Advanced seismic imaging of geothermal reservoirs in Nevada—Is there a geothermal seismic signature?

John N. Louie, Ph.D.
Great Basin Center for Geothermal Energy
University of Nevada, Reno

Satish Pullammanappallil, Ph.D.
Optim Inc.

crack.seismo.unr.edu/louie optimsoftware.com
“Integrative” versus “Differential” Geophysical Methods

Grav, Mag, MT, Refraction integrate over volumes

Seismic Reflection & Radar image point changes
Problem: Applying Seismic Exploration to Geothermal Projects

- “Cornerstone” of oil & gas exploration and development...
- ...But until recently, not used for geothermal projects
  - Lateral complexity prevented accurate velocity modeling
  - Lack of accurate velocity models prevented focusing of reflection data
  - Lack of focused reflectors equals poor seismic image
  - Poor seismic image results in lack of “added value” proposition

These problems deprived the geothermal industry of the basic means for economically mapping the subsurface.

- Too much exploration is being done with the drill bit—
  the riskiest, most expensive way!
Solution: Solve the Velocity Problem

- **Simulated Annealing Velocity Optimization**
  - Researched at the University of Nevada Seismological Laboratory during the early 1990’s
  - Commercially developed and released by Optim, under the name SeisOpt® in 1998

SeisOpt® iterates through hundreds of thousands of possible velocity solutions to find the single, or “global”, solution that best fits the seismic data, assuming no direction or magnitude of velocity gradient.
Advanced Seismic Technology

- **Proven effectiveness of SeisOpt® techniques**
  - Built on success of pilot studies in Dixie Valley, Nevada and Coso, California—both magmatic and extensional systems

- **Utilize new seismic acquisition parameters**
  - Designed to enhance results from advanced processing techniques

- **Image reservoirs with Prestack Kirchhoff Migration**
  - Characterize features significant for evaluating subsurface permeability
  - Correlate down-dip geometry of features mapped at the surface

- **Image tectonic structures**
  - To determine their relationship to faults and fractures controlling the reservoir permeability and production
In the Great Basin

A small network of 2D seismic lines targeted extensional faults

Dip lines and tie lines

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Central Nevada, Raw Record
• Only uses first-arrival picks from reflection records.
• Velocity resolution below base of sediments, in bedrock.
• 2x lateral velocity changes over short distances!
• Industry sections usually much smoother.
• Without such velocity resolution, PSDM is impossible.
Only the range-front fault manifests at the surface.
Conclusions from Advanced Imaging

The seismic survey imaged hidden basin-ward step faults directly as seismic reflectors.

- Network of 2-D lines explored prospect at a fraction of the cost of 3-D
- Acquisition specially designed for best SeisOpt® velocity results
- Good velocity info and PSDM imaged faults and alluvial stratigraphy
- Needs confirmation by drilling

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Astor Pass: 2-D WAZ Acquisition

- Upper 2 km
- 10-25 m V.R.
- Up to 240 channels
- Lines 2-7 km long
- Source-receiver spacing 17-67 m
Astor Pass: Fault Discovery with Direct Fault-Plane Images

No evidence for fault at A before imaging

Fault gouge in APS-3 at 1300 m depth, within 27 m (90 ft) of seismic interpretation
Astor Pass: Imaging Volcanic Stratigraphy

Strong reflectivity of Tertiary basalts

Rhyolite domes have less reflective interiors

Volcanic stratigraphy in upper 600 m of APS-3 interpreted in seismic with 10-m (30 ft) accuracy
Astor Pass Conclusions

The seismic survey discovered new fault sets.

- Fault-plane image quality depends on survey orientation- 3-D imaging in process
- Excellent imaging of Tertiary volcanic stratigraphy- domes versus flows
- Faults and stratigraphy verified from new wells
- Fault imaging allows seismic attribute, AVO analysis of geothermal reservoir
New well from seismic interpretation

Drilling intersected the fault within 15 m (50 ft) of seismic interpretation

New well provides enough heat to meet 60% of electrical needs of OIT campus
Benefits of Advanced Seismic Technology

- Large improvement in **drilling success**
  - At a 2011 Imperial Valley, Calif. prospect, 4 of 5 wells were economic
  - No more exploration with the drill bit!

