Appendix A to FAR 00-10

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

INCREASING EFFICIENCY OF GEOTHERMAL ENERGY GENERATION WITH HIGH RESOLUTION SEISMIC IMAGING

EISG AWARDEE
3DGeo Development Inc
465 Fairchild Drive, Suite 226
Mountain View, CA 94043-2251
Phone: (650) 969-3886
Email: Dimitri@3dgeo.com

AUTHORS
Dimitri Bevc, Principal Investigator
Moritz Fliedner, Project Geophysicist
Victor Pereyra, Consultant

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Legal Notice

Acknowledgement Page

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Abstract

This EISG project demonstrates the feasibility of improved seismic image resolution of geothermal reservoirs through the application of state-of-the-art seismic data processing techniques. Three representative 2-D seismic lines from a dataset acquired in 1999 in the Coso Geothermal Field for the US Navy Geothermal Program Office were preprocessed and imaged using 3DGeo's software and methodology, attaining much better results than have been previously achieved.

The processing sequence included the application of proprietary static corrections to move the data to a smooth floating datum, constant-velocity stacking analysis to derive rms-velocities for time processing, poststack processing and migration of the time sections, tomographic velocity inversion of first arrivals to derive a detailed shallow interval velocity model as a starting model for depth processing, wave-equation datuming of the preprocessed data to a flat datum, and prestack depth migration. The results are compared with a previous study by other researchers, and show that the methodology demonstrated herein is substantially superior. 3DGeo's imaging results have identified previously un-imaged geological structure associated with the producing geothermal field.

Keywords: Geothermal resource assessment, geothermal reservoir characterization, geothermal drilling risk reduction, seismic imaging, seismic tomography, geophysics.

Executive Summary

1. Introduction

This project targeted an important underutilized energy source in California, namely geothermal energy. The technology demonstrated herein has the potential of reducing the cost and risk associated with exploration and development of geothermal resources, and ultimately reducing energy costs for California ratepayers, while providing an environmentally sound alternative to fossil fuels, nuclear, and out-of-state sources. The recent energy crisis in California has focused attention on the importance of domestic alternative energy resources such as geothermal energy.

This EISG project has demonstrated the potential utility of high-resolution reflection seismic imaging applied to geothermal objectives. The results obtained herein represent a substantial improvement over previous results, and demonstrate that careful application of state-of-the-art technology by experienced personnel has great potential in geothermal applications.

2. Project Objectives

The overall project objective was to demonstrate accurate seismic imaging of geological structures in a heterogeneous geothermal environment. This has been achieved, and success is demonstrated in terms of image quality and improvement over previous processing results, and comparison to geologic information about the area.

The specific EISG Project Objectives were to modify algorithms for application to geothermal data, process and image reflection seismic data acquired over the Coso geothermal field. This was done to determine the validity and accuracy of seismic imaging in geothermal areas, thereby assessing the commercial utility of seismic imaging technology for geothermal objectives.

3. Project Outcomes

This project has been a thorough test study involving the application of 3DGeo's proprietary seismic imaging technology to a California geothermal data set. Aside from the scientific and engineering merits of conducting this study in what has been traditionally a very challenging data acquisition and processing environment, the project outcome of greatly improved image quality has increased the value of the seismic data itself, and provides an exemplary case study. Since the major goal of this study is demonstrating that seismic imaging of structures can be obtained in heterogeneous geothermal environments, the success of the experiment is assessed by reference to the seismic imaging results themselves.

4. Conclusions

This EISG project has resulted in, and demonstrated improved methodology for processing seismic data. Based on the demonstrated performance of the processing methodology in this EISG project, we have demonstrated the feasibility of performing this type of processing as a commercial service.

Active source reflection seismology has clear potential benefits to geothermal exploration and development. Quality seismic data processing is important to obtaining accurate and usable imaging results. The quality processing is not limited only to the high-end imaging algorithms, such as Kirchhoff migration, but also to the preprocessing applied to the data. Statics are critical to obtaining a good imaging result, as is prestack noise attenuation.

Previous processing applied to this data set, and other geothermal data sets, has erroneously omitted the application of preprocessing and statics, and has sometimes applied questionable imaging techniques. There is no reason for this to be done, as seismic imaging is a mature technology, and there are thousands of petroleum case histories in data areas similar to those encountered in geothermal regions. There is no question that geothermal areas generally produce challenging seismic data that push the limits of processing and imaging, but the challenges can be met with experienced personnel and the proper algorithms carefully applied. There is often a tendency to skimp on the processing, and not apply as much effort or expense in the processing as has been applied in the acquisition; this is a mistake.

5. Recommendations

It is recommended that this project be followed-up by further processing of the remaining Coso data, and that another survey, either 2-D or preferably 3-D, be acquired in Coso or elsewhere for further imaging and demonstration of the technology in a larger more in-depth effort.

Further development of this project through with a large scale demonstration of the technology will exemplify its full potential.

6. Public Benefits to California

The electric consumer is the ultimate beneficiary of this technology because it can lower the cost of finding and producing geothermal energy. Benefits of this technology to geothermal energy generation development in California are reduction in cost of development step-out production wells and injection wells, potentially saving 3 to 5 wells per 100 MW developed in a large new field, and 2 to 3 wells in a small 35 MW field for which drilling risk per MW is typically higher. These wells can cost $1.5 to $4 million each including access costs. This cost comes at an estimated investment of $1 million in seismic, to save up to $20 million in drilling cost. That is a return on investment (ROI) of 20 for a 100 MW field. These costs are likely to go down as further experience is gained and as more reflection seismic data is collected in geothermal fields.

Two significant public benefits of lowered geothermal energy costs include:

- A reduction in California’s reliance on out-of-state energy sources and a decrease in the likelihood of another energy shortage such as occurred in 2000/2001.
- Production of environmentally clean geothermal energy as an alternative to fossil fuels and nuclear energy.

Introduction

Background and Overview

The specific PIER subject area of this report is Strategic Energy Research for Geothermal Energy. The specific objective was to determine and demonstrate that reflection seismic imaging can be effectively applied to identify, characterize, and accurately map the subsurface location and extent of geothermal reservoirs and associated geologic structures. The potential direct benefit to California is reduced cost of exploration, reduced cost of exploitation, and improved management of geothermal energy resources.

High-resolution reflection seismic imaging has enjoyed great success in oil and gas exploration. It is the number one pre-drilling risk reduction technology, and is applied on a routine basis to virtually every oil and gas exploration and exploitation project. Seismic technology is credited with substantially reducing exploration cost, exploration risk, and environmental impact. Despite its potential promise, reflection seismic imaging has not been applied extensively, or with great success, to geothermal exploration. This EISG project was necessary to demonstrate the potential of reflection seismic to the geothermal industry.

The efficiency and economy of geothermal energy generation can be greatly increased by obtaining critical reservoir information from active-source reflection seismology. The objective of the project was to demonstrate improved resolution and imaging of geothermal reservoirs by applying innovative seismic data processing techniques that directly address the key issues which traditionally plague seismic data collected in geothermal areas; namely, (1) propagation through a highly variable near surface, and (2) imaging steeply dipping complex reservoir structures. We developed and demonstrated a data processing methodology that facilitates exploration in complex areas, improves geothermal reservoir characterization, and decreases the much higher costs of exploratory drilling.

The technology demonstrated in this project has the potential to directly reduce the life-cycle cost of geothermal electricity generation by improving the efficiency of resource exploration and assessment, permeability detection, mapping and well siting, resource drilling and completion, and reservoir monitoring. By developing and demonstrating 3-D seismic imaging technology tailored specifically to geothermal applications, we have obtained high-quality images of complex geological environments and geothermal reservoir zones. The processing methodologies demonstrated herein show that seismic imaging can play a significant role in geothermal exploration and development. Although data acquisition in geothermal areas is challenging, it does not differ significantly from challenging frontier areas addressed by the petroleum industry, and therefore, within the constraints of data quality, success comparable to that achieved in the petroleum industry has been demonstrated and can be expected.

The commercial market for the proposed seismic imaging technology is energy companies and government agencies involved in the development and production of geothermal power. This technology can potentially save hundreds of millions of dollars in drilling costs and in improved resource assessment. We have successfully demonstrated the technology and identified what must be done to successfully image seismic data acquired over geothermal areas. The technology is at a stage where it can be applied to commercial objectives.

Report Organization

This report is organized to:

- Present EISG project objectives
- Describe the project approach,
  - outline the seismic processing and imaging methodology
- Describe the project outcome,
  - present imaging results obtained on data from the Coso Geothermal field, and
  - compare new EISG Project results to previous results
- Present conclusions based on the imaging results
- Present recommendations for application of this technology
- Describe public benefits to California
- Describe the current development stage assessment

Project Objectives

The overall project objective was to demonstrate accurate seismic imaging of geological structures in a heterogeneous geothermal environment. This has been achieved, and success is demonstrated in terms of image quality and improvement over previous processing results, and comparison to geologic information about the area.

