

# High Resolution Seismic Reflection to Map Upper Permian Rock Units Across I-70 Sinkhole in Western Russell County, Kansas

## Summary

This high-resolution seismic reflection study will target rock layers in the upper Permian portion of the geologic section beneath an approximately 3 mile stretch of Interstate 70 (I-70) in western Russell County, Kansas, where surface subsidence has caused public concern and a transportation headache for more than 50 years (Figure 1). The principal goal of this study will be to delineate rock layers within and above the Hutchinson Salt Member beneath the three salt dissolution sinkholes centered at approximately mile marker 179 on I-70. We will attempt to appraise the current subsurface extent, overall growth rate in the subsurface, and subsidence mechanism and chronology in part by taking advantage of legacy data acquired almost 25 years ago across these same subsidence feature. State-of-the-art shallow high resolution seismic reflection techniques possess the potential in this kind of study to detect, delineate, and evaluate locally complex structures associated with the dissolution of the salt, structural failure of overlying sediments, and the resulting eventual surface subsidence.

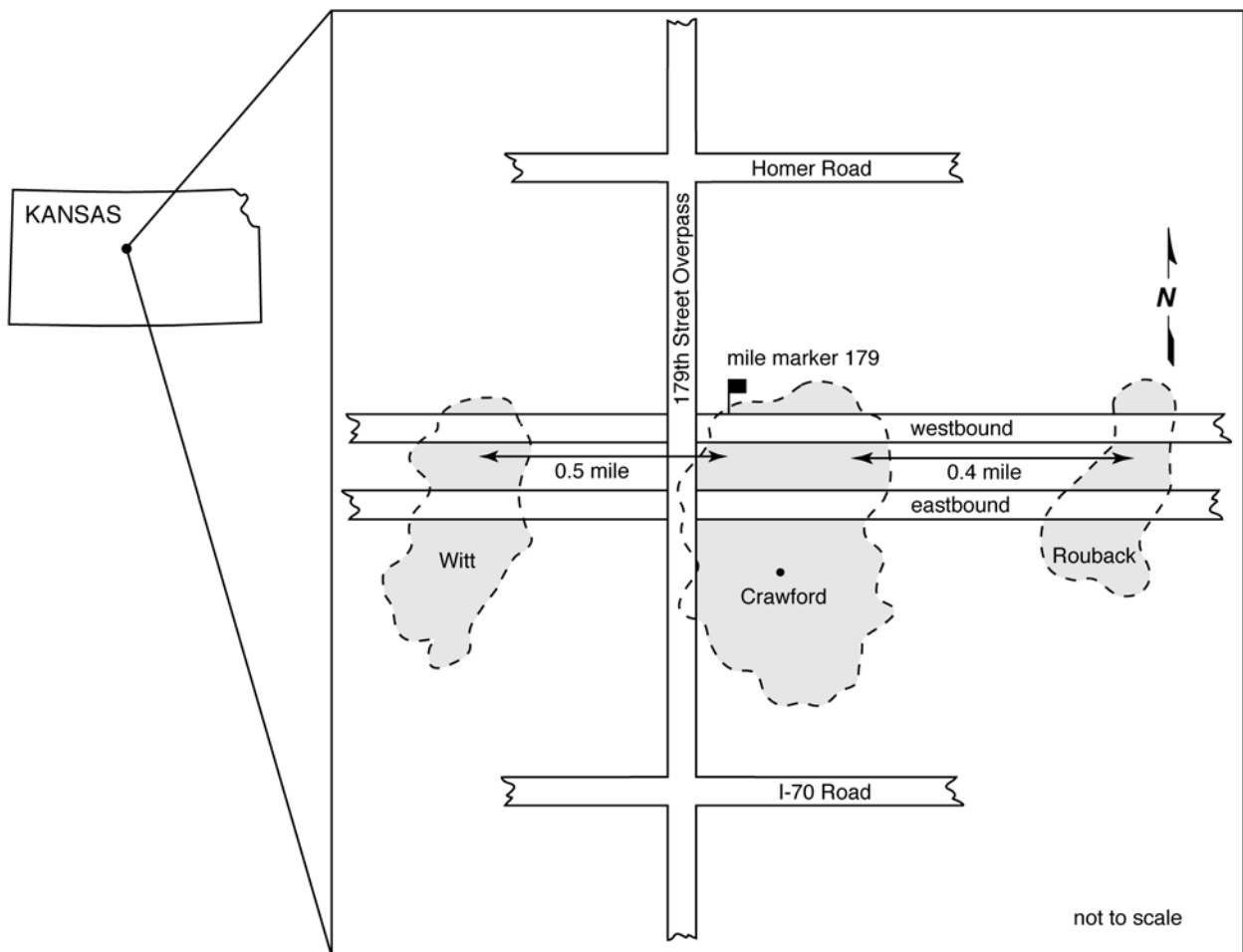


Figure 1.

Surface subsidence in this part of Kansas can range from gradual (an inch per year) to catastrophic (tens of feet per second) and can represent a significant risk to public safety. The unstable nature of the ground around mile marker 179 on I-70 is due almost exclusively to anthropogenic salt dissolution resulting from containment failure in brine disposal wells within the Gorham oil field (Walters, 1978). Considering the high density of wells penetrating the salt layer in this area, lateral subsurface growth the known sinkholes as well as the potential for yet undocumented subsidence features to have grown large enough to be detected is very likely since the 1980 seismic survey. With that in mind, it seems prudent that the proposed seismic investigation examine a subsurface volume that extends significantly beyond what is minimally necessary to capture the subsurface expression of the three known sinkholes. Confident projections of growth potential for the next 25 years as well as identification of suspicious areas or areas where unexpected growth might occur will be primary outcomes of this investigation. With those objectives in mind and considering the depth to salt, high resolution and fold subsurface images are needed at least three-quarters of a mile east and west of the bounding sinkholes (Witt and Rouback).

The project will consist of two major phases: testing and production. The testing phase will commence as soon as a mutually agreed time can be arranged between the Kansas Geological Survey (KGS) and the Kansas Department of Transportation (KDOT). The testing phase will consist of walkaway tests near the planned survey lines. Walkaway noise test data will be gathered according to common shot station and receiver offset and separated into distinct groups according to recording parameters (source, receiver, recording parameters, etc.). The quality and potential of the test data will dictate if the project proceeds to the production acquisition phase and the approach taken during that portion of the project. Both KGS and KDOT will jointly determine if the production phase will commence.

