High-resolution Seismic-reflection Imaging of I-70 Sinkholes, Russell County, Kansas

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Report to

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Summary

Growth and associated subsurface development of the three sinkholes affecting Interstate Highway 70 between mile markers 178 and 180 in western Russell County, Kansas, were seismically imaged in 1980 and again in 2005. Seismic reflection imaging improved our understanding of the consistent, gradual surface subsidence ongoing at two sinkholes in the Gorham Oilfield discovered beneath a stretch of I-70 through Russell and Ellis counties in Kansas in 1966 and a third sinkhole discovered in 1980. Surface elevation monitoring of the approximately 10 cm/year subsidence since discovery has been beneficial, ensuring public safety and optimizing maintenance. A miniSOSIE reflection survey conducted in 1980 delineated the affected subsurface and successfully predicted development of the third sinkhole at this site. In 2004 and 2005 a high-resolution vibroseis survey was completed to ascertain current conditions of the subsurface, rate and pattern of growth since 1980, and potential for continued growth. With time and improved understanding of the salt dissolution affected subsurface in this area it appears that these features represent little risk to the public from catastrophic failure. However, from an operational perspective the Kansas Department of Transportation should expect continued subsidence, with future increases in surface area likely at a slightly reduced vertical rate. Seismic characteristics appear empirically consistent with gradual earth material compaction/settling.

Introduction

A high-resolution seismic reflection study began in 1980 targeting rock layers in the upper Permian portion of the geologic section beneath an approximately 4.5 km stretch of Interstate 70 (I-70) in western Russell County, Kansas. Surface subsidence along this stretch of highway had caused public concern and a transportation headache since 1966 (Figure 1). The principal goal of this study was to delineate rock layers within and above the Hutchinson Salt Member, specifically beneath three salt dissolution sinkholes centered at approximately mile marker 179.

It has been the consistent goal of this lengthy study to appraise the subsurface extent, overall surface growth rate, and subsidence mechanism and chronology. State-of-the-art shallow high-resolution seismic reflection techniques were used for both surveys. Advancements in the technology are obvious between the 1980 and 2004 data sets. However, even with markedly different resolution and signal-to-noise ratios, both surveys accomplished their objectives of mapping and evaluating the locally complex structures associated with the dissolution of the salt, structural failure of overlying sediments, and the resulting sinkhole.

Surface subsidence in this part of Kansas can range from gradual (an inch per year) to catastrophic (tens of feet per second) and can represent a significant risk to public safety. The unstable nature of the ground around mile marker 179 is due almost exclusively to anthropogenic salt dissolution resulting from containment failure in brine disposal wells within the Gorham oil field (Walters, 1978). Considering the high density of wells penetrating the salt layer in this area, lateral subsurface growth of known sinkholes as well as the potential for subsidence features yet

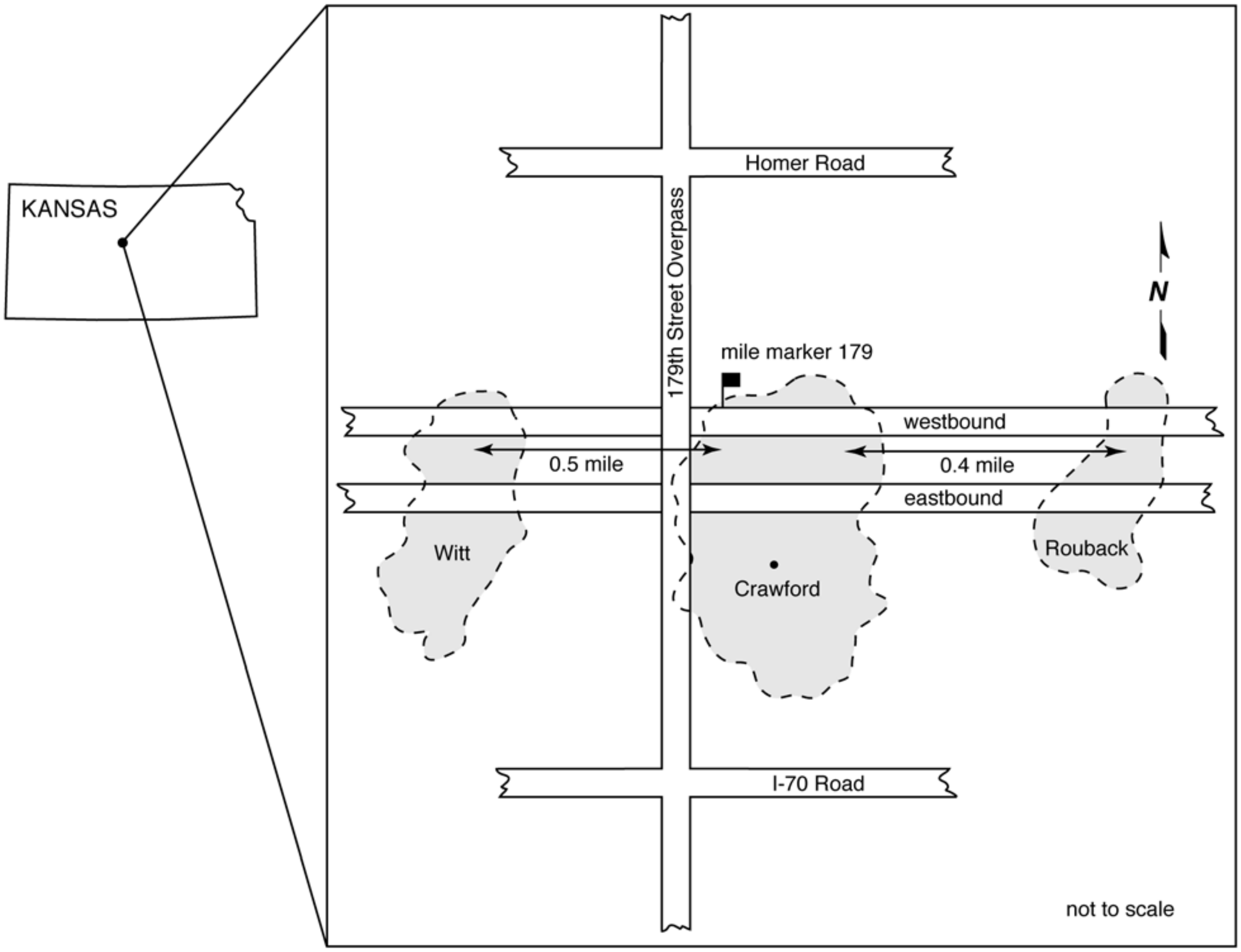

Figure 1. Site map of the study area showing location of the three sinkholes in relation to Interstate 70 in Russell County, Kansas.

to be discovered to grow large enough to be a problem is very likely. With that in mind, it seemed prudent to seismically monitor the subsurface volume where unstable ground was evident (i.e., the three known sinkholes) and could affect travel on I-70.

Shallow, high-resolution seismic reflection techniques have been successful delineating stratigraphic and structural features associated with several salt dissolution features throughout Kansas for almost three decades (Steeples, 1980; Steeples et al., 1986; Miller et al., 1993; Miller et al., 2005). Seismic reflection has proven to be a very effective tool to map structural aberrations in proximity of sinkholes and areas of greatest growth potential. No fewer than a dozen sinkholes have been examined with shallow seismic reflection in Kansas, generally resulting in a detailed structural map of significant layers above the salt as well as some suggestion as to the amount and extent of future subsidence. Seismic examination and comparisons of these I-70 sinkholes with other salt dissolution sinkholes affecting transportation has been the subject of several studies (Appendices A, B, and C).

Geologic and Geophysical Setting

The Permian Hutchinson Salt Formation underlies a significant portion of south central Kansas (Walters, 1978). The distribution and stratigraphy of the salt is well documented (Dellwig, 1963; Holdoway, 1978; Kulstad, 1955; Merriam, 1963). Variation in salt thickness throughout central and south central Kansas is due to a combination of increased salt and more and thicker interbedded anhydrites. The Stone Corral Anhydrite (a well documented acoustic marker) overlies the salt throughout Kansas (McGuire and Miller, 1989) and represents a primary marker reflector imaged during the I-70 seismic monitoring program. Directly above the salt is a thick sequence of Permian shales overlain by a portion of the lower Cretaceous section. At this location the Hutchinson Salt is approximately 1200 ft deep and about 300 ft thick.

Subsidence within the Gorham oilfield in western Russell County has been a nuisance, source of substantial repair expense, and focus of much public concern for KDOT over most of the last 40 years. Most significant has been the tens of feet of subsidence at the Crawford sinkhole that has distorted the paved superhighway and cement overpass located within the western half of that sinkhole. Uncontrolled release of unsaturated oil field brine and the resulting indiscriminate leaching of large volumes of salt around the Crawford disposal well bore began when the casing failed more than 50 years ago (Walters, 1978).

Once the salt void left from this leaching process grew to possess a top with an unsupported span that exceeded the strength of the roof rock, failure occurred and subsidence began. Even after wastewater disposal was halted, leaching continued since overlying fresh water had gained access to the salt when borehole confinement (casing-to-borehole seal) was lost. Natural confining properties of the rock layers surrounding the well bore were compromised when strain manifested itself as large faults generally centered around the well bore (Steeples et al., 1986). With failure and subsidence of rock layers surrounding the well bore and above the salt, new conduits for vertical migration of fresh water were established and the process proceeded unchecked.

Acquisition/Processing

Improvements in high-resolution data acquisition and processing techniques occurring over the last twenty years are evident in the dramatic increase in signal-to-noise ratio and data fidelity. Comparing and contrasting the 1980 and 2004 seismic surveys, the biggest improvements are in source, number of recording channels, dynamic range of seismograph, and pre-stack processing steps.

Seismic reflection data acquired in 1980 used the MiniSOSIE method (Barbier et al., 1976) to minimize the effects of traffic noise and avoid the expense and increased safety concerns of using high explosives. Vibroseis was employed in 2004 to increase the total energy, maintain non-invasive and non-destructive requirements, and tailor the amplitude spectra. Both are coded sources that by their nature reduce the effects of traffic noise in comparison to impulsive sources.