The specific EISG Project Objectives are:

- Modify imaging algorithms for application to geothermal data.
- Preprocess reflection seismic data acquired over the Coso geothermal field
- Image reflection seismic data acquired over the Coso geothermal field.
- Determine the validity and accuracy of seismic imaging.

The specific EISG economic objective is:

- Assess the commercial utility of seismic imaging technology for geothermal objectives, based on imaging results.

Project Approach

The subject technology of this EISG project is reflection seismology using active-source seismic data. Reflection seismology is used in petroleum exploration to obtain high-resolution 2-D and 3-D images of the earth's subsurface prior to drilling. The process of obtaining subsurface images from reflection seismic data is comparable to ultrasound imaging and computer assisted tomography (CAT scan) in medical imaging. Reflection seismic surveys involve the deployment of a multiplicity of surface sources and surface receivers. For each source, an elastic wavefield is propagated into the earth. This wavefield is reflected by subsurface geological structure (such as the geothermal reservoir and fracture zones) and recorded at the surface of the earth with a multiplicity of recording devices called geophones. The task of imaging the subsurface involves (1) processing these recorded seismic data to eliminate distortions caused by complex wavepaths, and (2) numerically propagating the data back into the subsurface. This back-propagation/imaging step (step 2) is called migration. In this EISG project, 3DGeo has applied its proprietary processing and migration algorithms to a seismic data set gathered over the Coso geothermal area.

Most of the published seismic work performed to-date in geothermal reservoirs has been either microearthquake studies or vertical seismic profiling. These two fields of seismology are completely different than active-source reflection seismology. Microearthquake data has been used to obtain tomographic velocity models of geothermal fields, which could be used as initial velocity models for surface seismic imaging. Some 2-D and 3-D seismic survey data has been collected over geothermal reservoirs, but the most routinely applied geophysical methods have been magnetotellurics, time domain electromagnetics, and resistivity. Although these later methods are successful, they do not have the potential to offer nearly the resolution that seismic methods are capable of. Traditional processing of the 2-D and 3-D seismic surveys has been plagued by the adverse field conditions that this proposal addresses and has surmounted.

The EISG project was broken down into the following tasks.

Task 1: Preprocessing

Seismic data acquired over the Coso Geothermal area in Eastern California was obtained from the U.S. Navy Geothermal Program Office. This data were carefully preprocessed using proprietary statics algorithms and prestack signal enhancement methodologies. This prepared the data for input to the depth imaging and tomography algorithms that comprise the bulk of this project effort. The data were also put through a standard time processing sequence for comparison to the depth imaging processing results.

Milestone: Preprocessed seismic data, standard processing result.

Task 2: Software customization

Software modifications were made accommodate the specific geometry and conditions of this geothermal data set. The modifications were minor and do not effect the core functionalities of the software modules. Most of the modifications pertained to the tomography code and were necessary to handle the irregular acquisition geometry.

Milestone: Software enhancement/modification.

Task 3: Near-surface velocity estimation

A near-surface velocity model was built by picking first-arrivals in the seismic data, and inputting these first arrivals into a turning ray tomography inversion. Although some first-break picks were supplied in the data headers, these supplied picks were inadequate, and the data had to be repicked.

Milestone: Near-surface velocity model.

Task 4: Removal of near-surface distortions

The preprocessed data were both downward continued through the near-surface velocity model using 3DGeo's wave-equation datuming program, and statically shifted to a floating datum which was a smoothed version of the actual topography. The floating datum data were determined to be optimal for further processing.

Milestone: Data set datumed on a floating datum surface with near-surface distortions removed.

Task 5: Velocity estimation and migration

Velocity estimation is a crucial step essential to generating a migrated depth image. For migration to properly image subsurface structure, the correct depth velocity model must be input to the migration algorithm. The migration velocity analysis (MVA) process was begun by migrating the data with an initial velocity model derived from the turning-ray tomography and from stacking velocity analysis. The data were then migrated and the resulting common reflection point (CRP) gathers were scanned for residual moveout (RMO). This procedure results in an updated velocity function to be used for prestack depth imaging.

This CRP RMO analysis was performed using multiple iterations of depth migration. Once the depth velocity model was built, the data were imaged using 3DGeo's 3-D prestack Kirchhoff depth migration (3DPSDM) package

Milestone: Velocity model for imaging, and seismic image of the geothermal reservoir.

Task 6: Wave-equation migration and other imaging approaches

For comparison, and to investigate the possible advantages of other migration methods, the data were prestack migrated with 3DGeo's ComAz wave-equation migration algorithm, prestack time migration, poststack time migration, prestack Kirchhoff depth migration. The best results were obtained using poststack time migration and prestack Kirchhoff depth migration.

Milestone: High-resolution migrated image of the geothermal reservoir.

Task 7: Comparison to other data

The accuracy of the final seismic images and the information from them were validated by comparison with published geological and geophysical information. The velocity model and images were assessed by comparing them to previous results obtained by other workers. The images are greatly improved, and are potentially much more usable for structural and lithologic information. These images add information about the geological structure and are much more likely than previous results to have utility and impact on drilling and reservoir management decisions.

Milestone: Final report and imaging results.

Project Outcomes

This project has been a thorough test study involving the application of 3DGeo's proprietary seismic imaging technology to a California geothermal data set. Aside from the scientific and engineering merits of conducting this study in what has been traditionally a very challenging data acquisition and processing environment, the project outcome of greatly improved image quality has increased the value of the seismic data itself, and provides an exemplary case study. Since the major goal of this study is demonstrating that seismic imaging of structures can be obtained in heterogeneous geothermal environments, the success of the experiment is assessed by reference to the seismic imaging results themselves.

Three representative 2-D seismic lines from a dataset acquired in 1999 in the Coso Geothermal Field for the US Navy Geothermal Program Office have been selected for preprocessing and imaging with 3DGeo's prestack Kirchhoff migration software. These include two parallel West-East lines and an intersecting North-South line (Figure 1). The same lines together with the remaining lines not considered in this study have been processed and analyzed by the team that acquired the Coso survey. Their results have been published in a geothermal workshop proceedings volume (Unruh *et al.,* 2001, and Pullammanappallil *et al.,* 2001). These publications provide a comparison for our results in this study.

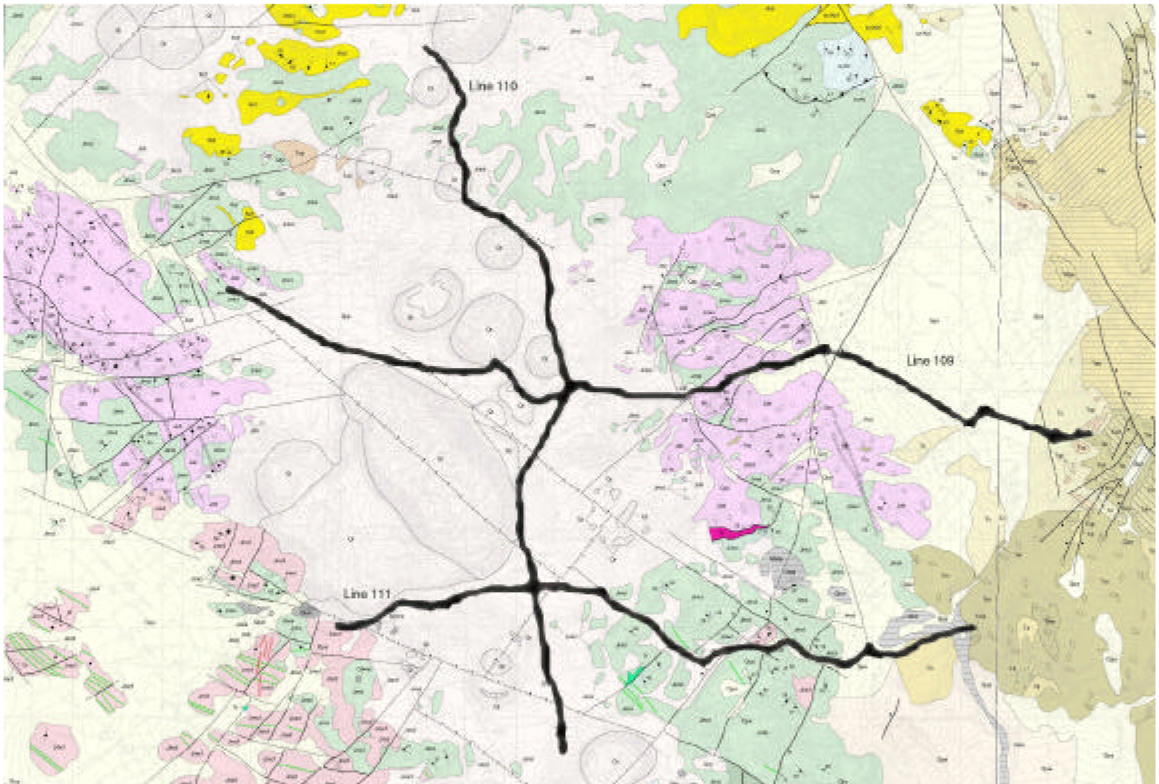

Figure 1. Three seismic lines from the Coso Geothermal Area used in this project.

