Development and Application of AVO Methods and Seismic Attribute Analysis for Characterization of the San Emidio Geothermal Reservoir, Northwestern Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geophysics

by

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May, 2015
UNIVERSITY OF NEVADA, RENO

THE GRADUATE SCHOOL

We recommend that the thesis prepared under our supervision by

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entitled

Development and Application of AVO Methods and Seismic Attribute Analysis for Characterization of the San Emidio Geothermal Reservoir, Northwestern Nevada

be accepted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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Abstract

Geothermal fields in the Basin and Range province are commonly found in highly faulted and fractured subsurface zones that provide the necessary permeability for vertical fluid flow. This study utilizes a 2D seismic reflection line to explore the geophysical signature of the San Emidio geothermal field’s production zone, located in NW Nevada. An rms-smoothed AVO analysis found low amplitude striations within and adjacent to the reservoir zone, which are coincident to both interpreted faults in our prestack depth migrated seismic image and the subsurface projection of faults mapped in the structural analysis of Rhodes (2011). Rms-smoothed AVO analysis provides new opportunity to utilize pre-stack data in difficult to migrate seismic data sets. Laterally homogeneous 2-layer AVO modeling results at San Emidio indicate that where faulting and fractures are present, pre-critical reflection amplitudes will be reduced by ~66-75% and the critical angle will be increased by ~50%. Far-offset and post-critical offset AVO modeling results are not consistent with empirical observations and potential causes are discussed. Preliminary results of a seismic attribute analysis derived from P- and S-wave velocity models identified a subvertical region of high Poisson’s ratio, associated with brine saturated low-aspect-ratio fractured rock, in the vicinity of the production wells that may show evidence of a geophysical geothermal signature.
Acknowledgements

There are many people I would like to thank for their cumulative inspiration, guidance, and support during my journey through this masters program. First, I would like to thank my parents for their endless love and encouragement. I would also like to thank my numerous siblings for providing me with the comic relief essential to maintaining a happy and balanced life.

Dr. John Louie provided invaluable inspiration, guidance and support during the course of this project. John was instrumental in assisting me with the functionality and use of his codes, scripts and Viewmat processing software in addition to providing me with opportunities to attend conferences, both professional and academic. I wish to thank Dr. Satish Pullamanappallil for providing valuable assistance producing the velocity models, obtaining data, and understanding key project details at San Emdio. Generous funding and support of my graduate education and research was provided by Optim Inc. through the University of Nevada, Reno foundation and through research contracts with Southern California Edison. Dr. Graham Kent provided valuable and necessary input on seismic processing and interpretation. Graham also contributed greatly to my scientific development by including me on two marine seismic exploration projects. I would like to thank Erik Williams and Lori McClelland for helping me navigate the treacherous UNR bureaucracy.

Kyle Reeder provided valuable and seemingly endless stimulating scientific and professional discussions on a near daily basis. Fellow UNR graduate students Andrew Sadowski, Annie Kell, Christine Ruhl, Kyle Gray, Steve Angster and Tyler Seaman all
provided much personal and academic support. I would additionally like to thank non-UNR graduate students James Holmes, Valerie Sahakian, and Weiliang Huang.

I would like to thank Emily Foley, Francis Rollins, Jesse Koch, Michael Schilly, Robert Chrisman, and Samantha Hayes from BP America for the vast scientific and professional guidance I received during my 2014 summer internship.

Finally I would like to thank Art Espinosa, David Patel, Hernan Espinosa, Ibe Djukic, Juan Bastardo, Matthew Waipa, Shannone Callos, Taylor Hayes and Whitney Glick for their belief and friendship during my graduate experience.
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Chapter 1  Introduction

This project began as an effort to develop and apply innovative geophysical methods to characterize an existing geothermal production zone with the goal of enhancing future exploration efforts at the San Emidio basin. In 2010, the current field lease owner and power plant operator, US Geothermal Inc., was awarded funds to explore the ability of advanced geologic and geophysical methods to detect geothermal resources in the San Emidio basin. Funding for this project was made possible by an award from the American Recovery and Reinvestment Act (ARRA) for the U.S. Department of Energy’s Validation of Innovative Exploration Technologies in the Geothermal Technologies Program.

The geophysical exploration and software company Optim Inc. was awarded a contract to lead the advanced seismic methods portion of the project. In 2010, ten approximately 3.2-km-long 2-D reflection seismic lines were collected along the southeastern edge of the San Emidio basin where known geothermal resources exist. Five seismic lines were collected near the producing geothermal reservoir and five seismic lines were collected to the north, where an epithermal mineral deposit hints at the existence of undiscovered economic geothermal resources (Teplow et al., 2011).

Optim, Inc. conducted the initial seismic processing necessary to image the structurally complex San Emidio basin. They produced prestack depth-migrated images in addition to high-resolution compressional- and shear-wave velocity models for each of the ten seismic lines.

