Enhanced Geothermal Systems - Imaging and Characterization

Course Number: SU-02-111

PDH: 3

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IMAGING AND CHARACTERIZATION

DOE has broad interests in characterizing the subsurface, and is therefore engaged with a variety of technologies for imaging and monitoring regions within Earth's crust (e.g., Snieder, et al., 2007) [25]. The needs of EGS are sufficiently distinct, however, that it is worth identifying promising opportunities for characterizing 1) regions being considered for future stimulation and production; 2) the spatial extent and characteristics of a stimulated volume; and 3) the spatial-temporal evolution of the region from which heat is being extracted.

Stimulation by hydrofracturing, for example, is expected to create vertical fractures because the principal normal stress is vertical at the depths being contemplated for EGS. Therefore, reflection seismology that is so heavily used in oil and gas exploration (because it typically gives the highest resolution over the greatest distances) needs to be performed at depth, in order to have near-normal incidence relative to the vertical fractures. This is in contrast to the (roughly) horizontal layering of oil and gas fields that allows data collection from Earth's (horizontal) surface for hydrocarbon exploration.

There is a tradeoff between range and resolution of features that can be imaged in the subsurface, with Figure 4-1 showing typical values for high-frequency seismic (kHz-MHz) and electromagnetic (MHz-GHz) methods. In detail, the values depend on material properties such as seismic-wave velocities and dielectric constant, the latter being especially sensitivity to the presence of moisture (a key factor in use of ground-penetrating radar, GPR). Nevertheless, resolution of meters or less generally requires imaging at distances less than tens to hundreds of meters, which implies getting sources and sensors near the region of interest.

This requirement of close-in imaging may be relaxed by turning to non-linear methods, which will be described in a subsequent section. We first describe an interferometric approach that can facilitate elastic imaging at depth.

4.1 Ambient-Field Seismic Imaging

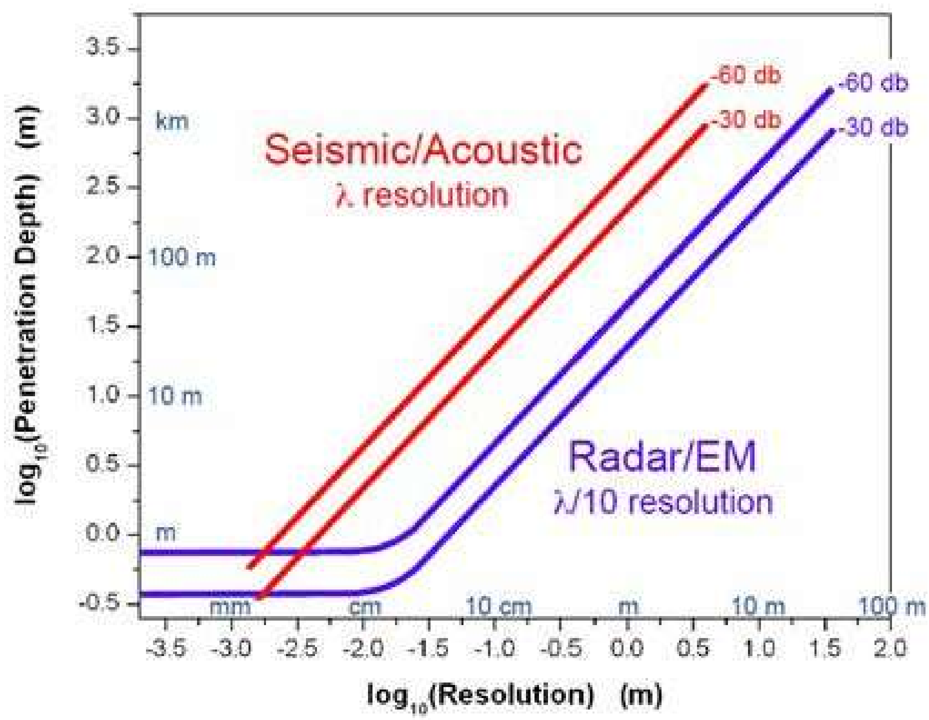

Figure 4-1: Calculated distances (penetration depth or range) over which high-frequency seismic (acoustic) and electromagnetic (Radar/EM) wave-based imaging can achieve a given resolution for return signals 3-6 orders of magnitude smaller than transmitted (-30 and -60 db). We assume linear elasticity and absorption (compressional-wave velocity and quality factor υ_p = 5 km/s and Q = 100 at seismic frequencies of 100-1500 kHz; attenuation increasing from 2 to 20 m^{-1} at 15-1400 MHz and corresponding variations in dielectric constant for EM), with assumed resolution criteria (λ and $\lambda/10$, 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 10^2 and 10^1 m, respectively.

The only means of achieving near-normal incidence for vertical fractures at depth is to emplace sources and sensors in the subsurface. This is possible through conventional drilling, and may in the future be significantly enhanced by micro-drilling approaches we describe below.

A major development in seismology is to dispense with sources – which in this case would also need to be deployed at depth (and in different locations from the sensors) – through the use of interferometry. In particular, the ambient seismic field (background seismic noise) present in the crust can be used as a form of seismic "daylight" that illuminates the subsurface (Snieder and Wapenaar, 2010; Snieder and Larose, 2010) [26, 27].

The basic idea is to cross-correlate the signals from distinct detectors, effectively turning one sensor into a virtual source with respect to the other detector(s). With an array, which could simply be a string of detectors down a borehole, one has enough detector-pair combinations to be able to reconstruct images akin to those of reflection seismology, and so make possible imaging of vertical structures in the subsurface.

