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Final Report to North American Salt Company
Hutchinson, Kansas

by

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FINAL REPORT TO

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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 the 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, 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) for North American Salt Company. The target of the seismic survey was a gradually subsiding sinkhole within a salt dissolution well field in Reno County, Kansas (fig. 1). A total of 351 shotpoints were collected on 8 ft centers along three interconnecting profiles. The seismic data were processed into pseudo 24-fold CDP stacked sections with an 8 ft horizontal subsurface sampling interval. Planned line lengths, number of lines, and line orientations were slightly modified prior to beginning the acquisition portion of the survey to maximize the effectiveness of the entire feasibility study.

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 (Miller 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 for 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 12-fold redundancy (fig. 1). The lines, which intersect less than 20 ft northeast of well 30, were laid out to maximize subsurface information near the sinkhole. Several dissolution wells (22, 23, 29, 39, and 92) potentially effecting the seismic data acquired along line 1 are too far off-line to confidently correlate to CDP locations on the site map.

A series of walkaway-noise tests were conducted prior to acquisition of the production seismic lines. The spectral and total energy characteristics of the downhole .50 cal. seismic source (Steeples, et al., 1987) made it the source of choice at this site, for this geologic target. 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. 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 (Steeples and Miller, 1990). Analysis of the noise tests allowed acquisition parameters and equipment to be optimized for the site conditions.

The production lines were acquired using an end-on source/receiver geometry. Analysis of the walkaway data allowed determination of an optimum source-to-nearest-receiver offset of 64 ft and source-to-farthest-receiver offset of 248 ft. The very attenuative near surface limited the maximum source-to-receiver offset from which high signal-to-noise ratio information could be recorded. One shot was fired into each 24-channel spread. After each shot was recorded, the 24-channel spread and shot location were uniformly incremented a single station interval (8 ft). This standard common depth point (CDP) roll-along acquisition procedure resulted in nominal 12-channel data sets for each sampled point in the subsurface.

The 24-channel data were analog filtered, amplified, A/D converted (11 bit plus sign), and recorded on an Input/Output DHR-2400 seismograph. The record length is 250 ms with a sampling interval of 0.5 ms. The 1/2 ms sampling interval equates to a sampling frequency of 2000 Hz and therefore an alias or Nyquist frequency of 1000 Hz. A 250-Hz high-cut filter with a 24 dB/octave rolloff acted as an anti-alias filter as well as reduced wind and higher modes of 60-Hz power line noise on line 1. Analysis of selected filter testing indicated that the highest quality and most potentially useful data could be acquired at this site with no low-cut filtering.

DATA PROCESSING

The CDP data were processed at the KGS using a proprietary set of algorithms developed by the KGS (*Eavesdropper*). 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 1). 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. CDP's were summed to increase the signal-to-noise ratio on final stacked sections. The general processing flow resulted in a pseudo 24-fold CDP stacked section for each of the three survey lines.

Table 1

Format to SEG-Y
Dead and noisy trace edit
Trace balancing (AGC)
First arrival muting
Surgical muting of coherent noise
CDP sort (divisor 2)
Datum statics correction
NMO correction
Surface consistent statics
Bandpass filtering
CDP stack

The prominent ground-roll arrivals on raw field files necessitated a severe surgical mute. The mute removed all energy after the first detectable arrival of ground-roll energy. This mute eliminated any chance of extracting useful seismic-reflection energy possibly present at very low signal levels beneath the large amplitude ground roll. After a series of digital filter tests it was determined that no seismic-reflection energy could be extracted from within the ground-roll wedge.

RESULTS

Reflection energy can be identified on raw field data in a time window between about 80 and 190 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, low frequency linear arrivals, identified on field files as ground roll, saturated the A/D conversion processes and were removed with a surgical mute. Air-coupled waves were within the ground-roll envelope and were surgically removed the ground-roll mute. Dominant frequency of reflection energy is approximately 75 Hz.

The effects of the 60 Hz electric lines, paralleling line 1, become obvious when field files from line 1 (fig. 4) are compared to files from lines 2 and 3 (figs. 5 and 6). The dominant 180-Hz component of the power-line noise hampered the use of low-cut filtering during acquisition. The presence of high-frequency, linear power-line noise drastically affected the usefulness of the digital bandpass filter to broaden the bandwidth of reflection energy toward the high frequencies. The overall quality and the resolving power of the seismic-reflection method can be maximized in this area by acquiring data at right angles (or at least oblique angles) to power lines.

Digital filtering and trace balancing of the raw field files increased the signal-to-noise ratio sufficiently to allow identification of reflections on most field files (figs. 4b, 5b, and 6b). Reflection events are easily identified by their distinctive hyperbolic curvature at times between about 80 and 200 ms on traces with source-to-receiver offsets in excess of 100 ft. The effects of variation in the near-surface velocity structure are evident on the line-3 field file (fig. 6) at about 210 ft source-to-receiver offset. The apparent change in slope, not only the reflections but also the refractions, is indicative of near-surface static irregularities. Depths calculated from reflection events interpreted on field files range from 150 to over 300 ft.

Care taken during the acquisition and processing to minimize excessively noisy traces resulted in relatively high signal-to-noise ratio on stacked seismic sections. As addressed earlier, the power lines parallel to line 1 induced a significant amount of linear noise altering the "normal" recording of the processing flow. Train activity was a noise source avoidable with proper care. During the acquisition of line 1, source and receivers were progressing from east to west. The noise generated by approaching trains appears as coherent energy with a linear slope opposite to the direction source-generated seismic energy (fig. 7). After the trains passed the recording spread ,the slope of the coherent train noise is similar to source-generated energy. The effects of cultural noise can be detrimental to the recording of high quality seismic-reflection data.

