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ORIGIN, DIAGNOSTICS, AND MITIGATION OF A SALT DISSOLUTION SINKHOLE  
 AT THE U. S. STRATEGIC PETROLEUM RESERVE STORAGE SITE,  
 WEEKS ISLAND, LOUISIANA

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ABSTRACT

A sinkhole was first observed in May 1992 over the edge of the two-level former salt mine that was converted for oil storage by the U. S. Strategic Petroleum Reserve (SPR). Diagnostic studies that included geophysical, geochemical, drilling, and hydrological methods suggest a direct connection exists between the surface collapse area and the underground mine as shown by correlative measurements of sediment slump rates and brine influx into the mine. The dissolution of salt below the sinkhole that initiated the leak into the mine was likely caused by several confluent geologic processes, and exacerbated by mining-induced stresses that created fractures which served as hydrologic flowpaths. Modeling studies of mine stresses show that years may be required before tensional cracking begins to occur, but once begun can continue to develop, and relieve the stress in that specific regime. The crack regime creates the avenue for incursion of groundwater, very slowly initially, but gradually enlarging as undersaturated groundwater dissolves salt on the sides of the crack. Mitigation measures include increasing the mine pressurization, slowing the dissolution by injecting brine into the sinkhole throat, and freeze grouting to restrict hydrologic flowpaths.

INTRODUCTION

A sinkhole measuring 11 m (36 ft) across and 9 m (30 ft) deep was first noted in the sediments that overlie the Weeks Island, Louisiana, salt dome in May 1992, but appeared to be about a year old, based on initial surface appearance and later reverse extrapolation of growth rates. Its position directly over the edge of the SPR oil storage chamber, a former room-and-pillar salt mine, caused immediate concern. The association of sinkholes over mines is well established and this occurrence suggested that groundwater influx was probably causing salt dissolution at depth, with associated collapse of soil at the surface. Leaks of groundwater into other salt mines in Louisiana have sometimes led to flooding and eventual abandonment. Consequently, much attention has been and continues to be given to characterizing this occurrence, and to possible mitigative actions. This paper summarizes current knowledge, and describes diagnostic and risk mitigation efforts being conducted by the U. S. Department of Energy, operator of the Strategic Petroleum Reserve (Bauer et al., 1994).

LOCATION, OCCURRENCE, AND CHARACTERISTICS

The Weeks Island salt dome is located 23 km (14 mi) 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 Intracoastal Waterway. Belle Isle and Jefferson Island are now closed to mining because of deliberate and inadvertent flooding, respectively.

The Weeks Island sinkhole occurs over the southern perimeter of the Upper Level of the two-level SPR mine (Figures 1, 2), which has held 73 million barrels of crude oil since 1981. The 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. Minor leaks of water had been noted at various times during the 75 years of active mining, but in-mine grouting was able to control inflow (Acres, 1987).

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The nearly vertical sidewalls in the surface sediments surrounding the sinkhole caused some perplexity initially, but were readily explained geologically as typical of Pleistocene loess deposits which cap the island. The sinkhole was also directly beneath a former residence of the now dismantled Morton townsite, which appears to have no relationship to the sinkhole origin.

The sediment cover, consisting of deltaic alluvium of the ancestral Mississippi River, is about 56 m (185 ft) thick over the top of salt, which is 30 m (100 ft) below sea level at the sinkhole. The water table conforms generally with sea level over the dome, but fluctuates with topography and frequent torrential rains.

The relatively small size of the sinkhole and lack of diagnostic evidence linking it with the SPR mine caused little concern initially. The location near both the edge of the dome and anomalous features in the salt stock suggested the possibility of an entirely natural origin (Neal, et al., 1993), although Martinez (1992) insisted that mine-induced factors were likely involved. A watch and wait position was adopted, and in March 1993 fluorescein dye was placed in the sinkhole as a means of detecting connections with the underground mine, or to the surface downdip of the sinkhole. But by mid-1993 it was apparent that the sinkhole was deepening, and there was monitoring data suggesting that the brine influx into the mine was increasing. Calculations of long-term geo-mechanical behavior showed that salt cracks would be predicted at peripheral positions over mined openings, thus providing a mechanism for eventual incursion of ground water (Figure 2).