	1980	2004
seismograph	12-channel I/O	240-channel Geometrics
	12-bit A/D	24-bit A/D
	fixed-gain amplifiers	floating-point gain amplifiers
source	MiniSOSIE 1 Wacker (earth compactor)	vibroseis minivibII (10,000 lbs)
receivers	-28 Hz	-40 Hz
station spacing	16 m	5 m
spread	split	fixed, asymmetric
source offset	64 m to 160 m	5 m to 600-900m

Both 1980 and 2004 surveys were 3 miles long and approximately centered on the Crawford sinkhole. Increased fold and improved characteristics of the source amplitude spectra was the most substantial improvement in the 2004 data set relative to 1980. No doubt doubling the sample size of the seismograph's A/D converter also played a significant role in overall improvements to data quality. The 1980 survey included 130 shot stations and required three days to acquire. In 2004 the survey included over 450 shot stations and took two days to acquire. Data were acquired between mile markers 177 and 181.

The basic architecture and sequence of processing steps followed during the generation of the final stacked sections was similar to conventional petroleum exploration flows (Yilmaz, 1987). All digital records and files from the 1980 survey were lost, so comparisons of processing approaches and steps, as well as equivalent data displays, are not possible. 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.

Discussion

Comparison of legacy and monitor seismic data characteristics clearly demonstrates the advancements of modern high-resolution shallow seismic reflection imaging in this extremely challenging setting. From the analog displays available for the 1980 survey it is possible to interpret the extent and degree of subsurface collapse at the time of the survey (Figure 2). In the 25 years following the 1980 survey the horizontal expression of the sinkhole has increased only slightly, but the character of the reflections from within the subsidence feature have changed dramatically.

The drop in dominant frequency and velocity beneath the sinkhole as well as the lack of consistency in wavelet character across the subsidence-affected area is indicative of changes in material making up the overburden (Figure 3). Major surface changes are likely related to KDOT filling the sinkhole twice prior to the 1980 survey and then once more between the 1980 and 2004 surveys; however, these surface activities do not fully account for the kinds of changes observed on the seismic sections. Two of the three confirmed subsidence features have cone-like vertical development and seismic characteristics consistent with paleosubsidence features

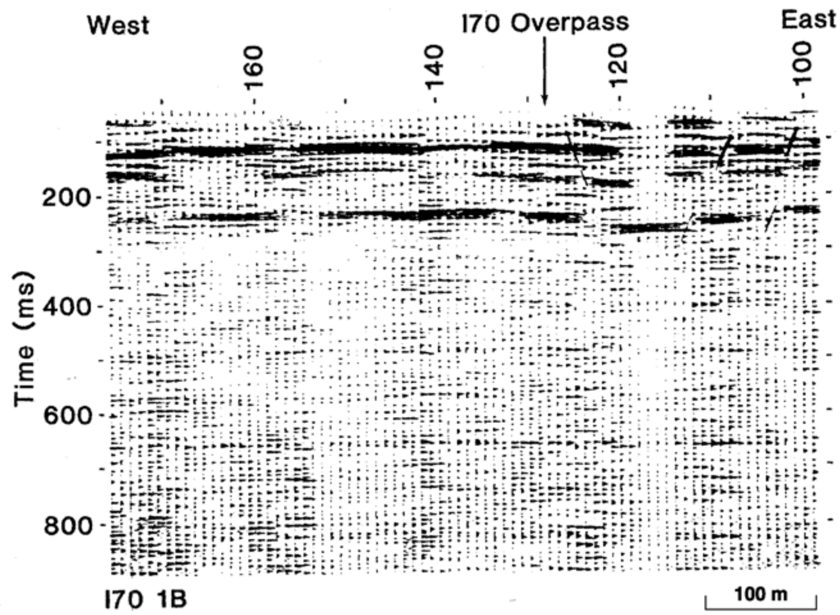

Figure 2. Interpreted seismic section from 1980 survey at the Crawford sinkhole located at station 110 (from Steeples et al., 1986).

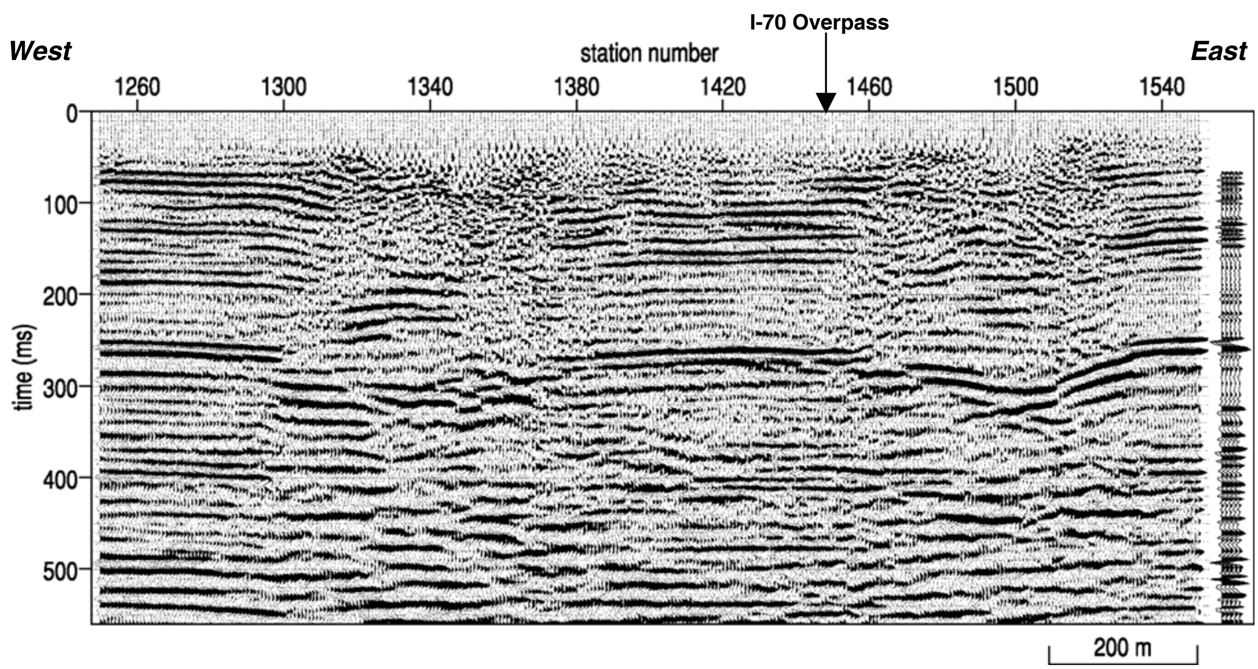

Figure 3. Witt sinkhole is located at station 1340 and the Crawford is at 1500. The high amplitude event at 260 ms is the 900 ft deep Stone Corral Anhydrite. Top of salt is at about 340 ms and is approximately 1200 ft below ground surface. The synthetic at the right was used to verify reflection identification.

identified on seismic reflection data acquired along the eastern dissolution front of the Hutchinson Salt (Figure 4). These paleosubsidence features appear near vertical on seismic data and have been interpreted as remnants of catastrophic collapse of overburden into naturally occurring salt dissolution voids.

There are notable differences between these two time-lapse seismic subsidence images, with the most obvious being the degree of wavelet character change within the affected area (Figures 2 and 3). Also noteworthy are the relatively flat reflections within the subsidence feature that define a much larger subsurface-affected area than the current surface expression. This is also evident in the upward-narrowing disturbed zone that defines the tensional dome (Davies, 1951). If the seismic interpretation of catastrophic paleofailure from the dissolution front is correct (Figure 4), then wavelet stretching, cone-shaped geometry, and flat-laying reflections within the disturbed volume as observed on seismic data from the Crawford/Witt sinkholes could be an indication of a slowing in the rate of vertical rock movement into the dissolution voids.

The cone-shaped appearance of the I-70 sinkholes on seismic data is consistent with active dissolution and subsidence as interpreted on several seismic investigations at similar sinkholes in Kansas. Based on a tensional dome failure mechanism, the two primary sinkholes at this site are still active with reverse faults defining the major collapse structures and area where active movement should be expected. Once horizontal roof rock failure of the salt interval slows or subsides, strain should begin to manifest itself as normal faults defining an ever-shallowing bowl structure. Subtle indications are evident in the salt overburden that this transition may have begun.

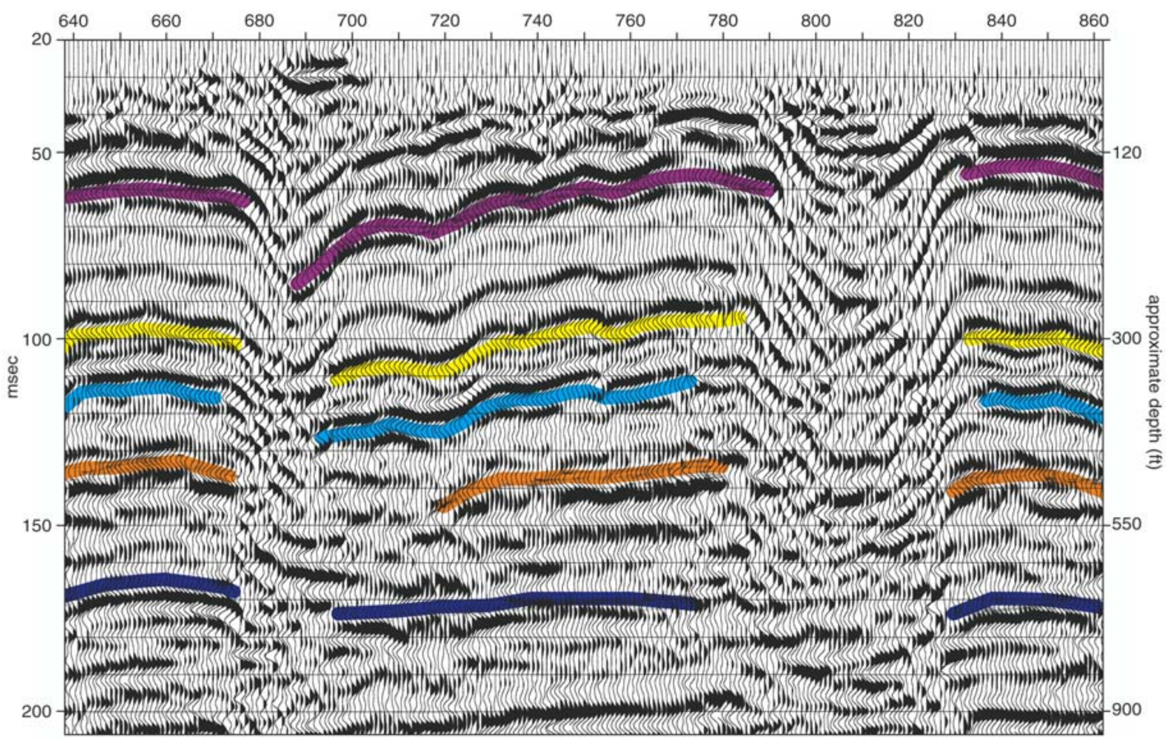

Figure 4. Seismic profile from along the eastern dissolution front of the Hutchinson Salt near Punkin Center in Reno County, Kansas.

