KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 90-32

SHALLOW SEISMIC-REFLECTION STUDY OF THE SIEFKES SALT DISSOLUTION SINKHOLE IN STAFFORD COUNTY FOR QUINOCO PETROLEUM

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Disclaimer

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FINAL REPORT TO

QUINOCO, INC.

DENVER, COLORADO

October, 1990

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INTRODUCTION

Subsurface dissolution of salt beds represents a hazard to surface and subsurface structures in many parts of the world. Naturally or artificially induced surface subsidence can occur either gradually or catastrophically. Determination of potential extent of future surface subsidence allows more accurate damage estimates and rehabilitation requirements. Seismic-reflection techniques have successfully detected the presence and extent of subsurface dissolution prior to and during surface subsidence (Steeples et al., 1986; Steeples et al., 1987; Miller et al., 1985; Knapp et al., 1989).

Seismic-reflection surveys offer a powerful method of imaging portions of the subsurface in the vicinity of some sinkholes. The successful use of the technique depends on several key conditions. First and foremost is the existence of acoustic velocity and/or density contrasts between geologic units in the subsurface. The second relates to the ability of the near-surface to propagate high-frequency seismic signal. Finally, the acquisition parameters and recording equipment must be compatible with the proposed target and required resolution of the survey.

This report displays and interprets seismic-reflection data acquired by the Kansas Geological Survey (KGS) on contract to Quinoco Oil Company to study the gradually subsiding Siefkes sinkhole in Stafford County, Kansas (fig. 1). A total of 352 shotpoints on two approximately 1/2-mile long crossing lines were collected on 5-m centers. The seismic data were processed into nominal 12-fold CDP stacked sections with a 2.5 m horizontal subsurface spacing interval. Planned line lengths, number of lines, and line orientations were modified prior to beginning the acquisition portion of the survey to better comply with site conditions and natural barriers.

GEOLOGIC SETTING AND SUBSIDENCE

Several major salt basins exist throughout North America (fig. 2) (Ege, 1984). The Hutchinson Salt Member of the Permian Wellington Formation underlies a significant portion of south-central Kansas (fig. 3) (Walters, 1977). The thickness of the salt increases from depositional edges on the west and north, an erosional edge on the east, and a facies change on the south to a maximum thickness of over 550 ft in central Oklahoma. This increasing thickness from the edges to the center of the salt is due not only to increased quantities of salt, but also thicker and more interbedded anhydrites. Overlying the salt is the Permian Stone Corral anhydrite (a key seismic marker bed) and approximately 400 ft of Permian shale sequences (red beds).

Salt dissolution can result in surface subsidence at various rates. The dissolution process remains active as long as flowing unsaturated brine solution or fresh water is in contact with a salt bed. This contact results in dissolution of the salt and the formation of a void (generally water filled) within the salt bed. In most cases, sufficient data (geologic or geophysical) do not exist to predict rate of subsidence prior to the surficial expression of subsurface dissolution.

Natural dissolution of the Hutchinson Salt is not uncommon in Kansas (Ege, 1984). Surface subsidence associated with natural salt dissolution occurred in Meade County, Kansas, in 1879. Faults extending through the Pleistocene sediments (sediments containing fresh water under hydrostatic pressure) are postulated as the conduits instigating the salt dissolution that eventually resulted in the Meade County sinkhole (Frye and Schoff, 1942). Paleo-sinkholes resulting from dissolution of the Hutchinson Salt prior to Pleistocene deposition have been discovered with high-resolution seismic-reflection surveys (Steeples et al., 1984). Natural dissolution of the Hutchinson Salt has been occurring for millions of years.

Land subsidence associated with salt mining and petroleum-related brine disposal has been documented in Kansas for at least the last 70 years (Walters, 1977). In cases related to solution salt mining, sinkholes generally have been the result of roof rock failure. Casing failure or faulty surface grouting have allowed petroleum by-product disposal wells to become conduits to the Hutchinson Salt (unsaturated brine solutions). Sinkholes related to brine disposal wells result from roof failure similar to sinkholes associated with solution mining of salt.

FIELD PARAMETERS

Three CDP seismic-reflection lines were acquired with nominal 24-fold redundancy (fig. 1). The lines were roughly centered on and intersect at the Siefkes disposal well. Lines 1 and 2 were acquired during March 1989 with line 3 acquired in March 1990. The original two lines (1 and 2) were collected with extremely dry near-surface conditions and abnormally high winds. It was determined, after digital processing lines 1 and 2, more subsurface information was needed east of the north-south county road. The third line was then acquired using the results of lines 1 and 2 to determine line length and location.

An extensive series of walkaway-noise tests was conducted prior to production acquisition (table 1). The compacted, dry near-surface sandy material made it impossible to use the downhole .50 cal. seismic source (the source of choice at this site, for this geologic target) and forced the use of a silenced .50 cal. surface gun. The .50-cal. silencer reduces source generated air coupled waves and acts as a containment device for stray debris. The surface configuration of the .50 cal. is not as energetic and does not generate as high and broad a bandwidth signal as the .50 cal. in the downhole mode (Steeples, et al 1987). The receiver array consisted of 3-40 Hz geophones equally spaced over approximately 1 m and centered on each station. The receiver array was designed in an attempt to attenuate some of the source-generated noise. The acquisition parameters and equipment for lines 1 and 2 were optimized for the less-than-ideal site conditions.

