Time-Lapse, High-Resolution Seismic Reflection Imaging (Line 1) of a Void in the Hutchinson Salt Beneath #1 Knackstedt Disposal Well, McPherson County, Kansas

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Summary

Voids resulting from solutioning of the Hutchinson Salt by wastewater from a breach in the #1 Knackstedt disposal well have been imaged using the high-resolution seismic reflection method. Breach of this disposal well at or near the depth of the Hutchinson Salt allowed produced water from oil and gas production to gain access to the salt and result in uncontrolled harvest of salt. Key to dissolution of rock below ground surface are flow paths that saturated fluids can use to gain access and move away from the dissolution front. Equally as important are highly permeable structures that allowed pregnant fluids to drain into deeper formations. The 2019 reflection study produced high resolution images of reflectors ranging in depth from the bedrock surface at 50 ft to the Precambrian basement at more than 4300 ft with striking images of the void and subsidence resulting from the uncontrolled wastewater release as well as paleo subsidence resulting from dissolution of the salt and subsidence of overlying strata potentially hundreds of thousands of years ago within early Pliocene-Pleistocene.

The principal void was discovered and investigated by the KCC in the late 1980s. An attempt to backfill the void with sediments was abandoned after little success was measured in reducing the air-filled void. This early investigation included a high-resolution seismic reflection using state of the art practices of the time. The 1988 vintage seismic reflection study produced low signal to noise ratio images with chaotic zones interpreted as consistent with the location of the void. Some diffractions were observed in this legacy data, but they lacked the focus expected for energy returning from an air-filled void. The well was plugged from the top of the salt to the ground surface and the county road routed around the extent of the void within the salt as interpreted on seismic reflection sections.

The 2019 reflection survey provides a high-resolution image of the void and associated subsidence evident in lithologic units above the salt and adjacent to the void (Figure 1). Evidence of paleo subsidence and its location relative to the current voids along with an apparent fault structure were key to understanding the development of the voids and providing an explanation for a lack of fluid in the void space. Interpretations of 1988 seismic data indicated the void predominantly east of the disposal well (Figure 2). From the 2021 seismic sections, it is clear solutioning and subsidence of rock layers resulting from the well breach extend about 100 ft above the top of the salt, principally west of the void (Figure 3). The current cavity extends about 50 ft west and 500 ft east of the well. East of the well, the cavity (tube, migration conduits) contacts a paleo subsidence feature and natural fluid pathways likely established during Pliocene-Pleistocene for saturated brine to cascade vertically to deeper permeable layers.

Based on the seismic reflection images, the salt has been altered west of the well to within about 50 ft of the county line road (Plum). Migration of the void to the ground surface would not likely impact the east/west county paved road (Comanche) along the original transect west of the disposal well. Based on the vertical extent of the void and amount of sediment that remains within the original Hutchinson Salt interval where solutioning is evident on seismic sections, the cavity does not appear to have sufficient volume to accommodate the collapse of the entire column of overburden. At a bulking factor of about 1.2 (accepted as high end for Permian sediments in this area—greatest vertical compaction), void migration would be arrested within

200 ft or so of the top of salt. The greatest potential for complete migration of the void and surface expression would be from 50 ft west of the disposal well to about 200 ft east of the well (Figure 4). The roof rock in this area still retains a roof without any apparent failure in roof rock. From a point 50 ft west of the well to within 80 ft of the intersection of the north/south and east/west paved county roads, the cap rock on the salt has failed with subsidence extending only about 100 ft above the salt at an elevation at which the roof appears to be stable.

Key to the understanding of the development and current state of this air-filled void is the discovery of apparent hydraulic connectivity between paleo subsidence features, the solution voids, disposal well, and a vertical discontinuity, interpreted as a fault or fracture system (Figure 5). This combination of related features provides the salt face with access to unsaturated brine and a drain to move the saturated fluids away from the solution front (Figure 6). Without this "drain" and fluid migration pathway, the only option for the saturated brine to leave the void solution face would have been the well bore at the base of the salt interval. This complete hydrologic system provides all the components necessary for the void to have formed and remained air filled rather than water filled as most in this area are.

The original objective of the 1988 study was to establish the risk of surface expression, the rate of vertical movement if the void migrated to the ground surface, and the potential size of a resulting sinkhole. The 1988 survey was only able to approximate with moderate confidence the rough size of the solution void and therefore potential affected surface area if subsidence did migrate to the ground surface. But from those findings, the east/west county paved road was rerouted around the well bore with a couple hundred feet of buffer between the paved road and well bore.

The 2019 reflection survey was undertaken to establish the maximum extent of a potential sinkhole, if failure of overburden occurred, based on the extent of solutioning evident in the salt layer. The ultimate goal was to select a stable location to install a permanent survey marker for reference during routine, high-resolution elevation surveys undertaken above the void as part of the public safety program established by the Kansas Corporation Commission. Data are excellent and the resulting CMP stacked sections from the 2019 survey allow highly confident interpretations of reflections from reflectors between the bedrock and basement.

