

SAN096-1884C

**CHARACTERIZING THE WEEKS ISLAND SALT DOME
DRILLING OF AND SEISMIC MEASUREMENTS FROM BOREHOLES**

by

SAND-96-1884C
CONF-9610163-3

Allan R. Sattler, Richard S. Harding, Ronald D. Jacobson, John T. Finger,
Russell Keefe, and James T. Neal

Sandia National Laboratories, Albuquerque, NM

for

Solution Mining Research Institute
1996 Fall Meeting
Cleveland, Ohio

RECEIVED

OCT 03 1996

OSTI

ABSTRACT

Four vertical and two slanted boreholes were drilled for geologic characterization and diagnostics of a sinkhole which developed over the salt mine converted for oil storage by the U. S. Strategic Petroleum Reserve. The primary purpose of the four vertical holes was to provide the geometry for cross-well seismic tomography, which would aid definition of the sinkhole collapse structure. An additional task was to obtain wireline core through the unstable overburden and salt, and to obtain geophysical logs. One of the slant holes was to penetrate the overburden and core through normal salt into the sinkhole; the other was to penetrate the surface expression of the sinkhole.

The requirements for the seismic holes were sometimes in conflict with those for wireline coring: hole spacing (close enough to receive signals, far enough from the sinkhole for a drill rig), minimum hole ID (big enough for transmitter and receiver to fit and be interchanged (impacting the wireline coring), and the avoidance, if possible, of nested tubulars in the well (making wireline coring contingencies difficult). The surface owner, Morton International, required successful cementing through the alluvium, and a 250 foot vertical depth limitation on the wells was agreed upon.

Crosswell seismic data were generated across the sinkhole along two separate vertical imaging planes. As crosswell data were taken, simultaneous recordings were made from surface geophones. Chevron's clamped borehole seismic vibrator was the energy source for both sets of measurements. A multi-station borehole seismic receiver system, developed by Sandia and OYO Geospace, was used to record the crosswell

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED 

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

data. Data acquisition from the crosswell and reverse vertical seismic profiles led to the production of 3D tomograms. These velocity images suggest the sinkhole collapse is complicated, not a simple vertical structure.

The coring operation was moderately difficult. Limited core was obtained through the alluvium; the quality of the salt core from the first two vertical wells was poor. Core quality improved with better bit selection, mud, and drilling method. After early differential sticking and hole stability problems, the drilling fluid program provided fairly stable holes allowing open hole logs to be run. All holes were cemented successfully, but it took three attempts in one case.

A remarkable result from one slant hole was coring through normal salt and penetrating into the sinkhole throat. Drilling of this slant hole was to be shut down when either: (1) the sinkhole was penetrated, or (2) when a total vertical depth of 250 feet was reached. Total vertical depth when the sinkhole was penetrated was 249 feet.

This work was supported by the U. S. Department On Energy under contract DE ACO-76P 0089.

INTRODUCTION

A sinkhole measuring 36 feet across and 30 feet deep was first observed in the alluvium overlying the Weeks Island Salt Dome in May 1992 (Neal, October 1995). It appeared to be about a year old based on initial surface appearance and subsequent reverse extrapolation of growth rates. The position of the sinkhole is directly over the edge of the U. S. Department of Energy (DOE) Strategic Petroleum Reserve oil storage cavern, a former room and pillar salt mine. The association of sinkholes over mines is well established, and this occurrence suggested that groundwater influx was probably causing salt dissolution at a shallow depth and associated collapse of overburden at the surface. Leaks of groundwater into other salt mines in Louisiana and elsewhere have led to flooding and eventual abandonment. Consequently, much attention has been and continues to be given to characterizing the sinkholes, and to mitigation of the dissolution process.

The presence and location of the sinkhole and its implications were a cause of concern. Six boreholes were drilled (Figure 1) for the purpose of geologic characterization and diagnostics of the sinkhole. The primary purpose of the four vertical wells was for crosswell seismic tomography across the sinkhole to image the sinkhole collapse structure (particularly hypothesized dissolution zones in the upper part of the salt dome). A secondary objective was to obtain continuous wireline core through the salt in all four wells and to core through the unstable deltaic alluvium overlying this Weeks Island salt dome in one or two cases. Another goal was to obtain geophysical logs in both the open and cased holes (the logs were previously described in Sattler, 1996).

The purpose of one of the slant holes was to penetrate the surface expression of the sinkhole. The other slant hole was to penetrate the overburden, core through the normal salt, and break into the sinkhole if possible.

This paper touches on the highlights of both the seismic data gathering and the drilling operation.

Construction, Drilling, Coring Requirements

The drilling of slant holes (as well as vertical holes) while optimizing core recovery generally suggests the use of minerals drilling/coring rigs (although other options are available). Many mineral rigs can drill both slant and vertical holes, and are also equipped to employ a casing advance system which is useful in penetrating unstable alluvium. They have a good history of core recovery, even in unconsolidated formations. Utilization of mineral rigs has been infrequent in Louisiana, except perhaps in the salt mines. However, we were unable to locate a minerals industry driller with the required Louisiana water well license.

Conventional water well rigs with larger drilling fluid systems (approximately 500 gallons/minute Vs 50 gallons/minute for a minerals rig) appeared more suitable for penetrating unconsolidated alluvium. Experience in drilling the Weeks Island Salt Dome was highly desirable. A combination of the two rig types would be ideal for this!

Stamm Scheele, Inc., an established Louisiana-licensed water-well firm, experienced in drilling the Weeks Island Salt Dome, was awarded the contract. They sub-contracted to Longyear Company (now Boart Longyear) to provide a minerals rig for drilling the slant holes and to provide core drilling tools.