In the following table we present the basic information on the data sets for the seismic lines considered. We must emphasize that due to the mountainous terrain these lines are very crooked and show considerable variation in altitude as can be seen in the plan map above.

Table 2. Statistics of the three seismic lines used for this project.

Tape	*Line Number*	*No. of Shots*	*No of Receivers*	*No. of picks*
3	111	85	116	6608
8	109	121	143	11108
9	110	94	132	10635

1. Software Modification and Enhancements

Very limited software modification was necessary to preprocess and image the seismic data. The modifications were routine, and not out of the norm of what would typically done in any special data case. The modifications largely stemmed from issues dealing with crooked-line data (see Figure 1) and irregular geometry, and were largely confined to the turning-ray tomography and inversion algorithms.

2. Preprocessing

Initial velocity models were generated using travel time tomography based on the picking of first breaks on pre-stack data (Figure 2.). The travel time tomography is performed using the INTEGRA system, which is capable of calculating accurate synthetic travel times via seismic ray tracing on variable media and inverting the data to obtain parameterized velocity tomograms (Pereyra, 2000). Figure 3 illustrates velocity tomograms obtained along all three lines. The data were preprocessed and statically shifted to a floating datum, applying proprietary static corrections and prestack energy enhancement (Figures 4 and 5).

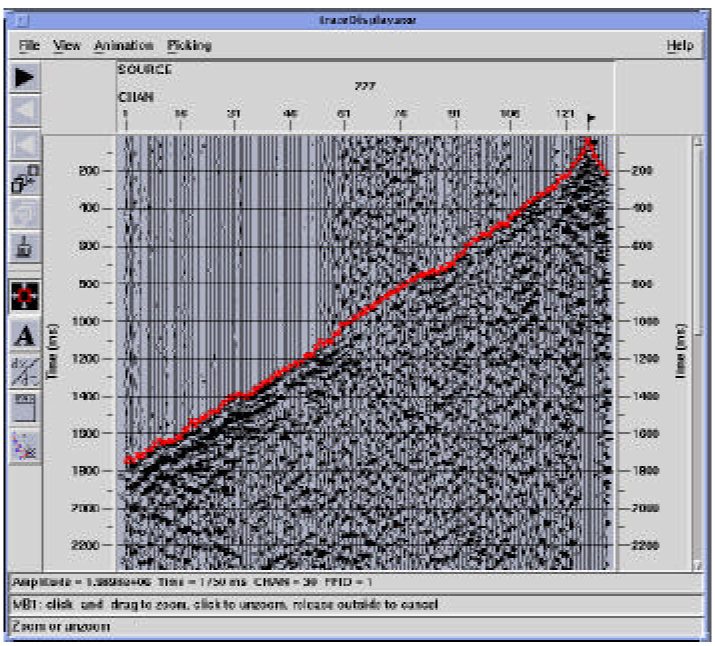

Figure 2. A representative raw seismic shot gather with first break picks shown in red.

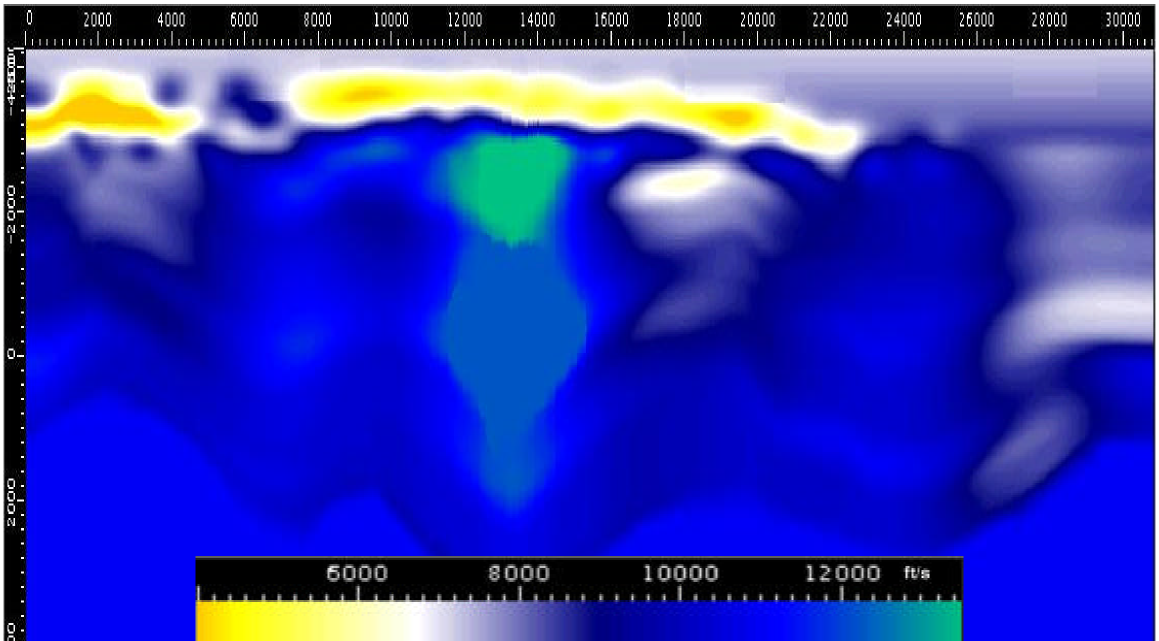

Figure 3. A representative depth velocity model based on turning ray tomography and prestack migration velocity analysis.

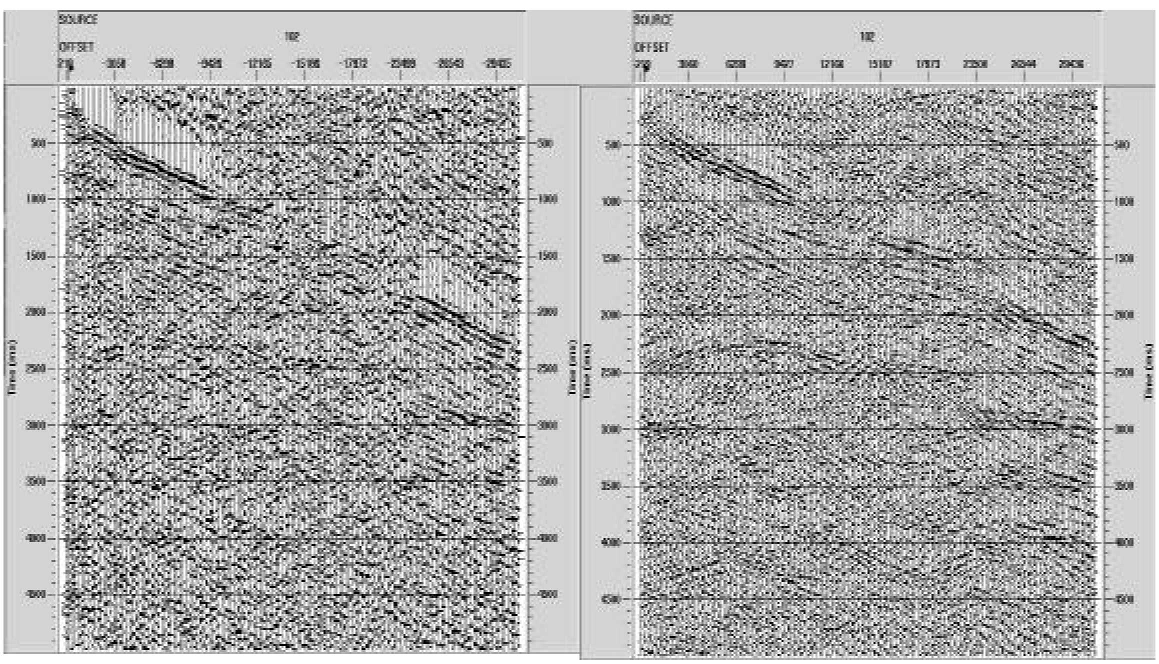

Figure 4. Shot point 102 of Line 109: raw data [left] and preprocessed and prestack enhanced data [right].

