HIGH-RESOLUTION SEISMIC IMAGING OF CATASTROPHIC SALT DISSOLUTION SINKHOLE IN CENTRAL KANSAS

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Abstract

High-resolution seismic reflection techniques successfully imaged structural features associated with a sinkhole that formed catastrophically as a result of dissolution of the Permian-age Hutchinson Salt in central Kansas. Symmetric steep sided chimney structure formed instantaneously, which over time has continued to gradually enlarge and elongate to the east, forming an open bowl. Orthogonal high-resolution seismic lines were acquired to map the upper thousand feet and resolve structural features controlling development and possibly appraise future threat this feature represents to surface activities and local groundwater. High frequency vibrator and high-resolution seismic methods were used to acquire data from a 204 channel fixed spread. Common mid-point stacked sections depict very distorted subsurface that has undergone multiple phases of loading, failure, and subsidence. Stress built-up in roof rock overlying the salt void until catastrophic failure occurred along reverse fault planes within the tensional dome. Strain associated with bridged layers outside that dome is occurring along normal faults, which appear to have minimal vertical connectivity between interpreted reflectors. Oil-field disposal practices provided original fluids and pathway that initiated the dissolution process. Currently shallower groundwater fuels the dissolution process with oil-field brines contributing little, if at all.

Introduction

Sinkholes represent hazards to property and human safety in various geologic settings. They can occur due to natural processes or human activities. Understanding this process and its affects on near-surface layers can assist in reducing or possibly eliminating their threat. Sinkholes generally form from roof rock failure over voids or cavities caused by the dissolution of limestone, gypsum, halite, or mining.

Localized dissolution of the Hutchison Salt in south central Kansas has been documented to result from improper brine disposal in wells. Disposal wells in central Kansas must penetrate the Hutchison Salt to reach target disposal layers at depth sometimes exceeding 1800 m. Leaching of the salt occurs when that salt section is poorly isolated from the brine disposal water due to inadequate grout or faulty casing in the wells. If this leaching continues for a long period of time it will create and enlarge a salt void beyond what the roof rock can support. This roof rock failure will usually end with sinkhole development at rates ranging from catastrophical to gradual. The subsidence rates are related to the type of deformation in the salt (ductile or brittle) and the physical properties of the overlying rock layer.

The rate of surface subsidence appears to be controlled by the geometries of the ever-growing bowl-shaped depression. If the growth geometries are constrained by normal faults then gradual surface subsidence is to be expected (Steeples et al., 1986; Anderson et al., 1995b). With catastrophic subsidence rock failure is generally brittle and the void area migrates to the surface as an ever-narrowing cone. The rock failure geometries are controlled by or result in reverse fault planes (Davies, 1951; Walters, 1980; Rokar and Staudtmeister, 1985). Once sinkhole strain changed from reverse to normal faulting it remains normal faulting throughout its development. Therefore, if subsidence is gradual it will likely remain gradual throughout its current active period. Existence of Paleosinkhole is usually a good indicator that subsidence in this area is possible but it will likely progress at a gradual rate.

Salt dissolution sinkholes in Kansas are found where the Hutchison Salt member is present in the subsurface. By using stem pressure tests and/or seismic reflection investigations, sinkholes can be confidently associated with failed disposal wells (Steeples et al., 1986; Knapp et al., 1989; Miller et al., 1995; Miller et al., 1997). Natural salt dissolution sinkholes are most common at the north and west depositional edge of this regionally expansive bedded evaporate sequence and the eastern erosional boundary (Frye and Schoff, 1942; Frye, 1950; Merriam and Mann, 1957; Anderson et al., 1995a)

Geologic Setting

The Permian Hutchison Salt Formation Underlies a significant portion of south central and central Kansas. The east edge of figure 1(b), where the contour lines are close, indicates an area of the dissolution front. This salt layer has a westward dip and not only has a great lateral depotional extent but also has been preserved since the Leonardian Stage of the Permian, about 250 million years. The average net thickness of the Hutchinson Salt in the Kansas area is 76 meters but it reaches a maximum of over 152 meters in the southern part of the basin. These halite beds are 0.15 to 3 meters thick and are interbedded with shale, minor anhydrite, and dolomite (Walters, 1978). The Permian/Pennsylvanian age boundary can be found at a depth of one kilometer. This is represented seismically by a strong sequence of cyclic reflecting events.

