Development of the Wink Sink in West Texas, U.S.A., Due to Salt Dissolution and Collapse

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ABSTRACT / The Wink Sink, in Winkler County, Texas, is a collapse feature that formed in June 1980 when an underground dissolution cavity migrated upward by successive roof failures until it breached the land surface. The original cavity developed in the Permian Salado Formation salt beds more than 400 m (1,300 ft) below ground level. Natural dissolution of salt occurred in the vicinity of the Wink Sink in several episodes that began as early as Salado time and recurred in later Permian, Triassic, and Cenozoic times. Although natural dissolution occurred in the past below the Wink Sink, it appears likely that the dissolution cavity and resultant collapse described in this report were influenced by petroleum-production activity in the immediate area. Drilling, completion, and plugging procedures used on an abandoned oil well at the site of the sink appear to have created a conduit that enabled water to circulate down the borehole and dissolve the salt. When the dissolution cavity became large enough, the roof failed and the overlying rocks collapsed into the cavity. Similar collapse features exist where underground salt beds have been intentionally dissolved during solution mining or accidentally dissolved as a result of petroleum-production activity.

Introduction

The Wink Sink, located 3.2 km (2 mi) north of the town of Wink in Winkler County, Texas (Fig. 1), formed on June 3, 1980, and within 24 hours it had expanded to a maximum width of 110 m (360 ft) (Baumgardner and others 1982). Two days later, the maximum depth of the sinkhole was 34 m (110 ft) and the volume was estimated at about 159,000 m^3 (5.6 million ft^3) (Fig. 2). The collapse occurred near the middle of Hendrick Field, a giant oilfield that has been operating since 1926; one abandoned oil well was incorporated within the sink itself, and a second oil well was plugged and abandoned because of its proximity to the sinkhole.

There appears to be no doubt that the Wink Sink resulted from an underground dissolution cavity that migrated upward by successive roof failures, thereby producing a collapse chimney filled with brecciated rock (Baumgardner and others 1982). The dissolution cavity had developed in salt beds of the Permian Salado Formation, which is about 260 m (850 ft) thick and lies about 400 to 655 m (1,300 to 2,150 ft) beneath the Wink Sink. Natural dissolution of salt beds in the Salado Formation in Winkler County and other areas of West Texas and New Mexico is well known, but the dissolution and collapse associated with the Wink Sink apparently resulted from, or at least was accelerated by, oilfield activity in the immediate vicinity of the sink. Whether the dissolution is due to natural causes or oilfield activity, there are four distinct requirements for salt dissolution to occur (Johnson 1981): (1) a deposit of salt through which water can flow, (2) a supply of water unsaturated with respect to NaCl, (3) an outlet whereby the resulting brine can escape, and (4) energy (such as hydrostatic head or density gradient) to cause the flow of water through the system.

Previous reports on the Wink Sink include widely distributed articles by Baumgardner and others (1980, 1982) and a limited-distribution government document by Johnson (1986). The current report is a summary of data presented by Johnson (1986).

Geologic History and Stratigraphy

Winkler County is located astride the boundary between the Delaware Basin on the west and the Central Basin Platform on the east (Fig. 1). These major structural provinces are both part of the greater Permian Basin of West Texas and southeast New Mexico and are characterized by different sequences of Permian-age strata. The provinces are separated by the Capitan Reef, a massive limestone and dolomite reef that fringed the Delaware Basin during Guadalupian time when different suites of sediment were deposited on either side of the reef.

Rock units of principal concern in the vicinity of the Wink Sink are all of sedimentary origin and are of Permian, Triassic, or Cenozoic age (Fig. 3). The Capitan Reef, the oldest Permian unit of interest, is a massive sequence of limestone and dolomite about 457 to 610-m (1,500 to 2,000-ft) thick and 13 to 16-km (8

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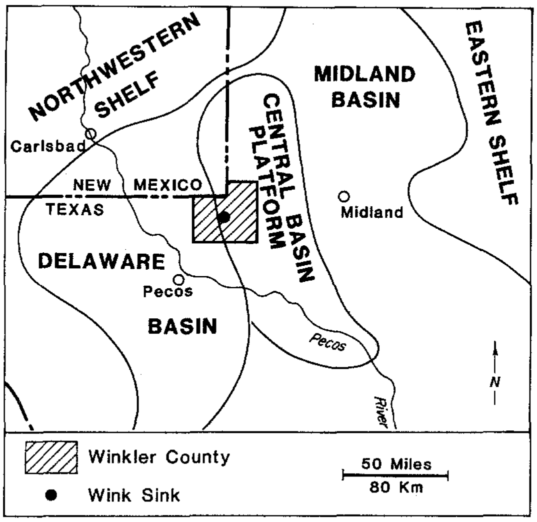

Figure 1. Map of west Texas and southeast New Mexico showing major geologic provinces and location of Wink Sink in Winkler County.

to 10-mi.) wide in western Winkler County (Garza and Wesselman 1959; Hiss 1975). Carbonate rocks in the Capitan typically have a high porosity and permeability. The Capitan grades eastward into contemporaneous back-reef carbonates and clastics of the Artesia Group; the two uppermost formations of the Artesia (the Yates and Tansill Formations) are present above the Capitan beneath the Wink Sink.

The Yates Formation consists of light-gray, white, and flesh-colored dolomite and limestone with some interbeds of fine-grained gray sandstone and shale (Ackers and others 1930). The Yates is about 85-m (280-ft) thick in the vicinity of the Wink Sink (Baumgardner and others 1982). Porosity occurs in the form of irregular solution cavities as large as 5 cm (2 in.) in diameter, and also as interstitial voids in the granular rocks. Solution cavities lined with calcite are commonly found in the oil-producing horizons.

The overlying Tansill Formation consists mainly of dolomite and limestone, interbedded with dolomitic shales, and a persistent bed of anhydrite that overlies the dolomitic sequence (Ackers and others 1930; Baumgardner and others 1982). The Tansill Formation is about 50-m (160-ft) thick beneath the Wink Sink, and the anhydrite in the upper part of the Tansill is generally 9 to 15-m (30 to 50-ft) thick. The top of the formation is at the base of the lowest salt unit in the Salado Formation (Baumgardner and others 1982).

