A new fractured-rock flow model and exploration technique for geothermal systems

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Abstract
Both natural and engineered geothermal systems are conceptually simple but face complex geological conditions and risks in field realization. The chief difficulties appear to be:
• The high cost of drilling.
• Large uncertainties in predicting in situ fluids flow.

Per-well drilling-costs are likely to continue to remain high. But progress can be made through finding ways for targeting and/or stimulating of what is termed here as '*in situ*' sites of high fluid permeability. The main issue here appears to be our understanding of how flow takes place in fracture dominated rock. We believe that the key factors in improving this understanding are to recognize and deal with:
• The physical origin of *in situ* flow uncertainty.
• That *in situ* flow admits no averaging solution.
• That *in situ* flow uncertainty can be modeled.
• Such models can be obtained from well-logs and cores.
• Sub-horizontal drilling technology will be needed high volume flows.

We discuss this sequence of points in the context of geothermal projects for both: (a) single wells in natural systems and (b) pairs of wells for fluid circulation in engineered ones. We will show that control of rock porosity φ and permeability κ by native fractures can be characterized by two spatial relations. We will then discuss how these relations can be used for both exploring for, and enhancing as needed, such fractures using seismic, electromagnetic, and advanced stimulation techniques.

At cm-scales, fluctuations in well-core porosity φ and permeability κ appear to be related by $\delta\varphi \sim \delta\log(\kappa)$, δ denoting spatial variation on the order of cm to m. At hundred-meter scales, variations in seismic velocity v and electromagnetic resistivity ρ appear related by $\Delta v \sim \Delta\log(\rho)$, Δ denoting spatial variations on the order of 10s to 100s of m. We suggest that small-scale well-core porosity φ and large-scale bulk seismic-velocity v are responding to spatial variations in fracture density at their respective scale lengths. (They are part of the same self-similar process.) We likewise propose that small-scale well-core permeability κ and large-scale bulk electrical-resistivity ρ are responding to variations in flow paths at their respective scales.

These two relations suggest that seismic and electromagnetic field data can be interpreted using joint inversion methods to find areas with high concentrations of native fractures. We illustrate this approach by case studies of Krafla, Iceland, and Olkaria Domes, Kenya, seismic shear-wave and magnetotelluric data that indicate the existence of stress-aligned-fractures at depth. These fractures induce shear-wave and resistivity anisotropy, which can be targeted for drilling high-productivity region of the geothermal area.

Keywords: Porosity-permeability and seismic velocity-resistivity relationship, inversion methods, drilling targeting, fractured rocks, enhanced production, geophysical methods, geothermal exploration.

Nuevo modelo de flujo en rocas fracturadas y nueva técnica de exploración de sistemas geotérmicos

Resumen

Tanto los sistemas geotérmicos naturales como los artificialmente mejorados son conceptualmente simples pero presentan condiciones geológicas complejas y riesgos en su desarrollo. Las principales dificultades parecen ser:

- El elevado costo de la perforación.
- Las grandes incertidumbres a la hora de predecir el flujo de los fluidos in situ.

Los costos de perforación probablemente permanecerán altos. Pero se puede mejorar encontrando maneras de ubicar y/o estimular los que aquí se denominan como lugares '*in situ*' de elevada permeabilidad del fluido. El principal problema se vuelve comprender cómo ocurre el flujo en rocas predominantemente fracturadas. Creemos que los factores clave para mejorar esa comprensión son reconocer y tratar con:

- El origen físico de la incertidumbre del flujo *in situ.*
- Que el flujo *in situ* no admite soluciones promedio.
- Que se puede modelar la incertidumbre del flujo *in situ*.
- Que tales modelos pueden obtenerse de registros de pozos y núcleos.
- Que flujos de gran volumen requerirán tecnologías de perforación sub-horizontal.

Discutimos esta secuencia de puntos en el contexto de proyectos geotérmicos para ambos tipos de pozos: (a) pozos individuales en sistemas naturales y (b) pares de pozos para circulación de fluidos en sistemas mejorados. Mostraremos que se puede caracterizar a la porosidad φ y la permeabilidad κ controladas por fracturas nativas mediante dos relaciones espaciales. Discutiremos después cómo se pueden utilizar estas relaciones tanto para explorar como para mejorar, según se requiera, tales fracturas, mediante técnicas sísmicas, electromagnéticas, y de estimulación avanzada.

