Velocity Calibration and VSP in Well 2A at the Legacy Vigindustries Hutchinson site: March-April 2025

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Executive Summary

Over the past decade, time-lapse comparison of shear-wave velocity profiles calculated from passive seismic energy has provided generalized insights into overburden stability and, indirectly, void dynamics at legacy salt dissolution wells in Hutchinson, Kansas. Velocity variability at well 2A suggested dynamic changes in stress that could be related to variations in roof rock properties. Well 2A was redrilled in late 2022 to directly investigate possible causes of the consistently observed time-lapse variability and invasively evaluate any void migration above the salt interval. Three large voids were encountered in the salt, the shallowest of which has a roof at the salt–shale contact. Interference between unique stress fields radiating from these stacked voids could result in complex interactions in bedrock stress and, therefore, exhibit variations in shear-wave velocity over time.

Three-component, multi-offset and azimuth vertical seismic profile (VSP) data were acquired in well 2A in February 2023 to identify reflecting interfaces and assess potential signals related to voids as a baseline for future monitoring surveys. Reflection-like events observed in the P-wave VSP are consistent with expected arrivals times for P-wave diffractions originating from the tops of three voids encountered drilling out this legacy wellbore. Results from numerical modeling are consistent with the VSPs collected in well 2A, strengthening the original interpretation. Seismic modeling indicates that, due to the relatively large wavelength/Fresnel zone, subtle changes in diffraction amplitude and phase would be evident even with minimal horizontal growth of the upper void. Vertical migration of the void would result in destructive interference with the top of salt reflection and notably reduce the diffraction amplitude, which makes this method sensitive to any vertical migration of the upper void.

Follow-up VSPs survey were acquired in November 2023 and September 2024 to assess any time-lapse changes in reflection characteristics (and, thus, changes in roof configuration). Little to no change was observed in the void signatures since the baseline survey. It is likely that little or no vertical growth has occurred since the 2023 baseline VSP given the relatively consistent amplitude of the upper void diffraction. Shear-wave velocity (Vs) calculated using passive surface wave analysis techniques at well 2A was elevated in the August 2024 survey, suggesting a period of increased stress. Elevated Vs observed in the passive seismic is likely caused by changes in Young's Modulus due to increased stress but either (1) not yet at a level sufficient for macro strain (failure) instigating vertical migration of the roof, or (2) the strain resulted in failure and has been actualized through increases in the horizontal expanse of the cavern roof without measurable vertical change.

Although the VSP method is sensitive to vertical migration, it only provides discrete snapshots in time and cannot provide real-time risk assessment. Passive downhole monitoring can be used to detect uniquely identifiable seismic events resulting from void migration of salt caverns (Contrucci et al., 2010). Once the volume of rock above a cavern is characterized for velocity and attenuation, it becomes feasible to uniquely identify seismic waveforms resulting from strain associated with failure of roof or wall rock ultimately resulting in collapse breccia accumulating on the bottom of the void. In this report, a compressional-wave velocity profile is calculated for well 2A before and after installation of permanent downhole receivers. Offset VSPs are used to image void diffractions. Given the consistency in the diffraction from the upper void, little to no change has occurred since the 2023 baseline survey. Additional VSPs at closer source offsets are recommended for future surveys to enhance image quality and track subtle changes in void signatures.

Introduction

Passive multichannel analysis of surface waves (MASW) has been used at the Vigindustries Site (Carey Boulevard Research Area, CBRA) to estimate shear-wave velocity (Vs) at numerous legacy salt dissolution wells since 2013 to monitor for changes in bedrock stresses in the vicinity of the solution mined voids (Peterie et al., 2025). Time-lapse comparison of Vs profiles has provided insights into consistency of overburden stability and, indirectly, void dynamics. Well 2A consistently experienced changes in shear-wave velocity, most notably in 2014, suggesting changes could be related to variations in bedrock properties/stress. Well 2A was drilled out in late 2022 to allow direct investigation for possible causes of the consistently observed, inconsistent time-lapse variability. The three largest voids in the salt were detected at depths of 125-137, 143-161, and 191-215 m. Convergence of the stress fields from these distinctly separate and stacked voids could result in complex variations in measured bedrock stress—and, therefore, shear-wave velocity over time. This setting could result in changes in measured overburden stress that could not be uniquely attributed to one or multiple caverns and therefore how the observed changes impact risk.