The Salado Formation is a thick sequence of interbedded salt (halite) and anhydrite. The formation is about 260-m (850-ft) thick beneath the Wink Sink, but it is as much as 400-m (1,300-ft) thick just to the east and only about 180-m (600-ft) thick just to the west (Fig. 3). Individual Salado anhydrite units in the area typically are 3 to 15-m (10 to 50-ft) thick, whereas the intervening salt units commonly are 3 to 30-m (10 to 100-ft) thick. Variations in thickness of the Salado Formation and of the individual salt units are largely due to dissolution of one or more of the salt units during Salado and post-Salado times. Dissolution of the salts in the Salado has been noted several times in earlier literature (Ackers and others 1930; Maley and Huffington 1953; Anderson and Kirkland 1980); and, most recently, Baumgardner and others (1982) and Johnson (1986) have shown that dissolution has occurred in each of the Salado salt units in the vicinity of the Wink Sink.

Overlying the Salado is the Rustler Formation, which consists of interbedded anhydrite, dolomite, limestone, shale (or mudstone), and sandstone (Ackers and others 1930; Baumgardner and others 1982). The Rustler is about 82-m (270-ft) thick beneath the sink, but locally it is as much as 95-m (310-ft) thick where it apparently thickens due to dissolution and collapse of underlying Salado salt units prior to or during Rustler deposition.

The Dewey Lake Formation consists of interbedded red-brown shale, sandy shale, and siltstone overlying the Rustler (Ackers and others 1930; Baumgardner and others 1982). The thickness of Dewey Lake strata in the area ranges from about 110 to 146 m (360 to 480 ft), and is about 137 m (450 ft) beneath the Wink Sink. The local sharp increase in thickness of the Dewey Lake indicates the likelihood that some of the dissolution of salt in the Salado occurred prior to or during Dewey Lake deposition.

Unconformably above the Dewey Lake Formation lies a sequence of Triassic shales and sandstones overlain by unconsolidated Cenozoic clastics; these strata are not readily differentiable in the area, and thus have been referred to as "undifferentiated Cenozoic and Triassic" strata (Fig. 3). This undifferentiated sequence increases in thickness markedly across the area from about 120 m (400 ft) on the east to as much as 457 m (1,500 ft) in the dissolution trough west of Wink Sink (Fig. 3). The abrupt thickening of these strata in the same area where the Salado salts reach minimum thickness supports the interpretation of salt dissolution and concurrent (or subsequent) basin filling during Triassic and Cenozoic times.

Natural dissolution of salt beds of the Salado Formation in western Winkler County began during Late Permian time and still may be going on today (Baum-

Figure 2. Aerial photograph of the Wink Sink (courtesy of Texas Bureau of Economic Geology). Oblique aerial photograph by R. W. Baumgardner, Jr., June 5, 1980; view is toward east southeast. Depth to water surface is about 10 m (33 ft).

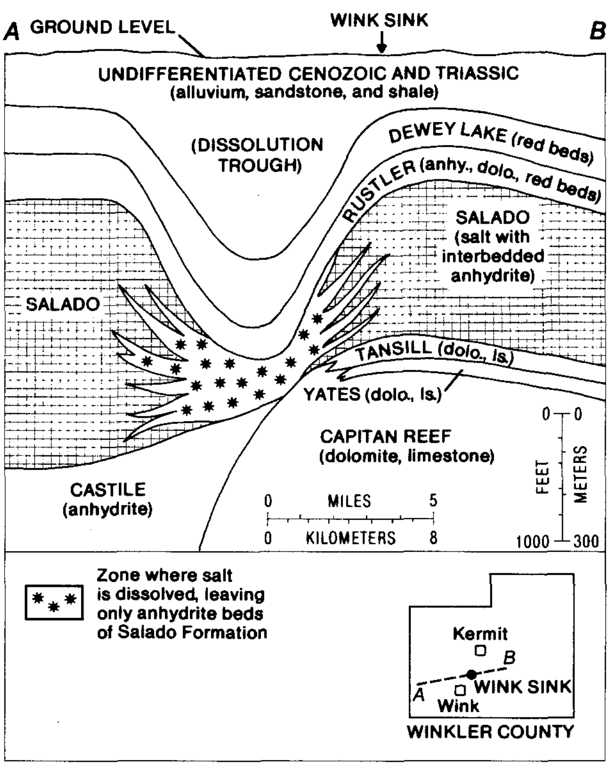

Figure 3. Schematic east–west cross section in Winkler County showing natural dissolution of Salado Formation salts on the eastern edge of the Delaware Basin (modified from Baumgardner and others 1982). All strata below the "Undifferentiated Cenozoic and Triassic" are Permian in age.

gardner and others 1982). Abnormal thinning and thickening of individual salt units in the Salado, as well as local thickening of each of the overlying formations of Permian, Triassic, and Cenozoic age, indicate that this process of dissolution and subsidence has occurred intermittently in the Wink area and began even before the end of Salado deposition (Johnson 1986).

Petroleum Activity in the Hendrick Field

The Hendrick Field, which includes the location of the Wink Sink (Fig. 4), is one of the giant oilfields of Texas. More than 1,400 wells have been drilled in the field since its discovery in 1926, and these wells have yielded a cumulative total of about 40.55 million m^3 (255 million barrels) of oil (one metric ton of crude oil equals 1.166 m^3). Drilling activity and oil production were phenomenally high in the first few years after the discovery well was drilled, but by the early 1930s, the activity was reduced greatly and has continued to decline to a relatively low level today. One of the major problems in the Hendrick Field since its beginnings is the great volume of oilfield brine that has been produced along with the oil and has required disposal.