- Direct imaging of fault reservoirs enables search for the **Geothermal Seismic Signature**
AVO: Hydrocarbon and Geothermal

Joe Dierkhising MS Thesis – Geothermal Amplitude vs. Offset

A) AVO initially used to locate and characterize gas sands
B) In the late 1990s early 2000s AVO methods applied to geothermal exploration in faulted basement rocks
C) A more comprehensive AVO classification scheme adapts AVO methods to non-HC exploration

(A) Rutherford & Williams, 1989 (B) Mazzotti & Zamboni, 2003 (C) Young & LoPiccolo, 2003
Theory: Amplitude versus Offset (AVO)

(A) Chopra & Castagna (2014)
(B, C, E) Young & LoPiccolo (2005)
(D) Dierkhising (2015)

A) P\textsubscript{incident} ray paths
B) CMP gather (offset)
C) I-G Method
D/E) Relationship between an AVO crossplot-pair and the petrophysical properties of reservoir rocks

Joe Dierkhising MS Thesis
Reservoir & Velocity Structure

A. Vp model
- Low velocity zone within highly faulted reservoir zone

B. Vs model

C. Close-up PSDM section
- Interpreted faults in yellow

Velocity Information Courtesy of Optim Inc.
AVO signature in a geothermal reservoir

Left: RMS-AVO horiz. slice of common-image gather (CIG) - reservoir zone is yellow dash
Location of the AVO anomaly (between A and A’) correlates to the highly fractured producing reservoir

Below: PSDM section of the 2-d reflection line traversing the geothermal reservoir

Conclusions: This study at a producing geothermal field suggests a correlation between the RMS AVO-anomaly and the presence of highly faulted reservoir zones
AVO signature in a geothermal reservoir

Dim spots in AVO map at each fault

Common-Image Gather Horiz. Slice

Joe Dierkhising MS Thesis
Velocity Models: Additional Information?

A) Poisson’s Ratio derivative section using Vp and Vs models

B) AVO-Intercept attribute section using Vp and Vs models, Gardner’s equation, and Smith & Gidlow’s approximation

Velocity Information Courtesy of Optim Inc.
Joint Seismic-Gravity Optimization

Kyle Reeder MS Thesis – Multi-scale assessment of lateral velocity heterogeneity to greater depths, for better imaging.

Joint inversion

Uses empirical velocity-density relationship to converge to a single model that fits both datasets simultaneously.
Validated First-Arrival Picking

San Emidio Line 6 Shot Record 676

Viewmat Plane 44

Observed
Calculated

Linear Ground Roll Mute

Observed
Calculated
Residual+0.6

Kyle Reeder MS Thesis
Seismic Forward Modeling

Line 6 SeisOpt Run #1 Velocity Model

Reeder Travel time contours (s)

Line 6 SeisOpt Run #1 Isotime Contour Plot

Reeder Travel time contours (s)

Kyle Reeder MS Thesis
Gravity Forward Modeling

High-Quality Seismic from Volcanic & Alluvial Basins

Shot #3 Raw Record

First Break Picks

Easting (m)

Kyle Reeder MS Thesis
Extending the $V_p-\rho$ Correlation to Soft Sediments

Velocity to Density Relationships

Density (g/cc)

P-wave Velocity (km/s)

Nafe–Drake
Christensen–Mooney
Godfrey
Gardner
This Study

Kyle Reeder MS Thesis
Balancing the Joint Optimization with Pareto Charts

Kyle Reeder MS Thesis

5000 trial models per dot
Joint Fit Not as Good as Single Fit

Gravity Models

- Observed
- SeisOpt
- Joint

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Time-Only PSDM vs. Joint PSDM

SeisOpt Velocity Model (m/s)

Joint Velocity Model (m/s)

SeisOpt Depth Migration

Joint Depth Migration

Kyle Reeder MS Thesis
Limited Offset-Range PSDM

Medium and far offsets are “turning-ray” reflections.

• Their uses?

Joint Gravity-Seismic Optimization greatly altered views on:

• Basin thickness and tilt sense
• Range-front fault location
• Structure on the Tertiary-Quaternary boundary
Now that we have direct fault images, we can analyze:

- Seismic attributes - amplitude, phase, frequency, edges, shadows, etc.
- AVO - amplitude versus offset, Poisson’s ratio
- AVA - amplitude versus azimuth, fracture orientation
- Seismic inversion - separate $\Delta \rho$, $\Delta \lambda$, $\Delta \mu$