PSSource-Generated Seismic Noise in 2-D Reflection Surveys in the Basin and Range Physiographic Province: Issues, Attenuation and Case Histories*

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Abstract

Geothermal and mineral resources occur mainly in association with igneous and metamorphic geology, even in primarily sedimentary settings. In sedimentary settings, there is often a transition to a metamorphic regime caused by hydrothermal solutions from geothermal cells. Sites associated with igneous and metamorphic rocks are notorious for seismic signal attenuation and scattering. Additionally, the reflection events in igneous/metamorphic settings can result from impedance contrasts along dikes, alteration zones, density changes and numerous features other than lithologic boundaries. Given these factors, continuous reflections across stacked sections at these sites are seldom apparent. Rather, acoustic interfaces will typically manifest themselves as a series of short, discontinuous reflection events within a background of scattered acoustic energy. The resulting data sets are not easy to process and interpret.

Seismic reflection techniques will usually image the interface between sedimentary and crystalline rock very easily due to the high acoustic impedance contrast at this boundary. The objective of seismic surveys conducted for geothermal and mineral exploration is usually to gain some understanding of structural features within igneous and metamorphic rocks, which may include faults, fracturing, lithologic changes, etc. In order to successfully image in this setting, special considerations need to be addressed in data acquisition, processing and interpretation. This paper discusses survey design considerations for 2-D data in these environments, dealing with coherent source generated noise trains, and identification of reflection events through an examination of intermediate processing steps.

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ABSTRACT

Igneous rocks present in geothermal and other hard rock sites are notorious for seismic signal scattering because of internal heterogeneities in those environments. The complex structural settings create intricate subsurface wave fields. Given these factors, continuous reflections across stacked sections at these sites are seldom apparent. Rather, subsurface acoustic interfaces will typically manifest themselves as a series of short, discontinuous reflections within a background of scattered acoustic energy. The resulting data sets are not easy to process and interpret.

A common problem in geothermal seismic data is coherent source-generated noise. This noise includes ground roll, which is amenable to attenuation by using appropriate source and receiver arrays, survey geometry, and specific processing algorithms. In addition to ground roll, these seismic data commonly include linear noise trains parallel to first breaks. A third type of coherent noise is reflection multiples.

The first section of this paper examines the causes of coherent noise, its attenuation during data acquisition and processing, and provides a review of basic quality control checks on the data acquisition and processing sequence. The second section of the paper contains case histories of successful 2-D seismic reflection surveys. The first is at a site where access was limited and the main objective was detection of vertical faults. Alteration of the underlying rocks is pervasive. The second is a hard rock site where low angle and intrusive features were of interest. Mining activities taking place during the survey added to the noise issues. Success at these sites resulted from application of various noise avoidance and attenuation factors discussed above, plus extensive collaboration between the project geophysicists and the client geologists and geophysicists.

INTRODUCTION

In data acquisition, processing and interpretation, geothermal seismic exploration presents unique challenges. Locations for these new seismic programs have shifted from deeper parts of Basin and Range sedimentary basins toward basin margins and up into hard rock mountainous areas, where volcanic rocks and Paleozoic metasediments have been extensively faulted and folded to a high level of complexity. Moving into these settings in search of geothermal resources increases the "difficulty" factor of Basin and Range seismic exploration. However, useful subsurface imaging is obtainable, as improved data quality and drilling success from recent 2-D seismic surveys have shown.

Igneous rocks present in geothermal environments cause seismic signal scattering by internal heterogeneities and complex structural settings producing intricate subsurface seismic wave fields when acoustic energy is applied. Unlike sedimentary basins, many lithologic interfaces within geothermal settings, such as the top of a basalt flow, are rugose in nature, in some cases causing the imaging targets themselves to be acoustic scatterers. Therefore continuous reflections across stacked sections in hard rock environments are seldom apparent. Rather, subsurface acoustic interfaces in volcanic rocks and meta-sedimentary rocks will typically manifest themselves as a series of short, discontinuous reflections within a background of scattered acoustic energy.

COHERENT NOISE

A seismic survey for geothermal exploration was conducted in December, 2008 in northwestern Nevada. The reflection data were acquired using an iVi Envirovibe vibroseis as a seismic source (peak force = 15,000 lbs.). The group interval was 60 feet; maximum fold roughly 65. Maximum far offset was 8,040 feet, with 134 channels live on every shot (walking on, walking off the receiver spread). This survey was conducted as part of early stage exploration into a geothermal resource, and was aimed at focusing exploratory drilling into areas of fractured and faulted rock. The geology in this area consists of a few hundred feet of fine-grained clastic sediments (Lahontan Lake sediments) overlying andesitic volcanic rocks. In this study, we examine coherent noise trains within the shot records, and then follow these through processing to look at how they are attenuated in the final product.

Figure 1 is an example of a raw shot record. Identified on this record are the ground roll (surface wave) noise cone and source-generated coherent noise trains, which are best described as reverberating refractions. The reverberating refractions are linear in nature and parallel to first breaks, which is indicative of acoustic energy trapped within the clastic unit bounded by the ground surface and the upper surface of the volcanic rocks.

