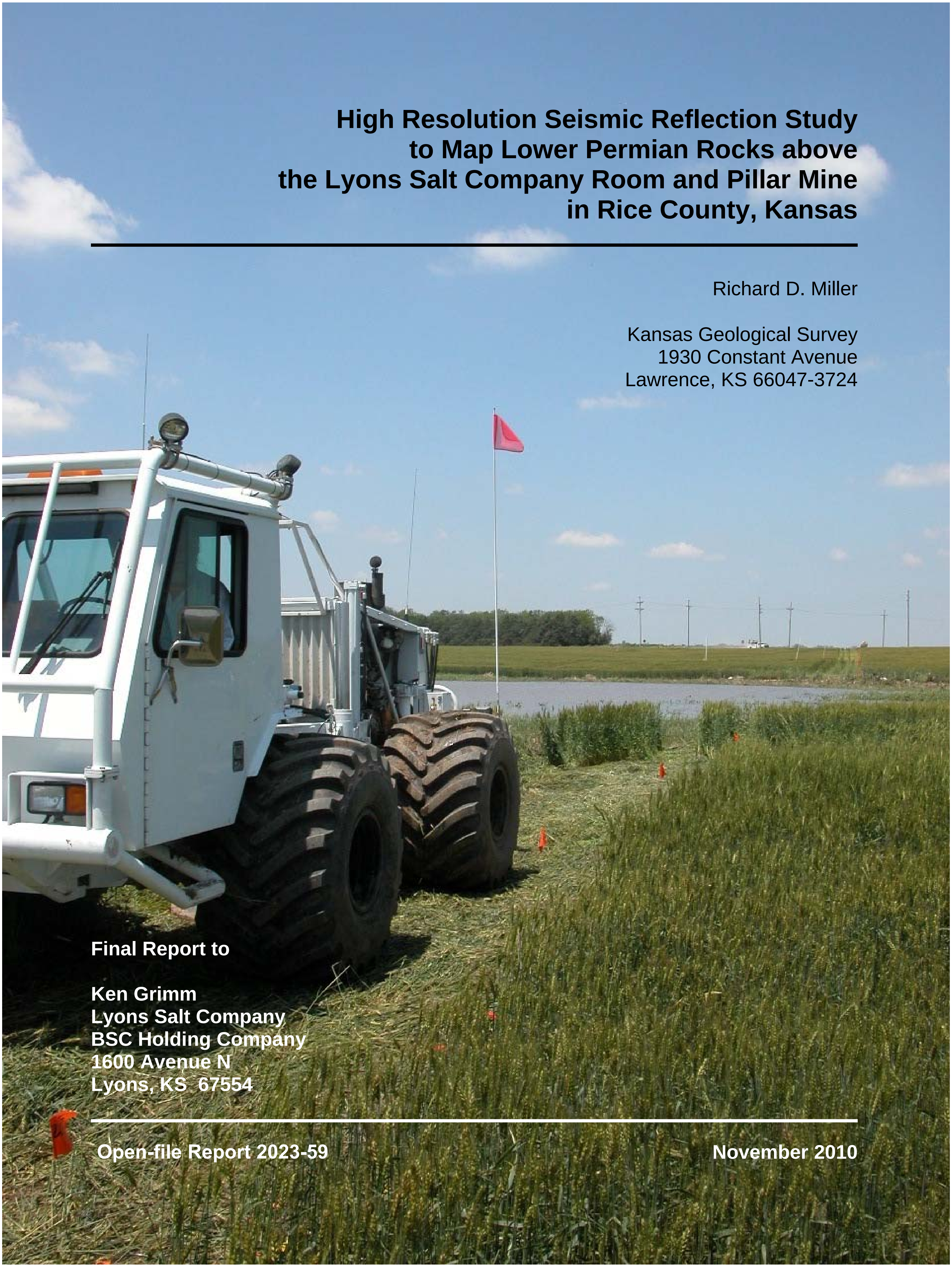

High Resolution Seismic Reflection Study to Map Lower Permian Rocks above the Lyons Salt Company Room and Pillar Mine in Rice County, Kansas

Richard D. Miller

Kansas Geological Survey
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Final Report to

Ken Grimm
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BSC Holding Company
1600 Avenue N
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Open-file Report 2023-59

November 2010

 This study was conducted in complete compliance with ASTM Guide D7128-05. All data, interpretations, and opinions expressed or implied in this report and associated study are reasonably accurate and in accordance with generally accepted scientific standards.

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Preface and Partial Summary

High-resolution seismic reflection proved reasonably effective imaging lower Permian rocks of the Sumner Group above a troubled mine area near Lyons, Kansas. The processed sections possessed sufficient clarity to realistically meet the proposed objectives in a fashion consistent with the focus of this study as spelled out in the proposal (Exhibit A of Lyons Salt Company Engineering Services Agreement with The University of Kansas Center for Research, Inc.). With the lack of site-specific detailed geologic information available prior to formulating the proposal and interpreting the seismic sections, many unforeseeable challenges and complications hindered the degree of success and ability to incorporate existing geologic/hydrologic findings with this seismic study. This study was undertaken and completed in full compliance with ASTM Guide D7128-05 and all research findings currently available in the scientific literature from previous seismic studies of the Hutchinson Salt in 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., 1995; Miller et al., 1997; Miller and Xia, 2002; Miller, 2003; Miller and Henthorne, 2004; Miller et al., 2005a; Miller et al., 2005b, Miller, 2006a; Miller, 2006b; Miller et al., 2006a; Miller et al., 2006b; Lambrecht and Miller, 2006; Miller and Millahn, 2006; Miller et al., 2008; Sloan et al., 2009; Miller et al., 2009).

Seismic evidence presented in this report is consistent with interpretations of collapse, bridging, bed terminations, bed offsets, extreme synformal structures, and multiple zones of collapse breccia accumulations (indicative of areas with complex distributions of voids) in rocks above the Hutchinson Salt in the study area. Remnants of subsidence structures can be interpreted within the upper 1000 ft across a large portion of the study area at locations where no current surface expression is apparent from topography measurements made during the seismic survey. With the apparent extent and unorganized nature of subsurface collapse/subsidence as deduced from seismic data, overburden strength is reduced and inconsistent across the study area. It is, therefore, no surprise that current subsidence is generally interpreted on seismic data as a chaotic volume of collapse breccia moving as a rock mass and forming a complex system of interconnected breccia pipes. This kind of dissolution and subsidence rarely includes seismically mappable coherent bed geometries that would be consistent with uniform, organized, coherent drape structures that are routinely observed in the beds of the Ninnescah Shale when dissolution and subsidence is purely anthropogenic or from a single localized episode.

Identifying areas with potentially active subsidence and associated void areas (as defined in next paragraph) relied heavily on mapping diffractions, scatter, and apparent bridging above draping structures or synforms. Diffractions and scatter is defined as *the change in the direction of energy travel because of collisions or inhomogeneity or anisotropy of the medium* (Sheriff, 2002). Diagnostic of void volumes that are remnants of salt dissolution and migrating to the surface are breccia pipes or breakdown blocks that produce significant clusters of diffractions (generally referred to as scatter in that context), leaving chaotic zones of scattered energy without confidently interpretable, laterally coherent reflections. Under the failure mechanisms interpreted on the seismic sections from this survey, reflection continuity across offset features (faults/fractures) and chaotic zones is not expected or observed.

Subsidence and stoping and/or vertical movement of collapse breccia associated with leaching of the salt, as interpreted on seismic data from within the survey area, has disturbed the Stone Corral. From these data it is possible to identify zones of reduced strength, less bulk density, and greater localized permeability between the Stone Corral and top of the Hutchinson Salt. Considering the angle of draw for this setting, a single dissolution zone with sufficient leached volume could produce a sinkhole more than 400 ft in diameter (angle of draw in these Permian rocks will be around 15°). It is not possible from a single seismic survey (snapshot in time) to identify zones of active rock or fluid movement, only potential pathways and structural alterations from the past.

"Void" is a term commonly used in the scientific literature when referring to aspects of karst features and migration of anomalous material balance (or lack of) to the ground surface. Voids as the term was used in the proposal for this study and is used in this report relates to volumes within the earth where some or all native rock material has been removed, compacted, substituted, rubbled, or displaced. This alteration in native rock conditions results in a disturbed volume of rock that is anomalous to material outside the volume, inconsistent with original sediment deposition and physical properties (such as Poisson's ratio, shear modulus, bulk modulus, and Young's modulus) of the native material, and possesses a bulking factor greater than 1. Dissolution voids can be filled with rubble, air, fluid, or any combination of the three. For example, a water-filled cavity above a void volume that includes a mixture of collapse debris, breakdown blocks, fluids, air, etc., all capped by a stoping roof, can define the migration path of a pre-sinkhole breccia pipe. Bottom line: a void space is not limited to air or fluid composition.

An area near the tie between lines A and D is interpreted from seismic data as having characteristics that justify elevated concerns for ground surface stability. Seismic reflection—like all geophysical techniques—is nonunique, meaning there is always more than one interpretation for any data set and feature. A unique sequence of diffractions with an apex located within a seismically quiet zone sandwiched between a combination of draping reflections and a set of overlying high-amplitude flat-lying reflections is strong evidence for bridging and elevated stress. The characteristics of this feature could indicate void space development consistent with a breccia pipe that has migrated through most of the shale overlying the Hutchinson Salt and is currently near the base of the Stone Corral. A boring located at station 1185 along line A and less than 400 ft deep should encounter and confirm/refute this observation.

From all seismic indications, the high amplitude reflector near the intersection of lines A and D is more than 100 ft in diameter, centered on about station 1180 on line A and bridging a volume with void characteristics (as previously defined in this text) that extend down to the top of the salt. The high amplitude character of the reflections interpreted as the top of this breccia pipe is the result of a dramatic decrease in velocity and/or bulk density beneath that interface. It is not possible with so much seismic noise (scattered energy from rubble/faults/fractures and diffusion of energy in this highly altered near-surface) to get an accurate estimate of the vertical extend of collapse breccia in the pipe. All the processed seismic reflection sections presented in this report have been migrated to collapse diffractions and correct for optical distortion related to dipping reflectors. The series of diffraction events interpreted as associated with this void are subtle but have been evident throughout the processing and interpretation flow.

Velocities estimated from these seismic data possess an accuracy of around ±500 ft/sec or 10% at the depth of the Stone Corral and around 7% within the Hutchinson Salt interval. Therefore, depth estimates carry an accuracy of around ±30 ft absolute at the Stone Corral and ±60 ft absolute within the Hutchinson Salt interval. Trace to trace relative precision is around 2 ft. The two-way traveltime depth of the Stone Corral is 90 ms at station 3220 on line C and after adjustment for the 20 ms start delay the depth to the Stone Corral at station 3220 is 225 ft ±30 ft. The top of the Hutchinson Salt beneath station 3220 on line C is at a time corrected value of 190 ms and using an 8000 ft/sec average velocity equates to a depth of 760 ft ±60 ft.

Based on the distorted reflections, chaotic zones, scatter packets, and lateral degradation in wavelet characteristics, most of the future subsidence appears likely to be constrained to the survey area with little chance of surface subsidence extending beyond the road on the north and west (estimated using a 15° angle of draw). Dissolution affecting the salt and migrating to the surface within the survey area appears initially to be confined to the middle half of the surveyed area. Reflection character throughout the salt interval appears coherent and unaffected by dissolution within a few hundred feet of the end of each seismic profile. Considering the angle of draw for dissolution voids in the salt at this site, once the void/disturbed areas detected on seismic data migrate to the ground surface and all the tensional stresses have relaxed, future surface subsidence will be confined to a perimeter approximately consistent with the end of each profile line (this assumes all leaching of the salt stopped at the time of the survey).

Diffractions and synforms interpreted within the near-surface suggest the current channel evident in the topographic plot crossing line D at around station 4170 and generally trending northeast will experience the most noticeable short-term, gradual subsidence. The channel will expand to the northwest, eventually connecting it with the north-south drainage ditch that crosses lines D and C at their intersection. Diffractions (bow tie) located beneath station 4145 on line D are indicative of very short radius synforms or bed termination points. It is very likely the surface depression that forms associated with this diffraction feature will manifest itself as an expansion of existing surface expressions.

Subsidence features formed during the vertical migration of voids leached by fluids that gain access to the Hutchinson Salt via boreholes will progress along markedly different evolutionary paths than collapse features resulting from the intermittent and somewhat chaotic progression of natural or paleodissolution and associated subsidence. Seismic images of several dozen salt dissolution-induced subsidence features in Kansas where the Hutchinson Salt had been subjected to uncontrolled release of fresh water or unsaturated brine solution through or as a result of boreholes provide the basis for determining of the progression of “classic” borehole-induced subsidence (Miller, 2007). During vertical migration of a void, the classic borehole-induced subsidence geometry is cylindrical, centered on the borehole, and bounded by high-angle reverse faults. The disturbed volume is characterized by low signal-to-noise, abundant scatter, and reduced resolution.

At the intersection of lines D and C, near the abandoned Habiger well, the rocks between the Stone Corral and base of the Hutchinson Salt are disturbed in a fashion consistent with dissolution-induced collapse. The collapse structure at this location has normal fault-bounded offsets with clearly disturbed reflections returning from within the upper Permian shale. After careful analysis of lines D and C near their intersection and in proximity of the old Habiger well, reflection geometries and seismic interference patterns do not appear indicative of classic borehole-induced dissolution in the salt interval and associated void migration to the ground surface that has been observed on seismic sections at several confirmed borehole-induced dissolution/subsidence sites (Miller and Millahn, 2006). Rock layers between the Stone Corral and base-of-salt interval at the Habiger well location are disturbed and have some characteristics resembling paleo- or natural dissolution and subsidence (e.g., bounding normal faults). There appears to be a minor amount of missing salt (dissolution on the top of salt) within 100 ft of the wellhead and an associated gentle collapse structure centered on the well with vertical offset expressed in reflections on the northeast side of the dissolution feature. This collapse structure extends upward through the Permian shales, appearing to terminate just below the Stone Corral. Clearly, rock layers beneath the location at the wellhead and base of salt have been structurally altered compared to native sections as observed at the ends of each seismic profile.

Previous seismic surveys acquired along the edges of sinkholes formed as a direct result of well-induced dissolution and migration of voids to the ground surface have produced seismic images with distinctive and unique draping reflection geometries. Unique synclinal structures centered on the well bore or chimney structures with chaotic seismic returns are both characteristic and in some settings diagnostic of well bore-induced dissolution and subsidence. Reflection surveys that cross directly over culprit wells possess predominantly scattered seismic energy within the pipe, where collapse breccia defines a void's migration to the ground surface, thereby inhibiting continuous mapping of reflectors across the pipe. However, clear seismic indications of incremental growth of collapse breccia and roof stoping are evident on seismic data acquired within the sinkhole that is adjacent to the actual pipe for single-episode sites with a point water source inlet and associated outlet. A very similar situation (active subsidence near, but not centered on an abandoned oil well) was seismically studied around 10 years ago near the dissolution front of the Hutchinson Salt immediately east Hutchinson, Kansas (Miller, 2008).

Isopach maps are a common product from seismic data when lithologic contacts and stratigraphic intervals are identified and can be correlated from well to well (isopach maps display thickness contours representative of a unit or interval). The Stone Corral interval is generally less than 15 ft thick in this area and the top of salt by definition is not an interval. Theoretical vertical resolution of the Stone Corral interval on the stacked seismic sections is around 15 ft, but 30 ft from a practical perspective (Miller and Xia, 2002). At 15 ft thick, the Stone Corral interval is near the ¼ λ tuning frequency and at or below the vertical resolution limits of these data. Therefore, rather than an isopach map, one of the products of this study is an isochron map. The isochron maps included in this report are for the top of the Stone Corral and the top of the Hutchinson Salt.

The principal goals of this study were to delineate rock layers within and above the Hutchinson Salt Member, identify potential dissolution zones that may represent hydrologic pathways supplying the water necessary to perpetuate leaching, and attempt to appraise the overall stability and current state of the rock column. The state-of-the-art shallow high-resolution seismic-reflection techniques used on this study are consistent with generally accepted scientific standards and all applicable ASTM guides. These data and associated interpretations reasonably meet those objectives based on current state of the science.

