High Resolution Seismic Reflection to Delineate Salt Dissolution Feature Affecting US Highway 50 West of Reno/Harvey County Line in Kansas

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Summary

This high-resolution seismic reflection study will focus on delineation of an active sinkhole currently threatening road stability near the intersection of US 50 and Victory Road in Reno County, Kansas (Figure 1). The primary goal of this study will be to delineate the sub-surface expression of a growing salt dissolution induced sinkhole near the subcrop of the Hutchinson Salt Member of the Permian Wellington Formation. 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 eventual surface subsidence.

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 next phase and the acquisition

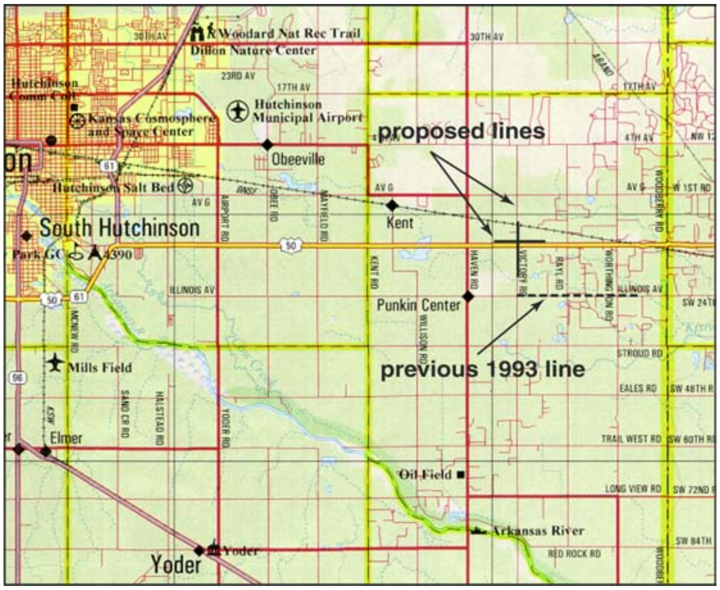

Figure 1. Site map with proposed lines and previous 1993 line.

approach taken during the production 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 (Steeples, 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). 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.

This study will focus on: 1) application of new seismic techniques in this noisy environment, 2) the resolution potential (both horizontal and vertical) in this structurally complex setting, 3) optimum source and acquisition geometries, 4) correlation of data from this study to that previously acquired 1 mile south of this location, 5) the current extent of the dissolution front, 6) 3-D geometry of the sinkhole down to the depth of the salt, and 7) the growth potential and risk to highway integrity at this site. Proven high resolution techniques (Steeples and Miller, 1990) will be used to acquire data on this survey. Production data will be acquired in a standard CDP format (Mayne, 1962) using roll-along acquisition techniques 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 extensive pre-production tests.

The production data will require 4 to 6 days (depending on conditions) and will follow well established shallow high resolution data acquisition procedures (Hunter et al., 1984; Knapp and Steeples, 1986; Steeples and Miller, 1990). The basic structure of both the acquisition and processing flow will be roughly designed around the findings of the preliminary testing. Ideally, an uphole or check shot survey should be acquired in a nearby borehole to enhance confidence and preliminary event identification. 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 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

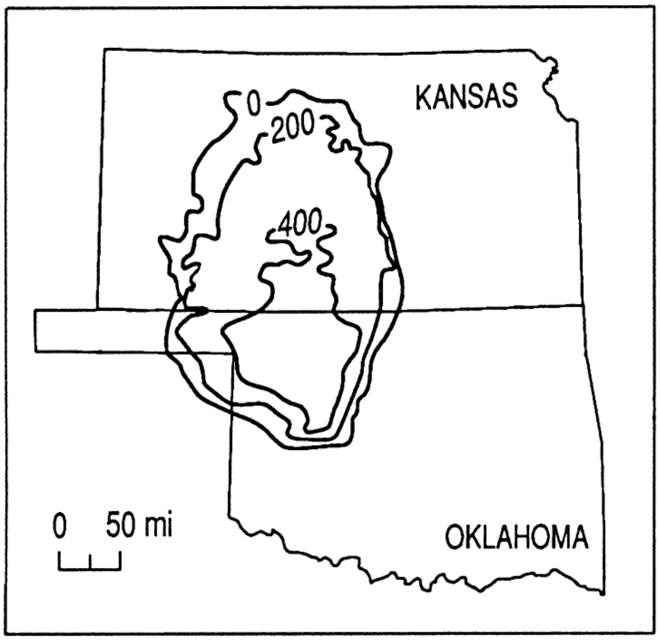

Figure 2. Approximate extent of salt formation.

faults and fractures) are not uncommon west of the main dissolution edge (Merriam and Mann, 1957).