Figure 2 is a schematic showing the ray paths of the acoustic energy producing these coherent noise trains. Acoustic energy moving down from the seismic source (vibroseis or dynamite) encounters the top of volcanic rock, and refracts along the interface, emanating acoustic energy back up at the ground surface as it progresses. The acoustic energy now moving upward is reflected back down into the subsurface at the alluvium/air interface, where it again refracts along the top of the volcanic rocks. The process repeats until attenuation fades the energy beyond detection levels. These reverberating refractions commonly will dominate raw field records in Nevada seismic data.

The best method of attacking this unwanted energy in processing is to use Linear Noise Attenuation (LNA) algorithms. Frequency-wavenumber (f-k) filtering is one of the most commonly used linear noise attenuators, but it is only a subset of a variety of processing algorithms designed to remove linear noise trains from seismic data. The LNA used on the records displayed here operates in the frequency space (f-x) domain, and uses weighted sums across traces to selectively attenuate any events that are linear in nature within a range of velocities defined by the seismic data processor. The linear events are not surgically muted or removed from the data, but rather the amplitudes of the linear signals are rescaled down to the level of background noise.

Figure 3 is an example of a shot record with spiking deconvolution, showing the original shot record on the left, an image after LNA-processing in the center, and on the right, the linear noise trains, both ground roll and reverberating refractions, that were removed from the shot record (created by taking the difference between the left and center panels). The LNA algorithm has effectively removed both ground roll and reverberating refractions from the shot record. The central panel, which will be sorted into the common depth point (CDP) domain and stacked, shows clear reflections with hyperbolic moveout.

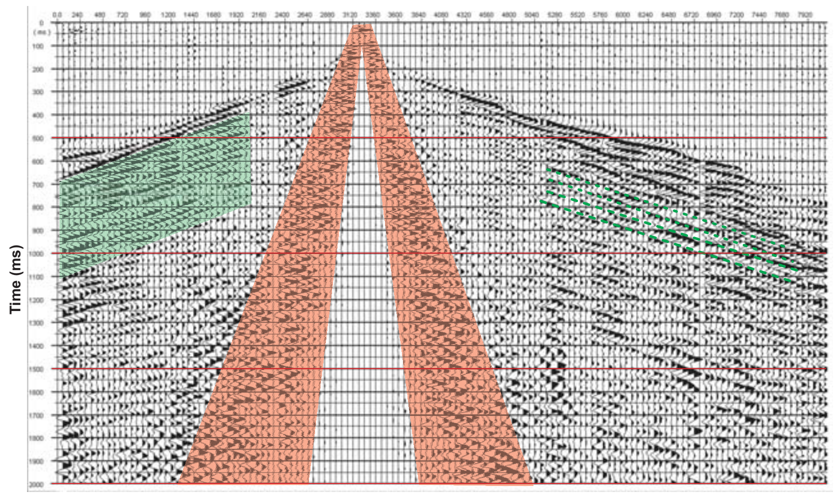

Figure 1: Raw shot record with ground roll cone (red) and examples of reverberating refractions are highlighted in green dashed lines on the right and in a shaded green outline on the left. This reverberating energy appears as linear arrivals paralleling the first break refractions.

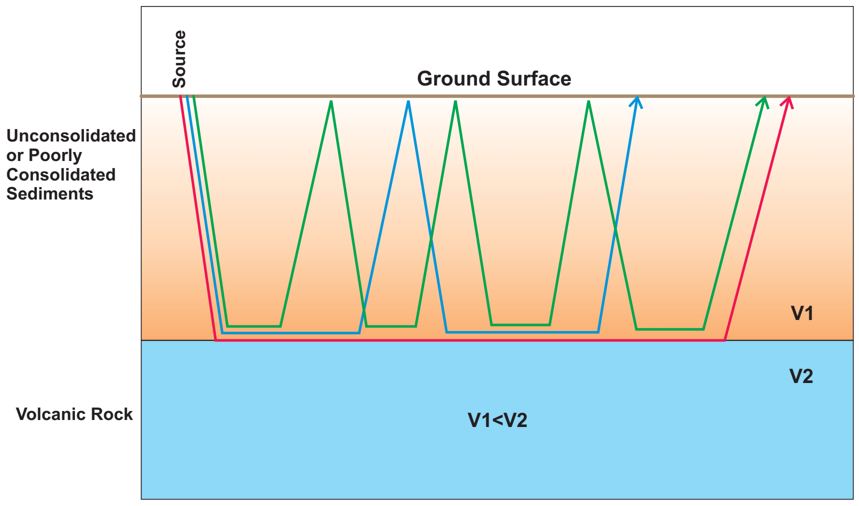

Figure 2: Schematic illustration of refraction multiples. Energy reverberates within low velocity surface layer refracting along the interface with the underlying faster layer (volcanic rock) and reflecting back down from the ground surface. This creates multiples that are parallel to the refractor first arrival.

