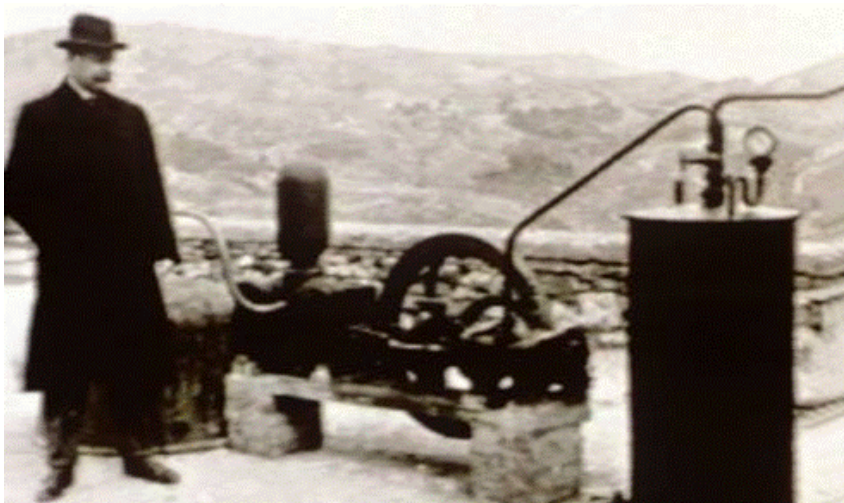
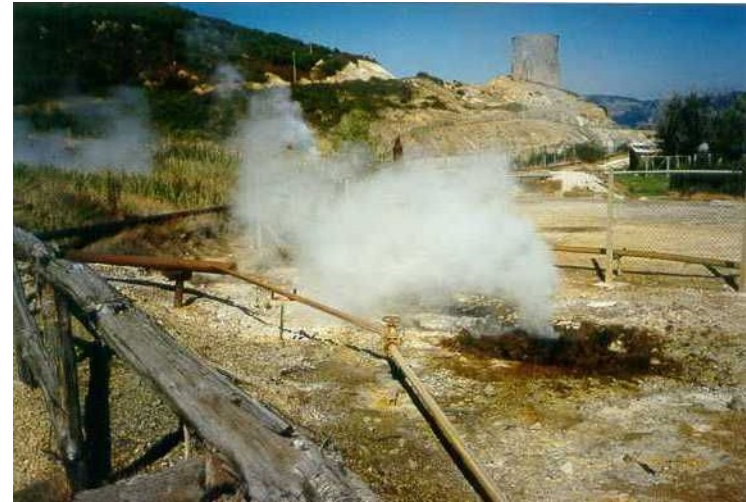


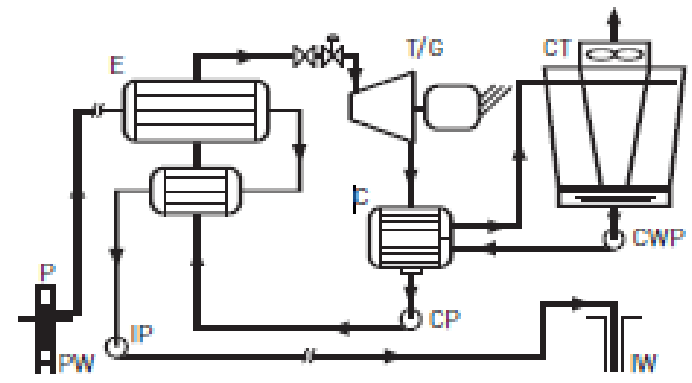
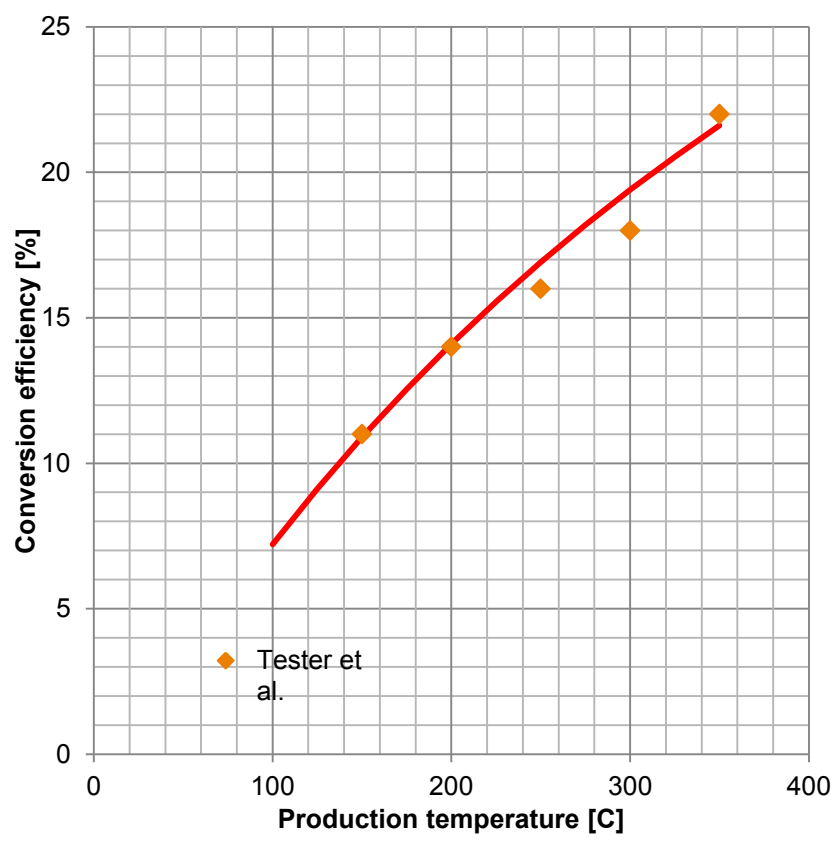
## Power from volcanic areas

**started in Italy – 1903  
(Larderello, tuscany)**

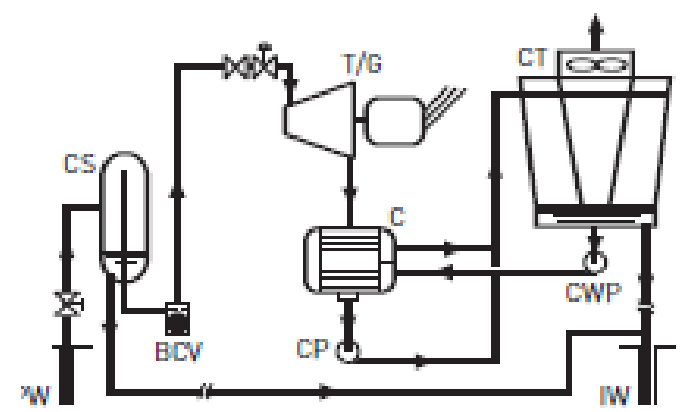
**ca 800 MWe today**



## Geothermal power: Conversion Efficiency

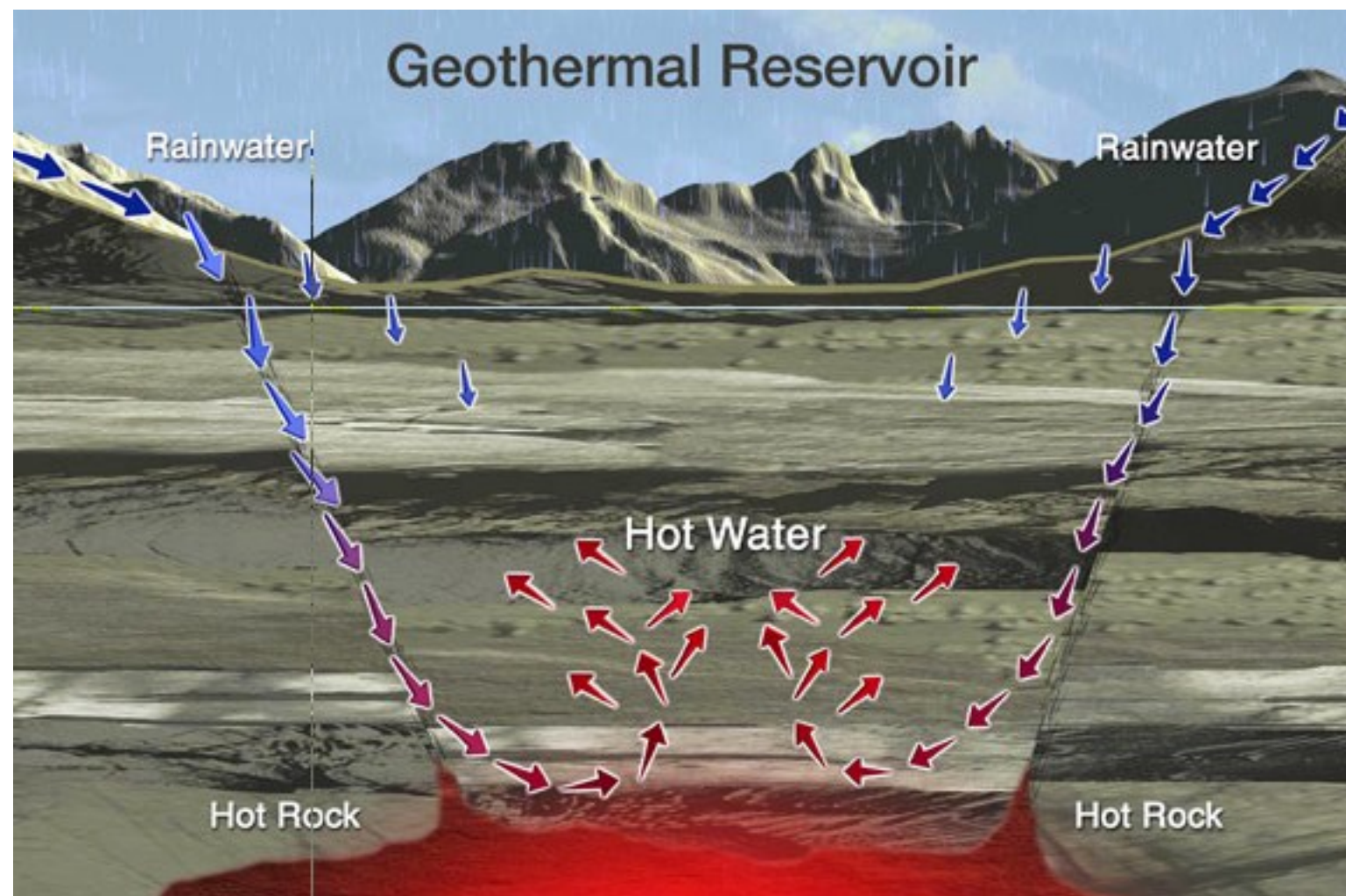


binary



flash

# Natural fluid flow in magmatic areas







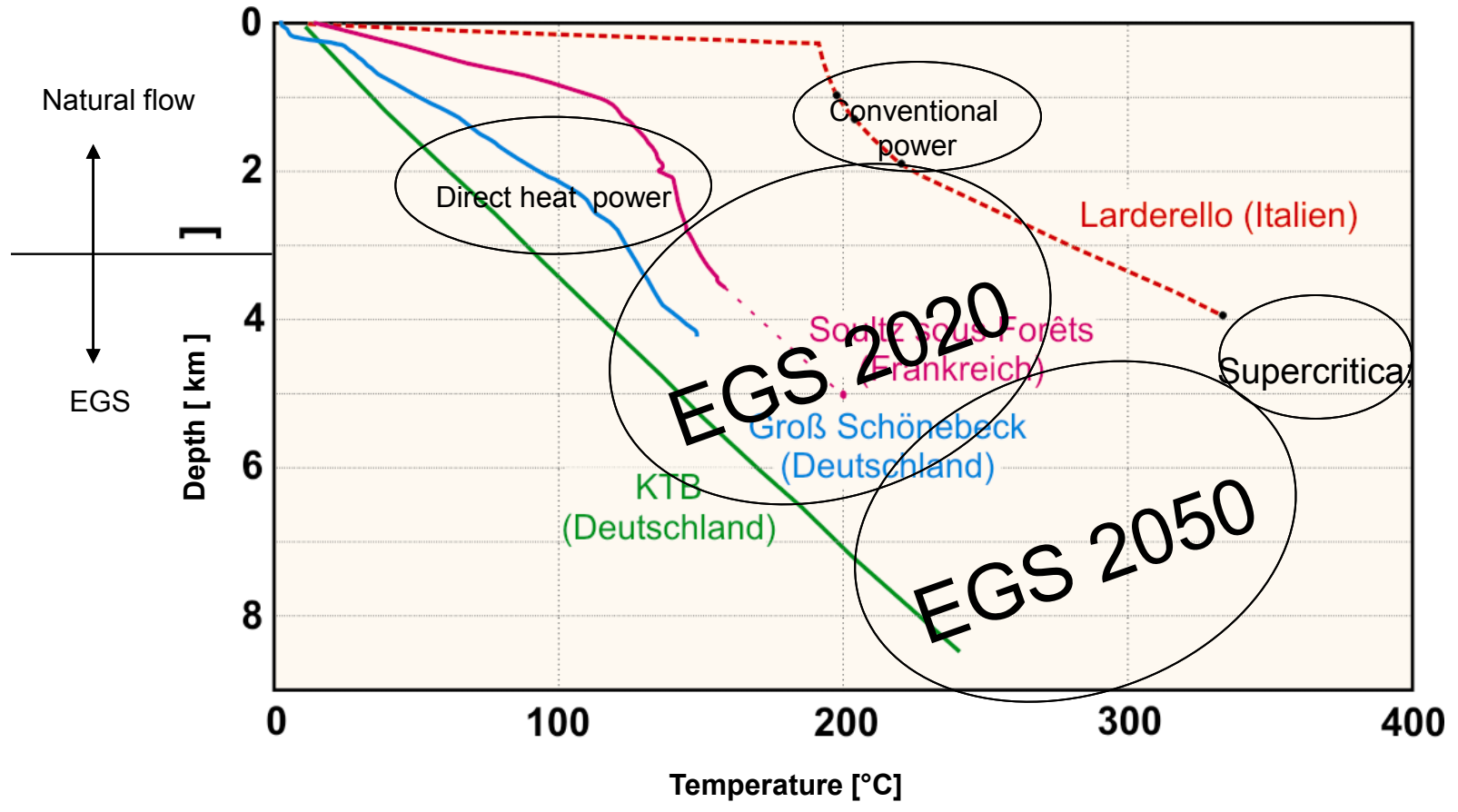
## Natural flow through the rocks

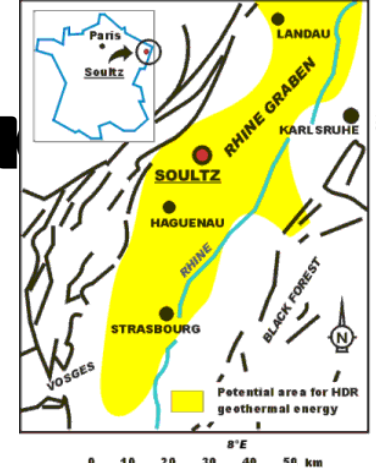
- › Requires
  - › Pores (in sedimentary and volcanic deposits)
  - › Fractures and faults
- › Less natural flow at depths larger than 2000m for pores



