HIGH-RESOLUTION SEISMIC REFLECTION TO IDENTIFY AREAS WITH SUBSIDENCE POTENTIAL BENEATH U.S. 50 HIGHWAY IN EASTERN RENO COUNTY, KANSAS

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Abstract

High-resolution seismic reflections were used to map the upper 200 m along an approximately 22 km stretch of U.S. 50 highway in Reno County, Kansas, where natural and anthropogenic salt dissolution is known to threaten ground stability. 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 public safety. Primary objectives of this study were to delineate the Permian Hutchinson Salt layer beneath the proposed alignment of the new U.S. 50 bypass around the City of Hutchinson. Of secondary interest were any features with subsidence potential beneath U.S. 50 east of the City of Hutchinson in Reno County, a distance of around 15 km crossing the dissolution front of the salt beds. The high signal-to-noise ratio and resolution of these seismic reflection data allowed detection, delineation, and evaluation of several abnormalities in the rock salt layer and overlying Permian sediments. Locations were identified where failure and associated episodes of material collapse into voids left after periodic and localized leaching of the 125 m deep, 40 m thick Permian Hutchinson Salt member were evident. Anomalies were identified within the salt and overlying rock layers with seismic characteristics consistent with collapse structures. Of particular interest were features with the potential to migrate to the surface in areas where no subsidence has been previously observed. Anhydrite and shale layers several meters thick within the salt are uniquely distinguishable and appear continuous for distances of several kilometers. High noise levels from the heavy traffic load carried on U.S. 50 and maintaining continuous subsurface coverage beneath the Arkansas River presented significant challenges to both the acquisition and processing of these data. Over a dozen unique features potentially related to subsidence risk were identified.

Introduction

Sinkholes are common hazards to property and human safety the world over (Beck et al., 1999). Their formation is generally associated with subsurface subsidence that occurs when overburden loads exceed the strength of the roof rock bridging voids or rubble zones formed as a result of dissolution or mining. Understanding sinkhole processes and what controls their formation rate is key to reducing their impact on human activities, and in the case of anthropogenic, potentially avoiding their formation altogether. Sinkholes can form naturally or anthropogenically from the dissolution of limestone (karst), gypsum, or rock salt, or from mine/tunnel collapse. With the worldwide abundance of limestone, karst-related sinkholes are by far the most commonly encountered and studied. Both simple and complex sinkholes have formed catastrophically and/or gradually, as the result of dissolution of limestone or rock salt, and by natural and man-induced dissolution processes in many parts of Kansas (Merriam and Mann, 1957).

In central Kansas most sinkholes are the result of leached out volumes of the Permian

Hutchinson Salt member of the Wellington Formation (Watney et al., 1988) (Figure 1). Sinkholes forming above salt layers have been studied throughout Kansas (Frye, 1950; Walters, 1978) and the United States (Ege, 1984). Studies of subsidence related to mining of the salt around Hutchinson, Kansas (Walters, 1980), disposal of oil field brine near Russell, Kansas (Walters, 1991), and natural dissolution through fault/fracture-induced permeability (Frye and Schoff, 1942) have drawn conclusions about the mechanism responsible for subsidence geometries and rates based on surface and/or borehole observations. Using only surface observations and borehole data, a great number of assumptions and a good deal of geologic/mechanical sense must be drawn on to define and explain these features and their impact. High-resolution seismic reflection profiling has proven an effective tool in 3-D mapping the subsurface expression and predicting future surface deformation associated with dissolution of the Hutchinson Salt in Kansas (Steeples et al., 1986; Miller et al., 1993; Anderson et al., 1995a; Miller et al., 1995; Miller et al., 1997).

Salt dissolution sinkholes are found in all areas of Kansas where the Hutchinson Salt is present in the subsurface. Sinkholes have been definitely correlated to failed containment of disposal wells injecting oil field brine wastewater using stem pressure tests and/or seismic reflection investigations at a variety of sites throughout central Kansas (Steeples et al., 1986; Knapp et al., 1989; Miller et al., 1995; Miller et al., 1997). Sinkholes that have formed by natural dissolution and subsidence processes are most commonly documented at the depositional edges on the west and north and erosional boundary on the east of the Hutchinson Salt (Frye and Schoff, 1942; Frye, 1950; Merriam and Mann, 1957; Anderson et al., 1995a). The vast majority of published works studying the source of localized leaching of salt in Kansas directly contradict suggestions that recent land subsidence in Kansas is mostly natural in origin (Anderson et al., 1995a).

Natural dissolution of the Hutchinson Salt is not uncommon in Kansas and has been occurring for millions of years (Ege, 1984). Faults extending up to Pleistocene sediments containing fresh water under hydrostatic pressure are postulated as the conduits instigating salt dissolution and subsidence along the western boundary of the salt in Kansas (Frye and Schoff, 1942). Paleosinkholes resulting from dissolution of the salt before Pleistocene deposition have been discovered previously with high-resolution seismic surveys (Anderson et al., 1998).

Subsidence can occur at rates ranging from gradual to catastrophic. Subsidence rates are to some extent related to the type of deformation in the salt (ductile or brittle) and the strength of rocks immediately above the salt layer. As salt is leached, the resulting pore space provides the differential pressure necessary to support creep (Carter and Hansen, 1983). If this pore space gets large enough to exceed the strength of the roof rock, the unsupported span will fail and subsidence occurs (Figure 2). Depending on the strength of the roof rock and therefore the size of the void, characteristics of the failure within and just above the salt will dictate how the void progresses upward until it eventually reaches the ground surface. In general, gradual surface subsidence is associated with ductile deformation that—besides vertically sinking—progresses outward, forming an ever-growing bowl-shaped depression with bed geometries and offsets constrained by normal fault geometries (Steeples et al., 1986; Anderson et al., 1995b). When rapid to catastrophic subsidence rates are observed, failure within the salt is usually brittle with void area migrating to surface as an ever-narrowing cone with bed offsets and rock failure controlled by reverse-type fault planes (Davies, 1951; Walters, 1980; Rokar and Staudtmeister, 1985).