3. Seismic Imaging of the Coso Geothermal area

Tomographic inversion of first arrival traveltimes was used to derive a detailed interval velocity model for the three lines as described above. These models cover a depth range of about 2000'. For the purposes of prestack depth imaging, we extend these models downwards with a constant velocity, and where there is sufficient coherent reflectivity in the CDP gathers, analyze residual moveout after migration to improve these starting velocity models below the reach of the traveltime tomography. We chose Line 109 to investigate whether migration velocity analysis improves imaging in this case, and determined that is does.

Due to the recording geometry of the Coso survey, CDP data fold varies along each line, with maximum fold in the center falling off to single fold at the ends. Since migration relies on constructive and destructive interference of energy from multiple offsets at each reflection point to focus seismic energy at the correct image point along its isochron, the quality of the migrated image vary in the same way as the data fold horizontally and in depth: with increasing depth only a narrowing area around the center of each line will be imaged properly. The ends of the line are increasingly dominated by migration "smiles", which indicate insufficient destructive interference from multiple offsets.

The prestack depth migration improves the reflector continuity over a depth range of about 12000' (down to 8000' bsl) equivalent to 1500 ms in the time-processed images (Figures 5 through 7). The depth image more clearly delineates the two basins on both sides of Coso Range (at about 20000' horizontal or shot point 200, Figure 5). The prominent 2500 ms reflector on Line 109 (Figure 5b) is imaged as a slightly west dipping feature between 7000 and 9000' bsl clearly visible between 14000' and 22000' distance (shot points 170 to 210). Although shallower, it most likely corresponds to reflector "A" (Figure 5) in Unruh *et al.*, (2001); poststack depth migration places the 2500 ms reflector at about 9000' bsl. A sharply east dipping reflector merges into it near shot point 180 (15000' distance), labeled "B" and interpreted as fault(s) in Unruh *et al.* (2001). Further possible faults can be identified as dipping away from shot point 195, the east dipping one has been identified as Coso Wash Fault by Unruh *et al.* (2001). Below 10000' bsl, the reflectivity becomes more sub-horizontal, possibly because the high heat flow of the geothermal area has moved the brittle-ductile transition zone locally to this shallow level as Unruh *et al.* (2001) suggest. Distinct reflectors could then indicate reservoirs of free fluid (e.g. melt).

Large scale figures of the individual images presenting in Figures 5 through 7 are presented in Appendix I.

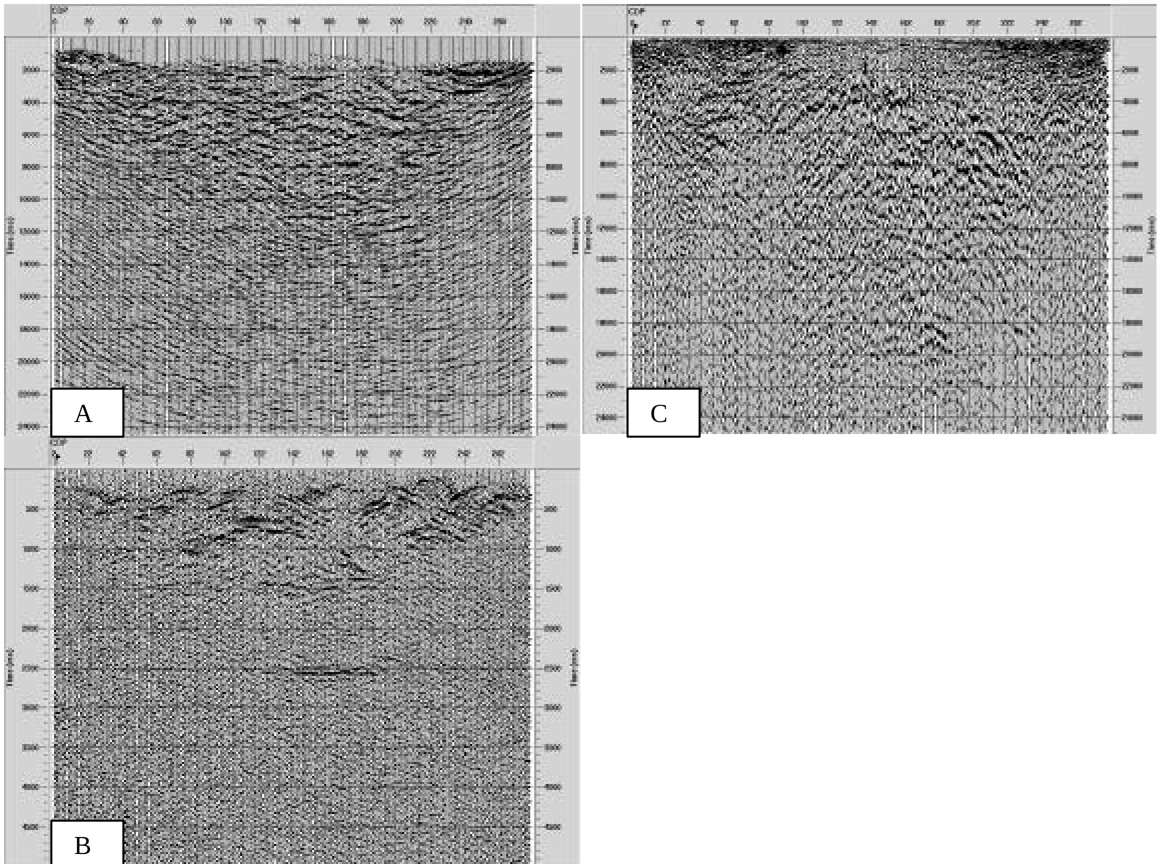

Figure 5. Imaging results for Coso Line 109. (A) 3DGeo depth migration, (B) 3DGeo time processing, and (C) previous processing depth migration. Vertical scale is in feet in A and C, and in milliseconds for B. The 3DGeo results (A and B) show many coherent reflection events that correspond to geological structure. The previous imaging results are much noisier and are much more difficult to interpret. Shallow structure is very evident in the time processed section B. Deeper structure is evident in both A and B. The flat reflection at 11,000 ft in A and 2500 ms in B is thought to be a reflection corresponding to the brittle/ductile transition in the crust. See Appendix I for large-scale images.

There is sufficient reflector continuity in the upper part of the Line 109 image (Figure 5) to extend the tomographic velocity model, which covers a depth range of only about 2000' by migration velocity analysis. In this analysis, residual moveout in the gathers migrated with the tomographic velocity model (extended downward with a constant velocity of 12000 ft/s) is automatically picked from semblance spectra and converted into a differential velocity update along the vertical above the analyzed depth point. The updates are tied to reflectors picked on the stacked image. In this way the velocity model for Line 109 was extended to a depth of about 3000' below sea level, deeper layer were kept at a constant velocity of 12000 ft/s. The new velocity model improves the continuity of the deeper reflections.