A escalas de centímetros, las fluctuaciones en la porosidad φ y la permeabilidad κ de muestras de núcleo de pozos parecen estar vinculadas por la relación: $\delta\varphi \sim \delta\log(\kappa)$, siendo δ la variación espacial de orden de centímetros a metros. A escalas de cientos de metros, las variaciones en la velocidad sísmica v y la resistividad electromagnética ρ parecen estar relacionadas por: $\Delta v \sim \Delta\log(\rho)$, en la que Δ denota variaciones espaciales del orden de decenas a centenas de metros. Sugerimos que la porosidad φ a pequeña escala en muestras de núcleo y la velocidad sísmica absoluta v a gran escala, responden a variaciones espaciales en la densidad de fracturas, a sus respectivas escalas. (Son parte del mismo proceso auto-similar.) Asimismo, proponemos que la permeabilidad κ de muestras de núcleo a pequeña escala y la resistividad absoluta ρ a gran escala, responden a variaciones en las trayectorias de flujo también a sus respectivas escalas.

Estas dos relaciones sugieren que los datos sísmicos y electromagnéticos de campo pueden ser interpretados utilizando métodos inversos comunes para encontrar zonas con alta concentración de fracturas nativas. Ilustramos este enfoque con casos prácticos en Krafla, Islandia, y en los Domos de Olkaria, Kenia, con datos de ondas sísmicas de cizalla (*shear-waves*) y magnetotelúricos que indican la existencia de fracturas de esfuerzo alineadas en profundidad. Estas fracturas provocan anisotropías o anomalías en el comportamiento de las ondas sísmicas y de la resistividad, que se pueden utilizar para definir objetivos de alta productividad en la perforación de una zona geotérmica.

Palabras clave: Relaciones porosidad-permeabilidad y velocidad sísmica-resistividad, métodos de inversión, objetivos de perforación, rocas fracturadas, producción mejorada, métodos geofísicos, exploración geotérmica.

Introduction

Finding *in situ* permeability has been a critical issue in achieving sufficient steam flow for economic geothermal power generation. This applies to both natural and engineered geothermal developments – in the latter case the in-place permeability is increased by stimulation procedures such as "fracking". For example, several decades of Engineered Geothermal System (EGS) projects in the US, UK, EU, and Australia have not succeeded in developing the technology needed to allow commercially viable steam flow rates (Tester *et al.* 2006). Goldstein *et al.* (2011) cite failure to achieve adequate *in situ* flow as, along with the high cost of drilling, the major impediment to expanding commercial geothermal production.

We suggest the reason for this barrier lays in the physical characteristics of fracture rock as revealed by, for example, borehole-base property measurements. Well-log and well-core data indicate that fluid flow is spatially far more heterogeneous at all scales than is generally taken into account in geothermal exploration and development (e.g. Leary & Al-Kindy, 2002; Leary & Walter, 2008). The prevailing assumption for permeability is that the rockmass and its fractures are quasi-homogeneous in some technically meaningful way (e.g., Gringarten *et al.*, 1975). The resulting view of standard geothermal flow modelling thus assumes:

a. rock is a continuum cut by random distributions of fractures that may or may not connect;
b. fractures are open planar surfaces of permitting laminar flow in 'effective' apertures;
c. low, non-economic, permeability can be improved by high pressure "fracking,"

In more advanced models, fracture reservoir rock is given dual permeabilities, in which the fractures are given a secondary permeability superposed on continuum or matrix permeability (e.g., Sanyal & Butler, 2005). These continuum approaches to permeability corresponds to hydrocarbon industry practice (Sayers & Schutjens, 2007; Sayers, 2007). However, with oil at ~50¢/L and hot water at ~0.5¢/L, geothermal wells must flow at 10 to 100 times the rate of oil wells to be economic. While the hydrocarbon industry is able to afford the cost of ignoring *in situ* flow spatial complexity, the geothermal industry cannot.

A new fractured-rock flow model

The well log and drill core data in Fig. 1 and 2 illustrate two important features of fractured reservoir rock. Fig. 1 shows the manner in which properties like the seismic velocity, gamma radiation, density, and chemical content vary with distance along a wellbore. Only in this case the well log data are displayed in terms of the strength of their variation versus the distance between peak values. The number scale on the horizontal axis is the number of peaks per km. (e.g. 10 represents 100 peaks per km, or peaks 10 m apart.) This figure is known as the wave number of the variation. The vertical axis is the strength of the property variation at the wave number indicated. This type of plot is known as the Fourier power spectrum of the well log measurements.