Introduction

The high-resolution seismic-reflection study conducted above a troubled part of the Lyons Salt Company (LSC) room and pillar mine in Rice County consisted of four intersecting 2-D profiles targeting the area where both hydrologic variability and subsidence within the overburden is suspected to be the greatest (Figure 1). All four profiles include areas in the

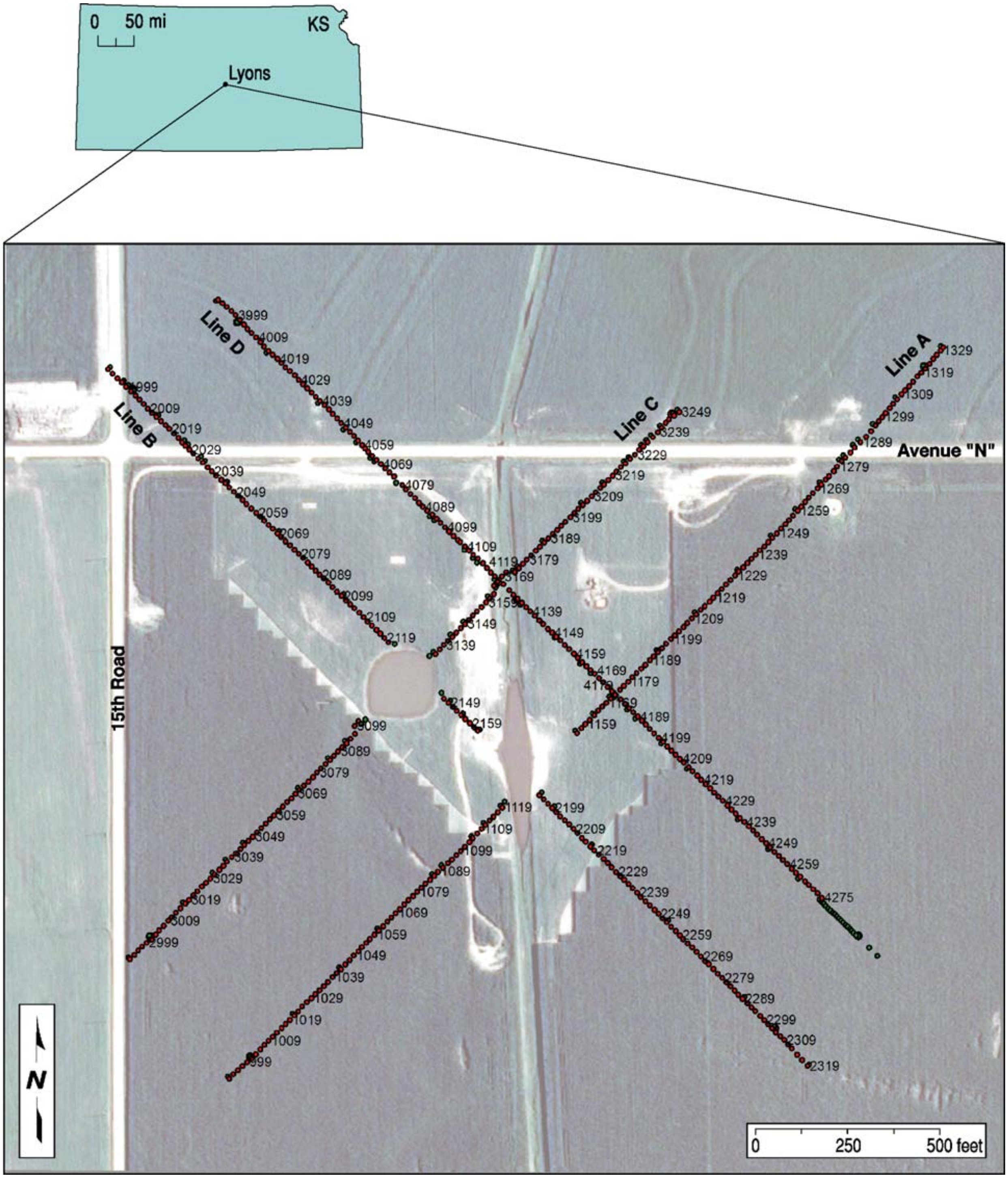


Figure 1. 2-D seismic profiles plotted from actual rtk GPS values measured by the seismic source during acquisition overlaying satellite photo.

subsurface where native conditions existed, where stable mine conditions are present, and where subsidence had been observed.

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., 1995; Miller et al., 1997; Miller and Xia, 2002; Miller, 2003; Miller and Henthorne, 2004; Miller et al., 2005a; Miller et al., 2005b, Miller, 2006a; Miller, 2006b; Miller et al., 2006a; Miller et al., 2006b; Lambrecht and Miller, 2006; Miller and Millahn, 2006; Miller, 2008; Miller et al., 2008; Sloan et al., 2009; Miller et al., 2009).

Proven high-resolution techniques (Steeples and Miller, 1990) were used to acquire data for this survey. Acquisition of the production data followed well-established procedures for shallow high-resolution data acquisition (Hunter et al., 1984; Knapp and Steeples, 1986; Steeples and Miller, 1990). Production data were acquired in a standard CMP format (Mayne, 1962) using a rolling fixed-spread acquisition technique. The geophone type and spacing, seismic source and configuration, source spacing, optimum fold, spread geometry, sampling interval, total samples, shots/point, and acquisition philosophy were all based on pre-production tests and decades of experience collecting this kind of data in this general area.

The entire seismic project and processing consisted of two distinct components: acquisition and processing/interpretation. With consideration for the interests and time schedule of LSC, the acquisition phase began immediately after completion of contract negotiations and on a timetable and at a level of commitment that exceeded the scope of work originally proposed by the Kansas Geological Survey (KGS). Wind and rain dramatically impacted the acquisition schedule and data quality. Collecting all the data within the available time window (May 24 to 28, 2010) required extended crew time, evening and night work, and data skips that could not be avoided due to flooding of low-lying areas. Acquisition parameters were optimized for the site, but with the daily changes in surface conditions due to highly variable soil moisture, the data quality noticeably changed line-to-line through the acquisition period. Processing and interpretation stages began immediately upon completion of the data acquisition.

The KGS proposal called for the acquisition of the two profiles (A-A’ [3500 ft] and D-D’ [2100 ft]), but, due to the need for extended results from the seismic survey, lines C-C’ and B-B’ were also acquired during the initial site visit. A total of five days were required to complete the acquisition. Each line was laid out and fully instrumented with receivers and seismographs to allow each vibrator sweep to be recorded by all receivers along the entire length of the profiles. This approach was easily accommodated by the KGS’s 480-channel Geometrics Geode distributed seismograph system. The source was an IVI minivib2 generating three (20 to 250 Hz, 10 sec) upsweeps per station. Receivers were triple 28 Hz Sensor geophones wired in series and placed every 8 ft along the profile lines. This system (seismograph, source, and receivers) is state-of-the-art in high-resolution near-surface profiling and provided the best data possible at this site and under the ground conditions that existed at the time of the survey. Ground impact and damage to wheat that was in the later stages of development (fully headed), was minimized to avoid excessive damage reimbursements to the farmer by LSC. The KGS acquisition system is generally considered to possess a “minimal footprint” in environmentally sensitive areas.

Site Characteristics: 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, 1959; 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 seismic marker bed) overlies the salt throughout Kansas (McGuire and Miller, 1989). Directly above the salt is a thick sequence of Permian shales.

The Stone Corral is well known as an interface that is regionally consistent, with high-amplitude and high-frequency returns, giving it a well-deserved reputation as a seismic marker bed (Miller and McGuire, 1989). Offset or drape in the Stone Corral is a key indicator of sub-sidence or near-surface static (Figure 3). Since the Stone Corral is present within the overburden at this site, the highest amplitude reflection on the common midpoint (CMP) stacked section was expected to be the Stone Corral, and it was anticipated to be separate from other reflection events by a wavelength or more. The Stone Corral was also expected to provide the most definitive glimpse at potential fluid pathways from the shallow ground water supplies to Ninnescah shales.

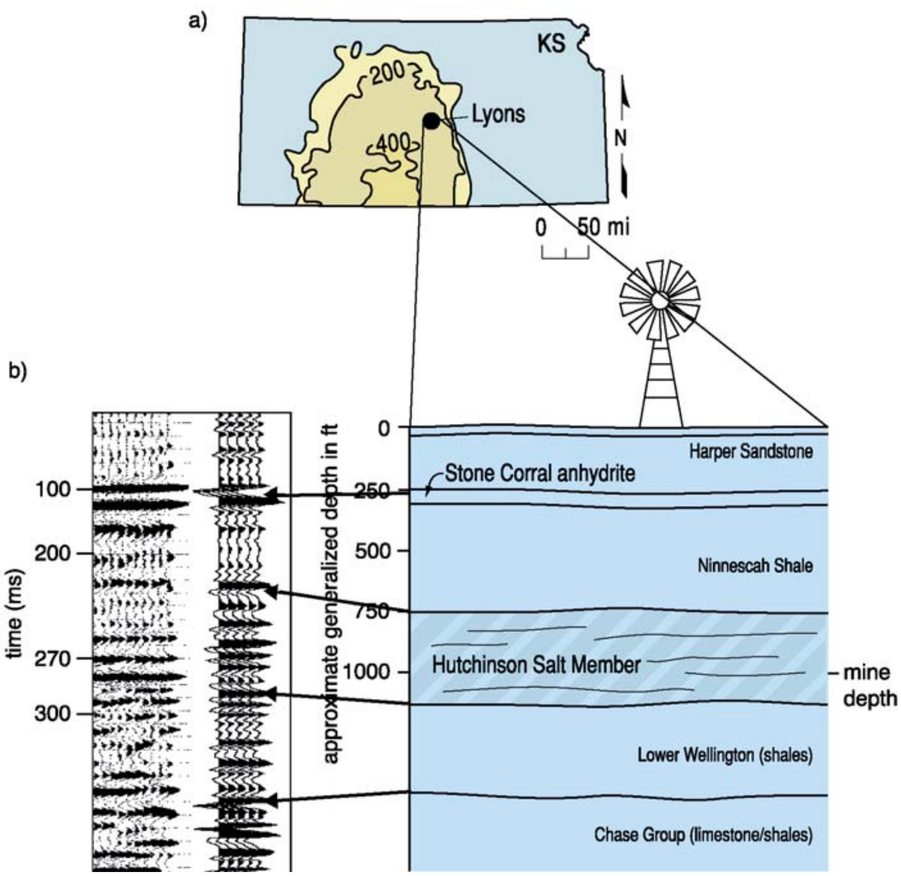


Figure 2. Generalized geologic section with site location and salt thickness (a) represented with a cross-sectional representation of the local generalized geology and a synthetic seismogram correlated to both geology and a portion of the stacked section (b). Stone Corral is dominant and considered essential for mapping void migration upward to shallow aquifers and the ground surface.

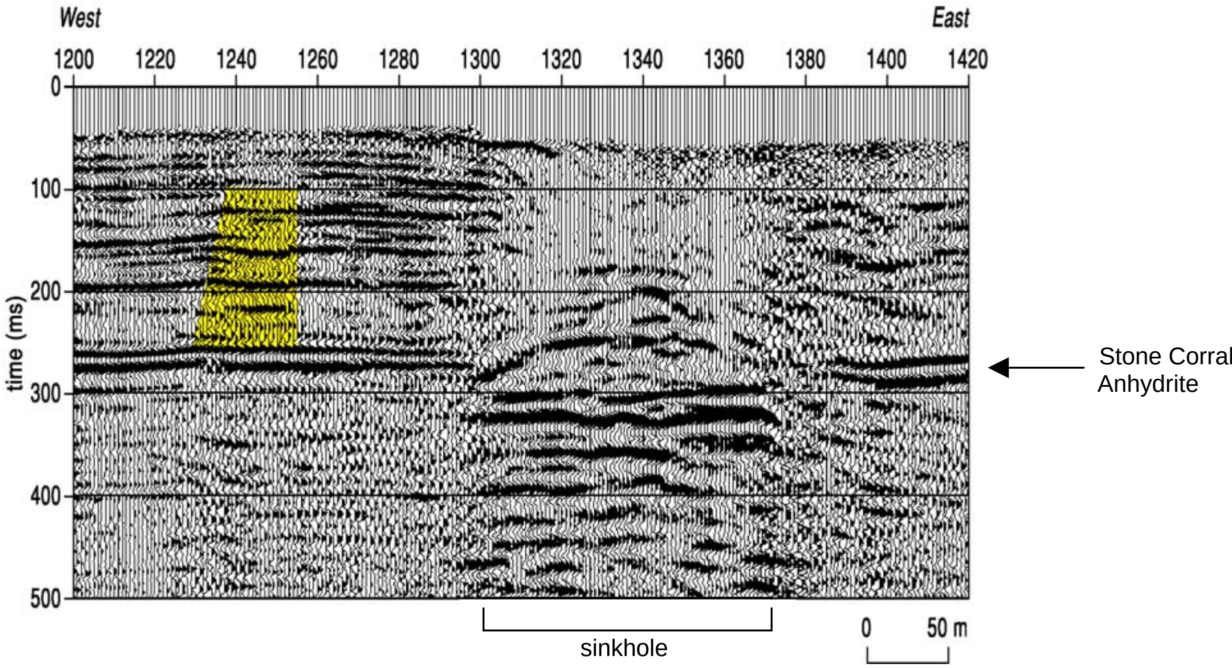


Figure 3. Profile from along I-70 in Russell County, acquired in 2004.

"Void" is a term commonly used in the scientific literature when referring to aspects of karst features and migration of anomalous material balance (or lack of) associated with dissolution features to the ground surface. Voids as the term was used in the proposal for this study and is used in this report relates to definable volumes within the earth where some or all native material has been removed, compacted, rubbled, substituted, or displaced. This alteration in native conditions results in a disturbed volume of rock that is 1) anomalous to material outside the volume, 2) inconsistent with original sediment deposition and physical properties (such as Poisson's ratio, shear modulus, bulk modulus, and Young's modulus) of the native material, and 3) possesses a bulking factor greater than 1. Dissolution voids can be filled with rubble, air, fluid, or any combination of the three. For example, within the migration path of a pre-sinkhole breccia pipe an air-filled void space can be capped with a stoping roof overlying a void volume, which includes a mixture of collapse debris, breakdown blocks, fluids, air, etc. Bottom line: a void space is not limited to air or fluid composition.

Identifying areas with active subsidence and associated void areas (as previously defined) relied heavily on mapping diffractions, scatter, and apparent bridging above draping structures or synforms. Diffractions and scatter is defined as *the change in the direction of energy travel because of collisions or inhomogeneity or anisotropy of the medium* (Sheriff, 2002). Breccia pipes or breakdown blocks will produce significant scatter leaving a chaotic zone on CMP stacked sections with no coherent reflections (Figure 4). Under the failure mechanism interpreted on the seismic sections from this survey, reflection continuity across offset features (faults/fractures) and chaotic zones is not expected or observed. Subsidence and stoping and/or vertical movement of collapse breccia associated with the leaching of the salt interpreted on seismic data from within the survey area has disturbed the Stone Corral. From these data it is possible to identify zones of reduced strength, less bulk density, and greater localized permeability between the Stone Corral and top of the Hutchinson Salt.

Diffractions from a large number of point sources appear on seismic sections as an unorganized cluster of coherent parabolic curves, open downward (Figure 5). The thousands of edges and fragments present in a pile of collapse breccia filling a subsidence pipe represent potential sources of scattered or diffracted seismic energy (Figure 4). These large collections of scatter points normally make reflection imaging impossible within a subsidence pipe formed through relatively rapid stoping of roof rock. In these cases, interpreting the apex of the major diffractions and defining scatter-free areas with coherent reflections as outside the pipe is a proven interpretation approach with seismic reflection sections.

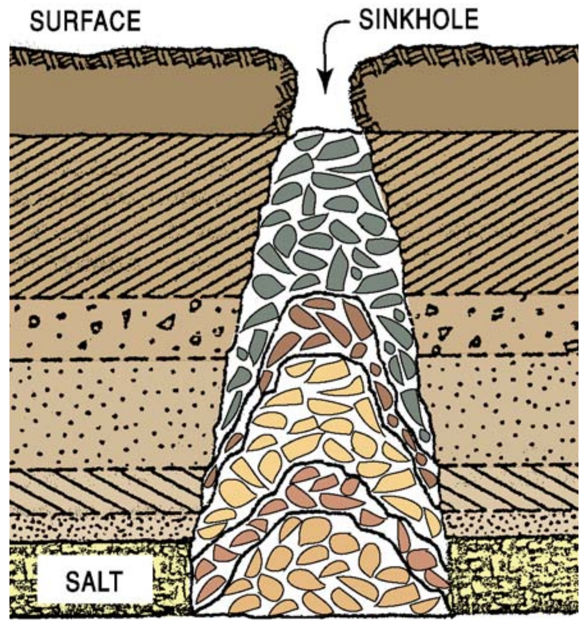


Figure 4. Sinkhole subsidence feature with segregated rock layers made up of collapse breccia.

Synforms that result from bed drape associated with subsidence and void migration can have a radius of curvature small enough to produce a diffraction looking event known as a "bow tie" in seismic vernacular (Sheriff, 2002). These features are diagnostic of extreme bowl shaped bed distortion and are commonly observed on seismic sections that cross active subsidence and/or paleosubsidence structures (Figure 6). From a modeling perspective tight curvature synforms are analogous to erosionally formed incised valleys and will have similar characteristics on seismic sections (Figure 7).

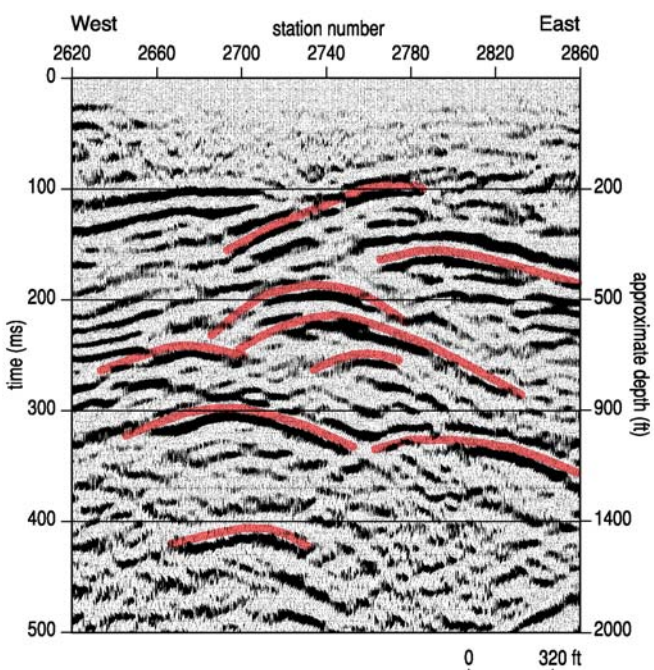


Figure 5. Diffractions interpreted on a CMP stacked section crossing over an active fault zone in north central Nevada.

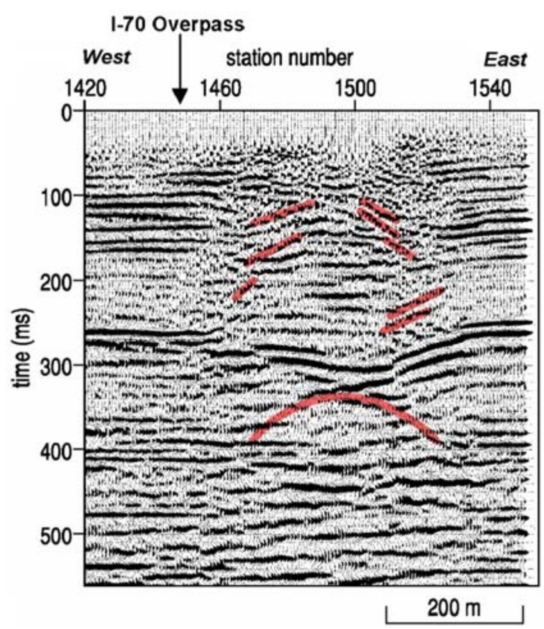


Figure 6. Diffractions from a gradual sinkhole along I-70 in Russell County, Kansas.