The top of Chase Group can be found approximately 570 meters deep. This group consists of 102 meters of marine limestones, dolomites, shales and siltstones. The Sumner Group, which consists of the Wellington, Ninnescah shale and Stone Corral formations, is where the Hutchinson Salt Member is located. It is located within the Wellington Formation with the “Upper Member” of dark gray shale on top of it at a 325 meters and the “Lower Member” of Anhydrite and gray shale with interbedded dolomite below at 425 meters. The Hutchinson Salt member consists of salt with interbedded anhydrite, shale, magnesite, and dolomite with the top portion located at 380 meters depth. Ninnescah Shale (275 meter deep) and Stone Corral Anydrite (250 meters deep) depict the onset of arid conditions during Lower Permian age. These consist of dolomite, anhydrite, gray siltstone, sandstone, reddish brown shale, and siltstone. The shallow most beds are the Harper Sandstone (top at 200 meters), and Salt Plain Formation (70 meters), which consist of red siltstone and shale along with sandstone (Watney et al., 1988). The beds can all be identified easily due to the isolated envelope of reflecting events. (Miller, in press)

There are two reasons the Halite beds are intact. First the salts are located in an area of little tectonics therefore they are flat lying with few natural sources of water infiltration. Second overlaying rock is Permian Shales, which act to protect the salt by maintaining an impenetrable seal. These Permian redbed shales that form roof-rock interval are the way to look at the past, present, and future of subsidence caused by the salt dissolution in this area. The failure and subsidence of this thick sequence of Permian shales and sandstones controls formation rates and sinkholes dimensions. The fracturing of these nonpermeable layers will open pathways for groundwater to gain access to the Hutchinson Salt.

Seismic reflection studies used to delineate localized structures in this area have relied heavily for structural control on the 12 meters thick dolomite and anhydrite Stone Corral Formation (250 m). The Stone Corral anhydrite is stratigraphically just above the Hutchinson Salt in areas where the salt is greater than 250 m deep, laterally continuous with widespread regional distribution. It is an excellent acoustical marker because it is a significantly high velocity material, incased within lower velocity shale (McGuire and Miller, 1989).

Dissolution structures will be visualized by mapping the affects that the absent of the Hutchison salt layer has on the overlying beds. Dominant reflections will be seen from the Stone Corral anhydrite. Primary target depths will not exceed 500 m and the salt depths will generally not exceed 600 m.

