SHEAR-WAVE VELOCITY AS AN INDICATOR OF INCREASED STRESS AND FAILURE POTENTIAL ASSOCIATED WITH DISSOLUTION-MINING VOIDS

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Abstract

The use of dissolution wells for mining salt has been common practice for over a century, leaving behind brine-filled "salt jugs" or voids in the subsurface which, over time, can migrate through overlying rock formations, potentially leading to sinkhole formation and public safety hazards. In an effort to determine the relative range of stress on the roof rock above these jugs at various stages of failure, evaluate the extent of void migration, and aid in remediation planning, shear-wave reflection surveys were conducted at a well field near Hutchinson, Kansas, where drill-confirmed dissolution features exist in the 125-m deep Hutchinson Salt Member. Since shear-wave velocity (V_s) is directly related to stress through the shear modulus, V_s profiles were analyzed at known well locations to determine if measurable variations in velocity were consistent with zones likely experiencing elevated relative stress and therefore, increased failure potential. Changes in V_s upwards of 20% were observed along lines where voids were known to be present and had experienced significant migration into the shale cap rock. Localized velocity changes were coincident with the findings of drilling and associated borehole investigations. Alluvium velocities for the same lines remained relatively constant, suggesting that V_s changes are constrained to consolidated rock above mapped subsurface dissolution voids and are not related to depositional changes in the unconsolidated overburden.

Introduction

Dissolution mining of the Hutchinson Salt Member over the last century has left a number of brine-filled "salt jugs" or unstable voids in the subsurface that can eventually lead to sinkholes. The current condition of many of these jugs is unknown, warranting investigation to assure public safety now and in the future. Geophysical methods represent the only viable site-wide approach to characterizing the static condition of abandoned wells prior to drilling out the well plugs. Of the various surface geophysical approaches that have potential to detect these voids, seismic methods have the necessary theoretical resolution and sensitivity to be successful.

Previous studies have demonstrated the ability of seismic-reflection methods to image the subsurface expression of sinkholes and bedding geometries within the disturbed zone using compressional waves (Miller et al., 1993; Miller et al., 2005); however, no work has been done to evaluate void-induced changes in the localized stress field or the effect on seismic properties that may be indicative of near-term roof failure potential.

Four sites within an old North American Salt Company mine field located in Hutchinson, Kansas, were chosen to test the use of shear-wave reflection methods as a technique to discriminate locations with increased potential for roof failure based on documented subsurface conditions, confirmed through drilling and the use of sonar and acoustic televiewer. This paper shows that changes in shear-wave velocity correlate to known subsurface conditions and appear indicative of relative changes in effective stress in rock layers overlying subsurface voids. The shear-wave velocities calculated using normal moveout estimates of reflections may serve as a measure of risk for vertical migration through roof-failure.

Sinkholes resulting from subsidence within dissolution mine fields in and around the city of Hutchinson, Kansas, have been reported for over ninety years (Walters, 1978). Sinkholes related to solution mining of the Hutchinson Salt to date have formed as a result of roof failure associated with the single-well mining method. In general, the single-well method involves injecting fresh water near the base of the salt and recovering the brine solution near the top of the salt through a multi-plumbed borehole (Figure 1a).

Problems with the single-well method begin to occur as the volume of salt removed below shale or anhydrite stringers within the salt reaches a point where the unsupported span exceeds a distance their strength will endure (Figure 1a). Failure of these beds in proximity to the well bore generally results in rupture of the fresh-water tubing and upward movement of the dissolution zone (Figure 1b). Once the failure and collapse cycle reaches the shale cap rock, the process becomes much more horizontal (Figure 1c). If two wells with developing voids are in proximity, horizontal void migration may eventually lead to a breach forming what is called a gallery where the two voids become interconnected (Figure 1d). The downward-pointing arrows in Figure 1d indicate subsidence related to the gallery.