Conclusions

An improved understanding of the subsidence process associated with failure of casing integrity was gained through seismic time-lapse investigations of the Witt, Crawford, and Rouback sinkholes beneath I-70. Improvements in methodology and equipment in the last 25 years for applications to near-surface high-resolution problems is clearly evident. It appears the dissolution process is still active at both the Crawford and Witt sinkholes and therefore the full surface expanse of these sinkholes is still unknown as well as a likely timeframe for surface stabilization.

Acknowledgments

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Summary

Seismic reflection images of dissolution subsidence features that have not yet developed any surface expression provide insights into potential growth mechanisms, development rates, and sinkhole risk. Vertical growth of small depressions or drape in reflectors several hundred meters below ground surface and in proximity to major salt dissolution sinkholes appear to be controlled by active dissolution in deeper salt layers and the size and competence of the unsupported span of roof rock. Gradual failure and continued upward movement of voids characterized by reflector drape are confined to the inverted cone geometry defining the stress regime or tensional dome. Time-lapse imaging of these yet-to-emerge sinkholes could provide key parameters for developing empirical models of sinkhole development. Ideally, these models would allow reasonable estimations of growth rates and mature sinkhole areal expressions.

Introduction

Sinkholes resulting from rock dissolution (karst) can develop at rates ranging from gradual (mm in years) to catastrophic (meters in seconds). Unexpected sinkhole formation represents a potential risk to property and safety the world over (Beck 1984). Detection prior to surface subsidence is preferable, but appraising the risk a juvenile subsidence feature represents is essential for minimizing the impact of these hazards on human habitation and the environment (Ruth et al. 1985). Disruption of ground stability by dissolution-instigated subsidence has affected transportation facilities, residences, manufacturing facilities, commercial buildings, underground utilities, as well as groundwater and aspects of the ecosystem (Beck 1987).

Dissolution of rock responsible for subsidence and ultimately the formation of a sinkhole can be initiated and/or influenced by natural or anthropogenic processes (Steeples et al. 1986; Wilson 1995; Brink 1984). Understanding the site-specific temporal variability of the mechanisms controlling subsidence as a function of changes in the surface and subsurface hydrologic and structural characteristics and the generalized failure process of a specific rock column is key to understanding and hopefully reducing the risk of unexpected or accelerated development of surface depressions (Kemmerly 1993).

Numerical models populated with uniform/generalized rock characteristics are a reasonable means for understanding the mechanism and potential risk for a subsidence prone area (Augarde et al. 2003). However, under field conditions small scale inhomogeneities in rocks not adequately defined through borehole measurements or generalized site geology predicate using generalized numerical model predictions as a high-confidence means of estimating the risk a particular site represents to public safety. Risk estimations from site-specific monitoring and empirically based predictions are preferable to generalized numerical model-based appraisals.

Dissolution of carbonates is extremely slow in comparison to the same process for evaporites. Evaporites, therefore, represent a much greater risk for anthropogenic errors to instigate or accelerate the dissolution process. However, human activity can be the catalyst for accelerated collapse in any karst setting through alteration of the unconsolidated overburden, such as changes in hydrology (Bell 1988; Kannan 1999; Tharp 1999).

Dissolution to the point of subsidence occurs in an evaporite unit at a much accelerated rate relative to limestones. Imaging changes in evaporite rocks at various stages through the dissolution (leaching) and failure (stress to strain) process can provide a greater range of empirical evidence to support generalizations about the maturation process for a given observation time than for equivalent studies in known limestone karst areas. Observing a relatively large number of sinkholes through various stages of their maturation within a relatively short time window allows some degree of confidence in qualitative statements and estimates of uniformity or commonality in the dissolution-related subsidence process. However, to more completely generalize failure due to dissolution of a rock, it is important to relate and contrast subsidence characteristics of both limestone and evaporite dissolution.

Geologic Setting

Several major salt basins exist throughout North America (Ege 1984). The Hutchinson Salt Member occurs in central Kansas, northwestern Oklahoma, and the northeastern portion of the Texas panhandle, and is prone to and has an extensive history of dissolution and formation of sinkholes. 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).

Permian shale layers overlaying the Hutchinson Salt Member are a primary target of any study looking at salt dissolution sinkhole development and associated risks to the environment and human activity in Kansas. Failure and subsidence of these shale units are responsible for many of the physical characteristics observed in modern sinkholes. Once failure occurs, the impermeable shales provide the pathways for groundwater to gain access to the salt. In proximity to the dissolution front fractures, faults, and collapse structures compromise the confining properties of the Permian shale bedrock and put the major fresh water aquifer (Plio-Pleistocene Equus Beds) in this part of southern Kansas at risk. Along the eastern boundary (dissolution front) the salt ranges in thickness from 0 to over 100 m and is buried beneath about 120 m of Permian red bed shales.

Seismic Data Acquisition and Processing

In general, data used in this study were acquired and processed as 2-D CMP sections, focusing primarily on high resolution and optimal signal-to-noise ratio. Most data included as part of this study have been acquired using the Vibroseis technique. Source and recording methodology were based on best fit to the individual survey requirements. Signal generated by high-sensitivity geophones were recorded on a Geometrics seismograph supporting from 96 to 240 channels.

Data processing relied on confident identification of reflections on shot gathers. Critical is the identification and awareness of a reflection event's optimum time window. Equally as important is the understanding and isolation/elimination of noise from signal. Noise for reflection data includes source generated (refractions, surface waves, air wave, and diffraction/scatter) and environmental (vehicles, facilities, power lines, wind, animals, etc.) noise. Minimal processing has proven beneficial in ensuring signal is being enhanced with little distortion and without the creation of artifacts common with overprocessing or inappropriate processing.

Discussion

Time-lapse images capturing a collapse feature's maturation through the stages of void development, initial roof rock failure of the void, migration of subsidence through the overburden, and eventual formation of a sinkhole would provide essential empirical characteristics necessary to refine site-specific theoretical models. Most numerical collapse models are based on uniform void geometries (sphere, ellipsoids, etc.) and laterally homogeneous layers between void and ground surface. Prediction of collapse rates and affected volumes at a particular site would require realistic models populated with parameters deduced from seismic images of subsurface subsidence recorded at representative sites.

Capturing earth material movement associated with roof rock failure of a dissolution void prior to subsidence is generally a matter of coincidence or reasoning through vague clues from borehole data or responses. Considering, in the best case scenario, borehole measurements (fluid levels and pressures) provide only subtle hints of containment problems in or around a well bore, it is not surprising the prefailure information has been extremely limited. To date, there are no cases reported in the scientific literature of time-lapse seismic images capturing an unintentional (natural or anthropogenic) subsurface collapse event.

As with many acts of nature, acquiring seismic images of pre-sinkhole subsidence is more a matter of coincidence than planning. On two occasions "juvenile" subsidence features have been interpreted on seismic data at sites where the target of the seismic reflection survey has been adjacent to active sinkholes. These apparent subsidence features have several distinctive characteristics both seismic and in relation to the geologic setting, suggestive of future sinkholes: first, presence of dissolvable rocks; second, bed distortion not attributable to tectonics; third, history of local dissolution; fourth, an available source of fluid and possible mechanism for moving saturated brine away from the dissolution front; and fifth, bed distortion observed only above the dissolvable rock.

An attempt to evaluate the growth of a series of sinkholes along a major four-lane interstate in central Kansas, USA, using seismic reflection has produced images of what could be a collapse feature actively migrating toward the ground surface. The target of this survey was the 150-m-wide sinkhole centered on station 1340 that has a subsurface seismic expression on the CMP section consistent with other sinkholes from this area (Figure 1). Top of Hutchinson Salt in this area is about 350 ms two-way travel time. A series of high amplitude and relatively high resolution reflections are prevalent throughout the predominantly Permian shale section, Jurassic, and the lower part of the Cretaceous section. The 270 ms Stone Corral Anhydrite is a regional seismic marker bed and lies around 150 m above the salt section. Diffracted seismic energy and relatively low velocity and low frequency reflections from within and adjacent to the subsidence feature beneath station 1340 could be artifacts of tight bed folding (ductile deformation and a "bow tie" resulting for extreme synclinal geometries) or scattered energy re-radiated from bed terminations resulting from brittle deformation.

Apparent drape in a series of reflections around station 1250 between the Stone Corral Anhydrite and a shallow Cretaceous layer about 100 m below ground surface is characteristic of subsidence features seismically mapped in this region. No surface expression was present at this location at the time of the seismic survey. It is, therefore, reasonable to suggest that this is a collapse feature resulting from dissolution of the Hutchinson Salt and migrating toward the ground surface. Improved processing and associated data enhancements will be necessary to determine the dominant failure mechanism at this site. It is assumed that casing failure in an oil field well opened a pathway for fluids to access the salt and initiated the dissolution process.