In 2011, University of Nevada Reno Master of Science student, Gregory Rhodes, used surficial geologic mapping along with the prestack depth-migrated images,
produced by Optim Inc., to make structural interpretations of the eastern San Emidio basin with implications on the structural controls of the geothermal system.

For the current project, I focus on developing new methods to enhance the characterization of existing geothermal resources and improve future exploration efforts. High-resolution compressional- and shear-wave velocity models were computed by Satish Pullammanappallil of Optim Inc. using SeisOpt® Pro™, provided to me as ASCII text files.

I modified a C Shell script written by John Louie, of the Nevada Seismological Laboratory and the University of Nevada Reno, to convert the ASCII velocity model files into Intel binary float files required to compute travel-time plots. Next, I produced travel time plots by modifying a travel time generating script written by John Louie. Pre-stack depth migrations were produced using a C code, written by John Louie, along with the specific migration parameters I determined by modifying a parameter file accessed by the C code.

I processed the raw shot gathers, common image gathers, and rms-smoothed AVO extractions using John Louie’s JRG/Viewmat software available for free online at http://crack.seismo.unr.edu/jrg. I also wrote a library of Matlab scripts and functions to:

1. use information about elastic rock properties to produce a model of the theoretical full angle seismic-amplitude response in a laterally homogeneous, 2-layer, infinite half space;
2. use the compressional- and shear-wave velocity models to produce several velocity model derived seismic attribute sections;
3. cross plot empirical AVO intercept and gradient data; and
4. model the sensitivity of various elastic parameters on the seismic-amplitude response.
John Louie was instrumental in assisting me with the functionality and use of his codes, scripts and Viewmat processing software. Satish Pullammanappallil provided much assistance producing the velocity models, obtaining data, and understanding key project details. Graham Kent provided valuable and necessary input on seismic processing and interpretation.

This paper will be submitted to *Geophysics* under the title “Development and Application of AVO Methods and Seismic Attribute Analysis for Characterization of the San Emidio Geothermal Reservoir, Northwestern Nevada”.
Chapter 2  Geophysics Paper

The following chapter is the manuscript that has been submitted to the journal *Geophysics*. I am first author on this paper and my co-authors are: John Louie and Graham Kent of the Nevada Seismological Laboratory, University of Nevada, Reno, Nevada and Satish Pullammanappallil of Optim Inc., Reno, Nevada.

2.1 Introduction

Accurately locating subsurface regions of high temperature and high fluid flow rate are essential to developing economic geothermal resources. In the Basin and Range province this typically amounts to locating high permeability faults and fractures in the subsurface (Faulds et al., 2006; Teplow, 2011). Amplitude Variation with Offset (AVO) together with seismic attribute analysis provides new opportunities to extract valuable information from new and existing seismic data.

Our AVO and seismic attribute methods are tested in the producing San Emidio geothermal field. The San Emidio basin is located in the northwestern Basin and Range province, approximately 105 km northeast of Reno, Nevada. The San Emidio geothermal field currently produces approximately 9.0 MW from a reservoir located in a highly faulted zone on the southeastern edge of the San Emidio basin (Figure 2.1). To the north of the proven geothermal reservoir is a hard-linked right step in the range front (Rhodes, 2011). To the west of the right step in the range front an epithermal mineral deposit, accompanied by a high density of faulting, hints at the existence of yet-to-be-discovered economic geothermal resources (Rhodes, 2011; Teplow, 2011). Careful characterization of the known reservoir in the southern part of this system may yield clues to identifying
economic drill targets to the north.

Faults and fractures oriented approximately orthogonal to the least principle stress direction are favorably oriented for subvertical fluid flow in highly permeable fault zones (Faulds et al., 2006). Favorably oriented faults and fractures in areas of high fault and fracture density are believed produce the permeability required for deep fluid circulation within the San Emidio geothermal system (Rhodes, 2011).

Normal faults in the San Emidio basin, favorably oriented for subvertical fluid flow, with a fault width greater than 15 cm we consider to be large aperture faults (LAFs) (Teplow et al., 2011; Ferrill and Morris, 2003). Production wells at San Emidio have encountered LAFs which directly correlate to the existing geothermal production zone (Teplow et al., 2011). For this reason, accurately identifying LAFs at depth is a crucial step to identifying new geothermal resources at San Emidio and numerous other basins in the region.

The growing application of seismic techniques, standard in the oil and gas industry, to geothermal characterization and exploration efforts is providing a detailed view of geothermal systems previously unavailable. The use of 3D seismic surveys is providing additional value by enhancing geologic and structural understandings of existing geothermal fields (Casini et al., 2010; Luschen et al. 2014). Studies utilizing converted wave and 3D-3C seismic data are adding to our understanding of anisotropic effects within geothermal basins in Northwestern Nevada (Kent et al., 2013).