Optimization of seismic images and eventual geologic interpretations from the depth range most susceptible to dissolution and/or collapse requires a well designed reflection survey intended to provide meaningful correlations to ground truth (subsurface geologic) and surface deformation. Shallow, high resolution seismic reflection techniques have been successful delineating stratigraphic and structural features associated with several salt dissolution features throughout Kansas (Steeple, 1980; Knapp and Steeple, 1981; Steeple and Knapp, 1982; Steeple et al., 1983; Steeple et al., 1986; Miller et al., 1985; Miller et al., 1988; Knapp et al., 1989; Miller et al., 1990a; Miller et al., 1993; Miller et al., 1995a; Miller et al., 1997; Miller and Xia, 2002; Miller et al., in press).

This study will focus on: 1) optimized application of seismic techniques in this noisy environment, 2) maximizing resolution potential (both horizontal and vertical), 3) optimum source and acquisition geometries, 4) correlation of data from this study to previously acquired reflection data over these three sinkholes in 1980 (Steeple et al., 1986), 5) the active/current dissolution front and failure history as determined from current bed geometries, 6) geometry and failure potential of any yet undiscovered dissolution related subsurface structures, and 7) the growth potential and risk to highway integrity. Proven high resolution techniques (Steeple and Miller, 1990) will be used to acquire data on this survey. Acquisition of the production data will follow well-established procedures for shallow high-resolution data acquisition (Hunter et al., 1984; Knapp and Steeple, 1986; Steeple and Miller, 1990). Production data will be acquired in a standard CDP format (Mayne, 1962) using a modified roll-along acquisition technique similar to conventional petroleum exploration data acquisition. The geophone spacing, seismic source,

source spacing, optimum fold, geophone type, spread geometry, sampling interval, total samples, shots/point, and acquisition philosophy will be based on previous experience in this area and extensive pre-production tests.

It will require about 1 week to acquire the west/east profile in the eastbound road ditch of I-70 and 2 days to acquire the south/north profile along 179th Street. The basic architecture of both the acquisition and processing flow will be roughly designed around the findings of the preliminary testing and legacy data. Step-by-step analysis during the acquisition and processing phases of the survey will be continuous with appropriate modifications made if deemed necessary to ensure the quality of the final product.

### Geologic and Geophysical Setting

The Permian Hutchinson Salt Formation underlies a significant portion of south central Kansas (Walters, 1978). The distribution and stratigraphy of the salt is well documented (Dellwig, 1963; Holdoway, 1978; Kulstad, 1955; Merriam, 1963). The salt reaches a maximum thickness of 560 ft in central Oklahoma and thins to depositional edges on the north and west, erosional sub-crop on the east, and facies changes on the south (Figure 2). The increasing thickness toward the center of the salt bed is due to a combination of increased salt and more and thicker interbedded anhydrites. The Stone Corral Anhydrite (a well documented acoustic marker) overlies the salt throughout Kansas (McGuire and Miller, 1989). Directly above the salt is a thick sequence of Permian shales.

Recent dissolution of the salt and resulting subsidence of overlying sediments forming sinkholes has generally been associated with mining or saltwater disposal (Walters, 1978). Many times these sinkholes manifest themselves as a risk to surface structures and activities. The rate of surface subsidence can range from gradual to catastrophic. Besides risks to surface structures, subsidence features potentially jeopardize the natural segregation of ground water

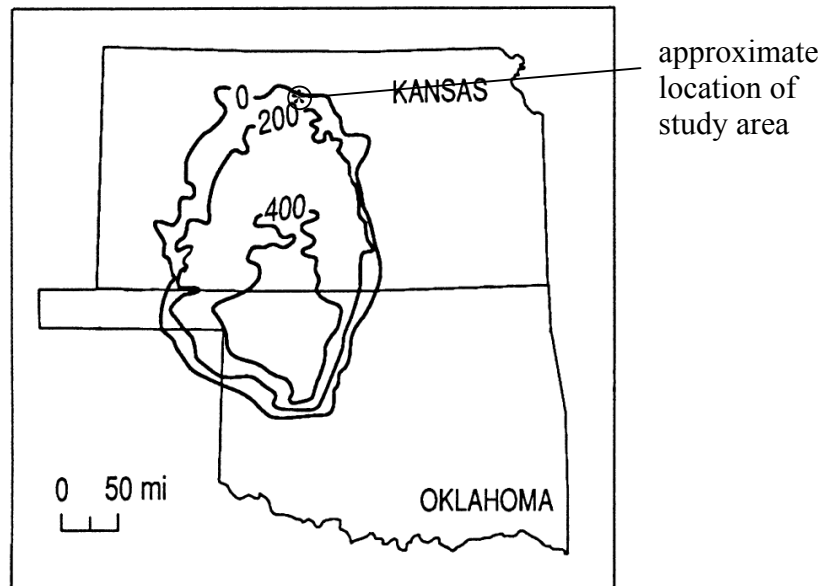


Figure 2. Approximate extent of salt formation.

aquifers, greatly increasing their potential to negatively impact the environment (Whittemore, 1989; Whittemore, 1990). Natural sinkholes resulting from dissolution of the salt by localized leaching within natural flow systems which have been altered by structural features (such as faults and fractures) are not uncommon west of the main dissolution edge (Merriam and Mann, 1957).

Subsidence within the Gorham oil field in western Russell County has been a nuisance, source of substantial repair expense, and focus of much public concern for KDOT over most of the last 50 years. Most significant has been the effect of the tens of feet of subsidence that has occurred in the Crawford sinkhole on the paved superhighway and cement overpass located within the western half of that sinkhole (Figure 3). Uncontrolled release of unsaturated oil field brine and the resulting indiscriminate leaching of large volumes of salt around the Crawford disposal well bore occurred when the casing failed over 40 years ago (Figure 4) (Walters, 1978). Once the salt void left from this leaching process grew to exceed the strength of the roof rock, failure occurred and subsidence began (Figure 5). Even after wastewater disposal was halted, leaching continued as overlying fresh water gained access to the salt when borehole confinement (casing to borehole seal) was lost (Figure 6). Natural confining properties of the rock layers surrounding the well bore were compromised when strain manifested itself as large offset radial faults generally centered on the well bore (Steeple et al., 1986). With failure and subsidence of rock layers surrounding the well bore and above the salt, natural new conduits for vertical migration of fresh water were established and the process proceeded unchecked.