Shallow seismic reflection techniques have been used throughout central Kansas to delineate the subsurface expression of surface subsidence features (Steeples, 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). Seismic reflection has proven to be a very effective tool mapping structural aberrations in the 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.

The sinkhole to be examined is located at the intersection of US 50 and Victory Road in Reno County and has begun to affect the stability of the US highway (Figure 3). To properly repair and maintain this portion of the highway, the subsurface stability must be appraised. As well, this feature represents a threat to water quality in this area.

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,

Figure 3. The intersection of US 50 and Victory Road.

which involve recording data from a variety of sources into a fixed spread. These data will be recorded on a 24 bit, 240-channel Geometrics StrataView seismograph. The test spread needs to be located in an area with a uniform, relatively undisturbed subsurface, far enough away from the highway to minimize the recorded vehicle noise. It will likely take around half a day to complete this aspect of the testing.

If access is possible to a near-by well/borehole, a vertical velocity survey measuring the acoustic travel time from the ground surface to various depths in the subsurface would greatly enhance the correlation of reflections to reflectors. The resulting velocity function would be used to establish the accuracy of the velocity function determined from curve fitting and semblance routines during the processing of the CMP data. A velocity survey in a borehole located near the survey line would greatly improve the interpretations of depth and bed thickness on CMP stacked section. Downhole information represents a measure of true average velocity and ground truth for the time-to-depth conversions.

Walkaway spreads will be deployed along one of the proposed seismic lines and as near to any control wells as possible. The walkaway will consist of source-to-receiver offsets ranging from 8 ft to approximately 1900 ft. The receiver interval for this testing will be 4 ft. The 8-gauge Auger Gun (Healey et al., 1991) (requiring only class C explosives), 50 cal downhole, and IVI Minivib high frequency vibrator will be evaluated to determine the optimum source for the near-surface conditions, target depth, resolution requirements, and environmental constraints. Each source will be evaluated with as near equivalent conditions and parameters as possible. Experience with source testing (Miller et al., 1986; Miller et al., 1992; Miller et al., 1994; Doll et al., 1994) will greatly enhance both the quality and the efficiency of source evaluations at this site.

The receivers available for testing will include both double 40 Hz Mark Products L-28E geophones and triple 10 Hz Mark Product U2w geophones wired in series. The 10 Hz geophones will be tested first, and from previous experience will probably produce the best response. The need for a strong signal from geophones with a high spurious noise threshold is paramount and from previous experience, lower quality geophones will not produce the desired output within the desired frequency band. If at any point during the noise testing an optimum parameter or component is identified, the affected portions of the remaining tests at that site could be bypassed.

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, receiver type, and low-cut filter tested. The final walkaway sections will be trace balanced and displayed in a variable-area wiggle trace format. Spectral analysis will be used in conjunction with forward modeling to determine the basic characteristics of reflection data collected with each of the sources tested. The uphole velocity files will be trace balanced and displayed individually in variable area wiggle trace format. 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

Optimally, two profiles will be collected that intersect orthogonally just to the north of the highway (Figure 1). This orientation will provide the optimum subsurface coverage for a minimum of cost and time. A 240-channel rolling spread, compressional wave survey will be acquired in the north road ditch of US 50 highway and the west road ditch of Victory Road. The two profiles will each be approximately 1 mile long and centered on the intersection of the lines. Based on previous experience, the IVI Minivib will be the source of choice to acquire the data. This non-invasive high frequency vibrator will provide optimum mobility with ample high frequency energy. Receiver spacing will likely be 8 ft; this suggestion is based on analysis of a 3 mile long CMP profile acquired by the KGS during the summer of 1993 one mile south of US 50 near Punkin Center (Figure 4). Dissolution features observed on this section possessed appropriate detail and resolution for the objectives of this study.

