KANSAS GEOLOGICAL SURVEY
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Seismic Reflection Surveys at the Knackstedt
Salt-water Disposal Well

Final Report to
Kansas Corporation Commission

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Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

SEISMIC REFLECTION SURVEYS AT THE KNACKSTEDT SALT-WATER DISPOSAL WELL

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The University of Kansas

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INTRODUCTION

This is a report prepared for the Kansas Corporation Commission (KCC) by the Kansas Geological Survey (KGS) on seismic reflection surveys performed in the vicinity of a known air-filled cavity beneath the Knackstedt salt-water disposal well in NWNW Sec. 30, T20S, R5W, McPherson County, Kansas. This cavity is similar in occurrence and geologic nature to a cavity that collapsed near Macksville, Kansas in July, 1988. The seismic surveys suggest that the size of the Knackstedt cavity is comparable to that which caused the sinkhole near Macksville. The sinkhole near Macksville is now roughly 300 feet in diameter and growing, and it is about 100 feet deep.

Appendix 1 at the end of this report is written for the reader who is not familiar with seismic methods. Appendix 2 is written for the professional geologist or geophysicist who wants to know the details of the seismic processing that was applied to the data.

Surface subsidence resulting from dissolution of the Hutchinson Salt Member at depths of several hundred feet is common in central and south-central Kansas. The dissolution of the salt has generally been associated with either natural active sinkholes or with salt water disposal wells. The KGS has found paleo-sinkholes (formed thousands or millions of years ago) in at least two locations where sinkholes are gradually forming at the present time. High-resolution seismic reflection has been used at several locations in Kansas to delineate the subsurface structure of sinkholes posing a risk to property or the welfare of local residents (Steeples et al., 1986; Miller et al., 1985; Miller and Steeples, 1984; Knapp et al., in press).

The most common cause of those sinkholes that are associated with activities of the petroleum industry is fluid leakage from brine-disposal wells. The loss of static fluid level in the #1 Knackstedt disposal well prompted an in-depth borehole investigation of the well. A borehole video camera detected the presence of an air-filled void from 318 to 478 feet in depth. The camera had a range of only a few feet, but did not detect walls of the cavity in any direction. These measurements were made after several thousand cubic yards of material had already been dumped down the hole in an effort to fill it. The disposal well responsible for the void is located within 100 feet of a major county road in McPherson County, Kansas, and therefore represents a potential risk to people and vehicles using the road. The eventual subsidence could be gradual or catastrophic. At the present time there is no reliable way to predict which rate of subsidence will actually occur.

Defining the boundaries of the void can sometimes be done accurately with a high-resolution seismic reflection survey. The air/rock interface at the ceiling of the void represents a significant acoustic interface that will reflect all down-going seismic energy incident on the void ceiling. At the Knackstedt cavity, the roughness of the ceiling was sufficient that the reflected energy was too diffuse to detect directly. However, the subsurface extent of the salt dissolution was indirectly interpreted by the absence of deeper seismic reflections on high-resolution CDP stacked seismic data. The potential risk area on the ground surface can be defined directly from a subsurface map derived from the seismic-reflection data.

GEOLOGIC SETTING

The Hutchinson Salt Member of the Permian-aged Wellington Formation extends from approximately 445 to 700 feet below the ground surface in this area. The dissolution of this salt member generally results in gradual subsidence of the overlying rock units which, in this area, are Permian red beds. The geologic conditions and dissolution rate necessary for the catastrophic formation of a sinkhole as opposed to the more common gradual subsidence rate are not known.

The void was discovered when investigations into the loss of static water level resulted in a wireline video inspection of the well casing. The video discovered the absence of casing as well as any borehole walls between 318 and 478 feet in depth. The bottom of the borehole, which originally extended to over 3000 feet, was plugged with neat cement. In an attempt to fill the void, 11,000 cubic yards of material have been poured into the well from the surface, raising the floor of the cavity from 520 feet to 441 feet. During the filling process, the hole was occasionally flushed with a saturated brine solution in an attempt to level the coning of the pile of material directly beneath the borehole opening in the ceiling of the void. No static fluid level was ever recorded after a brine solution flush. The absence of a measurable water level in the hole at any time during the past year suggests that the void is hydraulically connected by large conduit to an aquifer with a hydrostatic head at least 500 feet below the earth's surface.

The seismic survey was designed and conducted to determine the horizontal extent of the void. The first profile was collected from east to west, centering on the disposal well. The preliminary interpretation of that profile led to the placement of a second seismic profile running south to north. After correlating those two intersecting profiles, a third line was run to the north of the well with east-west orientation. In an attempt to more accurately define the boundaries of the void and the associated danger to traffic and to agricultural operations, three more reflection lines were acquired—two intersecting in the road and running NW to SE and SW to NE, and the third running north-south, located east of the well head. The orientation and location of each successive seismic line was determined after completion of initial processing and preliminary review of the line before.

Results of the Seismic Surveys

The seismic sections are shown in Figures 2-6, inclusive. Associated with each seismic section is an interpretation that shows where we believe the cavity to be located. The cavity location is indicated by the lack of seismic reflections on the seismic sections.

Interpretation of the seismic sections can be explained by an analogy to looking at rock layers exposed by excavation for roads. In many places in Kansas, multiple rock layers are exposed to view in such road-cuts. Inspection of the road-cuts by human eyes can reveal a good deal about the geology of the surrounding area.

A seismic section, like those shown in Figures 2-6, can be thought of as a road-cut exposure. The blackened coherent peaks on a seismic section correspond to hard rocks such as limestones. The space between the peaks corresponds to softer rock units such as shales. The absence of the blackened peaks implies either the absence of the limestones, or that the seismic energy did not penetrate to the depth of the respective limestones. In the seismic sections of this report, the absence of the coherent blackened peaks is interpreted as indicating the presence of the cavity. The presence of the cavity prevents the seismic waves from propagating deep enough to detect the deeper limestones that are present in the area.

Figure 7 shows the mapped location of the void based on the method of interpretation discussed above. This shows the bulk of the void to be to the east and north of the Knackstedt well. The seismic data do not show the exact location of the boundaries of the void because the seismic energy gets de-focused with increasing depth. The void could be somewhat smaller or somewhat larger than shown on the map. Our tendency is to believe that the void is probably somewhat larger than depicted on the map because we know it extends at least to several feet southwest of the Knackstedt well.

Our data do not give any indication of the vertical extent of the cavity. We know that it is over 100 feet high at the well location. The recent catastrophic collapse near Macksville had vertical extent of over 100 feet also. The vertical extent is somewhat dependent on the location of the outlet of brine from the salt dissolution cavity, and we have no idea where the outlet is. The fact that the cavity is not symmetric with respect to the well location suggests that the borehole might not have been the outlet for the dissolution brine.