Significant changes in both the near-surface conditions and land-access privileges during the March 1990 survey necessitated a new set of walkaway-noise tests for line 3 (table 1). Improved near-surface conditions allowed the use of the .50 cal. downhole gun. In the downhole configuration of the .50 cal., the gun barrel is lowered down an augered hole approximately 6 cm in diameter and 0.6 m deep. The downhole placement of the barrel greatly reduces both the source-generated air-coupled waves and the thickness of low velocity highly attenuative near-surface material that the seismic energy must travel through. Station spacing was identical to the 1989 survey as were the receiver arrays and source/receiver geometries. Consistent with the 1989 survey, the acquisition parameters and equipment were optimized to the site conditions and geologic target.

Table 1.

	3/90	3/91
Station increment	5 m	same as 3/90
Receiver array length	1.5 m	same as 3/90
Split-spread intervals *	10 - 125 m	same as 3/90
Source	.50 cal. surface	.50 cal. downhole
Receivers	L28E Mark Prod.	same as 3/90

* Source-to-nearest-and-farthest-receiver distance

The source/receiver geometry on all three lines resulted in a nominal 24-fold data set. Most shot locations were occupied twice, once pushing the 24-channel spread from low-numbered stations to high-numbered stations and then reversed, pushing the same spread from high-numbered stations to low-numbered stations. This acquisition procedure results in a pseudo 48-channel symmetric (with respect to the source location) split-spread geometry with two consecutive groups of 24 channels separated by three stations.

The 24-channel data were analog filtered, amplified, A/D converted (11 bit plus sign), and recorded on an Input/Output DHR-2400 seismograph. Analog low-cut filters helped to enhance the data bandwidth by decreasing the amount of low-frequency noise, allowing increased gaining of incoming post-filtered signal. The analog low-cut filters selected have a 24 dB/octave roll-off with a -3 dB point of 110 Hz for line 3 and 55 Hz for lines 1 and 2. The relatively severe analog low-cut filtering increased the dominant reflection frequencies and therefore improved the potential vertical and horizontal bed resolution.

DATA PROCESSING

The CDP data were processed at the KGS using a proprietary set of algorithms developed by Sytech Co. The processing flow was very similar to routine petroleum sequences with the exception of the severity and accuracy of the muting processes and the emphasis placed on near-surface velocity analysis (table 2). Extreme care was used during the editing processes to ensure removal of all non-seismic energy that could either be misinterpreted as reflections on stacked data or that hampered interpretations of real reflection events. Velocity analysis incorporated iterative constant velocity stacking with detailed surface-consistent statics to improve both accuracy of velocity corrections and time/depth conversion on interpreted cross sections. The general processing flow resulted in a nominal 24-fold CDP stacked section for each of the three survey lines.

Table 2

Format to SEG-Y
Dead and noisy trace edit
Trace balancing (AGC)
First arrival muting
Surgical muting of coherent noise
CDP sort
Datum statics correction
NMO correction
Surface consistent statics
Bandpass filtering
CDP stack

RESULTS

Reflection energy can be identified on raw field data in a time window between about 80 and 400 ms (fig. 4). Differentiation of reflection energy from seismic noise on field files is essential for confident and consistent interpretations on stacked seismic sections. Refraction arrivals, present as the first breaks (first source-generated energy recorded) on seismograms, were removed with a relatively severe first-arrival mute. Low velocity linear arrivals that can be identified on the nearest-to-the-source trace at about 50 ms and on the farthest-from-the-source trace at about 400 ms are the source generated air-coupled waves. Air-coupled waves were surgically removed from all shot gathers. Ground roll is the low frequency energy clearly visible on inside traces between 10 and 40 m source offset. The low frequency characteristics of the ground roll make attenuation with a properly designed bandpass filter very effective. Dominant frequency of reflection energy is in excess of 100 Hz.

Reflections from the Stone Corral anhydrite can be clearly identified at about 210 ms (fig. 4). The Stone Corral is a good seismic marker bed stratigraphically just above the Hutchinson Salt. The apparent reverse moveout on the Stone Corral reflection on this field file is interpreted to be the result of roof failure of a previous salt-dissolution void. Stone Corral reflections on seismograms from areas with competent salt would appear hyperbolic with a very subtle downward curvature at increasing receiver-to-source offsets. The reflection energy interpretable on this seismogram clearly indicates subsurface collapse.

Seismic line 1 was acquired with a maximum record length of 250 ms (fig. 5). The target on line 1 was the top of the Stone Corral. Faulting and subsidence interpreted on the Stone Corral is assumed to be the result of dissolution of the salt. Normal faults forming horst and graben structures can be interpreted on the Stone Corral reflection. Subtle coherent reflection events observed between CDPs 225 and 275 above the Stone Corral are most likely from within the thick Permian red-bed sequences. The lack of coherent events between the Stone Corral and surface from CDPs 275 to 325 is related to the poor near-surface and environmental conditions. Dissolution in the subsurface extends from approximately CDPs 220 to 320 on line 1.