# Temperature gradients in the upper crust

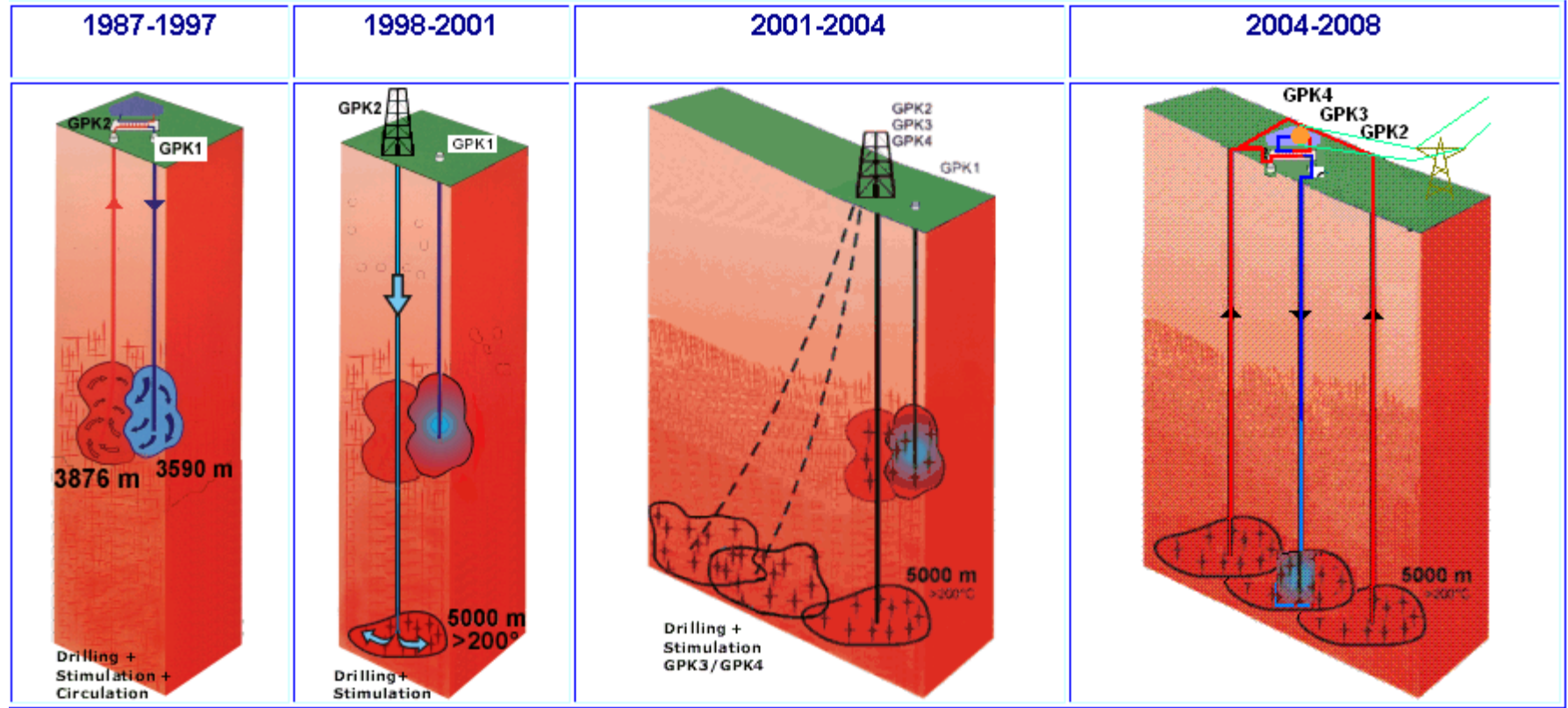
Regional temperature variations





# Enhanced Geothermal Systems

- EU research project > 20 years
- 3 wells > 5 Km deep
- Comprehensive Fracturing programme
- 3MW<sub>el</sub> Power via ORC plant



## Power production

- › Conversion 25%@300C, 10%@100C
- › What is required flow rate  $Q$  [kg/s] for  $E=1000$  MWe power for 300C resource geothermal fluid cooled down to 100C
- › Heat capacity of geothermal fluid ( $C_p=4000$  J  $\text{kg}^{-1}$ )
- ›  $Q = E / (C_p \Delta T 0.25)$
- ›  $Q = 5000$  kg/s
- › Well is no more than 100kg/s  $\rightarrow$  50 wells for 1000MWe, 20Mwe /well



# **GEO THERMAL ENERGY FROM EXPLORATION TO EXPLOITATION**



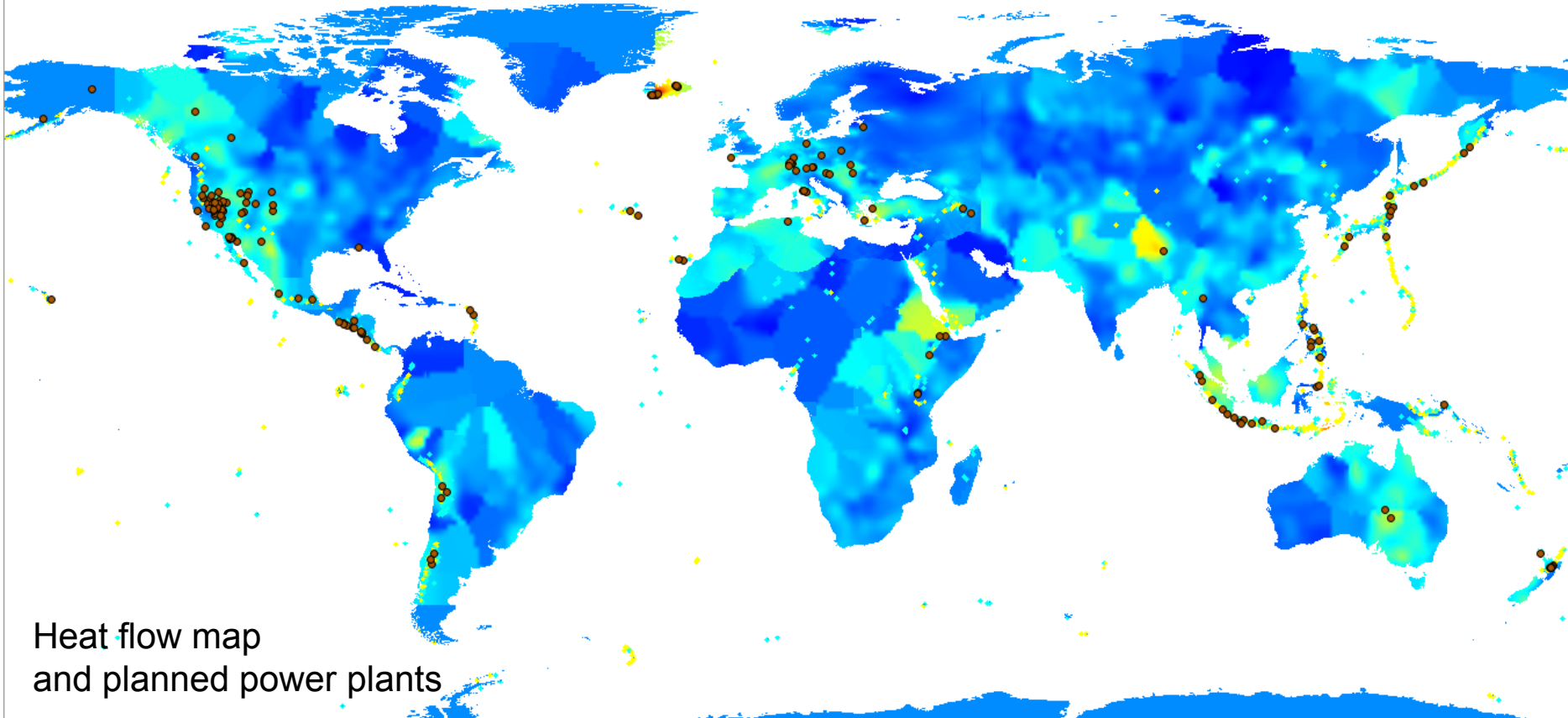
Adele Manzella  
CNR-IGG



## Exploration and Investigation: the quest

After 50 years of exploration a large amount of temperature data and significant knowledge of subsurface geology has been achieved.

Several prospective areas for geothermal exploration can be outlined in Europe and many regions in the World. On what base have them been defined?



Heat flow map and planned power plants

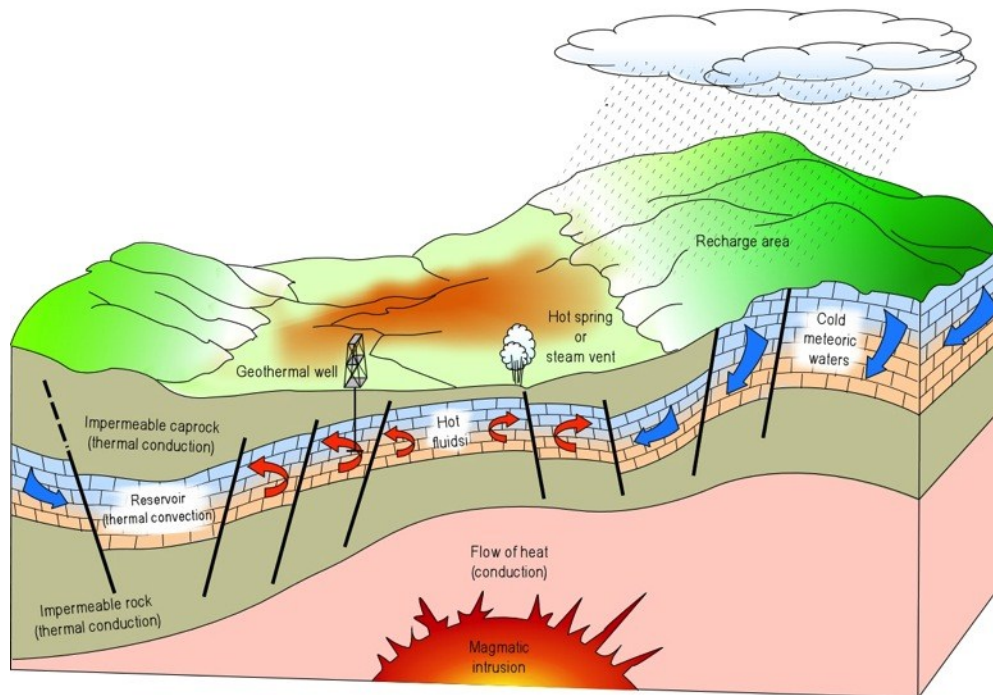
## Exploration and Investigation: the quest

Apart direct shallow heat exchange of Geothermal Heat Pumps installations, subsurface heat is not used directly for power and heat production, but through a ***mass of water*** that exchanges and extracts the heat stored in the rocks. Water is really only the vector, but is a main element in our quest.

The primary target of Exploration and Investigation (E&I) are the so-called ***hydrothermal systems***

## Hydrothermal systems

A *geothermal system* can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface".



# Hydrothermal systems

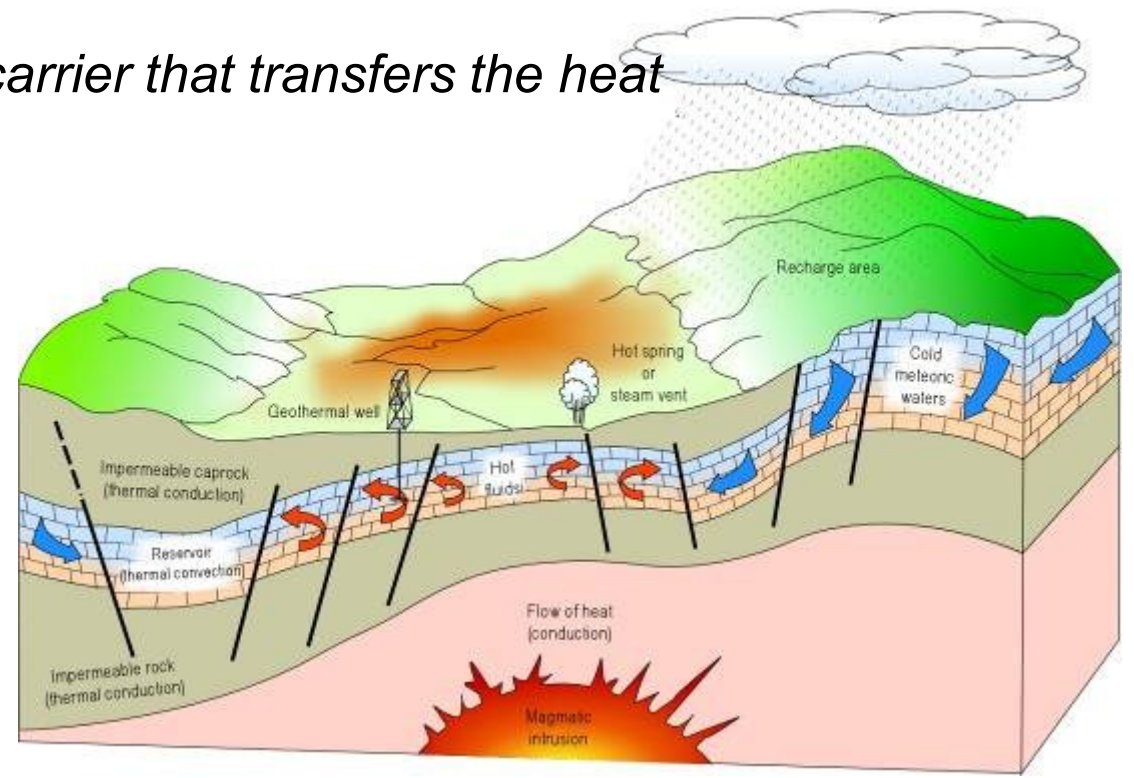
Elements of a hydrothermal geothermal system:

*a heat source*

*a reservoir*

*a fluid, which is the carrier that transfers the heat*

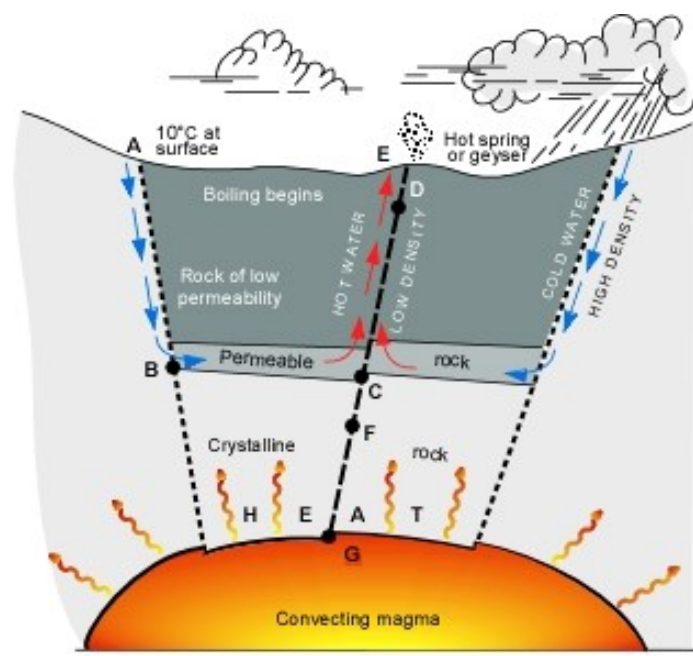
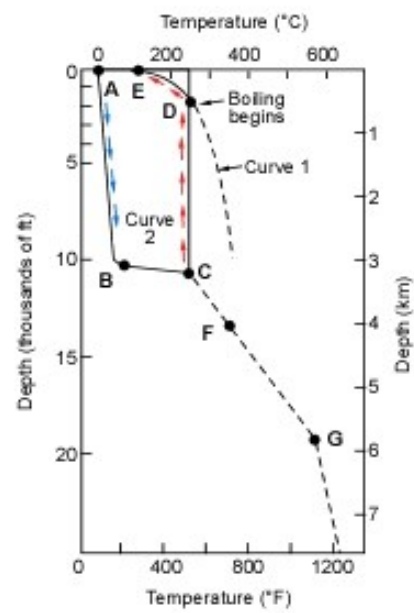
*a recharge area*



# Hydrothermal systems

The mechanism underlying geothermal systems is by and large governed by *fluid convection*.

Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field.



*Model of a geothermal system. Curve 1 is the reference curve for the boiling point of pure water. Curve 2 shows the temperature profile along a typical circulation route from recharge at point A to discharge at point E (From White, 1973).*



## Hydrothermal systems

A economically feasible geothermal reservoir should lie at depths that can be reached by drilling, possibly less than 4 km (**accessibility requirement**).

A geothermal system must contain great volumes of fluid at high temperatures - a reservoir - that can be recharged with fluids that are heated by contact with the rock.

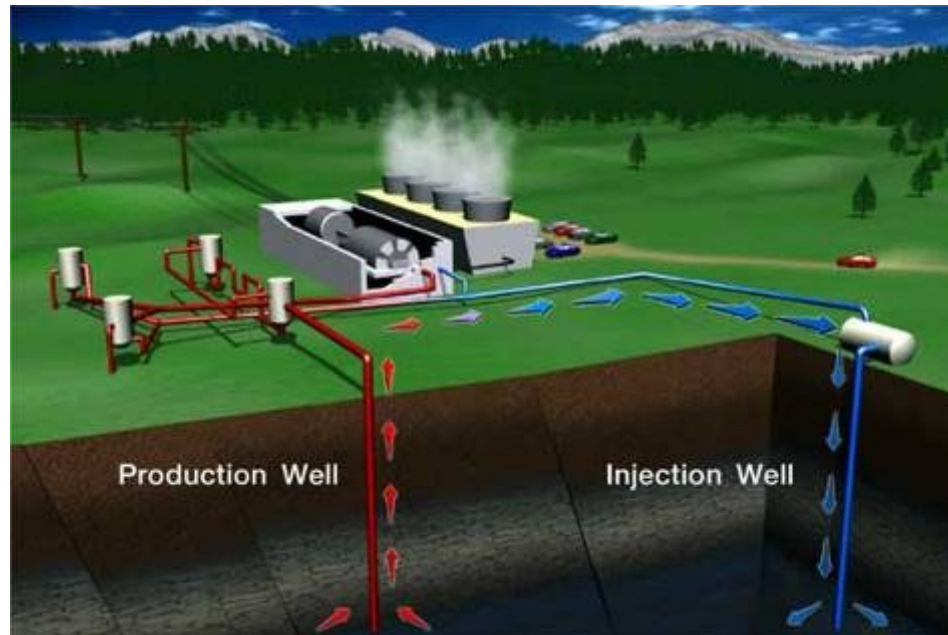
**productivity requirement**

For most uses, a well must penetrate permeable zones, usually fractures, that can support a high flow rate.

## Hydrothermal systems

When sufficient natural recharge to the hydrothermal system does not occur, which is often the case, a reinjection scheme is necessary to ensure production rates will be maintained.

This would ensure the **sustainability** of the resource.



## Hydrothermal systems

The geological setting in which a geothermal reservoir is to be found can vary widely. The largest geothermal fields currently under exploitation occur in rocks that range from limestone to shale, volcanic and metamorphic rocks.

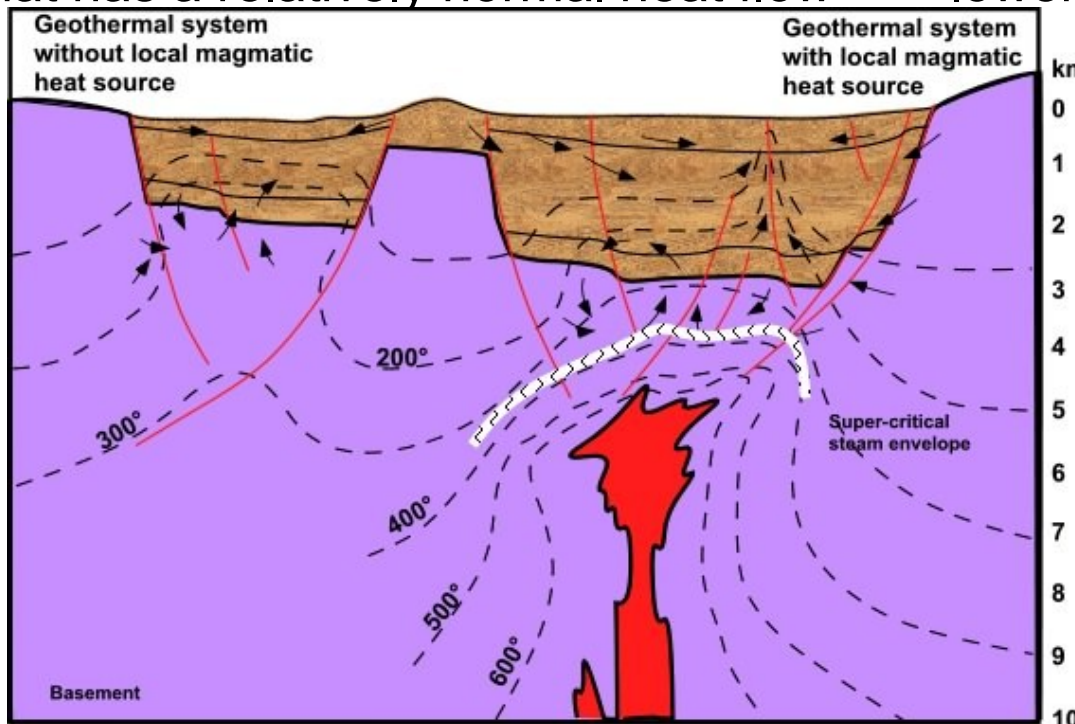
Volcanic rocks are the most common single rock type in which reservoirs occur.

Specific lithology do not define geothermal reservoirs

# Hydrothermal systems

High heat flow conditions → rift zones, subduction zones and mantle plumes.

Thick blankets of thermally insulating sediment cover basement rock that has a relatively normal heat flow → lower grade



Other sources of thermal anomaly:


- Large granitic rocks rich in radioisotopes
- Very rapid uplift of meteoric water heated by normal gradient

## Let us define what we need

Temperature as well as water amount are important for defining the feasibility of a geothermal resources for various, different uses.

Example: power production

Power is produced by the energy conversion of the thermal energy stored in the mass of water, into mechanical energy through a turbine, either directly (conventional flash technology) or undirectly (binary technology), and finally to electrical energy from the generator.

10 MW<sub>t</sub> (thermal)  1MW<sub>e</sub> (power)



## Let us define what we need

Example: power production (continues)

To produce 1 MW<sub>e</sub> we need (rule of thumb) :

- 7 - 10 t/h of dry steam (over 250 °C)
- 30-40 t/h of two-phase fluids at 200-250°C (flash technology)
- 400 - 600 t/h of water when using low enthalpy ORC binary cycles (120-160°C)

The lower the temperature, the higher the amount of fluid required to produce a unit quantity of thermal (and electric) energy.

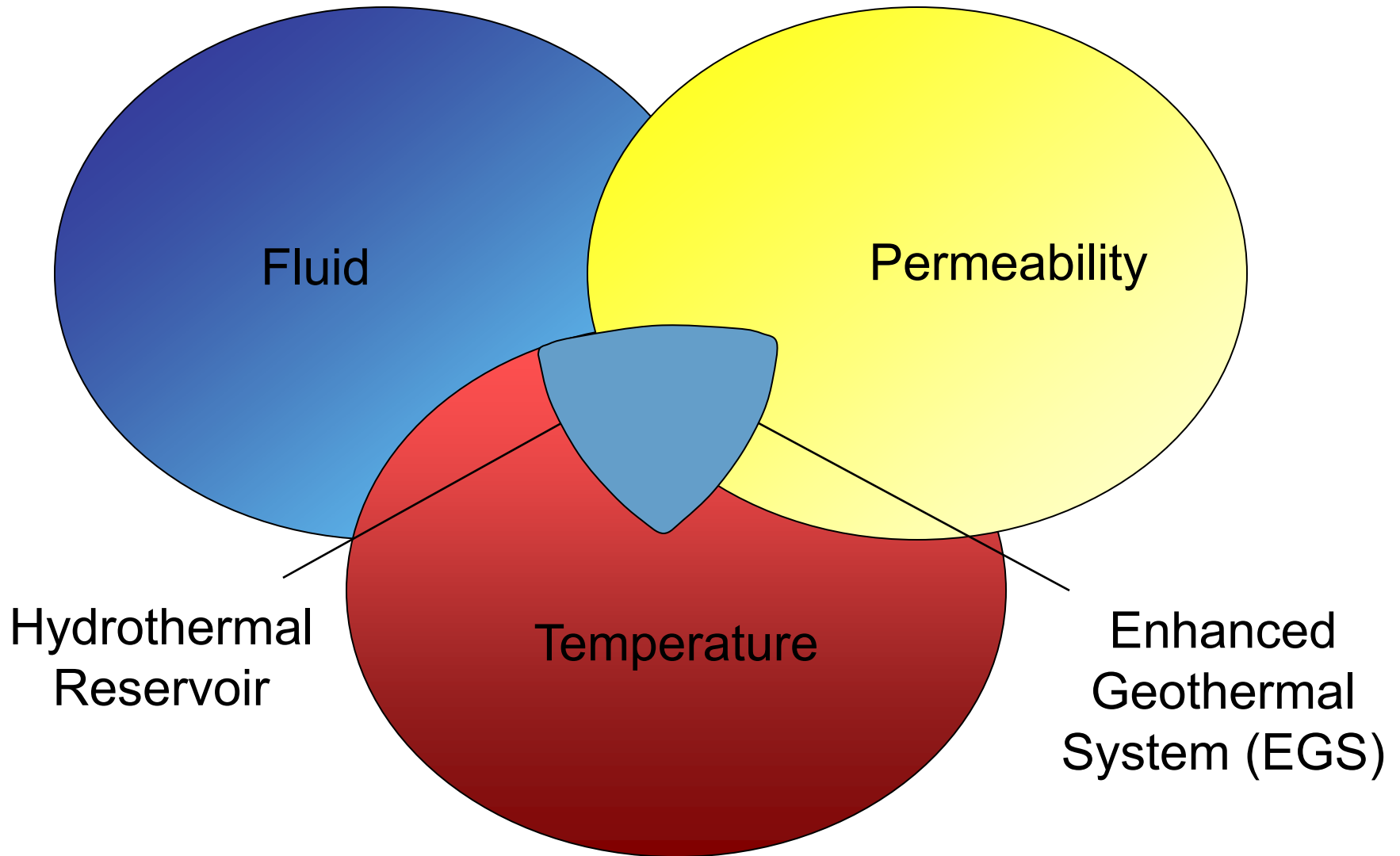


## Goal: increase production

In order to increase geothermal production, we need to increase the amount of fluid heated in the underground.

This goal may be achieved by increasing heat exchange surface at depth, therefore, permeability within suitable geologic units: EGS (Enhanced or Engineered Geothermal systems)

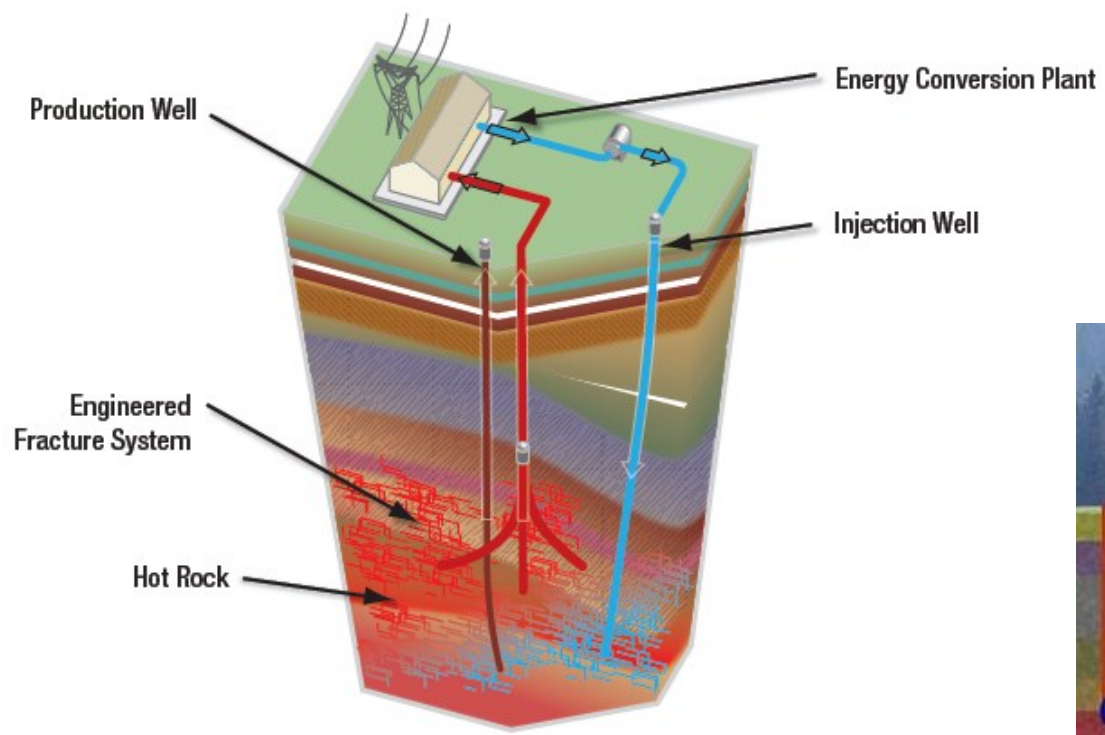
## The EGS concept is simple



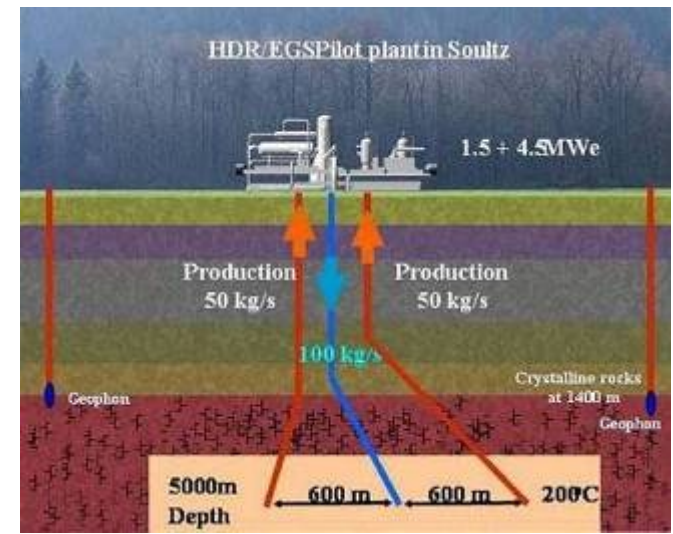
## The EGS concept is simple

### Goal: increase production

For all intents and purposes, heat from the earth is inexhaustible. Water is not nearly as ubiquitous in the earth as heat.