Figure 3. View of Crawford sinkhole from north approach overpass looking southeast, October 2003.

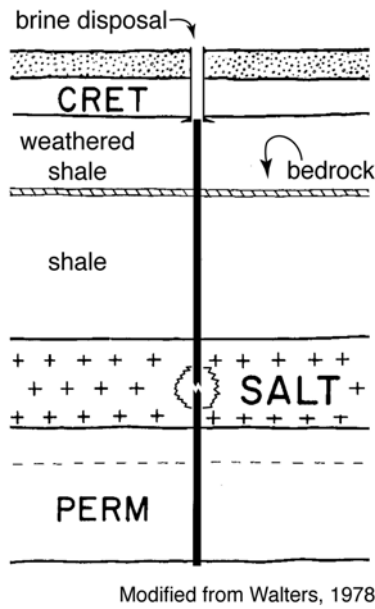


Figure 4

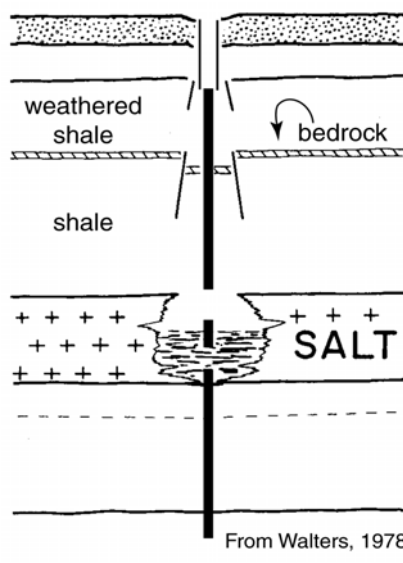


Figure 5

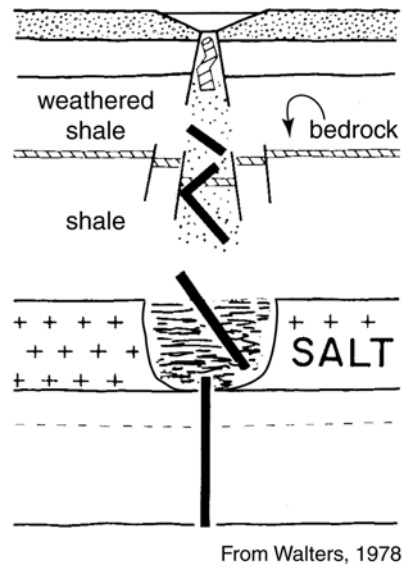


Figure 6

Shallow seismic reflection techniques have been used throughout central Kansas to delineate the subsurface expression of surface subsidence features (Steeple, 1980; Knapp and Steeples, 1981; Steeples and Knapp, 1982; Steeples et al., 1983; Steeples et al., 1986; Miller et al., 1985; Miller et al., 1988; Knapp et al., 1989; Miller et al., 1990a; Miller et al., 1993; Miller et al., 1995a; Miller et al., 1997; Miller and Xia, 2002; Miller et al., in press). Seismic reflection has proven to be a very effective tool to map structural aberrations in proximity of sinkholes. No less than a dozen sinkholes have been examined with shallow seismic reflection in Kansas, generally resulting in a detailed structural map of significant layers above the salt as well as some suggestion of the amount and extent of future subsidence.

At the I-70 sinkhole site in western Russell County the Hutchinson Salt is approximately 1400 ft deep and about 300 ft thick (Figure 7). Seismic reflection data acquired in 1980 used the MiniSOSIE method (Barbier et al., 1976) to minimize the effects of traffic noise and avoid the expense and increased safety concerns of using high

**GEOLOGIC PROFILE OF CRAWFORD SINK  
3 Exploratory Holes**

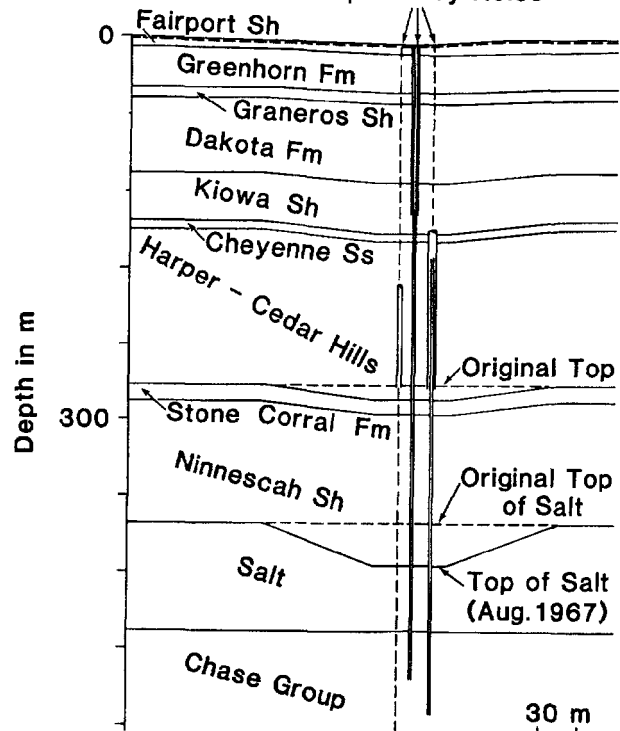


Figure 7. Cross-section from Kansas Department of Transportation based on drilling and logging in 1967. The Stone Corral dropped several meters between 1967 and 1980 (from Steeples et al., 1986).

explosives. Disturbed rock layers, evident beneath the Witt and Crawford, were evident and clearly associated with collapse of rock layers into voids left from the dissolution of the salt layer (Figures 8 and 9). Unexpected was the collapsed rock layers evident only in the subsurface approximately a half-mile east of the Crawford sinkhole (Figure 10). Since the 1980 survey this third subsidence feature has migrated vertically to the point it has now resulted in a noticeable depression in the highway and is known as the Rouback sinkhole. Considering the density of drill holes within 2 miles of these three sinkholes, expanding the investigation one mile east and west of the sinkhole area might provide insight and an early warning to future sinkholes along this high-risk stretch of I-70 (Figure 11).

Improvements in high-resolution data acquisition and processing techniques that have occurred over the last twenty years will be evident in the dramatic increase in signal-to-noise ratio and data resolution potential that this follow-up survey will possess. Comparing and contrasting the 1980 and 2004 seismic surveys the biggest improvements come in source, number of recording channels, dynamic range of seismograph, and pre-stack processing steps.

