 ft (152 m) thick (stippled area) overlie salt dissolution zones in center of basin and along eastern side. Other dissolution features coincide with subsurface trend of Capitan Reef on northeast side of basin. Adapted from Maley and Huffington, 1953; Nicholson and Clebsch, 1961; Hiss, 1975; and Bachman, 1976.

Figure 14. Evidence of salt dissolution/collapse in vicinity of Wink Sink. Four wells near Wink Sink lost fluids when drilled in 1927-1928: 8, 121 (no. 1 and no. 2), and 135. Loss indicates fractured or cavernous permeable conditions in vicinity. Closed depressions are older subsidence features, especially two small depressions north and southeast of sink. Data from wells 123, 163 and TDWR 46-16-101 used to determine hydraulic heads in formations in area (fig. 12).

Figure 15. Detailed east-west cross section C-C' at site of Wink Sink. Salt dissolution zones occur at several levels and can be traced laterally by noting

decrease in salt thickness between adjacent anhydrite beds. Note two dissolution zones beneath Wink Sink. Date below each well is date of well log. Elevations of top and base of Santa Rosa Formation approximate.

Figure 16. Local north-south cross section D-D' through Wink Sink. Several dissolution zones are documented including two beneath sinkhole that do not appear on cross section B-B' (fig. 7). Elevations of top and base of Santa Rosa Formation approximate.

Figure 17. Complete Bouguer anomaly values for gravity stations near Wink Sink. No significant perturbation near the sink is indicated. Values follow regional gravity gradients related to Central Basin Platform (fig. 5B).

Figure 18. Results of first-order levelling surveys. Maximum subsidence occurred on south side of sinkhole. A. July 19-August 24, 1980. Monuments 18 and 24 destroyed prior to completion of surveys. Limit of subsidence dashed where inferred. B. August 24-October 7, 1980.

Figure 19. Results of first-order levelling surveys. A. October 7-December 12, 1980. Note dramatic decrease in area of subsidence. B. Summary: July 19-December 12, 1980. Total maximum subsidence exceeded 1.4 ft (42.7 cm) on south side of sinkhole. Two areas flanking sinkhole rose slightly during time period. Limit of uplift dashed where inferred.

Figure 20. Total dissolved solids (mg/l) for water samples from wells in southern Winkler County. Wink Sink is near center of cluster of wells with high levels of dissolved solids. Data for water wells from Texas Department of Water Resources (1956-1979).

Figure 21. Hendrick Well No. 10-A, Section 41, Block B-5, PSL Survey, Winkler County. Condition of well recorded when abandoned in 1964 (Texas Railroad Commission, 1928, 1930, 1964). Stratigraphic section from area below Wink Sink (fig. 16). Note that (1) base of Santa Rosa is close to base of surface casing and (2) four dissolution zones are present here in Salado Formation. For lithic symbols, see figure 16. Inset shows location of well relative to Wink Sink.

Figure 22. Water used in waterflood projects, Winkler County, Texas, 1943-1956. Prior to 1952, only fresh water (TDS <1,000 ppm) was used. After 1952, amount of fresh water increased and was supplemented by more saline water. Adapted from Garza and Wesselman, 1959, figure 8.

Table 1. Stratigraphic section examined in this report.
(Modified from West Texas Geological Society, 1966.)

SYSTEM	SERIES	DELAWARE BASIN FORMATION/GROUP	CENTRAL BASIN PLATFORM FORMATION/GROUP
Quaternary		Alluvium	Alluvium
Triassic		Santa Rosa	Santa Rosa
		Tecovas	Tecovas
		Dewey Lake	Dewey Lake
	Ochoa	Rustler	Rustler
		Salado	Salado
		Castile	
Permian	Guadalupe	Delaware Mt. Group: Bell Canyon Cherry Canyon Brushy Canyon	CAPITAN AQUIFER Tansill Yates Seven Rivers Queen Grayburg San Andres Glorieta Artesia Group

Table 2. Thickness of Salado Formation shown on well logs used for cross sections B-B' and D-D'.

	WELL NO.	THICKNESS OF SALADO FORMATION		
		TOTAL (ft)	SALT (ft)	ANHYDRITE (ft)
CROSS SECTION B-B'	140	407	42	365
	139	666	306	360
	146	810	490	320
	147	780	480	300
	124	820	595	225
	87	950	700	250
	81	1010	750	260
	77	1140	880	260
	67	1220	945	275
	66	1240	925	315
CROSS SECTION D-D'	10	810	600	210
	109	625	415	210
	113	800	580	220
	163	830	600	230
	158	900	685	215
	155	860	635	225
	153	970	720	250
	269	970	710	260

Table 3. Formation pressure data from drill stem tests for two wells near Winkler County sinkhole. Formation pressures are great enough to support a column of water, either pure (TDS = 0 ppm) or saturated (TDS = 226,000 ppm), that would rise as high as Salado Formation, which is between elevation 650 and 1500 ft (200 and 450 m). Height of the water column was calculated using highest shut-in pressure. ISIP = Initial shut-in pressure. FSIP = final shut-in pressure. TDS = Total dissolved solids, expressed in ppm. MSL = mean sea level.

Well No.	Date	Ground Elev. (ft)	DST Data			Ht. of water column (ft) at TDS= 0	Elevation of water column (ft above MSL) at TDS= 0
			Depth of test (ft.)	Formation tested	ISIP (psi)	FSIP (psi)	
123	7/10/75	2824	2218-2510	Tansill-Yates	431	402	1455
			2500-2550	Yates	770	813	2176
			2545-2639	Yates-Capitan	958	958	2444
163	12/9/71	2823	2625-2652	Capitan	987	987	2464
						2279	2141

Table 4. Chemical analyses of water samples from Wink Sink and nearby wells reported as mg/l. Analyses from nearby wells are most recent available. Qal is Quaternary alluvium. SR is Santa Rosa Formation. TDS is total dissolved solids. Data for water wells are from Texas Department of Water Resources (1956-1979).

Location	Wink Sink	Water Well 1	Water Well 2	Water Well 3
Aquifer-Depth	---	Qal/SR-200'	SR-248'	QAL-200'
Date collected	6-7-80	10-15-70	12-12-68	2-21-69
Date analyzed	6-9-80	10-27-70	1-28-69	3-12-69
Calcium	840	890	600	870
Magnesium	158	195	138	143
Sodium and/or Potassium	935	730	630	670
Sulfate	1,674	2,070	1,250	1,220
Chloride	2,024	1,660	1,440	1,940
Iron	0.68	No data	No data	No data
Silica	No data	33	22	39
Total hardness as CaCO ₃	2,750	3,020	2,080	2,750
Bicarbonate	229	115	62	153
TDS	5,860	5,600	4,111	4,958
Hydrogen sulfide	0.0	No data	No data	No data
pH	7.46	7.6	7.2	7.1

Table 5. Driller's log for Well No. 10-A, T. G. Hendrick Lease, Section 41, Block B-5, PSL Survey, Winkler County, Texas. Data from records at Texas Railroad Commission. Dashed line separates log dated 1928 (upper) from 1930 log (lower). T. L. stands for "top of lime." S. L. means "steel line." BS and W means "bottom sediment and water."

Lithology	Color	Hard or Soft	Top (ft)	Bottom (ft)	Amount (ft)
Surface sand	Red	Soft	0	211	211
Sand rock	Brown	do	211	250	39
Sand	Red	Hard	250	404	154
Red beds and broken sand	do	Medium	404	474	70
Sand	do	Hard	474	594	120
Red beds and sand	do	Medium	594	670	76
Sand	White	do	670	720	50
Red beds and sand	Red	do	720	979	259
Sand	do	Hard	979	1050	71
Anhydrite	White	do	1050	1268	218
Anhydrite and salt	do	do	1268	1678	410
Anhydrite	do	do	1678	2193	515
Lime (T.L.)	do	do	2193	2198	5

Set and cemented 10" casing, standardized.

Lime	Blue	Medium	2198	2210	12
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Show of gas at 2198'.

Lime	White	Hard	2210	2220	10
Lime	Blue	do	2220	2235	15
Lime	White	do	2235	2295	60

Increase in gas at 2275'.

Lime	White	Hard	2295	2300	5
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Shot 160 quarts to straighten hole.

Lime (S.L. Correction)	White	Hard	2312	2365	53
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Reduced hole at 2317', more gas at 2365'.

Lime	White	Hard	2365	2428	63
Lime	Gray	do	2428	2450	22
Shale	Blue	Medium	2450	2460	10
Lime	Gray	Hard	2460	2525	65

Table 5. (continued)

Lithology	Color	Hard or Soft	Top (ft)	Bottom (ft)	Amount (ft)
Increase in gas at 2510'.					
Lime	Gray	Hard	2525	2552	27
Top Pay 2550', Estimated 5,000 barrels per day, showing 80% BS and W.					
Lime	Gray	Hard	2552	2568	16
Lime	Gray	Soft	2568	2570	2

APPENDIX A - DESCRIPTION OF STRATIGRAPHIC UNITS

STRATIGRAPHIC UNIT	LITHOLOGY	THICKNESS (ft)	FORMATION TOP
<u>CENOZOIC ALLUVIUM</u>	Unconsolidated sand, gravel, silt, clay; caliche with wind-blown sand on top.	0-1200	Surface
<u>TRIASSIC</u>			
Santa Rosa Fm	sandstone	200- 500	First clay siltstone or porosity break
Tecovas Fm	claystone	75- 125	Base of clean sand
<u>PERMIAN</u>			
Dewey Lake Fm	siltstone	300- 500	Break between siltstone and claystone (top of siltstones)
Rustler Fm	anhydrite dolomite anhydrite clay-siltstone sandstone clay-siltstone	250- 300 (Total) 100- 150 25- 50 10- 20 50- 75 25- 50 0- 20	Top of first anhydrite
Salado Fm	salt anhydrite with minor dolomite (carbonate)	400-1300 (Total) 0- 900 350- 450	Top of first salt in Salado Fm
Tansill Fm	- anhydrite dolomite with clastics (dolomitic muds)	75- 125 (Total) 50- 75 100- 150	Base of last salt in Salado Fm
Yates Fm	dolomite with clastics (sandstone, shales, and dolomitic muds)		First clastic mud break

APPENDIX B - WELLS CITED IN THE TEXT

Well No.	This Study	Operator	Lease and Well No.	Date of Log	Survey	Block	Section
8	Republic Prod. Co.		T. G. Hendrick #8	--	PSL	26	45
10	Gulf Oil Corp.		Grisham-Hunter W.S. #5	9-10-54	PSL	26	46
59	Frank & George Frankel		Driver #1	8-16-53	PSL	B-6	19
66	Reading & Bates Oil & Gas		Cowden "B" #2	5-22-61	PSL	B-5	39
67	Shell Oil Co.		Shell et al. Cowden A-1	10-31-58	PSL	B-5	39
77	Pan American Petr. Corp.		Hendrick-Weeks #6	9-15-59	PSL	B-5	40
81	Pan American Petr. Corp.		Hendrick-Weeks #2	6-17-59	PSL	B-5	40
87	Finley Co.		T. G. Hendrick #3	12-04-58	PSL	B-5	40
109	Rycade Oil Corp.		Atlantic-Hendrick E-5	7-20-57	PSL	B-5	41
113	Mallard Petr. Co.		Shell-Hendrick #1	7-13-64	PSL	B-5	41
121	Republic Prod. Co.		T. G. Hendrick #2	--	PSL	B-5	41
123	Monsanto Chem. Co.		T. G. Hendrick #9	6-01-75	PSL	B-5	41
124	Gulf Oil Corp.		Grisham-Hunter WS-5	9-10-54	PSL	B-5	41
129	Monsanto Chem. Co.		Hendrick "A" #1	1-13-58	PSL	B-5	41
135	Republic Prod. Co.		T. G. Hendrick #1-B	--	PSL	B-5	42
139	Tyra and Tyra		Hendrick #1	5-08-69	PSL	B-5	42
140	Logue & Patterson		Ida Hendrick #1	11-18-68	PSL	B-5	43
141	Pasotex Pipeline Co.		Butane Storage #1	2-08-65	PSL	B-5	32
146	Cactus Drilling Co.		Hendrick B #1	1-17-63	PSL	B-5	33
147	Worth Exploration Co.		Hendrick "A" #1	7-25-62	PSL	B-5	34
148	Worth Exploration Co.		Hendrick "A" #2	12-02-62	PSL	B-5	34
153	Humble Oil & Refining Co. and Monsanto Chem. Co.		T. G. Hendrick Gas Unit #1	7-05-59	PSL	B-5	34
155	Humble Oil & Refining Co.		T. G. Hendrick #13	8-14-57	PSL	B-5	34
158	Gulf Oil Corp.		Grisham-Hunter Surface Fee #WS-7	7-06-60	PSL	B-5	34
163	Stoltz, Wagner, & Brown		Hendrick #1	11-15-71	PSL	B-5	34
172	Pan American Petr. Corp.		Hendrick-Weeks #10	9-08-59	PSL	B-5	35
174	Humble Oil & Refining Co.		Fay Hunter Hogg #1	8-09-50	PSL	B-5	21
209	Pan American Petr. Corp.		E. W. Cowden #18	10-06-62	PSL	B-5	37
215	Pan American Petr. Corp.		Etta L. Milmo #1	4-05-61	PSL	B-6	17
269	Saxet Oil Co.		Hendrick A/C 128 #9	8-27-76	PSL	B-5	29
273	Hunt Oil Co.		University 21-10 #1	11-27-68	ULS	21	10
274	Ralph Lowe		University 1-7	10-21-60	ULS	21	7
278	Kern County Land Co.		Waddell #1	10-31-61	PSL	40	24
389	Cosden Petr. Corp.		S. B. Wright #1	1-05-55	PSL	40	22
403	The Texas Co.		J. A. Thomas #2	3-02-59	PSL	B-5	18
555	Cactus Drilling Co.		University D #1	7-19-65	ULS	20	12
556	Holbrook-Midland		University #1-10	8-14-68	ULS	20	10
637	Hunt Oil Co.		University 21-11 #1	5-01-71	ULS	21	11
738	Union Texas Petr. Co.		University 8-21 #1	10-29-74	ULS	21	8