The seismic data are internally consistent in determining the location of the cavity except for the north-south line located east of the well. The data quality along this line is poor despite major processing efforts and the fact that the data were collected a second time in the field to try to improve the quality. The data from this line are not shown in this report. There are at least three reasons why the data are poor along this line. Our equipment could have malfunctioned in the field during data collection, but we ran the line a second time at a later date after rechecking all of the equipment and still obtained poor data. The data could have been collected and processed improperly, but we reject this argument because all of the other lines have good data outside the cavity area. The poor data quality could also be caused by a fault zone or other unusual geologic conditions running north-south beneath the line. We believe this is probably the case and, if so, this could be a critical factor in the formation of the dissolution cavity.

At other locations, we have seen suggestions that some salt-water disposal wells may be predestined for difficulty because of the existence of pre-existing fracture zones or caverns. The existence of paleo-sinkholes at some locations indicates that water flow in the vicinity of the salt layer can sometimes occur naturally. We do not yet have enough data at enough locations to predict or determine which salt-water disposal wells are likely to cause problems.

Results of Gravity Surveys

The presence of an underground cavity produces small but measurable variations in the earth's gravitational attraction at surface locations above the cavity. The KGS conducted two micro-gravity surveys in an effort to delineate the location of the cavity. While we were initially enthusiastic about the results of the first survey, a second survey over a larger area revealed that the gravity data could not be trusted to give meaningful results.

Variations in the thickness of river sediments in the valley of the Little Arkansas River caused gravity variations of the same size as those due to the cavity. Therefore, it was impossible to tell which minute variations in gravity were due to the cavity and which ones were due to variations in the thickness of the river sediments.

CONCLUSIONS

We conclude that the cavity is several hundred feet in diameter and is located east and north of the Knackstedt disposal well as shown in Figure 7. We have no idea about its vertical dimensions. It is not possible to infer from existing seismic data whether the cavity was caused by faulty procedures in constructing the disposal well. We have not noted any indication of paleo-sinkholes around the Knackstedt well, but the seismic lines may have been too short to reveal any nearby paleo-sinkholes. There is some indication of complex geologic conditions such as faults along a north-south trend beneath line 4 of Figure 1. We do not have sufficient data to tell the extent or nature of these conditions, if they are present, nor do we know if such conditions could have directly or indirectly caused the formation of the cavity. We do not know whether the cavity will cause catastrophic collapse, or if the sinking of the surface will be gradual. There are indications from seismic-wave velocity measurements that the stress caused by the cavity has reached to within a few feet of the earth's surface, which suggests that caution would be prudent. The formation of a sinkhole at this locality sometime in the course of the next few years is a virtual certainty. We do not know when it will start, how fast it will form, or exactly how big it will get, but it will likely be similar in size to the new sinkhole near Macksville.

RECOMMENDATIONS

1. We recommend that the east-west county road that crosses the cavity be relocated away from the cavity. The safety considerations outweigh the costs, in our opinion.

2. We do not recommend trying to completely fill the cavity. The volume of the cavity may be hundreds of thousands of cubic yards, and there is no way to know for certain that the cavity is filled. Furthermore, we do not know that dissolution and expansion of the cavity would be stopped even if the cavity were filled, because we do not know where the outlet for brine is located.

3. We recommend fencing the location for safety reasons. The questions of settlement with the landowners and with McPherson County are not our domain, but we will work with interested parties to help settle these questions.

4. We recommend that agencies of the State of Kansas, affected county governments, affected landowners, and the petroleum industry work together to evaluate this growing problem and to design mitigation procedures. The occurrence of the catastrophic collapse near Macksville in July, 1988, and other previous sinkholes and known voids is a reminder that the problem is potentially present over a large area of central Kansas.

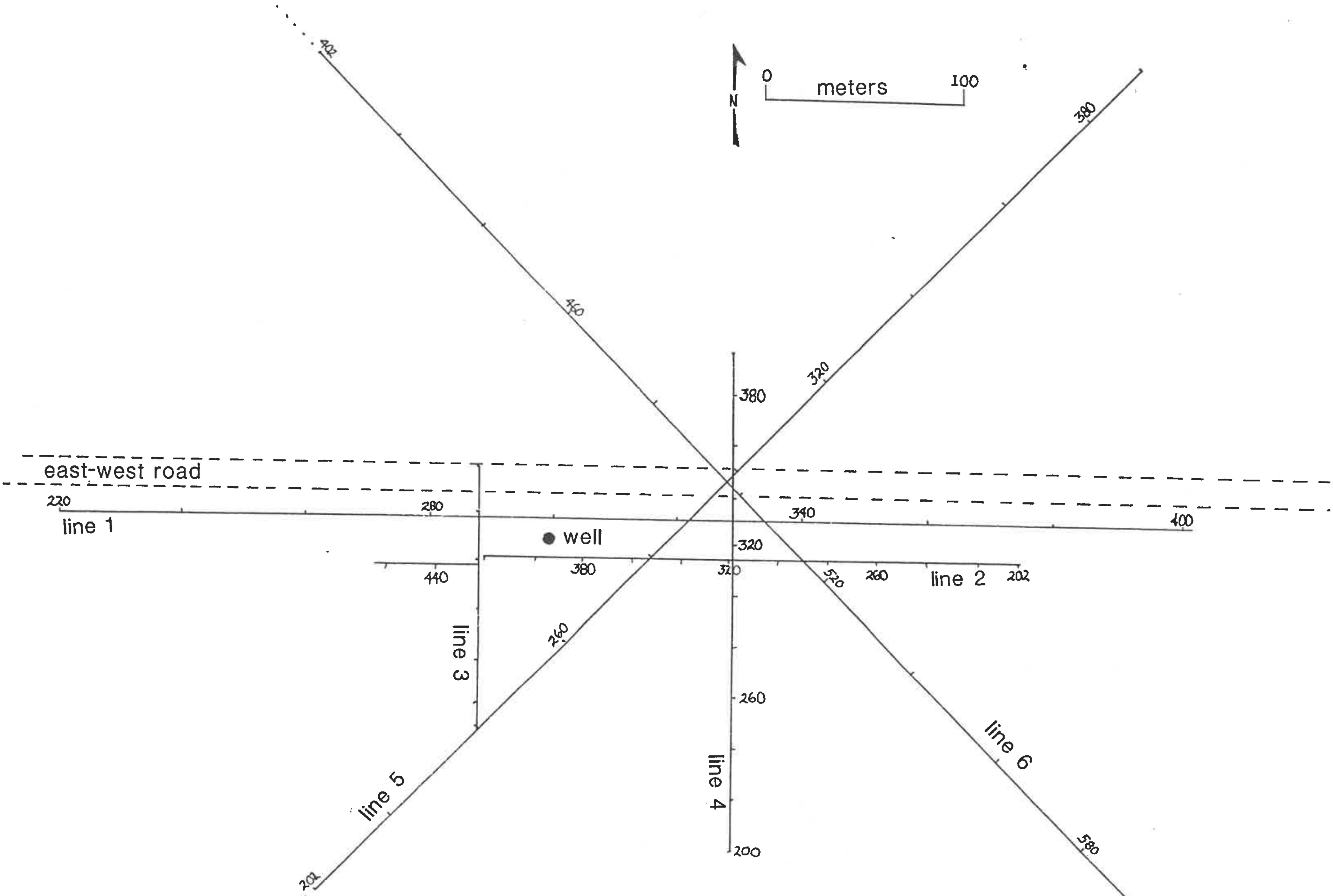


Figure 1. Map location of seismic lines relative to Knackstedt well and east-west McPherson County road.