The three seismic lines intersected approximately 15 ft east of well 30 (fig. 1). The seismic line intersection points can be used to correlate reflections interpreted from one section to the next. Lines 1 and 2 tie at station number 209 and 439. Line 2 ties with line 3 at station number 453 and 551. The tie points allow compensation for subtle static mis-ties between the various lines.

Interpretation of seismic line 1 indicates a subsurface disturbance approximately 150 ft in radius centered near well 30 (fig. 8). The disturbed appearance of the 140 ms reflection interpreted to be from a depth of approximately 250 ft, is probably associated with roof collapse into void(s) left as a result of dissolution. The very non-uniform appearance of reflections that are interpreted to correlate to the top of the collapse feature are consistent with reflections from dissolution sinkholes in this area (Knapp et al, 1989).

Two unique lense looking features, one directly above the subsurface collapse area (approximately station location 210 and 125 ms deep) and the other identified at approximately station location 137 at 110 ms, could be either an interference or stratigraphic phenomenon or related to the dissolution mining process. The general seismic appearances of the individual features are consistent and could suggest a similar subsurface environment. The interpreted lens features (line 1 at stations 210 and 137 and line 3 at station 550) could be indicative of well collapse in the very close proximity of the original well casing. If this is the case then the lens-type features could be early indicators of future collapse around a well head. Another seismic line needs to be acquired to determine exactly what might be indicated by these seismic features.

Evidence exists on the line-1 seismic section for continued eastward subsurface growth (fig. 8). Disturbed coherent events beneath the strong event at 140 ms and between station locations 170 and 190 are stippled indicating an area of potential subsurface collapse of the 140 ms reflection. The suggestion of future eastward surface slumping due to disturbance of the 140 ms reflection is speculative.

The key interpreted feature on line 2 is the subsurface disturbed zone centered on station location 440. The disturbed zone interpreted on line 2 is acoustically very similar to the feature interpreted on line 1 and centered on station 210 (fig. 9). The interpreted subsurface extent of the dissolution is from station 418 to at least station 480 on line 2. Well 30 is located at approximately station location 450 and off line about 15 ft. Some slumping can be observed in the reflection at 110 ms. The short length of line 2 does not allow a good identification of the exact boundaries of subsurface disturbed zone because we do not have enough "normal" background information. In other words, we should have made the seismic lines longer in the field.

The line 3 seismic section suggests the subsurface is disturbed from station 520 to station 560 (fig. 10). A lens-type feature similar to the ones identified on line 1 can be interpreted on line 3 at approximately station 550 at 110 ms. The exact geophysical or geologic explanation for these features is not known at this time. The general character of the seismic signature in the disturbed area on line 3 is consistent with the other seismic lines.

The approximate amount of subsurface subsidence and the relative size of the feature in the subsurface is consistent for all three lines. The general seismic appearance of the disturbance in the subsurface and line-to-line correlation of interpreted boundaries is consistent for all three lines. The subsurface disturbed area is approximately 320 ft across and accounts for almost 20 ft of subsidence.

The interpretation of the seismic data suggests that at some point in the future the sinkhole at well 33 could gradually grow to encompass not only the paved road but also the railroad spur (fig. 11). Without further dissolution, the sinkhole could grow horizontally to roughly 300 ft in diameter. The subsurface disturbance seems to be slightly oblong to the northwest and approximately centered about well 30. There is sufficient evidence to suggest that wells 30 and 41 are probably connected in the subsurface.

There is no way to determine from the seismic data if any dissolution is active at this time. The area identified on seismic line 1 as a potential subsurface collapse area could be a remnant from previous mining activity.

CONCLUSIONS

The subsurface subsidence associated with well 30 seems to correlate to a disturbed subsurface area that includes not only Carey Blvd., but also the railroad spur on the south side of the road. Extrapolation of the present subsurface collapse boundaries (as interpreted from the 140 ms reflection) to the ground surface suggests a potential 16-fold increase in the surface area of the present day sinkhole. Evidence exists to suggest at least a limited subsurface fluid tie exists between wells 30 and 41. Collapse of the 140 ms reflection at the present time is elliptical with the major axis trending northwest/southeast.

There is no way to determine from seismic data when the 140 ms reflection was actively subsiding. It is most likely that the subsurface disturbance as imaged on the seismic data was present long before the formation of the present surficial expression. The relatively coherent and high amplitude signal recorded from the 140 ms reflector could indicate a gradual as opposed to a catastrophic subsurface collapse. It could therefore be proposed that areas with a similar disturbed subsurface could be identified prior to surface subsidence.

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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 from line 1: (a) raw, (b) filtered and scaled. Reflections, refractions, and ground roll are identified.

Figure 5. 24-channel field file from line 2: (a) raw, (b) filtered and scaled. Reflections, refractions, and ground roll are identified.

Figure 6. 24-channel field file from line 3: (a) raw, (b) filtered and scaled. Reflections, refractions, and ground roll are identified.