As shown by each of the logged properties, the strength of the property variations falls off with decreasing distance between peaks. The more peaks per distance, the weaker the increases and

decreases in property. This is easily understood in the case of fractured rock: the big, widely spaced, fractures are the most important carriers of, for example, geochemical fluids, changes in velocity, and reductions in density. This type of behaviour is common in many physical systems and is known as a "power law" distribution of properties.

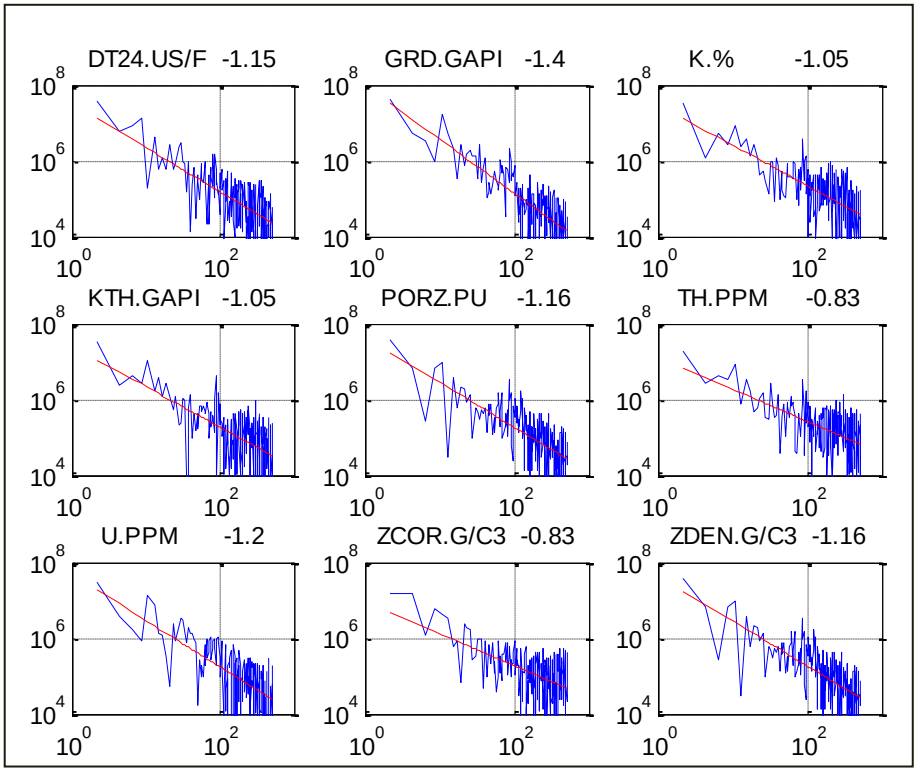


Fig. 1. Well-log power-spectra. The well interval was 475 m long. The spatial frequency is cycles/km; the slope of the red line is on the upper right of each plot and has a mean of 1.1 ±0.2.

The quantitative expression of the relationship between the frequency of peaks and their strength can be expressed as:

$$S(k) \propto 1/k^{\beta},\ \beta \approx 1. \qquad (1)$$

This power-law form is remarkable in 3 ways:

1. It is power-law over scales of greater than 1 per 100 m and less than 1 per 1 m
2. It is the same for every fracture related property, and is weakly influenced by geology
3. It has a specific power-law exponent, $\beta \approx 1$, i.e. different from values associated layers

Porosity and permeability due to fractures are directly evident in the spatial fluctuation properties of well-core measurements. As shown in Fig. 2 fracture porosity is directly related to permeability, with the difference being in their relative magnitudes –changes in permeability varying by orders of magnitude over changes porosity. These can be brought on to the same scale using either logarithms or exponentials:

$$\delta\varphi \approx \delta\log(\kappa) \quad \text{or} \quad \delta\kappa \approx 10^{\delta\varphi} \qquad (2)$$