PSL = Public School Lands

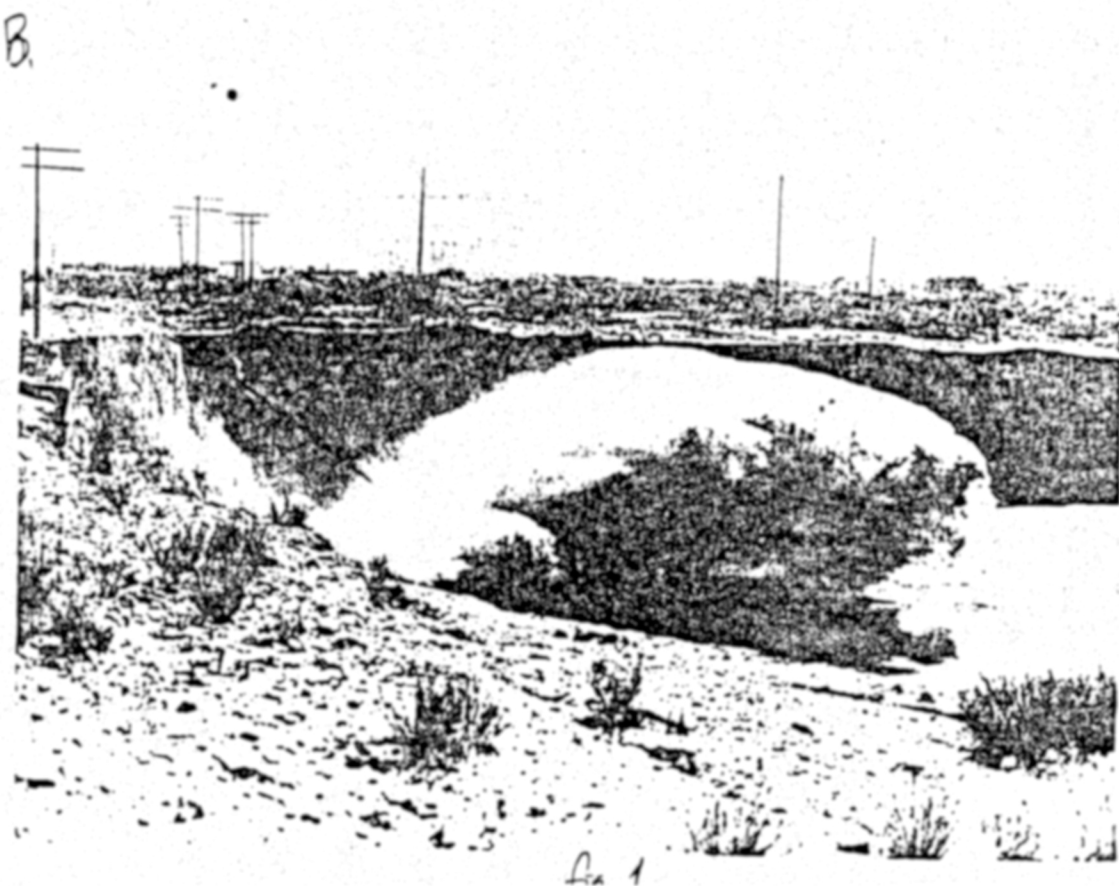
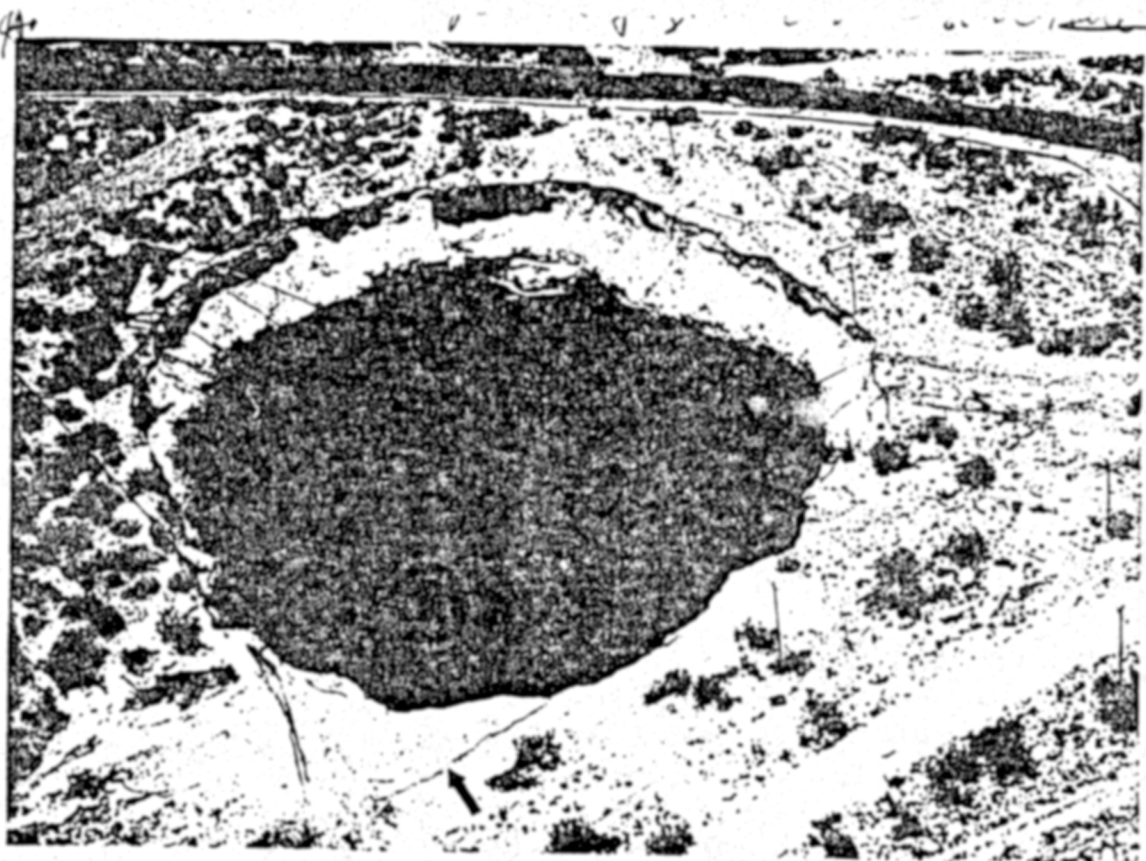
USL = University Land Survey

APPENDIX C - Changes in ground surface elevation at Wink Sink, July-December, 1980.
 All data are from first-order levelling surveys. Elevations expressed in feet.

Station no.	Elevation July 19	Change in elevation			Elevation Dec. 12	Summary net change
		July 19-Aug. 24	Aug. 24-Oct. 7	Oct. 7-Dec. 12		
1	2,824.687	-0.158	+0.024	-0.152	2,824.401	-0.286
2	2,824.451	-0.135	+0.057	-0.061	2,824.312	-0.139
3	2,823.445	-0.110	+0.060	0.000	2,823.395	-0.05
4	2,822.871	-0.011	-0.026	0.000	2,822.834	-0.037
5	2,821.566	0.004	-0.022	0.000	2,821.540	-0.026
6	2,822.124	0.000	0.000	0.000	2,822.124	0.000
7	2,824.355	0.000	0.000	0.000	2,824.355	0.000
8	2,813.469	-0.363	-0.063	-0.490	2,812.013	-1.456
9	2,817.896	-0.122	-0.340	-0.212	2,817.222	-0.674
10	2,818.733	+0.068	-0.097	0.000	2,818.704	-0.029
11	2,817.823	+0.006	+0.043	0.000	2,817.872	+0.049
12	2,816.380	0.000	+0.069	0.000	2,816.449	+0.069
13	2,815.699	-0.006	+0.079	0.000	2,815.772	+0.073
14	2,815.077	-0.008	0.000	0.000	2,815.069	-0.008
15	2,814.615	0.000	0.000	0.000	2,814.615	0.000
16	2,820.613	-0.009	+0.012	-0.361	2,820.255	-0.358
17	2,821.661	-0.006	0.000	0.000	2,821.655	-0.006
19	2,820.116	+0.006	+0.132	0.000	2,820.254	+0.138
20	2,820.868	-0.007	+0.173	0.000	2,821.034	+0.166
21	2,820.298	-0.004	+0.023	0.000	2,820.517	+0.219
22	2,820.257	-0.007	0.000	0.000	2,820.250	-0.007

APPENDIX C continued

Station no.	Elevation July 19	Change in elevation			Elevation Dec. 12	Summary net change
		July 19-Aug. 24	Aug. 24-Oct. 7	Oct. 7-Dec. 12		
23	2,824.189	-0.013	-0.222	-0.353	2,823.601	-0.588
25	2,826.749	-0.119	+0.154	-0.105	2,826.679	-0.070
26	2,827.512	0.000	+0.092	0.000	2,827.604	+0.092
27	2,827.320	0.000	+0.103	0.000	2,827.423	+0.103
28	2,826.664	0.000	0.000	0.000	2,826.644	0.000
29	2,827.643	0.000	0.000	0.000	2,827.643	0.000
30	2,816.863	+0.113	-0.102	0.000	2,816.874	+0.011
31	2,816.570	+0.138	-0.063	0.000	2,816.645	+0.075
32	2,816.096	-0.006	+0.165	0.000	2,816.255	+0.159
33	2,822.336	+0.068	-0.022	0.000	2,822.382	+0.046
34	2,823.981	+0.008	+0.115	0.000	2,824.104	+0.123
35	2,824.754	+0.086	-0.015	0.000	2,824.825	+0.071
36	2,815.703	-0.009	+0.056	0.000	2,815.750	+0.047
37	2,815.185	-0.005	+0.040	0.000	2,815.220	+0.035
38	2,815.940	+0.010	0.000	0.000	2,815.950	+0.010
39	2,817.063	-0.004	0.000	0.000	2,817.059	-0.004
40	2,818.781	-0.008	0.000	0.000	2,818.773	-0.008
41	2,820.560	-0.008	0.000	0.000	2,820.552	-0.008



Integrate w/ JLSA

Fig. 2
Plate 2

A.



B.



integrate w/fig. Plate 3
fig.