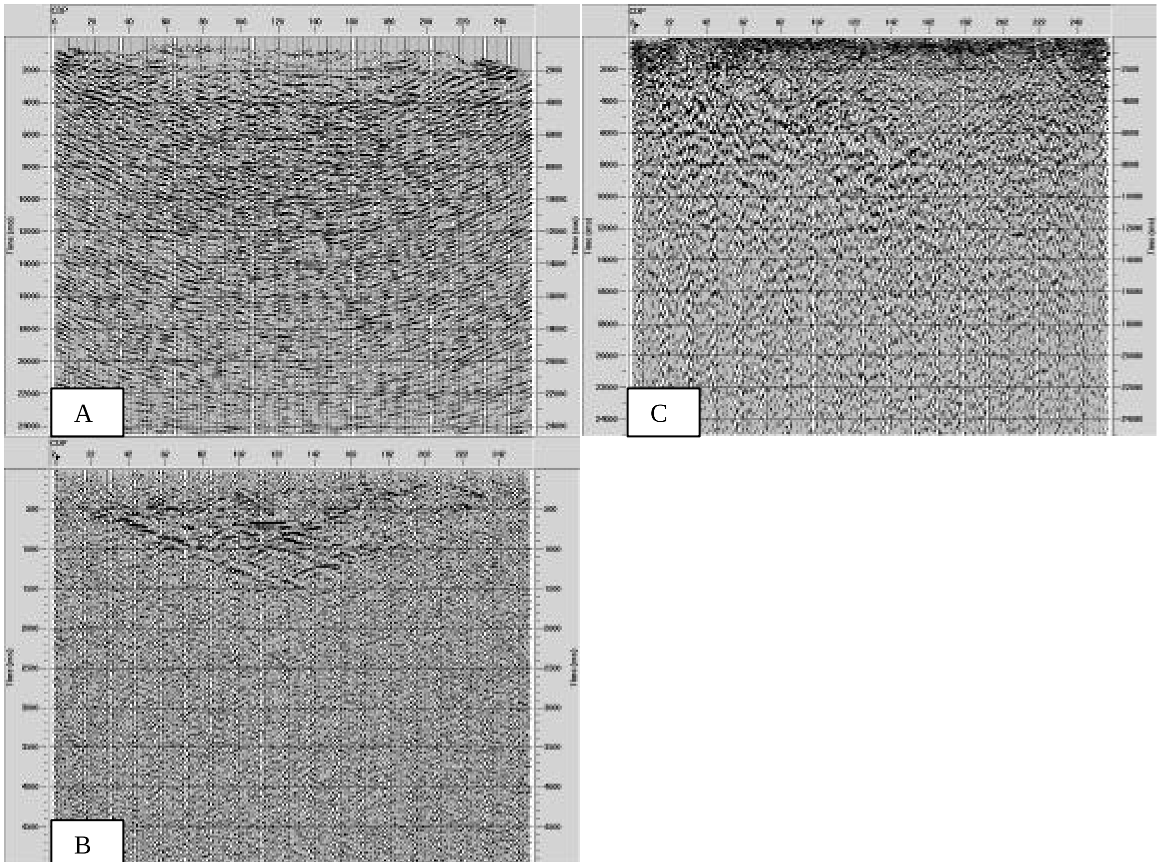

Figure 6. Imaging results for Coso Line 110. (A) 3DGeo depth migration, (B) 3DGeo time processing, and (C) previous processing depth migration. Vertical scale is in feet in A and C, and in milliseconds for B. The 3DGeo results (A and B) show many coherent reflection events that correspond to geological structure. The previous imaging results are much noisier and are much more difficult to interpret. This line is essentially a strike line imaging the north-south extension of the Coso basin. See Appendix I for large-scale images.

On Line 110 (Figure 6), prestack depth migration is able to resolve far more individual reflectors down to about 10000' bsl than the time processing. One of the advantages of the prestack migration is that it can take account of the crooked geometry of the recording line: this line has been migrated as 3-D data with a 2-D velocity model (i.e. the velocity model does not vary perpendicular to the strike of the line). This line runs along the strike of Coso range in the Coso basin, one expects therefore to find more subdued structure than on Lines 109 (Figure 5) and 111 (Figure 7). The poststack depth migration seems to outline the basin to a depth of 3000' bsl. The prestack depth migrated image (Figure 6A) shows a prominent discontinuity at 2000' bsl, which may be one of the major east-dipping faults identified on Line 109.

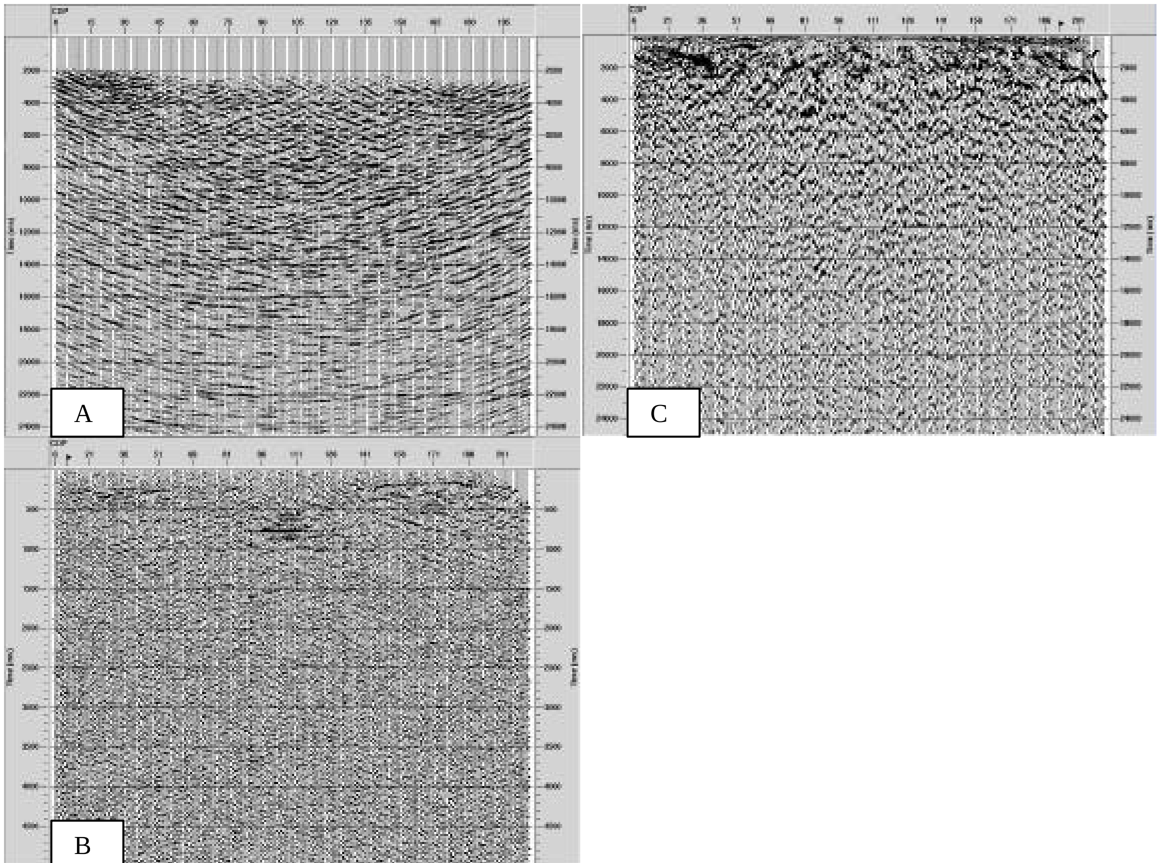

Figure 7. Imaging results for Coso Line 111. (A) 3DGeo depth migration, (B) 3DGeo time processing, and (C) previous processing depth migration. Vertical scale is in feet in A and C, and in milliseconds for B. The 3DGeo results (A and B) show many coherent reflection events that correspond to geological structure. The previous imaging results are much noisier and are much more difficult to interpret. Better resolution of flat deep structure is evident in A. See Appendix I for large-scale images.

Prestack depth migration has difficulties resolving shallow features unambiguously on Line 111 (Figure 7), probably due to the extensive high-angle faulting. In contrast, deeper, gently westward dipping reflectors between 4000' and 9000' depth are fairly well imaged in the high-fold center of the line, as well as more subhorizontal reflectors at 8000', 11000, and 13000' depth, possibly also at 17000' depth.

4. Validity and Accuracy of Seismic Imaging

The accuracy and validity of the EISG project results can be largely assessed by examining the imaging results themselves, and noting the considerable improvement in image quality over the previously obtained results (as displayed in Figures 5 through 7 in the previous section). Further validation of the 3DGeo processing is exemplified by the interpretability of the imaging results, and how the images conform to known geology. Figures 8 through 10 are interpreted migrated sections. These are images overlaid by colored lines corresponding to a geophysicists picks of reflection events which correspond to geology. Geological interpretation of seismic images is always as much a subjective art as an objective scientific analysis and depends crucially on the skill, experience and local knowledge of the interpreter. This is especially true in a volcanic field like Coso where there are no sedimentary strata that usually guide the interpretation. For these reasons, our interpretations should be viewed as suggestions by the processing geophysicist of what reflectivity could be reasonably used to build a geological model. Usually, logging data from wells drilled in the imaged area provide vital information both for the processor building a velocity model and the interpreter whose geological model must satisfy all available data. For this study, we did not have access to such information.

As displayed in Figure 8, the prestack depth migration improves the reflector continuity of Line 109 over a depth range of about 12000' (down to 8000' bsl) equivalent to the 1500 ms reflector in the time-processed images. The depth image more clearly delineates the two basins on both sides of Coso Range (yellow). The 2500 ms reflector is imaged as a slightly west dipping feature between 7000 and 9000' bsl clearly visible between 14000' and 22000' distance (shot points 170 to 210) as a packet of parallel events (red). Although shallower, it most likely corresponds to reflector "A" (Figure 15) in Unruh *et al.* (2001); poststack depth migration places the 2500 ms reflector at about 9000' bsl (Figure 15). Sharply east dipping reflectors (yellow and green) merge into it near shot point 180 (15000' distance), labeled "B" and interpreted as fault(s) in Unruh *et al.* (2001). Further possible faults can be identified as dipping away from shot point 195 (orange and pink), the east dipping one (yellow, basin bounding) has been identified as Coso Wash Fault by Unruh *et al.* (2001). At the eastern end, the near-surface reflection amplitudes increase where the line enters the Tertiary volcanics of the Coso formation, which provide stronger impedance contrasts than the adjacent alluvial fill of Coso Wash. Below 10000' bsl, the reflectivity becomes more sub-horizontal, possibly because the high heat flow of the geothermal area has moved the brittle-ductile transition zone locally to this shallow level as Unruh *et al.* (2001) suggest. Distinct reflectors (cyan and orange) could then indicate reservoirs of free fluid (e.g. melt).

