Passive Seismic Characterization of High Priority Salt Jugs near the Irsik & Doll Elevator in Hutchinson, Kansas

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Preliminary Report to

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Executive Summary

This applied research project correlated measured shear-wave velocities with the condition of rock above dissolution voids, targeting the stress as approximated from the shear-wave velocity of the overburden. Shear-wave velocities were estimated during this study using passive surface wave methods with data acquired along two profiles located on or near two key abandoned brine production wells. Multichannel analysis of surface waves (MASW) was used to estimate the shear-wave velocity, loosely map stratigraphic contacts above the top of the "three finger" dolomite, and evaluate the relative difference in the rock above possible salt jugs associated with the wells compared to rocks above undisturbed salt. Comparison of shear-wave velocity profiles over time (time lapse) was used to provide insight into void dynamics and overburden stability.

Passive MASW profiles were acquired during one night of data collection near the Irsik & Doll grain elevator in Hutchinson, Kansas, on May 28, 2015. Two lines and a 2-D grid of receivers were positioned over wells 2A and 4B. Continuous sampling was utilized to record and allow for evaluation of all available sources of passive source energy, ensuring optimal source orientation and surface wave characteristics for each line. Surface waves with frequencies as low as 4 hertz (Hz) were recorded with an average depth of investigation 65 meters (m), and in some places exceeding 80 m, successfully sampling deep beneath the bedrock surface at a depth of around 20 m.

With shear-wave velocity being a function of shear modulus and density, and the shear modulus is the ratio of stress over strain, it is possible to estimate relative stress of overburden rocks (shear modulus) by shear velocity values. Local increases in shear velocity without changes in lithology can be equated to increased stress associated with overburden roof load over dissolution jugs. Relative shear velocity lows may be associated with collapse features whose vertical movement has been arrested by bulking, reduced stress to within roof rock strength, or changes in strength due to geologic features related to natural variation in deposition or erosion.

The suppression of the increased velocity zone (inversion) above the low velocity area overlying the void in well 2A (as was observed in the November 2014 study) and the well defined reduced velocity zone, consistent with that previously observed on line 11(during November 2014 survey), suggests that incremental change of some kind appears to have reduced the strength and/or redistributed stress in the overburden above this void since the November 2014 survey. This change in strength or stress appears to be limited to depths of 25 m (~10 m beneath the top of bedrock) and greater.

Lack of a marked difference in the surface wave dispersion patterns over well 2A in the six months since the November 2014 survey suggests that the significant change that occurred in the subsurface between March 2013 and November 2014 was real. The disturbed zone from around 25 m below ground surface down to the maximum sampling depth of this study appears to have stabilized since the November 2014 survey with what appears to be only subtle redistribution of stress above the void since that time. A reduction in apparent velocity, relative to the November 2014 study, is observed in bedrock between wells 2A and 4B. However, the velocity trend south of well 4B is consistent with the baseline survey in March 2013, suggesting a normal/stable stress regime. Reduced velocity between the wells may be related to interference of multiple surface wave modes in this transition zone from low velocity at well 2A to normal velocity south of well 4B. Future monitoring at well 4B will be necessary to improve confidence in this interpretation.

Introduction

Material properties (specifically strength and stress accumulations) measured as a function of depth above abandoned salt jugs in Hutchinson, Kansas, appear related to the mobility and upward migration potential of these jugs. Localized escalation in stress (as indicated by increased shear-wave velocity) above subterranean voids is one indicator of an increased potential for roof failure and void migration (Eberhart-Phillips et al., 1989; Dvorkin et al., 1996; Khaksar et al., 1999; Sayers, 2004). Previous studies, using both active and passive seismic wavefield characteristics, suggest perturbations in the shear-wave velocity field immediately above voids can be correlated to characteristics of the unsupported roof spans of salt jugs in the Hutchinson area (Sloan et al., 2010).

The strength of individual rock layers can be qualitatively described in terms of stiffness/rigidity and empirically estimated from relative comparisons of shear-wave velocity measurements. Shear-wave velocity is directly proportional to stress and inversely related to non-elastic strain. Since the shear-wave velocity of earth materials changes when stress and any associated elastic strain on those materials becomes "large," it is reasonable to suggest load-bearing roof rock above mines or dissolution voids may experience elevated shear-wave velocities due to loading between pillars or, in the case of voids, loading between supporting side walls. This localized increase in shear velocity is not related to increased strength, but increased load as defined by Young's Modulus. High-velocity shear-wave "halos" encompassing low-velocity anomalies are suggested to be key indicators of near-term roof failure. All these phenomena have been observed within the overburden above voids in the Hutchinson Salt Member in Hutchinson at depths greater than 30 m below the bedrock surface.