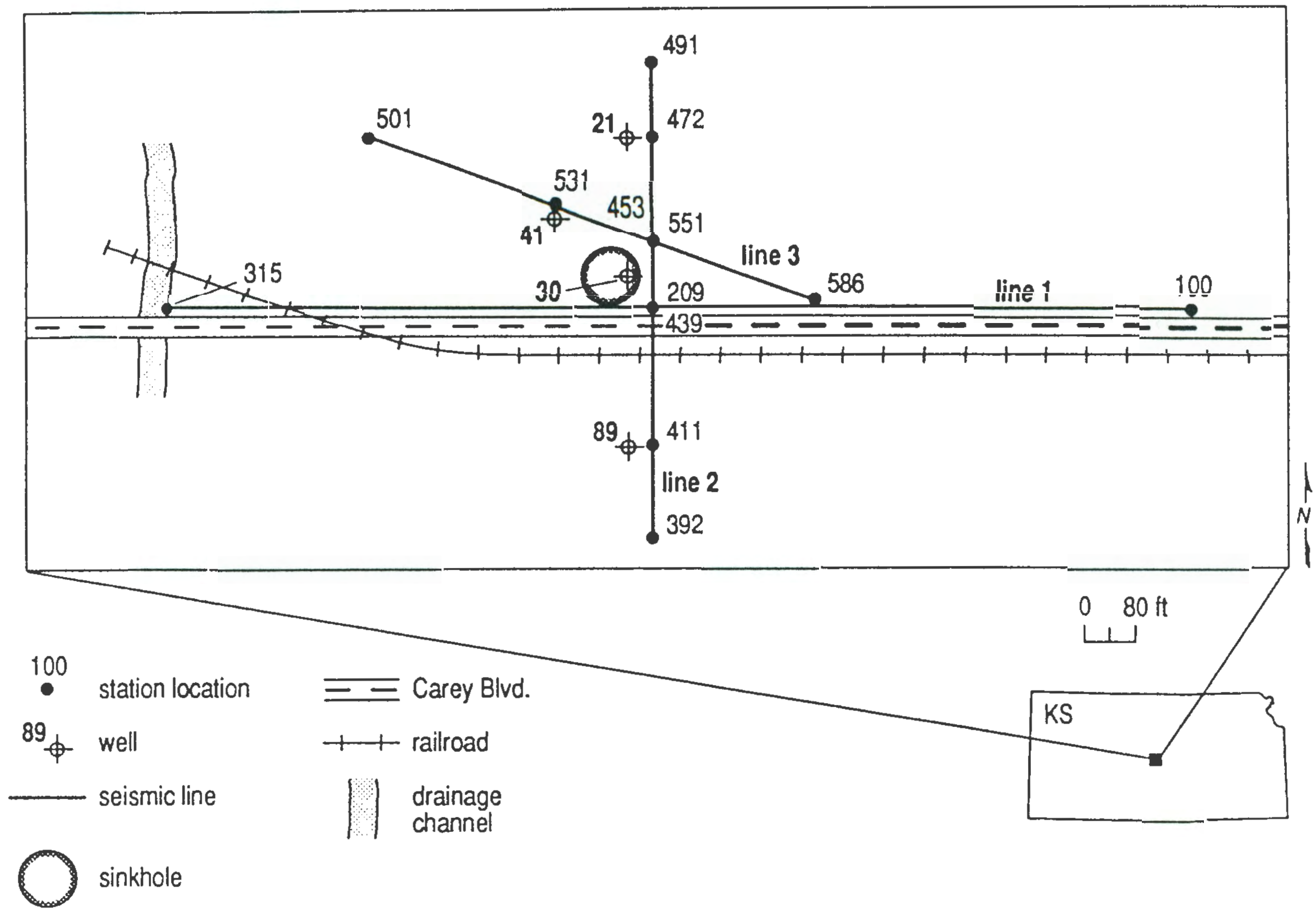
Figure 7. Two 24-channel field files from line 1 showing the effects of train noise on the seismic data: (a) the train is approaching the seismic recording spread, (b) the train is going away from the seismic spread.

Figure 8. Pseudo 24-fold CDP stacked section of line 1 on top and an interpreted version of the section on the bottom. The affected subsurface is indicated with stipling.

Figure 9. Pseudo 24-fold CDP stacked section of line 2 on top and an interpreted version of the section on the bottom. The affected subsurface is indicated with stipling.

Figure 10. Pseudo 24 fold CDP stacked section of line 3 on top and an interpreted version of the section on the bottom. The affected subsurface is indicated with stipling.

Figure 11. Inferred areal extent of the subsurface collapse zone. If the entire subsurface effected area was extrapolated to the surface Carey Blvd . and the railroad spur would be effected by the roof collapse of dissolution salt well 30.



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KS
100
station location
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seismic line
sinkhole
Carey Blvd.
railroad
drainage channel