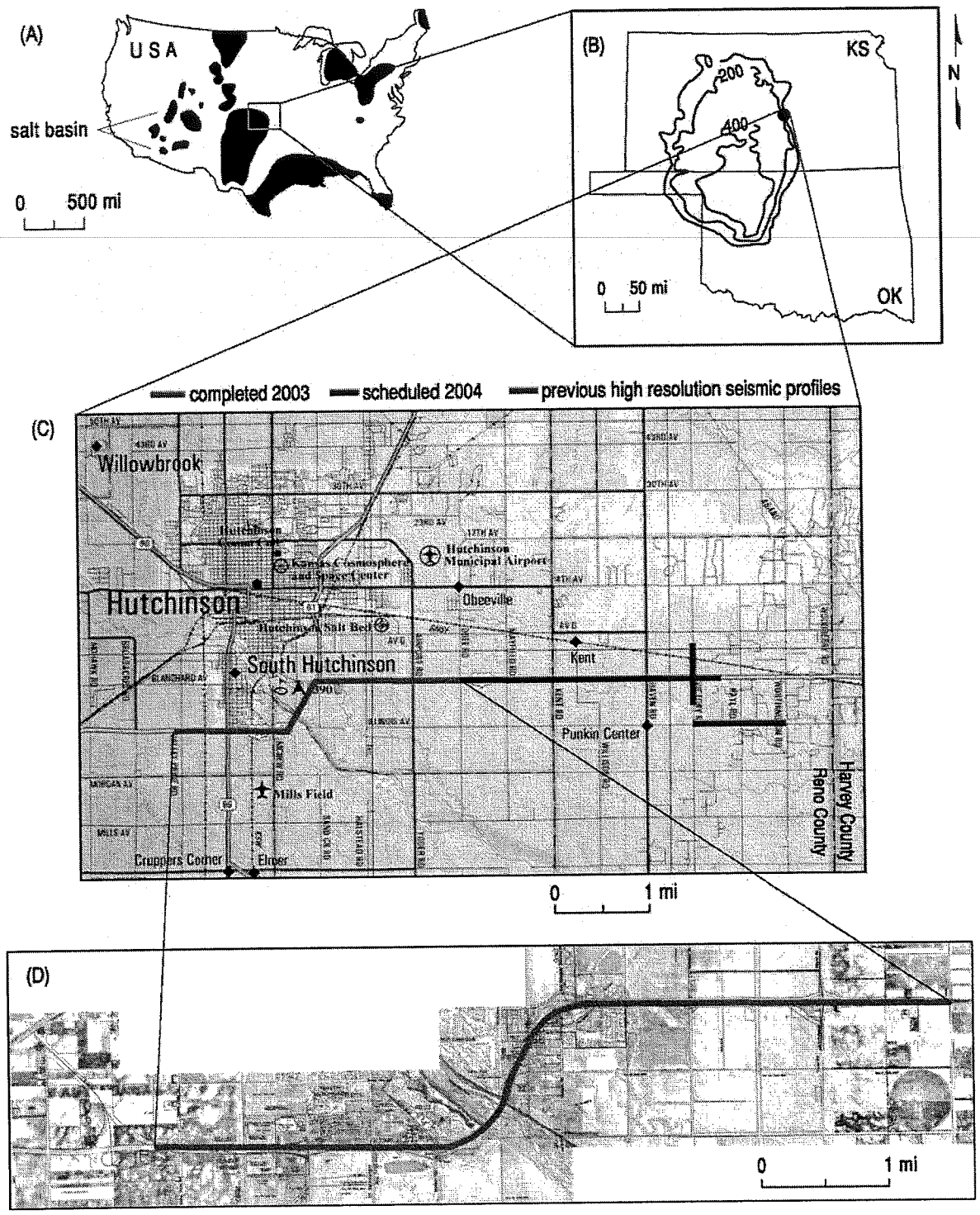

Figure 1. Site map for seismic reflection study along proposed new U.S. 50 bypass around Hutchinson, Kansas. Major salt basins of North America (A). Areas extent and thickness of the Permian Hutchinson Salt member in Kansas and Oklahoma (B). Seismic profiles acquired and planned along and near Highway U.S. 50 and the dissolution front (C). Seismic profile map along the proposed U.S. 50 bypass around Hutchinson (D).

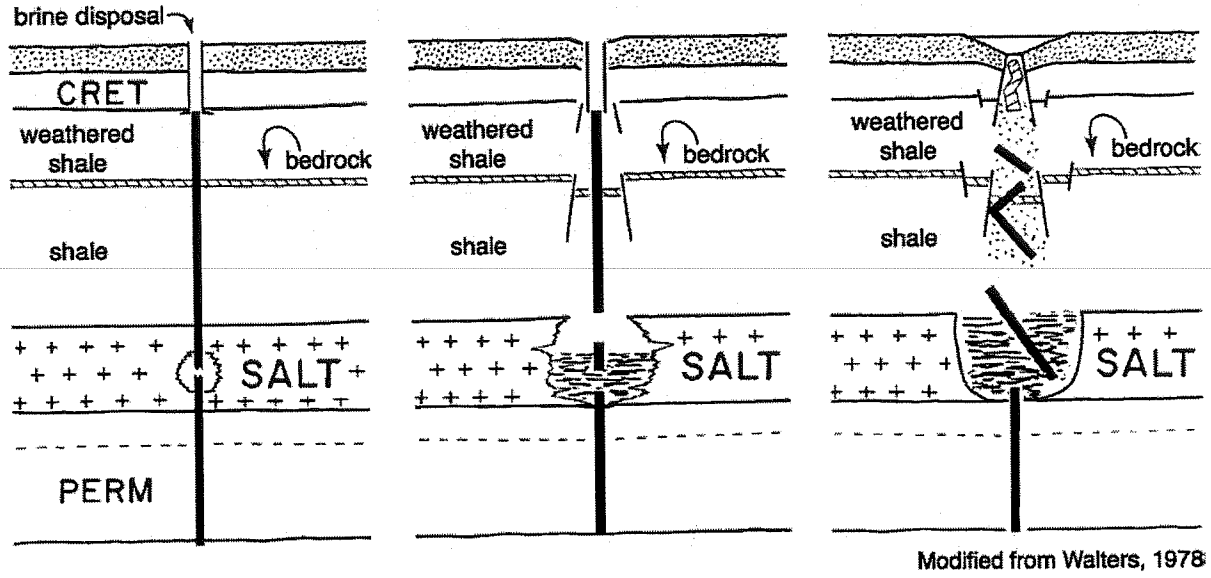

Figure 2. Cartoon of the dissolution and subsidence process across time when instigated by fluids introduced by lost containment in a disposal well.

Seismic reflection data targeting beds altered by dissolution and subsidence in this area have ranged in quality and interpretability from poor (Miller et al., 1995) to outstanding (Miller et al., 1997). Interpretations when data quality is poor have unfortunately been relegated to indirect inference of structural processes and subsurface expression (mainly from interpretations of structural deformation in layers above the salt) due to low signal-to-noise ratios. However, data with excellent signal-to-noise ratios and resolution have allowed direct detection of structures and geometries that appear characteristic of complex sinkholes. Resolution potential and signal-to-noise ratio of seismic data from this study are superior to any previously published that have targeted the salt interval. These data provide conclusive images of important structural features and unique characteristics that control sinkhole development.

Concerns for public safety and elevated maintenance costs associated with potential future surface subsidence along a newly proposed four-lane bypass around the city of Hutchinson, Kansas, are justified considering the tendency for sinkholes to form in eastern Reno County, Kansas, associated with the natural dissolution front, aging oil field wells, and voids (jugs) remaining from salt dissolution mining practices. As an example, the formation of a sinkhole just 15 km east of the proposed bypass on U.S. 50 has become a nuisance for maintenance crews, vehicle traffic, and public officials trying to calm the concerns of local residence. Subsidence of U.S. 50 below construction grade at its intersection with Victory Road totaled 30 cm when first measured during a 1998 elevation survey. Routine elevation surveys conducted since that time have monitored the pattern and rate of subsidence. At an average subsidence rate of around 20 cm/yr, the highway surface at its centerline has sunk about 1 m since its construction. The current sinkhole is symmetric, with a very regular bowl-shaped geometry around 100 m in diameter that retains water most of the year.

Geologic Setting

Several major salt basins exist throughout North America (Ege, 1984). The Hutchinson Salt Member occurs in central Kansas, northwestern Oklahoma, and the northeastern portion of the Texas panhandle, and is prone to and has an extensive history of dissolution and formation of sinkholes (Figure 1). In Kansas, the Hutchinson Salt possesses an average net thickness of 76 m and reaches a maximum of over 152 m in the southern part of the basin. Deposition occurring during fluctuating sea levels caused numerous halite beds, 0.15 to 3 m thick, to be formed interbedded with shale, minor anhydrite, and dolomite/magnesite. Individual salt beds may be continuous for only a few miles despite the remarkable lateral continuity of the salt as a whole (Walters, 1978).

Rock salt under a depositional load is almost incompressible, highly ductile, and easily deformed by creep (Baar, 1977). Plastic deformation of the salt associated with creep is expected naturally to occur in these salts (Anderson et al., 1995b). Thin anhydrite beds within the halite succession have a strong acoustic response. Considering the extreme range of possible strain rates the salt can experience during creep deformation, these thin interbeds can possess quite dramatic, high frequency folds within relatively short distances.

Redbed evaporites overlaying the Hutchinson Salt Member are a primary target of any study in Kansas looking at salt dissolution sinkhole development and associated risks to the environment and human activity. Failure and subsidence of these evaporite units are responsible for the eventual formation of sinkholes and provide a pathway for groundwater to gain access to the salt. In proximity to the dissolution front fractures, faults, and collapse structures compromise the confining properties of the Permian shale bedrock and put the major fresh water aquifer (Plio-Pleistocene Equus Beds) in this part of southern Kansas at risk. Along the eastern boundary (dissolution front), the salt, which ranges from 0 to over 100 m thick, is buried beneath about 120 m of Permian redbed evaporites.