EGS concept covers specifically reservoirs at depth that must be engineered to improve hydraulic performance



## Goal: increase production

Numerous problems must be solved to reach the numerical goals and many unknowns need to be clarified:

- irregularities of the temperature field at depth
- **favourable stress field conditions**
- long-term effects, rock-water interaction
- possible thermal and hydraulic short circuiting
- EGS induced seismicity (during stimulation but also due to production) becomes a real issue;
- uniform connectivity throughout a planned reservoir cannot yet be engineered.
- scalability



## Exploration and Investigation

E&I techniques are used in all the geothermal project phases

➤ *resource characterization*

- geothermal gradients and heat flow, heat capacity, recoverable heat
- geological structure, including lithology and hydrogeology
- Tectonics
- induced seismicity potentials

➤ *reservoir design and development*

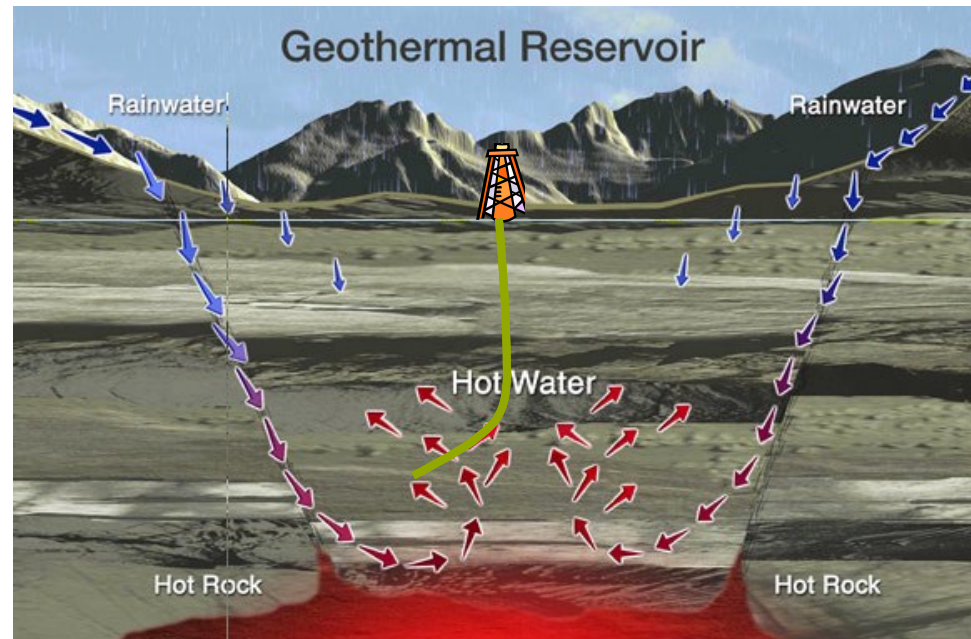
- fracture mapping and in-situ stress determination
- prediction of optimal re/injection and stimulation zones

➤ *reservoir operation and management*

- reservoir performance monitoring through the analysis of temporal variation of reservoir properties

## Goals to be achieved by E&I

- To provide all necessary *subsurface information* to guarantee the best exploitation efficiency, the sustainability of the resource and the lowest possible environmental impact
- To *reduce the mining risk* by cutting the exploration cost and increasing the probability of success in identification of GS and EGS in prospective areas



## Exploration & Investigation

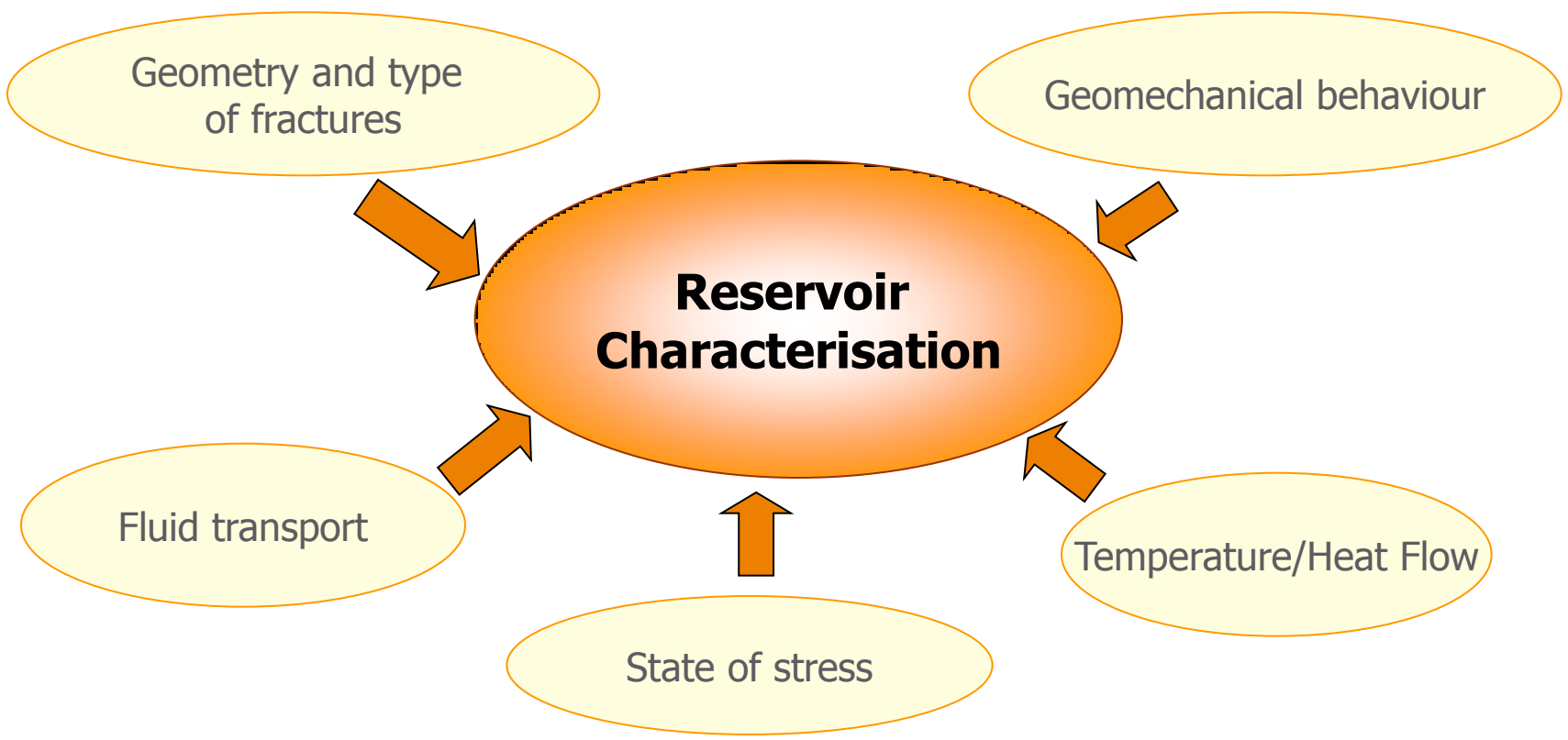
The objectives of *geothermal E&I* are:

1. To identify geothermal phenomena.
2. To ascertain that a useful geothermal production field exists.
3. To estimate the size of the resource.
4. To determine the type of geothermal field.
5. To locate productive zones.
6. To determine the heat content of the fluids that will be discharged by the wells in the geothermal field.
7. To compile a body of basic data against which the results of future monitoring can be viewed.
8. To determine the pre-exploitation values of environmentally sensitive parameters.
9. To acquire knowledge of any characteristics that might cause problems during field development.



# Exploration&Investigation

In order to understand the geothermal potential of a reservoir some relevant properties should be defined





## Exploration&Investigation

Because of the high temperatures involved, both in the geothermal reservoir and in the source of the geothermal system, we can expect major changes to have taken place in the physical, chemical and geological characteristics of the rock, all of which can be used in the exploration project.

Since heat diffuses alteration will be diffused too, and the rock volume in which anomalies in properties are to be expected will, therefore, generally be large.



# Exploration&Investigation

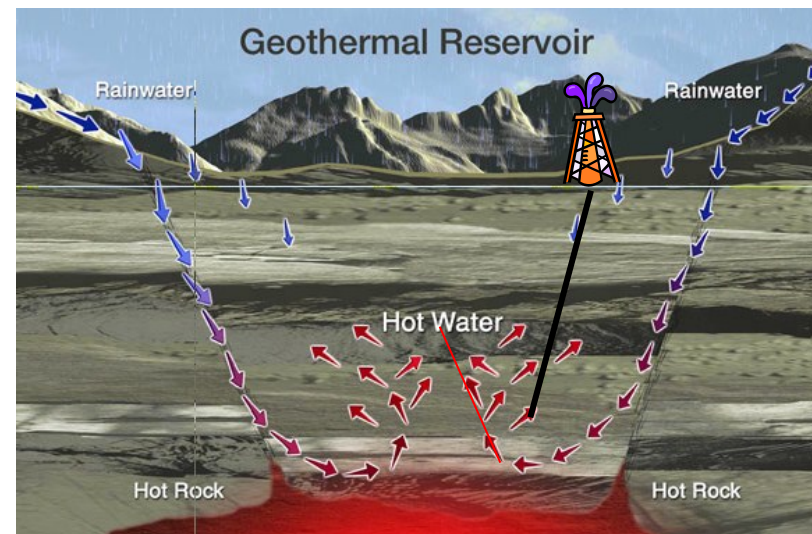
## Goals to be achieved by Exploration&Investigation 1: before and during production

- Identify prospective reservoirs prior to drilling
- Define boundaries (lateral and vertical) (**accessability**)
- Identify drilling targets (**productivity**)

Main permeability is driven by fracture and faults.

**wells \$\$\$**

**avoid not economic wells**





## Exploration&Investigation

### **Goals to be achieved by Exploration&Investigation 2: during and after production**

- Continuously characterize the reservoir during energy extraction
- Follow the effect of production and fluid re-distribution, including the formation of steam or gas cap
- Characterize the rock fabric to define fluid flow paths within reservoir
- Predict fluid circulation during stimulation
- Track injected fluids
- Characterize formations during deep drilling and stimulation in order to predict reservoir performance/lifetime (effectiveness and sustainability)

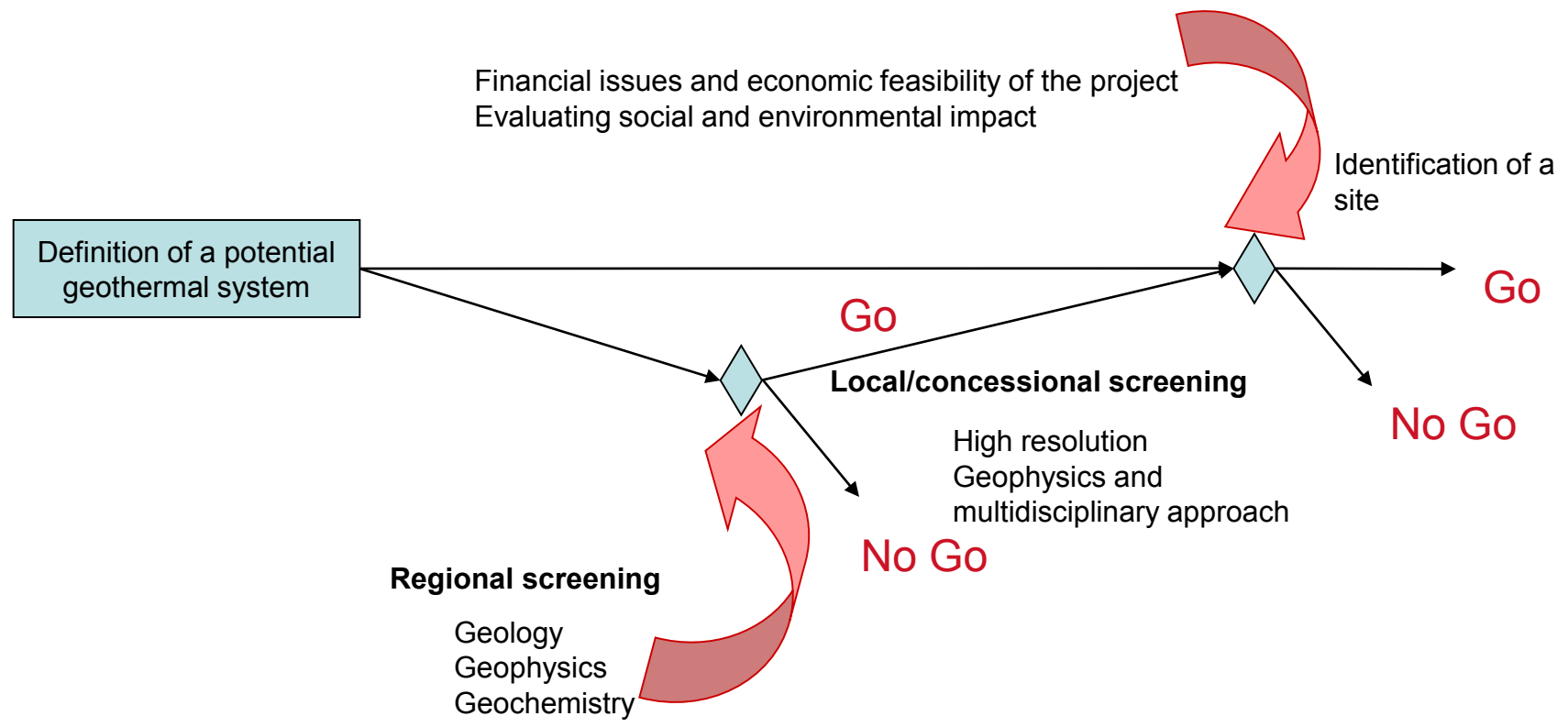


# Exploration & Investigation

It is not possible to define a specific sequence of methodologies to be applied for the E&I of geothermal systems