At a second site approximately 300 m shallower in the geologic section and 200 km southeast of the previous site (Figure 1), a gradually developing sinkhole with apparent subsurface ties to paleosubsidence features is adversely affecting a two-lane highway through south central Kansas. Several different subsidence mechanisms are and/or have been at work at this site (Figure 2). Clearly, the subsurface dissolution responsible for the current sinkhole is an order of magnitude or more larger than the sinkhole dimensions. Also, the predominant structures controlling at least the initial subsidence are a set of reverse faults.

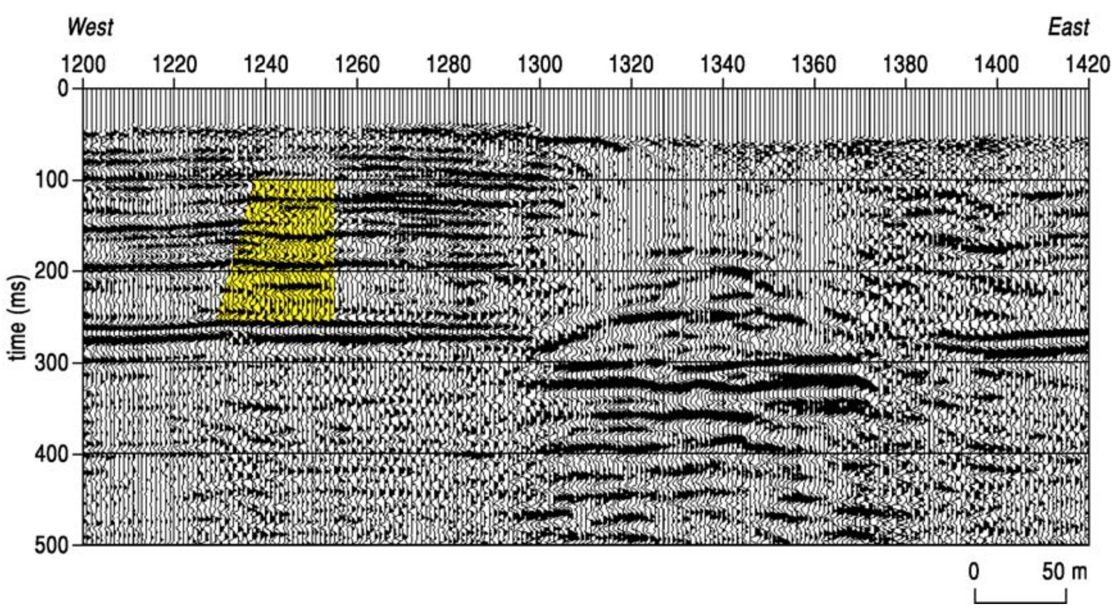

Figure 1. Possible collapse feature (highlighted). An existing sinkhole is centered at station 1340.

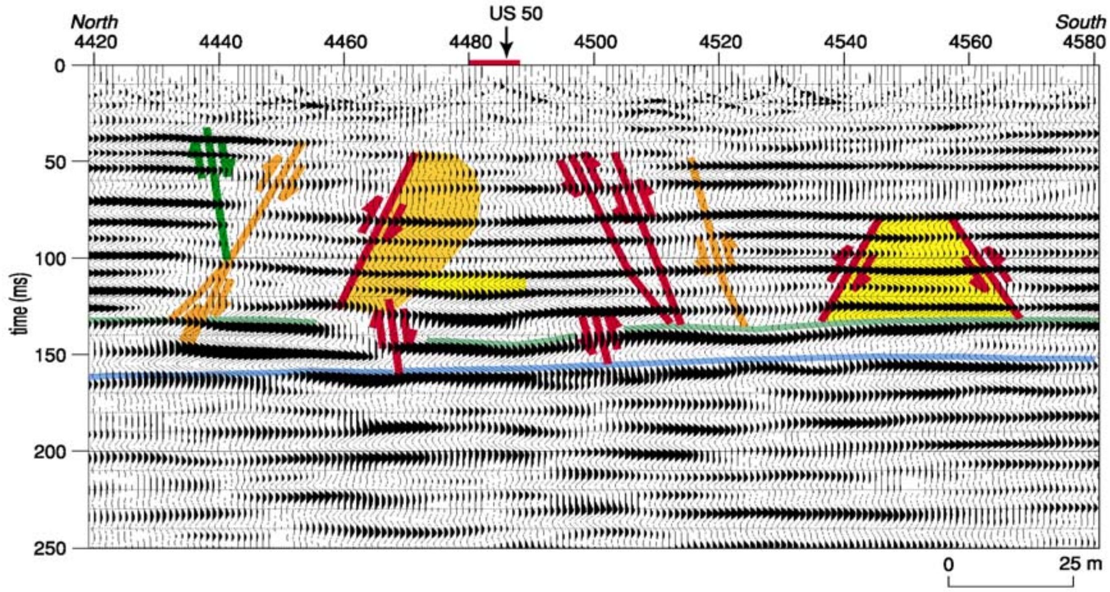

Figure 2. Gradually developing sinkhole with associated paleosubsidence features affecting a highway.

Adjacent to the sinkhole and its related dissolution and subsidences are a set of reflections from within the Permian shales that appears to drape. This drape is contained within an area defined by an inverted cone and truncates against a relatively high-amplitude reflection interpreted to be a dolomite separating the Upper Wellington Shale from the Ninnescah Shale (Figure 2). If this is an active feature, growth of the dissolution void in the salt will eventually result in an unsupported roof span at the base of the Ninnescah Shale that surpasses the strength of the dolomite and failure will result. Key will be how large the roof span becomes prefailure and the strength/resistance to failure of rocks 50 m below bedrock.

Conclusions

Capturing dissolution-related subsidence features at different stages of vertical expression can provide key stress/strain relationships key to predicting growth rates and maximum dimensions of mature sinkholes for different geologic settings. If these kinds of growth predictions can be made with reasonable confidence, it becomes possible to develop remediation strategies after the onset of dissolution but before the stoping advances to the point of sinkhole development. Key to these predictions is understanding the geology of the host rock and overburden as well as the fluid source (inlet) and departure point(s). By capturing seismic images at different stages of growth, empirical and numerical models can be developed predicting growth. Examples of “juvenile” subsidence features at stages of intermediate development exist for both anthropogenic and natural induced dissolution subsidence.

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Appendix B

Miller, R.D., D.W. Steeples, J. Xia, T.R. Rademacker, J.L. Lambrecht, 2006, Seismic reflection characteristics of subsidence affecting transportation: Keynote Presentation, Proceedings of the International Conference on Environmental and Engineering Geophysics, Wuhan, China, June 4-9, p. 2-9.

Seismic reflection characteristics of subsidence affecting transportation

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Summary

High-resolution seismic reflections have been used effectively to investigate sinkholes formed from the dissolution of a bedded salt unit found throughout most of central Kansas. Surface subsidence can have devastating effects on transportation structures. Roads and rails, bridges, and pipelines can be adversely affected by even minor ground instability. Areas susceptible to rapid surface subsidence represent a potential risk to public safety. Significantly larger subsurface expressions relative to surface depressions are a consistent observation on seismic images recorded over sinkholes in Kansas. It appears until subsidence reaches the ground surface, failure is controlled by faults with reverse orientation. Once a surface depression begins to form and dissolution of the salt slows or stops, subsidence along rock layers manifests itself with a more normal fault geometry. Detecting areas of rapid subsidence potential, pre-surface failure, is the ultimate goal of any geotechnical survey where the ground surface is susceptible to settling. Seismic reflection images have helped correlate present subsidence to paleofeatures, project the total horizontal growth of active sinkholes, and appraise the risk of catastrophic failure. It is likely active dissolution and the associated fluid movement within the salt interval correlates to collapse geometries observed in salt overburden rocks. Geologic structures play a significant role in both controlling sinkhole expansion and in the susceptibility for sinkholes to form in areas above the Hutchinson Salt in Kansas.

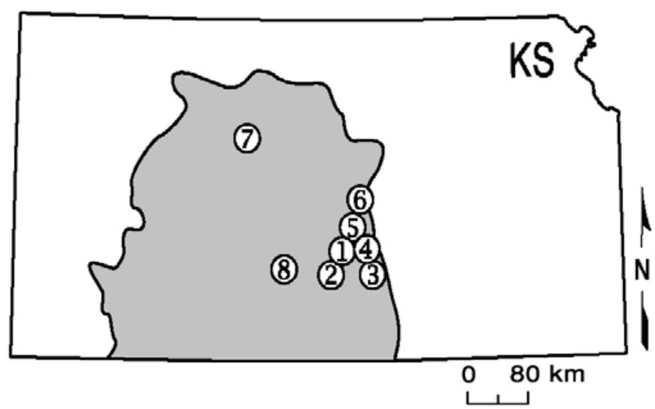
Introduction

Sinkholes are common hazards to property and human safety the world over (Beck et al., 1999). Their formation is generally associated with subsurface subsidence that occurs when overburden loads exceed the strength of the roof rock bridging voids or rubble zones formed as a result of dissolution or mining. Sinkholes can form naturally or anthropogenically from the dissolution of limestone (karst), gypsum, or rock salt, or from mine/tunnel collapse.

In central Kansas most sinkholes are the result of leached out volumes of the Permian Hutchinson Salt member of the Wellington Formation (Watney et al., 1988). Sinkholes forming above salt layers have been studied throughout Kansas (Frye, 1950; Walters, 1978) and the United States (Ege, 1984). Studies of subsidence related to mining of the salt around Hutchinson, Kansas (Walters, 1980), disposal of oil field brine near Russell, Kansas (Walters, 1991), and natural dissolution through fault/fracture-induced permeability (Frye and Schoff, 1942) have drawn conclusions about the mechanism responsible for subsidence geometries and rates based on surface and/or borehole observations.