The very high fold (redundant) data proposed here should result in sufficient split-spread source/receiver geometries to produce velocity profile maps at accuracy levels of 10% or better and cells sizes as small as 25 ft x 25 ft. Of key interest will be a comparison of the geometry of the sinkhole in the subsurface in comparison to the profile collected just one mile south. If conceptual geological models of the salt front (layer subcrop) are correct, the paleosinkholes observed on the southern line should also be interpretable on the east/west line proposed here. These paleosinkholes have very distinctive seismic characteristics and geometry. 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 four days or less. Acquisition equipment in general and source and receiver selection in particular will be a

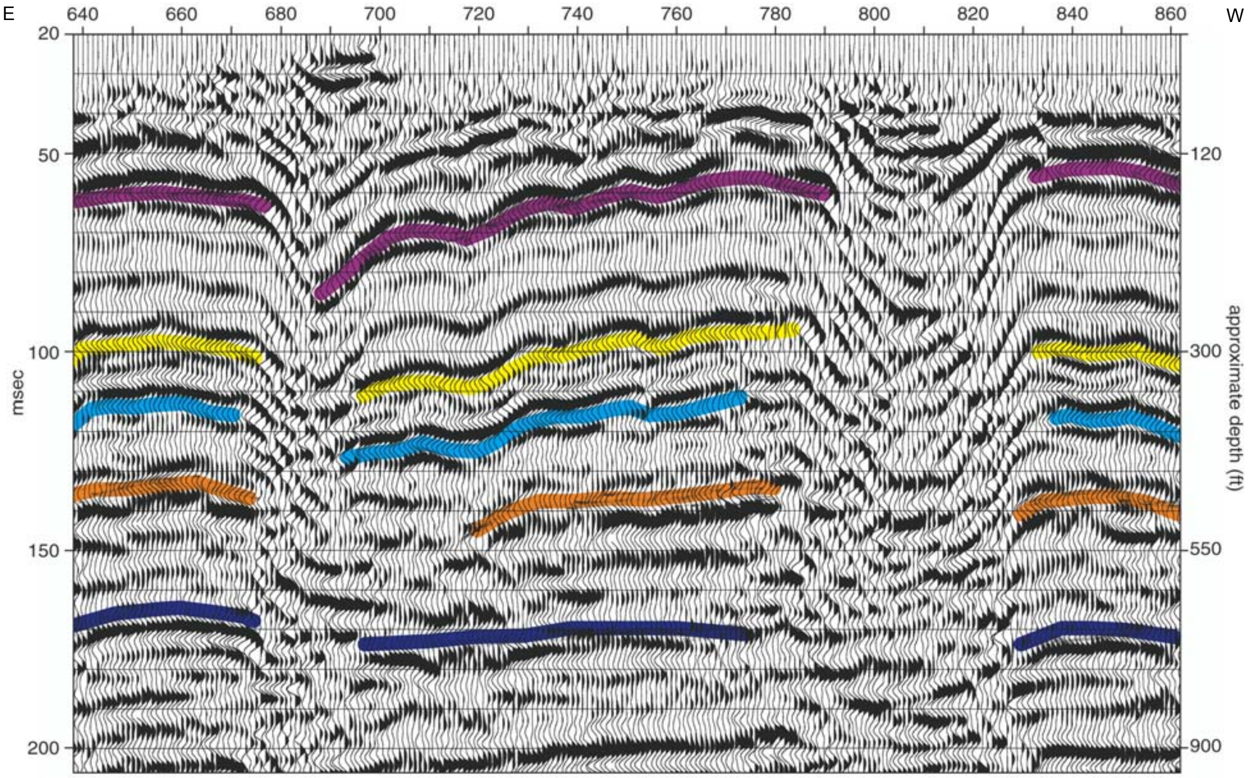

Figure 4. Profile from Punkin Center line acquired in 1993.

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. Based on experience at sites with similar near-surface and target intervals, the most probable source used for production will be the IVI high frequency vibrator. Triple U2w 10 Hz geophones will probably be the preferred choice for the receivers on the production line. The equipment parameters chosen to record the CMP lines will incorporate the results of both walk-away noise tests and previous experience from the profile collected one mile south in 1993.