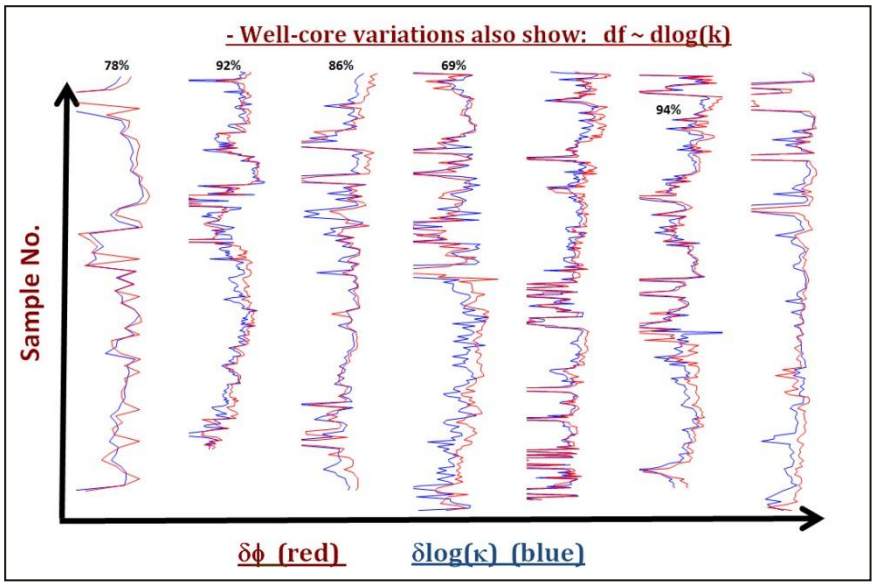


Figure 2. Overlays of well-core porosity (red) and log (permeability) (blue) for different well-cores. The cross-correlation coefficient is given above each overlay; mean coefficient is $\gamma \approx 86 \pm 8$ %.

This expression between variations in porosity and permeability basically establishes that permeability is governed by connectivity between fracture-related porosity. This equivalence could be anticipated from the well-log spectral evidence since it shows that fractured rock properties follow the same distributions.

Exploration techniques for fractured-rock models

The two relations suggest that geophysical techniques sensitive to such characteristics as subsurface fracture porosity might be used to find areas with high permeability. From this it follows that a combination of seismic and electrical methods that focus on the effects of fractures are likely to be most useful for this purpose. Data collection for this type of approach is illustrated in Fig. 3.

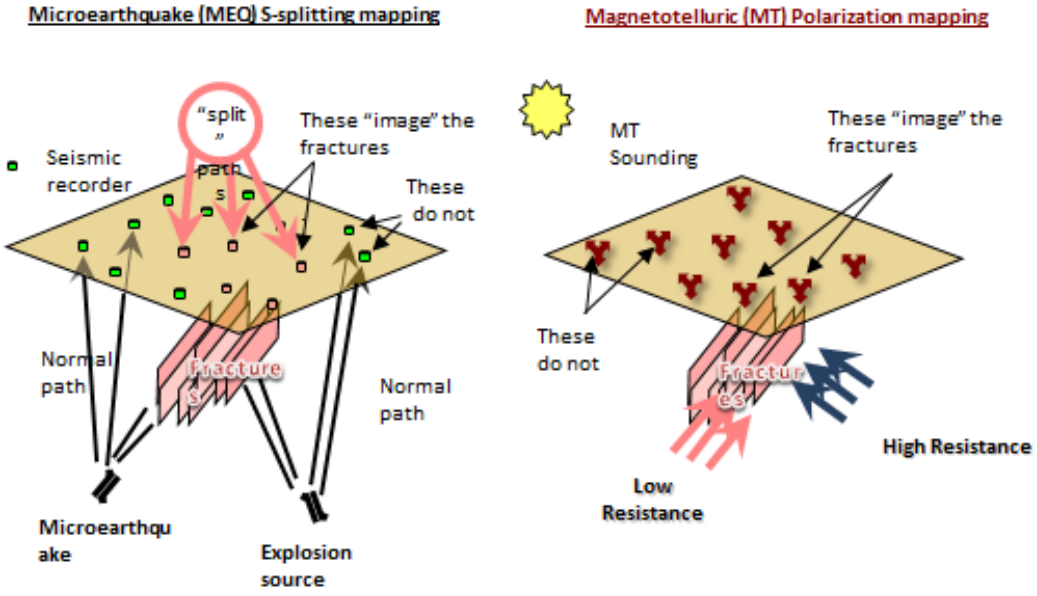


Fig. 3. Schematic diagram of seismic and electro-magnetic exploration techniques for fractures.

