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GEOTECHNICAL STUDIES ASSOCIATED WITH DECOMMISSIONING THE STRATEGIC PETROLEUM RESERVE FACILITY AT WEEKS ISLAND, LOUISIANA: A CASE HISTORY

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ABSTRACT

The first sinkhole at the Weeks Island Strategic Petroleum Reserve (SPR) site was initially observed in May 1992. Concurrent with the increasing dissolution of salt over the mined oil storage area below, it has gradually enlarged and deepened. Beginning in 1994 and continuing to the present, the injection of saturated brine directly into the sinkhole throat some 76 m beneath the ground surface essentially arrested further dissolution, providing time to make adequate preparation for the safe and orderly transfer of crude oil to other storage facilities. This mitigation measure marked the first time that such a control procedure has been used in salt mining; previously all control has been achieved by either in-mine or from-surface grouting. A second and much smaller sinkhole was noticed in early 1995 on an opposite edge of the SPR mine, but with a very similar geological and mine mechanics setting. Both sinkholes occur where the edges of upper 152 m and lower 213 m mined storage levels are nearly vertically aligned. Such coincidence maximizes the tensional stress development, leading to fracturing in the salt. This cracking takes 20 or more years to develop. The cracks then become flow paths for brine incursion, which after time progress into the mined openings. Undersaturated ground water gradually enlarges the cracks in salt through dissolution, leading to eventual collapse of the overlying sand to form sinkholes. Other geologic conditions may also be secondary factors in controlling both mining extent and sinkhole location.

KEYWORDS

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Geology, Creep, Subsidence, Sinkholes, Case History, Salt Dissolution, Salt Domes

INTRODUCTION

MASTER

The U. S. Department of Energy has established one of the Strategic Petroleum Reserve's (SPR) facilities in a massive salt dome at Weeks Island, Louisiana, in a former room and pillar two level mine in the salt. A sinkhole measuring 11 m across and 9 m deep was first observed in the alluvium overlying the salt dome in May 1992 (Sinkhole #1). However, based on initial surface appearance and subsequent reverse extrapolation of growth rates it was thought to be already about a year old. A second and much smaller sinkhole was identified in early 1995 (Sinkhole #2), nearly three years later. Their positions directly over the edges of the oil storage chamber has caused apprehension. The association of sinkholes with mines is well established. This occurrence suggested that groundwater influx was causing salt dissolution at shallow depth, and an associated collapse of soil at the surface. Leaks of groundwater into other salt mines in Louisiana and elsewhere have led

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to flooding and eventual abandonment (Coates et al., 1981). Consequently, much attention has been and continues to be given to the characterization and mitigation of these sinkholes. This paper summarizes current engineering geologic concepts of the sinkhole development at Weeks Island, and briefly describes diagnostic methods and mitigation efforts (Bauer et al., 1994).

LOCATION, OCCURRENCE, AND CHARACTERISTICS

The Weeks Island salt dome is located 23 km south of New Iberia, Louisiana, and is the central dome in the Five Islands chain, along with Belle Isle, and Cote Blanche, Avery, and Jefferson Islands. All five have been mined because of their near-surface salt, and their logistical advantage near the Gulf of Mexico and the Intra-coastal Waterway. Belle Isle and Jefferson Island are now closed to mining because of deliberate and inadvertent flooding, respectively.

The sediment cover at Weeks Island consists of deltaic alluvium of the ancestral Mississippi River and is about 56 m thick over the top of salt, which is 30 m below sea level at the sinkhole. The water table conforms generally with sea level over the dome but fluctuates somewhat with topography and frequent torrential rains. Sampling of subsurface water shows brine is unsaturated at distances greater than 4-5 feet above the top of salt.

The Weeks Island mine was originally opened in 1902 and salt was extracted commercially until 1977, at which time Morton Salt developed a new mine immediately adjacent to the northwest while the older workings were converted for oil storage and has contained 73 million barrels of crude oil since 1981. Minor leaks of water had been noted at various times during the 75 years of active mining, but in-mine grouting controlled inflow (Acres, 1987).

Sinkhole #1 occurred over the southern perimeter of the upper level of the two-level SPR mine (Figure 1). The nearly vertical sidewalls in the surface sediments surrounding the sinkhole were readily explained geologically as being typical of the Pleistocene loess mantle which caps the island.

