Session I: Geothermal Exploration

What is geothermal energy:

origin and relation with earth dynamics

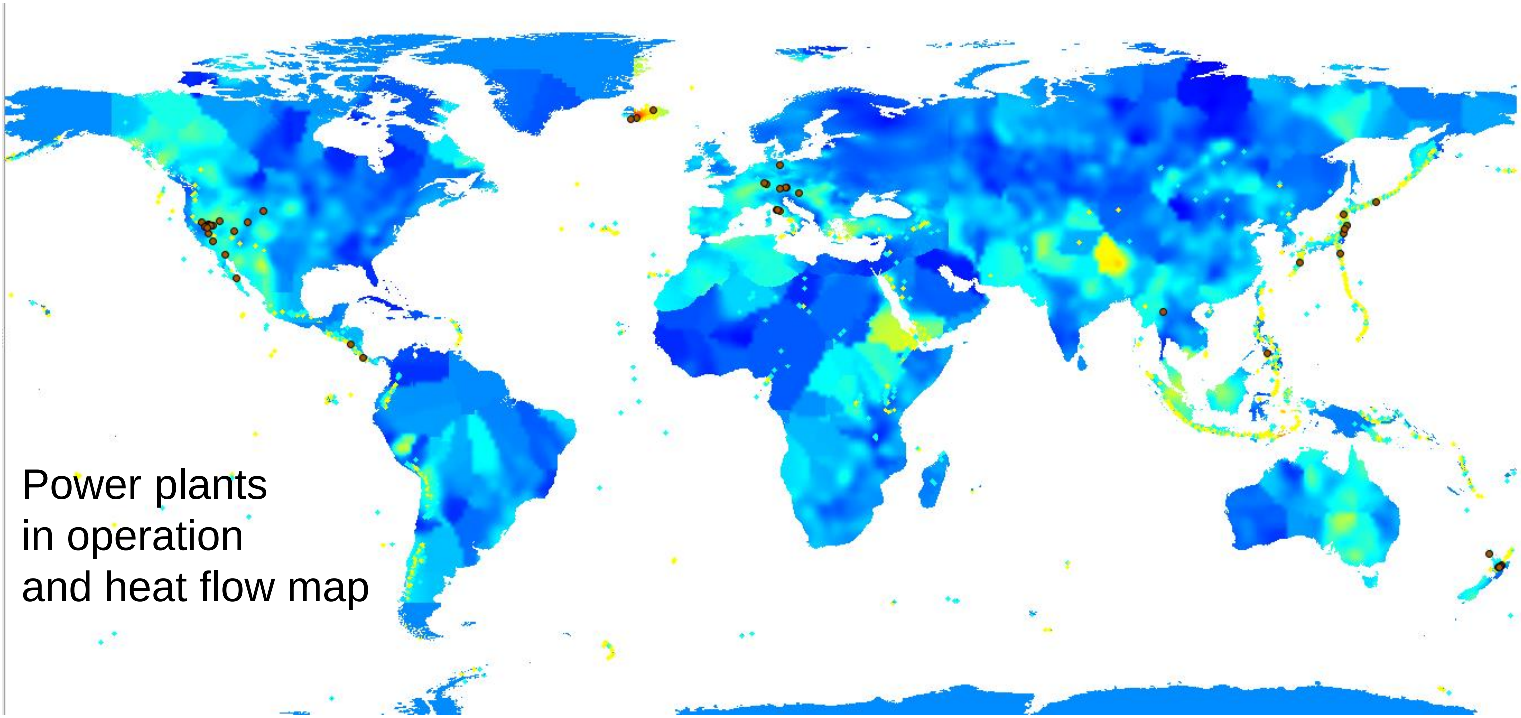
Resource assessment: targets and tools

An overview of targets

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?



Power plants
in operation
and heat flow map

Exploration and Investigation: the quest

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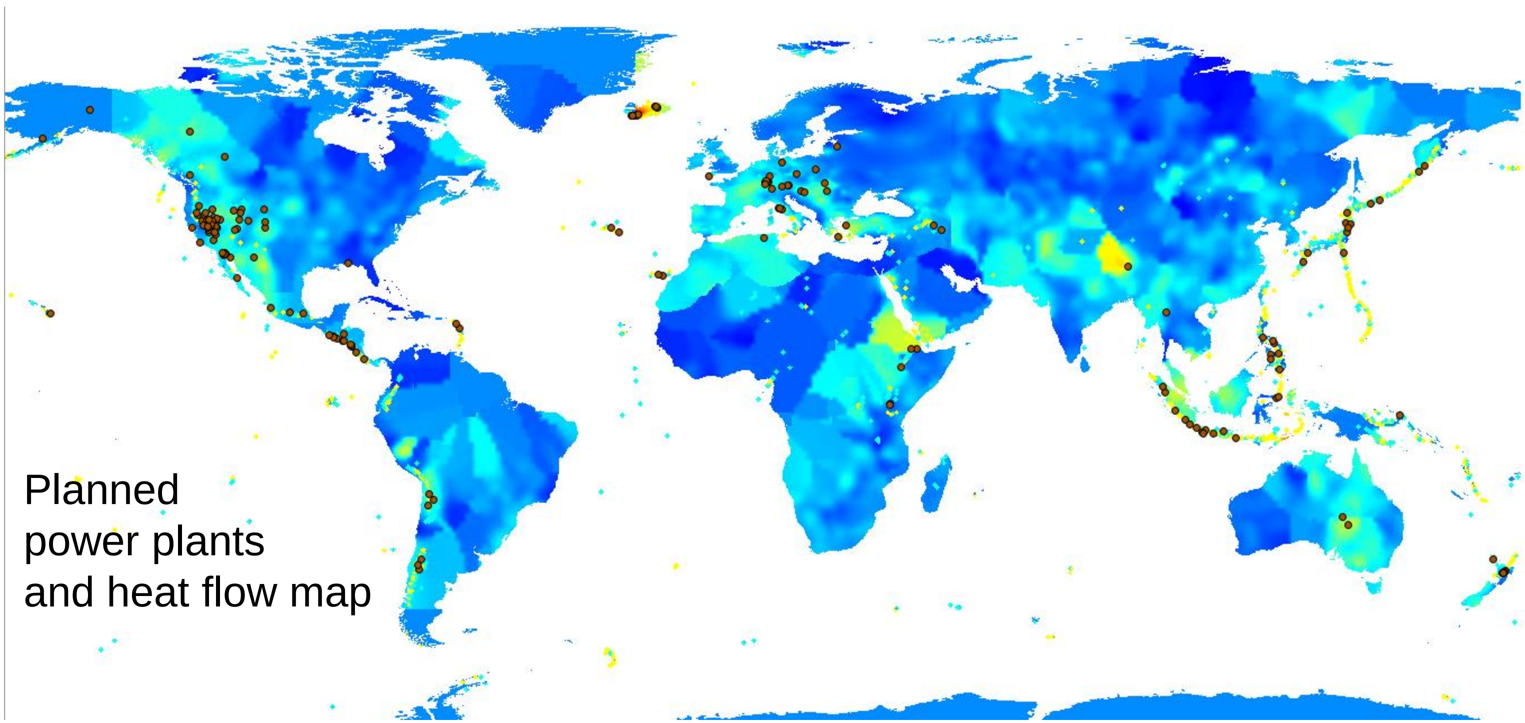


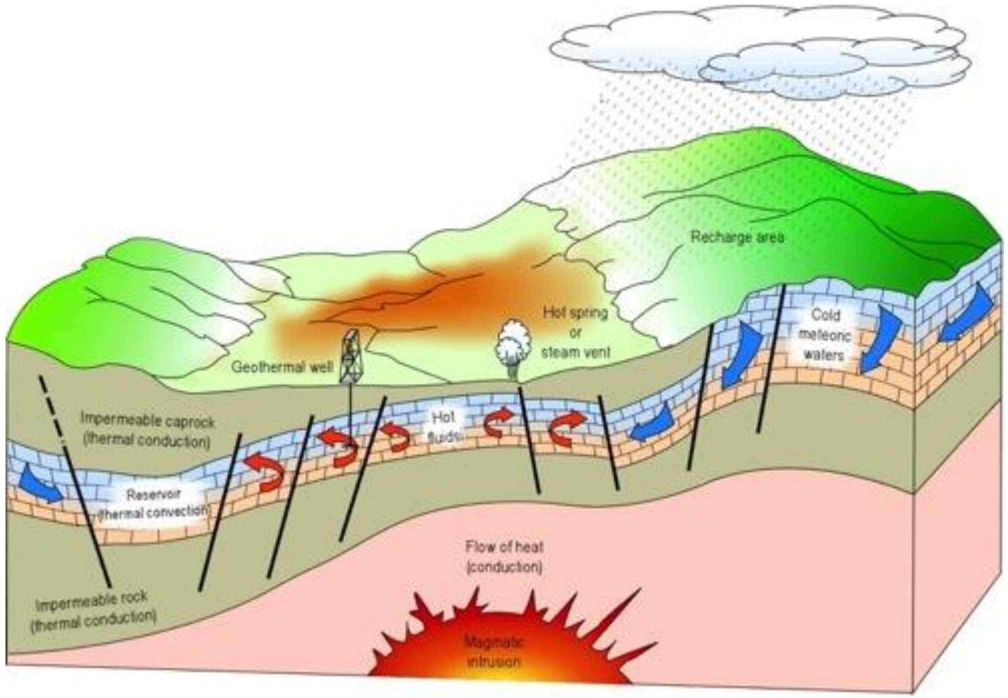
Exploration and Investigation: the quest

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

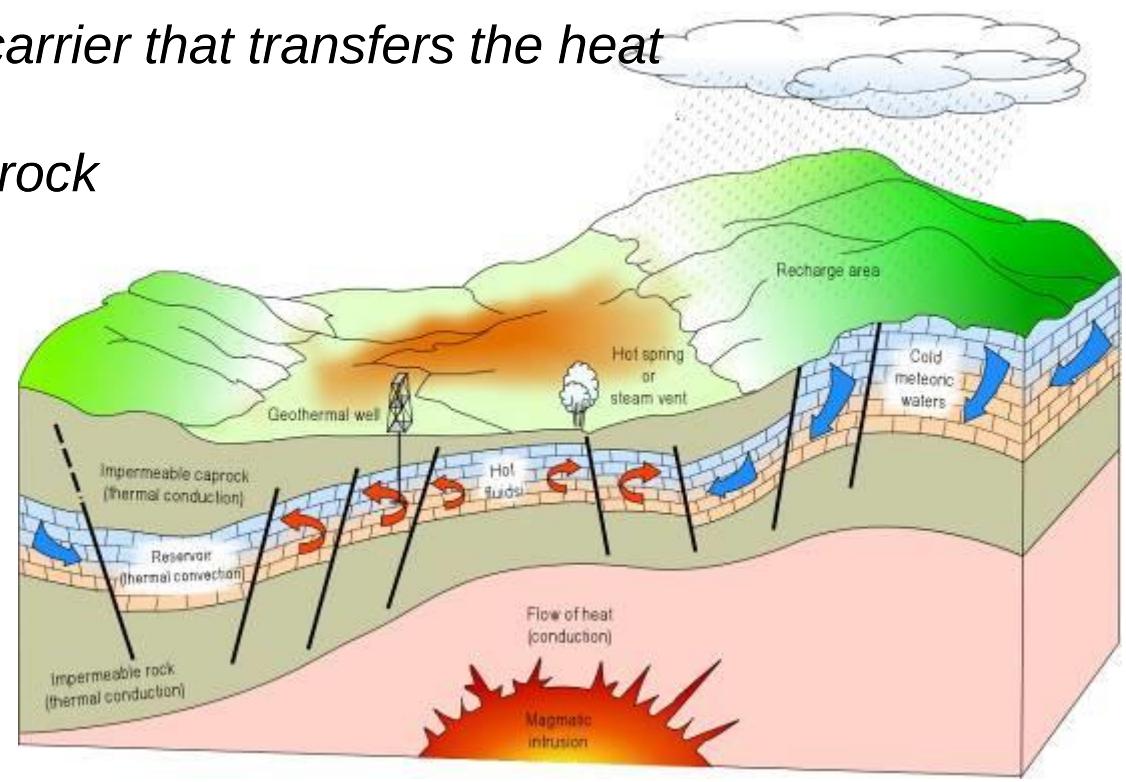
A *geothermal system* can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface".



Hydrothermal systems

Elements of a hydrothermal geothermal system:

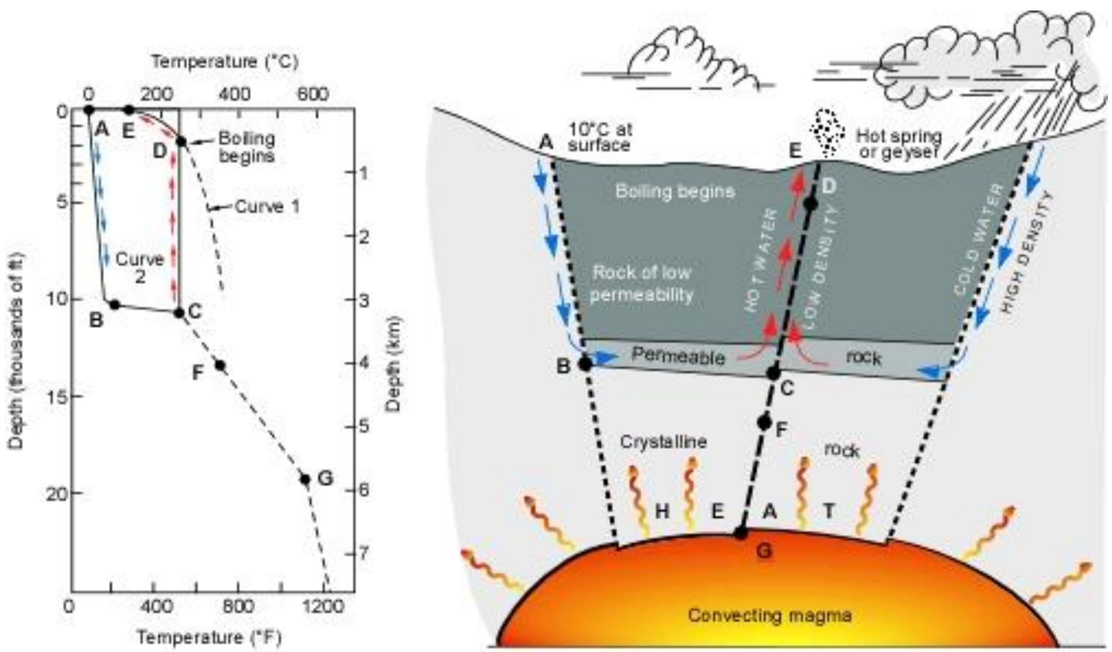
a heat source
a reservoir
a fluid, which is the carrier that transfers the heat
a recharge area
an impermeable caprock



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.

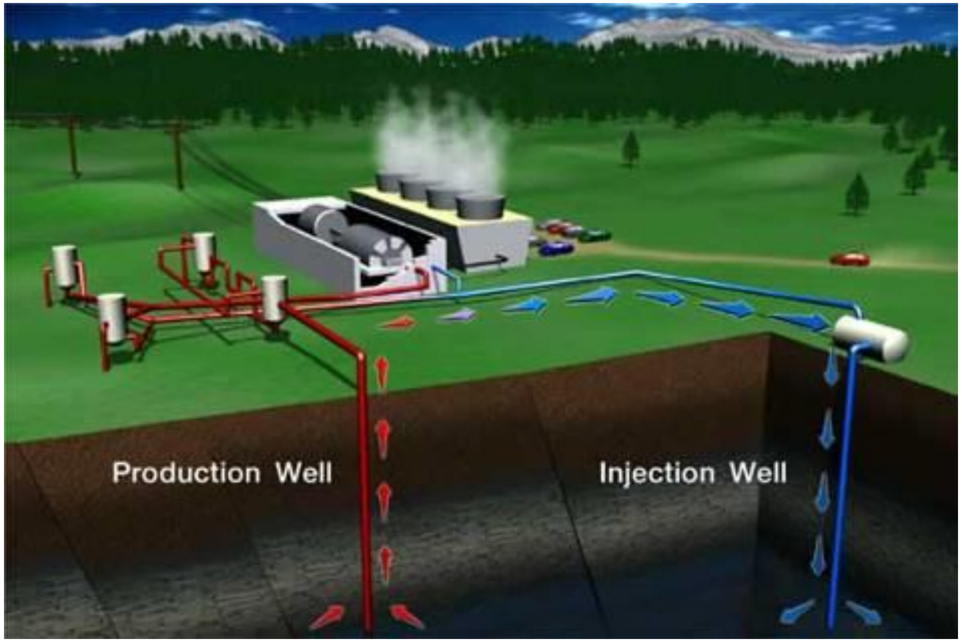
productivity requirement

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.

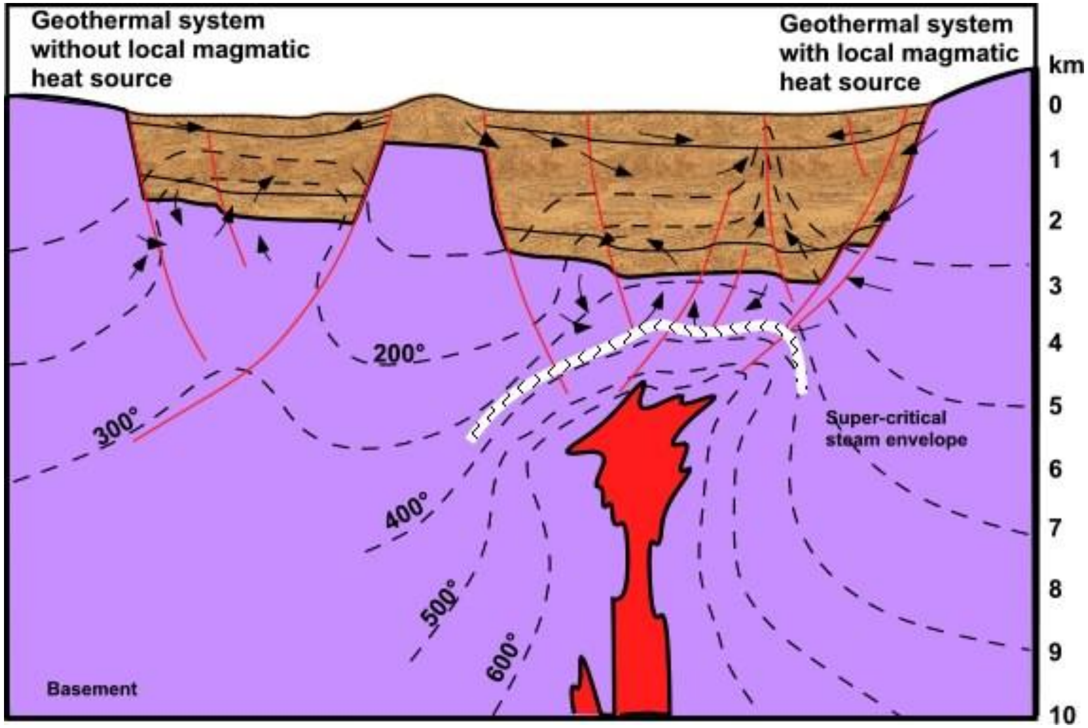
Volcanic rocks are the most common single rock type in which reservoirs occur.

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

Toward unconventional systems

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_t (thermal) $\Rightarrow$ 1MW_e (power)

Further objectives

Example: power production (continues)

To produce 1 MW_e 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)

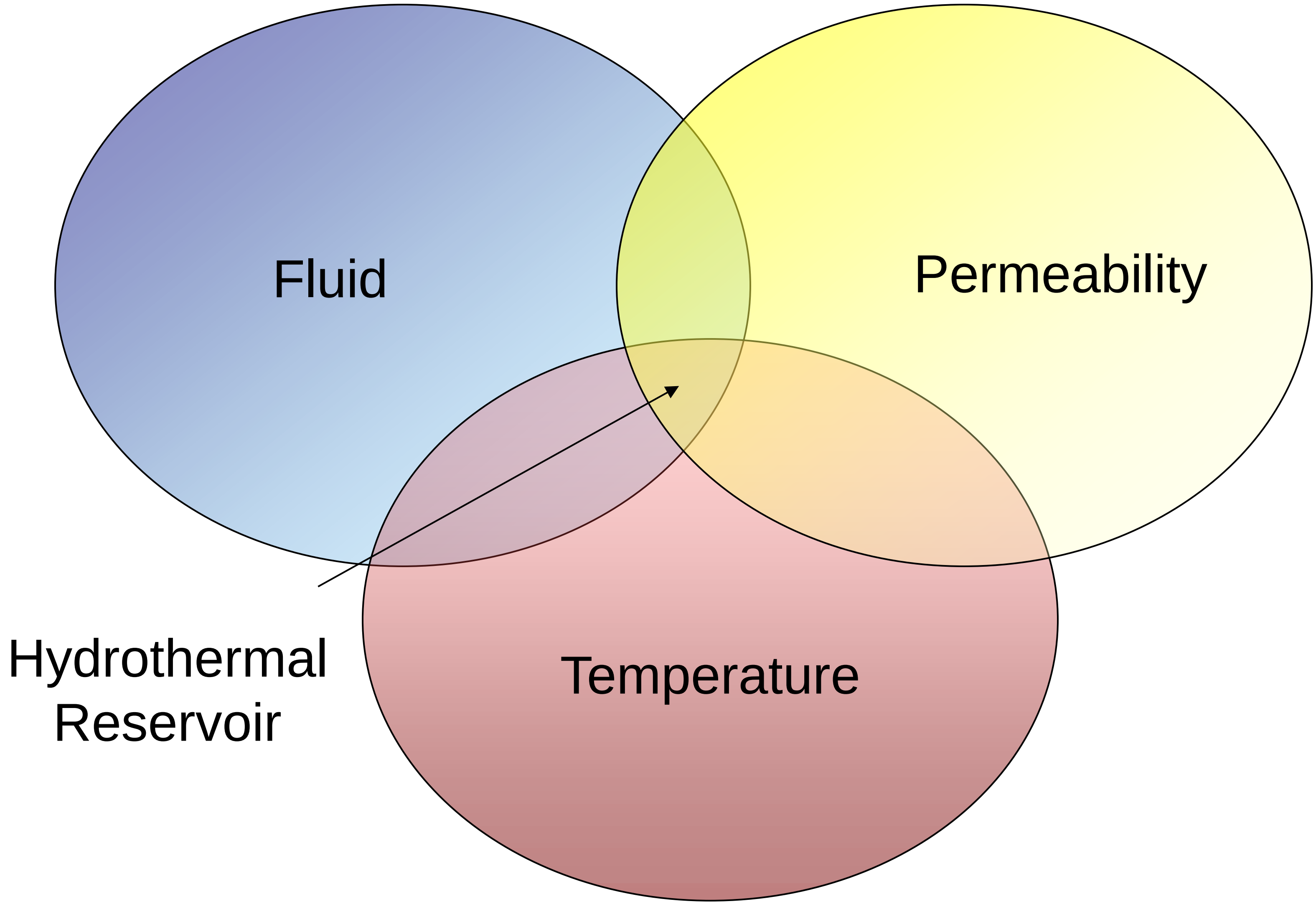
The lower the temperature, the higher the amount of fluid required to produce a unit quantity of thermal (and electric) energy.

Further objectives

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)

Further objectives



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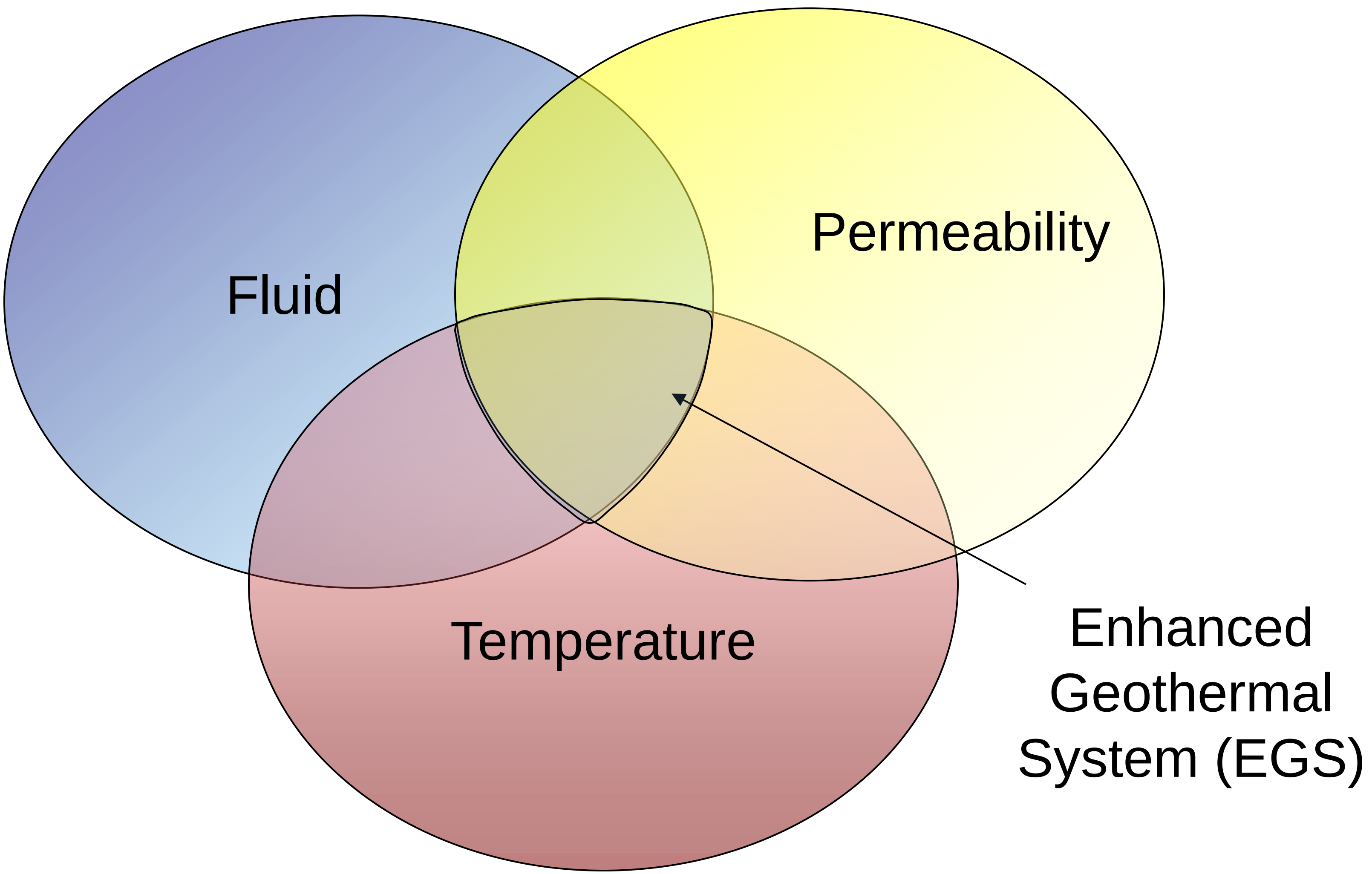
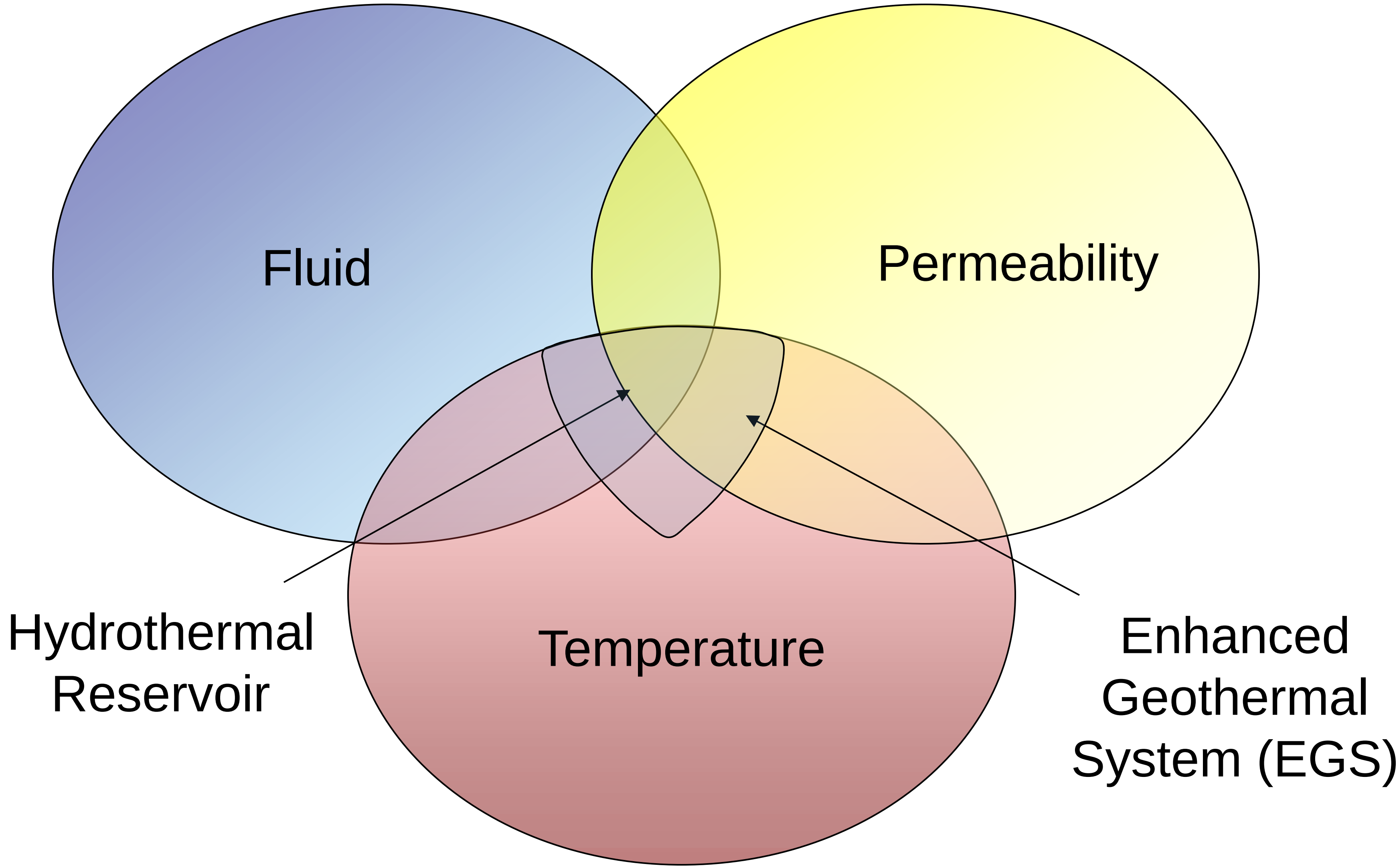


Further objectives



Further objectives

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
• induced seismicity (during stimulation but also due to production) becomes a real issue;
• uniform connectivity throughout a planned reservoir cannot yet be engineered.
• scalability

Enhanced Geothermal Systems: the concept

Enhancing and broadening geothermal energy reserves

- stimulating reservoirs in Hot Dry/Wet Rock systems and enlarging the extent of productive geothermal fields
- improving thermodynamic cycles
- improving exploration methods for deep geothermal resources
- improving drilling and reservoir assessment technology
- defining new targets and new tools for reaching supercritical fluid systems, especially high-temperature down-hole tools and instruments
- improving technology to produce from other kind of unconventional geothermal systems (geopressurized, magmatic and supercritical)

The role of E&I

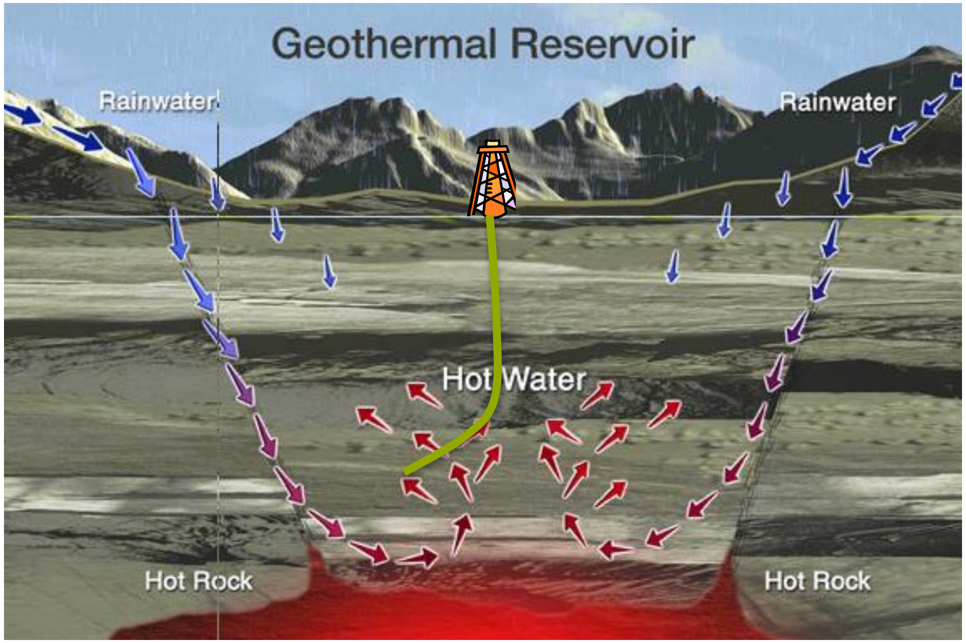
E&I techniques are used in all the geothermal project phases

- *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

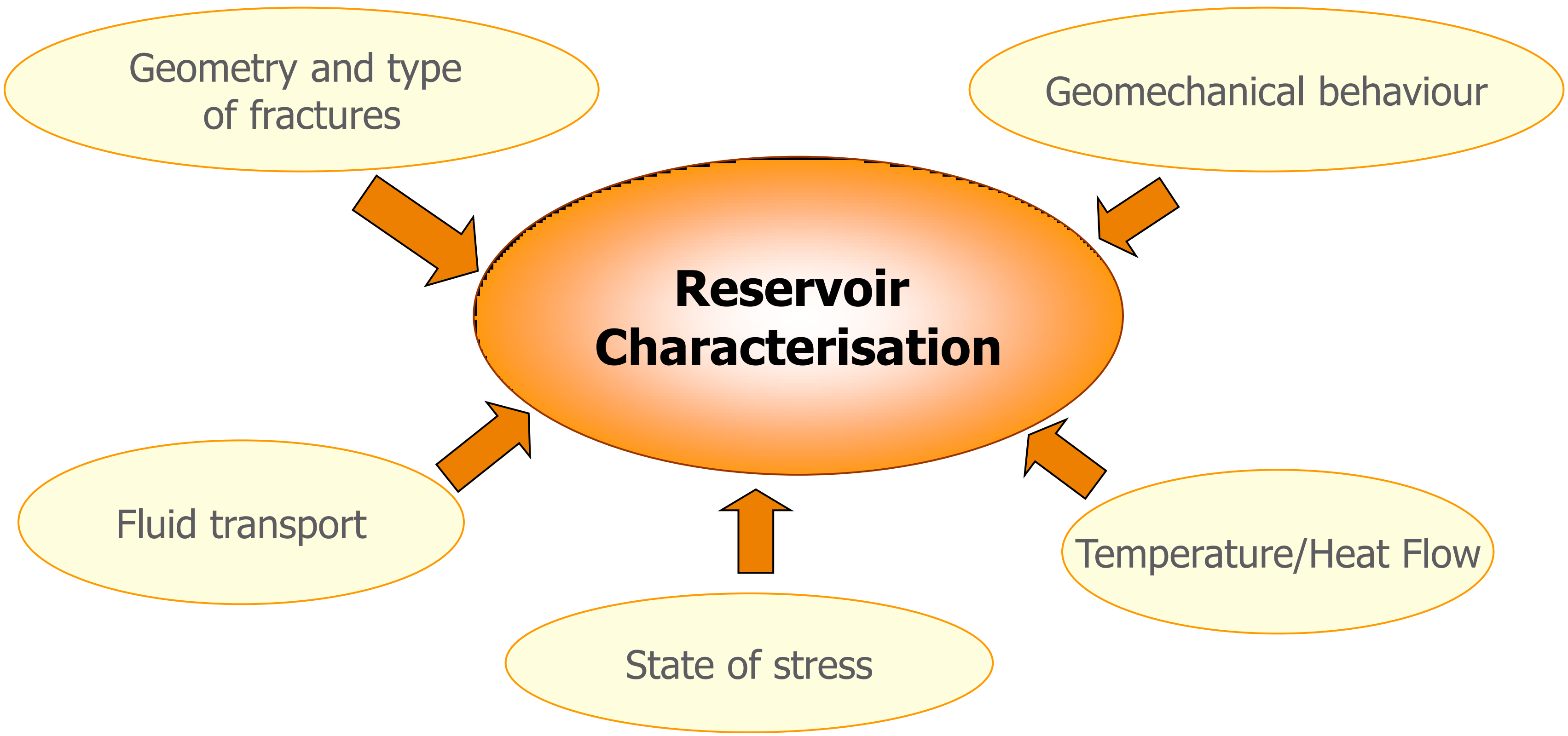


Goals to be achieved by E&I

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.

Goals to be achieved by E&I

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.

Resource assessment: targets and tools

Geophysical Methods
for geothermal exploration

Geophysics

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.

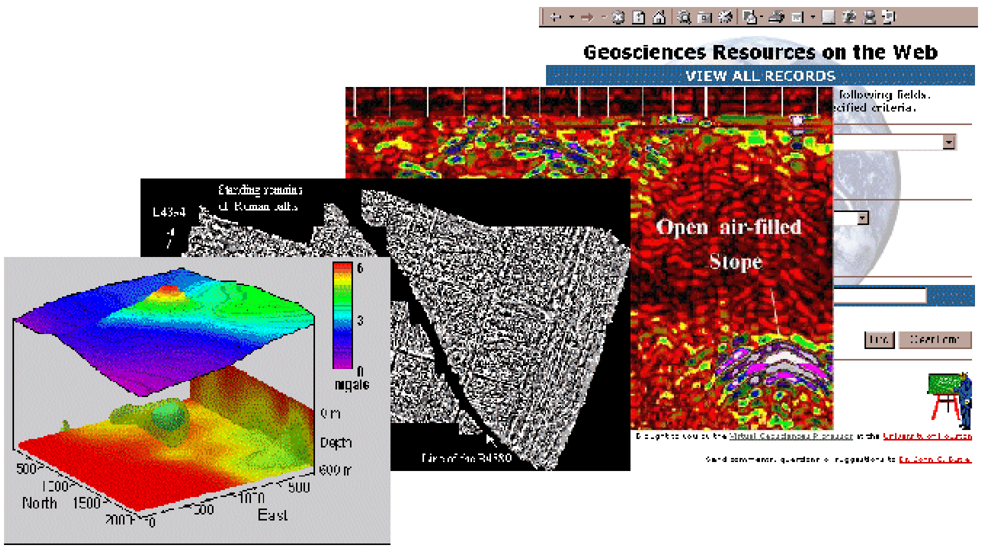
Geophysical techniques are indirect investigation surveys (from the surface or in hole) which allow to evaluate the distribution of some physical parameter:

- From these measurements model parameters are extracted;
- These parameters can be related in a second interpretation step to geological or applicative parameters.

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.

Geophysics

Geophysics provides an undirect evidence (an “image”) of certain features of the underground, like bio-medical images

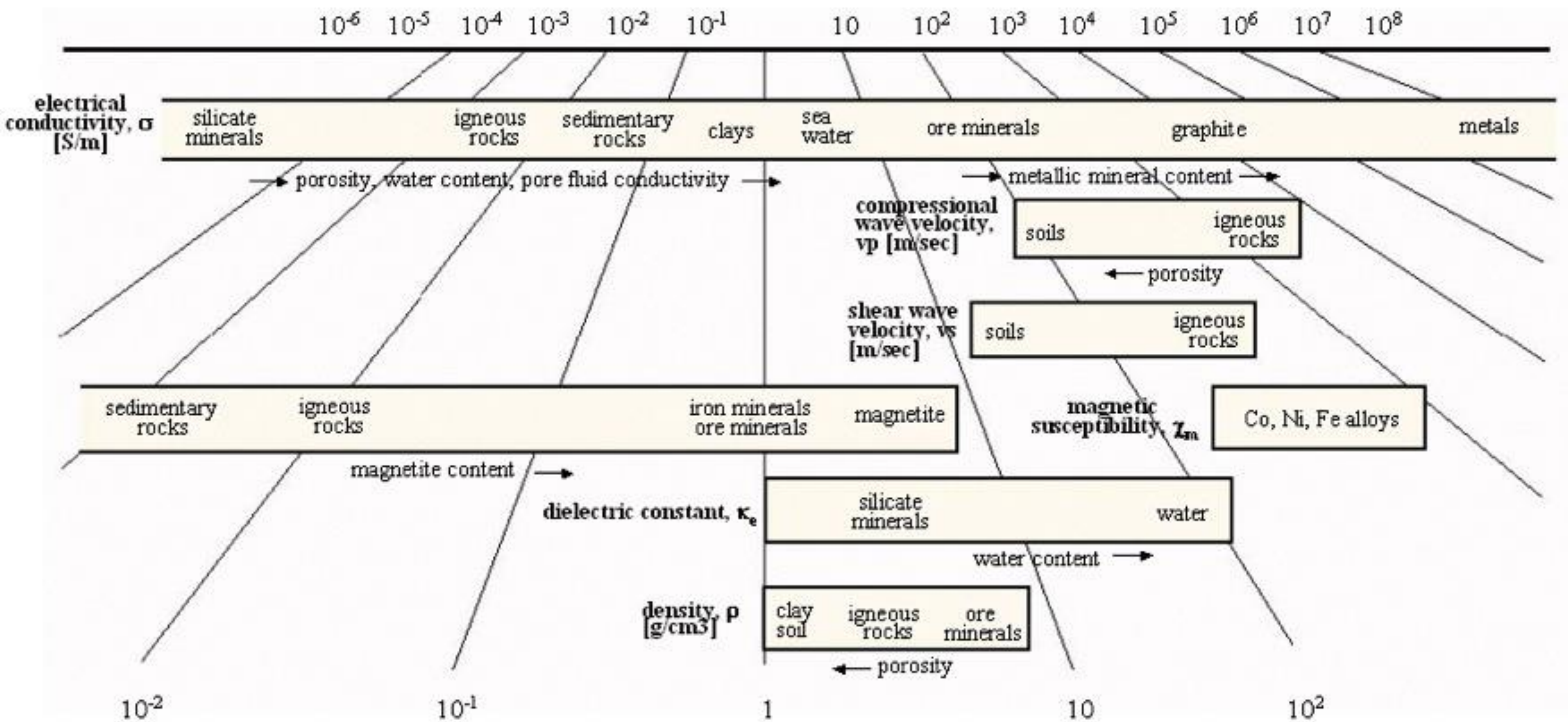


This is obtained by measuring the response of the medium under investigation to the passage of a certain “energy field”:

natural → passive tests or artificially induced → active tests

Geophysics

The range of values for the physical properties that can be measured with the methods of applied geophysics is very variable.



Geophysics

It is not wise to define a particular sequence of geophysical surveys as being applicable to all potential reservoirs

Physical property / Target	Density	Magnetic susceptibiity	Electrical resistivity	Dielectric permittivity	Seismic velocity
Porosity	Strong	None	Strong	Moderate	Moderate
Permeability	None	None	Weak	Weak	Weak
Water content	Moderate	None	Strong	Strong	Moderate
Water quality	None	None	Strong	None	None
Clay content	Weak	None	Strong	Weak	Moderate
Magnetic mineral content	Moderate	Strong	Weak	None	None
Metallic mineral content	Strong	None	Strong	None	Moderate
Mechanical properties	Moderate	None	Moderate	Weak	Strong
Subsurface structure	Moderate	Moderate	Moderate	Strong	Strong

Strong	Moderate	Weak	None

Degree of relationship

Geophysics

A geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface.

Changing physical parameters:

temperature (*thermal survey*)

electrical conductivity (*electrical and electromagnetic survey*)

elastic properties influencing the propagation velocity of elastic waves (*seismic survey*)

density (*gravity survey*)

magnetic susceptibility (*magnetic survey*).

Geophysics: GRAVITY SURVEYS

The earth's gravitational field is usually described by the vertical component of the gravitational acceleration g_z.

