Unique near-surface seismic-reflection characteristics within an abandoned salt-mine well field, Hutchinson, Kansas
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Summary
High-resolution seismic reflections have been used effectively to investigate sinkholes resulting from the dissolution of a bedded salt unit found throughout most of central Kansas. A seismic reflection survey was conducted to investigate the shallow subsurface between a sinkhole that formed catastrophically within a few tens of meters of a main east/west rail line. Data quality was significantly below expectations and not equivalent to other seismic data from this area where acquisition parameters, equipment, and target intervals were similar. Near-surface tomographic and MASW analyses revealed a highly irregular bedrock surface characterized by what appear to be a high concentration of short wavelength dissolution features. These bedrock features are below about 20 m of unconsolidated sediments with physical dimensions several meters deep and several meters wide. Data quality is quite good on other seismic reflection surveys from this general area where these bedrock features are not present. Pronounced static shifts and degradation in spectral characteristics of reflections where these bedrock features are present seems to be isolated to an area suspected to be the crest of a relatively broad anticlinal structure where surface fractures could have provided a conduit for fresh water to access shallow, thin evaporite layers within the thick shale sequence in the upper 200 m. Broadband high-resolution compressional-wave energy suffered significantly from this highly irregular bedrock topography.

Introduction
Concerns for public safety and the threat of property damage from a sinkhole that formed catastrophically within 40 m of a heavily traveled east/west railroad main line prompted a high resolution seismic reflection investigation of the subsurface between the sinkhole and the railroad tracks. Findings of this particular survey were inconclusive and prompted a more in-depth investigation to ascertain the reasons for the diversity in seismic responses observed at these different sites all within east central Reno County, Kansas.

Four seismic data sets, each from different sites in east central Reno County, Kansas, all targeting the upper several hundred meters of earth (including the Hutchinson Salt), were acquired because of the formation or threat of formation of a sinkhole (Figure 1). Of these four seismic data sets, two (1 and 2) are from investigations of collapse structures associated with brine wells for salt mining, one (3) is a reconnaissance survey in an area with no sinkholes—but at high risk of future subsidence, and a fourth (4) is in an oil field where a brine disposal well was suspected of containment failure, dissolution, and collapse. These four profiles were acquired with different equipment and using different techniques, but all are less than 10 km apart. One survey used vibroseis, two were impulsive using a 50-cal projectile source, and the fourth was impulsive employing an 8-gauge auger gun downhole source. Acquisition occurred over a 15-year period between 1990 and 2005.

Evidence exists throughout eastern Reno County for paleosinkholes not visible at the ground surface, which is an indication that fresh water has had access to the salt and a pathway to carry salt away from the dissolution front. Several naturally forming sinkholes in this area have seen recent reactivation and formation of surface depressions. No evidence existed prior to this seismic survey for karst type bedrock topography in this area that is a direct result of evaporite dissolution from rock layers other than the Hutchinson Salt.

Geologic Setting
Several major salt basins exist throughout North America. The Permian Hutchinson Salt Member occurs in a large portion of the Great Plains, and is prone to dissolution and subsequent formation of sinkholes. In Kansas, the Hutchinson Salt possesses an average net thickness of 76 m and reaches a maximum of over 152 m in the southern part of the basin. Deposition occurring during fluctuating sea levels caused numerous halite beds, 0.15 to 3 m thick, to be formed interbedded with shale, minor anhydrite, and dolomite/magnesite. Individual salt beds may be continuous for only a few miles despite the remarkable lateral continuity of the salt as a whole (Walters, 1978).
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Most of the upper 700 m of rock at the sites investigated here is Permian shales (Merriam, 1963). The Chase Group (top at 250 m deep), Lower Wellington Shales (top at 175 m deep), Hutchinson Salt (top at 125 m deep), Upper Wellington Shales (top at 70 m deep), and Ninnescah Shale (top at 25 m deep) make up the packets of reflecting events easily identifiable and segregated within the Permian portion of the section. Bedrock is defined as the top of the Ninnescah Shale with the unconsolidated Plio-Pleistocene Equus Beds making up the majority of the upper 30 m of sediment. Thickness of Quaternary alluvium that fills the stream valleys and paleosubsidence features goes from 0 to as much as 100 m, depending on the dimensions of the features.

Seismic Data Sets

1. **Principal Profile—Railroad Collapse**
   A continuous profile approximately 200 m long was centered on a sinkhole that formed catastrophically along an east/west railroad mainline in Hutchinson, Kansas (Figure 2). These data were acquired under significant site access restrictions, mainly related to physical limitations of working in a railroad drainage ditch along an active subsidence feature on one side and a railroad yard on the other. Data were recorded on a 240-channel Geometrics StrataView using two 40 Hz Mark Products geophones per station and a downhole 50-cal seismic source. Source spacing was 1.25 m and receiver stations were separated by 0.6 m. Data processing using WinSeis followed a very routine, proven high-resolution processing flow. These data possessed very limited bandwidth and raised concerns for data quality based on comparisons of data acquired just 2 km south of this railroad collapse site.