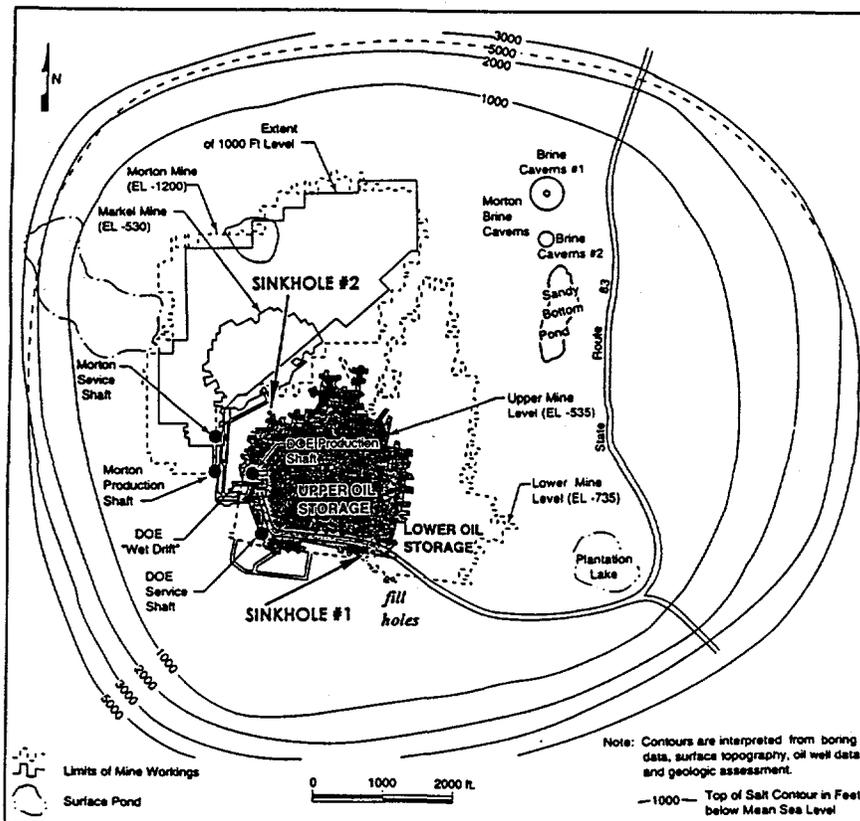


Figure 1 Weeks Island Louisiana salt dome, showing location of the two sinkholes, two fill holes, mined areas, and contours of the top the salt stock.

Because sinkholes may occur as a result of natural processes (Autin, 1984), the relatively small size of Sinkhole #1 and lack of diagnostic evidence linking it to the SPR mine caused little concern at first. The location near both the edge of the dome and anomalous features in the salt stock, including a salt valley, suggested an entirely natural origin was possible (Neal, et al., 1993), although Martinez (1992) insisted from the very beginning that mine-induced factors were likely involved. During the original mining, black salt, gas blowouts, and minor brine seeps were noted beneath the vicinity where the sinkhole developed, and Magorian (1987) later mapped a shear zone just south of the mine boundary. The latter effectively may have influenced the southerly extent of the original mining. Also sinkholes have formed at other mines in domal salt (Neal, 1994).

A watch and wait position was adopted. But by mid-1993 it was apparent that the sinkhole was deepening and monitoring data suggested that the brine influx into the mine was increasing. The evidence for increasing dissolution caused sufficient concern by late 1993 to initiate more detailed diagnostic study. In addition, engineering planning addressed actions to decrease the risk of continued oil storage and to relocate the inventory to other sites. Safety concerns also necessitated filling the sinkhole with sand as its depth of more than 12 m and location 15 m from the main access road had become hazardous.

As plans to move oil were being formulated in early 1995, Sinkhole #2 was identified on the northwest boundary of the mine in a similar geologic and stress-field environment that was seen Sinkhole #1. While the Sinkhole #2 was only 4.3 m wide and 3 m deep, its occurrence confirmed the progressive development of the processes causing them and the necessity of expedient mitigation.

SINKHOLE DIAGNOSTICS

A combination of geophysics, drilling, and hydrologic studies were undertaken in 1994 to provide definitive information needed to establish appropriate action and schedules. Salt mechanics modeling and solutioning processes were studied analytically to complement the field data. The variety of geophysical methods were employed to gain diagnostic information as follows:

Seismic reflection profiling identified an apparent deflection in the reflector near the sinkhole center that at first was thought to be a hydrologic cone of depression (Neal and Myers, 1995). Later detailed study showed this reflector was more apt to represent a structural or material discontinuity. But the perceived anomaly led the way to obtaining detailed data that showed a very flat piezometric surface near sea level within highly permeable sediments of the ancestral Mississippi River delta. *Cross-well seismic tomography* was conducted across the throat of the sinkhole through four wells drilled in quadrants outside the sinkhole. The velocity tomograms showed a distinct low-velocity zone typical of saturated sediments below the surface sinkhole but failed to reveal detailed throat geometry. The borehole locations in competent high-velocity salt confirmed an essentially vertical sinkhole structure at depth (Harding, 1994). *Self potential surveys* that showed hydrologic streaming potential at another mine sinkhole locality were attempted at Weeks Island. Although apparent anomalies were measured near the sinkhole, their interpretation was uncertain, but thought to show downward hydrologic flow along a planar sheet. *Gas mapping* of trace hydrogen and methane was conducted to test connectivity with the SPR mine or with anomalies within the salt. Although some anomalous areas around the sinkhole were observed, they did not reveal definitive diagnostic information (LSU, 1994).