Combining two of Newton's law

Universal law of gravitation $F=Gm_1m_2/r^2$

G gravitational constant 6.67 x 10^-11 m3 kg-1 s-2

Second law of motion F=mg

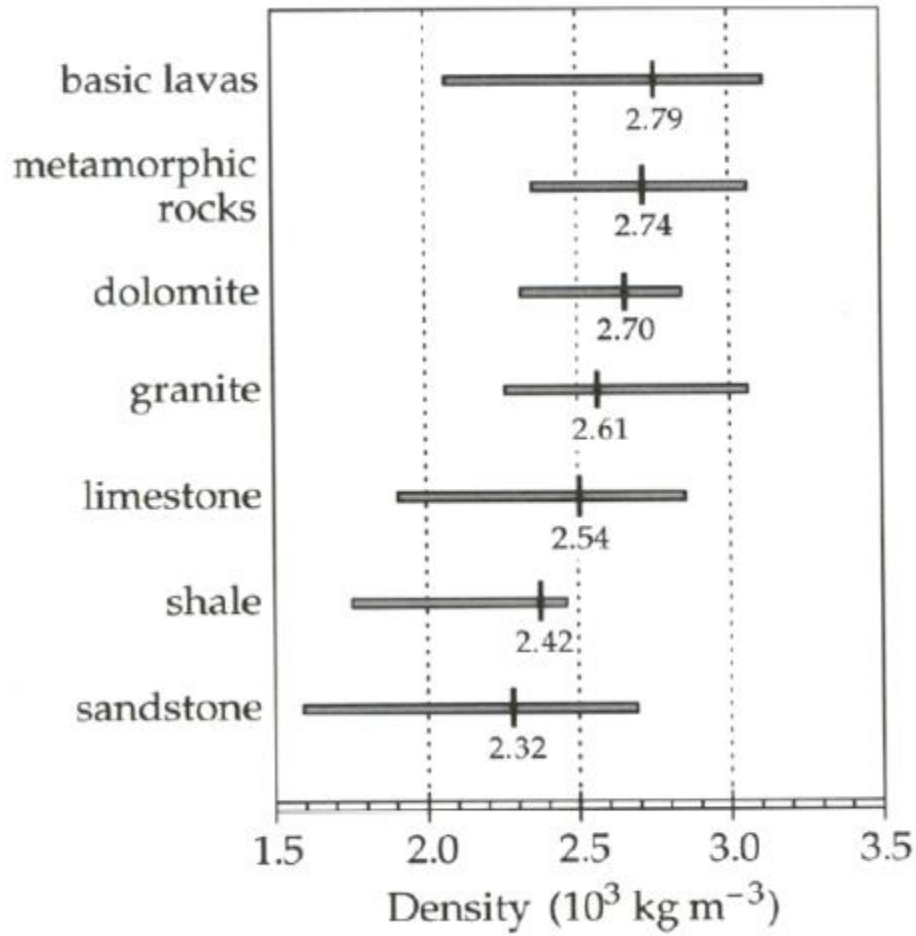
g gravitational acceleration or "gravity"

We obtain $g=GM_E/R^2$

Geophysics: GRAVITY SURVEYS

Positive gravity anomalies > higher density
associated with plutonic intrusions and dykes, deposition of silicates from hydrothermal activities during greenschist metamorphism.

Negative gravity anomalies > lower densities
caused by higher porosities or by highly fractured parts of a rock, alteration minerals produced by circulation of hot water



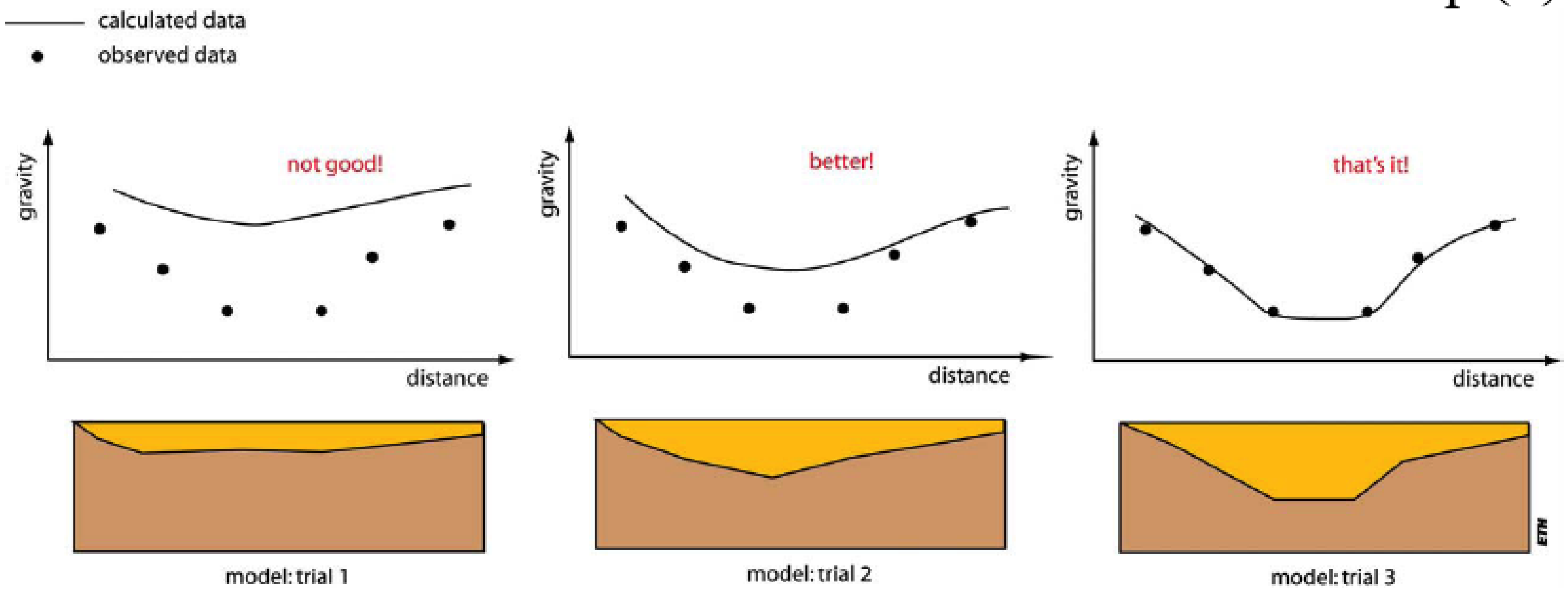
Geophysics: GRAVITY SURVEYS

(1) Construction of a reasonable model

(2) Computation of its gravity anomaly

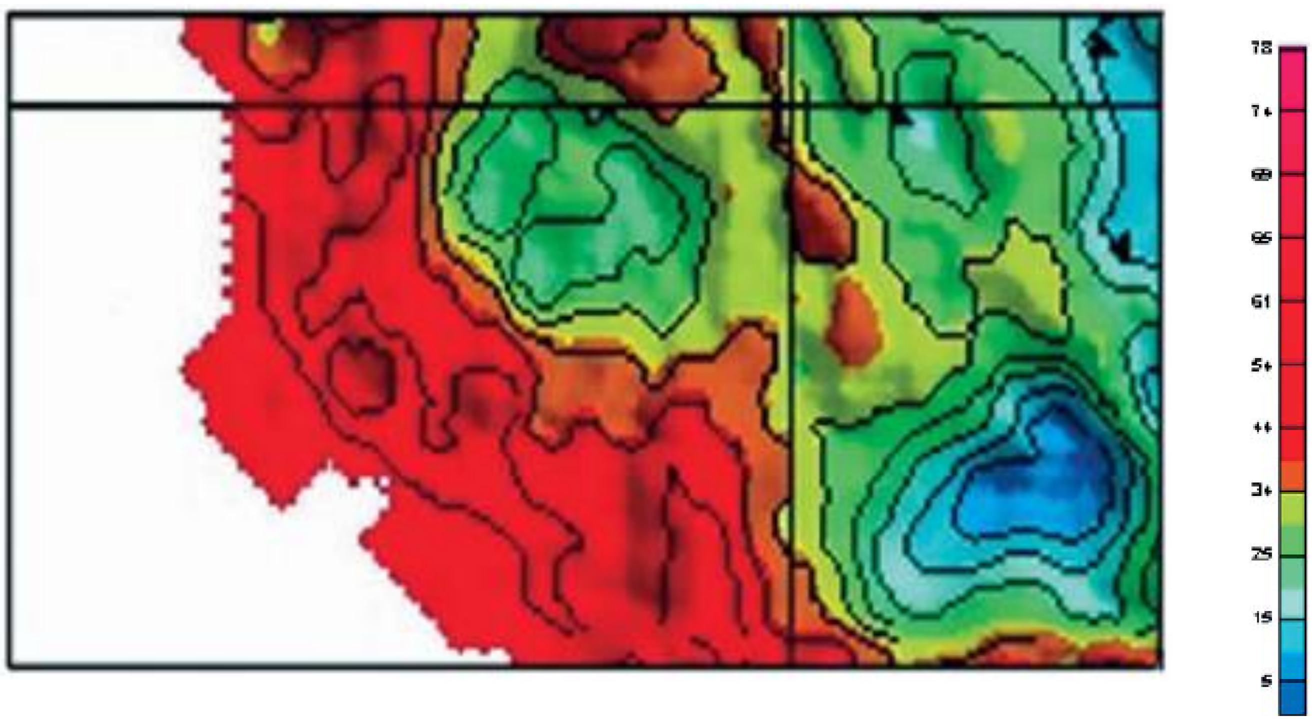
(3) Comparison of computed with observed anomaly

(4) Alteration of the model to improve correspondence of observed and calculated anomalies and return to step (2)



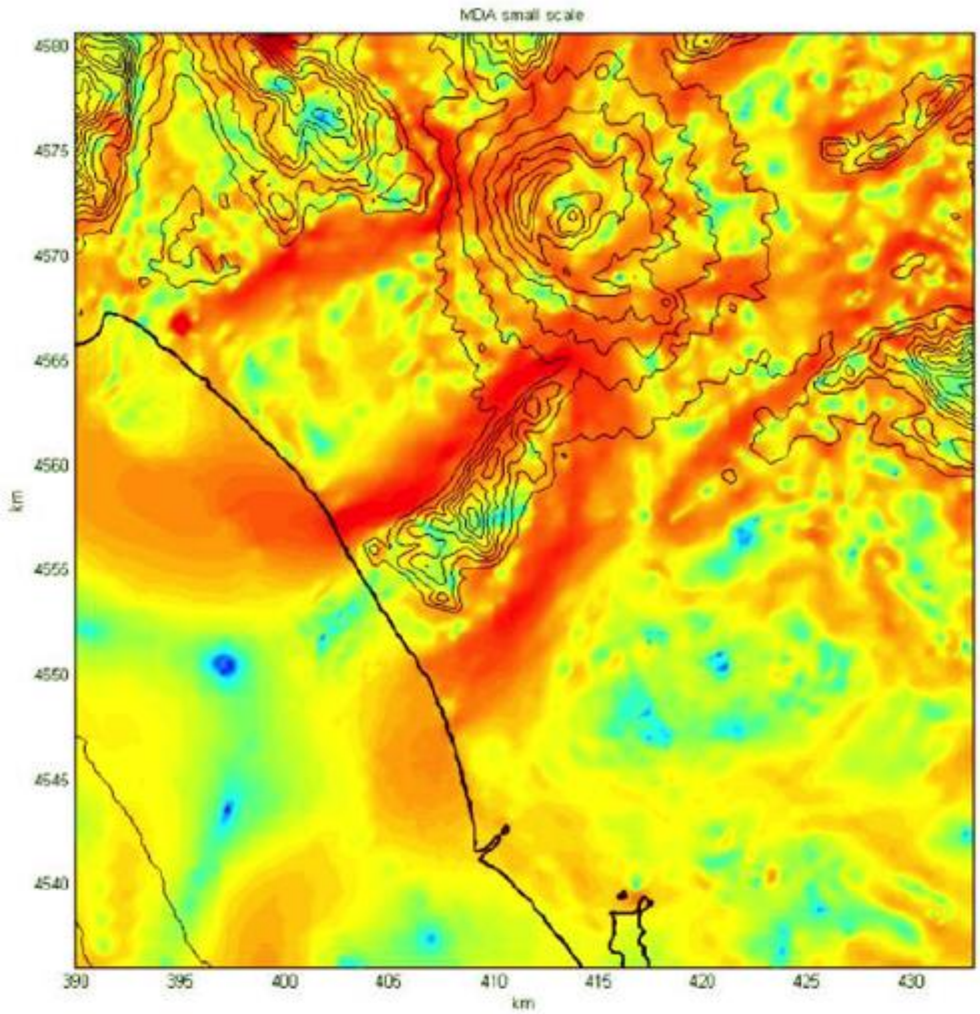
Geophysics: GRAVITY SURVEYS

Contour map of Bouguer anomaly with lines of equal gravity anomaly. These lines are called isogals - gal in memory of Galileo Galilei.



Gravity data in Tuscany. In the figure it is evident how the main geothermal fields of Larderello, Travale and Amiata can be recognized as areas of anomalously low density and high heat flow *(from Orlando, 2005)*.

Geophysics: GRAVITY SURVEYS



After careful data processing and modelling, gravity data may help in delineating structural features. In the figure it is evident how structural lineaments can be recognized in an area of Campania *(from La Manna et al, 2013)*.

Geophysics: GRAVITY SURVEYS

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.

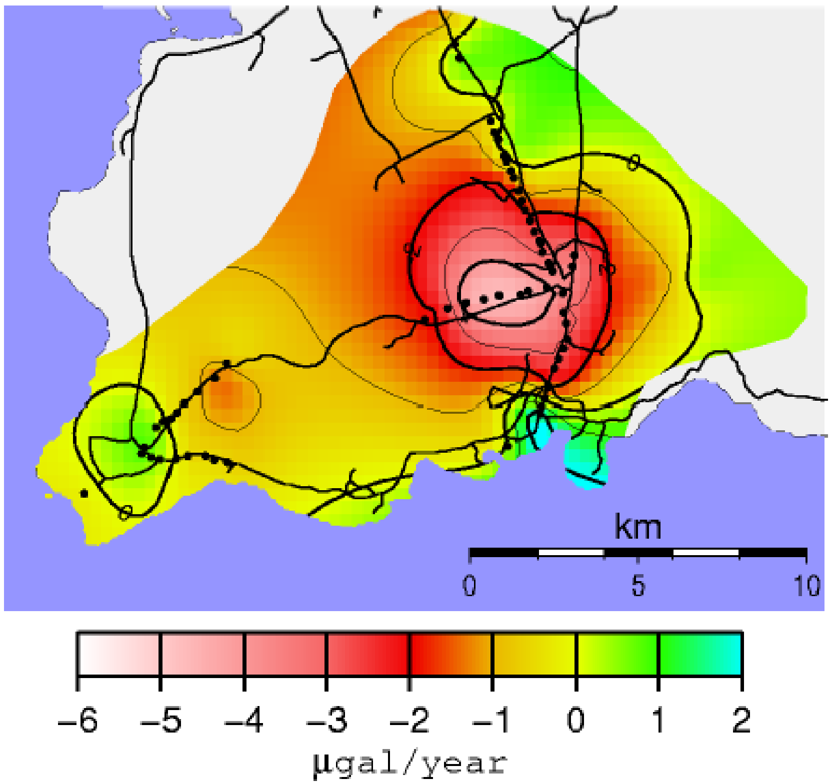


Figure 8. Mean gravity variation (μgal/year) from 1975 to 1999. Only points measured in 1999 and at least two times earlier are used.

from WGC200

Geophysics: GRAVITY SURVEYS

The advantages of gravimetric methods over other geophysical methods are that they are comparatively easy to use and fairly economical as far as their absolute cost is concerned.

They do provide a good estimate of the extent of bodies with certain density contrasts and can thus help constrain the location and extent of reservoirs.

The resolution and quality of data, however, decrease considerably with depth. Gravimetric studies therefore provide a useful tool to be used for shallow reservoirs in conventional systems and, given their often ambiguous results, *in combination* with other geophysical methods.

Geophysics: MAGNETIC SURVEYS

Investigation on the basis of anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks (magnetic susceptibility and remanance)

Several minerals containing iron and nickel display the property of ferromagnetism. Rocks or soils containing these minerals can have strong magnetization and as a result can produce significant local magnetic fields.

Rock magnetism is acquired when the rock forms, and it reflects the orientation of the magnetic field at the time of formation. But rock magnetism can also change with time, if the rock is subjected to temperatures above a certain point, called the Curie temperature, above which it loses its magnetic properties, and it is remagnetised once it cools down again, now induced by the magnetic field present at that time.

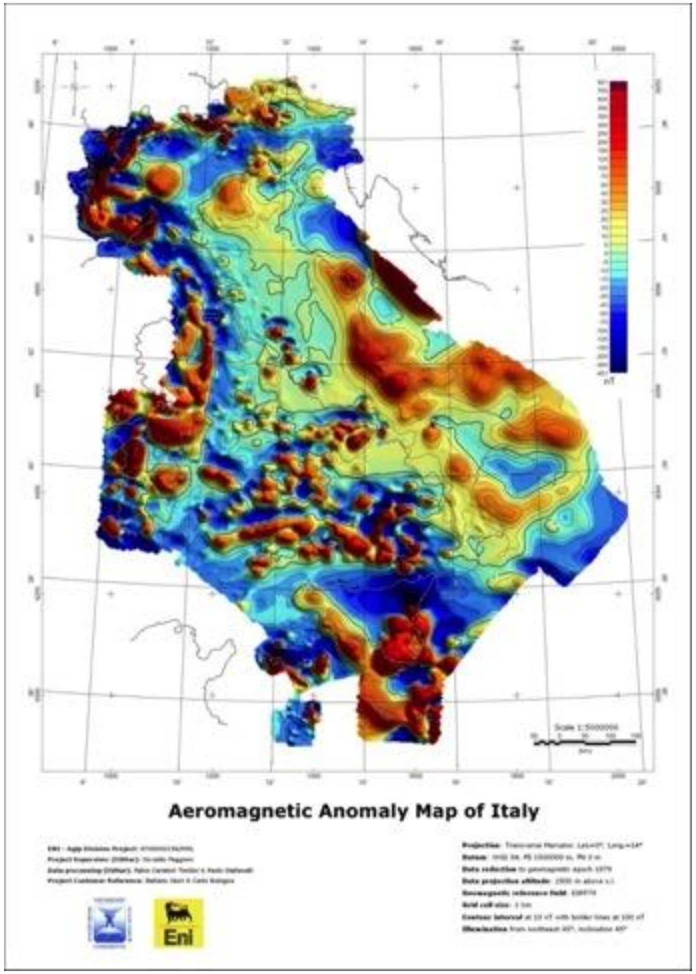
Geophysics: MAGNETIC SURVEYS

Measurements are performed using magnetometers either at the surface or airborne, if the objective is regional mapping.

Silicate minerals, rock salt (halite) and limestones (calcite) have a very low magnetic susceptibility and are therefore not useful for magnetic measurements.

Consequently, sedimentary rocks usually have much lower magnetic susceptibilities than igneous or metamorphic rocks. Thus the magnetic method has traditionally been used for identifying and locating masses of igneous rocks that have relatively high concentrations of magnetite, which is the most common of the magnetic minerals.

Strongly magnetic rocks include basalt and gabbro, while rocks such as granite, granodiorite and rhyolite have only moderately high magnetic susceptibilities.



Aeromagnetic Anomaly Map of Italy

Geophysics: MAGNETIC SURVEYS

Curie temperature is in the range of a few hundred to 570°C for titano-magnetite, the most common magnetic mineral in igneous rocks

Magnetisation at the top of the magnetic part of the crust

⇓

relatively short spatial wavelengths

Magnetic field from the demagnetisation at the Curie point in depth

⇓

longer wavelength and lower amplitude magnetic anomalies

This difference in frequency characteristics between the magnetic effects from the top and bottom of the magnetised layer in the crust can be used to separate magnetic effects at the two depths and to determine the Curie point depth.

Geophysics: ELECTRICAL AND EM SURVEYS

natural-source induction methods

(magnetotellurics, audiomagnetotellurics and self-potential)

controlled-source induction methods

(TDM, VLF)

direct current methods

(SEV, electric tomography)

Their objective is the mapping of electrical structures at depths that are meaningful in terms of geothermal exploration.

These depths must be several kilometres at least when looking for the anomaly in conductivity associated with HT geothermal reservoir rocks, and several tens of kilometres when seeking the thermally excited conductive zone associated with the heat source of a geothermal system.

Geophysics: ELECTRICAL AND EM SURVEYS

Electrical current may propagate thanks to the mobility of free charge carriers that allows current **conduction**

Main propagation mechanisms are:

Electronic ($<10^{-8}$ Ωm)	electrons	metals
Semi-conduction $10^{-5} \div 10^{-3}$ Ωm	electrons and ions	Solfurs
Electrolitic	ions	brines, salty water, melts

Geophysics: ELECTRICAL AND EM SURVEYS

Resistivity depends on of both host rocks and pore fluid properties

Rocks	Temperature & Pressure
	Lithology, Clays (Surface conduction)
	Microstructural properties (e.g., permeability, porosity)
Fluids	Amount
	Nature (liquid or vapor phase, other liquids and gases)
	Salinity

Geophysics: ELECTRICAL AND EM SURVEYS

Inductive methods usually provide information on conductivity-thickness products of conductive layers, whereas they usually provide only thickness information on resistive layers.

On the contrary, resistivity techniques usually provide information on resistivity-thickness products for resistive layers and conductivity-thickness products for conductive layers.

For this reason, inductive methods are the most suitable for geothermal exploration, since the target is conductive.

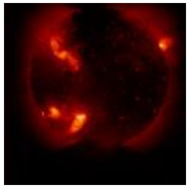
Geophysics: ELECTRICAL AND EM SURVEYS

MAGNETOTELLURICS (MT for short) is a technique which utilizes the earth's naturally occurring electromagnetic field to image the subsurface's electrical resistivity structure.

Natural electromagnetic waves are generated in the earth's atmosphere by a range of physical mechanism:

High frequency signals originate in lightining activity

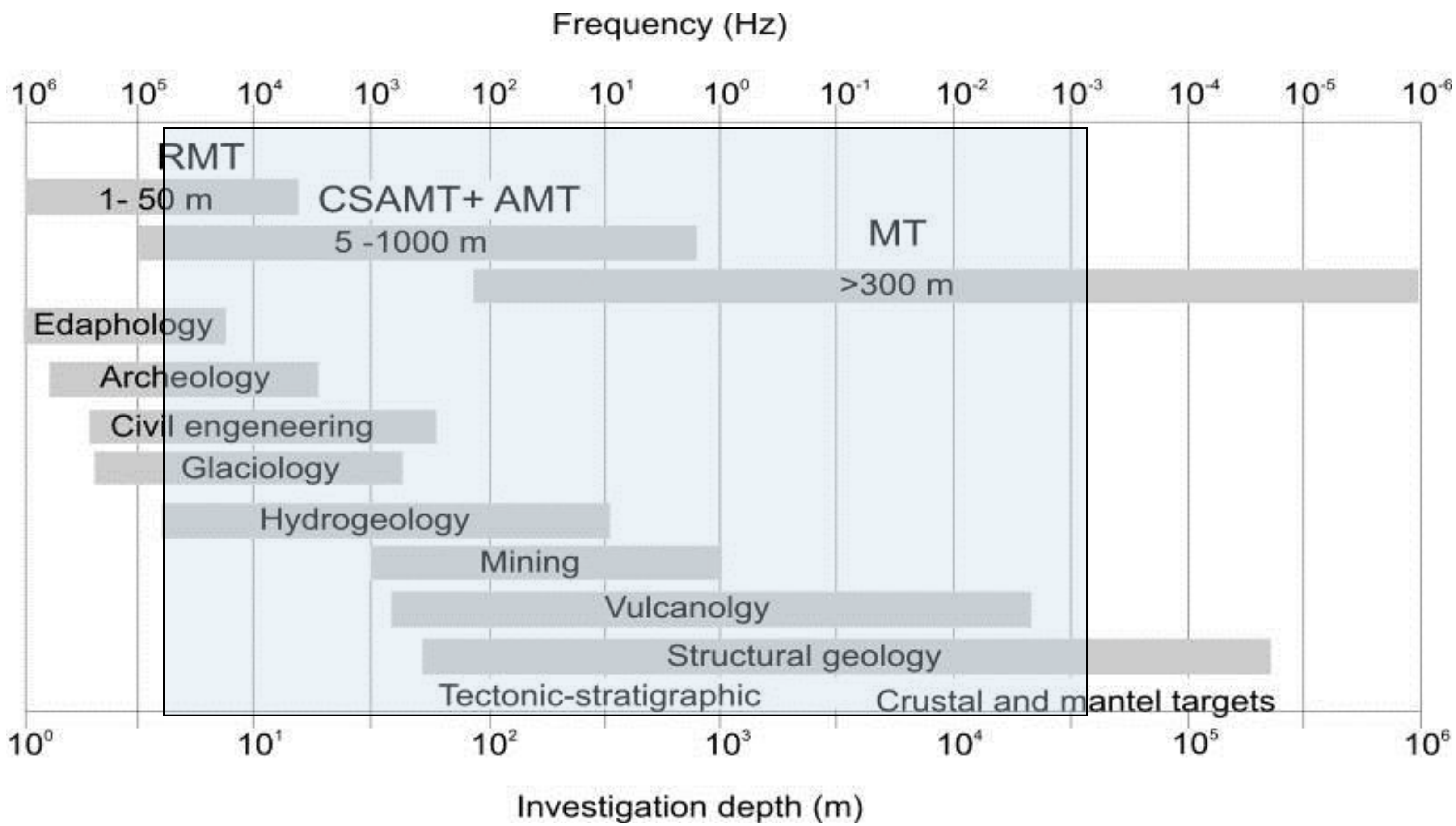
Intermediate frequency signals come from ionospheric resonances



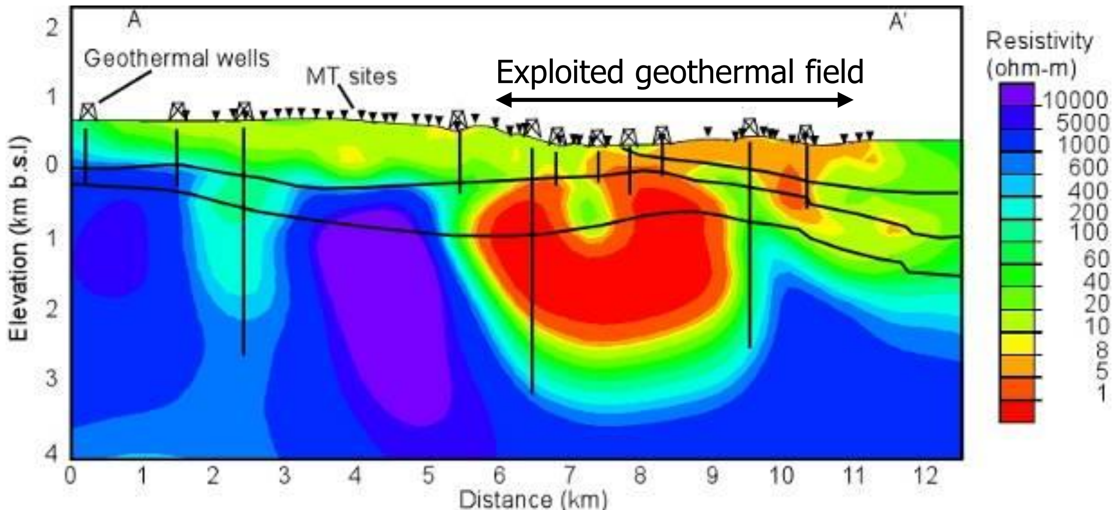
Low frequency signals are generated by sun-spots

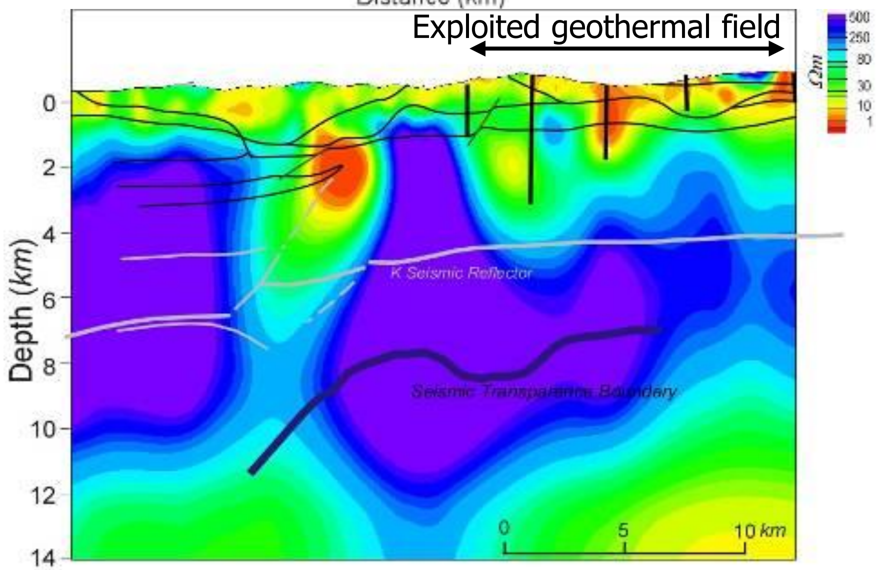
Even if the two types of sources create incident EM fields with different features, the almost plane-wave propagates on the vertical inside the ground, due to the large difference of resistivity between atmosphere and earth.

Geophysics: ELECTRICAL AND EM SURVEYS



Geophysics: ELECTRICAL AND EM SURVEYS



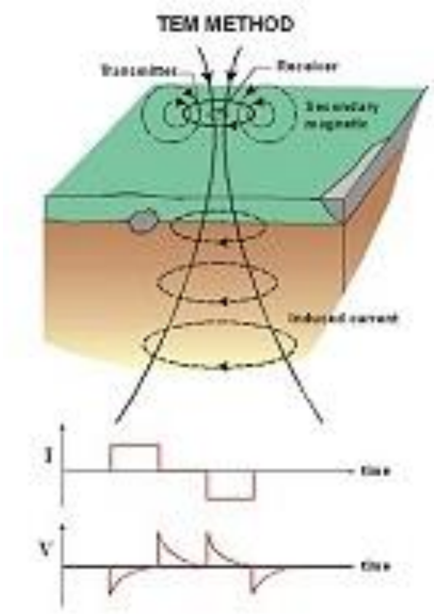


Magnetotelluric data, after processing and modelling, provide the resistivity distribution at depth of various km.

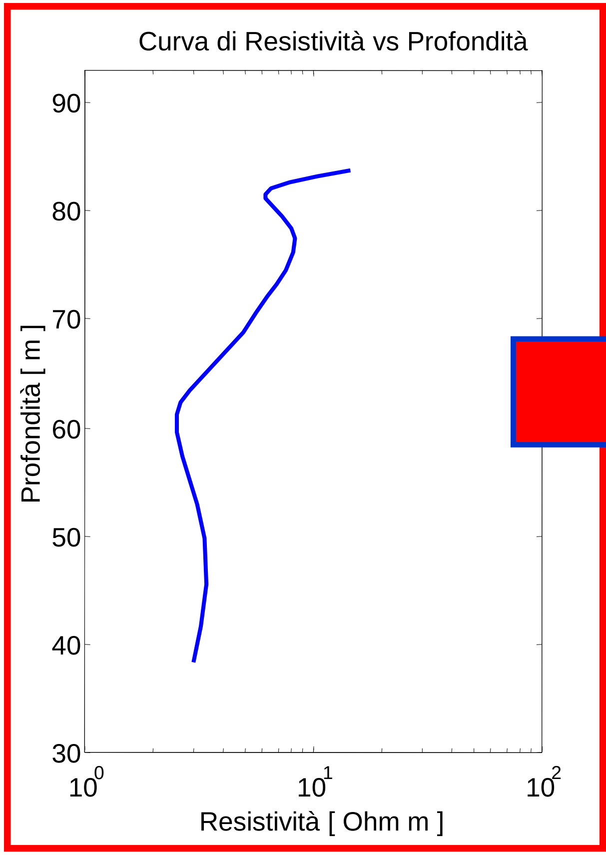
Example: The correspondence between areas of low resistivity inside the resistive basement and geothermal reservoirs was very evident in the Mt. Amiata water-dominated system *(from Manzella)*.

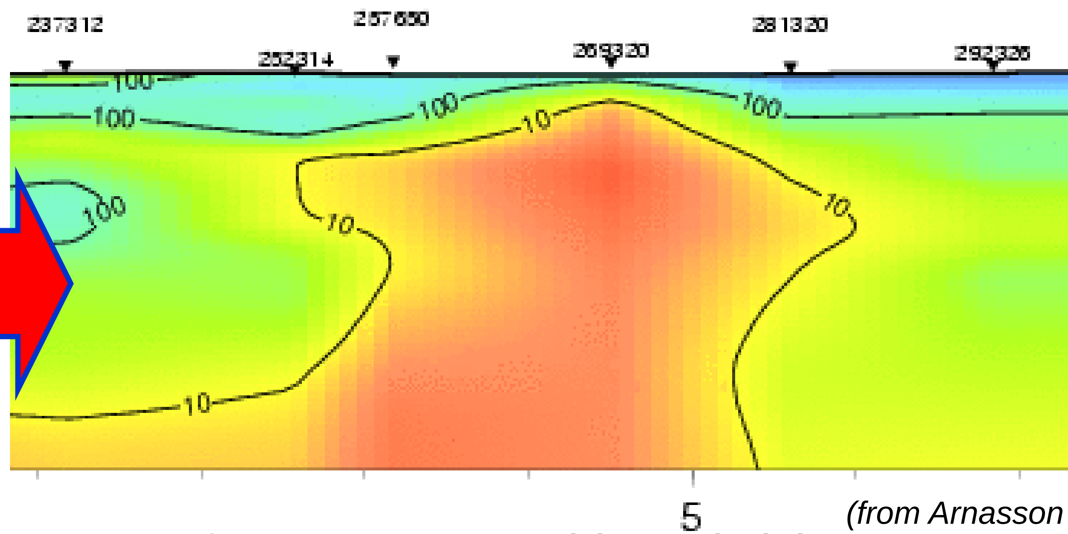
Geophysics: ELECTRICAL AND EM SURVEYS

Active electromagnetic (EM) methods are used mainly for shallow depth resistivity studies and to help with static shift corrections of MT data. Most commonly **CENTRAL LOOP TEM** is used, which is based upon inducing currents in the ground electro-magnetically via a loop laid on the surface. The loop has a square shape, each side measuring several hundred meters. A magnetic spool is placed at the centre of the square, after which DC current is applied to the loop. The current is abruptly switched off and the decaying magnetism induces eddy currents in the formation that try to counteract the magnetic decay. The spool at the loop's centre measures the magnetic decay at the surface with time elapsed since the current was switched off. This permits calculation of the formation resistivity below the loop.



Geophysics: ELECTRICAL AND EM SURVEYS





(from Arnasson et al)

As for MT, TEM provide resistivity distribution at depth.
By nterpolation of 1D models along profiles, it is possible to obtain 2D and 3D resistivity distribution at depth.

Geophysics: ELECTRICAL AND EM SURVEYS

The **DIRECT CURRENT RESISTIVITY METHOD** comprises a set of techniques for measuring earth resistivity that are significantly simpler in concept than the magnetotelluric method.

The magnetotelluric method is an induction method in which the depth of penetration of the field is controlled by the frequency of the signals analysed.

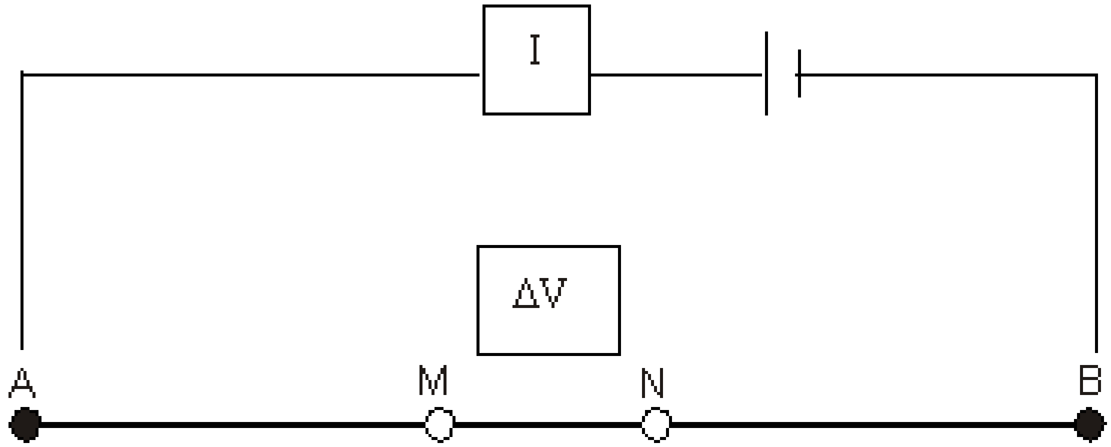
The direct current methods achieve control of the depth of the penetration by regulating the geometry of the array of equipment used.

Two principal variations of the direct current method have found use in geothermal exploration, though there has been some controversy in the literature over the relative merits of these techniques.

Geophysics: ELECTRICAL AND EM SURVEYS

The best tested of the techniques is the **Schlumberger** sounding method. With the Schlumberger array, electrodes are placed along a common line and separated by a distance, which is used to control the depth of penetration.

The outer two electrodes drive current into the ground, while the inner two, located at the midpoint between the outer two, are used to detect the electric field caused by that current.
The outer two electrodes are separated by progressively greater distances as a sounding survey is carried out, so that information from progressively greater depths is obtained.



Geophysics: ELECTRICAL AND EM SURVEYS

(from Rizzo et al. 3013)

Geophysics: SEISMIC SURVEYS

These methods can be divided into two main subclasses:

active seismic methods, which cover all seismic prospecting having an artificial sonic wave source;

passive seismic methods, which deal with the effects of natural earthquakes or those induced by fracturing related to geothermal fluid extraction and injection.

Seismic methods determine subsurface elastic properties influencing the propagation velocity of elastic waves and can be very helpful in obtaining structural information of the subsurface or even to outline a potential reservoir.

Geophysics: ACTIVE SEISMIC SURVEYS

SEISMIC REFRACTION SURVEYS have been used to a limited extent because of the amount of effort required to obtain refraction profiles giving information at depths of 5 to 10 km, and the problems caused by the generally high degree of complexity of geological structures in areas likely to host geothermal systems.

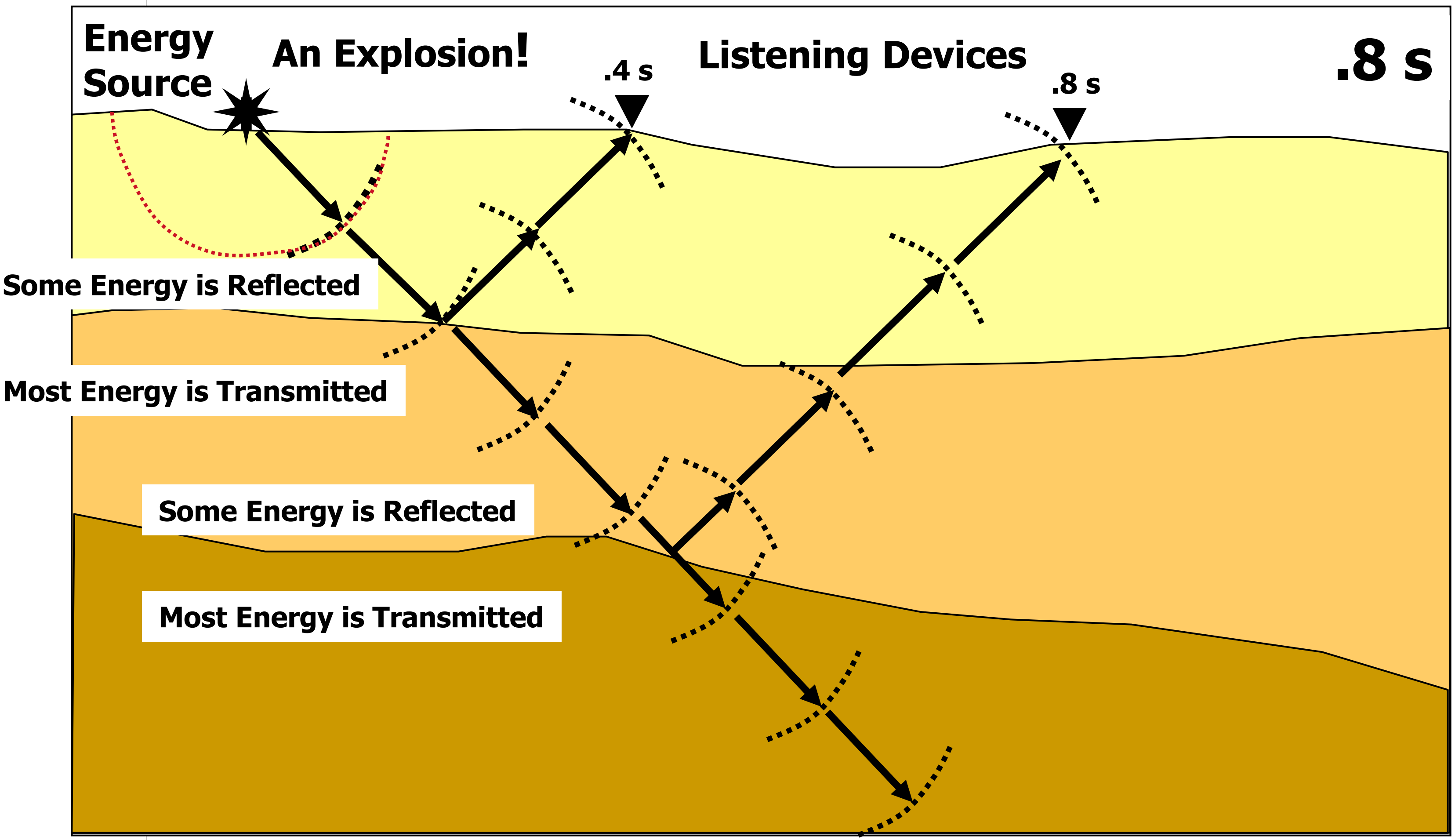
Seismic refraction is normally restricted to cases where the densities of the rocks and thus seismic **velocities increase** with depth. In addition, geophone arrays for refraction measurements need a **length of at least 4-** to 5 times (sometimes even 8 times) the sampling depth because of the very nature of refraction. The length requires higher shot energy (i.e., more explosives) and limits the applicability of refraction methods in exploration to shallower targets or to large-scale investigations of Earth's crust and upper mantle. Sometimes it can be used to get a first approximation about the velocity distribution at depth.

