Structural Characteristics of a Deep-Seated Dissolution-Subsidence Chimney in Bedded Salt

Peter B. Davies
Department of Applied Earth Sciences
Stanford University
Stanford, California, USA

ABSTRACT

Subsidence structures caused by natural salt dissolution occur in many salt-bearing sedimentary basins. Little is known about the structural characteristics of subsidence within salt because subsurface data on existing structures are very limited. Because of its potential for breaching a thick salt unit, deep seated dissolution-subsidence activity is a hazard requiring thorough assessment for nuclear waste repositories in bedded salt deposits.

On the northern margin of the Delaware Basin in New Mexico, a Pleistocene-age subsidence chimney was recently exposed in a potash mine. The mine workings reveal a transition, over a distance of approximately 55 meters (180 feet), from undisturbed subhorizontal evaporite beds to breccia of the subsidence chimney. Within the transition zone, bedding dips toward the chimney, reaching a maximum dip of 30 degrees at the breccia contact. The breccia includes clasts of halite, anhydrite, and polyhalite. The dissolution-induced morphology of halite clasts and the breccia matrix composition indicate that groundwater flowed through the chimney during and/or following subsidence. This subsidence structure formed in response to dissolution associated with groundwater flow in the Capitan reef, which underlies the evaporite section. However, because of the absence of deep drill hole data in the root area of the chimney, the exact nature of the dissolution zone cannot be determined at present. Salt dissolution in the lower portion of the Salado salt, producing incremental subsidence of the overlying strata, is proposed as a model for the formation of this deep-seated subsidence chimney.

INTRODUCTION

Salt dissolution, at depths of as much as 1,500 meters (5,000 ft), has occurred in many salt-bearing sedimentary basins (Johnson, 1901; Frye and Schoff, 1942; Landes, 1945; Malley and Huffington, 1953; De Mill et al., 1964; Christiansen, 1967, 1971; Gendzwell and Hajnal, 1971; Anderson, 1978, 1981; Anderson et al., 1978; Gustavson et al., 1980; Baumgardner et al., 1982). In some areas, this dissolution has occurred at the base of the evaporite section, causing subsidence of both the evaporite strata and the overlying carbonate/clastic units. Historical occurrences of sinkholes and deformation of Pleistocene deposits indicate that the dissolution-subsidence process has been active in the recent past and can be expected to continue into the future. Little is known about the structural characteristics of subsidence within salt because subsurface data on existing structures are limited and access for direct observation is rare. Because of its capacity for breaching a thick salt unit, deep seated dissolution-subsidence is a significant potential hazard for a nuclear waste repository constructed in bedded salt. Thorough assessment of this hazard requires a full understanding of the physical processes that control the development of subsidence structures.

The subsurface structural characteristics and formation of a deep seated dissolution-subsidence chimney are discussed in this paper. This research was carried out as part of a larger study aimed at developing a better understanding of the dissolution-subsidence process. The chimney is located on the northern margin of the Delaware Basin in New Mexico (Figures 1 and 2). At the ground surface, this chimney is expressed as a circular hill with a central core of down-dropped, brecciated material (Figure 3). Including the outward sloping flanks, the diameter of the hill is approximately 365 meters (1,200 feet), and the diameter of the brecciated core is approximately 240 meters

Mr. Davies first became involved with the geologic aspects of radioactive waste disposal in bedded salt deposits in 1976. He worked with the Boston based consulting firm, Geotechnical Engineers Incorporated, on the Lawrence Livermore Labs risk analysis model for the Nuclear Regulatory Commission. His PhD research at Stanford University on the salt dissolution and subsidence process, from 1979 to the present, has been an outgrowth of his earlier work on potential geologic hazards to bedded salt repositories. This research has included both field studies of subsidence structures in the Michigan and Delaware Basins and theoretical work on the mechanics of the subsidence process.

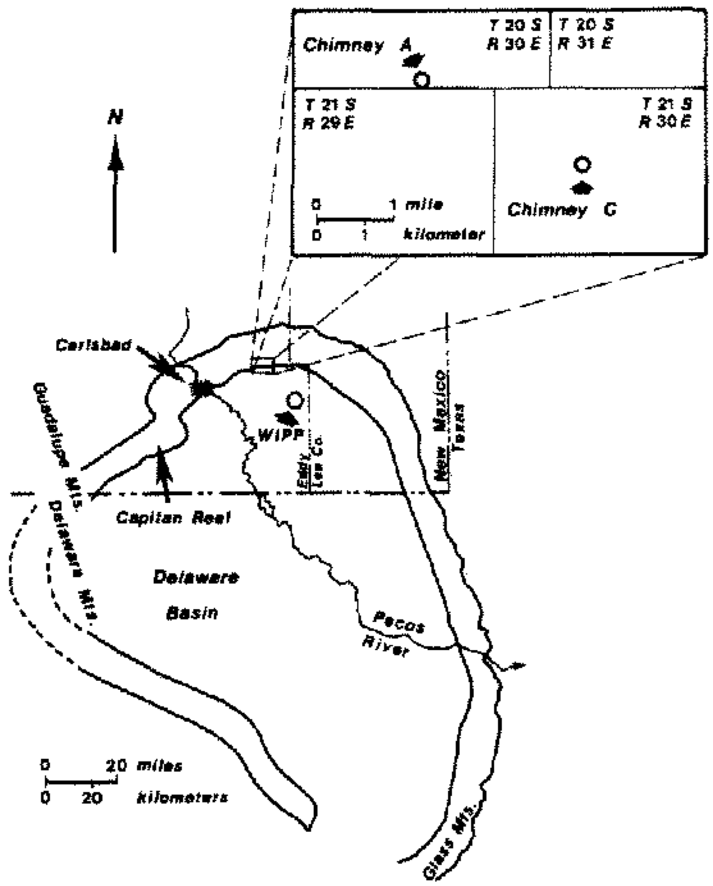

Figure 1. Location map.

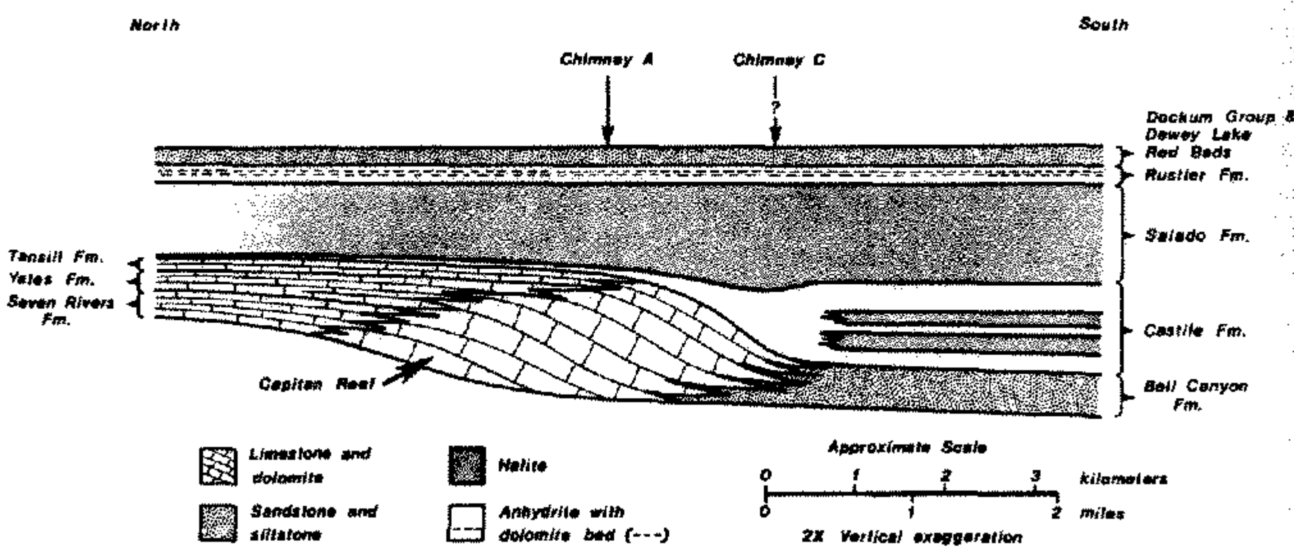

Figure 2. Schematic north-south cross section transecting the northern margin of the Delaware Basin. The approximate locations of subsidence chimneys "A" and "C" are shown, based on Hiss' (1975) and Gail's (1974) interpretation of the thickness and distribution of the Capitan aquifer. This cross section has been adapted from the work of King (1948), Jones and Madsen (1968), and Meissner et al. (1972).

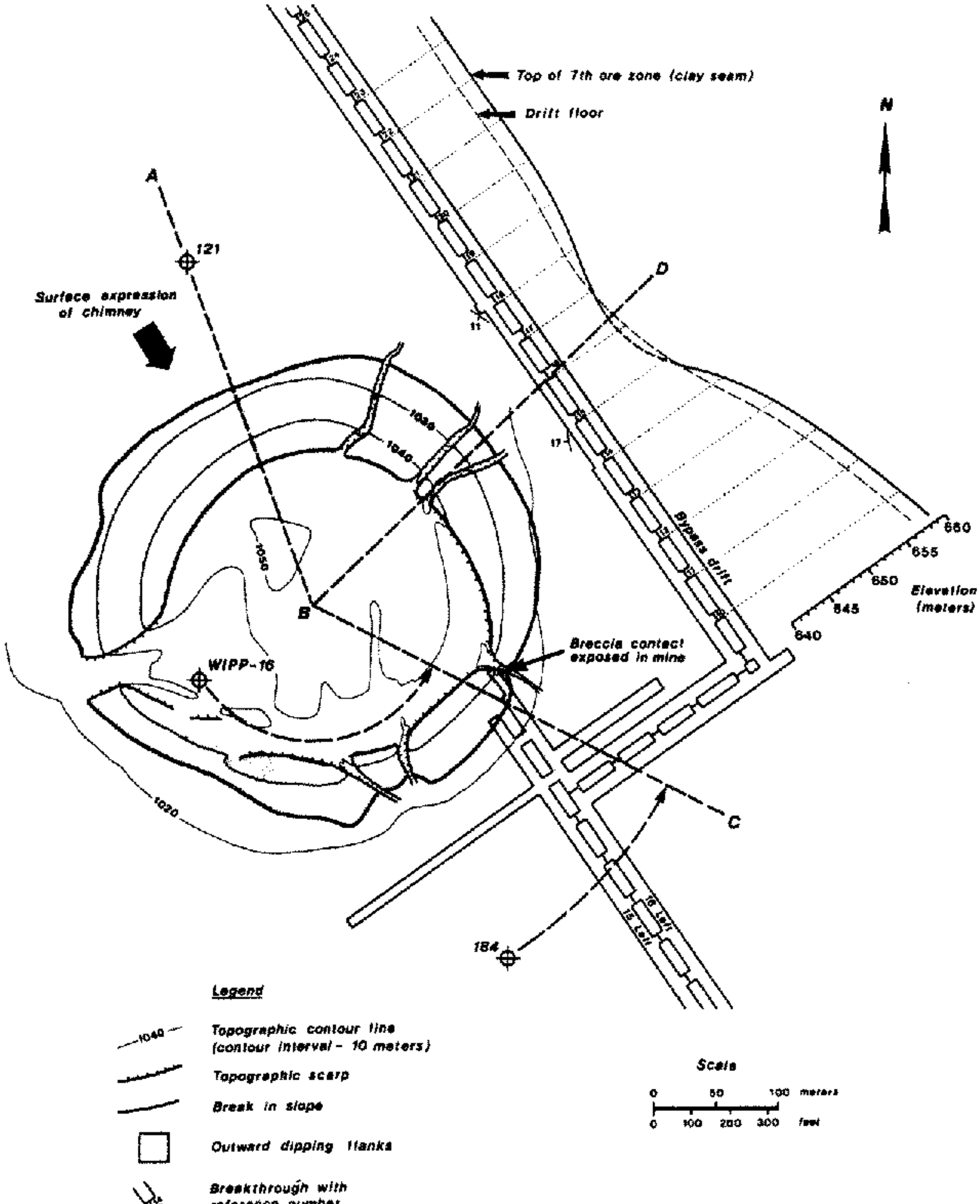

Figure 3. Map showing the ground surface expression of Chimney C and the underlying potash mine drifts. Because of the axisymmetric character of the chimney, the information from drill holes 184 and WIPP-16 has been rotated onto cross section A-B-C (Figure 4) along a circumferential path.