Evidence of dissolution of the salt as far back as pre-Quaternary can be interpreted from about 50 ft east of the intersection of Comanche and Plum Roads to about 500 ft east of the Fry Farm.

High resolution seismic reflection images from data acquired using a 450-channel fixed geophone sensor spread with receiver stations on 8 ft centers and vibroseis source stations on 16 ft centers allow the mapping of the current void and subsidence resulting from uncontrolled release of fluids from the well bore within the last 100 years and paleo subsidence with ancient flow paths accessing a vertical fault or fracture structure. Direct detection of a void using seismic reflection at more than 400 ft below ground surface has not previously been described in the scientific literature (Figure 7).

This time-lapse, high-resolution seismic reflection study provided outstanding images of rock layers in the Lower Permian Series portion of the geologic section beneath and approximately centered on the #1 Knackstedt disposal well and in close proximity to seismic data acquired in 1988. The principal goals of this study were to delineate rock layers within and above the Hutchinson Salt Member, identify dissolution zones, and attempt to appraise the geometry and any potential impact of the void on the overall stability of the rock column (Figure 8). State-of-the-art shallow high-resolution seismic reflection techniques allowed the void to be detected, delineated, and evaluated in association with localized structures associated with the dissolution of the salt, structural failure of overlying sediments, and estimate of maximum affected surface area if current voids migrate unimpeded to the ground surface (Figure 9). A previous survey completed in 1988 provided a poorly constrained, rough estimate of the void extent at the resolution potential and data quality considered state of the art of that time. Identifying the flow path of fluids accessing soluble rock is critical to forensic studies of the solution pathway, identifying areas most susceptible to subsidence, and developing a remediation plan. Using state-of-the-art near-surface seismic imaging techniques and equipment significantly increased the imaging potential of 2019 data compared to the detection potential of the 1988 survey.

Figure 1. Site map approximately centered on the #1 Knackstedt disposal well.

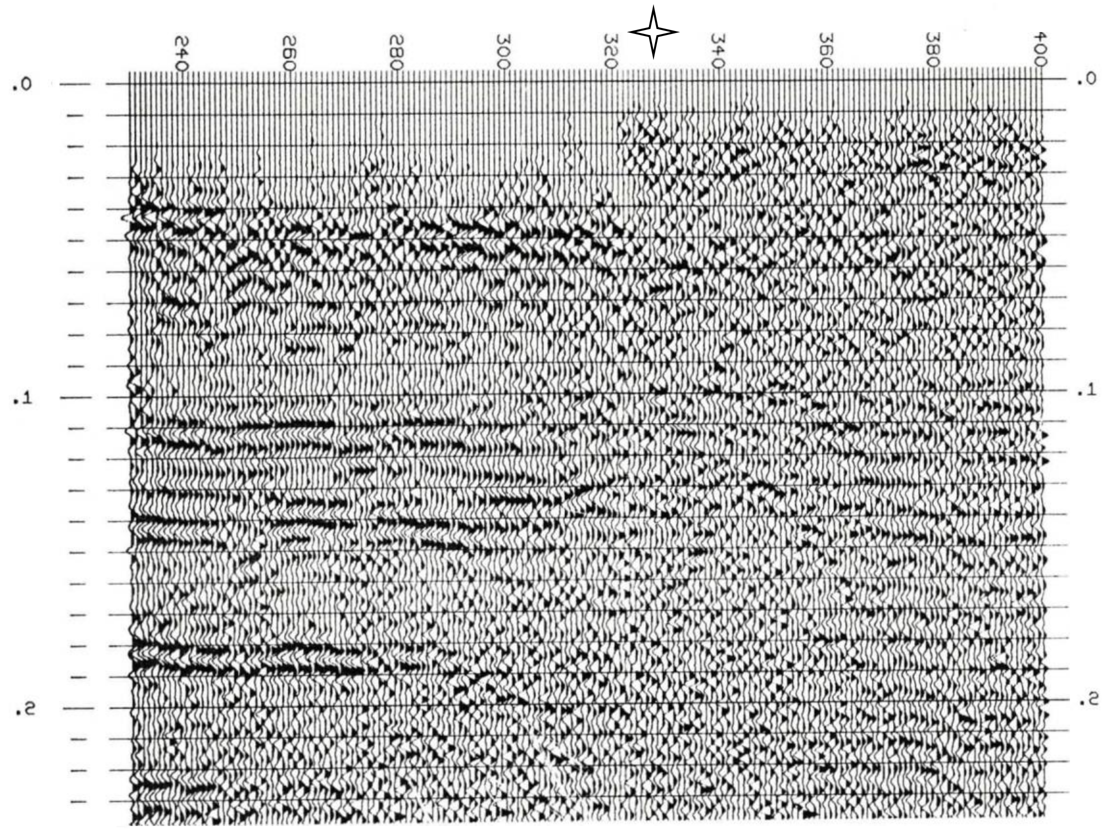

Figure 2. Line 1 from a 1988 seismic survey of the Knackstedt void. Line 1 was an east/west profile along a county road. Represents the approximate location of the disposal well.

