Geophysical methods for EGS investigation: an overview of actual and future perspectives

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and in particular Enhanced Geothermal Systems

Content

Geophysics for detecting and imaging:

- overall geological features 
- subsurface temperature 
- fluid pathways 
- stress field 

What is next? 

Geophysics for overall geological features

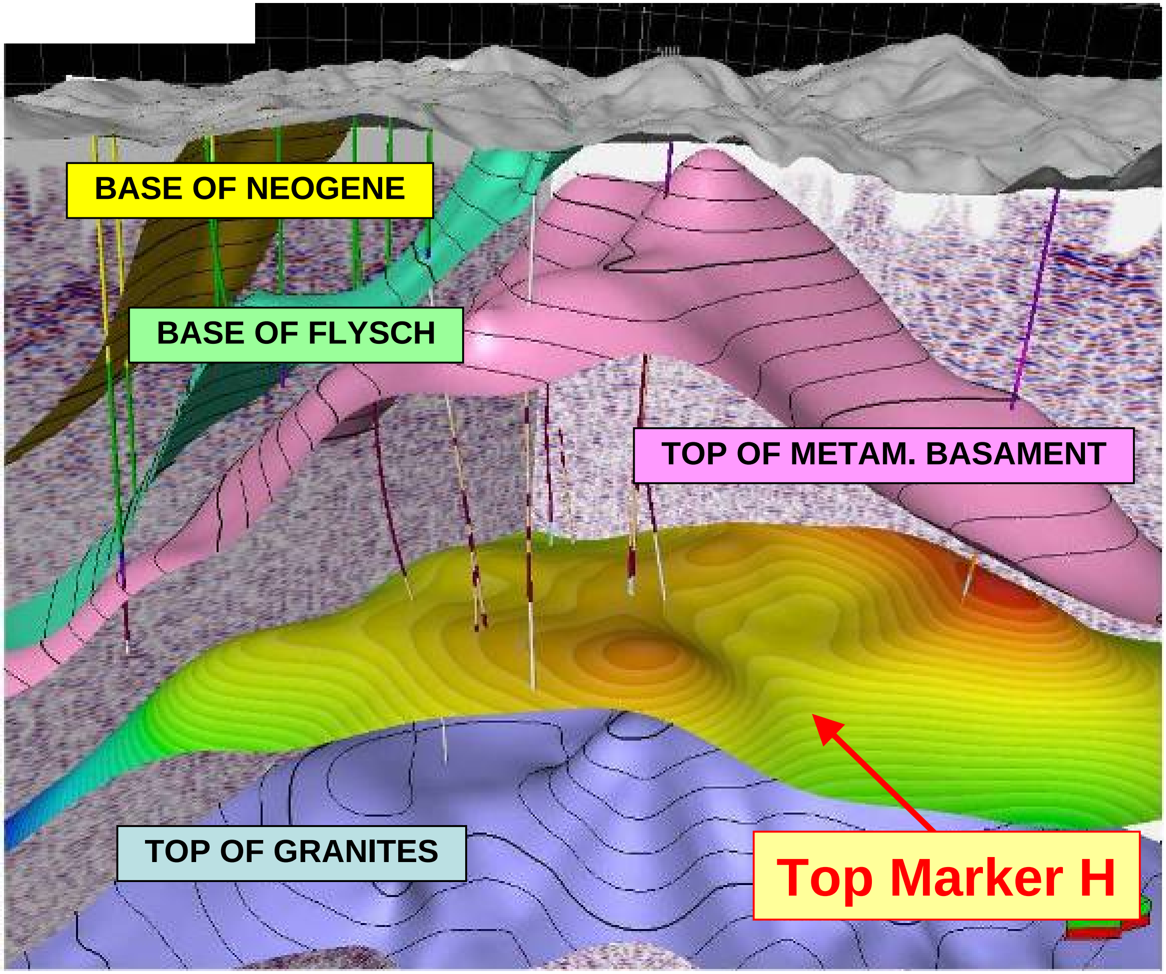
The best suited method in sedimentary and crystalline geological scenarios to extrapolate borehole information and to define and image the geological structure is the active seismic.

Nowadays 3D seismic surveys are becoming standard in oil and mining industry, but are still far from being a must in geothermal exploration. However, due to the intrinsic complex 3D structure of geothermal areas, a successful 3D survey is the best way to retrieve a high resolution image of the subsurface geometry.

2D or 3D seismic must be calibrated by a comprehensive set of geophysical well logging data and petrophysical data.