Sinkholes also had formed under very similar conditions at other mines in domal salt (Neal, 1994). Thoms (1994) suggested that the salt under the sinkhole may have been geologically susceptible in addition to being stressed by mine deformation, as evidenced by several anomalous conditions that were noted during the original mining, including black salt, blowouts, and minor seeps. Collectively the evidence suggested ongoing dissolution was increasing and that further study was required, in addition to engineering planning to address actions for decreasing the risk of continued oil storage and/or relocating the inventory.

#### DIAGNOSTIC EFFORTS

Unlike other mines where leaks can be observed underground, the SPR mine is sealed and must rely on indirect evidence such as changes in the oil/water interface, increased pressure, or changed isotopic composition of the contained water, which is about one percent of the total volume. The diagnostics are complicated by salt creep closure, which is gradually reducing the storage volume by one-fifth of one percent per year (~160,000 barrels), a very small amount overall, but a *very large* amount with respect to the few gallons per minute leaks which could explain the sinkhole.

*Water inflow* into the mine was suggested by increasing amounts of brine that was observable in the fill hole sump used for injecting oil during initial fill operations. While not a precise measurement, in early 1994 the inflow trend increased from one to nearly three gallons per minute. This increase was noticed immediately following filling of the sinkhole with sand; the decision to fill was made because it had deepened to more than 12 m (40 ft) and its location 15 m (50 ft) from the main access road was hazardous. As soon as the fill was placed, continued deepening of the sinkhole began occurring, at a rate of about  $1.5 \text{ m}^3$  (2 yds<sup>3</sup>) per day, requiring new fill weekly. This suggested that dissolution was ongoing, and there appeared to be a 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). Although inconclusive, earlier data suggested that the leak may have existed as early as 1987.

*Rock mechanics modeling* by Ehgartner (1993) showed that the areas near the mine perimeter would be in tension and that fractures in salt could have formed as early as 1970 (Figure 3). Such a crack could be exposed to undersaturated ground water and gradually enlarge at the same time the crack was extending. The modeling results are validated by actual survey data showing subsidence over the mine, which is in close agreement with Ehgartner's modeling.

*Seismic reflection profiling* was conducted in the area of the sinkhole in early 1994, being an expedient way to obtain subsurface information (Miller, et al., 1994). A prominent reflector first thought to be top-of-salt was noted throughout the area at shallow depth. Subsequent drilling, measurement, and geophysics showed that the reflector was essentially coincident with the piezometric surface, and that a localized 4 m (13 ft) deflection at the sinkhole was a possible drawdown created by the inflow of groundwater into the presumed point of leakage. A secondary anomalous step deflection was noted north of the main sinkhole, and caused some concern, realizing that sinkholes often progress and occur in multiples. Sediment permeabilities were later found to be very high and there is lack of agreement on the seismic reflector as it most likely cannot be the water table. The deflection of the reflector at the sinkhole may be a minor stratigraphic feature that is dipping into the dissolution void at the sinkhole.

*Crosswell seismic tomography* was conducted by placing sources and receivers in four boreholes on diagonals of the sinkhole. The boreholes also provided direct information on sediment and salt geometry, and the hydrologic environment. The tomograms showed clear evidence of low-velocity material below the top of salt, verifying that a sediment-filled void occurred between the much higher velocity salt on either side. The graphical displays did not show the high quality imaging that some had anticipated, but the nature of the method is inherently limited owing to the mapping of seismic velocity distribution rather than geometry. However, the combination of drilling and tomography showed that the area of dissolution below the sinkhole is laterally limited, and with a strongly-vertical dimension (Harding, 1994).

*Slanthole 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 4). *Slanthole BH-9*, adjacent to the sinkhole, was drilled at a high-angle approach directly over the top of the subsurface extension of the surface expression. It extended below the top-of-salt elevation encountered in the tomography holes. This wellbore provided the opportunity for injection of rhodamine dye into the apparent throat of the sinkhole. The dye, if detected in the fill hole sump, would provide unequivocal evidence of hydrologic connection with the mine. After seven months of monitoring, dye had not yet been detected in the mine although dye dispersion calculations predicted that it could take a year or more to reach the sampling point (Linn and Hinkebein, 1994).