Previous research projects at the Carey Boulevard Research Area (CBRA) correlated measured shear-wave velocities with the condition of dissolution voids and the physical properties of the overburden at selected locations on Vigindustries legacy solution mining property in Hutchinson. Shear-wave velocities were estimated from passive surface-wave data acquired along eight profiles that intersected 13 wells. Two of these 13 wells had been the target of a previous seismic investigation completed in 2008. As a result of that 2008 study it was determined that the integrity of the overlying strata could be reasonably estimated using shear-wave seismic imaging. The 2008 study quantified the effectiveness of shear-wave velocity to estimate local stress above voids of the size and depth prevalent at the Vigindustries site.

The lack of necessary ultra low-frequency surface waves in the recorded wavefield have negated attempts to use active source multi-channel analysis of surface waves (MASW) to estimate shear velocity in the lithified rocks near the top of bedrock (Miller et al., 2009). Uncontrolled, local industrial and transportation activities represent sound sources that have produced the necessary low frequencies and, when recorded and processed using passive methods, have extended the imaging depth to over 60 m (Miller, 2011). Key to this method is the ability to estimate shear-wave velocities to depths more double those possible with standard active sources at a particular site (Park et al., 2004). Results of passive MASW studies near this site suggest that this method is effective in identifying jugs with heightened risk for upward migration (Miller, 2011; Ivanov et al., 2013).

Wells 2A and 4B are located in proximity to the Irsik & Doll grain elevator. Three previous surveys were acquired at approximately 8-month intervals over these wells: August 2012 (well 2A only), March 2013, and November 2014. Passive MASW processing resulted in three two-dimensional (2-D) shear-wave velocity (Vs) profiles. Individually, each profile represents a snapshot in time that lacks any measure of the dynamics of void migration or change in time. A relative decrease in Vs centered on well 2A between March 2013 and November 2014 suggests a possible reduction in shear strength of the overlying bedrock (Peterie et al., 2015). In this study, two additional lines centered at well 2A were acquired to monitor for and evaluate further changes in Vs, and provide insight into void dynamics and overburden stability.

Geologic and Geophysical 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 (Figure 1). In Kansas, the Hutchinson Salt Member possesses an average net thickness of 75 m and reaches a maximum of over 150 m in the southern part of the basin. Deposition occurring during fluctuating sea levels caused numerous halite beds, 0.2 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).

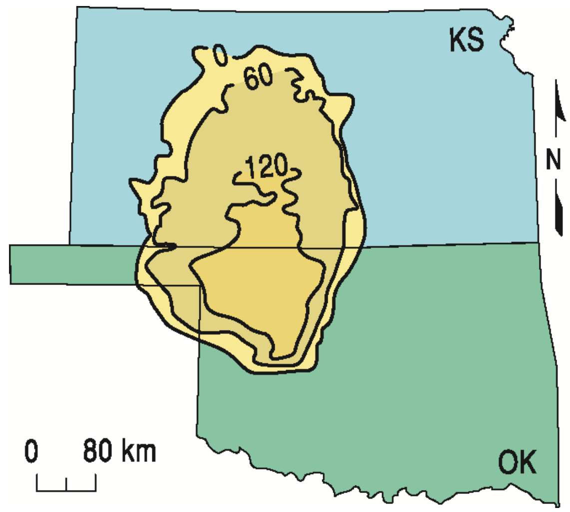

Figure 1. Approximate extent of salt formation, with contour intervals expressed in meters.

The distribution and stratigraphy of the salt is well documented (Dellwig, 1963; Holdoway, 1978; Kulstad, 1959; Merriam, 1963). The salt reaches a maximum thickness in central Oklahoma and thins to depositional edges on the north and west, erosional subcrop on the east, and facies changes on the south. The increasing thickness toward the center of the salt bed is due to a combination of increased salt, and more and thicker interbedded anhydrites. The Stone Corral Formation (a well-documented seismic marker bed) overlies the salt throughout Kansas (McGuire and Miller, 1989). Directly above the salt at this site is a thick sequence of Permian shale.

The upper 760 m of rock at this site is Permian shale (Merriam, 1963). The Chase Group (top at 300 m deep), lower Wellington Shale (top at 245 m deep), Hutchinson Salt (top at 120 m deep), upper Wellington Shale (top at 75 m deep), and Ninnescah Shale (top at 25 m deep) make up the packets of reflecting events easily identifiable and segregated within the Permian portion of the section (Figure 2). Bedrock is defined as the top of the Ninnescah Shale with the sediment. The thickness of Quaternary alluvium that fills the stream valleys and paleo-subsidence features goes from 0 to as much as 90 m, depending on the dimensions of the features.

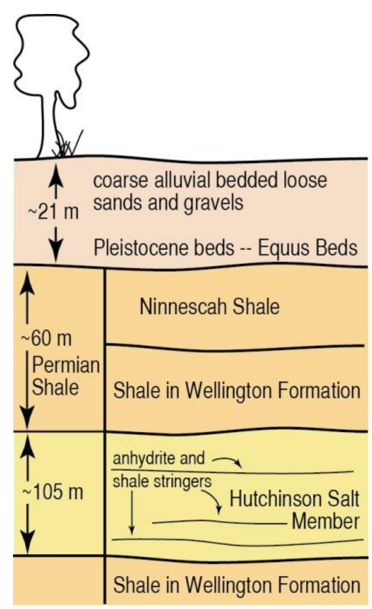

Figure 2. Generalized geology.

