DEEP-SEATED SALT DISSOLUTION IN THE DELAWARE BASIN, TEXAS AND NEW MEXICO

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ABSTRACT
Patterns of salt dissolution in the Delaware Basin are related to the bedrock geometry and hydrology that developed following uplift, tilting, and erosion in the late Cenozoic, and the greatest volume of salt has been removed since that time. During the Permian, some salt was dissolved from the top of the Castile Formation before deposition of the Salado Formation and from the top of the Salado before deposition of the Rustler Formation. In addition, some salt dissolution occurred after the Permian and before the Cretaceous. Post-uplift surface dissolution has progressed across the Delaware Basin from south to north and west to east and generally down the regional dip. Deep-seated dissolution has occurred around the margin of the basin where the Capitan Limestone aquifer is in contact with the Permian evaporites and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds of the middle and upper Salado. Dissolution has not advanced down regional dip uniformly but has left outliers of salt and has progressed selectively into structurally predisposed areas. This selective advance has significance for the stability of the U.S. Department of Energy’s Waste Isolation Pilot Plant (WIPP) site.

INTRODUCTION
The Delaware Basin of southeastern New Mexico and western Texas contains thick carbonate and evaporite sequences deposited during the Permian (Table 1). The upper Permian carbonate rocks of the Capitan reef form the margins of the Delaware Basin. Within and overlying this reef are thick evaporite deposits which are being considered as the host rock for the Department of Energy’s Waste Isolation Pilot Plant (WIPP). The dissolution history of these evaporite rocks is of primary importance for the stability of this repository site, and this paper discusses recent studies of dissolution in the basin.

The principal areas of salt dissolution in Cenozoic time within the Delaware Basin (fig. 1) were identified by Maley and Huffington (1953) who recognized that a number of deep structural depressions on the Permian Rustler Formation were filled with Cenozoic deposits. One major trend of these depressions has developed along the inner margin of the buried Permian Capitan reef (a major aquifer) along the eastern side of the basin (fig. 2) in areas of thin or missing Permian Salado Formation salt. A second trend follows the axis of the Pecos River in the central part of the basin, but the stratigraphic units affected by dissolution were not recognized until Anderson and others (1972) found that large quantities of bedded salt were missing from the middle of the evaporite sequence near the center of the basin. Further work (Anderson and others, 1978) demonstrated that large depressions in the basin were the result of selective dissolution of lower Salado salt beds and that a (previously unsuspected) variety of deep-seated dissolution processes had undermined the overlying salt beds in the basin.

Hiss’s (1976) map of the structure of the Rustler Formation provided a well-defined picture of the location and configuration of the depressions formed by this type of deep dissolution and resolved them into smaller isolated but interconnected depressions. Hiss’s (1975) report on the hydrology of the Delaware Basin provides a basis for interpreting a relationship between these patterns of dissolution and the regional basin and reef aquifers. These relationships, as well as the occurrence of a number of smaller more localized dissolution features, suggest how regional dissolution has progressed throughout the basin and how it is likely to proceed in the future. Additionally, these relationships suggest some mechanisms that might account for the patterns of deep-seated dissolution in the basin.

EXTENT OF DISSOLUTION
Extensive dissolution in the Delaware Basin has long been recognized by geologists studying the more extensive Permian Basin. Hills (1968) suggested that river underflow had worked down dip and reached far into the subsurface and that the disturbed hydrodynamic balance following uplift may have reached as far as the eastern edge of the Delaware Basin. The amount of salt dissolution in the Delaware Basin, however, has been difficult to document because the original extent of the salt beds was not known or recognized. The problem was simplified with the discovery that each salt bed in the Castile Formation (Table 1) in the eastern part of the basin had a correlative bed of dissolution breccia in the western part of the basin (Anderson and others, 1978). Dissolution breccias have also been recognized within 6 mi (10 km) of the western edge of the basin (Castile outcrop along U.S. Highway 62/180, near Texas State line; shown as H-I11 breccia on Figure 2). These breccias showed that the western edge of salt in the basin for all units is the result of dissolution, and original salt thickness followed trends that were approximately east-west in the basin. These breccias also showed that removal of salt and the subsequent uniting of anhydrite beds previously separated by salt beds were responsible for many of the difficulties in log (subsurface) correlation and interpretation within the evaporites. Revised correlations, based on this new information, showed that only a relatively narrow band of salt along the eastern side of the basin has escaped the effects of regional dissolution (fig. 2).

The original thickness of salt beds in the basin was reconstructed using the trends established in the undissolved areas (see Anderson and others, 1972; figs. 13, 15, 16, 17) and the original volume of salt in the major units was estimated (fig. 3). A comparison with the post-dissolution volume shows that approximately 50 percent of the salt originally in the basin now remains. The lower Salado has had the greatest proportion of salt removed, with about 27 percent of the original salt remaining, reflecting the dissolution that has undercut overlying salt beds recognized by Anderson and others (1972).
PRE-CENOZOIC DISSOLUTION

Adams (1944) was correct in identifying a significant break in deposition between the Castile and Salado formations. Correlations of laminae with records of geophysical logs indicate that this break was accompanied by dissolution of salt from the salt beds in the Anhydrite IV and Halite III of the Castile Formation (fig. 3) from around the margins but not in the center of the basin. The original delineation of a wedge of undercutting dissolution within the evaporites (Anderson, 1978) incorporated some of the missing salt beds from the upper part of the Castile, and it is now believed that some of this material was removed before the Salado was deposited, leaving a dissolution residue. The salt that was removed before Salado deposition was not used in estimating the percent of salt later removed from the basin (fig. 3).