(800 feet). In 1975, a potash mine drift (tunnel), located 365 meters (1,200 feet) below the ground surface, was driven into the southeast chimney margin. The mine workings offer the unique opportunity to examine and map in detail the transition from undisturbed, subhorizontal evaporite beds to breccia of the subsidence chimney. Structural features of particular interest in the transition zone are 1) the geometry of the downwarped beds; 2) the location, orientation, and offsets of faults; and 3) the geometry and nature of the contact with the adjacent subsidence breccia. Characteristics of particular interest in the breccia are 1) stratigraphic correlation of the breccia clasts; 2) structural fabric; and 3) the presence or absence of manifestations of fluid movement through the chimney during or soon after subsidence. Because of the absence of deep drill hole data in the root zone of the chimney, the exact nature of the dissolution zone cannot be determined at present. However, consideration of the hydrogeology of the underlying aquifer does provide information about the dissolution process.

The mine exposure of the subsidence chimney and adjacent transition zone was mapped and sampled in July and August, 1980. Horizontal control lines were surveyed onto the tunnel walls and tied into a plan view map. The walls were then photographed with a 35 percent overlap, and 1:20 scale panoramas were constructed. For the breccia exposures, 1:10 scale panoramas were also constructed. Mapping was then completed on this photographic base.

GEOLOGIC SETTING

The Delaware Basin is a 265 by 150 kilometer (165 by 95 mile) sedimentary basin in southeastern New Mexico and western Texas (Figure 1). The basic stratigraphic and structural framework of this basin has been discussed by King (1942,1948), Adams (1944), Hayes (1964), Anderson et al. (1972), Brokaw et al. (1972), Jones (1973), Bachman (1976), and Powers et al. (1978). The stratigraphy pertinent to dissolution-subsidence in the basin includes the late Permian evaporites (Castile, Salado, and Rustler Formations), the pre-evaporite water-bearing units (Capitan Reef and Bell Canyon Formation), and the post-evaporite clastic rocks (Dewey Lake Red Beds and Dockum Group). The lithologies and stratigraphic relationships of these units are summarized in Figure 2. Along the northern margin of the basin, the Castile Formation abuts the Capitan Reef. The Salado Formation, in turn, overlies both the Castile and Capitan Reef. Within the Salado, a sequence of anhydrite, polyhalite and potassium-rich interbeds provides a set of distinct marker horizons, which are useful for delineating structure. The subsidence chimney is located above the reef margin. However, because of the absence of deep drill holes in the immediate vicinity of the chimney, the exact position of the chimney relative to the reef is unknown at present.

PREVIOUS INVESTIGATIONS

The surface expression of this subsidence chimney was first described by Vine (1960), who referred to it as "Dome C." Bachman (1980) later referred to this surface structure as "Hill C." In keeping with this nomenclature, the entire chimney structure will be referred to hereafter as "Chimney C."

Vine hypothesized that Dome C and three similar structures nearby (Domes, A, B, and D) originated from solution enlargement of fractures in gypsum of the Rustler Formation and dissolution of salt at the top of the Salado Formation, followed by subsidence of the overlying strata. With this shallow dissolution scenario, Vine concluded that "it seems unlikely that the sinkholes are developed from the surface down more than a short distance into the Salado" (Vine, 1960, p. 1,910).

The next significant information on the Chimney C structure developed in 1975, when a potash mine drift encountered the southeast margin of the chimney 365 meters (1,200 feet) below the ground surface. This exposure of subsidence breccia, located approximately 110 meters (360 feet) below the top of the Salado salt, showed that the chimney had a deep-seated origin rather than being rooted at the top of the Salado as originally suggested by Vine.

As part of the regional salt dissolution studies associated with the proposed Waste Isolation Pilot Plant (WIPP), the U.S. Geological Survey and Sandia National Laboratories have produced more information on Chimney C. In 1976, a series of electrical resistivity and gravity surveys were completed over five known or suspected subsidence chimneys, including Chimney C (Griswold, 1977, pp. 11, 34–35, Figure 29). The gravity survey showed no anomaly in the vicinity of Chimney C. The resistivity survey revealed that the brecciated core of the chimney has a much lower resistivity than that of the surrounding strata.

Detailed mapping of the surface exposures of Chimneys A and C by the U.S. Geological Survey has provided important information on the age of subsidence (Bachman, 1980, pp. 62–70, Figures 13 and 14). Chimney A is expressed at the ground surface as a low, circular hill with a collapsed central core, similar to Chimney C. On the northeast rim of the chimney, a small channel filled with gravel of the Gatuna Formation (600,000 years B.P.) cuts across the peripheral collapse contact and rests unconformably on the brecciated central core. Apparently, this gravel was deposited in a topographic depression that formed when subsidence reached the ground surface. Since that time, the sinkhole topography has been inverted as the terrain surrounding the chimney has been lowered by shallow, regional salt dissolution at the top of the evaporite section. Tilted columnar soil structures in the Mescalero Caliche on the flanks of the chimney indicate that this regional subsidence of the surrounding terrain postdates the development of this 500,000-year-old caliche.

Surficial mapping has shown that Chimney C developed over the same time frame and in a manner similar to Chimney A, with one notable exception (Bachman, 1980, pp. 69–70, Figure 14). Along the eastern rim of the chimney, and possibly along the southeastern and southern rim, the caliche surface has been offset vertically by as much as 3 to 4 meters. The central, brecciated core has dropped downward relative to the adjacent flank, indicating a small increment of post-Mescalero subsidence. This surface subsidence resulted either from some form of structural readjustment within the chimney, or from a small amount of additional dissolution at the base of the chimney. The exact nature of this most recent subsidence cannot be determined at present.

Other recent work by the U.S. Geological Survey, Sandia Labs, and the University of New Mexico, includes two drill holes (WIPP-16 in Chimney C and WIPP-31 in Chimney A), 1:120 scale mapping of the potash mine exposure of Chimney C, and sampling of oil seeps and polyhalite clasts from Chimney C for geochemical analysis (Snyder and Gard, 1982; Palacas et al., 1982; and Brookins et al., 1980). The information and interpretations from these investigations are discussed where pertinent in the following sections.

SUBSURFACE STRUCTURAL CHARACTERISTICS OF THE SUBSIDENCE CHIMNEY

Transition zone—southeast chimney margin. The following section describes the transition from undisturbed, subhorizontal evaporite beds to subsidence breccia along the southeast margin of Chimney C. This transition zone is exposed in mine drift 16 Left, which elsewhere follows a sylvite-rich bed known as the 7th Ore Zone. A geologic map and cross sections of this transition zone are presented in Figures 4 and 5.

The outermost limit of subsidence-related deformation is difficult to discern. Structure contours on the 7th Ore Zone show a regional strike of north 20 degrees west and dip of 1 to 2 degrees to the northeast. The drift penetrating the chimney (drift 16 Left) runs subparallel to the regional strike, and therefore bedding should be horizontal along its trend. However, from approximately 80 to 55 meters (260 to 180 feet) out from the breccia contact, a clay seam at the top of the 7th Ore Zone dips 2½ to 3 degrees to the northwest, toward the chimney. Horizontal control lines were not surveyed out beyond 80 meters, and therefore dip measurements farther out were not made. Either this 2½ to 3 degree dip toward the chimney is the fortuitous result of a pre-subsidence local variation from the regional trend, or it is the outermost expression of subsidence related deformation. The latter interpretation is consistent with the more distinct downwarping of bedding at similar distances out from the chimney observed along the eastern and northern margins, which are discussed in the next section.

Moving from 55 to 45 meters (180 to 150 feet) from the breccia contact, the dip of bedding increases to 8 degrees and the 7th Ore Zone passes below the floor level. Approximately 43 meters (140 feet) out from the breccia contact, a large oil seep occurs along a fault, which has 7 meters (23 feet) of vertical displacement. The down-dropped block is on the northwest side, the side closer to the chimney. The location of the oil seep on the ceiling, mapped in drifts 15 and 16 Left, indicates that the trend of this fault roughly parallels the perimeter of the chimney. The extensive oil staining in the vicinity of the fault makes identification of specific rupture surfaces difficult.

In the region between the fault and the breccia contact, bedding is downwarped, dipping toward the chimney (Figure 6). As one moves northwest toward the chimney, successively higher portions of the stratigraphic section are exposed, including the 8th Ore Zone and marker beds 122, 121, and 120. Also as one moves closer to the chimney, the dip of bedding gradually increases from 17 degrees at the 8th Ore Zone to 29 degrees at marker bed 120. Although this portion of the transition zone is generally characterized by ductilely downwarped beds, it is not completely free of brittle deformation. Approximately 27 meters (89 feet) out from the breccia contact, a small normal fault cuts the section, dipping 65 degrees to the southeast (away from chimney). Similar to the larger fault to the southeast, the trend of this fault roughly parallels the perimeter of the chimney. A maximum dip separation of 0.5 meters (1½ feet) was measured on the upper portion of the north-east wall of drift 16 Left. This displacement decreases markedly along the fault trace, both downward and laterally to the southwest.

The contact between the downwarped beds of the transition zone and the breccia chimney is sharp and is marked by thin (1 cm) seams of clay and halite (Figures 5 and 7). This contact is an undulatory surface, which dips from 45 to 77 degrees to the southeast (away from the chimney). The chimney wall, between the ground surface and the mine exposure, dips 87 degrees to the southeast (Figure 4). The disparity between this general inclination and the local dips measured in the short segment of the contact observed in the mine indicates that the chimney wall is a somewhat irregular surface.