Recent dissolution of the salt and resulting subsidence of overlying sediments forming sinkholes has generally been associated with mining or saltwater disposal (Walters, 1978). Historically, these sinkholes can manifest themselves as a risk to surface infrastructure. The rate of surface subsidence can range from gradual to very rapid. Besides risks to surface structures, subsidence features potentially jeopardize the natural segregation of ground-water aquifers, greatly increasing their potential to negatively impact the environment (Whittemore, 1989; 1990). Natural sinkholes resulting from dissolution of the salt by localized leaching within natural flow systems which have been altered by structural features (such as faults and fractures) are not uncommon west of the main dissolution edge (Merriam and Mann, 1957).

Caprock and its characteristics are a very important component of any discussion concerning dissolution, subsidence, and formation of sinkholes. The Permian shales (Wellington and Ninnescah) that overlay the Hutchinson Salt Member are about 60 m thick in this area and are characterized as generally unstable when exposed to freshwater, being susceptible to sloughing and collapse (Swineford, 1955). These Permian shales tend to be red or reddish-brown and are commonly referred to as "red beds." Permian red beds 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 Member. The modern-day expanse and mere presence of the Hutchinson Salt is due to the protection from freshwater provided by these red beds.

Isolating the basal contact of the Wellington Formation provides key insights into the general strength of roof rock expected if dissolution-mined salt jugs (salt jugs are the jug-shaped cavities or voids in the salt that form after salt has been dissolution mined in proximity to the wells) reach the top of the salt zone. Directly above the salt/shale contact is approximately 6 m-thick dark-colored shale with joint and bedding cracks filled with red halite (Walters, 1978). Once unsaturated brine comes in contact with this shale layer, these red halite-filled joints and bedding planes are rapidly leached, leaving an extremely structurally weak layer.

Field Layout and Data Acquisition

To ensure the highest quality data, receivers were deployed during the day and train data were recorded at night when cultural and industrial noise was minimal to provide optimum signal-to-noise. Analysis of the previous seismic energy sources captured during passive recording at this site clearly indicated trains from a distance of 3 kilometers (km) or more away provided the best broad spectrum, low-frequency seismic energy (Miller, 2011). Because seismic energy with characteristics best suited for the purpose of this study may arrive when trains are at a distance greater than they can be detected by spotters, seismic records were recorded continuously during acquisition to ensure that optimum data was recorded.

Data were acquired over the course on the night of May 28, 2015. Two seismic lines were deployed directly over well 2A and near well 4B, as well as a 2-D grid of receivers to monitor passive seismic energy (Figure 3). Seismic receivers were single GeoSpace GS11D 4.5 Hz geophones spaced at 3 m intervals. The seismic lines totaled approximately 0.5 km in length. The 2-D monitoring grid consisted of 144 receivers spaced at 5 m intervals and was configured to form four concentric expanding squares with 10, 30, 50, and 70 m sides. Data were recorded during one night with a 300+ channel 24-bit Geometrics Geode distributed seismic system. Seismic records were 30 seconds (s) long with a 2 millisecond (ms) sampling interval. In total, 916 seismic records equivalent to 16.1 gigabytes (Gb) of data were recorded.

Figure 3. Aerial photo with GPS locations of seismic lines and wells in the study area.

Processing and Analysis

Data were processed using algorithms developed at the Kansas Geological Survey (KGS). The passive method used for this study is well published and provides good quality results at a similar nearby site (Park et al., 2004; Ivanov et al., 2013). Continuous data acquisition records energy from nearby energy sources at various orientations with respect to the seismic line. The 2-D grid was deployed to evaluate and optimize source alignment with respect to each 1-D seismic line to effectively identify void roofs with elevated stress and an elevated risk of vertical migration.

For each line, the surface wave amplitudes recorded by the 2-D grid were plotted as phase velocity versus frequency for a range of azimuths from 0 to 360 degrees with respect to the seismic line to determine which record had the best broad band, low frequency source with an azimuth near parallel to the line (Figure 4). The seismogram with optimum source characteristics was selected and divided into the shortest groups of receivers ("spread length") which provided dispersion patterns on phase velocity versus frequency plots with high amplitude fundamental mode Rayleigh wave energy and minimal higher-order surface wave interference