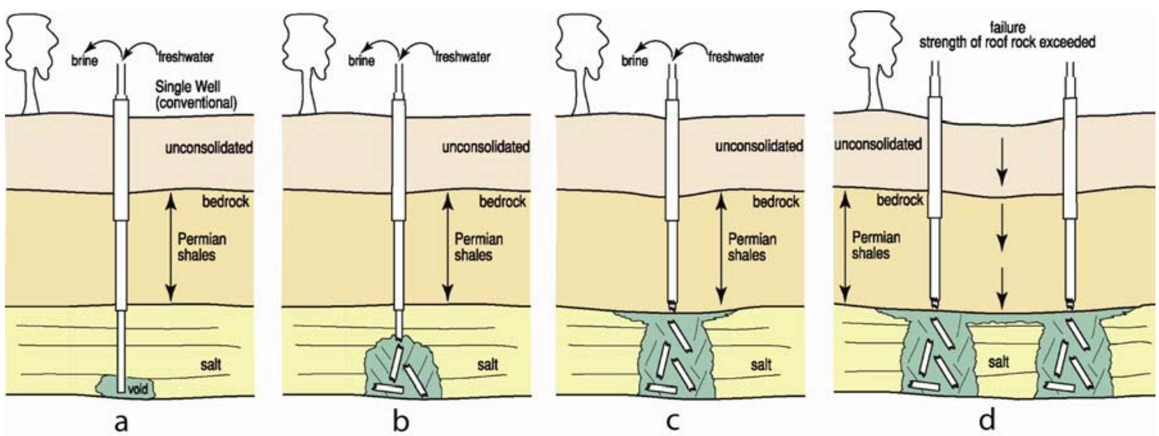

Figure 1. Illustration of void migration with the single-well mining method (a-c) and the formation of a gallery by two adjacent wells and associated voids (d).

When cap rock fails, vertical growth continues progressively upward layer by layer through the overburden as stress exceeds the strength in each successive unsupported span of new roof rock. Maximum potential vertical strain is limited by the void height. The void space available within the salt interval to accommodate roof collapse material is key to determining whether void movement through the entire overburden rock column proceeds as a rapid continuous process or in intermittent segments.

Geologic Setting

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. Near-surface materials at this site are comprised of ~20 m of Quaternary alluvium and unconsolidated Plio-Pleistocene Equus Beds. Bedrock is defined as the Ninnescah Shale, which overlies the ~5-m thick Three-Fingered Dolomite at a depth of ~70 m. The top of the Upper Wellington Shale is at ~75 m, followed by the top of the Hutchinson Salt at ~125 m.

Cap rock and its characteristics are a very important component of any discussion concerning dissolution, subsidence, and the formation of sinkholes. The Permian shales (Wellington and Ninnescah) that overlay the Hutchinson Salt are about 100 m thick in this area and are characterized as generally unstable when exposed to fresh water, being susceptible to sloughing and collapse (Swineford, 1955). These Permian shales tend to be red or reddish-brown and are commonly referred to as "redbeds." Permian redbeds are extremely impermeable to water and have provided an excellent seal between the freshwaters of the Equus beds and the extremely water soluble Hutchinson Salt.

Isolating the basal contact of the Wellington Shale provides key insights into the general strength of roof rock expected if dissolution-mined salt reach the top of the salt zone. Directly above the salt-shale contact is an approximately 6-m thick dark-colored shale with halite-filled joint and bedding cracks (Walters, 1978). Once unsaturated brine comes in contact with this shale layer, joints and bedding plains are rapidly leached, leaving an extremely structurally weak layer. It is not surprising that failure of roof rock is common in this area.

Stress-Velocity Relationship

Changes in shear-wave velocity are a key indicator of either previous subsidence activity or areas where voids have a strong potential for roof collapse. Shear-wave velocities are calculated from material responses to stress and strain. Since failure of consolidated rock is related more to the matrix than the pore conditions, monitoring changes in the shear-wave velocity should represent a highly sensitive method of detecting load-related changes in stress. Changes in V_s for a particular rock are related to differential stress and associated non-linearity in the stress-strain curve (Dvorkin et al., 1996).

Shear-wave velocity can be expressed as:

$$V_s = \sqrt{\frac{\mu}{\rho}} \, ,$$

where μ represents the shear modulus and ρ is the bulk density. Assuming that density remains constant, V_s is controlled by the shear modulus, which is the change in force across a unit area (stress) divided by the lateral change in cross-section for a given length (strain), expressed as:

$$\mu = \frac{\sigma}{\gamma} = \frac{\Delta F / A}{\Delta L / L} \, .$$

For a given material the shear modulus is assumed to remain constant under static pressure and within the elastic deformation portion of the stress-strain curve (Figure 2).