Baltz (1959), King (1942), and Adams (1944) recognized an angular contact between the Rustler and Salado formations in the western part of the basin. The amount of salt removed cannot be estimated, but the unconformity is not considered major and the contact between the two units within the basin is conformable (Kroenlein, 1939; Pierce and Rich, 1962).

Triassic rocks were eroded and stripped from an area west of the present Delaware Basin (McKee and others, 1959; Bachman, 1974), and Cretaceous beds rest directly on the Permian. Some dissolution of salt from the upper part of the evaporites may have occurred during this interval. More recently, Bachman (1980) has suggested that small patches of Cretaceous rocks resting on the Castile Formation inside the western part of the basin indicate a more profound episode of dissolution extending down into the Castile. This interpretation is difficult to support because similar isolated patches of Cretaceous rocks in the same area are found in younger collapse depressions at a stratigraphic level at least as high as the lower Salado and that, clearly, were implaced by collapse after late Cenozoic uplift (Castile A of Kirkland and Evans, 1976). Lang (1947) described how similar patches of Cretaceous rocks had been trapped in sinks or cavernous channels and were stratigraphically out of place. Also, Udden (1915) originally ascribed a Cretaceous age to the Castile Formation because he found Cretaceous age cuttings 265 ft (76 m) below the top of the Castile in an area overlain by the Rustler Formation and which could only have been emplaced by a deep collapse.

A truncation surface sufficient to allow pre-Cretaceous dissolution to reach into the Castile Formation would require a regional dip in the Cretaceous of 100 ft/mi (19 m/km) to account for even the present thickness of the stratigraphic section farther east in the basin. Inasmuch as this is the present regional dip following uplift, extensive pre-Cretaceous truncation and dissolution would allow no space for the recognized post-Cretaceous uplift.

The Salado and Rustler formations are now stripped from the western half of the basin, so it is not possible to determine if salt was dissolved before Cretaceous time. Isopach maps of the middle and upper Salado (Anderson, 1978, figs. 9, 10) show regionally normal thickness trends extending westward to the area of present truncation indicating that dissolution, if it took place, was confined to the upper part of the Salado in the western part of the basin.

CENOZOIC DISSOLUTION

Structural and Stratigraphic Controls

Large-scale dissolution of salt from the Delaware Basin occurred late in the Cenozoic Era with the uplift, tilting, and exposure of the Permian Capitan reef and evaporites. Understanding the present patterns of dissolution and how dissolution has progressed is,
Figure 2. Map of Delaware Basin showing location of Capitan reef, major dissolution depressions, and western dissolution edge of evaporites and of major salt units.
therefore, largely a problem in defining the existing geometry of the basin, the aquifers, and the nature of hydrologic flow. The Delaware Basin responded to uplift and tilting as a single unit. The uplift occurred mostly along the western side of the Guadalupe and Delaware mountains and tilted the basin east-northeast so that present regional dip of the evaporite beds and associated aquifers is about 100 ft/ml (19 m/km) to the east and northeast. The bounding faults on the western basin edge intersected the reef (Capitan aquifer) at the southern end of the Guadalupe Mountains in Texas (fig. 2). The uplift was somewhat greater in the south than in the north so that the Capitan aquifer became exposed and breached in the south first, and the uplifted mountain mass became a catchment area for surface waters. The reef was also exposed farther to the south in the Glass Mountains of Texas which became another catchment area (Hiss, 1975).

Following uplift, the evaporites and overlying clastic rocks of the Permian, Triassic, and Cretaceous Systems were systematically removed to develop the present beveled and truncated outcrop patterns approximately normal to the regional dip of the basin (figs. 2, 4). Much of this removal was accomplished by normal surface erosion and dissolution by ground-water flow on the top of the evaporites. The dissolution edge of this surficial type of salt dissolution has traveled about two-thirds of the way across the basin, approximately to the vicinity of the WIPP site in the northeastern part of the basin (fig. 2). The trailing dissolution edge, with the exception of the lower Salado, is about halfway across the basin. The eastward shift of the surface dissolution front was accompanied by some sapping and preferential dissolution adjacent to and beneath the overlying Rustler and younger units, a process which has been operating to form Nash Draw (fig. 2) and an earlier linear depression to the west of Nash Draw beneath Quahada Ridge (Vine, 1963). This near-surface sapping apparently resulted in ground-water flow westward into an ancestral drainage which ultimately was integrated into the present Pecos River.