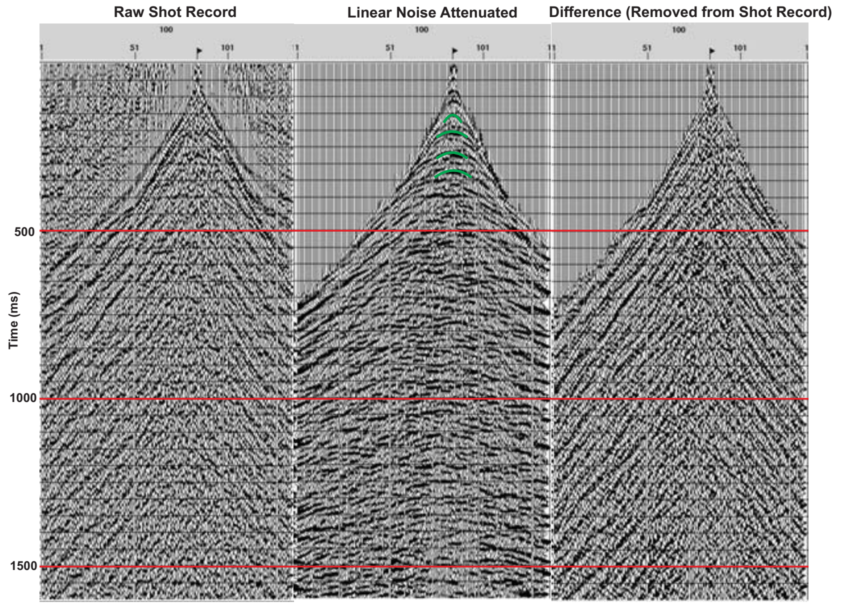

Figure 3: Sample shot record showing raw record with spiking decon (left panel), record with LNA applied (center panel) and difference record showing signal removed by linear noise attenuation filter (right panel). Green lines on center panel indicate potential reflection multiples.

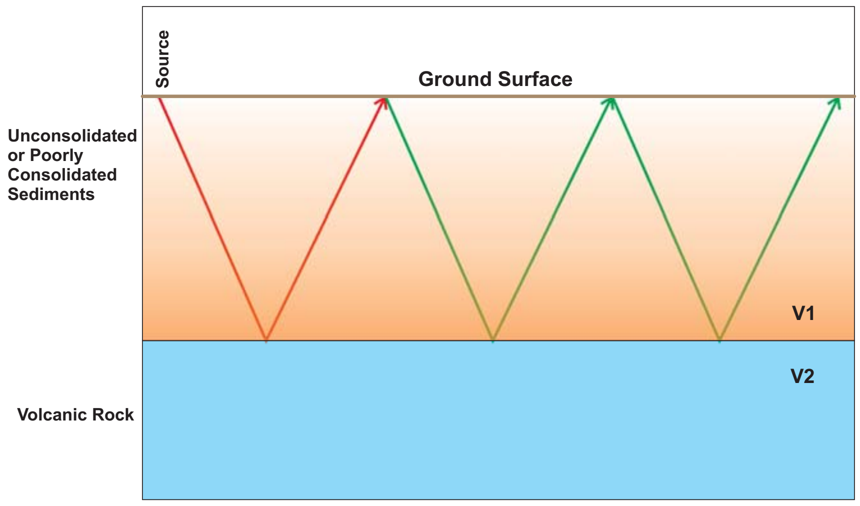

Figure 4: Schematic illustration of simple reflection multiples. In simple multiples, energy reverberates between the top and bottom of the layer. The red line represents the primary reflection and the green lines represent the first and second multiples. Unlike refraction multiples, reflection multiples will exhibit hyperbolic moveout in shot records.

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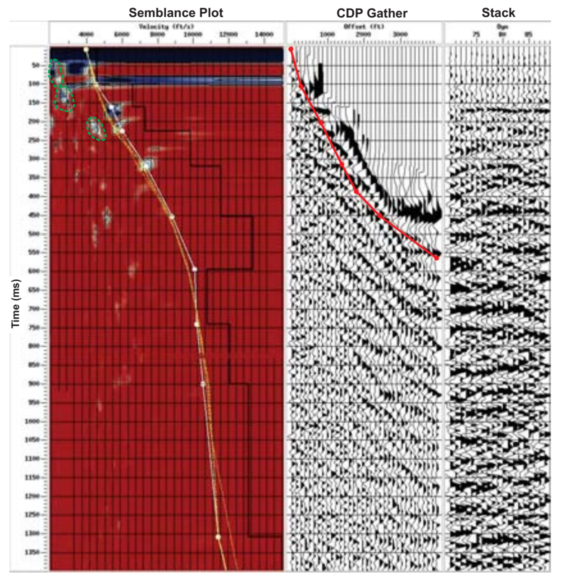

Figure 5: The three panels above include from left to right, a semblance plot for a CDP stack before LNA, a NMO corrected CDP and a sample of the stack section using the chosen stacking velocity field. The red line on the center panel represents the stretch mute which will remove all data above the line. Ground roll and refraction multiples manifest themselves on the semblance plot as zones of coherence with low velocity (outlined in green dashed lines).