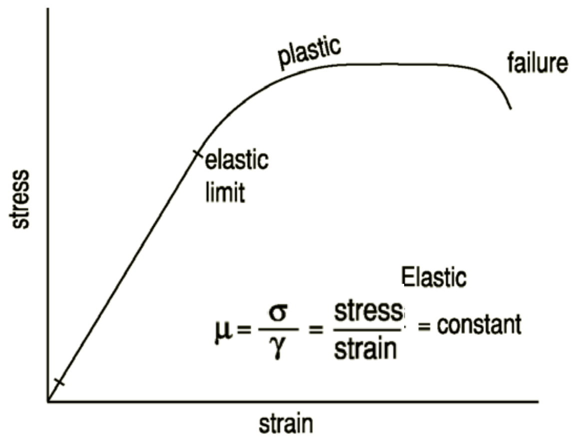

Figure 2. General stress-strain curve illustrating the elastic limits, plastic deformation, and failure for a given material.

Laboratory measurements of compressional and shear-wave velocities show marked, non-linear increases with increased confining stress (Khaksar et al., 1999). These measured changes in velocity of samples suggest variations in effective stress, like variations that would be present above a void with a large roof span or a reservoir under production pressures, could cause significant changes in velocity of the affected rocks. Carrying the confining stress to the logical extreme introduces plastic deformation and failure (Figure 2). At this end of the stress-strain curve, the strain response to small changes in stress is substantial. Shear-wave velocity is reduced when mechanical damage occurs in the rock as a result of stress-induced plastic deformation (Winkler, 2005).

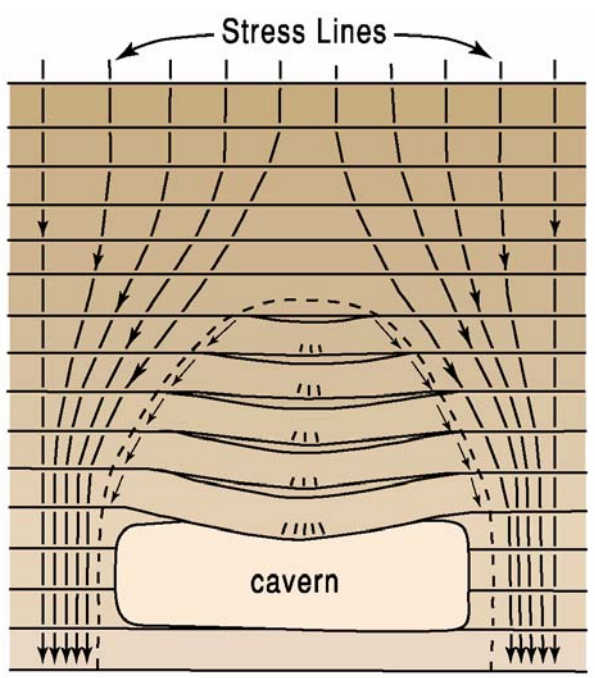

Figure 3. Tensional dome and distribution of stress lines around a cavern opening in horizontal strata (modified from Davies, 1951).

Once subsidence has resulted in sufficient strain to produce plastic deformation or failure, a notable localized decrease in V_s is likely to be observed. Conversely, localized increases in V_s are observable as effective stress associated with the tension dome surrounds subsurface cavities increases due to the increased load on the void walls (Figure 3).

The strength of individual rock layers can be qualitatively described in terms of stiffness or rigidity and empirically estimated from measurements of V_s. Shear-wave velocity is directly proportional to stress and inversely related to strain. Since the shear-wave velocity of earth materials changes when the stress on those materials becomes relatively large, it is reasonable to suggest that load-bearing roof rock above dissolution voids may experience elevated shear-wave velocities due to loading between load-bearing side walls (Figure 3). This localized increase in V_s is not related to increased strength, but is instead caused by increased load. High shear-wave velocity “haloes” are likely key indicators of near-term roof failure.