The areas of deeper dissolution adjacent to the eastern reef and identified by Maley and Huffington (1953) were probably not initiated by a surficial dissolution process. The Capitan aquifer that encircles the basin is the major water-carrying unit in the system. This aquifer transports waters from the catchment areas to the northeastern and lowest corner of the basin where they escape through leakage into the San Andres Limestone aquifer (Hiss, 1975). The reef aquifer directs the flow of water adjacent to and beneath the evaporites and has been the conduit for drawing off brine generated by deep dissolution processes (see later discussion).

The other major aquifer related to processes of deep-seated dissolution consists of the thick clastic units of the Delaware Mountain Group which underlie the evaporite sequence in the basin.
In contrast to the Capitan, this aquifer is relatively impermeable but is under high artesian pressure and does conduct water slowly eastward and northeastward across the basin to eventually emerge through leakage into the Capitan and San Andres aquifers (Hiss, 1975). The upper part of the aquifer (Delaware sand) is more permeable than the lower units. The catchment area includes part of the western reef and exposed aquifer west of the Castile and the evaporites west of the trailing dissolution edge (figs. 2, 4).

Cenozoic uplift and tilting were accompanied by minor differential warping and flexing and the development of well-defined fracture systems in the basin and reef-margin areas. Faults exist at depth, below the evaporites, along the inner eastern reef margin, and also parallel to the reef within the basin. These larger faults are not thought to have penetrated the evaporites (Haigler, 1962), but flexing along the reef margin accompanying uplift is thought to have fractured the reef and overlying evaporites (Adams, 1944, p. 1625; Adams and Frenzel, 1950, p. 301; Hiss, 1975, p. 118).

Within the basin, joint sets with both a northeasterly and northwesterly strike are recognizable. The northeasterly set appears to be better developed and has fractured the lower anhydrite of the Castile Formation in the western part of the basin where it is exposed and can be observed (King, 1948; Olive, 1957). This same direction of fracturing has also controlled the emplacement of dikes of biogenic calcite that with the aid of meteoric water, and hydrocarbons have developed upward from the basin aquifer into the middle part of the evaporites (Kirkland and Evans, 1976). A graben in the basin with a displacement of the aquifer of about 80 ft (24 m) also has the same trend (Smith, 1978). Seismic surveys beneath the WIPP area (fig. 2) show the development of faulting with a northwesterly trend that has intersected the basin aquifer (Powers and others, 1978, fig. 4.4-3), and a more recent survey shows that the "disturbed area" of the Castile at the WIPP site is bounded by an offset in the basin aquifer (U.S. Department of Energy, 1980, p. 7-45). It is the fault and fracture systems that are thought to have brought hydrologic communication between the aquifers and evaporites and initiated and sustained the deeper seated type of dissolution.

**Reef and Reef-Margin Dissolution**

The inner margin of the reef, where buried around the northern and eastern sides of the basin, is the locus of a number of deep-seated dissolution features. Some of the small isolated domes in the northern part of the basin described by Vine (1960) (fig. 2) have recently been cored as part of the WIPP exploration, and Dome A exhibits collapse and brecciation to a depth equivalent to the top of the reef (J. Powers, personal commun.). The eastern chain of large dissolution depressions of Maley and Huffington (1953) occupy an equivalent position with respect to the reef margin. The absence of Salado salt in the deeper part of these depressions indicates that they "root" in or above the Capitan reef aquifer. A depression occupying the same position with respect to the reef appears to have controlled the western edge of Salado salt where it crosses the reef in the northern part of the basin (fig. 2, and illustrated by Brokaw and others, 1972) and the surrounding depression, San Simon Swale (fig. 2), have developed relatively recently along the inner reef margin in the northeastern corner of the basin. A new sink developed in June, 1980 between Kermit and Wink, Texas (fig. 2) (Baumgardner and others, 1980) on the edge of one of the depressions defined by Maley and Huffington (1953).

Various stages in the reef-associated dissolution process can be seen at different places around the basin. Carlsbad Caverns and other caverns in the exhumed reef in the Guadalupe Mountains represent an early and now advanced stage of the process when breaching of the evaporite cover allowed for the development of an artesian flow system in the Capitan reef aquifer and initiated limestone dissolution. The development of another catchment area to the south in the Glass Mountains (fig. 2) also produced caverns and initiated the flow system that ultimately produced the
Figure 4. Diagrammatic cross section across Delaware Basin showing approximate thickness of major stratigraphic units and position of potentiometric surfaces (pot. surface) for the Bell Canyon and Capitan aquifers (line of section H in Figure 2), modified from Hiss (1975).

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brine is drained off laterally or downward through the aquifer and salt beds. According to this model, it is the density gradient between more concentrated brine at the dissolution interface and less concentrated brine. Inasmuch as the brine derived from dissolution accumulates in the lower part of the aquifer (Hiss, 1975), so that upward movement of undersaturated waters is possible.

