Enhanced Geothermal Systems - Imaging and Characterization

Course Number: SU-02-111

PDH: 3

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Module 4: Imaging And Characterization

Learning Objectives

By the end of this section, you will be able to:

- **Identify** key subsurface characterization requirements for Enhanced Geothermal Systems (EGS), specifically relating to fracture imaging and temporal evolution.
- **Evaluate** the technical trade-offs between linear and nonlinear seismic imaging methods at varying depths and resolutions.
- **Select** appropriate drilling and tracer methodologies to quantify reservoir permeability and heat transfer efficiency.

Executive Summary: Effective EGS development requires high-resolution imaging of vertical fractures at depth, typically achieved through subsurface sensors and interferometric methods. Characterization must transition from traditional linear modeling to nonlinear elastic assessments and tracer breakthrough analysis to accurately map the complex flow networks and time-dependent evolution of the reservoir.

Ambient-Field Seismic Imaging

Subsurface characterization for EGS is distinct from traditional oil and gas exploration. While petroleum geophysics often focuses on horizontal layering, EGS requires imaging **vertical fractures** created by hydrofracturing.

Imaging Fundamentals and Constraints

Traditional reflection seismology provides the highest resolution over large distances but requires **near-normal incidence** relative to the target structures. For vertical EGS fractures, this necessitates placing sources and sensors at depth rather than on the surface.

Key Trade-offs

- **Range vs. Resolution:** High-frequency seismic (kHz-MHz) and electromagnetic (MHz-GHz) methods show a clear inverse relationship between penetration depth and feature resolution.
- **Material Sensitivity:** Electromagnetic resolution (e.g., GPR) is highly sensitive to the **dielectric constant** and moisture presence.

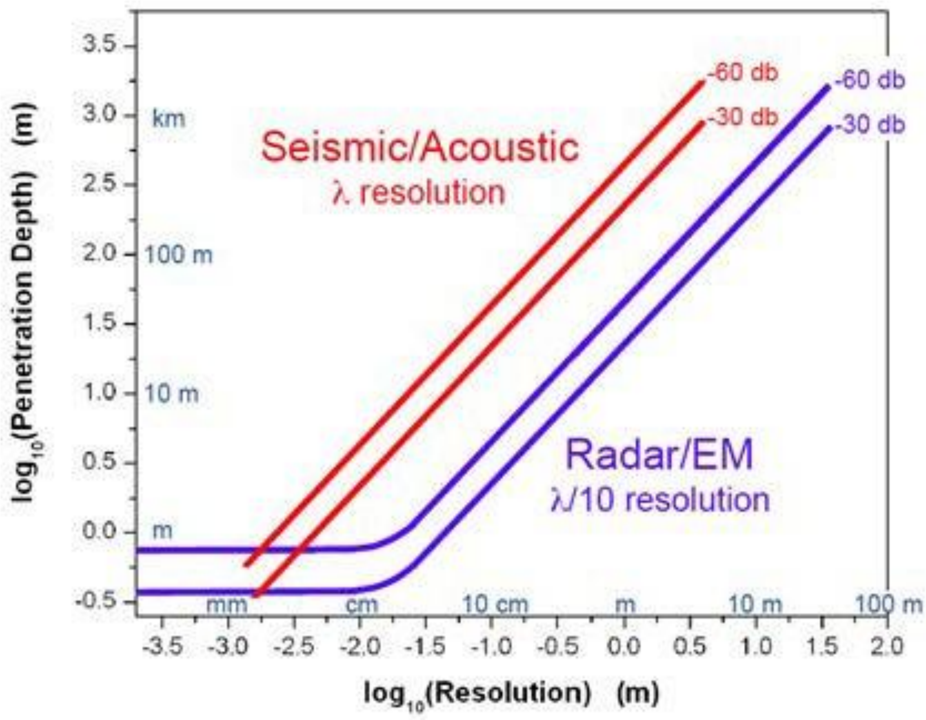

Figure 4-1: Calculated distances (penetration depth or range) over which high-frequency seismic (acoustic) and electromagnetic (Radar/EM) wave- based imaging can achieve a given resolution for return signals 3-6 orders of magnitude smaller than transmitted (-30 and -60 db). We assumelinear elasticity and absorption (compressional-wave velocity and quality factorvp = 5 km/s and Q = 100 at seismicfrequencies of 100-1500kHz; attenuation increasing from 2 to 20 m−1 at 15-1400 MHz and corresponding variations in dielectric constantfor EM), withassumed resolution criteria (λ and λ/10, with λ being wavelength) that depend on processing methods used. The plot, applicable to high-resolution seismic reflection and ground-penetrating radar (GPR) measurements, implies resolution of 1 m at distances of order 102and 101m, respectively.