Traditionally, AVO methods have been used in the oil and gas industry to explore and characterize gas accumulations in clastic reservoirs (Rutherford and Williams, 1989). The development of a comprehensive AVO classification scheme by Young and
LoPiccolo (2003) provide the framework to characterize the AVO response independent of any specific lithology and fluid fill. Traditional AVO methods, designed for clastic hydrocarbon systems, may be inappropriate for geothermal systems located in volcanic basins. However, Aleardi and Mazzotti (2015) have demonstrated the utility of AVO-methods specifically designed to characterize areas of high fracture density in the deep intrusive basement rock of the Larderello-Travale geothermal field located in southern Tuscany.

The availability of long-offset (~3.2 km) 2-D seismic reflection data, at the San Emidio geothermal field, provides the unique opportunity to observe and model the seismic response of geothermal systems in the highly faulted, extensional basins of the northwestern Basin and Range province. Seismic data were collected in 2010 as part of a contract awarded by the American Recovery and Reinvestment Act (ARRA) for the U.S. Department of Energy’s Validation of Innovative Exploration Technologies in the Geothermal Technologies Program. The geophysical exploration and software company Optim Inc. was awarded a contract to lead the advanced seismic methods portion of the project and oversee the seismic data collection. For the current project we use well constraints on the depth, location, and lithology of the producing reservoir to observe, model and characterize the AVO and seismic attribute response (Appendix D).
Figure 2.1: Map of the San Emidio geothermal field including the mountain range names, well locations, power plant location, seismic line location and Wind Mountain epithermal mine location. Hill shade and topographic background image is given courtesy of the U.S. Geological Survey. Data available at http://viewer.nationalmap.gov/viewer/
2.2 Geologic and Tectonic Setting

The San Emidio basin formed between the Lake Range, to the east, and the Fox Range, to the west (Figure 2.1). The eastern San Emidio basin consists of a Mesozoic basement, Tertiary volcanic and sedimentary rocks, and Quaternary alluvium, lacustrine sediments and hydrothermally altered rocks (Figure 2.2; Rhodes, 2011). The Mesozoic sequence, collectively referred to as the Nightingale Formation, consists of metamorphosed and folded low-grade argillaceous phyllite, with some slate, schist and interbedded carbonate, sandy and volcanic horizons (Moore, 1979; Wood, 1990). The overlain Tertiary volcanic and sedimentary sequence consists of the middle Miocene Pyramid sequence volcanic rocks and late Miocene sedimentary rocks correlated to the Truckee Formation (Drakos, 2007; Moore, 1979). Quaternary sediments, including alluvial fan deposits and Pleistocene Lake Lahontan silt, sands, tufa, and silicified sands are exposed at the surface along the western edge of the Lake Range (Teplow et al., 2011).

The San Emidio fault zone consists of a network of north to north-northeast striking normal faults that dip to the west and west-northwest respectively (Figure 2.2) (Rhodes, 2011). The roughly north-trending, west-dipping, curvilinear Holocene San Emidio fault is located approximately 1 km west of the Lake Range fault in the vicinity of the production wells. The current San Emidio geothermal power plant produces from a reservoir located within a faulted zone of geothermally altered volcanic ash and tuff (Appendix D). Fault and spring-related hydrothermal surface alterations are observed along the section of the San Emidio fault located near the current production well (Figure 2.2).
Figure 2.2: Geologic map used from Rhodes (2011). Simplified geologic map of the northern Lake Range and eastern San Emidio Desert showing locations of dated samples, production and injection wells, and seismic reflection lines. Bar and ball shown on downthrown side of normal faults. Lithologic units: TrJn-Nightingale metasedimentary rocks; Tptsu-tuffaceous volcaniclastic rocks; Tpb’-sparsely porphyritic basaltic andesite (sample C); Ts- sedimentary rocks; Tss-silicified sedimentary rocks and siliceous sinter; QTa- Late Tertiary-Quaternary basin-fill deposits undivided.
2.3 Methods

This study utilizes 2-D seismic reflection data from one ~3.2-km-long east-west trending line. Data were recorded using 3-component geophones with a ~17 m geophone spacing and a multi-directional vibroseis source with a ~67 m shot spacing. The seismic line used in this study was chosen due to its close proximity to the known geothermal resource and production wells in the San Emidio field. This east-west trending seismic line extends from the Lake Range fault to the east, through the north-trending San Emidio fault, into the center of the basin to the west (Figure 2.2).

2.3.1 AVO Modeling

AVO modeling was designed for two purposes: 1) to see if changes in rock properties, within the reservoir, would feasibly produce an AVO response that is distinguishable in real data; and 2) to use existing geologic and geophysical data to estimate the AVO response within the reservoir. The data available limit us to construct 1D, 2-layer, elastic and isotropic models of reflectivity versus offset. Consequently, anisotropic and resonance effects on offset related reflectivity are not taken into consideration in these models.