To assure reasonable image geometry, it was desirable to minimize the hole spacing for cross-well tomography, in this case between 100 and 150 feet. For safety reasons it was not desirable to place the vertical-holes drill rig, the Failing 2000, closer than 50 ft from the sinkhole. There were also construction constraints associated with overhead telephone wires and the need to avoid clearing groves of trees. The resulting BH-3 to BH-4 and BH-5 to BH-6 spacing were approximately 101 and 150 feet respectively. At near-surface depths, the BH-3 to BH-4 and the BH-5 to BH-6 ray paths would cross the sinkhole, Figure 2. The sinkhole to BH-5 and the sinkhole to BH-4 distances of approximately 50 and 61 feet were adequate. The sinkhole to BH-9 distance was only 40 feet but still considered safe because the rig used for this slant hole, the Longyear 44, is much smaller than the Failing 2000.

The vertical hole requirements for the geophysics were simple: cased holes six inches minimum inner casing diameter and 250 feet deep. These holes then would be large enough to exchange positions of the seismic energy source and multireceiver array in the holes, if desired. The 250 foot depth would leave approximately 300 ft of salt buffer between the bottom of the holes drilled and the top of the oil storage cavern at approximately 550 ft bgl. The holes were to be cased and cemented to the surface.

The principal coring requirement was for continuous four-inch salt core from the vertical wells, optimal for rock mechanics studies. A smaller size core, "H" core, 2.5 inches, was planned for the alluvium in the vertical wells and for core taken from the slant wells. (See Appendix A for drilling details.)

Seismic Data Acquisition

Data used in 3D tomography imaging were acquired using both reverse-VSP (borehole-to-surface) and crosshole source-receiver geometry (Figure 2) (Fairborn and Harding, 1996). As crosshole data were acquired, simultaneous recordings from surface geophone spreads were made. The surface geophones were laid out in 8 parallel lines. There were 24 geophone channels per line, an in-line geophone interval of 5 feet, and 10 feet between adjacent geophone lines. Two pairs of boreholes and two surface swaths were used to generate data, which were recorded on an OYO Geospace DAS I seismograph at 0.5 millisecond digital sample interval. The seismic energy source used in the survey was Chevron's clamped borehole axial hydraulic vibrator (Paulsson, 1988). At each source level a single linear sweep of seismic energy from 10-640 Hz was input. The sweep length was 6 seconds with a 0.5 second listening time. The borehole multireceiver system used in the survey was designed and built by Sandia and OYO Geospace (Sleepe et al., 1993). Each receiver module is equipped with a triaxial sensor package and A/D converter. A real-time fiber optic link transmits data to the surface at 5 Mbs. Four triaxial receiver modules were deployed, with 10 feet between modules.

As data were acquired in the field, on-site processing of crosshole seismic data was performed. The resulting 2D tomograms gave strong indications of dissolution zones in the salt, but lacked the resolution to map dissolution boundaries with great confidence. The development of 3D tomographic inversion was attempted to improve upon the 2D tomography results.

Data Processing Considerations

The combination reverse-VSP and crosshole tomography acquisition geometry gives rise to a wide spatial distribution of raypaths within the collapse zone and in the surrounding competent sand/salt host material, thus providing the necessary criteria for accurate tomographic inversion. In 2D tomography, actual seismic raypaths can travel outside the imaging plane leading to inaccurate velocity reconstruction in the imaging plane. Adding the third dimension allows for more realistic earth models and properly positions velocity features in 3D space. Also, combining crosshole and borehole-to-surface raypaths in the inversion increases the range of incident angles, particularly in the regions between the crosshole pairs. The borehole-to-surface raypaths tend to refract toward vertical due to the strong increase of velocity with depth, while the crosshole raypaths travel primarily in a near horizontal fashion.

The increased range of incident angles is particularly important, since the resolution and accuracy of the method require that the model cells be cut by rays from many different directions. The east-west, north-south, and vertical dimensions of the velocity model were divided into 20-by-18-by-25, 10-foot cells. The number of observations in the reverse-VSP and crosshole surveys totaled 17,000, resulting in 9,000 unknown velocities to be solved by 17,000 equations.

The reference model, used to bring stability to the inversion process contained known geologic/sonic properties derived from the logging program. This reference model consisted of 2 horizontal layers over a halfspace, representing a 2,000 ft/sec vadose zone (unsaturated sand) layer from 0 to 90 feet, a 6500 ft/sec saturated sand layer between 90 and 180 feet, and 13,000 ft/sec salt below 180 feet. Possible effects of a sinkhole were not incorporated in the reference model, so **unless the data gave evidence of a sinkhole, none would appear in the final velocity tomogram.** This model was used as a first guess in the velocity iteration process within each cell of the velocity mode.

Results of Seismic Measurements

Figures 3, 4, and 5 show 3D tomogram velocities in vertical, and horizontal cross-sectional images with P-wave velocities (ft/sec) shown at the left. Figures 3, an east-west slice at 100 ft, depicts tomogram velocities in the vertical cross section between BH-5 and BH-6, passing through the center of the sinkhole.

Figure 4, a depth slice at 40 ft with sinkhole indicated, depicts tomogram velocity variations in the shallow section above the water table. Prior to the field survey the sinkhole was backfilled with sand. As data were acquired the sand level in the center of the sinkhole subsided steadily at the rate of about 0.3 feet per day. The zone immediately below the sinkhole is characterized by lower velocity than in the surrounding undisturbed medium-to-coarse grained sandy soil. The lower velocity likely results from destruction of the native soil fabric, or replacement of native soil with relatively loose fill sand material. The water table is 90 feet below the ground surface.

The effects of the sinkhole are clearly seen in Figure 3 as anomalous low velocity within saturated soil and the salt. Note that below the water table, the zone of anomalous low seismic velocities moves east of the surface expression of the sinkhole. It is also interesting to note that anomalous P-wave velocities in the saturated sand below the water table (at 90 feet) are lower than water velocity. Given the high permeabilities and low water flow rate into the caverns, it is unlikely the low velocity is due to water table drawdown. A more likely explanation is that active subsidence during the survey brought unsaturated sand below the water table. Apparently the sand retained enough air in the pore space to drive the P-wave velocity down significantly.