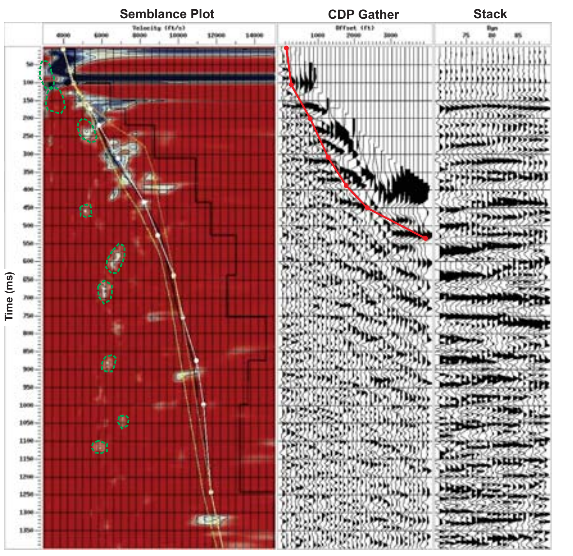

Figure 6: The three panels above include from left to right, a semblance plot for a CDP stack after LNA, a NMO corrected CDP and a sample of the stack section using the chosen stacking velocity field. The red line on the center panel represents the stretch mute which will remove all data above the line. Multiples of reflected energy are outlined in green dashed lines.

COHERENT NOISE (continued)

However, a close examination of the hyperbolic events in the data reveals that at least some of them occur at regular time intervals, leading to a suspicion that some of these events are simple multiples of acoustic energy reflecting many times between the ground surface and top of volcanic rocks. The raypath for multiple reflection energy is illustrated in **Figure 4**. In some ways, the geologic setting found in many geothermal areas in Nevada is analogous to a marine environment. In the oceans, the water column traps the acoustic energy, creating more obvious multiple reflections than can be seen here. In the central panel on **Figure 3**, hyperbolic events suspected to be multiple reflections are highlighted with green lines.

The process of velocity analysis is another opportunity to attenuate coherent noise trains within the dataset. **Figure 5** shows a semblance plot before applying LNA and **Figure 6** shows a semblance plot after applying LNA. Semblance plots are only one of the tools used in data processing to pick stacking velocities, and are usually used interactively in conjunction with displays of CDP gathers and short segments of stacked trace data (velocity panels). On a semblance plot, velocity is the horizontal axis, time is the vertical axis, and the color scale shows gradations in multi-channel coherency. The black blocky line on the figures is interval velocity and the solid line is connection of the semblance picks. For comparison the dashed lines are the semblance picks from the previous and next CDP gathers. When comparing the semblance displays, note that coherent noise trains comprised of ground roll and reverberating refractions form only a few identifiable targets on the upper left hand side of **Figure 5**. These semblance targets are high amplitude, and cause all other targets in the display to fade into background. As shown on this display, the velocities needed to stack in the coherent noise trains are less than 5,000 feet per second, which is, for the most part, unrealistic when dealing with the fast rock velocities found in geothermal settings.

Figure 6 shows the same semblance plot after coherent linear noise is removed. Taking out the highest amplitude targets results in a better display of what remains - coherence targets resulting from primary reflections and their multiples. Multiples form a chain of targets that are slower than primary reflections, and these are highlighted on **Figure 5**. On this display, coherence points for multiples are found at velocities below 8,000 ft per second, a value that becomes increasingly unrealistic with depth.

Figure 7 shows CDP gathers after deconvolution, LNA, velocity analysis and subsequent normal moveout (NMO) correction. The panel on the right side is highlighted with flat-lying, coherent events that, when all these traces are stacked, will sum constructively to produce a reflection event. The panel on the left side of **Figure 7** is the linear noise which has been removed (ground roll and reverberating refractions), sorted into the CDP domain and NMO corrected. Some faint line-ups are apparent, but the process of sorting into CDP gathers randomizes the majority of the linear noise. Additionally, after velocity analysis and NMO correction, any line-ups that remain are steeply dipping, so that the vast majority of peaks and troughs on this "noise" CDP gather will destructively interfere and cancel out during the stacking process.

Figures 8 and 9 show portions of uninterpreted and interpreted stacked seismic sections from the site. A series of high amplitude but discontinuous reflectors are apparent at the boundary between clastic sediments and volcanic rocks between 200 and 300 milliseconds. The discontinuous nature of these events is likely caused by the rugose and uneven volcanic surface over which the clastics have been deposited. Beneath these horizons are internal reflection events within the volcanic rocks. From an interpretation standpoint, it is important to note that reflection events in hard rock can and do result from situations other than changes in rock type. Density changes within the same volcanic unit or alteration zones that cut across numerous lithologic interfaces can occur. Sonic and density logs are useful in determining the location and source for reflections within the section.