The potential for dissolution in the early stages would be greatest up dip, or near the recharge area. This condition suggests that the development of brine flow, collapse, and expanded dissolution, according to this model, is a function of the degree of communication between the aquifer and salt beds. Also, the aquifer is in places "cavernous" along the eastern and northern margins of the basin (Hiss, 1975, p. 176), and collapse along areas of most active flow, perhaps along the inner part of the reef, may have provided the communication needed to initiate a dissolution cycle. A model of brine flow has been presented by Anderson and Kirkland (1980) to account for continued and expanded dissolution of salt once communication has been established between the aquifer and the salt beds. According to this model, it is the density gradient between more concentrated brine at the dissolution interface and less-concentrated waters in the aquifer below or subjacent to dissolution that drives a cycle of brine flow in which the heavy brine is drained off laterally or downward through the aquifer and is replaced by upward moving, less-concentrated waters in the artesian system. The potentiometric surface for brine in the Capitan aquifer is well up within the evaporites above the reef (Hiss, 1975) so that upward movement of undersaturated waters is possible.

There are several clues as to how these depressions may have been initiated and expanded. The flexing along the reef margin may have developed fracture communication between the aquifer and the overlying salt beds. Also, the aquifer is in places "cavernous" along the eastern and northern margins of the basin (Hiss, 1975, p. 176), and collapse along areas of most active flow, perhaps along the inner part of the reef, may have provided the communication needed to initiate a dissolution cycle. A model of brine flow has been presented by Anderson and Kirkland (1980) to account for continued and expanded dissolution of salt once communication has been established between the aquifer and the salt beds. According to this model, it is the density gradient between more concentrated brine at the dissolution interface and less-concentrated waters in the aquifer below or subjacent to dissolution that drives a cycle of brine flow in which the heavy brine is drained off laterally or downward through the aquifer and is replaced by upward moving, less-concentrated waters in the artesian system. The potentiometric surface for brine in the Capitan aquifer is well up within the evaporites above the reef (Hiss, 1975) so that upward movement of undersaturated waters is possible.

The potential for development of brine flow, collapse, and expanded dissolution, according to this model, is a function of the degree of communication between the aquifer and salt, and the density difference between waters in the aquifer and dissolving brine. Inasmuch as the brine derived from dissolution accumulates in the lower part of the Capitan aquifer (Hiss, 1975), the potential for dissolution in the early stages would be greatest up dip, or near the recharge area. This condition suggests that the development of the eastern depressions has progressed northward along the edge of the basin. A lake occupied the depression surrounding San Simon Sink (figs. 2, 4) in late Wisconsin time (radiocarbon date of 20,570 ± 540 C-14 years B.P. [before present]) and about 250 ft (76 m) of collapse in the sink has been recorded since then. The most recent collapse event was in 1927. A core from San Simon Sink (WIPP-15) penetrated 545 ft (166 m) of eolian sand and lake depos-

### Table 1. Summary of rock units of Permian (Ochoan and Guadalupian) and younger age, Eddy and Lea Counties, New Mexico (from Mercer and Orr, 1977).

<table>
<thead>
<tr>
<th>Age</th>
<th>Rock Unit</th>
<th>Thickness (meters)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Sand of Mescalero surface</td>
<td>0.4-6</td>
<td>Dune sand, uniformly fine-grained, light brown to reddish-brown</td>
</tr>
<tr>
<td></td>
<td>Alluvium</td>
<td>0.91</td>
<td>Sand, silt, and conglomerate</td>
</tr>
<tr>
<td></td>
<td>Caliche</td>
<td>0.15</td>
<td>Limestone, chalky, includes fragments of underlying rock</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Catuna Formation</td>
<td>0.114</td>
<td>Sandstone and siltstone, poorly indurated, dominantly reddish-orange</td>
</tr>
<tr>
<td></td>
<td>Ogallala Formation</td>
<td>7.6-53</td>
<td>Sandstone, fine- to medium-grained, tan, pink, and gray, locally conglomeratic and typically has resistant cap of well-indurated caliche</td>
</tr>
<tr>
<td></td>
<td>Chilie Formation</td>
<td>0.244</td>
<td>Mudstone, shaly, reddish-brown and greenish-gray, interbedded lenses of conglomerate, and gray and reddish-brown sandstone</td>
</tr>
<tr>
<td>Triassic</td>
<td>Santa Rosa Sandstone</td>
<td>42.7-91</td>
<td>Sandstone, medium- to coarse-grained, commonly cross-stratified, gray and yellowish-brown contains conglomerate and reddish-brown sandstone</td>
</tr>
<tr>
<td></td>
<td>Dewey Lake Red Beds</td>
<td>61-183</td>
<td>Siltstone and sandstone, very fine- to fine-grained, reddish-orange to reddish-brown, contains interbedded reddish-brown claystone, small-scale lamination and cross-stratification common</td>
</tr>
<tr>
<td></td>
<td>Rustler Formation</td>
<td>61-183</td>
<td>Anhydrite and rock salt with subordinate dolomite, sandstone, claystone, and polyhalite</td>
</tr>
<tr>
<td></td>
<td>Salado Formation</td>
<td>442-632</td>
<td>Rock salt with subordinate anhydrite, polylalite, potassium ores, sandstone, and magnesite</td>
</tr>
<tr>
<td>Permian</td>
<td>Castile Formation</td>
<td>396-610</td>
<td>Anhydrite and rock salt with subordinate limestone</td>
</tr>
<tr>
<td>Guadalupian</td>
<td>Capitan Limestone</td>
<td>488 ± 40</td>
<td>Limestone, massive, with dolomitized reef breccia</td>
</tr>
<tr>
<td></td>
<td>Bell Canyon Formation</td>
<td>305 ± 35</td>
<td>Sandstone, gray and brown, with limestone and minor shale</td>
</tr>
<tr>
<td></td>
<td>Cherry Canyon Formation</td>
<td>305 ± 35</td>
<td>Sandstone, gray and brown, with limestone and minor shale</td>
</tr>
<tr>
<td></td>
<td>Brushy Canyon Formation</td>
<td>305 ± 35</td>
<td>Sandstone, gray, with brown and black shale and brown limestone</td>
</tr>
</tbody>
</table>
its, and climatic dating indicates that the sediments in the deeper part of the depression can be no older than about 50,000 years. The youthful age and recent collapse activity at San Simon Sink support the idea that dissolution has advanced from south to north and is just now reaching the northeastern corner of the basin (the other depressions are presumably filled with Catuna Formation [Table 1] or earlier Pleistocene deposits).