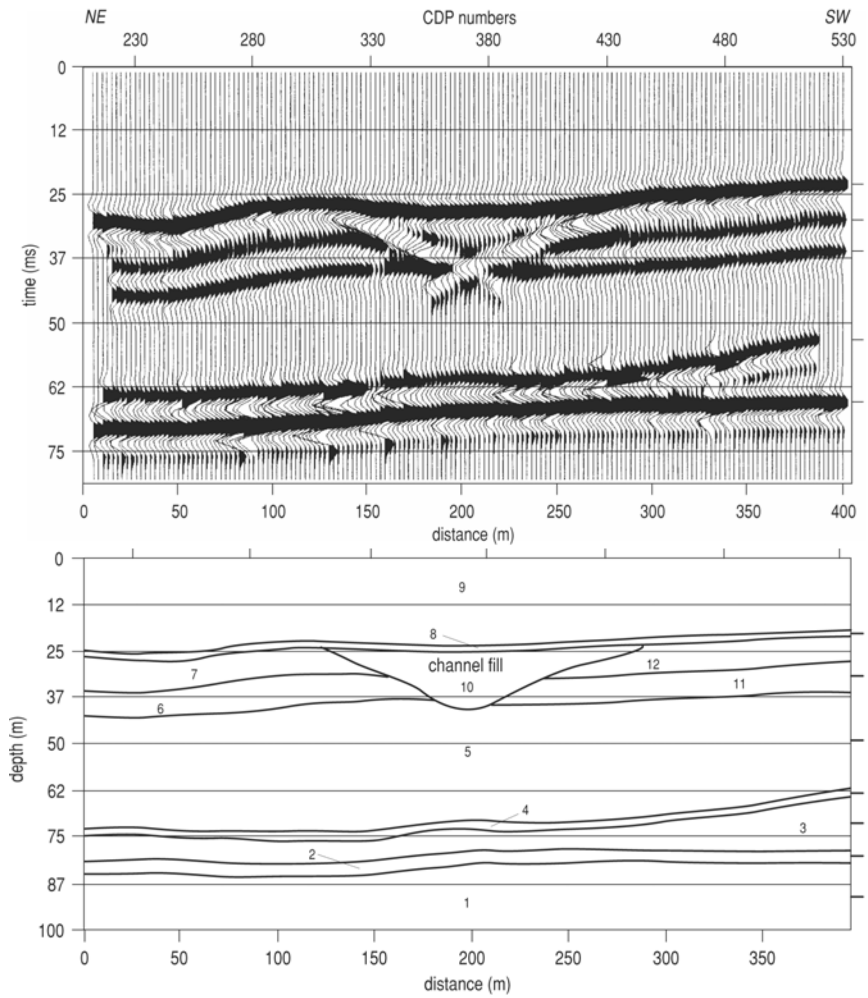


Figure 7. Numerical model with theoretical seismic response of a steep-sided synform. The “bow tie” feature is obvious on the seismic data.

Interpreting paleosubsidence features on seismic data is challenging. There are however several key characteristics that can provide definitive support for categorizing subsidence geometries on seismic sections as either paleo or current/active. Most noteworthy are relatively flat reflections within subsidence-induced synforms coincident with a general lack of scatter or diffractions. Paleosinkholes eventually fill with sediments as a result of normal erosion along the flanks of the sinkhole and through years of surface flood events stranding sediment-rich waters within their topographic low (Figure 8). Over thousands of years, bed terminations and offsets in shale-rich settings resulting from void migration tend to experience healing and elevated compaction (reducing the bulking factor over time), thereby appearing on seismic images as smooth synforms (Figure 9). Between the horizontal resolution of the seismic data

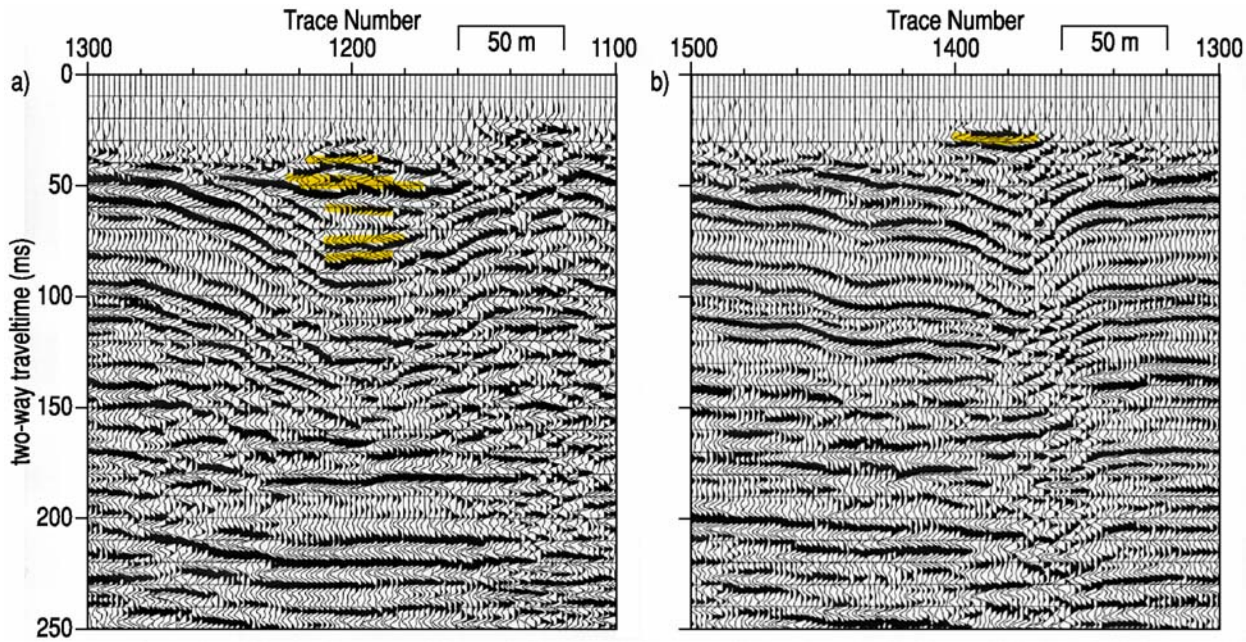


Figure 8. CMP-processed seismic sections from Punkin Center in Reno County, Kansas. Obvious solution-induced subsidence has produced dramatic bowl-shaped structures. These features have no surface expression and deposition of pre-Quaternary sediment into these bowl features appears undisturbed, indicative of dormancy.

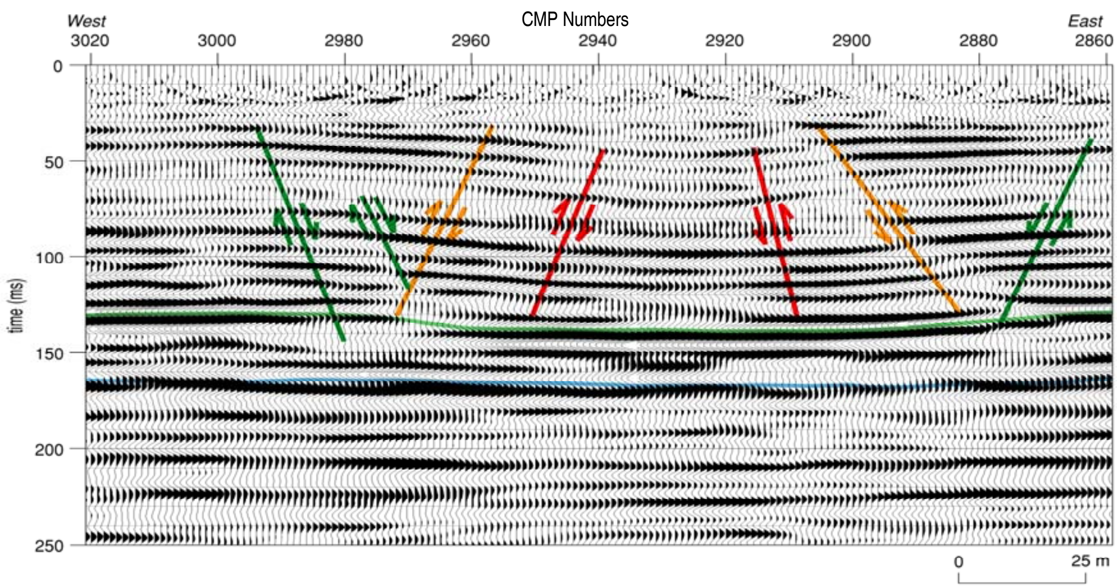


Figure 9. Paleosubsidence feature with no current surface expression. Dissolution of the upper portion of the salt is evident, with a high-amplitude reflection interpreted to be the top of salt. Failure likely occurred from middle of the feature out with the two pairs of reverse faults defining initial failure that occurred while the dissolution process was active, with normal-oriented offset beds in response to compaction into the dissolved and disturbed volume.

and in some cases millions of years of compaction these brittle structures take on a smooth ductile appearance without the characteristic diffractions prevalent in recent subsidence structures (Figure 10).

Interpreting overburden reflector geometries and areas with and without leaching when both paleosubsidence and active subsidence are present has proven challenging, but feasible along the dissolution front of the Hutchinson Salt in Reno County (Miller, 2008). Using the lack of diffractions associated with smooth subsidence features as principle criteria for interpreting paleo versus active subsidence proved consistent with well data and observations (Figure 11). As with all seismic reflection data, interpretations of geologic settings, lithologic variabilities, and structural abnormalities, no interpretation carries 100% confidence; some conjecture (as long as consistent with geologic and mechanical theory) is necessary and expected.

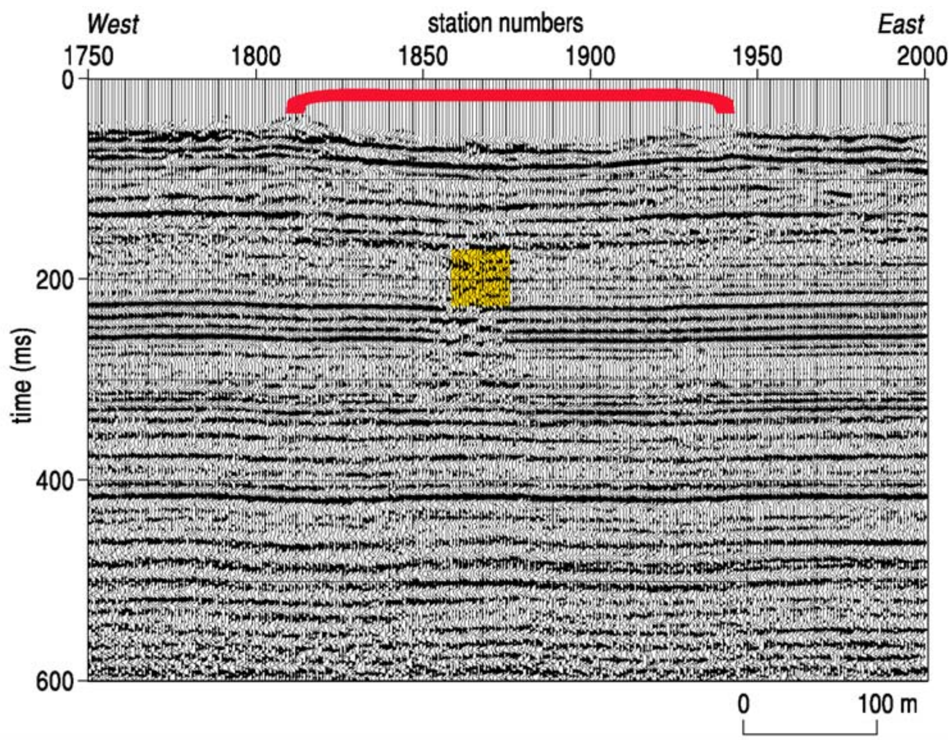


Figure 10. Dissolution-induced subsidence feature beneath U.S. 50 in Reno County, Kansas. Yellow zone is the Hutchinson Salt interval with associated break in coherency of underlying reflections resulting from an apparent fracture zone. No surface deformation exists associated with this exclusively subsurface feature.

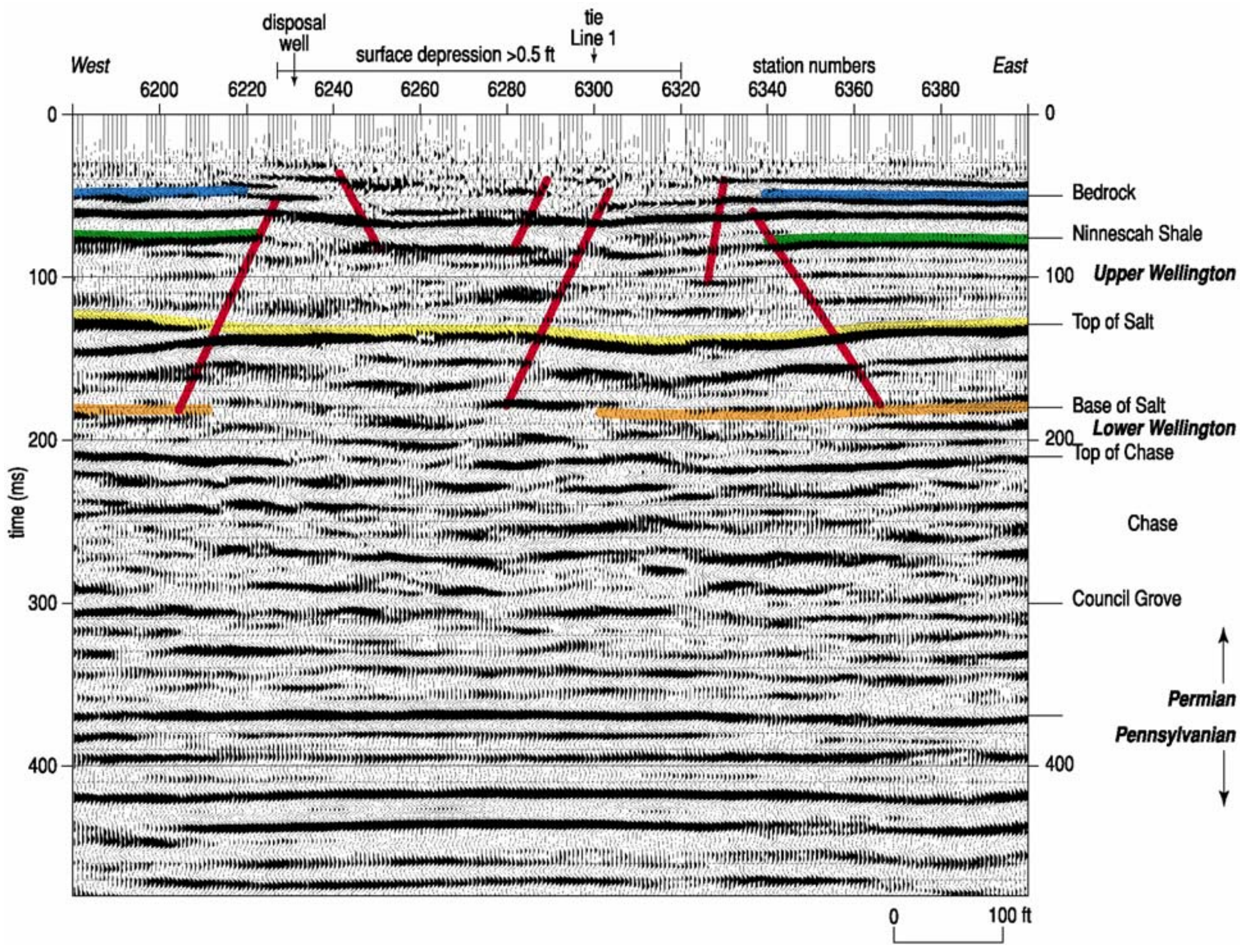


Figure 11. CMP stacked section with interpretation of reactivated subsidence feature beneath and immediately west of a house and major north/south county road. Current subsidence along eastern edge of dissolution zone is defined by reverse faults and is likely indicative of active leaching of salt beneath this section of line.

Data Acquisition Phase

Acquisition parameters were defined based on experience and walkaway tests along line D. The triple Sensor 28 Hz geophones were planted at 8 ft intervals in nominal 2 ft arrays. To insure good coupling, geophones were secured into firm to hard soil in small divots created by removing the top few inches of loose material. From ten to fourteen 24-channel Geometrics Geode distributed seismographs were networked to simultaneously record data from all stations along each line. An IVI Minivib2 delivered three 10-second, 20-250 Hz upsweeps at each shot location (shot interval was 16 ft); each sweep was recorded individually as unstacked, uncorrelated field files. For on-site QC, the ground force for each sweep was telemetried from the vibrator to the seismograph and recorded as an auxiliary trace on each shot record. Each of the three sweeps generated for each shot station was recorded individually and stored in an uncorrelated SEG-2 format with the ground-force pilot occupying channel 1 (aux channel) of each shot gather.

All sweeps were recorded from all receiver stations along each line while incrementally moving the source from shot station (every other receiver station was a shot station) to shot station. Since all shot records were recorded uncorrelated, QC involved visual inspection of the recorded pilot trace, audio monitoring of the pilot trace on a RF scanner, inspection of the vibrator power spectra after each shot, and review of source energy arrival pattern relative to noise on the time sections. With the exception of receiver stations not instrumented due to excess water or thick gravel on the road surface, the survey was recorded with 100% live receivers within the optimum recording window (Hunter et al., 1984).