Geophysical exploration routinely includes both electromagnetic and seismic survey data, the interpretation of which is usually done separately and then combined in some ad hoc way. Instead, because these data share geological constraints, combining them in some systematic, quantitative way is preferable. Aside from the shared geological background, a "joint" analysis can also dampen large errors and noise in one data set by less sensitive responses in the other. Here we describe both the idea

of Joint Geophysical Imaging in this context and its application to mapping "poroperm" heterogeneity in fractured reservoirs –the latter meaning the system of fluid-filled cracks that produce correlated splitting S-waves and polarization of electrical resistances.

Porosity and permeability play separate roles in determining the relationships between seismic velocities and electrical conductivities. A discussion of well-core cm-scale porosity-permeability ('poroperm') fluctuation relation $\delta\varphi \sim \delta\log(\kappa)$ by Leary & Malin (2009) shows that seismic velocities are more sensitive to rock porosities, while electrical conductivities are more sensitive to rocks with different fracture-associated permeability. In this case, the combination of seismic and electrical data helps locate high concentrations in these "poroperm" fractures.

Shear wave splitting is routinely used to detect fracture orientation since in aligned sets S-wave motions propagate faster parallel to their long dimension. S-waves thus split into fast and slow components. However shear wave splitting can also be caused by other geological phenomena such as 2-D layering. MT polarization can also be the result of preferred fracture orientation, as well as 3-D structural effects. The latter effects are notably different from those effecting S-waves. As a result, detecting similar orientation in shear wave splitting and MT polarization makes it clear that the cause is aligned fractures.

Our Krafla geophysical survey data show how such different measurements can be combined through joint quantitative analysis, using for example, weighted averages of simple linear and more advanced inversion schemes. The weights in these cases are taken to be the "error" estimates of the data used in the separate inversions. In some cases the examples have been subject to ground-truth through drilling and other methods, with noted improvement in the predictive capacities of the combined images.

Integrating Krafla, Iceland, reservoir geophysical data into a poroperm depth section

Fig. 4a shows a view of Krafla geothermal reservoir field microseismicity with seismic recording stations shown in red. The MT stations are distributed over the same area. Fig. 4b reviews the seismic velocity tomographic inversion of the Krafla field velocity structure. Fig. 4c shows a similar diagonal Krafla depth section expressed this time in electrical resistivity.

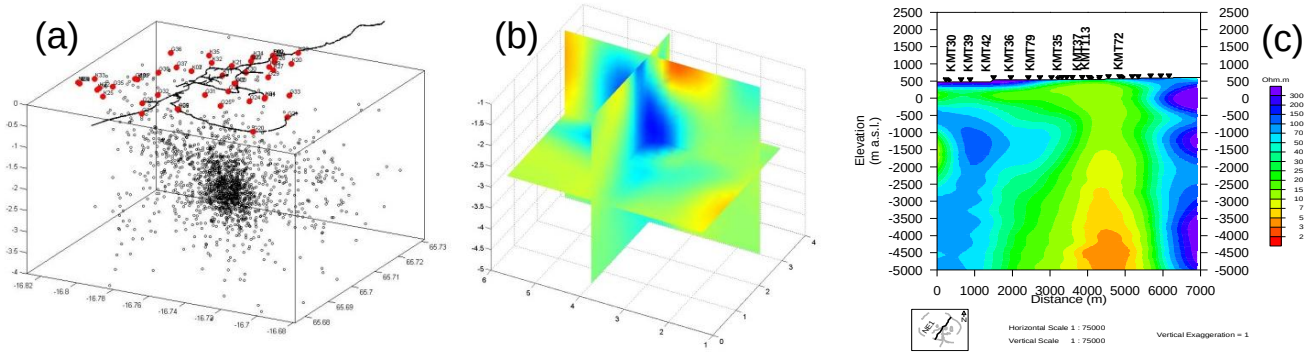


Fig. 4. (a) Krafla seismic net and events; (b) North and West P velocity cross sections; (c) NE resistivity cross section.