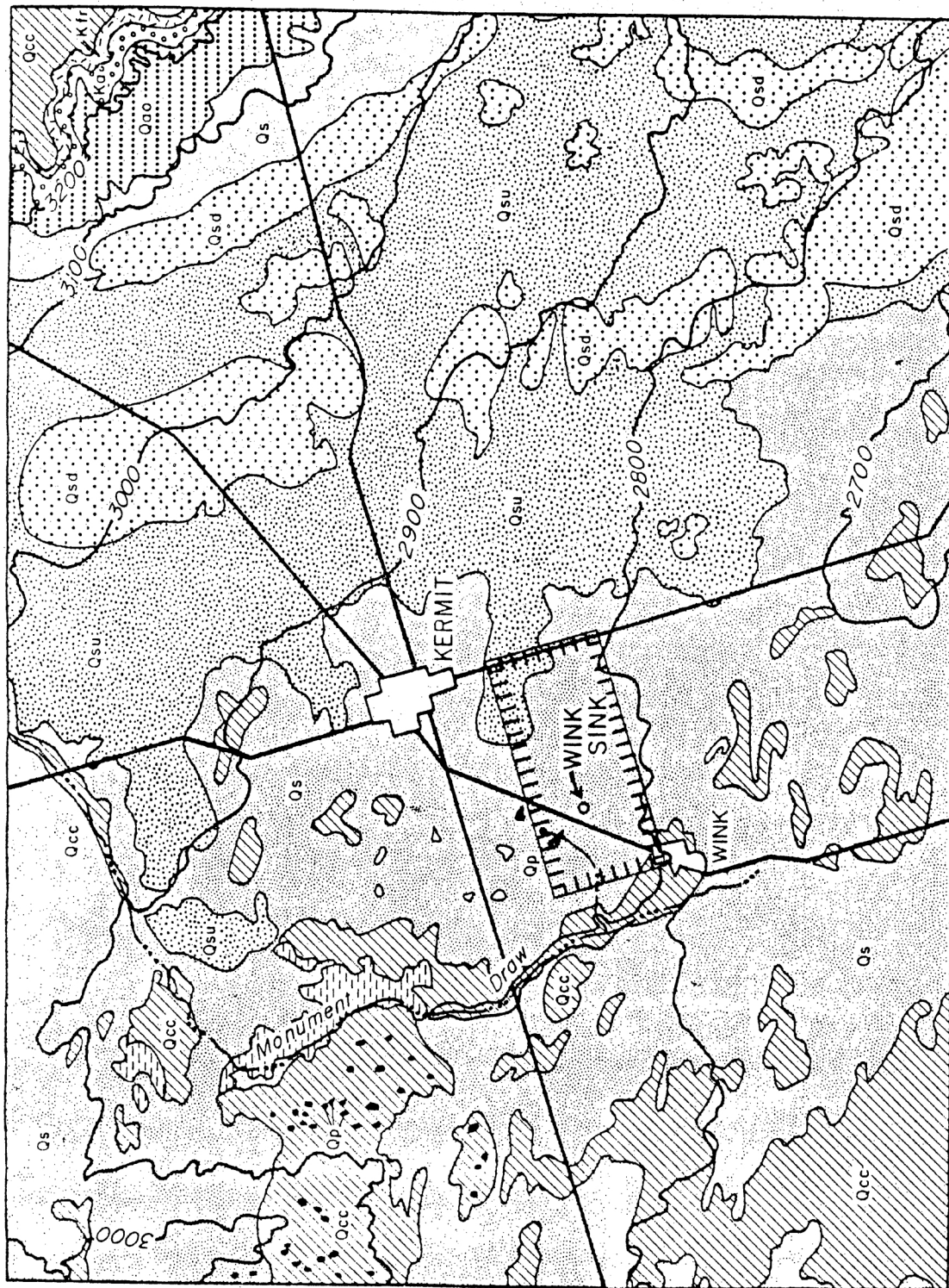
fig 3



B.



A.



Topographic C.I. = 100 ft

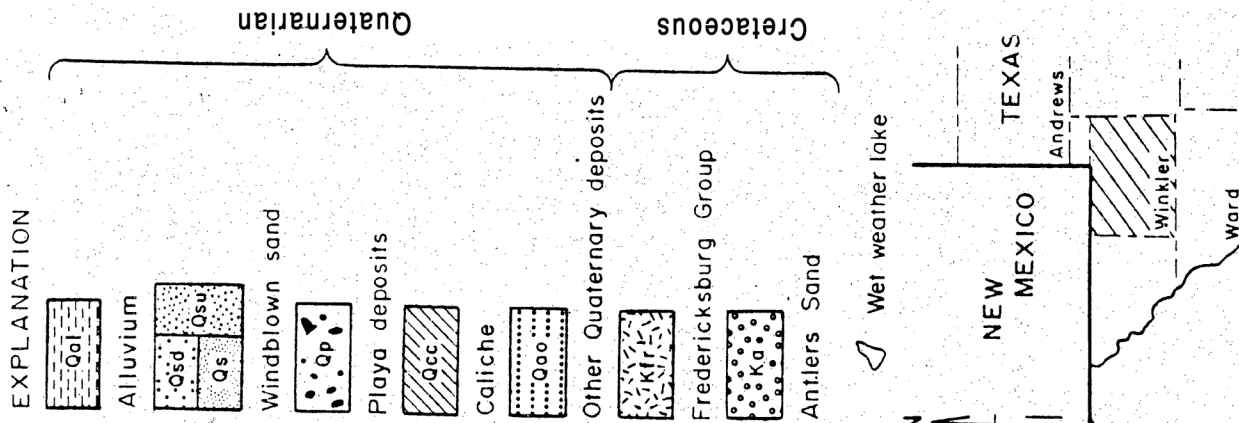
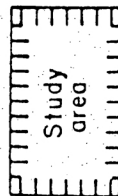
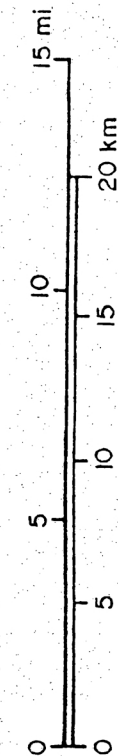


Fig. 4

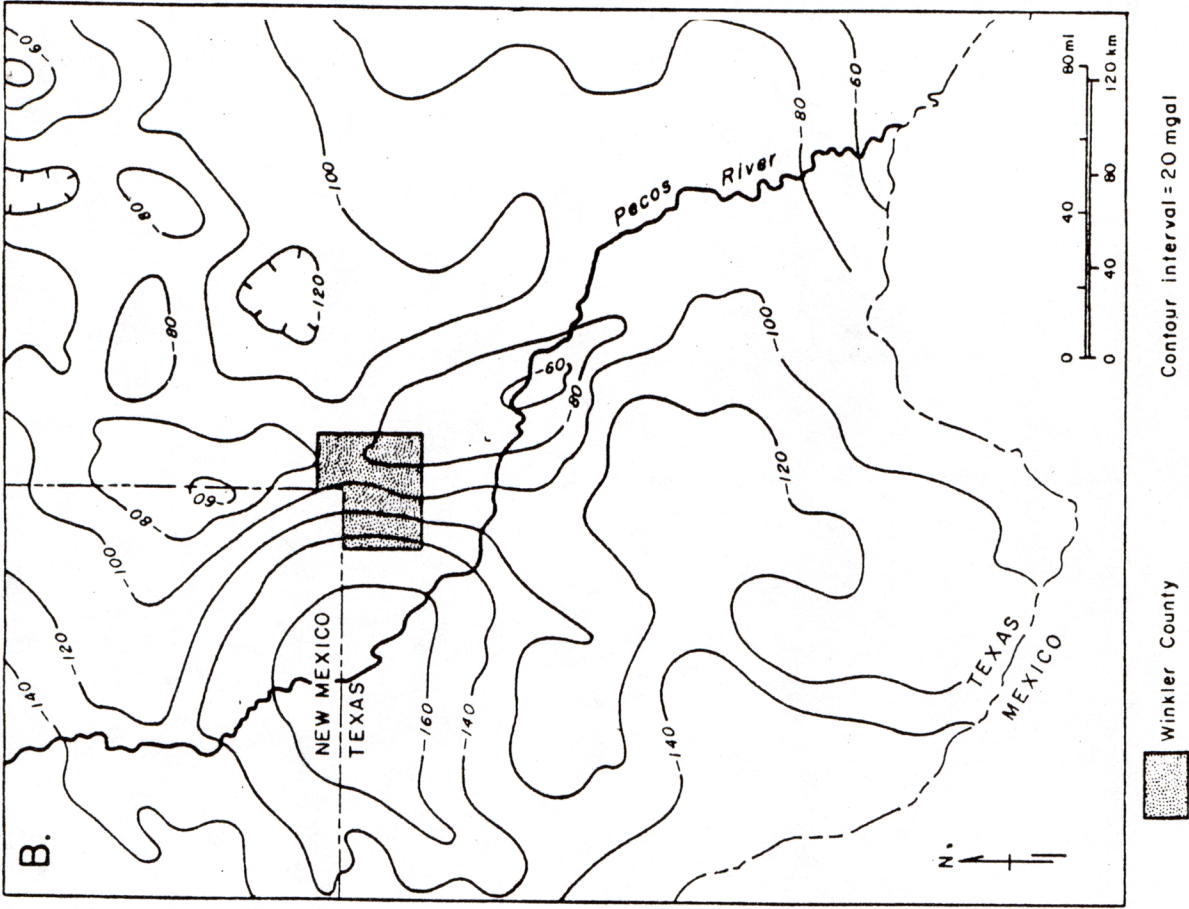
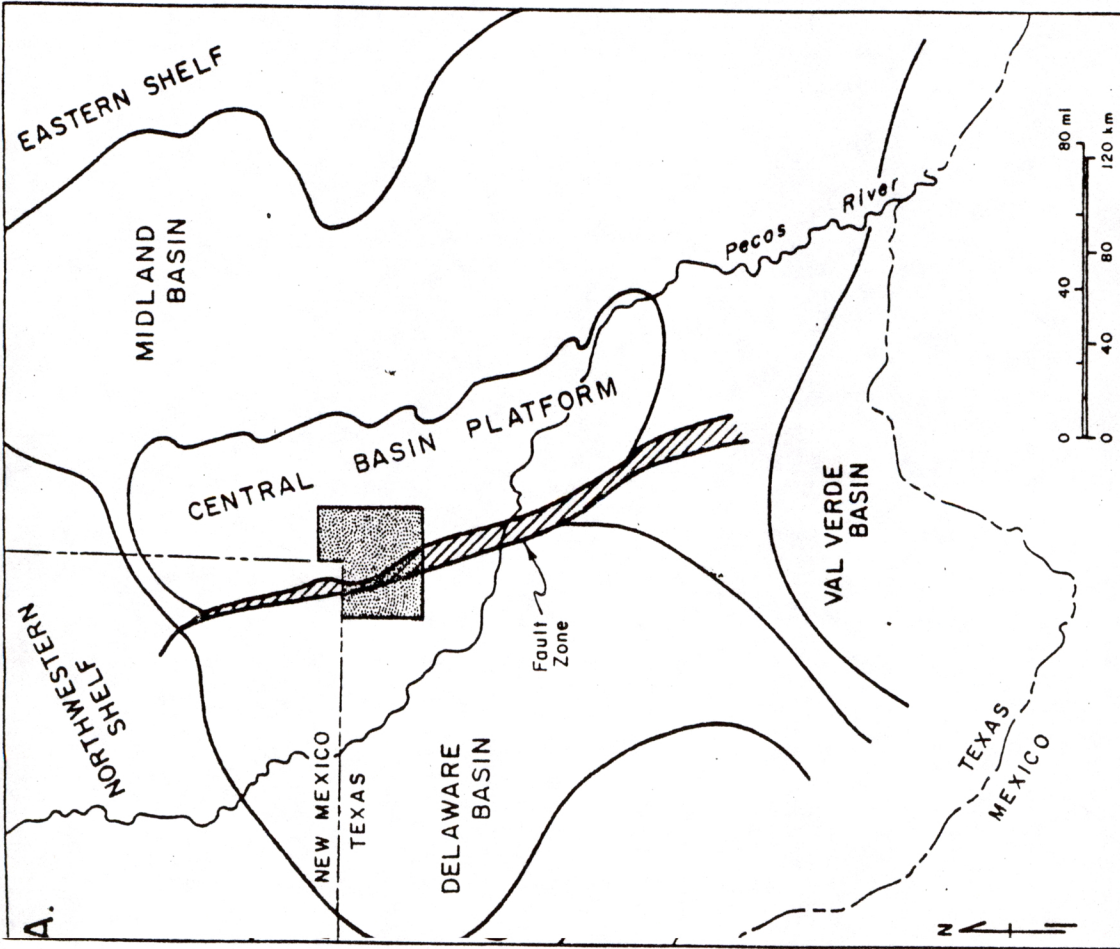
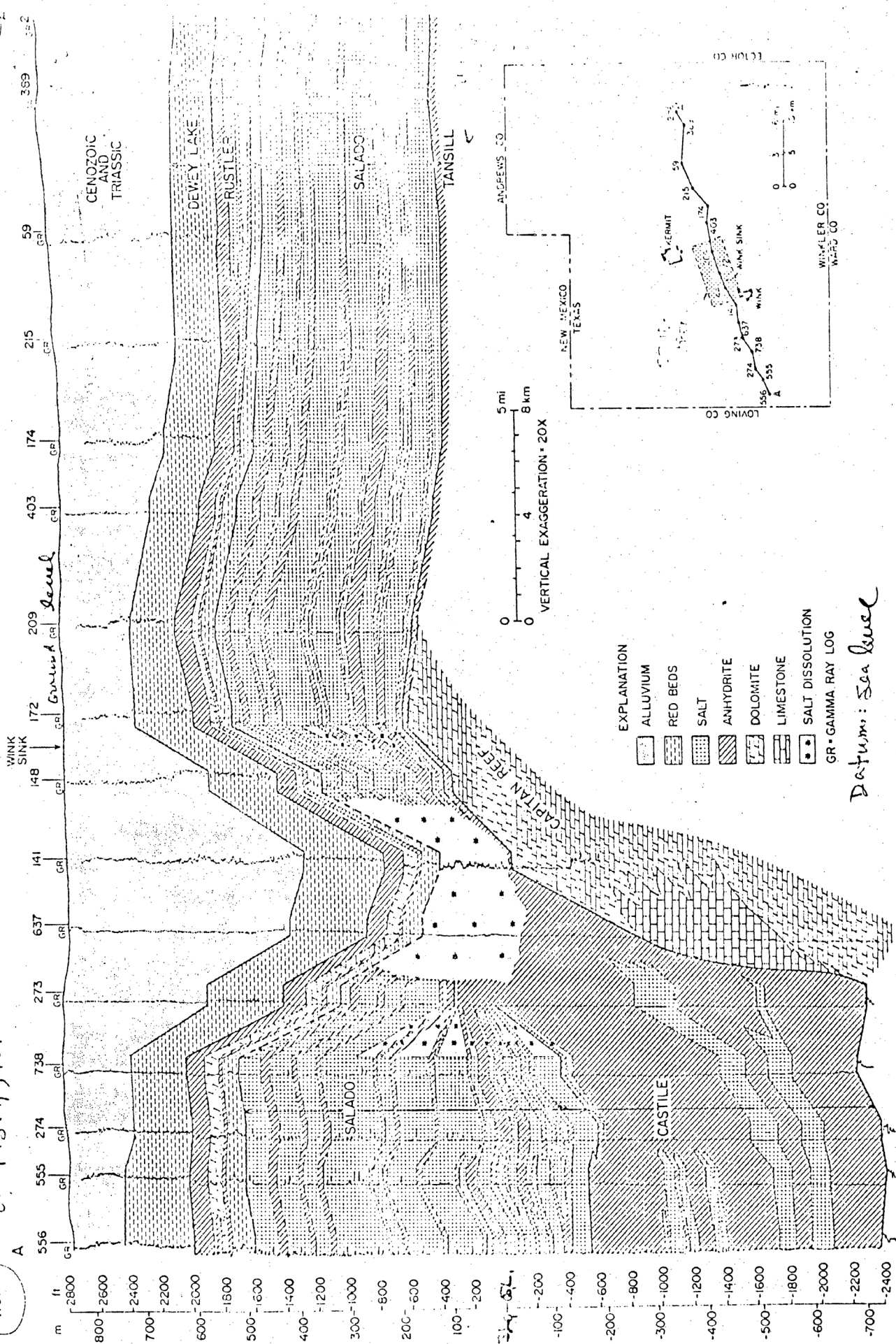