	<u>1980</u>	<u>2004</u>
<b>seismograph</b>	12 channels 12-bit A/D fixed gain amplifiers	240 channels 24-bit A/D floating-point gain amplifiers
<b>source</b>	MiniSOSIE 2 Wacker (earth compactors)	vibroseis minivibII (10,000 lbs)

### **Experimental (Testing) Phase**

Experimentation will focus on a series of tests designed to evaluate a variety of acquisition methods and parameters. These experiments will mainly consist of walkaway noise tests, which involve recording data with a variety of source settings into a fixed spread of geophones. All data for this study will be recorded on a 24-bit, 240-channel Geometrics StrataView seismograph (Appendix A3). The test spread needs to be located in an area with a uniform, relatively undisturbed subsurface. It will likely take around half a day to complete this aspect of the testing.

Walkaway testing will employ a single receiver spread with source-to-receiver offsets ranging from 8 ft to approximately 4000 ft. Based on success during previous surveys targeting the salt interval along busy highway systems (Miller and Xia, 2002) the IVI Minivib2 high frequency vibrator using the vibroseis technique will be the seismic source and method of choice (Appendix A4). The IVI Minivib2 is a non-invasive high frequency vibrator that should provide optimum mobility and minimal footprint with ample high frequency energy (Appendix A5). Specific to this survey, the source will be evaluated to determine its optimum settings for the near-surface conditions, target depth, resolution requirements, and environmental constraints of this site. Based on testing and performance during previous high-resolution surveys integrating this depth range, receivers will be triple 10 Hz Mark Product U2w geophones wired in series (Appendix A1). These high-output geophones provide a strong signal with a high spurious noise threshold (Appendix A2). If during the noise testing an optimum parameter or component is identified, the affected portions of the remaining tests could be skipped.

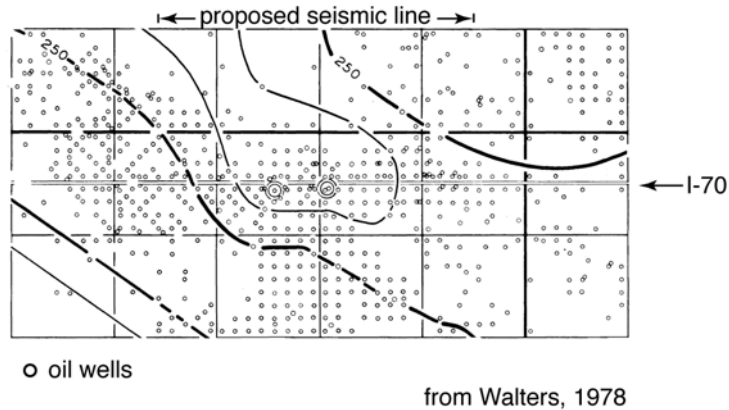


Figure 11

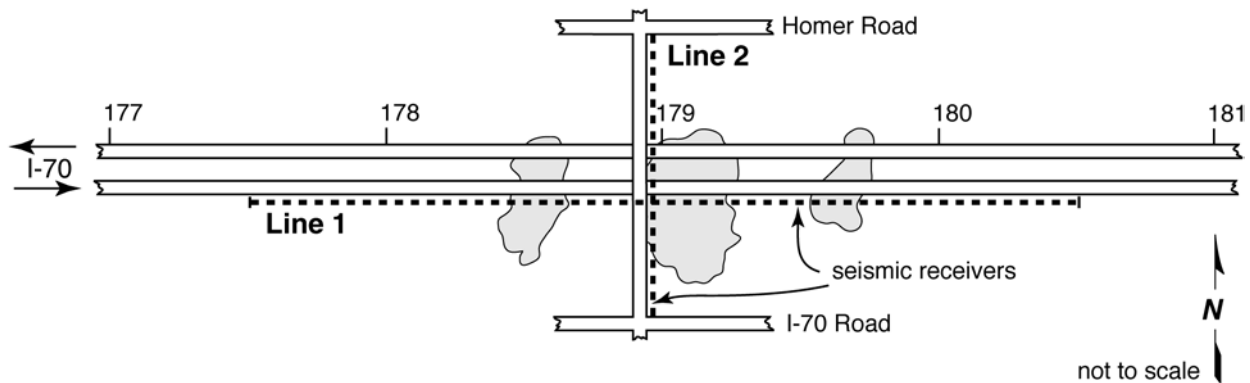


Figure 12

Data collected during the experimental phase of this survey will be reduced to the appropriate final display format on site. All walkaway noise tests will be displayed according to source-to-receiver offset with separate displays for each source configuration. The final walkaway sections will be trace balanced and displayed in a variable-area wiggly trace format. Spectral analysis will be used in conjunction with forward modeling to determine the basic characteristics and potential of reflection data. Determination of source configuration and field parameters for the CMP production lines at each site will be based on analysis of all walkaway tests.

### Production Acquisition

The production acquisition phase of this project will begin after the testing phase is completed and KGS and KDOT are satisfied with the parameter design. The data should be acquired in five to at most seven days. Acquisition equipment and parameters will be a qualitative choice based on frequency, potential penetration depths, quantity of ground roll relative to body waves, and physical site and near-surface constraints. Parameters such as sampling interval, record length, and sweep settings will be determined after careful examination of the dominant frequency and usable bandwidth of reflection energy.

Optimally, a continuous 3-mile profile will be collected from west to east in the east-bound road ditch of I-70 between mile markers 177 and 181 (Figure 12). This west/east line will be complemented with a 1 mile long south to north profile extending from I-70 Road to Homer Road along the east road ditch. The west to east 2-D profile will be acquired in such a way that it will mate with the 1980 seismic profile at the interpretation stage providing an excellent time lapse view of sinkhole development at this site.

Recording equipment and parameters will be designed to provide the highest fidelity and greatest signal-to-noise ratio section possible. A 240-channel rolling spread, compressional wave survey will be acquired with receivers in the south road ditch (Appendix A2). Based on the 1980 seismic profile and subsequent seismic reflection surveys targeting this depth range, receivers will likely be separated by 16 ft and source station spacing will probably be 32 ft. An IVI minivib2 will be the source of choice running a linear up sweep from approximately 20 to 250 Hz. Three to five sweeps will be recorded uncorrelated at each source station to allow pre-correlation processing and enhanced spectral characteristics prior to vertical stacking. Source locations will be on the eastbound extreme right shoulder at the edge of the asphalt. The source pad will need to be completely over and coupled to the asphalt surface (Appendices A4 and A5).