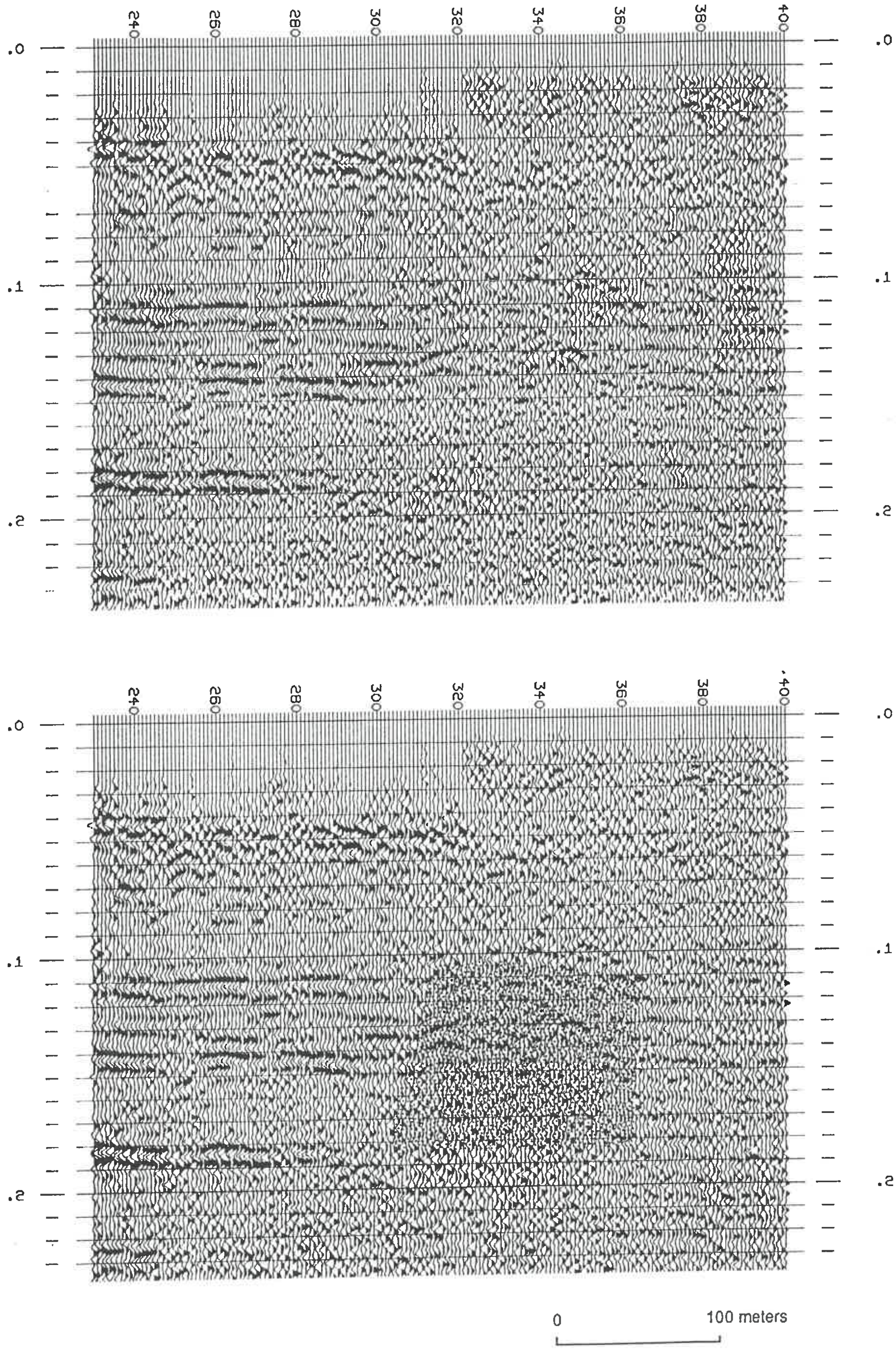


Figure 2. Seismic section for line 1. Interpreted cavity is from locations 305 to 365 on this line. The upper seismic section is uninterpreted, and the lower section has light stippling covering the location of the cavity.