Expensive → IGET Project → Cost reduction

Geophysics for overall geological features

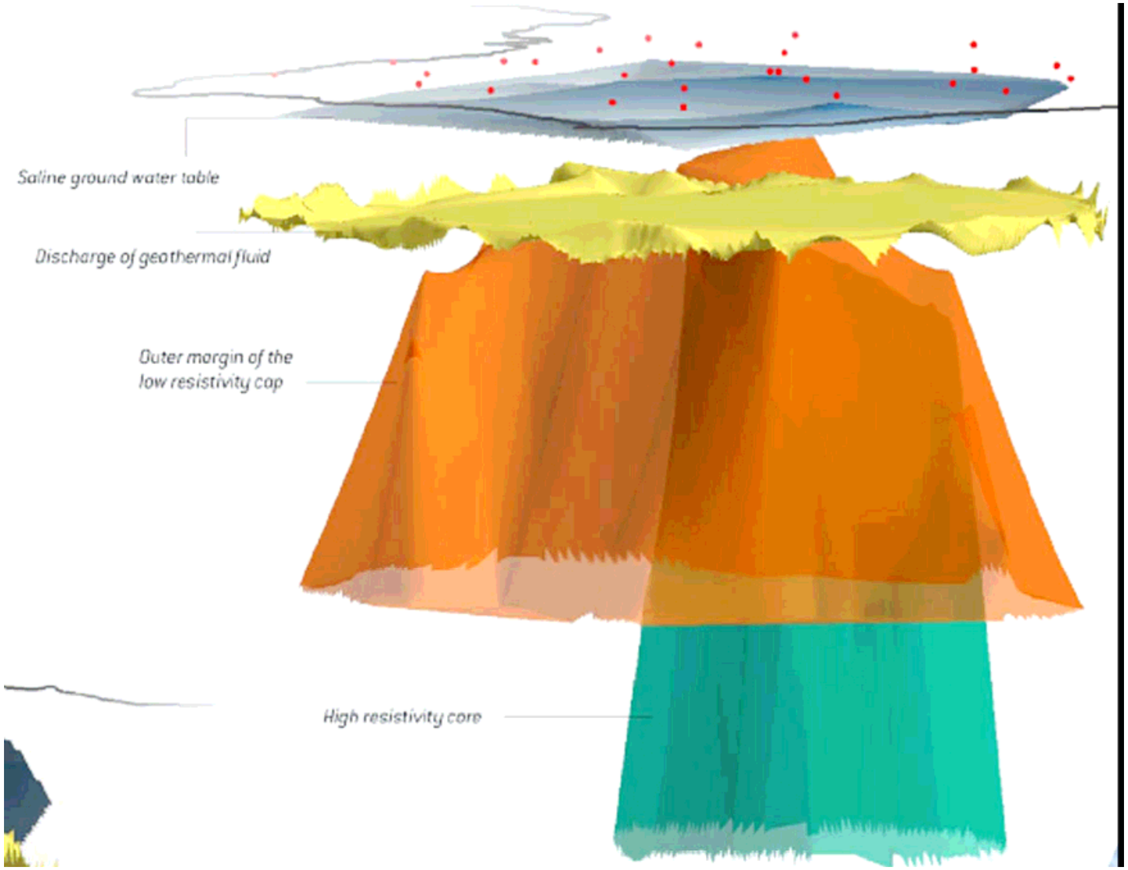


From ENEL, WS1

- 3D Seismic data
- Geological well data
- Geophysical well data

STRUCTURAL INTERPRETATION

In volcanic rocks TDEM and MT have defined the main structure, driven mainly by alteration minerals



From Karlsdottir, WS1

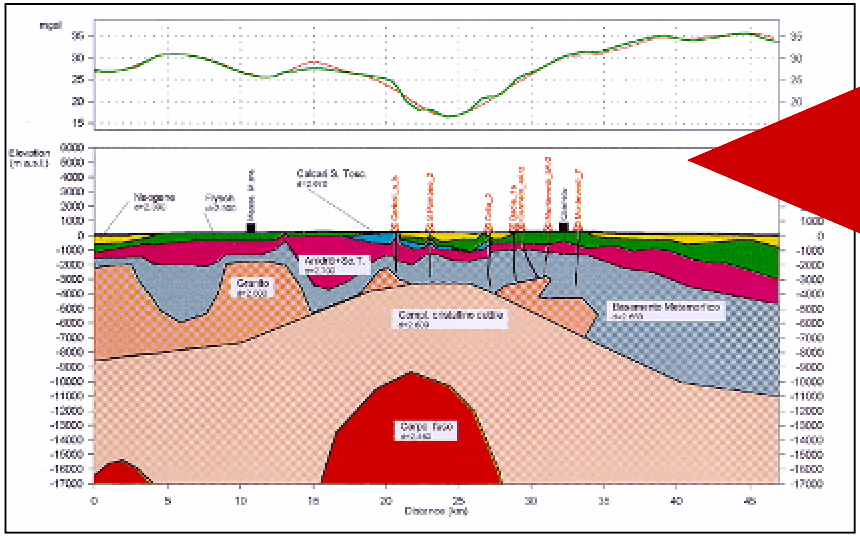
Geophysics for overall geological features

Partially molten intrusives, representing the heat source in most of geothermal fields, at depths as shallow as 10 to 20 km produce thermally excited rocks which define high regional heat flow

Demagnetised rocks confirm the existence of a hot rock mass in the crust

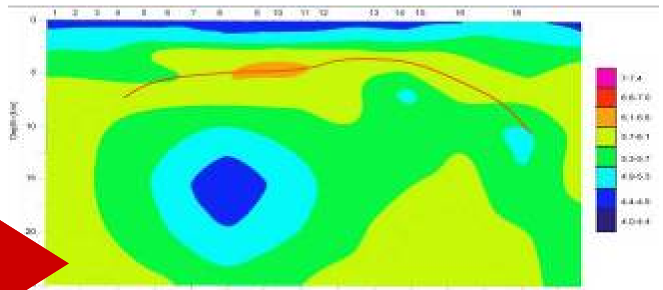
Anomalously hot mass of rock delay the transit of the compressional (p) waves from earthquakes and reduce the amplitude of the shear (s) waves