Seismic line 2 was acquired with a maximum record length of 500 ms (fig. 6). Coherent reflection information is identifiable between approximately 70 and 320 ms. The overall data quality on line 2 is better than line 1 due to decreased wind noise. Line 2 was recorded during late afternoon and into early evening when the strong gusting winds had decreased. The near-surface conditions were consistent for both lines 1 and 2. The Stone Corral reflection can be identified across the entire line. Several reflection events between the Stone Corral and the surface can also be interpreted across the entire expanse of line 2. The interpretative line drawing clearly shows the extent of faulting and the relatively uniform nature of the subsidence in the subsurface. The severity of reflector slump observed on line 2 appears to increase with depth. This apparent decrease in subsidence upward from the salt is probably related to differential compaction.

The predominant structural features on line 2 are the series of normal fault blocks that bound the graben formed as a result of dissolution and subsidence.

Line 3 was acquired east-west and is the most conclusive of the three seismic lines (fig. 6). The dominant frequency of the Stone Corral reflection is clearly in excess of 100 Hz. Subsurface subsidence on line 3 extends from CDP 250 to 340. Normal faults offset the Stone Corral reflection across the entire subsidence area. Only the normal fault interpreted at approximately CDP 325 offsets the 80 ms reflecting event. The 80 ms reflection is the shallowest interpreted reflector at a depth of approximately 50 m. Several high-frequency events are interpreted between the 80 ms reflection and the approximately 200 ms Stone Corral reflection. The relatively uniform, gradual slump of reflectors overlying the dissolved salt can be observed on all three lines.

The potential future surficial expression of dissolution voids in the Hutchinson Salt can be extrapolated from interpretations on the Stone Corral reflection (fig. 7). The dashed portions of the interpreted future sinkhole represent speculative interpolation between control points on the associated seismic lines. The apparent eastward elongation of the future sinkhole along line 3 indicates subsidence of the Stone Corral reflector (as indicated seismically by distortion of the Stone Corral reflection) was probably active along the eastern edge between March 1989 and March 1990. This ongoing subsidence of the Stone Corral may be indicative of active dissolution or delayed roof failure along the eastern portion of the salt void.

CONCLUSIONS

Optimum recording parameters for each line were selected after two separate extensive series of walkaway-noise tests, one for each trip (table 1) (Steeples and Miller, 1990). Adverse near-surface and environmental conditions, detrimentally affecting both geophone plants and propagation of high frequency seismic-reflection information, strongly contributed to a low signal-to-noise ratio on the 1989 survey. Improved site conditions on the 1990 survey allowed use of the downhole .50 cal. gun and 110 Hz low-cut filters which (in comparison to the 1989 survey) resulted in reduced levels of recorded environmental, instrument, and non-seismic reflection noise.

The subsurface subsidence associated with the Siefkes sinkhole in Stafford County, Kansas (at least as indicated by the Stone Corral anhydrite) seems to have been active as of March 1990. Extrapolation of the surface of the present subsurface dissolution boundaries (as interpreted from the Stone Corral reflection) suggests a potential four-fold increase in the surface area of the present day sinkhole. At some time in the future, the sinkhole could include part of the east-west and north-south county roads. Dissolution of the salt, as interpreted from seismic data, appears to be slightly asymmetric to the west with respect to the surface location of the abandoned disposal well.

There is no reason to suspect the apparent eastward growth of the subsurface dissolution front between the two acquisition dates has terminated. The actual subsurface dissolution front could be well east of the north-south county road that intersects line 1. It is also not unreasonable to suggest that the northeast boundary (as interpreted from line 2) may now be several tens of meters closer to the intersection of the two county roads. No seismic evidence exists (on the three seismic lines reported here) to suggest the surficial expression of the subsurface subsidence will reach the intersection of the north-south and east-west county roads. The north-south county road will eventually be affected by the salt dissolution which has already resulted in subsurface subsidence (as interpreted on the Stone Corral anhydrite) several tens of meters east of the road.

The interpreted subsurface subsidence on the western boundary appears to be consistent over the span of time between the two acquisition trips. Topographic evidence seems to suggest surface subsidence is presently active along the western boundary. There is no seismic evidence to suggest westward expansion of subsurface subsidence.

The apparent subsurface growth of the dissolution front to the east with no apparent associated surface subsidence suggests this gradually subsiding sinkhole has delay between roof failure of the salt unit and surficial expression. The apparent elongation of the surface expression of the sinkhole to the west over the year between the two acquisition trips with no obvious associated subsurface growth is probably related as well to a delay. The delay between roof collapse of the voids in the salt and surface subsidence is probably not uniform for all parts of the sinkhole. Alternatively, rate of dissolution may vary with azimuth from the center of the sinkhole, in which case the elongation noted above may not be indicative of active dissolution.

The results derived from interpretations of the three seismic lines suggest a continued gradual subsiding of the surface around the abandoned Siefkes disposal well. Due to the apparent active nature of the subsurface subsidence, the maximum future surficial expression of the salt voids and associated roof collapse cannot be ascertained from the three seismic lines collected between March 1989 and March 1990. There appears to be either continued subsurface growth of salt voids to the east or delayed roof failure of previously existing voids in the salt. A return visit to this site in approximately 2 to 3 years with the intent of acquiring data along line 3 should yield far more insight into subsurface growth and rate of roof failure.

ACKNOWLEDGMENTS

We wish to thank Randie Grantham, George Coyle, and Mubarik Ali for their assistance with data acquisition. Also, the work of Esther Price in manuscript preparation and Pat Acker's quality graphics are greatly appreciated.