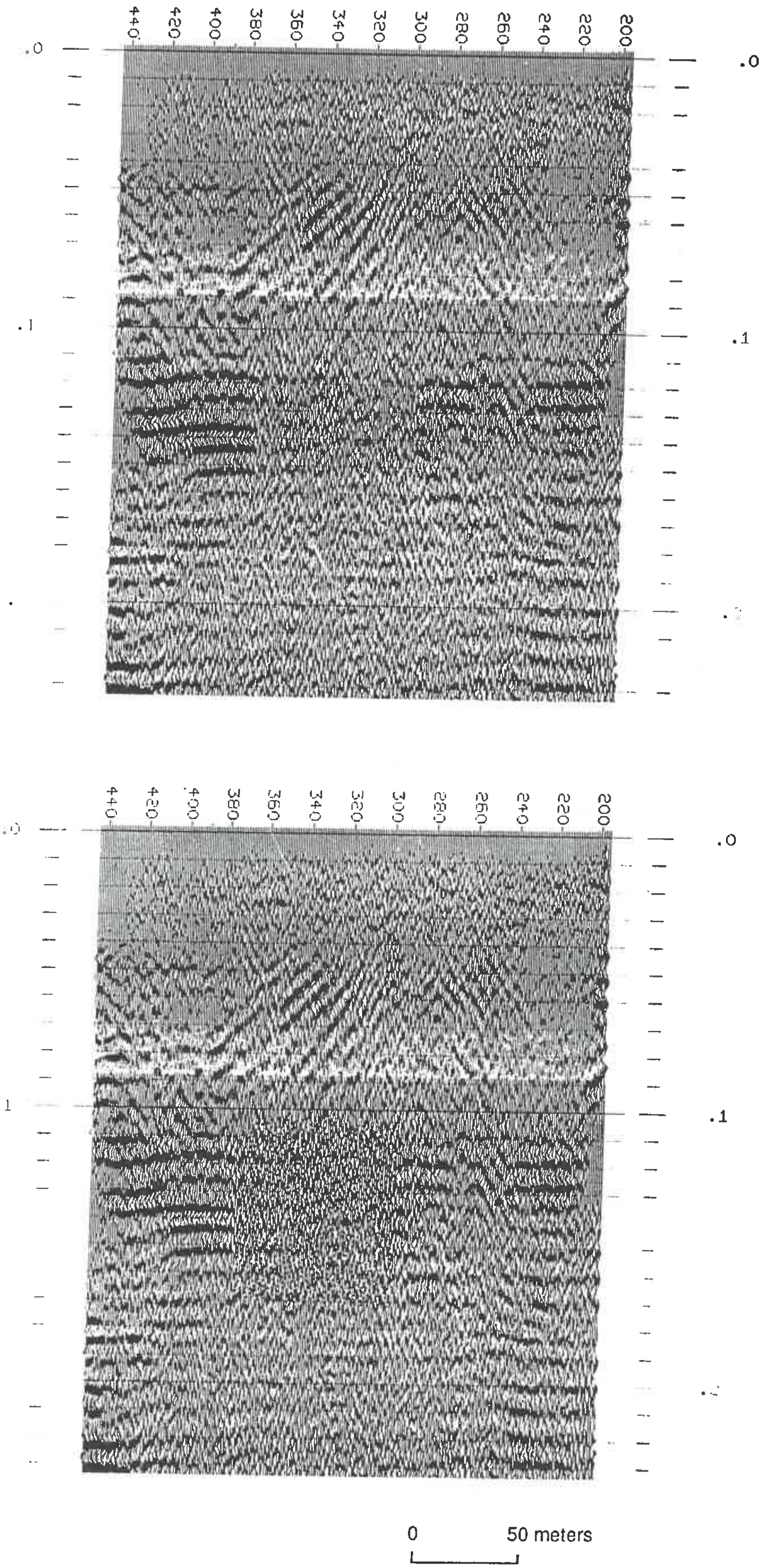


Figure 3. Seismic section for line 2. Interpreted cavity is from location 290 to 370.

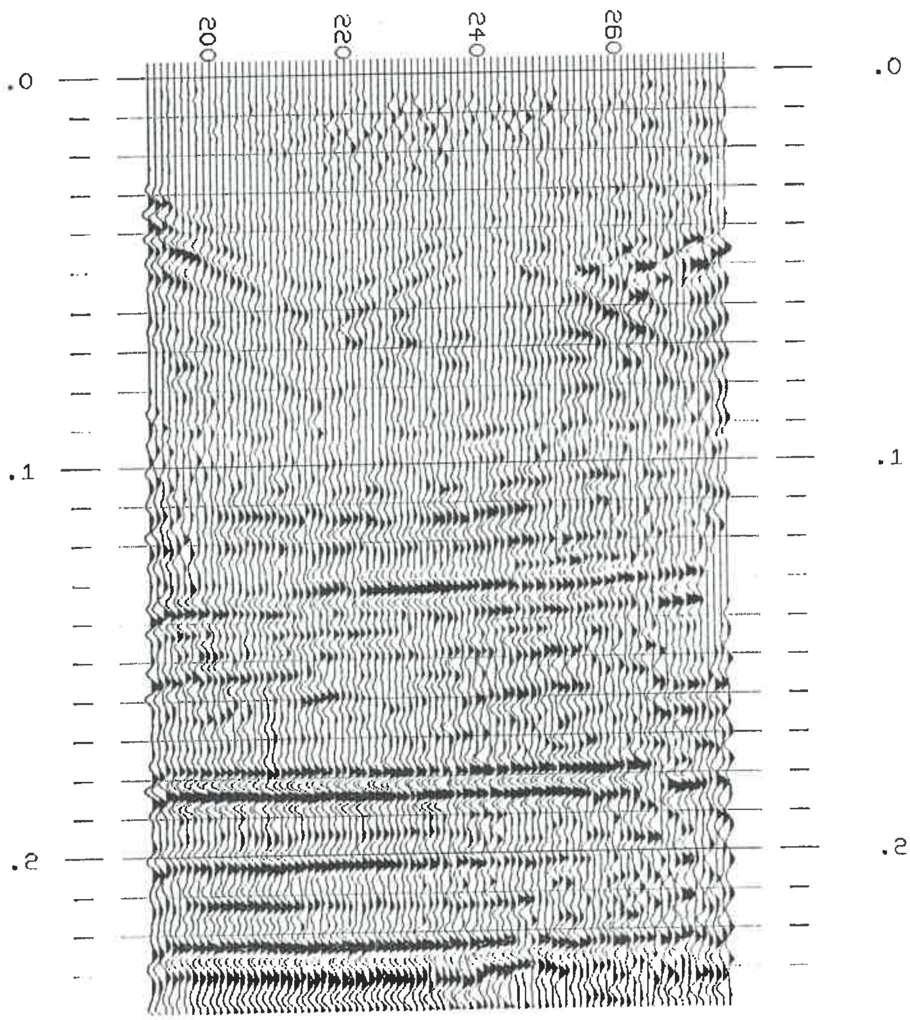


Figure 4. Seismic section for line 3. This is a north-south line located west of the well. It shows no indication of cavity.