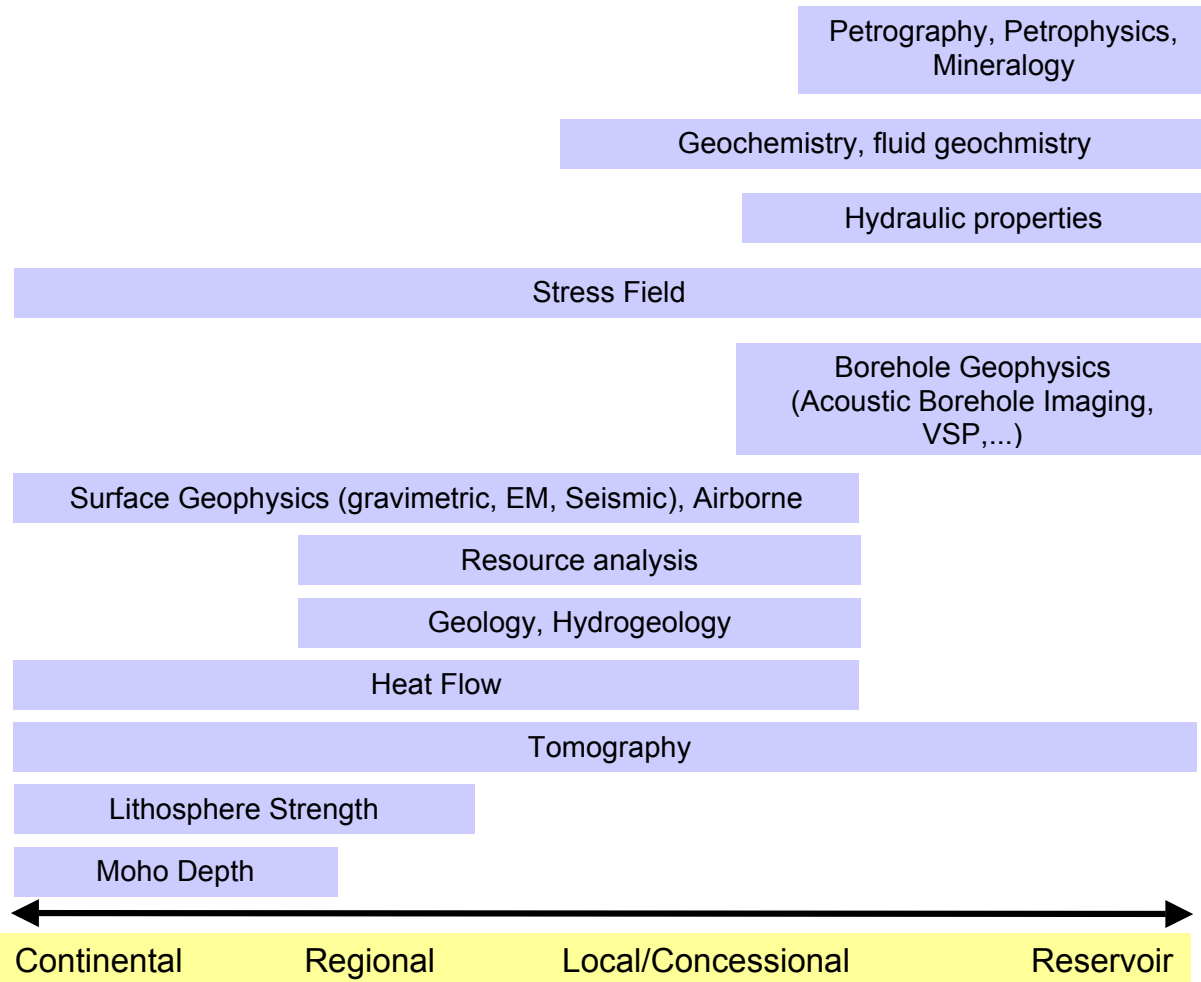
Choice is also related to cost

Financial issues and economic feasibility of the project  
Evaluating social and environmental impact





# A scale dependent approach



## Continental scale E&I

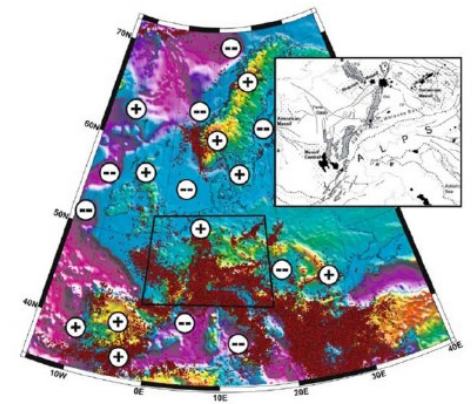
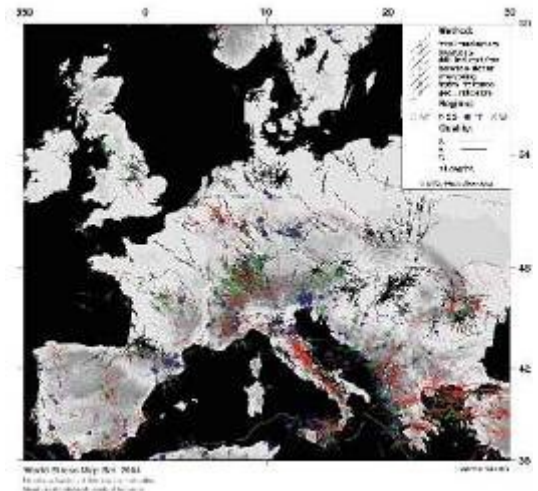
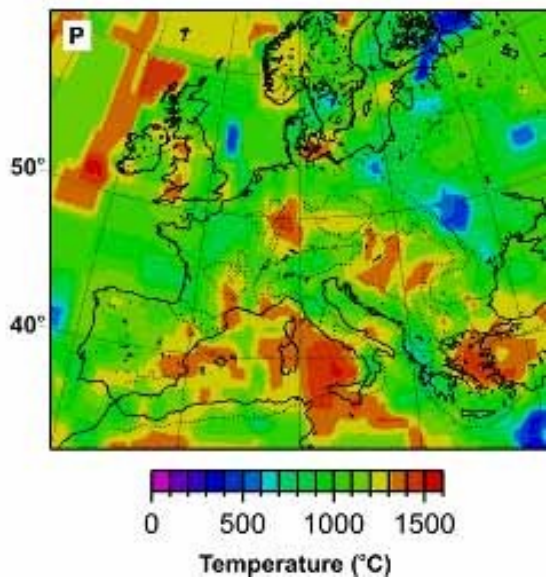
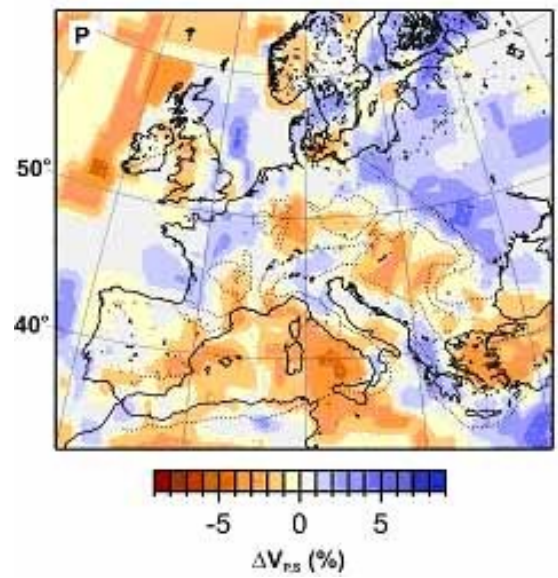
Identification of potentially interesting regions of interest is based on:

- Task: Identify thermal field at great depths (>10km)
  - from seismic tomography
  - from thermal modeling
- Task: Identify Deformation regime of the crust
  - from passive stretching models
  - Extensional regimes can be of high interest
- Task: Identify Stress regime (neo-tectonics)
  - from data cross-checking.
  - Strike-slip regimes and extensional are the most interesting

**Task: Identify regions of interest**



Continental scale E&I



Seismic velocity anomalies from tomography (left), conversion of velocities to temperature, stress field, distribution of seismicity.

## Regional scale E&I

- Heat flow analysis
  - temperature gradient
  - well data
- Seismic methods:
  - focal mechanisms of earthquake
  - smaller scale seismic events.
- Large-scale gravimetry:
  - geometric trends of deep layers
- 2D/3D seismic profiles
  - defining a geological model
- Electromagnetic prospection:
  - apparent resistivity of rocks  
(link to geothermal reservoir not clearly established)
- Remote sensing
  - identification of regional structures
  - characterization of temperature fields
- Geochemistry
  - identification of regional anomalies

**Task: Identify concessional areas**

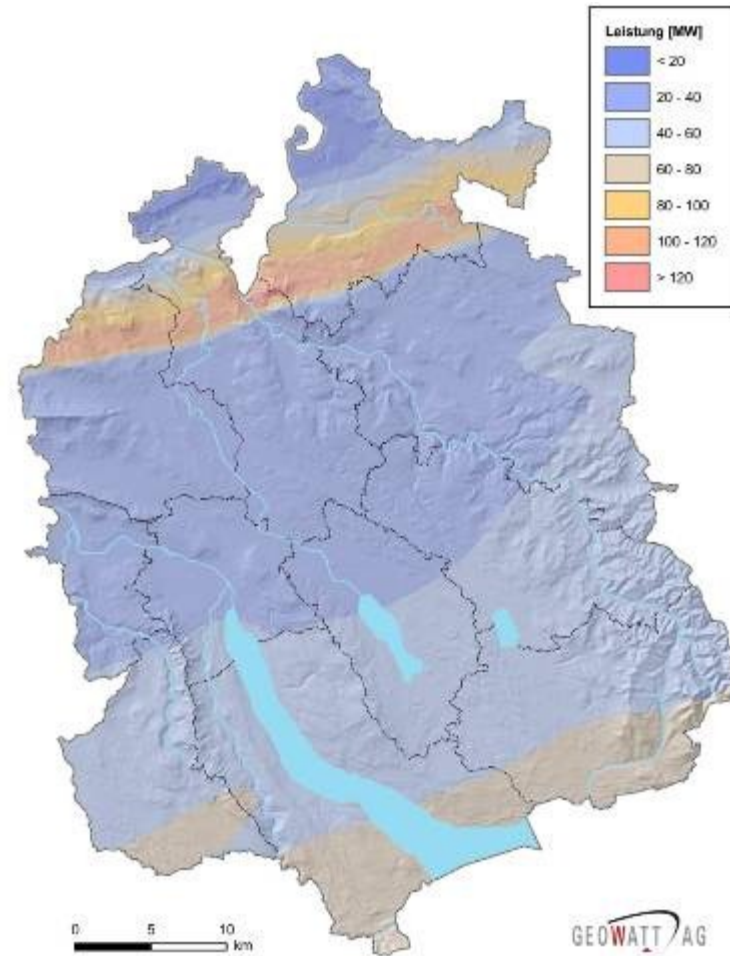
## Concessional scale E&I

- Classical geophysical tools:
  - 2D/3D seismic for geological mapping/identification of fault zones.
  - Electromagnetic methods (MT-TEM-DC).  
Geothermal reservoirs > Low resistivity zone ?
  - Gravimetry. Geothermal reservoirs can have a gravimetric signature
- Resource potential analysis:
  - integration of geological, hydrological, geochemical and geophysical data
  - Estimation of energy recoverable from the reservoir.
  - Cross-checking with infrastructure / areas of demand

**Task: Identify reservoirs**

# Concessional scale E&I

- Key Parameters:
  - Geometry of the aquifer
  - Temperature at depth
  - Hydraulic conductivity



From Kohl et al., ENGINE Mid-Term conference

## Reservoir scale E&I

- Well geophysics
  - Vertical seismic profile, allows identification of structures at a distance from the well
  - Borehole acoustic imaging and sonic log provides information about fractures crossing boreholes
  - Borehole gravimetry can help defining conditions into the reservoir
  - Gamma ray and resistivity logs provide information on the material surrounding the borehole
- Local stress determination
  - stimulation strategy
- Conceptual model can be built, and assumptions verified with reservoir numerical model.





# Reservoir scale E&I

In Soultz

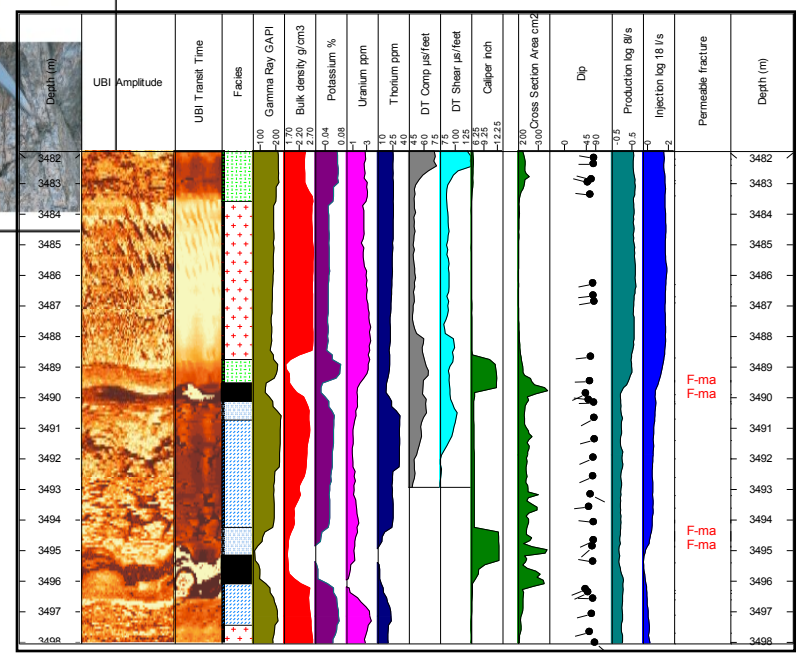
In Catalonia

Geological analogy: tectonic and petrographic analogies are found between "prospective" structure of the deep Soultz granite and the outcropping Catalan granite. Main extensive fault zones are observed in the field, with damaged zone, that could be related to the main structures observed in Soultz. The deep contact between the porphyric and the white granite is also identified in the field.