Several articles were published during the early boom period of the Hendrick Field (Dameron 1928; Vance 1928; Bignell 1929, 1930; Ackers and others 1930; Heithecker 1932; Carpenter and Hill 1936) and

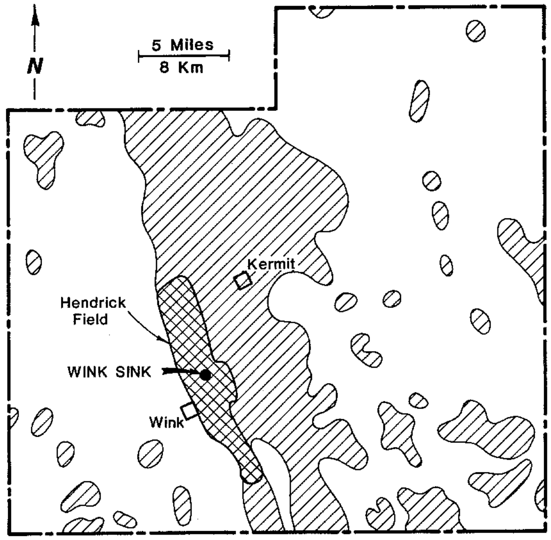

Figure 4. Winkler County, Texas, showing oil and gas-producing areas (diagonal lines) and location of Hendrick Field and Wink Sink.

these documents provide valuable insight into the methods of drilling, well completion, oil production, brine production, and brine disposal used in the field.

Production in the Hendrick Field has been predominantly oil, with small amounts of natural gas. Most of the oil has come from the Yates Formation, although some is produced from the overlying Tansill Formation. Initial daily production of individual wells, based on short-time gauges, ranged from 48 to 15,583 m^3 (300 to 98,000 barrels) of oil per day, and pilot-tube measurements of natural-gas production on some wells indicated as much as 2 million m^3 (70 million ft^3) per day. Most wells were drilled only 201 m (660 ft) from neighboring wells, with spacing throughout the field typically being one well per 4 or 8 ha (10 or 20 A) (Fig. 5). In parts of the field explosives were used to fracture the producing zones and thereby increase production of some of the wells with low yields (Vance 1928).

Many crooked boreholes were drilled in the early years of development of the Hendrick Field (Carpenter and Hill 1936). As a result, the lower part of some boreholes is shifted a hundred meters (several hundred feet) or more laterally away from the surface location. In surveys of some of the boreholes, it was found that the deflection of the holes at various depths was as much as 20 to 40 degrees from the vertical. In some of these boreholes where the deviation was excessive, such as in the Hendrick Well 10-A at the Wink Sink, explosives were used to fracture the rock and allow realignment of the hole.

Oilfield Brines in the Hendrick Field

Production and disposal of oilfield brines has been a serious problem in the Hendrick Field since shortly after the field was discovered. The vugs and fractures within the Tansill and Yates carbonate reservoirs yield saline formation waters along with the oil, and, in most cases, large amounts of brine were produced shortly after completion of an oil well. The brines generally contain from 5,000 to 48,000 parts per million dissolved solids. Water production ranged from about 95,400 to 139,000 m^3 (600,000 to 875,000 barrels) per day in the 1930s, and the water-oil ratio for the producing wells increased from about 16 to 1 in 1930 to as much as 50 to 1 in 1934 (Carpenter and Hill 1936).

Although no accurate totals are available, it is clear that a tremendous quantity of water has been produced in the Hendrick Field. By assuming an average production of 135,000 m^3 (850,000 barrels) of water per day from 1929 through 1957 (Garza and Wesselman 1959) and an average of 47,700 m^3 (300,000 barrels) per day from 1958 through 1982 (Johnson 1986), it is herein estimated that the cumulative production of water has amounted to about 1.86 billion m^3 (11.7 bilion barrels, or 1.5 million acre-feet).

The principal means for handling the great quantity of water produced with oil in the Hendrick Field consisted of disposal in unlined, natural, and artificial earthen "evaporation" pits (Heithecker 1932). In some places, dynamite was used to blast caliche or other hard rock units present in the floor of a pit.

It was realized from the outset that most of the water disposed of in the earthen pits was in fact lost through seepage into the ground (Heithecker 1932). The ground surface in most parts of the Hendrick Field consists of loose sand, and this covers the unconsolidated sand, gravel, silt, and clay in the Cenozoic Alluvium. Therefore, waters (including oilfield brines) were able to percolate down easily through the porous and permeable surface materials to reach and recharge the groundwater.

No public records have been kept of the location of these earthen pits, the period of their use, or the quantity of wastewater that was discarded into individual pits or into all pits combined. However, a series of aerial photographs taken in 1942, 1946, 1954, and 1968 show the location of a great many natural and artificial earthen pits that were used intermittently or continuously for disposal of water. By stereoscopic study of these photographs, the author has established that nearly 50 separate areas, ranging in size from 0.4 to 12 ha (1 to 30 A), were used at one time or another as disposal pits in the vicinity of the Wink Sink (Fig. 6). In fact, the largest pit, located in the northeast quarter

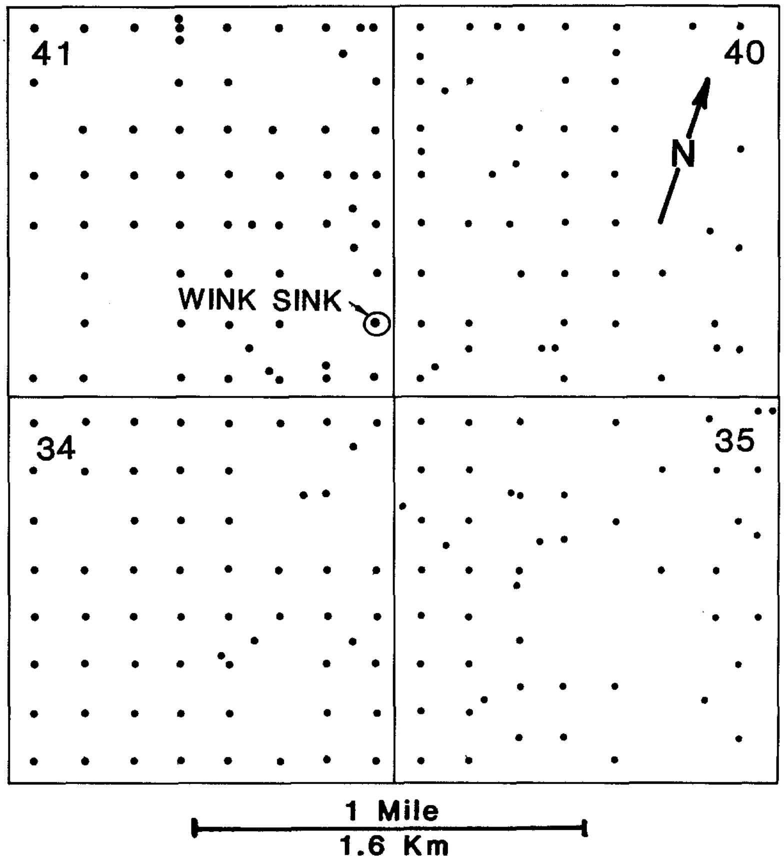

Figure 5. Location of the 227 petroleum tests and other boreholes drilled near Wink Sink in sections 34, 35, 40, and 41 of Block B-5, Public School Land Survey, Winkler County.

of section 34, is just 300 m (1,000 ft) south-southeast of the Wink Sink; portions of this pit have been used continuously from 1942 through 1968, and the pit may have been put in use as early as the early 1930s. Several smaller pits, located in the southeast quarter of section 41 (Fig. 6), are even closer to the Wink Sink, but have been in use for shorter periods of time.