The IVI minivib 2 was outfitted with a Trimble DGPS rtk survey-grade receiver that logged the location of each source point and its elevation with sub-inch accuracy x, y, and z. This system provided the ground topography survey data that was used to match the seismic data with satellite photos. Using a rover system, key receiver locations were also surveyed in separately. The elevation data from these surveys was required to correct the seismic section to the sloping datum selected for all seismic data points in this survey.

Site conditions were adequate but not ideal for a vibroseis survey. Ideal vibroseis conditions are generally found at sites with a rigid ground surface resulting in minimal plastic deformation when the 13,000 lbs of pre-load pressure from the source is fully exerted and the baseplate is tightly coupled to the ground. As the ground saturation increased over the week, the deformation between the vibrator baseplate and ground surface increased, reducing the performance of the vibrator. At no time was the performance reduced to a point that meaningful data was not acquired.

The four seismic reflection profiles were all acquired using the same equipment and parameters (Table 1). Lines were prioritized in order of significance to LSC. The line acquisition order was D, C, A, and B, with each taking a full day and evening to deploy equipment and acquire data (Figure 1). QC was maintained for all lines at a level that far exceeds industry standards (e.g., 100% active receivers were required, industry generally considers 90% highly acceptable). Data acquisition for lines D and C was carried out during evening and nighttime hours to minimize cultural and wind noise. Lines A and B were acquired in afternoon and late evening to minimize wind and traffic noise.

Acquisition of line D was completed without dropping stations due to wet ground conditions. Heavy rains prior to acquisition of lines C, A, and B filled low-lying areas with up to 4 ft of water, requiring receivers in the north/south drainage ditch and the bottom of the closed surface depression to be skipped. These kinds of data skips in critical parts of the line dramatically reduced the coverage in shallow portions of the subsurface. Undershooting obstacles provides deeper coverage, but close offsets are essential for imaging shallow.

The acquisition equipment operated at peak performance during the entire survey and site conditions were good to adequate throughout the acquisition period. Off-road vehicles were used to minimize the footprint of the survey. Six-wheel utility vehicles transported cables, phones, seismographs, and batteries where necessary along the four profiles. The vibrator is outfitted with 32-inch tires, thereby reducing ground pressure to less than 2 psi when the lugs are fully implanted into the soft soil. The type and use of the equipment was ideal for the conditions and minimized lost time due to ground conditions and reduced damage to crops.

Table 1
Acquisition Parameters

	Line A	Line B	Line C	Line D
Recording Channels	336	312	240	288
Receivers	Three 28Hz Sensor	Three 28Hz Sensor	Three 28Hz Sensor	Three 28Hz Sensor
Receiver Spacing	8 ft	8 ft	8 ft	8 ft
Source	IVI minivib2	IVI minivib2	IVI minivib2	IVI minivib2
Sweep	Three 20-250Hz 10 sec sweeps	Three 20-250Hz 10 sec sweeps	Three 20-250Hz 10 sec sweeps	Three 20-250Hz 10 sec sweeps
Source Spacing	16 ft	16 ft	16 ft	16 ft
Seismograph	14 distributed, 24-channel Geode units	13 units	10 units	12 units
Acquire Date	May 27	May 28	May 26	May 25

Data 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 included 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 12). 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.

The basic architecture and sequence of processing steps to be followed during the generation of the final stacked sections were 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 13). Shallow seismic reflection processing requires a heightened emphasis to be placed on velocity analysis (Miller, 1992), minimized use of wavelet processing, elevated care and precision placed on muting, step-by-step analysis of each operation’s effect on reflected energy, limiting statics operations to maximum shifts no greater than one-quarter wavelength of the dominant reflection energy across large correlation windows, and coincident iterative velocity and statics analysis.

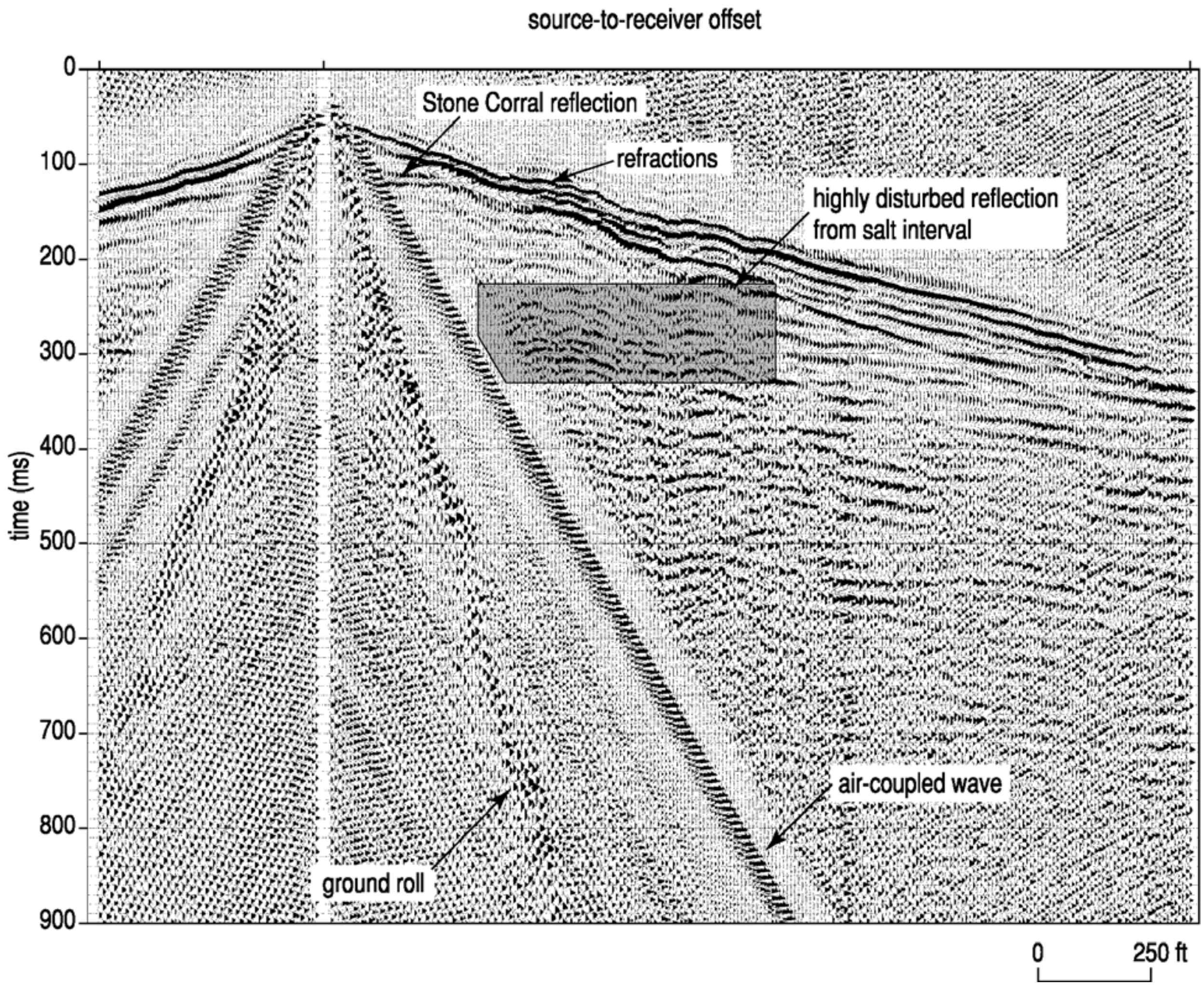


Figure 12. Correlated shot record with post-correlation AGC. The irregularities and apparent structural complexities in dissolution areas are obvious.

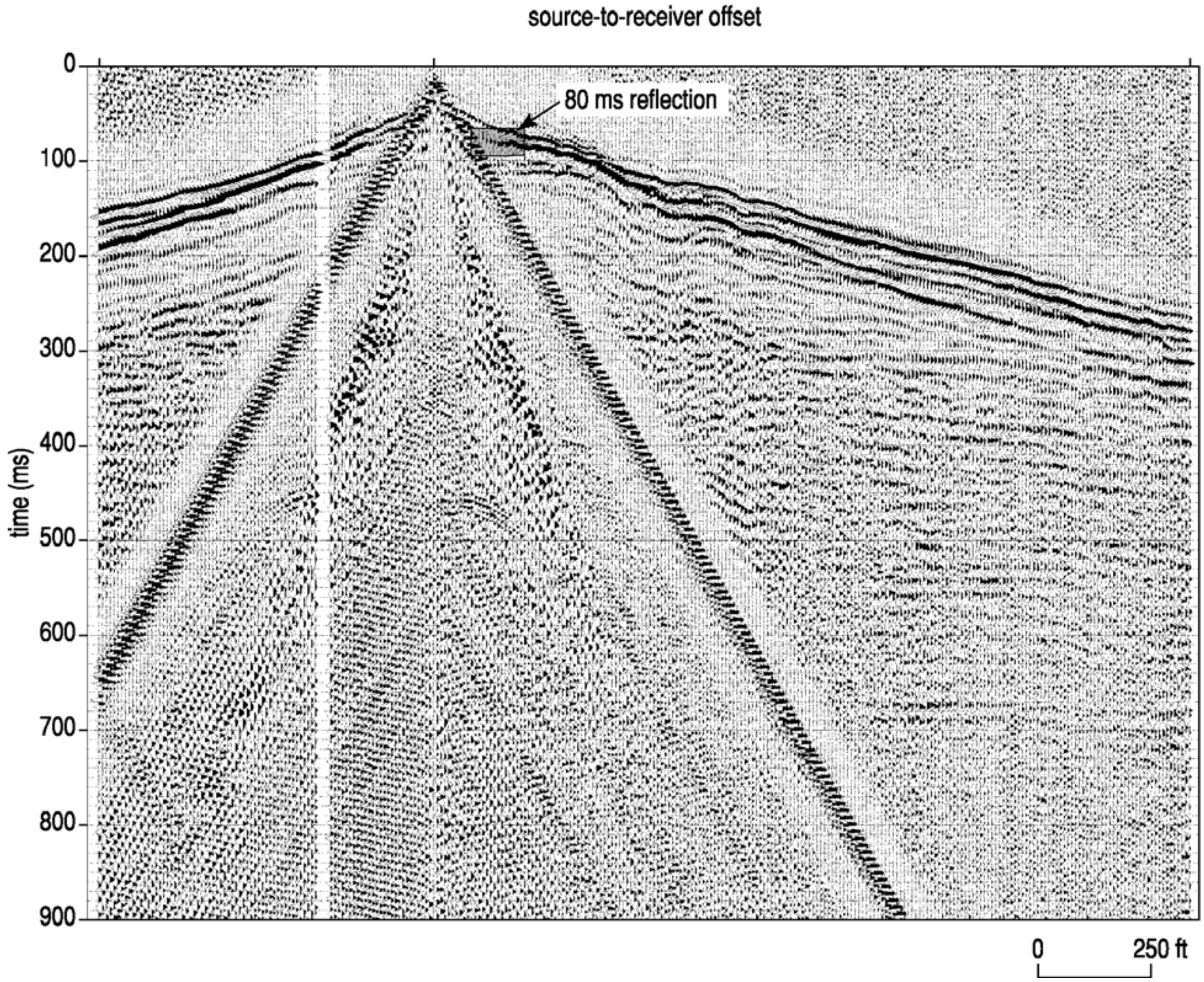


Figure 13. Correlated single sweep from line D with subtle indication of reflections as shallow as 80 ms.

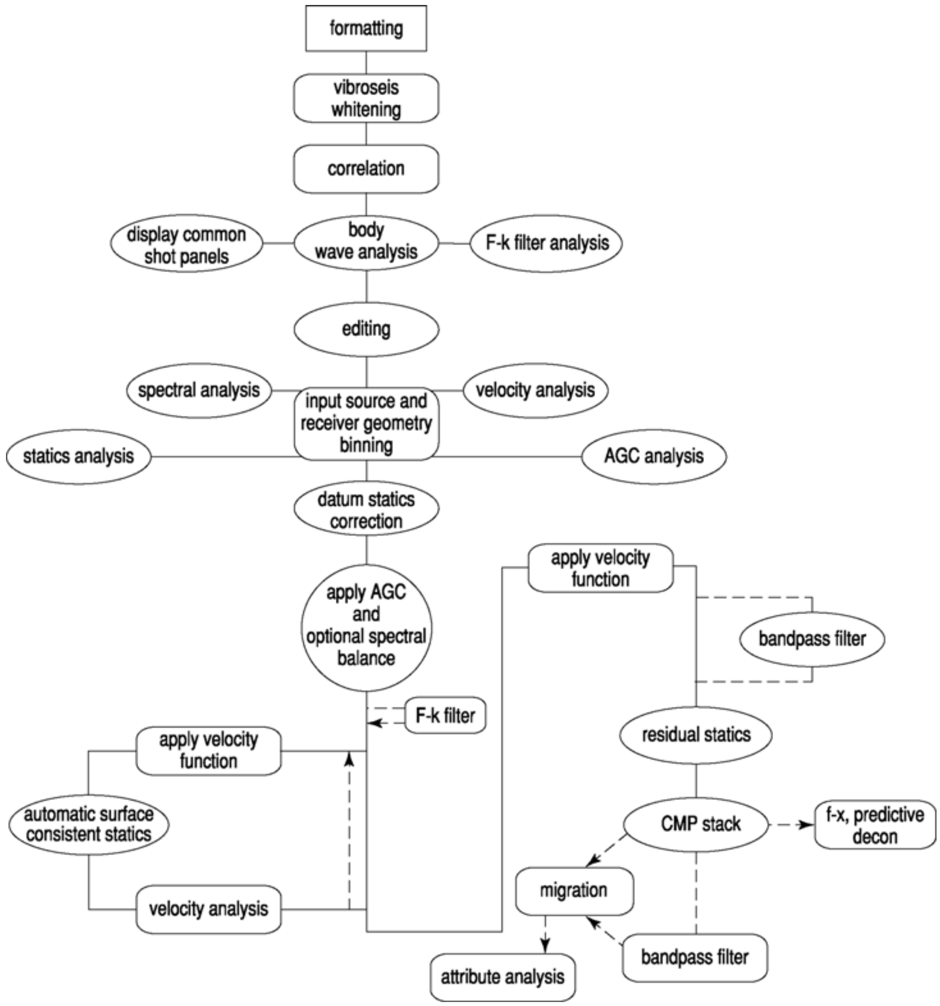


Figure 14. Generalized processing flow.

Special emphasis was placed on all analysis steps in the processing flow (Figure 14). Variability in near-surface materials and/or conditions required changes in processing parameters over distances of less than 50 ft. To ensure the highest quality, geologically representative stacked section velocity analysis was completed on every CMP. Because of the extreme inter-spread statics and short wavelength, complex fractured, faulted, and tilted structures, sub-spread length analysis lead to dramatic reduction in the potential fold. Only the offset and time window considered optimum for the depth and velocity structure was retained.

Assigning a representative normal moveout velocity function is a pivotal component of time-to-depth conversions of processed seismic reflection data and is critical to accurate depth assignments in this highly altered and geometrically complex subsurface setting. In association with point-by-point analysis, care was taken to ensure that all coherent events on stacked sections interpreted as reflections were reflections. Biasing processing parameters to enhance events interpreted as reflections that are actually coherent noise was 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 was not taken lightly (Steeples and Miller, 1990).

Outside the disturbed zone (area with clear bed alterations and associated extreme, subspread length velocity variability) the velocity accuracy is around ±250 ft/sec, making the depth error ±12 ft at the Stone Corral and ±20 ft at the Hutchinson Salt. Due to extreme distortion within the dissolution and subsidence volume it was not possible to define the velocity function horizontally and vertically in sufficiently small grids to allow generation of an accurate depth section. Therefore, all the interpretations and seismic sections are in their native measurement dimension of time in milliseconds.

Velocities estimated from seismic data within the disturbed portion of the profile possess an accuracy of around ±500 ft/sec or 10% at the depth of the Stone Corral and around 7% within the Hutchinson Salt interval. Therefore, depth estimates carry an accuracy of around ±30 ft absolute at the Stone Corral and ±60 ft absolute within the Hutchinson Salt interval. Trace to trace relative precision is around 2 ft. The two-way traveltime depth of the Stone Corral is 90 ms at station 3220 on line C and after adjustment for the 20 ms start delay the depth to the Stone Corral at that point is 225 ft ±30 ft. The top of the Hutchinson Salt beneath station 3220 on line C is at a time corrected value of 190 ms and with an 8000 ft/sec average velocity equates to a depth of 760 ft ±60 ft.

Step-by-step analysis during the acquisition and processing phases of the survey was continuous with appropriate modifications made when necessary to ensure the quality of the final product.

Interpretations

Shot Gathers

Key to the effectiveness of any seismic reflection survey is the quality and distribution of the seismic wavefield on the shot gathers (Figure 12). Each sweep was recorded individually with only the second and third sweeps vertically stacked during processing and used to produce the final CMP stacked sections. This approach minimizes problems due to changes in source coupling from sweep to sweep and allows transient noise (vehicles, wind gusts, intermittent pumping through petroleum line running along north property line, etc.) to be removed without eliminating entire receivers stations from the eventual shot gather for a particular shot station. From a single sweep along line D many of the data characteristics and associated difficulties imaging this collapse feature are obvious (Figure 12). The air-coupled wave, ground roll, and first-arrival refractions are all source-generated noise removed during processing. Reflections from the Stone Corral at around 110 ms are pronounced, have excellent separation from the first arrival and air-coupled wave, and possess a dominant frequency of around 100 Hz.