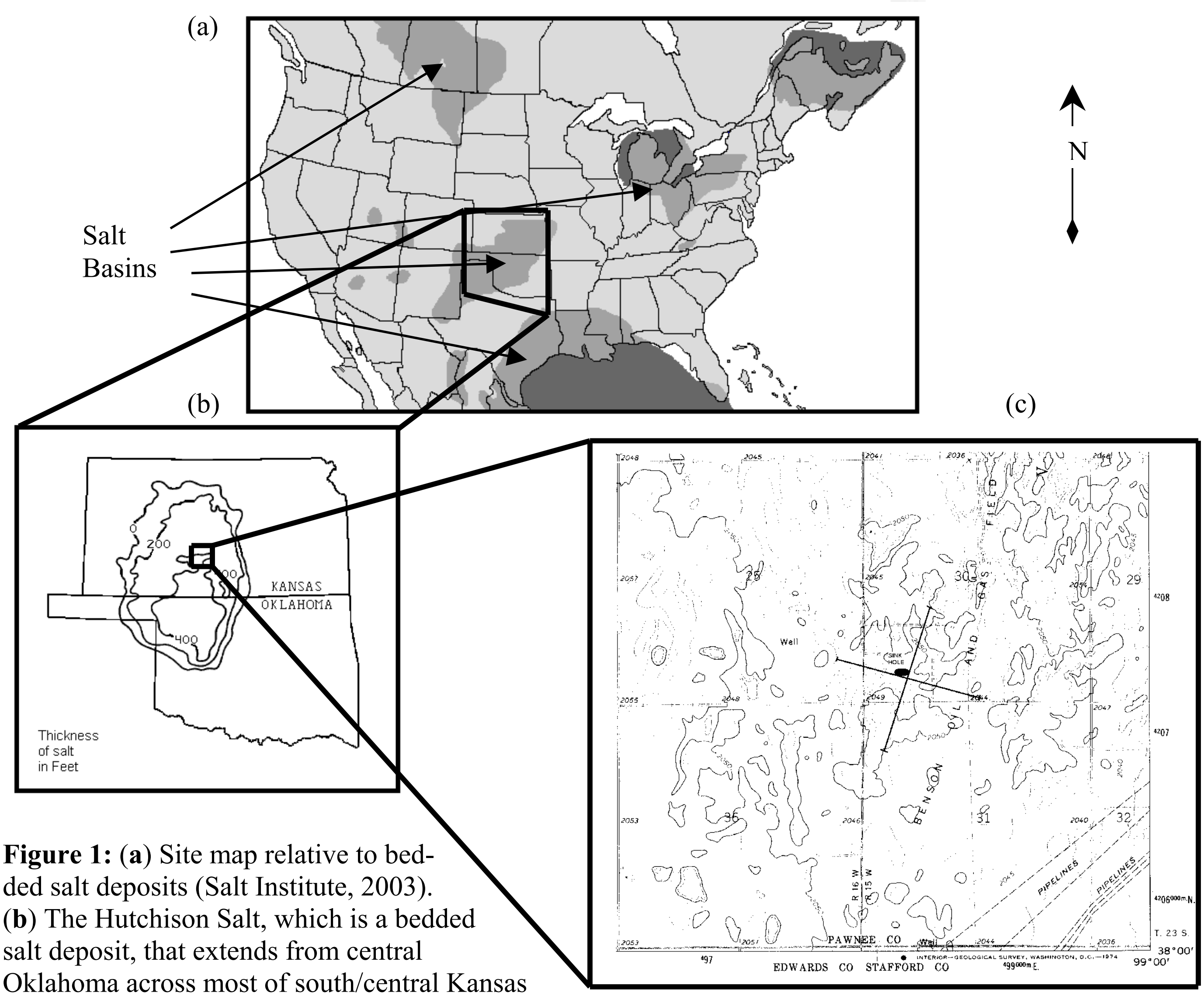

Figure 1: (**a**) Site map relative to bedded salt deposits (Salt Institute, 2003). (**b**) The Hutchison Salt, which is a bedded salt deposit, that extends from central Oklahoma across most of south/central Kansas (Walter, 1978). (**c**) Two one kilometer seismic profiles superimposed on topography, Edwards and Safford Counties, Kansas.

Seismic Acquisition

Two fixed 204 station spreads were deployed, one west to east the other was north to south, both were about one kilometer in length (figure 1(c)). The survey was designed to allow a clear image of the entire subsurface expression of the sinkhole.

Three 40 Hz Geophones were seated into damp sandy soil at a 5 m interval. The top few centimeters of loose soil and vegetation were removed at the planting location to maximize the coupling of the geophone with the ground. Four 60-channel, 24-bit Geometrics StrataView seismographs were used for the recording of the two 204 station fixed spread lines avoiding the need to roll. The source was an IVI Minivib that delivered four 10 second, 30-250 Hz up-sweeps at each of the shot locations. Source stations were also separated by 5 m. The four sweeps at each shot station were individually recorded and stored with the ground force pilot in an uncorrelated format.

