High Resolution Seismic Reflection to Image Upper Permian Rocks at the Leesburg Sinkhole, Stafford County, Kansas

Summary

This high-resolution seismic reflection study will target rock layers in the upper Permian portion of the geologic section beneath the actively forming Leesburg sinkhole in southcentral Stafford County, Kansas (Figure 1). The principal goal of this study will be to delineate rock layers within and above the Hutchinson Salt Member mapping the subsurface around and beneath this active sinkhole hopefully in sufficient detail to appraise the overall stability of the rock column, specifically as it relates to failure rates. Surface subsidence in this part of Kansas can range from gradual (an inch per year) to catastrophic (tens of feet per second), representing a significant risk to property and safety. 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 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 Corporation Commission (KCC). The testing phase will consist of walkaway tests along a planned survey line. Walkaway noise test data will be gathered according to common shot station and receiver offset and separated into distinct groups according to recording parameters. The quality and potential of the test data will dictate if the

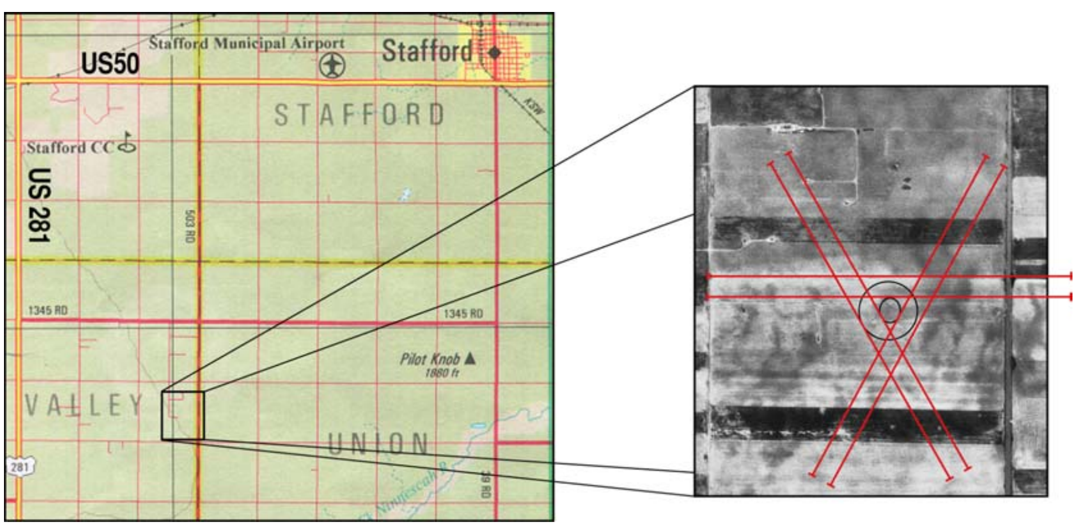

Figure 1. Site map with proposed lines.

project proceeds to the production acquisition phase and the approach taken during that portion of the project. Both KGS and KCC 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; Miller and Xia, 2002; Miller et al., in press).

This study will focus on: 1) optimized application of seismic techniques, 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 sets at the French and Macksville sinkholes, 5) the geometries of the salt units affected by dissolution and in proximity to mapped subsidence in the overlying sediments, 6) geometry and failure potential of the rocks overlying the disturbed salt, and 7) the future growth potential considering only the current volume of salt leached. Proven high resolution techniques (Steeples 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 Steeples, 1986; Steeples and Miller, 1990). 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 production data will require about one week for the approximately three to six 1-km lines intended to surround the sinkhole. The basic structure of both the acquisition and processing flow will be roughly designed around the findings of the preliminary testing. 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 (Dell-wig, 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

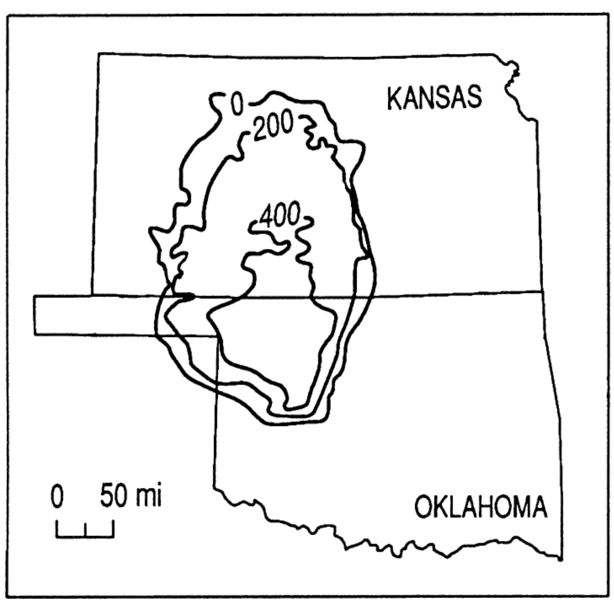

Figure 2. Approximate extent of salt formation.