Interferometric Approaches

To simplify operations, engineers can use **interferometry** to dispense with active sources at depth. This method utilizes the **ambient seismic field** (background noise) as a form of "seismic daylight" to illuminate subsurface structures.

- **Methodology:** Cross-correlate signals from distinct detectors to turn one sensor into a **virtual source**.
- **Applications:** Successful imaging has been demonstrated at the San Andreas Fault Zone using drilling noise as the energy source.
- **Advanced Characterization:** Shear-wave polarization determines fracture orientation, while cross-correlation of seismic and EM fields characterizes **subsurface permeability**.

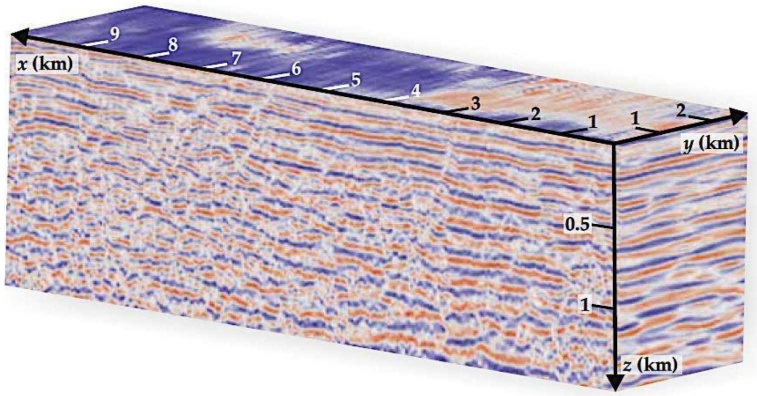

Figure 4-2: Three-dimensional reflection image of crustal structure beneath the Libyan desert based on data obtained by cross-correlating 11 hours of ambient noise measured at the surface, illuminating horizontal discontinuities in seismic velocities (rock layers) at depth (Snieder and Wapenaar, 2010, based on results of Draganov, et al., 2009) [26, 29].

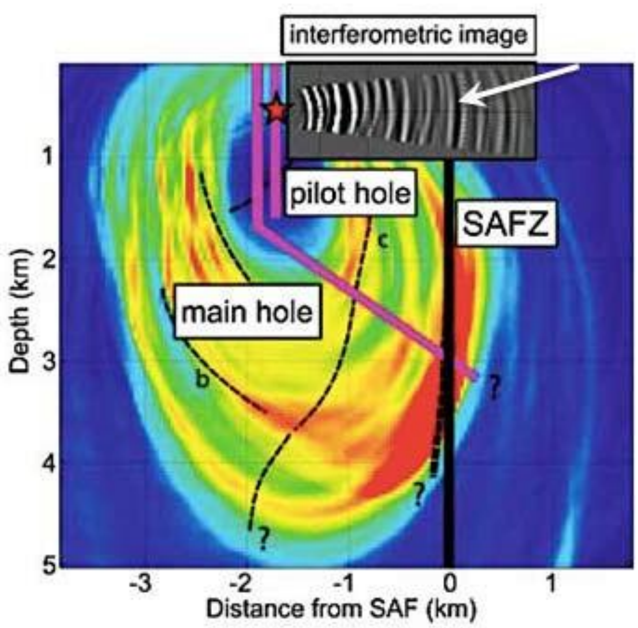

Figure 4-3: Interferometric image of the San Andreas Fault Zone (SAFZ) (inset) near Parkfield, CA, produced by recording in the pilot hole (right magenta line) drilling noise from the main hole (left magenta line), shows multiple reflections, including one due to the main SAF fault (white arrow). The target receiver used for imaging is indicated (red star), and the back- ground color image (with thin dashed lines, question marks, and "b" and "c" labels) is from independent seismic imaging (colors indicate seismic-velocity variations) [31].

Nonlinear Elastic Response

Nonlinear elasticity provides a unique advantage for EGS by detecting rock response deviations where strain is not directly proportional to applied stress.