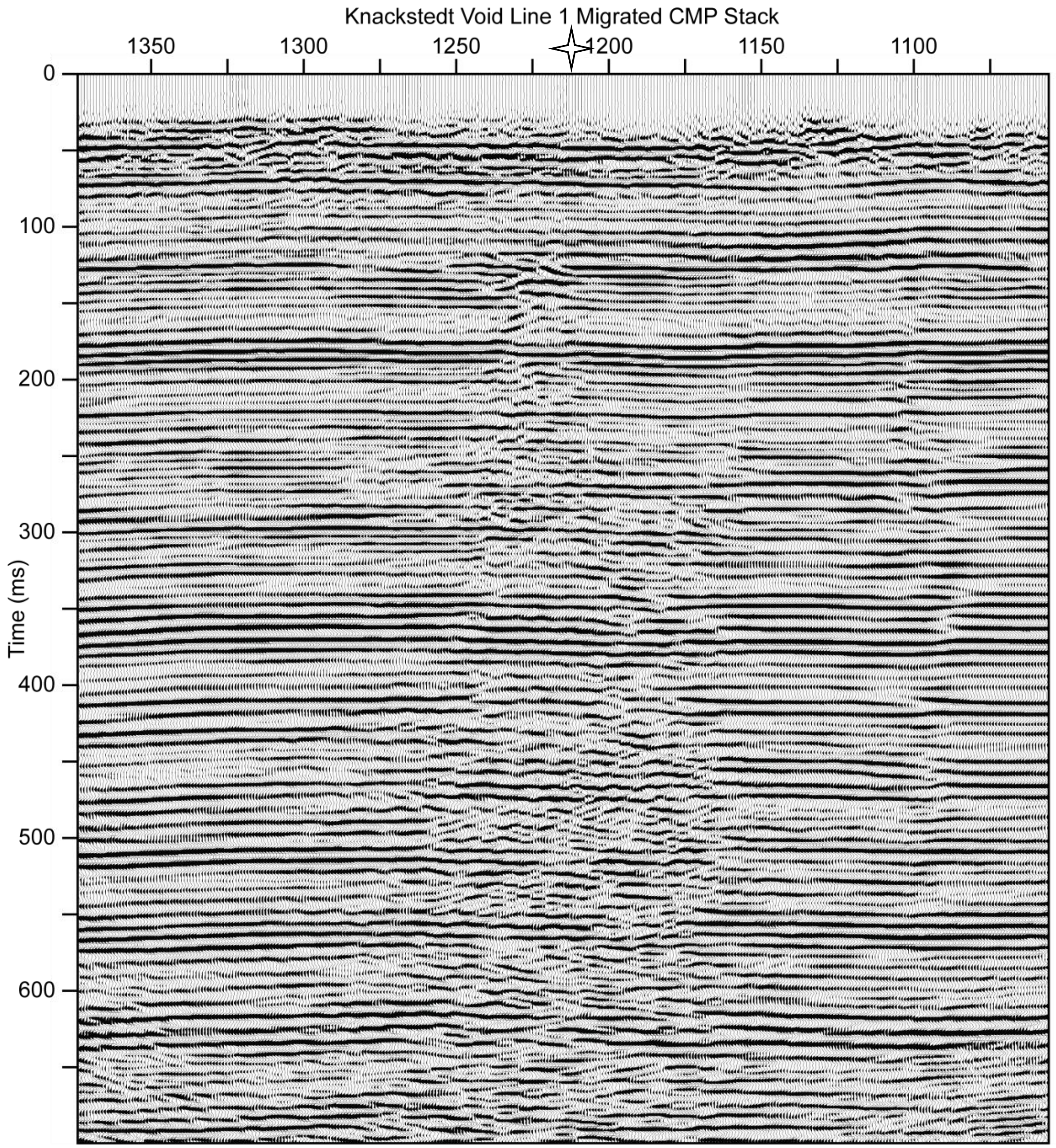

Figure 3. Migrated CMP stacked section from west to east along line 1. is the approximate location of the disposal well. Coherent reflections around 125 ms are interrupted by a series of high angle arrivals centered on station 1225. These arrivals are interpreted to be the cavity signature. The multiple scatters through time can be seen deeper in the section and generally below the void signature. Sag in the reflection around 70 ms beneath station 1150 and at the edge of the section around 1050 are paleo subsidence events. This 70 ms event is interpreted to be the top of the Wellington with the Ninnescah Shale overlying it. Reflections from the Ninnescah do have some indication of drape likely associated with the subsidence resulting from dissolution of the salt pre-Quaternary. There is no sinkhole evident at the ground surface in this area.