Most prominent on Line 110 (Figure 9) is the east dipping (cyan and purple) reflectivity in the northern half of the line, against which shallower sub-horizontal reflectivity terminates. This may mark the (probably fault-bounded) base of the Quaternary Coso basin fill (purple and blue). The poststack depth migration seems to outline the basin to a depth of 3000' bsl (Figure 20). The prestack depth migrated image shows a prominent discontinuity (yellow) at 2000' bsl, which may be one of the major east-dipping faults (Coso Wash Fault) identified on Line 109. Antithetic faulting interrupts a shallow pattern of strong horizontal reflectors (to both sides of the green fault reflection) that are probably caused by strong layering of the rhyolite flows at the surface (as has been observed in flood basalt provinces around the earth). The slight northward dip of the deep, parallel reflectivity (pink, orange, blue) suggests that the geothermal reservoir is centered on the southern half of Line 110.

In Figure 10, Line 111 shows again the distinction between steeply dipping reflectors above about 7000' bsl and sub-horizontal reflectivity below. The former come in two sets: shallow (green, orange purple) and deep (blue and brown), separated by a more gently dipping reflector (dark blue), possibly a décollement between the Quarternary Coso basin fill in the hanging wall and the Jurassic basement of Sugarloaf Mountain. Quarternary basaltic intrusions (in form of horizontal sills) and the Independence dike swarm also contribute to the small scale shallow (above sea level) reflectivity especially at the western end of the line. The deep reflectivity (cyan, yellow, red, pinks) again marks a ductile fabric, thus the top of the geothermal reservoir is probably delineated by the cyan reflector, its base possibly by the red reflector.

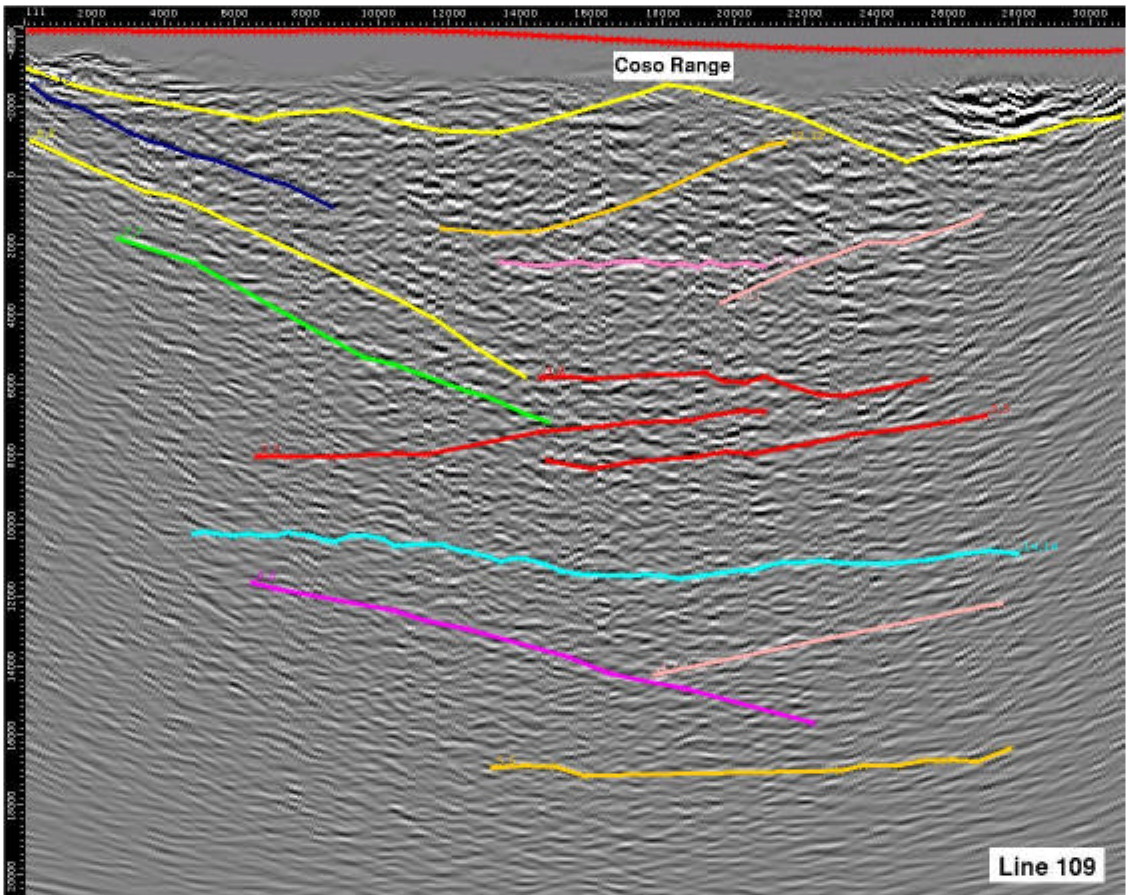

Figure 8. The prestack depth migration improves the reflector continuity of Line 109 over a depth range of about 12000' (down to 8000' bsl) equivalent to the 1500 ms reflector in the time-processed images. The depth image more clearly delineates the two basins on both sides of Coso Range (yellow). The 2500 ms reflector is imaged as a slightly west dipping feature between 7000 and 9000' bsl clearly visible between 14000' and 22000' distance (shot points 170 to 210) as a packet of parallel events (red). Although shallower, it most likely corresponds to reflector "A" (Fig. 15) in Unruh et al. (2001); poststack depth migration places the 2500 ms reflector at about 9000' bsl. (Figure 15). Sharply east dipping reflectors (yellow and green) merge into it near shot point 180 (15000' distance), labeled "B" and interpreted as fault(s) in Unruh et al. (2001). Further possible faults can be identified as dipping away from shot point 195 (orange and pink), the east dipping one (yellow, basin bounding) has been identified as Coso Wash Fault by Unruh et al. (2001). Below 10000' bsl, the reflectivity becomes more sub-horizontal, possibly because the high heat flow of the geothermal area has moved the brittle-ductile transition zone locally to this shallow level as Unruh et al. (2001) suggest. Distinct reflectors (cyan and orange) could then indicate reservoirs of free fluid (e.g. melt).