figure 1

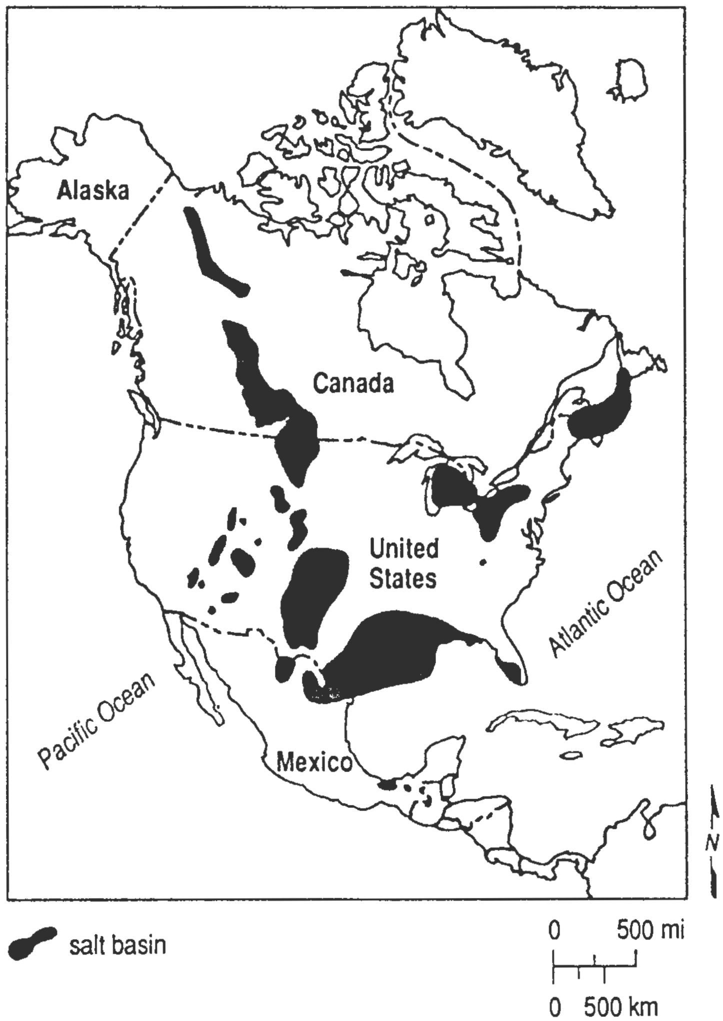
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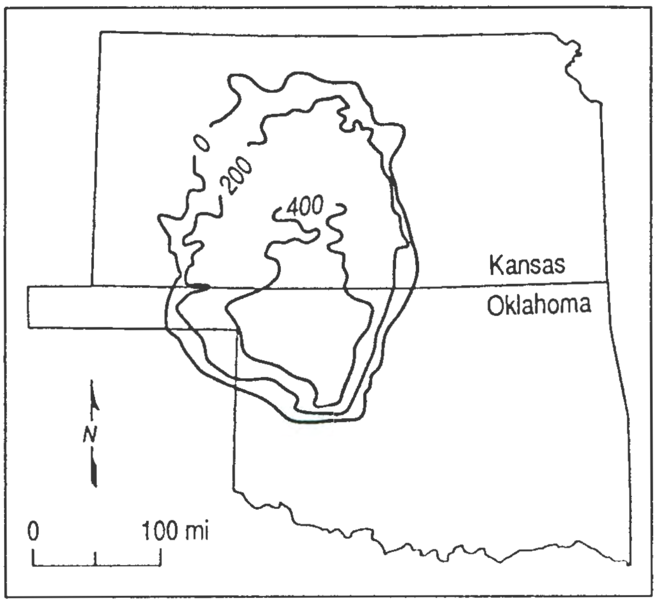
figure 2



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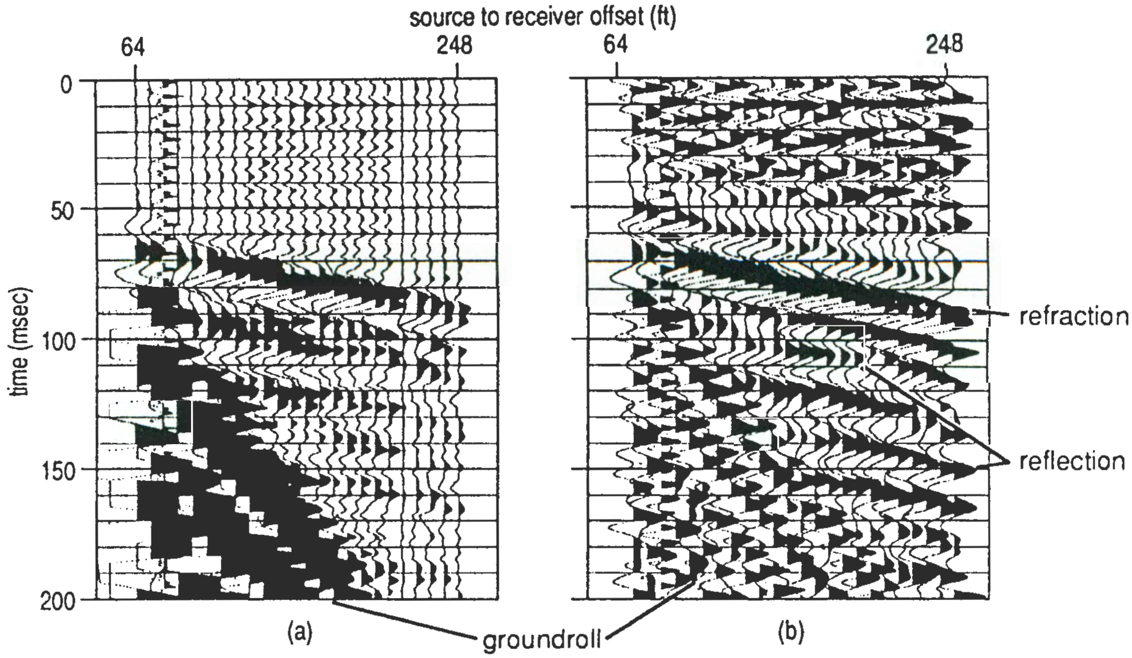
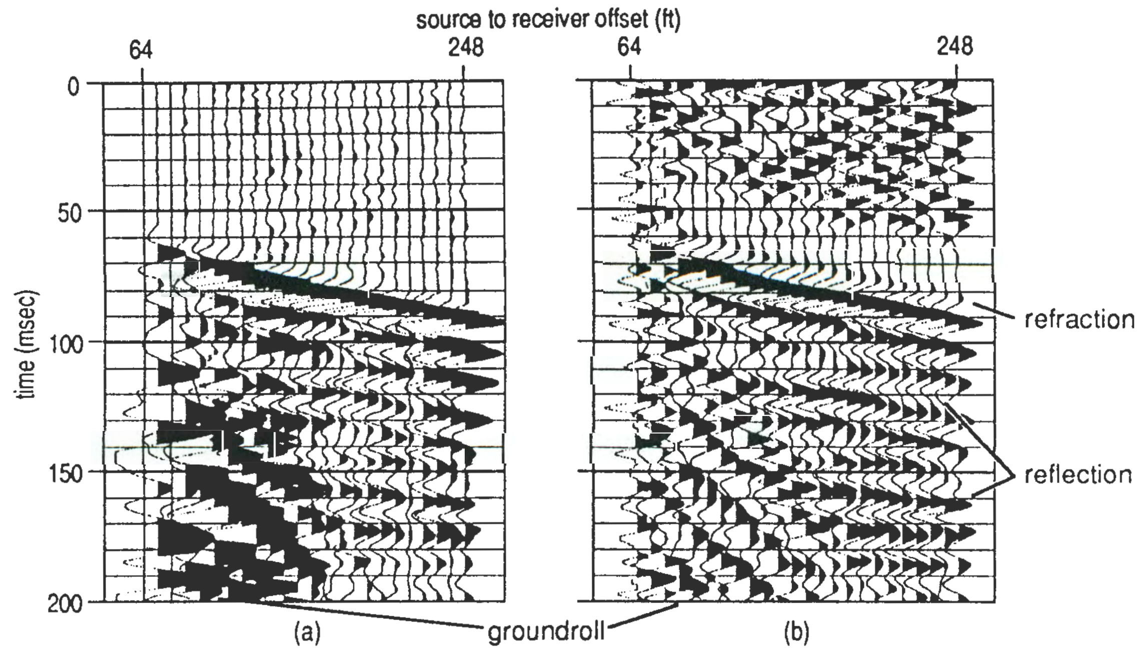