*Slanthole BH-7A* started at 60° inclination and was aimed at the sinkhole at depth. It penetrated the top-of-salt at the normal depth (~56 m) and then continued on through salt into a major sand-filled void at least 22 m (72 ft) deep and 2 m (7 ft) wide. A 3-D hydrologic flowmeter was installed in the void and operated for two weeks (Bauer et al., 1994; Ballard, 1995). The data indicated essentially vertical flow down the throat, with diminishing reaching 0.3 m / day. The 3 cm

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(~1 in) per 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 (18 ft) sand-filled void at about the same depth, further defining an elongated cross-section. *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 dimensions of 15 and 10 ft at two different depths. The drilling indicated a very irregular dissolution feature, but with strong vertical dimensions directly below the sinkhole.

Near-surface *gas mapping* (hydrogen, methane, others) in the vicinity of the sinkhole was conducted, as this method has been employed in identifying leaking hydrocarbon sources elsewhere, as well as for oil exploration. The surveys did find localized areas of high hydrogen, but not in the sinkhole. High methane levels were found in the sinkhole, which alone without ethane would not confirm crude oil vapor (LSU, 1994). This study has not yet provided conclusive interpretations based on limited data but should not imply that the method was unsuccessful, as other anomalies were consistently measured. Gas mapping of petrogenic methane may be useful in delineating salt stock features, e.g., anomalous zones elsewhere.

*Self Potential(SP) surveys* were successful at one other sinkhole at another mine by virtue of mapping streaming potential caused by groundwater flow; thus the method was tested at Weeks Island (Bauer, et al., 1994). As anomalous drawdown was believed to occur near the sinkhole, it was thought that this method might reveal other indications, and possibly more about secondary areas of leakage, hinted at by apparent anomalous seismic reflections northeast of the main sinkhole. The data did show anomalies near the sinkhole, but also contained ambiguities. The anomalous streaming potentials were interpreted to result from vertical fluid flow along near-vertical planar surfaces.

*Piezometric monitoring* and permeability testing was initiated in late 1994, as a means of observing the groundwater environment more directly. Permeability measurement was a high priority for determining grouting approaches, and for estimating other hydrologic conditions involving the water inflow. Permeabilities in the 35-90 Darcy range (averaging ~60 Darcies) were measured for the 30 m (100 ft)-thick saturated alluvial sediment sections during several pump tests (ViroGroup; Ostensen, 1994). These high permeabilities showed the difficulty of measuring any fluctuations in water levels, especially associated with a very small flow rate into the sinkhole leak area.

*Progression* of the sinkhole, including new occurrences, is anticipated but with unknown timing, based on similar experience elsewhere, and the continuing development of causative factors that produce the salt dissolution. In addition to monitoring subsidence annually over the entire mined areas, the surface over the perimeter of the mine has been visually observed for telltale changes. Because of the anticipated progression, several mitigation approaches were considered.

## MITIGATION EFFORTS

Once the geometry of a deep void or crevasse 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, approximately three gallons per minute are being gravity fed into the throat 22 m (72 ft) below the top of salt. The encouraging result was that subsidence at the sinkhole was arrested, and

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virtually no additional downward movement was measurable. In addition, the apparent groundwater depression at the sinkhole no longer was observable. The brine introduction evidently had stopped the dissolution of salt, but whether this could be a longer-term fix was problematic; a decision was then made to relocate the SPR oil inventory at an early date and by the safest means.

*Raising the internal mine pressure* from  $4.8 \times 10^4$  to  $1.7 \times 10^5$  Pa (7 to 25 psi) was instituted in mid-1994 as a means of reducing inflow of brine. Although this increase was only a small amount, raising the pressure has the effect of reducing the external pressure gradient, as well as slowing salt creep closure (Bauer et al., 1994).

*Grouting* was considered early but not yet instituted by late 1994 because of the effectiveness of introducing brine to control dissolution, combined with the uncertainty about the hydrologic environment and how and where to place grout, and the fear of doing more harm than good. In early 1995, following the completion of the diagnostics effort and mapping of the "plumbing," a decision was made that permeation grouting would be ineffective and that groundwater control could better be achieved by the installation of a freeze curtain; plans were underway to begin construction in 1995, followed by removal of oil from the mine and relocation at other SPR sites.

