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**HIGH-RESOLUTION SEISMIC REFLECTION  
INVESTIGATION OF A SUBSIDENCE FEATURE  
OF U.S. HIGHWAY 50  
NEAR HUTCHINSON, KANSAS**

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and  
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# HIGH-RESOLUTION SEISMIC REFLECTION INVESTIGATION OF A SUBSIDENCE FEATURE ON U.S. HIGHWAY 50 NEAR HUTCHINSON, KANSAS

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## Abstract

High-resolution seismic reflections were used to map the upper 150 m of the ground surface around and below an actively subsiding sinkhole currently affecting the stability of U.S. 50 highway in Reno County, Kansas. 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 the characteristically heavy commercial traffic load. 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 was constrained to a tensional dome 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.

Several episodes of subsidence are evident in most dissolution related features (current and paleo) imaged on these two 1 km long seismic profiles. The rate of destabilization and failure as well as the load bearing potential of the rock layers above zones of dissolution strongly influenced both the original subsidence geometries and dimensions as well as the subsequent reactivation of subsidence along the profiles. 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 bridging (roof rock) void or rubble areas that remained after the majority of the Tertiary to Quaternary subsidence had slowed or stopped could explain the most recent sinkhole development.

If salt dissolution has begun again at this site—anthropogenic or natural—it is not possible with these data alone to definitively identify a fluid source or pathway. However, with the superimposition of this modern sinkhole and the mid-Tertiary to early Quaternary subsidence feature, and considering the nearest disposal well with a history of fluid containment problems is more than 2 km away, the sinkhole is likely natural in origin. Unfortunately, considering the long history of oil field disposal well-induced dissolution in this area and the proximity of this particular site to the natural dissolution front, neither catalyst can be completely ruled out.

This study evaluated the effectiveness of using high-resolution vibroseis on the shoulder of U.S. 50 when traffic was slowed but not stopped. Previous data collected in this area was acquired 1.5 kilometers south along a quiet, east/west county road using a small recording channel seismograph and an invasive, low energy, impulsive source survey. Equivalent dominant frequencies were recorded on both surveys, but recent efforts resulted in significantly greater energy penetration and a signal-to-noise ratio that resulted in usable data regardless of cultural noise levels. The bed resolution, coherency of bedding within subsidence features, and overall signal-to-noise ratio were greatly improved using minivibroseis survey techniques.

## Introduction

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

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

Salt dissolution sinkholes are found in all areas of Kansas where the Hutchinson Salt is present in the subsurface. Sinkholes have been definitely correlated to failed containment of disposal wells injecting oil field brine wastewater using stem pressure tests and/or seismic reflection investigations at a variety of sites throughout central Kansas (Steeple et al., 1986; Knapp et al., 1989; Miller et al., 1995; 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., 1995a). The vast majority of published works studying the source of localized leaching of salt in Kansas directly contradict suggestions that recent land subsidence in Kansas is mostly natural in origin (Anderson et al., 1995a).

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

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

catastrophic subsidence rates are observed, failure within the salt is usually brittle with void area migrating to surface as an ever-narrowing cone with bed offsets and rock failure controlled by reverse-type fault planes (Davies, 1951; Walters 1980; Rokar and Staudtmeister, 1985).

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

Subsidence of U.S. 50 below construction grade at its intersection with Victory Road totaled 30 cm when first measured during a 1998 elevation survey. Routine elevation surveys conducted since that time have monitored the pattern and rate of subsidence. At an average subsidence rate of around 20 cm/yr, the highway surface at its centerline has sunk about 1 m since its construction. The current sinkhole is symmetric, with a very regular bowl-shaped geometry around 100 m in diameter that retains water most of the year.

The sinkhole is centered a few tens of meters to the northwest of the intersection. The symmetry and compact nature of the sinkhole as well as its subsidence rate is consistent with sinkhole formation conceptual models when salt is leached by borehole-released fluids (Miller et al., 1997). These similarities in geometry and subsidence rates raise suspicions that this feature might somehow be related to oilfield waste water disposal even though no records or surface installations exist to support that suggestion. Two seismic reflection profiles acquired orthogonally to each other and centered on the intersection of the highway and county road provided optimal coverage for mapping bed geometries, growth potential, and future surface footprint and for identifying structural characteristics that might someday put vehicle traffic at risk.

## Conclusions

Apparent undulations in the surface of the Hutchinson Salt layer could be indicative of dissolution features bridged by undisturbed rock layers with a span not yet sufficient for the accumulated load to instigate roof failure. Roof rock failure above these voids can proceed at varying rates and affect different portions of the overlying rock column. These undulations could also be indicative of changes in water chemistry (salinity) during or near the conclusion of salt deposition in this area. An apparent halt in the upward movement of a dissolution feature (downward movement of sediments) at the boundary between the Ninescah Shale and the Upper Wellington Shale could be a key indicator as to the effective unsupported span of roof rock these shallow shale layers can support.

With a subsidence history at this site potentially extending as far back as mid-Tertiary, it is unlikely subsidence will end within the next millennium. Until the highway started sinking at this location during 1998, little if any subsidence seems to have been associated with this paleosinkhole throughout late Quaternary. The long period of inactivity followed by the localized, rapid subsidence observed at this site suggests it is reasonable to expect other small sinkholes could form without warning above this paleofeature or other similar paleofeatures in this area. Considering the interpreted bed geometries, surface subsidence at the current sinkhole site will likely continue gradually along its northern and eastern edges, elongating the sinkhole in those directions. Besides the obvious disruption to the road system, unfortunately this subsidence feature provides a pathway between the fresh waters of the Equus Beds and the more brackish waters of the Permian. Surface subsidence will likely continue at a gradual rate for some time into the future. Sufficient bridging and undercompacted rock layers still exist beneath this sinkhole to sustain the current subsidence rate of around 0.3 m/yr for several years.

Interpretation of reflections from key stratigraphic horizons suggest plastic deformation of rock layers over dissolution voids was followed by roof rock failure along reverse fault planes within an earth volume known as the tension dome. The original tensional dome was centered on the dissolution volume and extended from the base of the salt interval to near the surface. A long period of relaxation of stress associated with layers outside the tensional dome occurred along normal fault planes for a significant portion of the late Tertiary and early Quaternary. A much smaller tensional dome located at the western extreme of the original tensional dome controls recent subsidence. Subsidence associated with failure defined by this most recent dome has followed a somewhat asymmetric path from salt to surface.

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