A best estimate of each parameter was chosen from a combination of geologic and geophysical data. In the absence of sonic log well data, we used information from our velocity models to estimate a range of P- and S-wave velocities reasonable within our reservoir zone. Density value estimates were taken from values determined by a basin-scale gravity survey in addition to values measured in laboratory conditions (Drakos, 2007; Mankhemthong, 2008; Teplow et al., 2011).
Offset-dependent reflection coefficients were computed using the full Zoeppritz equations from zero to ninety degrees (Zoeppritz, 1919). The intercept and gradient terms are calculated using a least squares regression of the reflection coefficients against the sine-squared of the offset at exclusively pre-critical offsets to avoid bias near the critical-angle (Chopra and Castagna, 2014; Young and LoPiccolo, 2005). Once the intercept and gradient terms are calculated they are crossplotted against each other and the AVO response is characterized using the methods of Young and LoPiccolo (2003).

### 2.3.2 Velocity Modeling

The reliability of our results at every step in this study is contingent to some degree upon the accuracy of the P- and S- wave velocity modeling process. For this reason, a significant emphasis has been placed on using the most accurate 2-D velocity models available. The P-wave and S-wave velocity models were computed individually by Optim Inc. using a simulated-annealing algorithm that utilizes a Monte Carlo optimization scheme to invert first-arrival picks for velocities (Pullammanappallil and Louie, 1994). Both velocity models used separate first arrival picks, rays and optimization runs. The complex structure at San Emidio requires a non-linear velocity optimization that avoids assumptions about structural geometry. The simulated-annealing algorithm iteratively converges on an optimized solution, while avoiding becoming fixed at local least-square error minima points. This method conceptually allows for accurate velocity models in the structurally complex San Emidio basin.

Travel time plots are constructed using a fast finite-differencing scheme that utilizes a solution to the eikonal equation (Vidale, 1988). Velocity data from the ~3.2 km
A seismic reflection line was rendered onto a 2-D grid that is 400 elements wide by 200 elements deep. Each square element has a width of 8.382 m (27.5 ft).

2.3.3 Seismic Attributes

The individually computed P- and S-wave velocity models were used to compute the Vp/Vs and Poisson’s Ratio values at each element location, corresponding to each subsurface location in the velocity model. The Vp/Vs ratio has a theoretical limit of infinity, while Poisson’s ratio has an upper limit of 0.5 for isotropic rocks (Gercek, 2007). Consequently, a max Vp/Vs value of 4 was used to clip any anomalously high Vp/Vs values. A minimum Poisson’s Ratio value of 0.13 was used to clip any anomalous near-zero values. Despite the physical significance of Poisson’s ratio, it is essentially a non-linear scaling of Vp/Vs that can illuminate features that are not easily observed in large-range Vp/Vs sections (Chopra and Castagna, 2014).

2.3.4 Seismic processing

Our seismic processing scheme is designed to optimize our ability to image tectonic structure and preserve amplitudes in our Kirchhoff prestack depth migrated (KPSDM) common image gathers (CIGs) for use in our AVO analysis, following Mahmoudian and Margrave (2009). The objective of this process is to suppress noise and isolate the reflectivity events in our section. Viewmat seismic processing software, developed by John Louie at the University of Nevada Reno, is used to process the seismic gathers in this study.

The seismic processing scheme applies a spherical divergence correction to adjust for amplitude attenuation due to geometric spreading of the wave front. A dip filter and
time-invariant band pass filter were applied to remove high amplitude shear-wave contamination and increase the signal-to-noise ratio of our P-wave reflections.

We implemented a KPSDM algorithm to preserve amplitude while migrating seismic energy in CIG-offset space. The KPSDM algorithm used in this study has been shown to image steeply dipping, near vertical structures in both synthetic and real data (Louie et al., 1988; Abbott et al., 2001). KPSDM is generally considered to produce reliable reflection amplitudes in areas of moderate structural complexity, making it an ideal candidate for AVO analysis (Feng and Bancroft, 2006). Migrations were achieved across a 400-by-200 element x-z plane, identical to the velocity model, with 51 elements in the offset dimension of the CIG at each x-location. Each element is ~65.7 m long in the offset-dimension. A migration anti-aliasing operator was applied to reduce the aliasing effect produced when the operator dip along the migration summation path is too steep for a given input seismic trace spacing and its frequency content (Lumley et al., 1994).

2.3.5 Rms-Smoothed AVO Extractions

Our pre-stack depth migrated CIGs were unable to migrate reflection energy with the sub-wavelength accuracy needed to easily measure the AVO response of any one coherent reservoir reflector in dGBES OpendTect. Consequently, we implemented an AVO-smoothed approach to compute the offset-dependent magnitude of seismic energy, within the reservoir zone, across the full 2-D seismic line. We applied an rms-smoothing kernel to the offset-depth slice at each CIG location. The smoothed data were clipped in depth from ~553-637 m to highlight the reservoir reflectors and from ~263-3286 m in the offset direction to remove near-offset shear-wave noise. A vertical sum and average
scheme was applied along the depth direction to produce an AVO extraction of the reflection energy at each offset, within the reservoir zone, across the seismic line.