Geophysics for overall geological features

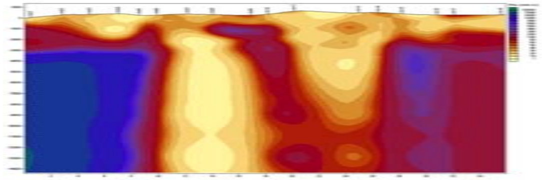


2/3D Modeling, properly balanced with experimental density data, pointed out deep low density bodies to be related to molten intrusions

From ENEL, WS1

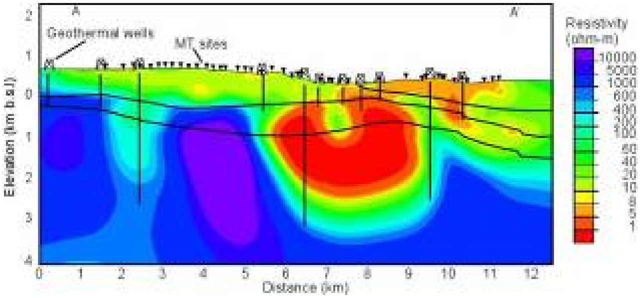


Low velocity bodies defined by teleseismic tomography and corresponding low resistivity bodies

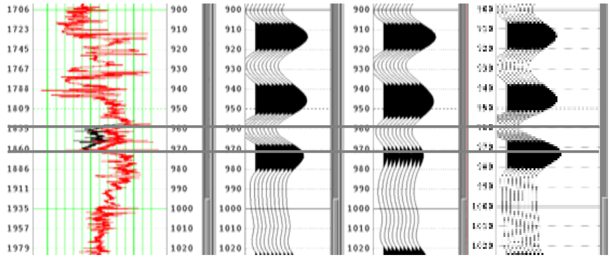


Geophysics for overall geological features

Resistivity decreases with increasing porosity and increasing saturation.

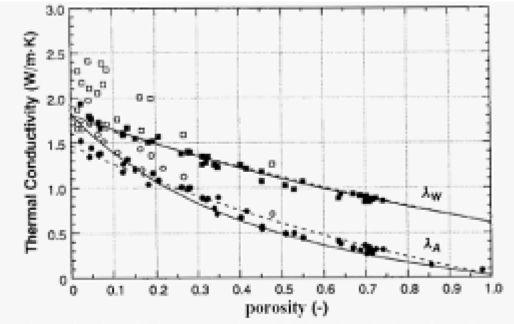


Wave velocity is reduced by increasing porosity but shows different behaviour for different saturation, with an inverse relationship when saturation is high (100/85%) and a direct relationship when saturation is low, being constant for saturation of 15-85%.

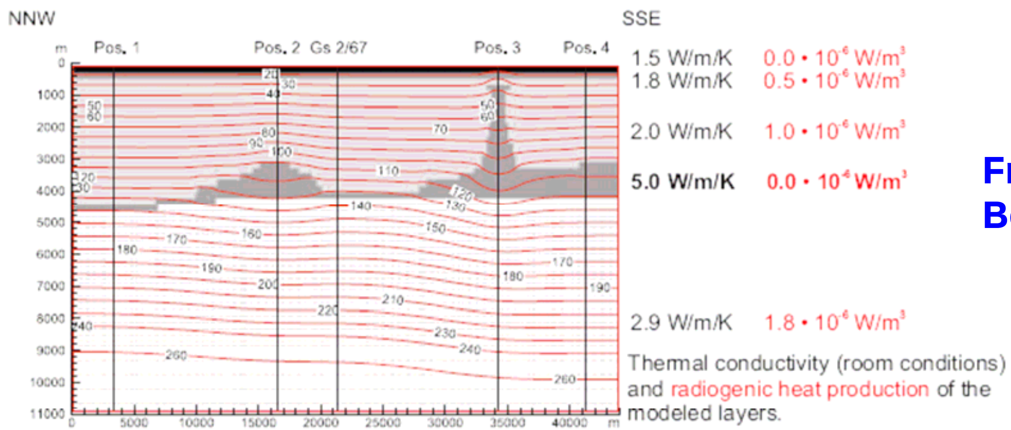


From Trappe, WS1

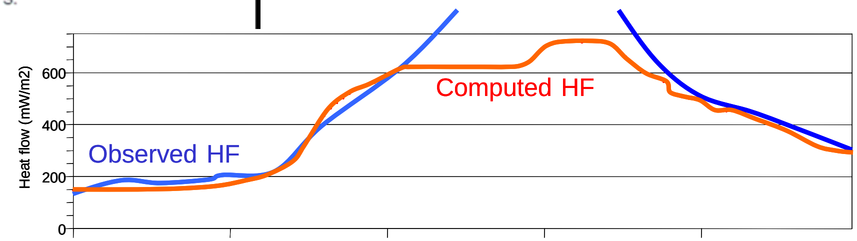
Thermal conductivity depends also on the porosity of the formation.