Salt dissolution sinkholes are found in all areas of Kansas where the Hutchinson Salt is present in the subsurface (Figure 1). Sinkholes have been definitely correlated to failed containment of disposal wells injecting oil field brine wastewater using stem pressure tests and/or seismic reflection investigations at a variety of sites throughout central Kansas (Steeples et al., 1986; Knapp et al., 1989; Miller et al., 1997). Sinkholes which have formed by natural dissolution and subsidence processes are most commonly documented at the depositional edges on the west and north and erosional boundary on the east of the Hutchinson Salt (Frye and Schoff, 1942; Frye, 1950; Merriam and Mann, 1957; Anderson et al., 1995).

Concerns for public safety and the threat of property damage from sinkholes forming in proximity to heavily traveled railroads, highways, and pipelines transporting environmentally hazardous or explosive materials justifies careful attention to the condition of rocks between the base of the salt and ground surface. Seismic imaging has proven effective in discerning changes in rock geometries associated with failure of rock layers due to salt dissolution voids. Seismic images have been obtained above and around sinkholes caused by dissolution of salt from fluid introduced during dissolution mining of salt, from casing failure during disposal of oil field fluids, by seal failure around well casings, and along natural fluid conduits such as faults and fractures. In all cases, the interpretations of the affected subsurface have lead to an improved understanding of the failure mechanisms and progression.



Seismic studies of sinkholes or in areas susceptible to sinkhole formation.
Numbers match indicated case studies.

Figure 1. Hutchinson Salt in Kansas indicated by shaded area.

Seismic reflection profiles acquired above eight different sinkholes with a history of affecting transportation structures begin to provide some basic clues to the details of the subsidence process at different locations in different geologic and geotechnical settings. Of this set of eight seismic data sets, three are from investigations of collapse structures associated with salt mining or brine disposal wells, four of the profiles are over active sinkholes related to natural processes and that have been active at different times in the geologic past, and one is part of a reconnaissance program searching for subsidence prone areas. These selected eight profiles were acquired over a period of around 15 years (1990 to 2005) with different equipment and using slightly different techniques. Six surveys used vibroseis, and two were impulsive; one employed a 50-cal. projectile source, and the other used an 8-gauge auger gun downhole source.

Geologic Setting

Several major salt basins exist throughout North America (Ege, 1984). The Permian Hutchinson Salt Member occurs in central Kansas, northwestern Oklahoma, and the northeastern portion of the Texas panhandle, and is prone to and has an extensive history of dissolution and formation of sinkholes. 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).

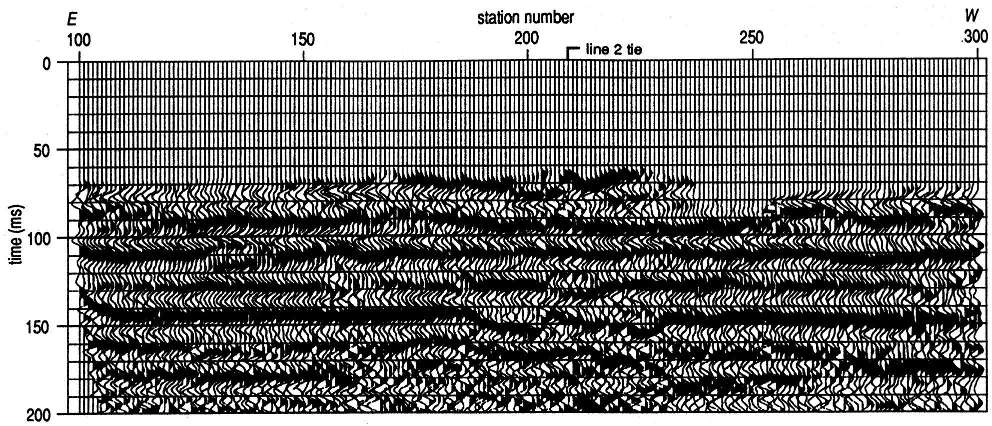


Figure 2. CMP seismic section with disturbed top of salt evident beneath station 210 at a two-way traveltime of 140 ms, equating to a depth of about 125 m.

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

Seismic Data Sets

1 Morton Road and Railroad Spur—Salt Mine Well Collapse

After catastrophic development of a sinkhole above a salt mine in a dissolution well field threatened a near-by city street and railroad spur, a 200 m seismic reflection profile was acquired adjacent to the sinkhole intersecting both the road and railroad spur. Data were acquired with a 24-channel I/O seismograph, triple 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.

A clearly definable void feature can be interpreted on the seismic reflection section (Figure 2). The seismic profile passed adjacent to the sinkhole but over ground that had not yet subsided. Rocks between the void and ground surface had not been distorted by subsidence. Strong evidence exists to suggest the void extends beneath the near-by city street and railroad spur. Drilling later confirmed the seismic interpretation of the affected subsurface, not yet observable on the ground surface.

2 Undisturbed Surface Profile—U. S. 50 Highway

A continuous profile, over 10 km in length was acquired along the existing U. S. 50 highway right-of-way around Hutchinson, Kansas. This survey was designed to explore for areas within or above the salt that could threaten future highway stability. A segment of this profile passed within less than 1 km from a known abandoned brine well field.

Data were acquired using the vibroseis technique, a 240-channel Geometrics StrataView and

StrataVisor, and dual 40 Hz Mark Products geophones. Receiver stations interval was 2.5 m with a 5 m source station spacing. Processing of these data were 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.

Several areas with seismic returns indicative of disturbed subsurface are interpretable and likely indicative of structurally weak zones (Figure 3). Paleosubsidence features were present at several locations but did not appear to represent a threat of high velocity subsidence. Highly disturbed areas with seismic characteristics consistent with voids from “salt jugs” were interpreted in an area thought to be the southern extreme of an old brine dissolution well field. Realignment of the highway was necessary.

3 Paleosinkhole Profile—Disposal Well Collapse Site

A single seismic profile approximately 3 km 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. Data were acquired using an impulsive 8-gauge auger gun source, 48-channel Geometrics ES-4801 seismograph, and triple 40 Hz Mark Products geophones. Both source and receiver station interval was 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.

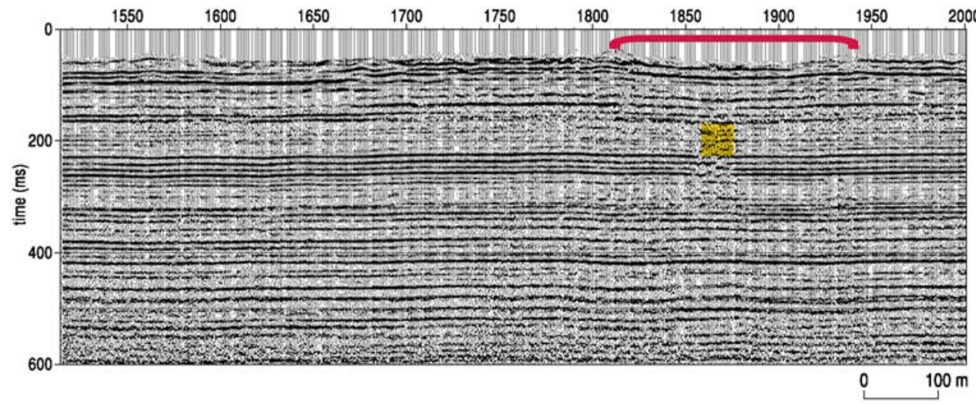


Figure 3. Paleosinkhole evident about 2 km from the beginning of profile and approximately beneath a stretch of highway that includes the overpass of Highway 96.

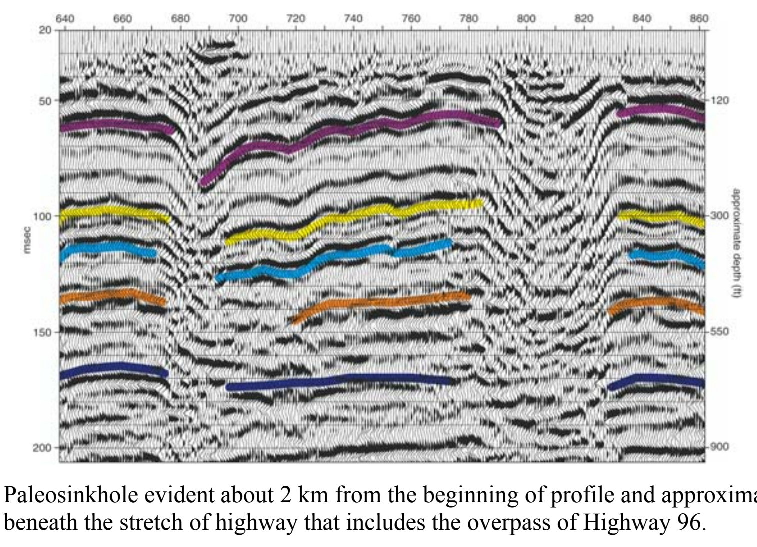


Figure 4. Paleosinkhole evident about 2 km from the beginning of profile and approximately beneath the stretch of highway that includes the overpass of Highway 96.

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 (Figure 4). Clearly the overwhelming difference between this site and most others west of the dissolution front is the highly distorted, short wavelength undulation in the salt overburden and bedrock surface.

4 Reactivated Paleosinkhole—U. S. 50 Highway, Reno County, Kansas

Two 1.5-km high-resolution seismic reflection profiles were used to map the upper 150 m of the ground surface around and below an actively subsiding sinkhole currently affecting the stability of US 50 highway in Reno County, Kansas (Figure 5). Primary objectives of this study were to delineate the subsurface expression of this growing salt dissolution-induced sinkhole and appraise its threat to highway stability and public safety.

The high signal-to-noise ratio and resolution of these seismic reflection data allowed detection, delineation, and evaluation of rock failure and associated episodes of material collapse into voids left after periodic and localized leaching of the 125 m deep, 40 m thick Permian Hutchinson Salt member. Mechanisms and gross chronology of structural failures as interpretable from stacked seismic sections suggest initial subsidence and associated bed offset occurred as accumulated stress was rapidly released and constrained to a cone defined by reverse fault planes. As the downward movement (settling, relaxation) of sediments slowed, with little or no incremental build up of stress, gradual subsidence continued in the subsurface advancing as an ever-expanding bowl, geometrically defined by normal fault planes.