2.4 Results

2.4.1 AVO Modeling

Our AVO modeling targets the simple, infinitely thin seismic impedance contrast between two homogeneous, isotropic layers, the sedimentary basin fill and the volcanic Pyramid sequence. In order to quantify the effect of faulting within our basin, we created an AVO model for the background case and the case where there is a decrease in P-wave velocity and density, due to faulting, in the underlying Pyramid sequence volcanic layer.

Figure 2.3 shows the P-wave reflection coefficients, at offsets ranging from 0 to 90 degrees, for an incident P-wave modeled using the full Zoeppritz equations. The background reflector has a zero-offset reflection coefficient that is 3-4 times higher than the faulted reflector. Both cases exhibit an AVO trend that decreases slightly with increasing offset, from zero offset to approximately 75% of the critical angle. In both cases the reflection coefficient is maximized to +1 at the critical distance and decreases to -1 at 90 degrees. A key observation is that the critical angle is extended from ~52 to ~73 degrees when faulting occurs. Assuming an estimated target boundary depth of 595 m, within the reservoir zone, the critical distance increases from 1.51 to 3.98 km in the case of faulting and increased fracture porosity of the lower medium.

Figure 2.4 shows our best estimate of the AVO intercept-gradient response between the sedimentary basin fill and the volcanic Pyramid sequence. The Young and LoPiccolo classification scheme characterizes the AVO intercept-gradient pair for both
the background and faulted cases as a type 1 response. Once a background trend has been established, deviations from this background trend can provide information about changes in rock properties within the reservoir zone. In this case we would expect a highly fractured zone to show significantly lower zero-offset reflection amplitudes that decrease less in pre-critical offsets. While normal faulting may be observed by offset reflectors in the summed seismic data, the degree of fracturing and the width of the damage zone can be better constrained by understanding the AVO response of the background versus the fractured AVO-trend in the pre-stack seismic data.
Figure 2.3: Theoretical P-wave reflection coefficients, at angles ranging from 0 to 90 degrees, for an incident P-wave modeled using the full Zoeppritz equations as corrected (Appendix D). The grey dotted lines highlight both zero-offset reflection coefficients.
Figure 2.4: Theoretical AVO intercept-gradient crossplot including our best estimate of the background and faulted AVO response for a simple infinitely thin interface between homogeneous, isotropic elastic media.
2.4.2 Velocity Model Attributes Sections

Figures 2.5a and 2.5b show P- and S-wave velocity optimization results computed from P- and S-wave first-arrival time picks on our seismic line. Figures 2.6a and 2.6b show the Vp/Vs and Poisson’s ratio sections derived from the velocity sections. Since there is a direct relationship between the value of Vp/Vs and Poisson’s ratio, and differences between the two sections are due to a non-linear scaling, we will be discussing both sections together (Chopra and Castagna, 2014). In general, we notice that the Vp/Vs section is more sensitive to higher values, while the Poisson’s ratio section is more sensitive to the lower values, rendering both sections useful in the interpretation process.

In hard rock such as the volcanic Pyramid sequence, Poisson’s ratio is known to vary with effective pressure, fluid saturation, the aspect ratio of fracture pores, and the density of fracture pores in a rock mass (Zhang and Bentley, 2005). Inverting seismic velocities measured experimentally, results for effective moduli and pore aspect ratio can be determined using the theoretical model of Kuster and Toksoz (1974), derived from scattering theory (Zhang, 2001; Zhang and Bentley, 2005). At an effective pressure of 10 MPa, round pores both dry and wet do not significantly influence Poisson’s ratio (Zhang and Bentley, 2005). In fractured rock, at the same effective pressure, a decrease in pore aspect ratio will decrease Poisson’s ratio in dry rock and increase Poisson’s ratio in wet rock (Zhang and Bentley, 2005). These finding are applicable to the San Emidio geothermal system because the 10 MPa results in the Zhang et al (2001) study is very similar to the ~11.1 Mpa estimated for the San Emidio reservoir (Appendix B). Chopra and Castagna (2014) observed that in most instances poorly consolidated and/or brine-
saturated rocks tend to have a high Poisson’s ratio, while highly lithified rocks tend to have values of Poisson’s ratio as low at 0.10 (Vutukuri et al., 1974; Hatheway and Kiersch, 1986; Gercek, 2007).