Slant hole drilling directly into and below the sinkhole provided the most direct confirmation of dissolution geometry as evidenced by the drilling of boreholes BH-7A and BH-9 (Figure 2). *Slant hole BH-9*, adjacent to the sinkhole, was drilled using a high-angle approach directly over the top of the subsurface extension of the surface sinkhole expression. It extended below the top-of-salt elevation encountered in the tomography holes. This wellbore provided the opportunity in July 1994 for injection of rhodamine dye directly into the throat of the sinkhole at -80 m depth, in addition to the fluorescein placed in the surface sinkhole in March 1993. The dye, if detected in the fill hole sump, would provide unequivocal evidence of hydrologic connection with the mine. Dye dispersion calculations predicted that it could take a year or more to reach the sampling point (Linn and Hinkebein, 1994), possibly explaining the lack of detection of the introduced dye.

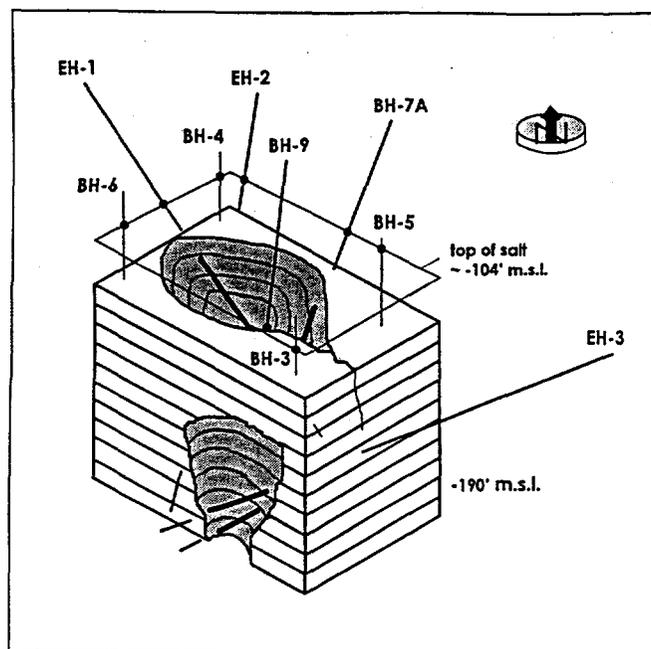


Figure 2 Diagrammatic representation of exploratory drilling and geometry of Sinkhole #1 throat. Boreholes BH-3, 4, 5, and 6 were drilled for crosswell seismic tomography; slantholes BH-7A and 9 were drilled for throat definition. EH-1, 2, and 3 further defined the throat and provided decisive information regarding grouting potential. Accentuated portions of boreholes define throat penetrations.

Slanthole BH-7A started at 60° inclination and was aimed at the sinkhole throat within the salt at depth. It penetrated the top-of-salt at the normal depth of ~ 56 m and then continued on through salt into a major sand-filled void at least 22 m deep and 2 m wide. A 3-D hydrologic flowmeter was installed in the sinkhole throat and operated for two weeks (Bauer et al., 1994; Ballard, 1995a, b). The data indicated essentially vertical flow down the throat, at 0.3 m/day. A 3 cm/day downward movement of the flowmeter itself also indicated that sediment was moving down the throat, presumably in response to dissolution of salt by undersaturated groundwater at some point below. This borehole also enabled the injection of more dye.

Slanthole EH-1, at 90° to BH-7A, transected a 5.5 m sand-filled void at about the same depth as BH-7A, further defining a cross-section elongated in the direction of the mine boundary. *Slanthole EH-2* between EH-1 and 7A did not enter the void, even after several offset attempts. *Slanthole EH-3* intersected the void from the opposite (east) side, with lateral void dimensions of ~ 5 m and >3 m at two different depths. The drilling indicated a very irregularly shaped dissolution feature, but with essentially vertical orientation directly below the sinkhole. Sand samples recovered from the sinkhole throat in EH-1 and BH-7A showed concentrations of rhodamine dye. Even though throat sand samples recovered from EH-3 and an EH-3 sidetrack showed no dye saturation, the throat was determined from hydrologic flow data to be hydraulically connected during attempts to place a flowmeter in EH-3 some 27.5 m below a flowmeter in BH-9.