Reflections can be interpreted on raw, correlated shot records (scaled for display purposes) from around 80 ms to two-way time depths in excess of 700 ms (Figure 13). Considering the optimum window of these data, it was imperative to keep a wide range of offsets through the processing flow to insure imaging of the entire target zone. Reflections with dominant frequencies around 100 Hz can be interpreted as deep as 250 ms, while the dominant frequency of reflections at 500 ms drop to around 70 Hz. As much as 10 ms of reflection wavelet mismatch from trace to trace is evident within the box defined as the “highly disturbed reflections from salt interval” on shot gathers (Figure 12). Much of this “chatter” (commonly referred to as static by reflection seismologists) observable between traces is indicative of the dramatic localized changes in material velocities and/or bed distortion associated with rock layer failure and

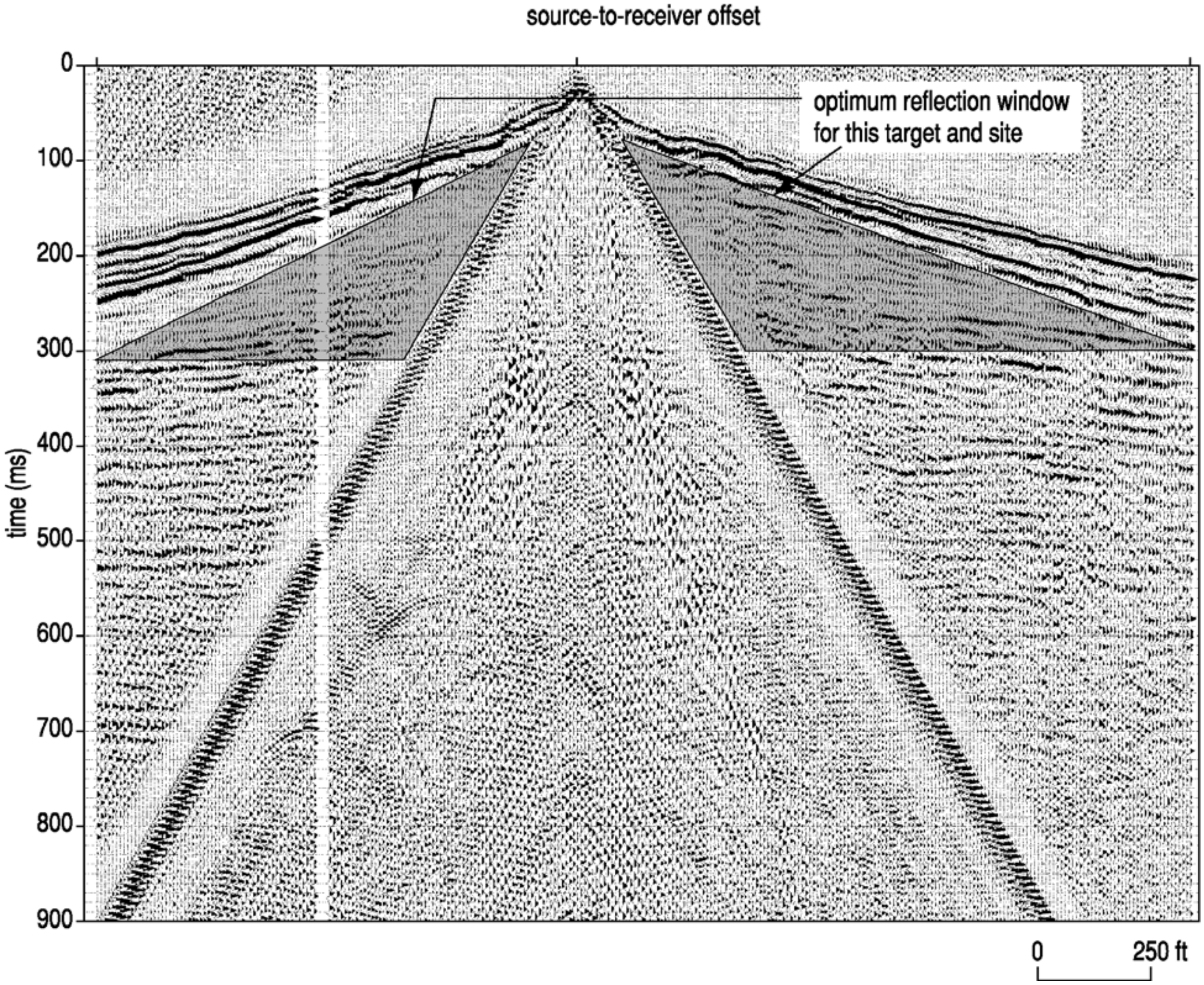


Figure 15. Reflections between 80 ms and 300 ms are returning from reflectors between 200 and 1200 ft below ground surface.

subsidence. It is critical that all static irregularities be compensated for before the data are CMP stacked.

With reflections from the Stone Corral important in establishing the impact of dissolution within the salt interval and associated subsidence, reflections from 80 ms to 300 ms are within the optimum recording window. Reflections from 80 ms can be seen on most shot gathers, but must be separated from source noise with extreme care (Figure 12). In many cases only two or three traces possess preservable reflection wavelets from this shallow depth. For most shot gathers the high signal-to-noise window possesses a good sampling of reflections that are the most dominant energy recorded (Figure 15).

Unique to this data set and something that came as a bit of surprise was the clarity observed in the reflections returning from the salt/mine interface (Figures 16 and 17). Although theoretically expected, normally interference and minimal mine foot print have inhibited definitive observations of coherent mine reflections. Reflections on shot gathers at times consistent with the mine depth from areas with no mine present versus reflections where mines are present

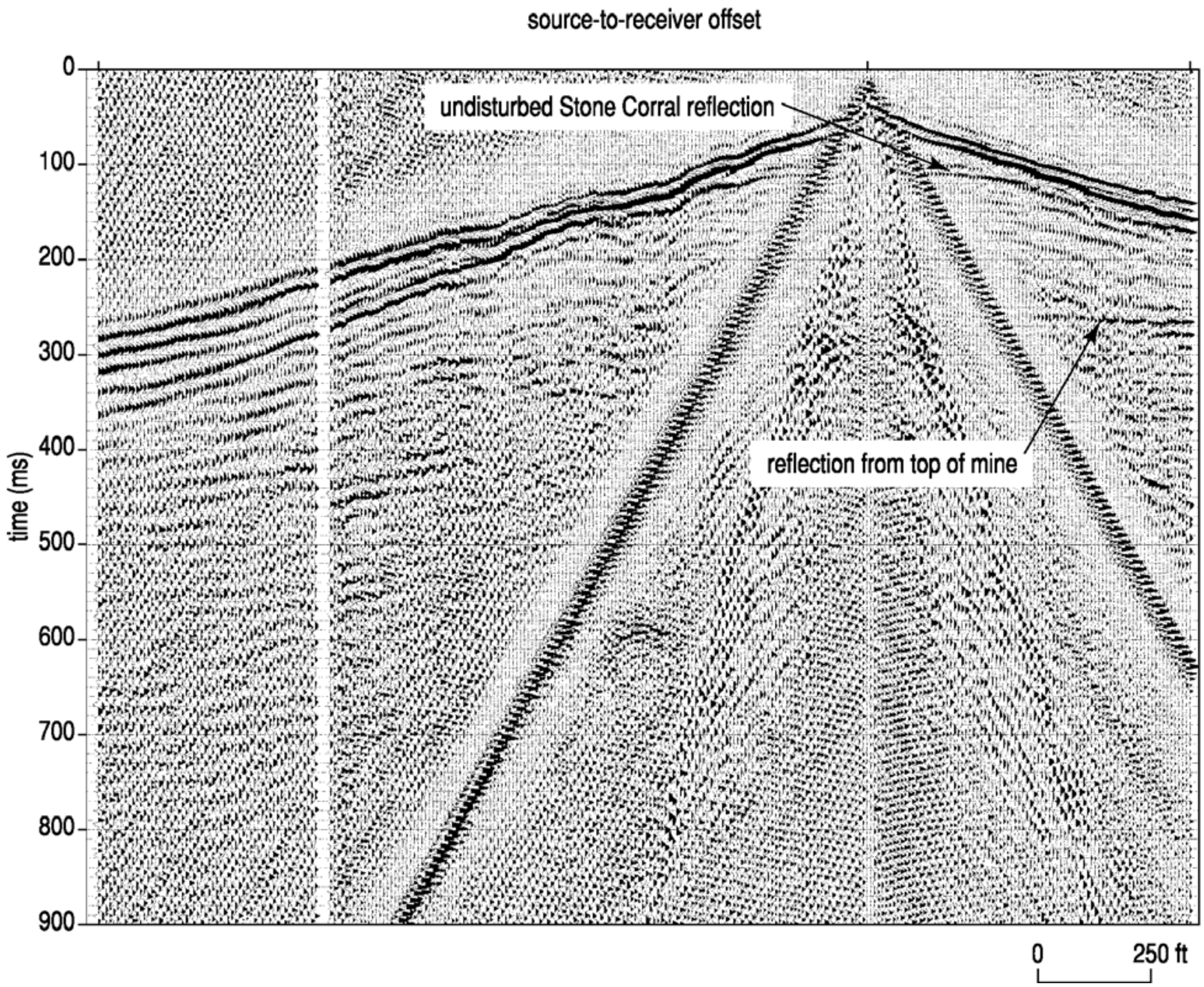


Figure 16. Reflections from the Stone Corral and top of mine are high quality and readily interpreted on these shot gathers. The irregularities observed in the arrival times are not characteristic of simple surface erosion and associated topography.

are markedly different (Figures 15 and 17). Associated with this extremely high amplitude reflection from the salt/mine interface is a noticeable change in reflection wavelet character below where the salt mine is present versus where it is not. This difference is related to the distribution of seismic energy transmitted/absorbed/reflected where the mine is present versus where it is not.

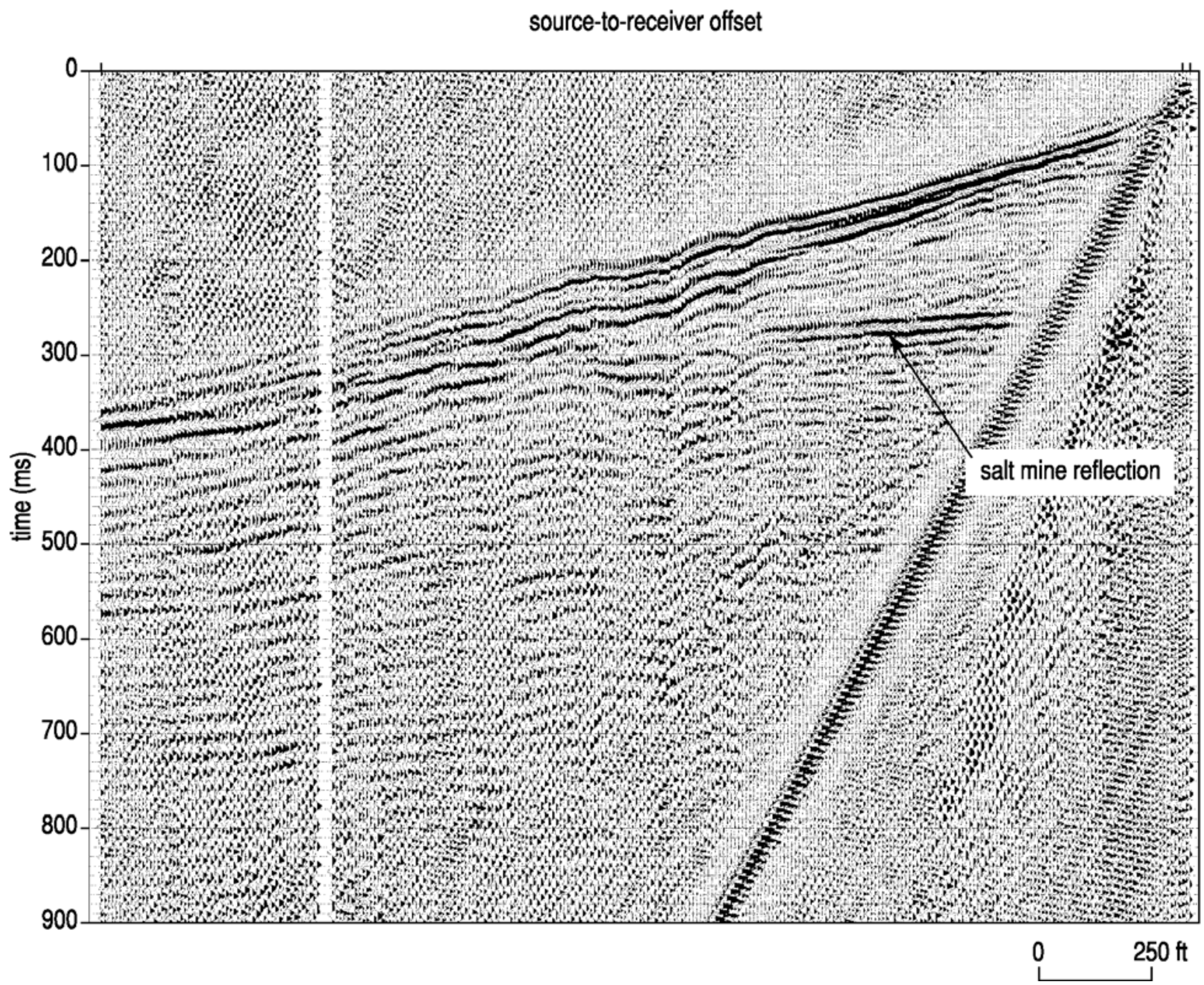


Figure 17. Reflections from top of mine pronounced due to extremely high reflectivity of contact between intact roof salt and air in mine. Note, over edge of mine refractions are disturbed (refractions are from the bedrock surface).

NOTE: Low-fold and/or no-data zones related to water-filled surface features have been clearly marked on stacked sections. These zones lack sufficient data quality and/or redundancy to provide meaningful interpretations. The zones have been defined based on the experience of the author. A more conservative or liberal designation of this line of confidence can be made based on a reader's individual and different set of experiences.

Line A

Data quality was good on line A with interpretable reflections from the Stone Corral and within the salt interval across many portions of the profile (Figure 18). This half-mile-long line was acquired when the north/south drainage ditch was full of water. The portion of the wheat field within 100 ft of the ditch was also under up to a foot of standing water. This standing water resulted in a reduction in receiver and source stations that could be occupied and therefore the data drops observed near the center of this and other profiles acquired after the heavy nightly rains. As a result of this source and receiver exclusion zone no interpretations should be made from seismic energy on CMP stacked sections of line A between stations 1105 and 1165.

Complete subsurface coverage with seismic reflection depends on recording a full range of offsets at each receiver location. When all receiver stations have active sensors and source stations have been occupied, the CMP stacked traces have the full complement of traces and therefore full depth coverage and nominal fold. Near the edges of the stacked section the fold (or number of individual traces summed to form the CMP trace) is lower (due to shooting onto and off of the line) and only close source-to-receiver offsets are included in the CMP stacked traces at the very end of the profile. These lower-fold (less redundancy in sampling) traces near the end (< 20 to 30 ft) of the sections cannot be interpreted with high confidence. Therefore, those low-fold traces were deleted from the stacked sections presented in this report. Traces near the middle of lines A, B, and C are shaded and defined as low-fold and/or no-data and cannot be used with confidence in interpretations.

This migrated section possesses several very distinctive reflection events and obvious character changes from one end of the section to the other (Figure 18). Dominant frequency is a measure of resolution potential. Vertical resolution potential is commonly defined as one-quarter the dominant wavelength (velocity divided by dominant frequency). On these stacked data 100 Hz reflection wavelets are common in structurally competent portions of the sections.

The migrated interpreted stacked section for line A presents a very complex subsurface (Figure 19). All interpreted stacked sections in this report are color coded to indicate the associated reflector and apparent condition of the reflector interpreted from the reflection event on the CMP stacked section.

Clear distortion in the Stone Corral reflection has been interpreted as related to subsidence and associated velocity distortion (Figure 19). No receivers were live in the drainage ditch, so there is about a 500 ft wide portion of the profile where no shallow reflections were recorded. A feature between station 1160 and about station 1210 has several key characteristics that make it a possible bridged void with failure potential. From station 1220 to the northeast end of the profile the Stone Corral reflection possesses the classic characteristic for which this seismic marker bed is regionally known.

The salt interval along this line appears to have the full gamut of interpretable conditions present (Figure 19). The mine reflection is distinct and quite distinguishable from the reflection packet indicative of native, competent salt. From station 1250 to the northeast end of the profile the salt appears intact with a strong and coherent intersalt reflection.

Figure 18. Nominal 60-fold CMP stacked section of Line A with surface topography and approximate extent of the mine workings represented by the gray bar along the top of the figure.

Figure 19. CMP stacked section of Line A with key intervals and interfaces interpreted. Low-fold or no-data zone is the direct result of no surface coverage due to high-water conditions. The gray bar along the top of the figure represents the approximate extent of the mine workings.

Further investigation is necessary between stations 1170 and 1210 on line A. All the characteristics of the reflection data between the Stone Corral reflection and the reflection from the base of the salt are consistent with a breccia-filled pipe (this statement is consistent with upcoming discussion of line D). The set of flat high-amplitude reflections between 100 and 150 ms is indicative of a large reflectivity boundary, much like that observed at the salt/mine contact. This kind of a contact will be susceptible to the kind of ringing (wavelet reverberation) observed in the reflection wavelet due to narrow bandwidth characteristics. This, of course, is not the only interpretation for the observed reflection character but it does align with the setting and seismic data from the other lines.

The apex of a diffraction event is directly beneath the high amplitude set of reflections between stations 1170 and 1210. This occurrence is suggestive of some kind of seismic anomaly or break in otherwise continuous, undisturbed native material. These and other observations are not necessarily conclusive on their own, but the collective supports the suggestion that further investigation of this feature is warranted.

Line B

Seismic reflections evident on the line B stacked section are of very good quality based on the experience of the author and can, for the most part, be interpreted with confidence (Figure 20). Data were acquired along line B following two days of rain that left as much as 4 ft of standing water in topographically low areas. Line B crosses both the well-defined closed surface topographic low and the north/south drainage ditch where neither source nor receiver could occupy. This large drop in receiver and source coverage resulted in the low fold or no data area evident in the center of the section. No interpretations should be made based on energy that has stacked between stations 2110 and 2205.