Near the range front at depths greater than ~250 m computed Poisson’s ratio values are generally below 0.27. Poisson’s ratio values, to the west in the deeper part of the basin are higher, ranging from 0.35 to 0.45, which is consistent with poorly consolidated ash tuff, alluvial, and lacustrine lithologies observed in the well logs (Vutukuri et al., 1974; Hatheway and Kiersch, 1986; Gercek, 2007; Appendix D).

Just east of the base of the production well, shown on figure 2.6b as a vertical white line with a red dash at the production zone, we observe locally high values of Poisson’s ratio that vary between 0.38 and 0.41. High values of Poisson’s ratio, in warmer colors on figure 2.6b, are consistent with the low-aspect-ratio wet fractured rock. This lithology was confirmed by the presence of large aperture faulting and geothermal fluids encountered during drilling operations and geothermal production (Teplow et al., 2011; Appendix D).

To the west of the production well we observe a region of low Poisson’s ratio, ranging from 0.22 to 0.33, which may indicate a generally harder lithology than the basin rocks to the west and/or the presence of less developed rock fractures with a higher pore aspect ratio.
**Figure 2.5:** a) P- and b) S-wave velocity models (2015, Pullammanappallil, pers. comm.) overlain on our pre-stack depth migrated section. The areas above the earth’s surface and below the deepest diving ray are blanked to solid white.
Figure 2.6: Image of the a) Vp/Vs and b) Poisson’s ratio sections overlain on our pre-stack depth migrated section. The areas above the earth’s surface and below the deepest diving ray are blanked to solid white.
2.4.3 Imaging and Structure

Accurately identifying the location and geometry of large aperture normal faults at depth in the San Emidio geothermal system is key to detecting economic geothermal resources. These faults are observed as seismic discontinuities, in both stacked and unstacked seismic data. We will consider vertical seismic discontinuities in high amplitude, otherwise coherent, reflectors as evidence of faulting. Data from surficial fault mapping, drilling logs and well lithology logs are integrated into our structural interpretations.

Figure 2.7a shows an un-interpreted KPSDM image of the seismic line, and Figure 2.7b shows the seismic line with the production well location and interpreted faults overlain. The acoustic impedance contrast between the ash tuff basin fill and the Pyramid sequence volcanic rocks likely produce the high amplitude reflector we observe in our seismic section at about 600 m depth. Figure 2.7b shows five faults are interpreted along the reflector in the center of the seismic section, marked F1-F5, by identifying reflector discontinuities and observing vertical offset in otherwise coherent reflectors. There is also a hint of steeply-dipping fault-plane reflections. Our interpreted faults have dips ranging from 65 to 69 degrees. Projection of faults, interpreted in the seismic section, to the surface are consistent with the surficial fault-mapping results of Rhodes (2011).
Figure 2.7: Kirchhoff pre-stack depth migrated image of the seismic line, uninterpreted above, with the production well location, interpreted Pyramid Sequence horizon, and interpreted faults overlain below. The areas above the earth’s surface and below the deepest diving ray are blanked to solid white. Faults F1-F5 were interpreted in this seismic section and correlate spatially to faults mapped by Rhodes (2011) at the surface.
2.4.4 Rms-Smoothed AVO Extraction

We implement a depth-sum-and-average rms-smoothed approach to observe AVO anomalies in the San Emidio basin. This approach overcomes difficulties isolating individual flat reflectors in the CIGs. Instead of measuring the sign-dependent amplitude of seismic reflectors, as in conventional AVO analysis, we observe the sign-independent magnitude of reflection energy at different offsets across the seismic line. This method effectively highlights the strong high-amplitude reflections, observed in figure 2.7a, in the central part of the basin, thought to be the impedance contrast between the sedimentary basin fill and the Pyramid sequence volcanics. Faults interpreted on the KPSDM image, shown on figure 2.7b, are coincident with low amplitude striations in the offset direction of the rms-smoothed AVO extraction, visible in figure 2.8.

Anomalously high rms-energy values are observed in the near and middle offsets of the smoothed AVO extraction (Figure 2.8). We observe high rms-energy values, believed to be shear-wave contamination, in the near offset reflections along the western margin of our seismic line, within the center of the basin. Low rms-energy values, at offsets greater than 1.91 km, are observed throughout the entire rms-smoothed AVO extraction (Figure 2.8).
Figure 2.8: Rms-smoothed AVO extraction from ~553-637 m depth, highlighted by two yellow dashed lines on the KPSDM reflection section above. Vertical green dashed lines connect interpreted faults within the reservoir zone of the stacked KPSDM image above to the vertical low amplitude striations in the AVO-energy response below. The rms-energy section below represents near-zero reflection amplitudes with purple and cooler colors, and large reflection amplitudes with warmer colors. Below, the dashed yellow line represents the offset at the critical angle from the simple "background reflector" model of Fig. 2.3. Offset increases down in the lower, energy image.
2.5 Discussion

Our laterally homogeneous 2-layer AVO modeling results at San Emidio indicate that where faulting and fractures are present, pre-critical reflection amplitudes will be reduced by ~66-75% and the critical angle will be increased by ~50%. Models using a reflection interface depth of 595 m in our area of interest (AOI) predict a change in critical distance from ~1.51 km to ~3.89 km. In the case of faulting, this would produce a critical offset located outside of the maximum offset range of our seismic data. Our AVO modeling suggest that the degree of fracturing and the width of the fault damage zone will have an effect on the AVO response distinguishable in prestack seismic data.