Current surface subsidence at the intersection of U. S. 50 and Victory Road is probably related to the reactivation of natural salt dissolution processes that produced the seismically imaged, 300-m-wide subsidence feature interpreted to have been active during Tertiary and/or Quaternary. Alternately, recent failure of Permian rock layers above the salt that had bridged (roof rock) void or rubble areas remaining after the Tertiary to Quaternary subsidence imaged on the seismic sections could explain the current development of this sinkhole.

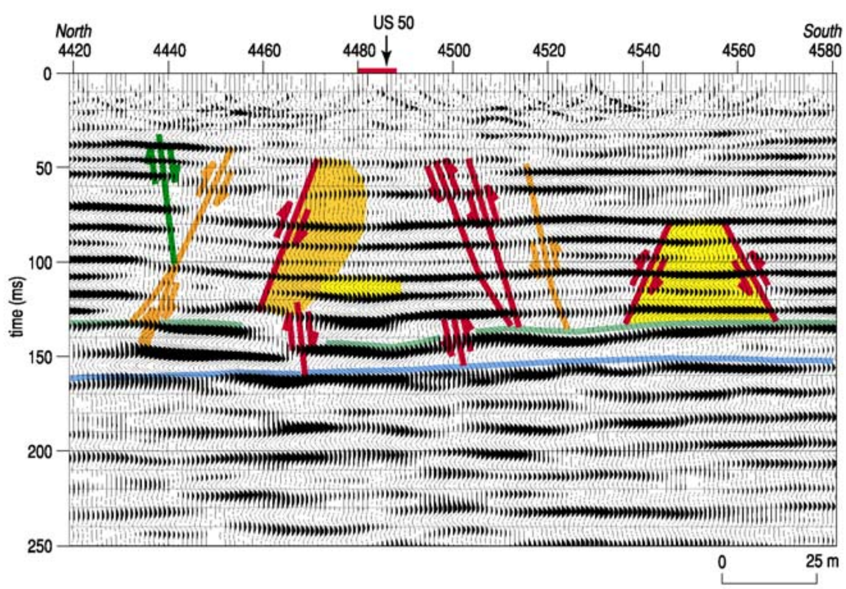


Figure 5. Interpreted CMP stacked section with disturbed salt interval at about 120 ms two-way traveltime and several possible offset features and layer distortion with the salt overburden.

5 Reactivated Paleosinkhole Coincident with Disposal Well—Rayl Sinkhole

A sinkhole that formed gradually grew to the point it began affecting a county road and house, including an abandoned disposal well. With a well bore located within the sinkhole, it was suggested that the two were related and therefore responsibility for this hazard was not clear. A high-resolution vibroseis survey was acquired that included two 1-km-long profiles intersecting approximately in the center of the sinkholes and on the road shoulder. These seismic data clearly captured the expressions of two different periods of subsidence (Figure 6). The two periods appear to be separated by a significant amount of time and the disposal well was coincidently located at the extreme western edge of the feature.

All evidence supports the suggestion that the disposal well had not influenced the current development of the sinkhole. Paleosubsidence had halted and with natural changes to the hydrology of this site, dissolution had reactivated along the north and eastern edge of the paleofeature, opposite of the disposal well.

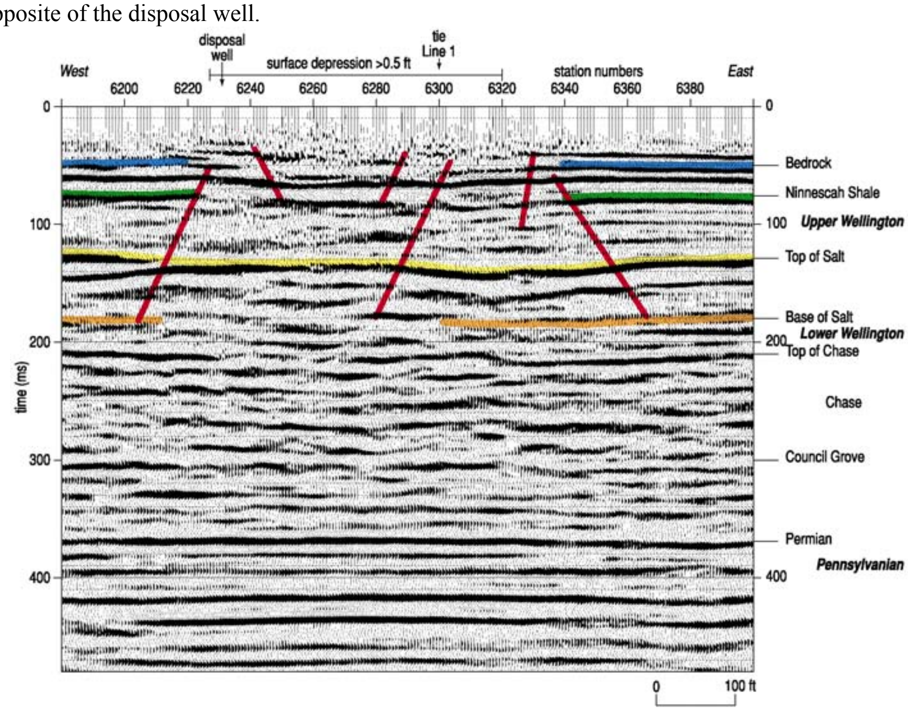


Figure 6. CMP stacked section with interpretation of reactivated subsidence beneath and immediately west of a house and major north/south county road.

6 Disturbed Salt at Dissolution Front—Inman Bypass Overpass

Land subsidence is not uncommon at the natural dissolution front of the Hutchinson Salt in Central Kansas. With the construction of a new superhighway came concerns by the Kansas Department of Transportation of rigid structure stability above sinking ground. Of primary concern was the potential for the highway to collapse from catastrophic failure of rock layers above natural voids in the salt. A 10-km-long seismic profile was acquired to address these concerns.

A high-resolution vibroseis survey with a subsurface sampling interval of 1.2 m and nominal fold exceeding 60 was acquired along the high-gradient portion of the proposed highway. Near the area projected by well data to have the most rapid thinning of salt, several features were identified that sufficiently concerned highway engineers to reroute the highway and modify placement of a multimillion dollar overpass. As expected, the salt topography changes very abruptly, with undulations as great as 100 m over distances as short as 1/4 km. The very ragged nature of the dissolution front has been suggested but never previously imaged.

7 Active Dissolution at Brine Disposal Wells—I-70 Sinkholes

Time-lapse seismic reflection imaging improved our understanding of the consistent, gradual surface subsidence ongoing at two sinkholes in the Gorham oilfield discovered beneath a stretch of Interstate Highway 70 through Russell and Ellis Counties in Kansas in 1966. With subsidence occurring at a rate of around 10 cm per year since discovery, monitoring has been beneficial to ensure public safety and optimize maintenance. A miniSOSIE reflection survey conducted in 1980 delineated the affected subsurface and successfully predicted development of a third sinkhole at this site. In 2004 and 2005 a high-resolution vibroseis survey was completed to ascertain current conditions of the subsurface, rate and pattern of growth since 1980, and potential for continued growth. With time and improved understanding of the salt dissolution affected subsurface in this area, it appears that these features represent little risk to the public from catastrophic failure. However, from an operational perspective the Kansas Department of Transportation should expect continued subsidence, with future increases in surface area likely at a slightly reduced vertical rate. Seismic characteristics appear empirically consistent with gradual earth material compaction/ settling (Figure 7).

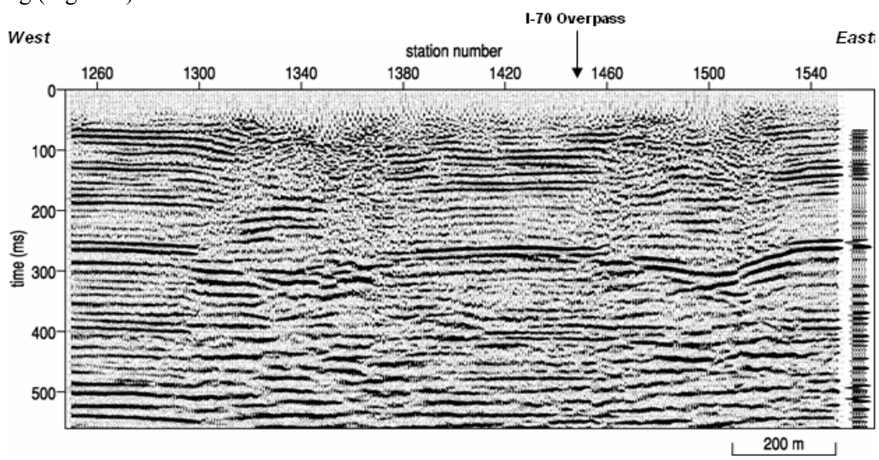


Figure 7. Witt sinkhole is located at station 1340 and the Crawford is at 1500. The high amplitude event at 260 ms is the 300-m deep Stone Corral Anhydrite. Top of salt is at about 340 ms and is approximately 400 m below ground surface. The synthetic at the right was used to verify reflection identification.

8 Multi-well Brine Disposal Well Casing Breech—Leesburg

Loss of well bore confinement observed during standard pressure tests clued regulators to a potential problem isolating well bore fluids from surrounding evaporites in Stafford County, Kansas. Attempts to plug the well and seal the borehole failed. With the casing severed, borehole fluid moved in and out of the salt and resulted in a gradually developing sinkhole. It was soon discovered that two boreholes within a hundred meters or so of each other lost containment and were in hydrologic connection.

Intersecting 2-D seismic profiles imaged an altered salt interval more than an order of magnitude larger in the subsurface than evident at the surface depression. Two 2-km-long, high-resolution vibroseis profiles were interpreted to possess reflections from the salt around 250 m below ground surface altered by dissolution of the salt and collapse of the overburden. A major north/south county road was more than 250 m from the center of the sinkhole, but directly over the subsurface edge of the dissolution-altered salt interval.