Data will be acquired on a 240-channel Geometrics StrataView seismograph using a standard CMP fixed rolling spread technique, resulting in a variable fold (averaging around 60) CMP stack section. Considering the targets unique characteristics an asymmetric split-spread source/receiver geometry will enhance continuity and increase velocity and dip control. The source-to-nearest receiver offset will probably be around 25 ft with a maximum source-to-receiver offset range from about 1500 to approximately 3000 ft. Modifications to the source/receiver geometries and offsets may be necessary after analysis of the data acquired during the testing phase.

Final design of the field geometries will be based on analysis of potential (using physical properties derived from the test data) versus required resolution (Miller et al., 1995b). The quarter-wavelength criteria of Widess (1973) will be used to determine the best vertical resolution with equipment and near-surface conditions present during the acquisition of the test data. The potential versus actual horizontal resolution will be based on the radius of the theoretical Fresnel zone. Oversampling of the first Fresnel zone will not exceed 15 times (Miller et al., 1990b) while a minimum of four times will be maintained throughout the survey (Knapp and Steeples, 1986).

Of key interest will be a comparison of the current sinkhole subsurface geometry and dissolution features with equivalent features interpreted on the 1980 data. Once acquired these data will allow a detailed interpretation of bed geometries and areas susceptible to new or continued subsidence. The high fold (redundant), close receiver spaced data proposed here should result in sufficient split-spread source/receiver geometries and spatial sampling to produce velocity profile maps at accuracy levels of 10% or better and cells sizes as small as 25 ft x 25 ft.

## QA/QC

The data acquired and processed on this survey will be managed to ensure the highest quality and most accurate acoustic representation of the geologic setting possible. Current state-

of-the-art techniques will be used in a fashion that is appropriate and verified with step-by-step QA/QC. The most important (possibly even essential) information that will be provided (besides the CMP stacked section itself) are data in a shot gather format as they look after application of each intermediate step. This information allows the geophysicist and geologist to make determinations as to the authenticity of processed seismic sections. Seismic processing software and techniques are very power tools that, if not used properly, can and most likely will result in bogus interpretations.

The equipment and recorded data will be continuously monitored during acquisition to ensure the highest quality CMP stacked section. The response amplitude of receivers will be monitored using a modified tap test performed after the planting of each geophone or group of geophones. The continuity and leakage of each active station will be meter monitored prior to each shot. The system will be subject to a series of pre-acquisition tests designed to insure the integrity of analog filters, consistency in system noise, and precision in digitally stored data. Visual analysis of general signal-to-noise ratio, environmental noise, DC bias, and variations in the optimum recording window will be performed on at least every fifth field plot.

### Production Processing

High-resolution seismic reflection data, by its very nature, lends itself to over-processing, inappropriate processing, and minimal involvement processing. Interpretations of high-resolution shallow reflection data must take into consideration not only the geologic information available, but also each step of the processing flow and the presence of reflection events on raw unprocessed data. Processing for the reflection portion of this study will include only operations or processes that enhance signal-to-noise-ratio and/or resolution as determined by evaluation of high confidence reflections interpreted directly on shot gathers (Figure 13). For the most part, processing of high-resolution shallow reflection data is a matter of scaling down conventional processing techniques and methods; however, without extreme attention to details, conventional processing approaches will produce undesirable artifacts. In-field processing of the reflection data will result in brute stacks

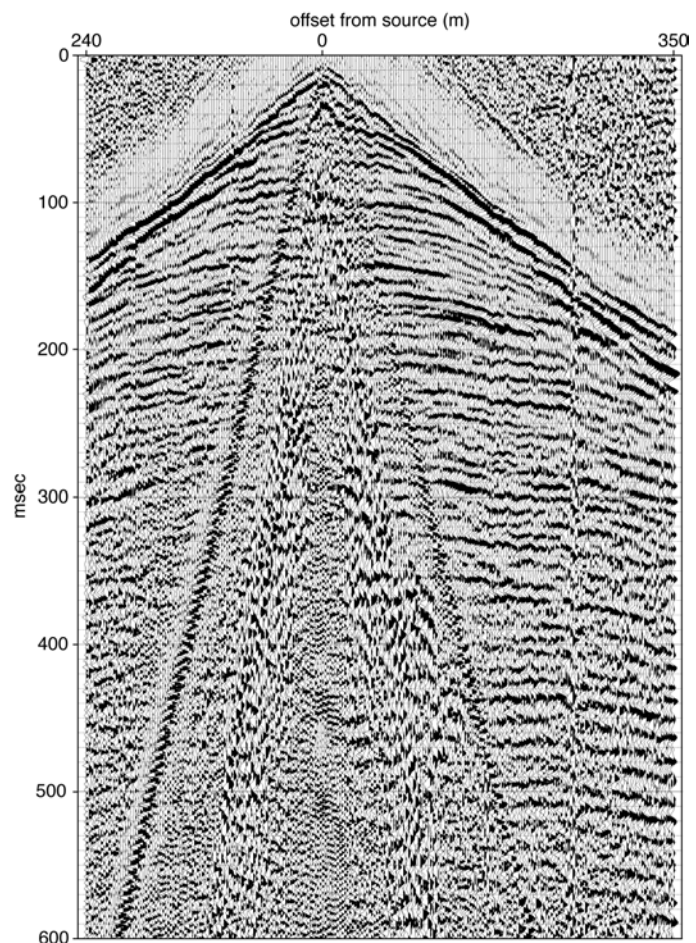


Figure 13. Representative 240-channel shot gather with 2.5 m receiver spacing and IVI minivib source, scaled for display. Dozens of reflections are interpretable in the upper 600 ms. Top of salt is indicated by the high amplitude reflection at about 130 msec.

that will be used to insure the data acquired are of sufficient quality to provide meaningful interpretations and to permit the merging of the different modes when final processing is completed several months after leaving the field. In-field processing will be coincident with data acquisition and will not impact the full day field schedules.

