High-resolution seismic reflection survey near SPR surface collapse feature at Weeks Island, Louisiana

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SUMMARY

Shallow high resolution 2-D and 3-D seismic reflection techniques are assisting in the subsurface delineation of a surface collapse feature (sinkhole) at Weeks Island. Louisiana. Seismic reflection surveys were conducted in March 1994. Data from walkaway noise tests were used to assist selection of field recording parameters. The top of the salt dome is about 180 ft below ground surface at the sinkhole. The water table is an estimated 90 ft below the ground surface. A single coherent reflection was consistently recorded across the entire area of the survey, although stacking velocity and spectral content of the event varied. On the basis of observed travel times and stacking veloc- ties, the coherent reflection event appears to originate above the op of the salt, possibly at or near the water table. Identification of his reflector will be made from borehole investigations currently planned for the sinkhole site. A depression or time sag in this reflection event is clearly evident in both the 2-D and 3-D seismic data in the immediate vicinity of the sinkhole. The time sag appears to be related to the subsurface structure of the reflector and not to fear surface topography or velocity effects. Elsewhere in the survey area, observed changes in reflection travel times and wavelet character appear to be related to subsurface geologic structure. These seismic observations may assist in predicting where future sinkholes will develop after they have been tied to borehole data collected at the site.

INTRODUCTION

A sinkhole discovered on May 18, 1992, is the subject of geotechnical investigations to determine its origin. Four 2-D seismic reflection profiles (Figure 1) were acquired to obtain redundant (24-fold) reflection coverage in the general vicinity of the sinkhole. These profiles were designed to assist in mapping subsurface hydrogeologic structure related to the existing sinkhole, as well as identifying potential future collapse structures. This approach has proved successful in previous surveys targeting dissolution features in bedded evaporite deposits (Miller et al.. 1993; Steeples and Miller, 1990; Steeples and Miller. 1987; Steeples et al.. 1986). In addition to the 2-D reflection profiles, experimental single-fold 3-D reflection data were acquired to enable detailed mapping of the subsurface extent of the existing sinkhole. As of this writing these data have not yet been fully incorporated into the interpretation.

Weeks Island is the highest point in southern Louisiana, reaching 176 ft above sea level at its highest point. The ground surface at Weeks Island is deeply incised by drainage features and 5 covered by a combination of tall trees and dense brush undergrowth. The water table is approximately at sea level, some 90 ft below the ground surface at the sinkhole location. The dome is covered by unconsolidated fine-grained marine sediments. Caprock is absent and brine-saturated soil lies in direct contact with the salt. Seismic reflection imaging of the rap of salt at Weeks Island has proved problematic in previous efforts (Kinsland and Rutter, 1994). The difficulty in obtaining reflections from the salt/sediment interface may be due to the irregularity of this surface. This conjecture is based on the recognition of similar surfaces at other domes where caprock is absent (Black and Voigt, 1982). At the time of the survey the sinkhole was about 40 ft in diameter and more than 30 ft deep.

Surface conditions in the area of the seismic reflection survey varied from heavily wooded to manicured grass along road shoulders. Seismic lines were cleared of undergrowth in a 5 foot swath. Underground utilities including a petroleum pipeline, a propane pipeline, high voltage power lines, a fiber optic communications link, standard telephone lines. and water lines prevented continuous coverage across portions of the survey area. The ground surface was generally soft and damp. Several significant topographic and cultural obstacles were present including ditches, relatively steep terraces. partially buried foundations remnants, and about 55 ft of elevation change on north/south trending lines.