Vertical seismic profiling (VSP) is a direct surface to downhole technique used for determining elastic velocities, mapping reflecting interfaces (contact between materials with different physical properties), and relating reflections to geologic features in close proximity to a borehole (Hardage, 1985a; Stewart and DiSiena, 1989). For a traditional VSP, the source is located near the borehole and provides a measure of seismic properties and images very near (an offset distance that is small relative to the deepest sampling point in the borehole) to the wellbore. For an offset VSP, the source is located at some distance from the borehole to provide imaging horizontally away from the borehole. Three-component, multi-offset and azimuth VSP data were acquired in well 2A in February 2023 to map reflecting interfaces and assess signal characteristics related to voids. Diffraction-like events observed in the vertical component of the 61 m source offset VSP were generally consistent with expected arrival times for compressional-wave (P-wave) diffractions from the tops of the three main voids encountered during drilling (Peterie et al., 2023).

To confidently characterize the signals expected from the shale–salt contact and voids, finite difference models (Zeng et al., 2011) were produced to simulate a downhole survey of three water-filled caverns embedded in the salt interval and assess changes in the modeled seismic signatures with horizontal and vertical growth of the upper void (Peterie et al., 2024). Three reflection/diffraction-like events represent the top of salt reflection superimposed with the diffraction from the upper void and diffractions from the two lower voids. These events are consistent with diffraction events interpreted in the baseline VSP, affirming and strengthening the original interpretation. Expanding the width of the upper void by 50% results in little to no change in the upper void diffraction. Increasing the height of the upper void just above the shale–salt contact results in a notable change in the amplitudes of the resulting diffraction due to superposition with the salt reflection, making this a sensitive indicator on seismic data of vertical migration of the upper void.

Follow-up VSPs survey were acquired in November 2023 and September 2024 to assess any time-lapse changes in reflection characteristics (and, thus, changes in roof configuration). Little to no change was observed in the void signatures since the baseline survey in February 2023. Relatively consistent amplitudes of the upper void diffraction suggest that little or no vertical growth occurred between the baseline and 2024 surveys. Vs calculated using passive surface wave analysis techniques at well 2A was elevated in the August 2024 survey, suggesting a period of increased stress (Peterie et al., 2024). Elevated Vs observed in the passive seismic is likely caused by changes in Young's Modulus due to increased stress but either (1) not yet at a level sufficient for macro strain (failure) instigating vertical migration of the roof, or (2) the strain resulted in failure and has been actualized through increases in the horizontal expanse of the cavern roof without measurable vertical change.

Although the VSP method is sensitive to changes in roof configuration, it only provides discrete snapshots in time. Spall of roof or wall rock generally occurs without warning or detection in abandoned salt caverns and tends to be influenced by dynamic conditions that act to slowly degrade localized material properties or site conditions to the point of failure. Detecting and quantifying subtle changes in void conditions or surrounding rock properties is essential in identifying dynamic changes in a void that can alter its steady state and stability. Passive downhole monitoring can be used to record the distinguishable and uniquely identifiable seismic events from salt cavern void migration (Contrucci et al., 2010). Once the volume of rock above a cavern is characterized for velocity and attenuation it becomes feasible to uniquely identifying seismic waveforms resulting from failure of roof or wall rock ultimately resulting in collapse breccia accumulating on the bottom of the void. In this report, a compressional-wave velocity profile is calculated for well 2A before and after installation of permanent downhole receivers. Additionally, analysis of multi-component offset VSPs is used to image compressional-wave diffractions from the voids and assess azimuthal shear-wave velocity.

Geologic and Geophysical Setting

The Permian-aged 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 natural and anthropogenic 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 more than 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).