The reef-margin depressions have expanded considerably since initiation and early dissolution. Apparently, with collapse and fill, the expanded drainage area served as an additional local recharge area and funneled surface waters into the depressions resulting in even more dissolution. The deeper of these depressions are filled with more than 1,200 ft (366 m) of Cenozoic sediments, and the depressions' depth and isolated character indicates that they were not formed by surface ground-water flow alone. In the absence of a connection at depth, heavy brine generated from dissolution will accumulate in the bottom of a closed depression. Unless drained off into the underlying aquifer, dissolution and expansion of the depressions cannot proceed.

Little information about the early stage of dissolution in the center of the depressions can be gleaned from geophysical logs because the salt is entirely absent. Several kilometers from the center of the depressions, however, acoustical logs across the expanded margin illustrates the selective lateral dissolution of the salt beds (fig. 5). In some cases, near the outer margin of a depression, only the surface (top of the Salado salt) flow into the depression has dissolved salt at the top of the section (well A of fig. 5). Closer to the center of a depression, however, the process is seen to be highly selective, extending to great depth in the salt but not necessarily moving downward as a single front. Rather, it is lateral dissolution of individual beds acted upon by waters moving through the depression that appears to be responsible for the lateral expansion of dissolution (well C of fig. 5). This is a pattern that might be expected if near-saturated brine had accumulated near the base of a depression prior to its drainage into the aquifer.

In some cases, the reef-margin depressions have expanded and extended out into the basin for considerable distances. This basinward expansion can be observed in Ward County, Texas where dissolution has extended beyond the reef margin for more than 10 mi (16 km). The edge of dissolution is at the top of the Salado salt, however, and is not as depicted in an earlier discussion by Anderson and Kirkland (1980, fig. 4). The earlier interpretation of an eastern dissolution wedge between the Castile and Salado formations was based on the nonrecognition of the significance of the unconformity between the Castile and Salado and attributing the missing salt to later dissolution. Undercutting dissolution does extend from the reef area into the basin from the east, but it appears to operate on the smaller scale of dissolution of individual salt beds.

Deep-Seated Dissolution in the Delaware Basin

Geometry and associations

The large, deep depressions within the basin (e.g., Poker Lake and Big Sinks area of fig. 2) form the leading edge of an eastward-advancing deep-seated dissolution process. Anderson and others (1978) present correlations and evidence that identifies the dissolution associated with these depressions as being most active at the lower Salado horizon. (In the Poker Lake and Big Sinks area the dissolution edge in the HII salt of the Castile [fig. 3] extends slightly farther eastward than the dissolution edge of the lower Salado. The HII edge in this area is not the result of pre-Salado removal but developed at the same time as lower Salado dissolution).

Figure 6, for example, shows the abrupt loss of salt at the eastern margin of the deep depression in Loving County, Texas. Correlation of marker beds within the Salado shows that the upper Salado is undissolved and that the depression of the Rustler which accommodated the Cenozoic fill is the result of removal of salt beds from the lower Salado. The abrupt loss of salt far exceeds the rate of facies change for salt-anhydrite units within the Salado, and the degree of compression of section and lowering of the Rustler agrees closely with thickness of the salt beds removed by dissolution (fig. 6). The close relationship between missing salt and the structure of the Rustler Formation means that Hiss's (1976) map of Rustler structure is an approximation of the extent and pattern of this type of dissolution. The depressions depicted in Figure 2 are based on Rustler structure and confirming acoustical logs.