The basic architecture and sequence of processing steps to be followed during the generation of the final stacked sections will be similar to conventional petroleum exploration flows (Figure 14) (Yilmaz, 1987). The primary exceptions relate to the step-by-step QC necessary for the highest confidence interpretations of shallow features and realization of full resolution potential (Miller et al., 1989; Miller et al., 1990b; Miller and Steeples, 1991). Specific distinctions relate to the emphasis placed on velocity analysis (Miller, 1992), lack of extensive wavelet processing, care and precision placed on muting, step-by-step analysis of effects of each operation on reflected energy, limiting statics operations to maximum shifts no greater than one-quarter wavelength of the dominant reflection energy with large correlation windows, and coincident iterative velocity and statics analysis.

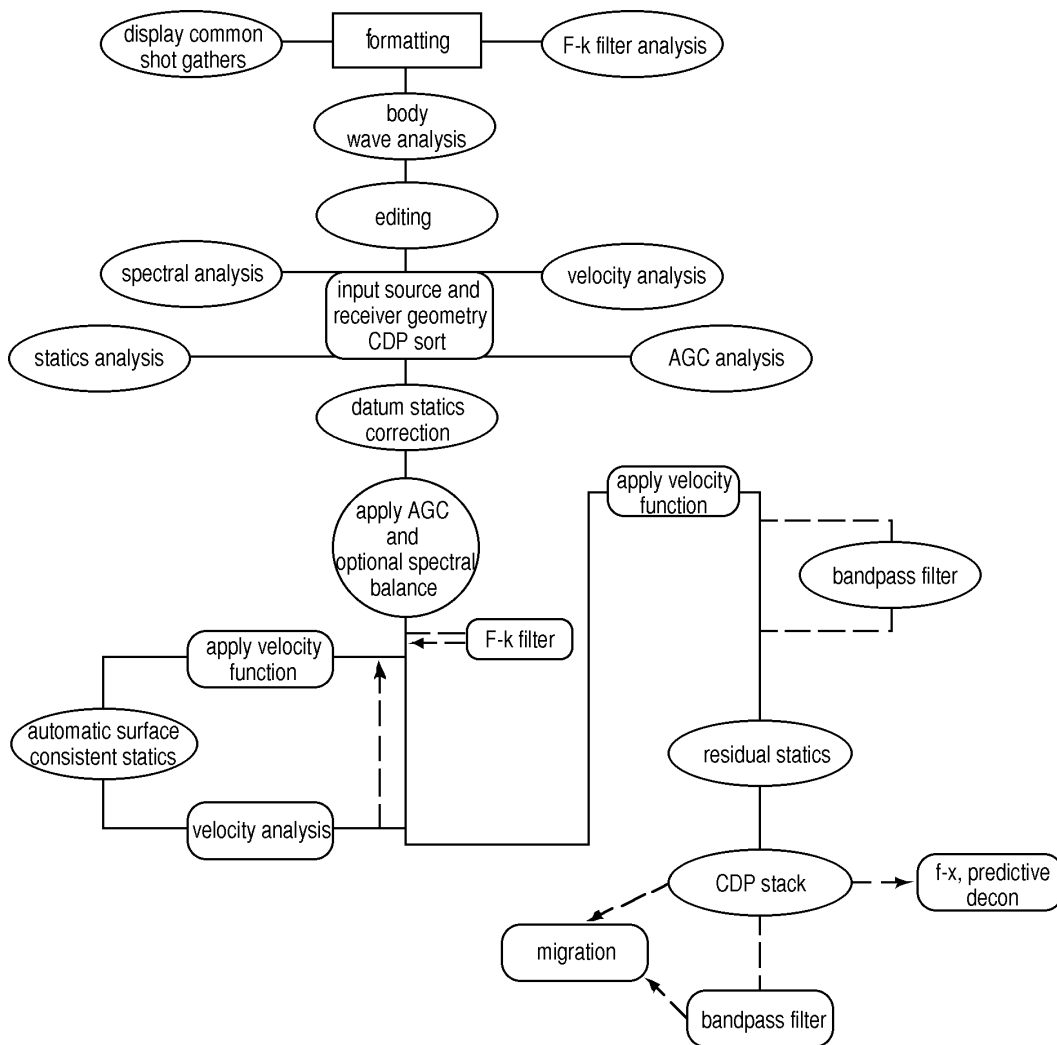


Figure 14. Processing flow.

Special emphasis will be placed on all the analysis portions of the processing flow. It has been proved necessary and most effective to do velocity, spectral, and on certain occasions deconvolution analysis on every CMP (Steeles and Miller, 1990). Many times variability in near-surface materials and/or conditions require changes in processing parameters over distances of less than 20 m. To insure the highest quality geologically representative stacked section velocity analysis of every CMP is necessary. Assigning a representative normal moveout velocity function is a pivotal component of time-to-depth conversions of processed seismic reflection data and will be critical to accurate geologic interpretations in this highly altered and geometrically complex subsurface setting. In association with point-by-point analysis, care must be taken to ensure that all coherent events on stacked sections interpreted as reflections are reflections. Biasing processing parameters to enhance events interpreted as reflections that are actually coherent noise must be avoided at all cost. Differentiating reflections from direct wave, refractions, air wave, and ground roll in the early portion of a stacked section is an extremely difficult task and must not be taken lightly (Steeles and Miller, 1990).

Each analysis step in the processing flow will be available for critique. Any additional information requested during the processing flow will be generated within a reasonable amount of time (amount of time determined jointly). All requested digital information will be delivered on the requested magnetic media (if readily available). Hardcopy printouts of any requested data will be delivered to on 300 dpi plots. Horizontal and vertical scale on hardcopy printouts will be set to maximize the analysis potential of these and existing data.

As much effort as possible will be made during processing of this data to interact with KDOT staff to insure the most accurate stacked seismic reflection sections. This proposal includes basic CMP processing but does not include extensive post-CMP processing models or extensive interpretations. The interpretation stage of this project will be critical and should involve integration of geophysical with geologic models. Interpretation of the resulting CMP stacked section and generation of associated geophysical models will require a cooperative effort to produce a representative cross-section.

## **Geologic Interpretation**

Geological interpretations will, for the most part, be consistent with well-established concepts and practices placing particular emphasis on velocity analysis, layer resolution, and reasonable bed distortion in making geologic inferences. Based on the proposed acquisition and processing plan it should be possible to developed a dissolution and subsidence chronology for the three sinkholes currently affecting highway stability.