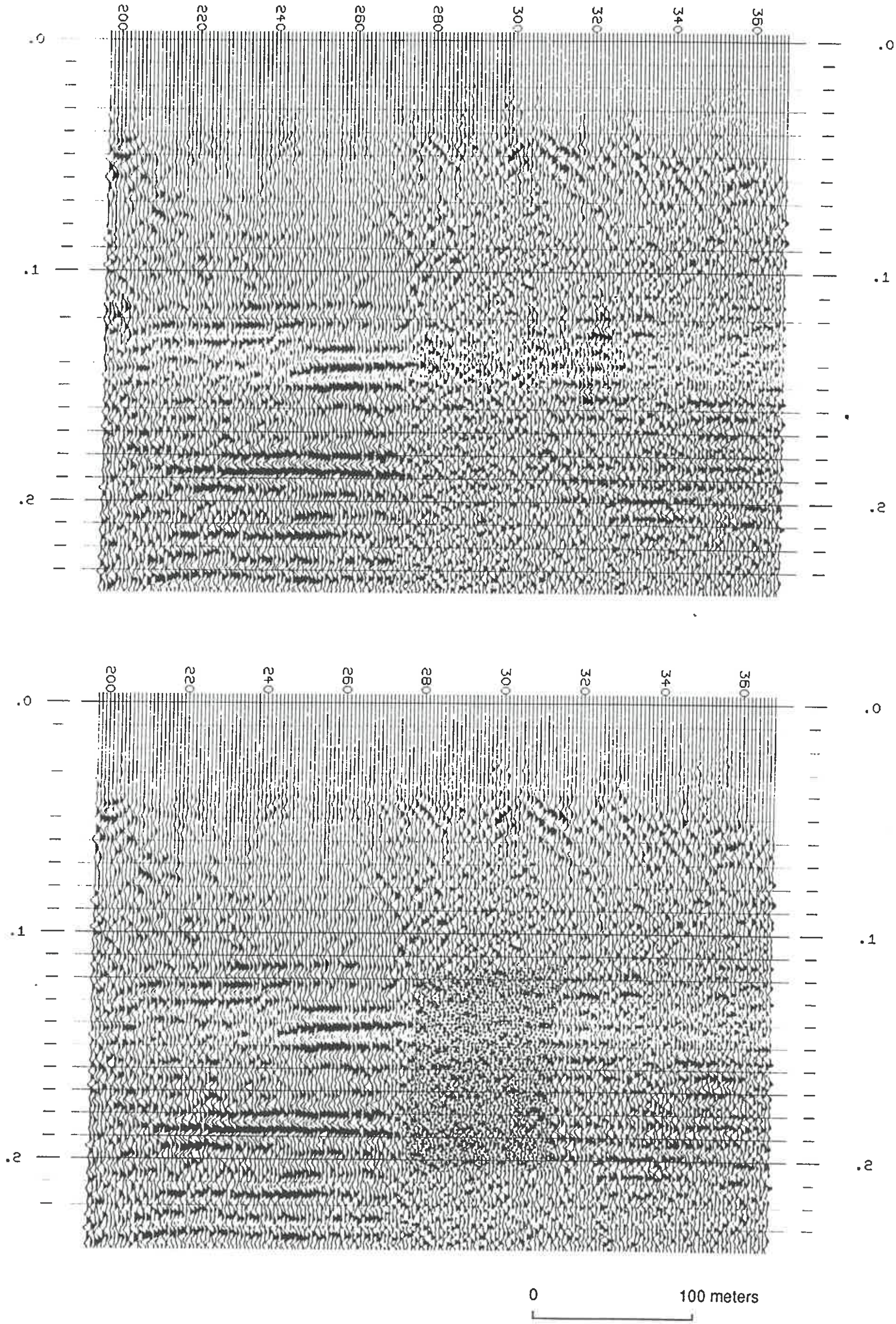


Figure 5. Seismic section for line 5. Interpreted cavity is from location 275 to 316.

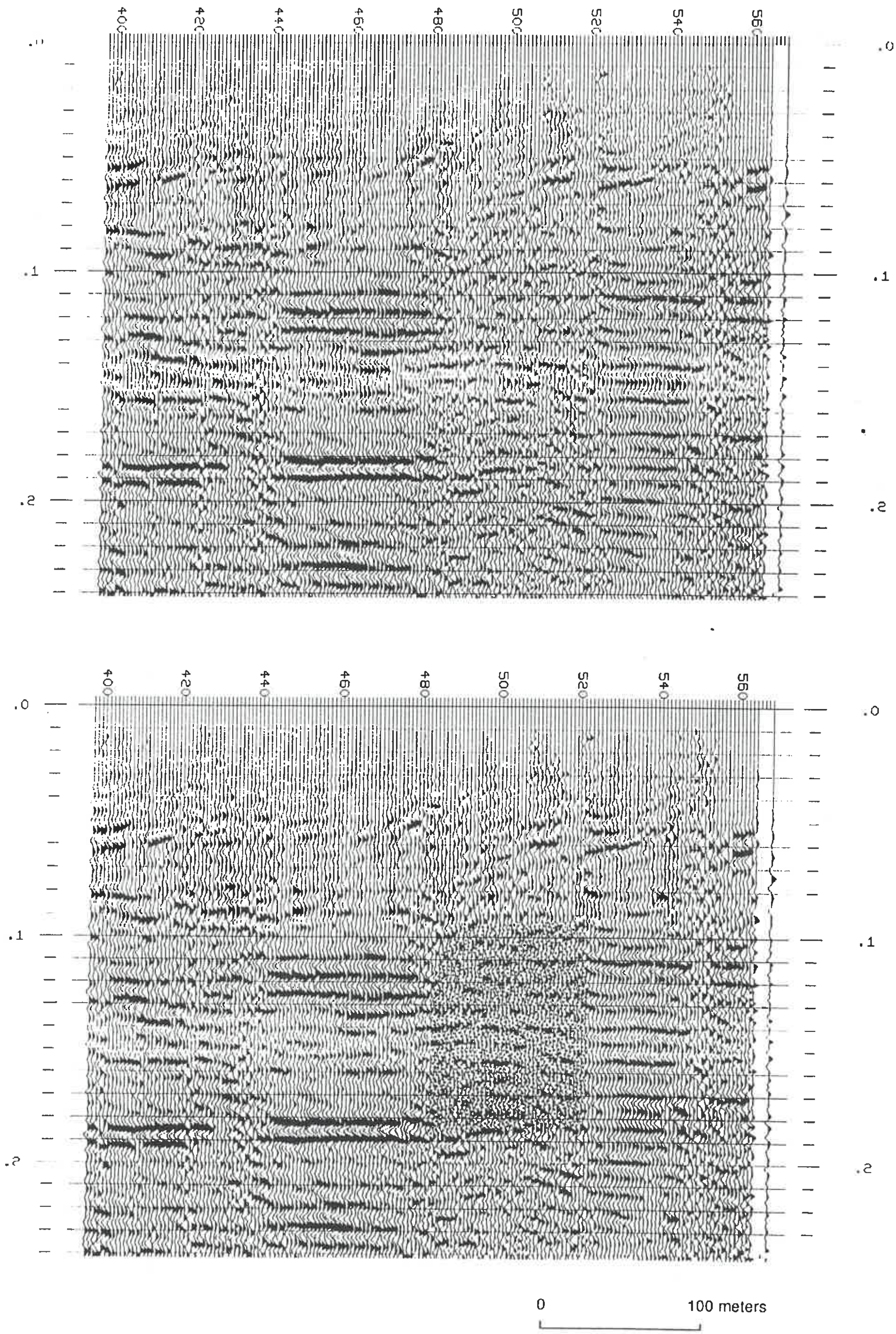


Figure 6. Seismic section for line 6. Interpreted cavity is from location 480 to 522.