Porphyric granite

"White" granite

## Analogue models





## Geophysical exploration

see separate presentations on:

- geochemistry
- geophysics



## Case studies

### **Geophysics is used for detecting and imaging**

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

## OVERALL GEOLOGICAL FEATURES

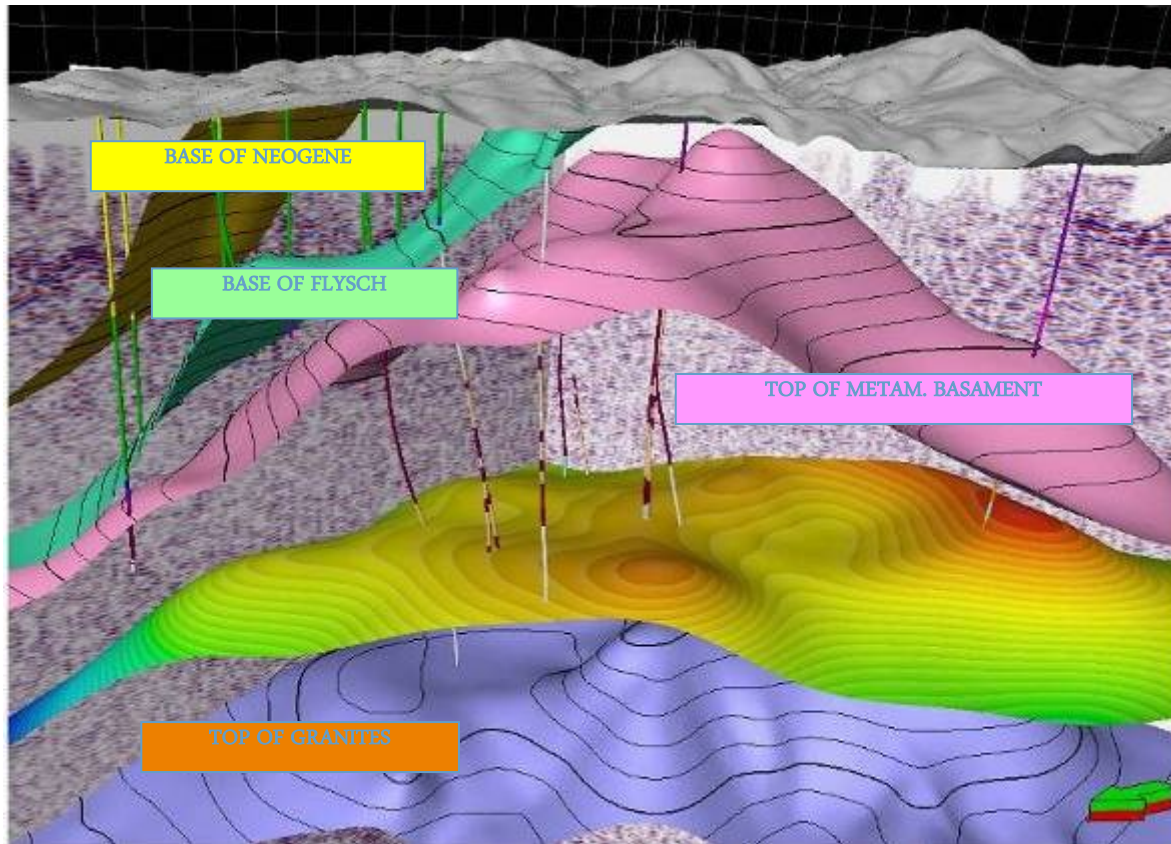
The best suited method in sedimentary and crystalline geological scenarios to extrapolate borehole information and to define and image the geological structure is the **active seismic**.

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.

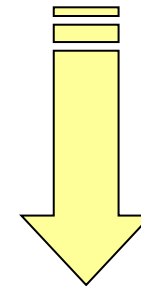
2D or 3D seismic must be calibrated by a comprehensive set of geophysical well logging data and petrophysical data.

Expensive  Cost reduction

# OVERALL GEOLOGICAL FEATURES



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



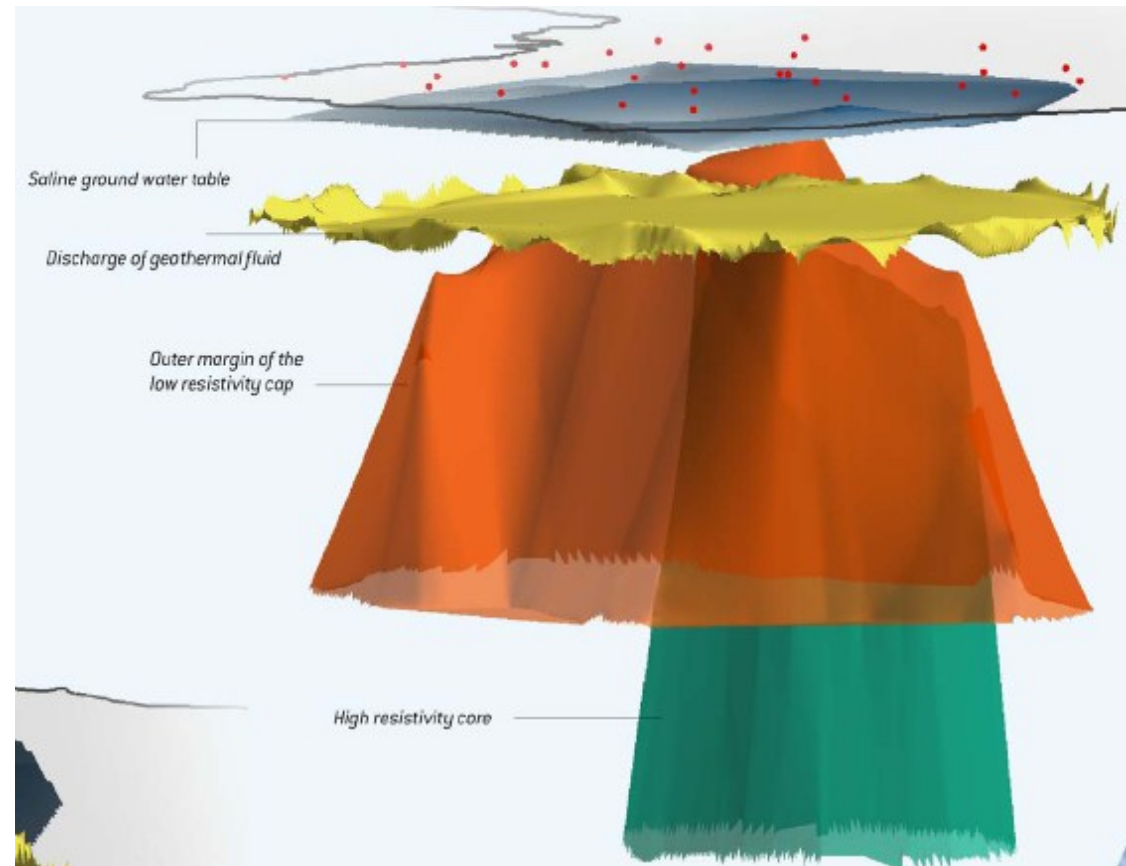
**STRUCTURAL INTERPRETATION**

From ENEL, ENGINE Workshop1



## OVERALL GEOLOGICAL FEATURES

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



From Karlsdottir, ENGINE Workshop1

## OVERALL GEOLOGICAL FEATURES

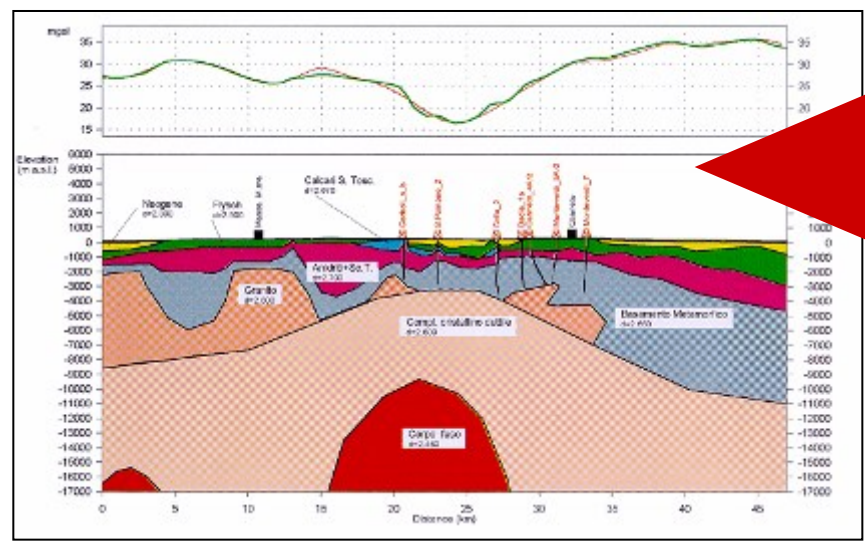
Partially molten intrusives, representing the **heat source** in most of geothermal fields, at depths as shallow as 10 to 20 km produce thermally excited rocks which define high regional **heat flow**

**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**

Density reduction due to partial melts may also be detected by **gravity anomalies**.

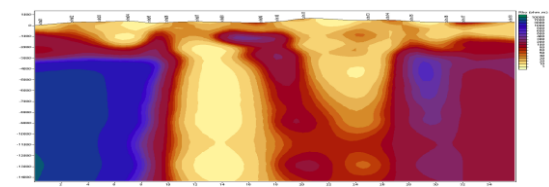
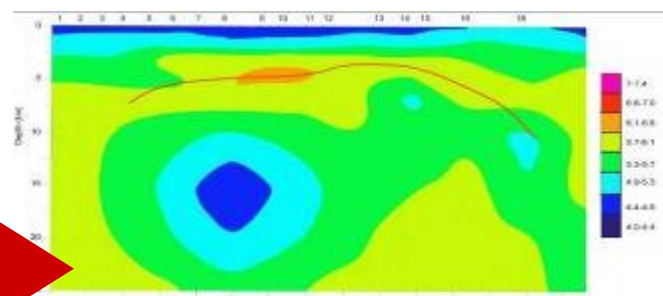
# OVERALL GEOLOGICAL FEATURES



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

From ENEL, ENGINE Workshop1

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



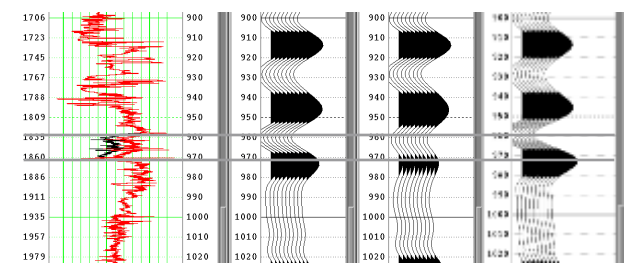
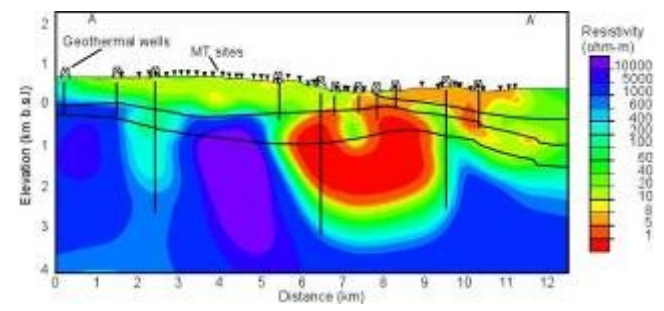


# OVERALL GEOLOGICAL FEATURES

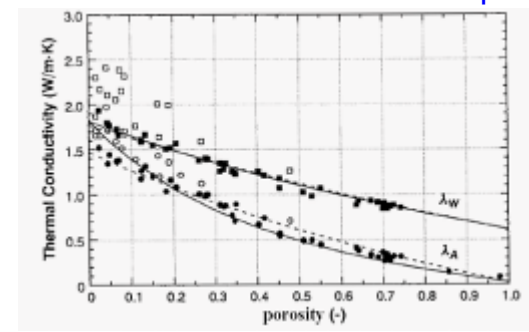
Resistivity decreases with increasing porosity and increasing saturation.

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%.

Thermal conductivity depends also on the porosity of the formation.

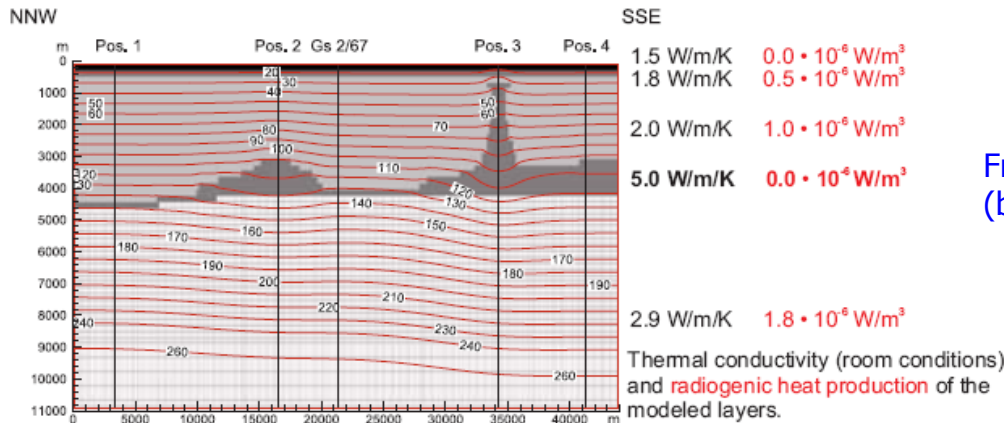


From Trappe, ENGINE Workshop1



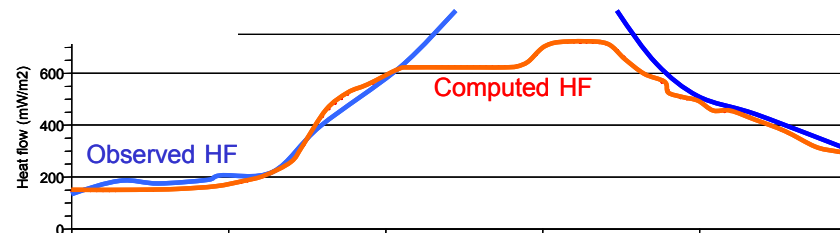


# SUBSURFACE TEMPERATURE

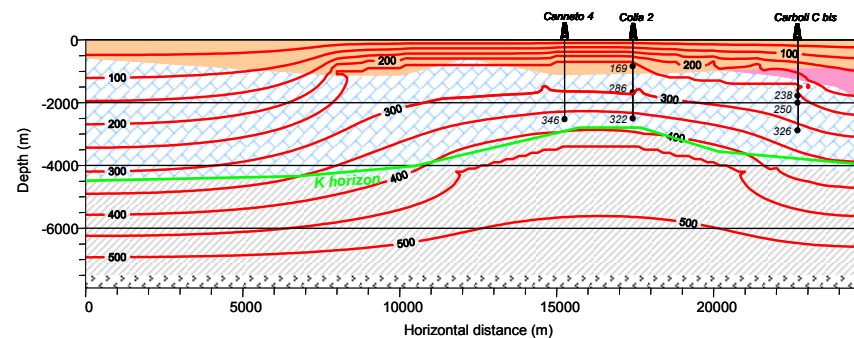


From Norden (left) and Bellani (below), ENGINE Workshop1

With proper care, **heat flow** and gradient data are able to define  $T^\circ$  distribution at depth