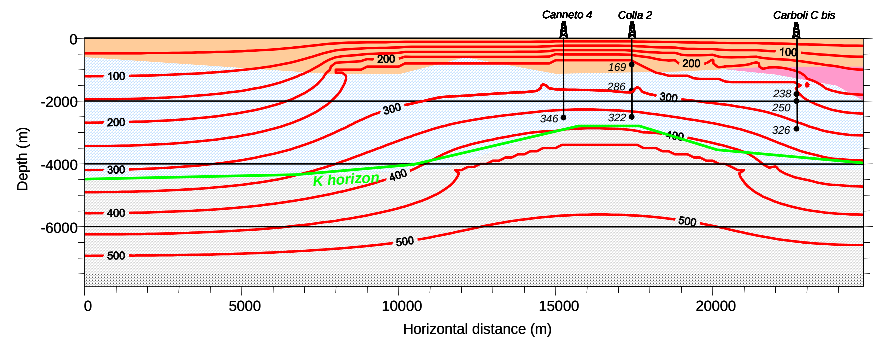


Geophysics for subsurface temperature



From Norden (left) and Bellani (below), WS1

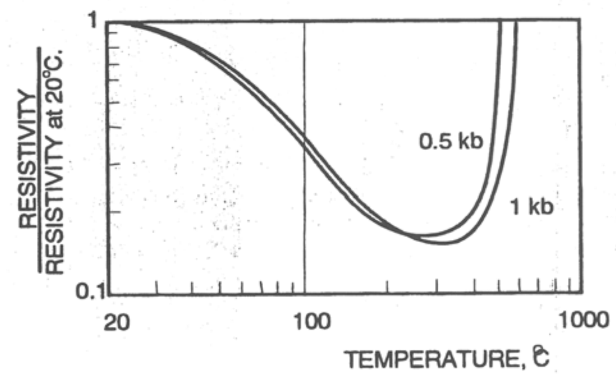




With proper care, heat flow and gradient data are able to define T° distribution at depth

Magnetic provides info regarding T° (demagnetization at Curie T°)

Geophysics for subsurface temperature



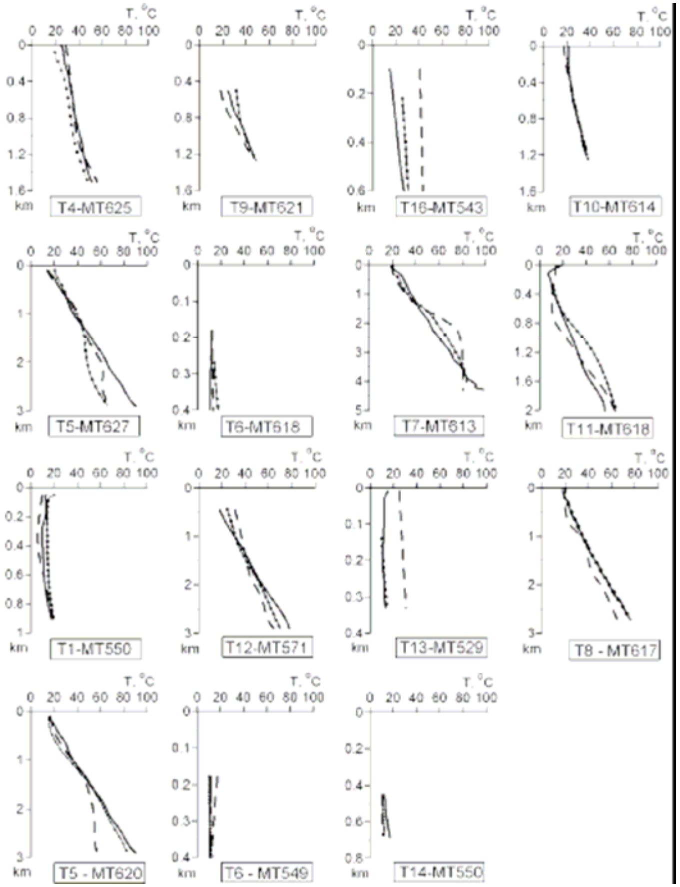
Resistivity is the physical parameter mostly affected by T° changes: in homogeneous conditions it would be able to map very clearly T° distribution at depth. Where mineralogical composition is graded by T° itself (clayey alteration minerals, abundant in volcanic rocks), resistivity is particularly affected by alteration zonation, and is used for mapping zones of high T° and fluid circulation (old and actual).

But what happens in EGS, where fluid circulation effects on mineralogy are much lower than for natural geothermal systems?

Geophysics for subsurface temperature

Through a neuronet analysis of MT and T° data, incorporating also geological information, electromagnetic data may be used as geothermometers.

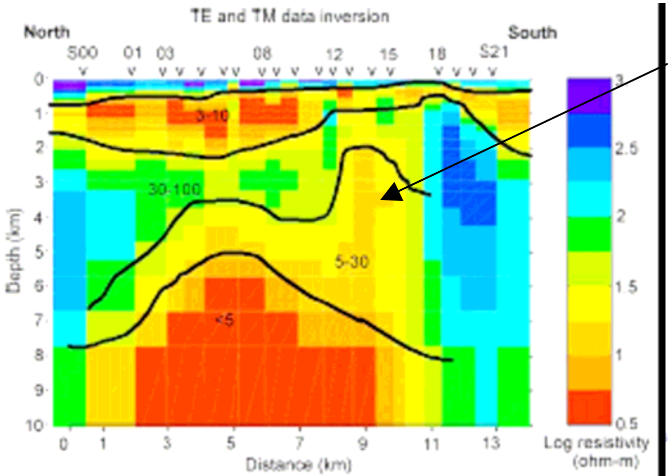
An example is shown for Bishkek site in Tien Shan (Spichak, WS1). Measured and modeled T° distribution in wells. Solid line: measured T°; dashed line: modelled T° based on T° data only; modelled T° based on T° and MT data.