Transition zone—northern and eastern margins. Exposures in the bypass drift and data from drill hole 121 suggest that the transition zone geometry on the northern and eastern margins of Chimney C is different from that observed on the southeast margin. Using the ground surface trace of the chimney wall as a horizontal reference position, note the following observations (Figures 3, 4 and 8). If "distinct, subsidence related downwarping" is defined

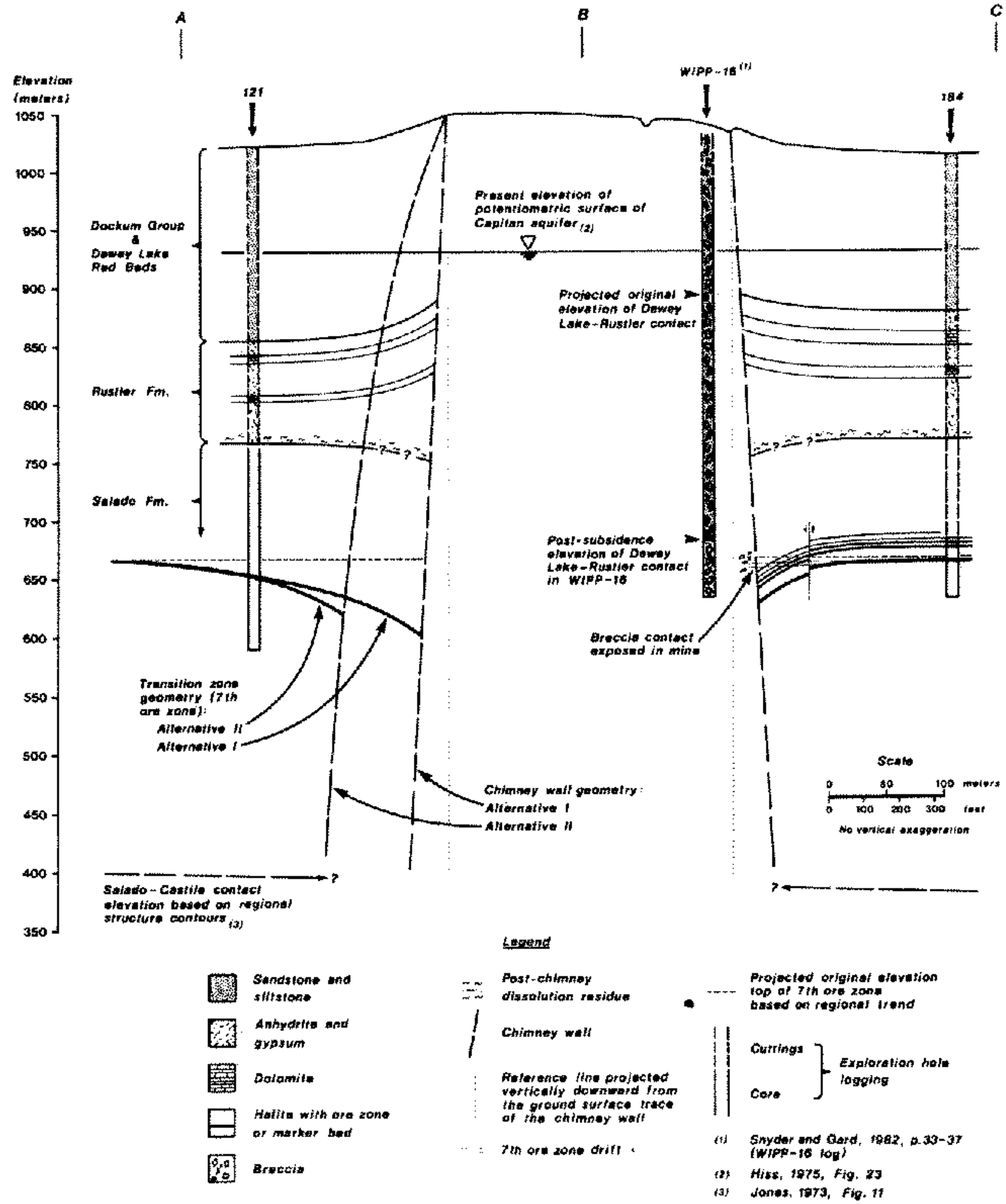

Figure 4. Cross section A-B-C.

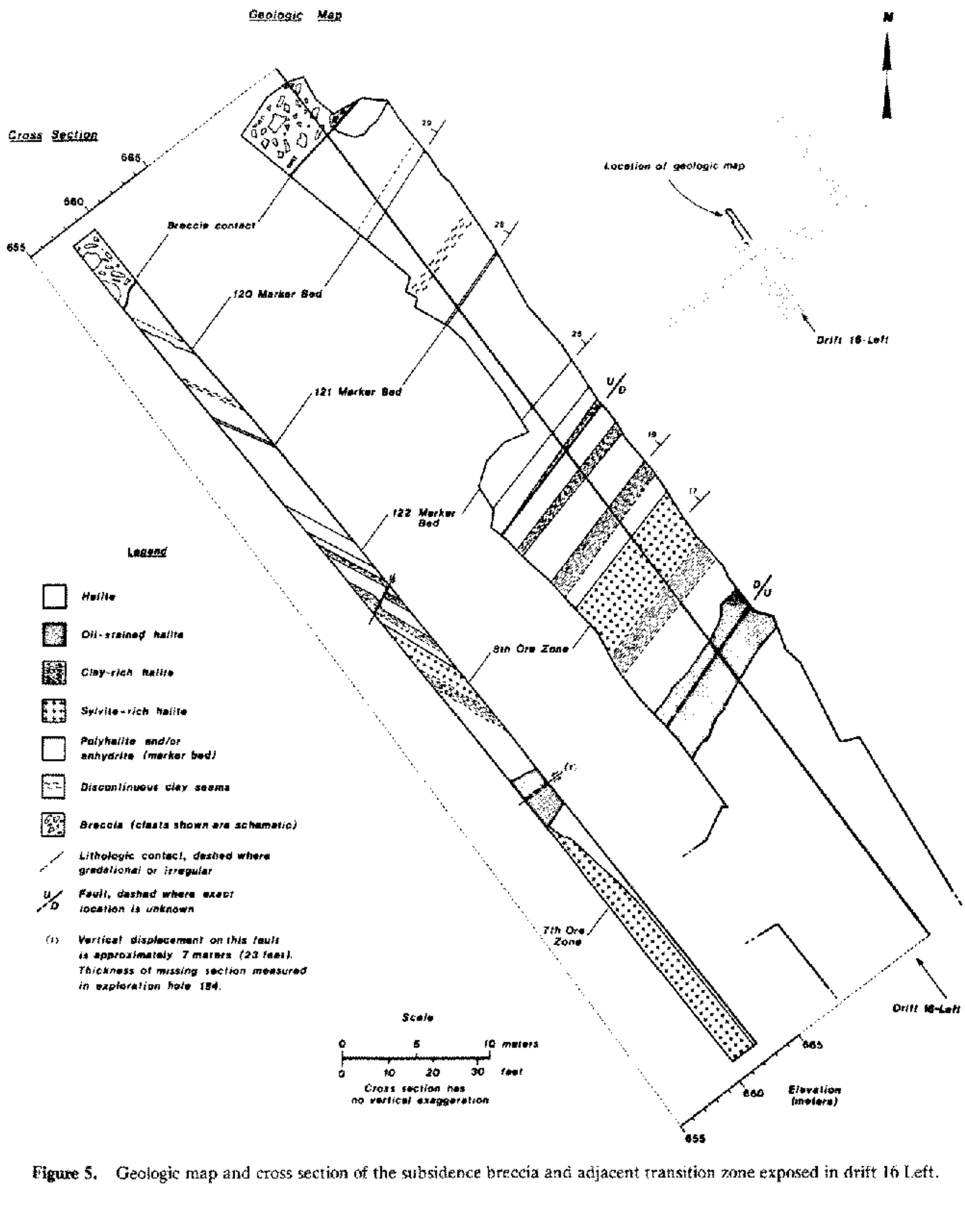

Figure 5. Geologic map and cross section of the subsidence breccia and adjacent transition zone exposed in drift 16 Left.

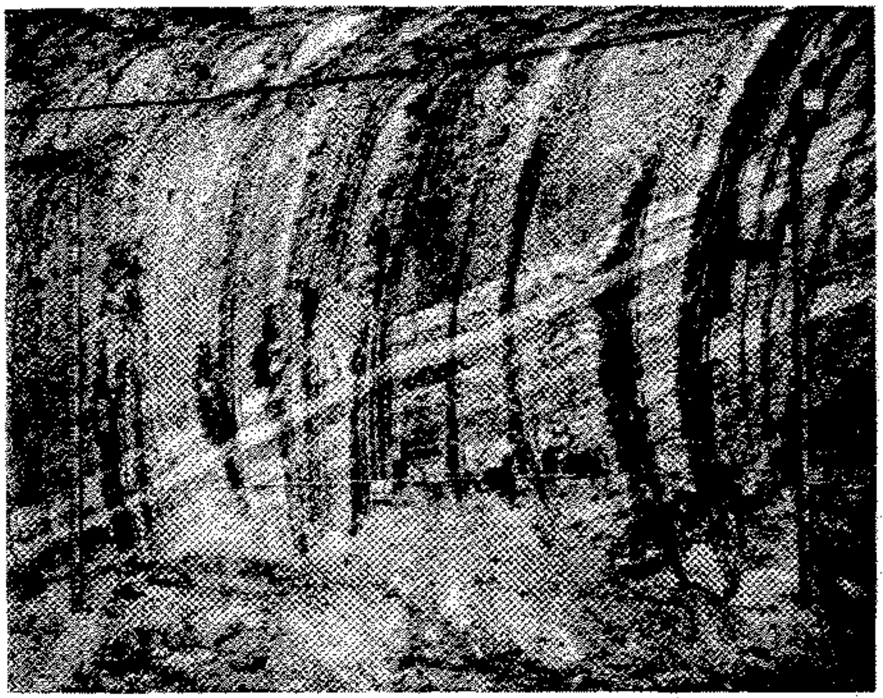

Figure 6. Thin anhydrite beds (122 Marker Bed) dipping toward the chimney, as exposed on the northeast wall of drift 16 Left. Survey rods marked in 1 cm intervals. Arcuate grooves on mine wall were produced by mining machinery.

as bedding that dips toward the chimney at greater than 3 degrees, then on the southeast margin, this threshold is passed approximately 75 meters (245 feet) out from the ground surface trace of the chimney wall (approximately 55 meters out from the chimney wall at the mine level). In contrast, on the eastern chimney margin in the bypass drift at breakthrough 18, approximately 140 meters (460 feet) out from the ground surface trace of the chimney wall, bedding dips toward the chimney at 11 degrees. At breakthrough 15, approximately 130 meters (425 feet) out from the ground surface trace of the chimney wall, bedding dips toward the chimney at 17 degrees. At breakthrough 16, approximately 130 meters out from the ground surface trace of the chimney wall, the elevation of the top of the 7th Ore Zone is 17 meters (56 feet) below its original elevation as predicted by the regional structural trend of this horizon. Finally, at drill hole 121 on the northern margin, approximately 170 meters (560 feet) out from the ground surface trace of the chimney wall, the top of the 7th Ore Zone is 14.5 meters (48 feet) below its original elevation. In summary, all four of these locations on the northern and eastern margins, ranging from 130 to 170 meters (425 to 560 feet) out from the ground surface trace of the chimney wall, show distinct, subsidence related deformation. In contrast, on the southeast margin, there is no distinct, subsidence related deformation beyond 75 meters (245 feet) out from the ground surface trace of the chimney wall.

Although subsurface information on the northern and eastern margins is less extensive than that on the southeastern margin, there is sufficient information to construct two alternative transition zone geometries. The first case assumes that the chimney itself is roughly axisymmetric, such that the chimney walls on all sides are similar to that observed on the southeast margin. In this case, the transition zone would be characterized by a very broad downwarping of beds, extending approximately 250 meters (820 feet) out from the chimney contact at the 7th Ore Zone level (Alternative I on Figures 4 and 8). The second case assumes that the transition zone will have minimal width with the constraint that dips not exceed 30 degrees (the dip observed in drift 16 Left adjacent to the chimney). A transition zone with these constraints would require a strongly asymmetric chimney wall. In this case, the transition is again a zone of downwarped beds. However, the zone would extend only 160 meters (525 feet) out from the chimney contact at the 7th Ore Zone level (Alternative II on Figures 4 and 8).