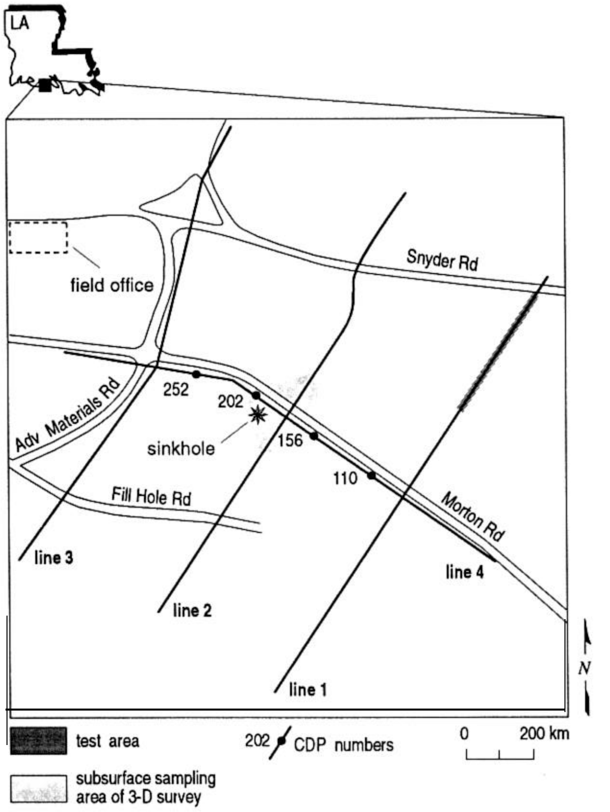

Figure 1. Site map indicating the relative location of Weeks Island and the survey orientation.

DATA ACQUISITION

Data for this study were acquired on a 48-channel EG&G Geometrics 2401x seismograph. The seismograph amplifies, filters (analog). digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. Analog filters have an 18 dB/octave rolloff from the selected -3 dB points. A 1/2 ms sampling interval and a record length of 500 msec were used. A 500 Hz high-cut filter with a 24 dB/octave rolloff acted as an anti-alias filter and to reduce wind noise. This floating point seismograph possesses a dynamic range that was more than adequate to record high-quality reflection information in the presence of source-generated and cultural noise at this site.

Walkaway noise tests were conducted on the northeast end of line I (Figure I). The source (E-gauge auger gun) (Healey et al., *1991)* and receivers (3 Mark Products L28E 40 Hz) were selected

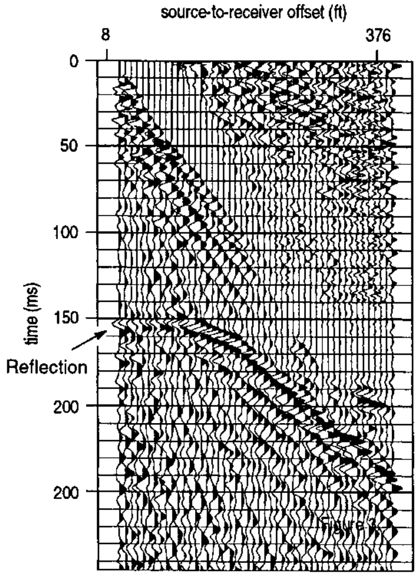

Figure 2. Walkaway noise test with analog low-cut filters of 100 Hz.

based on field conditions and previous experience. On-site testing concentrated on source/receiver geometries and recording parameters. Test data were recorded with analog low-cut filters out, 50 Hz, 100 Hz, and 200 Hz and source-to-receiver offsets ranging from 8 to 376 ft with adjacent stations separated by 8 ft (Figure 2). A strong reflection with a zero-offset time of about 140 to 150 msec possesses a calculated NM0 velocity of about 2100 ft/sec and correlates to a depth of around 150 ft: The data quality was sufficient to allow selection of optimum parameters and’geometries for acquisition of data at this site targeting reflectors between 50 and 250 ft deep.

Direct waves, refractions, ground roll, reflections, and air-coupled waves can all be identified on the walkaway data (Figure 2). The direct wave possesses a very uniform 1700 ft./sec velocity from the source out to about 300 ft of offset. The refraction is interpretable from about 304 ft to the end of the spread (376 ft), with an apparent linear velocity of about 11,000 ft/sec (this is an unreversed velocity and considering the local dip and topography is probably 20% to 30% higher than the true velocity). Two-layer refraction analysis places this first significant acoustic interface at a depth of about 130 to 140 ft. The previously identified 150 msec reflection possesses the greatest resolving power and potential depth control at near source offsets (i.e. < 200 ft). The prominent reflection may be from the same interface as the refracted waves.