The configuration of these lower Salado depressions and their location in the basin with respect to surface topography and associated aquifers provides information about the origin of the depressions and the way dissolution has progressed across the basin. In areas of close control, the depressions resolve into isolated centers of less than a kilometer to several kilometers in diameter (see Hiss's map of Rustler structure, 1976). These centers are also the loci of even deeper horizons of dissolution in the Castile salt beds that are less extensive laterally than in the lower Salado. In some cases it is difficult to distinguish missing salt at the base of these centers from salt-flow structures associated with deformation in the lower salt beds of the Castile. The association between Castile structure and expanded dissolution in the overlying evaporites is especially clear in the Poker Lake–Big Sinks area where the Poker Lake salt structure (Anderson and Powers, 1978) and the Big Sinks depression depicted byVertrees (1964) lie near the center of the northernmost depression in the basin (fig. 2). Isolated masses of HII salt remain in the center of these depressions (fig. 4) indicating that dissolution was present but decreased with depth in these structures. An isolated mass of upper middle Salado salt in the Big Sinks depression (fig. 4; also see cross-section of Vertrees, 1964) shows that dissolution was extensive but not total at higher stratigraphic levels near the center of the depression.

The northernmost, and apparently more recently formed, depressions in the basin lie east of, and roughly parallel to, the axis of the Pecos River (fig. 2). The southern ones lie west of the Pecos. The Pecos River itself through much of the basin appears to lie above the area of recent removal of lower Salado salt. The trend of the depressions corresponds approximately to a zone of decreasing chlorinity (<100 g/l [grams per liter]) in the underlying basin aquifer. East of this trend, the aquifer is nearly saturated with salt (Hiss, 1975, fig. 26).

The northernmost depression (Poker Lake–Big Sinks) lies east of a reentrant in the configuration of the basin that has been the discharge area for major streams from the Guadalupe Mountains and the area of deposition of extensive deposits of coarse gravels (see map of King, 1948, pl. 22). This association with modern topography suggests that surface discharge may have played a role in developing the depression.

Hydrodynamics of deep-seated dissolution

The extreme solubility of salt and the density of brine determine the hydrodynamics of salt dissolution. Without continual movement and circulation, undersaturated waters in contact with salt soon become saturated and dissolution stops. Ground-water movement over a salt surface and into a closed depression will direct the more dense brine into the bottom of the depression where it will accumulate and stagnate. In this type of flow system,
Figure 5. Location map and acoustical log correlation across eastern dissolution depression in Ward County, Texas. Note that depression has expanded laterally by the selective dissolution of individual salt beds and that dissolution has developed to a greater depth toward the center of the depression. (A) Hissom Drilling Co. Hathaway No. 1, sec. 6, Blk. 7, H&CN Survey, Reeves County; (B) H. L. Hurley Wilson No. 1, sec. 127, Blk. 34, H&TC Survey, Ward County; (C) T. F. Hodge Edwards No. 1, sec. 99, Blk. 34, H&TC Survey, Ward County; (D) Eastland Drilling Co. C. T. Hall No. 1, sec. 108, Blk. 34, H&TC Survey, Ward County. Structure contours on top of Rustler Formation from Hiss (1976); contours in feet.
Figure 6. Location map and acoustical log correlation across a deep dissolution depression within the basin in Loving County, Texas. Section I-M shown in Figure 7. Note the almost complete loss of Salado salt near the center of depression and the selective removal of salt beds progressing outward at the base of the Salado that corresponds to the degree of structural depression of the Rustler Formation. As in Figures 5 and 7, horizons of active dissolution and missing salt beds are also characterized by a prominent pattern resembling cycle-skips in the logs. (E) Texaco Loving "W" FEE No. 1, sec. 1, Blk. 55, T-2, T&P Survey, Loving County; (F) R. E. Sutton TXL No. 1-41, sec. 41, Blk. 54, T-1, T&P Survey, Loving County; (C) American Trade Sid Kyle 20 No. 4, T-1, T&P Survey, Loving County; (H) Texaco Loving "U" FEE No. 3, sec. 27, Blk. 54, T-1, T&P Survey, Loving County. Structure contours on top of Rustler Formation from Hiss (1976); contours in feet.
salt will only be dissolved from the upper surface where in contact with moving undersaturated waters. Hence, top-of-salt groundwater flow cannot be invoked to explain the development of deep "holes" extending downward from the upper surface of salt or explain dissolution beneath overlying salt within the body of evaporites.

The geometry of the missing salt in the Delaware Basin, however, shows that moving, undersaturated waters have somehow found access to salt deep within the evaporites and selectively dissolved large quantities of salt from beneath overlying salt beds (figs. 6 and 7). Figure 5 shows that dissolution has also developed to considerable depths in isolated "holes" and enlarged these holes laterally for distances of several kilometers.

One way, and perhaps the only way, to explain the dissolution geometry observed in the Delaware Basin is to provide for the leakage of brine away from the locus of dissolution and downward through the evaporites. Anderson and Kirkland (1980) have offered a model of brine density flow to explain this type of dissolution. In this model, heavy saturated or near-saturated brine is drained away from the site of dissolution, owing to its density, through fracture systems and into associated aquifers where it is ultimately removed from the flow system. Continuous circulation is maintained by replacing the brine with undersaturated waters supplied by aquifers under artesian pressure to the site of dissolution. Anderson and Kirkland (1980) used this mechanism to explain the development of biogenically-replaced breccia chimneys (see paper on castiles by Kirkland and Evans, 1976) in the western part of the basin that have stoped upwards from collapse chambers in the lower salt of the Castile into the overlying evaporites (Hinds and Cunningham, 1970).