source to receiver offset (ft)
64
248
64
248
0
50
100
150
200
time (msec)
refraction
reflection
groundroll
(a)
(b)

figure 4


source to receiver offset (ft)
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time (msec)
refraction
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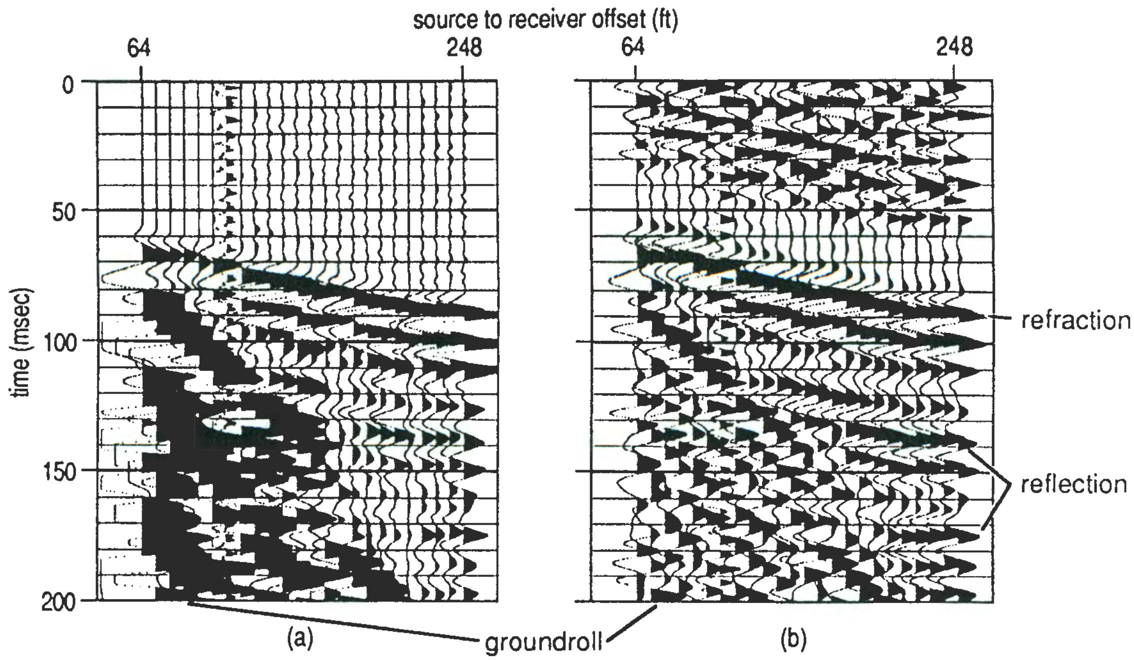
(b)