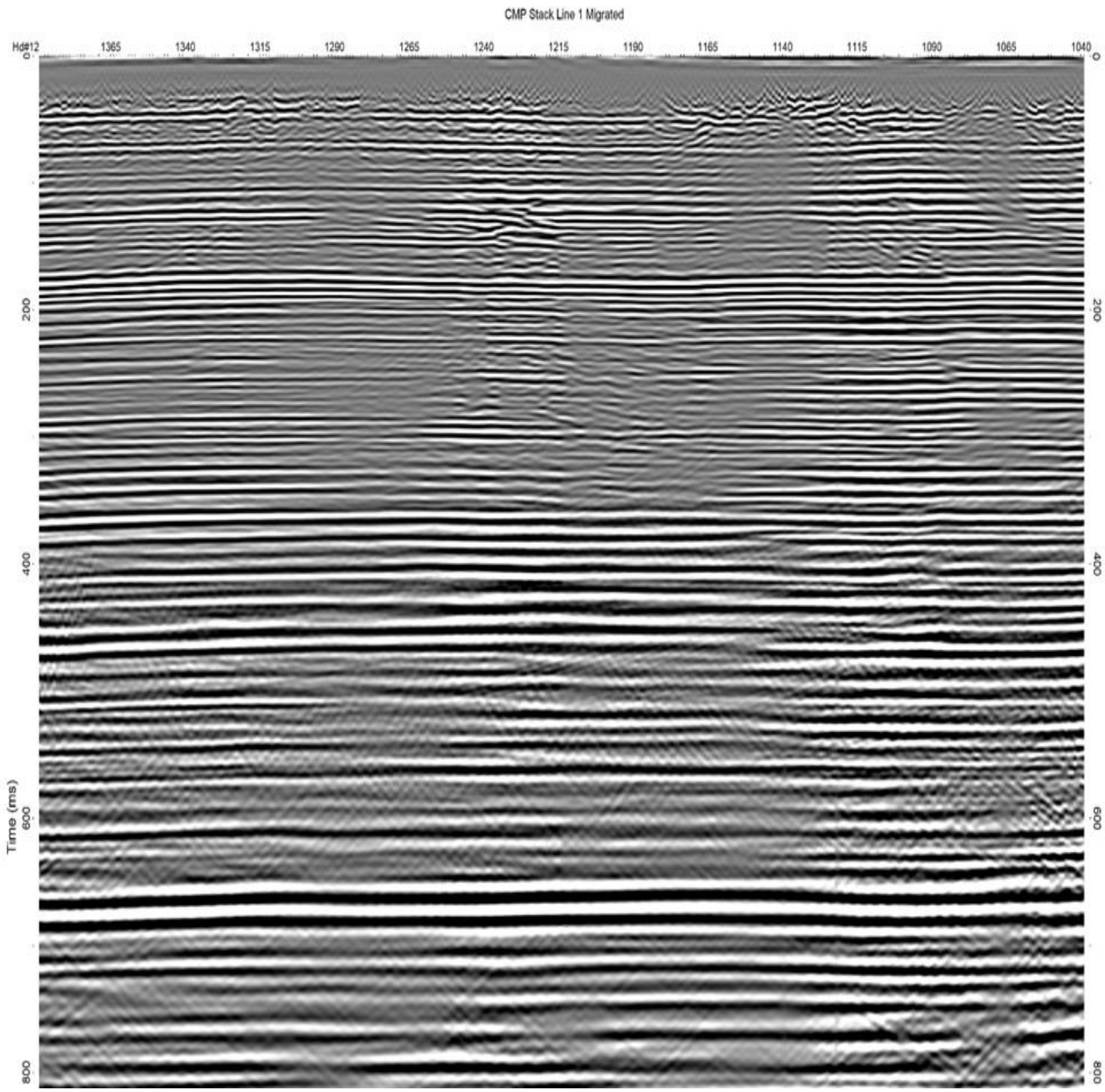

Figure 4. Migrated CMP stacked section from 2019 reflection survey displayed with gray tones. The primary void is easily interpreted beneath station 1230 on this image. Diffraction is evident beneath the void and associated with the paleo subsidence beneath stations 1140 and 1050. These diffractions are indicative of highly curved reflectors or bed terminations representing point source scatterers. Frequency change in reflection wavelets with depth is obvious and related to natural attenuation as seismic energy travels through the earth.