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FIGURE CAPTIONS

Figure 1. Site map indicating location of three seismic lines and approximate areal extent of the sinkhole.

Figure 2. Major salt basins of North America (Ege, 1984).

Figure 3. Areal extent and thickness of Hutchinson Salt Member (Walters, 1977).

Figure 4. 24-channel field file with Stone Corral reflection indicated.

Figure 5. Pseudo 24-fold stack seismic section of line 1 with associated interpretive line drawing.

Figure 6. Pseudo 24-fold stack seismic section of line 2 with associated interpretative line drawing.

Figure 7. Pseudo 24-fold stack seismic section of line 3 with associated interpretative line drawing.

Figure 8. Figure 1 with the potential future surficial expression of the subsurface subsidence into the voids left after dissolution of the Hutchinson Salt.

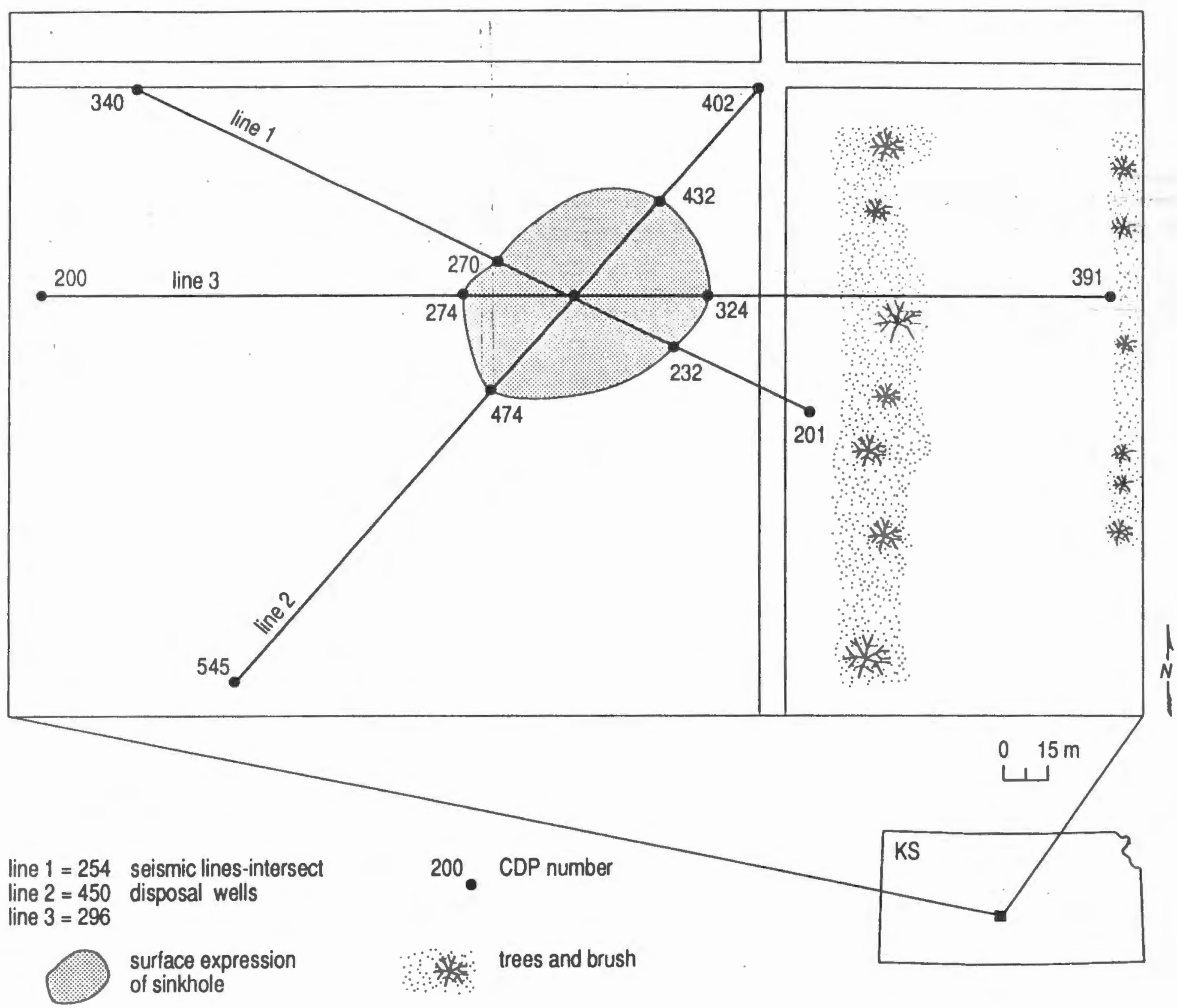
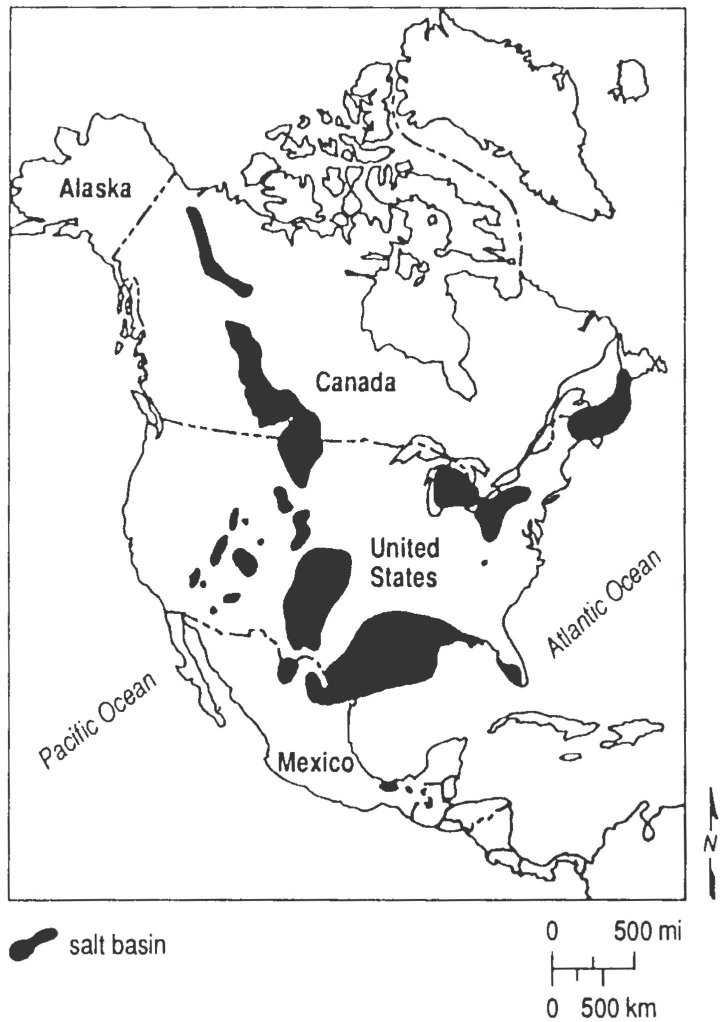