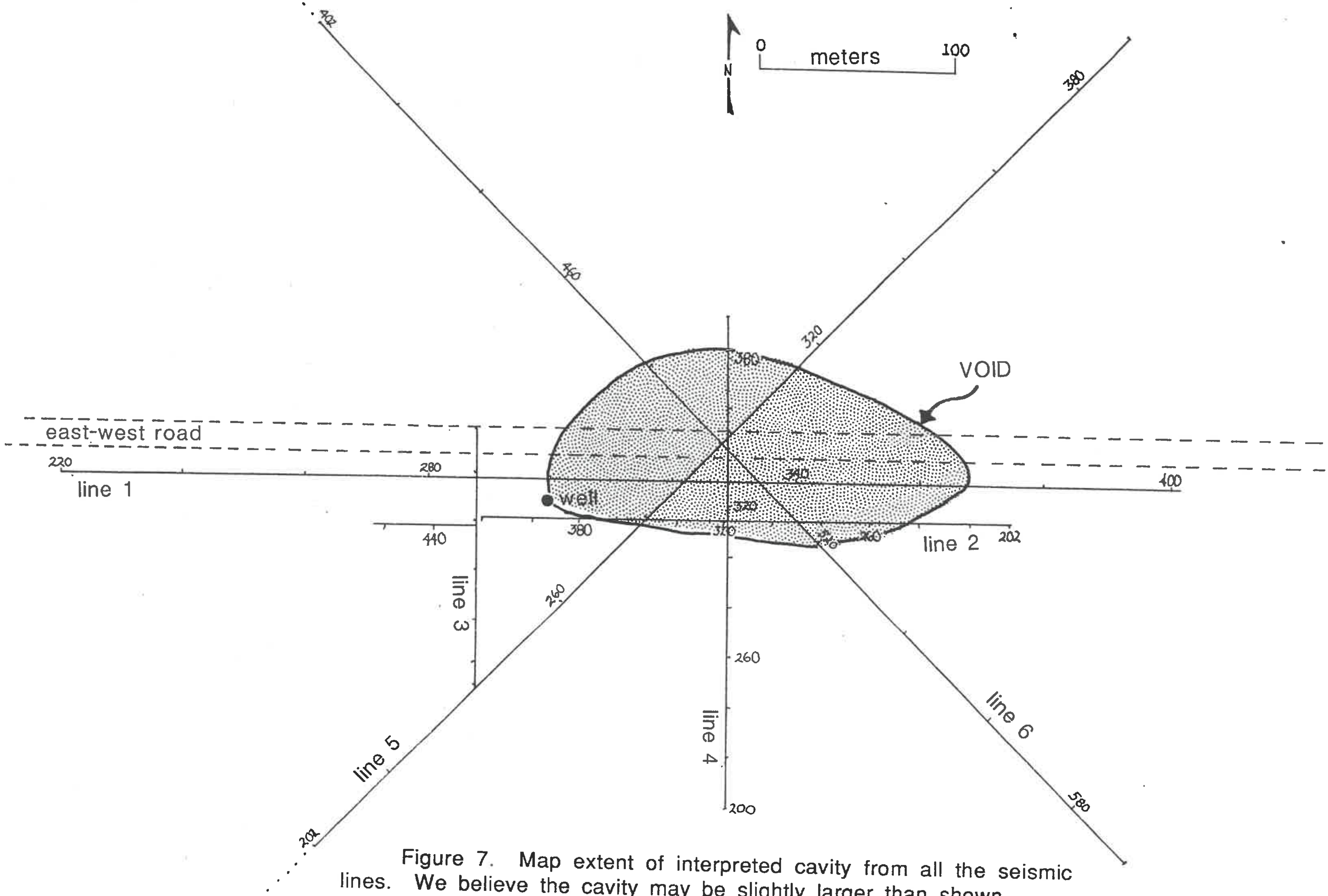


Figure 7. Map extent of interpreted cavity from all the seismic lines. We believe the cavity may be slightly larger than shown.

Appendix 1

CONCEPTS OF SEISMIC REFLECTION PROSPECTING

It is the purpose of this short paper and the attached figures to describe basic features of seismic reflection. The paper is intended primarily for those who have heard of seismic reflection but do not know how it works.

The seismic reflection method is a powerful technique for underground exploration that has been in use for over 60 years. The revolution in microelectronics during the past ten years has resulted in the construction of new seismographs and microcomputers for data collection and processing that permit the cost-effective use of seismic reflection in a wide variety of applications that were not feasible previously.

Seismic reflection techniques depend on the existence of acoustical contrasts in the subsurface. In many cases the acoustical contrasts occur at boundaries between geologic layers or formations, although man-made boundaries such as tunnels and mines also represent contrasts. Acoustical contrasts occur as variations in either mass density or seismic velocity. The measure of acoustical contrast is formally known as acoustic impedance, which is simply the product of mass density and the speed of seismic waves traveling within a material.

In the case of P-waves, which are compressional waves, the principles of sound waves apply and, indeed, P-wave reflections can be thought of as sound wave echoes from underground. P-waves propagating through the earth behave similarly to sound waves propagating in air. When a P-wave comes in contact with an acoustical contrast in the air or underground, echoes (reflections) are generated. In the underground environment, however, the situation is more complex because energy that is incident on a solid acoustical interface can also be transmitted across the interface or converted into refractions and/or shear waves.

Seismic reflection is sensitive to the physical properties of earth materials and is relatively insensitive to chemical makeup of both the earth materials and their contained fluids. The seismic reflection technique involves no a priori assumptions about layering or seismic velocity. However, no seismic energy will be reflected back for analysis unless acoustic impedance contrasts are present within the depth range of the equipment and procedures used. This is identical to the observation that sound waves in air do not echo back to an observer unless the sound wave hits something solid that causes an echo. The classic use of seismic reflections involves identifying the boundaries of layered geologic units. It is important to note that the technique can also be used to search for anomalies such as isolated sand or clay lenses and cavities.

The simplest case of seismic reflection is shown in Figure 1. A source of seismic waves emits energy into the ground, commonly by explosion, mass drop, or projectile impact. Energy is radiated spherically away from the source. One ray path originating at the source will pass energy to the subsurface layer and return an echo to the receiver at the surface first. In the case of a single flat-lying layer and a flat topographic surface, the path of least time will be from a reflecting point mid-way between the source and the receiver with the angle of incidence on the reflecting layer equal to the angle of reflection from the reflecting layer.

The sound receivers at the surface are called geophones and are essentially low frequency microphones. The signals from the geophones are transmitted by seismic cables to the recording truck which contains a seismograph. The seismograph contains amplifers that are very much like those on a stereo music system. The sounds from the earth are amplified and then recorded on digital computer tape for later processing and analysis. The purpose of the computer processing is to separate the echo sounds from other sounds to enhance them and to display them graphically.

In the real world, there are commonly several layers beneath the earth's surface that are within reach of the seismic reflection technique. Figure 2 illustrates that concept. The reader should note that echoes from the various layers arrive at the geophone at different times. The deeper the layer, the longer it takes for the echo to arrive at the geophone. The fact that several layers often contribute echoes to seismograms tends to make the seismic data more complex.

In the case of a multi-channel seismograph several geophones detect sound waves almost simultaneously. Each channel has one or more geophones connected to it. Reflections from different points in the subsurface are recorded by various geophones. Note in Figure 3 that the subsurface coverage of the reflection data is exactly half of the surface distance across the geophone spread. Hence, the subsurface sampling interval is exactly half of the geophone interval at the surface. For example, if geophones are spaced at a 50 foot interval at the earth's surface, the subsurface reflections will come from locations on the reflector that are centered 25 feet apart.

In Figure 4 we have placed source locations and receiver locations in such a way that path S1 - R2 reflects from the same location in the subsurface as path S2 - R1. This is variously called a common-reflection point (CRP) or a common-depth point (CDP), depending upon the preference of the author. The power of the CDP method is in the multiplicity of data that come from a particular subsurface location. By gathering common midpoint data together and then adding the traces in a computer, the reflection signal is enhanced. Before this addition can take place, however, the data must be corrected for differences in travel time for the reflected waves caused by the differences in source-to-geophone distance. The degree of multiplicity is called CDP fold. A seismograph with 48 channels, for example, commonly is used to record 24-fold CDP data.

The seismic-reflection method is used to determine the spatial configuration of underground geological formations. Figure 5 shows conceptually what we are trying to accomplish with such a survey. Note that the peaks of the seismic reflections have been blackened to assist in the interpretation. This example is a very simple version of typical near-surface geology that depicts a buried sand lens in a river valley. As the sand lens is moved to deeper layers below the surface, it becomes more difficult to detect, but the physical principles remain the same.