Within the Hendrik Field the shallow, freshwater aquifers have been recharded substantially by leakage of wastewater from the disposal pits (Garza and Wesselman 1959). Great volumes of water have seeped down through permeable, sandy soil in the central part of the field, including the location of the Wink Sink, creating a large groundwater mound that in 1956 extended about 13 km (8 mi) north–south and 6.5 km (4 mi) east–west (Garza and Wesselman 1959). It appears that the water table in the mound may have been raised some 15 to 30 m (50 to 100 ft) by that time. In 1956 the water table at the site of the Wink Sink was about 9 m (30 ft) below ground level.

History of Hendrick Well 10-A

An abandoned oil well, the Hendrick Well 10-A, is located within the circumference of the Wink Sink. The sink apparently did not breach the surface at the location of the borehole, but reportedly appeared to one side of the borehole (Baumgardner and others 1982). As the sink enlarged by slumping and caving of the sides, the surface casing of the well apparently was incorporated in the slump material, although no eyewitnesses reported sighting the surface casing.

The following discussion on the history of the Hendrick Well 10-A is modified slightly from an original discussion by Baumgardner and others (1982) based largely on data filed with the Texas Railroad Commission.

Republic Production Company began drilling the Hendrick Well 10-A on June 29, 1928, and completed it on October 25, 1928. The driller's log and the borehole representation (Fig. 7) show drilling, casing, and plugging procedures reported to the Texas Railroad Commission during the life of the well. The well was drilled with rotary tools to the top of "brown lime of the Tansill Formation" at a depth of 668 m (2,193 ft), and cable tools were used to complete the well in the Yates Formation at a depth of 778 m (2,552 ft). Initial daily production from the well was estimated to be 159 m^3 (1,000 barrels) of oil and 636 m^3 (4,000 barrels) of water.

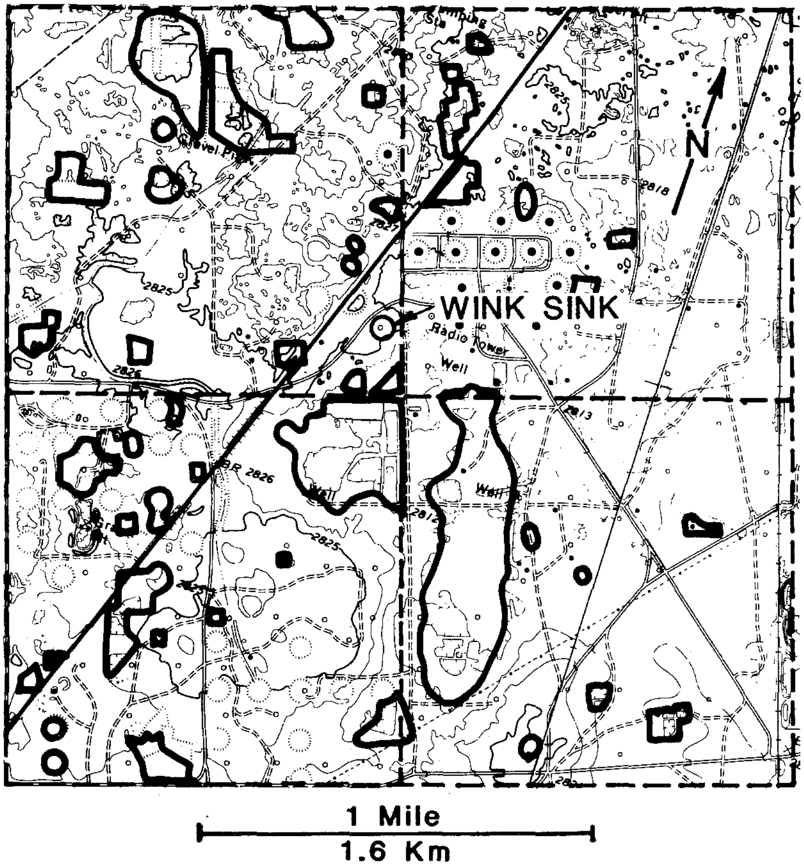

Figure 6. Map showing location of earthen ponds and pits (heavy lines) used for disposal of oilfield brines in 4-section area surrounding the Wink Sink in Winkler County.

The casing program consisted first of setting surface pipe, 39.4 cm (15.5 in.) in diameter, at a depth of 122 m (400 ft) and cementing it with 300 sacks of cement. Second, 25.4-cm (10-in.) casing was set at a depth of 669 m (2,196 ft) and cemented with 800 sacks of cement. Finally, casing 21 cm (8.25 in.) in diameter was set at a depth of 744 m (2,440 ft) but was not cemented. No casing was set below 744 m (2,440 ft).

The Hendrick Well 10-A was a crooked borehole that deviated too much from the vertical; it was straightened at a depth of 701 m (2,300 ft) by exploding 151 liters (160 quarts) of nitroglycerine in the borehole.

Republic Production Company later deepened the well to 783 m (2,570 ft) in January 1930. They then filed an application to again deepen the well to 945 m (3,100 ft) in December 1931, but no data are on file with the Texas Railroad Commission to indicate that the well was drilled deeper than 783 m (2,570 ft).