340
line 1
402
432
270
200
line 3
274
324
391
232
474
201
line 2
545
N
0 15 m
KS
line 1 = 254
line 2 = 450
line 3 = 296
seismic lines-intersect disposal wells
200
CDP number
surface expression of sinkhole
trees and brush

figure 1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United States
Mexico
Pacific Ocean
Atlantic Ocean
N
salt basin
0 500 mi
0 500 km

figure 2

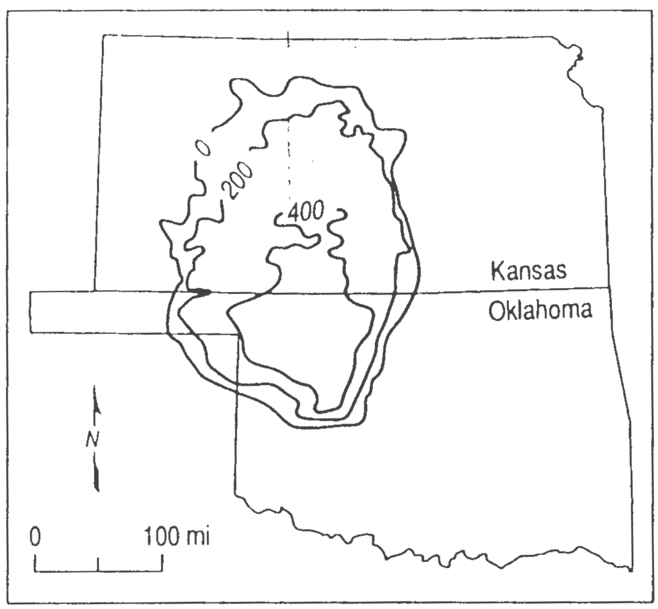


figure 3

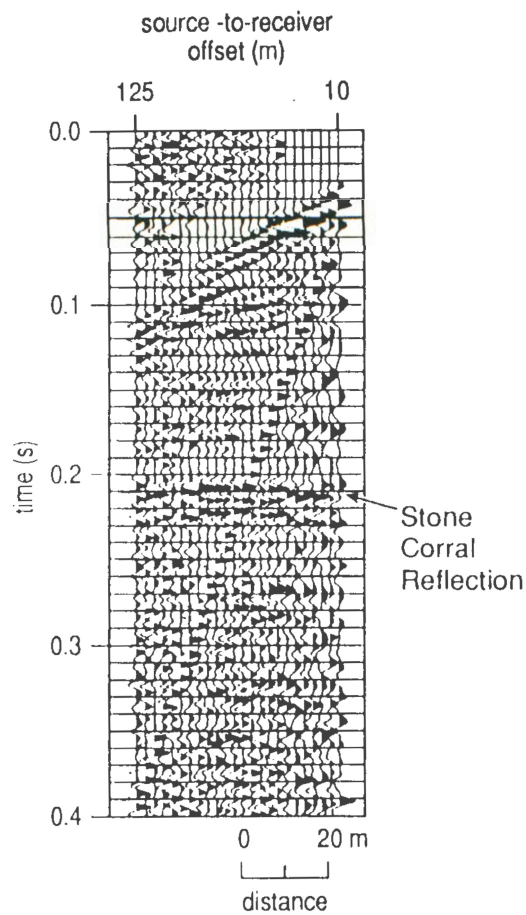

source -to-receiver
offset (m)
125
10
0.0
0.1
0.2
0.3
0.4
time (s)
Stone
Corral
Reflection
0
20 m
distance