The production portion of the survey took just over 2 days and included 673 shotpoints along three northwest/southeast lines and one southwest/northeast tie line. Based on the walkaway data and the dynamic range of the recording instrument, the source and receiver -geometry was split-spread-with a source-to-nearest-receiver spacing of 12 ft and a furthest offset of 196 ft. The recording parameters included an analog low-cut filter of 50 Hz. The 8-gauge auger gun allowed detonation of a 400 grain black powder load 2 to 3 ft below the ground surface in a water saturated, tightly stemmed 2” hole. The rough wooded terrain, rubble and fill material, shallow tree roots, as well as the narrow paths made the auger gun an ideal source for the conditions and the required data quality. The three geophones were placed in a 3 ft in-line array to help attenuate source-generated air-coupled waves. The source was detonated in and the receivers were planted into competent material beneath the organic surface layer. Identification of various unique arrivals on the walkaway data allowed for confident selection of parameters and geometries used for the CDP portion of the survey. A 3-D test was also performed that consisted of 45 shotpoints and was located near the sinkhole along lines 2 and 4.

DATA PROCESSING

Data processing was done on an Intel 80486-based microcomputer using *Eavesdropper,* a set of commercially available algorithms. The processing flow was similar to those used in petroleum exploration (Yilmaz, 1988). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, and extra care during muting operations. A very low percentage allowable NM0 stretch (< 20%) was extremely critical in avoiding wide-angle reflections, maximizing resolution potential, and avoiding distortion in the stacked wavelets. Many processing techniques that have not routinely been effective on shallow data sets (including f-k migration, deconvolution, and f-k filtering) were tested to evaluate their potential on this data set. Processing/processes used on these data has/have been carefully executed with no *a priori* assumptions and with care not to create anything through processing, but to simply enhance and correct what can be interpreted on unstacked data.

The experimental 3-D reflection array was collected at the intersection of line 2 and line 4. This data set possesses 1-fold redundancy and was processed using parameters established through analysis of 2-D data from line 2 and line 4. The data have been filtered, scaled, muted (based on source offset), elevation corrected, deconvolved, sorted (binned), NM0 corrected, and displayed. The software used was a special set of algorithms developed in association with *Eavesdropper* for the PC.

RESULTS

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. Raw field files acquired during the production portion of the survey from each line have reflection events identifiable between 70 and 150 msec. The reflections have an average dominant frequency of approximately 80 Hz and an apparent NM0 velocity ranging from 1350 to 2100 ft/sec. These would result in an approximate depth to the reflector of between 80 and 150 ft. All depth estimates in this paper assume flat-lying reflectors, i.e., no DMO corrections were made. The signal-to-noise ratio on the raw field files is very good and allows confident identification of reflections on 90% of the raw field files.

The shallowest significant acoustic impedance contrast suggested from analysis of first arrival information on field files was a layer that varied in depth from approximately 150 ft in the northern part of the survey area to less than 70 ft in the south (the surface elevation changes about 70 ft across this same expanse of line and is probably responsible for most of this depth change). Based on direct wave and refraction analysis, the near-surface material across the entire survey area ranges in velocity from 1200 to 2000 ft/sec. The first refracting horizon possesses an unreversed phase velocity of between 7,200 and 11,000 ft/sec. Based on refraction analysis performed on most files with an interpretable first-arrival crossover and the lack of any indication of reflection information shallower than the previously identified prominent reflection arrival, data processing beyond brute stack focused on enhancing events deeper than 100 msec.

A strong coherent event can be interpreted across the nominal 24-fold CDP stacked sections (Figure 3). Data are processed relative to multiple sloping datums (as many as five on some lines). There is but a single, confidently correlatable event above 200 msec. The irregularity of the reflector, as interpreted on the stacked data is very suggestive of either a highly variable (dissolved/faulted and folded) surface or significant velocity variation in the near surface. From analysis of field files very little variation in velocity of direct refracted and reflected waves is observed within the length of a spread. However, across the expanse of an entire line the near-surface velocity may change by as much as 30%. The single strong reflection event ties extremely well line-to-line.

The uniformity in the near-surface material and the lack of significant elevation variation across line 4 was probably key to the quality of this stacked section (Figure 3). With the dominant stacked reflection frequency about 80 Hz and an approximate average velocity of 1500 ft/sec, the vertical resolution based on 1/4 wavelength criteria of Widess (1973) is approximately 5 ft and the radius of the first Fresnel zone is about 25 ft. The most striking feature on this line is the depression between CDP 180 and 210. This area is directly adjacent to the sinkhole. Based on the stacking velocities, the depth to the reflecting interface at the edge of the disturbed zone is about 75 ft. The depth of the depression, as interpreted from the seismic data, is about 15 ft. If the diameter of this subsurface depression is significantly less than the radius of the first Fresnel zone, the depression could extend vertically much more than the suggested 15 ft and not be resolved with these data.