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 where not eroded off (McGuire and Miller, 1989). Directly above the salt at this site is a thick sequence of Permian shale capped with a saturated interval of Pliocene-Pleistocene sediments.

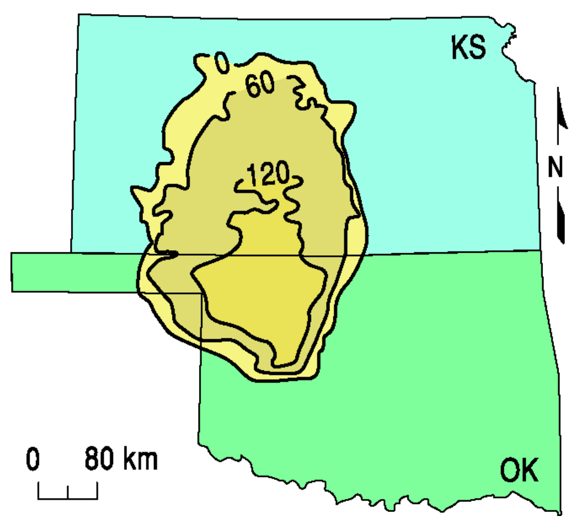

Figure 1. Approximate extent of salt formation, with contour intervals expressed in meters.

The upper 760 m of rock at this site is Permian shales (Merriam, 1963). The lower Wellington Shale (top at ~225 m deep), Hutchinson Salt (top at ~120 m deep), upper Wellington Shale (top at ~70 m deep), and Ninnescah Shale (top at ~15 m deep) make up the Permian portion of the section (Figure 2). Bedrock is defined as the top of the Ninnescah Shale with the unconsolidated Pliocene-Pleistocene Equus beds making up the majority of the approximate upper 15 m of sediment. Regionally, the thickness of Quaternary alluvium that fills stream valleys and paleosubsidence features extends from 0 to as much as 90 m, depending on the dimensions of the features.

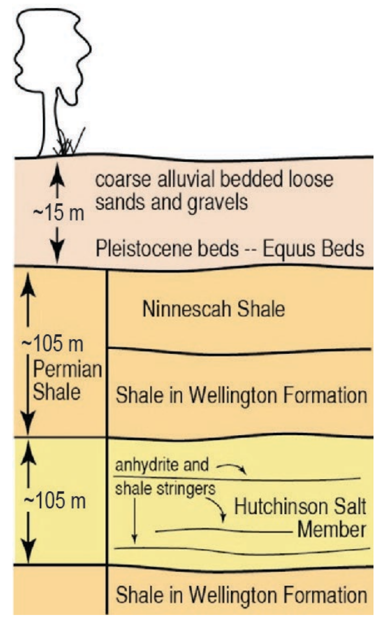

Figure 2. Generalized geology.

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 groundwater 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 that 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 highly variable and can range from less than 60 m to more than 100 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 freshwater 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.

The basal contact of the Upper Wellington Formation shales provides key insights into the general strength of roof rock expected if dissolution-mined salt jugs (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 an unsaturated brine encounters this shale layer, these red halite-filled joints and bedding planes are rapidly leached, leaving an extremely structurally weak layer.

Calibration Survey: Acquisition and Processing

A downhole velocity survey and multi-component offset VSP were collected at well 2A on March 5, 2025 (Figure 3). For the velocity survey, the seismic source was a 16 lb sledgehammer impacting a seated steel plate. The source locations were 6 m west and 6 m north of the well. For the VSP, the source was a sledgehammer with steel plate and shear block oriented in both longitudinal and transverse directions relative to well 2A. The source was located 61 m north of the well. The downhole receiver was a three-component (3-C) Geostuff BHG-2 geophone with steel band clamping mechanism. Multipurpose rubber coating was applied to the exterior housing of the downhole tool and weatherstripping was applied to the band prior to the baseline survey to improve coupling and reduce mechanical oscillations in the transverse direction. The receiver was incrementally lowered and clamped to the casing wall at 3 m intervals down to a maximum depth of 109 m. A minimum of three consecutive shots were acquired and individually saved at each depth to ensure sufficient signal.