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; Miller and Xia, 2002; Miller et al., in press). 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.

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 A1). The test spread needs to be located in an area with a uniform, relatively undisturbed subsurface, far enough away from the sinkhole to allow imaging of undisturbed sediments. It will likely take around half a day to complete this aspect of the testing.

The walkaway will employ a spread with source-to-receiver offsets ranging from 8 ft to approximately 2000 ft. Based on its success during previous seismic surveys that have investigated sinkholes in this area, the IVI Minivib high frequency vibrator will be the seismic source of choice (Appendix A2). The IVI Minivib is a non-invasive high frequency vibrator that should provide optimum mobility and minimal footprint with ample high frequency energy (Appendix A3). Specific to this survey, the source will be evaluated to determine its optimum settings for the near-surface conditions, target depth, and resolution requirements of this site. Based on testing and performance during the 2001 survey, the receivers used for this survey will be triple 10 Hz Mark Product U2 geophones wired in series. These high-output geophones provide a strong signal with a high spurious noise threshold. If during the noise testing an optimum parameter or component is identified, the affected portions of the remaining tests could be skipped.

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 wiggle 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

Optimally, six 1-km profiles will be collected that surround the Leesburg sinkhole (Figure 1). These 2-D profiles are designed with two objectives: first, to fully image the current subsurface rock geometries that have been altered as a result of salt dissolution, and second, to examine a sufficient subsurface volume to insure with future surface and subsurface growth, reoccupation and further studies are possible. It is important that the seismic profiles be expansive enough to provide continuous subsurface coverage of the disturbed and surrounding undisturbed salt interval and overlying strata to allow reoccupation and changes in time to be fully analyzed. A 240-channel fixed spread, compressional wave profile will be acquired along each proposed line forming two triangular-shaped survey grids (Figure 1). Based on analysis of the French Sinkhole profiles acquired by the KGS during 1996-1997 approximate 10 miles northwest of the Leesburg sinkhole and two 1-km CMP profiles acquired by the KGS during 1998 at the Macksville sinkhole, receiver spacing will likely be 16 ft with a 32 ft source interval. Dissolution features observed on sections from the French and Macksville sinkholes possess appropriate detail and resolution to successfully meet the objectives of this study.

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. Of key interest will be a comparison of the geometry of the sinkholes and dissolution features imaged on the two previous seismic surveys—one resulting from catastrophic failure the other gradual—with similar features expected across this rapidly developing sinkhole. With the apparent connectivity between two wells at this site and subsidence currently centered on one of the wells, catastrophic failure cannot be ruled out even though the subsidence rate at this site has been gradual to date.

The production acquisition phase of this project will begin after the testing phase is completed and KGS and KCC are satisfied with the parameter design. The data should be acquired in four or five 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.

The data will be acquired using a standard CMP fixed spread technique that will result in a variable fold (maximum around 60) CMP stack section. The data will be acquired using an asymmetric split spread source/receiver geometry to enhance continuity and increase velocity and dip control. The source-to-nearest receiver offset will probably be on the order of 25 ft with a maximum source-to-receiver offset range from about 2000 to approximately 2500 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 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. 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 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 (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 3). 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.