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The concept of brine flow may be adapted to explain the larger-scale depressions within the basin as well as the deep depressions through the evaporites.
along the margin of the eastern reef. Fracture communication and brine drainage into the reef aquifer can be assumed to develop with the initial collapse of a cavity in or above the reef. In the basin, however, communication had to be established between the lower Salado and the underlying Delaware Mountain Group aquifer. Fracture permeability could have developed within the basin through the dissolution and collapse of lower Castile salt and subsequent stoping to the stratigraphic level of the lower Salado (fig. 8). Collapse to this level can be demonstrated in at least one of the castiles (Hill A) described by Kirkland and Evans (1976). Fracture communication may also have developed in association with the salt deformation structures developed in the Castile Formation (fig. 8). The occurrence of partially dissolved anhydrite beds along the flank of the ERDA #6 anticline (Anderson and Powers, 1978) suggests that pathways for brine movement are present in these structures. The presence of large quantities of trapped brine in this and other anticlinal structures in the basin also suggests that fluid communication may exist between the basin aquifer and salt at higher stratigraphic levels in the evaporites. Once communication between the basin aquifer and the lower Salado is established, the brine produced at the lower Salado horizon may be drained off into the basin aquifer.

The geophysical log sections in Figures 6 and 7 show that the efficacy of dissolution was greatest in the lowermost salt beds of the Salado and decreased upward. This relationship suggests that the pathway for initial penetration of undersaturated waters was at or near the base of the Salado or between the Castile and Salado formations. For some reason, the undersaturated surface waters moving downward through fractures and solution channels in the exposed gypsum up dip and to the west found an easier path of communication in their down-dip movement at the lower Salado horizon. A pre-Salado dissolution residue may have predisposed this horizon through increased permeability or, as observed by Hills (1979), the Salado is especially vulnerable to down-dip dissolution owing to the presence of numerous seams and beds of clays and sands.

The mechanism suggested here to account for the selective removal of salt at the lower Salado horizon is the down-dip movement of undersaturated surface waters to a point of contact with salt and the down-gradient movement of brine into conduits communicating with the basin aquifer. As dissolution expands and extends to higher salt beds, the undersaturated waters move in above the back-flowing brine as depicted schematically in Figure 8. The rate of down-dip advance of the dissolution is determined largely by the availability of conduits. The rate of advance will slow significantly on the down-dip side of conduits because of the backward (up-dip) drainage of brine. When a new conduit is encountered the rate of dissolution is significantly increased to form a more isolated and expanded depression. Hence, the edge of dissolution can be visualized as both a slowly moving front and as a

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![Diagram](image-url)
“leap-froging” process controlled by the availability and development of conduits. This explanation most closely approximates the configuration of dissolution depicted in Figures 2, 6, and 7. Ultimate control on the rate of advance is determined by the availability of water moving down dip, the degree of communication in conduits, and the density of brine accumulated in the basin aquifer (brine flow is a function of density difference [Anderson and Kirkland, 1980]).

The location of the Poker Lake–Big Sinks depression, adjacent to gravels and large stream discharges, suggests that availability of water may at times be a factor in the rate of advance. The location of the edge of saturated brine in the basin aquifer is just east of and parallel to the edge of dissolution in the lower Salado, suggesting that the present position of the wedge, as well as the present position of the Pecos River and surface runoff, is ultimately controlled by the rate of leakage of brine from the basin aquifer. The salinity of water in the Delaware Mountain Group beneath the evaporites is greater than for the permeable units at greater depth in the basin (McNeal, 1965) suggesting that the saturated brine in the eastern part of the Delaware Mountain Group aquifer is derived from the overlying evaporites.

A potential difficulty for the brine-draining hypothesis is the requirement that substantial quantities of brine be drained through the sluggish aquifer underlying the evaporites. The hydrologic information compiled by Hiss (1975) can be used to estimate the volume of water and salt moving through the aquifer. Using the calculation method of Lohman (1972, p. 10) with a value of hydraulic conductivity equal to 0.0049 m/day (Hiss, 1975, p. 154) and a chlorinity of 150 g/l (Hiss, 1975, fig. 26), the basin aquifer, if leakage is assumed where it is in contact with the reef, can remove the volume of salt missing from the lower Salado in 1.5 m.y. (million years). These crude estimates and assumptions suggest that brine leakage is of the order of magnitude required to account for the development of a lower Salado dissolution wedge.

**STAGE AND RATE OF DISSOLUTION**

Compared to some other evaporite basins on the continental platform containing even older salt beds, such as the Michigan Basin or the evaporites in Saskatchewan, the Delaware Basin with 50 percent of the salt removed has reached a rather mature stage of dissolution. This is reflected in the size, abundance, and distribution of dissolution features.