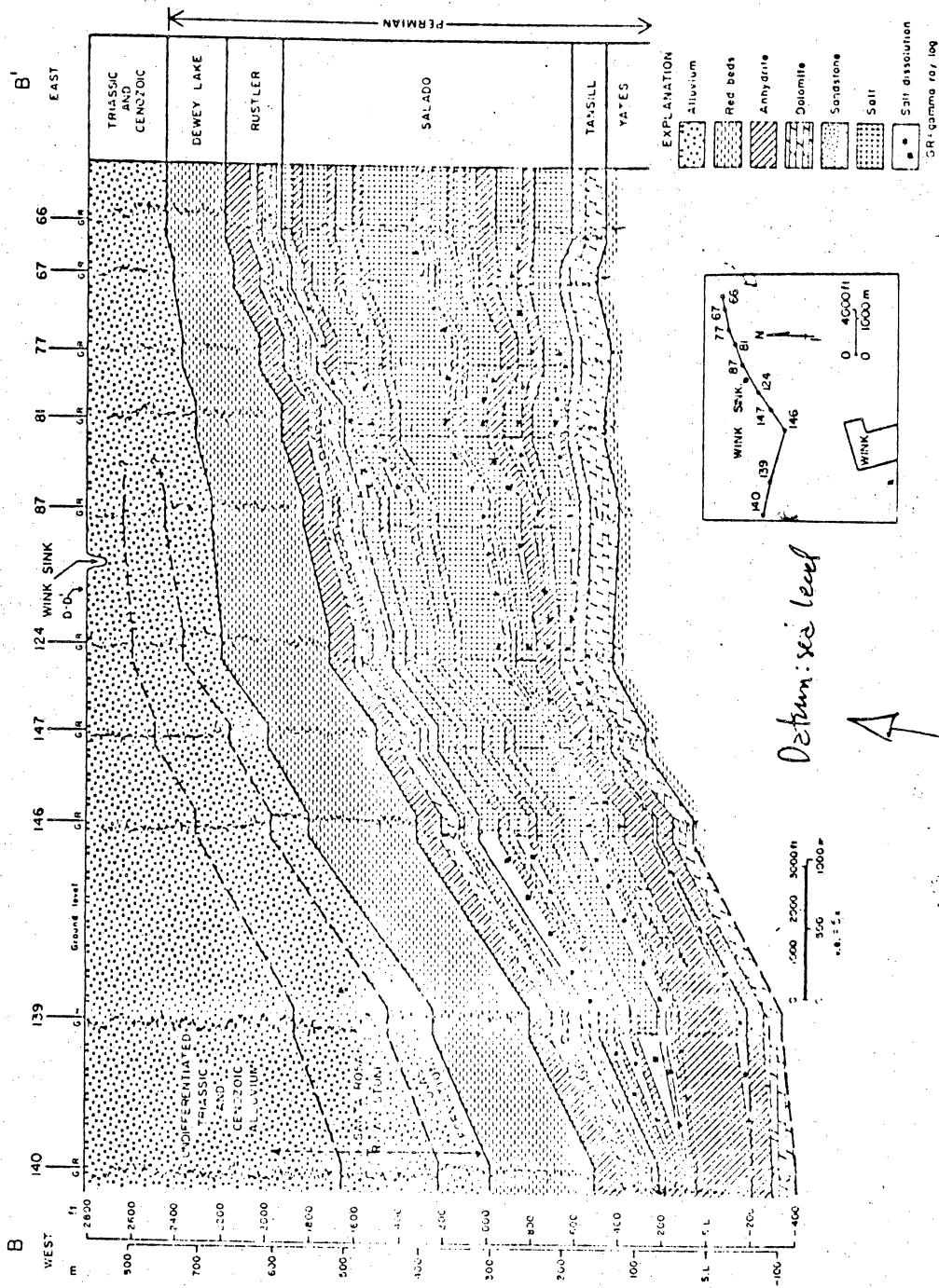
Fig. 2

West on F.S. 47, 13.