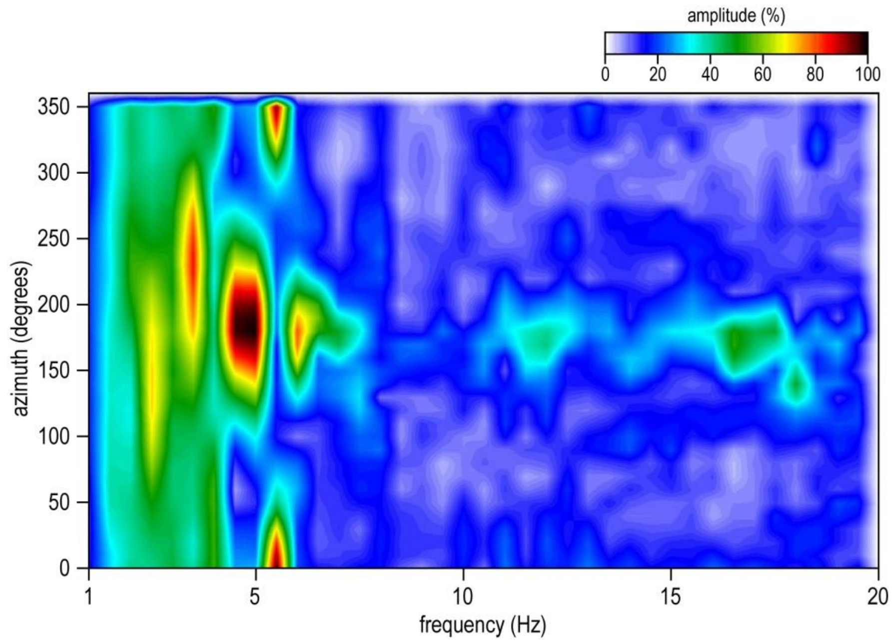

Figure 4. Azimuth plot indicating the direction of the dominant passive source energy (in degrees counter-clockwise from east). Here, the dominant passive source energy is centered on approximately 180°.

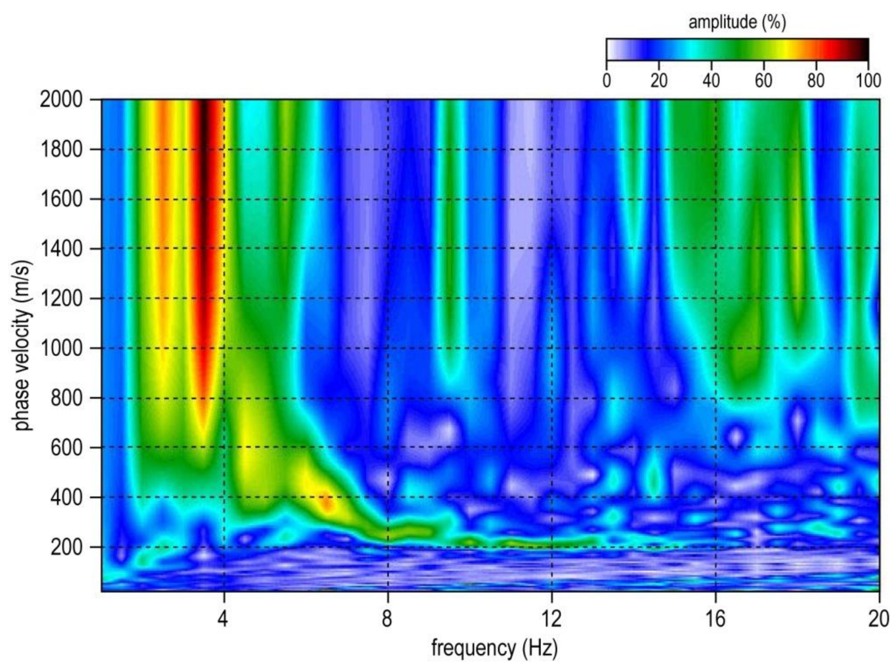

Figure 5. Dispersion pattern with high signal-to-noise ratio of the fundamental mode Rayleigh wave.

(Figure 5). Fundamental mode dispersion curves were picked and inverted to obtain a 2-D section of shear-wave velocity as a function of depth. The apparent velocity (v_{app}) is:

$$v_{app} = \frac{v_{act}}{(\cos\theta)} \tag{1}$$

where v_{act} is the actual seismic velocity and θ is the azimuth of the source with respect to the seismic line determined from the azimuth versus frequency plot. Thus, the increase in velocity (Δv) is:

$$\Delta v = \frac{1}{\cos\theta} - 1 \tag{2}$$

Equation 2 was used to calculate the increase in velocity due to the source azimuth for each line (Table 1).