In Figure 3 the top of the salt is also clearly seen. A breach in the top of the salt is seen along with a depression, or dissolution feature, evident to a depth of about 230 feet. The asymmetry of the sinkhole structure is clearly seen in both the alluvium below the water table and in the salt (Figure 5).

Below 230 feet, no ray paths are present, and the tomogram velocity is that of the reference model. The tomogram velocity image at the top of salt which show a deepening of the breach in the top of salt in the area directly east of the sinkhole is generally consistent with available information from borehole penetration data in that a breach in the salt was found (see below).

BH-7A Penetration into the Sinkhole Itself

After cementing the casing and casing advance shoe in the alluvium of BH-7A, the salt was cored with "H" coring tools with excellent quality and recovery (see Appendix A for drilling details). All parties agreed that the 300 ft buffer between the oil cavern and maximum hole depth must be preserved. Therefore, either the sinkhole had to be penetrated before the total vertical depth (TVD) of 250 ft was attained or the drilling/coring of BH-7A had to be shut down. It was desirable to penetrate the sinkhole at a relatively shallow angle so a quantity of competent salt would be recovered before penetrating the sinkhole. At a slant depth of 275.5 feet, and a true vertical depth of 249 feet, circulation was lost, the core pipe fell 3 to 4 feet, and sand was recovered. **The sinkhole had been penetrated.** Approximately 54 feet of competent salt was cored, but the last piece of core was eroded with only fill sand to be recovered in the core barrel after that. (Later holes EH-1 and EH-3 not only penetrated the sinkhole, but emerged into competent salt on the other side.)

Conclusions

The drilling of vertical holes provided a suitable test bed for borehole seismic studies. Core and logs (both open and cased hole) were obtained from these and the slant holes. One slant hole, BH-9, presumably crossed the alluvium-fill sand interface and the other slant hole, BH-7A, penetrated the sinkhole within the salt dome and indicated dissolution of the upper part of the salt dome.

Thus, the large velocity contrasts seen in the seismic data with the implied salt dissolution were verified. Even though the depth range of BH-7A is extends just below the volumes of earth imaged by 3D tomography, the seismic data from Weeks Island demonstrate the potential of 3D seismic velocity tomography for imaging shallow geologic structure. The 3D velocity image data is in general agreement with available borehole data; moreover, the 3D data suggest that the sinkhole collapse structure is not a simple "chimney"-like structure.

REFERENCES

Fairborn, J. and Harding R., 1996, 3D Seismic Velocity Tomography at the SPR Sinkhole Site, Weeks Island Louisiana," to be published in the Expanded Abstracts of the 66th Meeting of the Society Of Exploration Geophysicists, Denver, November 1996.

Neal, J., Bauer, S., and Eghartner B., 1995, "Sinkhole Progression at the Weeks Island, Louisiana, Strategic Petroleum Reserve Site," Solution Mining Research Institute fall 1995 Meeting, San Antonio, TX, 16 p., in Deerfield, Illinois meeting archives.

Paulsson, B.N.P., 1988, Three-component downhole seismic vibrator, Proceedings of the 58th Annual SEG Meeting, Anaheim, California, 139-142.

Sattler, A., 1996, "Log Analysis of Six Boreholes in Conjunction with Geologic Characterization Above and on Top of the Weeks Island Salt Dome," Solution Mining Research Institute spring 1996 meeting, Houston, TX, 19 p., in Deerfield, Illinois meeting archives.

Sleefe, G. E., et al., 1993, Rapid Acquisition of Full Wavefield Data, Proceedings of 63rd Annual SEG Meeting, Washington, DC, 5-8.

APPENDIX A, Brief Highlights of the Drilling Operation

For much of the operation two rigs were on site - the Failing 2000 and the Longyear 44. Coordinating the activities of the two rigs went smoothly, in spite of unforeseen plan changes, operational problems, and design changes. These different rigs gave flexibility to the operation for the vertical holes.

The original plans for the vertical wells were to use two different well designs. The first well was to be a seismic receiver well, BH-6, to be first cored with the Longyear 44 to the top of salt with 2.5 inch "H" core taken; then opened with a 6-5/8 inch casing advance system. The 6-5/8 inch casing itself would be used as a temporary liner for coring the salt to target depth (TD) with 4 inch coring tools. The casing would then be advanced to TD and removed for logs or cemented in place.

The second well design for the Failing 2000 would be a seismic source well, BH-4, to be drilled with a 9-7/8 inch hole to top of salt, and then a temporary 6-5/8 inch liner would be set. The salt would then be cored to TD with 4 inch BSF wireline coring tools. (The use of minerals-coring tools on a water well rig is quite unusual.) The liner would then be pulled and the hole opened to 9-7/8 inch to TD and then cased as above. Both designs had a contingency to case the alluvium and lost circulation areas if necessary. The designs for the next two vertical wells would be optimized on results from these two wells.

Results of the Longyear 44 wireline coring BH-6 in the unconsolidated alluvium were disappointing. Only 13 of first 170 feet cored were recovered. Changing core catcher schemes resulted in some improvement. Changing to salt saturated drilling fluid resulted in 100% core recovery from 170 to 175 feet, but also resulted in getting differentially stuck. Plans for advancing casing over stuck pipe and continuing the BH-6 hole were put on hold until the Failing 200, then on BH-4, became available. Plans to core additional alluvium overburden or core additional salt through temporary liners in open hole, with the Longyear 44, were abandoned. Completion of BH-6 would be left to the Failing 2000 starting with fishing the stuck pipe after this rig completed BH-3 and BH-5.

Drilling BH-4 with the Failing 2000 to the top of salt at 183 feet went well but the 6-5/8 inch temporary liner became differentially stuck 2 feet off bottom. Coring the salt commenced through the stuck pipe utilizing a power swivel, and 4 inch BSF wireline tools. Core recovery was 100% but the core had many drilling-induced fractures. The stuck liner and coring tools were washed over with a 12-1/4 inch washover shoe on 8-5/8 inch line pipe to TD. The liner and coring tools were removed, and the 8-5/8 inch line pipe cemented in place, Figure A1.