At the northern extreme of the seismic image the profile passed over an abandoned well where reflections from the salt interval suggested dissolution was or had been active at one time. The relatively small affected salt volume at this north location is likely insufficient for collapse up through the entire column of overburden and thereby not capable of initiating sinkhole development at this time.

Discussion

Clearly the threat to transportation structures and elevated maintenance costs associated with unstable ground above dissolution-prone rock layers can unexpectedly become a reality in many parts of Kansas. Seismic reflection has proven not only an effective tool in delineating the subsurface extent of dissolution features—and therefore plays an important role in predicting surface risk areas—it also has provided a variety of important clues as to dissolution and resulting subsidence processes and controls. Catastrophic collapse is rare, but represents the most obvious risk to public safety. Predicting catastrophic collapse represents one of the most significant potential accomplishments for seismic investigations of these extremely active phenomena.

Failure rates and growth patterns of sinkholes are controlled by a combination of hydrodynamics and overburden material properties. Seismic reflection has attempted to address both aspects of sinkhole development, with greater success in overburden structural evaluations and predictions than defining the fluid processes active within and associated with the salt interval. Time-lapse has begun to provide significant enhancements to our thinking about the process. Continued study of more than a dozen "typesection" sinkholes in Kansas related to salt dissolution will provide key insights in both pre-surface failure predictions and growth modeling and eventual stagnation of the leaching of the salt.

Acknowledgments

Kansas Department of Transportation (especially Neil Croxton and Bob Henthorne) and the Kansas Corporation Commission (especially Steve Durrant and Morris Korphage) provided financial support for the majority of these projects. We thank the KGS acquisition crew, led by David Laflen, for their work in the field, and Mary Brohammer for her assistance in manuscript preparation.

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Appendix C

High-resolution seismic-reflection imaging 25 years of change in I-70 sinkhole, Russell County, Kansas

Richard D. Miller, Kansas Geological Survey; Don W. Steeples, Department of Geology, University of Kansas; Jamie L. Lambrecht, Kansas Geological Survey; and Neil Croxton, Kansas Department of Transportation*

Summary

Time-lapse seismic reflection imaging improved our understanding of the consistent, gradual surface subsidence ongoing at two sinkholes in the Gorham Oilfield discovered beneath a stretch of Interstate Highway 70 through Russell and Ellis Counties in Kansas in 1966. With subsidence occurring at a rate of around 10 cm per year since discovery, monitoring has been beneficial to ensure public safety and optimize maintenance. A miniSOSIE reflection survey conducted in 1980 delineated the affected subsurface and successfully predicted development of a third sinkhole at this site. In 2004 and 2005 a high-resolution vibroseis survey was completed to ascertain current conditions of the subsurface, rate and pattern of growth since 1980, and potential for continued growth. With time and improved understanding of the salt dissolution affected subsurface in this area it appears that these features represent little risk to the public from catastrophic failure. However, from an operational perspective the Kansas Department of Transportation should expect continued subsidence, with future increases in surface area likely at a slightly reduced vertical rate. Seismic characteristics appear empirically consistent with gradual earth material compaction/settling.

Introduction

A high-resolution seismic reflection study began in 1980 targeting rock layers in the upper Permian portion of the geologic section beneath an approximately 4.5 km stretch of Interstate 70 (I-70) in western Russell County, Kansas. Surface subsidence along this stretch of highway had caused public concern and a transportation headache since 1966 (Figure 1). The principal goal of this study was to delineate rock layers within and above the Hutchinson Salt Member, specifically beneath three salt dissolution sinkholes centered at approximately mile marker 179.

It has been the consistent goal of this lengthy study to appraise the subsurface extent, overall surface growth rate, and subsidence mechanism and chronology. State-of-the-art shallow high-resolution seismic reflection techniques were used for both surveys. Advancements in the technology are obvious between the 1980 and 2004 data sets. However, even with markedly different resolution and signal-to-noise ratios, both surveys accomplished their objectives of mapping and evaluating the locally complex structures associated with the dissolution of the salt, structural failure of overlying sediments, and the resulting sinkhole.

Surface subsidence in this part of Kansas can range from gradual (an inch per year) to catastrophic (tens of feet per second) and can represent a significant risk to public safety.

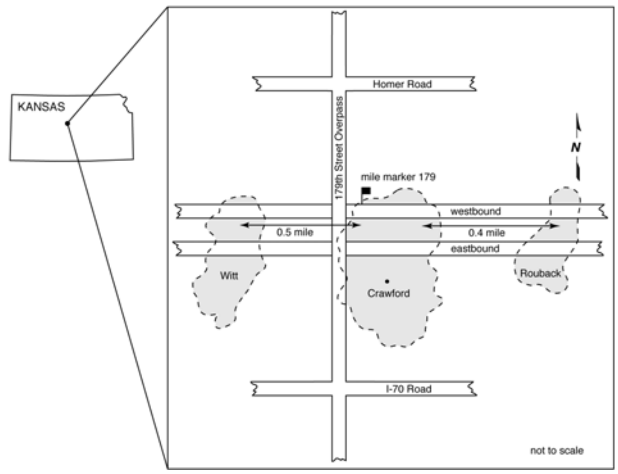

Figure 1. Site map of the study area showing location of the three sinkholes in relation to Interstate 70 in Russell County, Kansas.

The unstable nature of the ground around mile marker 179 is due almost exclusively to anthropogenic salt dissolution resulting from containment failure in brine disposal wells within the Gorham oil field (Walters, 1978). Considering the high density of wells penetrating the salt layer in this area, lateral subsurface growth to known sinkholes as well as the potential for subsidence features yet to be discovered to grow large enough to be a problem is very likely. With that in mind, it seemed prudent to seismically monitor the subsurface volume where unstable ground was evident (i.e., the three known sinkholes) and could hinder travel on I-70.

Shallow, high-resolution seismic reflection techniques have been successful delineating stratigraphic and structural features associated with several salt dissolution features throughout Kansas (Steeples, 1980; Steeples et al., 1986; Miller et al., 1993; Miller et al., 2005). Seismic reflection has proven to be a very effective tool to map structural aberrations in proximity of sinkholes. No less than a dozen sinkholes have been examined with shallow seismic reflection in Kansas, generally resulting in a detailed structural map of significant layers above the salt as well as some suggestion of the amount and extent of future subsidence.

Geologic and Geophysical Setting

The Permian Hutchinson Salt Formation underlies a significant portion of south central Kansas (Walters, 1978). The distribution and stratigraphy of the salt is well documented

(Dellwig, 1963; Holdoway, 1978; Kulstad, 1955; Merriam, 1963). Variation in salt thickness throughout central and south central Kansas is due to a combination of increased salt and more and thicker interbedded anhydrites. The Stone Corral Anhydrite (a well documented acoustic marker) overlies the salt throughout Kansas (McGuire and Miller, 1989) and represents a primary marker reflector imaged during the I-70 seismic monitoring program. Directly above the salt is a thick sequence of Permian shales overlain by a portion of the lower Cretaceous section. At this location the Hutchinson Salt is approximately 400 m deep and about 100 m thick.

Subsidence within the Gorham oilfield in western Russell County has been a nuisance, source of substantial repair expense, and focus of much public concern for KDOT over most of the last forty years. Most significant has been the multiple meters of subsidence at the Crawford sinkhole that has affected the paved superhighway and cement overpass located within the western half of that sinkhole. Uncontrolled release of unsaturated oil field brine and the resulting indiscriminate leaching of large volumes of salt around the Crawford disposal well bore occurred when the casing failed more than fifty years ago (Walters, 1978).

Once the salt void left from this leaching process grew to exceed the strength of the roof rock, failure occurred and subsidence began. Even after wastewater disposal was halted, leaching continued as overlying fresh water gained access to the salt when borehole confinement (casing-to-borehole seal) was lost. Natural confining properties of the rock layers surrounding the well bore were compromised when strain manifested itself as large faults generally centered around the well bore (Steeples et al., 1986). With failure and subsidence of rock layers surrounding the well bore and above the salt, natural new conduits for vertical migration of fresh water were established and the process proceeded unchecked.

Acquisition/Processing

Improvements in high-resolution data acquisition and processing techniques occurring over the last twenty years are evident in the dramatic increase in signal-to-noise ratio and data fidelity. Comparing and contrasting the 1980 and 2004 seismic surveys, it is evident that the biggest improvements come in source, number of recording channels, dynamic range of seismograph, and pre-stack processing steps.

Seismic reflection data acquired in 1980 used the Mini-SOSIE method (Barbier et al., 1976) to minimize the effects of traffic noise and avoid the expense and increased safety concerns of using high explosives. Vibroseis was employed in 2004 to increase the total energy, maintain non-invasive and non-destructive requirements, and tailor the amplitude spectra. Both are coded sources and reduce the effects of traffic noise compared to impulsive sources.

Both 1980 and 2004 surveys were 4.5 km long and approximately centered on the Crawford sinkhole. Increased fold and improved amplitude spectra of the source was the most substantial improvement in the 2004 data set. No doubt

	1980	**2004**
seismograph	12-channel I/O	240-channel Geometrics
	12-bit A/D	24-bit A/D
	fixed-gain amplifiers	floating-point gain amplifiers
source	MiniSOSIE 1 Wacker (earth compactor)	vibroseis minivibII (10,000 lbs)
receivers	-28 Hz	-40 Hz
station spacing	16 m	5 m
spread	split	fixed, asymmetric
source offset	64 m to 160 m	5 m to 600-900m

doubling the size of the seismograph's A/D converter also played a significant role in overall data quality improvements. The 1980 survey included 130 shot stations and took three days to acquire. In 2004 the survey included over 450 shot stations and took two days to acquire. Data were acquired between mile markers 177 and 181.