Our AVO modeling results predict post-critical reflection energy up to 4 times higher than what is present in pre-critical offsets (Figure 2.3). The results of our rms-smoothed AVO extraction do not support our AVO modeling at post-critical offsets. Explanations for these differences include: (1) reflection point smearing and anisotropic effects due to laterally inhomogeneous reflection interfaces (Chopra and Castagna, 2014; Kent et al., 2013); (2) interference of mispositioned events due to errors in the velocity modeling process; and (3) thin bed interference and transmission coefficient loss (Swan, 1991; Hussenoeder et al., 1996).

A distinct region of low pre-critical amplitudes, in both the summed KPSDM image and the rms-smoothed AVO extractions, in the vicinity of the production zone, support the utility of AVO methods in exploring for geothermal resources in our study area. Despite difficulties predicting seismic amplitudes at post-critical reflections and far-offsets, utilizing an rms-smoothed approach to AVO analysis may help illuminate AVO features in difficult to migrate areas.
Results of our Poisson’s ratio attribute-section are consistent with the limited information available on the subsurface geology along our seismic line. Currently, there is considerable uncertainty in these results and further work is required to test these methods in other areas with greater well constraints. Additionally using this technique on jointly inverted P- and S-wave velocity models may provide greater accuracy in this method.

Two lost circulation zones, approximately 70 feet apart, were encountered in a thick tuff and ash sequence during drilling (Appendix D). The upper lost circulation zone was encountered at a depth of ~500 meters and had a vertical thickness of ~15 meters. The lower lost circulation zone was encountered ~20 meters deeper with drilling concluding ~10 meters into this zone. The ~20 meter interval between the upper and lower lost circulation zones consists of altered ash and tuff deposits.

Two possibilities to explain the two distinct lost circulation zones are considered: (1) both lost circulation zones are within the damage zone of a San Emidio Fault strand (F5) strand encountered at depth; or (2) the two lost circulation zones represent the area near the intersection of the San Emidio fault strand; and (F5) the Empire fault at depth (Figure 2.7b). We prefer the second possibility in this case. Supporting this interpretation is the spatial correlation between the subsurface projection of the northern termination of the Empire fault, a fault oriented for maximum dilation, and the subsurface projection of the eastern San Emidio fault strand (F5). Additionally, the ~20 meter interval between the two wide lost circulation zones suggest the presence of more than one fault at depth. The combination of these two factors would help explain the existence of the geothermal anomaly in this area.
Furthermore, the eastern margin of the high amplitude reflector, thought to be the impedance contrast between the ash tuff lower fill and the Pyramid sequence volcanic rocks, terminates in the vicinity of the lost circulation zones encountered during drilling. Our AVO modeling results predict significantly diminished pre-critical reflection amplitudes at the boundary between ash tuff and faulted Pyramid sequence basaltic andesite. Our rms-smoothed AVO extractions are consistent with this interpretation at near and middle offset ranges.

2.6 Conclusion

Our empirical AVO analysis suggest utilizing an rms-smoothed AVO approach on difficult to migrate seismic data may help extract additional information from prestack seismic gathers that may provide added value in characterization and exploration efforts. While faults can often be interpreted by observing offset reflectors in stacked seismic sections, the degree and width of fracturing may be more clearly evident in the amplitude response of rms-smoothed AVO extractions.

Interpreting velocity model derived seismic attributes, in addition to interpreting velocity models directly, may yield easily obtainable information that can aid in an understanding of the subsurface rock properties (Jaya et al., 2010). Careful research to further test and refine these methods needs to be done before any further conclusions can be drawn.

Our KPSDM images support the surficial structural mapping work of Rhodes (2011) along our seismic line. Our KPSDM images combined with the public well data suggest the presence of 2 normal faults in the reservoir zone along our seismic line.
2.7 Acknowledgements

We thank Optim Inc. for their generous support of our research and for providing the P- and S-wave velocity models necessary for this project. We also thank US Geothermal for allowing us to use and publish data collected at San Emidio and the Nevada Seismological Laboratory for their funding and support of this research.
Chapter 3 Conclusion

The work completed in this thesis provides several new methods to characterize and explore geothermal resources in the complex geology of the Basin and Range province. These methods provide additional pathways to extract economically and environmentally valuable information out of existing data sets. The rms-smoothed AVO extraction method used in this thesis allows information to be extracted from migrated pre-stack gathers that would otherwise be missed and its benefits ignored. The new Kirchhoff pre-stack depth migrated images partly support the work done by a previous University of Nevada Master of Science student Gregory Rhodes and provide an avenue to integrate the work of geologists and geophysicists in this area.