The eastern margin of the salt was exposed during late Tertiary where erosion and leaching began the 30 km westward progression of the front to its present day location (Bayne, 1956). The ability of the front to migrate while under as much as 100 m of sediments was a direct consequence of ready access to an abundant supply of groundwater (Watney et al., 1988). Subsidence of Permian, Cretaceous, and Tertiary rocks has progressed along the migration front as the salt has been leached away. While this subsidence was going on, Quaternary alluvium was being deposited in volumes consistent with the salt that was being removed. This processes resulted in today's moderate to low surface relief that masks the extremely distorted (faulted and folded—non-tectonic) rock layers within the upper Wellington and Ninnescah shales (Anderson et al., 1998).

Seismically, all Permian and younger reflectors are important to accurate interpretation of the stacked sections. Model studies show significant time delays (static) and geometric distortions that are to be expected below recent subsidence (Anderson et al., 1995b). "Pull downs" in time result from the localized decreases in material velocities within a sinkhole. The velocity structure and small radius of curvature of the synforms, characteristic of salt dissolution and subsidence in this area, can produce diffractions and distort reflections on vertically incident reflection sections. Reflections from beneath the salt will have a subdued expression of the post-salt subsidence. Estimations of subsidence and therefore volume of rock salt removed based on time section estimations alone (without compensation for velocity variability) may exceed actual by

as much as 25 to 50 percent in this area. Considering this geologic setting, it is reasonable to compensate for compaction-related static causing this lateral decrease in velocity by "flattening" on the top of the Chase Group.

Most of the upper 700 m of rock at this site is Permian shales (Merriam, 1963). The currently disputed Permian/Pennsylvanian boundary is about 700 m deep and seismically marked by a strong sequence of cyclic reflecting events. The Chase Group (top at 250 m deep), Lower Wellington Shales (top at 175 m deep), Hutchinson Salt (top at 125 m deep), Upper Wellington Shales (top at 70 m deep), and Ninnescah Shale (top at 25 m deep) make up the packets of reflecting events easily identifiable and segregated within the Permian portion of the section. Bedrock is defined as the top of the Ninnescah Shale with the unconsolidated Plio-Pleistocene Equus Beds making up the majority of the upper 30 m of sediment. Thickness of Quaternary alluvium that fills the stream valleys and paleosubsidence features goes from 0 to as much as 100 m depending on the dimensions of the features.

Seismic Reflection Fundamentals

Seismic reflection is a powerful geophysical tool, in use since the 1920s that uses sound energy for underground exploration (Waters, 1987; Dobrin, 1976; Coffeen, 1978; Telford et al., 1976; Sheriff, 1978). For most of the first sixty years seismic reflection, surveys targeted rock layers of petroleum interest at depth generally exceeding 1 km. Using seismic reflection techniques to image targets less than 100 m has only been attempted with published success since the 1980s. Key to using seismic reflection to image shallow targets is the production and recording of high frequency signal. Most recently the technique is finding new applications characterizing geologic and hydrologic settings at depths between 3 and 30 m below the ground surface.

Seismic reflection techniques depend on the existence of discrete seismic velocities and/or mass density changes in the subsurface known as acoustic impedance contrasts. Mathematically, acoustic impedance is simply the product of the mass density and acoustic wave velocity. Acoustic impedance contrasts occur at natural boundaries between geologic layers, although manmade boundaries, such as tunnels and mines, also represent contrasts. The classic use of seismic reflection is to identify the boundaries of layered geologic units. However, the technique can also be used to search for localized anomalies such as sand/clay lenses and cavities.

For the purposes of this paper we will focus on compressional waves (P-waves), which propagate through the earth behaving similar to sound waves propagating through the air. When sound waves (voices, explosions, horns, etc.) come in contact with a wall cliff, or building (all representing acoustic contrasts between air and a solid material) it is common to hear an echo. When a P-wave comes in contact with an acoustical contrast underground, echoes (reflections) are also generated. P-waves reflections can be thought of as sound wave echoes from underground acoustic impedance contrasts. In the underground environment, the situation is more complex than in the air because some P-wave energy impinging on a solid acoustical interface can also be transmitted across the interface, refracted at the interface and/or converted to other types of seismic waves at the interface.

Seismic methods are sensitive to the physical properties of earth materials and relatively insensitive to the chemical makeup of contained fluids in earth materials. Electrical methods are sensitive to contained fluids and the presence of magnetic or electrically conductive materials.

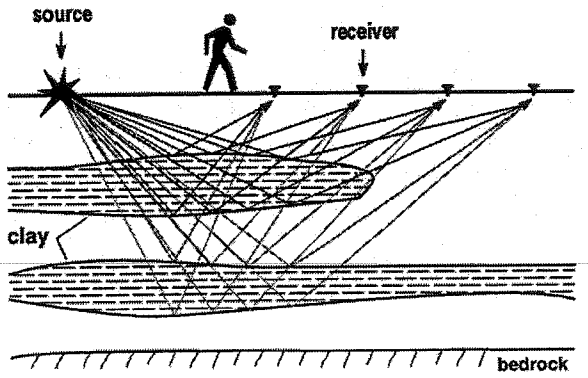

Figure 3. Simple layered earth model with clay layers above bedrock. A seismic source imparts sound energy to the ground. The seismic waves (ray as drawn here) propagate through the material, reflecting uniquely from each boundary between different material types. Seismic energy is recorded at the ground surface using a regular grid of receivers.

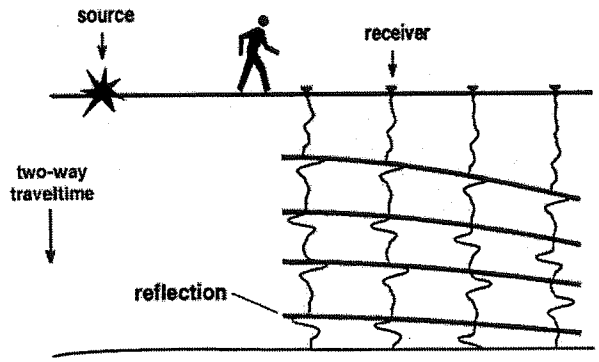

Figure 4. Seismic representation of layered earth. Two-way travel time from the start of energy moving through the ground until recorded by receivers at ground surface. The hyperbolic or curved nature of the reflections is related to the non-linear increase in travel path of reflected energy with linear increase in offset of receiver.

The measurable physical properties upon which seismic methods depend are quite different from the important physical properties for electrical and magnetic methods. Methods such as seismic reflection, refraction, crosshole tomography, and vertical seismic profiling all rely on similar physical properties of the earth. Ground penetrating radar (GPR) is a reflected wave technique that also relies on contrasts in earth materials, but rather than acoustic property changes, GPR is sensitive to changes in electrical conductivity.

Understanding seismic reflection is best accomplished using models of a simple layered earth (Figure 3). Seismic energy introduced into the ground from a point is radiated spherically away from that point at the velocity of the earth material. This process can best be visualized by recalling how waves generated from a pebble in a still pond move outward across the water's surface. A water wave like that just described propagates in two dimensions, whereas seismic energy moves through the earth as a three-dimensional phenomenon. An arbitrarily large number of rays can be traced outward from the source, but one will follow Fermat's principle of least time and will travel the shortest distance between the source, reflecting point, and receiver. The reflecting point will be represented as a pulse or wavelet on time measurements of ground motion. This echo from underground rock layers is referred to as a reflection. In the case of a single, flat-lying layer and a flat topographic surface (Figure 3), the path of least time will be from the energy source to a reflecting point midway between the source and receiver, and then straight to the receiver. The incident angle of the down-going ray will be equal to the angle of the up-going reflected ray.

Seismic energy is measured in time. Reflections returning from acoustic contrasts (reflectors) arrive some time after the energy was released from the source. The time required for a seismic pulse or wavelet to travel from the source to the reflector and then to the receiver is referred to as the two-way travel time. The two-way travel time of a reflection arrival increases hyperbolically as the offset between the source and receiver increases linearly (Figure 4). A

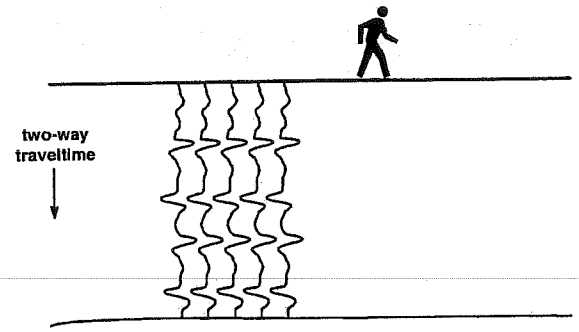

Figure 5. Seismic section with reflection arrivals corrected for offset and therefore different length travel paths.