The data will be acquired using a standard CMP fixed rolling spread technique which will result in a variable fold (averaging around 60) CMP stack section. The geophone station interval will be confirmed by computations and qualitative judgments made from data acquired during the testing phase and from previous surveys in this area. The most probable geophone spacing is 8 ft. The data will probably be acquired using an asymmetric split spread source/receiver geometry to enhance continuity and increase velocity and dip control. The source-tonearest receiver offset will probably be on the order of 25 ft with a maximum source-to-receiver offset range from about 1000 to approximately 1500 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).

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 CDP 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 5). 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 a brute stack 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 (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) (Figure 5). 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.

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 digital information will be delivered on the requested magnetic media (if readily available). All hardcopy printouts of analysis steps as well as any specially 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.

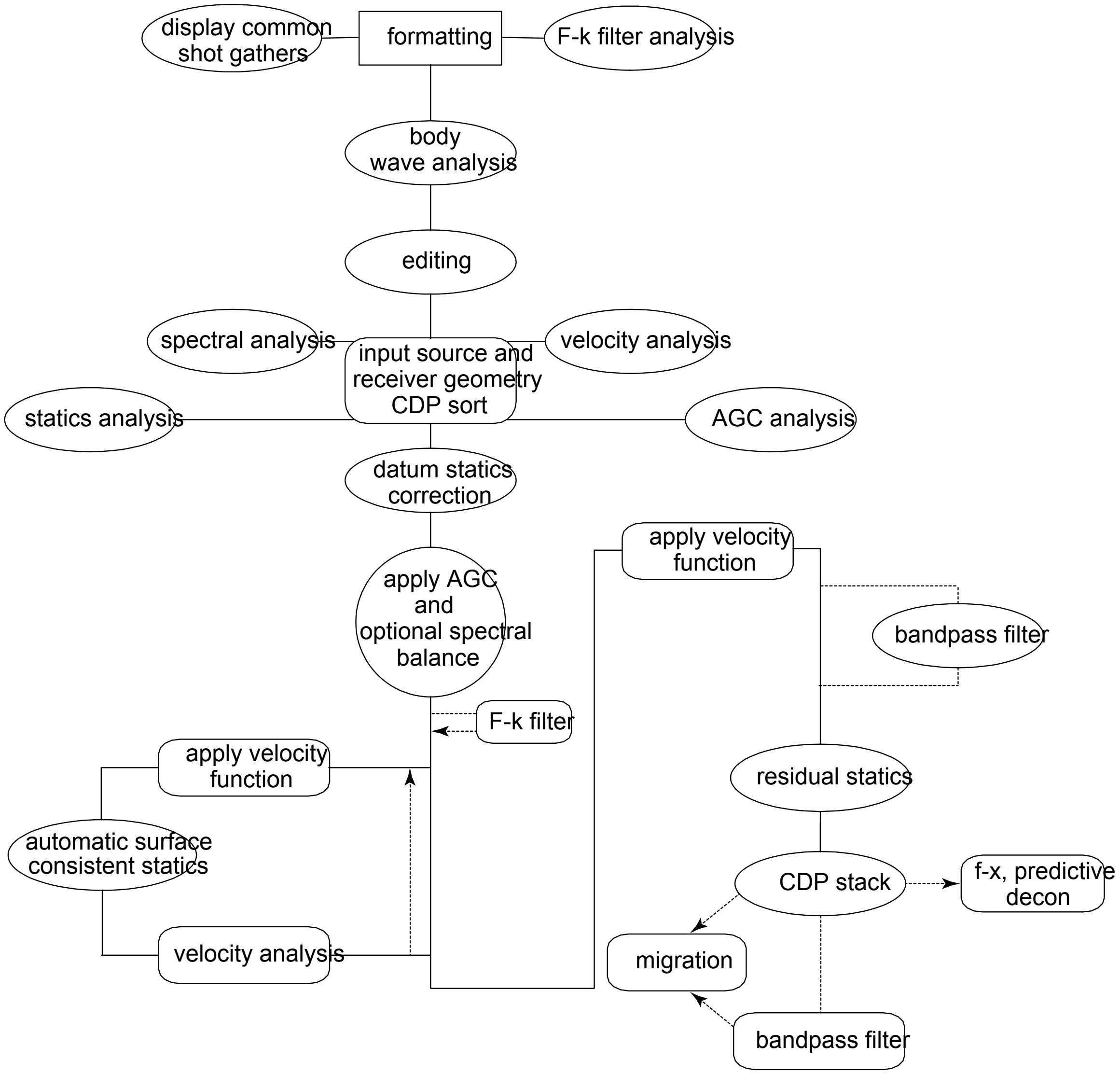

Figure 5. Processing flow.