Once the geometry of the sand filled void was identified, with direct measurement of downward flow of water, the suggestion was made by Diamond and Mills (1994) to *feed saturated brine* directly into the throat through Borehole 7A. Beginning in August 1994 and continuing at present, 3-6 gallons per minute are being gravity fed into the throat 22 m below the top of salt. Some of the injected brine flows down into the mine, the rest flows up and out of the throat as evidenced by the upward flow recorded in the flowmeter. The upward flowing brine displaces the unsaturated brine of the local ground water at the top of salt. The encouraging result was that subsidence at the sinkhole was arrested, and virtually no additional downward movement of fill sand has been measured. The local hydraulic head is continuously monitored and maintained by varying the rate of brine inflow. In addition, growth of the apparent groundwater depression at the sinkhole is no longer observed. The brine introduction evidently has stopped the dissolution of salt. Whether this could be a longer-term fix was problematic. As a result, a decision was then made to relocate the SPR oil inventory at an early date and by the safest means.

The construction of a freezewayall to isolate Sinkhole #1 and arrest the flow of ground water into the sinkhole began in mid 1995 and was completed by the end of the year. This involved the construction of 56 wells in three circumferential rings around the sinkhole which were used for circulating the refrigerant. Testing of the freezewayall was completed in late 1995 and provided reasonable confirmation that a hydrologic barrier had been achieved.

CAUSAL FACTORS AND ANALYSES

Unlike other mines where leaks can be observed underground, SPR must rely on indirect evidence such as changes in the oil/brine or oil/air interfaces, or changed isotopic composition of the contained brine. These diagnostics are complicated by contained brine ($\sim 750,000$ barrels or $1.2 \times 10^5 \text{ m}^3$), about one percent of the total volume, and by salt creep closure, which gradually reduces the storage volume by one-fifth of one percent per year ($\sim 160,000$ barrels; $2.5 \times 10^4 \text{ m}^3$). These are very large amounts of water relative to the few gallons per minute leaks that could explain the sinkhole.

Water inflow into the mine was fortunately suggested by increasing amounts of brine which were measurable in the fill hole sump. In early 1994 the inflow trend increased from one to nearly three gallons per minute. This increase was noticed almost immediately, when continued deepening of the sinkhole began occurring at a rate of about 1.5 m^3 per day. This suggested that dissolution was ongoing. There was reasonable correlation with the amount of increasing brine that was observed in the fill holes and the increasing sinkhole volume.

Brine hydrochemistry is frequently analyzed in salt mines to distinguish meteoric water from connate water. At Weeks Island a decided change in isotopic composition was evident in comparing 1993 water from the fillhole sump with that obtained in late 1991, about the same time postulated for the sinkhole origin (Knauth, 1994). Earlier isotope trends suggested that a smaller leak may have existed as early as 1987.

Magorian (Acres, 1987) mapped a shear zone just south of the mine edge, based on external dome structure, surface topography, and gas outbursts experienced during mining. Recent coring in salt during construction of a freezewayall around Sinkhole #1 also showed shearing and fracturing at depths near -61 m . Magorian's mapping also showed that both sinkholes are situated in the center of troughs or valleys having relief of 15 m in the top of salt (**Figure 3**). These troughs may reflect boundaries of differential motion of separate segments in the salt stock.

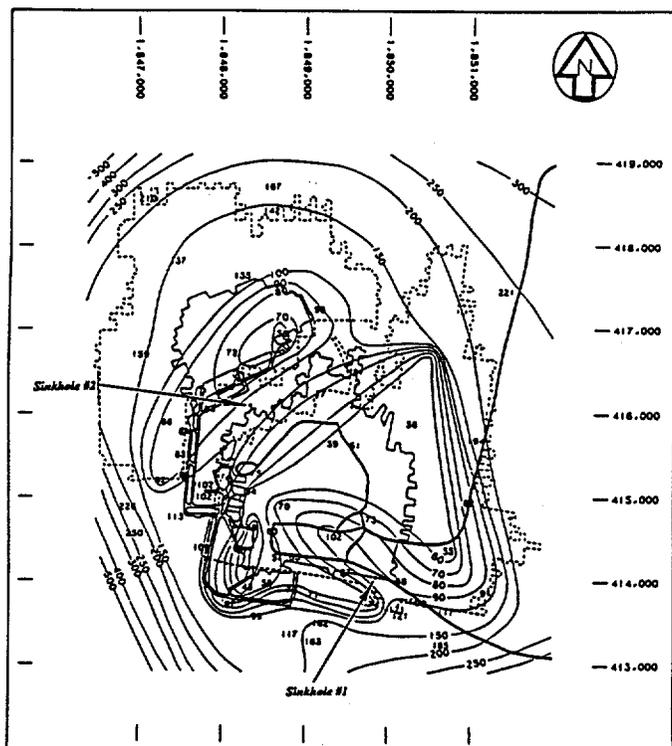


Figure 3 Top of salt contours with detail over mined openings. Sinkholes #1 and #2 are located in apparent troughs, possibly separating individual lobes or spines (from Acres, 1987; SAND87-7111).