The reflection event is very coherent and well defined on the northern end of the three north/south lines, but data acquired south of Morton Road possess decreased signal-to-noise ratio and reflection wavelet bandwidth. The dominant frequency north of Morton Road is about 80 to 100 Hz with a drop to about 50 to 70 Hz on the south. The near-surface velocity ranges from 2000 ft/sec to less than 1200 ft/sec, while the stacking velocity ranges from 2300 ft/sec to 1900 ft/sec. These changes in-velocity do not correlate to the bandwidth decreases and are-not a surprise, based on the variability of the surface material and elevation across the three north/south lines.

Several localized irregular features interpreted on the north/south lines are suggestive of significant offset or rapid changes in the surface of the reflection. Most of these features have no significant surface disturbance responsible for their appearance, The surface of the reflector on the south seems to be much smoother with less abrupt changes than on the north. All the north/south lines possess a distinct change in data characteristics about midway through the line, suggestive of either changes in the reflecting interface or changes in the material between the reflector and the ground surface.

Some of the very well defined offsets in the reflection interpreted on the north/south lines have a very narrow offset zone and no apparent energy scatter associated with them. These offsets may relate to lineament and shear zones previously suggested, from remote sensing methods, to be present on Weeks Island (Martinez et al., 1976). It is very likely, based on the general appearance of the reflection, that some of these offset features are the effects of the formation of the dome and not recent dissolution.

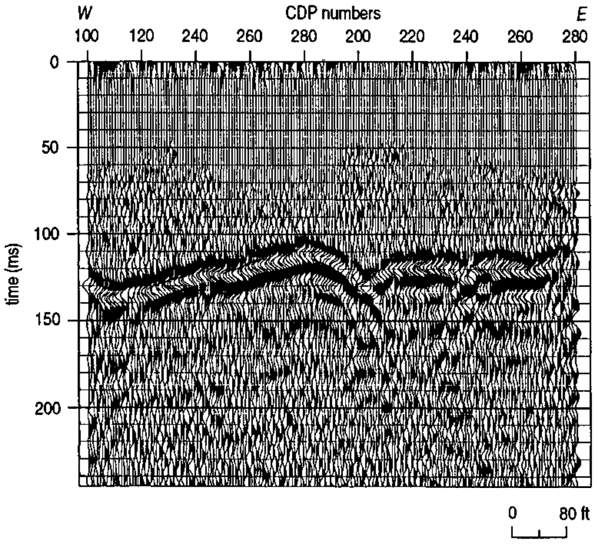

Figure 3. 24-fold CDP stacked section of line 4.

The sinkhole seems to lie along the northern edge of a lineament defined by a distinct drop in both bandwidth and resolution on the southern end of the three north/south lines. Long linear features have been suggested previously on Weeks Island. Water seeps, vertical chimneys, and highly folded black salt identified within the Weeks Island salt mine prior to its use as a petroleum storage facility were suggested to be related to these shear zone boundaries (Martinez et al., 1977). The distinct change in wavelet characteristics on seismic data represents an apparent boundary of unknown origin.

Line 2 passes within about 50 ft of the eastern edge of the sinkhole. The portion of line adjacent to the sinkhole does not seem to detect any significant change associated with the subsidence. The presence of the sink may have affected the reflection interpreted north of the intersection of lines 2 and 4. The apparent subsurface disturbance extends from about the southern road ditch to about the middle of the wooded area between Morton Road and Snyder Road. If this depression in the reflector is related to subsidence, additional subsidence could occur.

The depth to the reflector changes slightly across line 4. As a result of the lower stacking velocity on the east end of the line, the calculated depth to the reflector is relatively consistent between 75 and 80 ft between CDP 10 and CDP 180. The stacking velocity increases from about CDP 250 to the west end of the line. This increased stacking velocity corresponds to an increase in depth to the reflector on the west (CDP 260 = 94 ft; CDP 250 = 110 ft). The only other noteworthy features on line 4 are the changes in reflection wavelet character observable at CDP 110 and 240. These changes in wavelet characteristics are similar to those observed on all three north/south lines. Based on the stack of line 4, the anomaly observed in the 120 msec reflection between CDP 180 and 210 is directly related to the surface subsidence near CDP 200.