Table 1. Directions of the passive seismic sources and the seismic lines (in degrees counterclockwise from east), the angle of the source with respect to the line (θ), and the percent increase in apparent velocity (Δv) attributable to oblique source orientations.

	source orientation	line orientation	θ	Δv
line 10	163°	160°	3°	< 1%
line 11	180°	175°	5°	< 1%

Results and Observations

Line 10 is oriented W-E and is centered on well 2A, located at station 10042. The velocity of the upper layer is approximately 175 meters per second (m/s) (Figure 6a), which is consistent with the shear-wave velocity of unconsolidated sediment. The velocity gradient at approximately 15 m depth is indicative of top of bedrock. An approximately 20% decrease in Vs

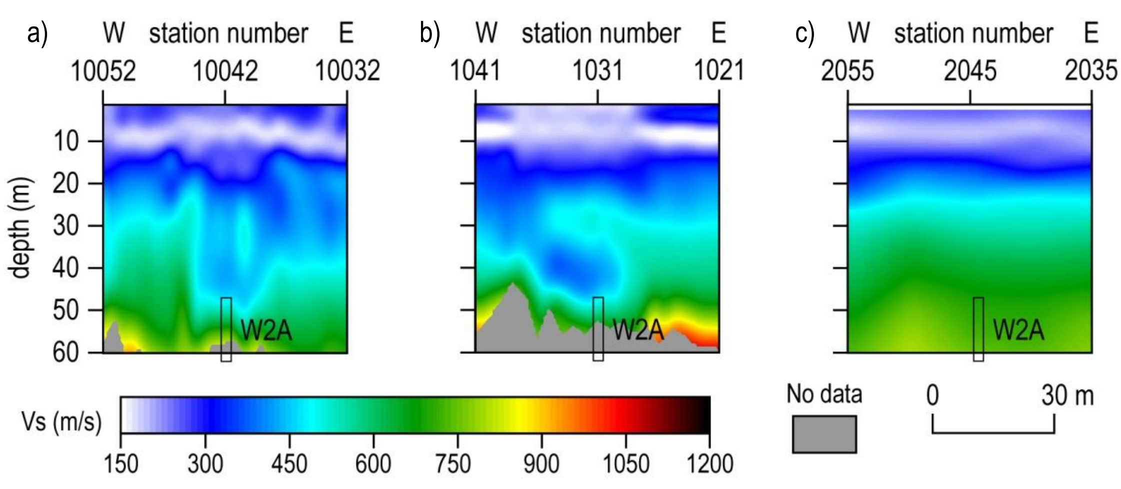

Figure 6. Shear-wave velocity profile of line 10 from (a) the present study, (b) November 2014, and (c) the baseline study in March 2013. Approximate well locations are indicated at the bottom of the profile.

relative to adjacent stations is observed at a depth of 35-50 m from stations 10038-10045, centered at the location of well 2A. An apparent increase in depth to bedrock is also observed within this range of stations. Dispersion patterns across the line are relatively consistent within the frequency range that corresponds to the top of bedrock (approximately 8 Hz). Although variability in the top of bedrock above well 2A cannot be ruled out, the apparent variability is low confidence and may be an artifact of the inversion process.

Line 11 is oriented N-S and is centered on wells 2A and 4B, located at stations 11061 and 11038, respectively. The velocity of the upper layer is approximately 175 m/s (Figure 7a), which is consistent with the shear-wave velocity of unconsolidated sediment. The velocity gradient at 10-15 m is indicative of top of bedrock. An approximately 20% decrease in Vs is observed from stations 11054 to 11065, centered on well 2A, relative to bedrock velocity on the north and south ends of the line. A 15% decrease in Vs is observed between well 2A and 4B from stations 11040 to 11054.

Interpretation and Discussion

Well 2A

The apparent bedrock velocity over well 2A on line 10 is relatively consistent with the previous survey in November 2014. The dispersion pattern at well 2A (Figure 8a) is similar to the dispersion pattern at the equivalent location in the November 2014 survey (Figure 8b), suggesting that no significant change in material properties has occurred in the interim six months. The velocity inversion at 25 m depth observed in November 2014 (Figure 6b) is not observed in May 2015 (Figure 6a), which may indicate a reduction in strength and/or stress extending downward from 25 m below ground surface. As described in the previous study, this does not necessarily imply that the roof of the void has physically collapsed, but that some kind of physical change (possibly a macroscopic failure) has reduced strength in the overburden and/or redistributed stress within bedrock above the well, but at least 10 m below the bedrock surface. An essential observation and a key component to establishing a path forward at well 2A is the demonstrated, highly repeatable nature of this application of the passive surface wave method for measuring shear velocity (related to stress) and therefore the confidence that can be placed in the observed subsurface change in shear velocity that occurred between March 2013 and November 2014.

The apparent velocity above well 2A on line 11 (Figure 7a) is consistent with the velocities observed on line 10 (Figure 6a). Velocities at a depth of 30-40 m are approximately 10% lower at this location relative to November 2014 (Figure 7b). Dispersion patterns from line 11 at well 2A (Figure 9a) indicate that the surface wave phase velocity decreased in the time since the previous survey (Figure 9b). This suggests a change in material properties consistent with incremental failure and/or redistribution of stress in the interim 6 months, supporting the observations from line 10. The change in velocity is relatively small and appears to be limited to 25 m and deeper.