Geophysics: ACTIVE SEISMIC SURVEYS

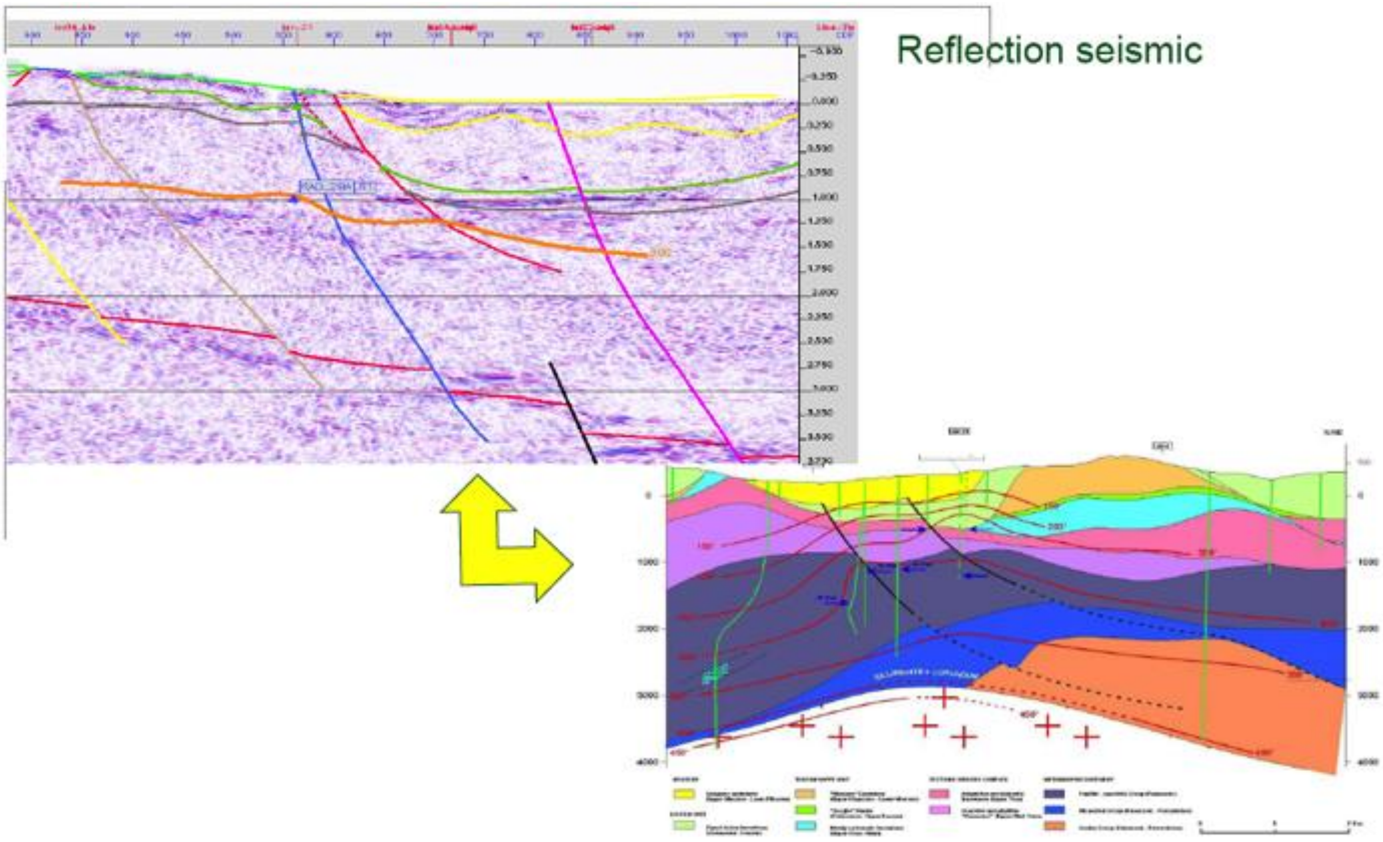
REFLECTION SEISMIC methods are more commonly used in geophysical exploration, as they require much shorter profiles and therefore less shot energy and have a much higher lateral resolution.

However, reflection signals are much more complex to detect and to analyse than refraction signals as they never arrive first, which implies time and labour intensive filtering and detection from a multitude of overlapping data. Moreover, the specific setup for reflection measurements requires more logistic preparation and personnel, which makes it generally a lot more expensive than refraction methods. It is nonetheless the method of choice in hydrocarbon exploration, as it can resolve structural details of a reservoir.

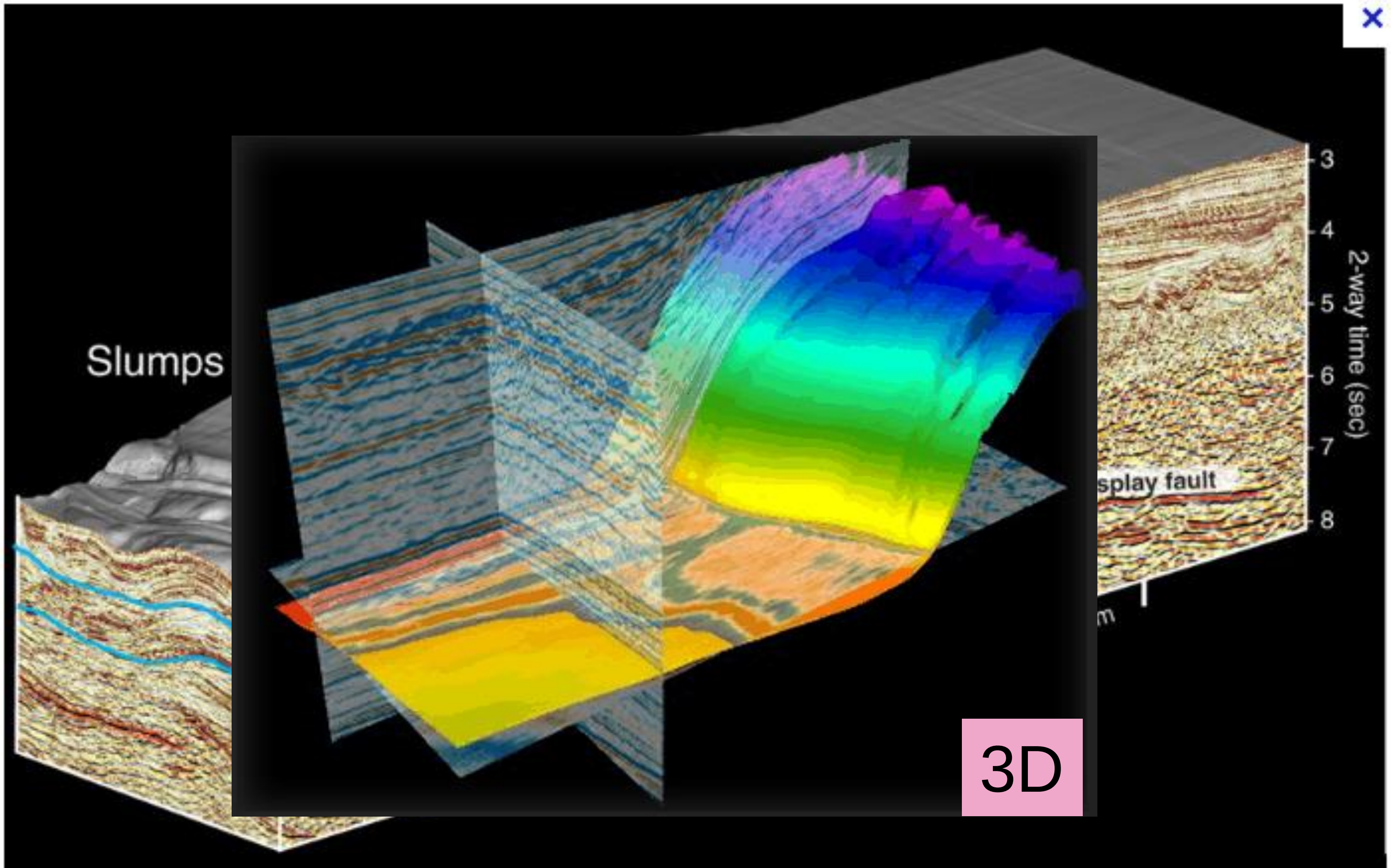
Reflection Seismic Method



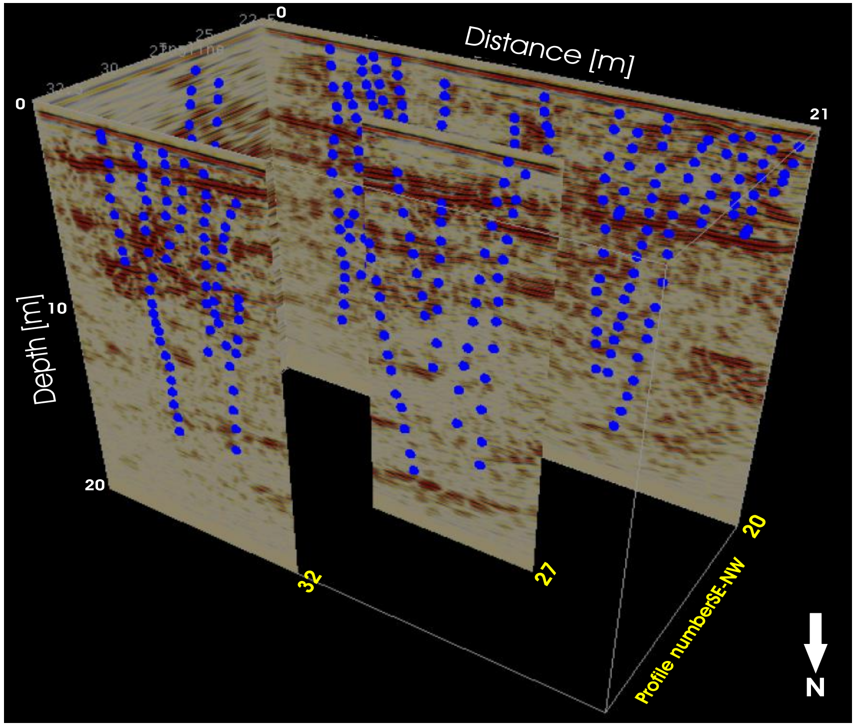
Geophysics: ACTIVE SEISMIC SURVEYS

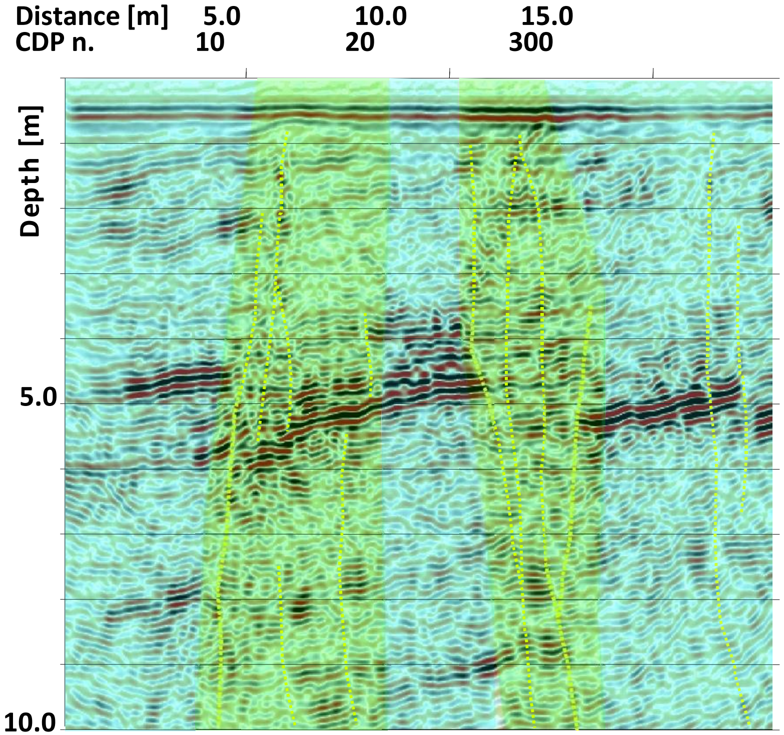


Geophysics: ACTIVE SEISMIC SURVEYS



Data integration-interpretation





3D Discontinuities mapping and

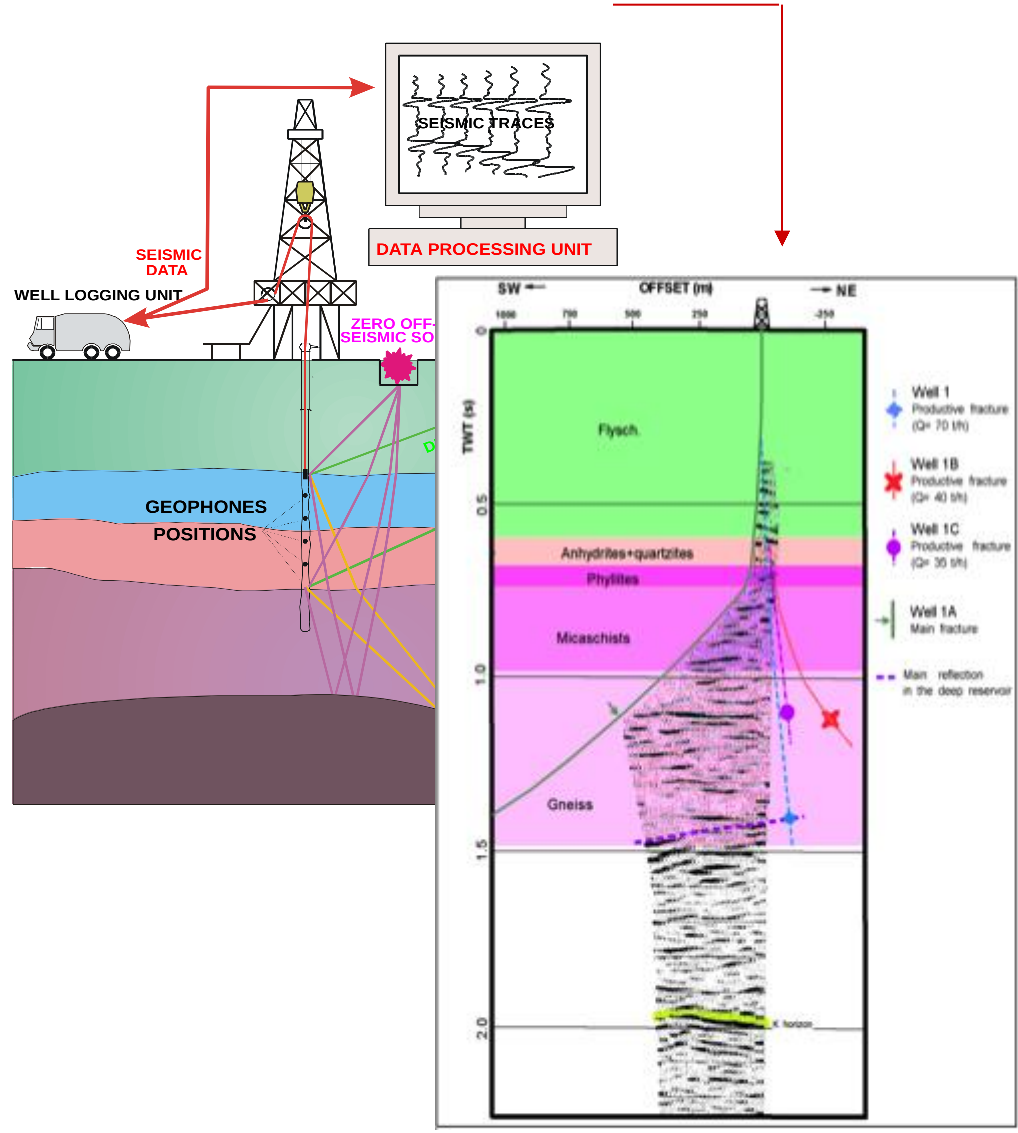
HIGH fractures density

LOW fractures density

Homogeneous zones definition ➔ geomechanic rock characterization

Geophysics: ACTIVE SEISMIC SURVEYS

Seismic signals generated and detected at the service are commonly restricted to horizontal or gently dipping reflectors. To detect and image vertical structures, **VERTICAL SEISMIC PROFILING (VSP)** was developed, which takes advantage of an existing well. VSP not only allow resolution of vertical reflectors such as faults but also provides highly reliable calibration tool for surface seismic and is useful in projects involving seismic anisotropy.



Geophysics: PASSIVE SEISMIC SURVEYS

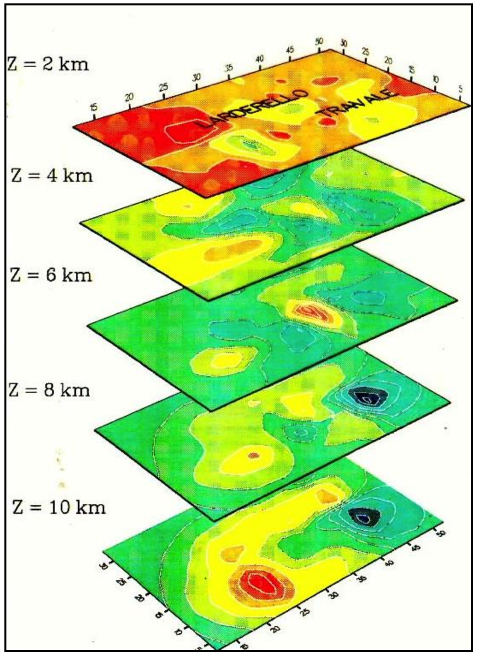
Geothermal areas are often characterized by microseismic activity, although there is not a a one-to-one relationship.

Microseismic activity characterises modern tectonic activity, controlled by the same factors that control the emplacement of a geothermal system

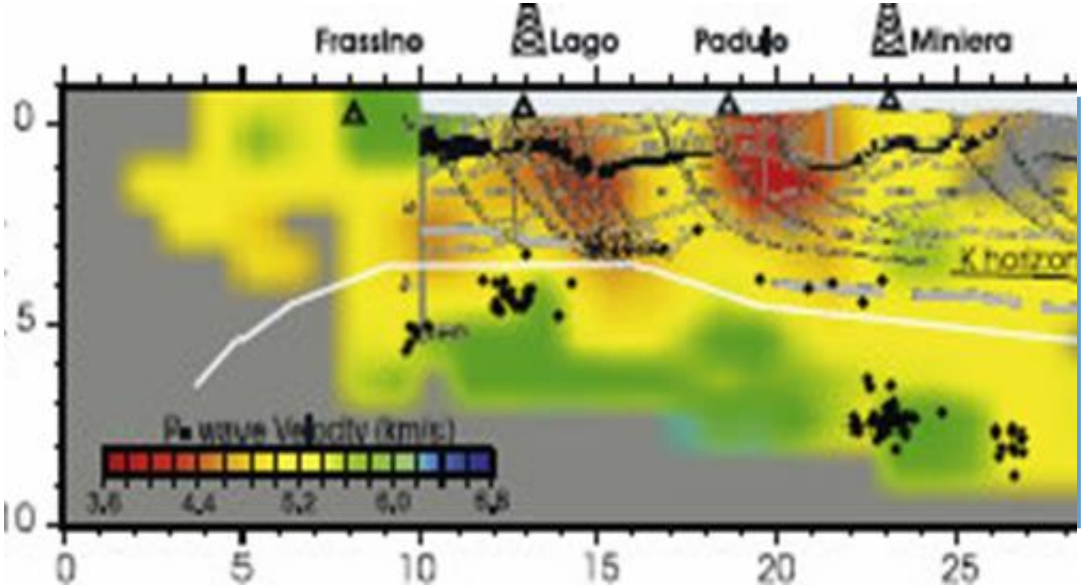
Thus passive seismic studies have been found to have a promising potential in pinpointing active faults or fracture systems that are not always found on the surface, as well as their elevation and inclination.
Studies of microseismic activity can serve as a guide when drilling into fractured rocks in a geothermal reservoir whose production levels are expected to be high.

Geophysics: PASSIVE SEISMIC SURVEYS

Seismic tomography may help to define main velocity anomalies linked to thermal/fluid circulation effects



From Block et al.,



From Chiarabba et al.

VP-VS ratio

Vp/Vs ratios are known to be sensitive to phase changes in geothermal systems. Water and steam filled pore spaces affect both P and S wave transmission differently. Vp/Vs ratios normally increase from vapour saturated [low pore pressure] condition to liquid saturated [high pore pressure] condition.

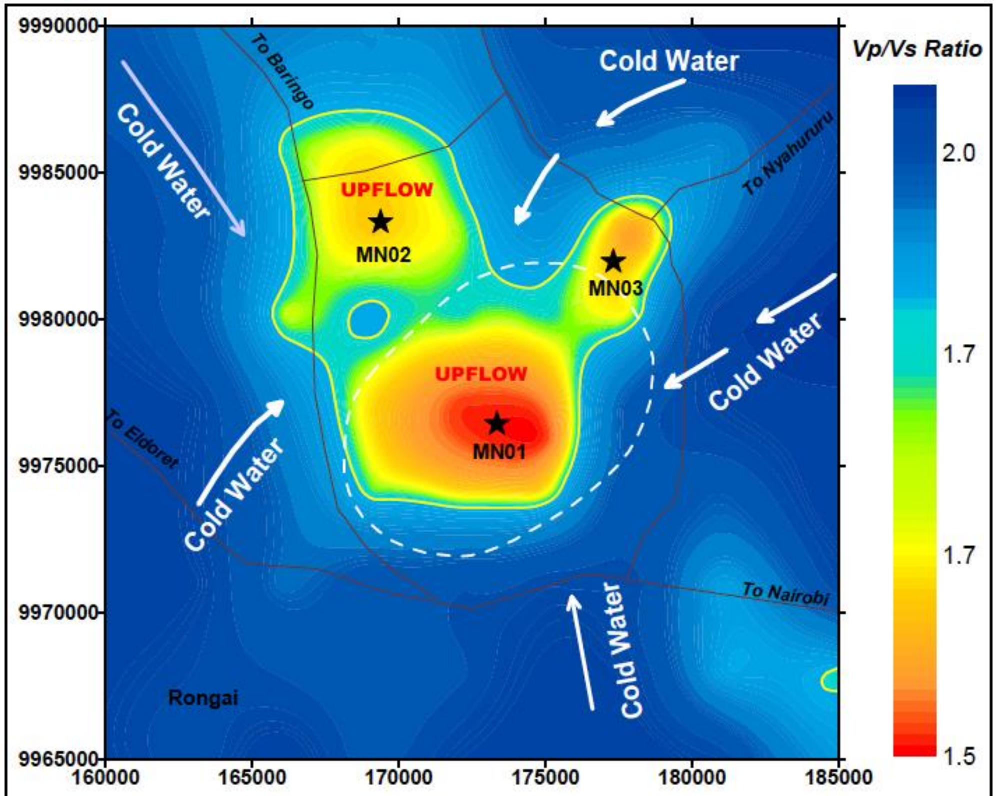


Figure 5.1. Average Vp/Vs rartion variations in the Menengai study area showing proposed test drill sites [Stars], interpreted upflow zones and fluid recharge for the system

From Simiyu 2009

Geophysics: PASSIVE SEISMIC SURVEYS

Microseismicity is often not only natural but also induced by geothermal activity. One major cause appears to be injection, which results in the reservoir rock being rapidly cooled. At the Geysers geothermal field injection has increased by about 50% the number of M=2.4 events being recorded, with no increase observed in M=2.5 events.

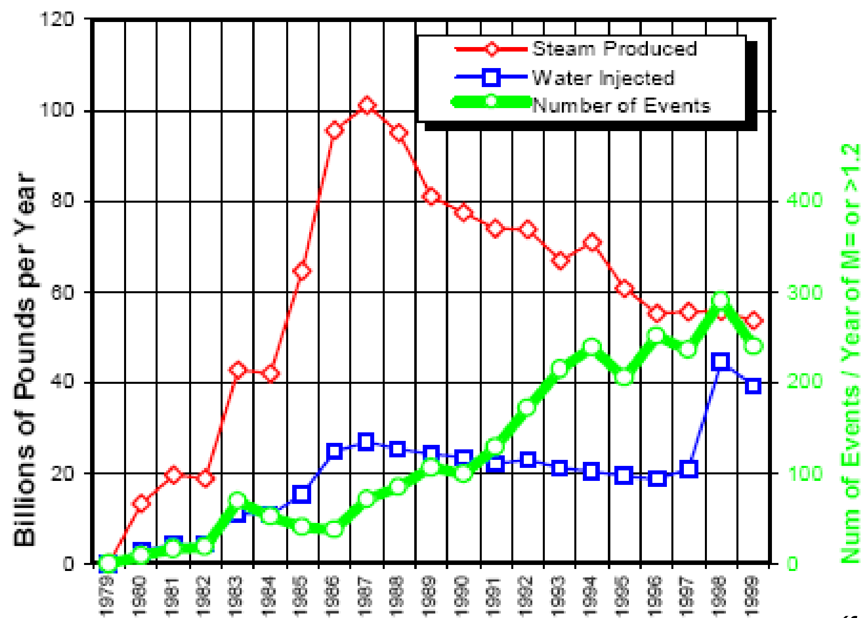
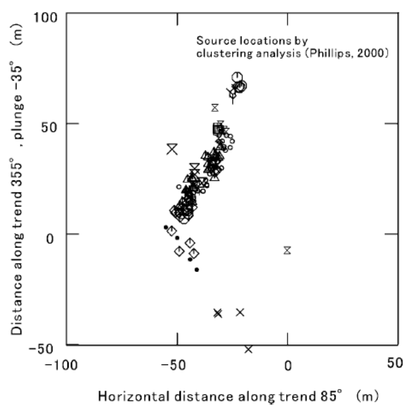


Fig.4 Annual Production, Injection & Seismicity, SE Geysers

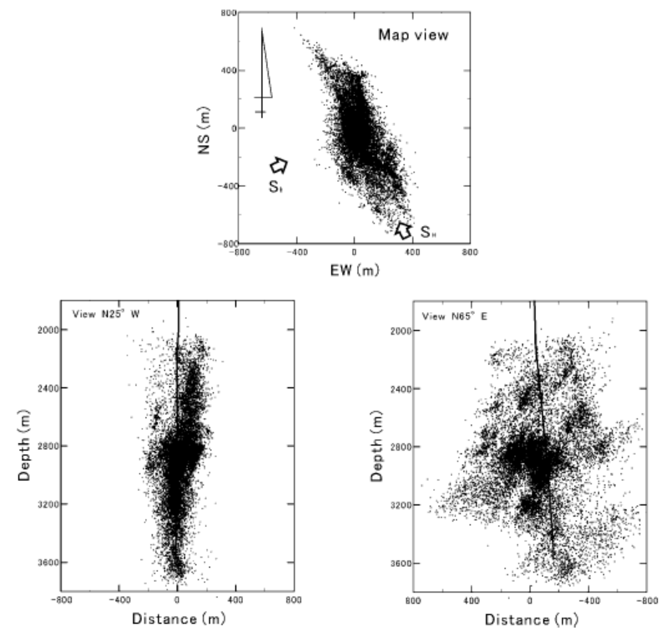
(from WGC2000)

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**. It is actually the only routinely available method to follow the development of a fracture in time and space.



Moriy, Niitsuma, Baria, Bull. Seism. Soc. Am.

Source location in Soulz geothermal project (EGS)



Resource assessment: targets and tools

Geochemical Methods
for geothermal exploration

Resource assessment: targets and tools

Geological and Hydrogeological Methods for geothermal exploration

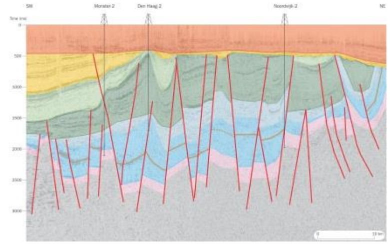
Darcy's law is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance.

$$Q = \frac{-kA}{\mu}\frac{(P_b - P_a)}{L},$$

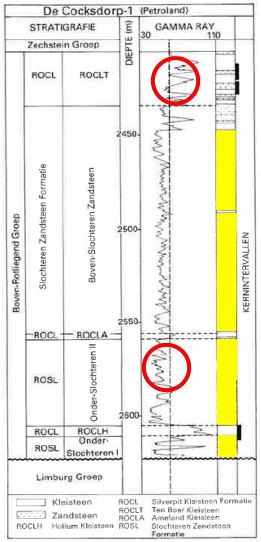
The total discharge, Q (units of volume per time, e.g., m^3/s) is equal to the product of the intrinsic permeability of the medium, k (m^2), the cross-sectional area to flow, A (units of area, e.g., m^2), and the pressure drop (Pb - Pa), all divided by the viscosity, μ (Pa·s) and the length over which the pressure drop is taking place (m). The negative sign is needed because fluid flows from high pressure to low

Units of permeability cast in Darcy, 1 Darcy ~ 1e-12 m2

Dutch database: over 50 billion Euro of data



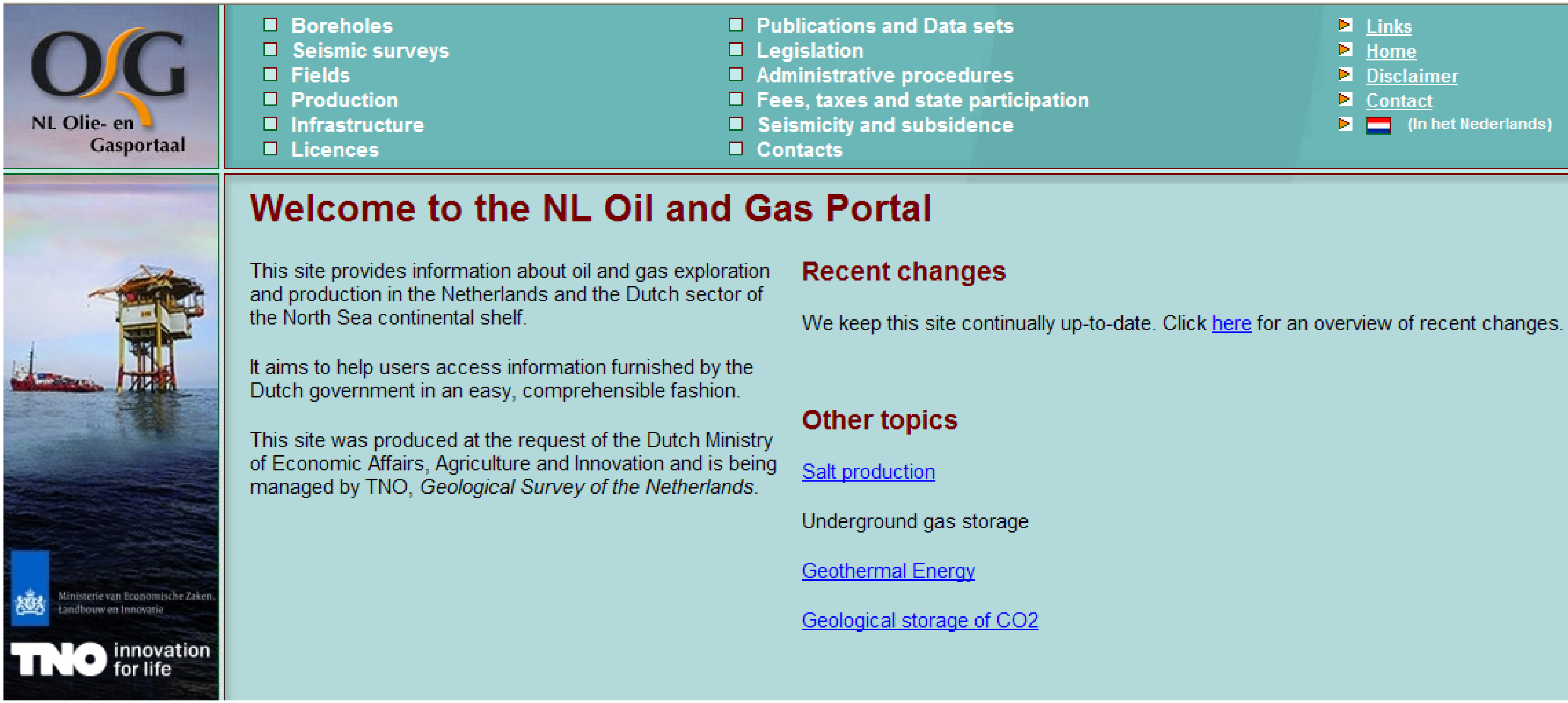
Well & Seismic Data
Wells: 5876
Seismic: 72.000 km



Log data
Gamma ray
Sonic
Resistivity
Neutron, etc

Petrophysics
Cores: 100 km
Poro/perm: 60.000 measurements
(300.000 total)

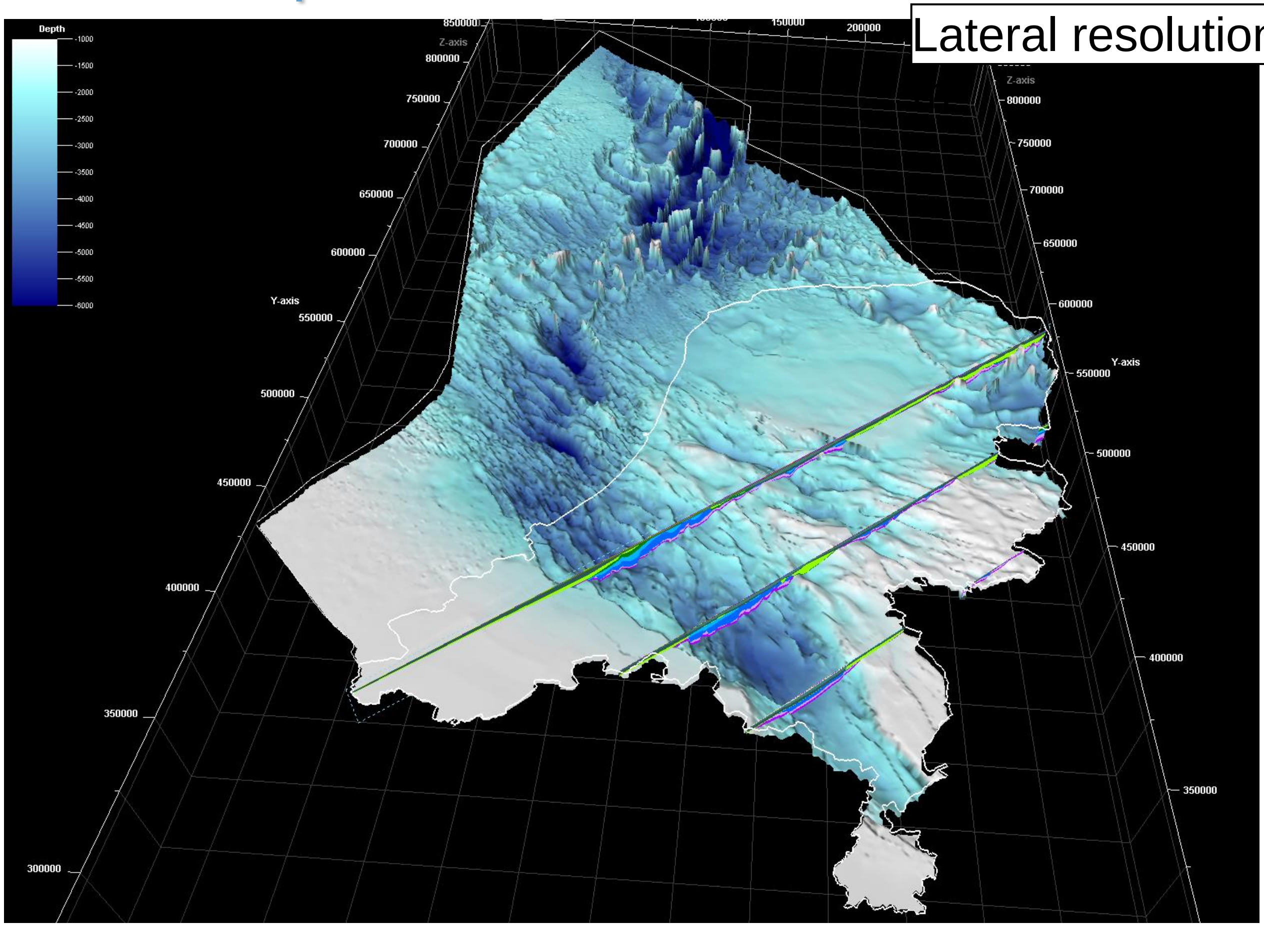
www.NLOG.nl

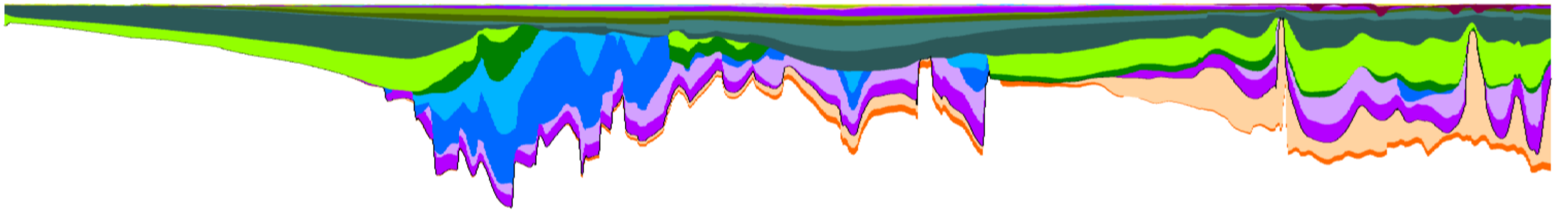


- All kinds of well data & seismic data accessible and free to download

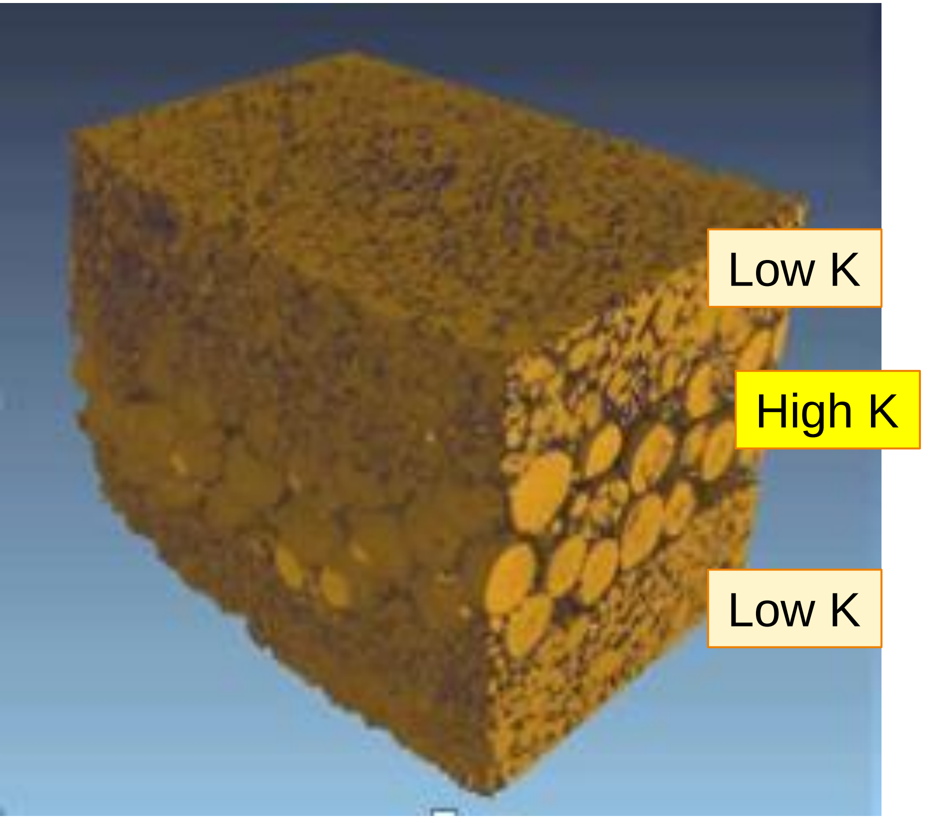
Seismic interpretation

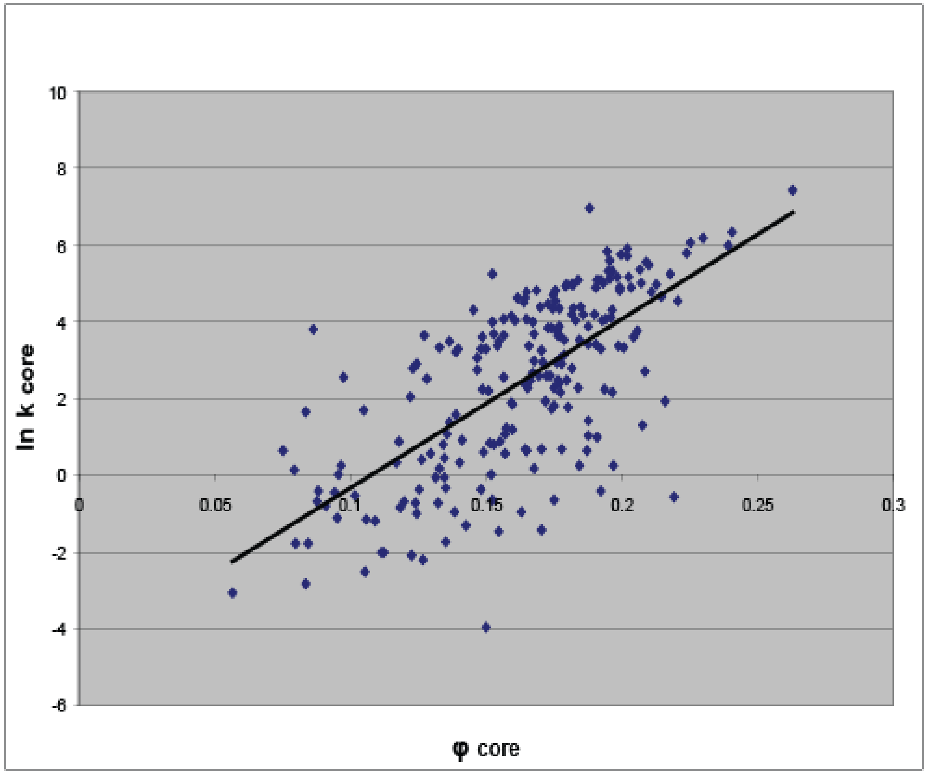
Lateral resolution 250





Pore Permeability





Units of permeability mDarcy

$$q = \frac{k}{\mu} A \Delta p$$

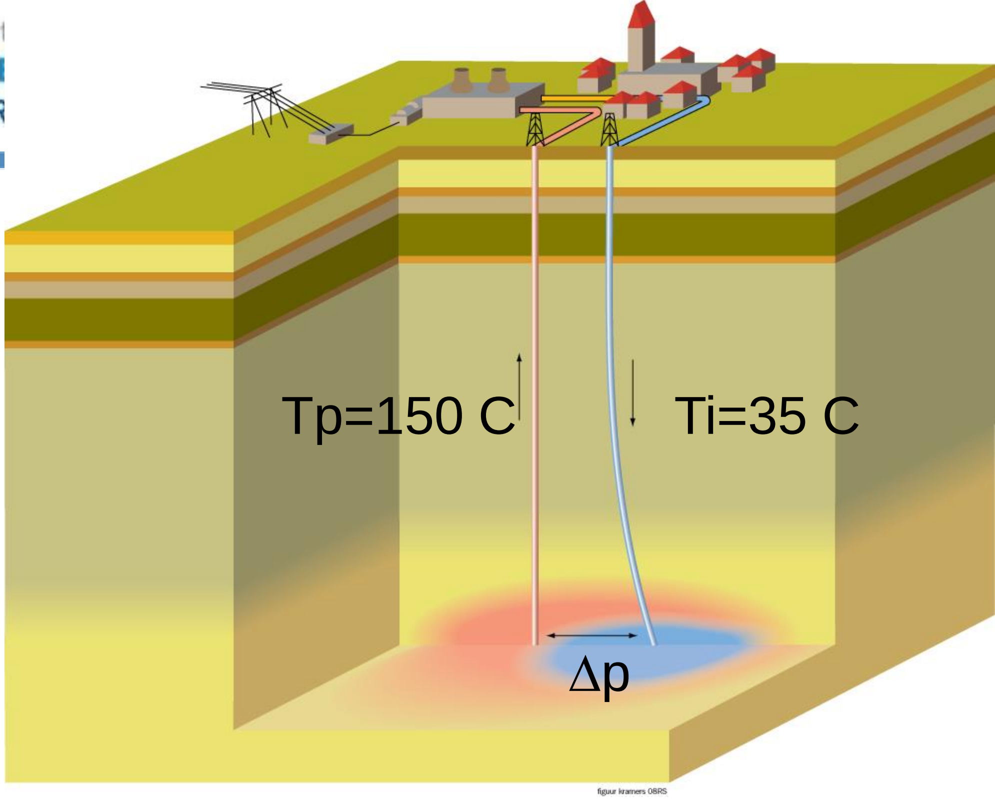
parameter	unit	
Well radius rw	m	0.15
Thickness H	m	100
Area A	m2 (2 π rw H)	?
permeability	mDarcy (x1e-15= m2)	200
DP	Bar(x1e5= Pa)	20
μ	Pa s	1e-3
q	m3/s	?