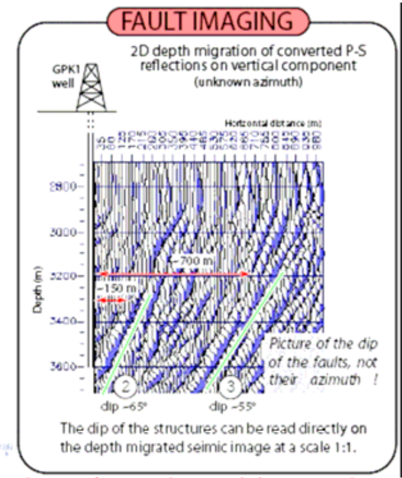
Geophysics for fluid pathways

Definition of fracture and faults

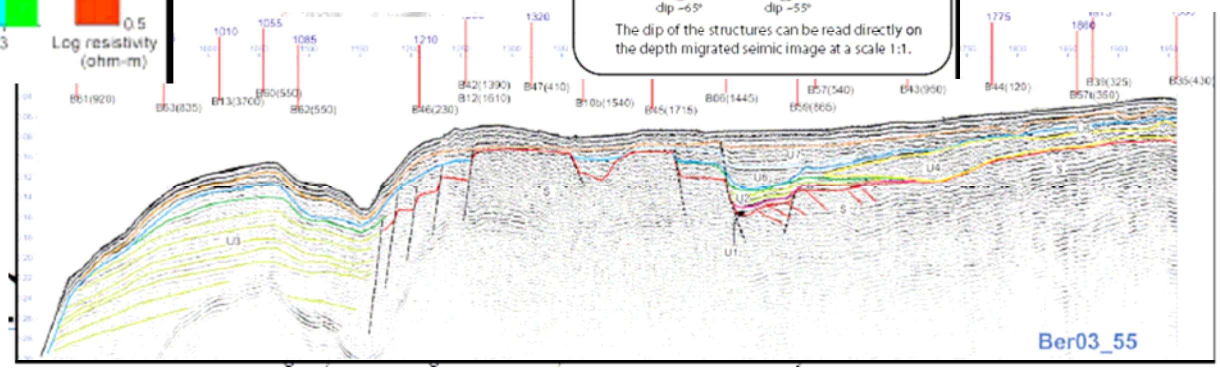
Many geophysical methods are able to map main lineaments and faults



Inferred fault



From Place, WS1



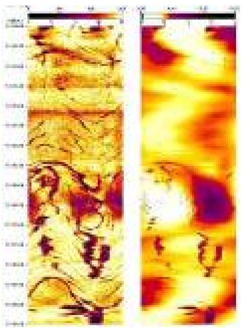
But this is not enough since there is still no direct evidence of fluid circulation

Geophysical well logging by means of:

Elastic/Acoustic and resistivity parameters

Waveform analysis

360° Hole Imaging

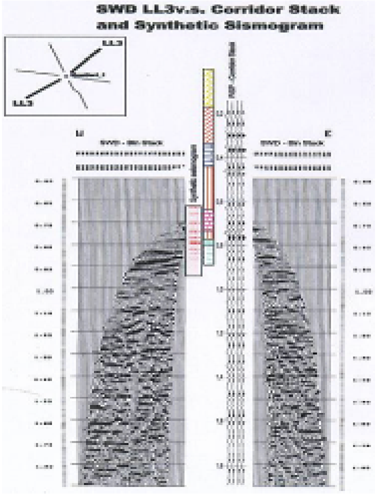


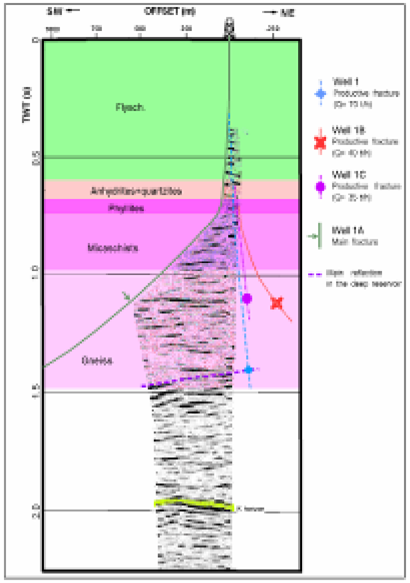
From Dezayes, WS1

WSP (Well Seismic Profiling):