Methods

Downhole Velocity

A downhole seismic survey was used to obtain a one-dimensional velocity profile that tied reflectors to surface-seismic velocity measurements. A three-component borehole geophone was used to collect data at ~6-m intervals beginning at a depth of ~114 m. A sledgehammer impacting a steel plate and shear-wave block were used as the energy sources to generate five stacks each of vertical-, transverse-, and radial-component data at each spatial sample interval. Figure 4 shows an example plot of the downhole data and average velocity-depth profile resulting from the first-break picks. The downhole velocity profile and borehole data were used to generate synthetic seismograms representative of the site geology. The forward model aided in the design of data acquisition parameters and interpretation of common-source gathers.

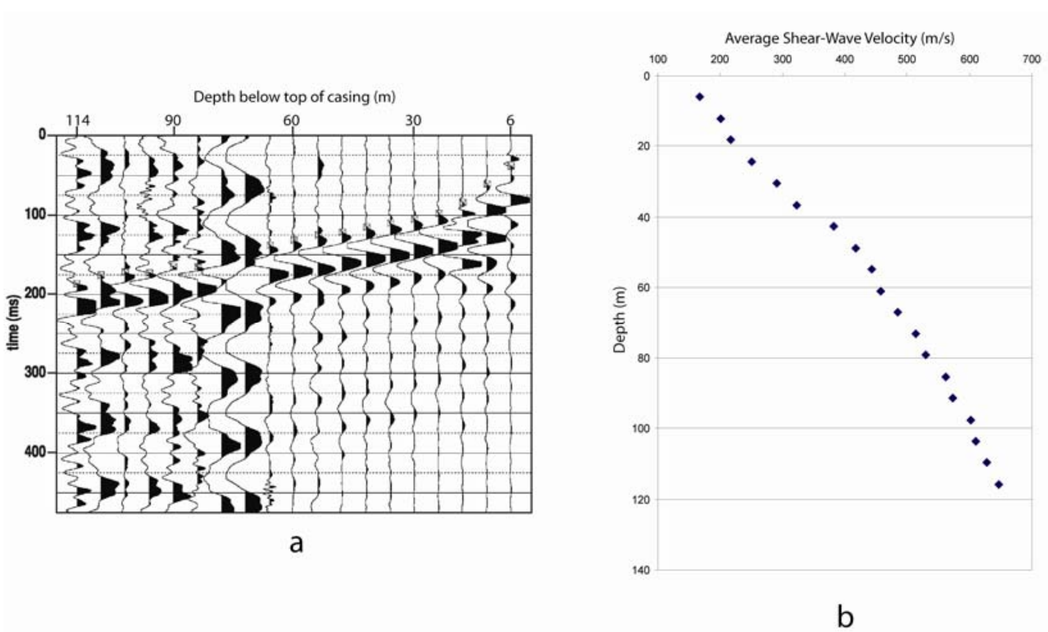

Figure 4. Downhole data (a) used to determine the average shear-wave velocity with depth (b).

Seismic Reflection

Maximum 120-fold common-midpoint (CMP), horizontally polarized shear-wave (S_H) reflection profiles were acquired along two lines at each well location with different known subsurface conditions.

A fixed 239-m spread of 240 14-Hz horizontal-component geophones planted on 1-m spacings was deployed along each line. An IVI Mini-Vibe I with a horizontally oriented mass and waffle-style base plate served as the source of three 10-s long linear upsweeps ranging from 15–150 Hz recorded at each source location. The source walked through the spread with shot points spaced 2 m apart. Data were recorded using four networked 60-channel Geometrics StrataView seismographs with 24-bit A/D conversion. The sampling interval was 1 ms producing record lengths of 12 s. Positioning of the lines was restricted by surface obstacles and access constraints, necessitating less than ideal locations for some receiver spreads. Data were acquired along lines bulldozed to remove brush and the upper few inches of soil. This line preparation greatly improved geophone and source coupling and subsequent data quality.