## CONCLUSIONS

The sinkhole at Weeks Island formed over the edge of the mine as a result of geological, hydrological, and mine-induced factors. The location near the edge of the dome, astride a probable geologically anomalous zone, set the stage for the mine configuration and boundaries. Mine geometry and excavation-induced stresses placed the mine periphery in tension, probably favoring crack development as early as 1970. Eventual incursion of undersaturated ground water traversed the 107 m (350 ft) salt back over the mine, allowing entry of brine into the SPR mine. Gradually increasing dissolution enlarged a void at the top of salt, creating the collapse environment for the sinkhole which formed circa 1990-91. Exploratory drilling and geophysics defined the void or crevasse beneath the sinkhole, enabling the introduction of saturated brine directly into the throat. The brine arrested the continuing subsidence at the sinkhole, apparently as a result of controlling ongoing dissolution. Additional drilling diagnostics and hydrologic analyses determined that mitigation could best be achieved by constructing a freeze wall around the sinkhole to control groundwater, prior to removing oil from the mine.

## ACKNOWLEDGMENT

This paper summarizes the collective efforts of literally dozens of people at Sandia National Laboratories, DynMcDermott Petroleum Operations Company, and The U. S Department of Energy.

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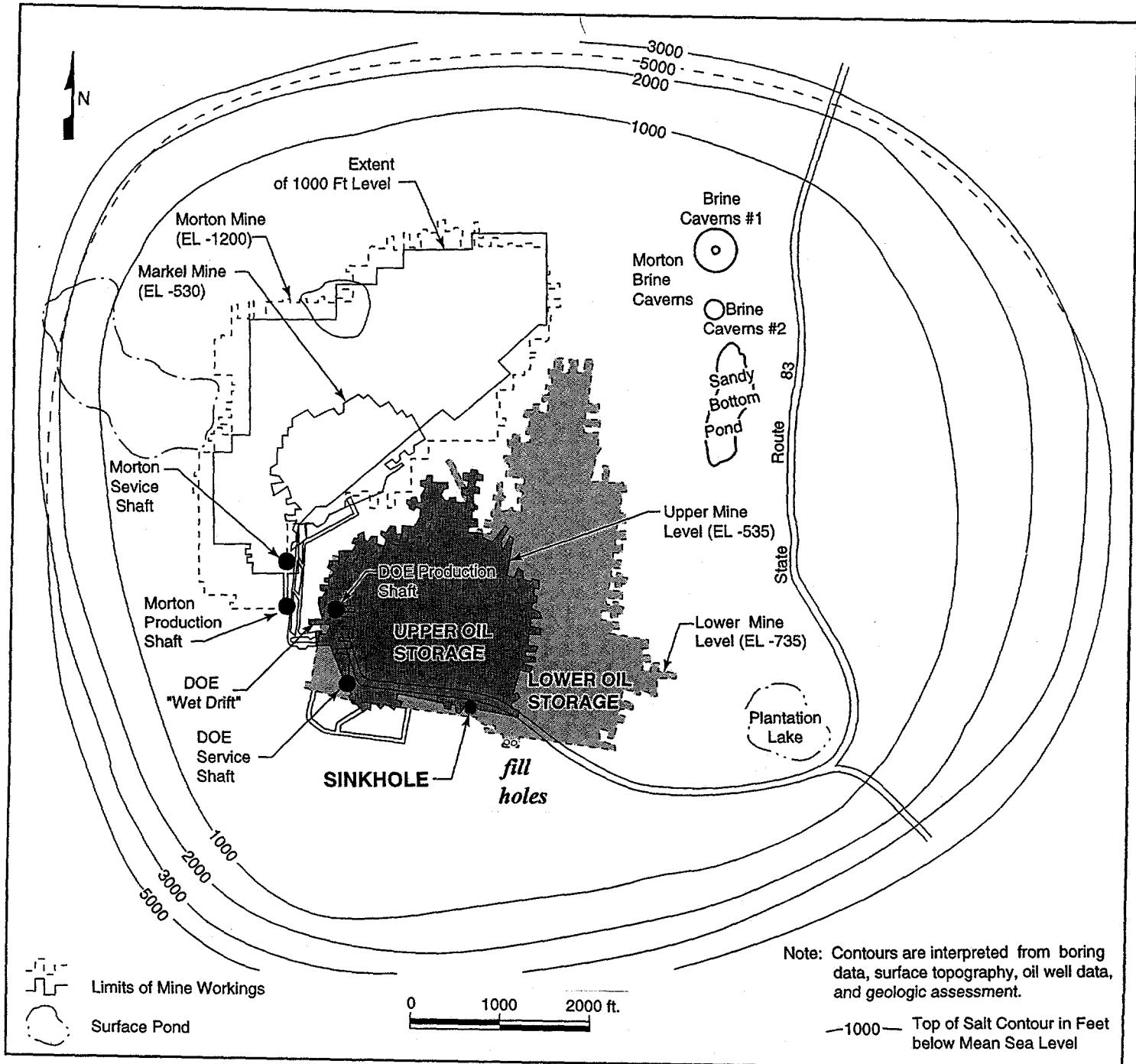
## FIGURES

**Figure 1** Weeks Island salt dome, Louisiana, showing location of the sinkhole, fill holes, mined areas, and contours atop the salt stock (below mean sea level).