Forty-five shotpoints of 1-fold 3-D data were acquired with the center of the profile at the intersection of lines 2 and 4 (Figure 1). The data for the 3-D survey were acquired coincident with the acquisition of line 4. Maintaining a fixed spread, the source was walked south along line 2, crossing Morton Road and line 4 until 24 shotpoints south of line 4 had been recorded. The survey effectively consisted of a fixed 48-channel, 376 ft split-spread source/receiver geometry between stations 66 and 113 on line 4 with 48 unique off-line offsets, each separated by 8 ft and starting 188 ft north of the intersection of lines 2 and 4 and ending 188 ft south of that intersection. The surface configuration of this 1-fold survey was a 90-degree cross with the 48 shotpoints along one arm and the 48 receivers along the other.

The data quality (i.e., signal-to-noise) of the 3-D data was sufficiently high to allow a representative interpretation of the data when displayed in a volumetric wiggle-trace diagram (Figure 4). The processing parameters were determined using the analysis already completed for lines 2 and 4. The lack of redundancy would have inhibited accurate processing of the 3-D data without the 2-D data. Even with the 2-D to assist with parameter selection, the signal enhancement potential of multi-fold data would have improved the signal-to-noise and wavelet consistency. The resulting data clearly show the depression on the surface of the prominent reflector identified on the high-fold 2-D lines.

Incorporating the interpretations of the 2-D data and the 3-D data should present a picture of the subsurface that will determine precisely if the sinkhole is a single chimney feature or an elongated dissolution pattern with the major axis approximately northeast/southwest. Both interpretations put the area including Morton Road at risk of subsidence. It is suggested on some of the 3-D displays that some separation exists between the present sinkhole's subsurface expression and the apparent subsurface subsidence interpreted on the 2-D line 2.

CONCLUSIONS

Both the 24-fold 2-D and single-fold 3-D reflection data display a single coherent reflection at two-way times between .090 and .155 seconds. The reflection is clearly evident both on raw field records and on processed data. Identification of the reflecting interface will be made using data from borehole investigations currently planned for the sinkhole site. Seismic velocity information derived from the data (e.g., stacking velocities, direct and refracted arrival velocities, etc.) places the reflector at a depth between 75 and 150 ft below the ground surface. Lateral velocity gradients in the overlying soil are suggested by substantial stacking velocity variations across some of the lines. The reflector undergoes a significant depression or time delay beneath the surface expression of the sinkhole. This features does not appear to be related to near surface topography or lateral velocity changes. The 2-D data alone are insufficient to delineate the lateral extent of this feature. Incorporation of the single-fold 3-D seismic and borehole data is expected to substantially improve the ability to determine the lateral extent of the collapse feature in the subsurface.

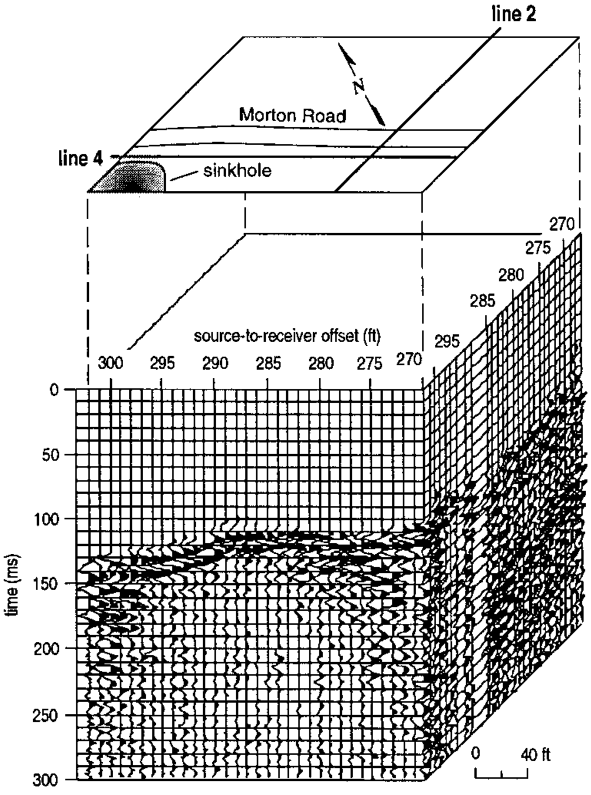

Figure 4. 3-D volumetric seismic section.

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