A=100

Q= 100 200e-15/1e-3 / Pa =2e-8 / Pa
Q =4e-2 m3/s= 40l/s

(Doublet) performance

E [MWth] = Q*ΔT * C_P



Flow-rate Q

Permeability X thickness

$$Q = \Delta p \frac{2\pi k H}{\mu\left(\ln\left(\frac{L}{r_w}\right) - S\right)}$$

Viscosity

distance

Δp generated by pumps
Which consume electricity
→ COP target

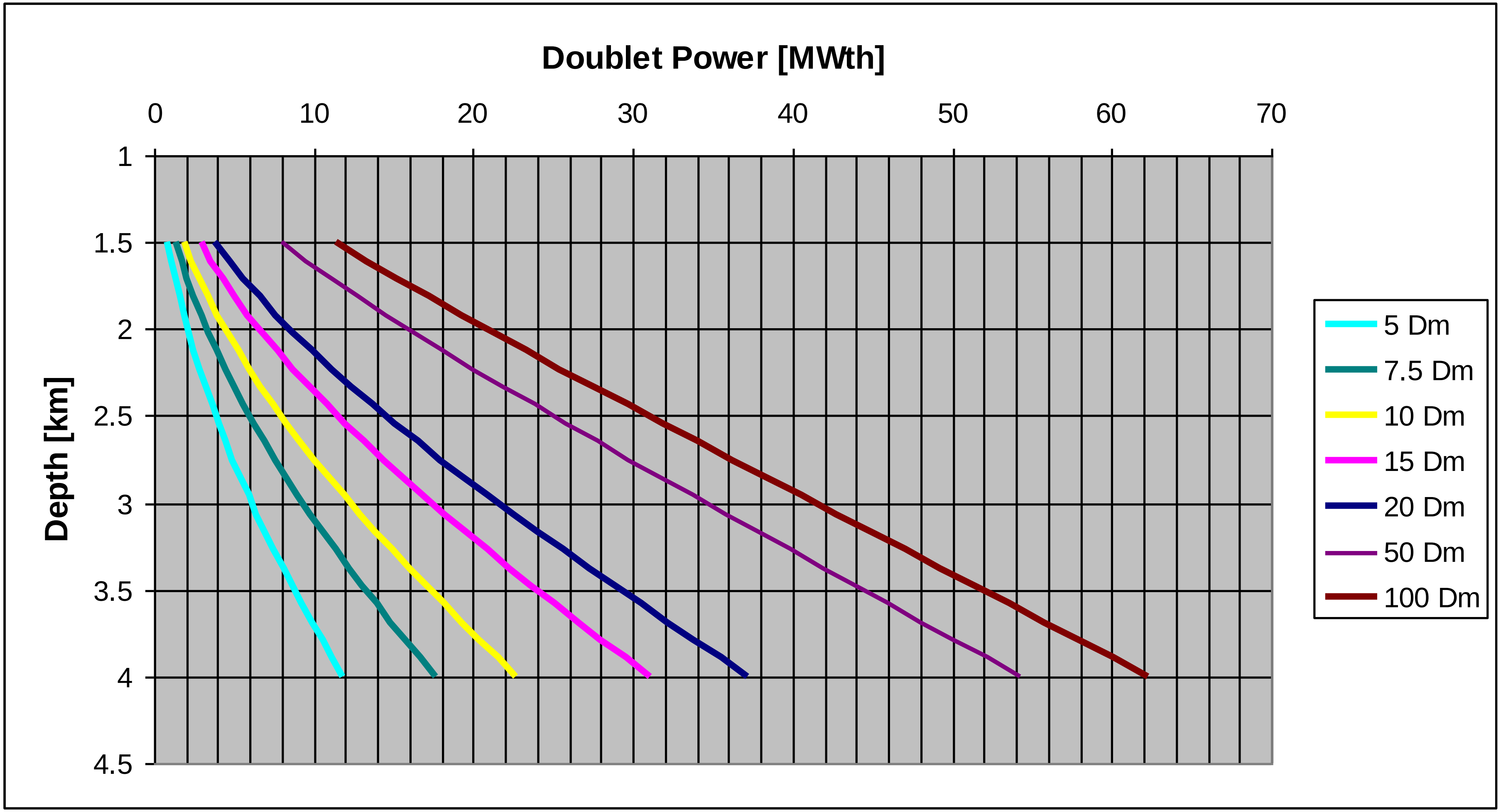
Δp is restricted by safety measures

Δp at surface does not linearly lead to Higher flow rates (friction in tubes)

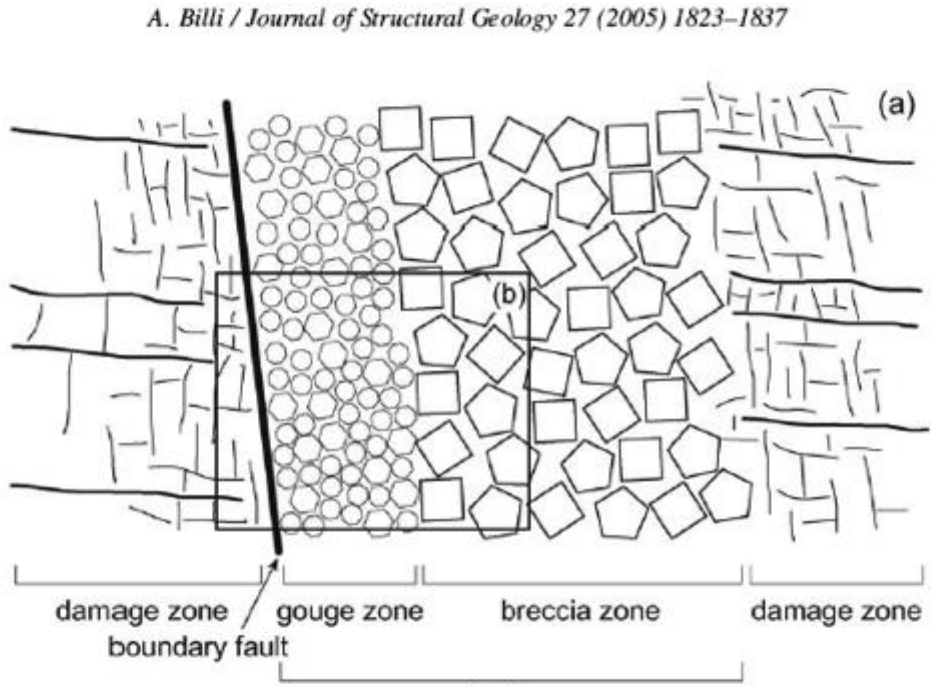
Van Wees et al., 2012

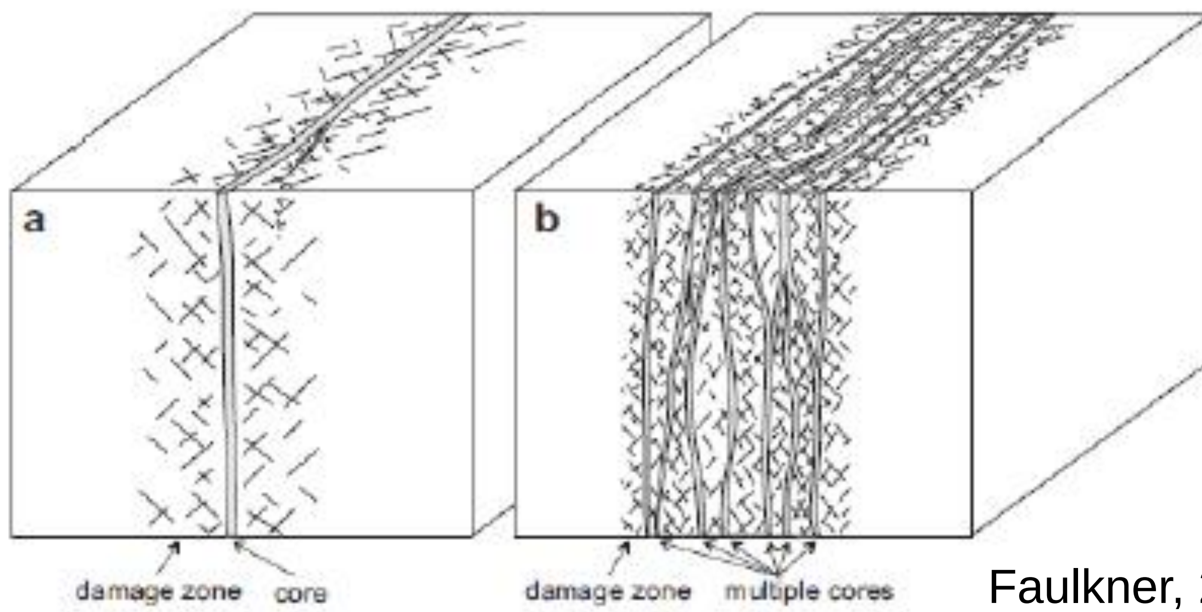
Sensitivity to transmissivity (kH)

Thermal gradient =30C/km
COP = 15



Fr





Faulkner, 2010

Hydraulics: Fracture Mechanics

- Bandis (1983) fracture mechanics:
  - Elastic opening due to pressure increase

$$\Delta w = \frac{a\sigma_n{}'}{1 + b\sigma_n{}'}$$

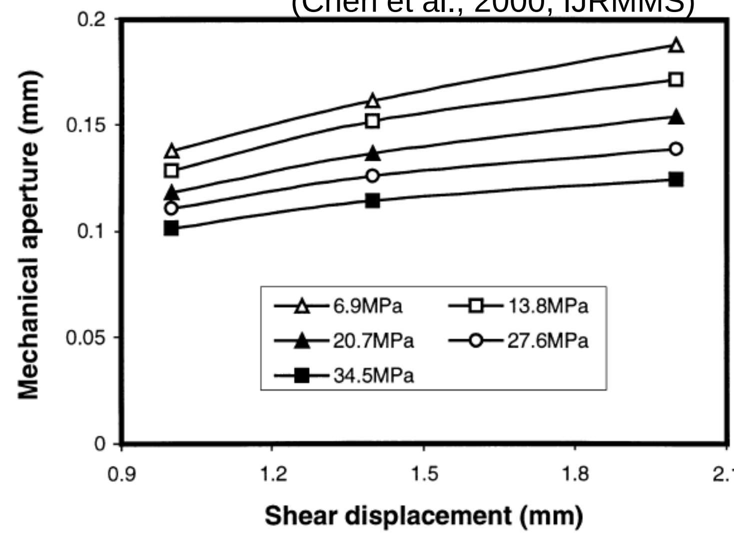
  - Shearing accompanied by dilational opening

$$\Delta w = a_c + U \cdot \tan\phi_{dil}$$

- Darcy with „cubic law“

$$\mathrm{k} = \frac{w^2}{12}$$

(Chen et al., 2000, IJRMMS)



$$q = \frac{k}{\mu} A \Delta p, \quad k = \frac{w^2}{12}$$

parameter	unit	
Well radius rw	m	0.15
Thickness H	m	W=0.0001
Area A	m2 (2 π rw H)	?
permeability	mDarcy (x1e-15= m2)	?
ΔP	Bar(x1e5= Pa)	20
μ	Pa s	1e-3
q	m3/s	?

A=1e-4
K = 1e-7 = 10,000 Darcy
Q= 1e-7 1e-4 / 1e-3 Pa =1e-8 / Pa
Q =2e-2 m3/s= 20l/s

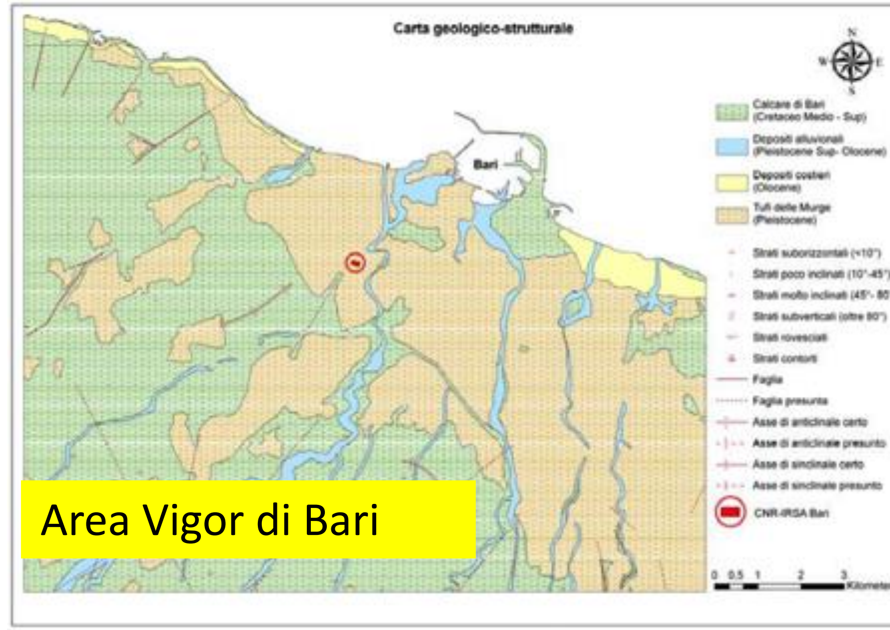
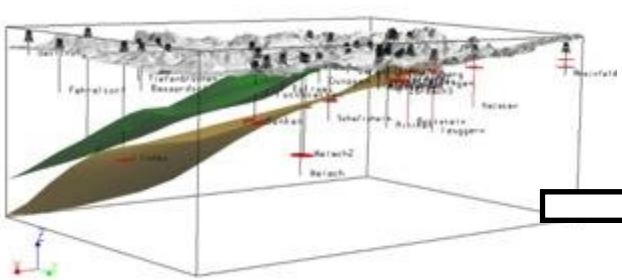
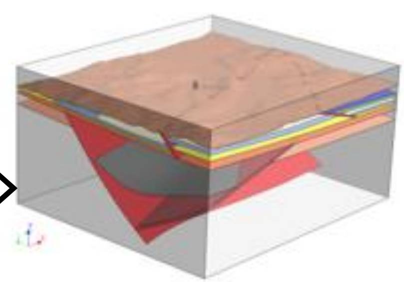


Figura 10: Carta geologico-strutturale dell'area campione di Bari

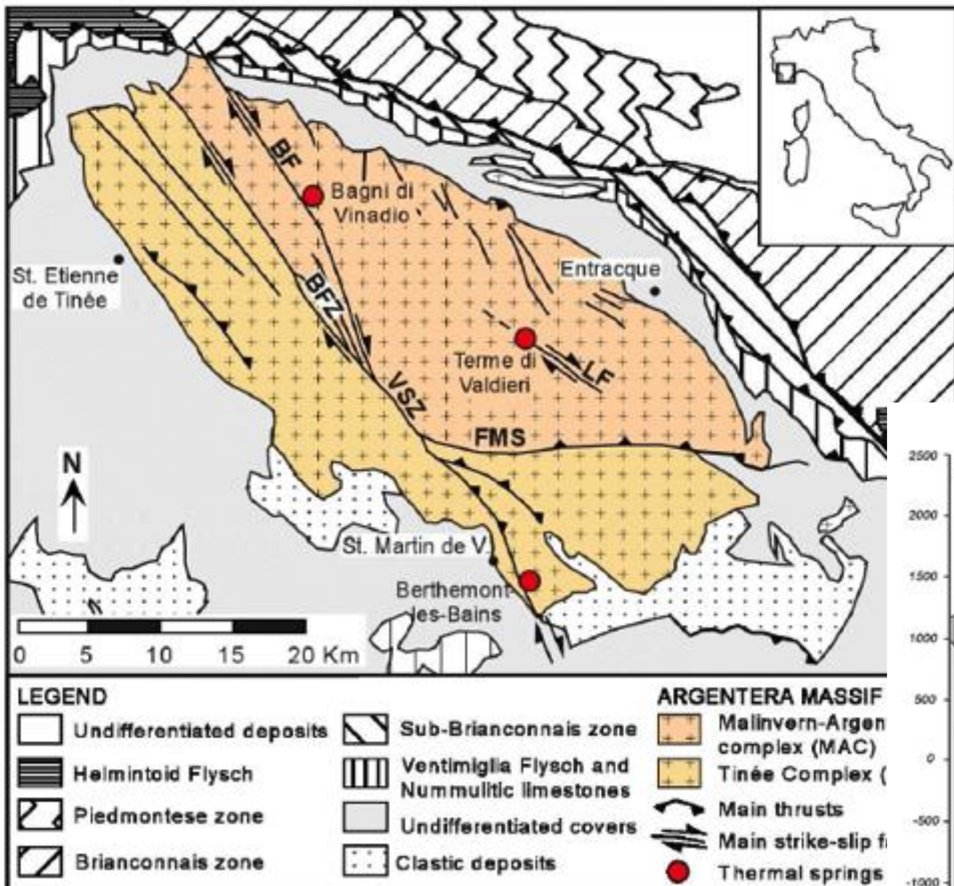
Data collection



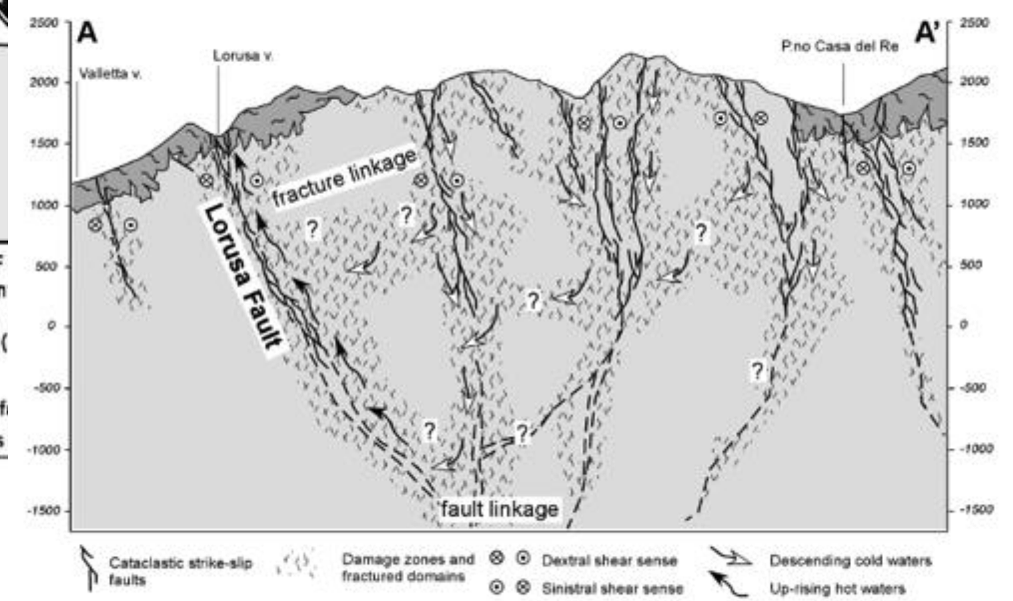
3D geological model

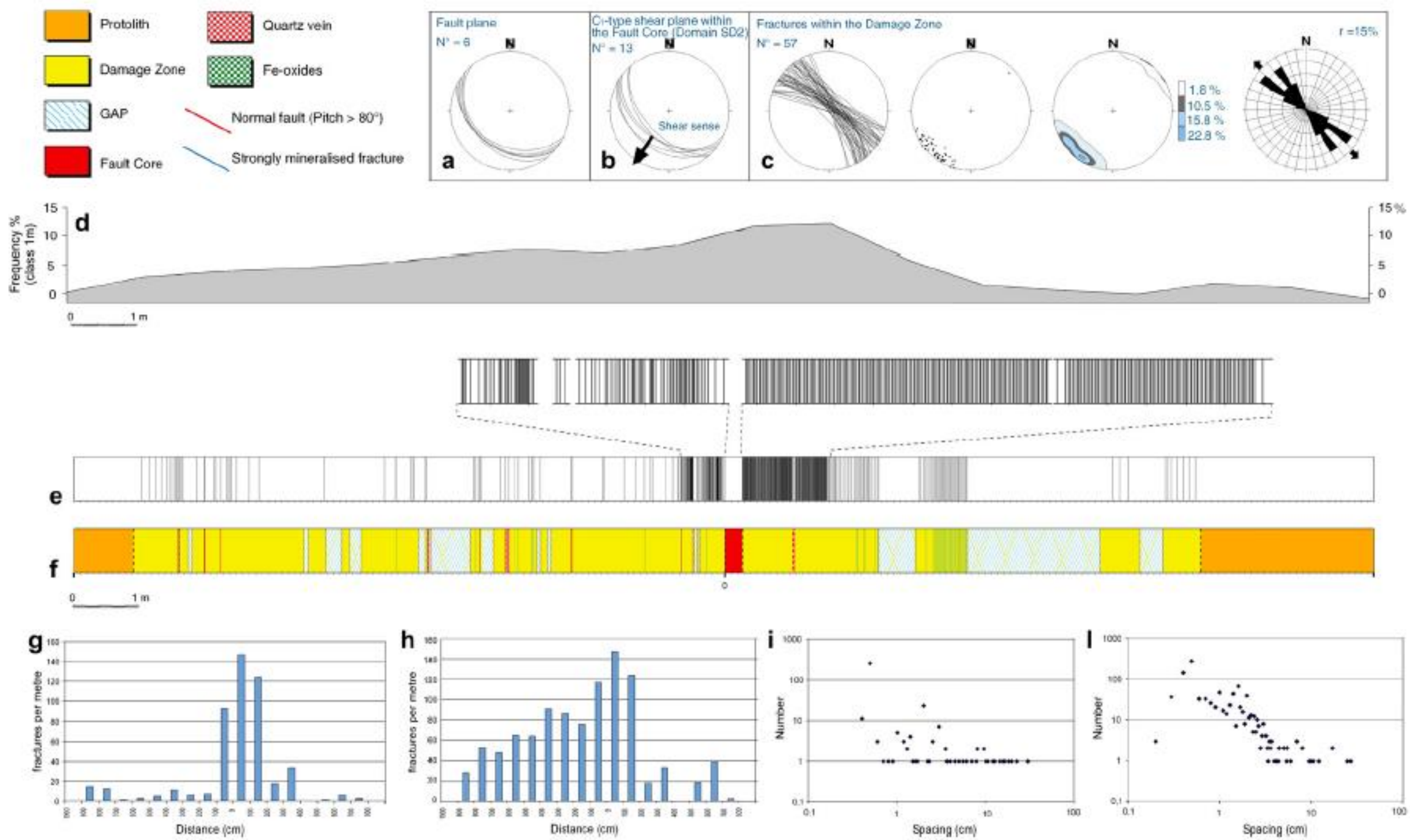


- ***Geometry***
- ***Fracture field***



WHAT IS THE REASON OF A FRACTURE FIELD?





A. Brogi / Journal of Structural Geology 30 (2008) 237–256

Fig. 9. Scan line across the fault zone exposed in Area 2 shown in Fig. 5. Structural information concerning kinematics, geometry and density of fractures are illustrated in the diagrams a–l: the equal-area plots (Schmidt diagram, lower hemisphere) indicate: (a) the great circles of the fault plane; (b) the cyclographic traces of the C_1-type shear planes occurring within the domain SD_2 of the fault core (see Figs. 7 and 15); (c) the cyclographic traces, poles, contouring of poles and rose diagram of the fractures occurring in the damage zone. (d) Diagram showing the frequency distribution of the fractures (spacing 1 m) in the damage zone; (e) position of the fractures and minor faults within the fault zone; (f) lithological information of the fault zone; (g) histograms indicating fractures (spacing 1m) vs. distance; (h) histograms indicating fractures, minor faults and relict fractures (spacing 1 m) vs. distance; (i) fractures (spacing 1 m) vs. spacing; (l) fractures, minor fault and relict fractures vs. spacing.

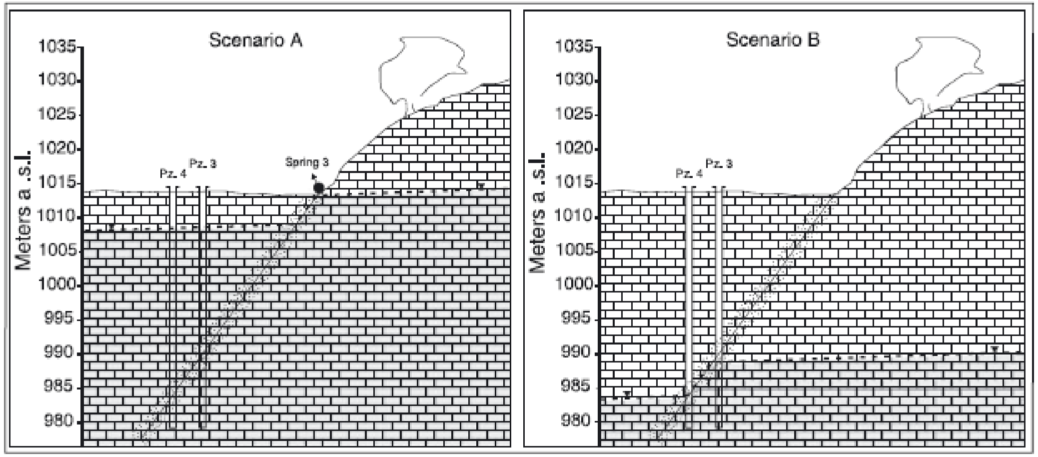


Fig. 8 Evolution of the hydrogeological setting in the fault zone over time (Scenario 'A' – hydraulic gradient monitored in the protolith; Scenario 'B' – hydraulic gradient monitored in the fault core).

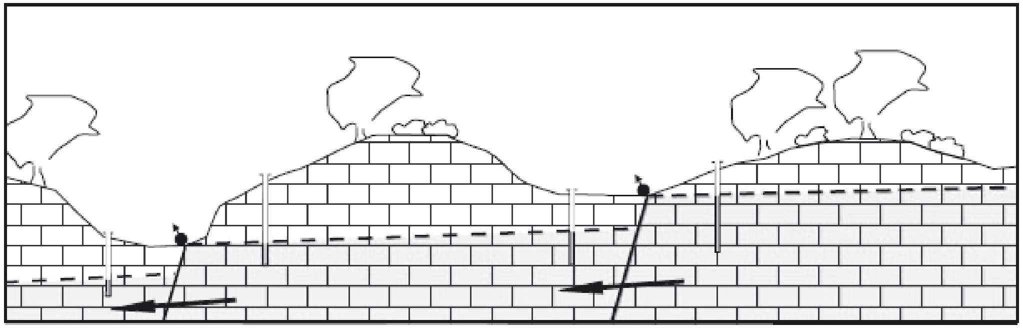
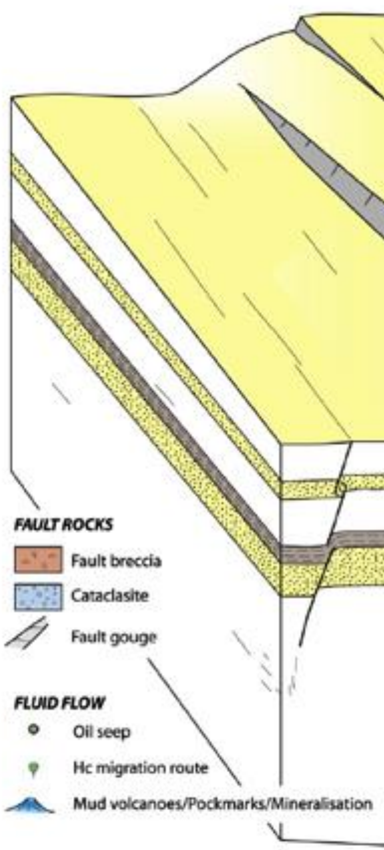


Fig. 9 Schematic representation of a basins-in-series aquifer system (the arrows represent the groundwater flowthrough in fault zones).



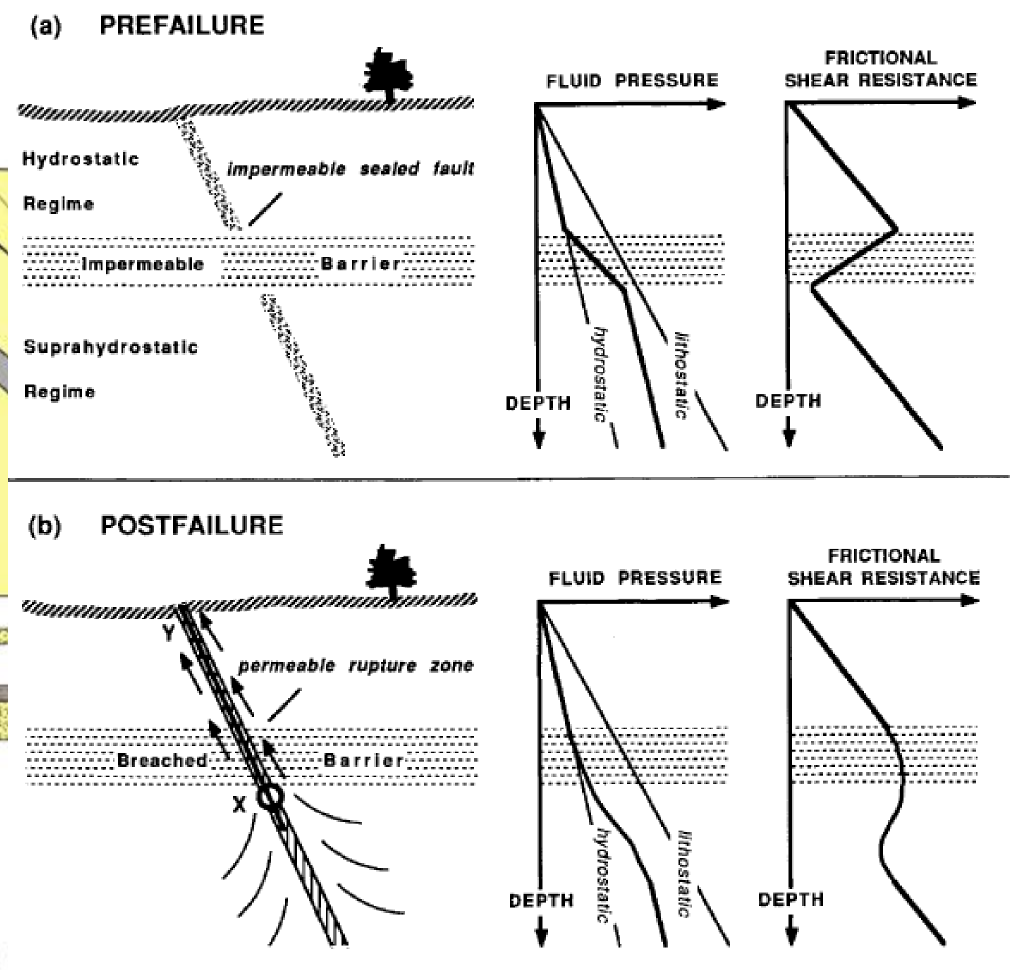
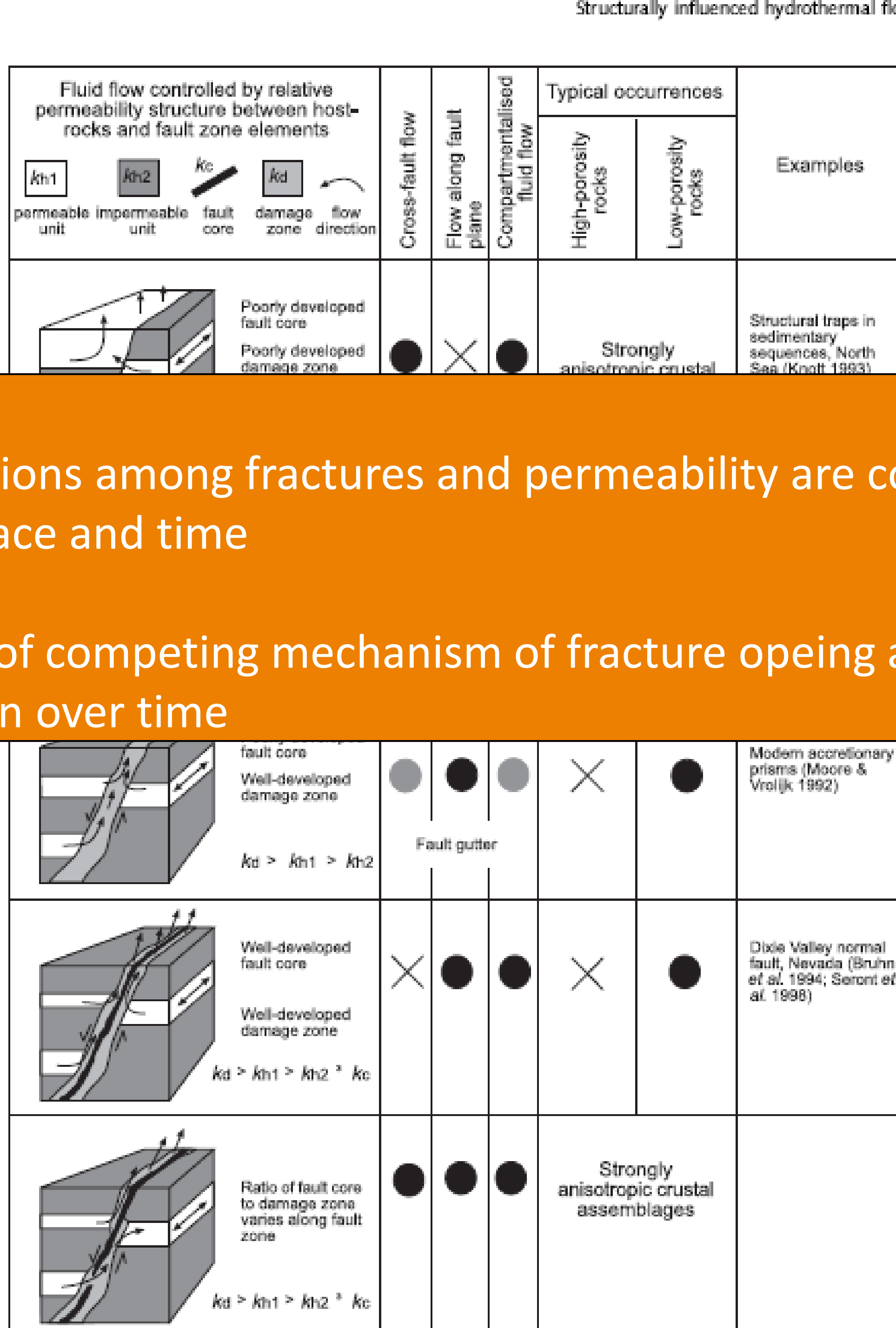


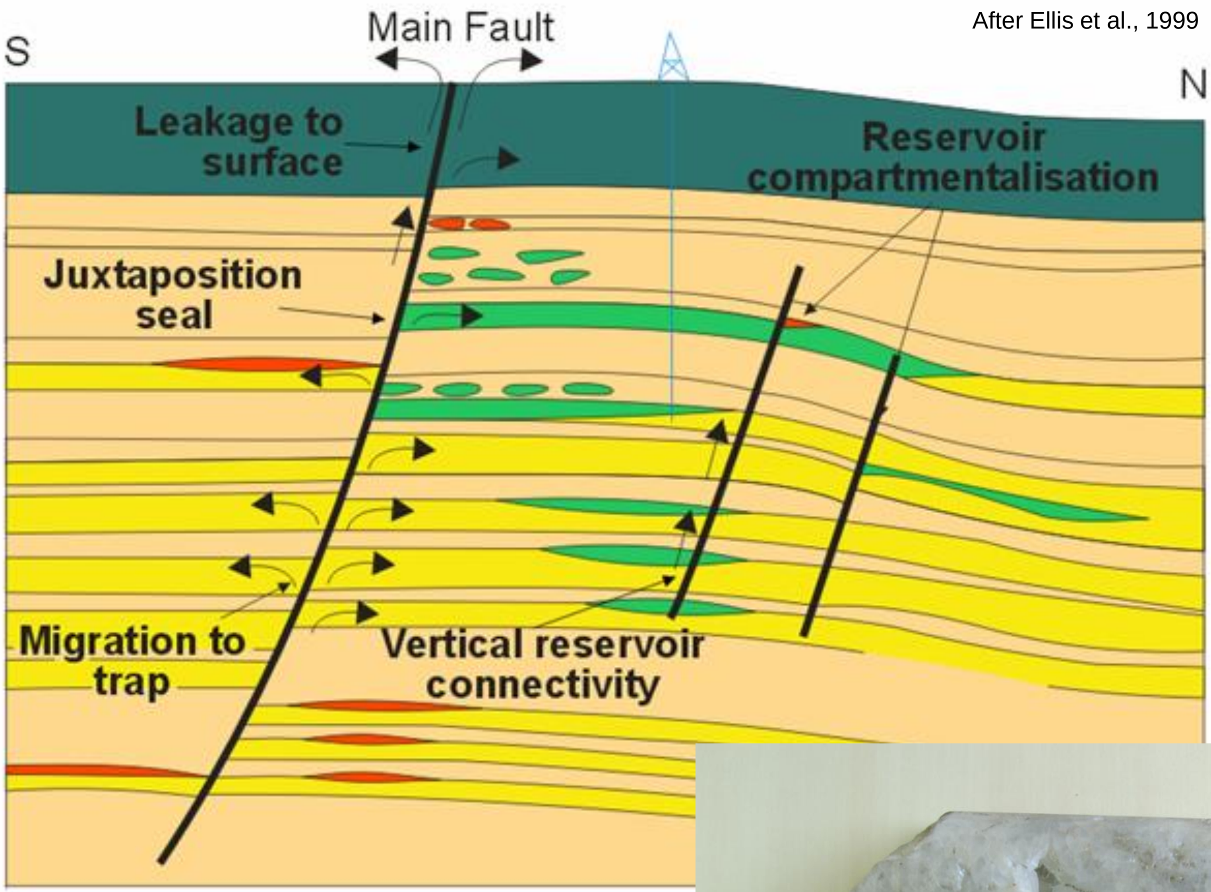
Fig. 5. Potential for fault-valve behaviour (a) Impermeable barrier separating hydrostatic and suprahydrostatic fluid pressure regimes. (b) Breaching of barrier by fault rupture X-Y, leading to an upwards discharge of fluids.

Fig. 2. Block diagram showing the evolution, from left to linkage of the individual faults, incorporating the slices o which then gets "eaten up" as the fault continues to grow. A few simple fluid trapping and migration pathways are also shown for illustration.



……. the relations among fractures and permeability are complex and varying in space and time

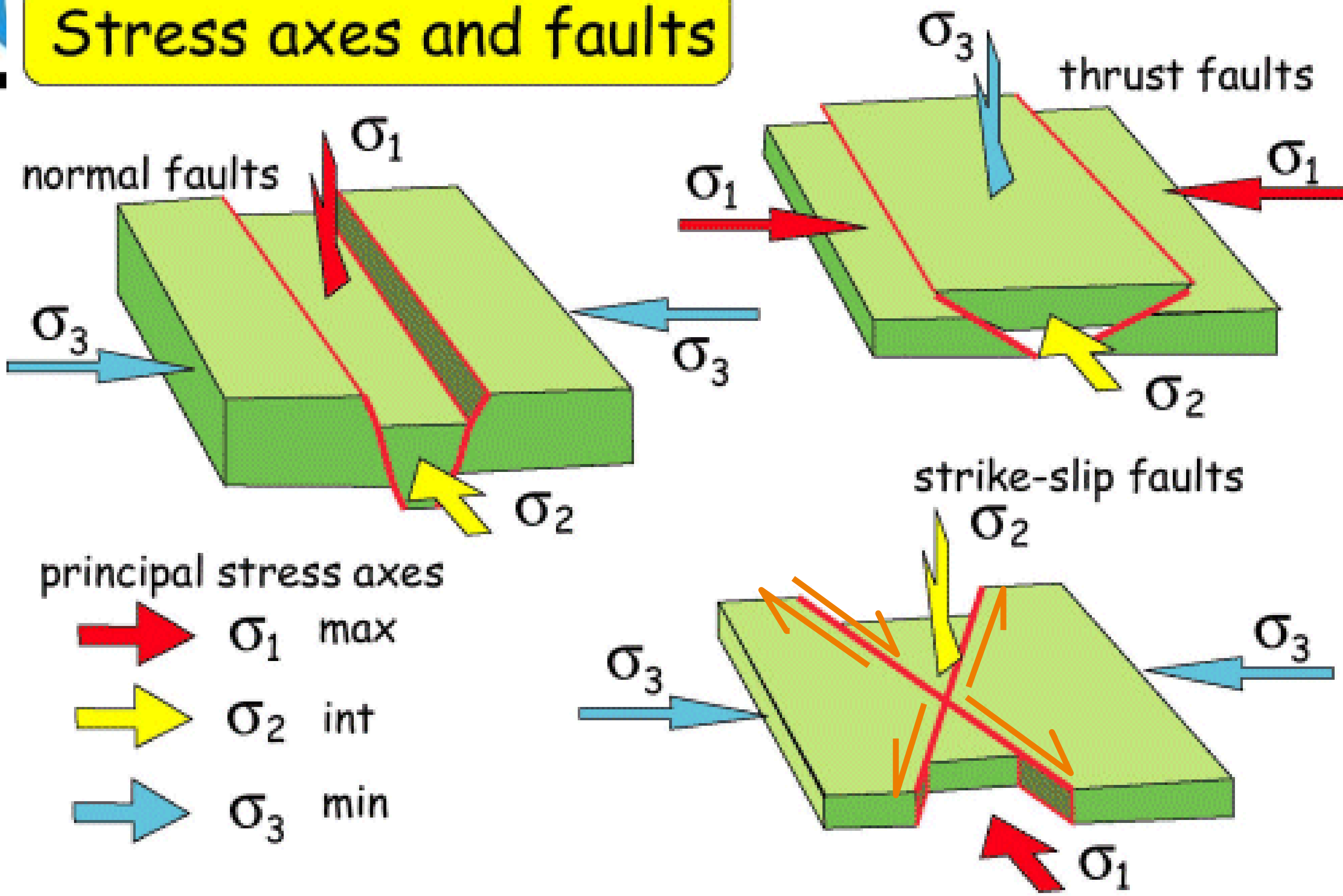
....also think of competing mechanism of fracture opeing and mineralization over time

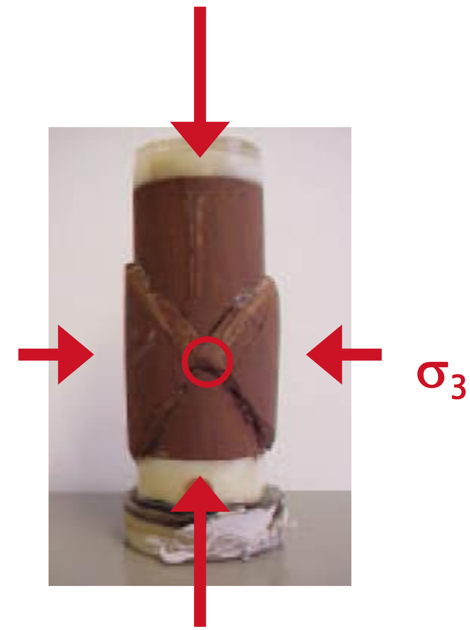


Soultz, core of fault zone
4 km depth (HAFZ)

Active faults allow hydro-thermal conduit zones

Stress axes and faults





Conjugate faults are excellent indicators of stress directions

FAULT SYSTEMS

The simplest association of faults is formed by conjugate faults

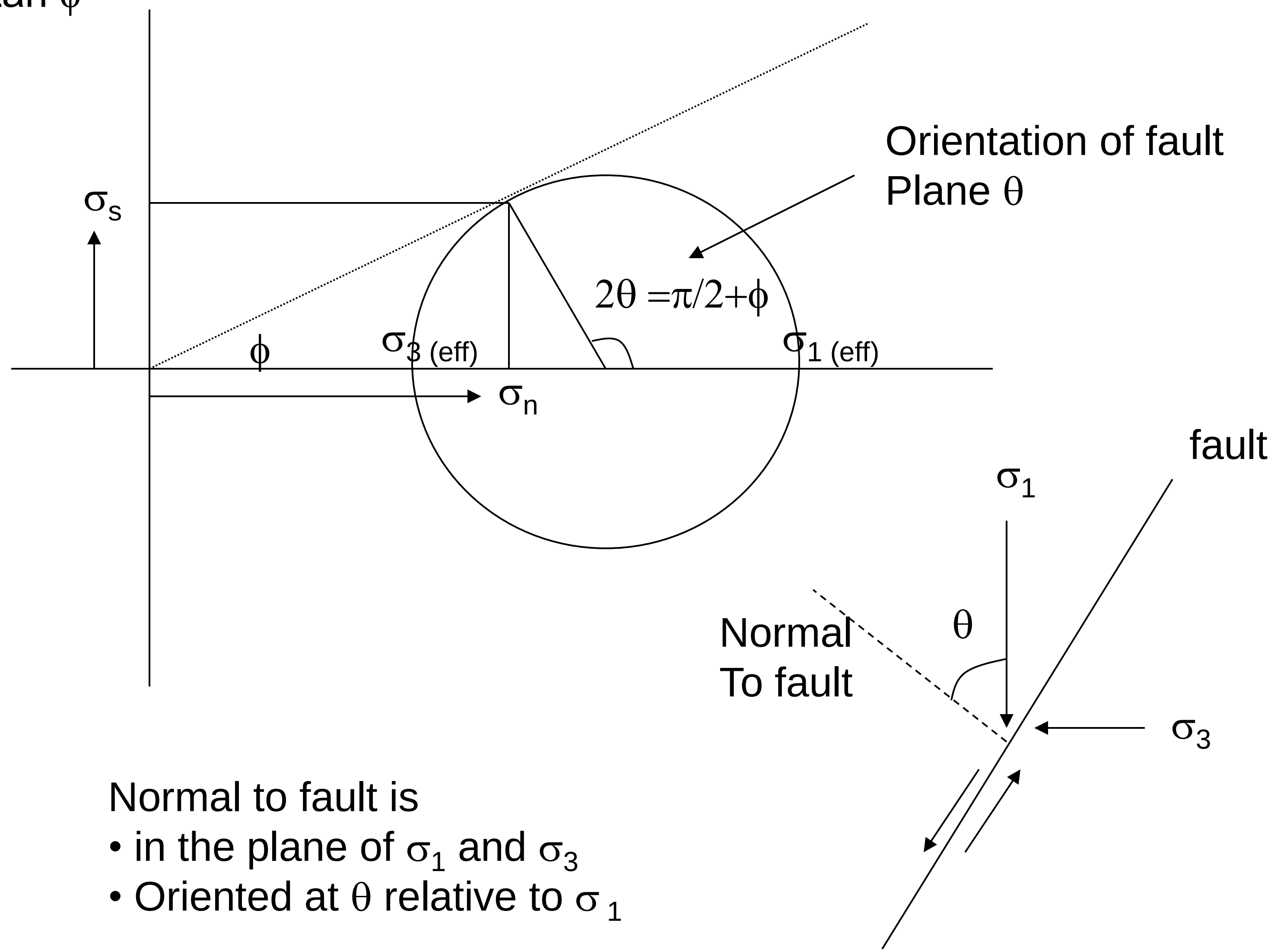
These faults formed during the same deformation event