be consistent — See also

Fig 10



Return sea level

Add

Fig 3 - Fig 7

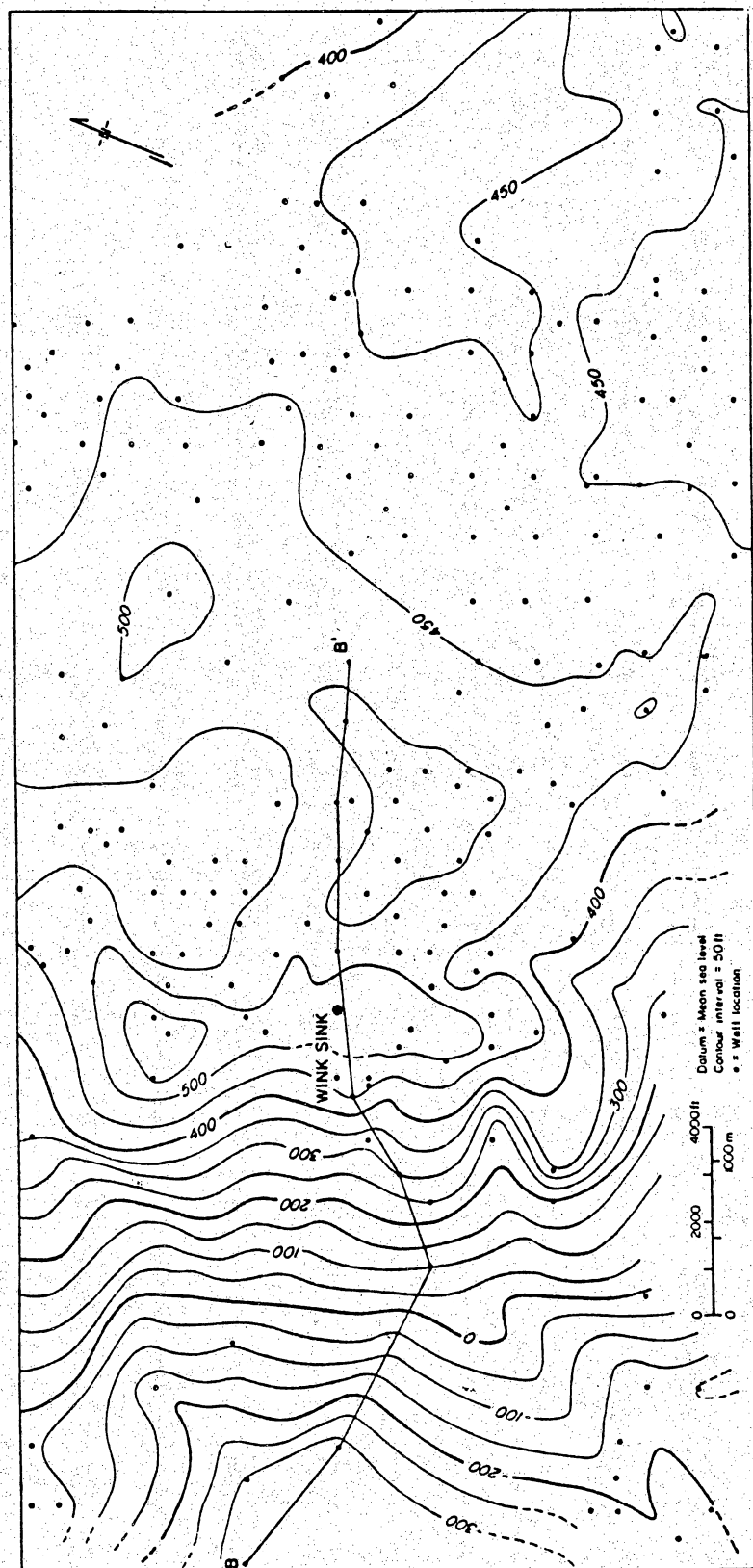


Fig. 8

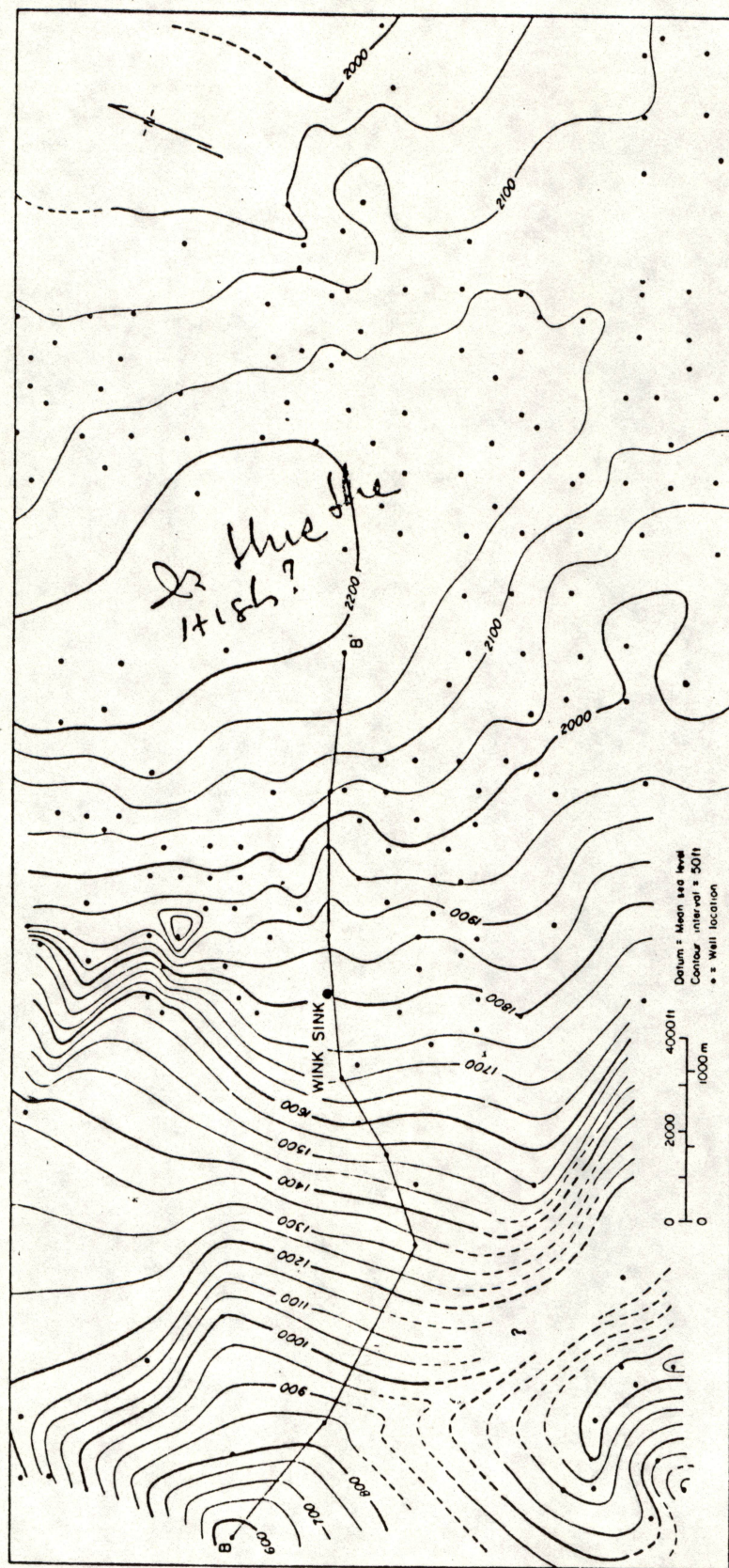


Fig 9

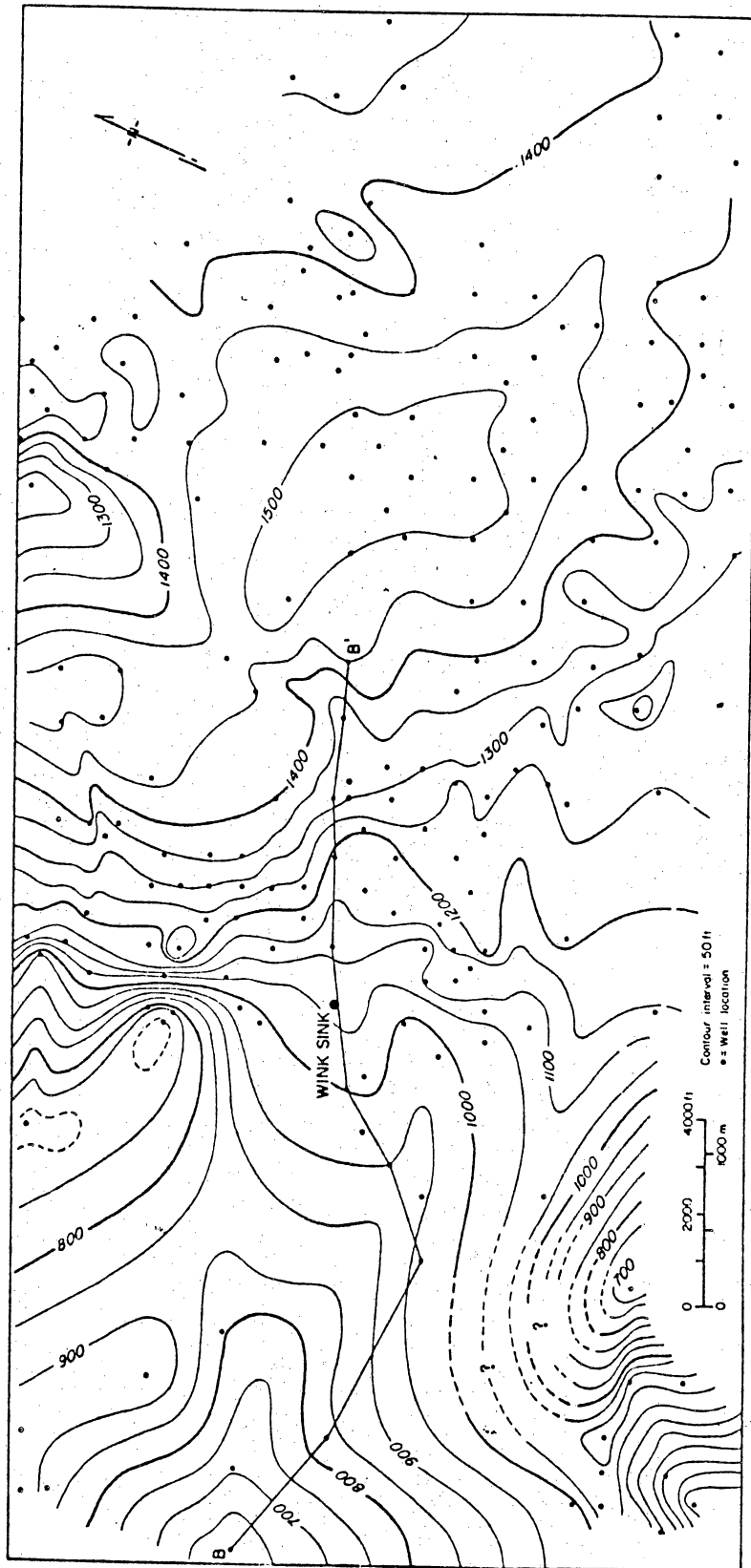


Fig 10

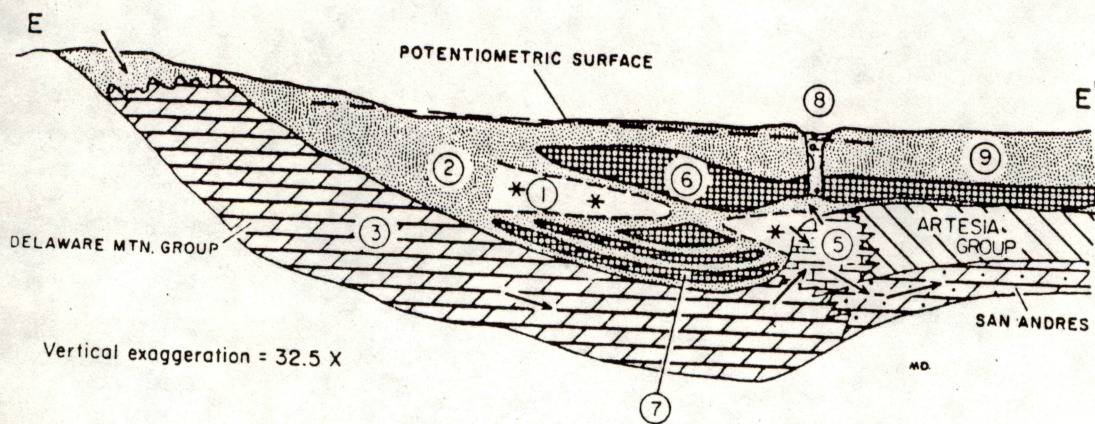
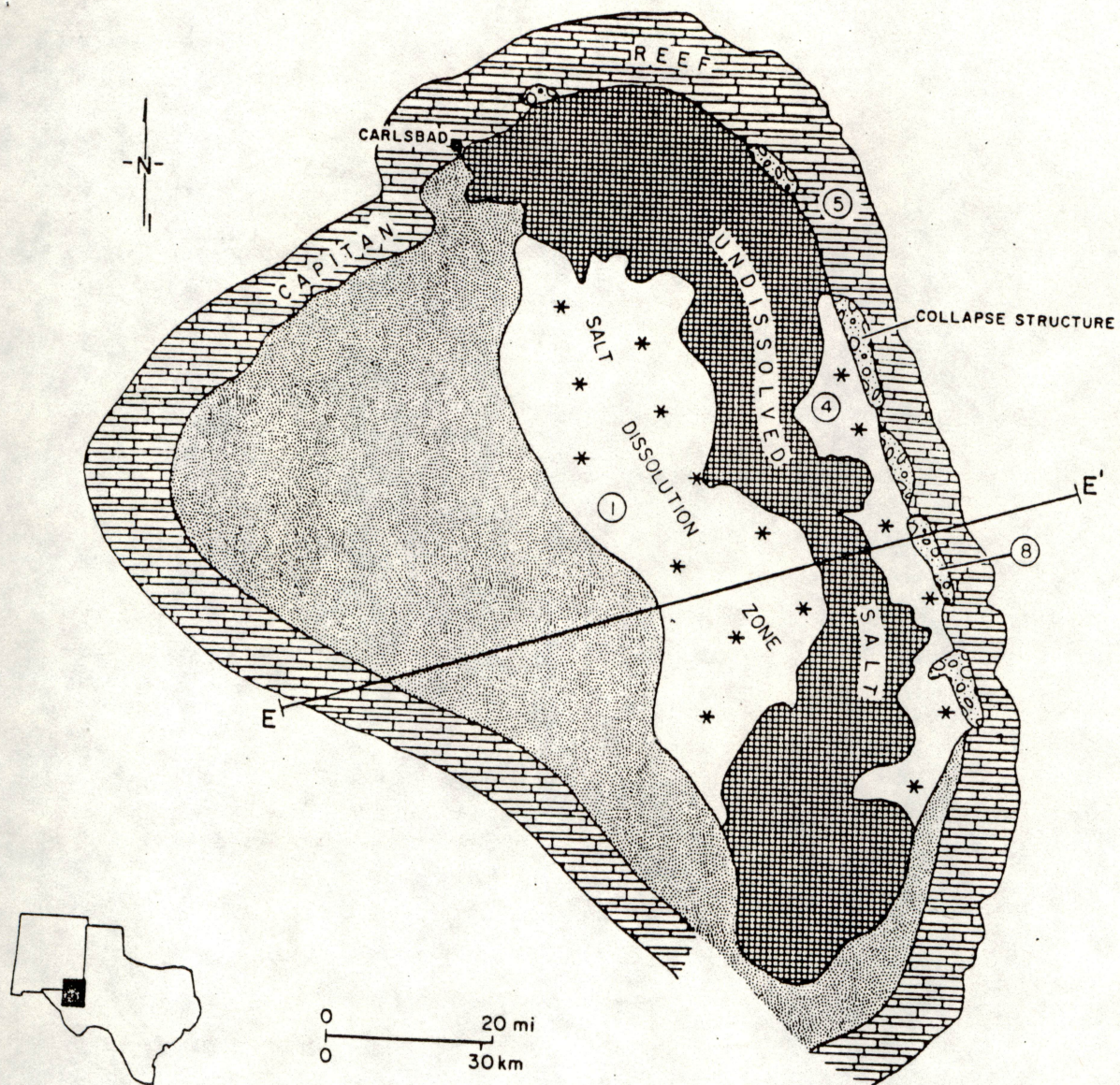
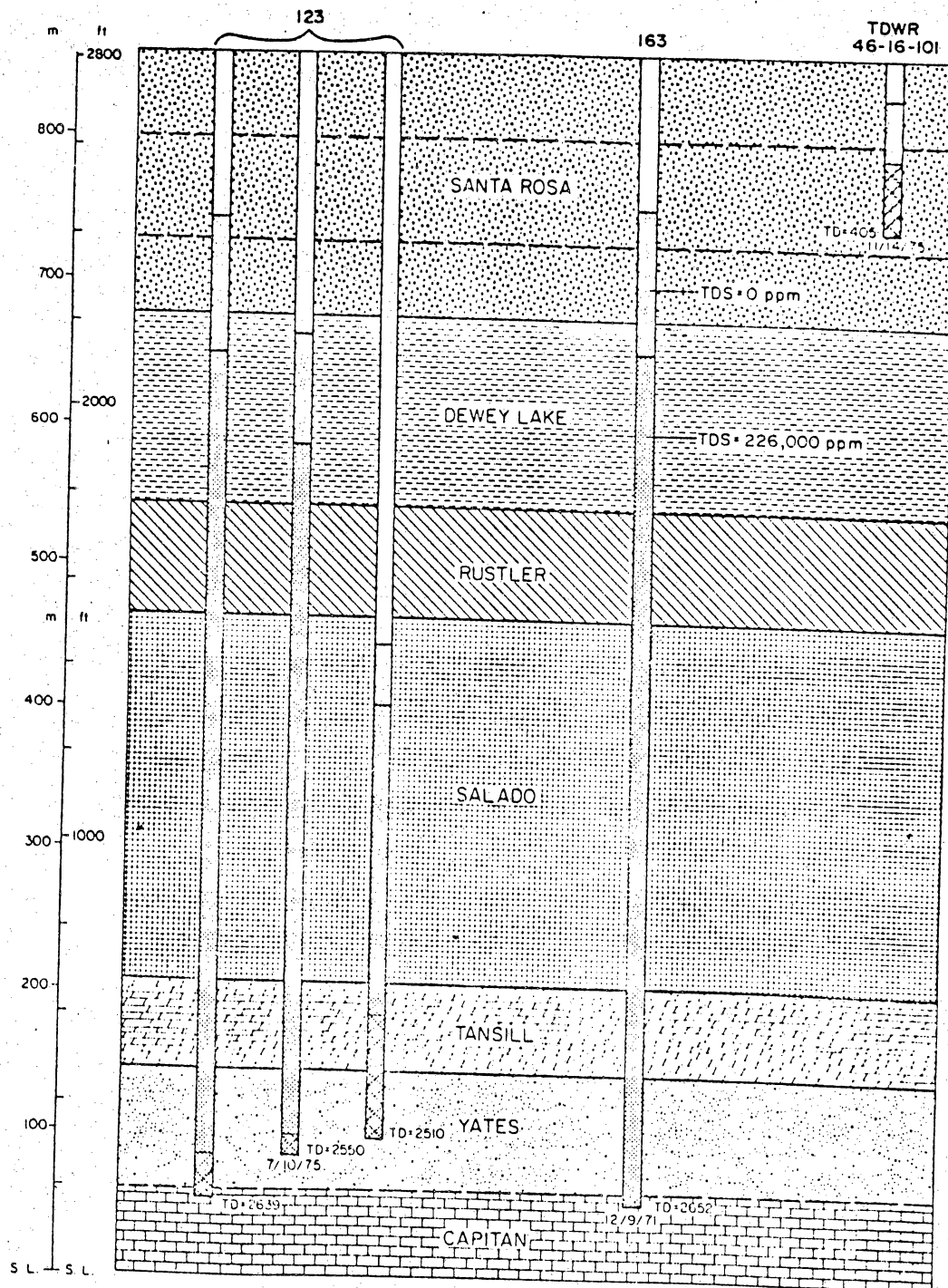