A 13 inch hole in BH-3 was drilled to the top of salt at 187 feet, 10-3/4 inch casing was set, and cemented. The Failing rig was moved, and the minerals rig moved on BH-3. A 6-5/8 inch liner was run and drilled into the cement in the bottom of the hole. BSF 4 inch core was then cut to 250 feet, with 100% recovery and excellent quality, with few drilling induced fractures. The minerals rig was moved for slant hole drilling.

BH-5 was to be drilled with the same design as BH-3 but after drilling the 13 inch hole to top of salt at 188 feet, the 10-3/4 inch casing could not be brought to bottom due to crooked casing. It was decided to core the salt in this hole with conventional oil-field coring tools already on site. A DBS 8-5/8 inch by 4 inch salt coring bit and 30 foot core barrel were used. Core recovery was 75%, the core was highly rubbleized, unusable for laboratory testing. The cored portion of BH-3 was then opened to 13 inches to TD. Then 6-5/8 inch casing was set and cemented, Figure A1.

After completing BH-5, the Failing rig, then set onto BH-3, opened the cored portion of BH-3 to 9-7/8 inches and ran a 6-5/8 inch liner from 167 feet to 250 feet. The liner was cemented in place, thus completing the well, Figure A1.

The Failing 2000 resumed operations at BH-6. The stuck HQ core pipe was washed over and removed. The original 7-5/8 inch conductor casing was also washed over and removed for a larger conductor pipe, consistent with the BH-3 design. A 21 inch hole was drilled to 34 feet and 16 inch conductor casing was cemented. A 15 inch hole was then drilled to top of salt at 192 feet and 10-3/4 inch casing was set and cemented from 192 feet to the surface. In preparation for 4 inch BSF coring, a 6-5/8 inch liner was run and drilled into the cement. Because the minerals rig was occupied with the slant wells and not available for coring; another attempt was made coring with the Failing 2000 using wireline coring tools. A Longyear Syndax bit was used to increase core quality. Coring was accomplished to 248 feet, with good recovery and better quality than with the first Failing 2000 coring attempt on BH-4. Nonetheless, core quality was not nearly as good as it was for the core taken from the minerals rig. The cored portion of BH-6 hole was opened to 9-7/8 inch and cased with a 6-5/8 inch overlapped liner as in BH-3, Figure A1.

Both slant holes, BH-9 and BH-7A (Figure A2), were established with the casing advance system. The angle of BH-9 was approximately 12.5 degrees off vertical and the angle of BH-7A was approximately 30 degrees off vertical. As drilling proceeded in both wells the angle to vertical decreased because of gravity; for BH-7A it was approximately 2 degrees for every 50 ft drilled.

Circulation was lost in BH-9 at 136 ft, presumably at the interface between the sinkhole and the "virgin alluvium." The hole was drilled blind to 180 ft where the HW (4-1/2 inch x by 4 inch) casing with a 6-5/8 inch casing shoe was set. After cementing the HW casing, "H" core was attempted to 190 feet with recovery of 4 feet of sand.

The HW casing twisted off at 133 feet slant depth while drilling BH-7A. The casing left on bottom was recovered. The hole was redrilled with a BSF (5-1/2 inch x 4-7/8 inch) core pipe casing advance system. The BSF pipe is stronger than the HW casing, and has a smaller annulus, which should help hold hole angle. This system drilled to 214 feet slant depth, 194 feet TVD, approximately 2 feet into salt.

In spite of the unstable alluvium, running casing went smoothly and open hole logs were run in three out four cases (vertical wells). Much was attributed to the drilling fluid system that evolved. The optimum drilling fluid system consisted of four pounds of dextrinite starch/bbl, 1/4-1/2 lb. cellulose/bbl, salt to saturation, and minor amounts of detergent. Drilling/coring in the slant holes was improved by augmenting the mud system that came with the Longyear rig and after that, no further problems were encountered in utilizing this rig.

Saturated salt cement was used for cementing. Little trouble was encountered in cementing (with returns to the surface) except in BH-9 and BH-6. Not surprisingly, lost circulation was encountered in the drilling of BH-9. Four "top jobs" were necessary to bring returns to the surface in BH-9. Three cement jobs were

necessary in BH-6, the final (successful) cement job placed cement through an open drill pipe directly at the top of the overlap between the 6-5/8 inch liner at the bottom and the 10-3/4 inch casing through the alluvium (Figure A1). Gravel just above the salt was very prominent and interfered with the BH-6 coring operation.