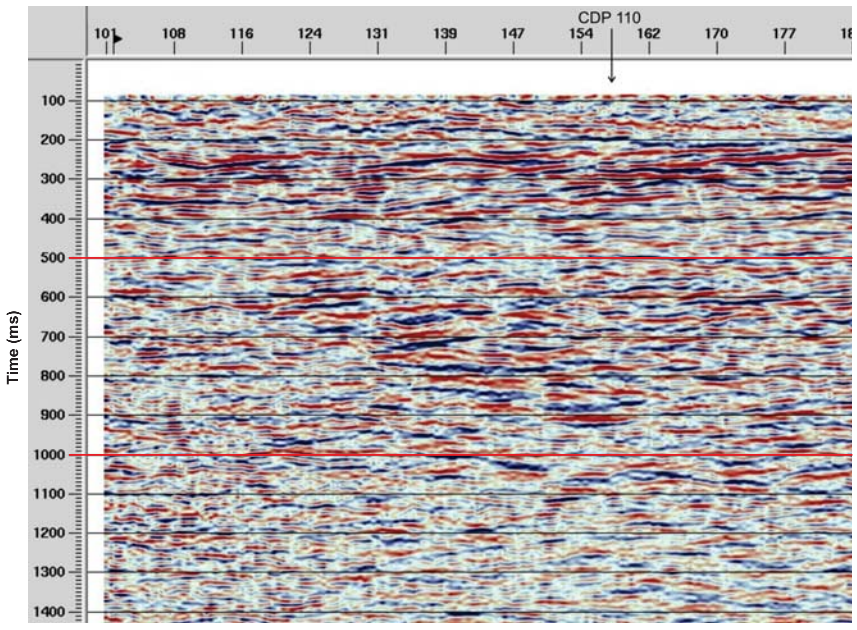

Figure 8: Sample of a processed seismic section. Blue is positive amplitude and Red is negative amplitude.

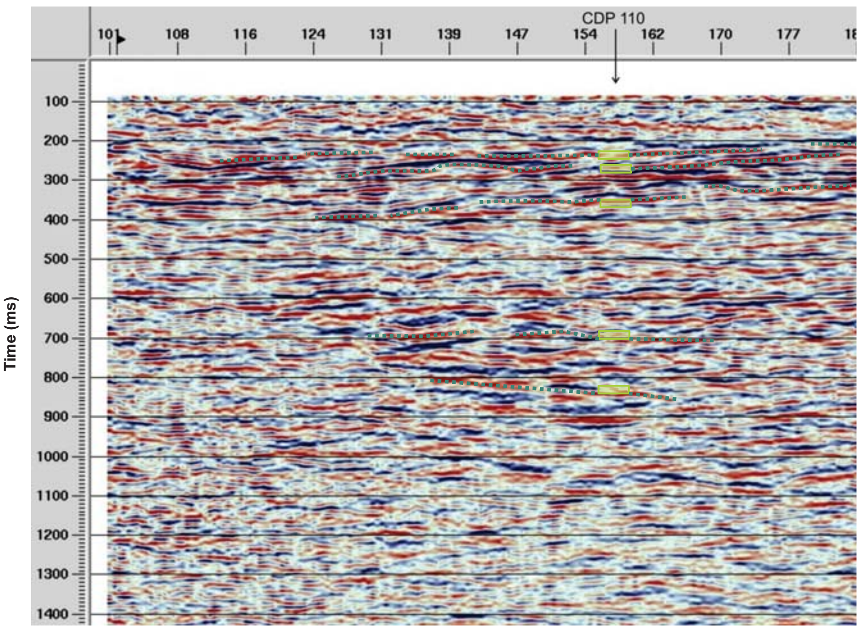

Figure 9: Sample of processed seismic section with major discontinuous reflectors identified with green dashed lines. Major reflectors identified on CDP gather (Figure 7) are shown as (🟩). Offsets are due to datum corrections.