The advanced stage of dissolution in the Delaware Basin developed after a relatively recent history of uplift and exhumation. According to King (1948, p. 120-122) minor uplift may have taken place in early Cenozoic time, but the earliest identifiable phase was probably in Miocene to early Pliocene time. The main phase of the uplift occurred in late Pliocene to early Pleistocene time (King, 1948; Hayes, 1964), or perhaps 2-6 m.y. ago. A more recent study since those of King and Hayes has identified the Salt Basin grabens, the Guadalupe Mountains, and the Delaware Basin uplift as features marginal to, and associated with, the Rio Grande rift (Seager and Morgan, 1979). The development of the rift in southern New Mexico culminated about 4 m.y. ago.

This schedule of uplift and exhumation agrees quite well with the age of the stratigraphic and geomorphic units associated with dissolution in the basin for which some age information is available. Substantial dissolution is associated with the Catuna Formation which is probably early Pleistocene and pre-Kansan in age (Bachman, 1974, p. 28). The Mescalero surface, which is developed on top of Catuna sediments and which developed after the formation of the major features in the central part of the basin (i.e., Big Sinks depression), has been dated indirectly with an ash bed at about 600,000 years (Bachman, 1980). Deposits associated with the recent development of Nash Draw are placed in the Wisconsin, San Simon Swale and Sink sediments are no older than about 50,000 years.

The association of major dissolution features with still active aquifers and the occurrence of youthful dissolution features and events means that the processes of dissolution are continuing. The age of the older features as well as the younger ones indicates that the most active area of dissolution has now reached the eastern part and northeastern corner of the basin. While the progress of dissolution may have been irregular or episodic, depending upon fluctuations in Pleistocene climate, there is no reason to assume that the progress of dissolution has stopped and will not be subjected to advances in the future.

**ENVIRONMENTAL INFERENCES**

The environmental problem most closely linked to progressive dissolution in the Delaware Basin is the stability of the proposed WIPP site (see Brookins; Powers; and Mercer and Gonzales, this volume). The horizon selected for the repository, according to the preceding sketch of the progress of dissolution, is the one with the most active history of dissolution. If dissolution proceeds as it has in the past, the WIPP site will be breached at the horizon of the repository before the overlying salt is removed by surface groundwater flow. Hence, estimates of site stability based upon the rate of movement of a surface dissolution front (U.S. Department of Energy, 1980, p. 7-98) may not be pertinent.

A highly “disturbed zone” of structural complexity in the Castile Formation with associated displacements of the underlying aquifer has been inferred from seismic evidence in the northern part of Zone II at WIPP (Powers and others, 1978; fig. 4-4; U.S. Department of Energy, 1980, p. 7-45). Trapped brine and pressurized brine flows with large volumes (Criswold, 1980) are associated with dissolution effects in similar Cenozoic salt structures in the area around the site. The brine at ERDA #6 anticline is believed to have been isolated in the structure for nearly 1 m.y. (Barr and others, 1979). However, the size of the flows suggests an initial meteoric origin before isolation, implying that brine entered the structures through conduits connected to the basin aquifer. The presence of dissolved anhydrite and remobilized and reprecipitated salt in the ERDA #6 structure (Anderson and Powers, 1978) and at WIPP #11 can be explained if the original charging of the aquifer was accompanied by artesian movement of undersaturated brine into the trapping structures. Continued brine drainage into the aquifer with dissolution up dip has accumulated saturated brine in the lower part of the aquifer and decreased the density difference, temporarily stopping or slowing dissolution. It is conceivable that dissolution during the early charging of the aquifer or slower dissolution at present brine gradients (see map of chlorinity in Hiss, 1975) has produced uncollapsed chambers in the “disturbed zone” beneath part of the site.

These indications of the movement of fluids through the lower part of the evaporite units agree with the proposed model for the initiation of a cycle of deep-seated dissolution, and structurally, the area resembles other places in the basin that were the loci for expanded dissolution at the lower Salado horizon. In this respect the site does not meet previously established stability criteria for high level wastes (National Academy of Sciences, 1978, 3.21).

Expressing stability in terms of a regional dissolution front or rate (U.S. Department of Energy, 1980, 1-4, 7-98, 7-100) does not consider the manner in which the lower Salado type of dissolution has
progressed in the basin. Typically, the process has moved ahead of regional dissolution patterns to predisposed areas where dissolution is initiated on a local scale and then expanded with the resultant collapse of overlying beds. The appropriate question for site stability is one of investigating predisposed areas where the early effects of dissolution may already be manifest such as the “disturbed zone” which extends under the northeastern part of the WIPP site. The methods for examining this deep-seated type of dissolution in its early stages, however, may be site-destructive. Assuring stability in a basin that exhibits an advanced stage of dissolution is more problematical than in a nearly undissolved basin and for this reason any site in the Delaware Basin can be expected to have a higher risk factor than sites in less-dissolved evaporite basins.

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Pyramid Butte, near Fort Wingate, with promontories of the Wingate sandstone in front. The butte is composed of the Zuñi sandstones. Photographed on wood. (From U.S. Geological Survey, Sixth Annual Report, 1885.)
Waste Isolation Pilot Plant

Compliance Certification Application

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