They

- **have an angle of ~60˚ between each other**
- **the angle is dissected by the maximum compressional stress**

- Slip along a fault plane occurs if

$\sigma_s/\sigma_n \geq \tan\phi$



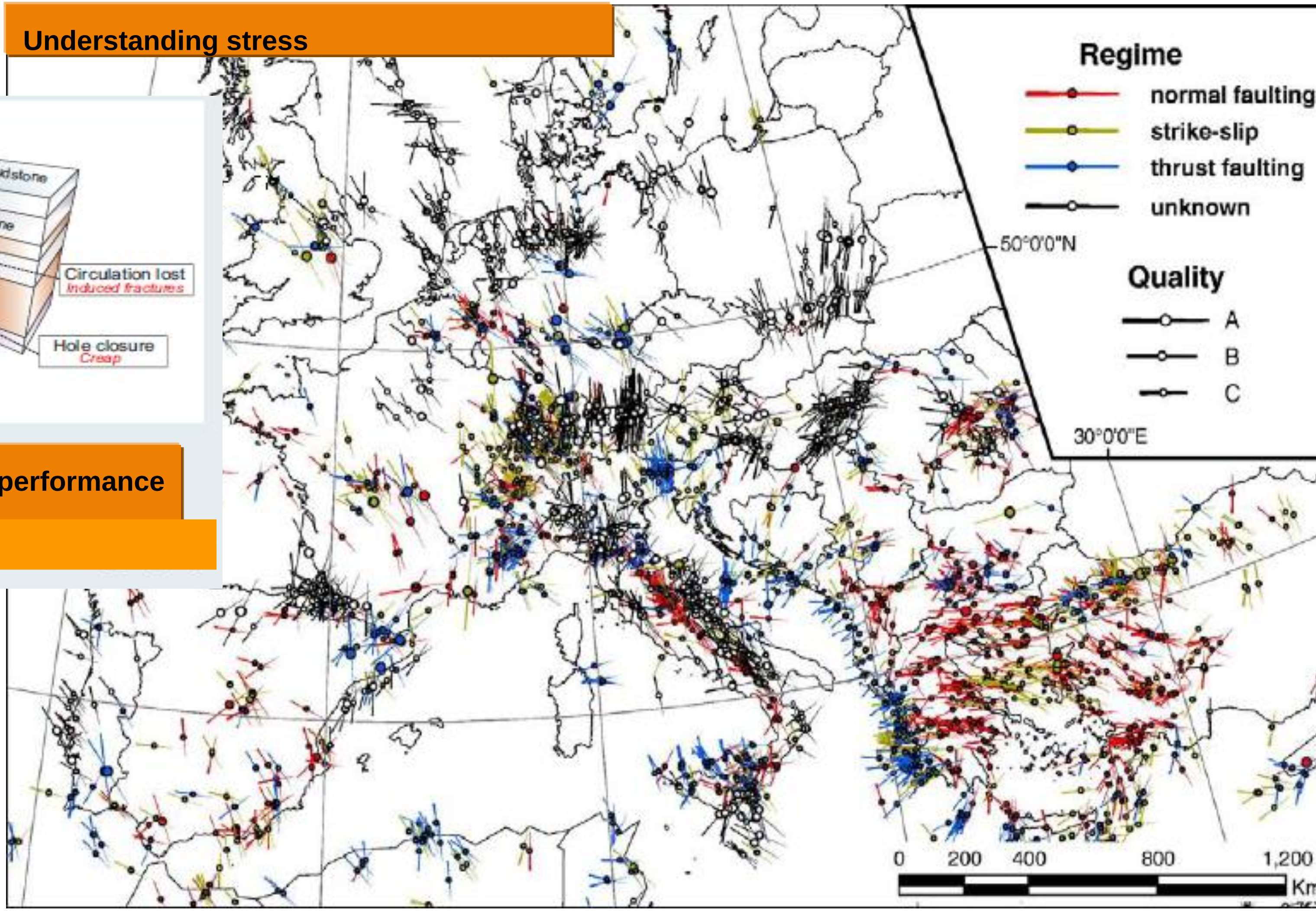
Normal to fault is
- in the plane of σ_1 and σ_3
- Oriented at θ relative to σ_1

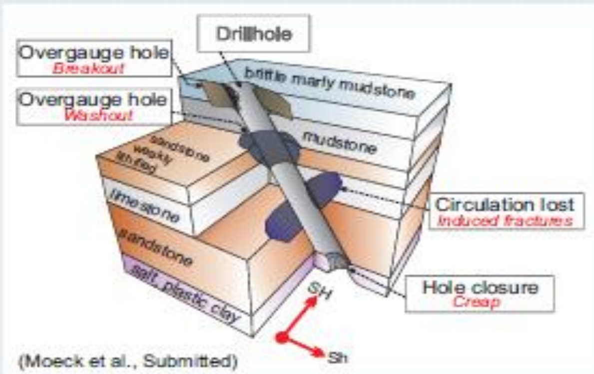
Different stress systems ($\sigma_1 > \sigma_2 > \sigma_3$)

Normal faulting	Strike slip	Thrust faulting
$\sigma_1 = \sigma_z$ $\sigma_2 = \sigma_H$ $\sigma_3 = \sigma_h$ Faults dipping ca 60 degrees	$\sigma_1 = \sigma_H$ $\sigma_2 = \sigma_z$ $\sigma_3 = \sigma_h$ Faults vertical	$\sigma_1 = \sigma_H$ $\sigma_2 = \sigma_h$ $\sigma_3 = \sigma_z$ Faults dipping ca 30 degrees

Enhancing reservoir performance →Stress is critical

Understanding stress



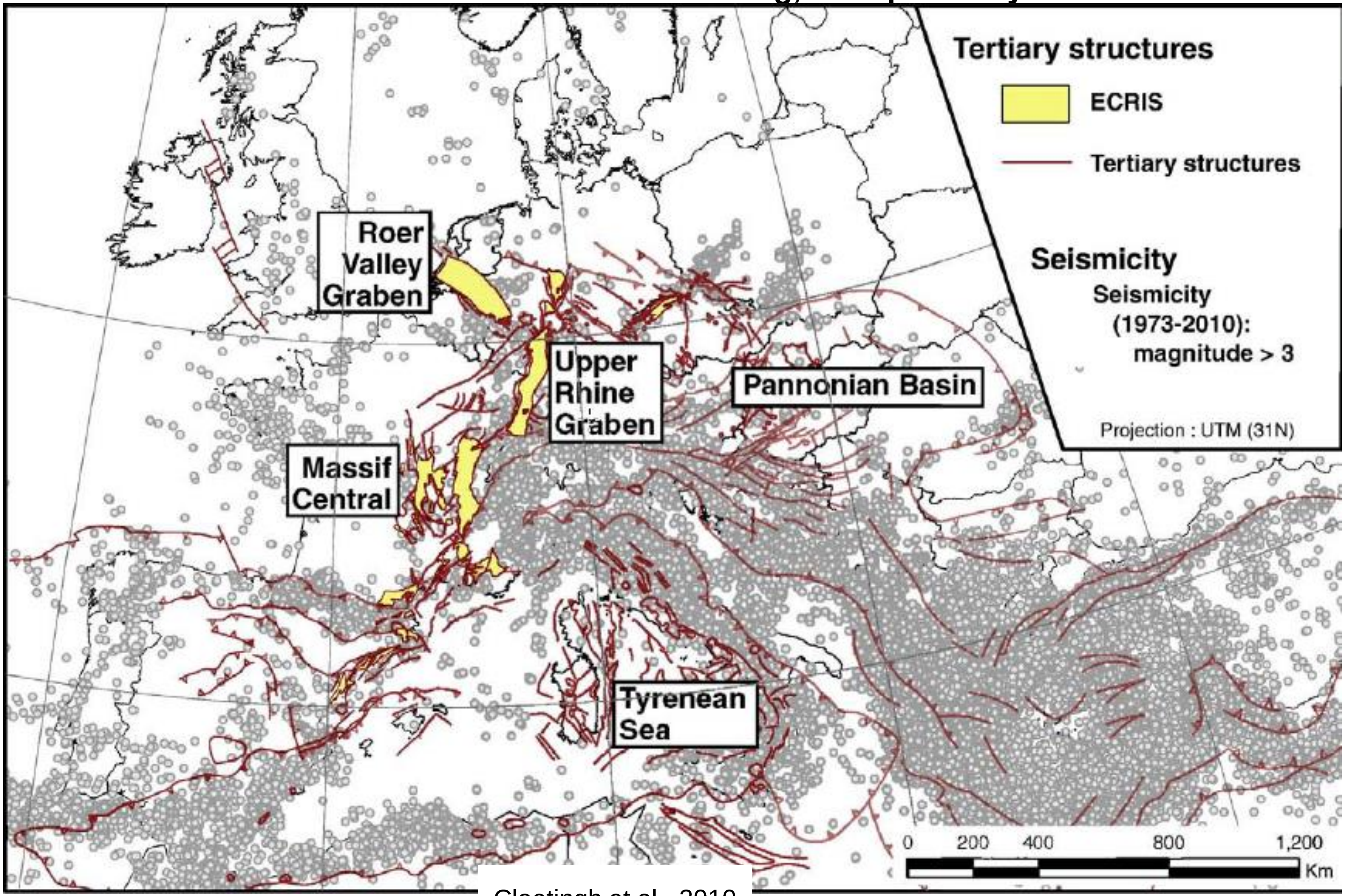


Enhancing reservoir performance

Natural laboratories

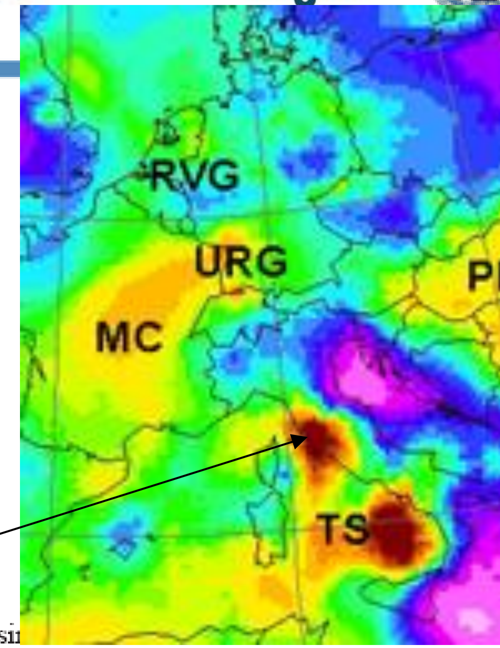
Cloetingh et al., 2010

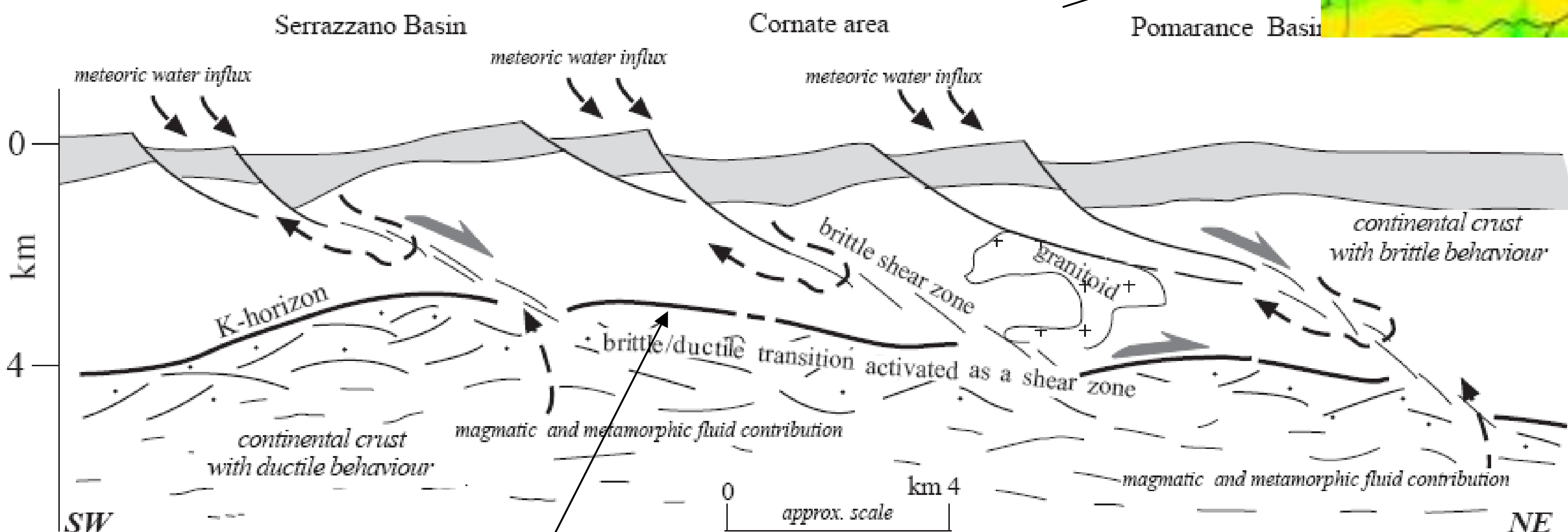
Active tectonics - ease of fraccing, fluid path ways



Cloetingh et al., 2010

Geothermal fields Larderello **(Italy)**
→ ca 800 MWe





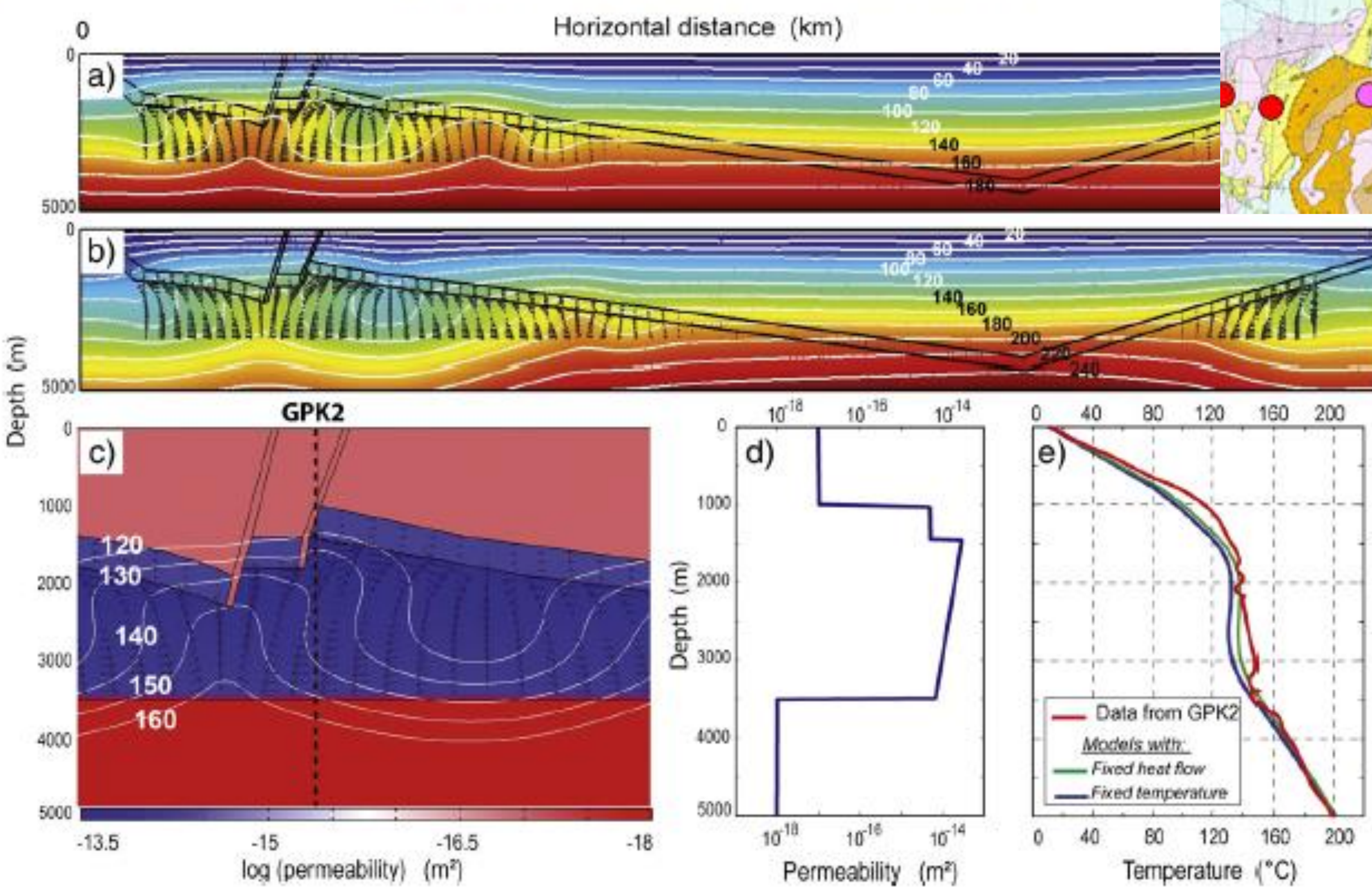
400 C

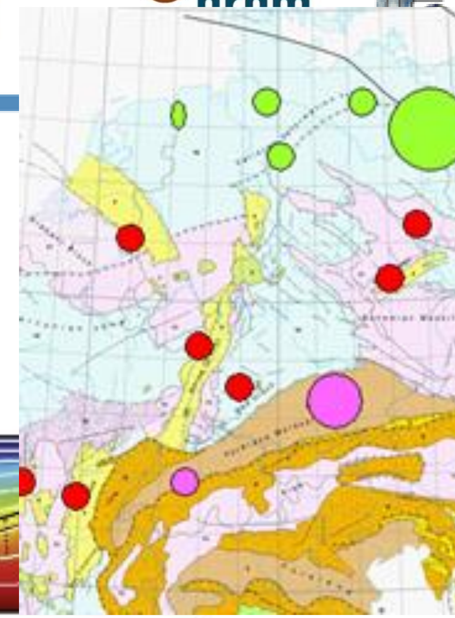
Ranalli and Rybach, 2005

Supported by INTELLIGENT ENERGY EUROPE

Soultz - Fluid circulation appears to play an important role in enhancing shallow heat flows at the expense of diminishing heat flow at deeper levels

46 L. Guillou-Frottier et al. / Journal of Volcanology and Geothermal Research 256 (2013) 29–49





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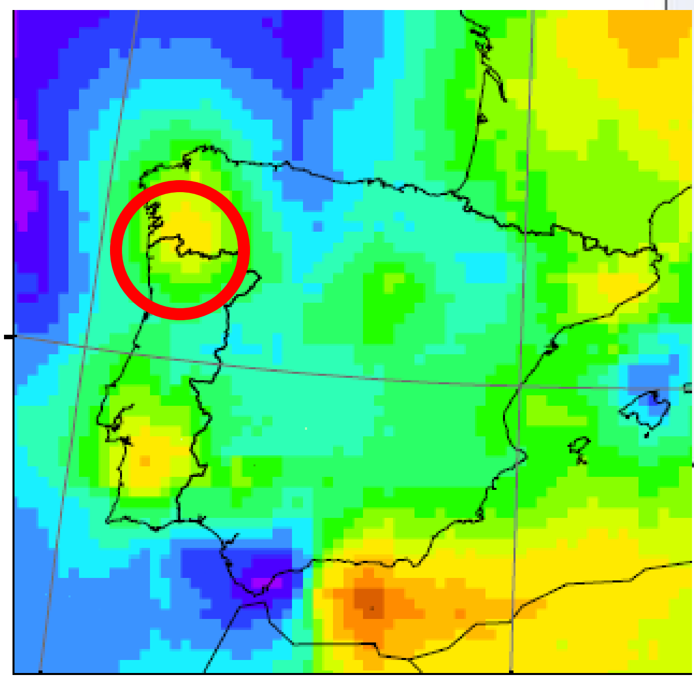
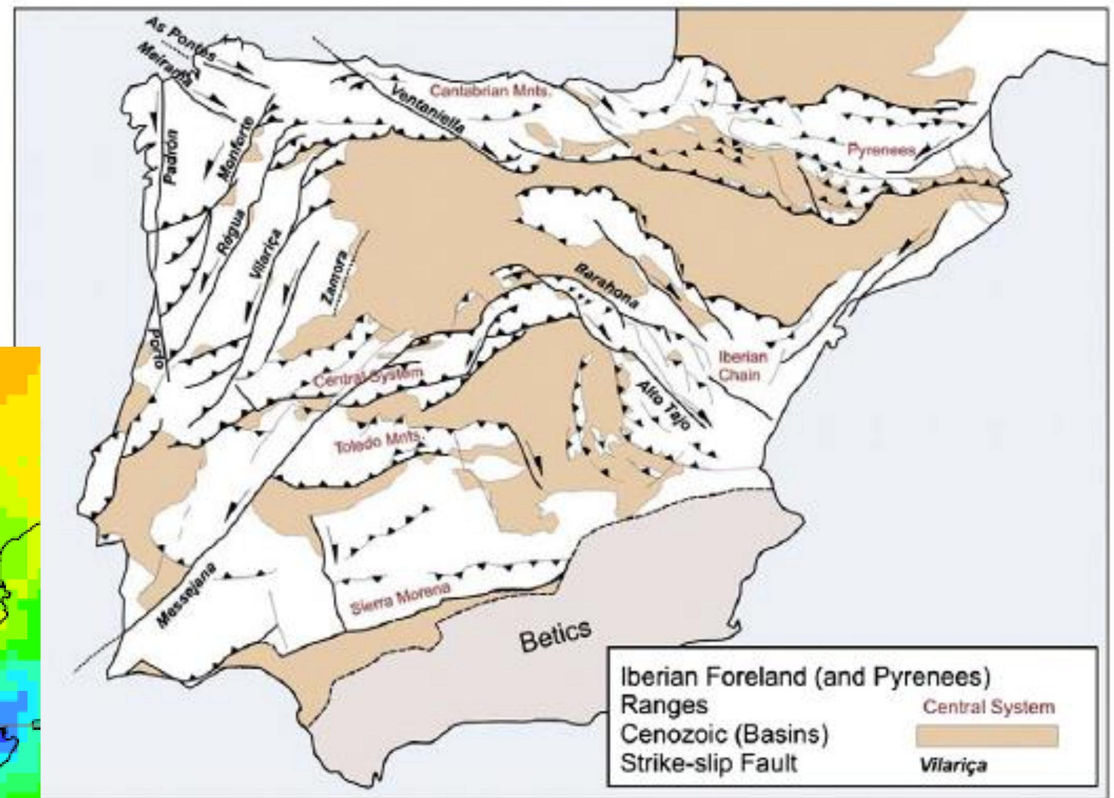
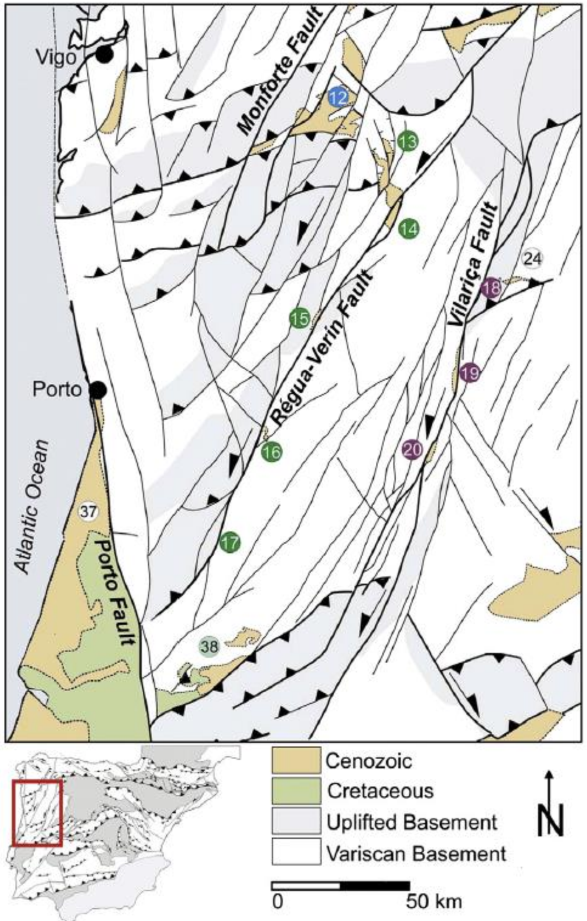


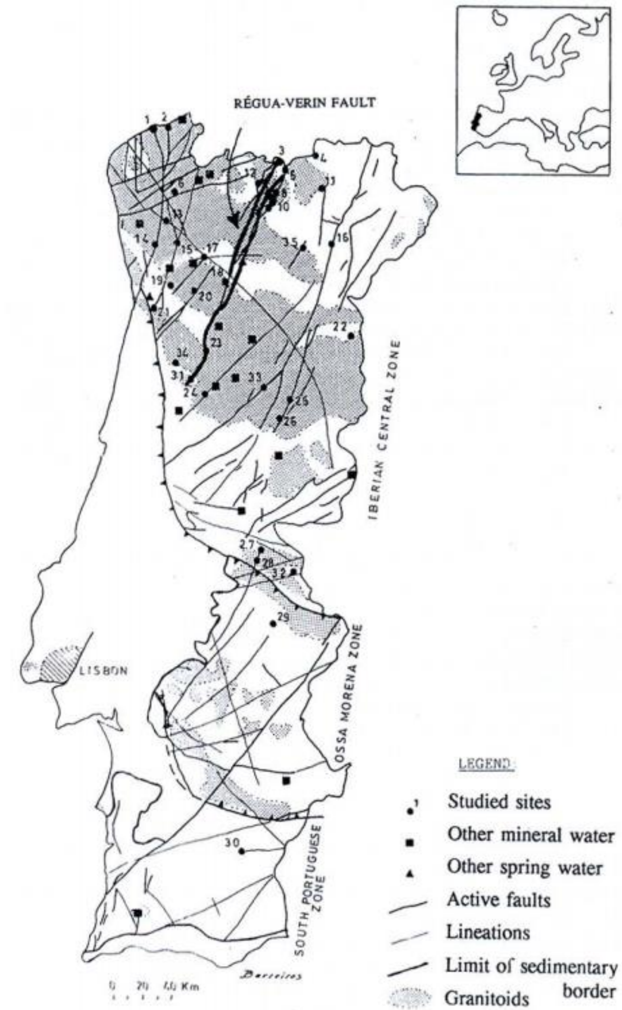


deVicente et al. 2011 (Tectonophysics)

tive faults, fault g fluid-path ways

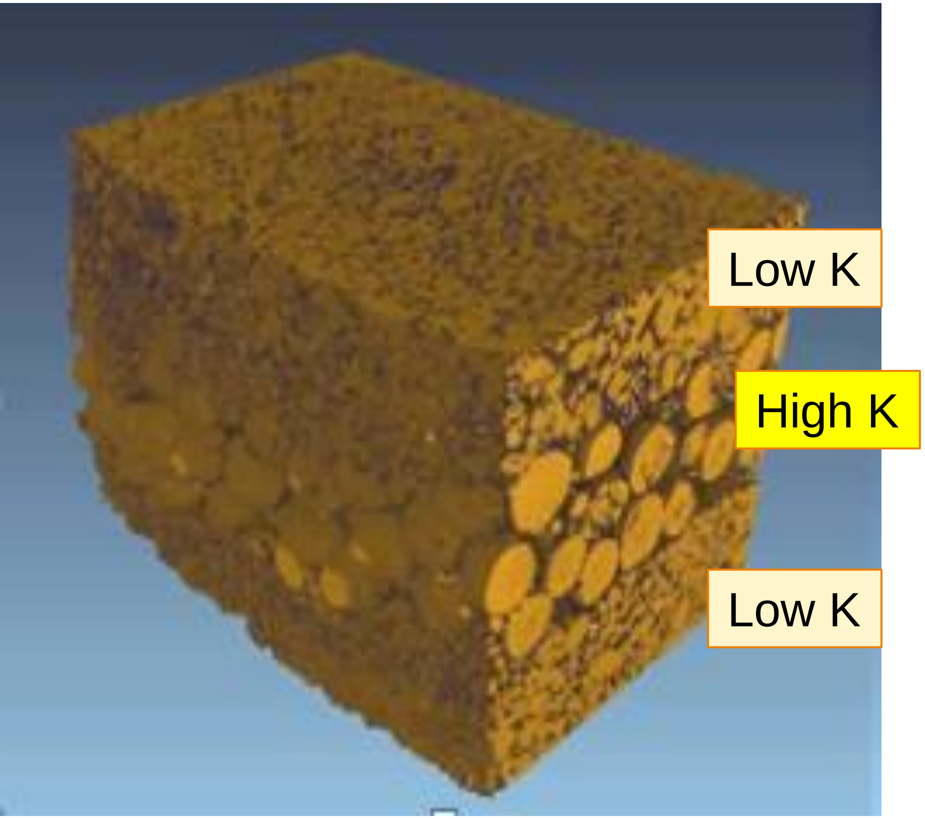


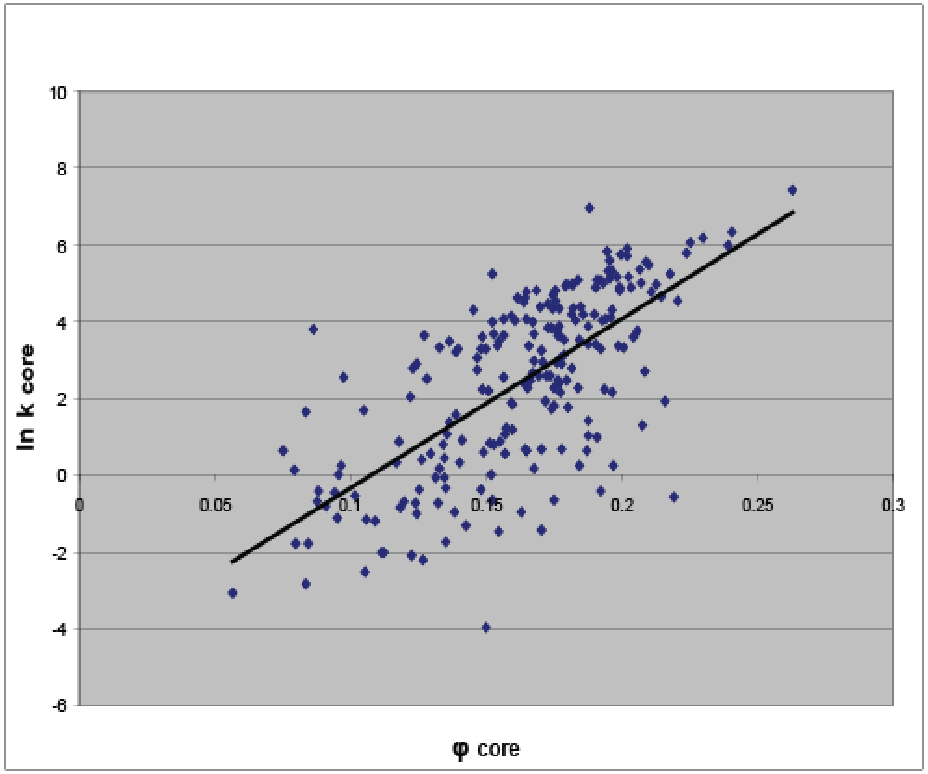
deVicente et al. 2011 (Tectonophysics)



Carvalho 1993

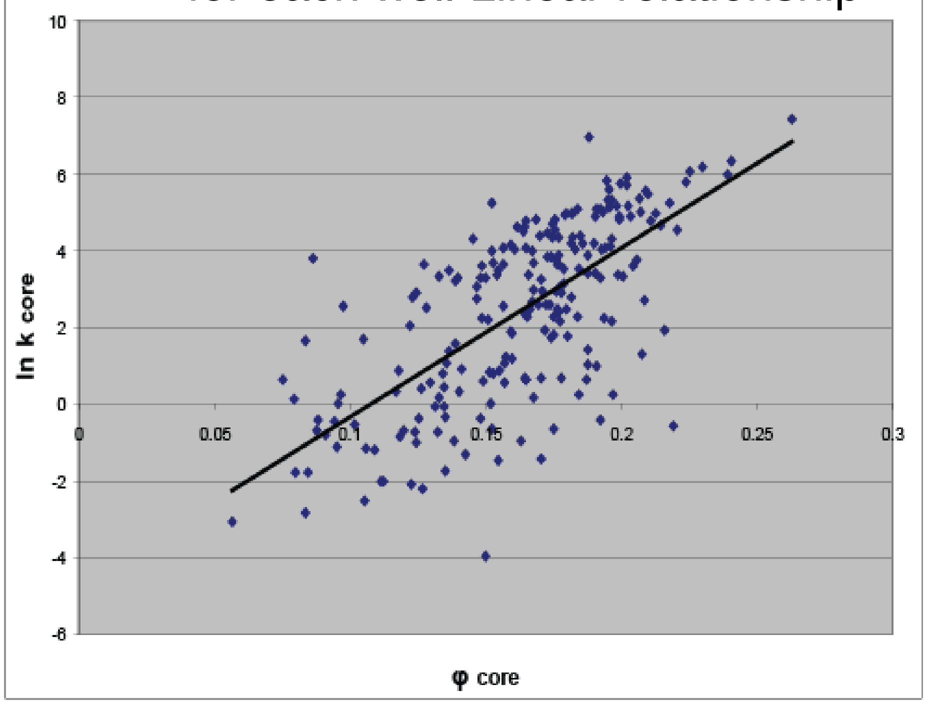
Fracture Permeability and flow patterns





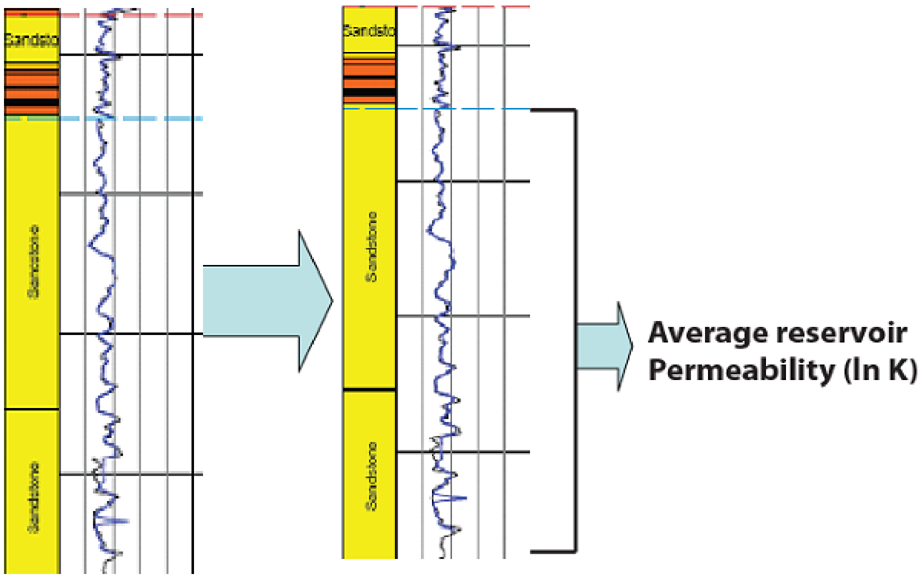
STEP 1: Porosity → Permeability in wells

Over 150,000 core-plug data for each well Linear relationship

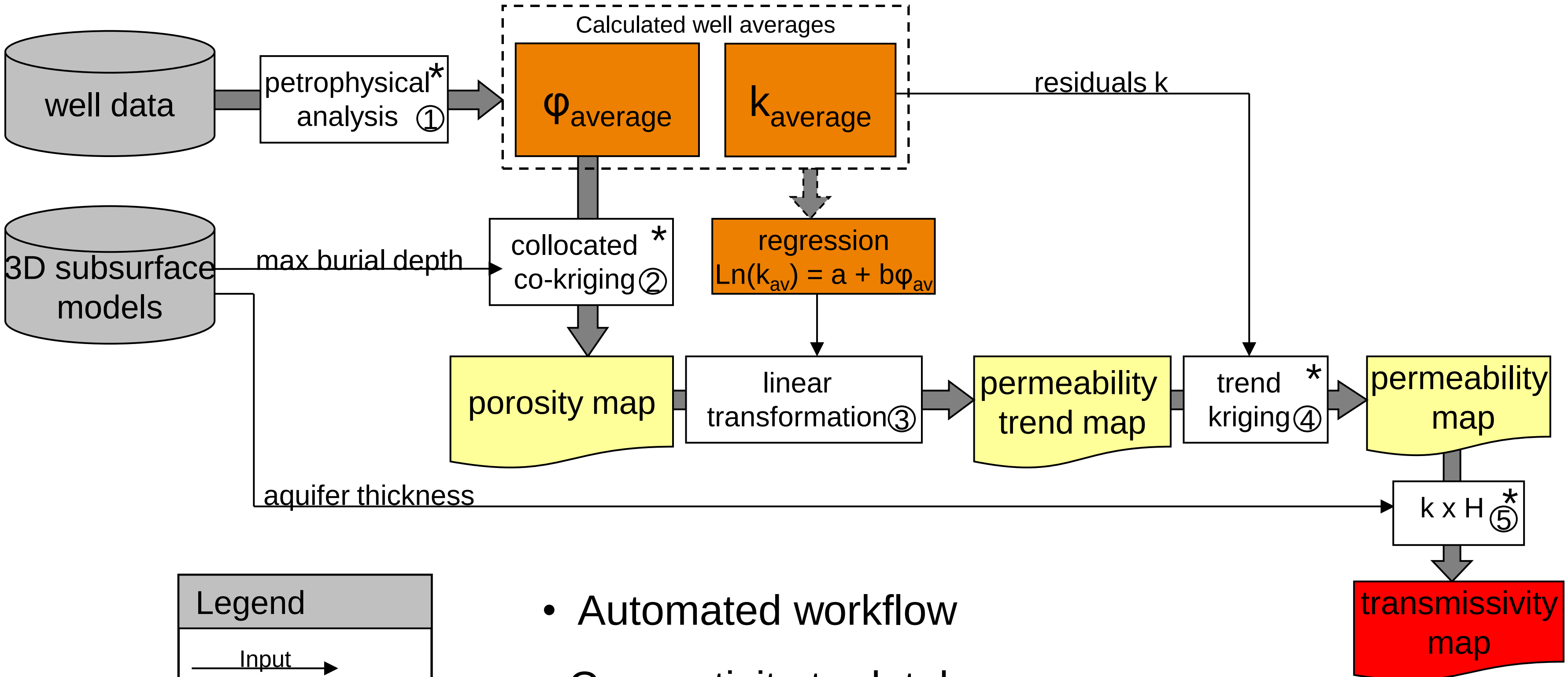


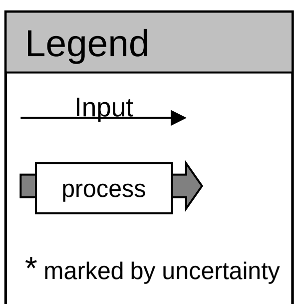
Porosity log

Permeability log



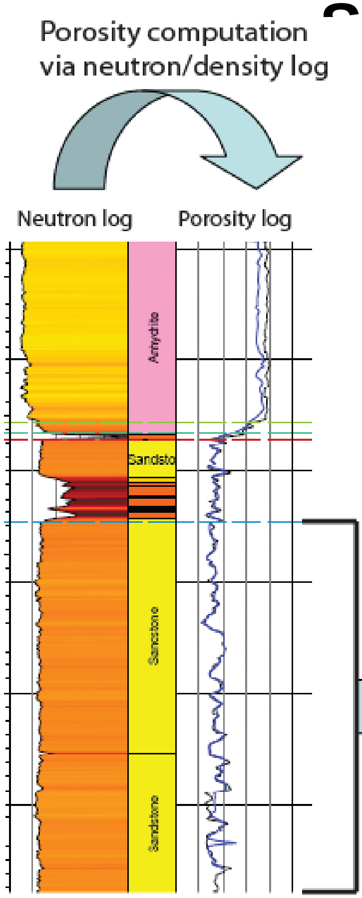
Property mapping





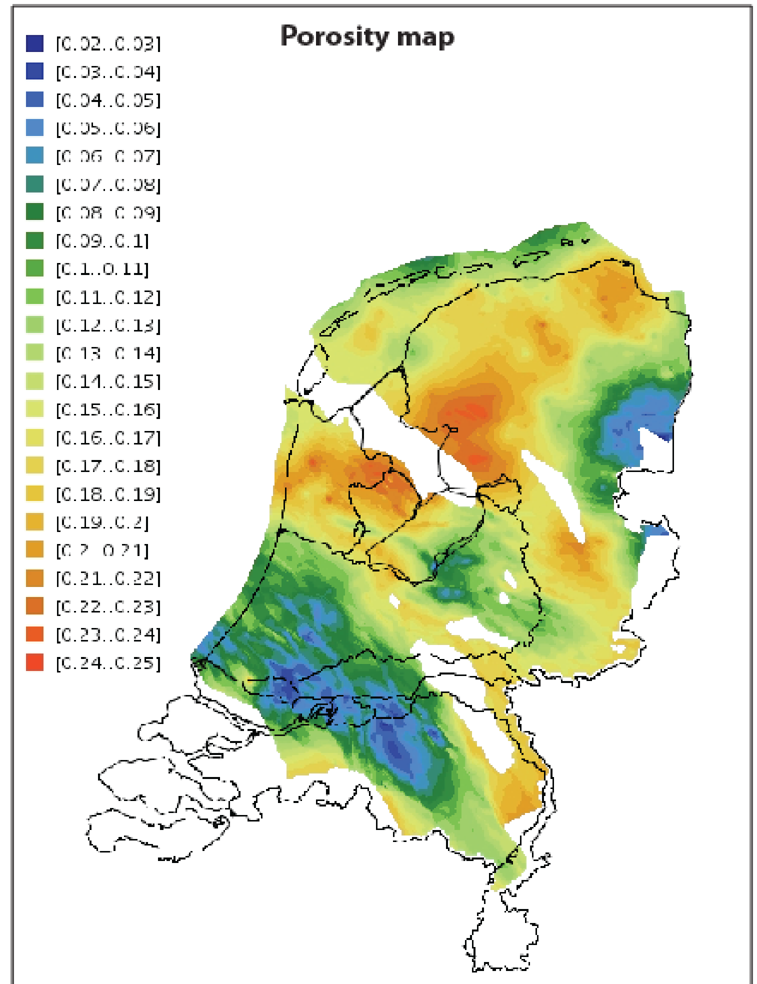
- Automated workflow
- Connectivity to database
- Geostatisics for uncertainties

STEP 2 – From well porosity to porosity maps



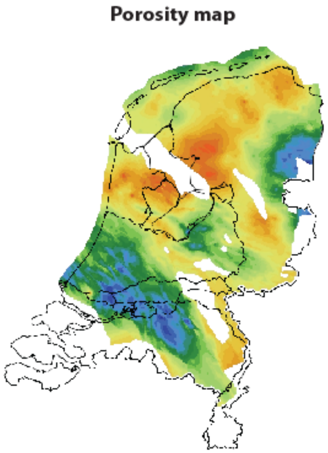
Average Porosity (Φ)