Anomalous zones, including shear zones, occur frequently in Gulf Coast salt stocks, often reflecting differential movement of separate lobes or spines of salt and incorporating a variety of distinctive (anomalous) salt features and/or geologic conditions (Kupfer, 1990; Neal, et al., 1993). Kupfer believes that three or more of these features should occur in combination to be labeled anomalous zones. At Weeks Island the geology has several distinctions at and near the sinkhole(s) that may indicate it is near an anomalous zone, even though exploratory and freezeway drilling reported few impurities that would directly suggest anomalous salt, (Lock, personal communication, 1995).

The southern mine boundary was apparently influenced by the nearby intersection of anomalous salt features, specifically gas outbursts, brine seeps, and black salt. The occurrence of linear gas outbursts experienced during mining does not by itself support an anomalous zone designation according to Kupfer (Neal, 1993), but it appears that their orientation is a non-random process. Thoms and Gehle (1995) indicated a zone of black salt, an anomalous feature, was mapped during mining near the location of the sinkhole. Brine seeps were also mapped near the subsequent sinkhole location, and although at the time judged not meteoric in character, the brine chemistry showed some deviation from normal connate analyses (Martinez, 1995).

Thoms and Gehle (1995) suggested that an association of factors may be responsible for sinkhole formation at Weeks Island. In addition to the very localized mining-induced stresses adjacent to underground openings that create a *disturbed rock zone*, there are additional influences that may work together to localize the initial sinkhole on the southern edge of the mine. *Horizontal extension zones* result from subsidence over the mine and extend beyond the mine perimeter, leading to dilatancy and eventual fracturing over time. *Anomalous zones* are often more prevalent near the edges of salt stocks and are one element of *susceptible salt zones*, which may include a variety of local geologic conditions. Thoms and Gehle (1995) believe the association and combination of these elements at Weeks Island probably produced *leak prone areas* and thus the sinkhole(s). The deviations from "normal" geologic conditions noted above seem to support the notion of *susceptible salt zones* influencing sinkhole development at the initial location. However, no sinkholes have been observed along the east boundary of the mine (also a zone of gas outbursts, etc.) suggesting susceptible salt zones are only secondary factors in sinkhole development. The primary causal factor is most likely the mechanics associated with mine subsidence.

Vertical displacement data has been collected at Weeks Island for the past 13 years (The measurements are made relative to a location off the dome). These data have been analyzed such that subsidence rates for given time periods can be deduced (Figure 4). The greatest subsidence rates (negative displacement rates) are consistently concentrated in areas above the DOE facility and the Morton facility to the north west. Positive vertical displacements (uplift) are observed in areas away from the subsurface mines and are indicative of upward movement of the dome of a few millimeters a year. This displacement rate array predominantly reflects downward motion of the salt in response to creep closure of the mine.

Finite element modeling by Ehgartner (1993) using two dimensional (2D) simulations showed that the areas near the mine perimeter would be in tension and that fractures in the top of salt could have formed as early as 1970 (Figures 5, 6). The cracks initiate at the top of salt and grow toward the mine because of bending and stretching of the salt as a result of creep closure. Such cracks could be exposed to undersaturated ground water and gradually enlarge at the same time the crack was extending toward the mined openings. These analyses established a reasonable mechanism for eventual incursion of groundwater. They are also validated by survey data showing subsidence over the mine, which is in close agreement with values from the modeling. This mechanism was verified using three dimensional (3-D) simulations as developed by Hoffman (1994). His analyses predicted tensile zones similar to Ehgartner's 2-D model, particularly over the vertically-aligned edges of the upper and lower mine levels. In addition, using a criterion developed from previous rock mechanics tests on Weeks Island salt by Ehgartner (1994), a dilatant zone (Figure 7) was predicted to extend from the top of salt to the edges of the mine. The model shows a 28 year progression of deformation, if the mine was left unfilled. Dilatancy is characterized by increased porosity, hence permeability, caused by microfracturing. Thus the time-dependent mine subsidence results in tensile and dilatant zones that potentially explain the groundwater incursion into the mine. With both sinkholes occurring almost exactly over aligned levels of the mine, the mechanisms explained above are credible, independent of the presence of anomalous geologic features.