Data Processing

CMP data were processed according to a generalized processing flow using techniques commonly applied to near-surface seismic-reflection data (Figure 5). Large vertical changes in normal-moveout (NMO) velocity ranging from ~200 m/s in the unconsolidated overburden to ~550–650 m/s in the Ninnescah Shale necessitated the use of offset-dependent subsets to achieve optimal reflector imaging. Steeply dipping, low-velocity reflections often require severe stretch muting to avoid stacking low-frequency stretched portions of the wavelet following NMO corrections (Miller, 1992), which will eliminate valuable reflection information from deeper reflecting events, leading to poorer S/N and degraded images (Miller and Xia, 1998). The data were divided into near- and far-offset subsets, separating the bedrock reflection (nears) from the dolomite and salt reflections (fars). Each subset was NMO corrected independently and then recombined into a single data set prior to CMP sorting and stacking.

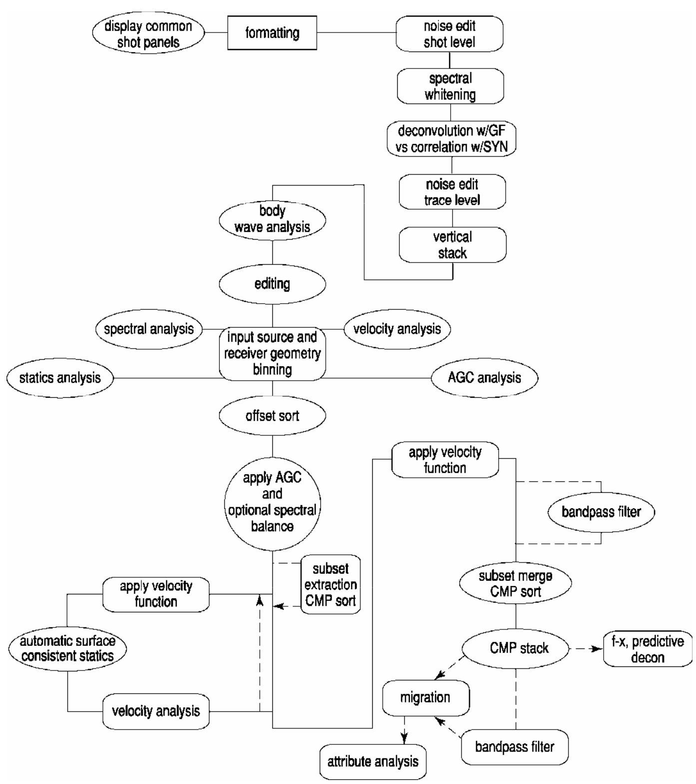

Figure 5. Generalized flow used to process the shear-wave reflection data.

Results

Comparison of a synthetic seismogram, generated using the down-hole seismic information, with a raw common-source gather from the reflection survey provides conclusive verification of both the presence of reflections and the match between borehole-measured velocity and NMO velocity (Figure 6). Reflections from the tops of the Ninnescah Shale, Three-Fingered Dolomite, and Hutchinson Salt are indicated by the arrows and correlate very well with the synthetic data and drill records. P-S converted energy is also observable between the bedrock and dolomite reflections at ~350 ms.