Bradberry and Sasser Company later filed a plugging record for the well in July 1951, referring to the well as being on the T. G. Hendrick "A" lease. The record stated that the well was shot "to part casing," but the depth (or depths) of these shots and their effect on the casing were not reported. The record did show, however, that the well was plugged with cement at depths from 783 to 655 m (2,570 to 2,150 ft). The wellbore above this was filled with mud and plugged at depths from 122 to 113 m (400 to 370 ft) with 25 sacks of cement, and then plugged at the surface with 15 sacks of cement. The well was then abandoned for 13 years.

In 1964, Mallard Petroleum Company removed the shallow cement plugs and attempted to deepen the well. However, the drillers were unable to reenter the hole "because of junk" in the borehole. The well was then replugged in March 1964 with 90 sacks of cement at a depth of 323 m (1,060 ft), and with 10 sacks of cement at the surface. During this reentry attempt, the company removed more than 183 m (600 ft) of 25.4-cm (10-in.) diameter casing, leaving an unlined borehole (presumably filled with mud) between 324 and 122 m (1,062 and 400 ft), or from the upper part of the Rustler Formation to just below the Santa Rosa Formation.

Salt Dissolution by Natural Causes in the Wink Sink Area

A number of studies have been conducted on salt

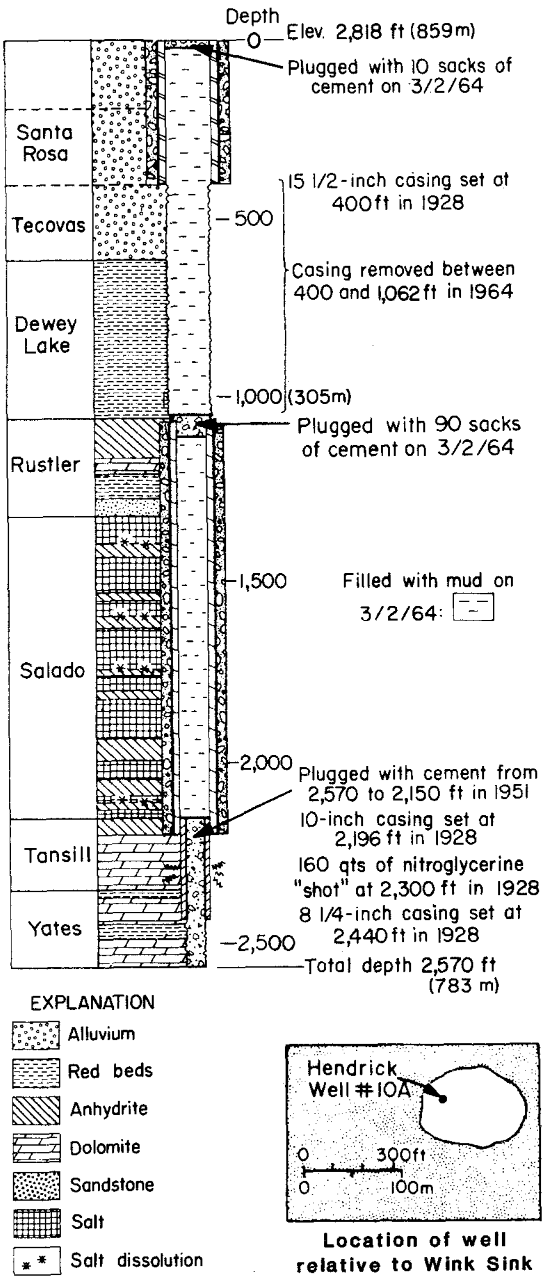

Figure 7. Stratigraphic section of Hendrick Well 10-A, section 41, Block B-5, Public School Land Survey, Winkler County, Texas (modified from Baumgardner and others 1982).

dissolution in various parts of the Delaware Basin and nearby areas, including work by Ackers and others (1930), Adams (1944), Maley and Huffington (1953), Hills (1970), Anderson and others (1972, 1978), Bachman (1976), Kirkland and Evans (1976), Mercer and Hiss (1978), Powers and others (1978), Anderson and Kirkland (1980), Baumgardner and others (1980, 1982), Lambert (1983), and Johnson (1986).

In addition, there is overwhelming evidence that salt has been partly dissolved by natural processes in the vicinity of the Wink Sink (Baumgardner and others 1982, Johnson 1986). Abnormal and abrupt thinning of salt units with concurrent thickening of overlying rock units in the same area is major proof for this natural dissolution (Fig. 3). The dissolution has been episodic in various parts of the Wink area, with evidence that it began as early as Salado time and then recurred during later Permian, Triassic, and Cenozoic time. Some natural dissolution of Salado salts may be going on at the present time, but there is no evidence currently available to confirm or refute this.

There is no evidence that a natural cavern existed in the vicinity of the Wink Sink prior to drilling of the Hendrick Well 10-A. No cavities were reported in 1928 during drilling of the well, and subsurface conditions at and near the sink have not been examined by boreholes or other methods since development of the sink. The presence of permeable fracture zones or cavities in the area is indicated by the loss of fluids during the drilling of four of the oil wells located within 1.6 km (1 mi) of the Wink Sink (Baumgardner and others 1982). The wells, drilled in 1927 and 1928, lost circulation at depths ranging from 291 to 699 m (956 to 2,293 ft). One well lost circulation during drilling in sand and red beds of the Dewey Lake Formation; one well lost circulation in dolomite of the Tansill Formation; and the other two wells lost circulation during drilling in the Salado Formation. These lost-circulation zones are permeable pathways that can allow for the movement of fluids within, above, and below the Salado Formation.

Salt Dissolution Related to Petroleum Activity in the Wink Sink Area

Although it is clear that most of the salt dissolution in the Wink area (including the dissolution trough) has resulted from natural processes, it is equally clear that some of the early-day oilfield practices employed during the boom period of the Hendrick Field may have contributed to the accelerated dissolution of salt in the vicinity of the Hendrick Well 10-A and this may have caused the collapse of the Wink Sink. Similar collapse features have developed in the past above caverns that resulted from solution mining of salt or from unplanned borehole enlargement in salt beds penetrated during oil and gas operations.