VSP

SWD



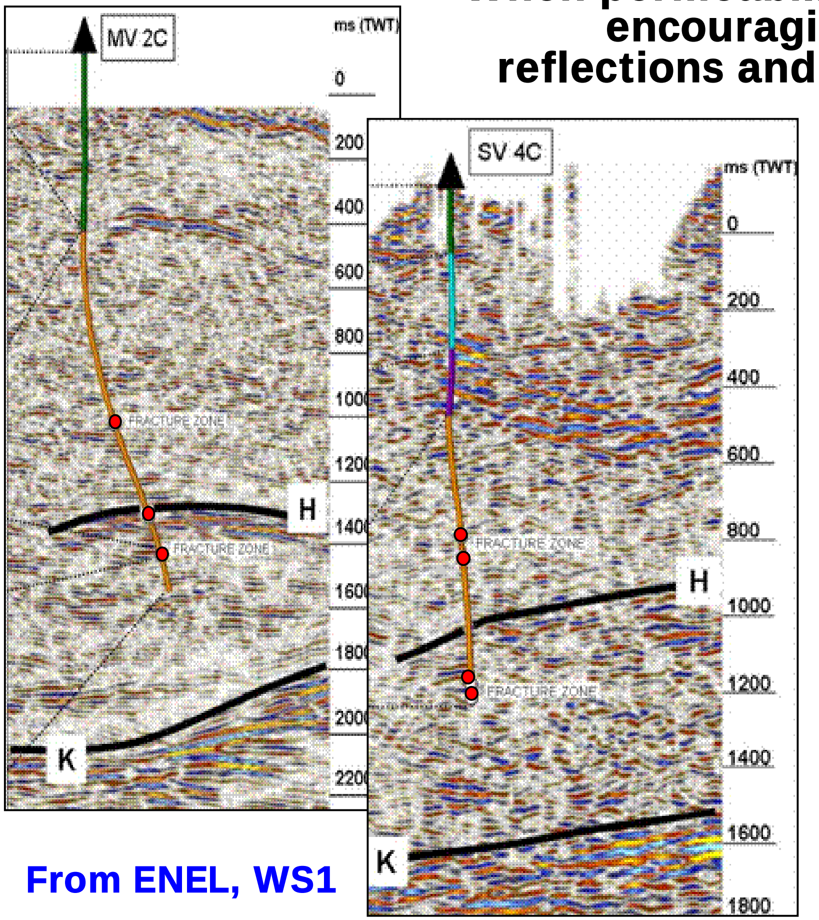


From ENEL, WS1

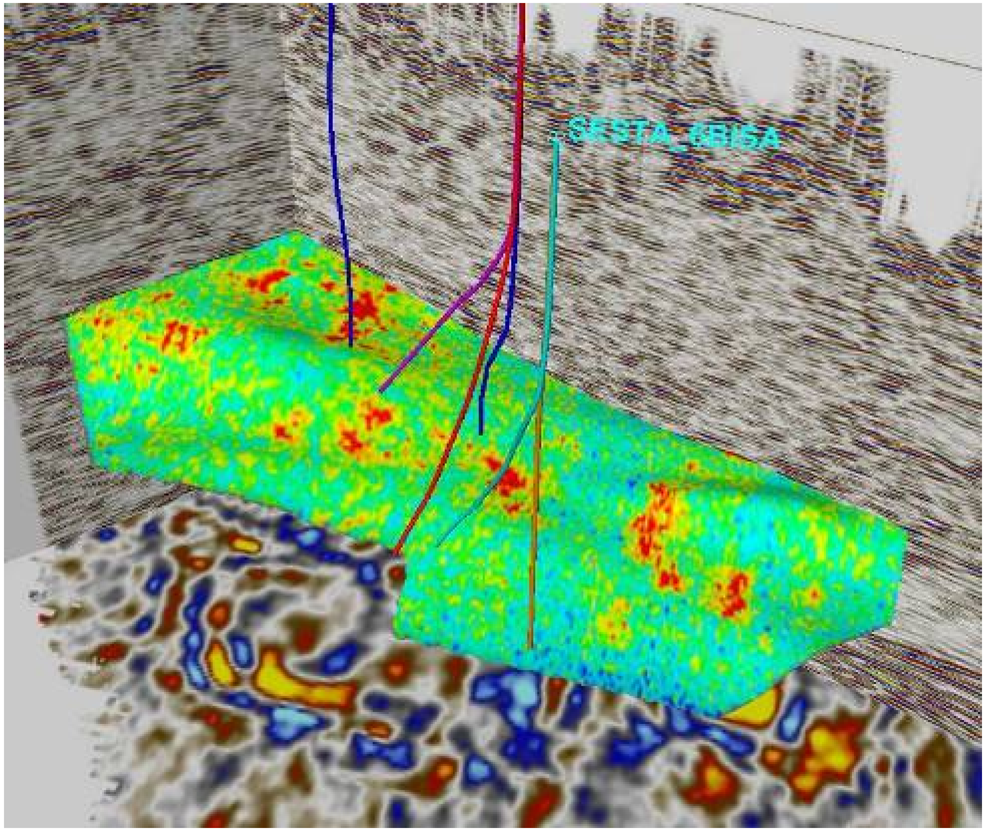
These data contrains seismic and MT, which are necessary for 3D extrapolation

Geophysics for fluid pathways

When permeability concentrate in sub-horizontal layers an encouraging correlation was found between seismic reflections and fractures (red dots) through AVO analysis