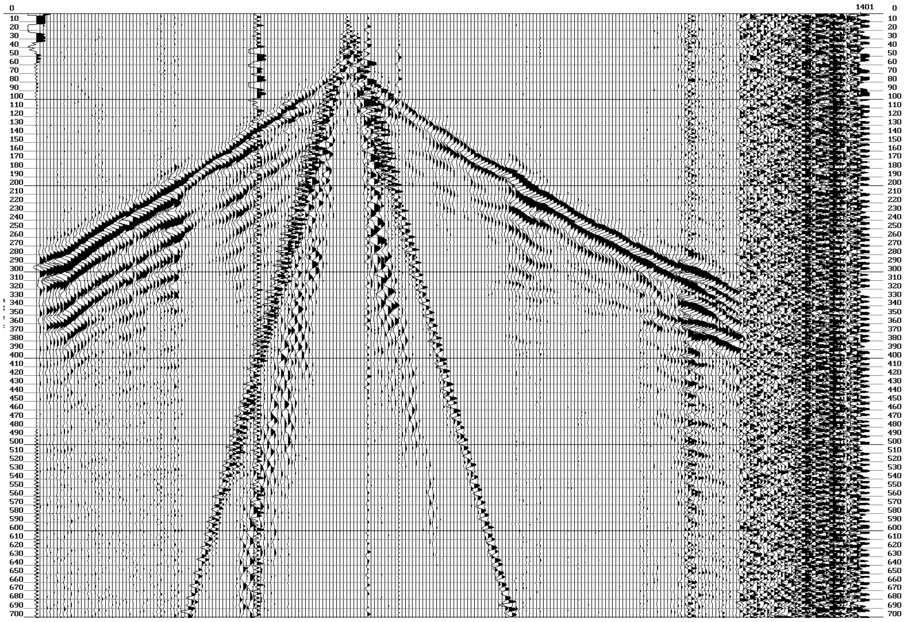

Figure 2: Shot gather from the west to east line.

Seismic Processing

The basic common midpoint processing flow was consistent with a 2-D high-resolution seismic reflection processes (Steeples et al., 1990). All lines were processed using WinSeis2, beta seismic data processing software (developed at the Kansas Geological Survey). The subsurface is highly disturbed and the data are plagued with static problems.

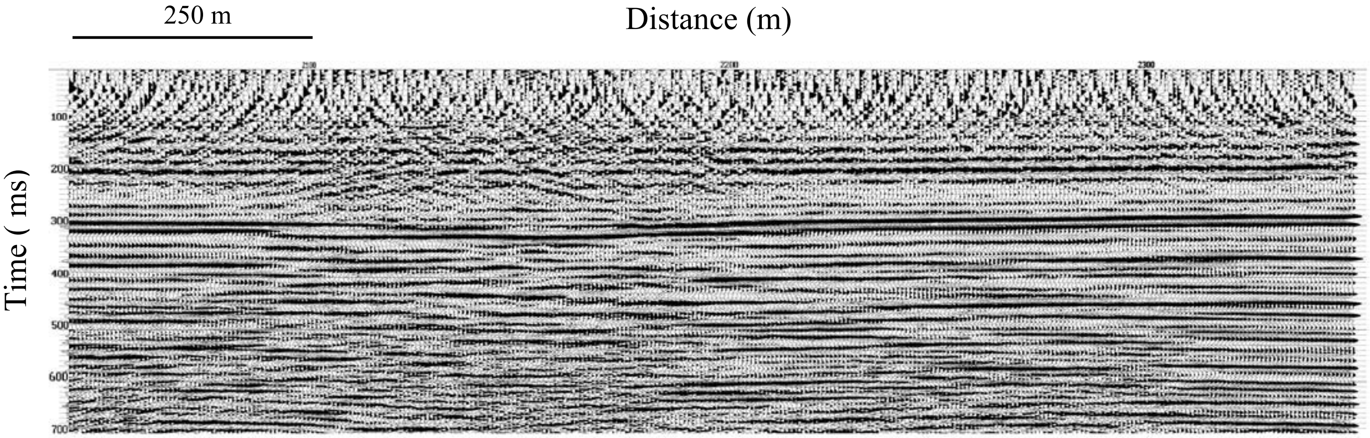

Figure 3: Macksville uninterrupted line that runs from west to east.