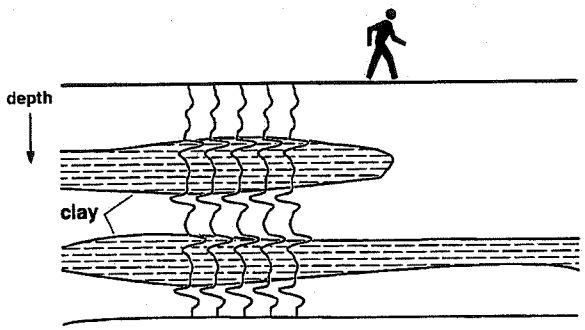

Figure 6. Time-to-depth converted seismic traces with reflections matched with reflectors. Geology can be inferred by trace-to-trace coherency of reflection wavelets.

discriminating characteristic of reflection events on shot gathers is their hyperbolic arrival pattern referred to as "moveout." The curvature of the reflection event as mapped from trace to trace is directly related to the average velocity of earth materials between the source/receiver and reflector.

Mapping reflectors requires the variability in reflection arrival times be removed or at least minimized so the seismic section approaches equivalence with a geologic cross-section, many times compared to a highway road cut. Adjusting for variable travel paths requires some knowledge of the average material velocity the seismic energy traveled through. Using coherency of the reflection arrivals from trace to trace a unique hyperbolic curve can be extracted which, based on arrival time of the reflections, distance between traces, and distance from source, can be used to estimate the overall velocity along the travel path. This velocity calculated in this fashion is referred to as the normal moveout velocity (NMO) and for most cases and applications can be used interchangeably with the average velocity. Using this NMO velocity, reflections can be adjusted to simulate vertically incident seismic wave travel paths (Figure 5).

Matching reflections with reflectors requires time-to-depth corrections and correlation of reflection wavelets from the same interface between adjacent traces. This process is generally accomplished using the NMO velocity function, defined in time and spatially relative to stations or receivers on the ground surface, to determine the time adjustment necessary to simulate a vertical travel path. Once adjustments are made wavelet characteristics can be used to infer reflector characteristics (Figure 6). For example, changes in polarity along a trace generally represents dramatic changes in material properties or acoustic impedance across a layer such as harder material to softer material and then back to a harder material; also, changes in wavelet characteristics from trace to trace can be indications of lateral changes in layer thickness or lithology. Considering the resolution of the seismic method (related to the finite bandwidth of reflected wavelets) and the non-infinite signal-to-noise ratio, a significant amount of ambiguity is always associated with geologic interpretations of seismic data.

Seismic reflection data is normally complicated by noise and interference of one reflection with another as a result of resolution limits associated with a narrower reflection bandwidth, lower reflection upper corner frequency, and relatively thin beds. Each "wiggle" does not have a unique meaning that can or should be extracted from the data. A cross-section of earth will have an acoustic impedance contrast at each change between layers (Figure 7). This sequence of

acoustic impedance contrasts can be represented by a series of spikes with a length related to the reflectivity or difference between the acoustic impedance of the material above relative to the material below the interface. This "spike" trace is also known as the reflectivity series for this earth model (Figure 7b). Each source generates a source wavelet with different characteristics controlled by the source itself and the earth materials the source is coupled to. Starting with an earth model, generating a reflectivity series, and then convolving with a source wavelet is the process used to produce a synthetic seismic trace. Starting with the seismic trace and then working to a geologic model is the most commonly used approach for interpreting real seismic data.

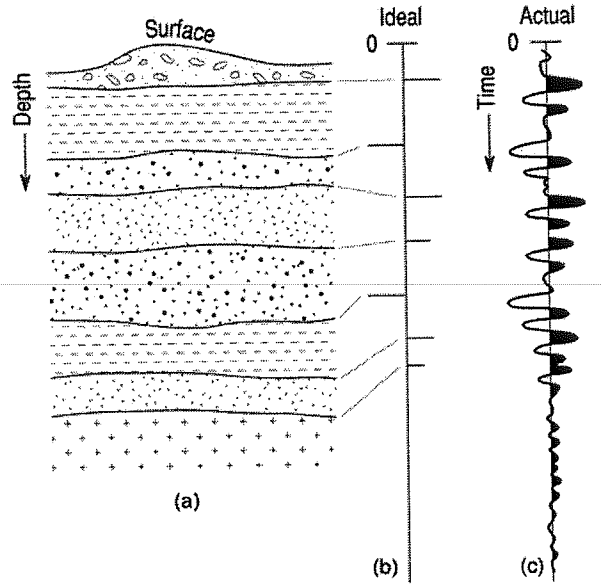

Figure 7. Depth and materials (a) represented as a time series of spikes with length indicative of reflection strength (b) and model reflection trace with finite bandwidth reflection wavelets as would be expected from zero offset seismic traces (c).

Seismic Acquisition

A continuous profile, a little over 10 km in length was acquired along the existing U.S. 50 highway right-of-way around Hutchinson, Kansas (Figure 1). In moving to meet the ever-growing vehicle load on the current highway, engineers proposed several possible transects skirting the southern edge of Hutchinson intended to accommodate a new four-lane limited access highway generally consistent with the current two-lane road that is there. With the known threat sinkholes in this area represents—both naturally occurring and as a result of dissolution mining—the subsurface between the base of the salt and bedrock beneath the proposed highway transect was examined using high resolution seismic reflection. The objective of this survey was to expose any feature lurking below ground that might someday threaten the stability of the road surface. These data were acquired using a rolling fixed-spread design that eliminated the need for a roll-along switch and extended the range of far offsets available during processing. This survey design provided the wide range of source offsets necessary for detailed velocity analysis, close receiver spacing for improved confidence in event identification, and maximized the range of imageable depths.

Even though no sinkholes were visible at the ground surface, evidence for historical dissolution and subsidence not visible at the ground surface has been observed in several locations around eastern Reno County, Kansas. This historical dissolution and subsidence, referred to as "paleosinkholes," is an indication that fresh water has had access to the salt in this area previously and has found a pathway to carry the dissolved salt away from the dissolution front. Several naturally forming sinkholes in this area have seen resent reactivation and formation of a surface depression. Therefore, looking for paleosinkholes and old salt mine dissolution jugs will be critical to final placement of this proposed bypass around Hutchinson.

Acquisition parameters were defined based on experience and walkaway tests near the start of the profile on the western end of the survey. Twin Mark Products L28E 40Hz geophones were planted at 2.5 m intervals in approximate 1 m arrays. Geophones were planted into firm to hard soil at the base of the road ditch in small divots left after the top few inches of loose material were removed to insure good coupling. Four 60-channel Geometrics StrataView seismographs were networked to simultaneously record 240 channels of data. An IVI Minivib1 using a prototype Atlas valve delivered three 10 second, 25-250 Hz up-sweeps at each 5 m spaced shot location. Experiments at this site were consistent with bench tests, which suggested this new rotary valve design will produce up to four times the peak force of conventional valves at 250 Hz. The pilot was telemetried from the vibrator to the seismograph and recorded as the first trace of each shot record. Each of the three sweeps generated per shot station was individually recorded and stored in an uncorrelated format with the ground force pilot-occupying channel 1.

All sweeps were recorded into the fixed 240-channel spread with the source incrementally moving from shot station to shot station through the middle half of the spread. Once the center 120 receiver stations (60 shot stations) were shot through, the back 120 receiver stations were moved to the front and the process repeated. Since all shot records were recorded uncorrelated, QC involved visual inspection of the recorded pilot trace, audio monitoring of the pilot trace on an RF scanner, inspection of the vibrator power spectra after each shot, and review of a correlated shot record after every 5 to 10 shot stations. With the exception of receiver stations not instrumented due to excess or thick gravel or asphalt or stations taken off-line when their offset exceeded 300 m, the survey was recorded with 98 percent live receivers within the optimum recording window (Hunter et al., 1984).