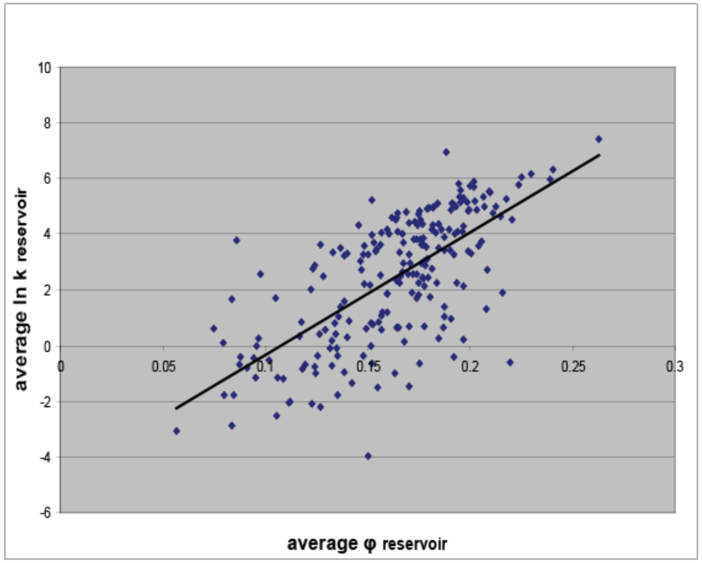
Co-Kriging with depth

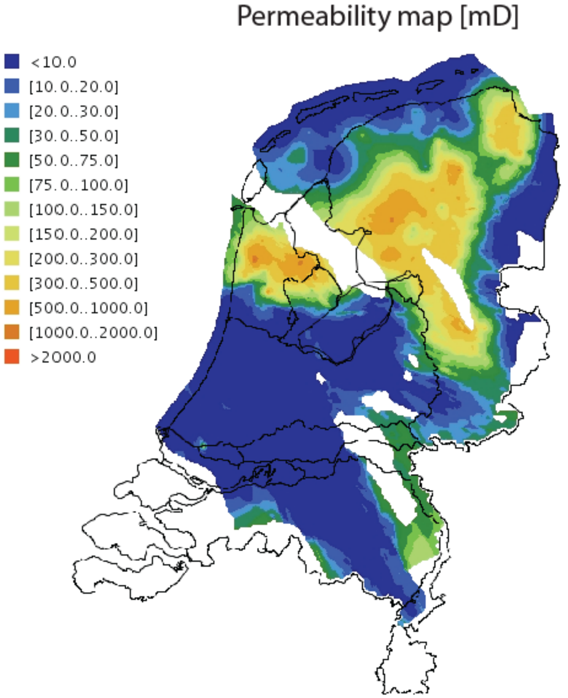


Average porosity – average permeability

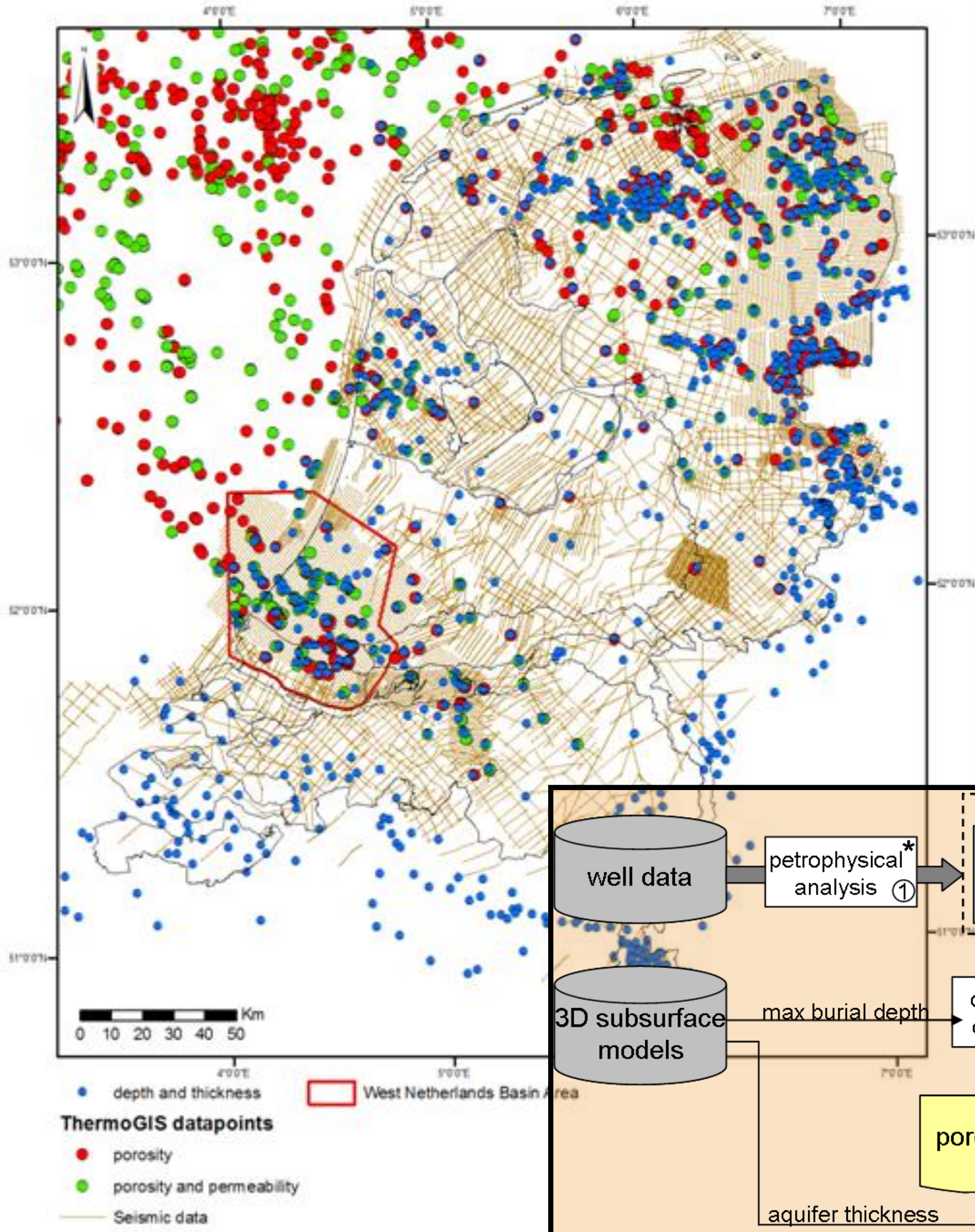
Step 3

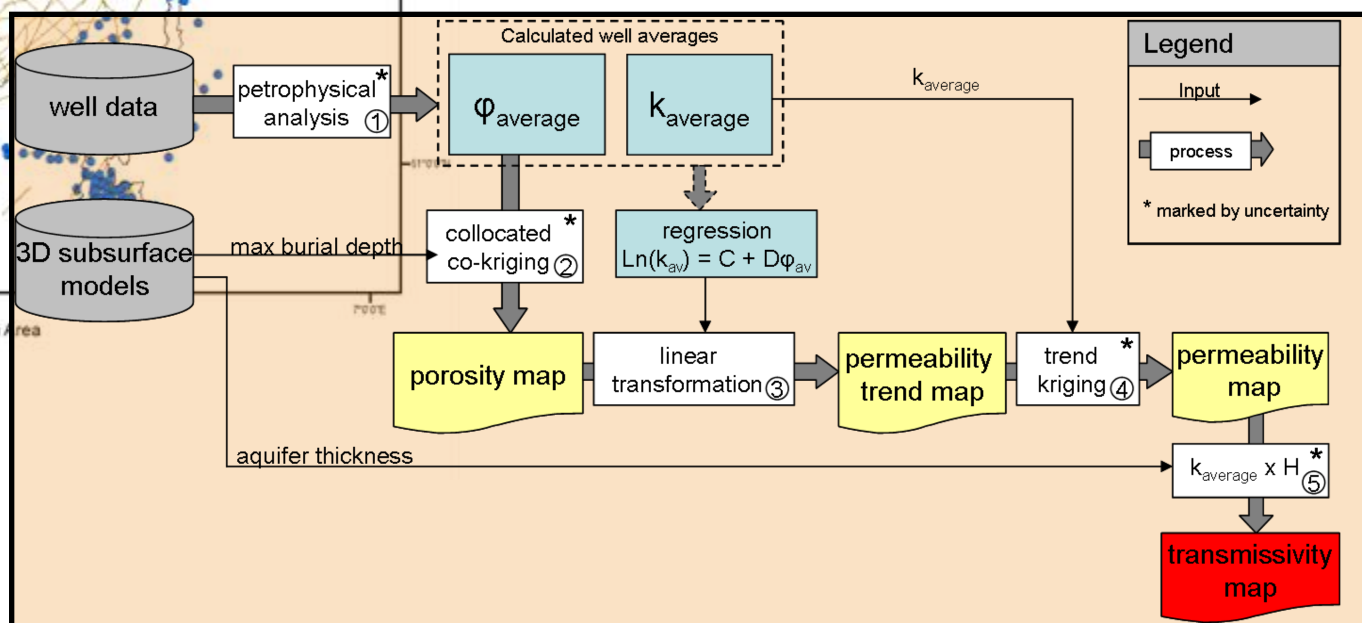




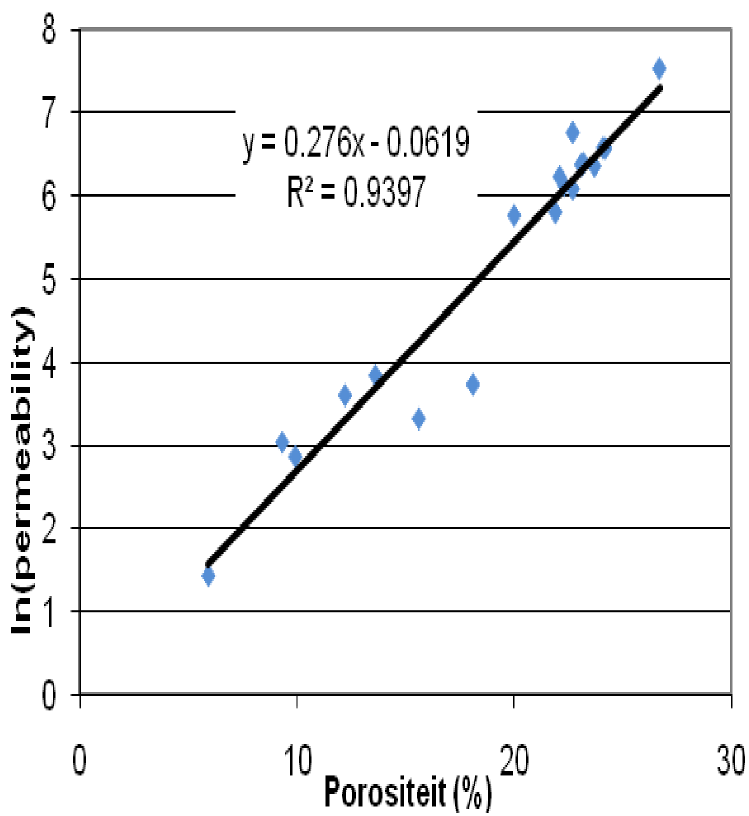


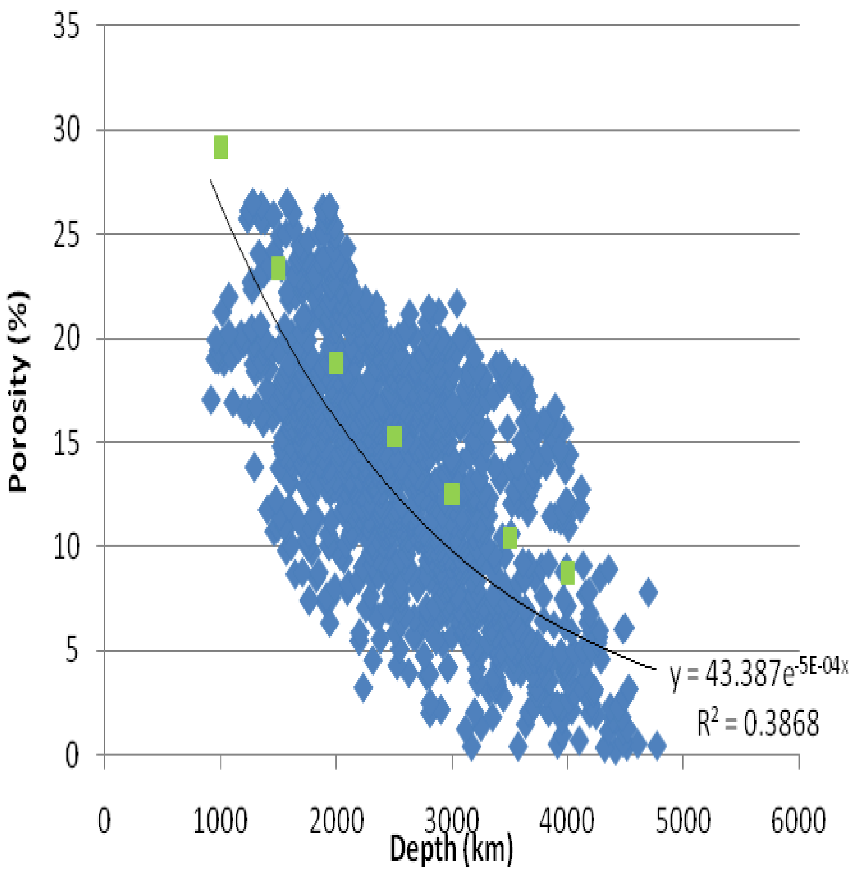
Porosity permeability and thickness control



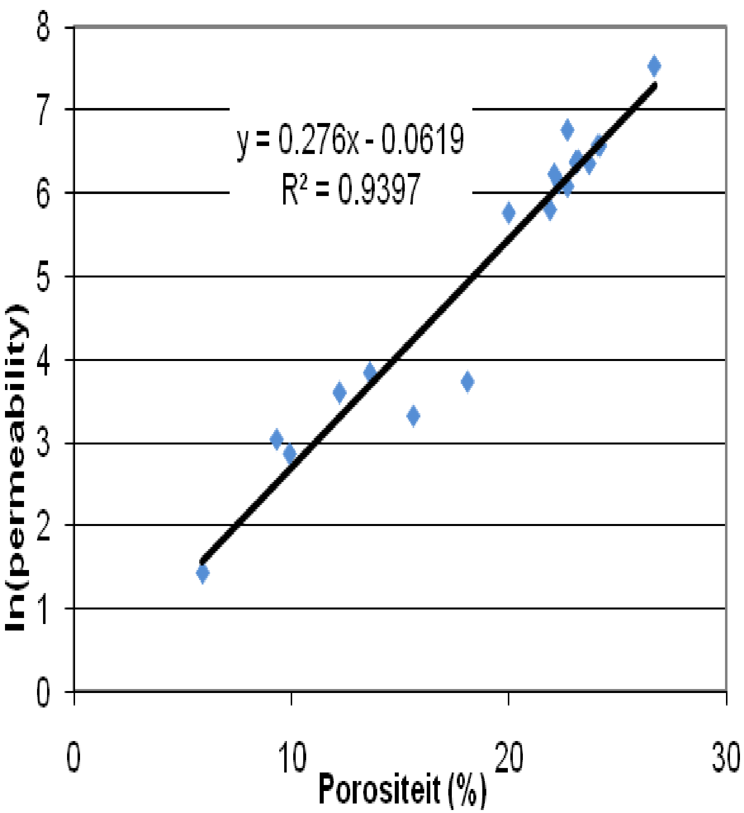


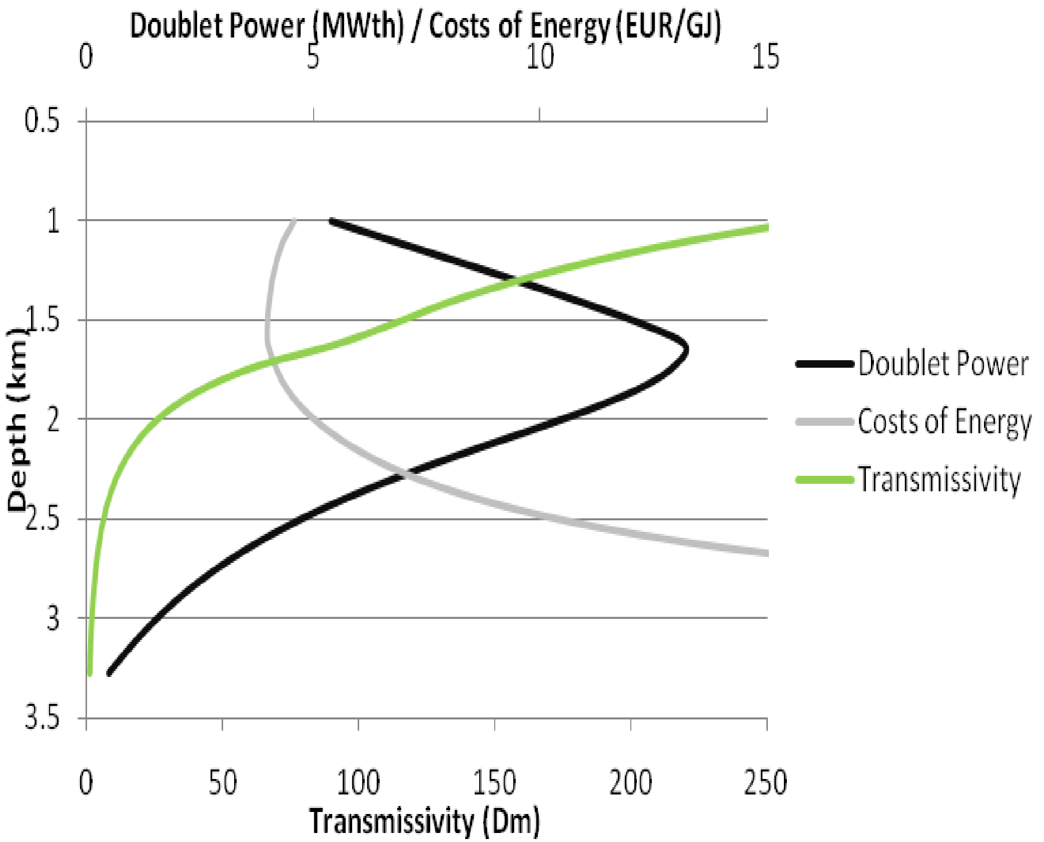
Permeability is determined using poro-perm relationship
Porosity generally decreases with depth….



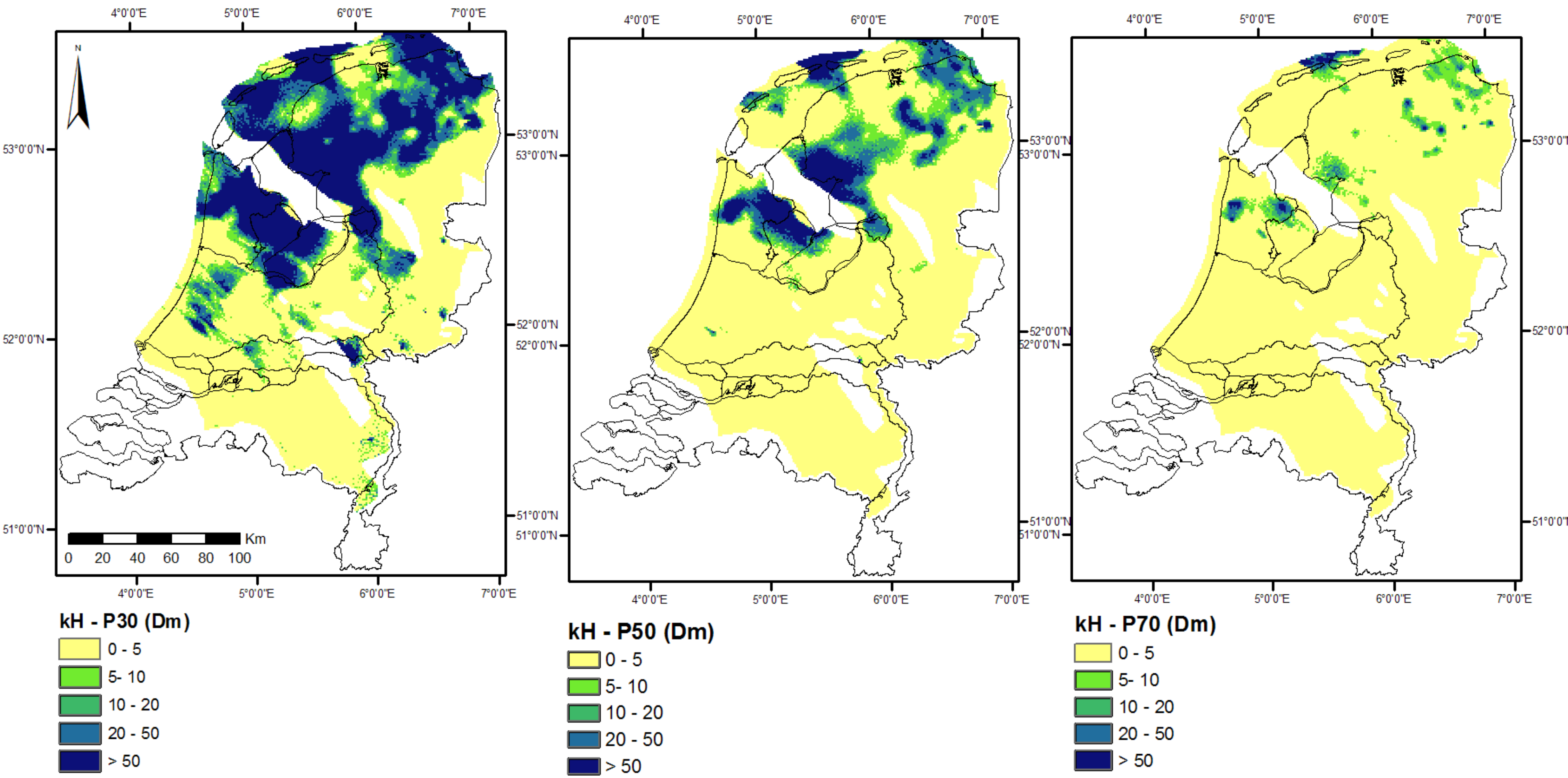


Performance is predicted to decrease with depth as a function of porosity



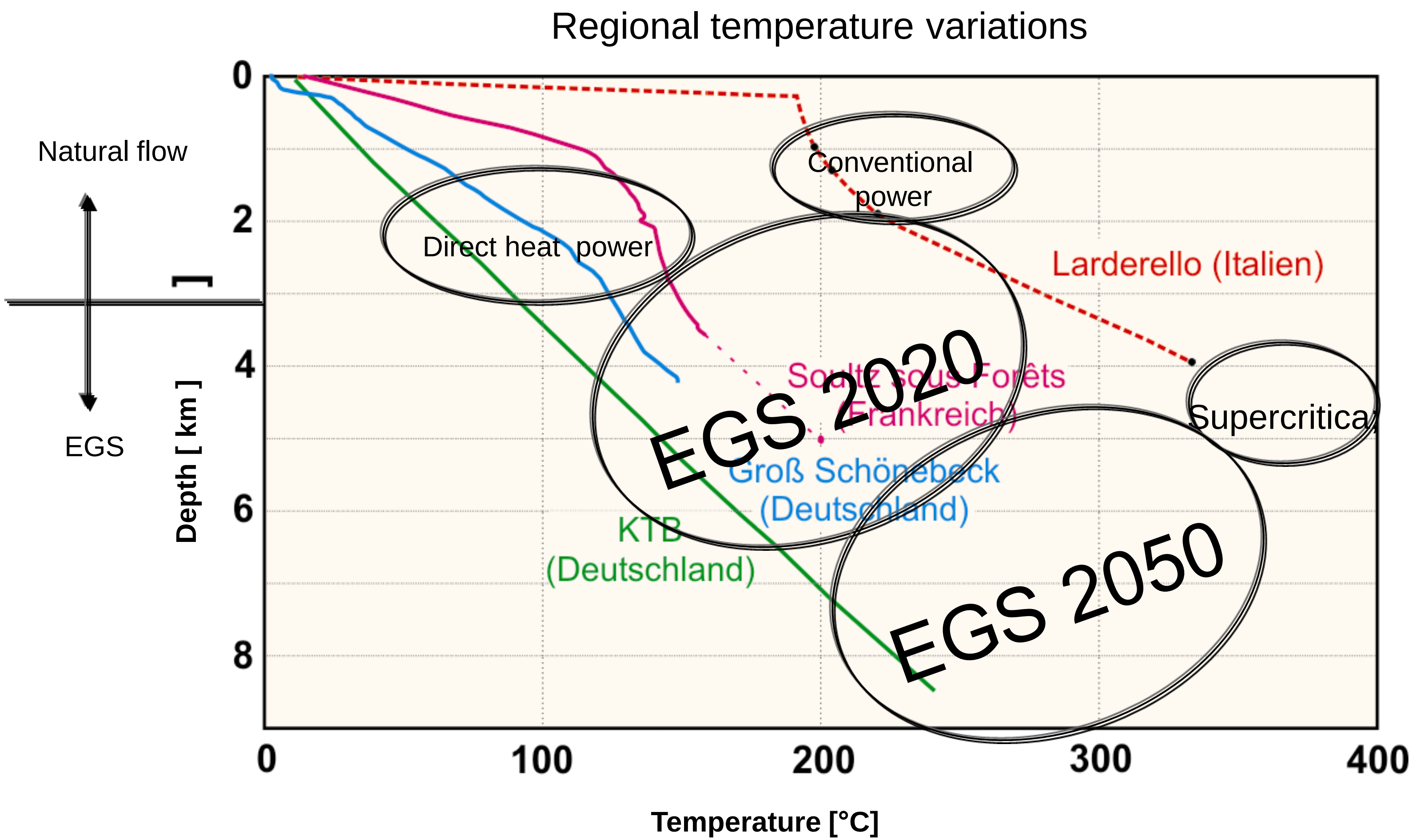


Property mapping and uncertainties (3)



Rotliegendes aquifer

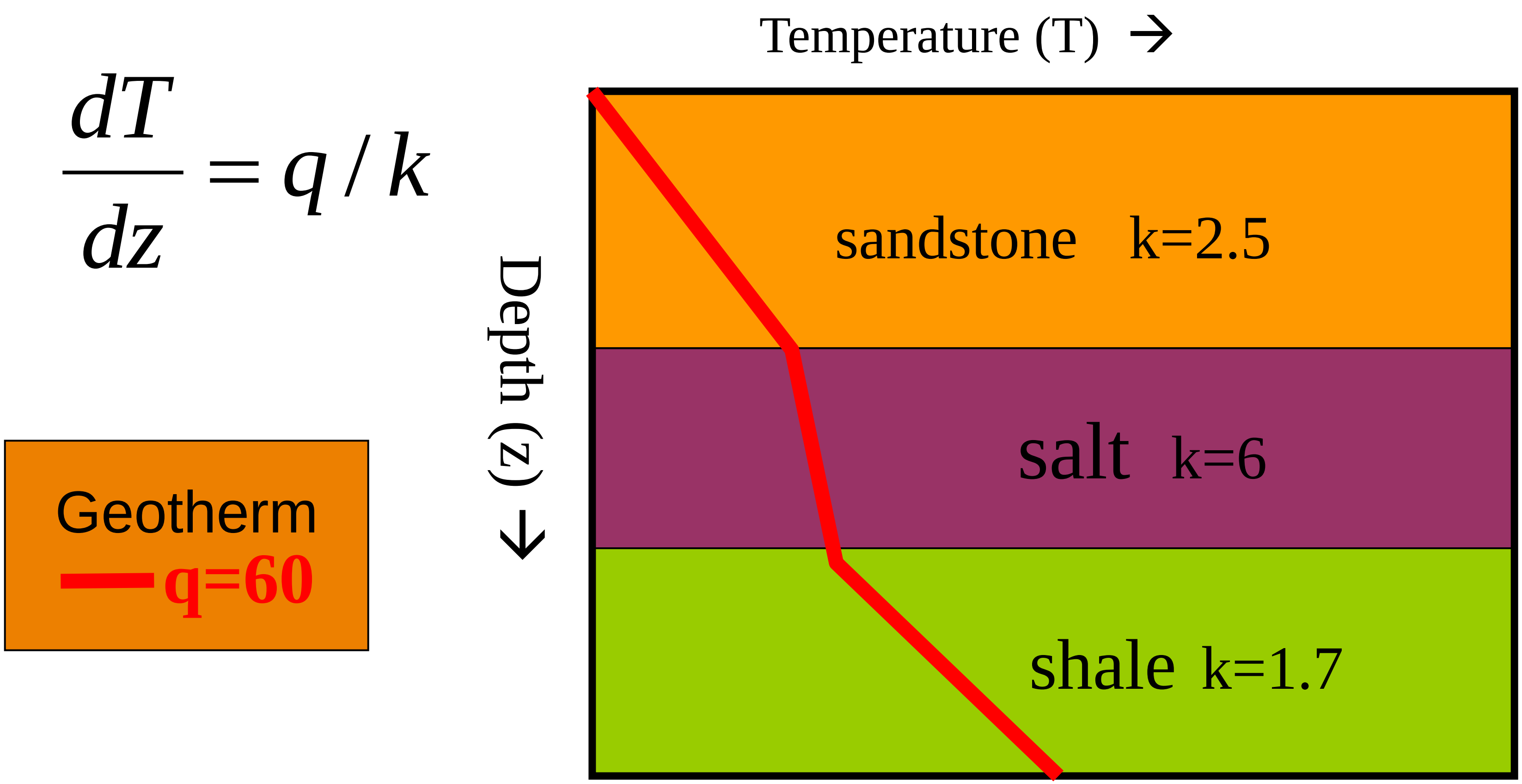
Temperature gradients in the upper crust



Temperature is reconstructed using a steady state geotherm (conductive approach)

- **Heat flow q** [mW/m^{-2}] is an important boundary condition in basin modeling. It determines the temperature gradient in sediments in conjunction with **rock conductivity k** [W m^{-1} C^{-1}]

$$\frac{dT}{dz} = q / k$$



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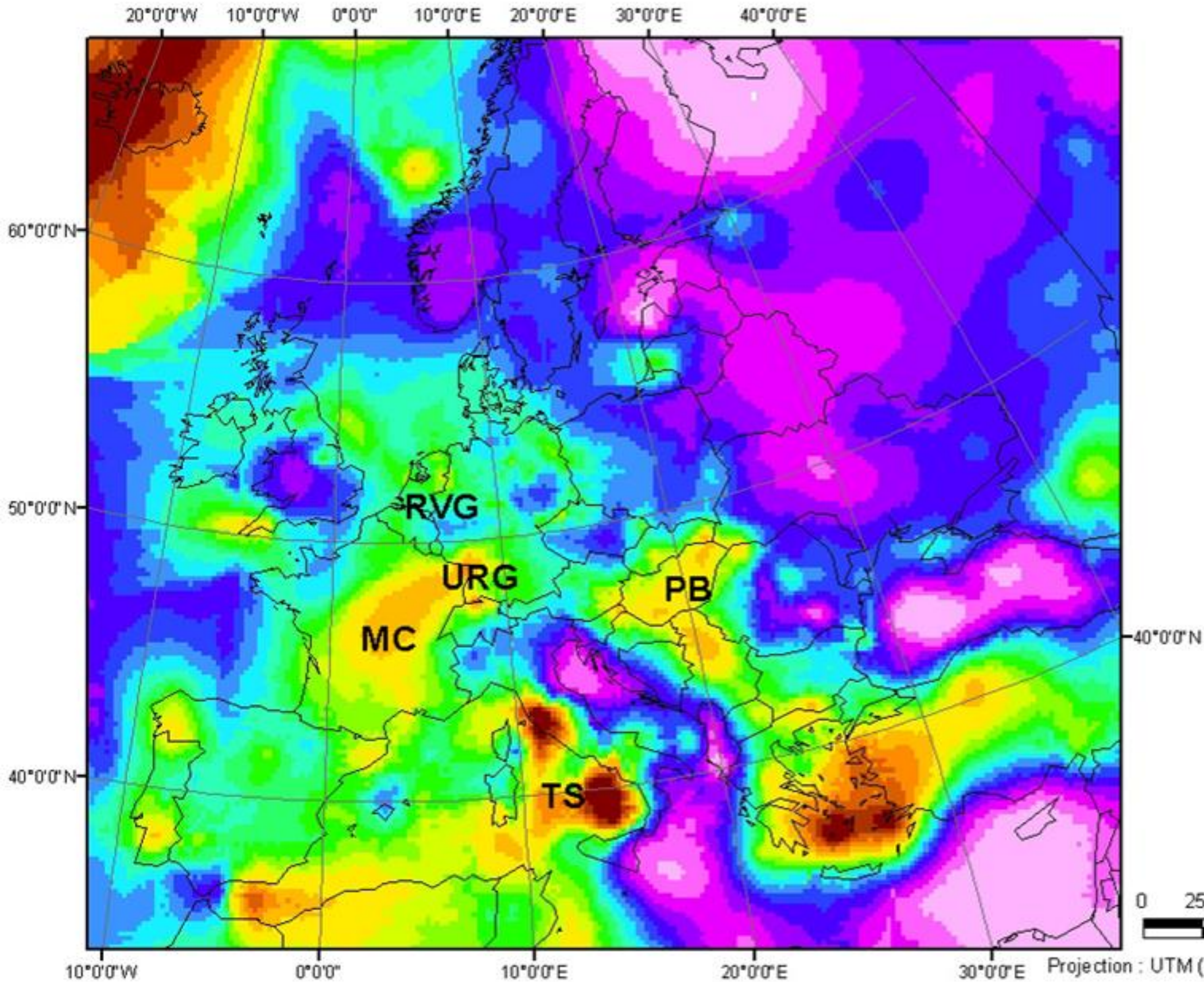
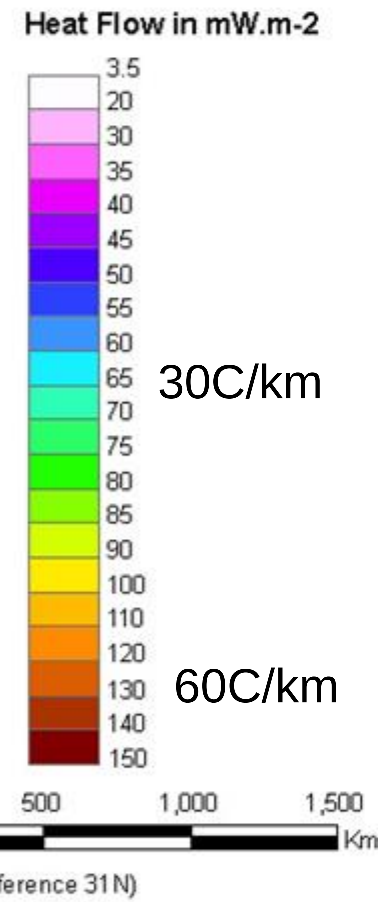
Heat Flow map of Europe





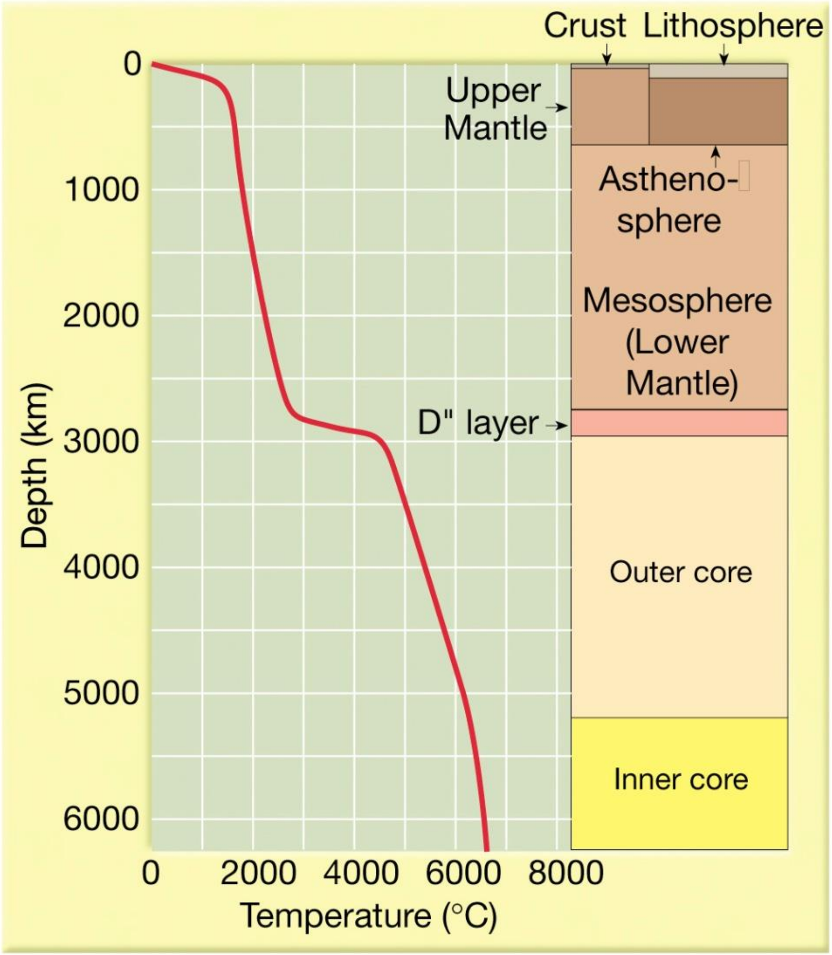
30C/km

60C/km

Cloetingh et al., 2010, Earth Science Reviews

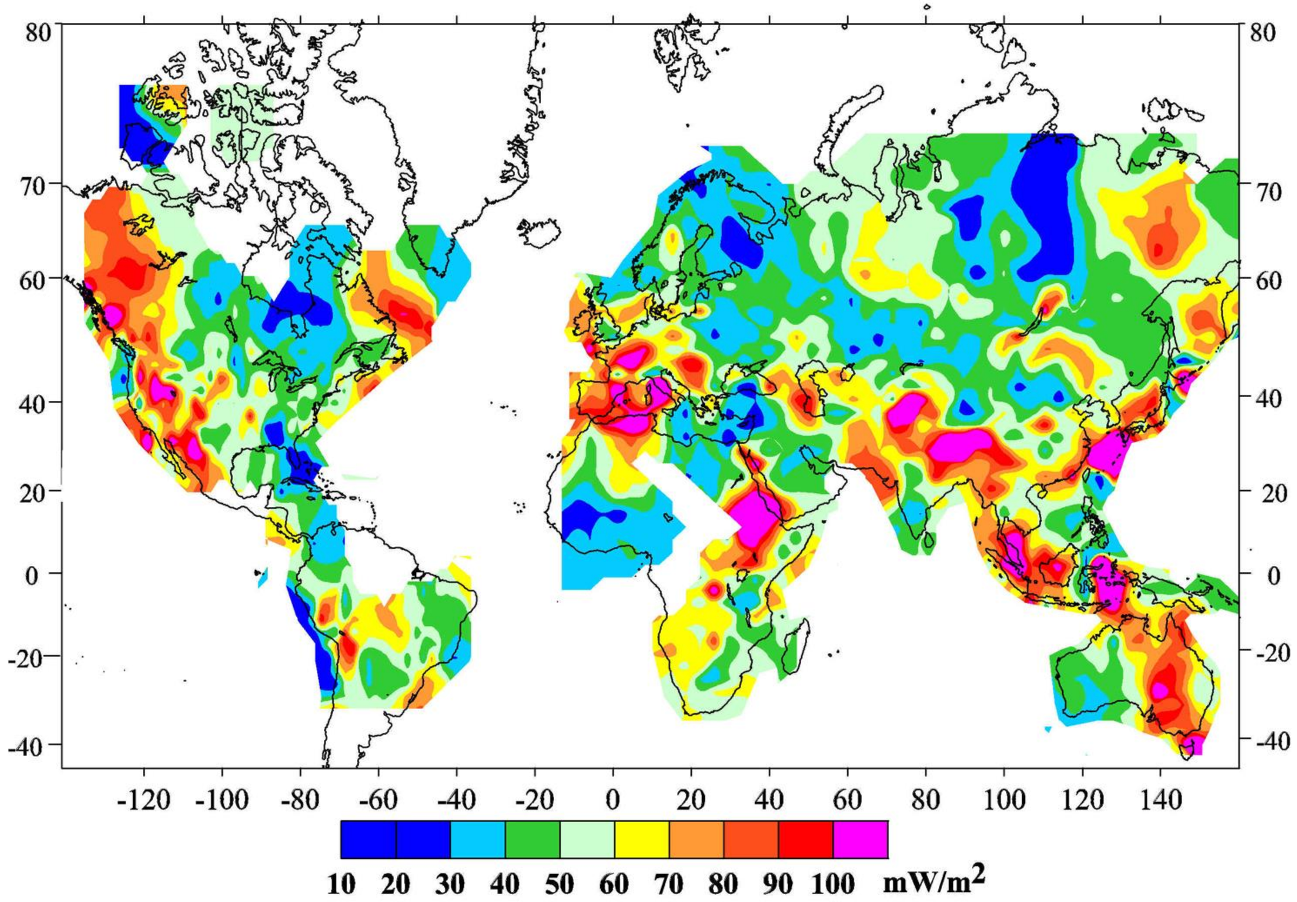
Geotherm and geothermal gradient

- gradient varies depending on location
- surface gradient is average 20-30 oC/km
- lithosphere bottom is 1300C
- ? Gradient variation dependent on lithosphere thickness
- ? Gradient variation dependent on thermal properties

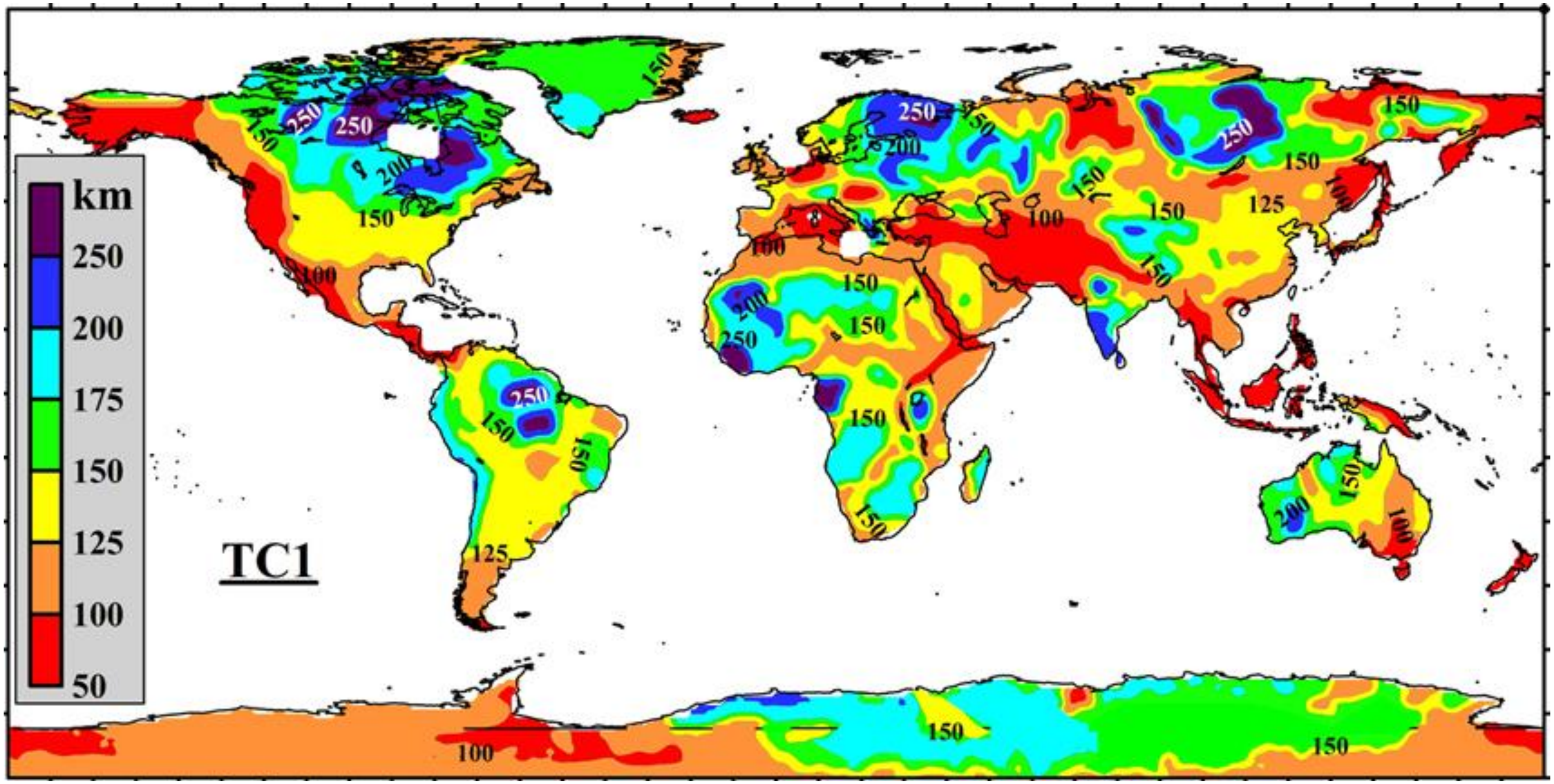


Heat flow at Earth's surface

Continental lithosphere: heat flow is heterogeneous as a consequence of thickness variations, composition and thermal age