Well 4B

Slightly lower velocities are observed between stations 11040-11054 on line 11 (Figure 7a). The dominant surface wave energy transitions from a low-velocity trend at well 2A to a higher-velocity trend south of well 4B, and dispersion patterns between these wells represent surface wave energy from both velocity trends. In a transition zone with multiple surface wave

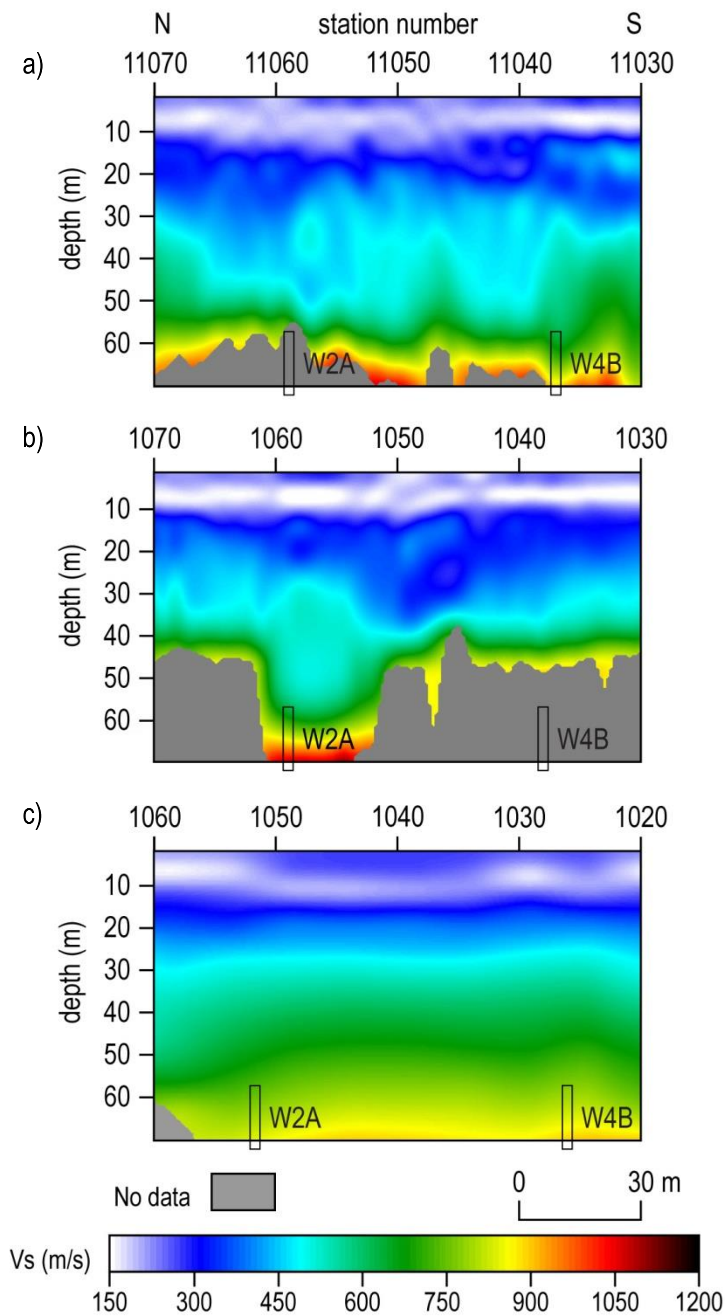

Figure 7. Shear-wave velocity profile of line 11 from (a) the present study, (b) November 2014, and (c) the baseline study in March 2013. Approximate well locations are indicated at the bottom of the profile.