**Figure 2** Geomechanical modeling by Ehgartner (1993) showed mechanism for crack development in tension zone that would develop over mined openings after a number of years, and progressing through weakened dilatant zone. Based largely on these modeling results, crosswell tomography was conducted and angled boreholes were planned to intersect such features.

**Figure 3** Conceptual development of Weeks Island, Louisiana, sinkhole, based on geomechanical modeling and presumed hydrologic connection with undersaturated groundwater. Sinkhole 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.

**Figure 4** Diagrammatic representation of exploratory drilling and geometry of sinkhole throat. Boreholes BH-3, 4, 5, and 6 were drilled for crosswell seismic tomography; slanholes 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.



**Figure 1** Weeks Island salt dome, Louisiana, showing location of the sinkhole, fill holes, mined areas, and contours atop the salt stock.

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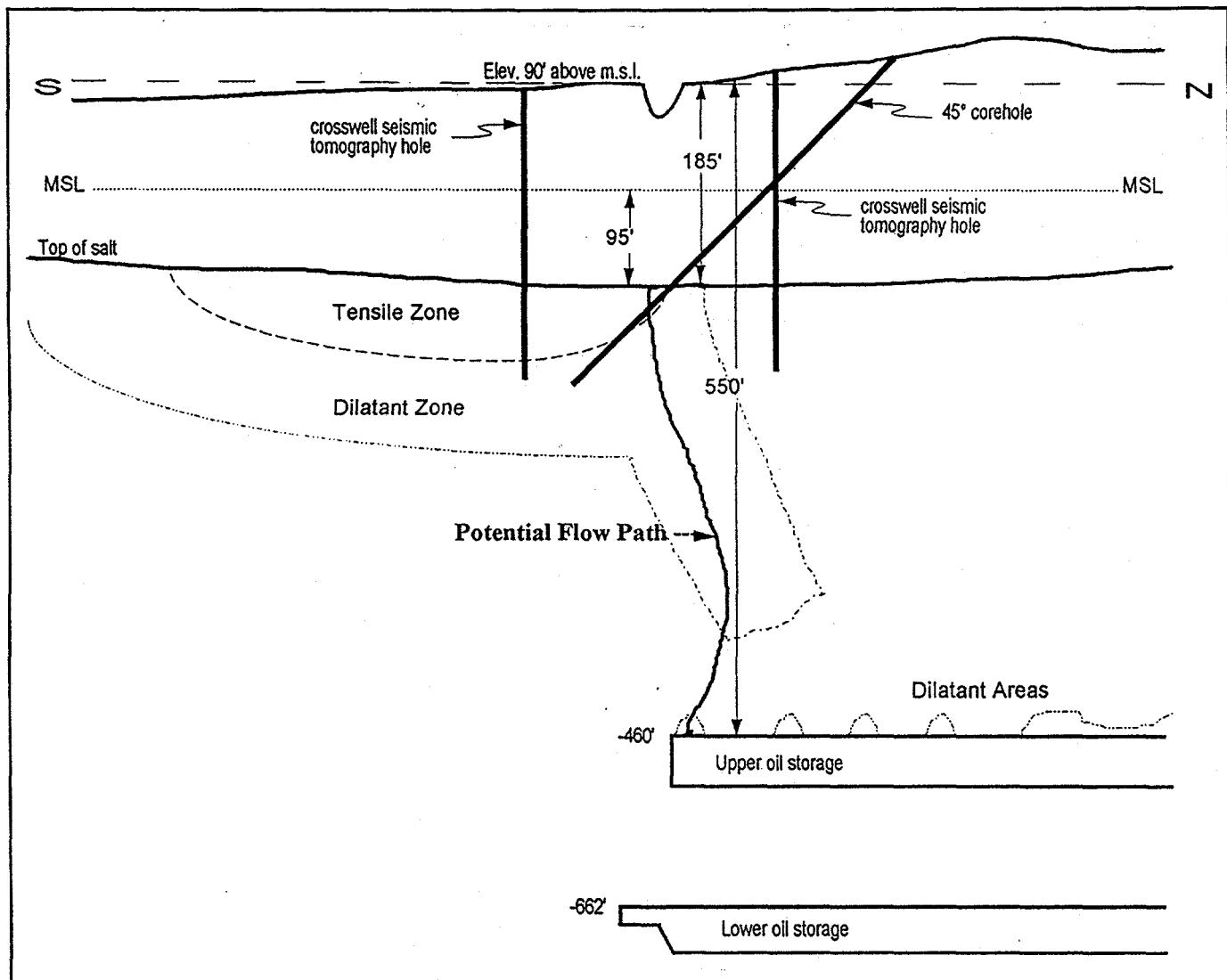
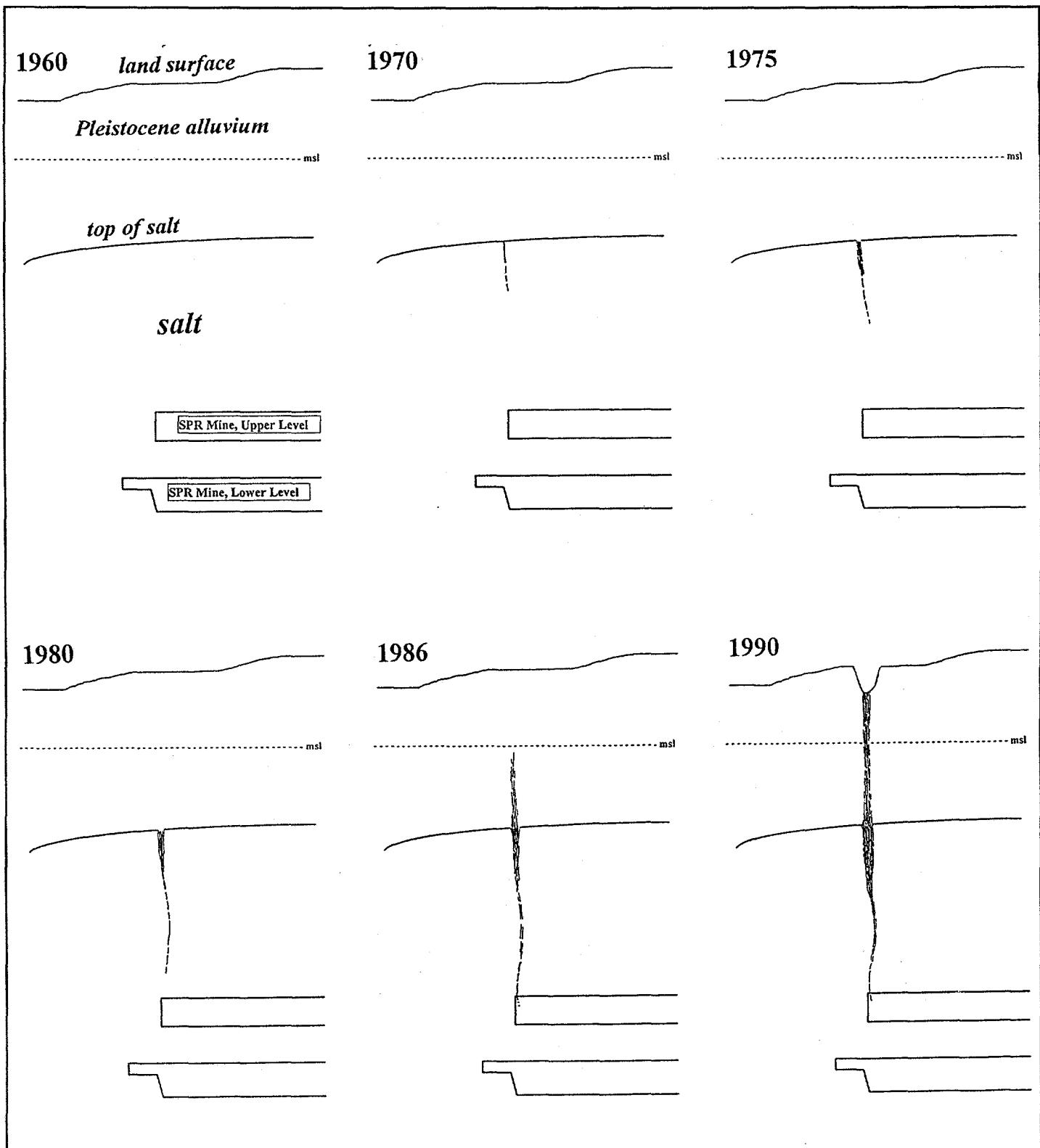