Consecutive shots at each station were vertically stacked during processing to maximize the signal-to-noise ratio (S/N). Data from the 6 m offsets were used to calculate average and interval P-wave velocity (Vp). First breaks were picked on the compressional records, and average and interval velocities were calculated using picked arrival times and path length from the source to receiver. Data from the 61 m source location were processed with conventional VSP techniques (Hardage, 1985b) using SeisUtilities software developed at the KGS. Vertical (P-wave) records were frequency-wavenumber (*f-k*) filtered to attenuate the down-going direct waves and enhance up-going events (e.g., reflections). Static corrections based on picked first arrival times were applied to flatten reflections with a narrow *f-k* filter applied to attenuate sloping noise in the upgoing direction.

Permanent Downhole Array

A permanent array of downhole geophones was installed in well 2A on March 17, 2025. The downhole cable was secured to a 1” steel pipe with steel zip ties above and below the pods housing the geophones. Additional plastic zip ties secured the cable to the pipe between pods. The pipe was lowered to refusal and cemented in place using a retrievable plastic tremie. Receivers are spaced at 4 m intervals from 44 to 112 m below ground surface (bgs) (Figure 4). All pods contain a 30 Hz vertical geophone, and pods at 88, 100, and 112 m bgs also contain orthogonal (unoriented) 30 Hz horizontal geophones. Characteristics of ambient energy (e.g., train noise) was assessed to evaluate downhole sensor performance. Consistent trace-to-trace characteristics indicated live traces with no apparent compromise in sensor performance.

A downhole survey was collected with the permanent array on April 17, 2025 (Figure 3). Five shots were recorded separately at offsets of 3, 15, and 61 m west-southwest of well 2A at the same location/heading of prior VSP surveys. First arrivals were picked and used to calculate interval Vp and generate VSPs, as described in the previous section.

Figure 3. Source locations in the March (yellow) and April (cyan) surveys relative to well 2A (white).

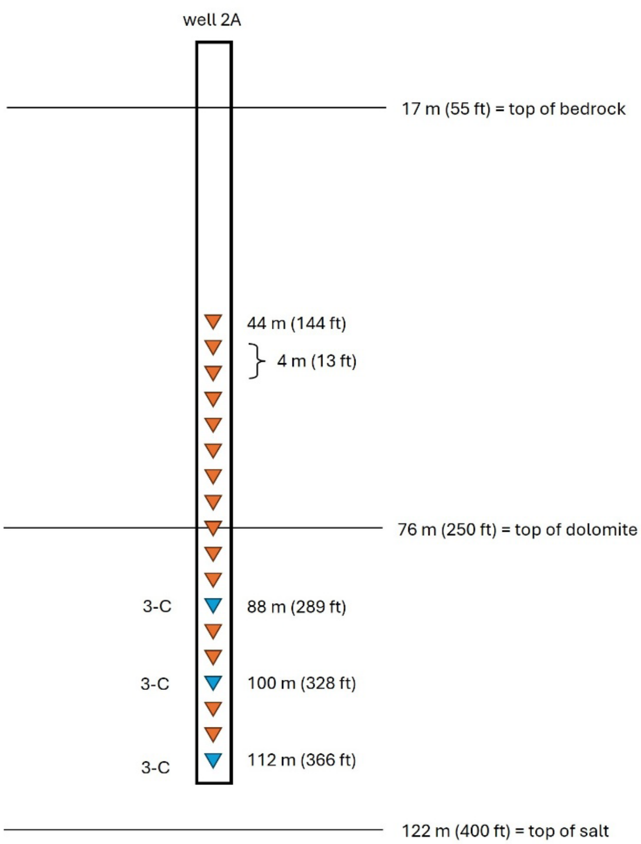

Figure 4. Configuration of the permanent downhole array in well 2A.