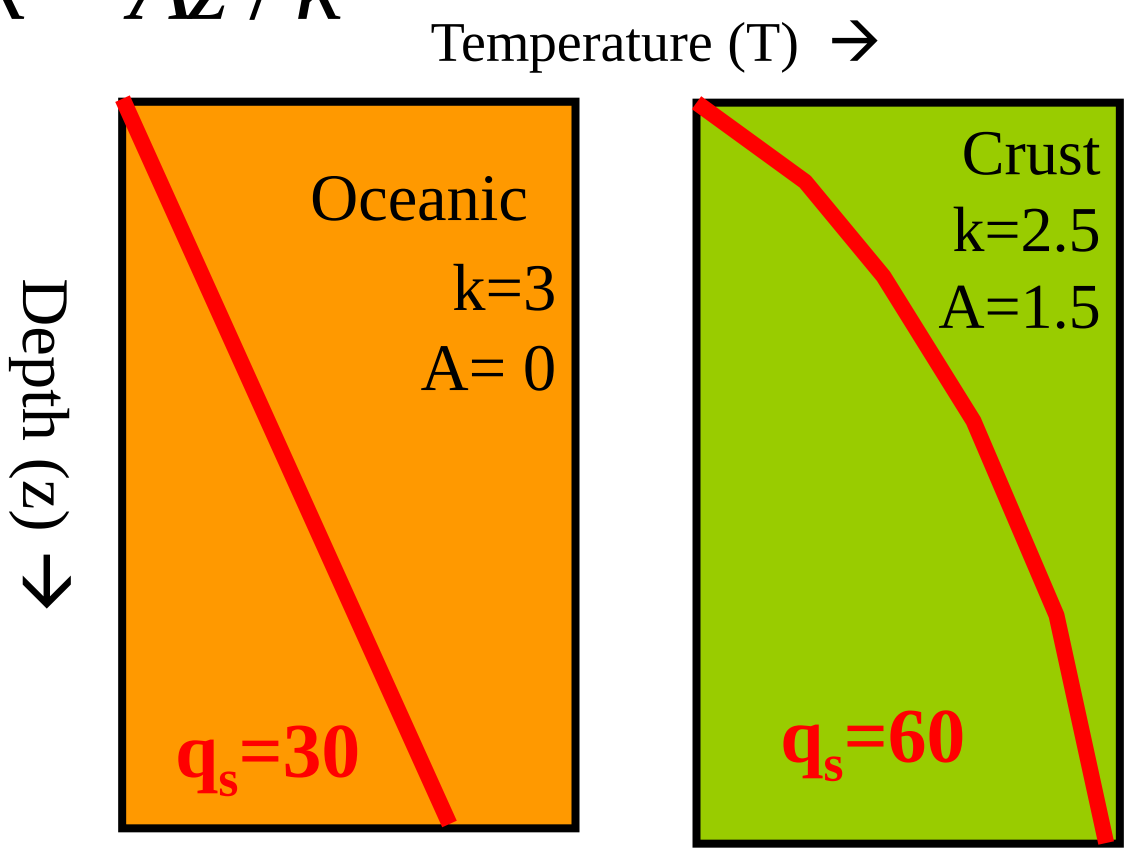


Lithosphere Bottom

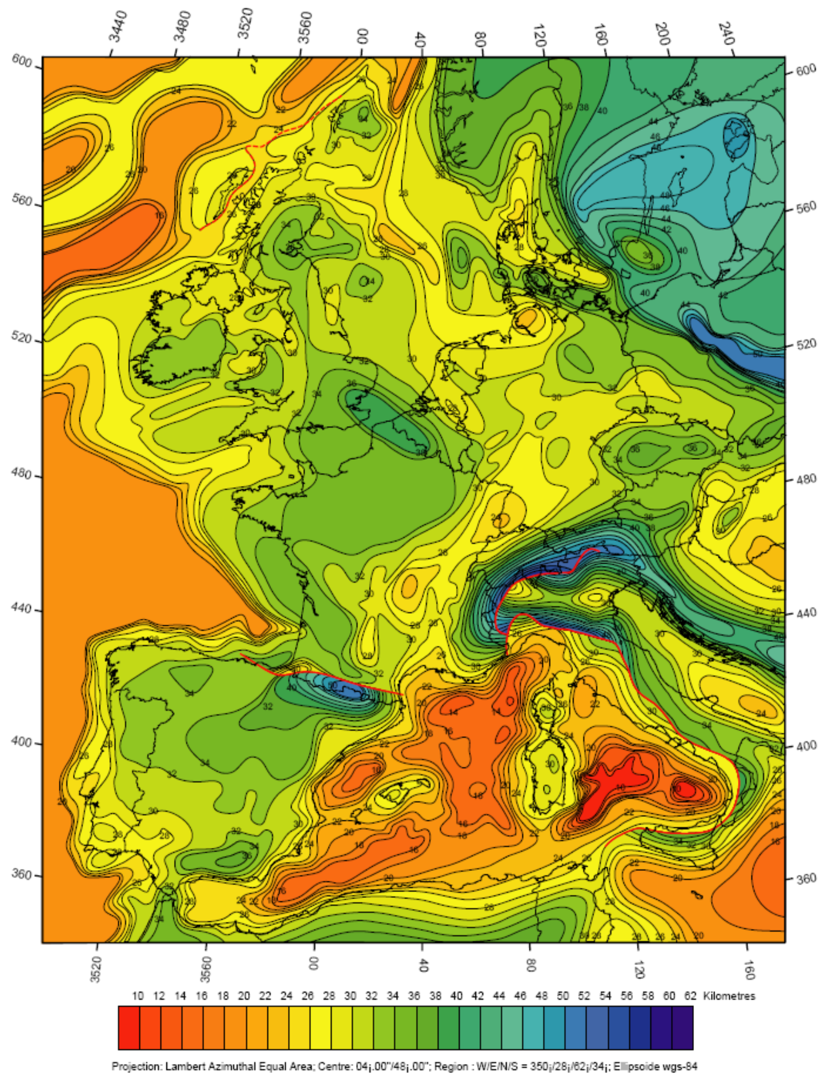


Radiogenic heat generation A **[µW m³] is a function of relative abundance of radiogenic minerals in rock. It influences the steady state geotherm**

$$\frac{dT}{dz}(z) = q_s / k - Az / k$$



Properties


10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 Kilometres
Projection: Lambert Azimuthal Equal Area; Centre: 04¡.00"/48¡.00"; Region : W/E/N/S = 350¡/28¡/62¡/34¡; Ellipsoide wgs-84


North Sea
United Kingdom
Danmark
Denmark
Ireland
Nederland
Netherlands
België
Belgique
Belgium
Deutschland
Germany
Česká Rep
Czech Rep
Celtic Sea
Österreich
Austria
France
Bay of Biscay
Hrvatska
Croatia
Italia
Italy
Tyrrhenian Sea
Portugal
España
Spain

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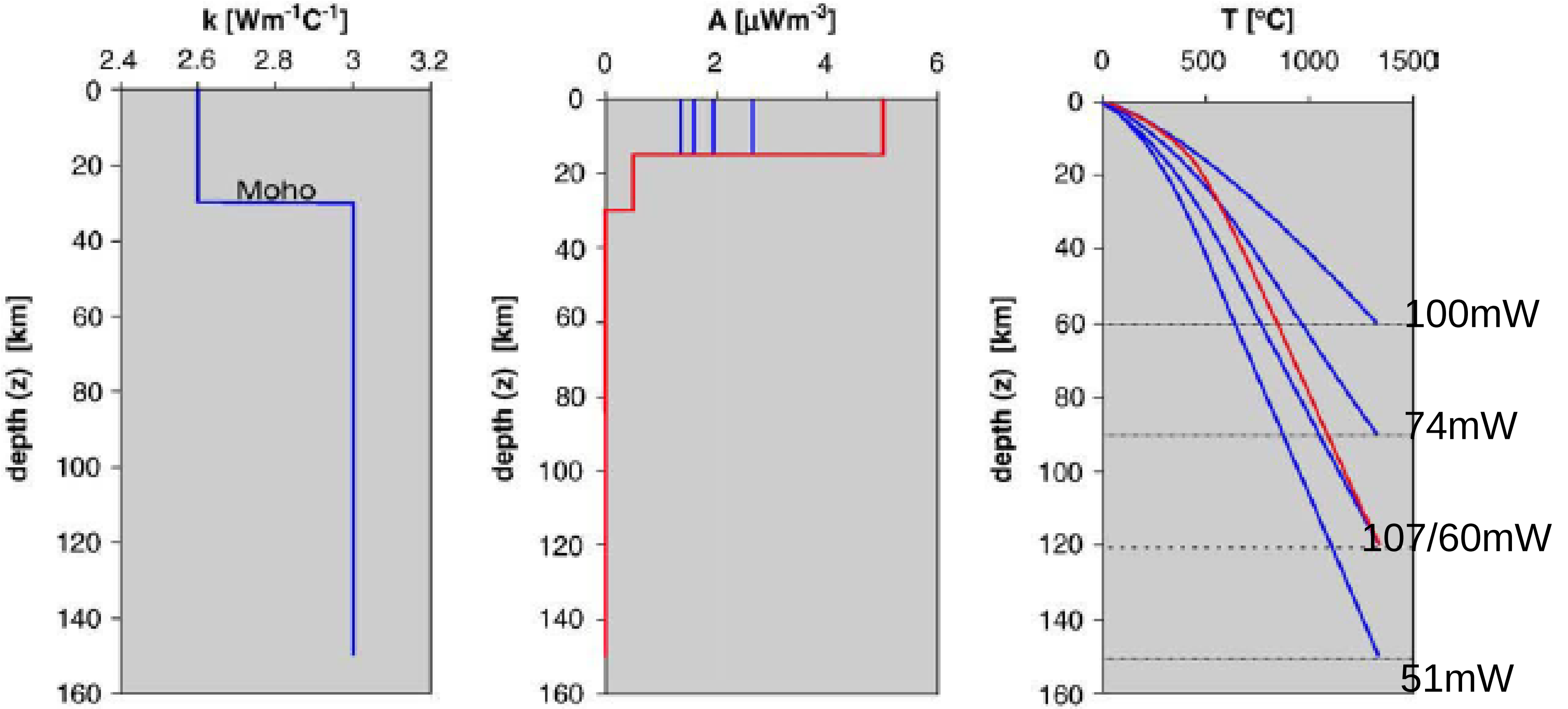
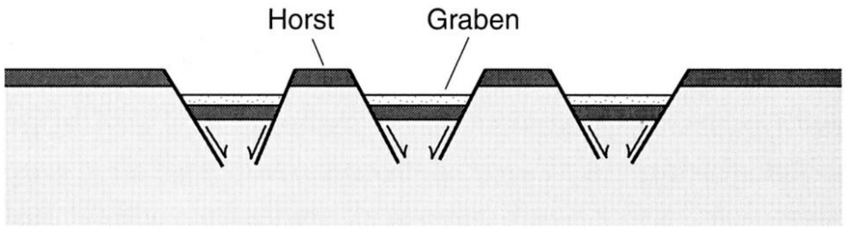
Crustal heat production and geothermal gradients

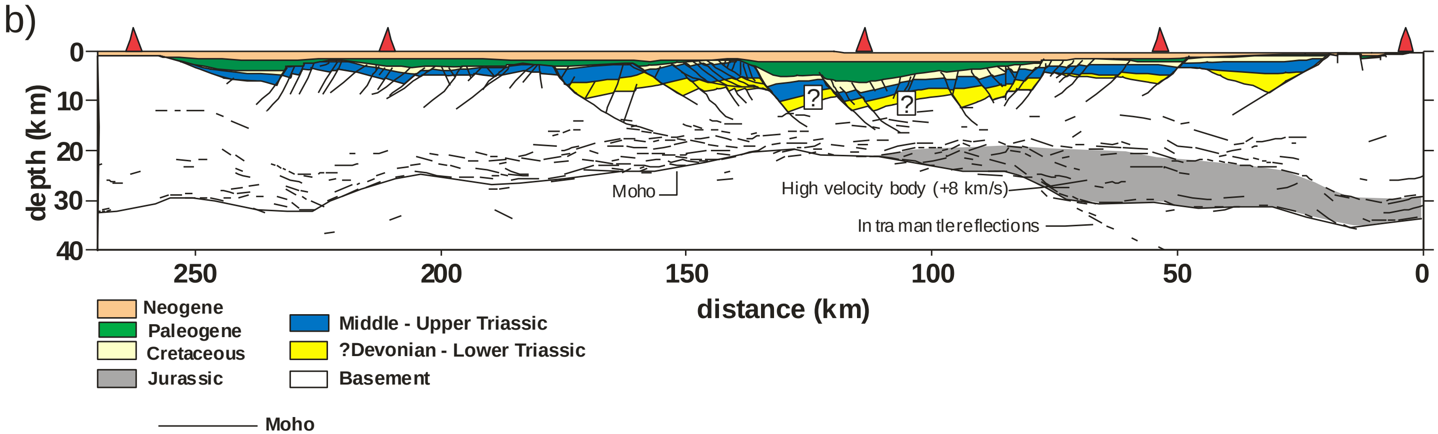


FAULT SYSTEMS

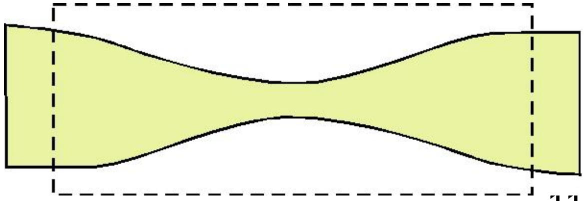


Assemblage of planar faults

Assemblage of listric faults

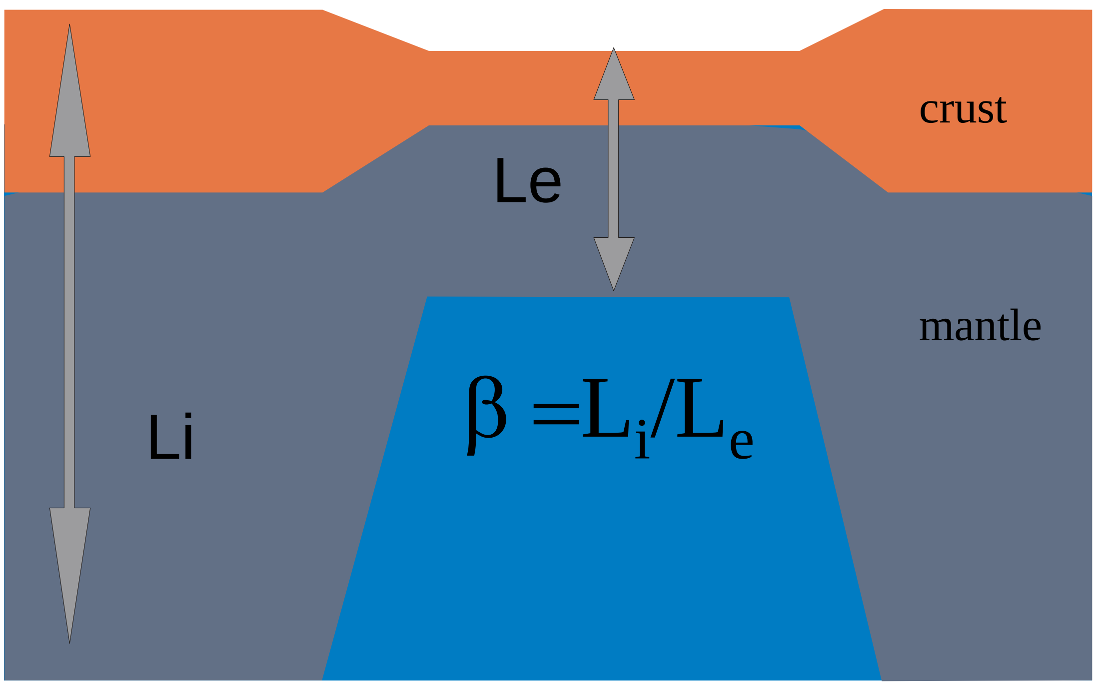


Note: these faults accommodate a pure shear deformation (also called non rotational

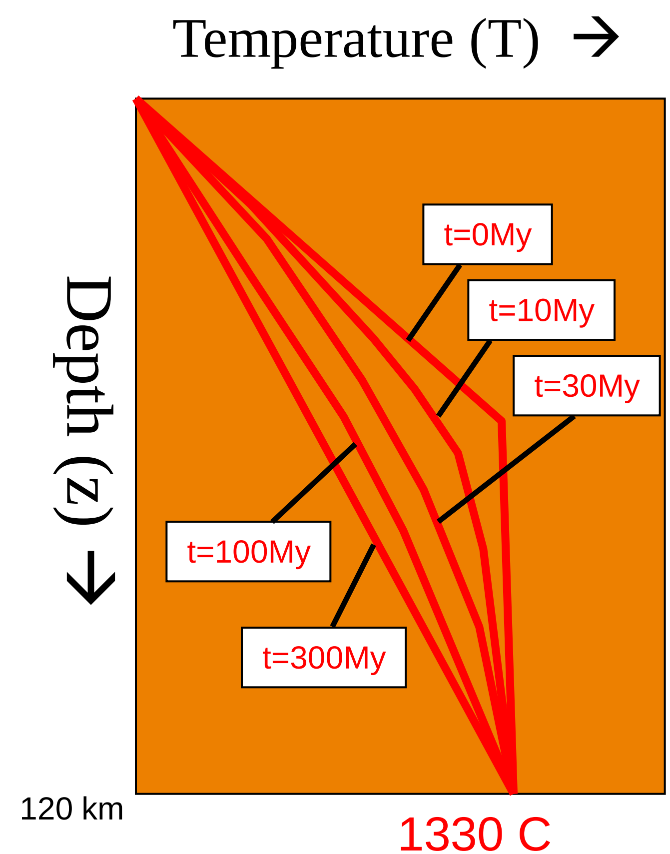


Tectonic Numerical kinematic models predict temperature effects of lithosphere deformation. The 1D McKenzie Model (1978) is a classic for continental lithosphere extension (rifting)

Numerical Temperature Model. t=time after rifting Temperature at surface and bottom are fixed (Mckenzie, 1978)



McKenzie model: lithosphere is instantaneously thinned by factor β



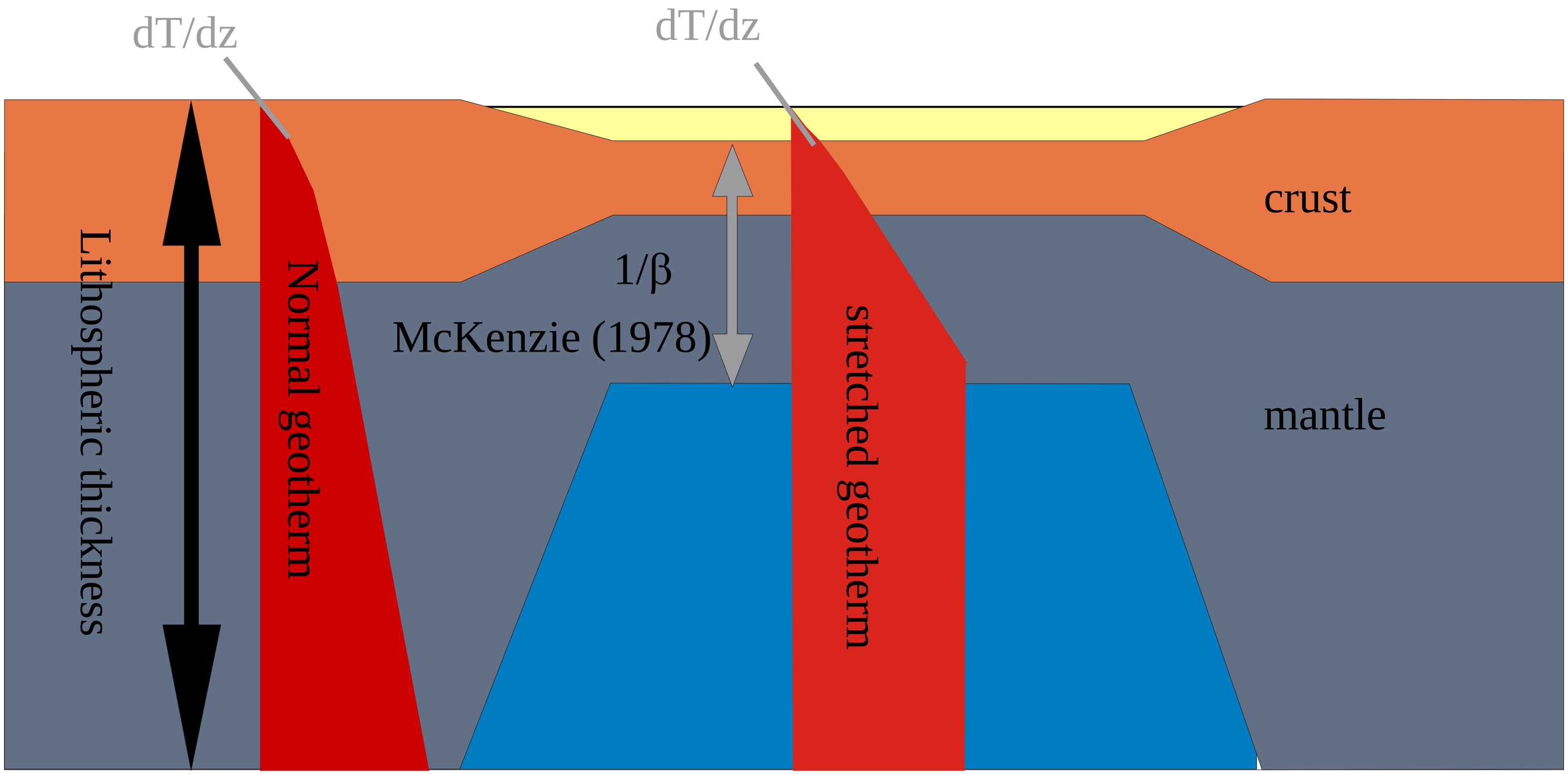
For the McKenzie model a very simple analytical solution for the heat flow exist

120 km

McKenzie heat flow
No Good:

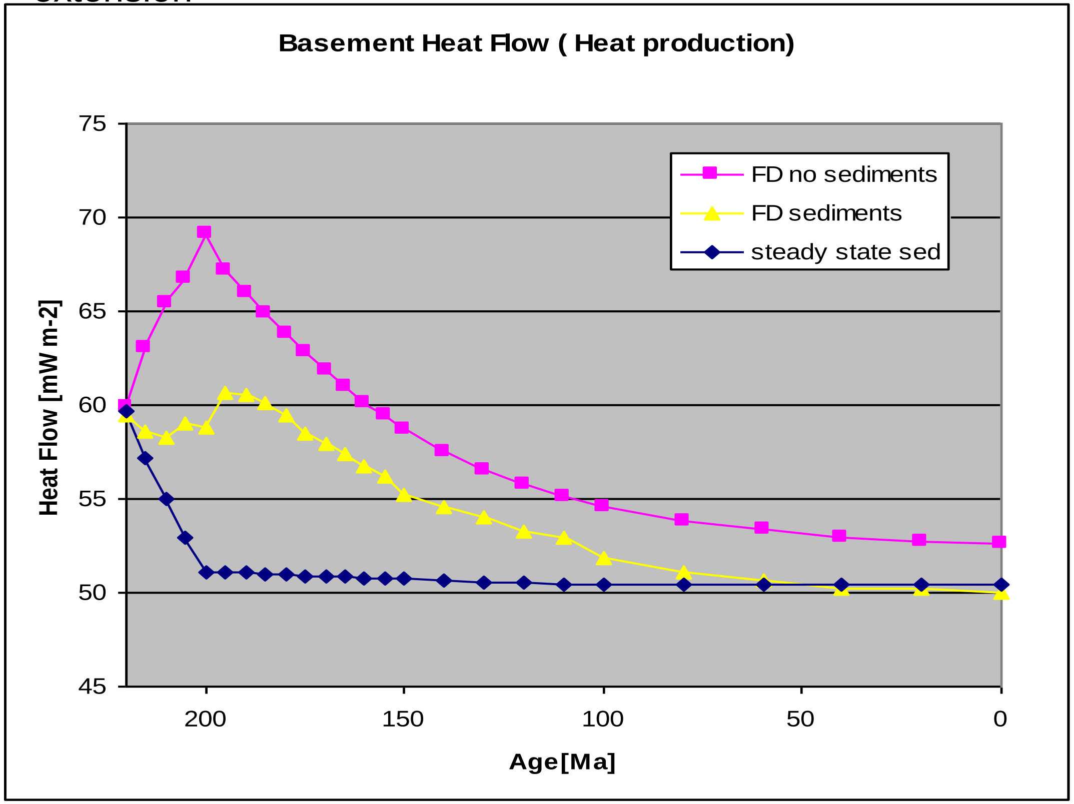
- No crustal heat production
- No sediment infill

- Some More on Modelling: heat flow should include sediments→heat flow is lower because of cooling effect of sediment infill.



Effects of crustal heat production

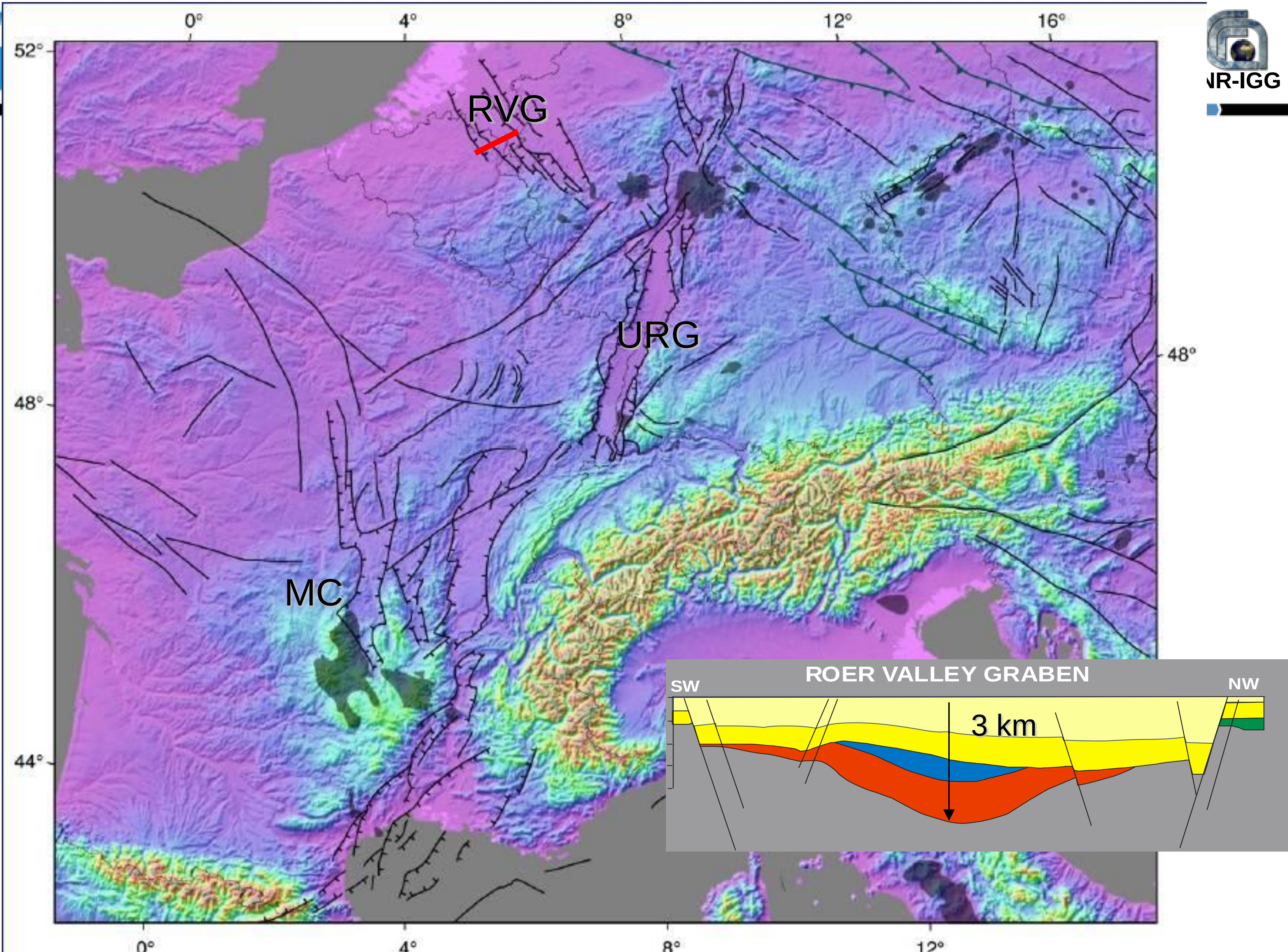
- Classis models such as Mckenzie, neglect effects of crustal heat production. Crustal heat production accounts to ca 50% of the surface heat flow, however it diminishes as a result of crustal thinning during extension and is not fully compensated by heat production of sediment replacing crust. The net effect is a reduction of heat flow after extension



Example for rifting β=1.44 (220-200Ma), with heat production in crust

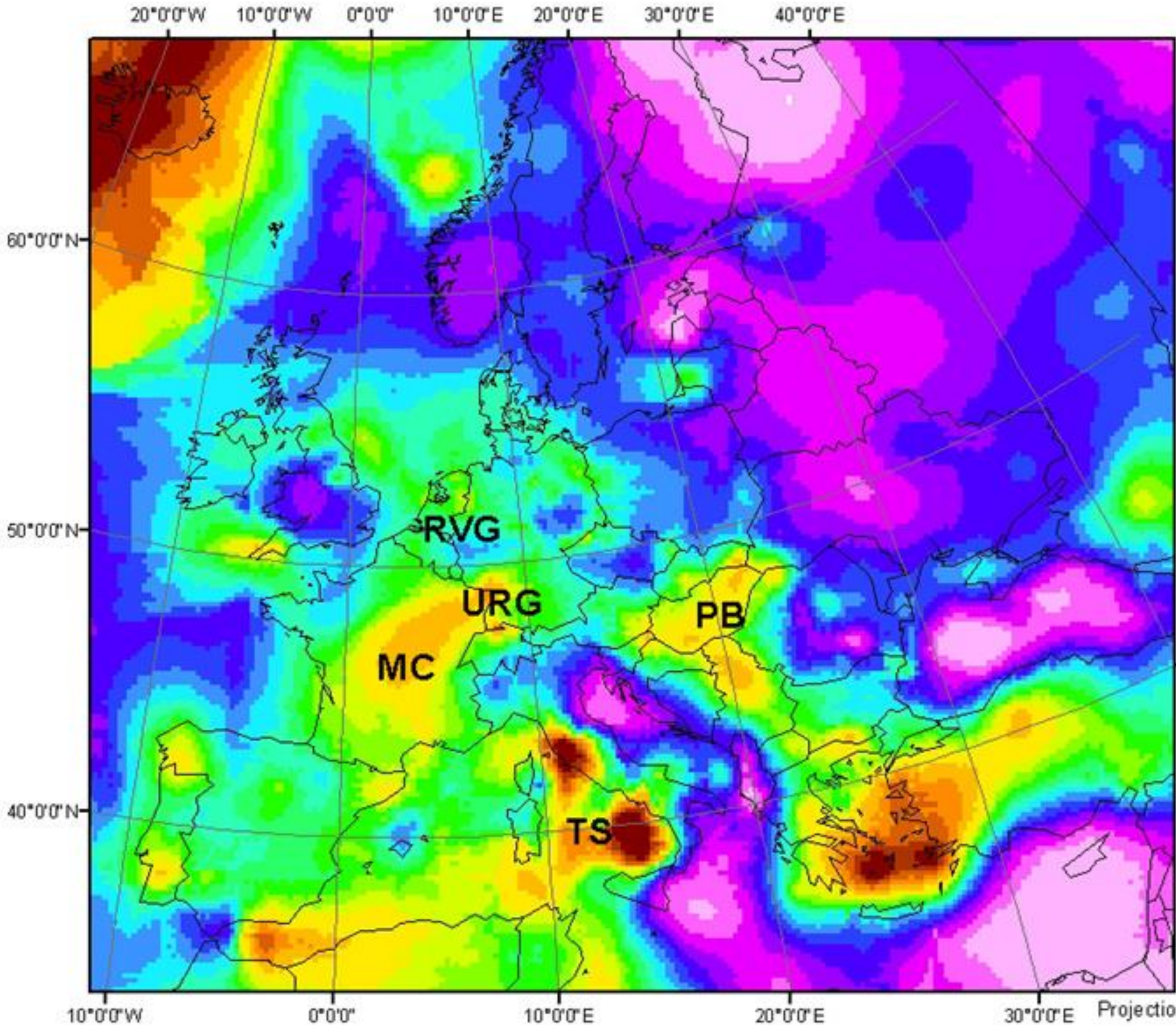
Sedimentation during rifting is ca 100 m /My, resulting in 15% reduction of basement heat flow.

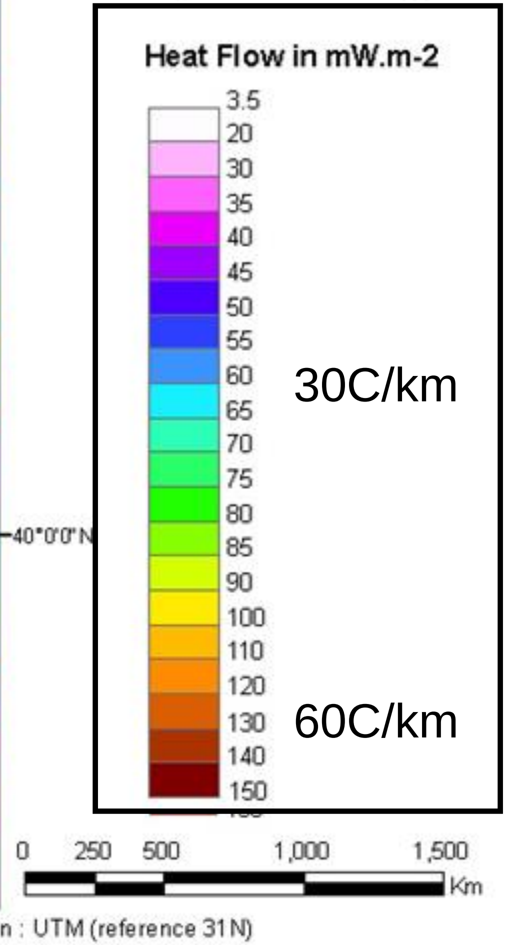
(from Van Wees et al., 2007)



Ziegler and Dezes, 2008

Heat Flow map of Europe





GEOELEC
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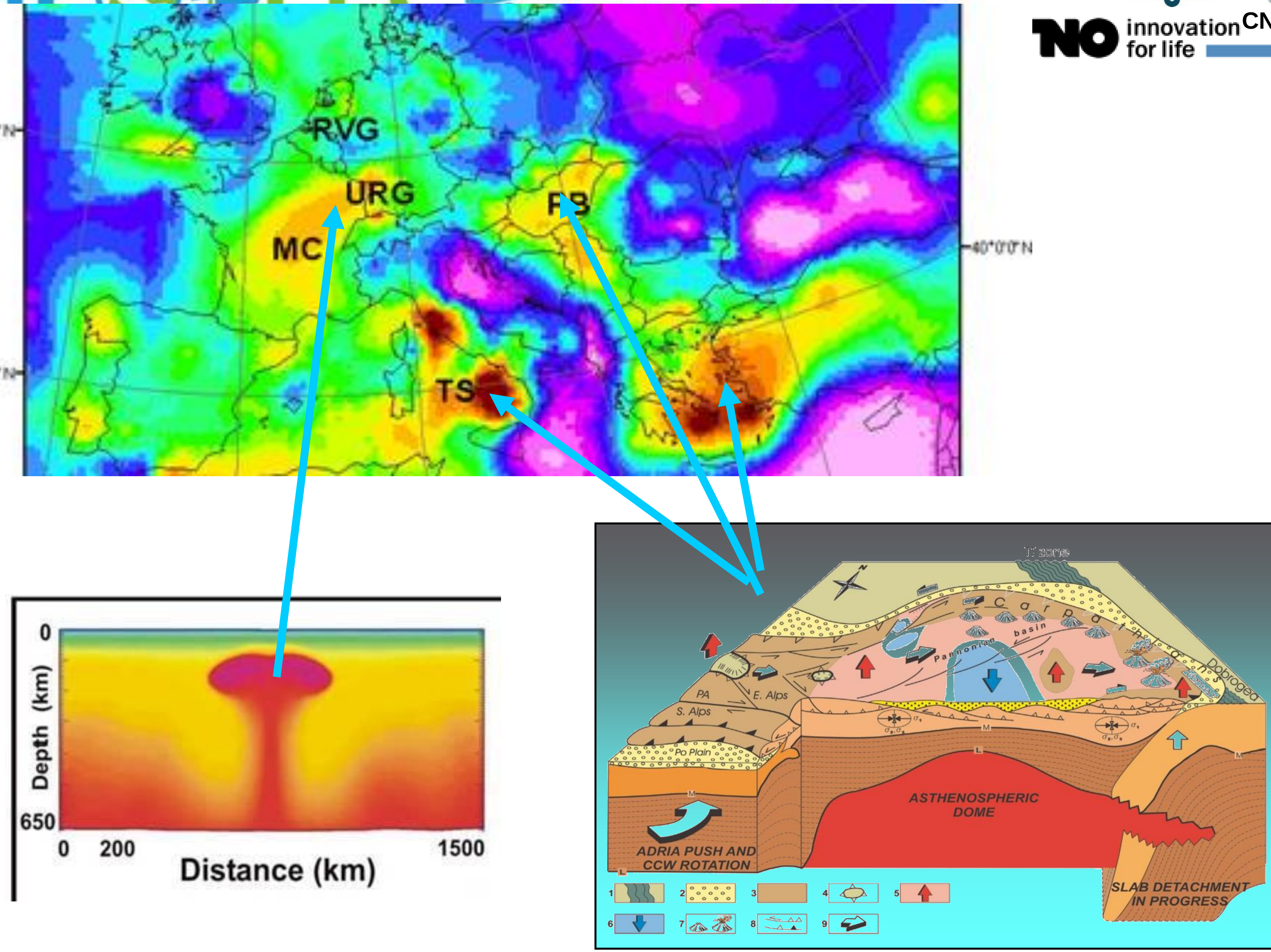
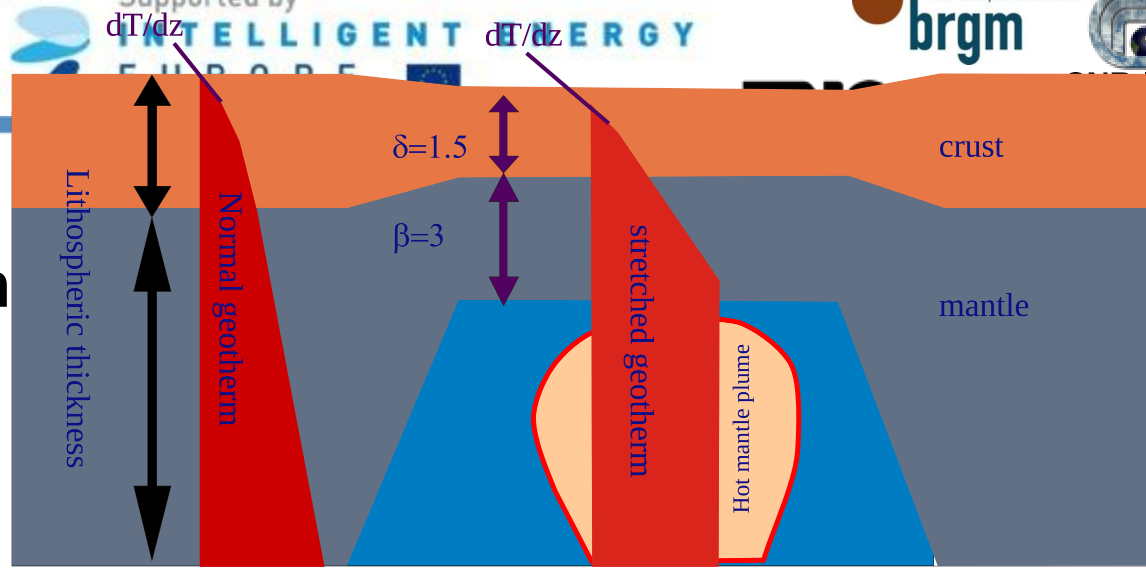
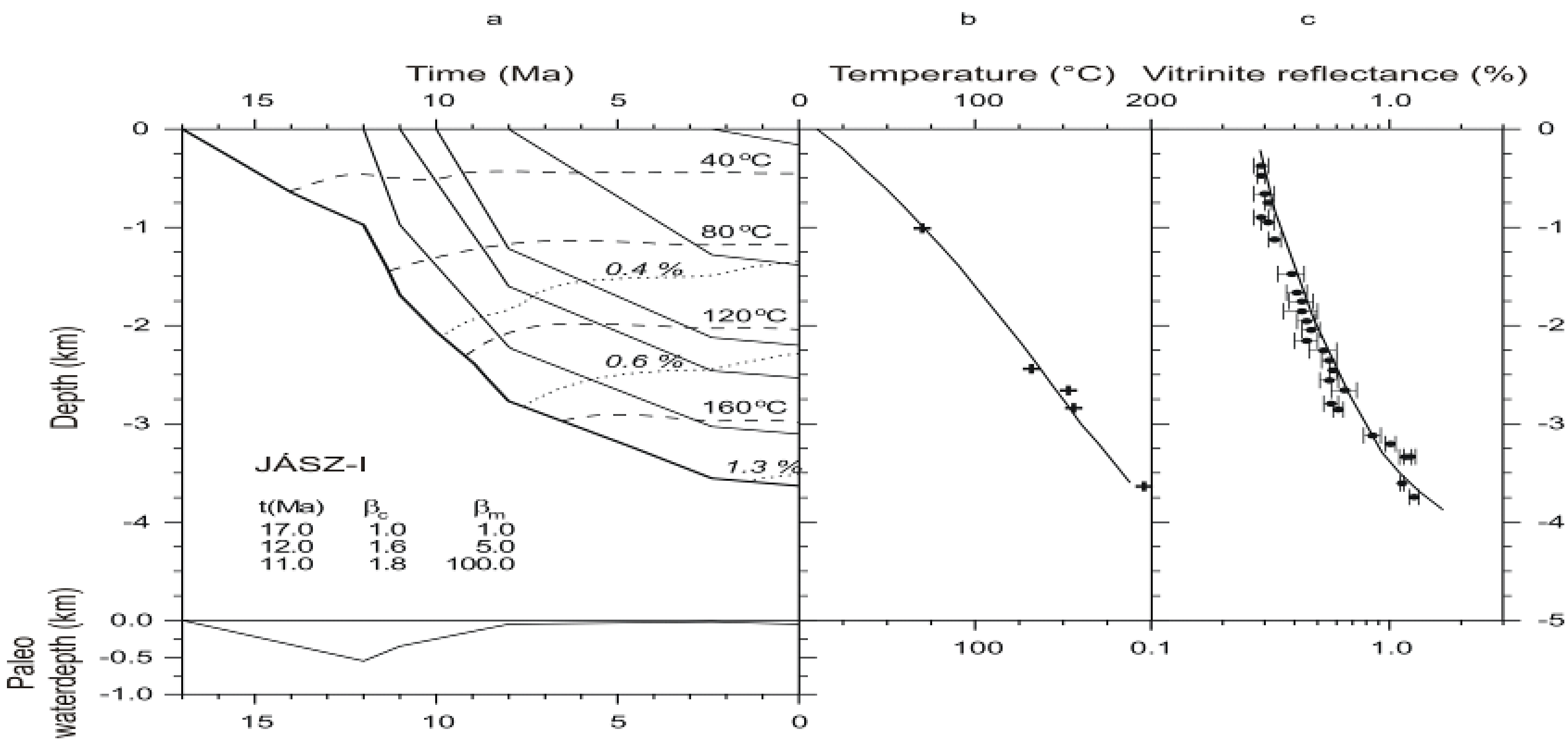
brgm Géosciences pour une Terre durable
TNO innovation for life
CNR-IGG