figure 4

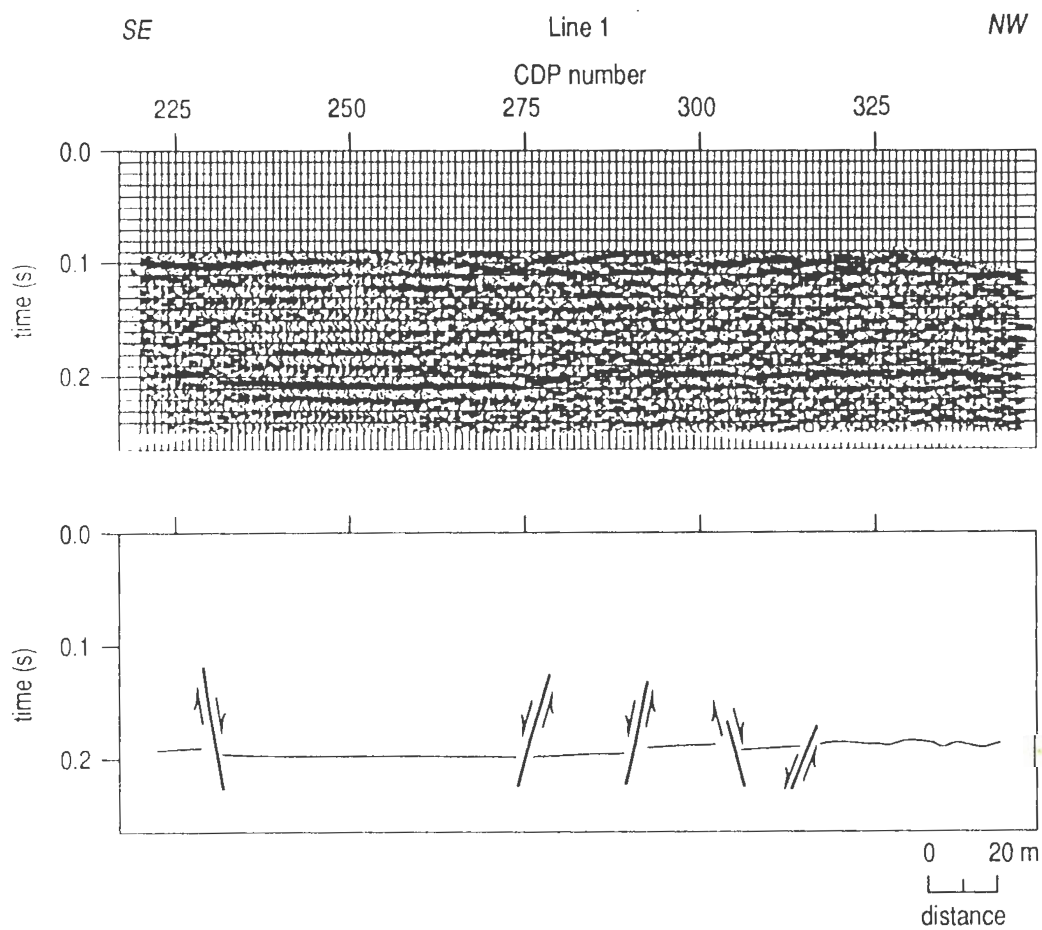
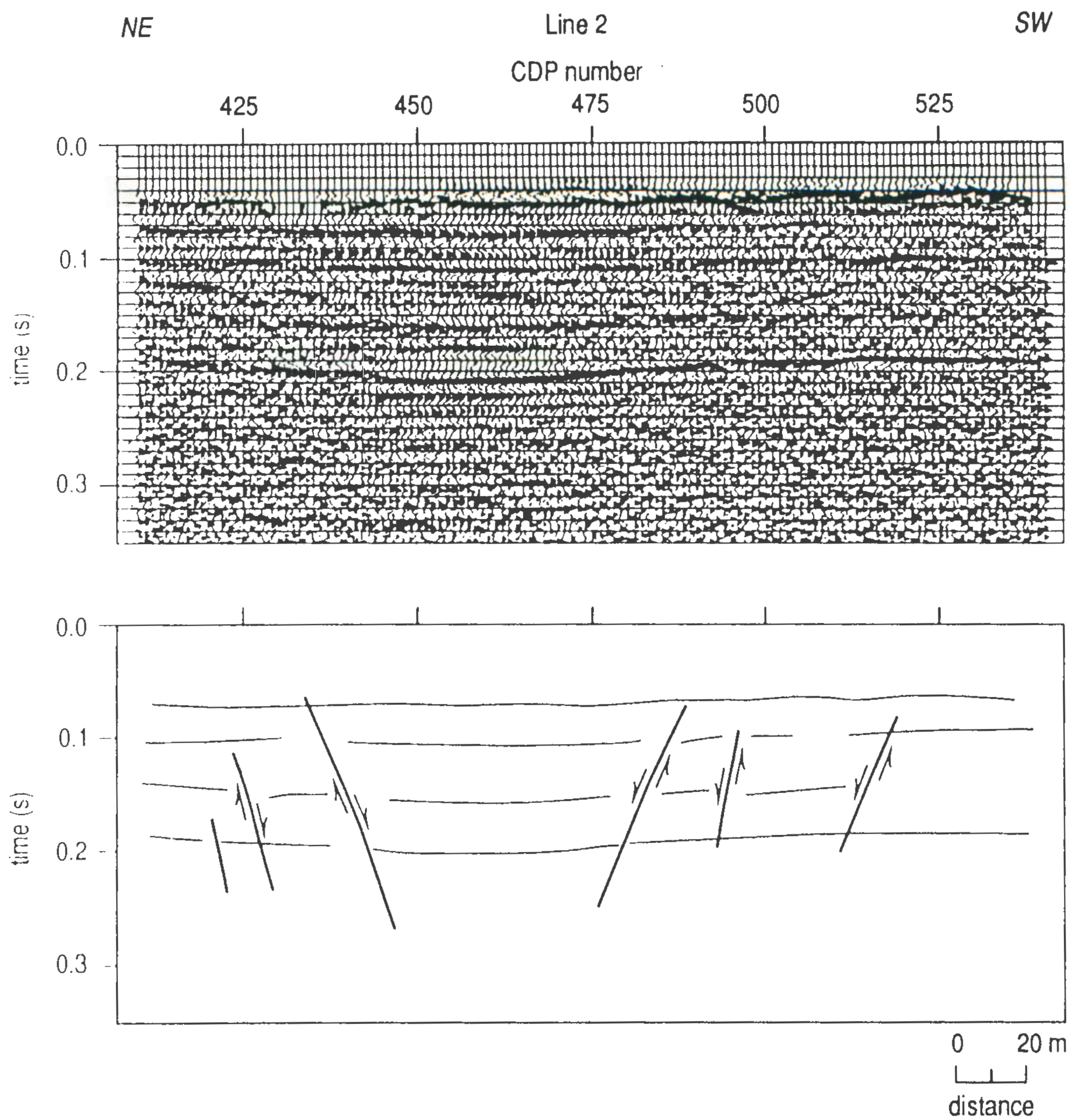