figure 5



source to receiver offset (ft)
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time (msec)
refraction
reflection
groundroll
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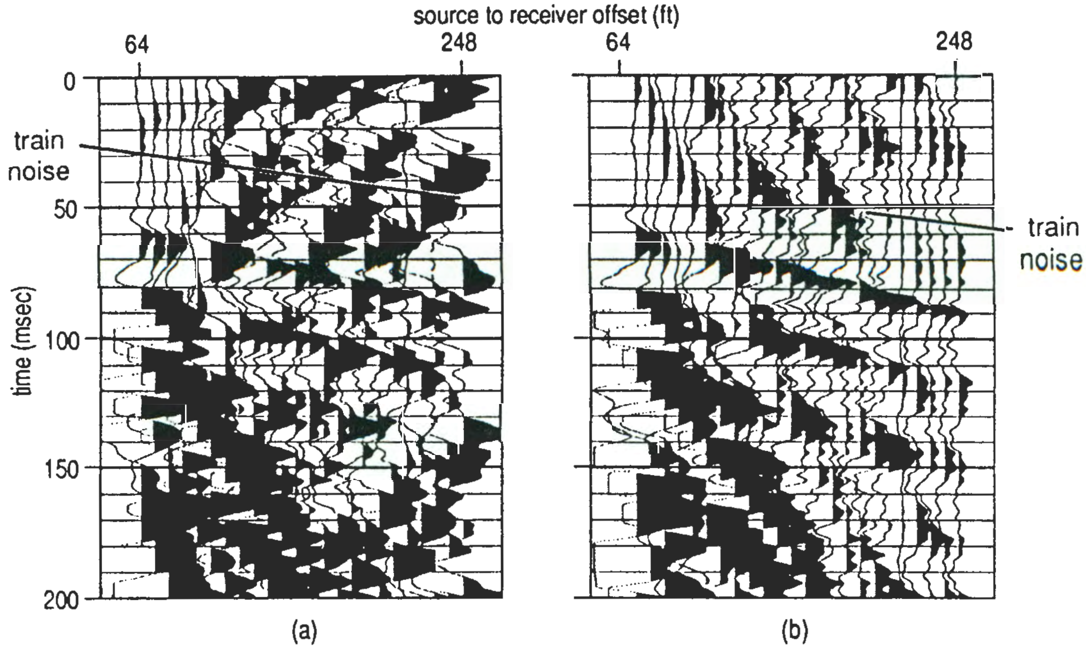
(b)

figure 6


source to receiver offset (ft)
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train noise
train noise
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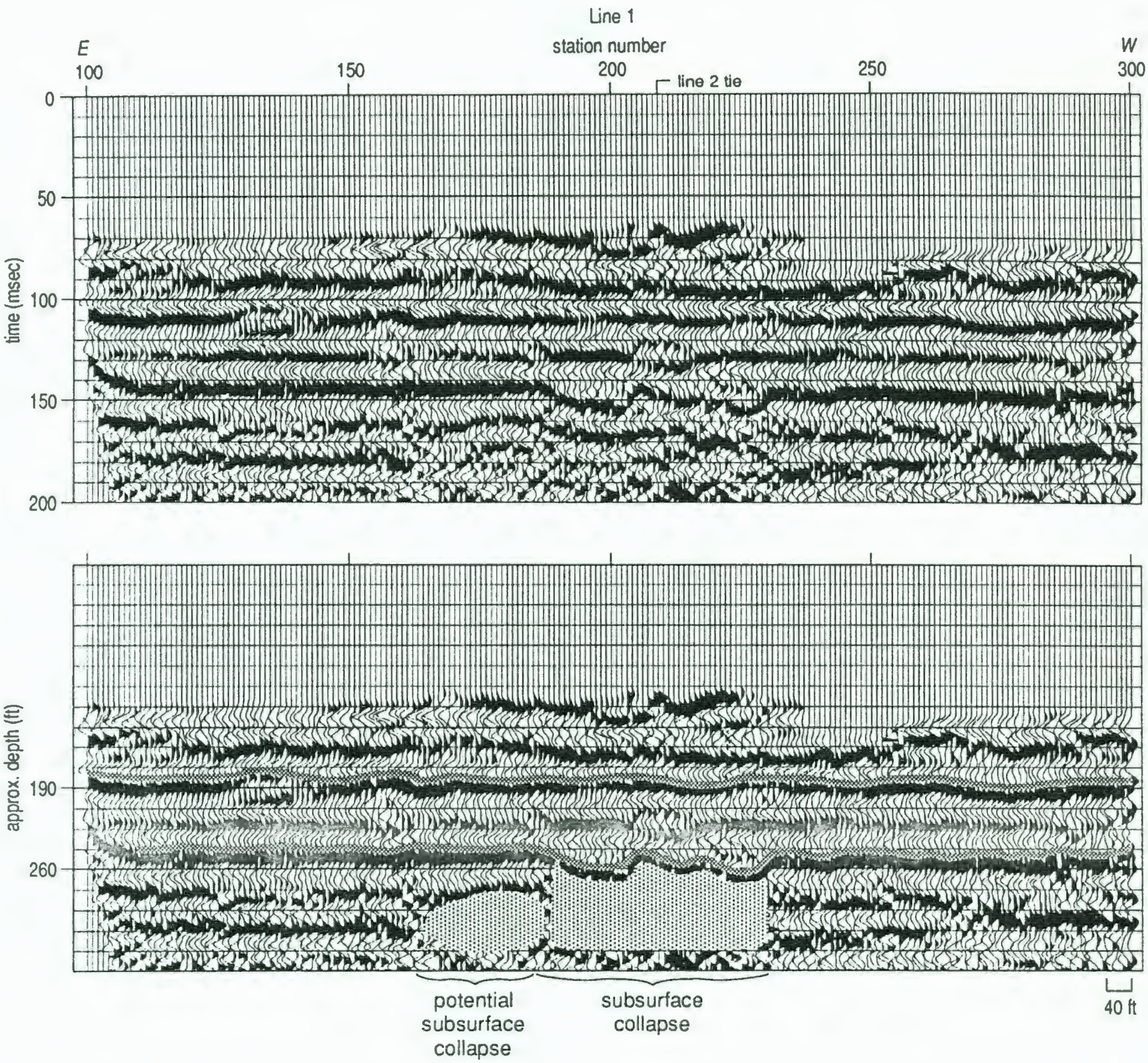
figure 7