Data was stored uncorrelated allowing tests to be ran with different methods of correlation and using different pilot traces for the correlating. The data was correlated using a synthetic drive signal. The emphasis of data processing was placed on suppressing the noise, maintaining the true amplitude, and compensating for the velocity irregularities that come from the static problems. The noise suppression focused on the surface waves, first arrivals, and air-coupled waves. The four individual shot gathers acquired at each shot-point were vertically stacked after all the nose suppression

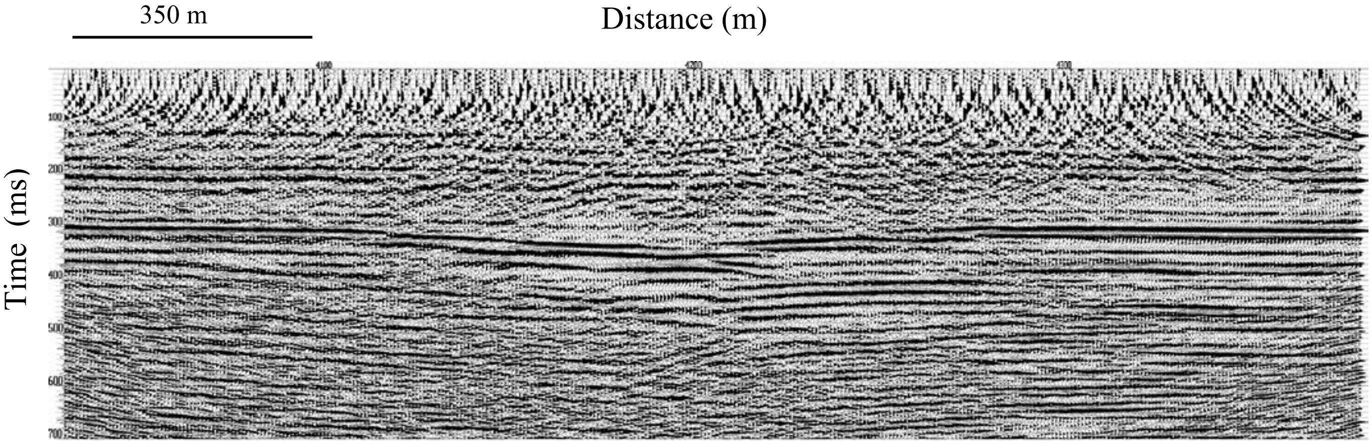

Figure 4: Macksville uninterrupted line that runs from north to south.

Seismic Interpretation

Interpretable reflections throughout the primary time-depth target window (250 ms to 450 ms) have broad spectral bandwidths and sufficient coherency to clearly interpret reflections across several traces on shot gathers. Individual reflection events cannot be traced through the air-coupled wave and ground roll wedge. Asymmetry of the reflection hyperbolae is observed in the shot gathers across both lines as a result of the dipping layers and velocity variability. These distortions will adversely affect the NMO velocity corrections.

To accurately represent the subsurface on the CMP stacked sections CMP gathers must be thoroughly analyzed and corrections must be accurate. To minimize the offset-dependent nature of frequency and amplitude characteristics only close offset traces were included in the stacked sections. NMO velocities were extensively defined for several of the primary reflection interfaces to insure minimum decay in the frequency content after the stacking.