Seismic Processing

A basic common midpoint (CMP) processing flow was used in a fashion consistent with well-established 2-D high-resolution seismic reflection methodologies (Steeples and Miller, 1990). All lines were processed using WinSeis2, beta seismic data processing software (next generation of WinSeis Turbo) from the Kansas Geological Survey. Any reflection data acquired in this highly disturbed subsurface setting will be plagued with static problems and subject to dramatic swings in NMO velocity over relatively short distances; this data set was no exception.

Data were recorded and stored uncorrelated to allow precorrelation processing in hopes of increasing the signal-to-noise ratio and resolution potential (Doll and Çoruh, 1995). Removal of noisy traces and amplitude scaling were precorrelation processing steps that significantly enhanced signal-to-noise and resolution potential. Attempts to improve the data quality precorrelation through frequency filtering, spectral whitening, and frequency-wave number (F-k) filtering were unsuccessful. Storing data uncorrelated also allowed tests to be run with different methods of correlation and correlating with different pilot traces. These data were optimally correlated using the synthetic drive signal. Storing data uncorrelated and unstacked required 30 times more storage space, about 50 percent more acquisition time, and 5 times more data transfer time. Improvements in signal-to-noise ratio and resolution made these increases cost effective.

Emphasis was placed on noise suppression, maintaining true amplitude, and compensating for velocity irregularities. Noise suppression focused on vehicle noise from the highway, livestock along the lines, powerline noise, surface waves, first arrivals, and air-coupled waves. Muting and hum filtering (Xia and Miller, 2000) improved signal-to-noise appreciably. The

three individual shot gathers acquired at each shotpoint were vertically stacked after all the noise suppression operations were complete. With the exception of the 1 sec AGC used precorrelation and display gains, only spherical divergence was used to adjust trace amplitudes. With the large depth window of interest, a relatively wide optimum offset window was maintained, which after noise mutes resulted in true trace folds ranging from 1 to a maximum of 30 (Liberty and Knoll, 1998). Velocity was defined in groups of 20 CMPs with at least one control point for each 100 ms time window and a minimum of five points selected in the first 200 ms. Each line is defined by a velocity function with over 400 time/velocity pairs determined with the aid of several iterations of correlation static corrections and velocity analysis.

Even when reflections were interpretable within the noise cone an inside mute was applied after the air-coupled wave to avoid signal degradation of reflection wavelets on CMP stacked sections. Inside mutes are a common practice for shallow (upper 1 km) seismic reflection processing (Baker et al., 1998). It is however, uncommon and counterintuitive to remove confidently identifiable reflection events regardless of where they are relative to other energy arrivals. The likelihood of wavelet distortion sufficient to reduce the resolution potential or lose the trace-to-trace coherency of reflections is significantly increased when surgically muting noise immersed in signal. Analogous to inoperable tumors, attempts to precisely remove just noise—especially air-wave noise—at tolerances of a millisecond or two run the risk of cutting too severely and/or defining mute tapers that are too steep, thereby irreparably altering the reflection waveform. Stacking waveforms into the fold that have been distorted by overly aggressive mutes will compromise the accuracy of the information contained in the waveform, and in some cases produce artifacts that can be misinterpreted as true earth response.

Powerline noise was pronounced on shot gathers where power lines were located along the south side of the road. A complex combination of 60 Hz, 120 Hz, and 180 Hz noise bleeding from overhead power lines masked most of the seismic energy even after correlation along portions of the road. A hum filter was very effective in eliminating powerline noise without affecting the amplitude or phase of the seismic data (Xia and Miller, 2000). This predictive filter produced a noticeable increase in signal-to-noise without loss of resolving potential.

Interpretation

Confidently interpretable reflections on shot gathers are essential to optimizing the acquisition, processing, and interpretation of high-resolution seismic reflection data. Reflections can be interpreted on raw, correlated shot records (scaled for display purposes) from around 50 ms to two-way time depths in excess of 500 ms (Figure 8). Considering the optimum window for these data, it was imperative to keep a wide range of offsets to insure the entire target zone was imaged. Reflections with dominant frequencies of around 200 Hz can be interpreted as deep as 200 ms, while the dominant frequency of reflections at 500 ms have dropped to around 100 Hz. With dominant frequencies of some reflections exceeding 200 Hz, a 2.5 ms static between adjacent traces represents a 180° phase shift and complete cancellation. Therefore, it is critical that static irregularities be compensated for before the data are CMP stacked. Reflection events can be traced through the air-coupled wave and just into the ground roll wedge. To avoid any contamination by air-coupled wave, all energy after the airwave was removed during processing.

For quality control reasons it is important that reflections interpreted at two-way times less than 50 ms on CMP stacks can be correlated with equivalent 50 ms reflection hyperbolae on

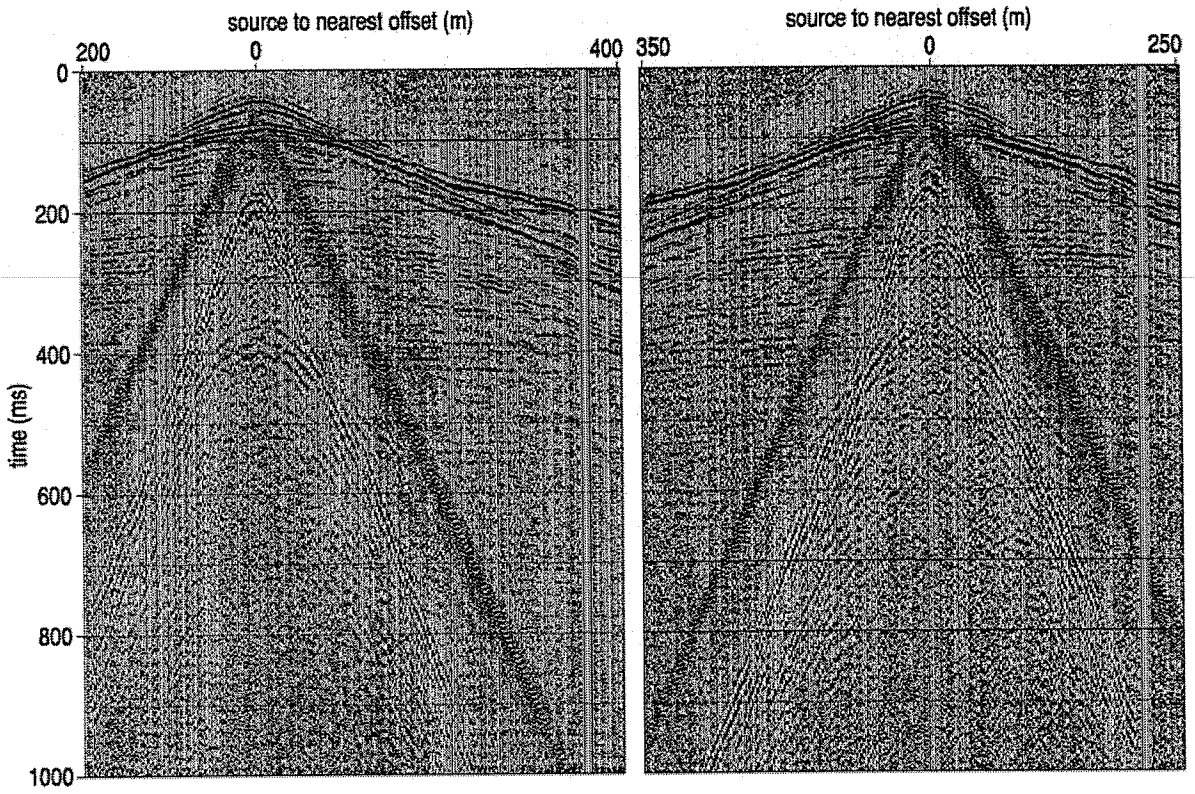

Figure 8. Correlated shot gathers from along profile. Reflection events have diagnostic curvature and high frequency wavelets.

shot gathers. Identification of these reflections on field files and tracking of them throughout the processing flow was necessary to ensure CMP sections were correctly stacked and interpreted. Ultra shallow reflections (< 50 ms) were a critical aspect in discerning the periods since Permian that these sediment-filled sinkholes may have been active.