3.1 Additional Work

To further the work done in this study additional work should be done on the remaining seismic lines in the San Emidio basin. If additional seismic or well data becomes available from past projects it should be integrated into the work done in this project. Additional seismic data collected in the vicinity of the existing production wells, with acquisition parameters optimized for AVO analysis, combined with compressional-, shear-wave and neutron-density well data would allow for improved modeling and seismic characterization techniques. AVO modeling implementing thin bed and laterally heterogeneous impedance variations may help explain differences between the empirical AVO observations and the AVO modeling of this thesis.

Existing 3-D seismic data sets exist in other geothermal basins in the area, which would serve as a great setting to further test and develop these methods. More spatially
robust AVO and seismic attribute models could be produced. Additionally, a study into the effect of fracture anisotropy could be done to quantify the directional variability in these methods.

The velocity derived attributes methods would be best tested in areas where full waveform inversion methods are available that invert for compressional- and shear-wave velocities simultaneously.
Appendix A: Responsibility Agreement

I understand that I am responsible for follow-up, revisions, etc. of the preceding paper upon submittal to Geophysics, a Society of Exploration Geophysicists publication. I agree to include co-authors on revisions and to ask them for clarification on anything I am uncertain about.
Appendix B: San Emidio Seismic Acquisition and Reservoir Details

- Number of lines = 10
- Type of data = 2-D seismic reflection
- Geophone group spacing = 55 ft
- Shot (vibroseis) spacing = 220 ft
- CMP spacing = 55/2 ft = 27.5 ft
- ~49 shot points per line
- Record length = 6 seconds
- Sampling rate = 2 ms
- Nyquist frequency = 250 Hz
- Channels = 193

Hydrostatic pressure due to overburden is determined to be 11.1 MPa

\[
\text{(Pressure)} = \text{(depth)} \times \text{(density)} \times \text{(gravity)} = \\
(595\text{m}) \times (1900\text{kg/m}^3) \times (9.81\text{m/s}^2)
\]
Appendix C: Correct Zoeppritz Matrix for a Down-Going P-wave

I corrected the term in the fourth row and third column.

\[
\begin{pmatrix}
\cos \theta_i & \frac{V_{p1}}{V_{S1}} \sin \phi_r & \frac{V_{p1}}{V_{p2}} \cos \theta_i & -\frac{V_{p1}}{V_{S1}} \sin \phi_r \\
-\sin \theta_i & \frac{V_{p1}}{V_{S1}} \cos \phi_r & \frac{V_{p1}}{V_{p2}} \sin \theta_i & -\frac{V_{p1}}{V_{S1}} \cos \phi_i \\
-\cos 2\phi_r & -\sin 2\phi_r & \frac{\rho_2}{\rho_1} \cos 2\phi_i & -\frac{\rho_2}{\rho_1} \sin 2\phi_i \\
\sin 2\theta_i & -\frac{V_{p1}^2}{V_{S1}^2} \cos 2\phi_r & \frac{\rho_2}{\rho_1} \frac{V_{S2}}{V_{S1}} \frac{V_{p2}}{V_{p1}} \sin 2\theta_i & \frac{\rho_2}{\rho_1} \frac{V_{p2}}{V_{S1}} \cos 2\phi_i
\end{pmatrix}
\times
\begin{pmatrix}
R_{PP} \\
R_{PS} \\
T_{PP} \\
T_{PS}
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta_i \\
\sin \theta_i \\
\cos 2\phi_r \\
\sin 2\theta_i
\end{pmatrix}
\]

Medium One:
- $R_{PP}$ = P-P Reflection Coefficients
- $R_{PS}$ = P-S Reflection Coefficients
- $V_{p1}$ = P-wave Velocity Top Layer
- $V_{S1}$ = S-wave Velocity Top Layer
- $\rho_1$ = Density in Top Layer
- $\theta_i$ = P-wave Incident Angle
- $\phi_r$ = S-wave Reflection Angle

Medium Two:
- $T_{PP}$ = P-P Transmission Coefficients
- $T_{PS}$ = P-S Transmission Coefficients
- $V_{p2}$ = P-wave Velocity Bottom Layer
- $V_{S2}$ = S-wave Velocity Bottom Layer
- $\rho_2$ = Density in Bottom Layer
- $\theta_i$ = P-wave Transmission Angle
- $\phi_i$ = S-wave Transmission Angle
Appendix D: San Emdio Lithlog for Nearest Production Well (Kosmos 76-16)

Additional public data can be obtained at ftp://ftp.nbmg.unr.edu/pub/Geothermal/


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