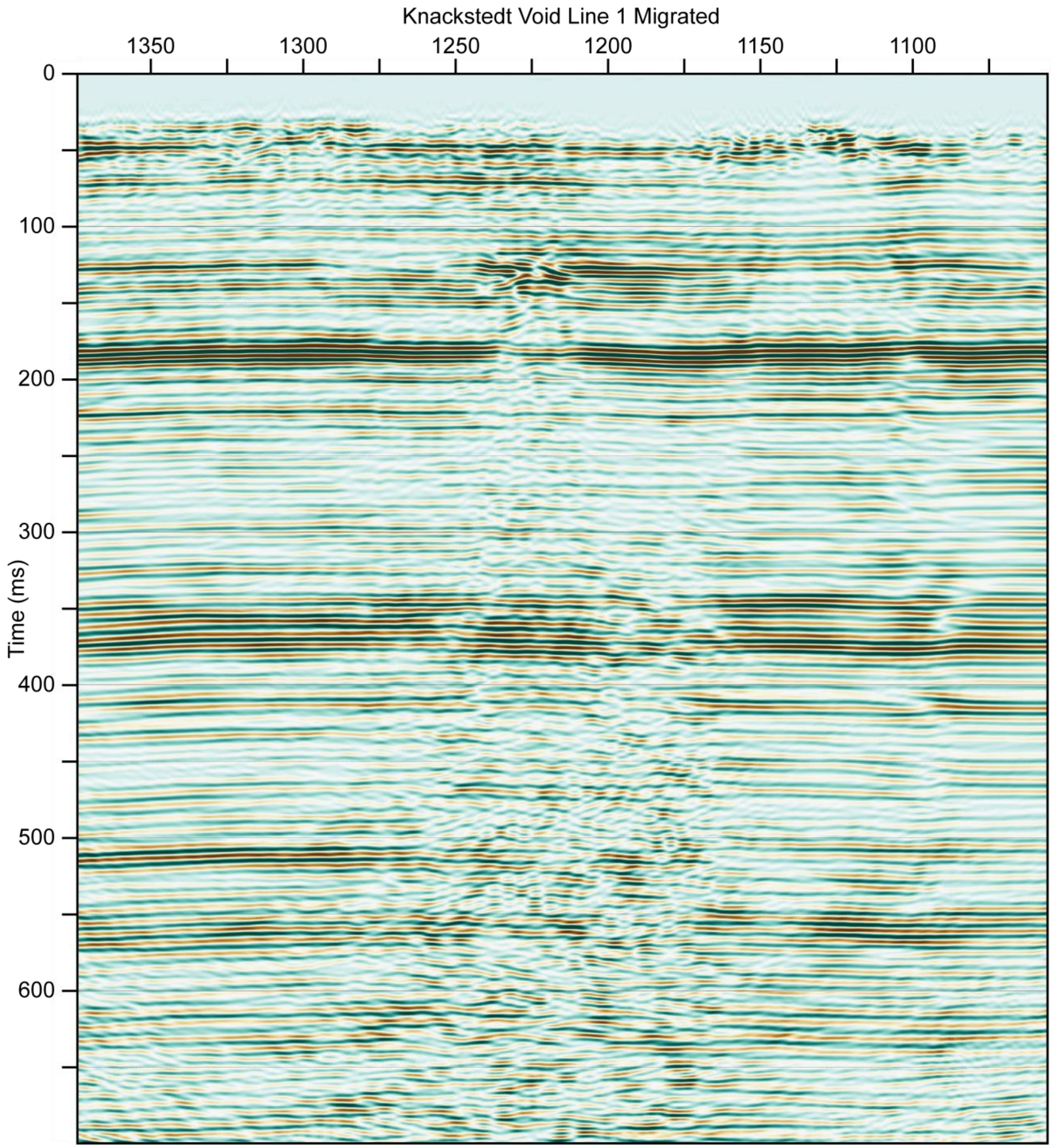

Figure 5. Migrated CMP stacked section of line 1 with color amplitude plot. This display format improves the contrast that the void represents with its significantly higher reflectivity. From this section, the subsidence at the top of the salt, west of the well, is evidenced by a dramatic drop in amplitude and reflection coherency between stations 1290 and 1240 immediately above the salt around 125 ms. This subsidence event does not penetrate the entire upper Wellington. There is no evidence of subsidence in the Ninnescah Shale west of the well. A subtle drop in amplitude and drape in reflections from station 1150 to 1120 and from 1090 to the east end of the profile are related to a subsidence event that is not centered on this profile but out of the plane, north or south. The sequence of north/south lines will provide critical clues as to the orientation of these paleo subsidence features.