Note that for either alternative, the inferred transition zone widths (160 and 250 meters) on the northern and eastern margins are three to five times wider than the transition zone width observed on the southeast margin (55 meters). A possible explanation for this contrast between the northern and eastern margins versus the southeast margin is that along the southeast margin a large component of the total strain was localized along the fault,

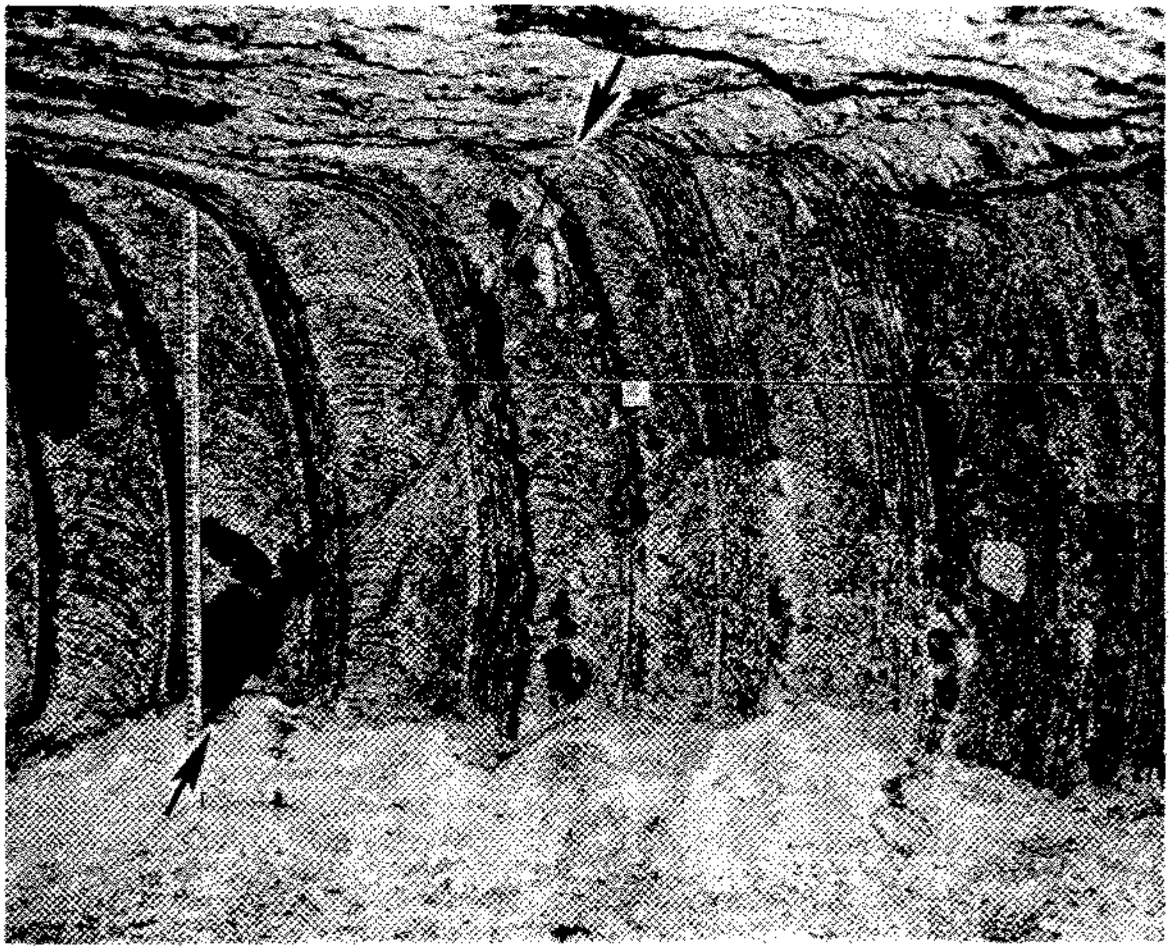

Figure 7. Breccia contact (arrows) as exposed on the southwest wall of drift 16 Left. Thin (1 cm) seams of clay and halite are located along the contact, which separates a bed of massive orange halite to the left, from subsidence breccia, to the right. The breccia comprises clasts of halite, anhydrite, and polyhalite, with a matrix of clear, recrystallized halite. The black patches on this wall are oil stains. Survey rod marked in 1 cm intervals. Arcuate grooves on mine wall were produced by mining machinery.

whereas along the northern and eastern margins, the strain was distributed over a much broader zone.

Subsidence breccia. The present-day physical characteristics of the breccia reflect both the original subsidence process and the movement of fluids through the chimney. The breccia exposed in the mine consists of clasts of halite, anhydrite, and polyhalite in a matrix of clay, clear halite crystals, and interspersed small fragments of anhydrite and polyhydrite. The clasts range in size from one meter blocks to sand size fragments.

Estimates of the vertical displacement of the breccia material can be made by tracing the possible source horizons for the clasts. One large block of anhydrite exposed in the northwest, terminus wall of drift 16 Left is particularly useful because there are only two interbed units in the upper Salado, the 103 and 109 Marker Beds, that have sufficient thickness to be the the source horizon for this block. The vertical distance between the 7th Ore Zone (which drift 16 Left follows) and the 109 Marker Bed in exploration holes in the chimney vicinity ranges from 103 to 119 meters. The 103 Marker Bed is another 37 to 49 meters above the 109 Marker Bed in areas where recent (post-chimney) shallow dissolution has not removed the halite from this uppermost portion of the Salado (Jones et al., 1960, Figure 1). Therefore, the vertical displacement of the material in the mine exposure is between 103 and 168 meters (340 and 550 feet). In drill hole WIPP-16, which is located a few tens of meters in from the chimney wall, the vertical displacement of the subsidence breccia is approximately 210 meters (690 feet) (Figure 4). The difference between the vertical displacement of the breccia observed in the mine versus that observed in WIPP-16 may be as large as 107 meters (350 feet). This difference in vertical displacement at two positions within the chimney illustrates that the downward movement of material was not uniform throughout the chimney.

The structural fabric of a subsidence breccia is a function of the subsidence process. On one extreme, if sub-

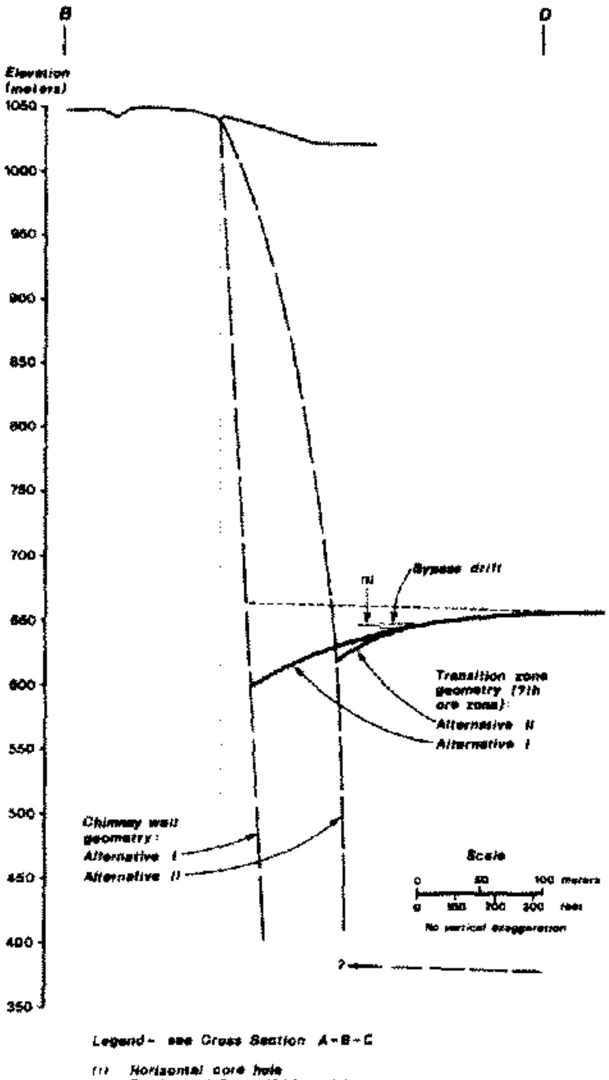

Figure 8. Cross section B-D.

sidence occurs as a sudden, catastrophic collapse, then one might expect that the resulting rubble would consist of a relatively chaotic mass of blocks and fragments. On the other hand, if subsidence occurs as a more gradual lowering and fracturing of the rock mass, then one might expect to see some remnant of an original, more orderly geometry. Therefore, an important textural characteristic of the breccia exposed in the mine is the presence or absence of a preferred orientation of elongate clasts. While a single drift wall provides only a two dimensional view of a given clast, measurements from a second, perpendicular wall yield information about the third dimension. For the breccia exposed in the mine, the aspect ratio and orientation angle was measured on the base map photos for each clast larger than 4 to 5 centimeters. The results of these measurements are presented in Figure 9.

In quantitative terms, there are three basic components to the statistical description of such orientation data: 1) the direction and dip angle of the preferred orientation; 2) the intensity (standard deviation) of the preferred orientation; and 3) the level of statistical significance. The orientation data from the breccia clasts was analyzed using the method outlined by Jizba (1971, pp. 322–333). On the northeast and southwest walls of drift 16 Left, which are perpendicular to the chimney wall, the elongate clasts are preferentially oriented, dipping 60 degrees toward the chimney (standard deviation = 45°). On the northwest drift wall, which is parallel to the chimney wall, the elongate clasts are preferentially oriented, being near horizontal (standard deviation = 40°). Both of these preferred orientations are statistically significant at the 5 percent level, which means there is a 5 percent probability that the measured preferred orientations were produced from an isotropic population. The preferential orientation of clasts, dipping steeply toward the chimney, indicates that larger vertical displacements occurred at locations closer to the central portion of the chimney. This interpretation is consistent with the previous observation that the vertical displacement of material observed in WIPP-16 is larger than that observed in the mine, adjacent to the chimney wall. The existence of a preferred orientation of the breccia clasts may imply that subsidence occurred not as a sudden, catastrophic collapse, but rather, as a continuous or incremental lowering of the rock mass.

Two features resulting from late stage movements that affected both the clasts and the matrix are halite-filled fractures and slickensided surfaces. The halite-filled fractures range in width from a few millimeters to a few centimeters, and they cut across matrix material (Figure 10) as well as a number of clasts. However, nowhere was a single continuous halite vein found that cut both clast and matrix. Slickensided and polished surfaces in apparently random orientations were found in the matrix and along the margins of some clasts. One set of slickensides that cut across both matrix and an adjacent halite-filled fracture indicates that some, if not all, of the slickensides post-date these veins (Figure 11). In fact, the slickensides could be the result of small, mining inducing movements, rather than of late stage subsidence.