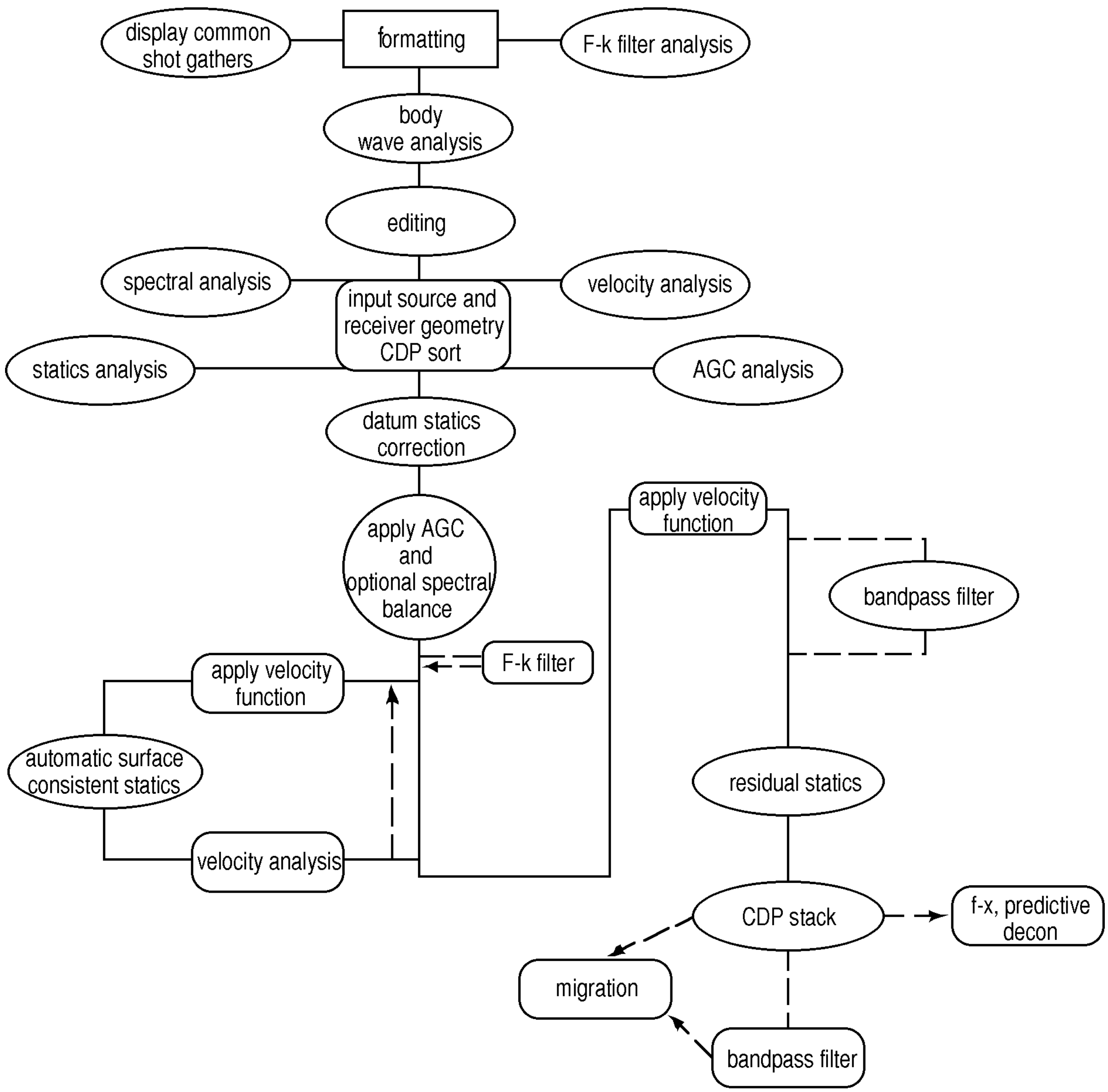

Figure 3. Processing flow.

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. 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 (Steeples and Miller, 1990).

As much effort as possible will be made during processing of this data to interact with KCC staff to insure the most accurate stacked seismic reflection sections. 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 2-D data into a local 2½-D section allowing extrapolation of interpreted features from line to line. Considering the uncontrolled movement of freshwater through boreholes since the initial development of this sinkhole, continued subsidence is a certainty, the only questions relate to rate of subsidence and eventual aerial extent of the sinkhole. Bridging, layer drape, and faulting will be structural features used to infer the subsurface subsidence history and most probably future at this site. Establishing subsurface characteristics indicative of failure rate has been the overall goal of the sinkhole seismic reflection program at the KGS for over 25 years. With the deployment scheme planned here it will be possible to observe the growth of this sinkhole in time throughout the next several years, therefore, providing key insights into failure mechanisms.

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 amounts and extent possible on the ground surface and study currently active faults and previous faulting within the subsidence structure and try to correlate displacement orientations with subsidence rates. Some attempt will be make to correlate and contrast these features and geometries identified on this survey with those discovered at the French and Macksville sinkholes.

Overall Project Goal

The principal goal of this study is to appraise the integrity of the rocks above the Hutchinson Salt member beneath the Leesburg sinkhole. Of critical importance to understanding the geology is accurate and high resolution images. Imaging and resolving structural and stratigraphic features within the upper 1000 ft in and around a sinkhole is essential to evaluate the risk and extent of future surface subsidence. 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; correlation with other sinkhole finds from this general area; 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
   - triple 10 Hz U2 Mark Products geophones
   - IVI Buggy mount high frequency vibrator (15 to 500 Hz, 8500 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
   - 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), 240 recording channels, 10 Hz geophones, 16 ft receiver spacing, 32 ft source spacing, and rolling fixed spread.

4) Planned Research Schedule:

	Approximate Duration
Mobilization/Demobilization	1 week
Travel	1 day
Walkaway noise testing	1/2 day
Two lines KCC requested	2 days
Four lines KGS added	3 days
Processing of around 720 shotpoints of CMP data	6 months
Interpretation of six 1-km lines	3 months
Reporting	3 months

6) Deliverables Schedule:
   Oral review of preliminary findings 2-3 months after completion of fieldwork.
   Preliminary report 6 to 9 months after completion of fieldwork.
   Final Report after review and comment by KCC.

Figure A1. 240 channel Geometrics StrataView with support electronics (line checker, IVI source synchronizer, time break conditioner, etc.).

Figure A2. 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 A3. 300 lb mass and 300 lb baseplate with new prototype Atlas rotary valve.