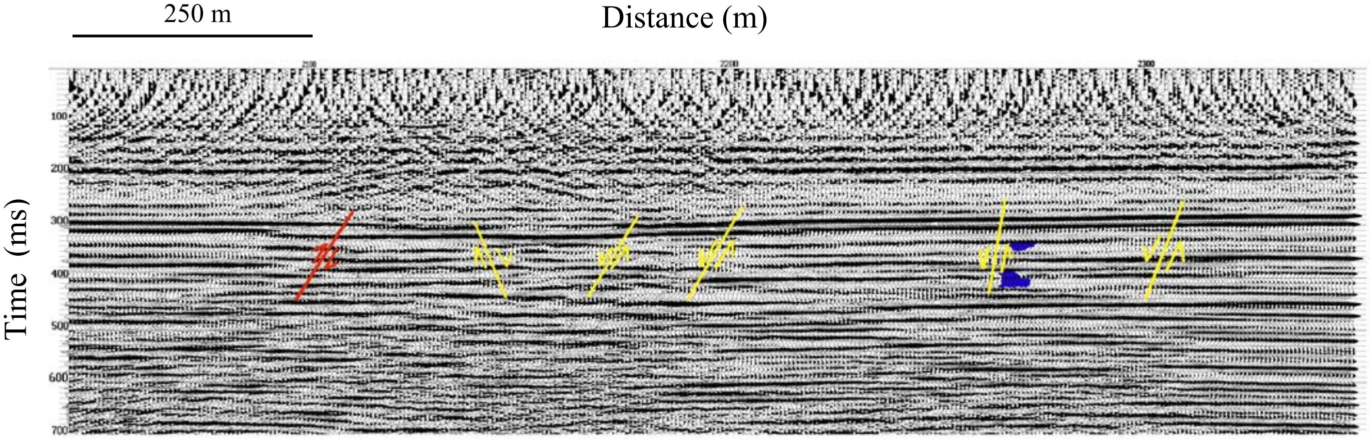

Figure 5: Macksville interpreted line that runs from west to east. There are Normal type faults (yellow), Reverse Fault (red), and Dissolution front (blue) appearing in this seismic line.

The vertical bed resolution is on the order of 3 to 5 m, depending on the specific reflection. This was more than ample for confident interpretation of rock layers distorted after collapse into voids left once the rock salt was leached away. The Stone Coral surface varies in depth around the salt dissolution feature and site from 280 to 300 ms. The Hutchison Salt surface is interpreted at about 330 to 350 ms.

Rock layers distorted by the subsidence extend more than 850 m from north to south and 565 m in the east west direction. Changes in the dip of collapsed layers across this feature providing evidence to help decipher the sequence and timing of dissolution and subsidence that led to the current sinkhole geometry.

Lateral coherency and the signal-to-noise ration were improved by migration. Migration also corrected for the optical distortion related to the slight dip angle of the reflections. In the migration data the salt layer is clearly defined by the relatively lower frequency and the higher amplitude reflections. These lower frequency signals are form the shale and anhydrite layers that are interbedded with the halite.

The sinkhole has many fluctuations between times of high and low stress release. At the times when the stress rates were high strain produced the reverse faults that show an ever-narrowing cone structure extending to the surface of the ground.

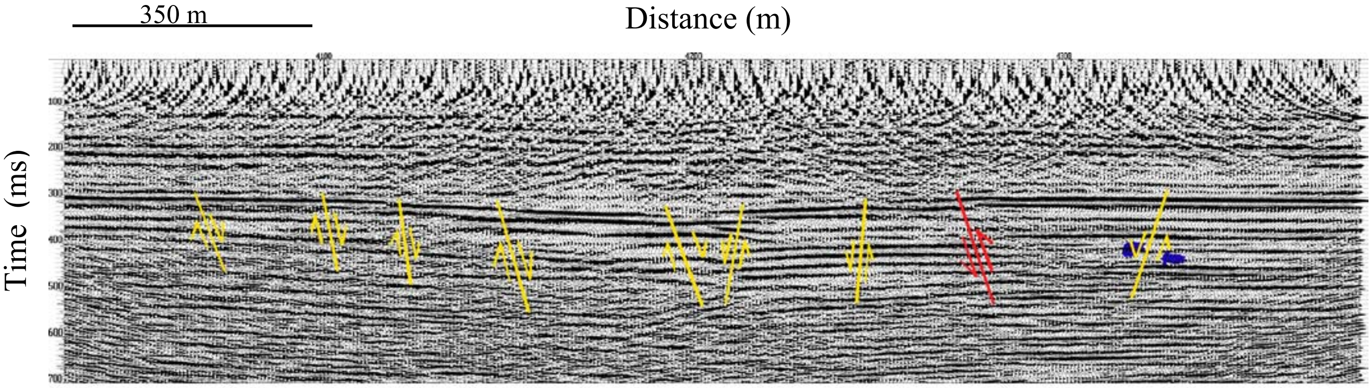

Figure 6: Macksville interpreted line that runs from north to south. There are Normal type faults (yellow), Reverse Fault (red), and Dissolution front (blue) appearing in this seismic line.

Conclusion

This salt dissolution feature will continue to subside on the northern and eastern fronts (seen in figure 5 and 6). The reflections suggest a plastic deformation of the rock layers over the dissolution voids. This was followed by the roof rock failure along reverse fault planes within an earth volume, the tension dome. There has been a period of normal faulting and reverse oriented faults. There exits the possibility for water to have found its own path into the Hutchison Salt layer through the Stone Corral. The surface subsidence will more than likely continue at a gradual rate for some time into the future.

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