Fig. 5 illustrates the JGI interpretation of Fig. 4b and 4c applying at reservoir scale the fracture-based poroperm relations. Assuming that seismic velocity travel times are related to porosity parameter β_τ,

and that electrical resistivity fluctuations are related to resistivity parameter $þ_\rho$, and that these parameters follow the well-core relationship $\delta þ_\tau \sim \delta\log(þ_\rho)$, we form the weighted mean

$$þ = (þ_\tau/\sigma_\tau + \log(þ_\rho/\sigma_\rho))/(1/\sigma_\tau + \log(1/\sigma_\rho))$$

with σ_τ= P-wave tomography error and σ_ρ = MT resistivity error. Using this weighted mean, the upper two panels of Fig. 5 are processed into the lower panel of Fig. 5 as the GJI poroperm reduction of seismic velocity and electrical resistivity data at Krafla.

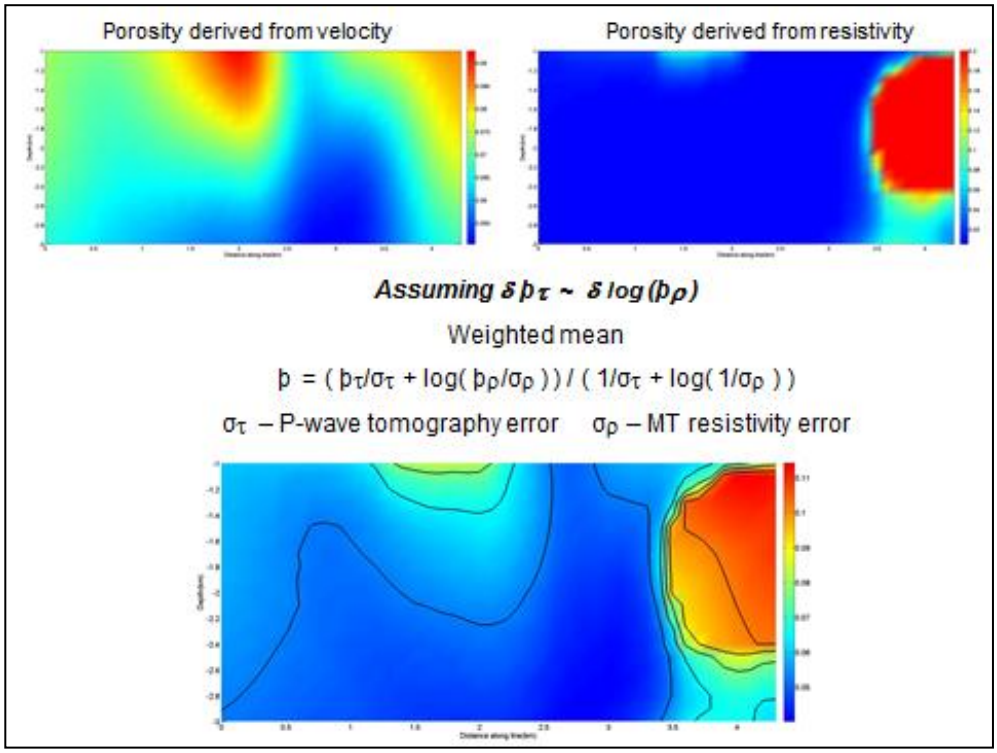


Fig. 5. A Joint Geophysical Image combining seismic velocity and resistivity for well targeting.

Figures 6a&b show Krafla geophysical data that can be interpreted in terms of stress-induced anisotropy due to aligned microfractures –just as illustrated in Fig. 3. The directional difference in the MT apparent resistivity curves indicates that the ability of the ground to conduct current varies with direction at different depths. The red and blue apparent resistivity curves of Fig. 6a are processed to maximise their difference as a function of the effective electrical current orientation. The effective electrical current sensor orientations that record the maximum different in MT response are shown in Figure 6b. The inferred fracture orientation depends on location and can be seen to trend NE in one area and SE in another.

Summary of fracture geophysics at Krafla

- Deep fractures influence both seismic velocity and electromagnetic resistivity;
- Orientation of S-wave splitting and MT electrical current polarisation data indicate that the same fracture set controls porosity-sensitive seismic velocity and permeability-sensitive electrical conductivity;
- Joint-inversion of macro-scale heterogeneity in seismic velocity v and electrical resistivity ρ is compatible with a long wavelength relation $\delta v \sim \delta\log(\rho)$ between porosity-sensitive velocity

and permeability-sensitive permeability; a similar relation $\delta\varphi \sim \delta\log(\kappa)$ sensitive to cm-scale porosity φ and cm-scale permeability κ;

- The joint correspondences in porosity-sensitive and permeability-sensitive geophysical data imply that fractures operate over a large range of scale lengths to control reservoir flow heterogeneity at the Krafla geothermal field.