Sensitivity to Low Effective Stress

The nonlinear response is highly sensitive to fractures when fluid pressure matches overburden stresses (**low effective stress**). This state is critical for:

- Identifying regions susceptible to stimulation.
- Quantifying stimulation success and spatial extent.
- Monitoring temporal evolution of the zone.

💡 **Design Tip:** Engineers should focus on imaging the entire **incipiently fractured zone** (meters to hundreds of meters) rather than individual crack widths (millimeters). This significantly relaxes spatial resolution requirements.

Imaging Mechanisms

Fractures open and close under externally imposed low-frequency stresses. By insonifying a region with mixed waves:

1. **Low-frequency waves** force the opening/closing of cracks.
2. **High-frequency pulses** scatter off these opening cracks.
3. **Scattered waves** at sum or difference frequencies are measured to localize fractured volumes.

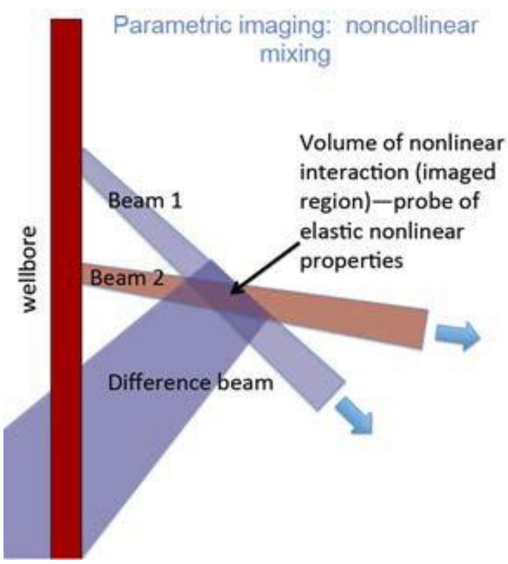

Figure 4-4: Schematic of nonlinear elastic imaging as applied to the sub- surface, using arrays of transducers in a borehole to send two beams (low- frequency forcing beam plus high-frequency probe beam) in order to insonify and image a region of interest, as revealed by the difference (and/or sum) beam that emerges from the volume of nonlinear interaction (courtesy of P. A. Johnson).

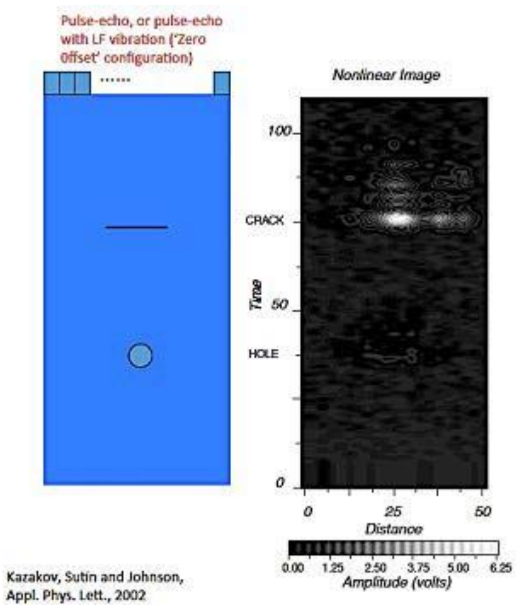

Figure 4-5: Laboratory demonstration of nonlinear elastic imaging of a crack in a steel plate that also contains a hole (after Kazakov, et al., 2002 [37]). The nonlinear image (right) shows the presence of the crack, as illustrated in the schematic (left). Because of its thin dimension, the crack is barely visible in a linear-elastic image (not shown).

Drilling Technologies

Drilling is the primary method for directly sampling rock and providing instrument access. EGS drilling leverages hydrocarbon industry advancements but faces distinct challenges in **high-temperature hard rock**.

Conventional Holes

Traditional drilling relies on friction-based shear stress to induce tensile and shear failure in the rock.

- **PDC Bits:** Polycrystalline diamond compact bits have largely replaced roller cone bits due to a 33% increase in average run lengths in hard rock.
- **Advanced Materials:** Microwave sintering and nanopolycrystalline diamond materials are under development to further increase wear resistance in deep geothermal environments.

Microholes

Defined as holes **less than 5 inches** in diameter, microholes offer several engineering advantages:

- **Cost Efficiency:** Faster drilling (100–200 ft/hr) and light casing.
- **Environmental Impact:** Minimum waste and reduced rig footprint.
- **Improved Monitoring:** Better seismic coupling of geophone arrays for tomographic mapping.