Results and Discussion

Velocity Calibration

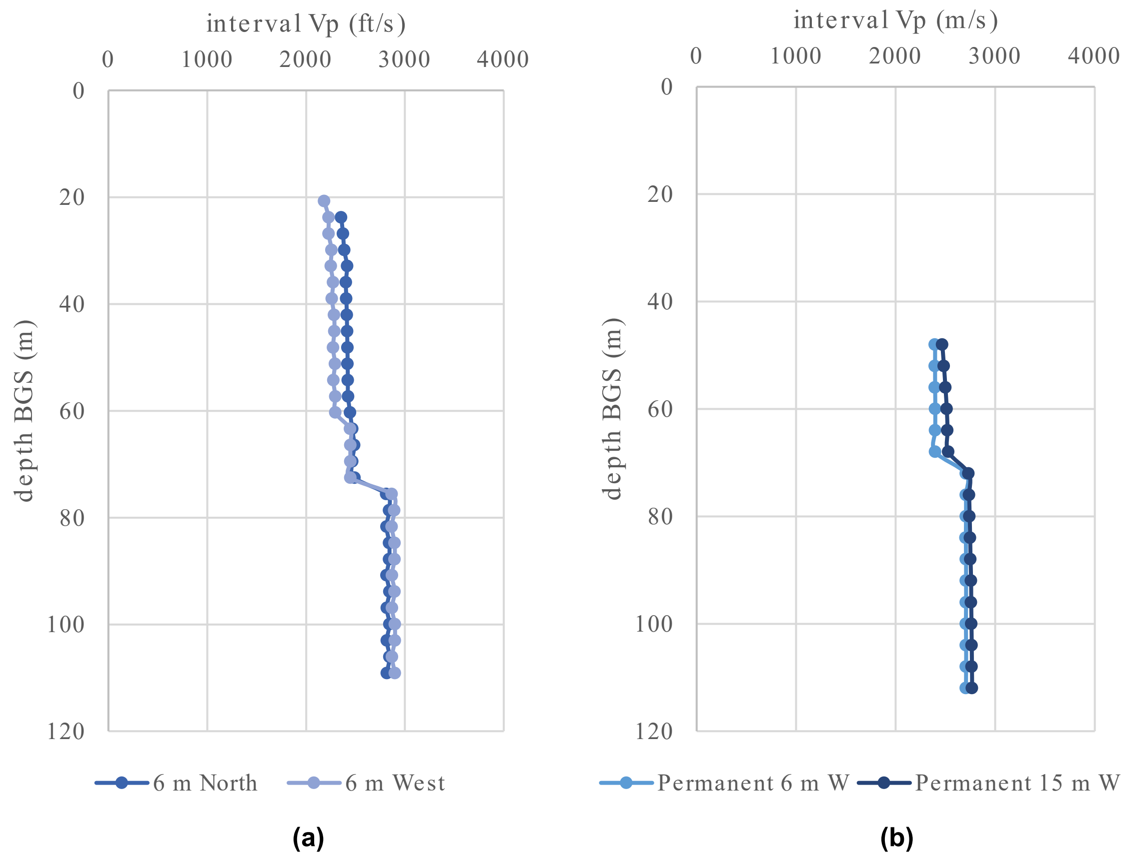

Figure 5. Interval Vp from (a) the wall lock geophone, and (b) the permanent downhole array.

Interval Vp of the upper 60 m calculated from the data collected at the 6 m north source station is about 5% faster than data collected at the west station (Figure 5). This is slightly greater than the uncertainty of the velocity estimation method, and could be related to either natural variability in the stiffness and bulk modulus of bedrock or near-well effects of drilling. Vp below 60 m is consistent at both source locations. This relatively small velocity variation/uncertainty within the depth range of only a few permanent downhole receivers will have little to no impact on passive monitoring algorithms. Vp profiles from the permanent downhole array are consistent with the calibration survey (within about 5%).