SE
Line 1
NW
CDP number
225
250
275
300
325
0.0
0.1
0.2
time (s)
0.0
0.1
0.2
time (s)
0
20 m
distance

figure 5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Line 2
SW
CDP number
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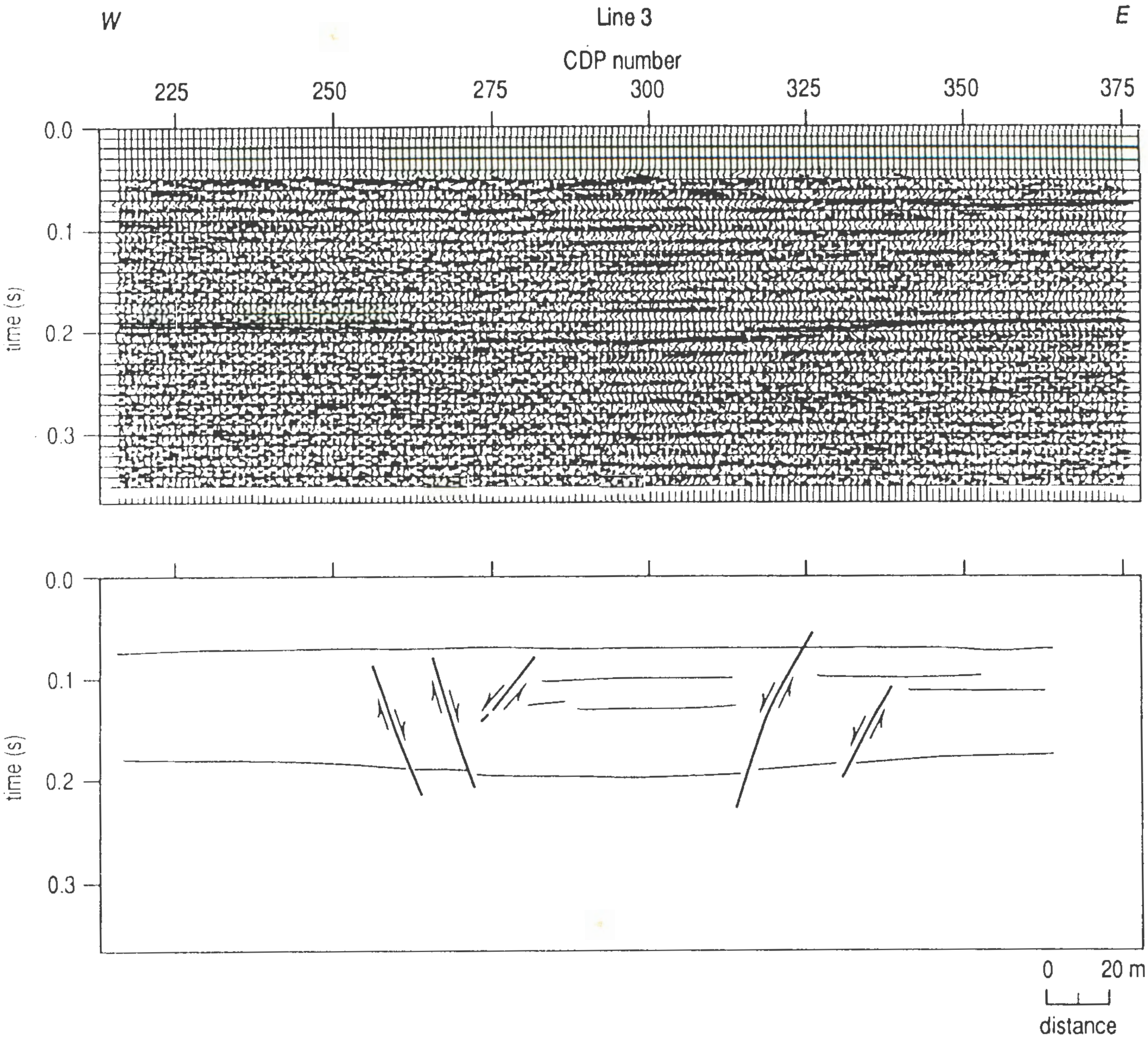
450
475
500
525
0.0
0.1
0.2
0.3
time (s)
0.0
0.1
0.2
0.3
time (s)
0
20 m
distance