Ambient-field reflection seismology has been demonstrated from the surface (Figure 4-2) (Draganov, et al., 2007, 2009) [28, 29], with an application to imaging a geothermal field summarized by Tibuleac and Eneva (2011) [30], for example. In principle, one ought to be able to similarly image vertical structures in the subsurface through ambient-field seismic-reflection imaging in boreholes. In fact, the concept has been demonstrated through imaging of the San Andreas Fault from the side, in this case with nearby drilling serving as the source of seismic energy (Figure 4-3).

Snieder and Wapenaar (2010) [26] point out that shear-wave polarization can be used to determine fracture orientations at depth, and that cross-correlation of ambient seismic and electromagnetic fields can additionally provide a basis for characterizing subsurface permeability and fluid flow through poro-elastic effects. deRidder and Biondi (2013) [32] offer a recent

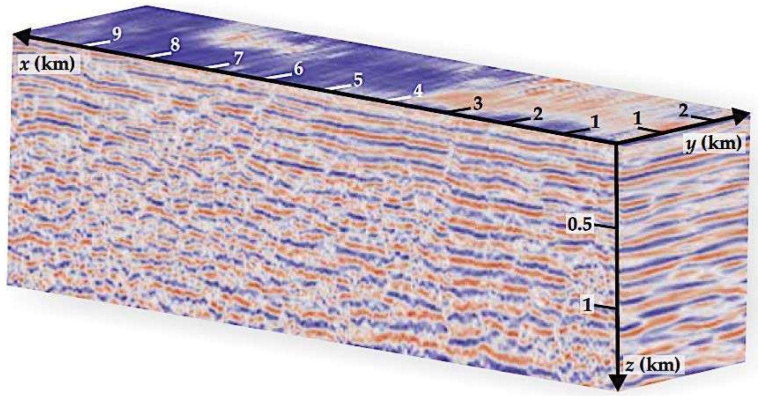

Figure 4-2: Three dimensional reflection image of crustal structure beneath the Libyan desert based on data obtained by cross-correlating 11 hours of ambient noise measured at the surface, illuminating horizontal discontinuities in seismic velocities (rock layers) at depth (Snieder and Wapenaar, 2010,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

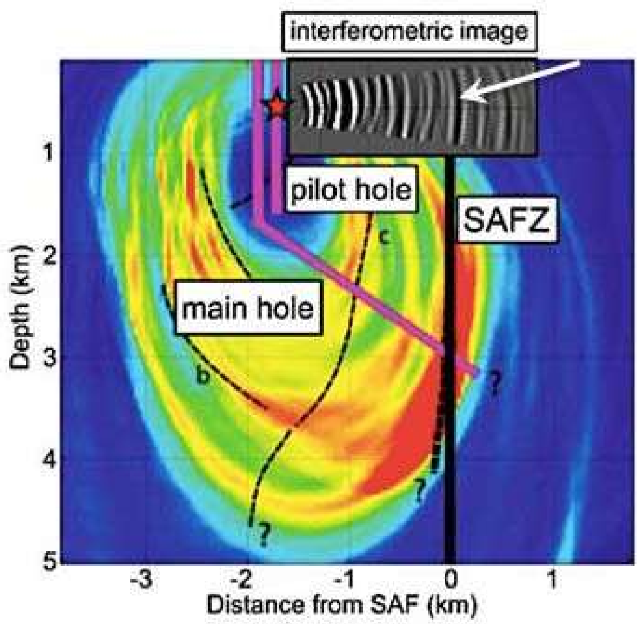

Figure 4-3: Interferometric image of the San Andreas Fault Zone (SAFZ) (*inset*) near Parkfield, CA, produced by recording in the pilot hole (*right magenta line*) drilling noise from the main hole (*left magenta line*), shows multiple reflections, including one due to the main SAF fault (*white arrow*).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

example of monitoring daily changes in an oil field at several hundred meters depth through ambient seismic noise.

4.2 Nonlinear Elastic Response

Nonlinear elasticity potentially offers unique benefits for subsurface imaging relevant to EGS. First, the nonlinear response of rock – deviations of observed strain from being directly proportional to the stress applied to a volume of rock – is highly sensitive to the presence of fractures under low effective stress (i.e., when fluid pressure inside the fractures closely matches the normal stresses due to overburden). The condition of low effective stress is of interest for i) identifying subsurface regions susceptible to stimulation for EGS; ii) quantifying the degree (success) and spatial extent of stimulation; and iii) monitoring the temporal evolution of a stimulated zone at depth.

Second, it is not individual fractures but the zone that is (incipiently) fractured that is imaged: that is, dimensions of meters to perhaps hundreds of meters instead of crack widths of millimeters to meters. Therefore, the need for spatial resolution is far less demanding than required for the usual linear-elastic imaging of structures (Figure 4-1).

The basic idea is that fractures can be opened and closed by externally imposed stresses, assuming a condition of low effective stress. The elastic response of a fractured volume differs greatly (non-linearly), depending on whether the cracks are in the process of opening up or are clamped shut (e.g., shear waves with polarization in the plane of the cracks being scattered or not, respectively). Therefore, regions of a rock insonified with a mix of, say, low-frequency waves (that open and close fractures, where present) and high-frequency pulses (that scatter off opening cracks) can in principle be used to reveal the presence of fractured zones (Figure 4-4).

Imaging depends on matching the timing, at each location in the rock volume, between high-frequency (probe) waves being present at a fracture