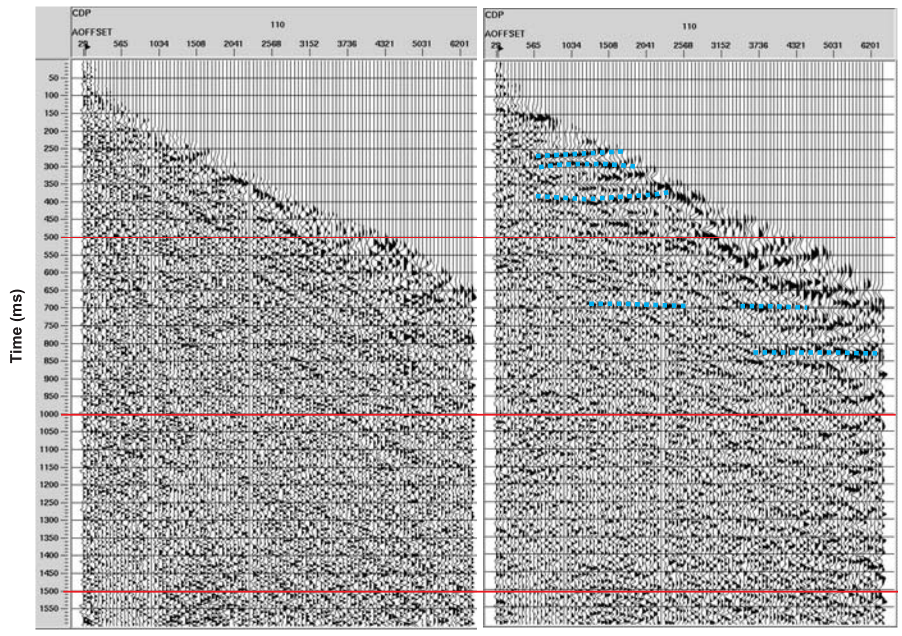

Figure 7: Left panel shows an NMO corrected CDP gather of coherent noise removed by LNA. Right panel shows the same NMO corrected CDP gather with linear noise attenuation applied. Dashed blue lines indicate reflection events.

SOURCE GENERATED NOISE: CONCLUSION

Reflections in geothermal settings typically manifest themselves as short, discontinuous segments within a background of scattered acoustic energy. The attenuation of ground roll (surface waves) during data acquisition can be achieved through source/receiver arrays and shooting configuration. In processing, the application of Linear Noise Attenuation algorithms is very effective at removing ground roll and reverberating refractions, which are common forms of coherent noise that plague seismic reflection acquisition in the Basin and Range. A review of shot records and CDP gathers before and after LNA application is recommended to assure that these coherent noise trains are being effectively attenuated. Semblance plots provide an easy way to verify that stacking velocities are picked to line up reflections rather than remnant source-generated noise. An examination of NMO-corrected CDP gathers can be useful in identifying reflectors of interest on the stacked sections. In conjunction with sonic and density logs, the source for these reflections can be determined as well as positioned correctly with respect to depth. Displays of the various intermediate processing steps described here can be used as basic quality control for reflection seismic data processing.

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CASE HISTORY, TUSCARORA, NEVADA

The area is at the north end of Independence Valley, along the Hot Creek drainage. The drainage in this area is bounded on both sides by low sage-covered hills with outcrops of volcanic rock and hot springs-deposited siliceous and carbonate sinter generally occurring along the crests. A thin veneer of colluvium and alluvium covers most of the hillsides, and thickens within the creek drainages. Well control and previous seismic data show that the general structure of the subsurface consists of a narrow north-south trending graben bounded by steeply dipping normal faults. The rocks encountered in the subsurface are primarily mafic volcanics, with significant portions hydrothermally altered to smectite clays. (Goranson, 2005). The area was explored for geothermal potential by AMAX and others, dating from the 1980s. These data were combined into a first pass conceptual model (Goranson and Van de Kamp, 2005) which was used as a guide to obtain 2-D reflection seismic data acquired by Zapata Incorporated's geophysics group in November and December 2006.

Figure 10 shows the location of the seismic lines. In this case study, the seismic survey was used to delineate fractures and fault locations. The seismic reflection data displayed linear disruptions within the interpreted Paleozoic section that appeared to be attributable to fracturing and/or faulting. The seismic sections for Lines A and D are shown in **Figures 11 and 12** below. Interpreted faults/fractures in the seismic sections were correlated with faults interpreted from detailed surface mapping and air photos. The seismic lines appear to image two intersecting sets of Paleozoic faults/fractures, oriented nearly orthogonal to each other. This area of intersecting faults/fractures was deemed worthy of further investigation and was outlined by the red box on the plan map (Figure 10). Subsequent drilling in this area of interest led to a substantial increase in produced hot water.

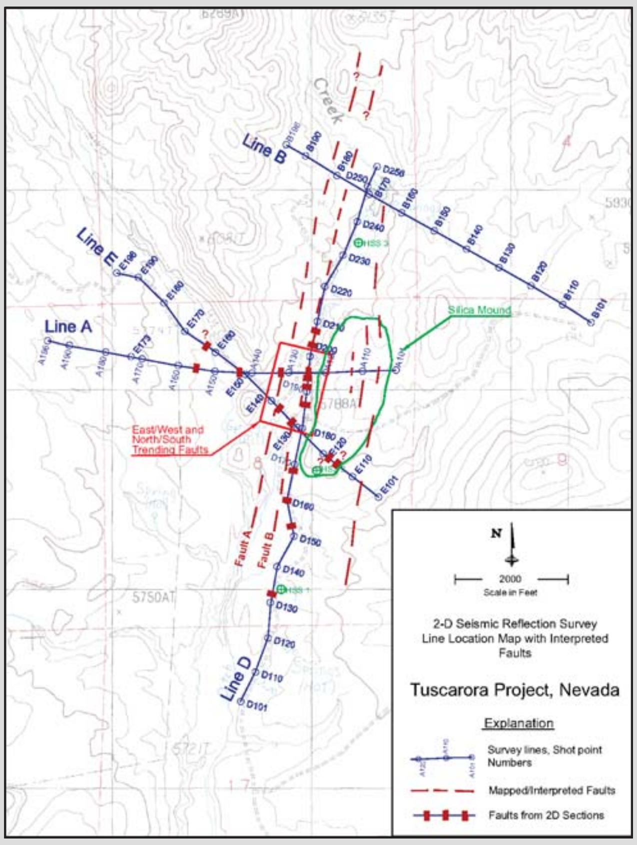

Figure 10: Site plan map showing location of seismic lines.