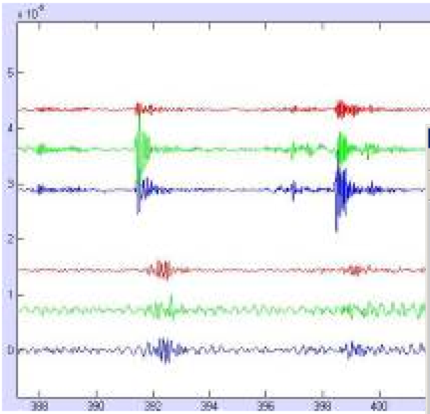
From ENEL, WS1

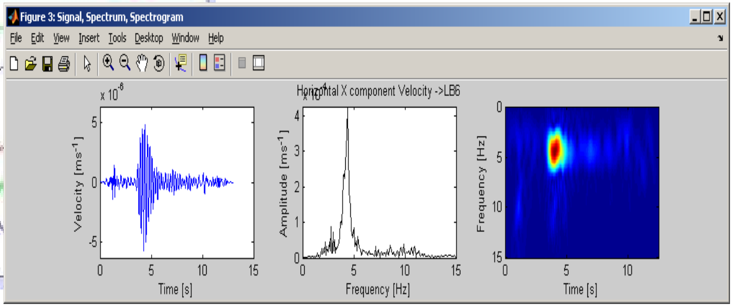


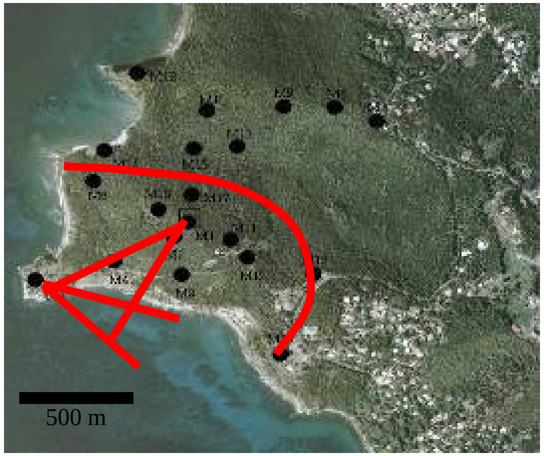
By full wave 3D modelling of broadband seismological data it is possible to detect the formation of gas bubbles in the fluid due to pressure decrease.

Definition of:

- **Source location related with hydrothermal manifestations along known faults**
- **Geometry of fractures**
- **Gas/liquid ratio of the fluid**

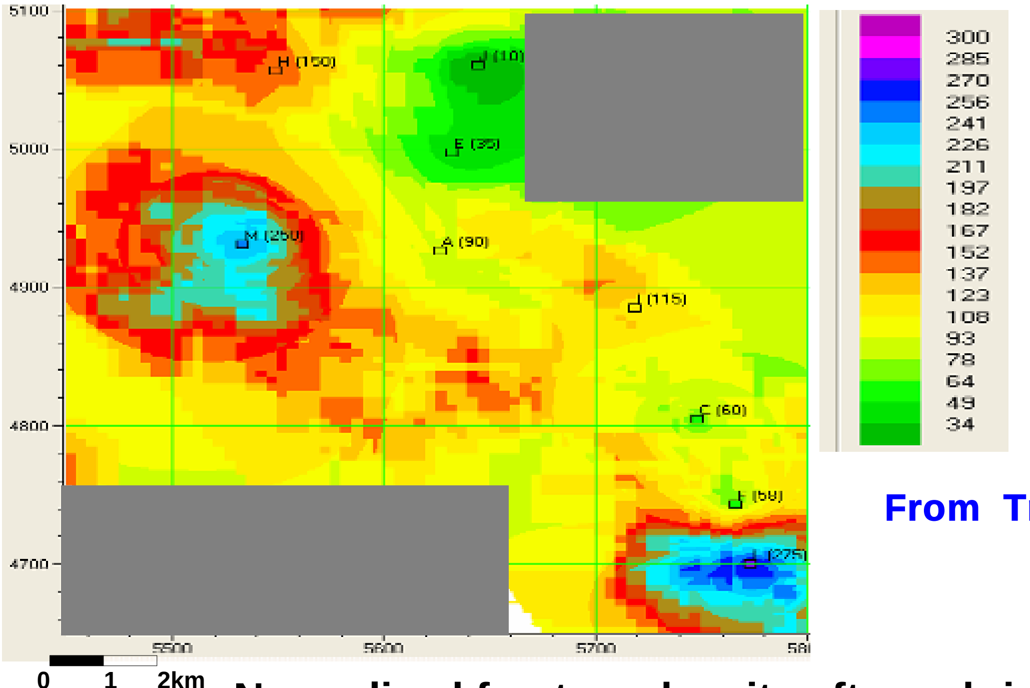






Geophysics for fluid pathways

Quantitative fracture prediction is made possible by modern reflection seismic concepts



