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

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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 a suite of solutions that fit 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
Pumpernickel Valley Raw Record
Pumpernickel Valley Velocity Line 5
Pumpernickel Valley - Preliminary interpretation of seismic data

Only the range-front fault is manifested at the surface
Pumpernickel Valley, Nevada

Preliminary fault traces based on seismic only
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 allowed imaging faults and alluvial stratigraphy
- Needs confirmation by drilling
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

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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

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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**
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 $\Delta \rho$, $\Delta \lambda$, $\Delta \mu$
AVO: Hydrocarbon and Geothermal

A) AVO was initially used to explore and characterize gas sands

B) In the late 1990’s early 2000’s AVO methods started to be applied to geothermal exploration in faulted basement rocks

C) A more comprehensive AVO classification scheme encouraged using AVO methods for non-HC exploration

(A) Rutherford & Williams,1989 (B) Mazzotti & Zamboni, 2003 (C) Young & LoPiccolo, 2003

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**Theory: Amplitude versus Offset (AVO)**


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

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Reservoir & Velocity Structure

A) Compressional-wave velocity model
   - Low velocity zone located within the highly faulted reservoir zone

B) Shear-wave velocity model

C) Close up stacked seismic section
   - Interpreted faults in yellow
   - Pre-stack depth migrated image

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

**Left** An RMS-Amplitude section of P-P reflection amplitudes within the reservoir zone (highlighted below in yellow).
- Note that the location of the AVO-anomaly (the area between A to A') correlates to the highly fractured reservoir zone at this location.

**Below** A PSDM image of the 2-d reflection seismic line traversing the geothermal reservoir.

**Conclusions** The study at this geothermal location suggests a correlation between the RMS AVO-anomaly and the presence of highly faulted subsurface zones.
**Vp & Vs Models: Additional Information?**

(A) Poisson’s Ration derivative section using the P- & S- wave velocity models

(B) AVO-Intercept attribute section using the P- & S- wave velocity models, Garner’s equation and the Smith & Gidlow approximation

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

Joint inversion:

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

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Advanced First Arrival Picking

San Emidio Line 6 Shot Record 676

Observed
Calculated

Linear, Reservoir, Mine

Other, Ground, Rail, Mine

Viewmat Plane 44

Observed
Calculated
Residual + 0.6

Time (s)

Receiver Number (group spacing 55 feet)

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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)
Simulated Annealing Results

**Traveltime Only**

**Joint Time and Gravity**

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Restricted Offset-Range Migrations

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