In an earlier part of this discussion, we briefly touched on the analogy between a seismograph and a stereo music system. A stereo music system has control knobs to enhance high frequencies (like a flute) or low frequencies (like a bass drum). A seismograph has similar capabilities in choosing the sound frequencies that are recorded. A seismologist selects the frequencies to be enhanced depending on the depth and size of the underground geologic features of interest.

In order to detect small geologic features, it is necessary to use a seismograph that can record and enhance the high frequency sound waves. The use of high-frequency seismic waves in reflection seismology is known as "high-resolution" seismic exploration. As research and instrumentation developments allow recording higher and higher seismic frequencies, it is becoming possible to prospect for progressively smaller geologic targets.

Figure 1. Reflection from one layer

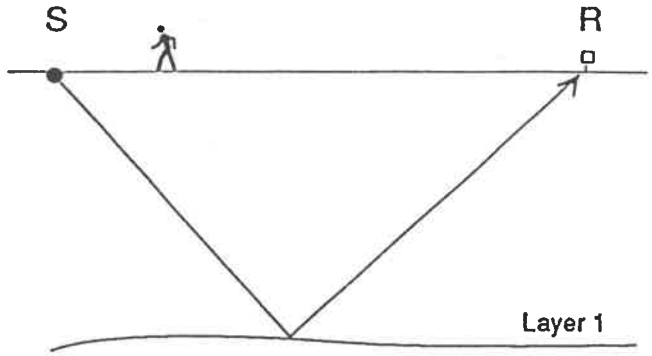
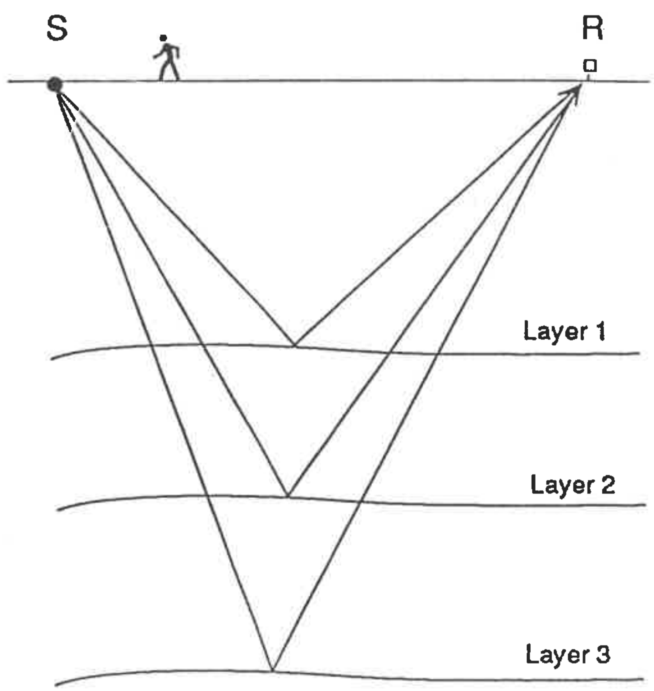


Figure 2. Reflection from three layers



Simple Reflection Ray Paths

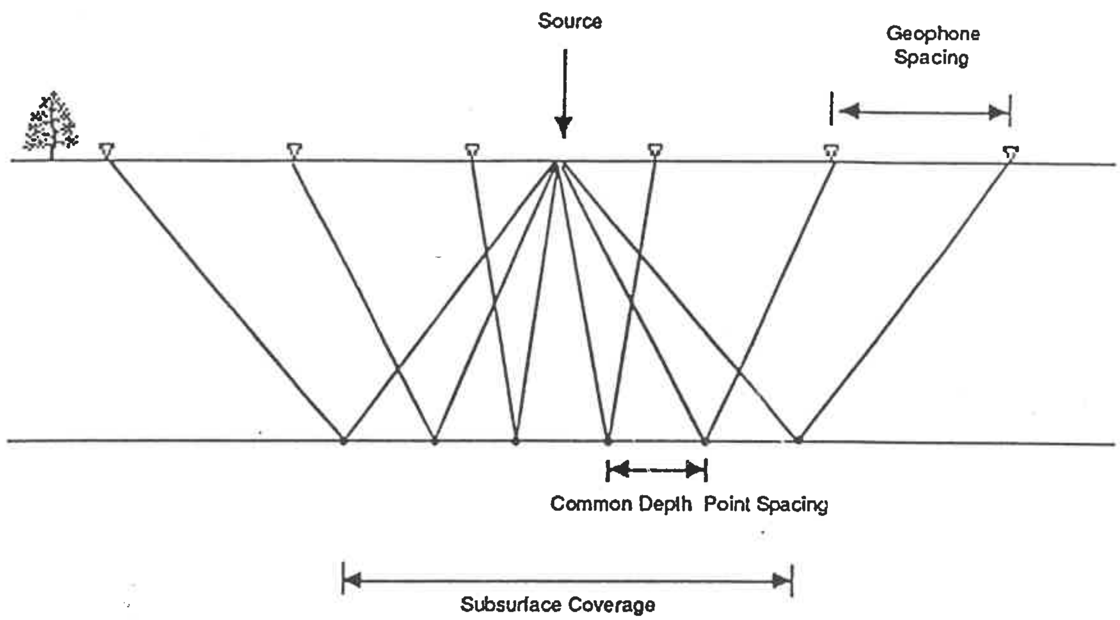


Figure 3. Schematic drawing of seismic ray paths for a single shot with a six-channel reflection seismograph.