It will be the intent of this survey to provide a geologic interpretation of the subsurface, loosely correlating major reflections with reflectors and any distortion in otherwise uniform bedding related to the surface subsidence. Extrapolation of any areas with deformation and volume estimations from layers at or just below the salt to the surface will provide a reasonable estimation of subsidence possible on the ground surface, areal extent of these potential future sinkholes, and if possible delineate bridging or layer droop within subsidence cones. A major effort will be made to correlate and contrast features interpreted on these data with those observed and interpreted on the 1980 survey.

## Overall Project Goal

The principal goal of this study is to appraise the integrity of the rocks above the Hutchinson Salt member beneath the one mile of I-70 currently subsiding due to uncontrolled dissolution of the 1500 ft deep bedded salt. Of critical importance in understanding the risk and future surface changes is to understand the geology, hydrology, and the mechanical process and chronology of salt leaching and associated roof rock failure linked to disposal wells at this site. Imaging and resolving structural and stratigraphic features within the upper 2000 ft will be essential in understanding and accurately appraising continued subsidence risk. The results of this study will include: an appraisal of the high resolution seismic method (resolution/signal-to-noise); an empirically based estimation of horizontal and vertical layer distortion, current and potential; time-to-depth converted interpreted CMP stacked sections focusing on correlation with geologic units; structural features and potential mechanisms associated with this localized feature; time lapse interpretation of subsidence on the Witt, Crawford, and Rouback sinkholes; and evaluation of current equipment and methodologies.

## References

- Anderson, N.L., A. Martinez, J.F. Hopkins, and T.R. Carr, 1998, Salt dissolution and surface subsidence in central Kansas: A seismic investigation of the anthropogenic and natural origins models: *Geophysics*, 63, 366-378.
- Barbier, M.G., P. Bondon, R. Mellinger, and J. Viallix, 1976, Mini-SOSIE for land seismology: *Geophysical Prospecting*, 24, 518-527.
- Dellwig, L.F., 1963, Environment and mechanics of deposition of the Permian Hutchinson Salt Member of the Wellington Shale: Symposium on Salt, Northern Ohio Geological Society, Cleveland, 74-85.
- Doll, W.E., R.D. Miller, and J. Xia, 1994, Non-invasive shallow seismic source comparison for hazardous waste site investigations [Exp. Abs.]: Soc. Explor. Geophys., p. 591-594.
- Healey, J., J. Anderson, R. D. Miller, D. Keiswetter, D.W. Steeples, and B. Bennett, 1991, Improved shallow seismic-reflection source: Building a better Buffalo [Exp. Abs.]: Soc. Explor. Geophys. v. 1, p. 588-591.
- Holdaway, K.A. 1978, Deposition of evaporites and red beds of the Nipewalla Group, Permian, western Kansas: Kansas Geological Survey Bulletin 215.
- Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.S. Good, 1984, Shallow seismic-reflection mapping of the overburden-bedrock interface with the engineering seismograph—Some simple techniques: *Geophysics*, 49, 1381-1385.
- Knapp, R.W., and D.W. Steeples, 1981, Investigation of salt dissolution collapse using high-resolution MiniSOSIE reflection seismology: *EOS*, Trans. American Geophysical Union, 62, 954-955.
- Knapp, R.W., and D.W. Steeples, 1986, High-resolution common depth point seismic reflection profiling: Field acquisition parameter design: *Geophysics*, 51, 283-294.
- Knapp, R.W., D.W. Steeples, R.D. Miller, and C.D. McElwee, 1989, Seismic reflection at sinkholes: Geophysics in Kansas, D.W. Steeples, ed., Kansas Geological Survey Bulletin 226, 95-116.
- Kulstad, R.O., 1959, Thickness and salt percentage of the Hutchinson Salt: Symposium on Geophysics in Kansas, Kansas Geological Survey Bulletin 137, 241-247.
- Mayne, W.H., 1962, Horizontal data stacking techniques: Supplement to *Geophysics*, 27, 927-938.
- McGuire, D., and B. Miller, 1989, The utility of single-point seismic data: Geophysics in Kansas, D.W. Steeples, ed., Kansas Geological Survey Bulletin 226, 1-8.
- Merriam, D.F., 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin 162, 317 p.
- Merriam, D.F., and C.J. Mann, 1957, Sinkholes and related geologic features in Kansas: *Transactions of the Kansas Academy of Science*, v. 60, no. 3.
- Miller, R.D., 1992, Normal moveout stretch mute on shallow-reflection data: *Geophysics*, 57, 1502-1507.
- Miller, R.D., N.L. Anderson, H.R. Feldman, and E.K. Franseen, 1995b, Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in Southeastern Kansas: *Geophysics*, 60, 423-430.
- Miller, R.D., S.E. Pullan, D.W. Steeples, and J.A. Hunter, 1992, Field comparison of shallow seismic sources near Chino, California: *Geophysics*, 57, 693-709.