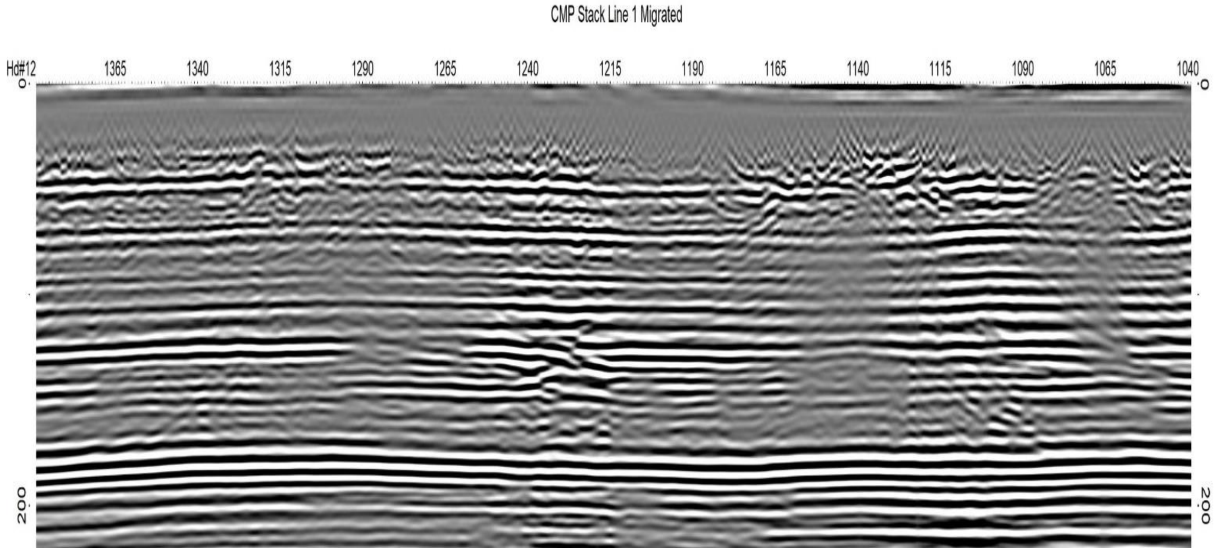

Figure 6. A more focused display with the voids evident at higher amplitude reflections relative to returns from the same reflector in solution-affected areas of the section. These graytone data focusing on the section between the base of salt and the bedrock surface provide improved contrast in amplitudes useful in mapping the effects of rock failure (plastic or brittle behavoir in particular). Areas with diminished amplitudes are likely indicative of some form of failure. Subsidence noted in previous version of these data beneath stations 1285, 1150, and 1070 are evident in this section as subdued/suppressed reflection amplitudes. Especially evident in these data are scattering/diffractions within the salt and overburden at the east end of the profile where paleo subsidence has been interpreted on previous display formats. Migration, when optimally applied, will compress scatter/diffractions back to the point source. Ideal compression requires highly accurate velocity. Here the velocity function is just slightly off real and at the limits of conventional velocity analysis.