**Magnetic** provides info regarding  $T^\circ$  (demagnetization at Curie  $T^\circ$ )



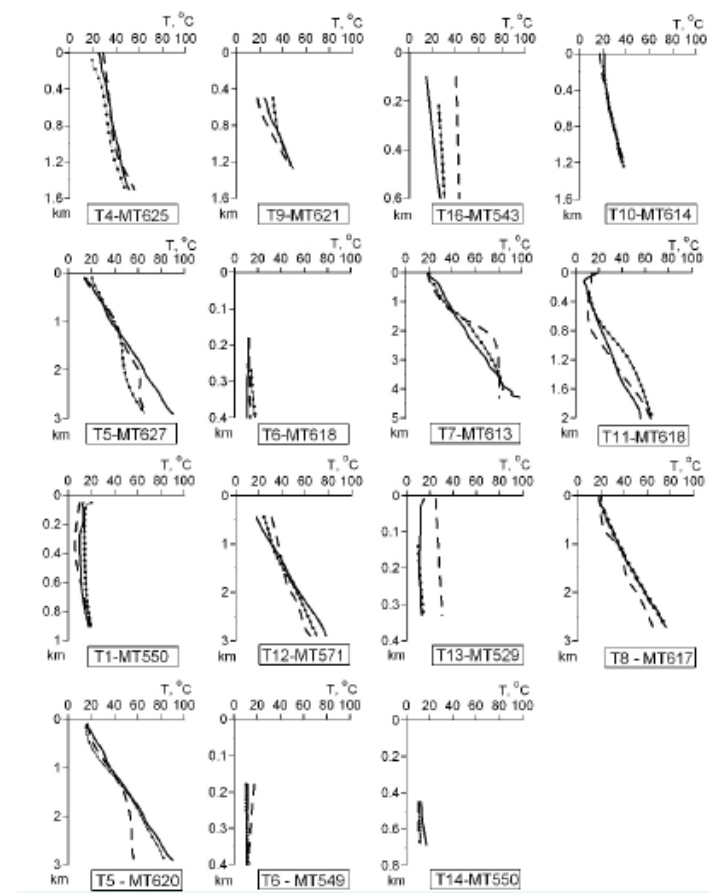




# SUBSURFACE TEMPERATURE

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

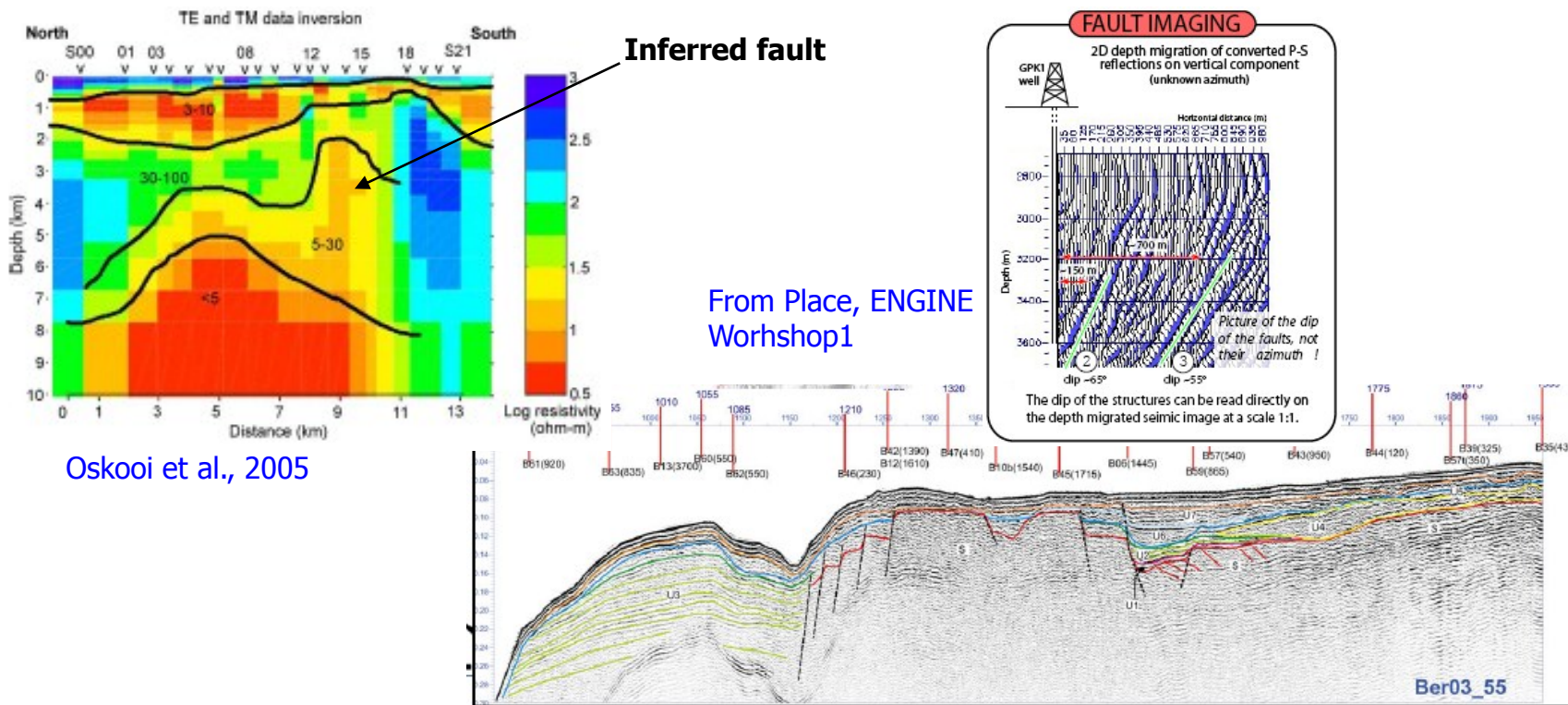
An example is shown for Bishkek site in Tien Shan ([Spichak, ENGINE Workshop1](#)). Measured and modeled  $T^\circ$  distribution in wells. Solid line: measured  $T^\circ$ ; dashed line: modelled  $T^\circ$  based on  $T^\circ$  data only; modelled  $T^\circ$  based on  $T^\circ$  and MT data.





# FLUID PATHWAY

Many geophysical methods are able to map main lineaments and faults



Oskooi et al., 2005

Inferred fault

From Place, ENGINE Workshop1

**FAULT IMAGING**  
 2D depth migration of converted P-S reflections on vertical component (unknown azimuth)

Picture of the dip of the faults, not their azimuth!

dip -65°      dip -55°

The dip of the structures can be read directly on the depth migrated seismic image at a scale 1:1.

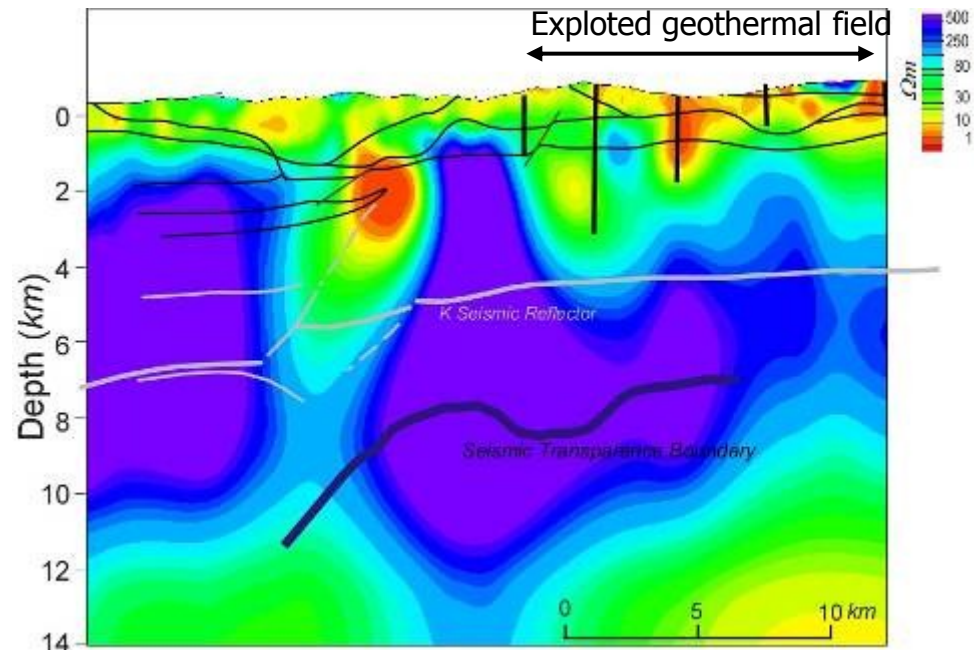
But this is not enough since there is still no direct evidence of fluid circulation

## FLUID PATHWAY

The correspondence between areas of low resistivity inside the resistive basement and geothermal reservoirs was very evident in the Mt. Amiata water-dominated system.

When a fault defined by 2D reflection seismic corresponds to a low resistivity anomaly > water and/or clay

Heat flow provide extra data



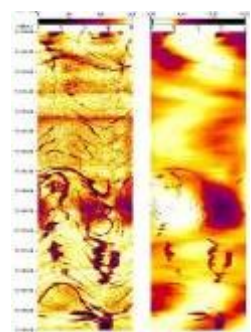
# FLUID PATHWAY

Geophysical well logging by means of:

Elastic/Acoustic and resistivity parameters

Waveform analysis

360° Hole Imaging

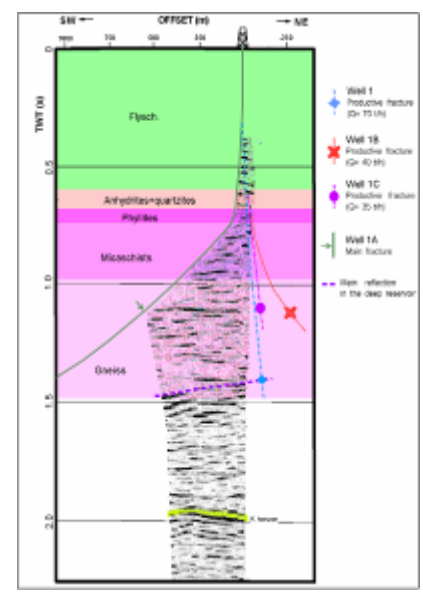
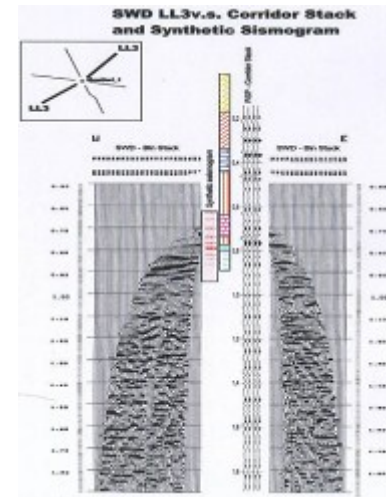


From Dezayes, ENGINE Workshop1

WSP (Well Seismic Profiling):

VSP

SWD



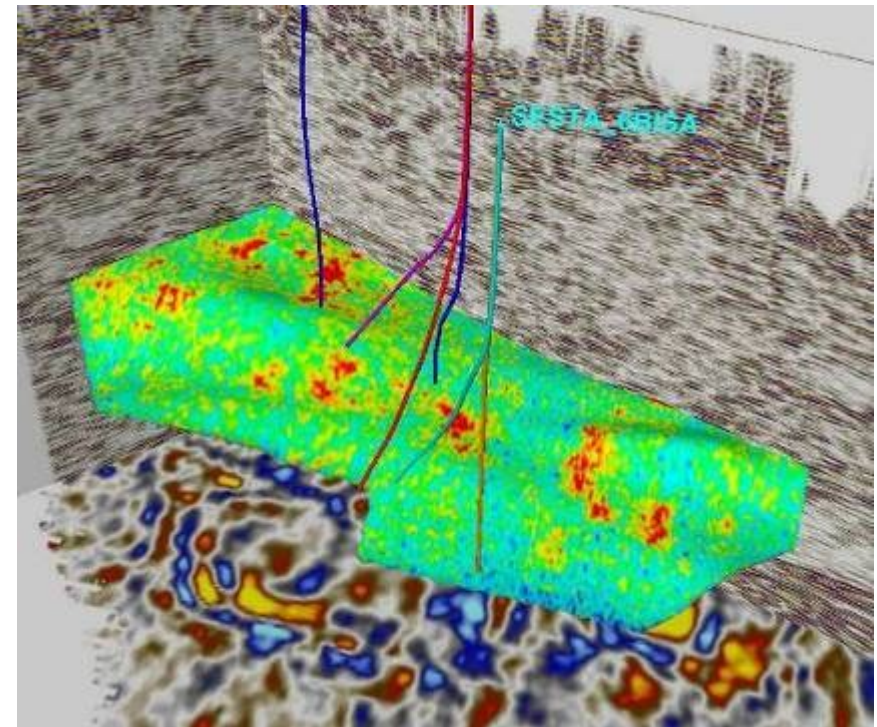
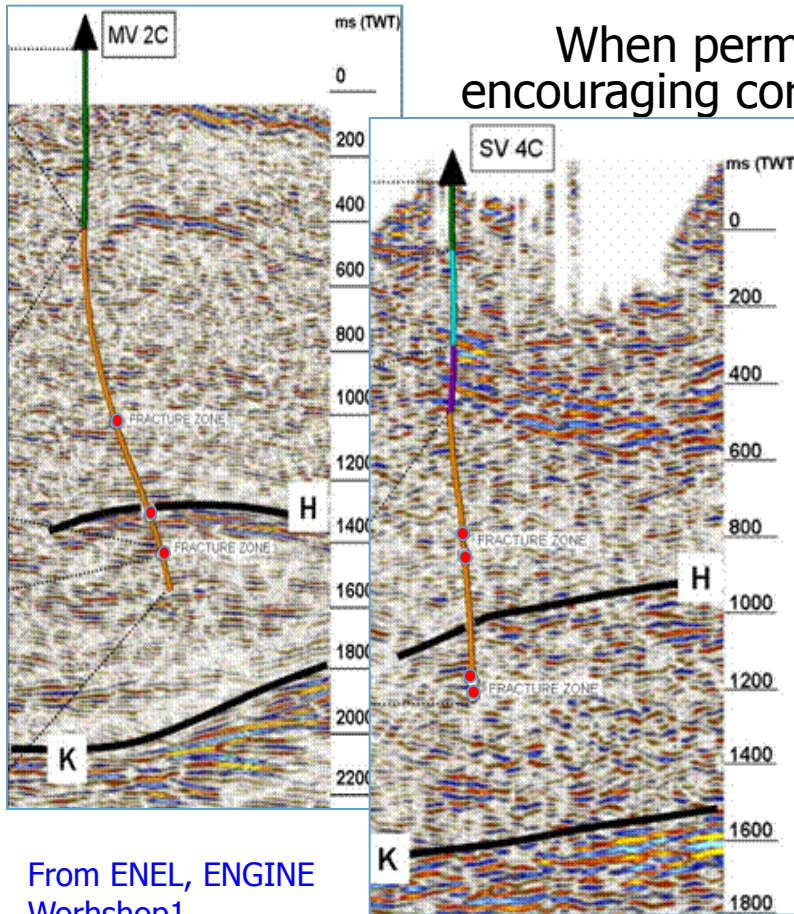
From ENEL, ENGINE Workshop1

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



# FLUID PATHWAY

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

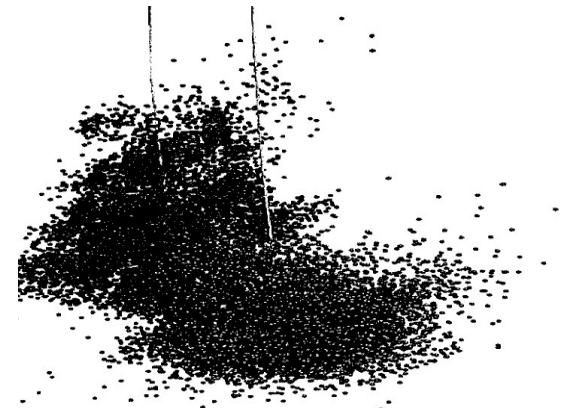


From ENEL, ENGINE Workshop1



## FLUID PATHWAY

Observing small mining produced seismic event has been called **seismic monitoring**. Events produced from fluid flow but also from internal subsidence have been successfully recorded and used to study fluid flow in time and space. Much larger events in reservoirs are generated during stimulation with artificial hydro-fracs. Monitoring the development of those fracs is usually called **fracture monitoring**.