- Miller, R.D., S.E. Pullan, D.W. Steeples, and J.A. Hunter, 1994, Field comparison of shallow P-Wave seismic sources near Houston, Texas: *Geophysics*, 59, 1713-1728.
- Miller, R.D., S.E. Pullan, J.S. Waldner, and F.P. Haeni, 1986, Field comparison of shallow seismic sources: *Geophysics*, 51, 2067-2092.
- Miller, R.D., and D.W. Steeples, 1991, Detecting voids in a 0.6-m coal seam, 7 m deep, using seismic reflection: *Geoexploration*, Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 28, 109-119.
- Miller, R.D., D.W. Steeples, and M. Brannan, 1989, Mapping a bedrock surface under dry alluvium with shallow seismic reflections: *Geophysics*, 54, 1528-1534.
- Miller, R.D., D.W. Steeples, R. Hill, and B. Gaddis, 1990b, Identifying intra-alluvial and bedrock structures shallower than 30 meters using seismic-reflection techniques: Soc. Explor. Geophys., *Investigations in Geophysics no. 5*, Volume on Environmental Geophysics, S. Ward, ed., 89-97.
- Miller, R.D., D.W. Steeples, P.B. Myers, D. Somanas, 1988, Seismic reflection surveys at the Knackstedt salt-water disposal well: Kansas Geological Survey Open-file Report 88-31.
- Miller, R.D., D.W. Steeples, L. Schulte and J. Davenport, 1993, Shallow seismic-reflection feasibility study of the salt dissolution well field at North American Salt Company's Hutchinson, Kansas, facility: *Mining Engineering*, October, p. 1291-1296.
- Miller, R.D., D.W. Steeples, and J.A. Treadway, 1985, Seismic reflection survey at a sinkhole in Ellsworth County, Kansas [Exp. Abs.]: Soc. of Expl. Geophys., 154-156.
- Miller, R.D., D.W. Steeples, F.T. Wirnkar, and D.A. Keiswetter, 1990a, Shallow seismic-reflection study of the Siefkes salt dissolution sinkhole in Stafford County for Quinoco Petroleum: Kansas Geological Survey, Open-file Report 90-32.
- Miller, R.D., D.W. Steeples, and T.V. Weis, 1995a, Shallow seismic-reflection study of a salt dissolution subsidence feature in Stafford County, Kansas: in N.L. Anderson and D.E. Hedke, eds., *Geophysical Atlas of Selected Oil and Gas Fields in Kansas*: Kansas Geological Survey Bulletin 237, p. 71-76.
- Miller, R.D., A. Villella, and J. Xia, 1997, Shallow high resolution seismic reflection to delineate upper 400 m around a collapse feature in central Kansas: *AAPG Division of Environmental Geosciences Journal*, v. 4, no. 3, p. 119-126.
- Miller, R.D., A. Villella, J. Xia, and D.W. Steeples, in press, Seismic investigation of a salt dissolution feature in Kansas: *Special Publication: Near-Surface Geophysics, Volume II*, Society of Exploration Geophysicists.
- Miller, R.D., and J. Xia, 2002, High-resolution seismic reflection investigation of a subsidence feature on US highway 50 near Hutchinson, Kansas: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2002), Las Vegas, Nevada, February 10-13, Paper 13CAV6, published on CD.
- Steeple, D.W., 1980, Seismic reflection investigations of sinkholes in Russell and Ellis counties, Kansas: Progress report to the Kansas Department of Health and Environment and the Kansas Department of Transportation, 14 p.
- Steeple, D.W., and R.W. Knapp, 1982, Seismic investigation of sinkholes in Russell and Ellis counties, Kansas: Final report to the Kansas Department of Health and Environment, 13 p., 15 pl.
- Steeple, D.W., R.W. Knapp, and C.D. McElwee, 1983, Seismic reflection surveys of a catastrophically collapsed sinkhole, Ellis County, Kansas [Exp. Abs.]: Soc. of Expl. Geophys., p. 296-298.
- Steeple, D.W., R.W. Knapp, and C.D. McElwee, 1986, Seismic reflection investigations of sinkholes beneath interstate highway 70 in Kansas: *Geophysics*, 51, 295-301.
- Steeple, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. *Investigations in Geophysics no. 5*, Volume on Environmental Geophysics, S. Ward, ed., p. 1-30.
- Walters, R.F., 1978, Land subsidence in central Kansas related to salt dissolution: Kansas Geological Survey Bulletin 214, 82 p.
- Watney, W.L., J.A. Berg, and S. Paul, 1988, Origin and distribution of the Hutchinson Salt (lower Leonardian) in Kansas: Midcontinent SEPM Special Publication No. 1, p. 113-135.
- Whittemore, D.O., 1989, Geochemical characterization of saltwater contamination in the Macksville sink and adjacent aquifer: Kansas Geological Survey Open-file Report 89-35.
- Whittemore, D.O., 1990, Geochemical identification of saltwater contamination at the Siefkes subsidence site: Report for the Kansas Corporation Commission.
- Widess, M.B., 1973, How thin is a thin bed: *Geophysics*, 38, 1176-1180.
- Yilmaz, O., 1987, Seismic data processing; S.M. Doherty, ed.; in Series: *Investigations in Geophysics*, no. 2, E.B. Neitzel, series ed.: Soc. Explor. Geophys.

## Appendix A

### Summary of Equipment, Specific Tests, and Timeline of Proposed Program (pictures of specific pieces of equipment are included)

- 1) Seismic system – 240-channel R60 Strata View w/Strata Visor controller from Geometrics
- 2) Equipment and testing parameters
  - triple 10 Hz U2w Mark Products geophones
  - IVI Buggy mount high frequency vibrator (15 to 500 Hz, 10,000 lb peak force with prototype valve)

Testing will include:

- various source configurations
  - geophone response and sensitivity
  - several different types of linear sweeps within the 20-400 Hz range
  - number of vibrations to obtain optimum vertical stacking
  - optimum receiver station spacing
  - source power and offset
  - determination of sampling interval (spatial/time) based on appropriate oversampling
  - 240-trace, continuous walkaway w/source offsets from 8 ft to 4000 ft
  - spectral analysis
- 3) Likely optimal design for **P-wave reflection**: Vibrator (3 sweeps/station), 240 recording channels, 10 Hz geophones, 16 ft receiver spacing, 32 ft source spacing, and rolling fixed spread. Approximately 4 miles (7 days) of profile will be acquired on two continuous lines starting at between mile marker 177 and 178 and ending between mile marker 180 and 181, with the second line starting at I-70 Road on the south and ending at Homer Road on the north.

- 4) Planned Research Schedule:

	<u>Approximate Duration</u>
Mobilization/Demobilization	2 weeks
Travel	1 day
Walkaway noise testing	½ day
Acquisition 2 lines (3 mile and 1 mile)	1 week (7 days)
Processing of around 660 shotpoints of CMP data	4 months
Interpretation of two lines, coincident with data from 1980 and any other supporting data (i.e., uphole, geologic logs, etc)	2 months
Reporting	3 months

- 6) Deliverables Schedule:

Oral review of preliminary findings 2-3 months after completion of fieldwork.  
Preliminary report 6 to 8 months after completion of fieldwork.  
Final Report after review and comment by KDOT.

## Appendix A



Figure A1. Two Mark Products L28E 40 Hz geophones separated by about 1 ft to form a 2 ft effective array.



Figure A2. Receivers were “planted” at the base of the road ditch to insure highest possible quality coupling.



Figure A3. 240 channel Geometrics StrataView with support electronics (line checker, IVI source synchronizer, time break conditioner, etc.).



Figure A4. IVI minivib with Atlas rotary valve. Approximately 800 ft-lbs of force can be applied at 100 Hz, while around 2000 ft-lbs are possible in some conditions at 250 Hz.



Figure A5. 300 lb mass and 300 lb baseplate with new prototype Atlas rotary valve.