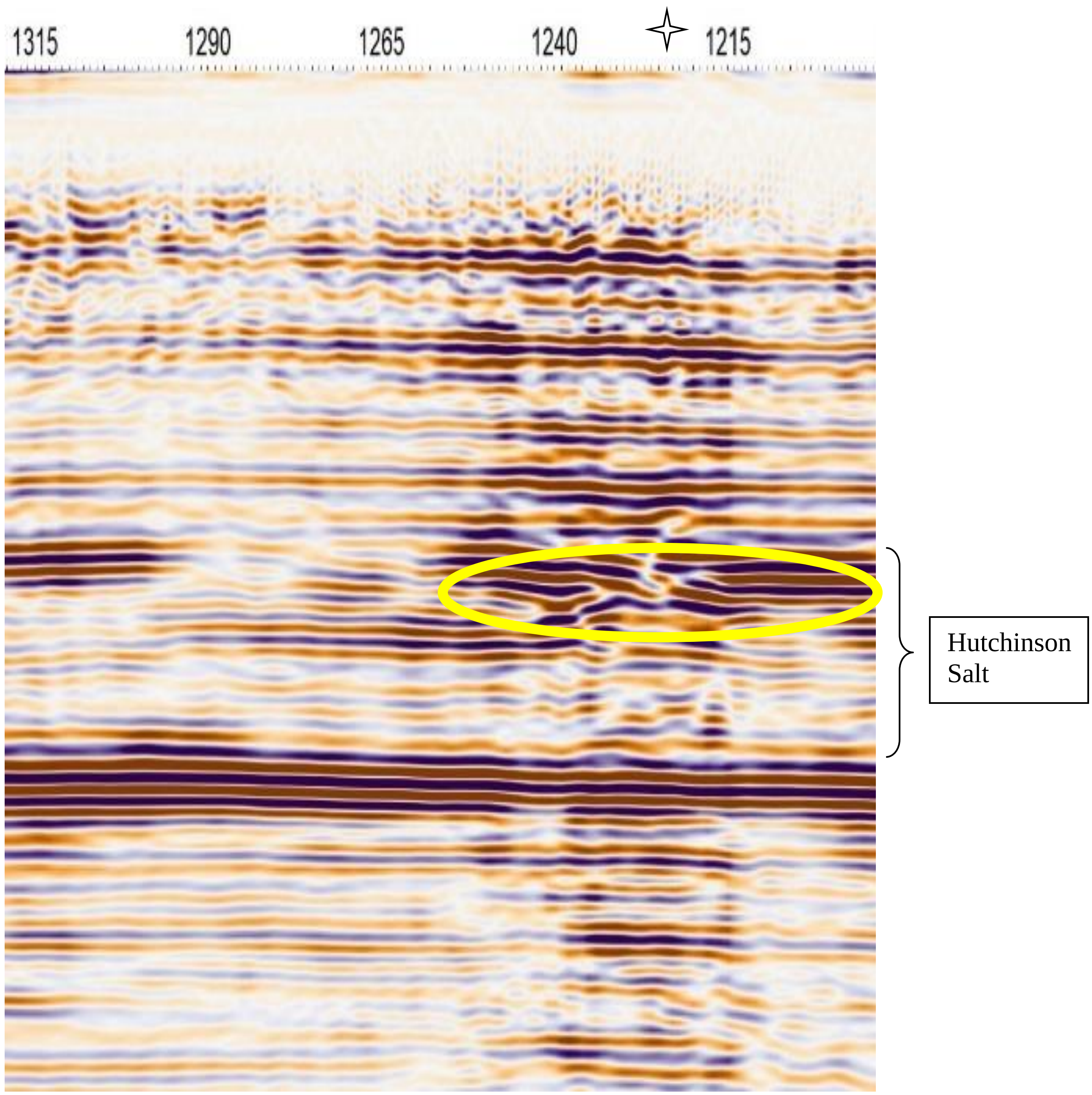

Figure 7. Color amplitude section with the primary void identified with the yellow ellipse. ✧ is the approximate location of the disposal well. Hutchinson Salt has several reflectors within the interval, likely indicative of anhydrite or shale layers within this unit. This display is trace-by-trace normalized so vertical amplitude banding is an artifact of that process, but with this approach relative amplitude changes vertically between local reflections are more pronounced. The very distorted orientation of the reflections within the yellow ellipse is a result of the three-dimensional nature of the void. Out-of-the-plane energy is returning and stacking at locations that are offset laterally from their actual reflecting point.