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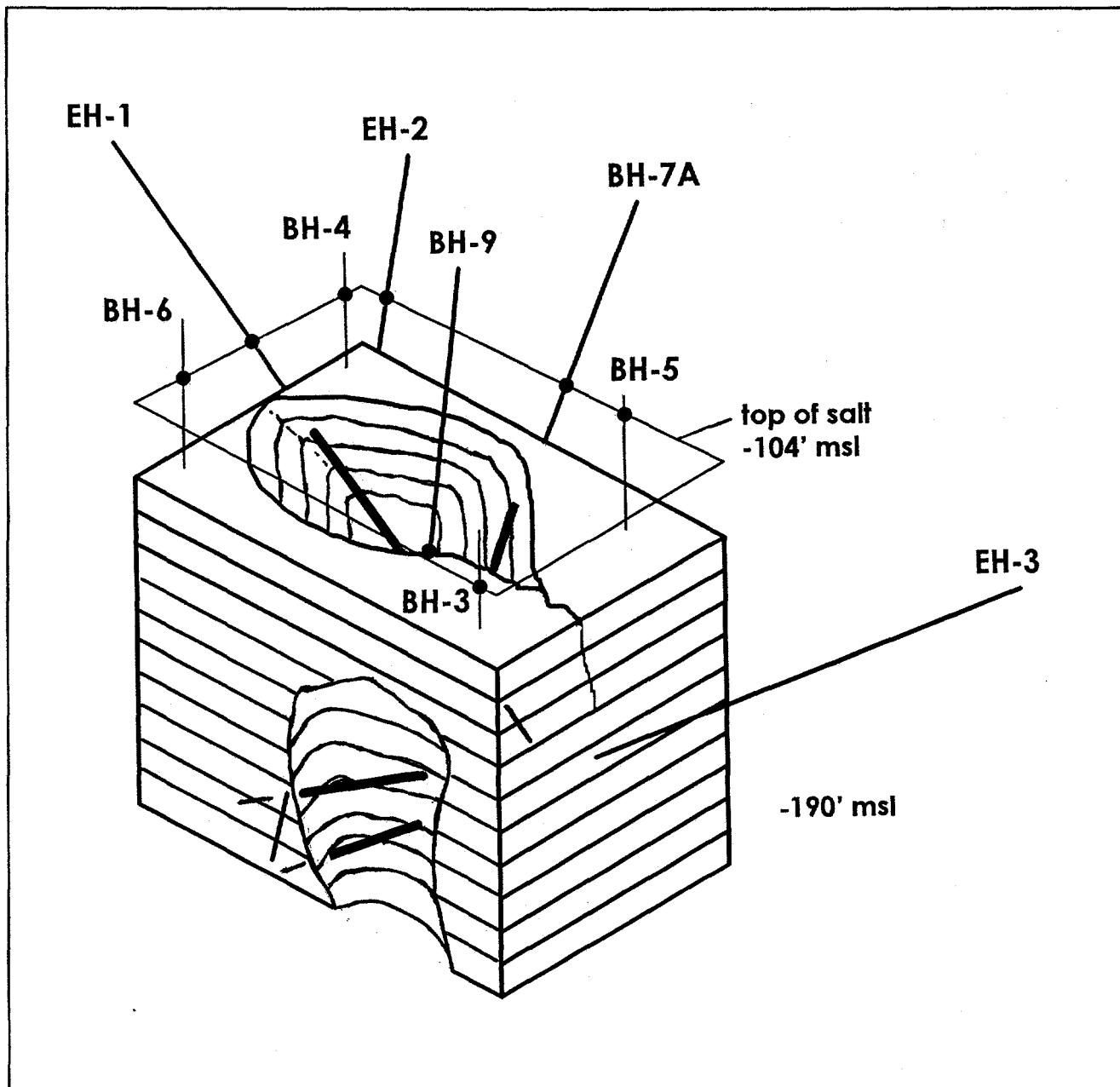


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