The basic architecture and sequence of processing steps followed during the generation of the final stacked sections was similar to conventional petroleum exploration flows (Yilmaz, 1987). All records and files from the 1980 survey for both data and processing flow and the ability to match display parameters were lost, so comparisons of processing approaches and steps are not possible. 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.

Discussion

Comparison of seismic data characteristics from the legacy and monitor seismic data clearly demonstrates the advancements in high-resolution shallow seismic reflection imaging in this extremely challenging setting. From the analog displays available for the 1980 survey it is possible to interpret the extent and degree of subsurface collapse at the time of the survey (Figure 2). In the 25 years following the 1980 survey the horizontal expression of the sinkhole has only increased slightly, but the character of the reflections from within the subsidence feature have changed dramatically.

The drop in dominant frequency and velocity beneath the sinkhole as well as the lack of consistency in wavelet character across the subsidence-affected area is indicative of changes in material above the salt (Figure 3). Major surface changes are related to KDOT filling the sinkhole twice prior to the 1980 survey and then once more between the 1980 and 2004 survey; however, these surface activities do not totally account for the kinds of changes observed on the seismic sections.

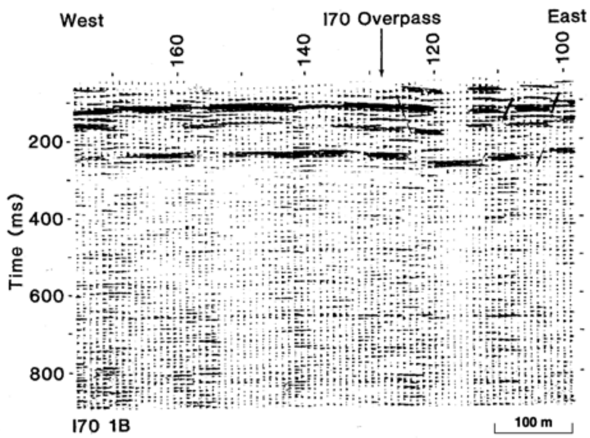

Figure 2. Interpreted seismic section from 1980 survey at the Crawford sinkhole located at station 110 (from Steeples et al., 1986).

Two of the three confirmed subsidence features have cone-like vertical development and notable seismic characteristics consistent with several unique paleosubsidence features discovered on a seismic reflection profile acquired 200 m away along the eastern dissolution front of the Hutchinson Salt (Figure 4). These paleosubsidence features appear near vertical on seismic data and have been interpreted as remnants of catastrophic collapse of overburden into naturally occurring salt dissolution voids.

There are notable differences between these two time-lapse seismic subsidence images, the most obvious being the degree of wavelet character change within the affected area (Figures 2 and 3). Also noteworthy are the relatively flat reflections within the subsidence feature that define a much larger subsurface-affected area than surface expression. This is also evident in the upward-narrowing disturbed zone defining the tensional dome. If the interpretation of paleocatastrophic failure is correct on reflection sections from the dissolution front (Figure 4), then wavelet stretching, cone-shaped geometry, and flat-laying reflections within the disturbed volume observed on seismic data from the Crawford/Witt sinkholes could be indicative of a slower rate of vertical rock movement into voids in the salt.

The cone-shaped appearance of the I-70 sinkholes on seismic data is consistent with active dissolution and subsidence as interpreted on several seismic investigations at similar sinkholes in Kansas. Based on a tensional dome failure mechanism, the two primary sinkholes at this site are still active with reverse faults defining the major collapse structures. Once horizontal roof rock failure of the salt interval slows or subsides, strain should begin to manifest itself as normal faults defining an ever-shallowing bowl structure. Subtle indications are evident in the salt overburden that this transition might have begun.

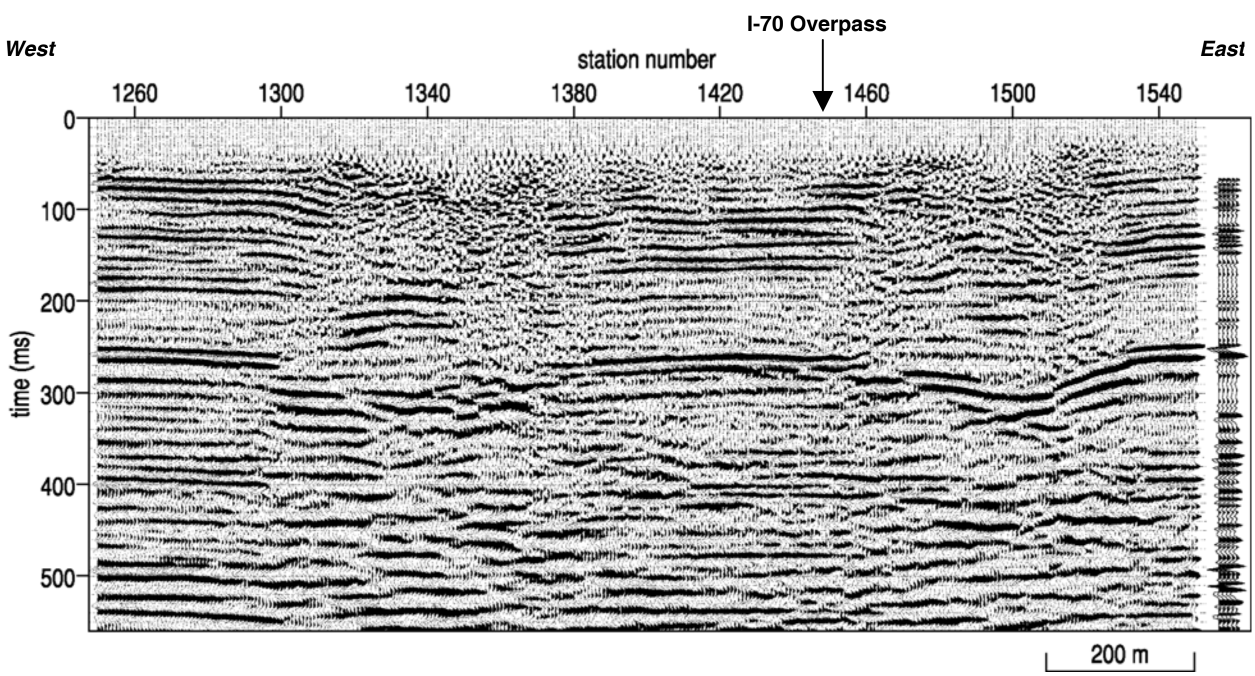

Figure 3. Witt sinkhole is located at station 1340 and the Crawford is at 1500. The high amplitude event at 260 ms is the 300-m deep Stone Corral Anhydrite. Top of salt is at about 340 ms and is approximately 400 m below ground surface. The synthetic at the right was used to verify reflection identification

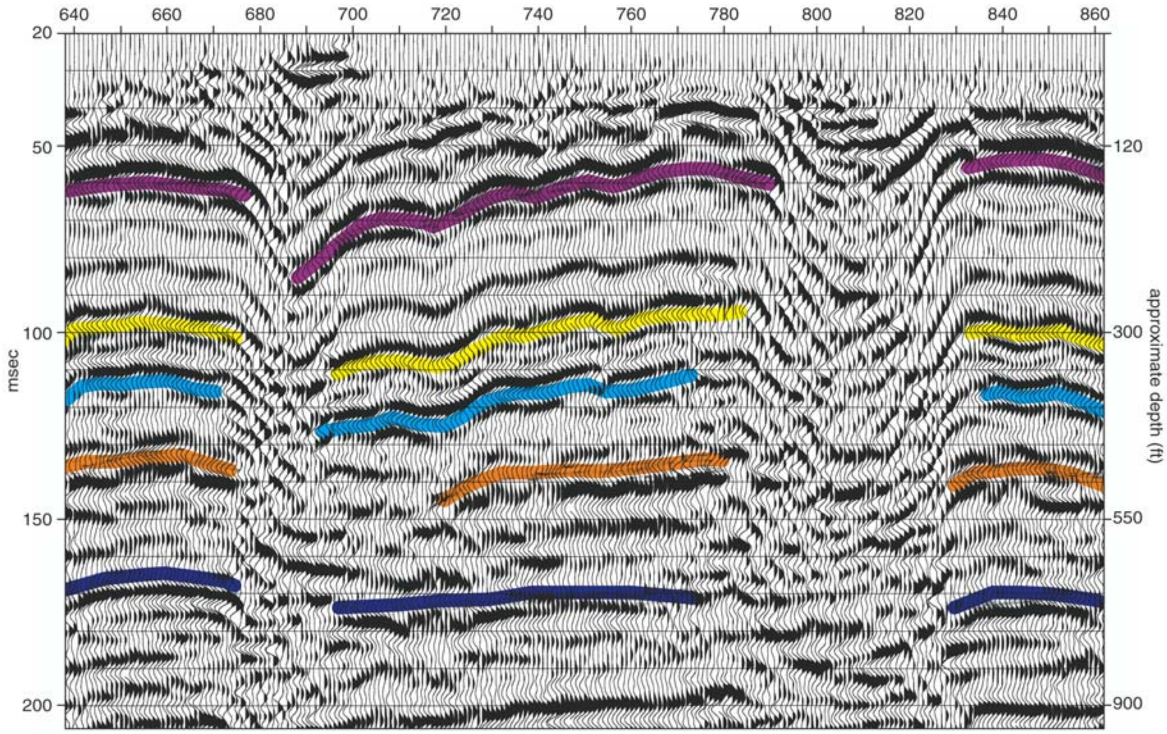

Figure 4. Seismic profile from along the eastern dissolution front of the Hutchinson Salt near Punkin Center in Reno County, Kansas.

Conclusions

An improved understanding of the subsidence process associated with failure of casing integrity was gained through seismic time-lapse investigations of the Witt, Crawford, and Rouback sinkholes beneath I-70. Improvements in methodology and equipment in the last 25 years for applications to near-surface high-resolution problems is clearly evident. It appears the dissolution process is still active at both the Crawford and Witt sinkholes and therefore the full surface expanse of these sinkholes is still unknown as well as a likely time-frame for surface stabilization.

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