Characteristics of both the clasts and the matrix indicate that fluids moved through the chimney during and/or following subsidence. Samples of the matrix clays were analyzed using X-ray diffraction in order to determine the source of this clay material. The clay mineral assemblage consists of illite, chlorite, and a mixed layer chlorite-smectite (Figure 12). This assemblage is characteristic of the Salado Formation (Bodine, 1978, pp. 23–25), which indicates that the matrix material was locally derived by means of dissolution of halite with interspersed clay and subsequent halite recrystallization. The relative proportion of clay to halite is much higher in the breccia matrix

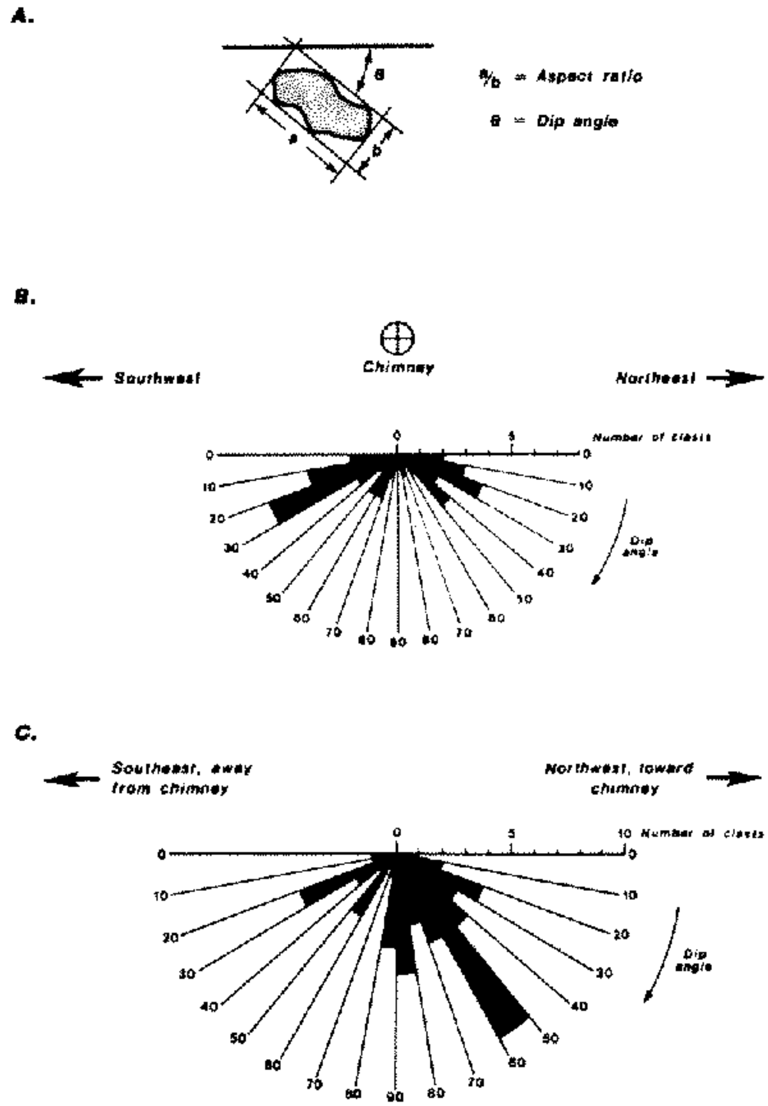

Figure 9. Preferred orientation measurements of elongate (aspect ratio ≥ 1.5) breccia clasts: A) method of measurement; B) orientation of elongate clasts in a plane parallel to the chimney wall (NW, drift terminus wall); C) orientation of elongate clasts in planes perpendicular to the chimney wall (NE and SW drift walls).

than in the average Salado halite, indicating a net loss of halite during this dissolution and recrystallization process.

The breccia clast morphology also reflects this dissolution process. The anhydrite clasts are predominantly highly angular in shape and have abrupt contacts with adjacent matrix material (Figure 13). In contrast, the shapes of the halite clasts range from subangular to well-rounded. The contacts between halite clasts and adjacent matrix material range from fairly sharp to gradational and highly irregular (Figure 14). This contrast in the shape and character of matrix contacts of anhydrite versus halite clasts is consistent with their relative susceptibility to dissolution. In other words, the corners and margins of the halite clasts have been subject to limited dissolution by water moving through the chimney, while the less soluble anhydrite clasts have retained their angular shape and abrupt contacts.

The most striking evidence of fluid movement both within and adjacent to the breccia chimney is the presence of oil. In the transition zone adjacent to the chimney, oil seepage is most notably associated with the fault located 43 meters out from the chimney boundary. Smaller oil seeps are associated with the breccia contact and with some of the nonsalt interbeds within the transition zone. Oil is also found in the breccia matrix. Here, it commonly

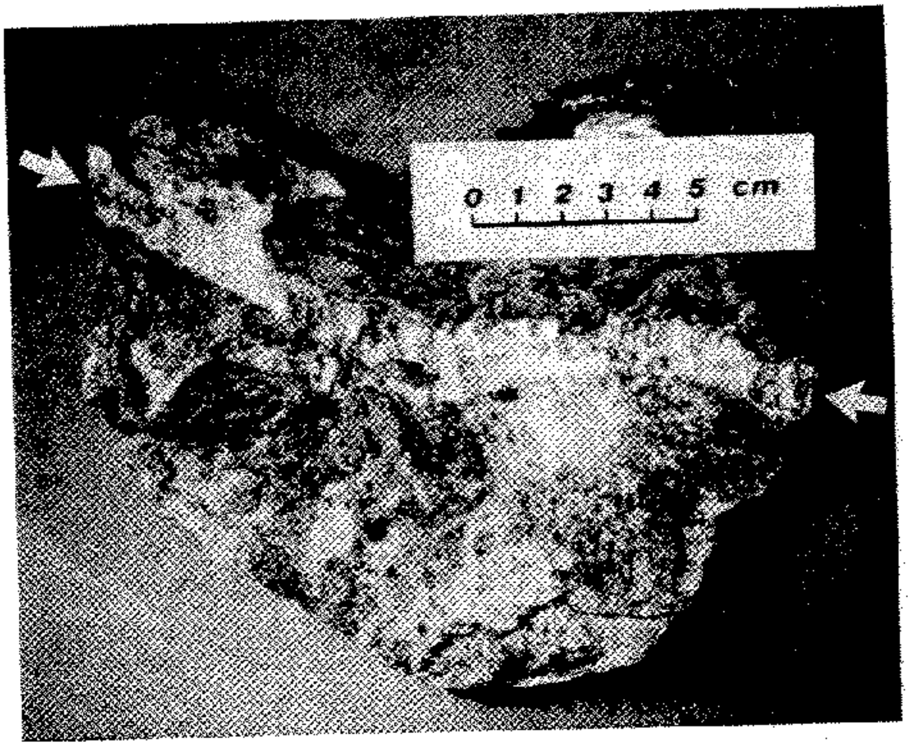

Figure 10. Halite filled fracture (arrows) that transects the breccia matrix.

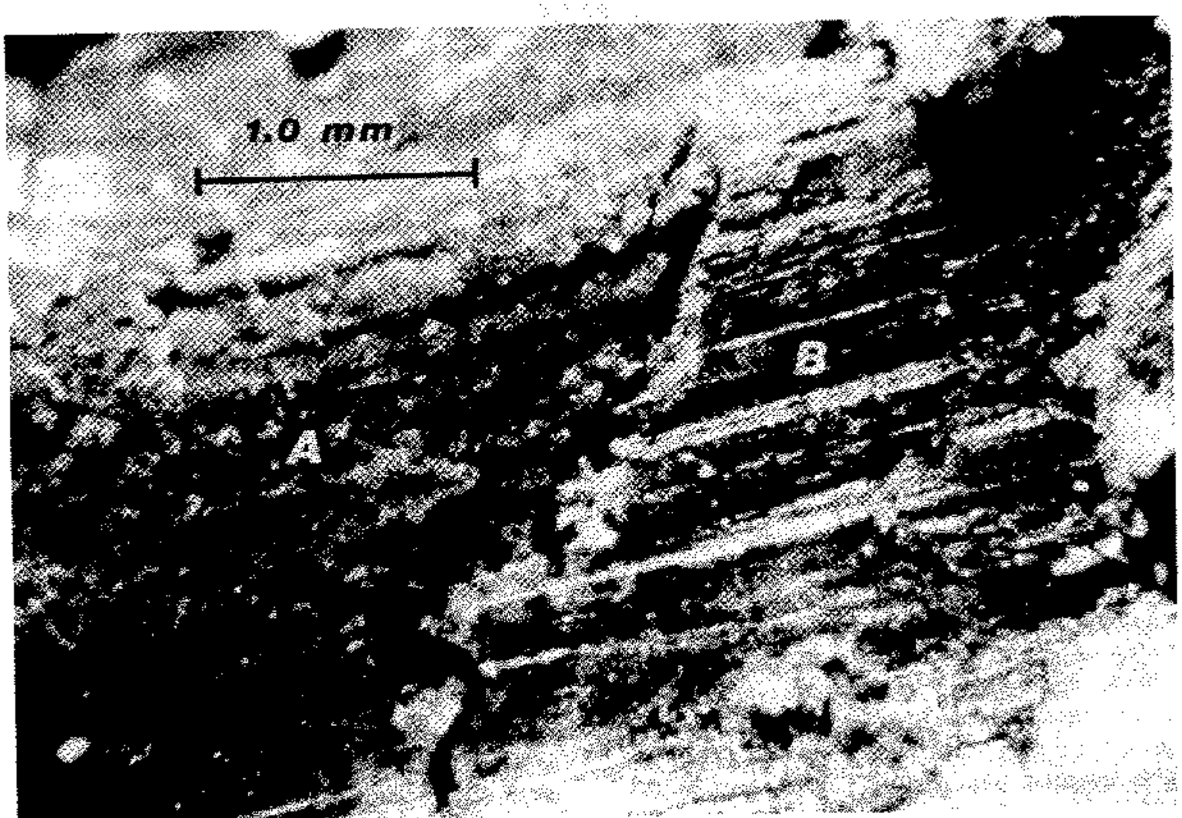

Figure 11. Slickensided surface that transects both matrix material (A) and a halite filled fracture (B).

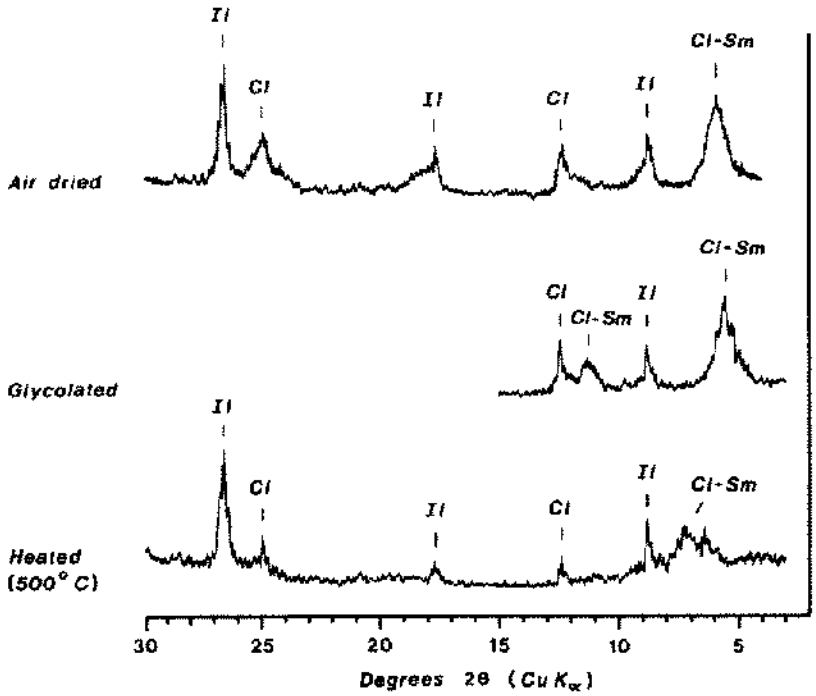

Figure 12. X-ray diffraction traces for clay from the breccia matrix. The clay mineral assemblage consists of illite, chlorite, and a mixed layer chlorite-smectite. This assemblage is characteristic of the clays that are interspersed within the halite of the Salado Formation.

occurs in small (1 mm), cubic cavities within the halite crystals and along crystal boundaries (Figure 15). Oil also occurs in small quantities within the clay portion of the matrix. Geochemical analyses by the U.S. Geological Survey indicate that the source of the oil is the Yates Formation, which abuts and partially overlies the Capital Reef (Figure 2) (Palacas et al., 1982). This oil has, in effect, documented the upward movement of fluids through the chimney.