Drilling and completion of the Hendrick Well 10-A apparently were consistent with standard industry practices of West Texas during the late 1920s. In retrospect, however, several factors and events can be identified that may have contributed to development of a dissolution cavern in the Salado salt around this borehole. These include the probable use of a freshwater drilling fluid, use of nitroglycerine to straighten the hole, the possibility of poor cement jobs inadequately sealing off the salt beds behind the casing, possible corrosion of casing by saltwater, and removing some of the casing upon final plugging of the borehole. Such factors and events may have assisted in making the borehole a pathway whereby shallow groundwater could have flowed down to and through the Salado salts.

Data are not available on the nature of drilling fluids used in drilling the Hendrick Well 10-A, but in all probability the fluid consisted of freshwater (from local water wells) mixed with clays to increase its weight and viscosity. Such a freshwater fluid would have dissolved some of the salt adjacent to the borehole during drilling operations, and thus would have enlarged or "washed out" the hole within the Salado salt sequence. Walters (1978) points out that oil wells drilled by similar rotary methods in central Kansas during the 1930s were enlarged considerably through the Hutchinson salt beds; holes drilled with 23-cm (9-in.) bits were washed out to 1.5 m (5 ft) or more in the salt section. Therefore, it is quite likely that the Hendrick Well 10-A borehole was at least somewhat enlarged and washed out within the Salado salt section during drilling.

Baumgardner and others (1982) indicate that the 800 sacks of cement used to set the 25.4-cm (10-in.) casing at 669 m (2,196 ft) in the Hendrick Well 10-A had filled all the annular space in the hole behind the casing from a depth of 669 m (2,196 ft) up to about 328 m (1,075 ft) (Fig. 7). This does not seem likely, however, because if the 800 sacks of cement had filled the annulus for this entire 342 m (1,121 ft) of hole, it would average about 2.33 sacks of cement per meter (0.71 sack of cement per foot) of hole; that would indicate a very narrow space behind the casing and account for little or no hole enlargement through the salt section. Walters (1978) reported that 1,000 sacks of cement filled only 46 m (150 ft) of hole that had been washed out to about a 1.4-m (4.5-ft) diameter in the Hutchinson salt at the Panning Sink in central Kansas. Therefore, it seems likely that the 800 sacks of cement used in the 10-A well were sufficient to cement the 25.4-cm (10-in) casing only in the lower part of the hole, leaving most of the salt section uncemented behind the casing.

The explosion of 151 liters (160 quarts) of nitroglycerine to realign the hole at a depth of 701 m (2,300 ft) may have fractured the cement lining of the borehole, and thus may have created pathways for water movement adjacent to the Salado salt (Baumgardner and others 1982). The explosion certainly fractured the Tansill Formation and/or other rock units near the bottom of the hole and thereby increased their permeability to circulating brines.

Also, the need to straighten the hole with explosives shows that the Hendrick Well 10-A deviated from the vertical, and the lower part of the hole had shifted some distance away from the surface location of the borehole. The direction and magnitude of that shift were not reported, but it is possible that the borehole penetrated the top of the Salado Formation at a distance some 15 to 30 m (50 to 100 ft) east of its surface location, at a site directly below the center of the present Wink Sink (Fig. 8a). This would be a borehole deviation of only 2 to 4 degrees from the vertical at the top of the Salado.

Poor cement jobs or fractures in the cement lining of the Hendrick Well 10-A may have opened pathways for movement of water either up or down the borehole, thus allowing the water to come in contact with the Salado salts (Baumgardner and others 1982). Surface casing was set at a depth of 122 m (400 ft), approximately at the base of the freshwater Santa Rosa Aquifer. If this casing were set too shallow to seal off the aquifer, or if water also were present in some of the siltstone or sandstone beds of the underlying Tecovas Formation, it would be possible for freshwater to leak into and down the borehole outside the casing (Fig. 8b, upper part). Also, a poor cement job at the base of this surface casing in 1928, or fracturing of the cement during later workover, reentry, or plugging operations, could have allowed freshwater from the Santa Rosa to leak down the borehole outside the casing. Baumgardner and others (1982) also point out that the absence of cement plugs or cement lining in the borehole below a depth of 669 m (2,196 ft) during the period from 1928 to 1951 may have allowed water to move upward under artesian pressure to near the base of the Salado Formation.

Casing in the well may have been perforated by corrosion, thus permitting water to circulate outside the casing where it could encounter the Salado salts (Baumgardner and others 1982). Pumping large amounts of saline water (Hendrick Field brines range from 5,000 to 48,000 parts per million dissolved solids) from this well from 1928 to 1951 may have caused excessive corrosion of the casing. Baumgardner and others (1982) report leaks in the casing of a nearby well of similar age: the Hendrick Well 3-A, drilled 201 m (660 ft) south-southeast of the well, was drilled and cased in 1928 and also had an initial fluid production of about 795 m^3 (5,000 barrels) per day (it yielded 90 percent water, whereas the Well 10-A yielded 80 per-