First arrivals and surface wave energy from the reflection data were processed to improve on the characterization of the shallow subsurface. Based on static effects observed on the shot gathers, poorer than expected data quality was blamed on static shifts between bedrock and ground surface, a distance of about 20 m. Turning-ray tomography and MASW cross sections suggest an extremely altered bedrock surface, with what appears to be a karst-type topography.

2. **Comparison Profile—Salt Mine Well Collapse**
   After catastrophic development of a sinkhole above a salt mine dissolution well field became a threat to a nearby city street and railroad spur in the early 1990s, a 200 m seismic reflection profile was acquired adjacent to the sinkhole intersecting both the road and railroad spur (Figure 3; Miller et al., 1993). Data were acquired with a 24-channel I/O seismograph and three 40 Hz Mark Products geophones, and a downhole 50-cal was used for the seismic energy source. Shot and receiver stations were separated by 2.5 m. Processing followed a very routine flow for near-surface reflection data and produced several lower resolution reflections on CMP stacked sections. Reflection bandwidth was relatively narrow, with little to no reflection energy returning from the bedrock.

   To investigate the possibility that extreme bedrock topography could be responsible for static irregularities that have inhibited maximizing the CMP stacked sections along this line, these data were processed using turning-ray tomography and MASW analyses to image the upper 30 m. As with the site immediately northwest along the railroad tracks, the bedrock under this line is also very irregular with very irregular bedrock topography.

![Figure 2. Railroad collapse seismic profile within salt dissolution mine field (1).](image-url)
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A continuous profile over 10 km in length was acquired along the existing U.S. 50 Highway right-of-way around Hutchinson, Kansas (Figure 4; Miller and Henthorne, 2004). This survey was designed to explore areas within or above the salt that could threaten future highway stability. A segment of this profile passed within 2 km of the brine well field where the primary and comparison profiles were acquired. Acquisition parameters and some of the equipment was different, but comparisons were still reasonable and possible. Data were acquired using the vibroseis technique, a 240-channel Geo- metrics StrataView and StrataVisor, and two 40 Hz Mark Products geophones. Receiver stations interval was 2.5 m with a 5 m source station spacing. Processing of these data was very basic with a minimal flow. Reflections are broadband and high frequency. Overall the signal-to-noise ratio is quite good with a practical resolution potential of around 5 m within the salt interval.

Following the notion that data quality issues observed at the salt mine collapse sites are from static irregularities related to bedrock surface topography, a selected portion of this profile was subjected to turning-ray tomography and MASW analyses. Contrasting the non-reflection analysis between the datasets clearly suggests the extremely irregular bedrock surface is isolated to the salt mine collapse site and the degree of lateral variability observed would dramatically alter any body wave traveling incident to the bedrock surface.
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Figure 5. Paleosubsidence features from profile less than 10 km from salt mine collapse (©).

Paleosinkhole Profile—Disposal Well Collapse Site

A single seismic profile approximately 3 km long was acquired along the eastern dissolution front of the Hutchinson Salt in eastern Reno County to discern the origin of a sinkhole that formed around an oil field brine disposal well (Figure 5; Miller et al., 1998). Data were acquired using an impulsive 8-gauge auger gun source, 48-channel Geometrics ES-4801 seismograph, and three 40 Hz Mark Products geophones. Both source and receiver station intervals were 2.5 m. Processing was limited to a basic flow using WinSeis. These data were very high quality with a resolution potential less than 5 m within the salt interval.

Along the dissolution front, natural leaching of the salt is expected and paleosinkholes are common. Along this profile several paleosinkholes were imaged, resulting in a very irregular and distorted Permian rock sequence between the salt and bedrock. However, as evident from turning-ray tomography and MASW analysis, the bedrock surface is relatively uniform with only long wavelength undulations associated with the paleosubsidence. Clearly the overwhelming difference between this site and the salt mine collapse sites is the highly distorted, short wavelength undulation in the bedrock surface. There is no doubt the extremely inconsistent shallow bedrock velocities resulted in both spectral degradation and static problems.

Discussion

Differences in uniformity of rock in the upper several meters of bedrock at the salt mine collapse site has dramatically altered the signal quality and potential of the high-resolution seismic reflection data collected to investigate the sinkhole that formed catastrophically above an abandoned salt dissolution well. This very distorted bedrock surface seems to be regionally unique to this site. Seismic reflection data targeting the salt in other parts of this county do not suffer from the same poor data quality and do not possess the same highly irregular bedrock surface. The uniqueness of the bedrock topography and the associated seismic artifacts could be related to a regional anticlinal structure suggested to extend beneath the central part of Reno County.

With the high evaporite concentrations within the Permian shale sequences between the bedrock surface and the top of the Hutchinson salt, if fractures formed along the crest of this structure during its formation, fresh surface and shallow subsurface waters could have gained access to interbedded evaporites close to the bedrock surface. If sufficient fluid movement was possible, dissolution voids could have formed consistent with the fractures, resulting in subsidence features and the karst topography apparent on the bedrock surface.

An extreme topography of the nature described would have an overwhelming impact on both the spectral and velocity characteristics of seismic reflection data. Using the tomography and MASW data velocity reconstruction is possible with improvements to static correction processes. Attenuation and interference of higher frequency components of the reflection wavelets cannot be recovered.

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EDITED REFERENCES

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