Two other factors that must be taken into account when evaluating fluid movement through the chimney. The first is the obvious, but easily overlooked, fact that although the halite clasts have been subject to dissolution, a significant proportion of these highly soluble clasts is still present. The second factor is that potassium-argon dating of a sample from a polyhalite breccia clast yielded an age of 198 ± 7 million years before present (Brookins et al., 1980, p. 481). This date indicates that this polyhalite clast has not been subject to extensive, recent recrystallization. These two factors indicate that fluids moving through this portion of the chimney were either limited in quantity or close to saturation with respect to the evaporite minerals.

HYDROGEOLOGIC FACTORS IN THE DEVELOPMENT OF CHIMNEY C

Hydrogeology of the Capitan Reef. The aquifer responsible for the dissolution that generated Chimney C is the Capitan Reef (Figures 1 and 2). The hydrogeology of the Capitan aquifer in the area that includes Chimney C has been studied by Gail (1974) and Hiss (1975). Lithologically, the Capitan aquifer consists of dolomite, dolomitic limestone, and limestone of the back-reef, reef, and reef-talus facies. The width of the Capitan aquifer varies from 16 to 23 kilometers (10 to 14 miles). The thickness is quite variable, ranging from as much as 700 meters (2,300 feet) at local carbonate mounds to as little as a few hundred meters where submarine canyons deeply incise the reef (Hiss, 1975, pp. 74, 197). These canyons play an important hydrologic role because the filling material has a significantly lower hydraulic conductivity than the adjacent and underlying reef. Therefore, some of the more deeply incised canyons cause significant local reductions in transmissivity and restrict water flow through the aquifer.

The present porosity and permeability of the Capitan aquifer are largely a product of tectonic and nontectonic fracturing along with the preferential dissolution of limestone by groundwater (Hiss, 1975, pp. 65–66, 169–175). During the late Permian, prior to burial of the reef by evaporites, the reef complex was repeatedly exposed to subaerial processes such as desiccation and leaching during low stands of sea level. Also during these periods of low sea level, ground water moving through the reef under water table conditions contributed to the development of solution porosity. Fissuring parallel to the reef trend caused by seaward slumping of sediment and differential

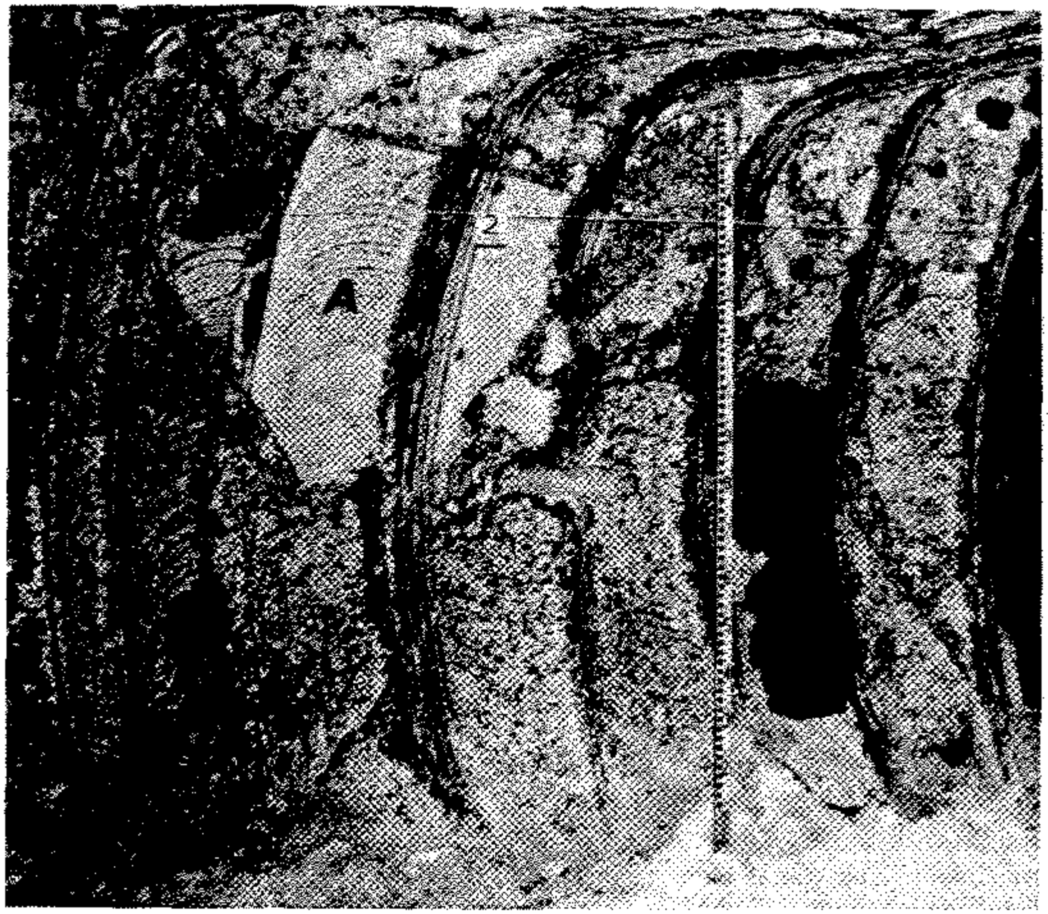

Figure 13. Typical anhydrite clast (A), characterized by its angular shape and abrupt contact with the adjacent matrix. Survey rod marked in 1 cm intervals. Arcuate grooves in mine wall were produced by mining machinery.

settlements caused by water loss during low stands of sea level produced fractures and crevices. During the late Pliocene and early Pleistocene, faulting and uplift of the Guadalupe Mountains on the west side of the Delaware Basin increased fracture porosity in the reef. This uplift also created the topographic relief necessary to drive the present regional ground water flow system. Flow through this system has contributed to further development of solution porosity. Ground water flow, under water table conditions, from the Guadalupe Mountains to the Pecos River at Carlsbad (Figure 1) has dissolved large amounts of limestone, creating a highly porous stretch of aquifer, which includes the famous Carlsbad Caverns.

Gail (1974) studied the distribution of pore space in the Capitan aquifer to the east of Carlsbad (including the Chimney C area). Along this stretch of aquifer, higher porosities tend to be located in the basinward and upper portions of the aquifer. Both Gail (1974, p. 48) and Hiss (1975, pp. 176–177) have reported the existence of relatively thin zones of anomalously high porosity in the limestones near the forereef edge. However, these zones of anomalously high porosity are not thought to be true caverns such as the caves found in the reef to the southwest of Carlsbad. Rather, they are limestone with either original highly porous textures or secondary "honeycomb" solution structures.

The Capitan aquifer flow system has evolved through two distinct stages (Hiss, 1975, pp. 289–292) that are important to the development of Chimney C. The first stage began with the uplift of the Guadalupe Mountains on the west side of the basin during the late Pliocene and early Pleistocene. This uplift initiated the development of the present regional flow system in the Delaware Basin. Water entering the Capitan aquifer in the Guadalupe Mountains flowed northeastward and then eastward along the reef. At the northeast corner of the basin, this water joined water flowing northward in the reef along the eastern margin of the basin and discharged to the east-

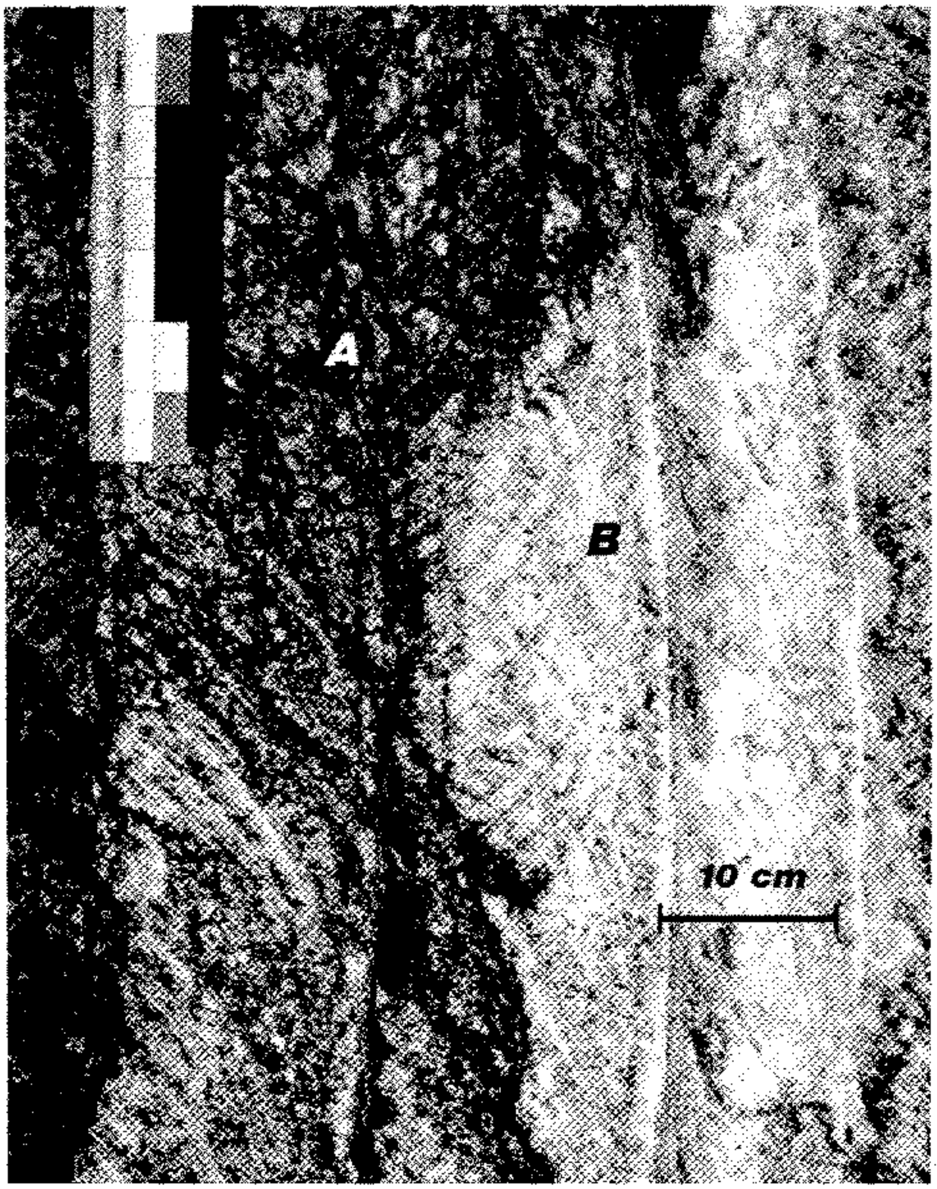

Figure 14. Typical halite clast (B) characterized by its irregular, gradational contact with the adjacent matrix (A).

northeast via the shelf aquifers. The quantity of flow along the northern branch of this system was somewhat smaller than that along the eastern branch because of the restrictive effect of a series of deep submarine canyons that incise the reef in the vicinity of the Eddy-Lea County lines (Hiss, 1975, pp. 181–197). The initial stage of the flow system was significantly altered in the early or middle Pleistocene when the down-cutting Pecos River breached the confining evaporite beds and established hydraulic communication with the Capitan aquifer. This new discharge point in the system increased flow from the Guadalupe Mountains to the Pecos River at Carlsbad. Discharge from the Capitan aquifer into the Pecos at Carlsbad also significantly lowered the potentiometric surface and decreased flow in the Capitan aquifer to the east of Carlsbad, including the Chimney C area.