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 (Steeples 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. 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 (Steeples and Miller, 1990).

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 is for the basic processing of data acquired in a CMP format and does not include 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 extend the interpretation of these data into a local 2½-D section by incorporating the three-mile long east/west line collected in 1993 into this analysis. Paleosinkholes observed along the eastern erosional subcrop of the Hutchinson Salt have been postulated to be the result of subsidence after dissolution by fluids that gained access to the salt through fractures (remnants of tectonic activity) in overlaying and interbedded non-permeable shale or aquatard layers (Anderson et al., 1998). It has been suggested that these fractures became active fluid conduits as the dissolution front moved westward. If this is the case, areas susceptible to natural subsidence should align along these fracture lineaments with existing sinkholes overlying rocks that have been faulted or folded. Identification of lineaments is essential to substantiating this theory. If intraconnectivity along such features cannot be established, it is unlikely this theory accurately portrays the mechanism responsible for these sinkholes.

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 current areas with deformation and volume estimations from layers at or just below the salt to the surface will provide a reasonable estimation of amount of subsidence likely to eventually be evident on the ground surface, areal extent of potential surface expressions, and if possible delineate bridging or layer droop within the subsidence cone. Considering the active nature of the salt in this area it would be quite unexpected to acquire a one-mile profile and not encounter paleosinkholes. Some attempt will be make to correlate and contrast these features with those discovered in 1993.

Overall Project Goal

The goal of this study is to determine the feasibility of imaging and resolving structural and stratigraphic features within the upper 1000 ft in close proximity to a dissolution feature at the intersection of US Highway 50 and Victory Road in Reno County, Kansas, based on seismic reflection stacked sections. 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; evaluation of effort and potential to extrapolate between stacked section several miles apart; and evaluation of current equipment and methodologies.

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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
   - double 40 Hz L-28E Mark Products geophones
   - triple 10 Hz U2w Mark Products geophones
   - single 3 component hole lock Geostuff geophone
   - downhole 50 cal projectile source
   - IVI Buggy mount high frequency vibrator (15 to 500 Hz, 6500 lb peak force)
   - 8 -gauge auger gun

   Testing will include:
   - various source configurations
   - geophone response and sensitivity
   - several different types of linear sweeps within the 20-400 Hz range
   - number of shots or vibrations to obtain optimum vertical stacking
   - optimum receiver station spacing
   - source power and offset
   - determination of sampling interval (spatial/time) based on appropriate oversampling
   - 480-trace, pseudo-continuous walkaway w/source offsets from 8 ft to 1900 ft
   - spectral analysis

3) Likely optimal design for **P-wave reflection**: Vibrator (3 sweeps/station) or downhole 50 cal, 240 recording channels, 10 Hz geophones, 8 ft receiver spacing, 16 ft source spacing, and rolling fixed spread. Approximately 2 miles (3 days) of profile will be acquired on two lines centered approximately at the intersection of US 50 and Victory Road.

4) Likely optimal design for downhole seismic (VSP):
   - 3-component hole lock geophone and/or single hydrophone (depending on coupling)
   - 400 ft maximum vertical profile
   - 5 ft vertical station spacing
   - as many as 3 source offset positions
   - source selection based on characteristics

5) Planned Research Schedule:

	Approximate Duration
Mobilization/Demobilization	2 weeks
Travel	1 day
Walkaway noise testing and analysis/VSP	3/4 day
Line 1–North/South along Victory Road	2 days
Line 2–East/West along US 50 (likely north road ditch)	2 days

Processing of around 660 shotpoints of CMP data (line 1 & 2)	2 months
Interpretation of line 1 & 2, coincident with data from 1993 and any other supporting data (i.e., uphole, geologic logs, etc)	1 months
Reporting	2 months

6) Deliverables Schedule:
   Oral review of preliminary findings, 2-3 months after completion of fieldwork.
   Preliminary report 5 to 6 months after completion of fieldwork.
   <u>Final Report</u> after review and comment by KDOT.