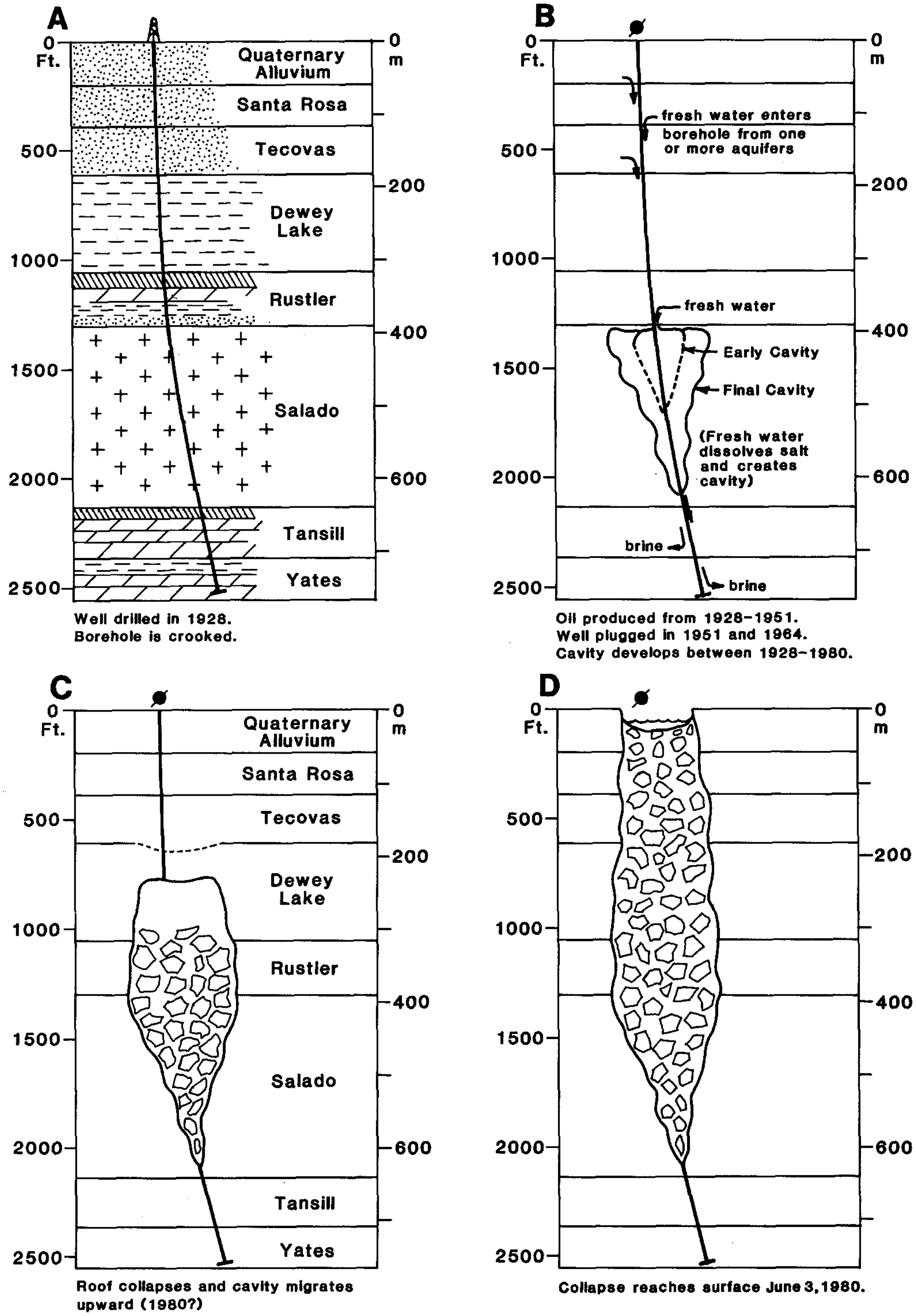

Figure 8. East–west cross section through the Hendrick Well 10-A showing possible relationship of well to development of the Wink Sink. Freshwater may have circulated down the borehole to dissolve the salt and create a cavity; by successive roof failures, the cavity migrated upward to the land surface.

cent water). An attempt to circulate cement behind the casing in Well 3-A in early June 1980 (prior to formation of the Wink Sink) had failed because of leaks in the casing, and presumably these leaks were caused by corrosion. The similar ages and production histories of both wells suggest that the casing in Well 10-A may also have been perforated by corrosion (Baumgardner and others 1982).

Removal of 25.4-cm (10-in.) casing between the depths of 324 and 122 m (1,062 and 400 ft) in 1964 left an unlined borehole in the interval extending from near the base of the Santa Rosa to the top of the Rustler for a period of 16 years, until development of the Wink Sink. This would have enhanced the access of freshwater to the upper part of the borehole, particularly if water from the Santa Rosa aquifer could enter the borehole below the surface casing or through fractured cement at the base of the surface casing. The well was plugged in 1964 at a depth of 323 m (1,060 ft), and therefore this should have prevented any water in the upper part of the borehole from migrating deeper into the Salado salts. However, fractures or other imperfections in the cement plug, or the presence of fractures, cavities, or other permeable pathways in the upper part of the Rustler Formation, may have allowed water in the upper part of the borehole to bypass this plug and enter the salt beds in the lower part of the well.

Regardless of conditions of the cement or casing in the upper part of the borehole, or whether water could enter the borehole from any aquifer above the Salado and gain access to the salt sequence, it still was necessary for an outlet to exist, whereby the resulting brine could escape, and energy to cause flow of water through the system for extensive dissolution to occur (Johnson 1981). The lower part of the Hendrick Well 10-A contained several outlets whereby brine could have escaped the borehole, and the energy required to force the water down the borehole was the hydraulic-head difference between the shallow aquifers and permeable strata below the salt sequence.

All three formations underlying the Salado salts in the Hendrick Field have moderate to high porosity and permeability. The Tansill, Yates, and Capitan carbonates typically contain vugs and irregular solution cavities, whereas the sandstones commonly have interstitial porosity; the various formations and rock types also are well interconnected by fracture systems. The high porosity and permeability of these formations are substantiated by the large yields of oil and water from wells drilled into these reservoirs: initially 795 m^3 (5,000 barrels) of oil and water were produced per day from the Hendrick Well 10-A. Furthermore, the natural porosity and permeability of pre-Salado strata in the Hendrick Well 10-A were undoubtedly increased by exploding 151 liters (160 quarts) of nitroglycerine in the Tansill Formation in 1928.

It is also possible for brine to escape the borehole by moving laterally through preexisting dissolution channels that may have existed in the salt or anhydrite beds of the Salado Formation. There is no question that some of the Salado salt units have been partially or totally dissolved by natural processes in various parts of the Hendrick Field, and the Hendrick Well 10-A probably penetrated one or several of these preexisting dissolution zones. Solution channels, brecciated rock, and other openings that conducted fluids through the various Salado salt beds in the past would still be potential pathways for movement of fluids away from a dissolution cavern such as may have developed around the Hendrick Well 10-A. The ultimate outlet for brines that may have escaped the borehole through preexisting Salado dissolution channels probably would still be the highly porous and permeable carbonates that underlie the Salado. Access of the brines to these pre-Salado strata would be through preexisting natural pathways or through other boreholes in the area that might permit open communication between the dissolution channels and the pre-Salado strata.

The energy necessary to drive shallow freshwater down to the salt in the Hendrick Well 10-A, and to drive the resultant brine into underlying pre-Salado strata would be the hydraulic-head difference between water-bearing strata above and below the Salado Formation. Drill-stem tests from wells near the Wink Sink in 1975 show that the hydraulic head in the Santa Rosa Formation was higher than that in the Tansill, Yates, or Capitan Formation (Baumgardner and others 1982). Therefore, if the Santa Rosa Aquifer were connected with the permeable pre-Salado strata by pathways through or near the Hendrick 10-A borehole, then downward flow into the deep reservoirs would result (Fig. 8b).