Across most of the profile the Stone Corral reflection is high-amplitude and high-frequency with excellent coherency. The reflection interpreted to be from within the salt interval changes character from the northwest to the southeast ends of this profile. On the northwest end of the profile it is higher-amplitude but relatively lower-frequency in comparison to the reflection on the southeast which, besides being high-amplitude and higher-frequency, it is also much more coherent.

Color interpretations of the stacked section provide a glimpse at what this structurally complex subsurface might look like (Figure 21). Immediately obvious is the synform structure on the Stone Corral reflection between station 2060 to at least station 2100. Again as on line A, this feature has a bowl shape with bounding faults on the northwest that, as interpreted, are representative of a compressional stress regime and indicative of mature subsidence. The disturbance evident in the rock column has resulted in attenuation of some of the reflection bandwidth and is likely why the reflection from the top of salt beneath this feature has a lower frequency and narrower bandwidth appearance than where undisturbed rocks overlay mined areas. Scattered seismic energy and a lack of coherency in reflections from within the Ninnescah Shale are evident within this portion of the section as well.

The southeast end of line B is seismically well behaved, with a very pronounced reflection interpreted as the top of the salt mine and another relatively undisturbed reflection with characteristics of the Stone Corral (Figure 21). There are a few reflection abnormalities within the Ninnescah Shale. A synform extending from the Stone Corral well down into the Ninnescah Shale interval is interpretable between station 2220 and the southeast side of the low-fold or no-data zone (2210). There are notable similarities between the character of this synform and the

Figure 20. Nominal 60-fold CMP stacked section of Line B with surface topography and approximate extent of the mine workings represented by the gray bar along the top of the figure.

Figure 21. CMP stacked section of Line B with key intervals and interfaces interpreted. Low-fold or no-data zone is the direct result of no surface coverage due to high-water conditions. The gray bar along the top of the figure represents the approximate extent of the mine workings.

one interpreted between station 2060 and the northwest side of the low-fold or no-data zone (2110). Without close offsets through the closed topographic low and drainage ditch it is not possible to confidently correlate these two features.

The mine reflection at around 250 ms two-way traveltime undergoes an abrupt transition beneath station 2220. This change could be suggestive of a progression from competent roof rock to slumping or collapsing roof rock or parting of layers within the salt interval above the mine. This seismic section appears to have captured three different states of the mine and surrounding salt. The effects of the low-fold or no-data zone have been captured within the box identified on each seismic section and consideration outside the defined box for these non-interpreted zones during interpretation is not necessary.

Diffractions are interpreted beneath station 2090 within the Ninnescah Shale on line B. As previously pointed out, these diffractions are indicative of point sources capable of reradiating seismic energy (bed terminations, rubble zones, fractures, faults, etc.). It is generally rare to find large scatter groupings like the ones observed beneath station 2090 associated with paleosubsidence features. Paleosubsidence features that have been seismically studied in central Kansas all consistently lack scatter groupings and distinctive diffraction hyperbolae. However, paleosubsidence features that are or recently have undergone reactivated dissolution and subsidence do possess the more characteristic scatter events.

Line C

Data quality on Line C is good relative to the data set as a whole, with locations along the profile where reflection signal is excellent (Figure 22). The dominant frequency at the Stone Corral is around 110 Hz to120 Hz while at the mine depth the dominant reflection frequency is about 70 Hz. Dominant reflection frequencies from within the salt interval where no mine reflection is observed are closer to 90 Hz. Inter-Permian or Ninnescah Shale reflections are quite pronounced on this profile and possess excellent continuity. Northeast of the sinkhole there is a clear transition in reflection character through the thick shale interval at around 300 to 750 ft below ground surface. Reflections returning from depths greater than 1000 ft have a distinctly different character on the northeast end compared to those on the southwest end.

Reflections from the southwest end of line C appear to have good coherency and uniformity in wavelet properties from the start of the profile to about station 3050 (Figure 23). Below station 3050 and continuing to station 3060 there is an obvious change in the reflection signature around 1000 ft below ground surface. This change is too far from the low fold or no data area to be related to coverage issues.

Since line C crossed the surface depression after the rains that resulted in several feet of standing water in topographic lows, there was a span of the profile that neither source nor receivers could occupy, resulting in signal drops. No confident interpretations can be made between stations 3090 and 3150. Longer-offset reflections are coherent and can be interpreted with caution at depths greater than 750 ft beneath this low-fold or no-data area. Beneath the low-fold or no-data area and depression in the center of the profile is a reflection from the mine depth with a different character than observed in other locations. It must be kept in mind that the adverse effect on data resulting from a loss in surface coverage decreases with depth (common technique called undershooting).

The northeastern end of Line C possesses a multitude of features and anomalies that appear consistent with paleodissolution and subsidence as interpreted on other seismic profiles from this area (Figure 23). The Stone Corral reflection appears to have subtle and, to some degree, uniform (both from a structural and trace-to-trace wavelet character perspective)

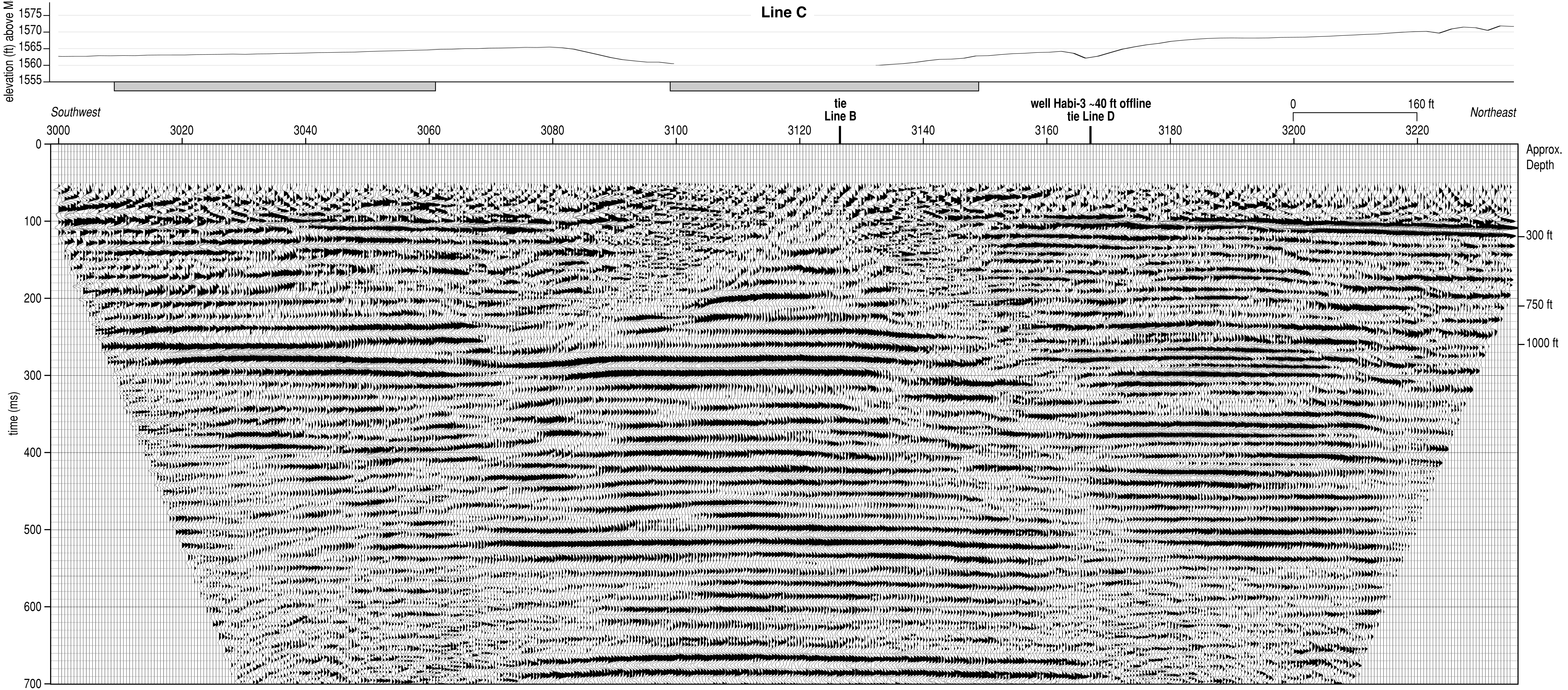


Figure 22. Nominal 60-fold CMP stacked section of Line C with surface topography and approximate extent of the mine workings represented by the gray bar along the top of the figure.

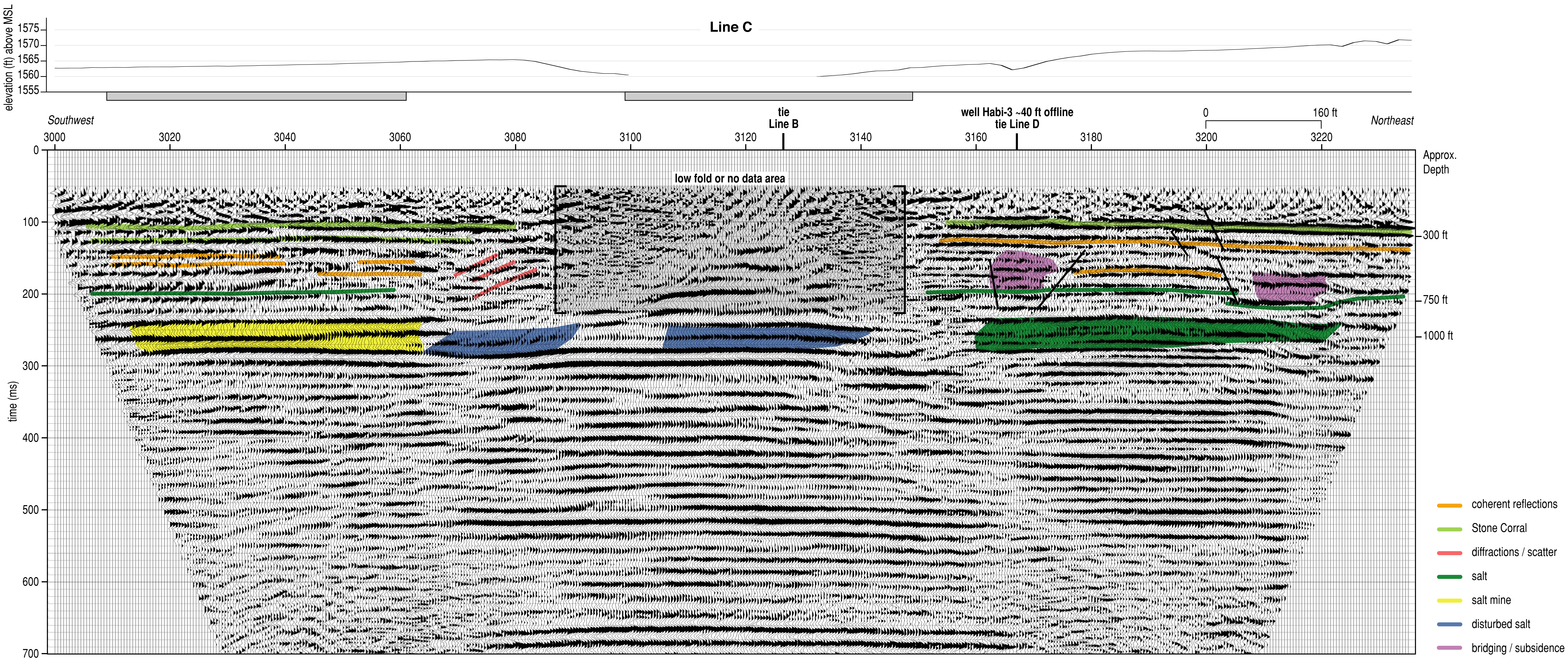


Figure 23. CMP stacked section of Line C with key intervals and interfaces interpreted. Low-fold or no-data zone is the direct result of no surface coverage due to high-water conditions. The gray bar along the top of the figure represents the approximate extent of the mine workings.

variations in depth across the northeast end of the profile. Reflections within the Ninnescah Shale between stations 3180 and 3200 appear native and unaltered. Northeast of 3200 the bowl or synclinal-like structure evident within the Ninnescah Shale can be traced to the Stone Corral. The vertical displacement of the bedding at approximately 300 ft is less than 5 ft and is consistent with the observed depression near the top of salt. Low-fold portions of the section at the ends of each profile have been muted so only interpretable data remains.

A series of diffractions can be seen beneath station 3080 that are outside the low confidence zone marked as low fold or no data area. These point source scatter events are real and are indicative of faults, fractures, rubble zones, bed truncations, etc. These have geologic meaning at this location and need more ground truth to determine their origin.

After careful analysis of line C near the old Habiger gas well, reflection geometries and seismic interference patterns don't appear indicative of classic single point source dissolution in the salt and associated void migration as has been observed on seismic sections at several confirmed borehole-induced dissolution/subsidence sites in central Kansas (Miller and Millahn, 2006) (Figure 24). There are clear indications on the seismic sections that layers between the Stone Corral and salt interval at the Habiger well location are disturbed. There appears to be a minor amount of dissolution on the top of salt within 100 ft of where the well would have penetrated the salt and a gentle collapse structure centered on the well as defined by offset reflections on the northeast side of the feature. This collapse structure extends upward through the Permian shales, terminating just below the Stone Corral.

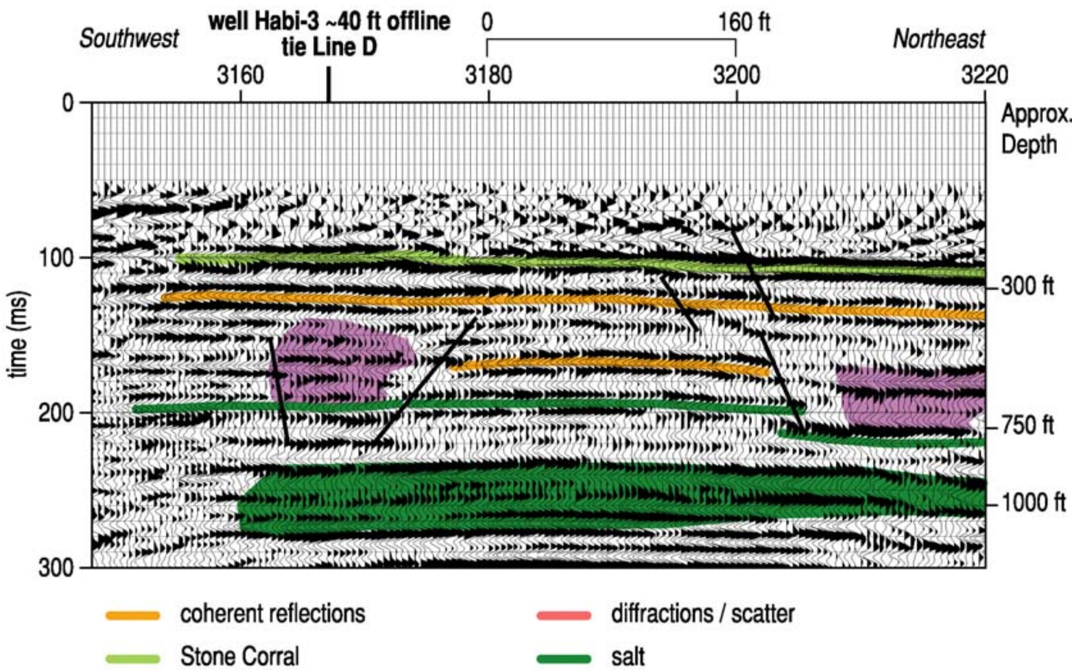


Figure 24. Selected portion of the interpreted CMP stacked section from line C. Changes in wavelet character and arrival time at the top of sale and a hundred or so feet into the sale interval are consistent with salt dissolution.

Line D

From the onset of this project, line D was identified as the highest priority line (Figure 25). Line D has good quality reflections on shot gathers, but due to an extremely complex sequence of structures, many of the features and anomalies along/beneath this profile change dramatically within sub-spread lengths, thereby making static and velocity corrections problematic. However, through aggressive muting and stringent quality requirements for retaining traces, the stacked section is interpretable and possesses some very useful clues as to the current subsurface condition.

Reflections interpreted along line D change in character from one end of the profile to the other (Figure 26). From the beginning of line D to around station 4040 the Stone Corral seems reasonably native in appearance. The reflection from within the salt interval from station 4000 to station 4040 is consistent with previous interpretations of unaltered salt. However, around station 4040 the interval from the Stone Corral to the top of salt appears altered. As was observed on line C, there is a coherent and unaltered reflection within the Ninnescah Shale interval from about station 4040 to station 4070. This occurrence clearly indicates complexity and non-linearity in the interplay between the various layers. The salt reflection appears altered from near station 4070 to station 4200.

From station 4220 to the southeast end of the profile the reflection packet between the base of the salt interval to the top of the Stone Corral appear relative undisturbed with a character consistent with expectation for an area with no or minimal subsidence. The Stone Corral reflection in this area is not as well defined and coherent as observed on other profiles, but it is clearly much better behaved than the reflections from the same interval in the middle of line D.

Near the intersection of lines D and A there is a set of diffractions and a similar high-amplitude set of reflections near the base of the Stone Corral reflection (Figure 26). This combination of diffractions and high amplitude reflections correlates very well between the two profiles. A diffraction between stations 4200 and 4220 seems to suggest some kind of fracturing or faulting in this area. A second diffraction with an apex that appears to be in the salt interval is beneath pointer 2 on the interpreted version of line D.

Line D includes the most pronounced set of diffractions seen on any of the profiles. The apex of this massive diffraction sequence is around station 4150 (pointer 1, Figure 26). From the range of slopes observed on the various diffraction events, some of these are from outside the 2-D plane represented by the CMP stacked section of line D. Comparing surface topography with the diffraction apex, there is no indication of subsidence at the ground surface beneath the synclinal reflector at around 80 ms (corrected two-way time-depth). The major diffraction set beneath pointer 1 could be a “bow tie” curve associated with a distorted reflection focus due to an extreme synform radius of curvature (Figure 27).