Time-Lapse VSPs with Wall Lock Geophone

The diffraction from the top void on the March VSP collected with the wall lock geophone is relatively clear, similar to VSPs from prior surveys (Figure 6). Diffractions from the lower voids have much lower S/N, which may be due to greater interference from noise (filtered out during processing) and a difference in source locations and, thus, raypath. The diffraction from the top void has similar characteristics to the prior VSPs, suggesting little to no change in the roof configuration since the previous survey in September 2024.

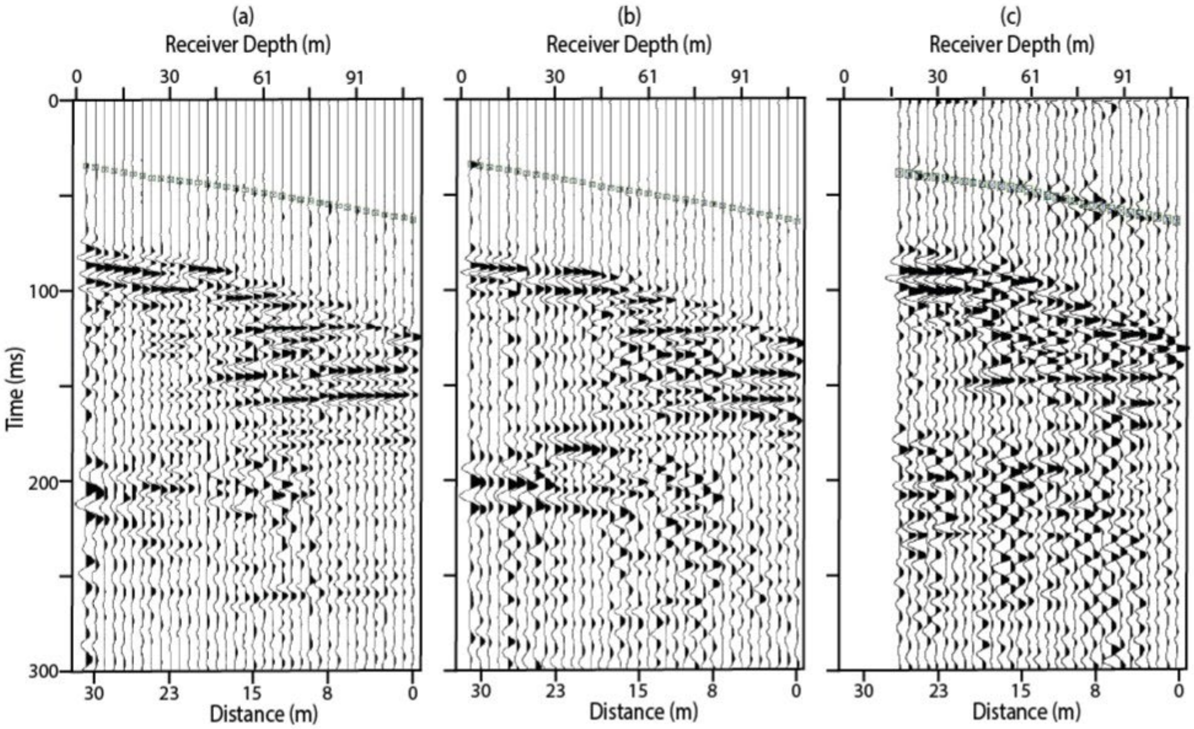

Figure 6. Offset VSPs from (a) the baseline survey in February 2023, and time-lapse surveys in (b) September 2024, and (c) March 2025.

Wall Lock Geophone and Permanent Downhole Array Comparison

Data acquired with the wall lock geophone have lower S/N than data acquired with the permanent array, as evidenced by greater amplitude of pre-arrival noise (Figure 7, left). Improved coupling and reduced noise are a result of cementing the downhole geophone cable. These high S/N data are ideal for passive monitoring of low-amplitude spall events.