Relationship between Chimney C and the Capitan aquifer. Because of the absence of subsurface data at elevations below the middle of the Salado Formation in the immediate vicinity of Chimney C, neither the exact position of the chimney relative to the reef margin nor the precise nature of the dissolution zone can be determined. Studies of the thickness and distribution of the Capitan aquifer in this area (Gail, 1974, Hiss, 1975) indicate that the chimney does not directly overlie the reef but, rather, lies just south of the basinward margin (Figure 16). How-

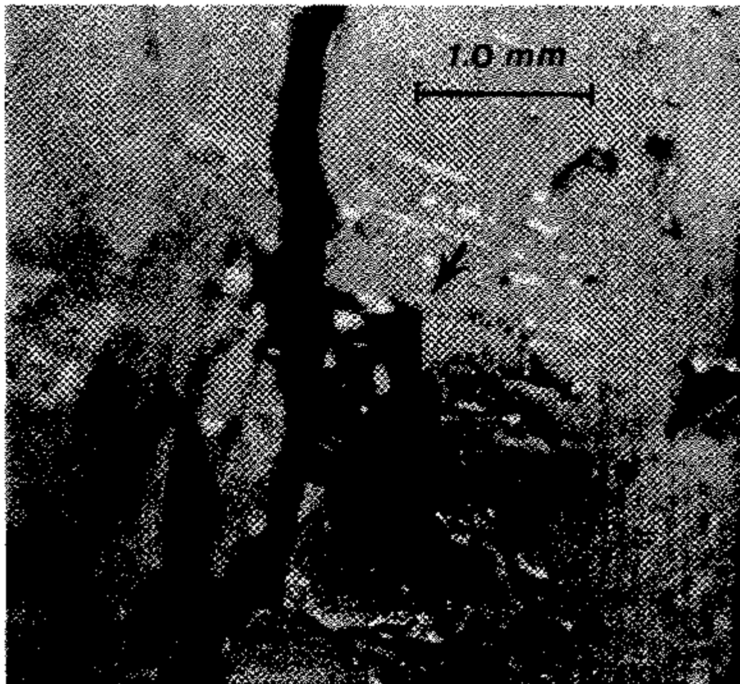

Figure 15. Small pocket of oil in a cubic cavity (arrow) within a halite crystal from the subsidence breccia matrix.

ever, drill hole information in the region is not of sufficient density to preclude the possibility that the chimney may, in fact, overlie a portion of the reef.

If the reef does extend beneath the chimney, then the dissolution-subsidence model proposed by Snyder and Gard (1982, pp. 61–65) for Chimney A may apply. The major components of the Snyder and Gard model are as follows:

1. Ground water moving through the Capitan formed a large cavern by the same limestone dissolution mechanisms that formed the numerous caves in the Capitan to the southwest of Carlsbad.
2. Sudden, catastrophic collapse of this cavern formed a collapse chimney, which penetrated up into the Salado salt. The presence of "jumbling of material in the collapse chimney" and "a great deal of intermingling of various strata" in WIPP-31 and WIPP-16 are cited as the evidence for the catastrophic nature of collapse.
3. The sudden collapse forced water, unsaturated with respect to halite, up into the salt, dissolving some halite prior to draining back down into the reef. After collapse reached the ground surface, the resulting sinkhole served as a catchment basin and surface water percolated downward, dissolving nearly all of the remaining Salado halite. Over 300 meters (1,000 feet) of salt was removed by dissolution in Chimney A.

If the reef does not extend beneath Chimney C, then the model proposed by Snyder and Gard would not apply. However, even if the reef does extend beneath the chimney, this model still has a number of shortcomings:

1. Many of the cave systems in the Capitan reef to the southwest of Carlsbad have developed along well defined levels, such as the three distinct levels of Carlsbad Caverns. This type of development is characteristic of dissolution just below the water table in the shallow phreatic zone (Swinnerton, 1932 and Thrailkill, 1968). The presence of water table conditions has been cited by many investigators as an important parameter in the development of cave systems in the Capitan southwest of Carlsbad (Black, 1954; Motts, 1959; Moore, 1960; Dunham, 1972; and Gale, 1977). An alternative mode of cavern development involving dissolution by sulphuric acid rich vadose waters has also been proposed by Jagnow (1977, 1979). Neither of these cavern forming mechanisms, however, could have operated in the Chimney A–C vicinity during the late to middle Pleistocene. While water table conditions existed to the southwest of Carlsbad, to the east, the reef passed below the evaporite section and was under confined, artesian conditions. Therefore, the cavern forming mechanisms that have created numerous caves to the southwest of Carlsbad can not have been operating in the Chimney A–C area. This

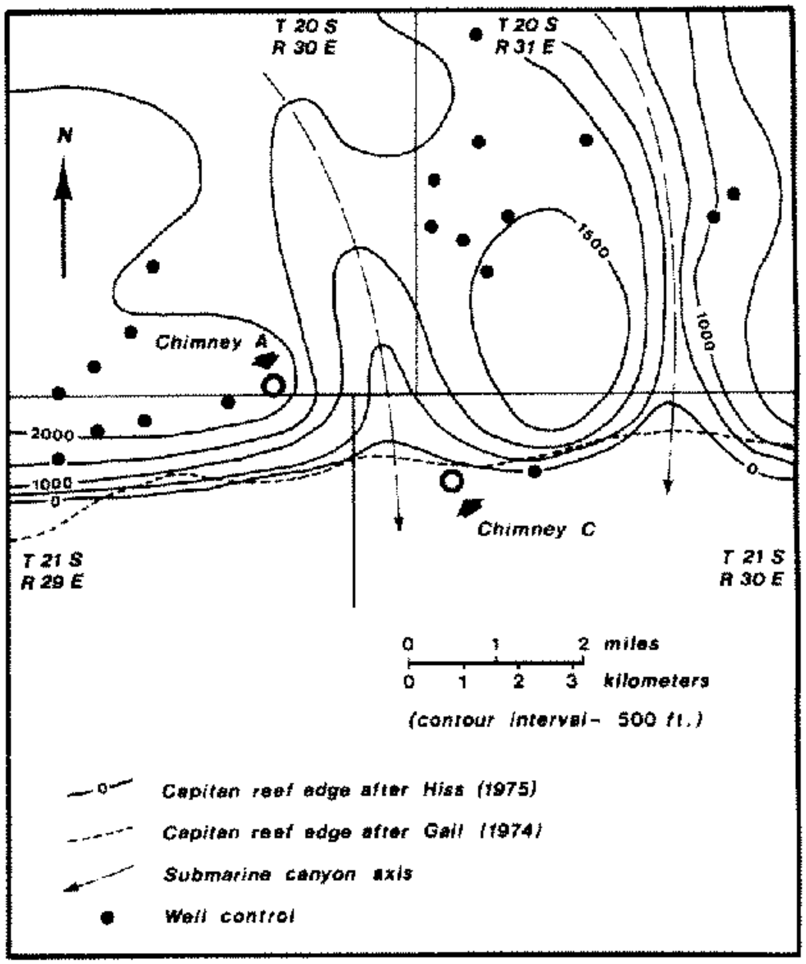

Figure 16. Isopach map showing the thickness and distribution of the Capitan aquifer in the Chimney A-C area, adapted from Hiss (1975). Note that Chimney C lies to the south of the reef edge.

is not to say that limited dissolution of the limestone in this area has not occurred. As mentioned earlier, both Gail (1974) and Hiss (1975) have noted the presence of thin zones of anomalously high porosity, which may represent secondary "honeycomb" solution structures. Such limited dissolution might even be sufficient to produce minor, local subsidence. However, as noted by Hiss, no large caverns have been found to the east of Carlsbad. Therefore, it appears unlikely that dissolution of the Capitan could produce the type of large, catastrophic collapse proposed by Snyder and Gard in the Chimney A-C area.

2. Salt dissolution in the Snyder and Gard model is essentially a secondary process that occurs after collapse, with significant amounts of salt being removed by water percolating downward from the surface depression. A possible problem with this interpretation is that the Capitan aquifer was under artesian conditions at the time of subsidence and water may well have been moving upward through the chimney rather than downward. The present potentiometric surface of the Capitan aquifer in the Chimney A-C area is 930 meters (3,050 feet) above sea level, well above the elevation of the dolomite aquifers in the Rustler Formation (Figure 4). The present potentiometric surface in the Rustler aquifers in the Chimney A-C area is approximately 950 meters (3,115 feet) above sea level (Mercer, 1983, Figure 17). Prior to the withdrawal of large amounts of water from the Capitan aquifer for secondary oil recovery operations and for agriculture, the Capitan potentiometric surface in the Chimney A-C area was 15 to 30 meters higher (Hiss, 1975, Figure 22). Prior to the middle Pleistocene breaching of the Capitan aquifer's confining beds by the Pecos River at Carlsbad, the potentiometric surface in the Chimney A-C area was even higher, possibly significantly higher

than the potentiometric surface in the Rustler aquifers. Although the exact relative elevations of the potentiometric surfaces in the Capitan and Rustler aquifers cannot be determined for the early to middle Pleistocene when the subsidence chimneys formed, the present and projected past hydrologic conditions indicate that most likely groundwater flowed upward through the chimney during and/or following subsidence. Upward movement of fluids is also evidenced by the trace amounts of oil from lower horizons, which are present in both Chimneys A and C.

3. Finally, evidence for the catastrophic nature of subsidence in Chimneys A and C is not conclusive. Catastrophic collapse produced by underground nuclear detonations does not necessarily cause extensive intermingling of strata from various horizons (Boardman et al., 1964, p. 114). The intermingling of strata from different horizons is indicative of mixing that accompanies differential movements within the chimney. Large, catastrophic collapse is not required in order to produce such differential movements. Nonuniform salt dissolution during the course of chimney development can readily produce differential movements. Also, in the uppermost portion of the chimney, some mixing is accomplished as shallow rock units slump into the sinkhole and are carried downward by subsequent subsidence.

Taking into account both the hydrology of the Capitan aquifer and the structural characteristics observed in Chimney C, the following alternative, conceptual model for the dissolution-subsidence process is proposed:

1. Hydrologic access to the highly soluble Salado salt was provided by fracturing of the anhydrite that lies between the Capitan aquifer and the Salado. Such fracturing, generated by a mechanism such as differential compaction of the reef margin area by sediment loading during the late Permian and Mesozoic, may have preceded the late Cenozoic establishment of the Capitan aquifer flow system. Alternatively, such fracturing may have been an integral, early stage component of a dissolution process in which limited amounts of anhydrite and/or limestone were dissolved with associated subsidence.
2. Dissolution at the base and within the lower portion of the Salado salt produced continuous or incremental subsidence in the overlying strata. As the chimney developed, the rate of salt dissolution was not uniform throughout the entire basal area. This nonuniform dissolution caused differential subsidence and local mixing of material from various strata.
3. Near the ground surface, occasional slumping of the uppermost rock units into the surface depression and subsequent subsidence contributed to the mixing observed in the upper portion of the chimney.
4. Fluid potential in the Capitan aquifer may have been sufficient to drive groundwater upward through the chimney, causing limited dissolution of the subsiding halite. Along with this water, trace amounts of oil also moved upward through the chimney.
5. This dissolution-subsidence process occurred in the early or middle Pleistocene, prior to the breaching of the Capitan aquifer by the Pecos River. This breach significantly reduced groundwater flow through the Capitan in the Chimney C vicinity, effectively terminating dissolution activity. If dissolution activity had not been terminated at this time, the process may well have continued, producing a much larger subsidence structure, similar to the large elongate structural depressions above the reef front along the eastern margin of the basin, which have been described by Maley and Huffington (1953), Hiss (1975) and Anderson (1978, 1981).