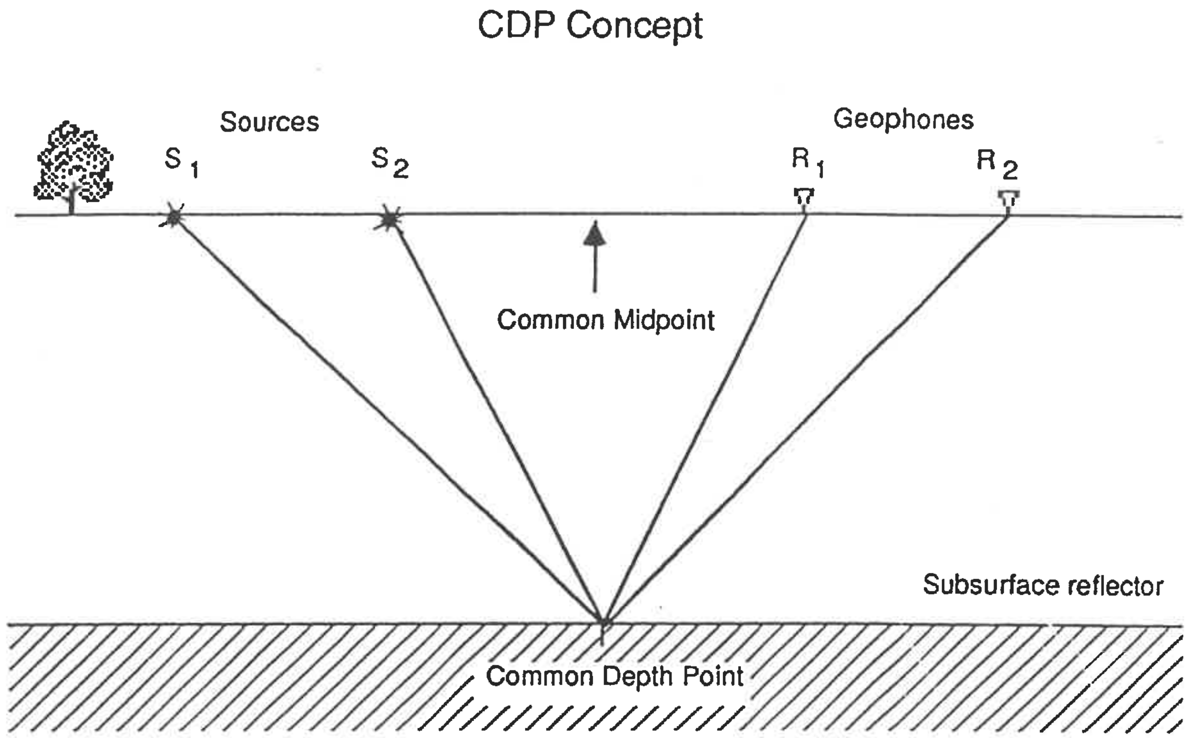


Figure 4. The concept of Common Depth Point (CDP). Note that ray paths from two different shots (S_1 and S_2) reflect from a common point in the subsurface.1

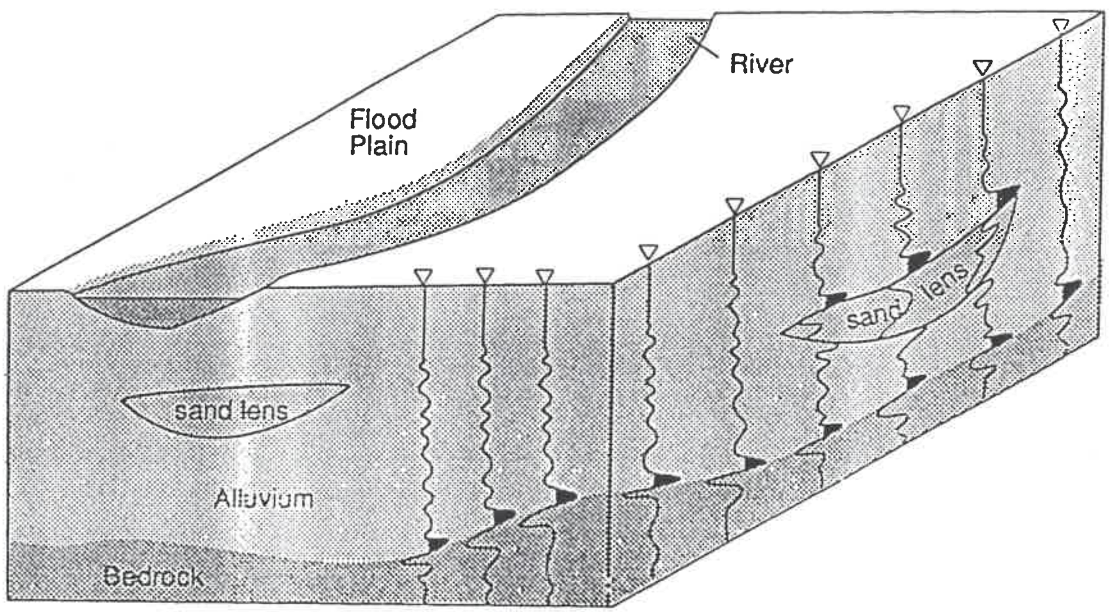


Figure 5. Schematic showing a seismic section relating to real-world geology.

APPENDIX 2

DATA COLLECTION PROCEDURES

The data were recorded using a standard CDP acquisition method. This method is discussed in some detail in Appendix 1 of this report. The source and receiver spacing for lines 1, 5, and 6 was 16.5 feet and for lines 2, 3, and 4, it was 6.5 feet. The source was a downhole .50-caliber single-shot rifle with the barrel 2 feet below the ground surface in a 2-inch borehole. The receivers for lines 1, 5, and 6 were two 100-Hz geophones connected in series, and for lines 2, 3, and 4, three 40-Hz geophones connected in series. Both types of receivers had 5-1/2 inch long spikes. The lower natural frequency geophones were necessary to record reflection information on lines 2, 3, and 4 due to the high-amplitude wind noise that saturated the high frequency part of the reflection spectrum. Maximum recordable reflection frequencies were maintained partly as a result of the careful attention to source and receiver coupling to the ground at all stages of the acquisition process. In order to optimize the available equipment and the recording parameters used during acquisition, an extensive series of field tests was performed before collecting data on each line.

The data were recorded on an I/O DHR 2400 seismograph. All the fixed-gain data were converted analog-to-digital (A/D) to an 11-bits-plus-sign value and then stored-on magnetic tape in a modified SEG-Y format. A record length of 250 msec with a sampling interval of 0.5 msec was chosen since the dominant frequency was expected to be around 150 Hz and the depth of interest was less than 1000 feet. The recording systems amplifiers possess 72 dB of dynamic range with a 120-nanovolt RMS noise level. The anti-alias filters used have a 60-dB-per-octave roll-off with a -60-dB point of 2000 Hz. The selected low-cut filters were essential to the quality and success of this survey.

DATA PROCESSING

The data were processed at the Kansas Geological Survey on a 32-bit Data General MV-20000. The software used was a proprietary set of algorithms that has been in standard use on TIMAP seismic systems marketed by Texas Instruments. The general processing flow was very similar to that used on seismic data for petroleum exploration. The major distinctions were meticulate attention to bad-trace editing, no wavelet extraction processing, and no "advanced" muting, mixing, or spectral balancing operations. Many of these "advanced" techniques, if not used with extreme caution, can lead to inaccurate interpretations. The thorough and careful processing of the data ensured that the data on the final processed seismic sections were true reflections and not remnants of processing. This decreases the chance for errors in interpretation. An accurate interpretation is essential, given the potential danger of the void to the general public. No processing procedure or step after the detailed velocity analysis, altered the general overall appearance or interpretation of the data.

The coherency of the stacked reflection data was improved with the application of surface consistent statics and residual statics corrections. The signal-to-noise ratio on the west half of lines 5 and 6 was sufficiently high for a surface-consistent statics operation to effectively remove distortions in the reflection arrivals resulting from locally variable (on the order of a few feet) near-surface material. Due to the poorer quality (i.e., signal-to-noise ratio) data collected on the east half of lines 5 and 6, a residual statics operation was necessary to extract the reflection information from the noise. The final processed sections have had a residual static operation preformed only on the east portion of the line. Since the residual static was not necessary on the west portion, it was not applied.