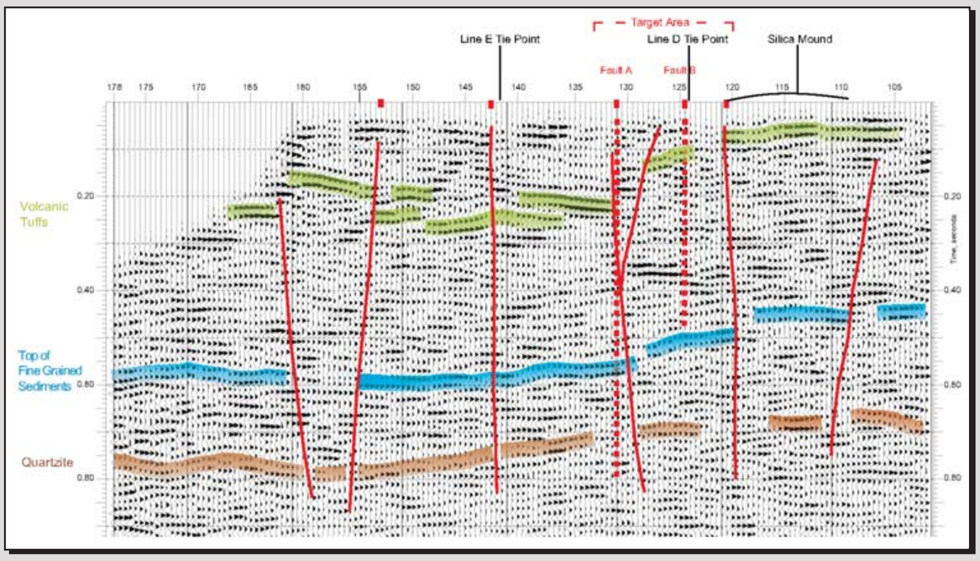

Figure 11: Seismic Section along Line A.

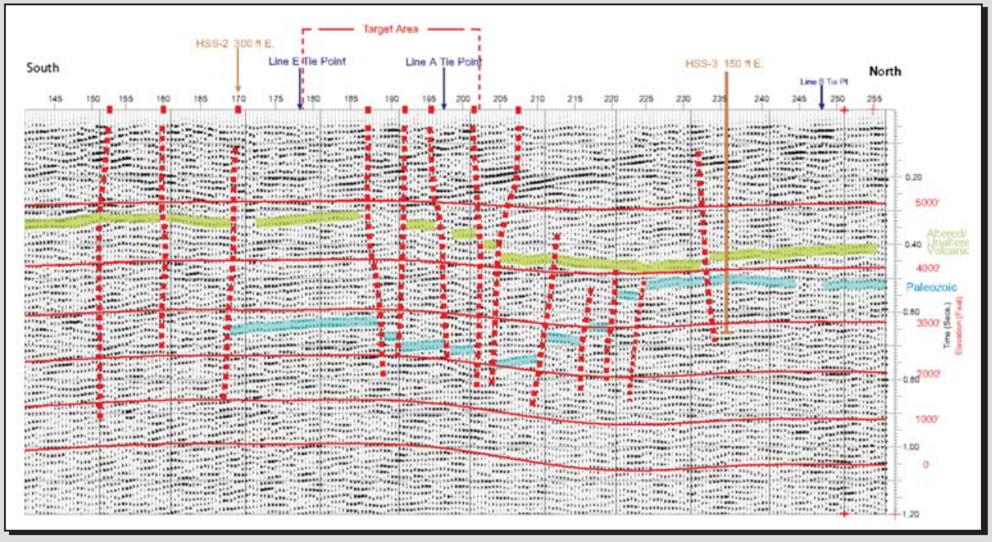

Figure 12: Seismic Section along Line D.

CASE HISTORY, HARD ROCK MINING SITE

This 2nd case history shows un-interpreted **(Figure 13)** and interpreted **(Figure 14)** seismic sections from Central Nevada showing an igneous laccolith confirmed by drilling. Both the top and bottom of the igneous feature have been imaged with short, discontinuous reflection events, as is typical of hard rock environments. Contact metamorphics extend to the surface above the laccolith. The feeder dike is not in the plane of the section.