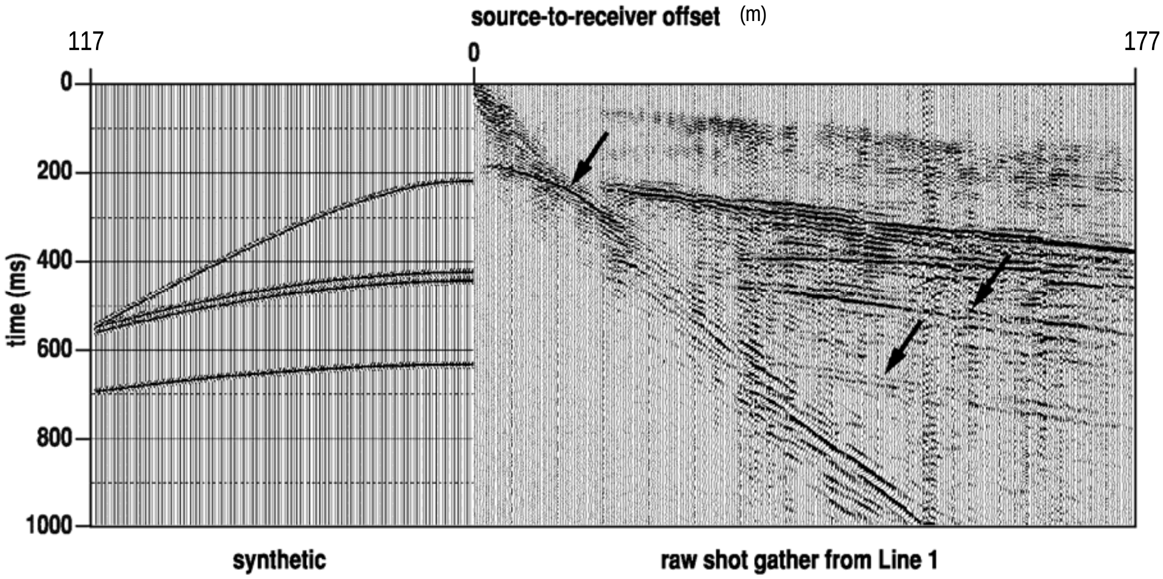

Figure 6. Comparison of a synthetic gather (left) created using velocities from the downhole data and a raw shot gather (right) from Line 1. Reflections from the Ninnescah Shale, Three-Fingered Dolomite, and the Hutchinson Salt are indicated by the arrows.

The data in Line 1 (Figure 7) were collected over an area representing native conditions unaffected by void-induced changes in the localized stress field. Line 5 (Figure 8) was collected over an area with known voids in the subsurface where vertical migration had progressed upward through the Upper Wellington Shale. Both the presence and extent of the void would be expected to cause a relative increase in the effective stress manifested as changes in the shear-wave velocity of the overlying materials.

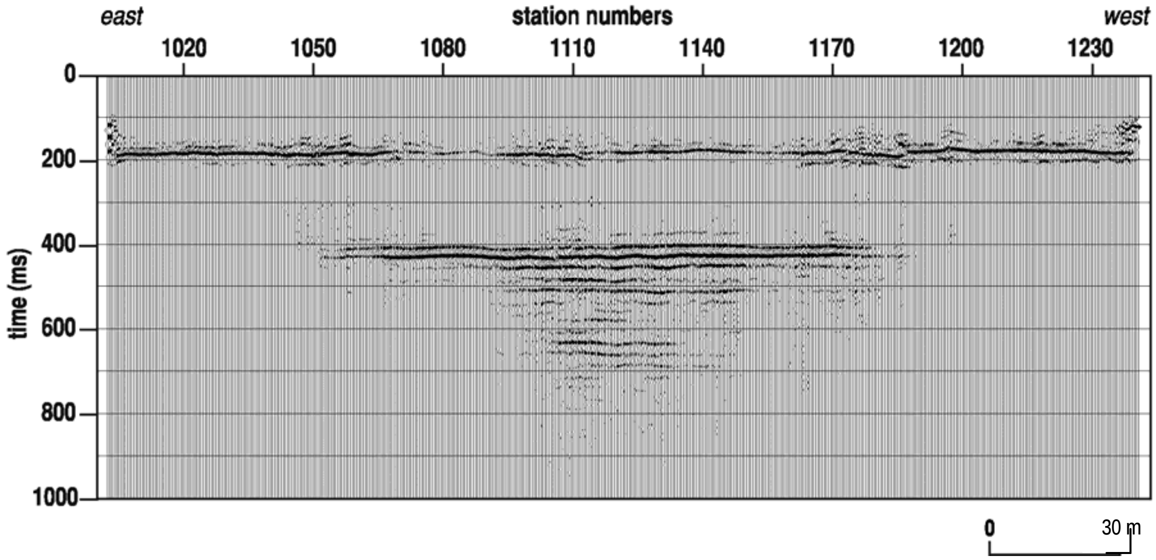

Figure 7. Stacked S_H reflection section from Line 1 acquired over an area representative of native subsurface conditions. Reflections can be observed from the top of the Ninnescah Shale (~180 ms), the Three-Fingered Dolomite (~410 ms), and the top of the Hutchinson Salt (~650 ms).