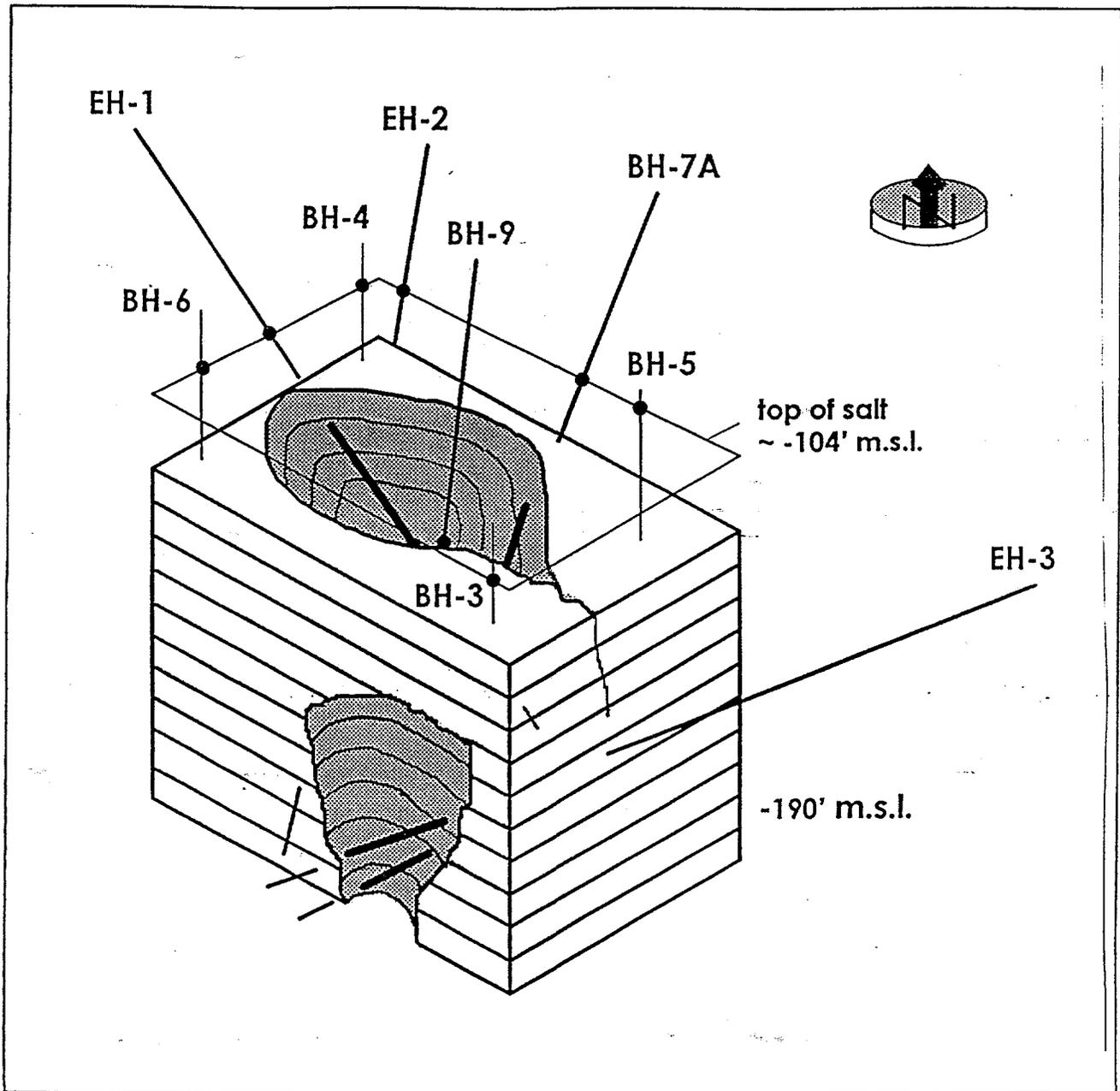


Figure 1 Diagrammatic representation of exploratory drilling and geometry of Sinkhole #1 throat. Boreholes BH-3, 4, 5, and 6 were drilled for crosswell seismic tomography; slantholes BH-7A and 9 were drilled for throat definition. EH-1, 2, and 3 further defined the throat and provided decisive information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

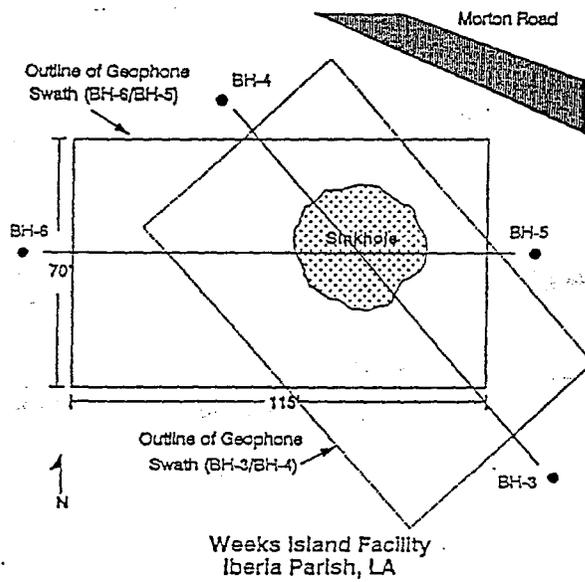


Figure 2

Weeks Island SPR Sinkhole

East-West Slice at

100 ft.