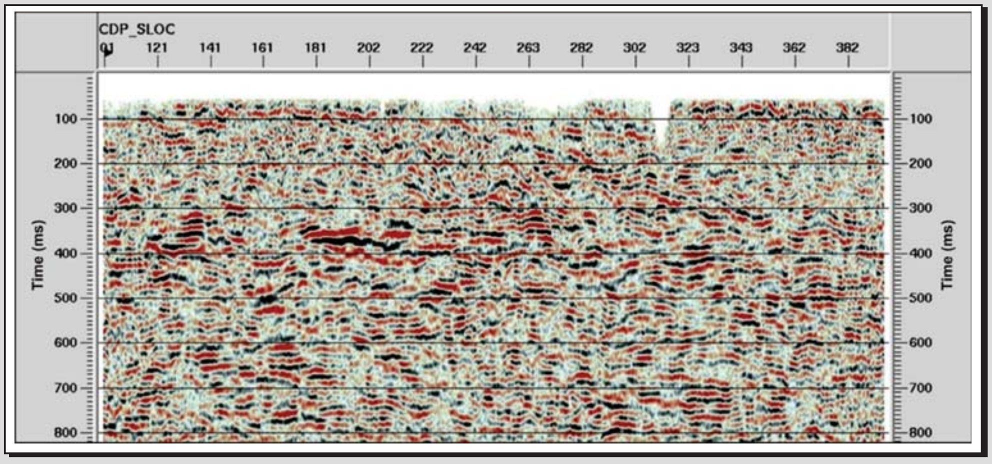

Figure 13: Un-Interpreted Seismic Section

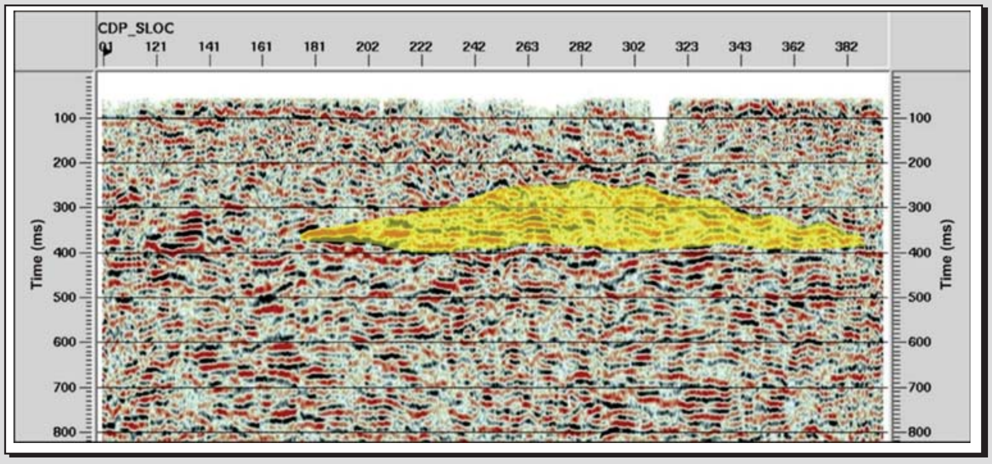

Figure 14: Interpreted Seismic Section

SUMMARY AND CONCLUSIONS

Geothermal and mining prospects are often situated in a highly complex geologic environment of igneous rocks, both intrusive and volcanic, and are often structurally complex, characterized by extensive faulting and hydrothermally altered zones. This setting creates a difficult environment for seismic exploration. However, with current improvements in seismic equipment, data acquisition methods and data processing, valuable structural geologic information can be obtained at geothermal sites. Because of the complexity of the velocity field in geothermal settings, to obtain the most benefit from the seismic survey, one or more check shots or sonic and density logs are necessary to accurately tie reflecting horizons with depth. Additionally, a co-operative interpretation involving the geologist, the processing geophysicist and the interpreting geophysicist is imperative to developing an accurate and useful interpretation of the seismic data. Geothermal and other hard rock environments are extremely complex compared with most sedimentary environments and are difficult to interpret without local knowledge, structural mapping inferred from both surface and drill hole data and expertise in site-specific geology.

Currently, many seismic investigations for geothermal prospects are 2-D surveys because of lower costs and higher fold than typical 3-D surveys and these 2-D surveys work reasonably well in the Basin and Range in areas of linear faulting.

We conclude that surface 2-D seismic reflection surveys can be successful and productive if conducted with properly chosen parameters and rigorous quality control. Additionally, it is critically important that the interpretation is carried out using all available information, including check shot surveys and/or sonic and density logs. Seismic data acquisition parameters needed for successful imaging within geothermal settings require wider apertures, higher data redundancy, noise attenuating array geometries, high levels of source effort and large source bandwidth, with particular emphasis on the low frequency end of the spectrum.

Recent advances in seismic data processing are also critical to better imaging in geothermal settings. Modern noise attenuation algorithms, better static solutions and powerful new migration algorithms all lead to better clarity in subsurface imaging.

Acknowledgements

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