Weeks Island Subsidence Rate (ft/yr), 3/94-2/96

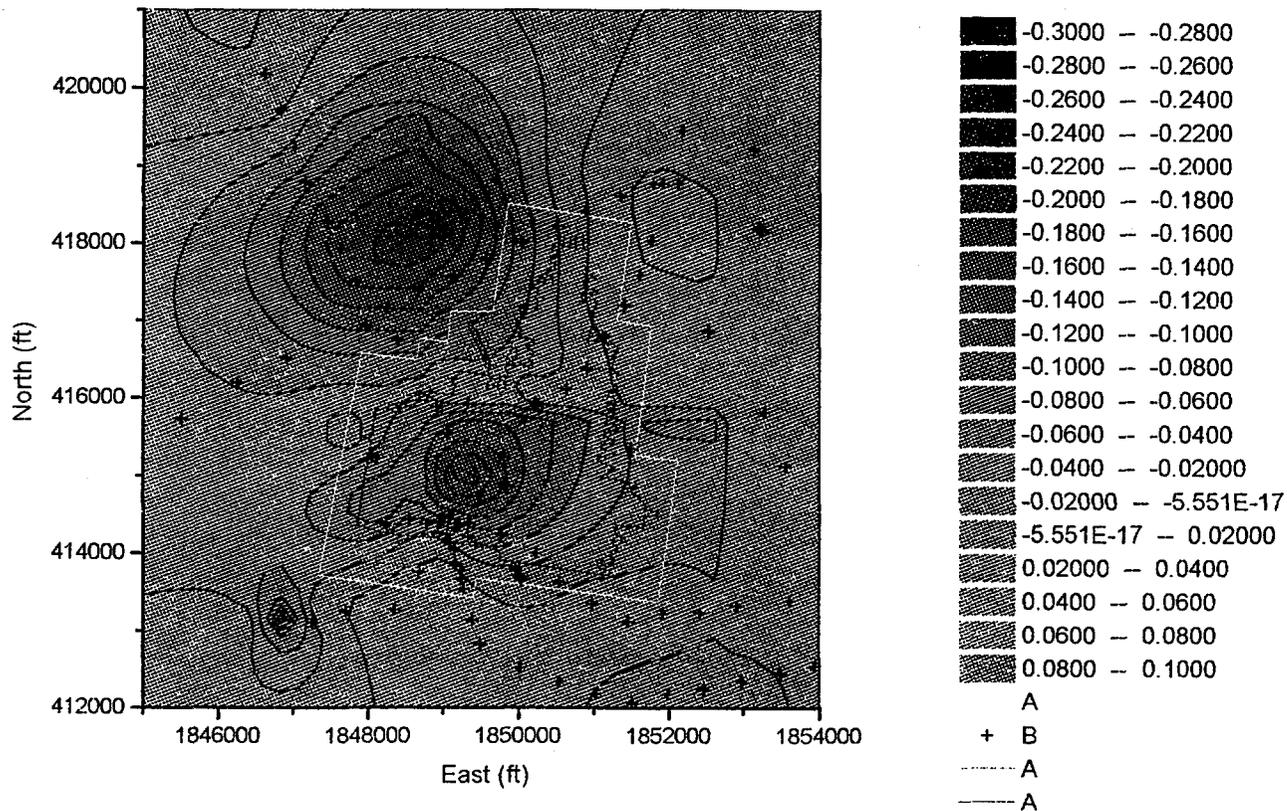


Figure 4 Subsidence rate contour map at Weeks Island for the 3/94-2/96 time period. The greatest rates are concentrated in areas over the DOE facility (yellow outline) and the Morton facility (adjacent and to the northwest).