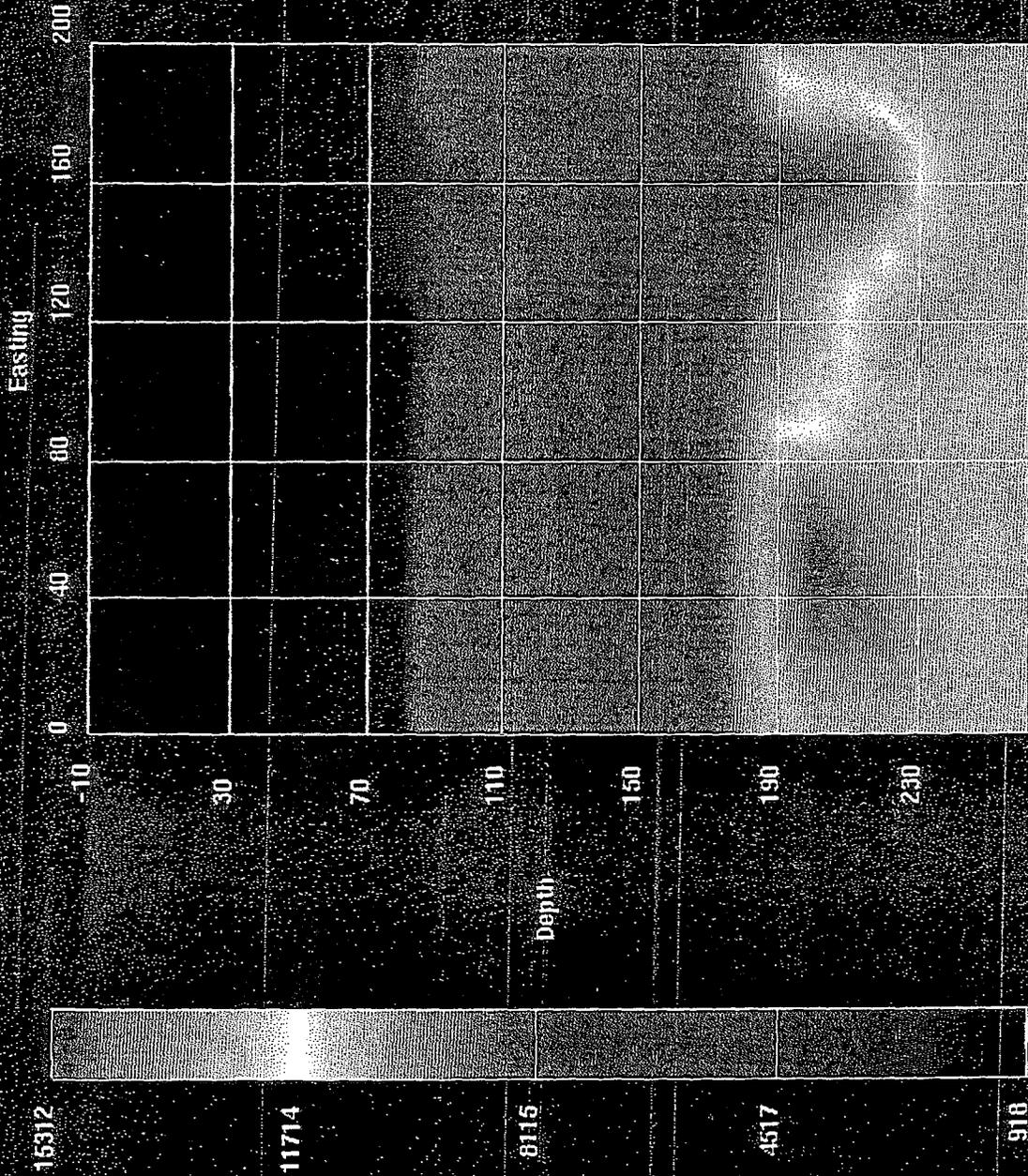


FIGURE 3

Weeks Island SPR Sinkhole

Depth Slice at 40 ft.