Fig. 11



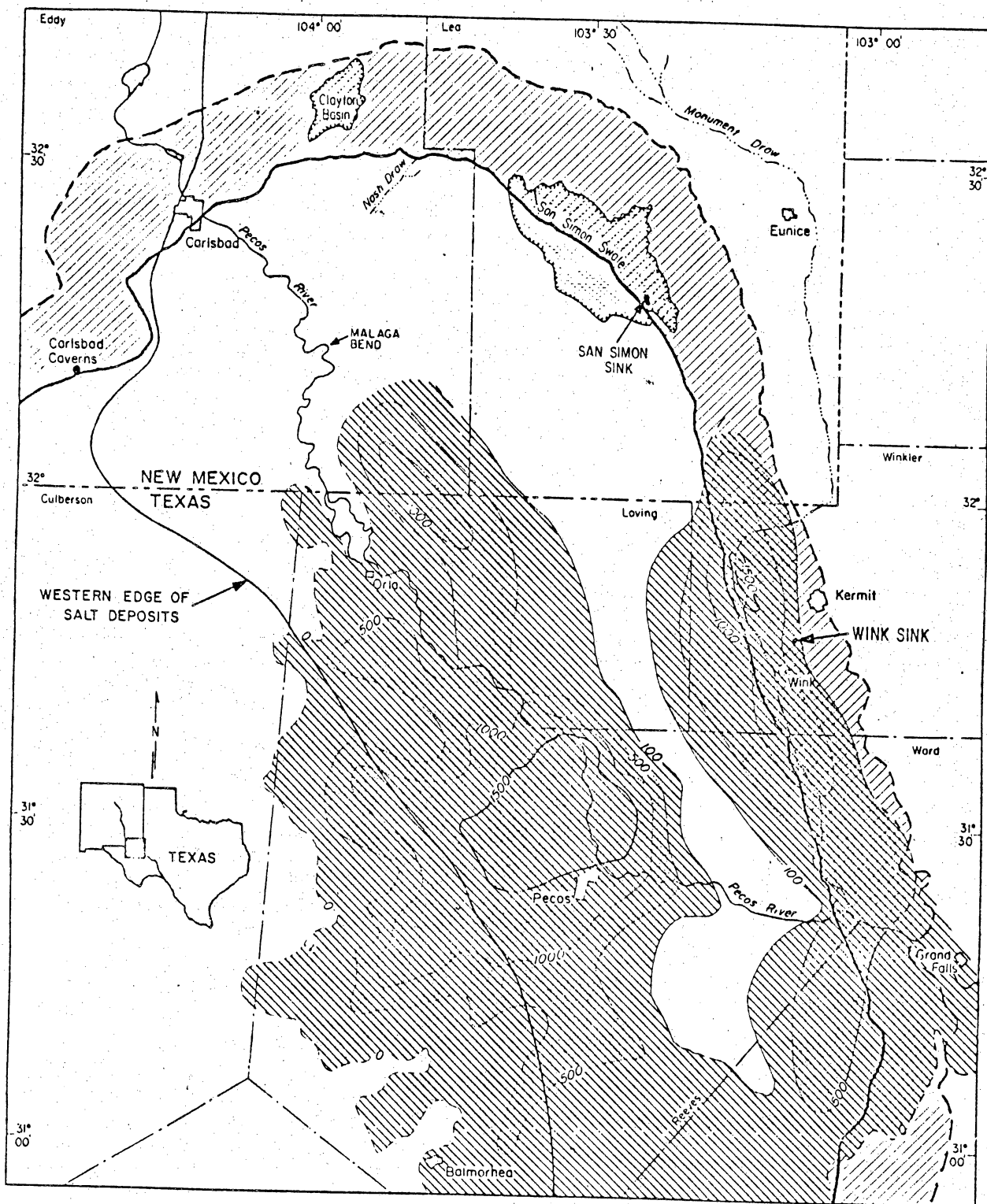
Horizontal distance not to scale

= Completion or DST interval

NO horizontal scale

Datum: sea level

Fig. 13
9 12



- Cenozoic fill. Limit dashed where inferred.
- Cenozoic fill over 500 feet thick
- Capitan reef. Margin dashed where inferred.

0 10 20 mi
0 10 20 30 km
Contour interval = 500 ft

Fig 13

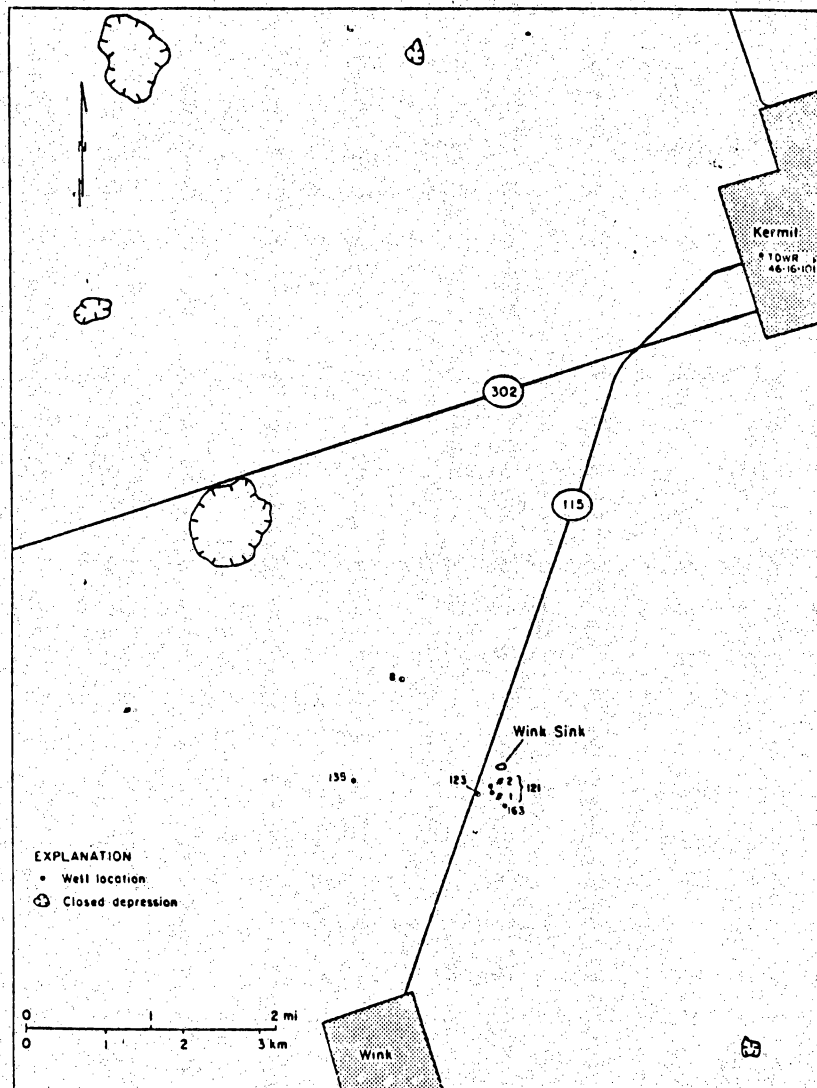
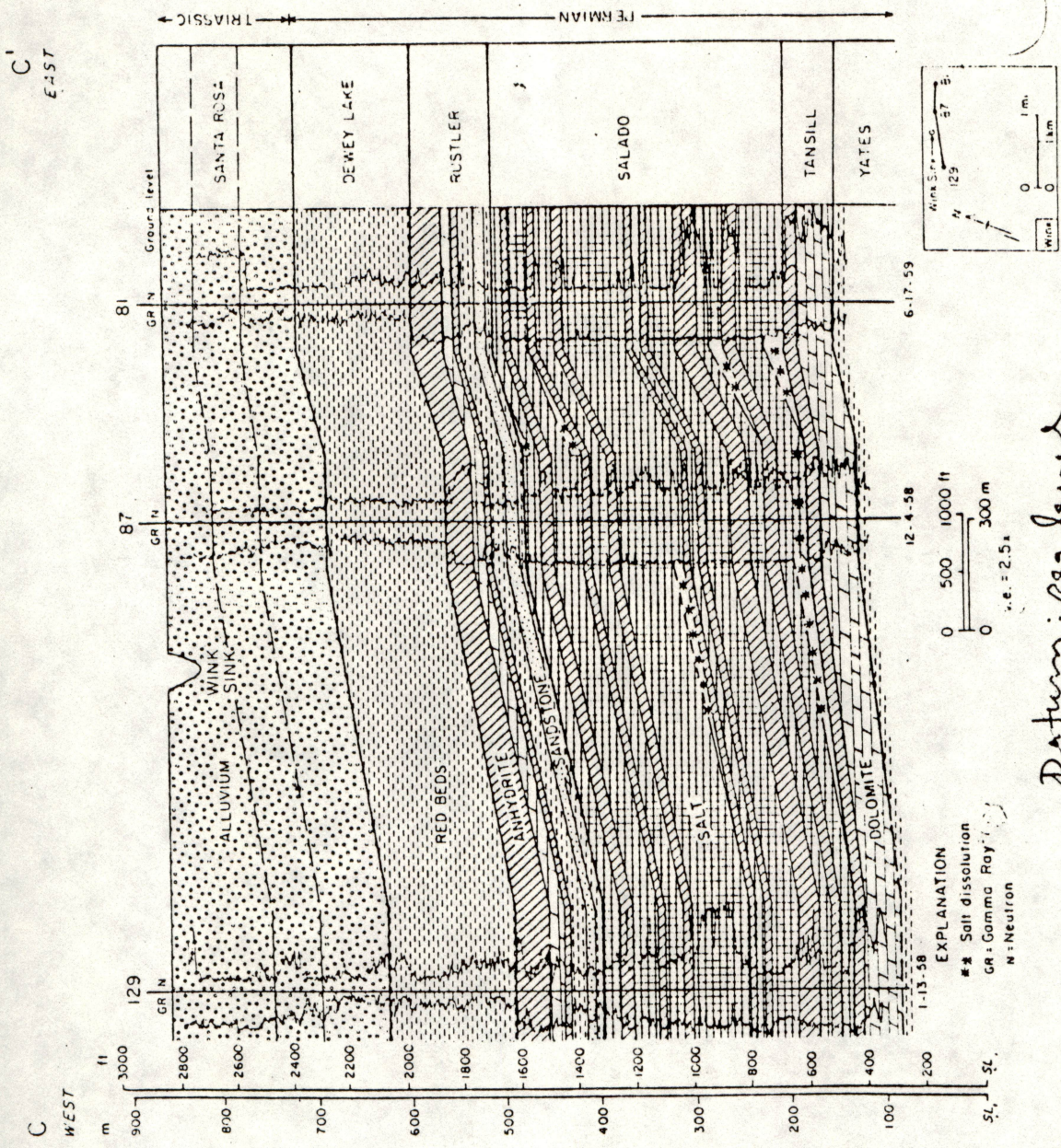