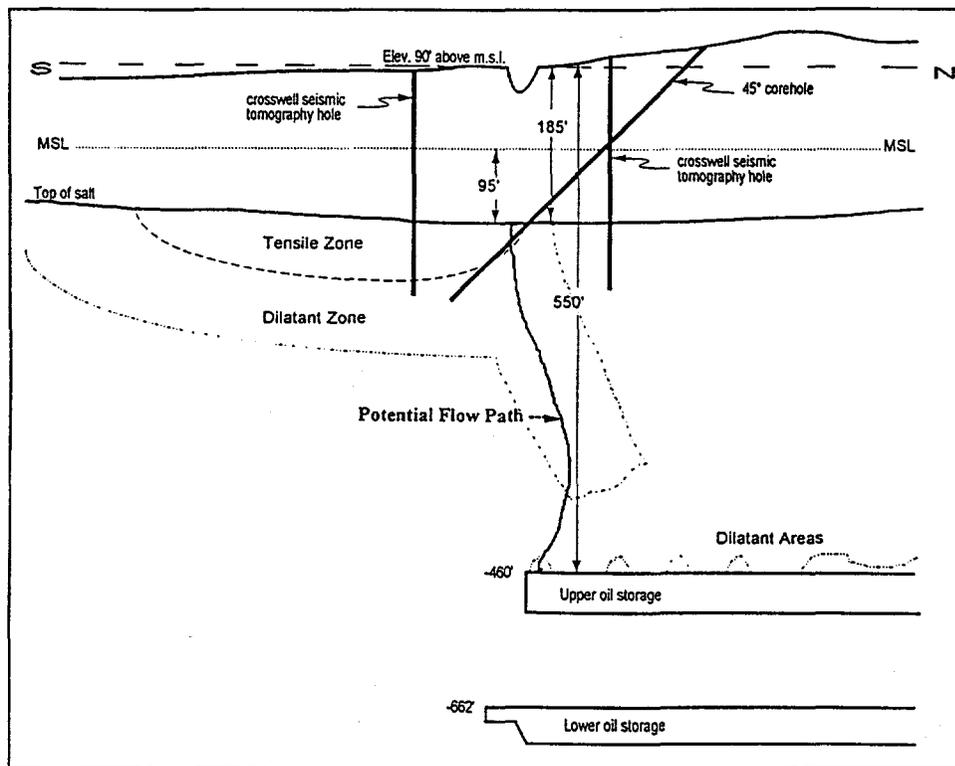


Figure 5 Geomechanical modeling by Ehgartner (1993) and Hoffman (1994) showed mechanism for crack development in tension that would develop over mined openings after a number of years, and progressing through weakened dilatant zones. Largely as a result of this modeling, crosswell tomography was conducted and angled boreholes were planned to intersect such features.