From interpretations of reflection from raw shot gathers it can be estimated that reflectors from 15 m to over 1 km were imaged by these data (Figure 8). Even under these extremely noisy conditions, contending with wind, vehicles, and power lines along with an extremely variable near surface at overpasses, access road fill, the Arkansas River, and railroad grade, the data are of exceptional quality. Bed resolution using the half-wavelength criteria is around 2 m at the top of the salt unit. Reflections identified on the shot gather extend from the Permian through the upper Pennsylvanian.

CMP stacked section from this 10+ km survey are all of excellent quality (Figure 9). Data from the western extreme of the profile provide an excellent look at the seismic character of a segment of Permian rocks not disturbed by dissolution-induced subsidence. The salt interval has been identified using a combination of nearby well logs and depth estimates from NMO velocity conversions. Two-way travel time to the top of the salt is around 170 ms with a salt interval that is clearly distinguishable on seismic data from the surrounding Permian rocks.

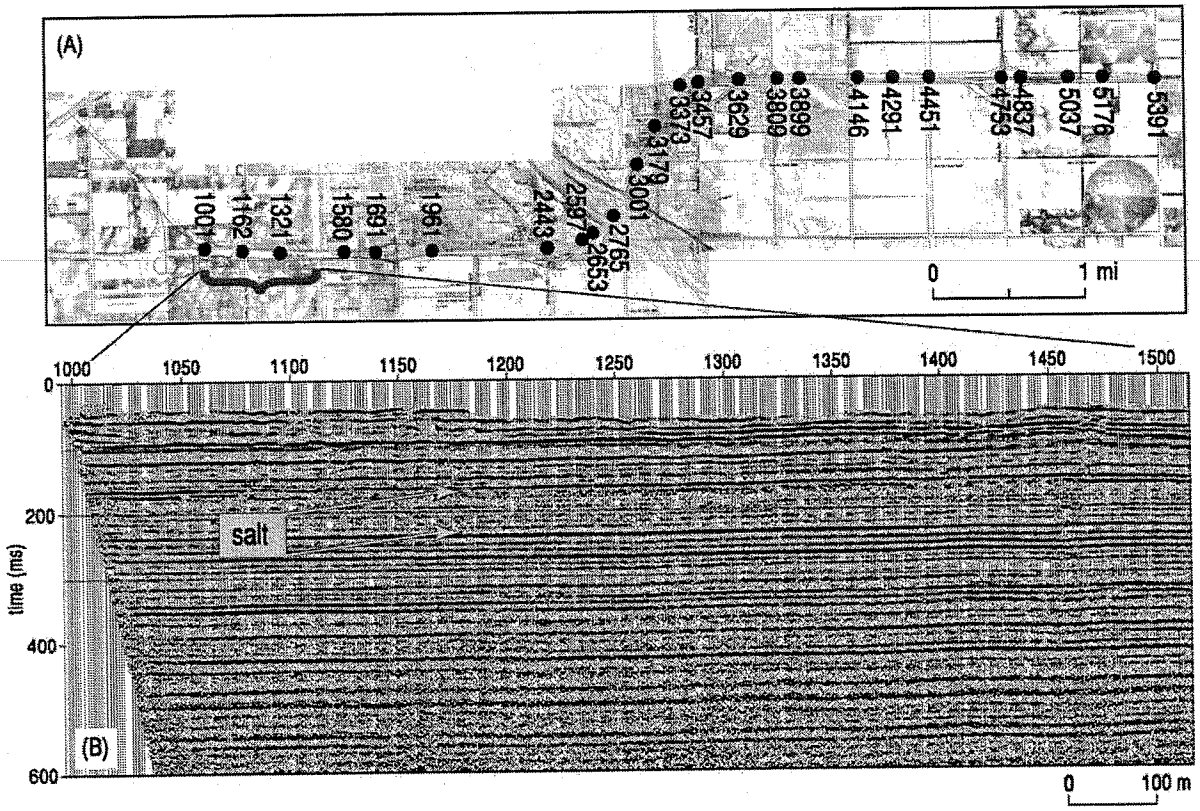

Figure 9. Seismic stations were DGPS located to within ±2 cm (x, y, z) (A). Seismic section from first 1.25 km clearly demonstrates the data quality and signature of undisturbed salt (B).

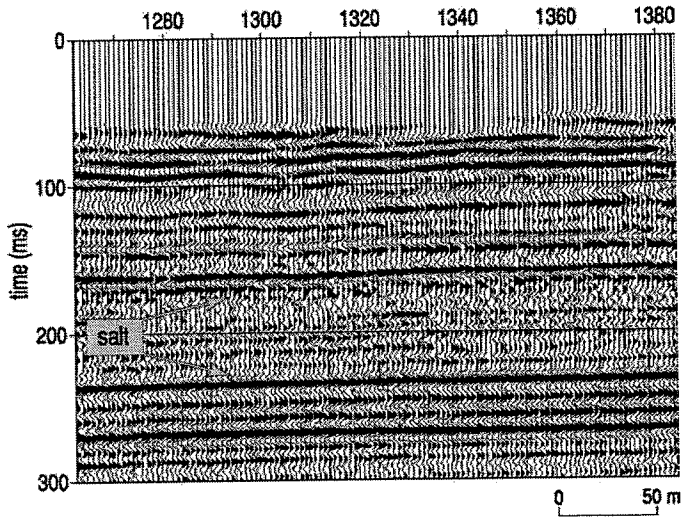

Figure 10. Expanded view of salt interval and layers above and immediately below. Reflections from within the salt are unique in comparison to those from surrounding Permian layers.

Critical to identifying areas of disturbed salt and any overburden that might be susceptible to collapse due to irregularities within the salt is a clear understanding of how native, undisturbed salt and overburden appear on CMP stacked seismic sections. A strong reflection at about 170 ms interpreted to be the Milan Limestone marks the top of the salt, followed by a subdued set of relatively discontinuous reflections to about 230 ms where another high amplitude reflection, likely the Carlton Limestone, is interpreted to be the basal contact between the salt and surrounding rocks of the Sumner Group (Figure 10). Reflections

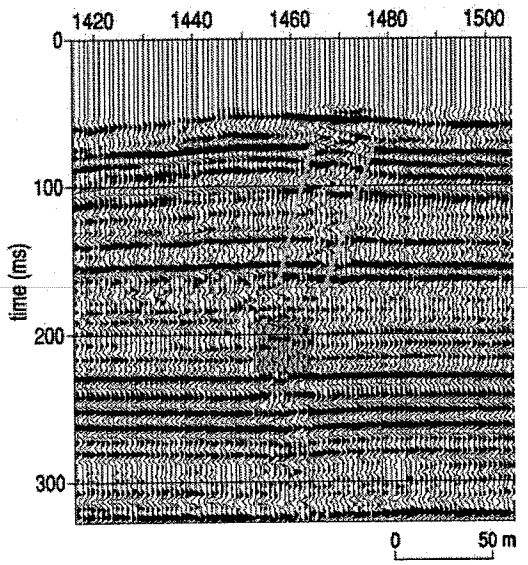

Figure 11. Disturbed area within the salt and associated chimney where rocks between the salt and bedrock appear altered.

from within the salt layer possess geometries consistent with channel-cut-and-fill deposition. These intra-salt beds are likely shales and anhydrites.

A somewhat unusual feature interpreted on these seismic data is a small area of disturbed salt with a volume of rock extending upward from the salt to near the bedrock surface that appears to be disturbed and possibly offset with some related subsidence (Figure 11). The disturbed area within the salt can be identified by the loss of continuity of the intra-salt reflections. Immediately below the basal salt contact at about 230 ms is a slightly disturbed zone that increases in area with depth that is likely the shadow effect (scatter and decreased overburden velocity) related to the disturbed reflections within the salt and is an artifact. A chimney feature extending toward the bedrock surface appears to be a fracture zone associated with the anomaly in the salt. Localized layers above the salt and this anomaly appear to form a very subdued syncline. This fracture zone could well be related to salt creep and not dissolution. With the many zones where water is confined in the Permian redbeds between the salt and bedrock surface, this fracture zone could well have allowed water access to the salt, but without an exit point for the saturated brine solution to leave the salt. The leaching process started but was halted before sufficient salt was dissolved to create a void of sufficient size for large-scale subsidence to occur.