The 61 m offset VSP from the permanent downhole array has similar characteristics to previous VSPs recorded with the wall lock geophone, with prominent diffractions from the top and middle void and a lower-amplitude diffraction from the bottom void (Figure 8). Because the March 2025 VSP was collected with a different source location, the September 2024 VSP is used for direct comparison. The dominant frequency is slightly lower, likely due to variation in ground conditions and source coupling. The amplitudes of the diffractions (especially from the top and middle voids) are overall higher in data recorded with the permanent downhole array, as expected given the overall improvement in S/N of the permanent array data (Figure 8).

VPSs were also calculated with data collected with the permanent downhole array at 3 m and 15 m source locations during the April 2025 survey (Figure 9). These VSPs contain distinctive arrivals from each of the three voids, as well as a reflection from the dolomite between 72-76 m depth. The shorter offset VSPs (Figure 9) have higher overall S/N than the 61 m offset VSP (Figure 8b). The reduced angles of incidence improved the static corrections (flattening) and coherency of void signatures. Although the 61 m offset VSPs allow for subsurface imaging further away from the borehole, the improvement in image quality of the shorter offset source locations is optimal for monitoring subtle changes and will be collected in future surveys.

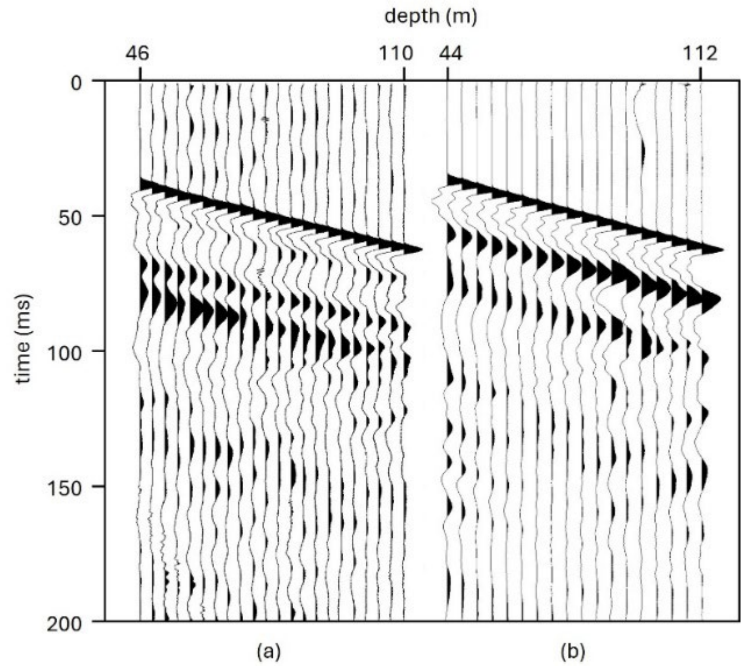

Figure 7. Unprocessed data collected with (a) the wall lock geophone at the 6 m W source location in the March 2025 survey and (b) the permanent downhole array at the 3 m W source location in the April 2025 survey. Original records were truncated to approximately the same depth ranges.