Fig 4

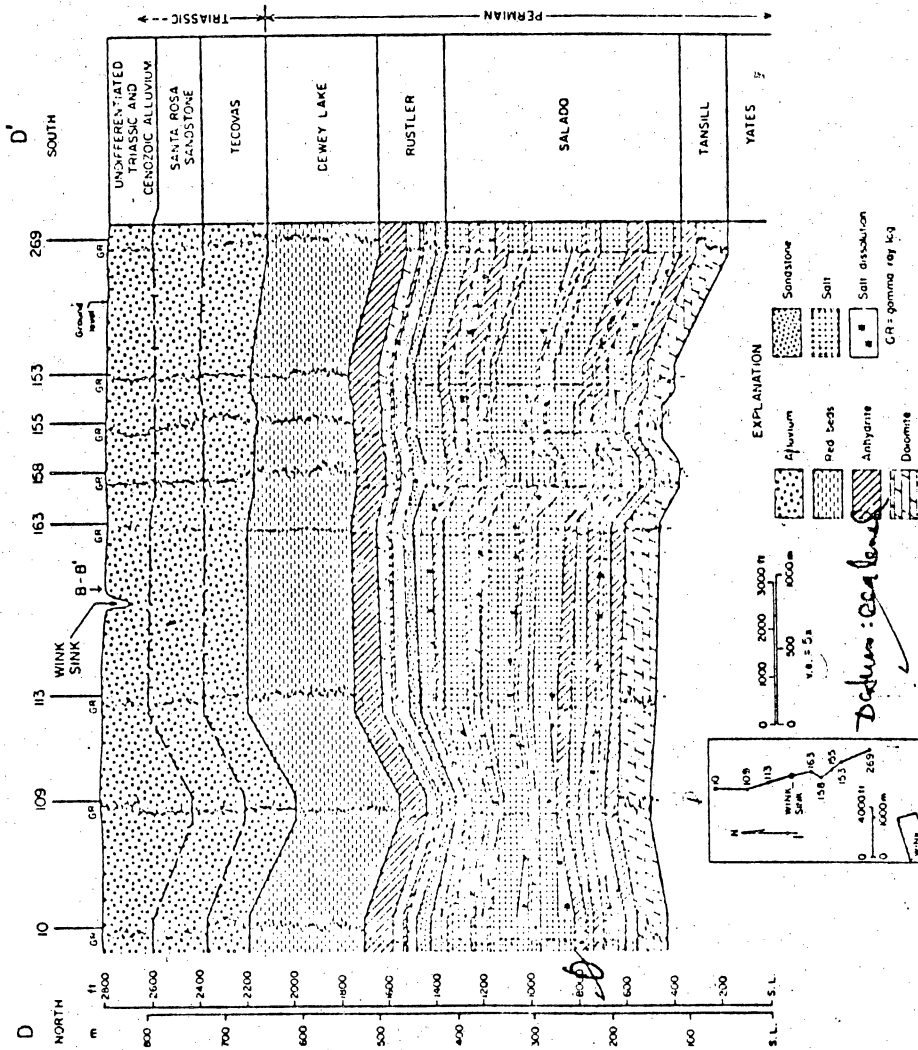


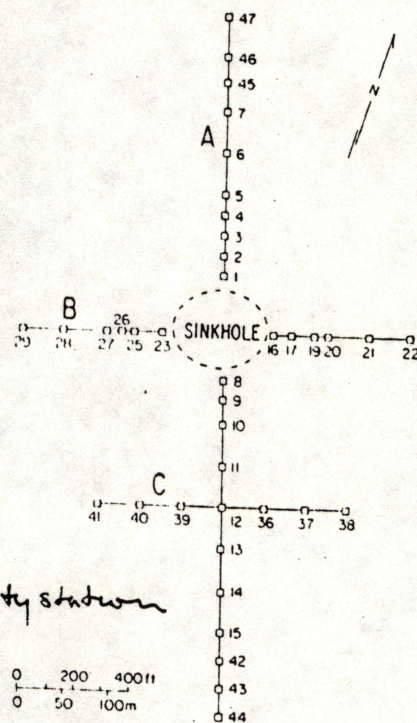
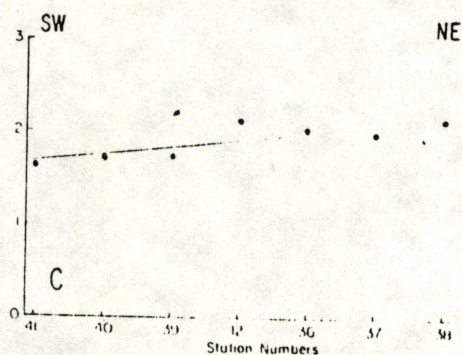
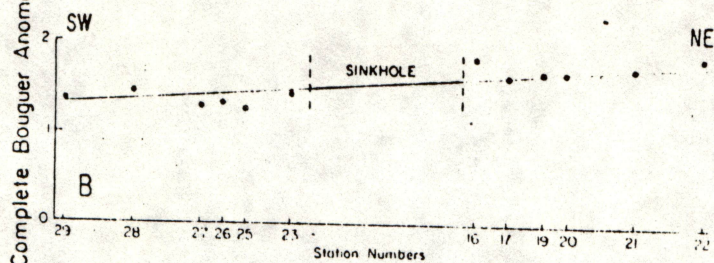
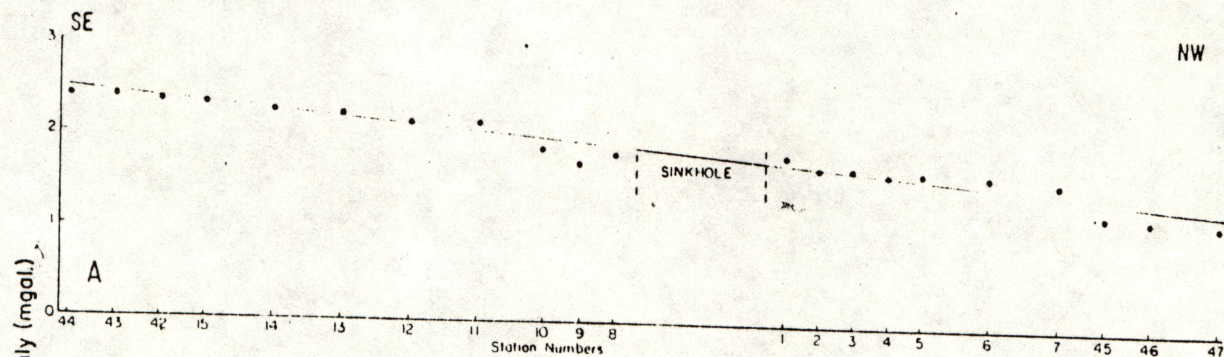
Datum: sea level