The only clearly identifiable paleosinkhole across the 10 km profile was identified near the intersection of U.S. Highway 50 and Kansas state Highway 96 (Figure 12). Reflection

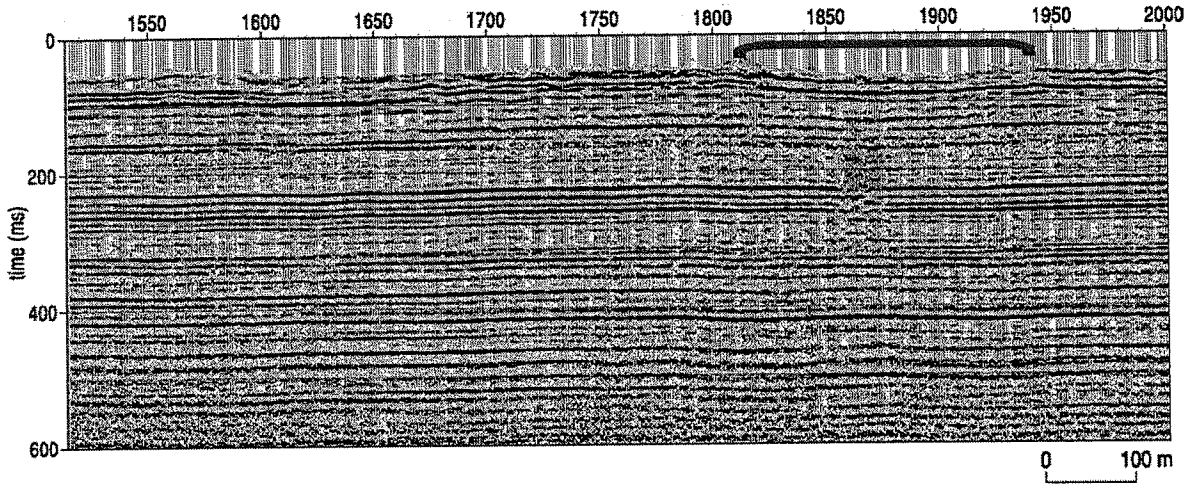

Figure 12. Paleosinkhole evident about 2 km from the beginning of profile and approximately beneath the stretch of highway that includes the overpass of Highway 96.

characteristics of the salt and overlying sediments across the almost 1 km between the anomaly identified beneath station 1470 and 1800 appear very undisturbed with "normal" depositional features interpretable in reflections within the upper 300 m. Between stations 1800 and 1950 a very pronounced depression in the shallower sediments is evident. In general, this anomaly possesses the classical reflection drape above the salt indicative of plastic deformation that occurs as salt gradually dissolves and overlying sediments subside into the void. The only significant faulting evident in this feature is at the edges of the bowl-shaped structure indicative of more brittle deformation.

A close-up of the paleosinkhole beneath station 1870 provides a very intriguing view of this ancient, yet potentially dangerous feature (Figure 13). Clearly all the leached salt responsible for this more than 300 m wide feature at the bedrock surface came from little more than a 50 m wide stretch of salt. Key to this discovery is what appear to be competent layers within the salt that are beneath the bedrock expression of the sinkhole. This implies dissolution occurred within a relatively small volume, then due to salt creep this 50 m wide zone of dissolution reduced the pressure regime and affected salt more than 100 m away. As salt creeped toward this low-pressure area, wide expanses of unsupported roof rock began forming until subsidence occurred, with the edges of salt creep defined by faults that extended to the bedrock surface.

Immediately south of an area known to have been dissolution mined in the past are scatter features which could be related to old mining activities (Figures 14 and 15). Scattering of seismic energy is generally related to bed terminations or other point source features. Considering the scatter points (apex of seismic energy) are within the salt, at the contact between the salt and cap rock, within the Ninnescah shale, and most strongly at the bedrock surface, it is difficult to say with confidence these features are a remnant of dissolution mining. With scatters coming from what appears to be the bedrock surface or very near the bedrock surface, this area should already be experiencing surface subsidence if these scatters were from an old salt jug. More

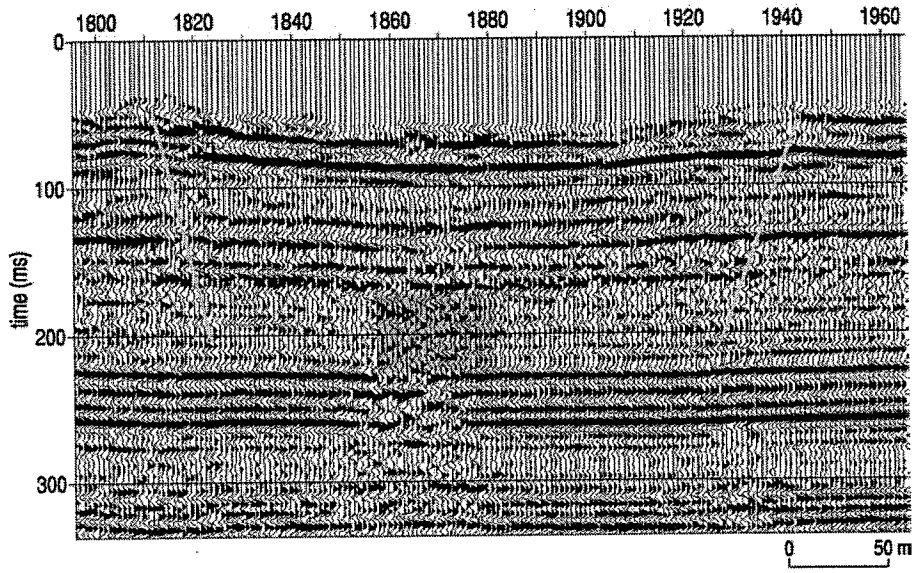

Figure 13. An area of active dissolution from where the salt was previously dissolved, allowing creep and the formation of a much larger surface depression than salt void volume.

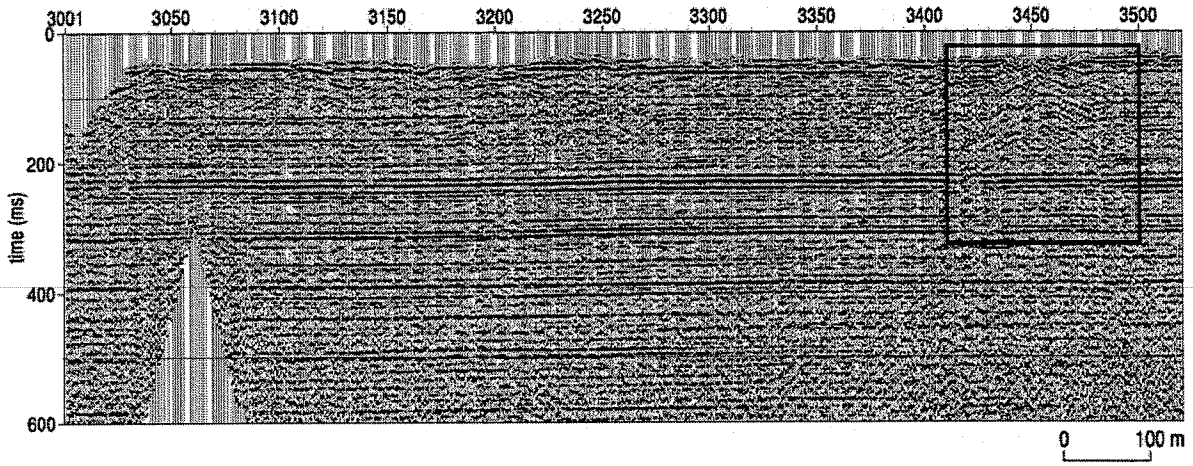

Figure 14. Scatter seismic energy related to bed termination. These highly developed scatter patterns are areas for more concentrated study. The most likely scenario involves uncompensated surface noise, out-of-the-plane features, or bedrock abnormalities. However, this type of seismic signature could be indicative of a void or anomaly such as an abandoned salt jug.

