Landtech Geophysics

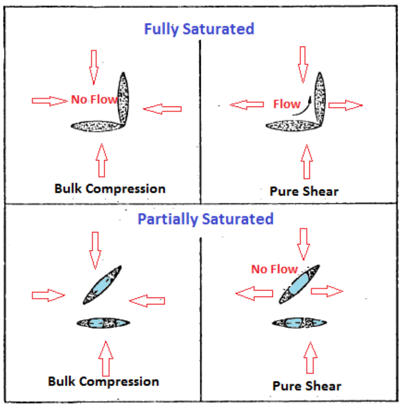
Three dimensional images of geothermal systems using Passive Seismic Tomography

Geothermal microearthquakes, and the seismic waves they generate, provide a rich source of information about physical processes associated with Enhanced Geothermal Systems (EGS) experiments and other geothermal operations. Seismically active geothermal areas are well-suited to local-earthquake tomography because earthquakes are often well-distributed throughout the reservoir and production zone. LandTech-Geophysics has studied several geothermal fields, including both unexploited and heavily exploited reservoirs, using V_p, V_s and V_p/V_s tomography. Experience has shown that V_p/V_s is particularly useful in imaging exploited fluid zones. A low V_p/V_s ratio is thought to be caused by abundance of fractures filled with hot water. In fact, the mechanism of water steam transition has a stronger effect on compressibility than shear modulus, leading to low V_p/V_s ratios. The relationship between low V_p/V_s ratios and geothermal areas is so sound that the study of the V_p/V_s ratio is a promising technique to identify geothermal resources and monitor their exploitation. Contrarily, melt inclusions reduce S-wave velocity more than P-wave velocity, resulting in high V_p/V_s ratios.Also, progressive depletion of reservoirs can be monitored by tomography repeated every few months. Also, accurate microearthquake locations can potentially delineate faults that represent valuable zones of permeability and desirable targets for new production wells.

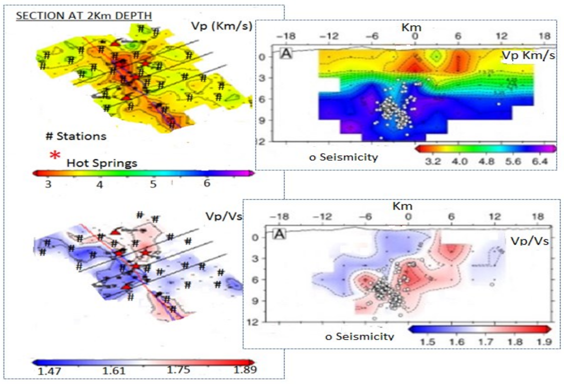
In general the application of a PST survey in a geothermal region can lead to the following results:

- Tomography from wave propagation can image reservoir for seismic velocity and attenuation, geologic structure, and lithology
- Accurate plotting of microseisms can delineate fracture zones
- Interpretation of tomography results (rock physics) can identify altered or permeable zones, phase states of fluids, crack density, and saturation
- Improve resolution for drilling targets
- Improve success estimates for drilling targets – Monte Carlo Coupled inversion
- Monitor existing wells and production
- Variations in lithology observed in elastic constants
- Increase of velocity and decrease in attenuation with depth due to closing of small cracks because of pressure
- Decrease in velocity and increase in attenuation due to fracturing
- Decrease in velocity due to chemical alteration
- Extreme temperature gradient works to decrease velocity with depth
- Fluid saturation acts to stiffen the pores to deformation; affects P-waves, but not shear-waves
- Saturation increases the density of the material and increases both compressional- and shear-wave velocity, and increases attenuation
- Dilatency can cause expansion and permeability

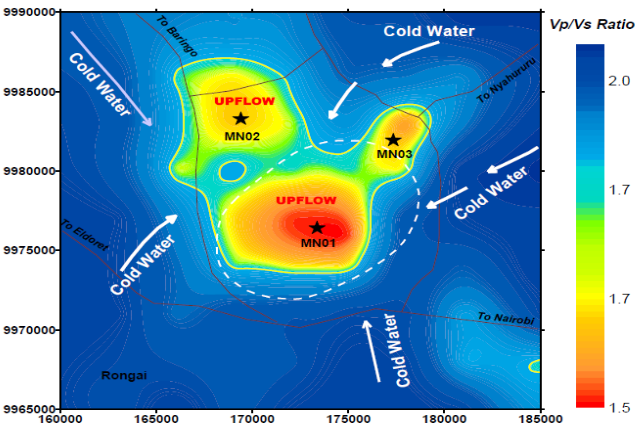
In addition to determination of velocity and Vp/Vs volumes LandTech has developed the technology to obtain 3D volumes of seismic attenuation (or alternatively the Q_p quality factor). Increasing pressure closes pores and decreases attenuation. Seismic attenuation is again very low in dry rocks whereas in partially saturated rocks (Sw =: 95%) attenuation is significant probably due to intracrack fluid flow, with P attenuation about twice as large as S. In fully saturated rock, intercrack flow is eliminated, Q_p is sharply lowered and again shear attenuation due to intercrack fluid flow is maximized. The following figure illustrates schematically how the change from partial to full saturation changes the types of pore fluid flow induced by passing strain waves which may occur within rocks and hence changes the relative amounts of attenuation in compression and shear.



In fully saturated rocks first order intercrack flow may occur only in shear, not in compression. Since the P wave is strongly affected by bulk compression it is less attenuated than an S wave. In partially saturated rock flow will occur within all pores, induced by bulk compression; whereas shear induces flow only in properly oriented pores. Consequently S attenuation is less than P. In rocks containing no liquid phase, no flow occurs and attenuation is low for all waves. Hence, the ratio of P to S attenuation may allow us to distinguish between a partially saturated and dry or fully saturated rocks.



In the figure to the left, it is evident how a PST survey delineated a geothermal field and pinpointed new drilling sites. Clearly a combination of V_P and V_p/V_s sections revealed regions of geothermal interest. Variation of V_p/V_s ratios is related to reservoir fluid phases where low values are related to a decrease in P-wave velocity in the area with low pore pressure, high heat flow, fracturing and steam/gas saturation in the reservoir. In general, high velocity ratios were found in the relatively liquid-saturated high pressure fields that these ratios are useful tools for monitoring reservoirs under exploitation.



In the figure to the left, we present another example on how a PST survey revealed clearly the mechanisms controlling a geothermal field in Kenya. We observe a strong V_p/V_s anomaly that corresponds to the most highly intruded part of the field. This anomaly indicates low pressure and dry conditions caused by boiling of pore water due to limited fluid inflow. The low values correspond to a decrease in P-wave velocity due to high heat flow, fracturing of rocks and steam saturation. The geothermal reservoir area that is based on the 1.71 V_p/V_s ratio is about 80Km2 and the main productive zone would be in the depth range of 1200-2500m. Based on these, three possible drilling sites (stars) are proposed.

Landtech Geophysics Ltd Ty Menter Navigation Park, Abercynon CF45 4SN United Kingdom.
Tel: +44 (0)2921 660272, Fax: +44 (0)8707 303 051, E-mail: info@landtechsa.com