*Can't see what would be
you describe in
P. 17*

Fig 15

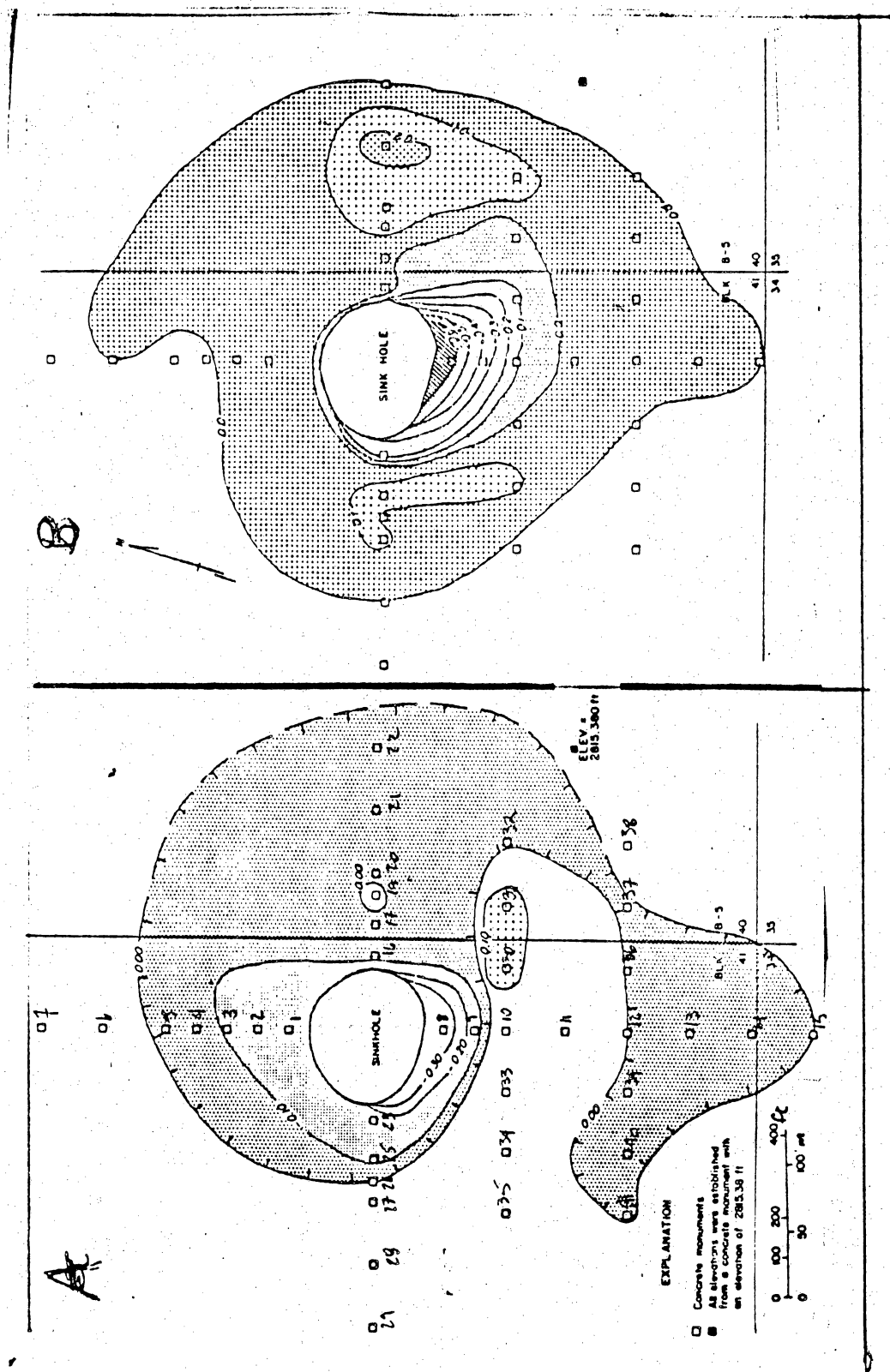
216
fly





Gravity station

17



81.18

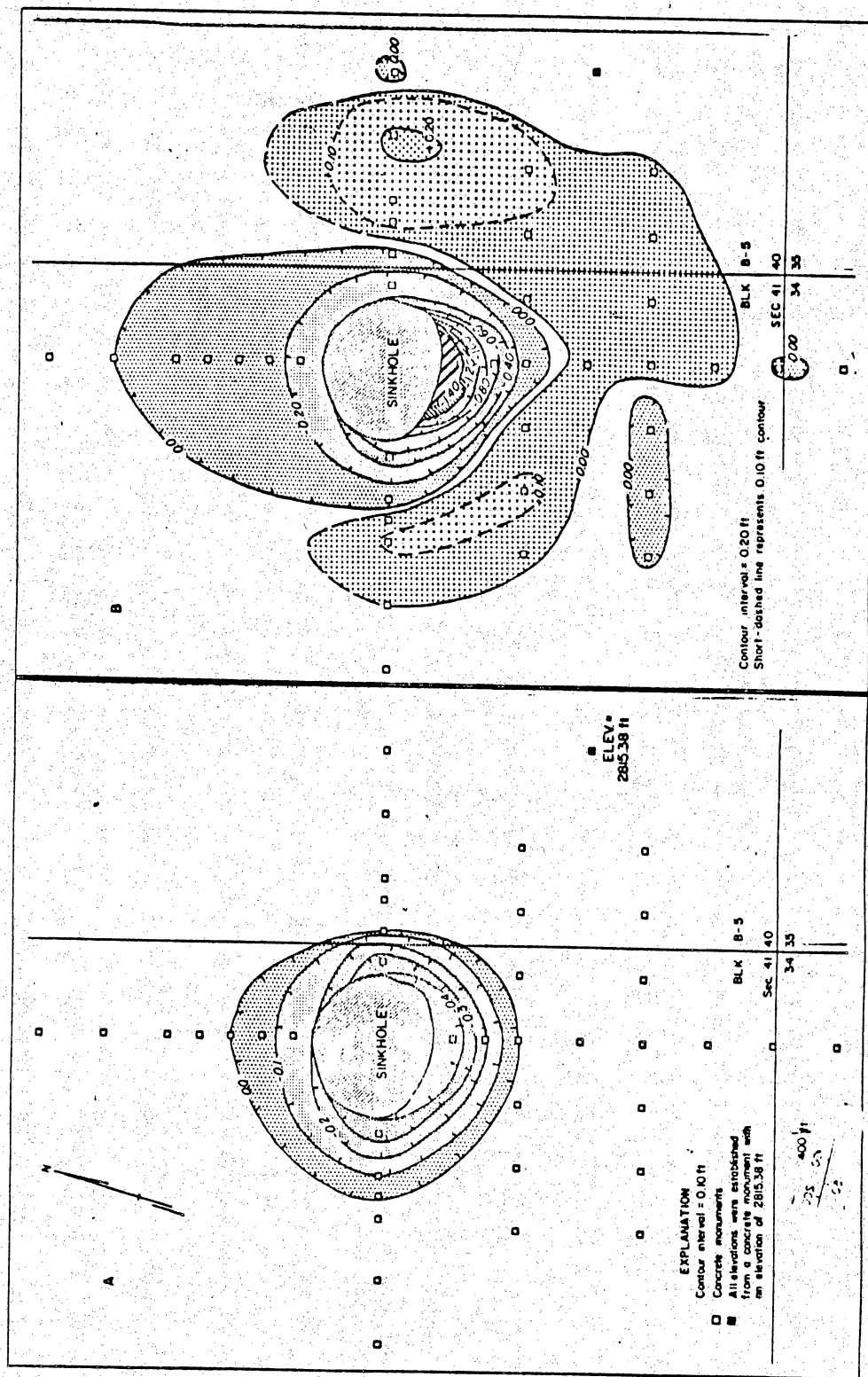
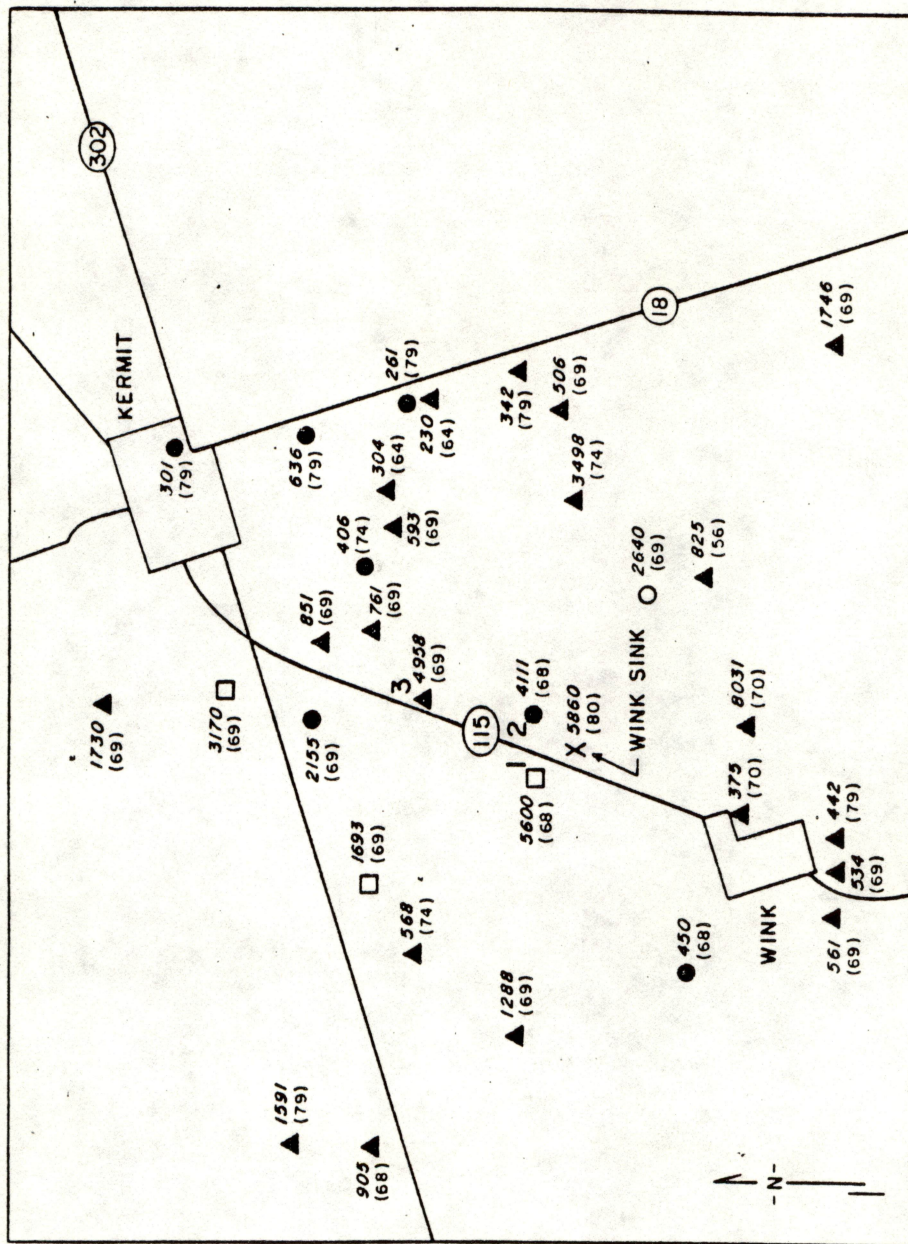


Fig. 19



EXPLANATION

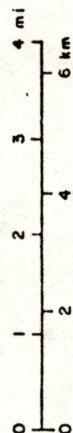
Aquifers

- ▲ Alluvium
- Santa Rosa
- Alluvium / Santa Rosa
- Unidentified

5860 TDS (mg/L)

(69) Year of sample collection

| Well discussed in text



179. 88-20

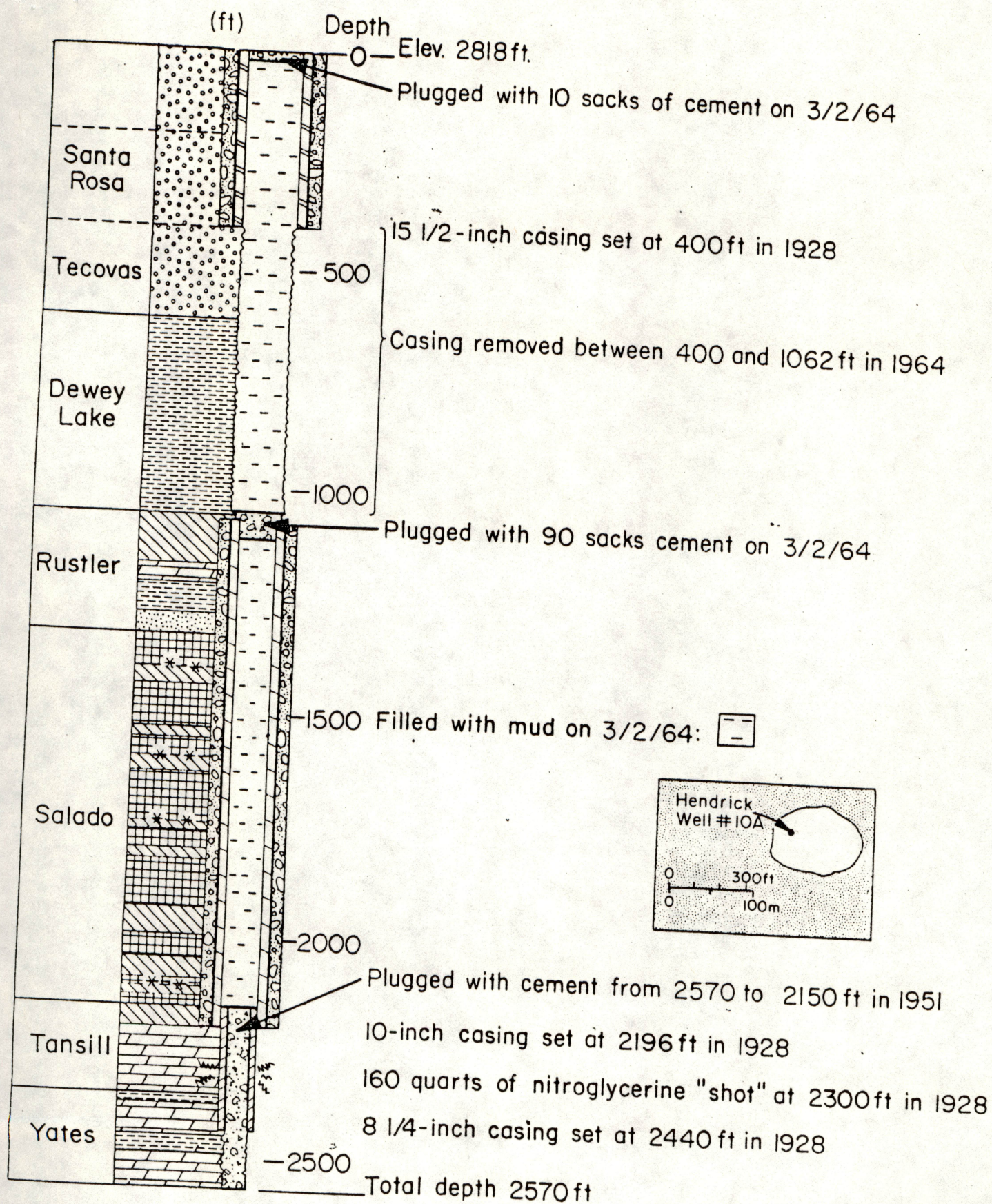


Fig. 2.11