CONCLUSIONS

The potash mine exposure of Chimney C has provided a unique opportunity to observe directly some of the subsurface structural characteristics of a subsidence chimney in bedded salt. The steep-walled chimney contains downdropped, brecciated, evaporite and post-evaporite strata. Adjacent to the chimney is a broad transition zone containing both faulted and ductilely downwarped beds. The dissolution-induced morphology of halite clasts and the breccia matrix composition indicate that groundwater flowed through the chimney during and/or following subsidence. The hydrologic conditions in the Capitan aquifer and the presence of trace amounts of oil from lower horizons suggest that the direction of flow was upward.

Because of the absence of drill hole extending to the root of Chimney C, neither its exact position relative to the Capitan Reef, nor the precise nature of the dissolution zone can be determined. Snyder and Gard (1982) have proposed that Chimneys A and C resulted from catastrophic collapse into a large cavern produced by limestone dissolution in the underlying Capitan Reef. Considering the subsurface structural characteristics of Chimney C, the hydrologic conditions in the Capitan aquifer, and the possibility that the Capitan does not extend directly beneath Chimney C, an alternative model is that these chimneys were produced by salt dissolution at the base and within the lowermost portion of the Salado Formation. This salt dissolution caused incremental subsidence rather than catastrophic collapse of the overlying strata.

Both of these subsidence chimneys formed as the result of dissolution associated with the Capitan aquifer system. Because the Capitan aquifer does not extend below the proposed Waste Isolation Pilot Plant site (Figure 1), subsidence structures resulting from dissolution along the Capitan cannot adversely affect the site. However, the possibility of dissolution-subsidence associated with groundwater flow in the Bell Canyon Formation or within fractured Castile anhydrites, which do underlie the WIPP site, is another issue (Griswold, 1977; Anderson, 1978, 1981, 1982; and Lambert, 1983). For the WIPP site and for the more general problem of selecting and evaluating waste repository sites in bedded salts, the results of this research illustrate the importance of an integrated consideration of both the structural and hydrologic components of the dissolution-subsidence process.

ACKNOWLEDGMENTS

I thank Jim Walls, vice-president and general manager of the Mississippi Chemical Corporation, for providing access to the mine exposure of Chimney C and to the exploration hole logs for the Chimney C vicinity. The mine mapping was carried out with assistance from my wife and colleague, Tarin Smith Davies. Critical reviews of this manuscript by my Stanford University colleagues, Jean Bahr, Tarin Davies, Steve Martel, and Dorothy Merritts, are greatly appreciated. This research was supported by Geological Society of America Research Grant No. 2606-80.

REFERENCES

Adams, J. E. 1944. Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 28(11): 1,596–1,625.

Anderson, R. Y. 1978. Deep-dissolution of salt, northern Delaware Basin, New Mexico: Report to Sandia Laboratories, 106 pp.

Anderson, R. Y. 1981. Deep-seated salt dissolution in the Delaware Basin, Texas and New Mexico: New Mexico Geological Society, Special Publication No. 10, pp. 133–145.

Anderson, R. Y. 1982. Deformation-dissolution potential of bedded salt, Waste Isolation Pilot Plant site, Delaware Basin, New Mexico, *in* Lutze, W., ed., Fifth international symposium on the scientific basis of nuclear waste management: Elsevier Scientific Publishing Company, pp. 449–458.

Anderson, R. Y., W. E. Dean, D. W. Kirkland and H. I. Snider. 1972. Permian Castile varved evaporite sequence, west Texas and New Mexico. Geological Society of America Bulle tin, v.83:59–86.

Anderson, R. Y., K. K. Kietzke and D. J. Rhodes. 1978. Development of dissolution breccias northern Delaware Basin, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 159, pp. 46–52.

Bachman, G. O. 1976. Cenozoic deposits of southeastern New Mexico and outline of the history of evaporite dissolution: U.S. Geological Survey, Journal of Research, v. 4(2): 135–149.

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

Baumgardner, R. W., A. D. Hoadley and A. G. Goldstein. 1982. Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 114, 38 pp.

Black, T. H. 1954. The origin and development of Carlsbad Caverns: New Mexico Geological Society, Fifth Field Conference Guidebook, pp. 136–142.

Boardman, C. R., D. D. Rabb and R. D. McArthur. 1964. Contained nuclear detonations in four media, geological factors in cavity and chimney formation: Proceedings of the 3rd Plowshare Symposium, pp. 109–126.

Bodine, M. W. 1978. Clay-mineral assemblages from drill core of Ochoan evaporites, Eddy County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 159, pp. 21–31.

Brookins, D. G., J. K. Register, M. E. Register and S. J. Lambert. 1980. Long-term term stability of evaporite minerals: geochronological evidence, *in* Northrup, C. J., ed., Scientific basis for nuclear waste management: Plenum Press, pp. 479–486.

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

Christiansen, E. A. 1967. Collapse structures near Saskatoon, Saskatchewan, Canada: Canadian Journal of Earth Sciences, v. 4:757–767.

Christiansen, E. A. 1971. Geology of the Crater Lake Collapse Structure in southeastern Saskatchewan: Canadian Journal of Earth Sciences, v. 8:1,505–1,513.

DeMille, G., J. R. Shouldice and H. W. Nelson. 1964. Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geological Society of America Bull., v. 75: 307–316.

Dunham, R. J. 1972. Capitan Reef, New Mexico and Texas: facts and questions to aid interpretation and group discussion: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication 72-14.

Frye, J. C. and S. L. Schoff. 1942. Deep seated solution in the Meade Basin and vicinity, Kansas and Oklahoma: American Geophysical Union Transactions, v. 23:35–39.

Gail, G. J. 1974. Subsurface geology of Capitan aquifer northeast of Carlsbad, Eddy and Lea Counties, New Mexico: Unpublished Masters thesis, The University of New Mexico, Albuquerque, New Mexico, 61 pp.

Gale, B. T. 1977. Geologic development of the Carlsbad Caverns, *in* Hayes, P. T., Geology of the Carlsbad Caverns East Quadrangle, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-98.

Gendzwill, D. J. and Z. Hajnal. 1971. Seismic investigation of the Crater Lake Collapse Structure in southeastern Saskatchewan: Canadian Journal of Earth Sciences, v. 8:1,514–1,524.

Griswold, G. B. 1977. Site selection and evaluation studies of the Waste Isolation Pilot Plant (WIPP), Los Medanos, Eddy County, New Mexico: SAND-77-0846, 48 pp.

Gustavson, T. C., M. W. Wiley, C. R. Handford, R. J. Finley, S. P. Dutton, R. W. Baumgardner, K. A. McGillis and W. W. Simplins. 1980. Geology and geohydrology of the Palo Duro Basin, Texas Panhandle—A report on the progress of Nuclear Waste Isolation Feasibility Studies (1979): The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 80-7, 99 pp.

Hayes, P. T. 1964. Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey Professional Paper 446, 67 pp.

Hiss, W. L. 1975. Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and west Texas: Unpublished PhD thesis, University of Colorado, Boulder, Colorado, 396 pp.

Jagnow, D. H. 1977. Geologic factors influencing speleogenesis in the Capitan reef complex, New Mexico and Texas: Unpublished Masters thesis, The University of New Mexico, Albuquerque, New Mexico, 203 pp.

Jagnow, D. H. 1979. Cavern development in the Guadalupe Mountains: Cave Research Foundation, 55 pp.

Jizba, Z. V. 1971. Mathematical analysis of grain orientation, *in* Carver, R. E., ed., Procedures in sedimentary petrology: New York, Wiley-Interscience, pp. 313–333.

Johnson, W. D. 1901. The High Plains and their utilization: U.S. Geological Survey, 21st Annual Report, Part IV, pp. 609–732.

Jones, C. L. 1973. Salt deposits of Los Medanos area, Eddy and Lea Counties, New Mexico: U.S. Geological Survey Open-File Report 4339-7, 67 pp.

Jones, C. L., C. G. Bowles and K. G. Bell. 1960. Experimental drill hole logging in potash deposits of the Carlsbad District, New Mexico: U.S. Geological Survey Open-File Report 60-84, 22 pp.

Jones, C. L. and B. M. Badsen. 1968. Evaporite geology of Fifth Ore Zone, Carlsbad District, southeastern New Mexico: U.S. Geological Survey Bulletin 1252-B, 21 pp.

King, P. B. 1942. Permian of west Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 26(4):535–763.

King, P. B. 1948. Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey Professional Paper 215, 183 pp.

Lambert, S. J. 1983. Dissolution of evaporites in and around the Delaware Basin, southeastern New Mexico and west Texas: SAND 82-0461, 93 pp.

Landes, K. K. 1945. Mackinac breccia, *in* Landes, K. K., Ehlers, G. M., and Stanley, G. M., Geology of the Mackinac Straits region: Michigan Geological Survey, Publication 44, pp. 123–154.

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

Meissner, F. F. 1972. Cyclic sedimentation in Middle Permian strata of the Permian Basin, west Texas and New Mexico, *in* Elam, J. G. and Chuber, Stewart, eds., Cyclic sedimentation in the Permian Basin (2nd ed): West Texas Geological Society, Publication 72-18, pp. 203–232.

Mercer, J. W. 1983. Geohydrology of the proposed Waste Isolation Pilot Plant site, Los Medanos area, southeastern New Mexico: U.S. Geological Survey, Water-Resources Investigations Report 83-4016, 113 pp.

Moore, G. W. 1960. Geology of Carlsbad Caverns, New Mexico, *in* Guidebook to Carlsbad Caverns National Park: National Speleological Society Guide Book Series No. 1, pp. 10–17.

Motts, W. S. 1959. Age of the Carlsbad Caverns and related caves in southeastern New Mexico (abs.): Geological Society of America Bulletin, v. 70, no. 12, pt. 2, p. 1,737.

Palacas, J. G., R. P. Snyder, Baysinger, J. P. and C. N. Threlkeld. 1982. Geochemical analysis of potash mine seep oils, collapsed breccia pipe oil shows and selected crude oils, Eddy County, New Mexico: U.S. Geological Survey Open-File Report 82-421, 40 pp.

Powers, D. W., S. J. Lambert, S. E. Shaffer, L. R. Hill and W. D. Weart, eds. 1978. Geological report, Waste Isolation Pilot Plant (WIPP) site, southeastern New Mexico—volumes I and II: SAND 78-1596, 1,224 pp.

Snyder, R. P. and L. M. Gard. 1982. Evaluation of breccia pipes in southeastern New Mexico and their relation to the Waste Isolation Pilot Plant (WIPP) site: U.S. Geological Survey Open-File Report 82-968, 73 pp.

Swinnerton, A. C. 1932. Origin of limestone caverns: Geological Society of America Bulletin, v. 43:663–694.

Thrailkill, J. 1968. Chemical and hydrologic factors in the excavation of limestone caves: Geological Society of America Bulletin, v. 79:19–46.

Vine, J. D. 1960. Recent domal structures in southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 44(12):1,903–1,911.