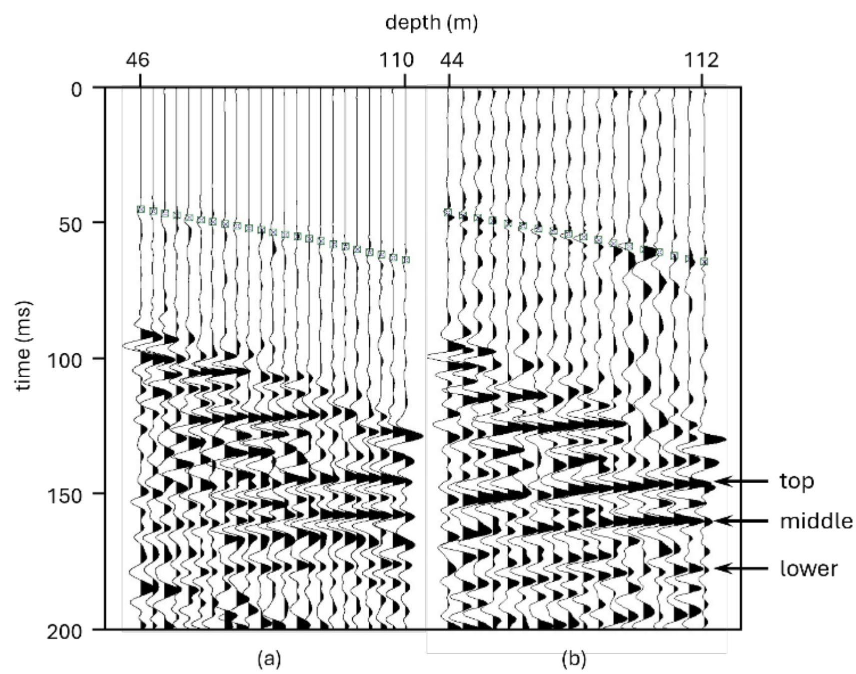

Figure 8. VSPs collected with (a) the wall lock geophone in September 2024, and (b) the permanent downhole array in April 2025 over approximately the same depth ranges.

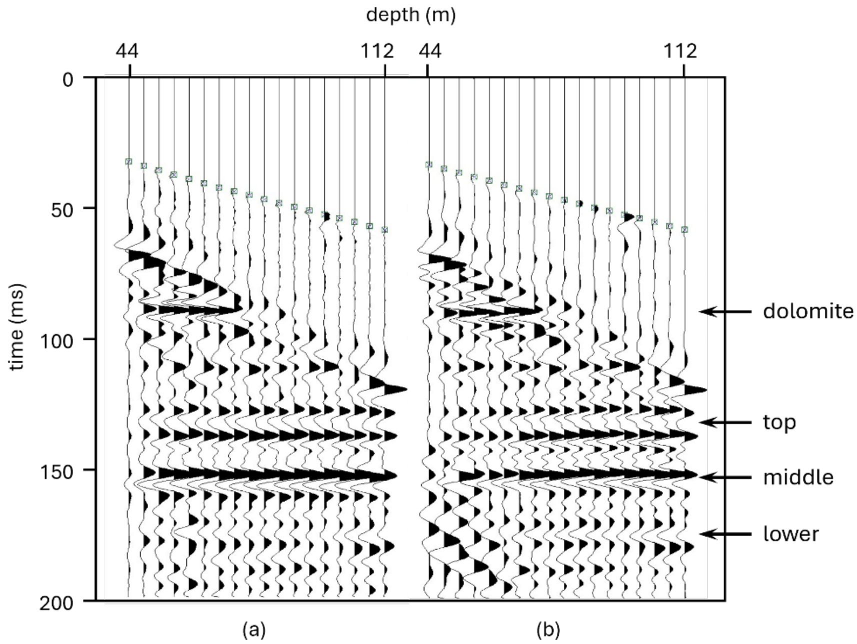

Figure 9. (a) 3m and (b) 15 m offset VSPs from the April 2025 survey.

Conclusions

Data recorded with the permanent downhole array has greater S/N compared to data recorded with the wall lock geophone. Despite variability in source coupling, amplitudes of the void diffractions are equal or better than those recorded with the wall lock geophone on resulting VSPs. The Vp profile collected with the permanent downhole array is consistent with the Vp calculated from the calibration survey using the wall lock geophone. The arrival time of the reflection from the top of salt/upper void diffraction is about 140 ms in both the 2023 baseline and March 2025 time-lapse surveys. The arrival time, amplitude, and phase characteristics of this event appear consistent between surveys, suggesting little to no vertical growth has occurred since the baseline survey. Seismic modeling suggests that while the VSP method is not particularly sensitive to horizontal growth of the void, it is quite sensitive to vertical migration, which represents the greatest concern for hazard development and risk of impacting the bedrock surface or shallower. This unique approach and tailored application of the method will allow direct detection of any void migration and with continuous monitoring allow accurate tracking and assessment of the potential for any future bedrock surface expression/breakthrough. Additional VSPs at closer source offsets are recommended for future surveys to enhance image quality and improve tracking of subtle changes in void signatures and therefore characteristics

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