A secondary set of diffractions centered on pointer 2 is also consistent with several bowl-shaped or synclinal structures, likely indicative of subsidence on the Stone Corral. From these two subsurface subsidence features it appears the channel structure obvious at the ground surface (topography map on top of line D between stations 4150 and 4180) could be the result of subsidence, with continued enlargement to the northwest likely. Considering the size of this feature in the subsurface, there is a strong likelihood that at some point the channel between stations 4150 and 4180 will join the north/south drainage ditch located between about 4120 and 4125 on line D.

The combination of pronounced diffraction patterns and a disturbed salt interval is likely indicative of active subsidence/leaching. Elevated noise from diffraction tails and lateral

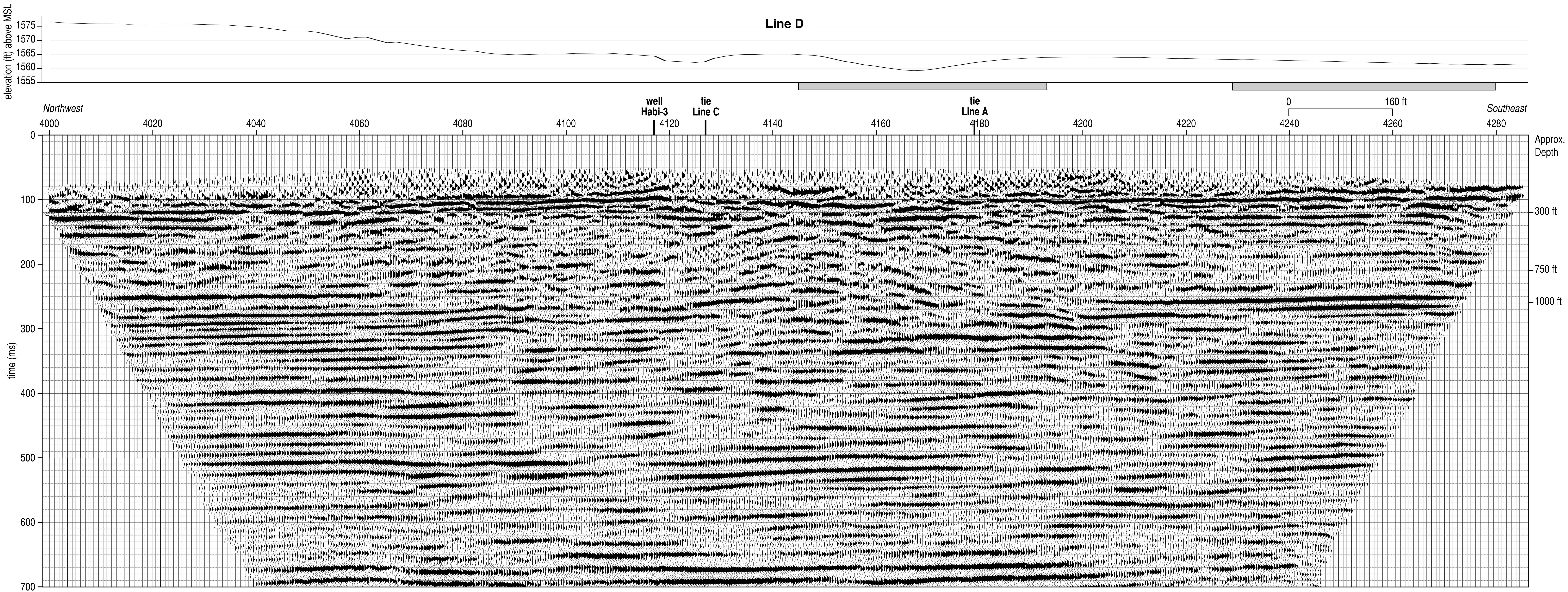


Figure 25. Nominal 60-fold CMP stacked section of Line D with surface topography and approximate extent of the mine workings represented by the gray bar along the top of the figure.

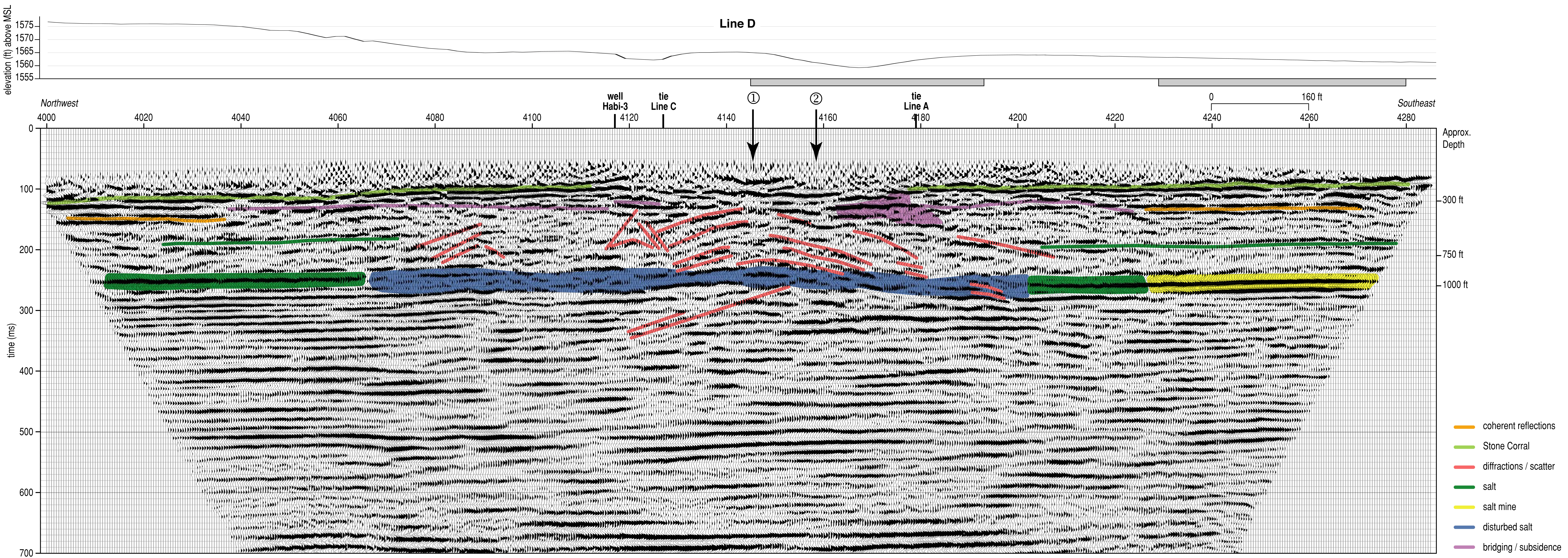


Figure 26. CMP stacked section of Line D with key intervals and interfaces interpreted. Low-fold or no-data zone is the direct result of no surface coverage due to high-water conditions. The gray bar along the top of the figure represents the approximate extent of the mine workings.

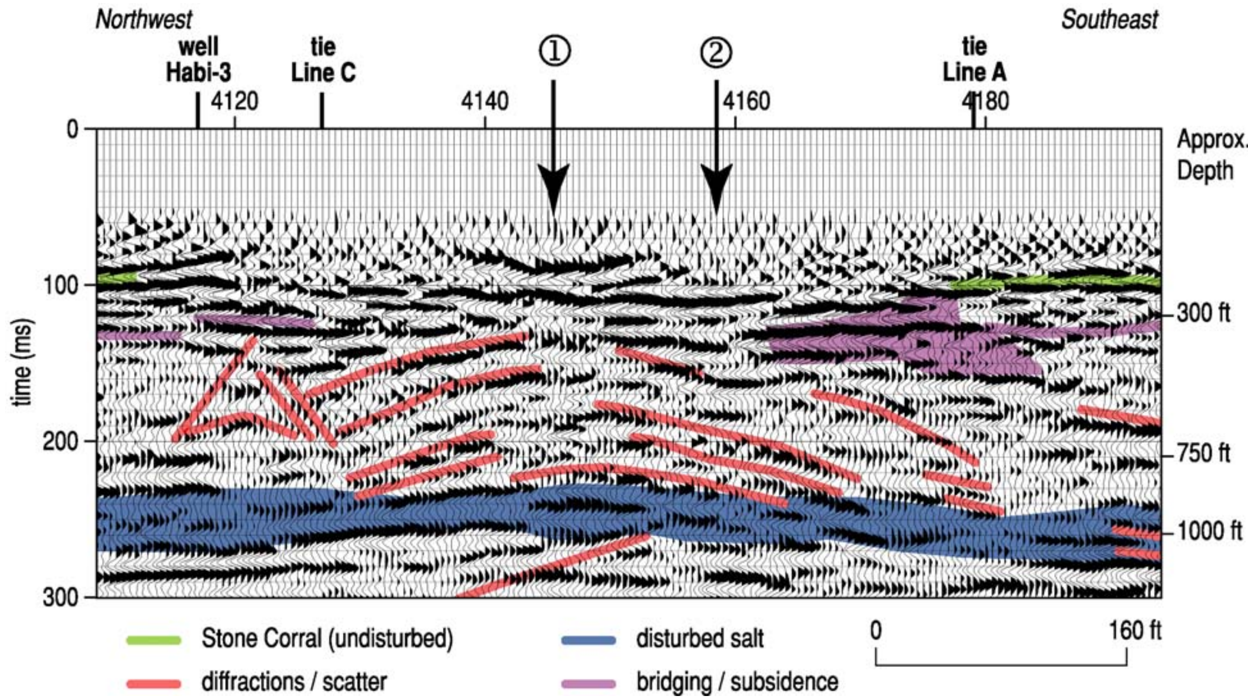


Figure 27. High density of diffractions on line D, with pronounced structures consistent with subsidence.

resolution limits inhibits interpretation of specific or isolated zones where the salt has been leached beneath the sequence of diffractions. Salt beneath this sequence of diffractions is being or has been leached and the diffraction sequence clearly represents the subsidence pipe where void space migrating to the surface is likely filled with collapse breccia.

Considering the importance of the Stone Corral and any anomalies that might be present within the Ninnescah Shale, a portion of these data were reprocessed specifically focusing on the very tight synclinal structures, bridging and high amplitude reflections, and diffractions in the shallow portion of the section (Figure 28). The vertical scale on this section has been expanded, but the spatial scale is the same as previous stacked sections.

Several key areas are highlighted and warrant discussion (Figure 28). Near the intersection of line A (at pointer 3) is a synform with what appears to be a flat reflection overlying it. This kind of feature/combination has proven to be characteristic of bridging as observed on other seismic investigations in this part of Kansas (Figure 8). In the area around pointer 3 there are several sets of diffractions and quite dramatic changes in wavelet character. Probably the most significant and clustered set of diffractions is obvious beneath pointer 4. There are only two possible explanations for these diffractions: first, when synforms have extremely small radius relative to seismic wavelengths, spatial sampling, and depth, diffraction-like events will result (bow-tie features), or second, a significant cluster of fractures or a fault zone will produce diffractions of this type. Either interpretation suggests an active rock mass.

One key objective of this reflection program was to determine if Habiger 3 was in any way contributing to the dissolution of the salt, instability of the overburden, or hydrogeology of the site (Figure 28). After careful analysis of line D in proximity to the old Habiger gas well, reflection geometries and seismic interference patterns don't appear indicative of classic single point source dissolution in the salt and associated void migration as has been observed on seismic sections at several confirmed borehole-induced dissolution/subsidence sites around

Figure 28. CMP stack of Line D processed to enhance near-surface reflections and diffraction scatter. Apex of diffractions pinpoint point scatters. The gray bar along the top of the figure represents the approximate extent of the mine workings.

Kansas (Miller and Millahn, 2006). There are clear indications on the seismic sections that layers between the Stone Corral and base of the salt interval at the Habiger well location are disturbed and have undergone subsidence. Therefore, dissolution at the top of salt beneath the Habiger wellhead is evident and that dissolution is likely responsible for the observed depression in overlying reflections. Normal faults interpreted to bound the dissolution zone at the top of salt and extending into the overlying Permian shales are indicative of a mature structure.

Isochron Maps

Isochron maps were produced for the Stone Corral and top of Hutchinson Salt. The two-way traveltimes on CMP stacked sections were adjusted for the 20 ms of bulk static applied after correlation based on the cross-correlation of the ground-force pilot with the synthetic sweep. The times plotted are two-way traveltimes with time-to-depth conversions possible using the NMO velocities calculated from the constant velocity stack analyses. Considering the accuracy of the NMO velocity estimates were ±500 ft/sec, time contours provide a realistic representation of the surface at an accuracy of ±20 ft for the salt and ±12 ft for the Stone Corral.

The Stone Corral isochron has good correlation between lines with the general trend on the surface in a north/south direction (Figure 29). The Stone Corral possesses a regional dip of around 2° per mile; clearly the structural texture of the Stone Corral as indicated by these contours is quite variable and anomalous to that 2° average. The velocity changes quite significantly across the site and therefore so does the depth for a given time contour. A well-defined trough intersects both lines D and B. Very little topography is evident on the surface of the Stone Corral across the southern one-third of the survey area. Areas with significant time structure are indicative of areas with highly altered rock columns.

The top of salt is much more difficult to identify due to a highly irregular and diffuse surface (Figure 30). Across the northeastern quarter and southern third of the survey area the top of salt was interpretable with sufficient confidence to allow time picks and contours to be made. The southern one third of the survey area has a very well behaved and uniform top of salt reflection. A low is evident in the northeastern portion of the study area. Across most of the northwestern quarter of the site the top of salt is too diffuse and unorganized to make confident picks. Areas with a diffuse top-of-salt are strong candidates for locations where leaching has been or is active.

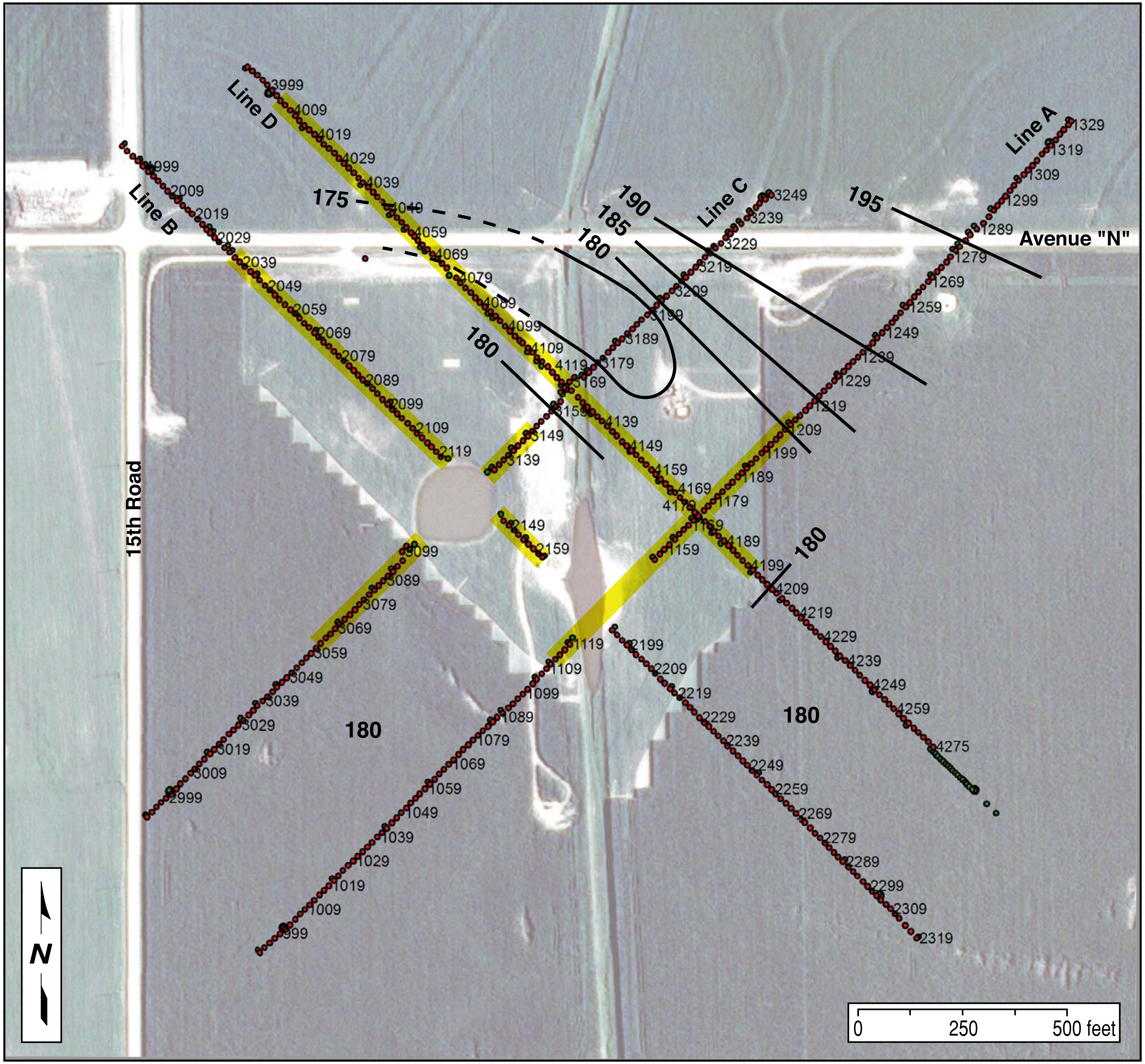
Conclusions

Rocks above the Hutchinson Salt in the study area show evidence of subsidence. Apparent subsidence structures can be interpreted within the upper 1000 ft across a large portion of the study area at locations where no associated surface topographic depressions have been observed or measured. In areas where historical/ancient subsurface subsidence has been in play come dramatic reductions in overburden strength. It is, therefore, no surprise that, based on these seismic data, current subsidence is generally interpreted as various rock mass groupings moving as volumes of collapse breccia, gradually and irregularly migrating vertically toward the surface.