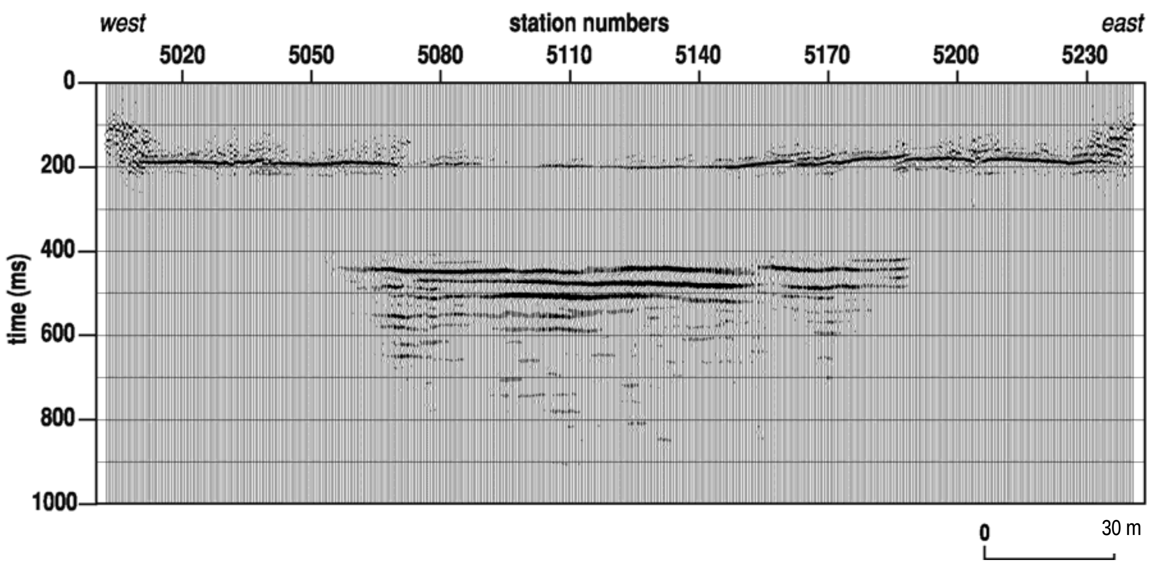

Figure 8. Stacked S_H reflection section from Line 5 acquired over an area where subsurface voids are known to exist. Reflections can be observed from the top of the Ninnescah Shale (~190 ms) and the Three-Fingered Dolomite (~440 ms). The gap in the bedrock reflection is due to a lack of subsurface coverage where a drainage ditch crossed the line.

The decreasing lateral extent of the reflections with depth is a consequence of the fixed receiver spread where the longer offsets required to image deeper reflectors are not recorded as the source was in the middle of the line. NMO velocities were picked at every 10^{th} CMP location using constant velocity stacks with 10 m/s steps and unstacked curve fitting. Figure 9 is a plot of NMO velocities for the bedrock and dolomite reflections along Lines 1 and 5. Of particular interest is the discrepancy between the NMO velocities from the dolomite reflection in Lines 1 and 5, representing a change upwards of 20%. The velocity of the unconsolidated overburden remains relatively constant between the two lines, suggesting the observed change in dolomite reflection velocity is related only to changes in the Ninnescah Shale with no influence from overlying unconsolidated sediments.