Line 1
station number
E
W
100
150
200
250
300
line 2 tie
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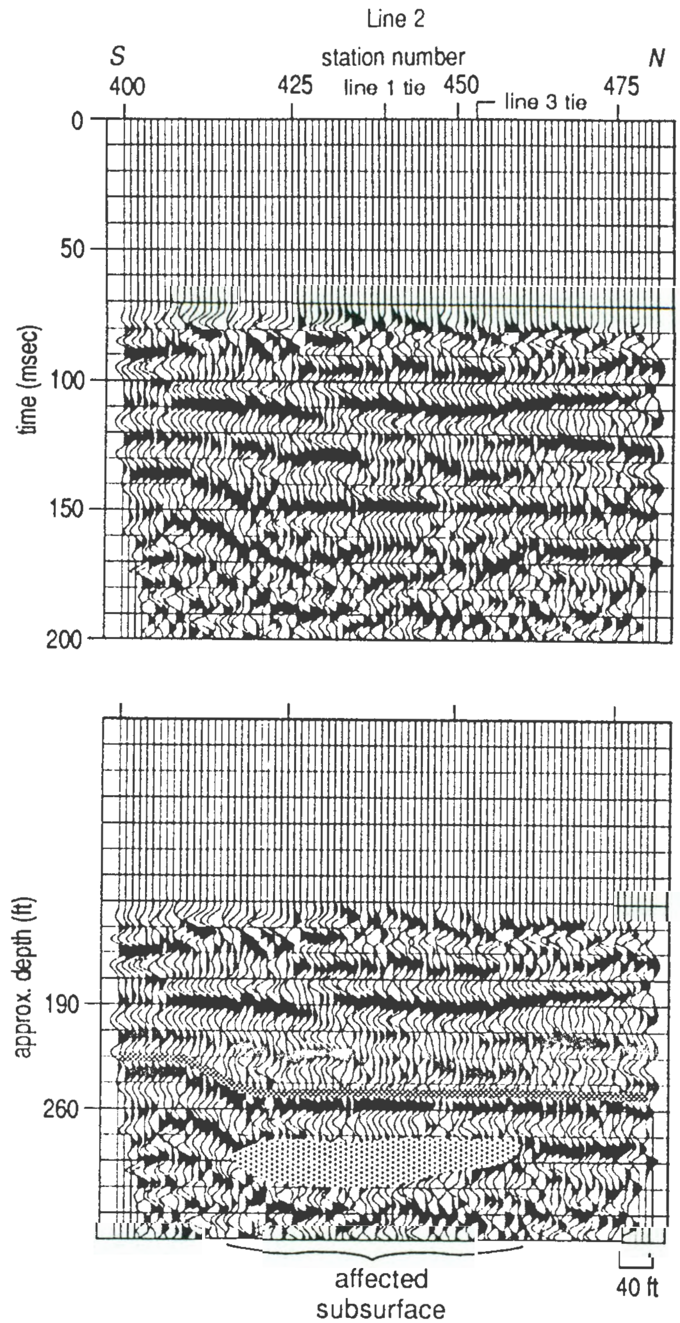
100
150
200
time (msec)
approx. depth (ft)
190
260
potential subsurface collapse
subsurface collapse
40 ft

figure 8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station number
N
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425
line 1 tie
450
line 3 tie
475
0
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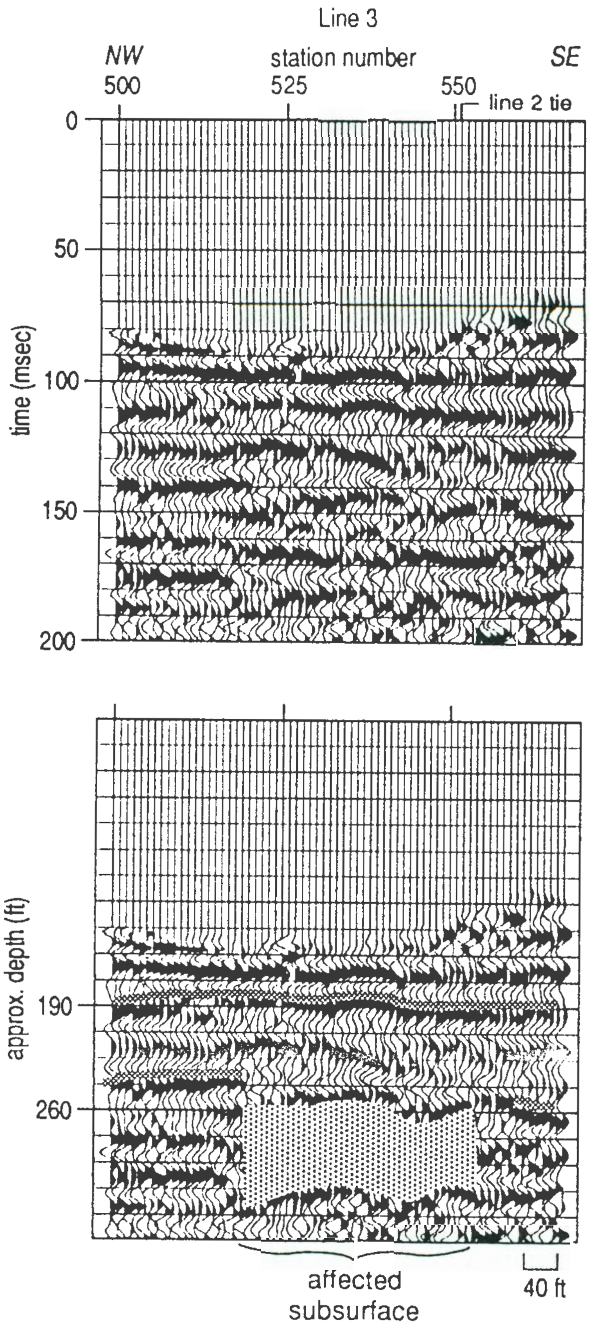
100
150
200
time (msec)
approx. depth (ft)
190
260
affected
subsurface
40 ft