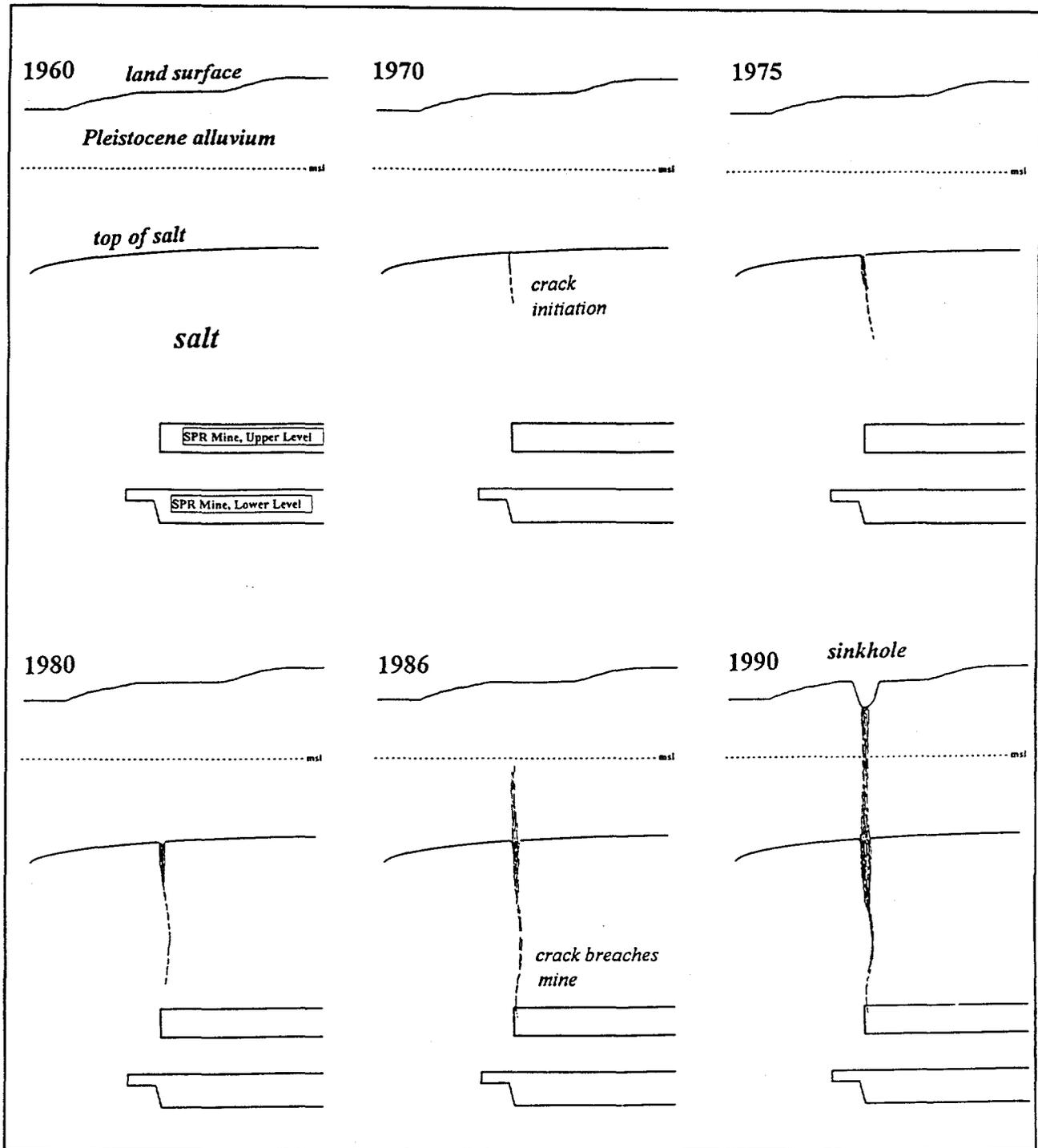


Figure 6 Conceptual development of Weeks Island, Louisiana, sinkholes, based on geomechanical modeling and presumed hydrologic connection with undersaturated groundwater. Sinkhole #1 was first observed in 1992, but likely took years to develop. Progressive enlargement of the dissolution channel was initiated following formation of tension crack(s) ca. 1970, but not manifesting as a sinkhole until about 1990-91. Sinkhole #2 was first observed in early 1995.

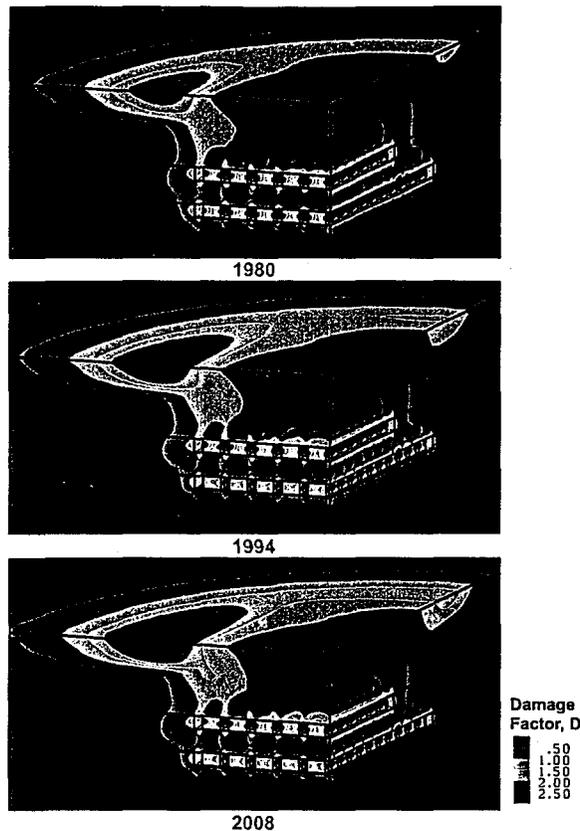


Figure 7 Dilatant damage at simulation times corresponding to: 1980 (oil fill), 1994, and 2008. Damage is indicated where $D > 1.0$.

SUMMARY AND CONCLUSIONS

In summary, the analyses indicate that a stress state has developed at the Weeks Island storage facility, resulting from the presence of the mined openings, that is conducive to subsidence and crack growth in the salt. No cap rock exists atop the salt at Weeks Island, only unconsolidated sand and gravel. These sediments likely fell into developing cracks during their formation and growth. The progressive dissolution/void filling/collapse mechanism stopped its way to the surface culminating in sinkhole formation. The analyses completed indicate that the processes of subsidence and fracturing caused by continuing salt creep around the mined openings will continue until the mine is refilled with brine. This work justifies the following conclusions:

- The limits of the original mining at Weeks Island were controlled partly by geological factors, including a variety of anomalous features: gas outbursts, shear zones, sand, oil seeps, black salt, and brine incursions. Mining terminated along a planar zone characterized by gas outbursts, black salt, and brine seeps.
- Salt creep has resulted in subsidence localized to regions above the underground mines; the dome continues to rise.
- The two level mine produced a stress state conducive to bending and stretching as a result of salt creep toward areas of lower stress. The bending and stretching likely caused the cracks to extend from the top of salt to the mine in the vicinity of Sinkholes #1 and #2. The apparent crack development is in regions over locations where the edges of the two levels of the mine are vertically aligned.
- Once established, brine flow through fracture pathways eventually produce dissolution voids on the top of salt. Sediment collapse into such voids produced the sinkholes.
- Sinkhole #1 has been temporarily stabilized by injecting saturated brine into the solution throat. Construction of a freezeway around the sinkhole has provided added hydrologic control during drawdown and relocation of the oil. Sinkhole #2 is sufficiently small and stable, as of late 1996, to warrant no additional study or mitigation efforts.

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