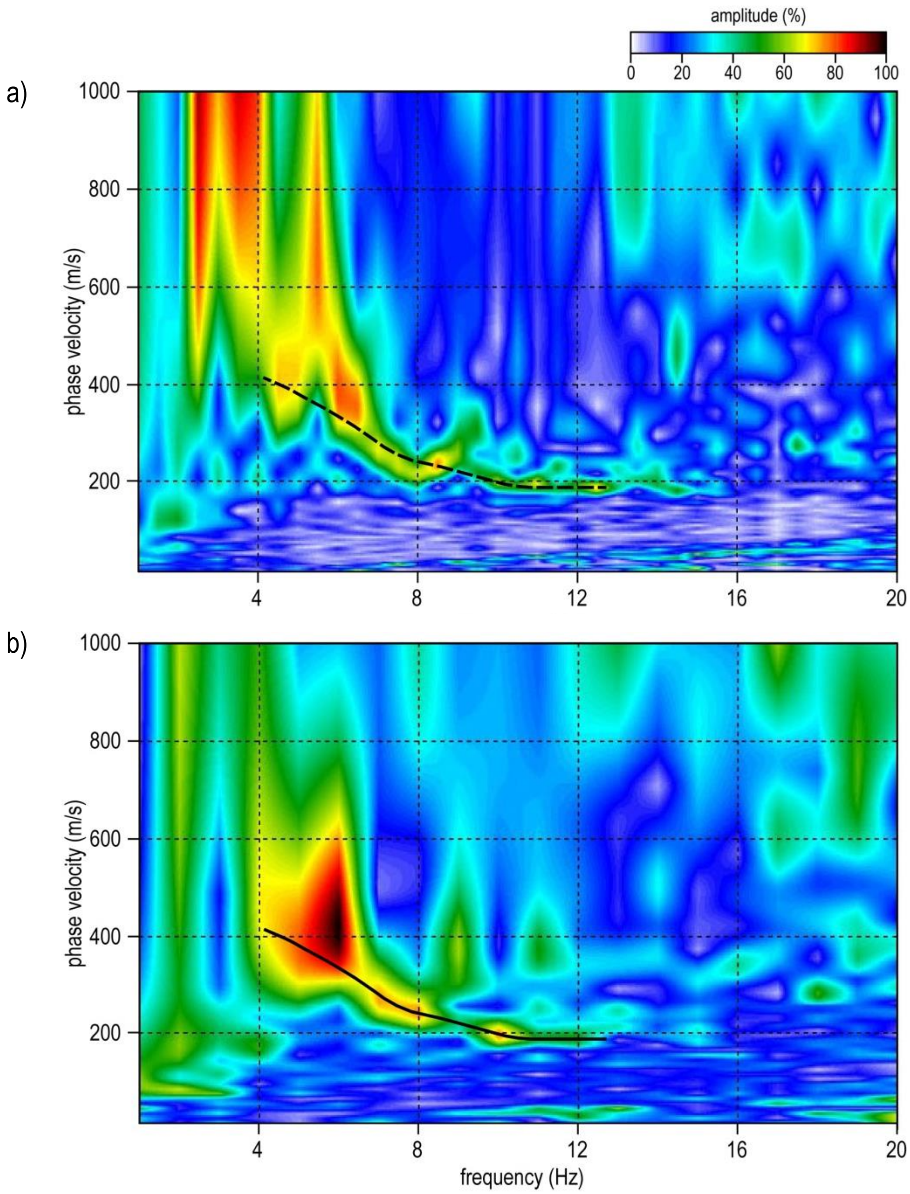

Figure 8. Dispersion patterns at the location of well 2A on line 10 from (a) the May 2015 survey and (b) the November 2014 survey. The dispersion curve from November 2014 (solid black line in (b)) is superimposed in (a).