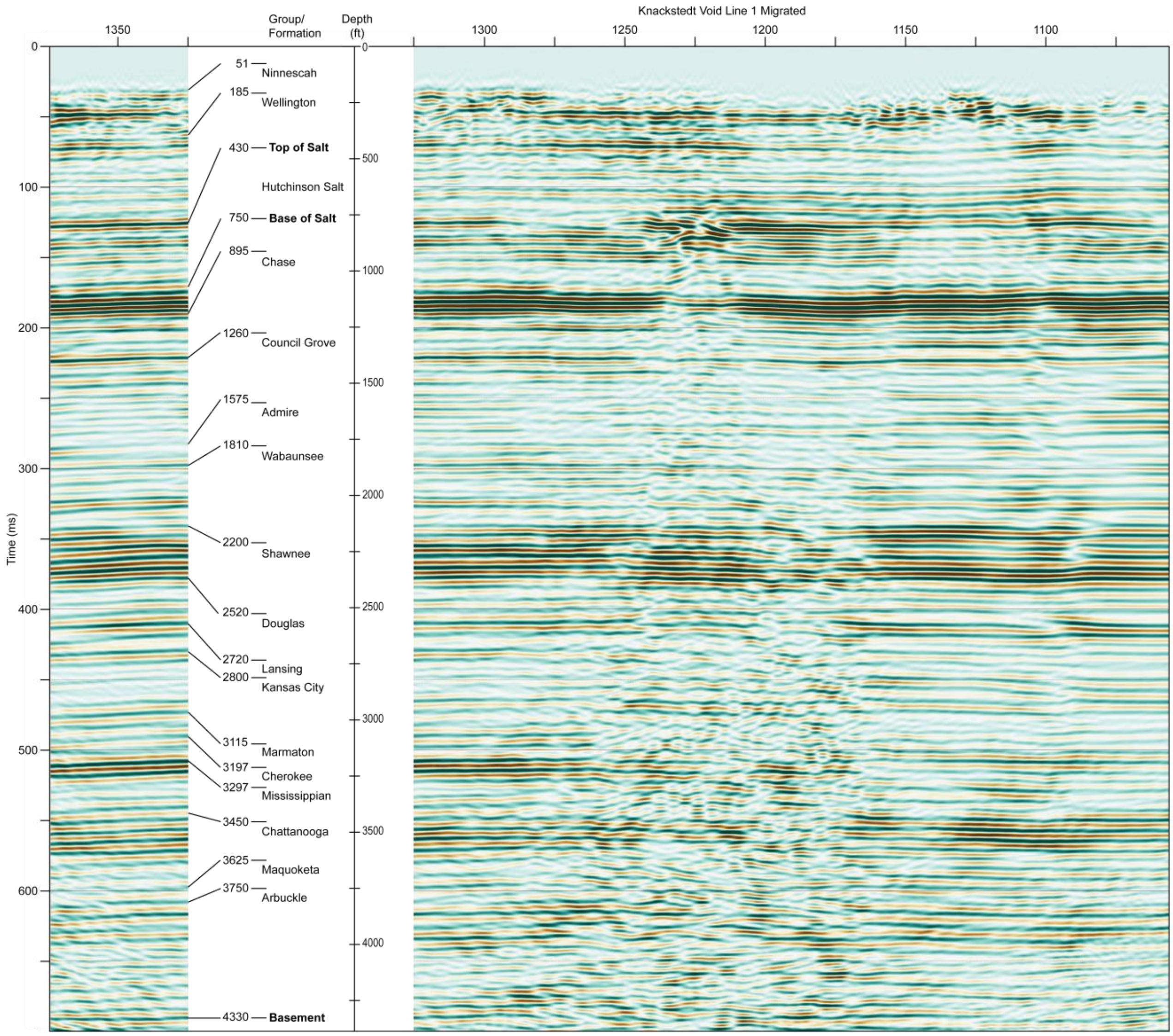

Figure 8. This version of Figure 5 of this report includes the geologic log as inferred from local wells. Although not a perfect match with changes in rock intervals, in general there is good correlation in the upper 2000 ft. The top and bottom of salt are very distinctive and were the focus of the acquisition geometry and parameters.

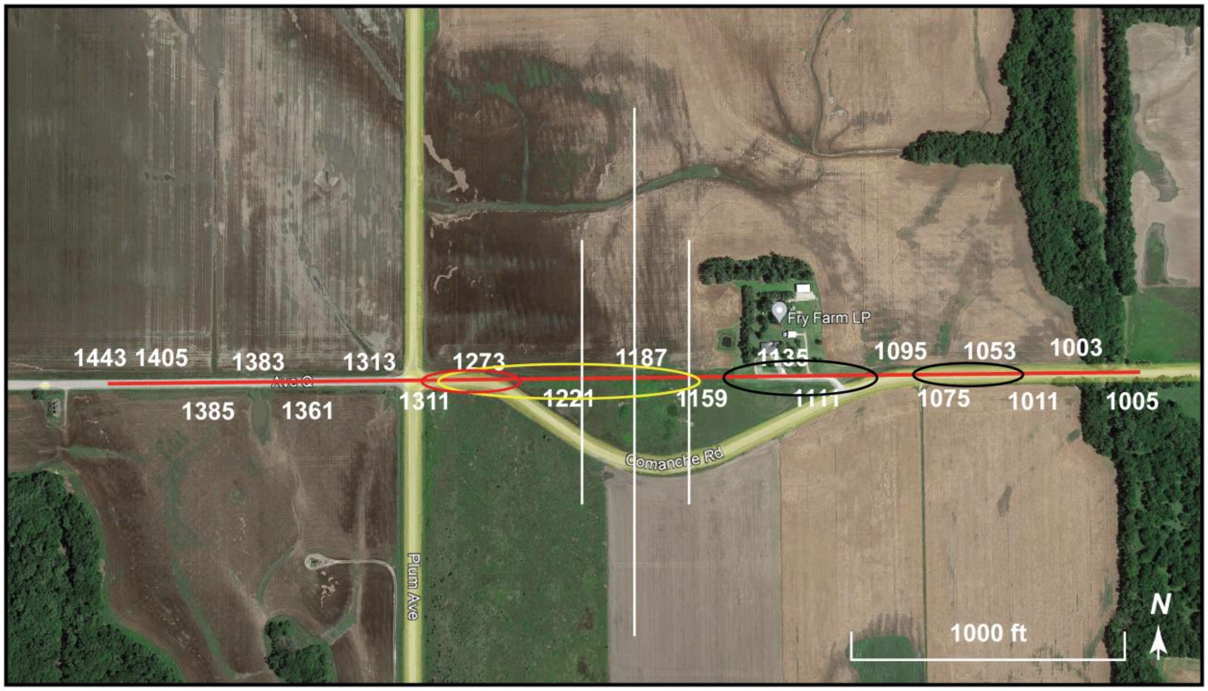

Figure 9. Site map with areas where the subsurface is or could be impacted by dissolution, either anthropogenic or paleo. Black ellipses are paleo features, the yellow ellipse is an area with a current void or solutioning that has some potential to result in surface expressions, and the red ellipse is an area where some evidence of solutioning is evident but the chance of a void migrating to the surface is extremely improbable.