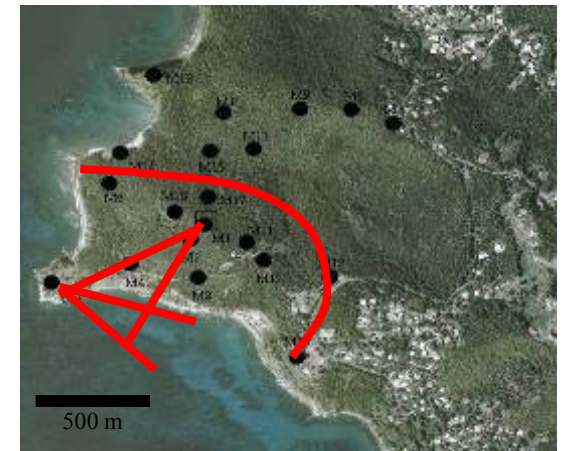
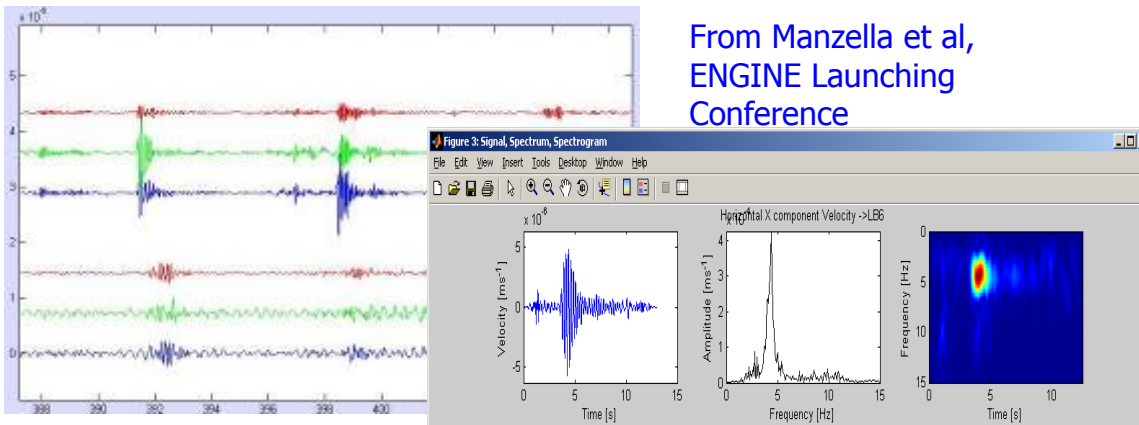


# FLUID PATHWAY

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

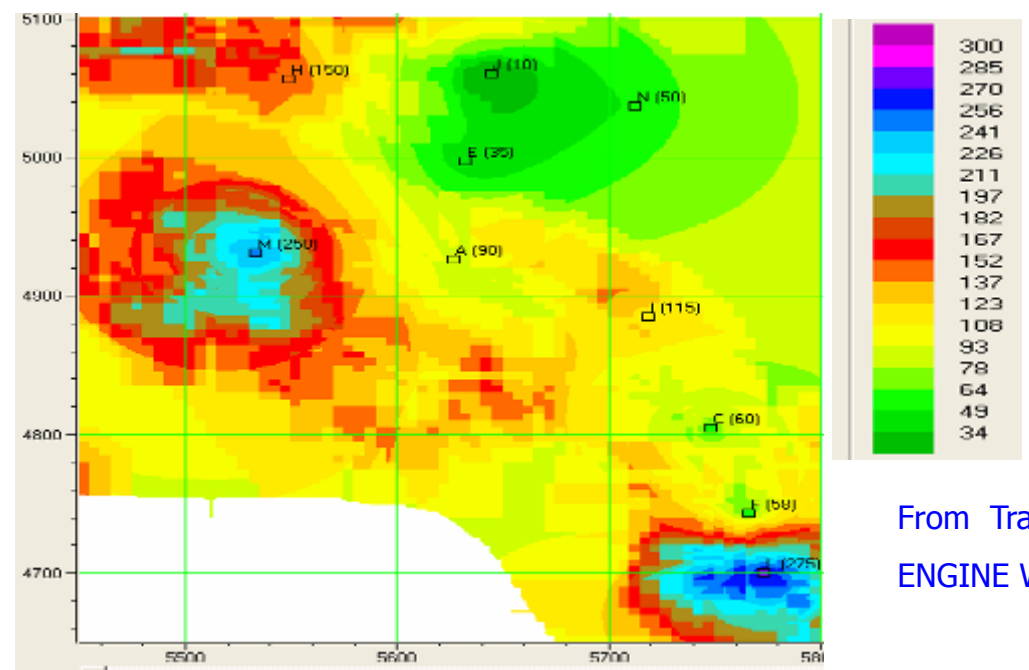






# FLUID PATHWAY

Quantitative fracture prediction is made possible by modern reflection seismic concepts



Normalized fracture density after cokriging

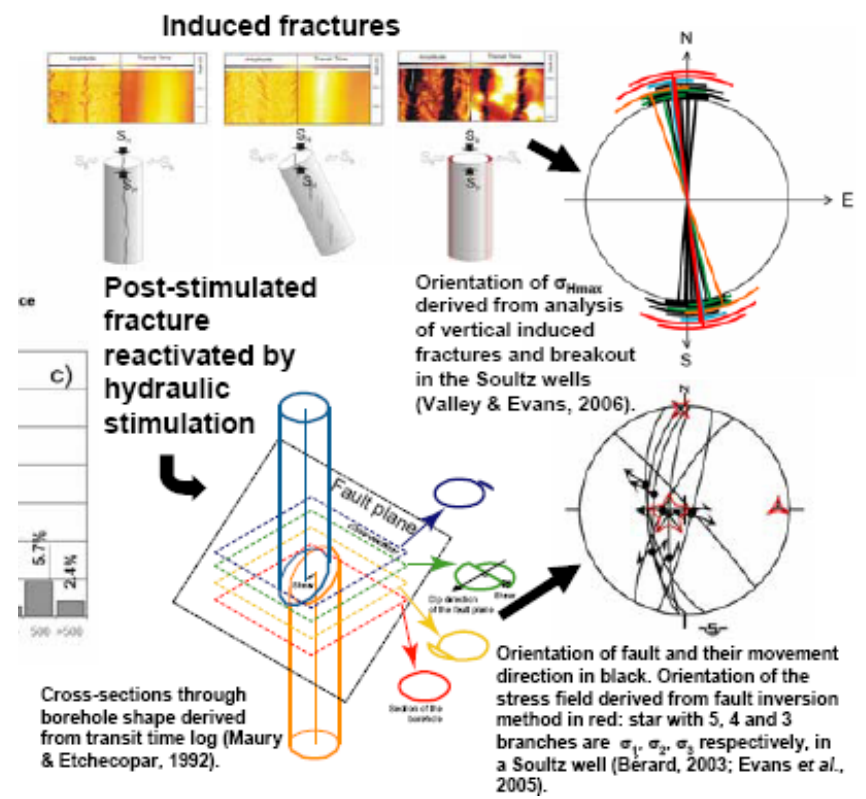
From Trappe,  
ENGINE Workshop1

# STRESS FIELD

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

Induced fractures (vertical induced fractures, enéchélon 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 Dezayas, ENGINE Workshop1



## MONITORING

Gravity monitoring surveys are performed also to define the change in groundwater level and for subsidence monitoring.

Fluid extraction from the ground which is not rapidly replaced causes an increase of pore pressure and hence of density. This effect may arrive at surface and produce a subsidence, whose rate depends on the recharge rate of fluid in the extraction area and the rocks interested by compaction.

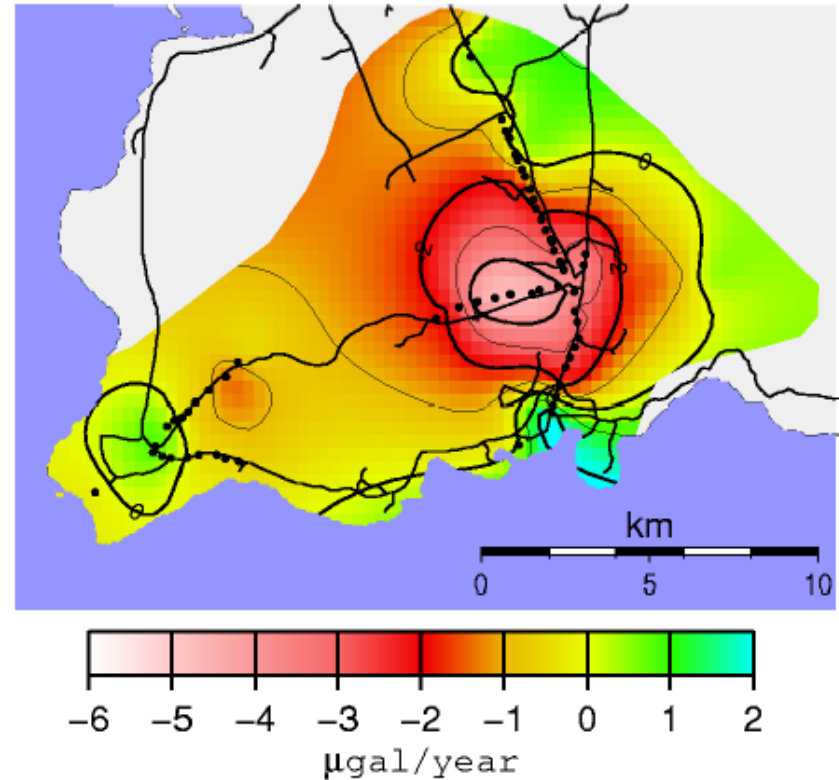
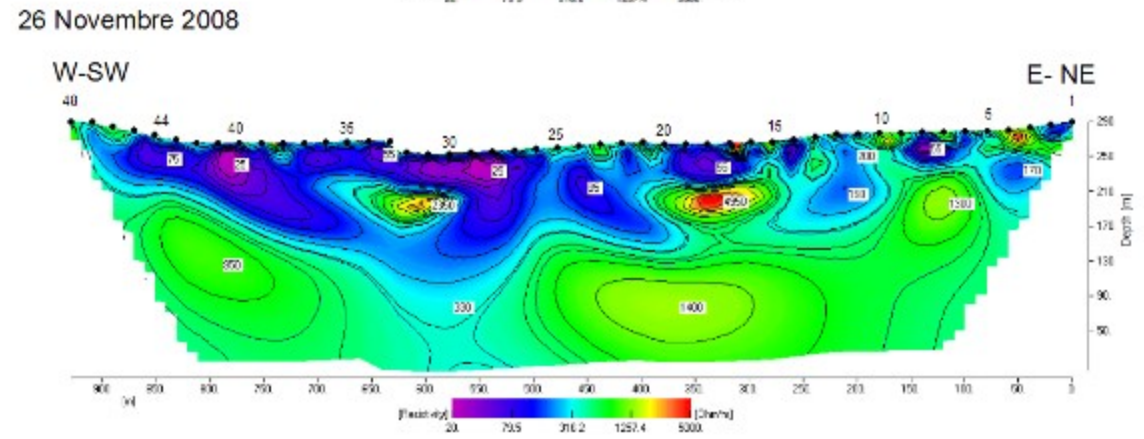
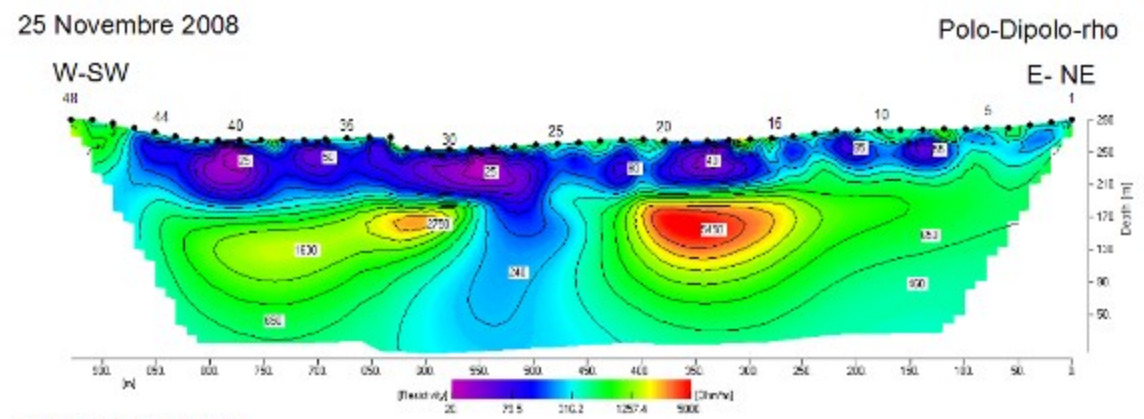


Figure 8. Mean gravity variation ( $\mu\text{gal}/\text{year}$ ) from 1975 to 1999. Only points measured in 1999 and at least two times earlier are used.



# MONITORING

Geothermal exploration at a low enthalpy field using ERT. The low resistivity zone is coincident with a known fault where warm and saline fluids mix with surface and fresh water. An example of monitoring the effect on resistivity change when fresh water is pumped out from a well at the center of profile: the increase of salinity and temperature in the subsurface decreases the resistivity





# MONITORING

Phase change of pore fluid (boiling/condensing) in fractured rocks can result in resistivity changes that are more than an order of magnitude greater than those measured in intact rocks

Production-induced changes in resistivity can provide valuable insights into the evolution of the host rock and resident fluids.

No examples or applications found in literature

Some examples from SP (electric field) showing interesting results: is it possible to use the same kind of information in MT? To be defined