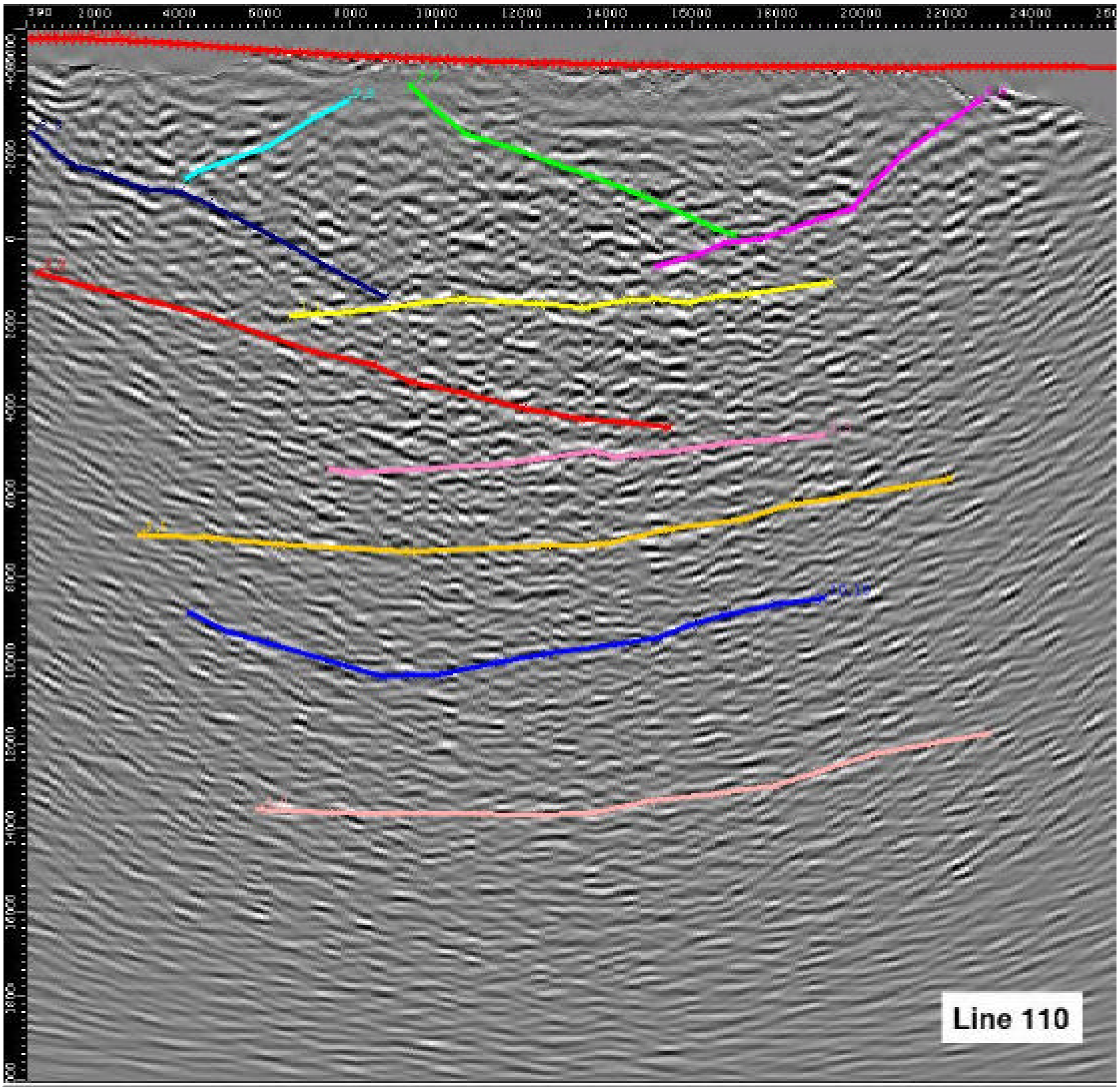

Figure 9. Most prominent on Line 110 is the east dipping (cyan and purple) reflectivity in the northern half of the line, against which shallower subhorizontal reflectivity terminates. This may mark the (probably fault-bounded) base of the Quaternary Coso basin fill (purple and blue). The poststack depth migration seems to outline the basin to a depth of 3000' bsl (Figure 20). The prestack depth migrated image shows a prominent discontinuity (yellow) at 2000' bsl, which may be one of the major east-dipping faults identified on Line 109.

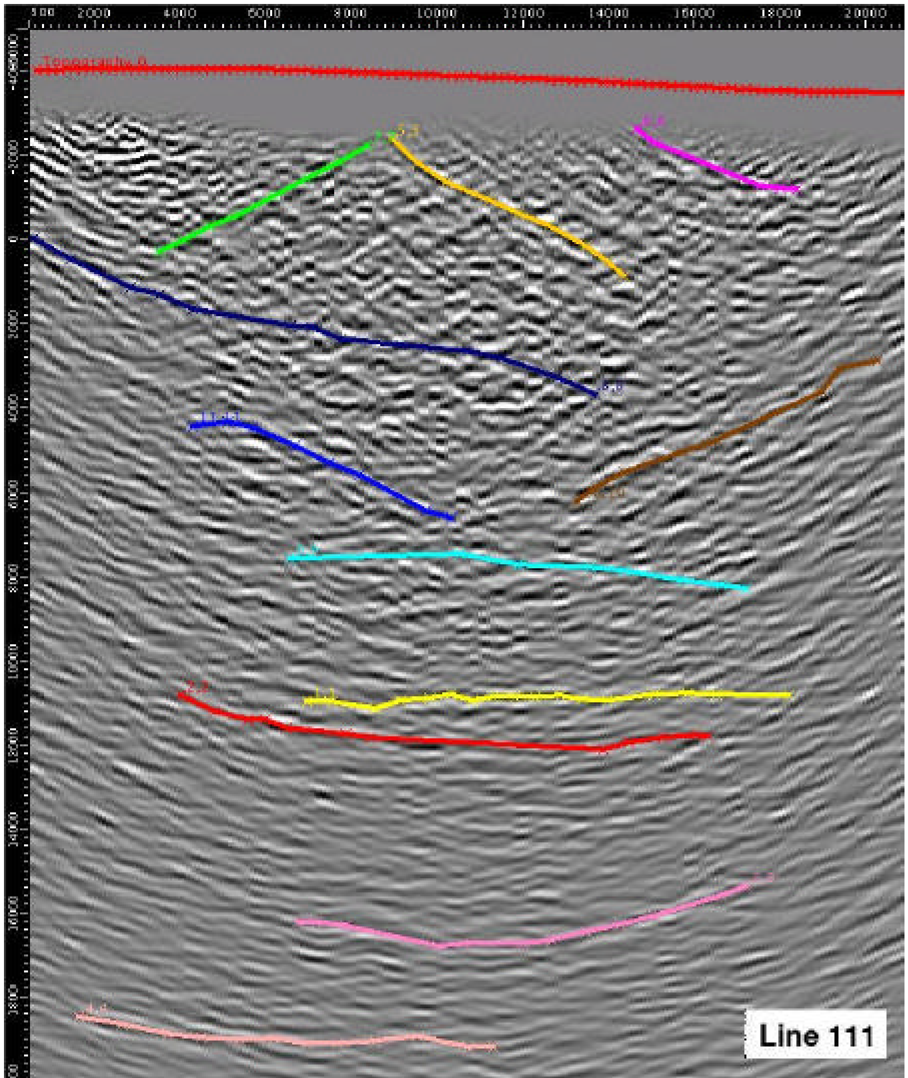

Figure 10. Line 111 shows again the distinction between steeply dipping reflectors above about 7000' bsl And subhorizontal reflectivity below. The former come in two sets: shallow (green, orange purple) and deep (blue and brown), separated by a more gently dipping reflector (dark blue), possibly a décollement between different tectonic formations. The deep reflectivity (cyan, yellow, red, pinks) again marks a ductile fabric.

5. Commercial Application

The outcome of this project, namely the imaging results and interpretations presented in the preceding sections, have commercial application and utility in that they will add to the knowledge of the Coso Geothermal Area. The process demonstrated here, and the knowledge and conclusions gained, give 3DGeo expertise and credibility to apply the technology to other field areas without undue experimentation or research. There is room to improve the processing results and the data acquisition geometry and data acquisition design in future surveys. 3DGeo can advise enterprises in these commercial applications based on experience gained in this EISG project.

Conclusions

Overall, the time processing seems to work better for the shallow structures, whereas depth processing is better in resolving deeper features. Successful depth imaging depends on careful preprocessing of the raw data, especially the application of static corrections that reduce the effects of the rugged topography and the complex near-surface layer and a good starting velocity model at least at shallow depths.

In order to image not only the center of each line well over the entire depth range, longer recording lines are desirable. Extending the recording spreads beyond the ends of the shot lines would ensure an even CMP coverage over a wide range of offsets.

Compared to the previously published imaging results using the same seismic data (Unruh *et al.*, 2001, and Pullammanappallil *et al.*, 2001), this EISG project resulted in images that are more coherent and less noisy and show a higher frequency content (better resolution), consequently revealing more geological structures. It needs to be pointed out, however, that this comparison is based solely on the published images. An entirely fair comparison ought to be made between images derived from the same velocity models, which was not possible in this case.

This EISG project has resulted in, and demonstrated improved methodology for processing seismic data. Based on the demonstrated performance of the processing methodology in this EISG project, we have demonstrated the feasibility of performing this type of processing as a commercial service.

Recommendations

Active source reflection seismology has clear potential benefits to geothermal exploration and development. Quality seismic data processing is important to obtaining accurate and usable imaging results. The quality processing is not limited only to the high-end imaging algorithms, such as Kirchhoff migration, but also to the preprocessing applied to the data. Statics are critical to obtaining a good imaging result, as is prestack noise attenuation.

Previous processing applied to this data set, and other geothermal data sets, has erroneously omitted the application of preprocessing and statics, and has sometimes applied questionable imaging techniques. There is no reason for this to be done, as seismic imaging is a mature technology, and there are thousands of petroleum case histories in data areas similar to those encountered in geothermal regions. There is no question that geothermal areas generally produce challenging seismic data that push the limits of processing and imaging, but the challenges can be met with experienced personnel and the proper algorithms carefully applied. There is often a tendency to skimp on the processing, and not apply as much effort or expense in the processing as has been applied in the acquisition; this is a mistake.

Recommendations stemming from this EISG project fall in three categories:

1) Further work on this Coso data set
2) Further seismic work in the Coso geothermal area, and
3) General recommendations for reflection seismic in geothermal areas.

1. Further work on this Coso data set

There are eight lines in this Coso data set, only three were processed in this EISG project; therefore, we recommend that the other lines be processed using the same workflow 3DGeo has demonstrated on these three lines.

It is recommended that data from all eight lines be used for a joint 3-D tomographic inversion of the near surface velocity structure. Based on the convergence of the 2-D tomograms, and the potential from improvement in 3-D, it is likely that a more accurate and detailed velocity model could be obtained from a joint inversion of all lines simultaneously.

It is recommended that more detailed preprocessing be performed on the Coso data. This preprocessing can further enhance coherent reflection events based on the images obtained in this EISG project. This would constitute an iterative preprocessing that could greatly enhance imaging.