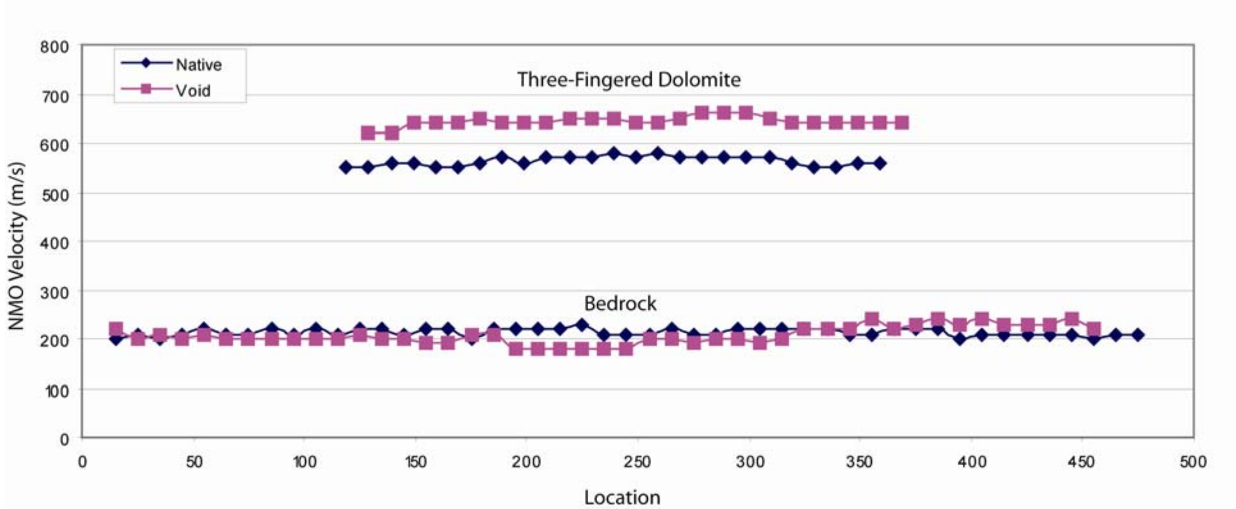

Figure 9. Plot of shear-wave NMO velocities for the Three-Fingered Dolomite and bedrock reflections for lines acquired over native conditions (blue) and over known voids.

At least one void is known to have migrated into the Upper Wellington Shale along Line 5. Several other wells are also located adjacent to the seismic line that are of the same construction and vintage. The elevated velocity along the entire line suggests that more than one void may be influencing the velocity measurements. A localized velocity increase is observed between locations 275–300, which is coincident with the location of a dissolution well. This particular well has not been drill-investigated to determine the condition of the borehole or location/condition of a jug, but results of the seismic investigation suggest the presence of elevated stress conditions indicative of an upward migrating void.

Conclusions

Lateral variability in the velocity gradient can theoretically be related to changes in stress field as defined by principles governing the elastic moduli in rocks. Reflection data from this study are the first known to provide empirical evidence relating the changes in stress associated with the tensional dome concept of Davies (1951) to non-invasively measured shear-wave seismic-reflection velocities. These reflection data provide some of the most conclusive evidence for the feasibility of direct detection of salt jugs from surface geophysics. Variations in shear-wave velocity correlate to areas where jugs have migrated above the Upper Wellington Shale-Hutchinson Salt contact. These changes are likely diagnostic of changes in rock properties or layer geometry related to voids. For shear-wave seismic reflection to be a viable method to characterize the degree of change in stress associated with a single cavern at this site, resolution must be improved and velocity discrimination techniques must be developed that can isolate changes in shear velocity to sub-optimum offset distances.

References

Davies, W. E., 1951, Mechanics of cavern breakdown: *National Speleological Society*, v. 13, 6-43.

Dvorkin, J., A. Nur, and C. Chaika, 1996, Stress sensitivity of sandstones: *Geophysics*, v. 61, 444-455.

Khaksar, A., C. M. Griffiths, and C. McCann, 1999, Compressional- and shear-wave velocities as a function of confining stress in dry sandstones: *Geophysical Prospecting*, v. 47, p. 487-508.

Miller, R. D., J. Ivanov, D. W. Steeples, L. W. Watney, and T. R. Rademacker, 2005, Unique near-surface seismic reflection characteristics within an abandoned salt-mine well field, Hutchinson, Kansas: 75th Annual Meeting, Expanded Abstracts, SEG, 1041-1044.

Miller, R. D., and J. Xia, 1998, Large near-surface velocity gradients on shallow seismic-reflection data: *Geophysics*, v. 63, 1348-1356.

Miller, R. D., D. W. Steeples, L. Schulte, and J. Davenport, 1993, Shallow seismic-reflection feasibility study of the salt dissolution well field at North American Salt Company's Hutchinson, Kansas, facility: *Mining Engineering,* October, 1291-1296.

Miller, R. D., 1992, Normal moveout stretch mute on shallow-reflection data: *Geophysics*, v. 57, 1502-1507.

Swineford, A., 1955, Petrography of upper Permian rocks in south-central Kansas: State Geological Survey of Kansas Bulletin 111, 179 p.

Walters, R. F., 1978, Land subsidence in central Kansas related to salt dissolution: Kansas Geological Survey Bulletin 214, 82 p.

Winkler, K.W., 2005, Borehole damage indicator from stress-induced velocity variations: *Geophysics*, v. 70, n. 1, p. F11-F16.

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