Areas with active subsidence and associated voids are correlated to diffractions, scatter, and apparent bridging above draping or bowl-like structures. From these data it is possible to identify zones of reduced strength, less bulk density, and greater localized permeability.

Stone Corral Isochron
two-way traveltime (ms),
corrected for 20 ms
bulk static

Figure 29. Stone Corral isochron with two clear trends. A north/south trending low and a high near the center of the survey area. These contours are on 5 ms intervals equal to approximately 12 to 15 ft.



Top of Salt Isochron
two-way traveltime (ms), corrected for 20 ms bulk static

top of salt reflection highly altered with no confident pick possible +/- 10 ms accuracy

Figure 30. Top of salt isochron. The 5 ms time contours correlate to about 20 ft invervals.

Near the tie between lines A and D is an area identified as having an elevated stability concern. Seismic reflection, like all geophysical techniques is nonunique, meaning there is always more than one interpretation for any data set. This feature is interpreted to be more than 100 ft in diameter, centered on about station 1180 of line A, and could include a volume that extends several hundred feet vertically below a set of high amplitude reflections. From a surface stability perspective, there are two other areas identified by pointers 4 and 6 on line D that also warrant concern (Figure 28).

The focus of future subsidence appears likely to be in proximity to areas with observed existing irregular surface topography. The greatest likelihood for future surface subsidence is generally within a couple hundred feet of the box defined by the intersection of lines A and D, A and B, C and B, and D and C. Diffractions and synforms within the near-surface rocks strongly suggest the current channel in the tilled field that is evident on the ground surface crossing line D at around station 4170 and generally trending northeast will continue to expand, migrating to the northwest. Eventually the channel will connect with/intersect the north-south drainage ditch that crosses lines D and C at their intersection and runs from the road south into the middle of the quarter section. Diffractions located beneath station 4145 on line D are indicative of very short radius synclinal structures (bow tie) or bed termination points. With no ground depression at this location at the time of the survey, this general area needs an invasive investigation and will eventually experience subsidence. Assuming a 15° angle of draw, current dissolution will affect the ground surface in an area immediately north of the east/west road to just east of the north/south road.

There is no evidence of structures or seismic interference patterns on any of the profiles that would unequivocally be considered solely the consequence of localized dissolution and subsidence associated with a well or boreholes. Within a volume of earth approximately centered on the Habiger well, rock layers within the Upper Permian shales are locally disturbed, the top of salt appears to possess a synform-type depression consistent with dissolution, and this altered volume is bound by normal faults. There is no strong indication that the Stone Corral has experienced seismically detectable subsidence directly beneath the Habiger well. Leaching of the salt and subsidence of overlying Permian rocks below the Stone Corral are evident beneath the Habiger well site on the seismic section.

The principal goals of this study were to delineate rock layers within and above the Hutchinson Salt Member, identify potential dissolution zones that may represent hydrologic pathways supplying the fresh water necessary to perpetuate leaching, and attempt to appraise the overall stability and current state of the rock column. The state-of-the-art shallow high-resolution seismic reflection techniques used on this study allow a glimpse at the locally complex structures associated with dissolution of the salt, the current state of structural failure in overlying sediments, and a baseline for estimating rate of change with follow-up surveys.

High-resolution seismic reflection would be an invaluable tool for time-lapse studies of subsidence structures, pre-mining salt interval appraisals (mine planning), and identification of anomalies within the salt interval inconsistent with uniform ore deposits in this area. Complications and complexities observed in these data are very localized and constrained to this dissolution and subsidence area of the mine site. Imaging over undisturbed portions of the salt would provide outstanding data and high quality geologic and material interpretations and appraisals.

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APPENDIX
Glossary of Key Dissolution, Subsidence, and Seismic Reflection Terminology

AGC (automatic gain control)—Changing the output amplitude so that at least one sample is at full scale deflection within a selected moving window (moving in time).

Allochthonous salt—Sheetlike salt bodies emplaced at stratigraphic levels above the *autochthonous* source layer. Allochthonous salt lies on stratigraphically younger strata.

Alluvial—Relating to, composed of, or found in the clay, silt, sand, gravel, or similar detritus material deposited by running water.

Angle of draw—Angle of inclination from the vertical of a line.

Anhydrite—A mineral, anhydrous calcium sulfate (chemical formula $CaSO_4$), occurring naturally in salt deposits. Anhydrite is much less soluble than salt, so anhydrite solids must be removed from brine before the brine can be disposed of in the ocean or injected into underground wells.

Aquifer—A body of rock or soil that is capable of transmitting ground water and yielding usable quantities of water to wells or springs. A permeable region of rock or soil through which ground water can move.

Autochthonous salt—Salt body resting on the original strata or surface on which it accumulated by evaporation.

Borehole—A hole made by drilling into the ground to study stratification, to release underground pressures, or to construct a production well, a disposal well, or a storage cavern in salt rock.

Breakdown debris—Blocks of rock fallen from the walls or roof of a cave or void.

Breccia pipe—Column of breakdown debris above a collapsed cave chamber.

Brine—Water with a salt concentration greater than 35 parts per thousand. Sea water has a similar average concentration. In comparison, discharged brine has a typical concentration of 263 parts per thousand.

Brittle—Structural behavior in which a material deforms permanently by fracturing.

Brittle limit—The stress limit beyond which a material fractures, rather than behaving in a ductile or elastic fashion.

Bulk modulus (elastic constants)—Elasticity deals with deformations that vanish entirely upon removal of the stresses that cause them. For small deformations, Hooke's law holds and strain is proportional to stress.

Caprock—A comparatively impervious stratum immediately overlying an oil- or gas-bearing rock.

Caprock sinkhole—Sinkhole in insoluble rock formed by collapse into underlying cavernous rock.

Casing—Steel pipe used in oil wells to seal off fluids from the borehole and to prevent the walls of the hole from sloughing off or caving. There may be several strings of casing in a well, one inside the other.

Cavern—An underground chamber or cavity created in a salt dome by solution mining and used for storing petroleum.

Check shot survey—direct measurement of traveltime between the surface and a given depth. Usually sources on the surface are recorded by a downhole geophone to determine the time-to-depth relationships at a specified location down a well.

Coded source—A seismic energy-producing device that delivers energy throughout a given time in a predetermined or predicted fashion.

Collapse breccia—Various size and shapes of debris that has broken loose from the roof or walls of a void or cave, collecting to forms a pile within a void or cave with differential compaction and material type contributing to the bulking factor of the pile.

Collapse chamber—Cave chamber modified by wall and roof collapse.

Collapse sinkhole—Sinkhole formed by collapse of rock into a cave passage or chamber.

Common mid-point (CMP) or common depth point (CDP) method—A recording-processing method where each source is recorded at a number of geophone locations and each geophone location is used to record from a number of source locations. After corrections these data traces are combined (stacked) to provide a common-midpoint section approximating a coincident source and receiver at each location. The objective is to attenuate random effects and events whose dependence on offset is different from that of primary reflections.

Compaction—Reduction of pore space between individual particles as the result of overlying sediments or of tectonic movements.

Compression—Squeezing a material from opposite directions.

Compressional wave velocity—Also known as *P*-wave velocity. In seismic usage, velocity refers to the propagation rate of a seismic wave without implying any direction, i.e., velocity is a property of the medium. Particle displacement of a compressional wave is in the direction of propagation.

Creep—The time-dependent deformation of materials. The very slow, generally continuous movement of material under the influence of gravity or pressure. In engineering usage, creep is any general, slow displacement under load.

Density—Mass per unit volume. Commonly measured in g/cm^3 or kg/m^3, often without the units being expressed explicitly. Bulk rock densities vary mainly because of porosity and are generally in the range of 1.9–2.8 g/cm^3.

Differential loading—Creation of lateral pressure gradients on salt caused by lateral variations in thickness, density, or strength of the overburden. Such variations may be sedimentary (for example, fans, deltas, or lobes) or structural (for example, thinning by rifting or thickening in growth-fault hanging walls).

Dissolution front—Area of active salt leaching where unsaturated brines harvest salt, pregnant brines transport that salt away from the salt face, with unsaturated brines refreshing fluids at the salt face. Fluids necessary to form a dissolution front can be from either natural or anthropogenic sources.

Dissolution sinkhole—Same as solution sinkhole or doline.

Doline—Closed depression in karst, often known as a sinkhole. The most representative landform of the karst surface. The name derives from the word *dolina*, a Slav term indicating any depression in the topographical surface.

Ductile—Structural behavior in which a material deforms permanently without fracturing.

Elastic—Non-permanent structural deformation during which the amount of deformation (strain) is proportional to the stress.

Evaporite—A mineral or rock deposited directly from a solution (commonly seawater) during evaporation. For example, gypsum and halite are evaporite minerals.

Fault—The surface of rock rupture along which there has been differential movement of the rock on either side.

Filter—A process or component of a system that discriminates according to specific criteria. FK filter removes portions of the recorded energy based on apparent slop in the frequency and wavenumber domain. Frequency filter (band pass) removes frequency bands outside a specified range.

Fold (or redundancy)—The multiplicity of common-midpoint data or the number of midpoints per bin. Where the midpoint is the same for 12 source/receiver pairs, the stack is referred to as "12-fold" or 1200 percent.

Foot wall block—The body of rock that lies below an inclined fault plane.

G-force—Measure of acceleration relative to the gravitational force of the earth.

Gather—A side-by-side collection/display/grouping of seismic traces that have some acquisition parameter or characteristics in common. Shot gather, receiver gather, common offset gather, common midpoint gather, etc.

Halokinetic—Form of salt tectonics where salt flow is powered entirely by gravity—that is, a total lack of lateral tectonic forces.

Hanging wall block—The body of rock that lies above an inclined fault plane. Compare foot wall block.

Head (hydraulic)—The level to which ground water in the zone of saturation will rise.

Karst —A terrain with special landforms and drainage characteristics due to greater solubility of certain rocks in natural waters than is common.

Leaching—The removal of soluble constituents from a rock or soil by moving ground water or hydrothermal fluids.

Normal fault—A dip-slip fault on which the hanging wall block is offset downward relative to the foot wall block. Compare reverse fault.

Normal moveout (NMO)—The difference in reflection-arrival time as a function of shot-to-geophone distance because the geophone is not located at the source point. Usually applied to common-midpoint gathers, it is the additional traveltime required because of offset, assuming that the reflecting bed is not dipping and that raypaths are straight lines. This leads to a hyperbolic shape for a reflection. Because the raypath actually curves as the velocity changes, fitting a hyperbola assumes that the actual velocity distribution is equivalent to a constant NMO velocity, but the NMO velocity changes with the offset. However, the assumption often provides an adequate solution for offsets less than the reflector depth.

Normal moveout velocity (stacking velocity)—Velocity calculated from normal-moveout measurements and a constant-velocity model. Used prior to common-midpoint stacking.

Optimum window—Range of offsets between source and receiver that provide reflections with the best signal-to-noise and resolution potential.

Paleosubsidence—collapse structures that are the result of ancient, natural dissolution of rock with subsidence occurring in response to vertical void migration. Generally, the dissolution and subsidence has occurred pre-Quaternary.

Permeability—Capacity for transmitting a fluid a given distance through an interval of time.

Pipe—Cylindrical or conical mass of clay and sand that fills a solution sinkhole, shaft, or cave.

Poisson's ratio—The ratio of the fractional transverse contraction to the fractional longitudinal extension when a rod is stretched. If density is known, specifying Poisson's ratio is equivalent to specifying the ratio of V_s/V_p, where V_s and V_p are *S*- and *P*-wave velocities. Values ordinarily range from 0.5 (no shear strength, e.g., fluid) to 0, but theoretically they range from 0.5 to –1.0.

Radial fault—A fault belonging to a system that radiates from a point.

Ravelling—Breakdown and disassociation of soil that falls away from the roof and walls of a ground cavity.

Raypath—A line everywhere perpendicular to wavefronts (in isotropic media). A raypath is characterized by its direction at the surface. While seismic energy does not travel only along raypaths, raypaths constitute a useful method of determining arrival time by ray tracing.

Reflection—The energy or wave from a seismic source that has been reflected (returned) from an acoustic-impedance contrast (reflector) or series of contrasts within the earth.

Reflector—A contrast in physical properties (elasticity and/or density) that gives rise to seismic reflection.

Reverse fault—A dip-slip fault on which the hanging wall block is offset upward relative to the foot wall block. Compare normal fault.

Sag—Generally refers to as an enclosed subsidence zone, loosely circular in nature, that forms as a result of bed deformation associated with mine or void collapse. Elongated subsidence zone associated with subsurface collapse or settlement is referred to as a trough.

Salt diapir—A mass of salt that has flowed ductilely and appears to have discordantly pierced or intruded the overburden.

Salt dome—A subsurface geologic structure consisting of a vertical cylinder of salt that may be anywhere from 0.5 to 6 miles (1 to 10 kilometers) across and up to 20,000 feet (6,100 meters) deep. Domes are formed when salt from buried salt pans flows upward due to its buoyancy.

Salt reduction—Mass transfer of salt over time, resulting in an obvious change in salt area in cross section.

Salt sheet—Allochthonous salt whose breadth is several times greater than its maximum thickness.

Salt tectonics—(syn. **halotectonics**) Any tectonic deformation involving salt, or other evaporites, as a substratum or source layer; it includes *halokinesis*.

Seismic sensor—Receivers designed to couple to the earth and record vibrations (e.g., geophones, accelerometers, hydrophones).

Seismic sensor spread—Multiple receivers connected to a single recording channel, generally deployed in an array designed to enhance or attenuate specific energy.

Seismogram—A seismic record or section.

Seismograph-distributed—***Seismograph***–seismic recording instrument. ***Distributed***–grouping of seismographs deployed along the recording lines that individually and simultaneously record and digitize portions of the seismic record that can be gathered as a collective to produce a gather for each individual shot.

Shear modulus (elastic constants)—Elasticity deals with deformations that vanish entirely upon removal of the stresses that cause them. For small deformations, Hooke's law holds and strain is proportional to stress.

Shear strength—The resistance of a body to shear stress.

Shear stress—The stress on an object operating parallel to the slope on which it lies.

Shear wave velocity (S-wave velocity)—Speed of energy traveling with particle motion perpendicular to its direction of propagation. *S*-wave velocity is related to the ratio of shear modulus to density.

Shear zone—A tabular area of rock that has been crushed and broken into fragments by many parallel fractures resulting from shear strain; often becomes a channel for underground fluids and the seat of ore deposition.

Shot gather—A side-by-side display of seismic traces that have a common source location. Also referred to as "field files."

Sinkhole—Depression in ground surface caused by collapse into a cave below. Small closed depression in karst, also known as a doline. A depression in the land surface that results from the collapse or slow settlement of underground voids produced by solution weathering. The rock being dissolved is normally limestone but can also be salt, gypsum, or dolostone.

Slump—Downward and outward rotational movement of earth materials traveling as a unit or series of units.

Solution mining—The process of creating space in rock salt by dissolving the salt with injected water and removing the resultant brine.

Solution sinkhole—Sinkhole formed by dissolutional lowering of the rock surface in and around zones of drainage into a cavernous rock.

Source-to-receiver offset—The distance from the source point to the center of the geophones deployed at a single receiver station.

Source to seismic sensor offset—The distance from the source-point to the center of a geophone group.

Strain—Change in the shape or volume of a body as a result of stress.

Strength—The ability to withstand a stress without permanent deformation.

Stress—The force per unit area acting on any surface within a solid; also, by extension, the external pressure that generates the internal force.

Stoping—Progressive collapse of roof rock that causes a cavern to migrate upwards.

Subrosion—Subsurface solution of salt. Dissolution of subsurface rock salt due to ground water flow.

Subsidence—The geological sinking or downward settling of an area on the earth's surface, resulting in the formation of a depression.

Sump—The space below the bottom end of a well pipe where liquid collects.

Tension—A stress that tends to pull a body apart.

Takeout—A connection point to a multiconductor cable where seismic sensors can be connected. Takeouts are usually physically polarized to reduce the likelihood of making the connection backwards.

Tap test—Gently touching a receiver while monitoring on real-time display, to qualitatively appraise phone response.

Tensional dome—An area within the subsurface defined by the stress field associated with a void or rubble zone with a span of unsupported roof rock. Rupture of rock layers above a void occur along an arch where stress radiating toward the ground surface from support structures (pillars) is the greatest.

Tumor sinkhole—Collapse sinkhole formed by undermining, where no large chamber ever existed.

Turbulent flow—Fluid flow in which the flow lines are confused and mixed. Fluid moves in eddies and swirls.

Twist test—Light rotational pressure applied to each seismic sensor to insure no motion and, therefore, a solid ground coupling point.

Seismogram—A seismic record or section.

Void—Volumes within the earth where some or all-native rock material has been removed, compacted, substituted, rubbled, or displaced. This alteration in native rock conditions results in a disturbed volume of rock that is anomalous to material outside the volume, inconsistent with original sediment deposition and physical properties (such as Poisson's ratio, shear modulus, bulk modulus, and Young's modulus) of the native material, and possesses a bulking factor greater than 1. Dissolution voids can be filled with rubble, air, fluid, or any combination of the three. For example, a water-filled cavity above a void volume that includes a mixture of collapse debris, breakdown blocks, fluids, air, etc., all capped by a stoping roof, can define the migration path of a pre-sinkhole breccia pipe. A void space is not limited to air or fluid composition.

Wavetrain (wavefield)—(1) Spatial perturbations at a given time that result from passage of a wave. (2) All components of seismic energy traveling through the earth as the result of a single impact.

Wiggle trace—A graph of amplitude against time, as on a conventional seismic recording with mirror galvanometers. Also called "squiggle" recording.

Young's modulus—Relates stress and strain for compression.

Sources

Definitions for many of these terms came from http://geology.com/geology-dictionary.shtml.

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