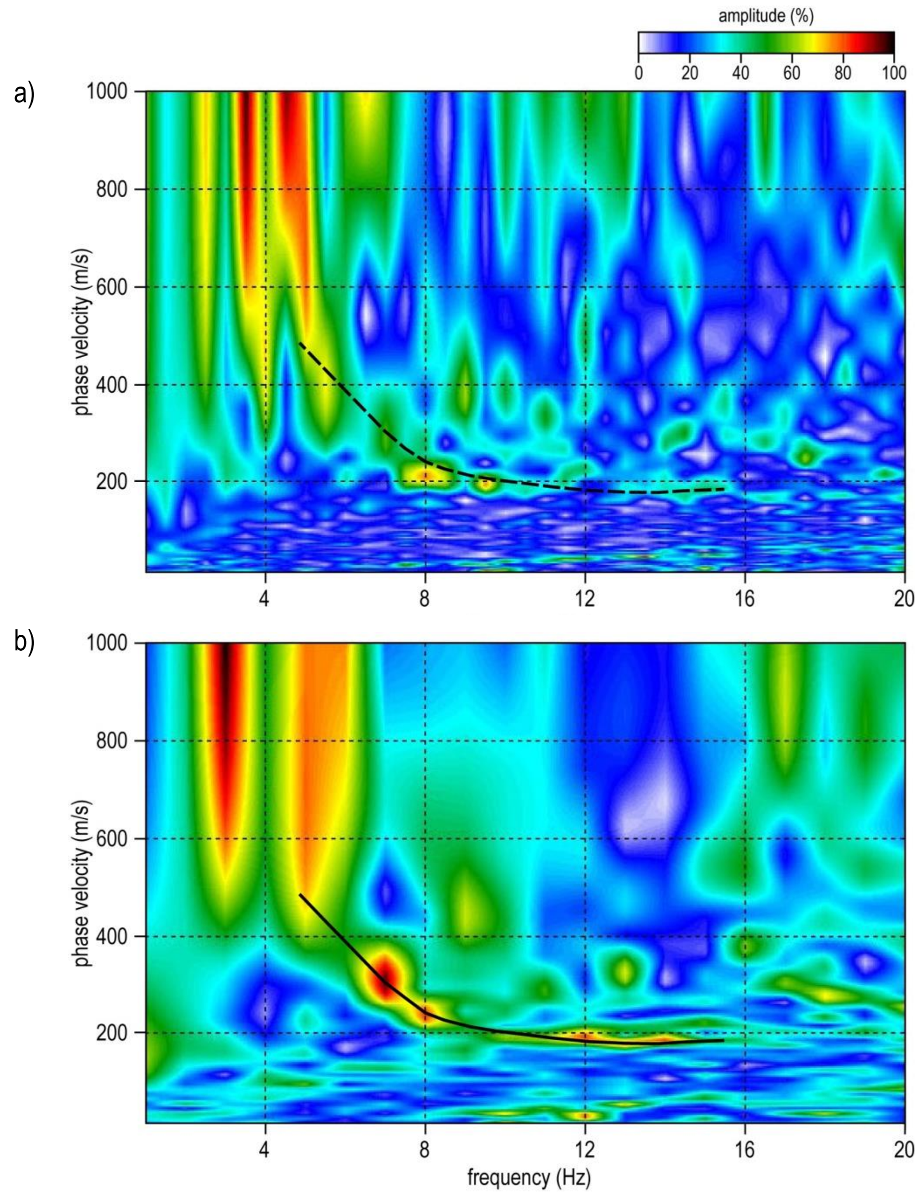

Figure 9. Dispersion patterns at the location of well 2A on line 11 from (a) the May 2015 survey and (b) the November 2014 survey. The dispersion curve from November 2014 (solid black line in (b)) is superimposed in (a).

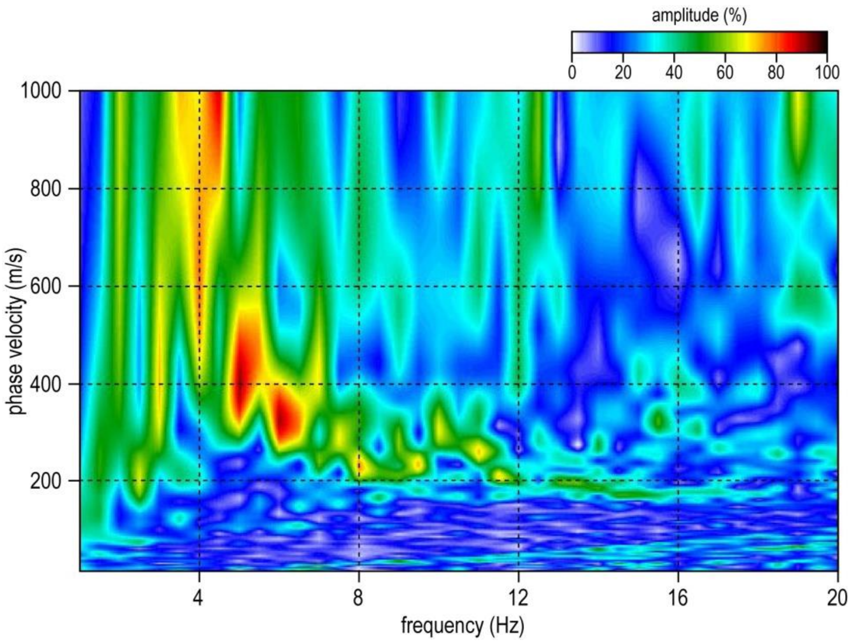

Figure 10. Dispersion patterns at the location of well 4B on line 11 from the May 2015 survey.

dispersion patterns, the general practice is to select the trend with the dominant amplitude. Although both dispersion patterns have similar amplitudes between stations 11040-11054 (e.g. Figure 10), the lower-velocity trend was slightly more dominant and, therefore, inverted to produce the final 2-D Vs profile.

Due to the presence of two surface wave modes between wells 2A and 4B on line 11, confidence in the resulting bedrock velocities is low within this transition zone. The velocity trend south of well 4B is consistent with the baseline survey in March 2013 (Figure 7c), suggesting a stable stress regime south of this well. Although a reduction in bedrock velocity cannot be ruled out, it is possible that the low bedrock velocity between wells 2A and 4B is only apparently low due to superposition of the two dispersion patterns within the transition zone. Future monitoring for dynamic changes may be required to improve confidence in the interpretation.

Conclusions

Subtle drops in sub-bedrock velocity over well 2A observed during the last couple years suggest some kind of incremental change has occurred above the old dissolution jug that may have reduced strength and/or redistributed stress very locally in the overburden. This change in strength or stress appears to currently be confined to depths greater than 25 m below ground surface—approximately 10 m beneath the top of bedrock. Dispersion patterns at well 2A are similar to those observed at this location in November 2014, suggesting that no significant change has occurred during the interim six months, but the change is real. Reduced bedrock velocities between wells 2A and 4B are likely the result of interference of more than one surface wave mode, possibly an artifact associated with the abrupt transition from the dispersion pattern associated with lower bedrock velocity above well 2A and the dispersion pattern associated with a normal stress regime south of well 4B. Although the amplitude of the lower velocity dispersion pattern was slightly more dominant (suggesting reduced bedrock velocities between wells 2A and 4B), this area should not garner immediate concern, but should be an area of interest during future monitoring to establish if more conclusive changes at well 4B are observed to improve confidence in our interpretation.

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