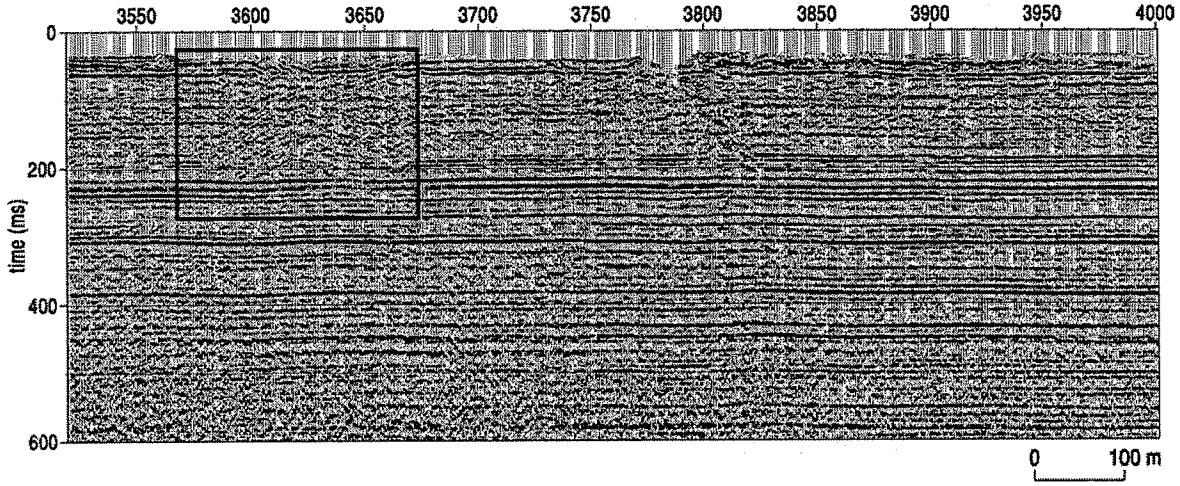

Figure 15. As observed on Figure 14, this scatter pattern of seismic energy could be an indication of bed terminations into void associated with old salt jugs.

likely explanations include out-of-the-plane features, uncompensated surface noise, or bedrock abnormalities. Since it is still possible that these features are related to old salt jugs, they need to be studied further to determine if previous mining activities or unrelated dissolution of the salt is involved in any way.

Probably one of the most intriguing, yet least significant feature for highway planners, is what appears to be a large fault zone beneath station 4430 (Figure 16). This fault zone appears to have minimal vertical offset, but possesses a marked change in character of reflections across this zone. The reflection identified as from the top of the salt changes in both frequency and amplitude, as well most events above about 250 ms appear to have changes in character across

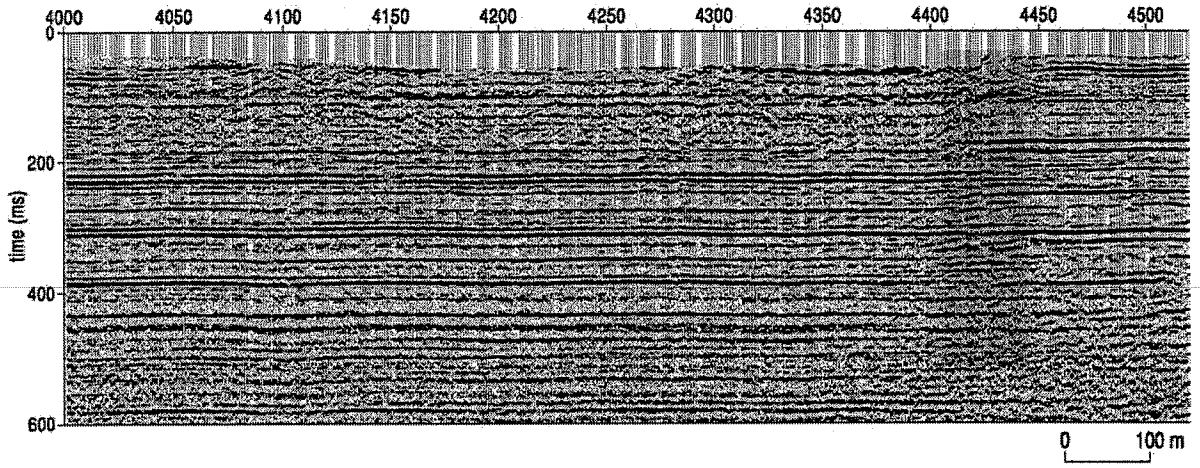

Figure 16. A fault is clearly evident on these data beneath station 4430. An abrupt change in reflection characteristic, diffraction, and apparent bed offset are all key indicators of faulting.

this fault that range from dramatic to subtle. Below 250 ms the fault zone is still evident but lacks as much change in seismic wavelet characteristics as shallower in the section. From a purely speculative perspective this fault has all the characteristics expected from a predominantly strike-slip fault. Correlations with local geology are not yet complete, but will likely provide key insights into this feature.

Near the end of this 10+ km seismic profile is what appears to be a change in the basal salt contact (Figure 17). Around station 4630 the reflections from near the base of the salt layer at about 230 ms change gradually across about a kilometer from a relatively distinctive higher amplitude single-wavelet event to what appears to be a very cyclic lower resolution wavelet. This change appears to be consistent with an apparent thinning in the salt layer. However, from

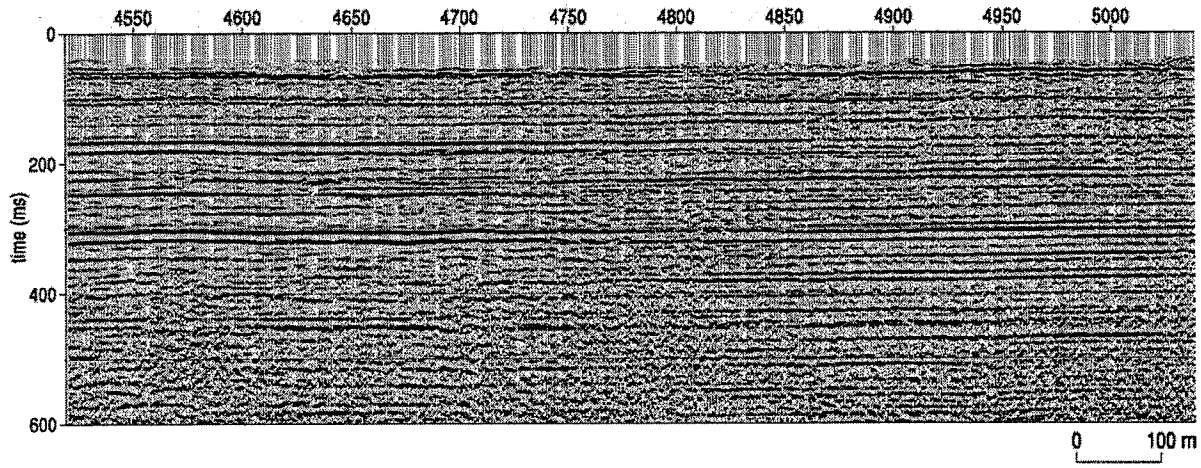

Figure 17. Near the eastern end of this 10+ km survey the seismic signature of the salt layer appears to change, thinning some with reflection frequencies within the salt layer dropping notably.

a highway stability perspective this change is not significant. Throughout the last 1.5 km of the profile the salt layer changes seismically, indicative of a change in geology, but it does not appear to possess abnormalities associated with missing salt or with clear subsidence potential.

Conclusions

High-resolution seismic reflection provided a relatively continuous view of key rock layers above the base of the Hutchinson Salt beneath the proposed new alignment of the U.S. 50 bypass south of the city of Hutchinson, Kansas. Several features with the potential to affect the ground surface along or beneath the future highway were discovered. A paleosinkhole with indications of reactivation since it originally formed represents a risk of gradual subsidence in the highway surface at some point in time. Also, chimney features associated with salt creep are areas for monitoring. A fault intersecting the highway alignment cannot be avoided by the new highway and it has not provided a conduit for fresh water to gain access to the salt at this time. The area above the fault will also require monitoring for any indication of ground subsidence, but does not represent a significant threat to highway stability. Diffraction or scatter associated with bed terminations or point source re-radiation was identified in two locations adjacent to known areas where dissolution salt mining has been active previously. It is not unreasonable to suggest these features might be related to that mining activity. If they are related to dissolution mining activity, they represent the most significant risk of accelerated failure and subsidence in this area. More study of these diffraction/scatter features is needed to better define their source.

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