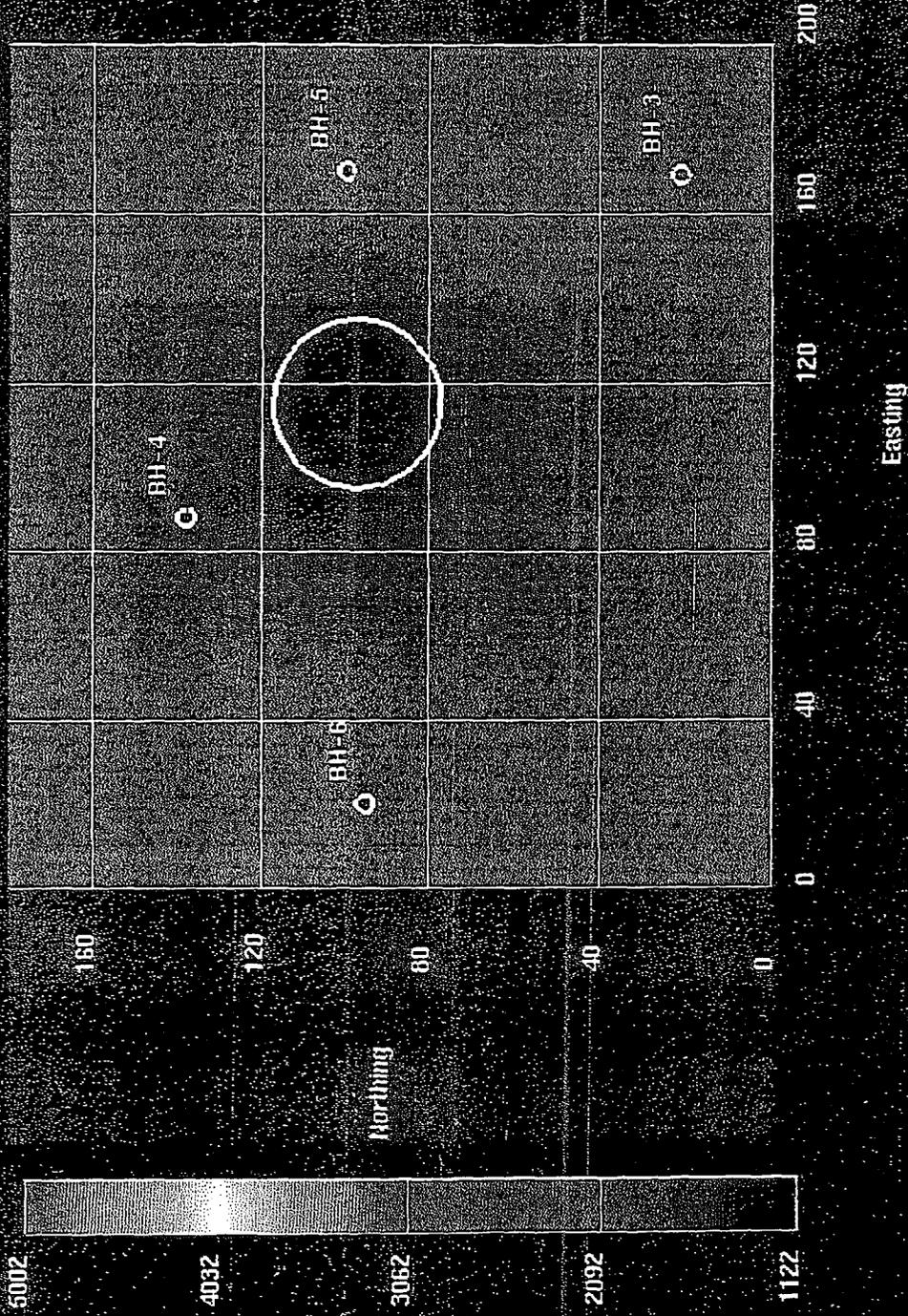


FIGURE 4

Weeks Island SPR Sinkhole

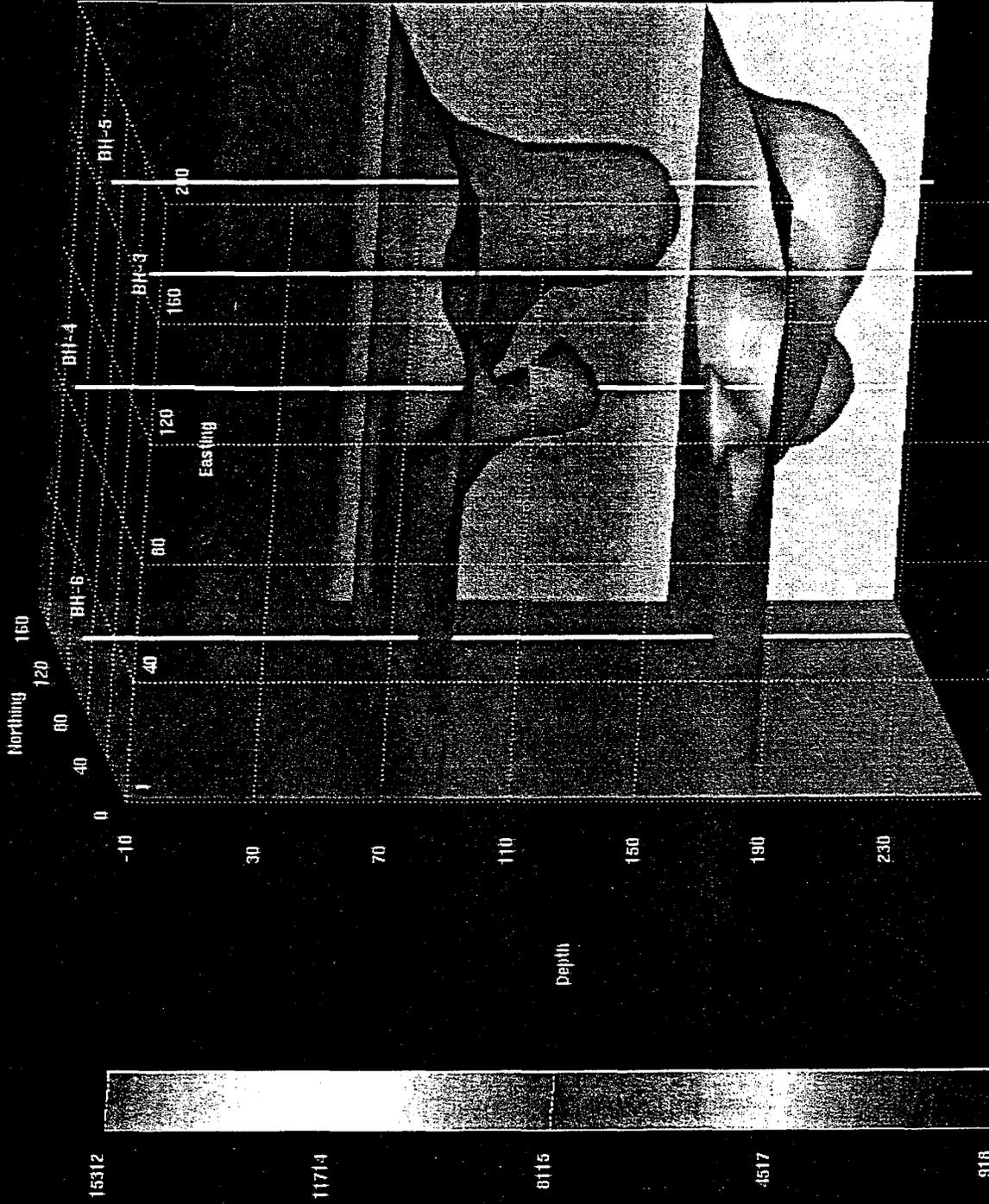
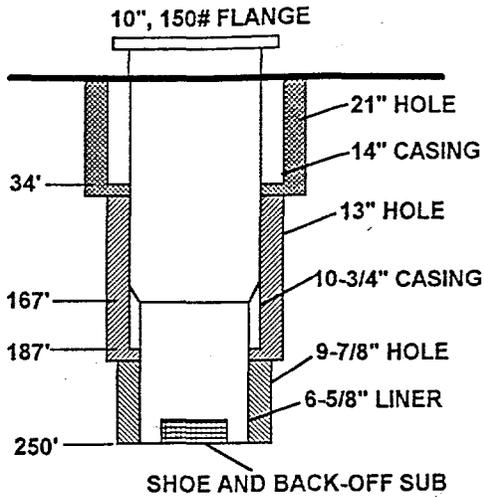


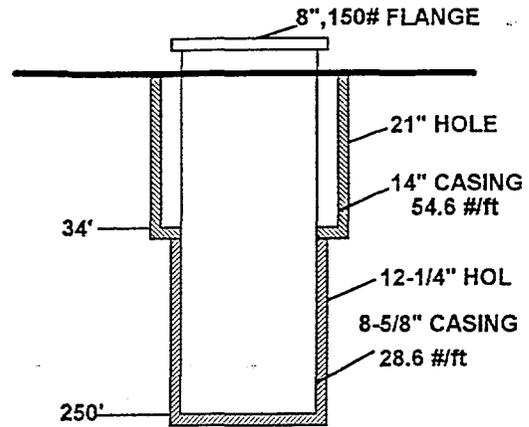
FIGURE 5

BH-3 AS DRILLED



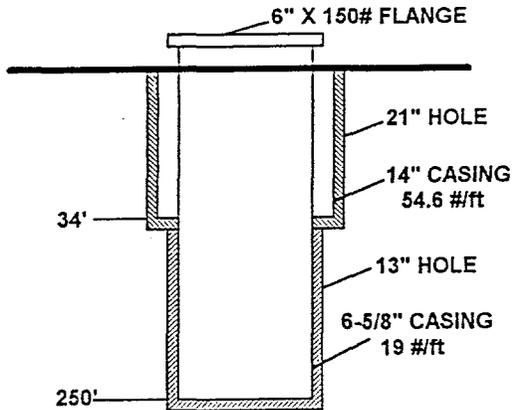
Wellhead @ (La. State Plane Coor. System)
 x: 1,849,892.99 y: 414,006.63