It is recommended that a more detailed velocity model be built for the existing 2-D data lines by performing tomographic MVA and utilizing interpretive input from geologists familiar with the area to constrain velocity models. The velocity obtained in this EISG project would constitute the starting point for a more detailed geology-based velocity model.

2. Further seismic work in the Coso geothermal area

For optimal imaging, it is recommended that longer 2-D seismic lines are acquired over the Coso geothermal area. Although the current data set is of high quality, better imaging resolution could be obtained by acquiring longer seismic lines. The current line length permits imaging only in the central portion of the seismic lines because full-fold coverage is only attained for the central mile or two of the line. This is an issue of illumination: better illumination from all sides (i.e. greater line length) will result in better imaging.

Acquisition of a 3-D data set would be extremely difficult and costly due to the rugged terrain of the Coso geothermal area, but a high quality full-fold 3-D seismic data set would result in the best possible imaging of the subsurface geothermal resources and geological structure. To our knowledge, no such 3-D data set has been acquired and optimally processed in any geothermal area. Such 3-D surveys are routine and mandatory in petroleum exploration. 3-D seismic has met with tremendous success in the petroleum industry, and under certain conditions, is credited with increasing drilling success from 20% (with 2-D seismic) to 80%. Such potential cost and risk reduction warrants investigating the application of 3-D seismic to either this, or some other geothermal filed.

3. General recommendations for reflection seismic in geothermal areas

Reflection seismic could have substantial impact on geothermal exploration and development, and on the reduction of electrical energy costs. However, the seismic must be applied judicially, with good pre-survey planning, and with quality seismic acquisition, and with quality seismic processing and imaging.

3DGeo recommends that drilling and exploration programs in geothermal areas consider seismic as a possible risk reduction technology. Before acquiring a costly seismic survey, it is recommended that a modeling study be conducted to determine if seismic is appropriate. The modeling study should entail a ray-tracing illumination study to determine the best survey design for the given target objective. Once the survey is designed and acquired (2-D or 3-D), the data must be carefully processed, with attention to preprocessing, statics, prestack enhancement, noise reduction, velocity model building, and high-end imaging. It is likely that the processing and imaging challenges will be substantial, and it is possible that processing and imaging costs could approach acquisition costs, but the challenges are surmountable.

Accomplishments needed to advance the technology

What is required to advance the technology and lead to a market breakthrough is a convincing 3-D reflection seismic case history. All that is required is a comprehensive survey design, quality data acquisition, and thorough quality processing. The project would require close cooperation and interaction between geologists and engineers familiar with the field area, and a processing/imaging team with experience and resources necessary for the project.

The next logical research objectives to advance this technology are

- the recommended work described for this data set, and/or
- a well planned and executed 3-D experiment in either this, or some other geothermal field area.

Public Benefits to California

The benefits to the California energy industry are twofold:

1) California benefit directly from the increased reservoir information obtained about the Coso geothermal field used for this study, and the resulting potential increases in electric generation, production efficiency, and reservoir life.
2) This project has developed and demonstrated a data processing methodology which will be applicable to other California geothermal fields and larger 3-D data sets, thereby improving exploitation of geothermal energy statewide.

Benefits of this technology to geothermal energy generation development in California and worldwide are for positioning development step-out production wells and injection wells, potentially saving 3 to 5 wells per 100 MW developed in a large new field, and 2 to 3 wells in a small 35 MW field for which drilling risk per MW is typically higher. These wells can cost $1.5 to $4 million each including access costs. The data could also provide important support for the overall conceptual model that is used to assess resource capacity. The incremental value of the data in this case would be difficult to quantify, but the investment affected might easily total several hundred million dollars.

The technology demonstrated in the EISG project improves the imaging of geothermal fields with complex near-surface geology in which, up until this point, current imaging technologies have not performed well.

Development Stage Assessment

Table 2 displays the Stage Activity of the EISG project, which has been completed to Stage 3 in this project. However, the outcome of this project has demonstrated that several of the later stages are in place.

Table 2. Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

Marketing

The Market for seismic imaging technology is energy companies involved in development of geothermal resources in California and worldwide. Preliminary research has been conducted to assess the potential market size and identify target customers. The greatest benefit of this technology will however accrue to the State and to end users in the form of increased geothermal development and reduced costs. A product is ready for market (Stage 4) and the technology has outperformed the competition (Stage 5).

Engineering/Technical

A criteria and test plan is outlined in Recommendations, and parts of Stage 4 (candidate site), Stage 5 (field test at Coso), and 6 (initial 2-D demonstration) can be considered accomplished based on the outcome of this EISG project.

Legal/Contractual

U.S. Patents have been issued, and several are pending on certain key 3DGeo technologies that have been applied in this EISG project (patents and applications are based on prior work).

Risk Assess/Quality Plans

Application of this technology to geothermal exploration and exploitation reduces environmental risk through reduction in drilling errors, and reduction of cross-contamination of aquifers and reservoirs. This project has laid the groundwork for developing a Quality Plan to assess the reliability and applicability of the technology in applications to different geothermal areas.

Strategic

This project has no known dependencies to other known PIER projects. It offers a technology to exploit and expand the scope of geothermal development in California, and as such is strategic in helping circumvent future potential California energy problems, such as those experienced in 2000/2001. This project extends the scope of, and is complimentary to, known Federal R&D programs.

Production Readiness

The seismic imaging technology demonstrated through Stage 5 in this EISG is fully production ready. Further demonstration of the technology through Stage 6 with an extended project, as outlined in the recommendations for further work, would validate the production readiness.

Public Benefits/Cost

The electric consumer is the ultimate beneficiary of this technology because it can lower the cost of finding and producing geothermal energy. Benefits of this technology to geothermal energy generation development in California are reduction in cost of development step-out production wells and injection wells, potentially saving 3 to 5 wells per 100 MW developed in a large new field, and 2 to 3 wells in a small 35 MW field for which drilling risk per MW is typically higher. These wells can cost $1.5 to $4 million each including access costs. This cost comes at an estimated investment of $1 million in seismic, to save up to $20 million in drilling cost. That is a return on investment (ROI) of 20 for a 100 MW field. These costs are likely to go down as further experience is gained and as more reflection seismic data is collected in geothermal fields.

Two significant public benefits of lowered geothermal energy costs include:

- A reduction in California's reliance on out-of-state energy sources and a decrease in the likelihood of another energy shortage such as occurred in 2000/2001.
- Production of environmentally clean geothermal energy as an alternative to fossil fuels and nuclear energy.

Further development of this project through Stage 6 with a large scale demonstration of the technology will exemplify its full potential. There is public interest in demonstration testing, as exemplified by the donation of the seismic data to this project by the Coso operators.

Glossary

2-D: two-dimensional.

3-D: three-dimensional.

BSL or bsl: below sea level.

CRP: Common reflection point gather. A gather of migrated seismic data at a fixed reflection point.

Datum: a reference surface from which seismic data are processed.

Datuming: the process of correcting seismic data to a datum. Could be performed by static shifting or wave-equation datuming.

Floating datum: usually a smoothed version of the topography from which data are referenced and processed after static correction.

Inversion: method of solving simultaneous system of equations for tomographic problems.

Kirchhoff Migration: method of seismic imaging using an integral equation solution to the wave equation. This is the most commonly used imaging method in the petroleum exploration industry. It can be applied in time or depth migration applications.

MVA: Migration velocity analysis. The method of obtaining migration velocity from migrated data and updating/building a subsurface velocity model.

Migration: method of imaging seismic data by numerically repositioning recorded events to their correctly position subsurface locations.

Poststack: seismic data or process applied after the process of stacking.

Prestack: seismic data or process applied before the process of stacking.

RMO: Residual moveout.

RMS: Root mean square.

Stacking, Stack: the process of summing seismic data along offset to create images.

Statics: method of correcting prestack seismic data for near surface velocity irregularities and topography.

Time Processing: seismic imaging and processing method which produces subsurface images with a vertical axis expressed in two-way reflection traveltime in seconds or milliseconds. Generally less accurate in areas of complex geology where velocity has substantial lateral variability.

Tomogram: generally a 2-D velocity slice, or 3-D velocity volume, resulting from a tomographic inversion.

Tomography: an accurate method of determining subsurface velocity which generally consists of tracing rays through the subsurface and solving for a system of equations which relates theoretical rays to observed traveltimes.

Turning-ray tomography: the method of tomography where the traveltimes input to the system of equations are from rays which turn in the subsurface due to a vertical gradient or refraction. Also called diving-ray tomography.

Velocity: propagation velocity of acoustic and elastic waves in the subsurface

Wave-equation datuming: process of numerically propagating seismic data from one datum to another.

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Pullammanappallil, Honjas, Unruh, and Monastero, *Use of advanced data processing techniques in the imaging of the Coso geothermal field*, Proc. **26** Workshop on Geothermal Reservoir Engineering, Stanford University (2001).

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