figure 6


W
Line 3
E
CDP number
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250
275
300
325
350
375
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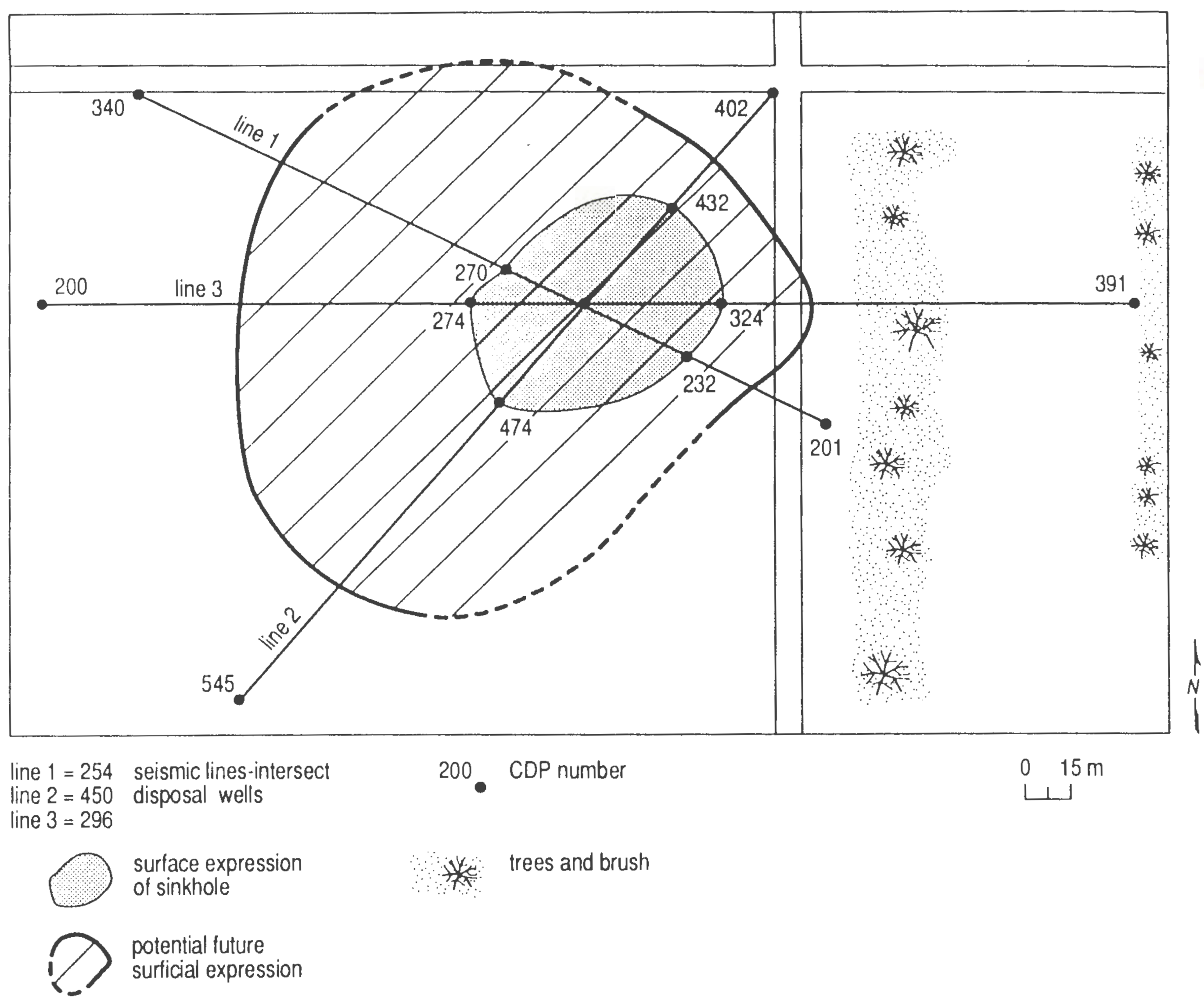
0.1
0.2
0.3
time (s)
0
20 m
distance

Figure 7



340
line 1
402
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line 3
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474
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line 2
545
N
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line 2 = 450
line 3 = 296
seismic lines-intersect
disposal wells
200
CDP number
0 15 m
surface expression
of sinkhole
trees and brush
potential future
surficial expression

figure 8