BH-4 AS DRILLED



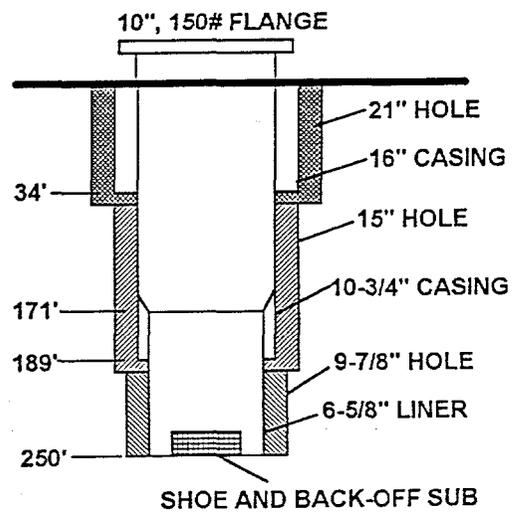
Wellhead @ (La. State Plane Coor. System)
 x = 1,849,810.55, y = 414,126.46

BH-5 AS DRILLED



Wellhead @ (La. State Plane Coor. System)
 x = 1,849,893.05 y = 414,085.04

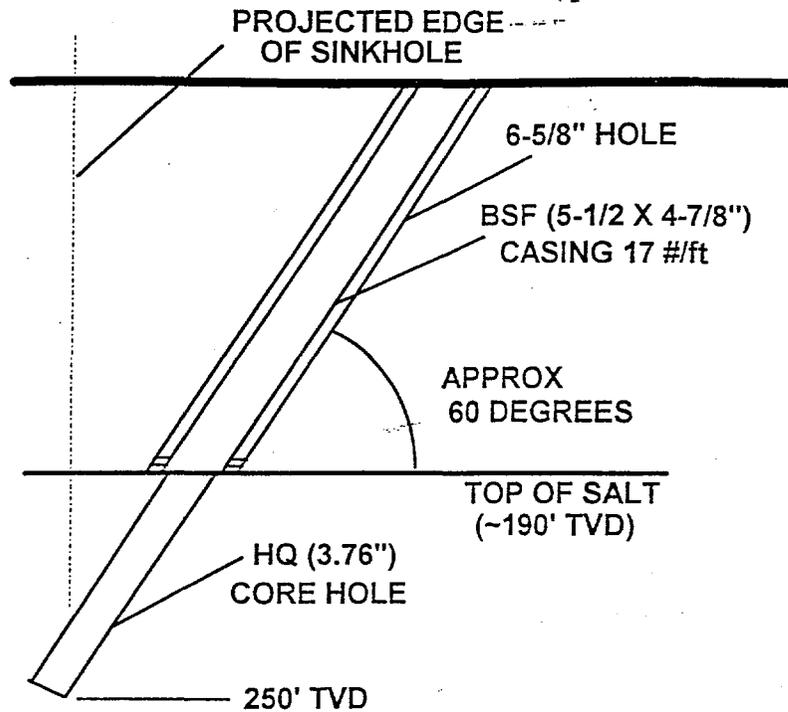
BH-6 AS DRILLED



Wellhead @ (La. State Plane Coor. System)
 x = 1,849,742.33 y = 414,081.06

FIGURE A1 - AS-BUILT DRAWINGS OF VERTICAL WELLS

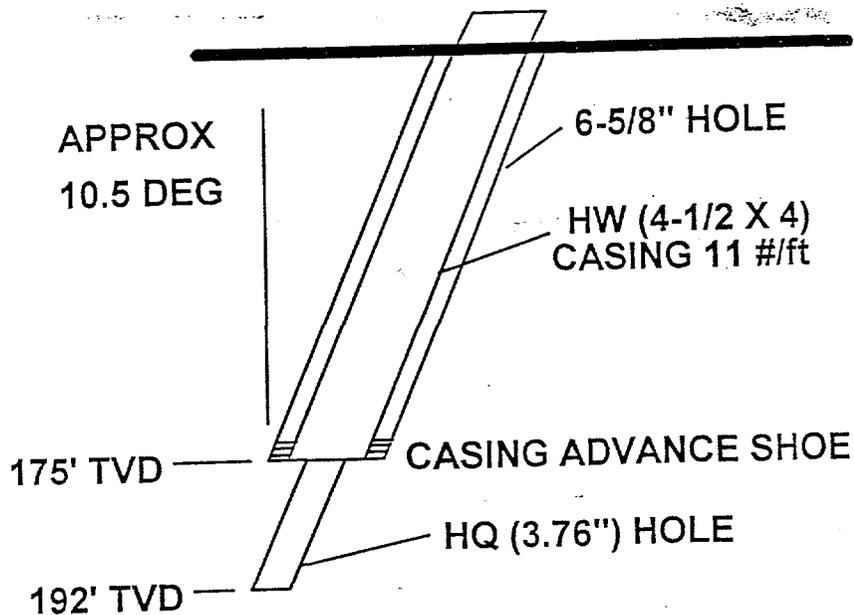
BH-7 AS DRILLED



Wellhead coordinates (La. State Plane Coor. System)

x = 1,849,906.59 y = 414,184.70

BH-9 AS DRILLED



Wellhead coordinates (La. State Plane Coor. System)

x = 1,849,833.36 y = 414,121.65

FIGURE A2 - AS-BUILT DRAWINGS OF SLANT WELLS