Other shallow aquifers, such as the Cenozoic alluvium and perhaps even the Rustler Formation, also have hydraulic heads higher than those of the pre-Salado reservoirs; thus, waters in these shallow aquifers would also flow down through the borehole if they were interconnected with the deep reservoirs (Fig. 8b). The Cenozoic alluvium is an unconfined aquifer well above the hydraulic heads of the Tansill, Yates, and Capitan Formations, and clearly would have yielded water to the Hendrick Well 10-A. However, data on the Rustler Aquifer in the vicinity of the Wink Sink are lacking. Water yields and permeability of the Rustler are highly variable, and therefore it is uncertain whether the Rustler might have yielded much water to the Hendrick Well 10-A in the past. Furthermore, although the Rustler had static water levels higher than those of the Tansill and Yates Formation north and northwest of Kermit in the mid 1950s (Garza and Wesselman 1959), there are no data to prove that a similar situation has existed in the vicinity of the Wink Sink.

Most of the estimated 1.86 billion m^3 (11.7 billion barrels) of brine produced with oil in the Hendrick Field were eventually returned to the subsurface by seepage from unlined earthen pits or by injection wells. This brine was unsaturated with respect to salt, and thus it would have increased the supply of shallow groundwater that could flow down to and dissolve the Salado salts if these shallow aquifers were interconnected with the deep reservoirs by an open borehole.

The amount of oilfield brine that has been disposed of in the vicinity of the Wink Sink is unknown, but available data indicate that it must have been a considerable amount. Aerial photographs taken between 1942 and 1968 show that several earthen pits 213 to 305 m (700 to 1,000 ft) away from the Wink Sink must have contributed large amounts of water to the local groundwater system. Also, a large groundwater mound created by seepage of oilfield brines in the central part of the Hendrick Field embraced the location of the Wink Sink. The water table in the mound may have been raised some 15 to 30 m (50 to 100 ft) by that time.

If downward flow of undersaturated water into and through the Salado salts in the Hendrick Well 10-A had occurred, a dissolution cavity might well have developed, probably in the upper part of the salt sequence (Fig. 8b). The period of cavity development is unknown, but it may have occurred at any time between 1928 and 1980. Eventually (probably shortly before June 3, 1980), the cavity became sufficiently large that the roof collapsed and, by successive roof failures, the cavity migrated upward (Fig. 8c) until it finally reached the surface on June 3, 1980, causing development of the Wink Sink (Fig. 8d).

Conclusions

Natural dissolution of salt in the Salado Formation has occurred in many parts of the Delaware Basin from Permian time up through the Cenozoic. It is attested by the abrupt thinning of Salado salt units above and just to the west of the buried Capitan Reef and also by the presence of a great, sediment-filled dissolution trough directly above the area where the Salado is anomalously thin. Although natural dissolution of portions of several of the Salado salt units has occurred within short distances of the Wink Sink, and may have occurred immediately below the sink itself, it is highly likely that petroleum activities were instrumental in bringing about the dissolution cavity and the collapse that created the sink.

The Hendrick Well 10-A, an abandoned oil well, was located at the site of the sinkhole, and it appears likely that it was a pathway for water to come in contact with the Salado salt. In all likelihood, the well was drilled using a freshwater drilling fluid that enlarged or washed out the borehole within the salt sequence. Poor cement jobs or fractures in the cement lining may have opened pathways for water movement up or down the borehole outside of the casing. Because of undoubted borehole enlargement during drilling in the Salado salts and the use of only 800 sacks of cement to set 342 m (1,121 ft) of outside casing, it is likely that this casing was cemented only in the lower part of the hole, thus leaving most of the salt section uncemented behind the casing. Casing in the well probably was perforated by corrosion due to production of great quantities of oilfield brine; this would parallel the casing corrosion observed in the nearby Hendrick Well 3-A, which had a similar history. Use of explosives to realign the well during drilling in the Tansill Formation not only fractured the rock and increased the permeability locally, but also may have fractured the cement lining further up the borehole. In addition, final removal of casing left an unlined borehole in the interval from the base of the Santa Rosa to the top of the Rustler Formation for a period of 16 years.

All of the above-mentioned activities, although consistent with standard industry practices during the life of Hendrick Well 10-A, would have aided in conducting freshwater from shallow aquifers down the borehole to the salt beds. Outlets for high-salinity brine formed by dissolution of salt in the borehole included the porous and permeable strata underlying the Salado Formation, as well as possible preexisting dissolution channels within the Salado. Thus, a dissolution cavity may well have been formed around Well 10-A, probably in the upper part of the salt sequence, and this cavity eventually would have become sufficiently large to permit collapse of the roof. By successive roof failures, the cavity then migrated upward until it finally reached the land surface and created the Wink Sink.

Freshwater is abundant in the Cenozoic alluvium and the Santa Rosa Sandstone near the Wink Sink, and this supply was increased by the seepage of great quantities of waste oilfield waters from unlined earthen pits. Several of these pits had been operated for moderate to long periods of time within 213 to 305 m (700 to 1,000 ft) of the 10-A borehole, and a groundwater mound some 15 to 30 m (50 to 100 ft) high apparently was built up over a large area due to seepage from these and other nearby pits. Oilfield brines also have been disposed of in the Hendrick Field through injection wells, and the disposal zones commonly were in permeable sand or gravel units or into the Rustler Formation. Thus, there was a large source of unsaturated water that could, because of its high hydraulic head, flow down the borehole to the salt beds and then exit the dissolution cavity through the borehole or through preexisting natural dissolution pathways.

It is clear, therefore, that boreholes or other artificial openings that penetrate salt beds are potential pathways for vertical movement of waters that could flow through and partially dissolve the salt. If the salt beds are not isolated from such circulating waters, and if energy exists to cause inflow of unsaturated water and outflow of brine, then a cavity can be created by dissolution of the salt. If the dissolution cavity becomes large enough, it is possible for successive overlying rock layers to collapse into the cavity until it finally reaches the land surface to create a subsidence or collapse feature.

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