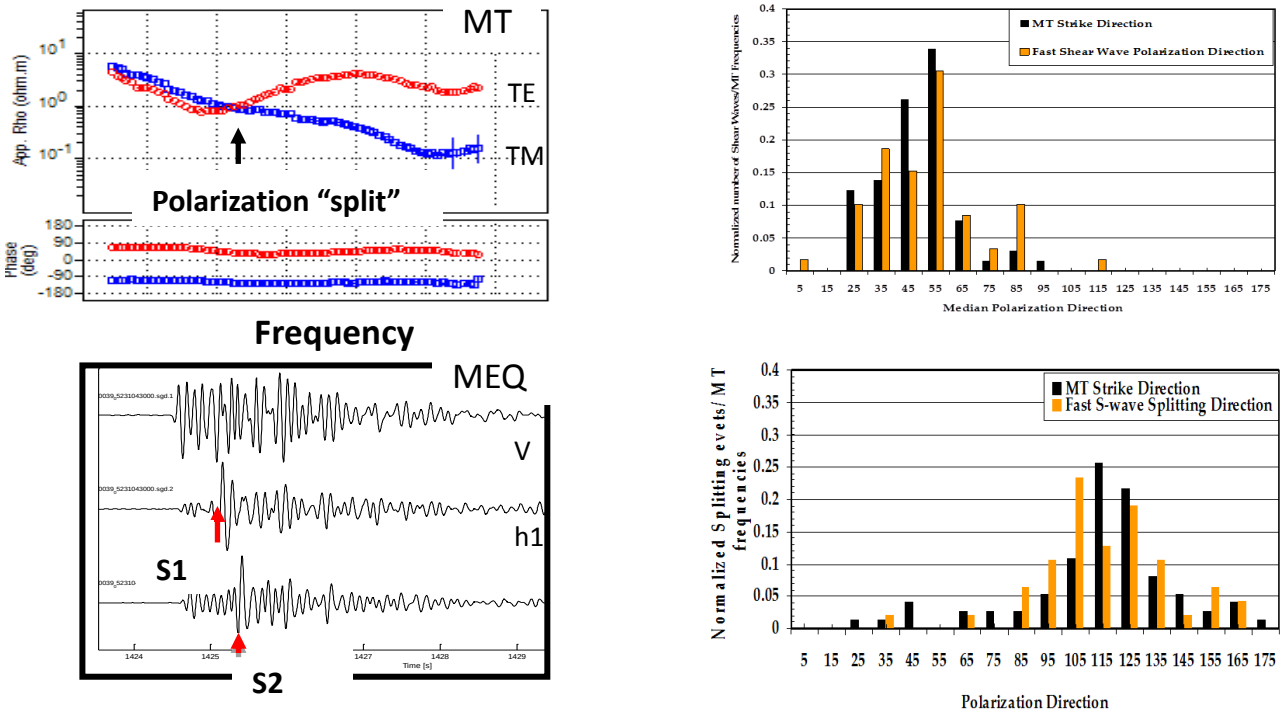


Fig. 6 *(a) MT splitting & MEQ splitting data due to subsurface fractures. (b) Alignment of MT & MEQ splitting. In the top diagram the fractures appear to control both MT and S-wave splitting in the NE direction, while the bottom one is in the SE direction.*

Summary and Conclusions

We argue:

- well-log and well-core systematics show that fracture systems are important conduits for geofluid flow on all scales in all rock, with particular reference to aquifer rock currently targeted for heat extraction;
- power-law scaling well-log spectra indicate that small-scale rock samples fundamentally do not represent the range of rock property fluctuations likely to occur at large scale lengths;
- in absence of utility from small-scale sampling of rock properties, and in light of essentially unlimited fluctuations in rock properties on large scales, it is logical to consider large scale sampling of rock formations for information on *in situ* permeability;
- large scale measurements of fracture distributions are particularly relevant where geofluid flow rates are essential to drill hole success;
- in geothermal fields, where fractures are almost universally acknowledged to control geofluid flow, MT resistivity profiles and MEQ data indicate that geofluid flow is greatest where known fracture/fault trends intersect; enhanced production well flow has validated MT data as a geophysical guide to well siting.

We conclude from these arguments that MT and MEQ surveys of potentially exploitable hot aquifers are a plausible investment in advance of costly drilling.

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