figure 9



Line 3
NW
station number
SE
500
525
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line 2 tie
0
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100
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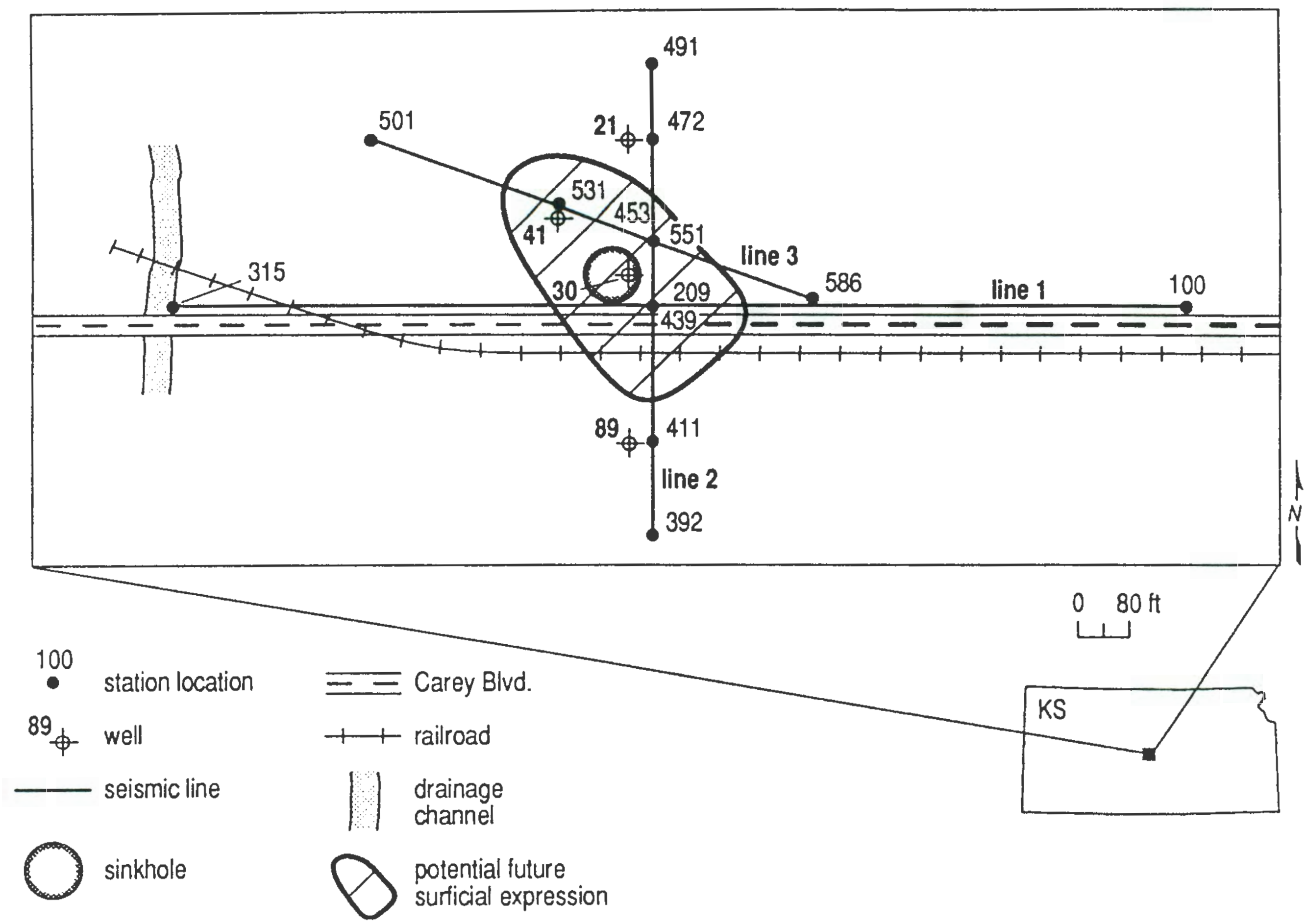
time (msec)
approx. depth (ft)
190
260
affected subsurface
40 ft

figure 10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line 2
392
N
0
80 ft
100
station location
89
well
seismic line
sinkhole
Carey Blvd.
railroad
drainage
channel
potential future
surficial expression
KS

figure 11