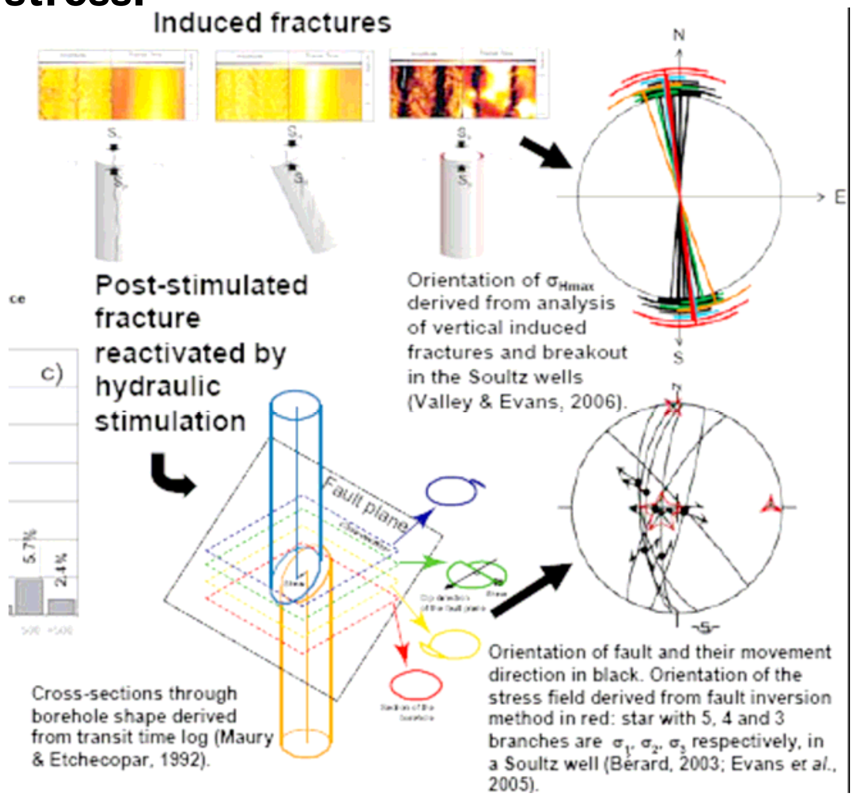
From Trappe, WS1

Normalized fracture density after cokriging

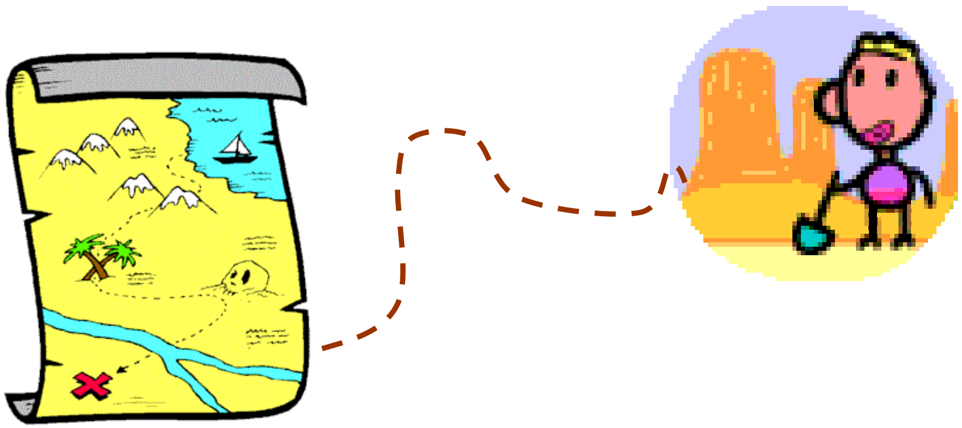
Passive seismology, active seismic and borehole geophysical logging provide information regarding regional and local stress.

Induced fractures (vertical induced fractures, enéchelon fractures, mechanic breakout or thermal breakouts) and post-stimulated fractures could be interpreted and measured on borehole image logs in Soultz.

Their geometrical relationship with the present-day stress field could be derived or computed. From Dezayes, WS1



Where to go...



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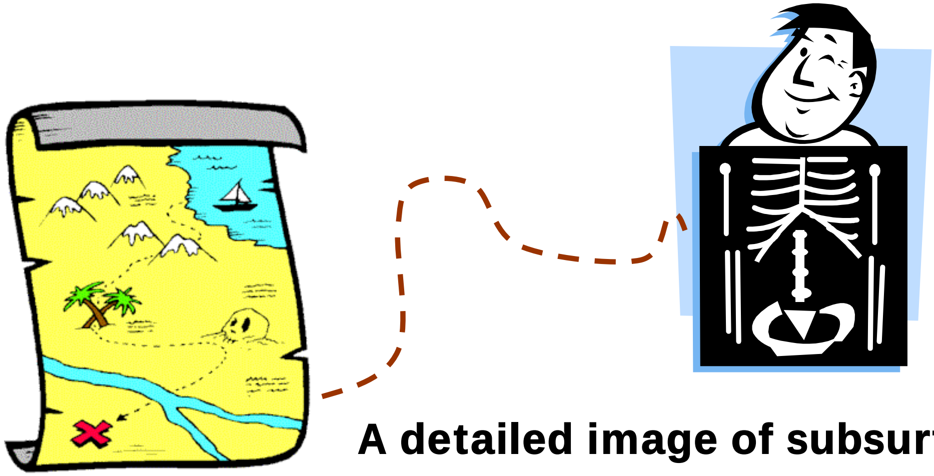

A detailed image of subsurface, including:

- **Structural models (sedimentary and crystalline scenarios)**
- **Temperature**
- **Fractures and faults**
- **Fluid flow: location, direction(!) and composition / phase**
- **Stress field**

Where to go...

A complete set of physical simulation coupled with 3D thermo- and hydrodynamic modelling

Analogous: a geothermal analogous (*shallow* hydrogeophysics) upscaled by a factor in *x,y,z* dimensions and then shifted in the depth dimension to simulate subsurface structures, to use as test for seimic, gravity, magnetic, resistivity methods. Tests for data processing, depth estimation techniques, fracture detection techniques.

A complete set of geophysical surveys during stimulation in orther to define other ways to detect waterfront. Other stimulation techniques (gas gun followed by hydraulic stimulation. To be done in the right place...) may be of help.

With whom?

Hydrogeophysicists for imaging hydrological features

Volcanology geophysicists for imaging stress/strain

Oil exploration geophysicists for reservoir assessment

Without forgetting geologists and geochemists