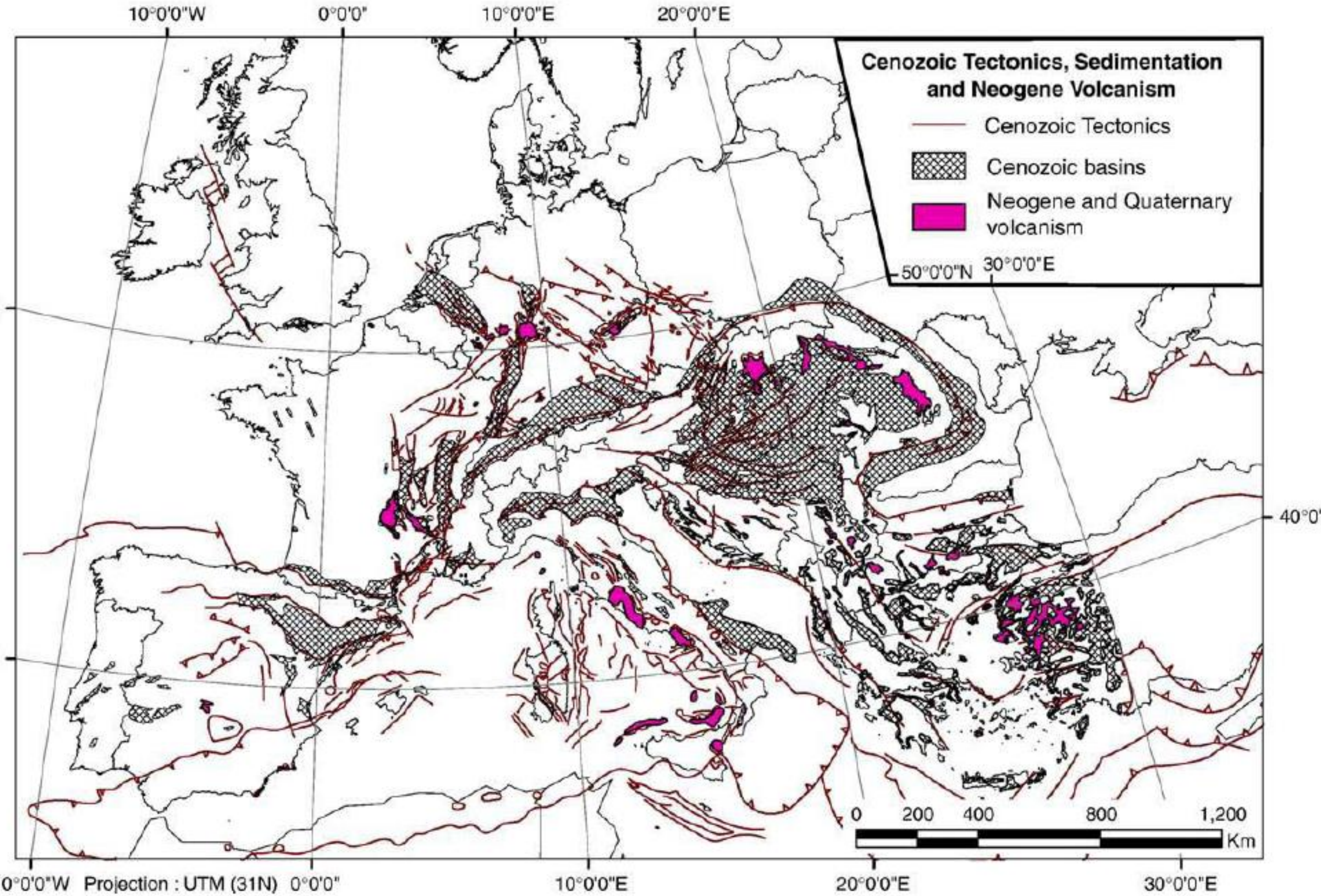


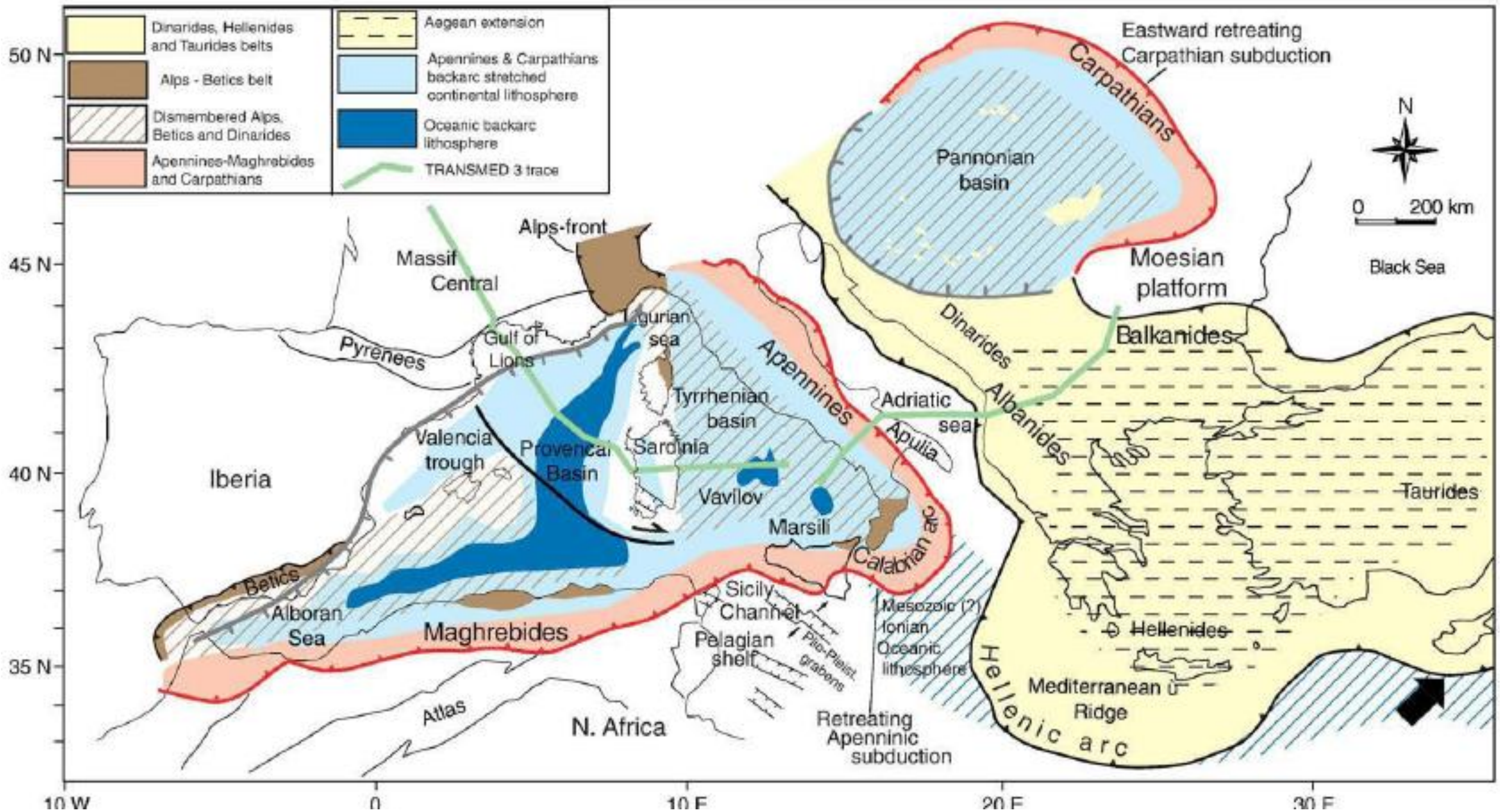
Cloetingh et al., 2006

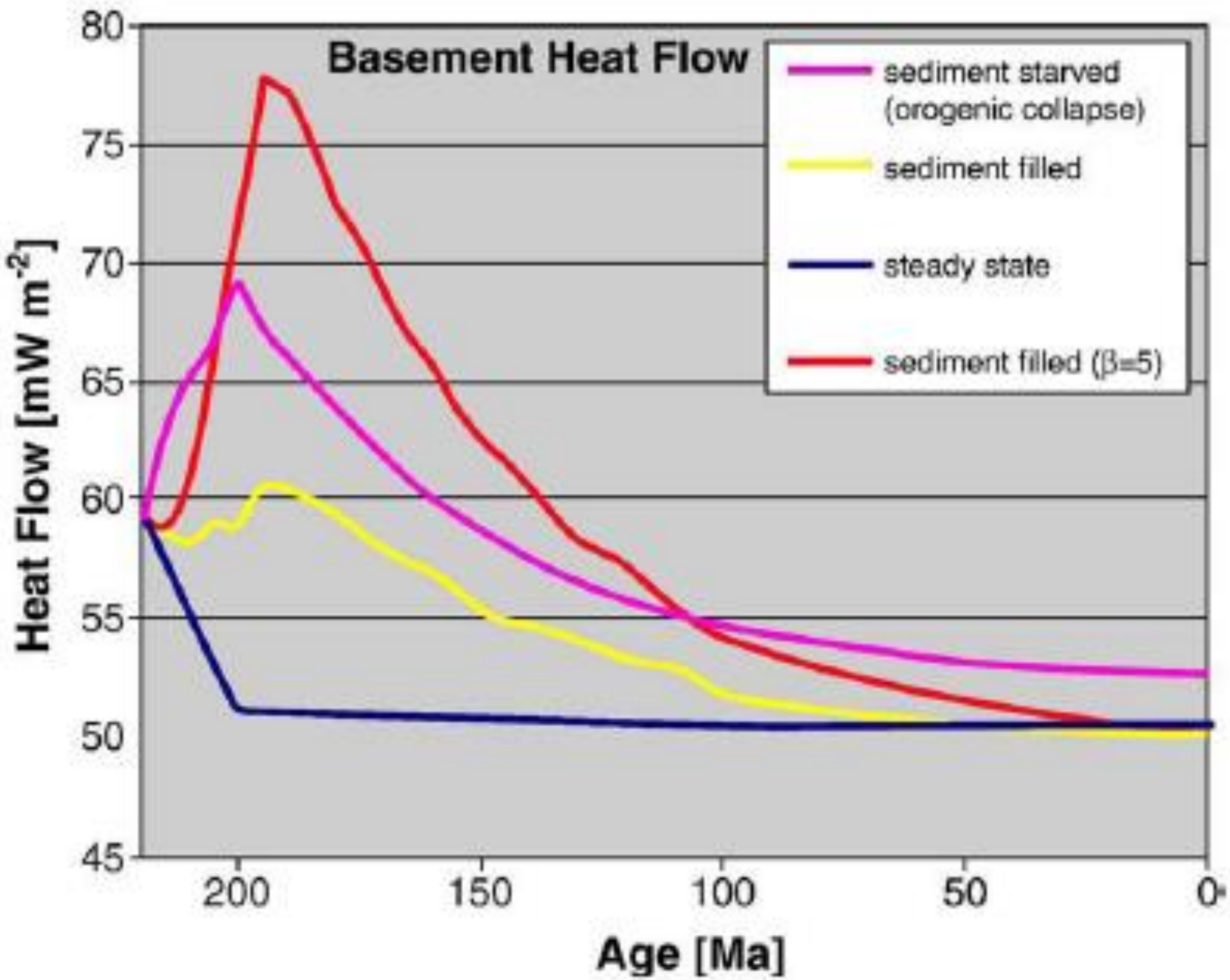
Panon


dT/dz
dT/dz
Lithospheric thickness
Normal geotherm
δ=1.5
β=3
stretched geotherm
Hot mantle plume
crust
mantle

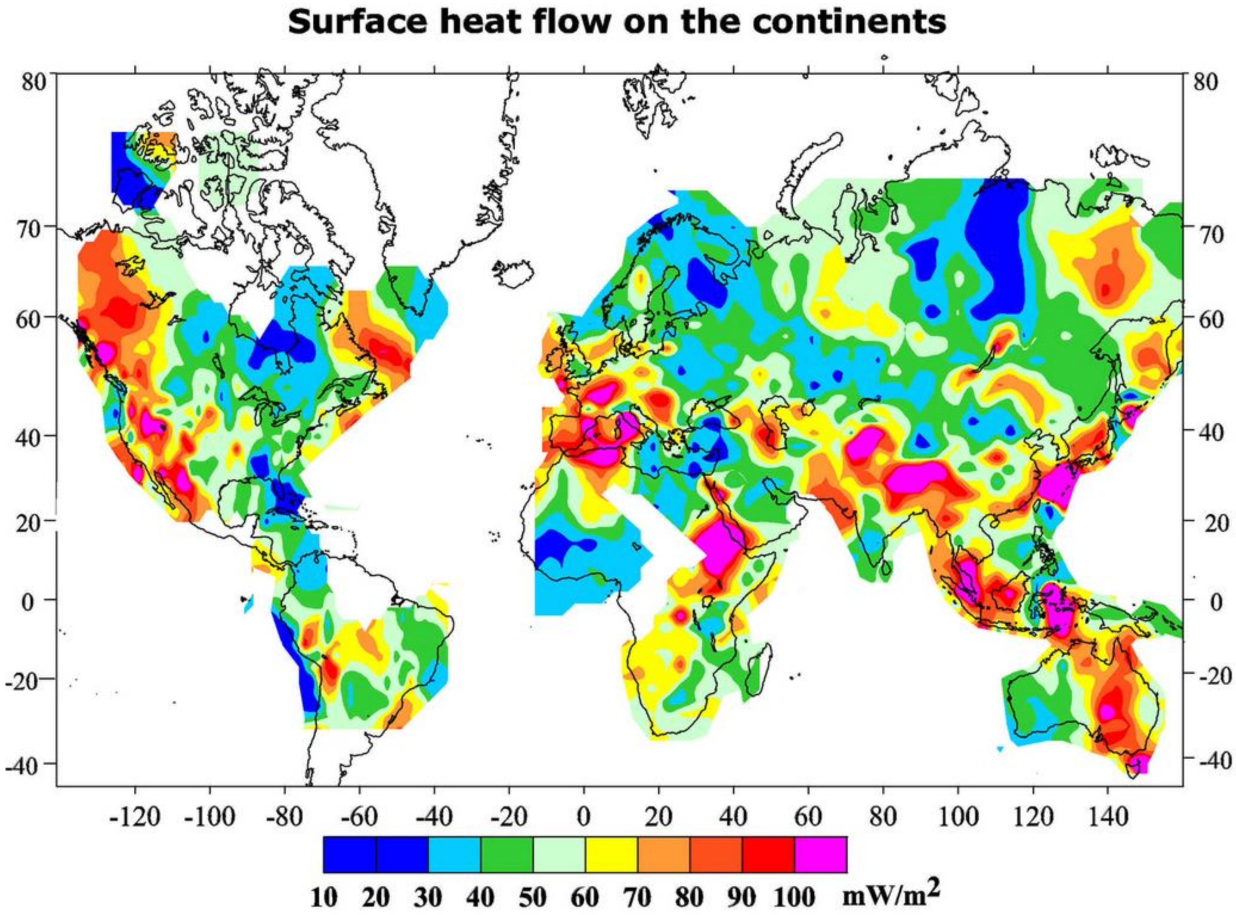

a
b
c
Time (Ma)
Temperature (°C)
Vitrinite reflectance (%)
Depth (km)
Paleo waterdepth (km)
40 °C
80 °C
0.4 %
120 °C
0.6 %
160 °C
1.3 %
JÁSZ-I
t(Ma) βc βm
17.0 1.0 1.0
12.0 1.6 5.0
11.0 1.8 100.0


Cenozoic Tectonics, Sedimentation and Neogene Volcanism
Cenozoic Tectonics
Cenozoic basins
Neogene and Quaternary volcanism
10°0'0"W
0°0'0"
10°0'0"E
20°0'0"E
50°0'0"N
30°0'0"E
40°0'
0
200
400
800
1,200
Km
0°0'0"W
Projection : UTM (31N)
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E


Dinarides, Hellenides and Taurides belts
Alps - Betics belt
Dismembered Alps, Betics and Dinarides
Apennines-Maghrebides and Carpathians
Aegean extension
Apennines & Carpathians backarc stretched continental lithosphere
Oceanic backarc lithosphere
TRANSMED 3 trace
Eastward retreating Carpathian subduction
Carpathians
Pannonian basin
N
0 200 km
Moesian platform
Black Sea
Alps-front
Massif Central
Ligurian sea
Gulf of Lions
Pyrenees
Apennines
Dinarides
Balkanides
Tyrrhenian basin
Adriatic sea
Albanides
Apulia
Valencia trough
Provencal Basin
Sardinia
Iberia
Vavilov
Marsili
Taurides
Calabrian arc
Betics
Alboran Sea
Maghrebides
Sicily Channel
Pelagian shelf
Plio-Pleist. grabens
Mesozoic (?) Ionian Oceanic lithosphere
Hellenides
Mediterranean Ridge
Hellenic arc
Atlas
N. Africa
Retreating Apenninic subduction
50 N
45 N
40 N
35 N
10 W
0
10 E
20 E
30 E

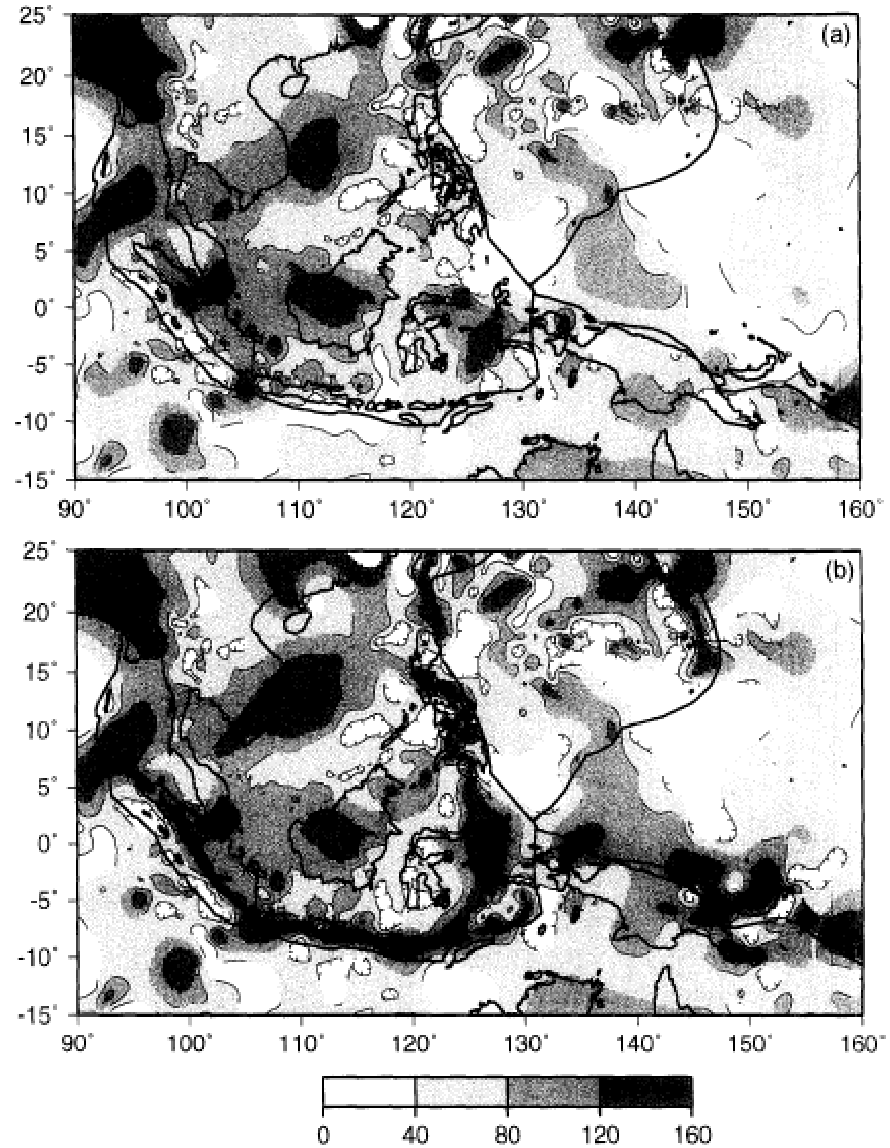

Basement Heat Flow
sediment starved
(orogenic collapse)
sediment filled
steady state
sediment filled (β=5)
Heat Flow [mW m-2]
80
75
70
65
60
55
50
45
200
150
100
50
0
Age [Ma]

Interpolation using all datapoints

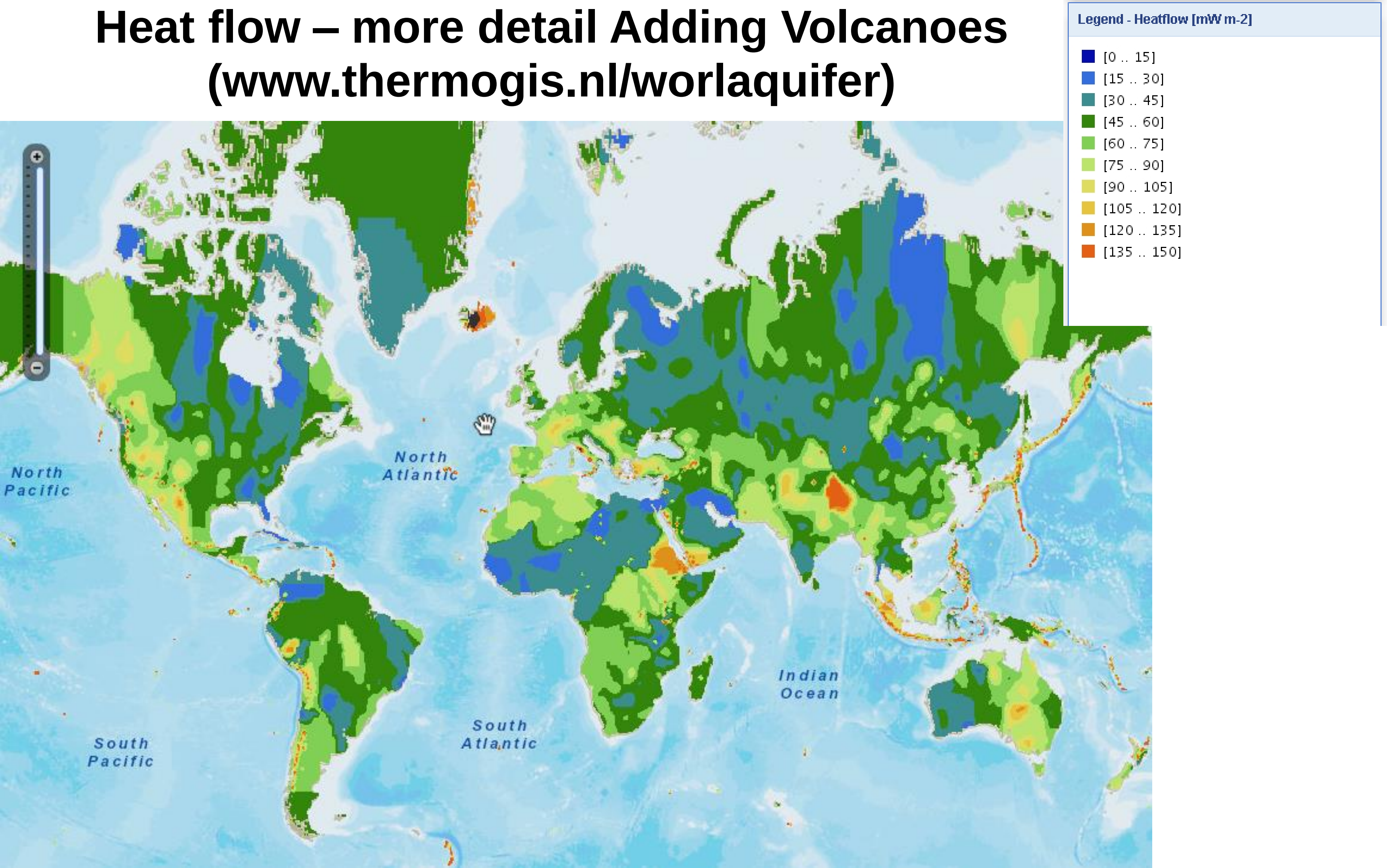


Artimieva et al,2001 and 2006

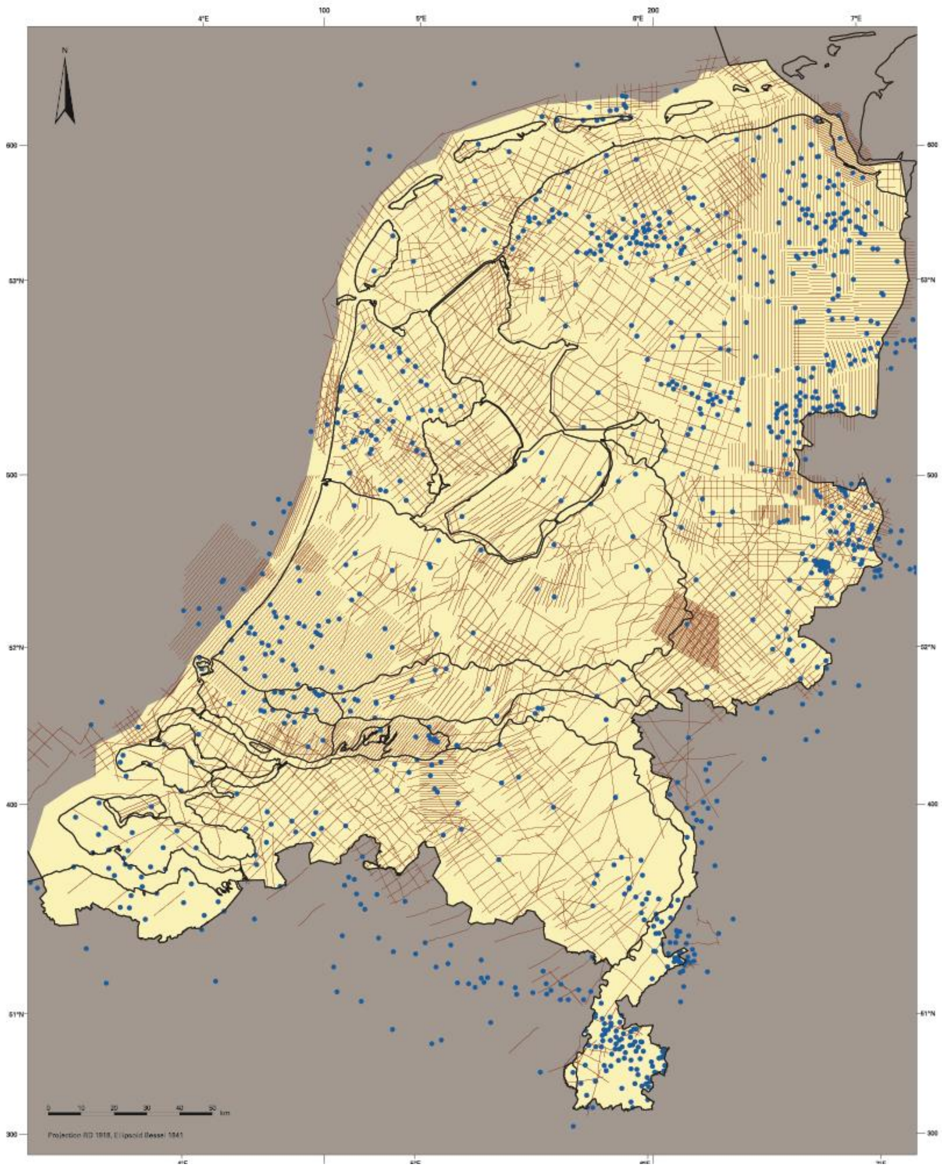
- Treat each historic active as 150mW (Nagao and Uyeda,1995)
- Treat holocene as 80mW



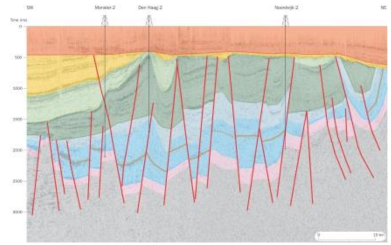
Heat flow – more detail Adding Volcanoes (www.thermogis.nl/worlaquifer)



A closer look at europe – active volcanoes – holocene and younger

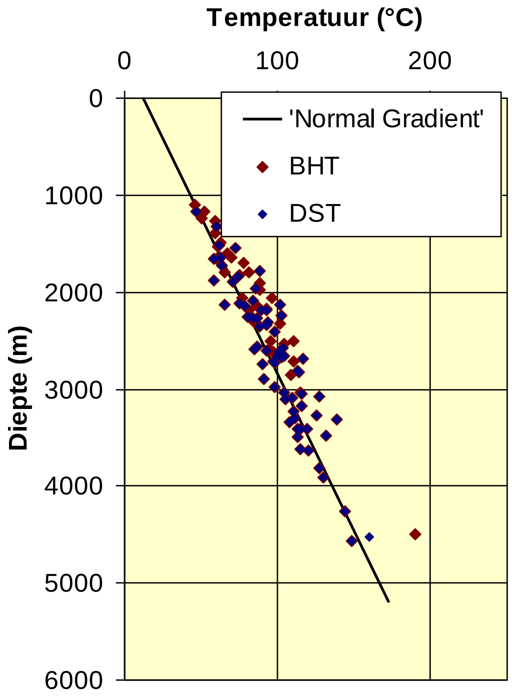


Well & Seismic Data



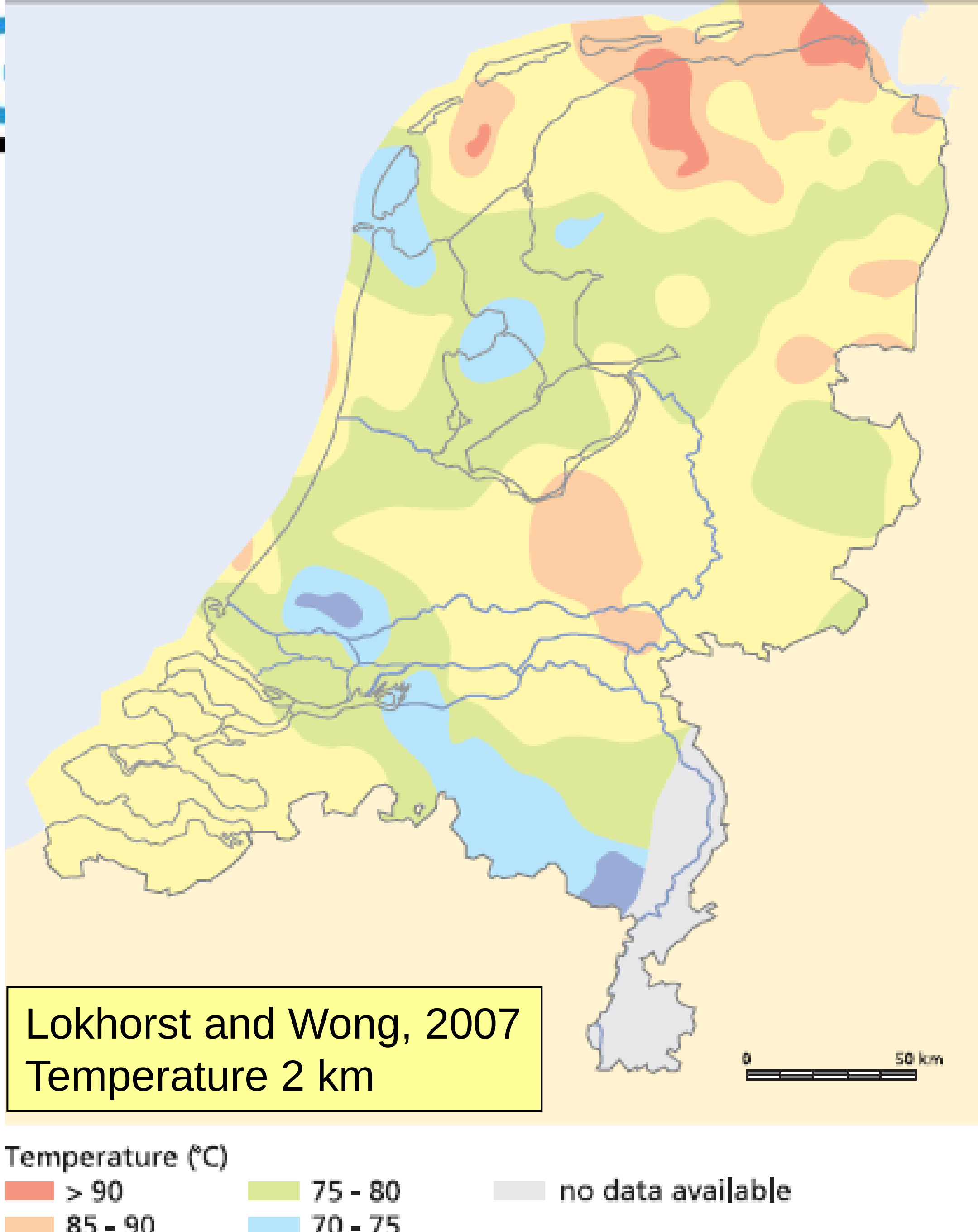
Wells: 5876 (onshore/offshore)

Seismic: 72.000 km (2D+3D lines)

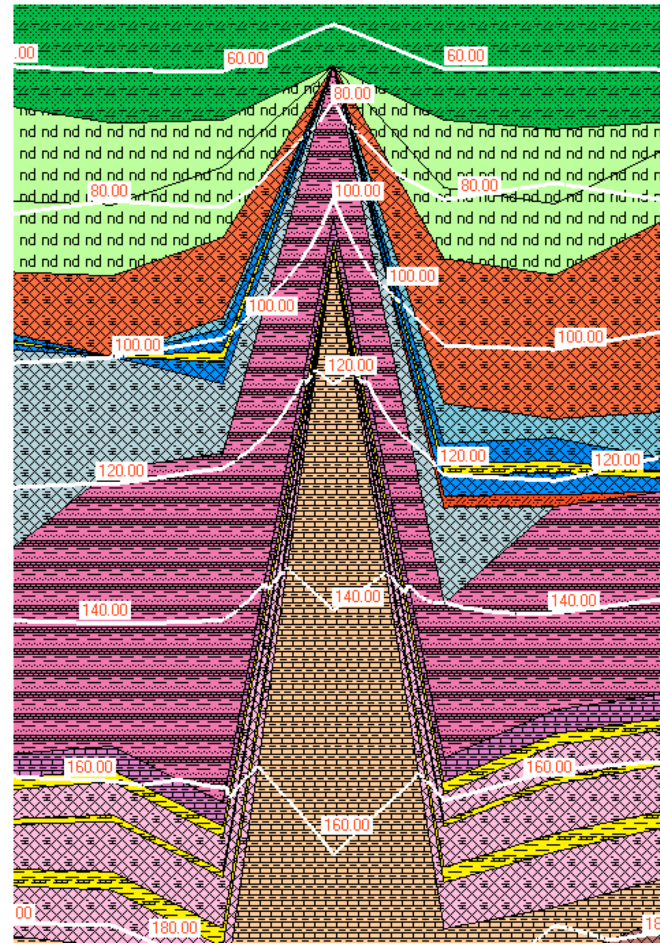


Over 1000 BHT and DST data

Deeper/lateral Requires better models



Lokhorst and Wong, 2007
Temperature 2 km



average ca 30C/km

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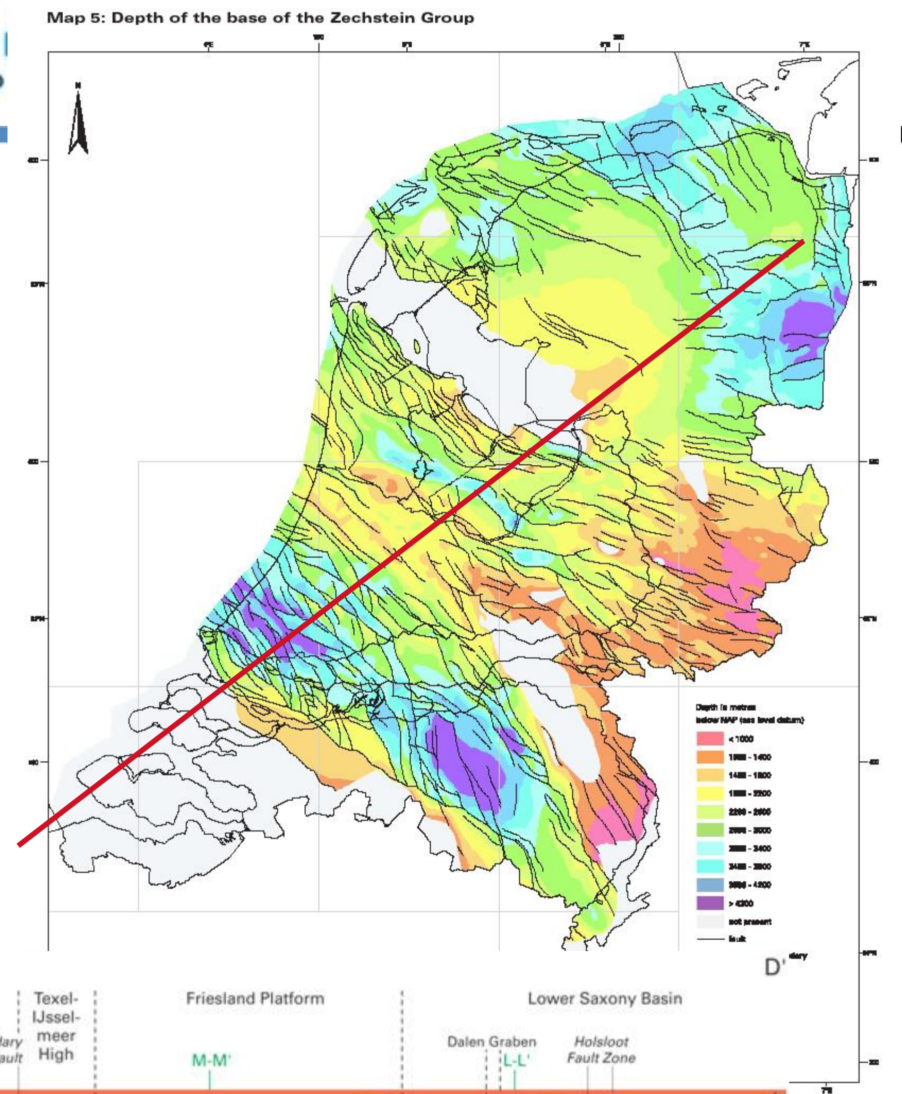
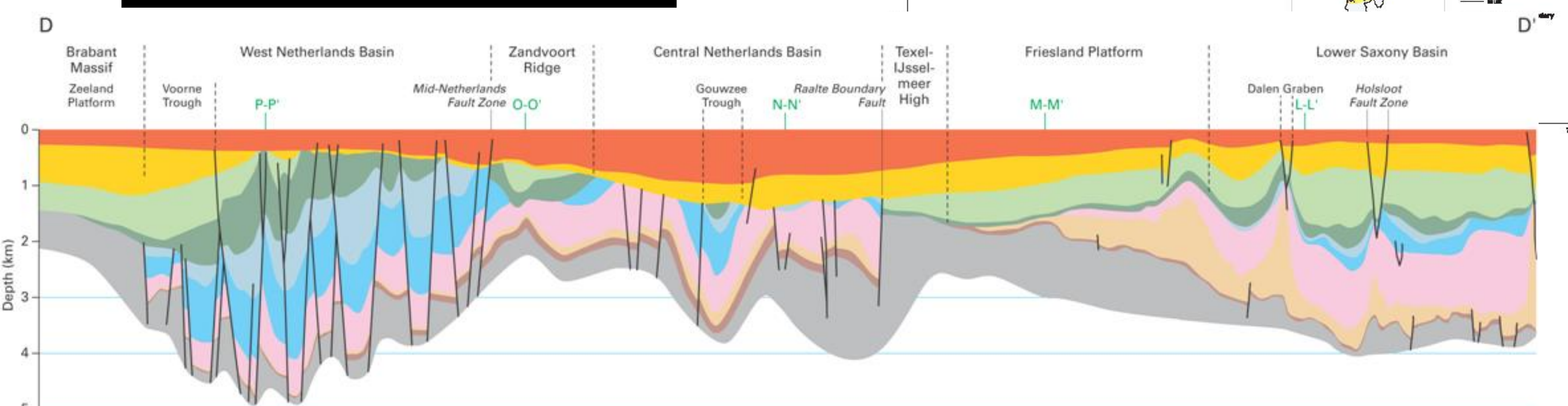
Knowledge of subsurface
Ongoing mapping (public)

- Upper North Sea Group
- Lower and Middle North Sea Groups
- Chalk Group
- Rijnland Group
- Schieland and Niedersachsen Groups
- Altena Group
- Lower and Upper Germanic Trias Groups
- Zechstein Group
- Lower and Upper Rotliegend Groups
- Limburg Group
- Carboniferous Limestone Group
- Devonian
- Silurian
- Ordovician

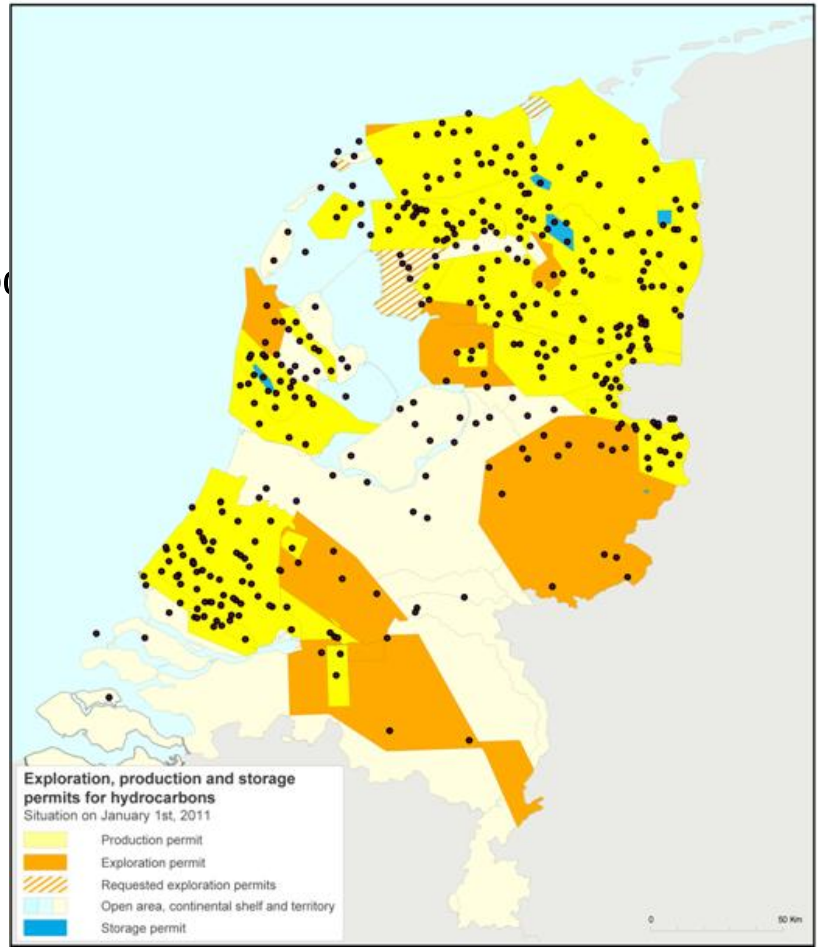




BHT data (n=1241)

BHT wells and E&P licenses

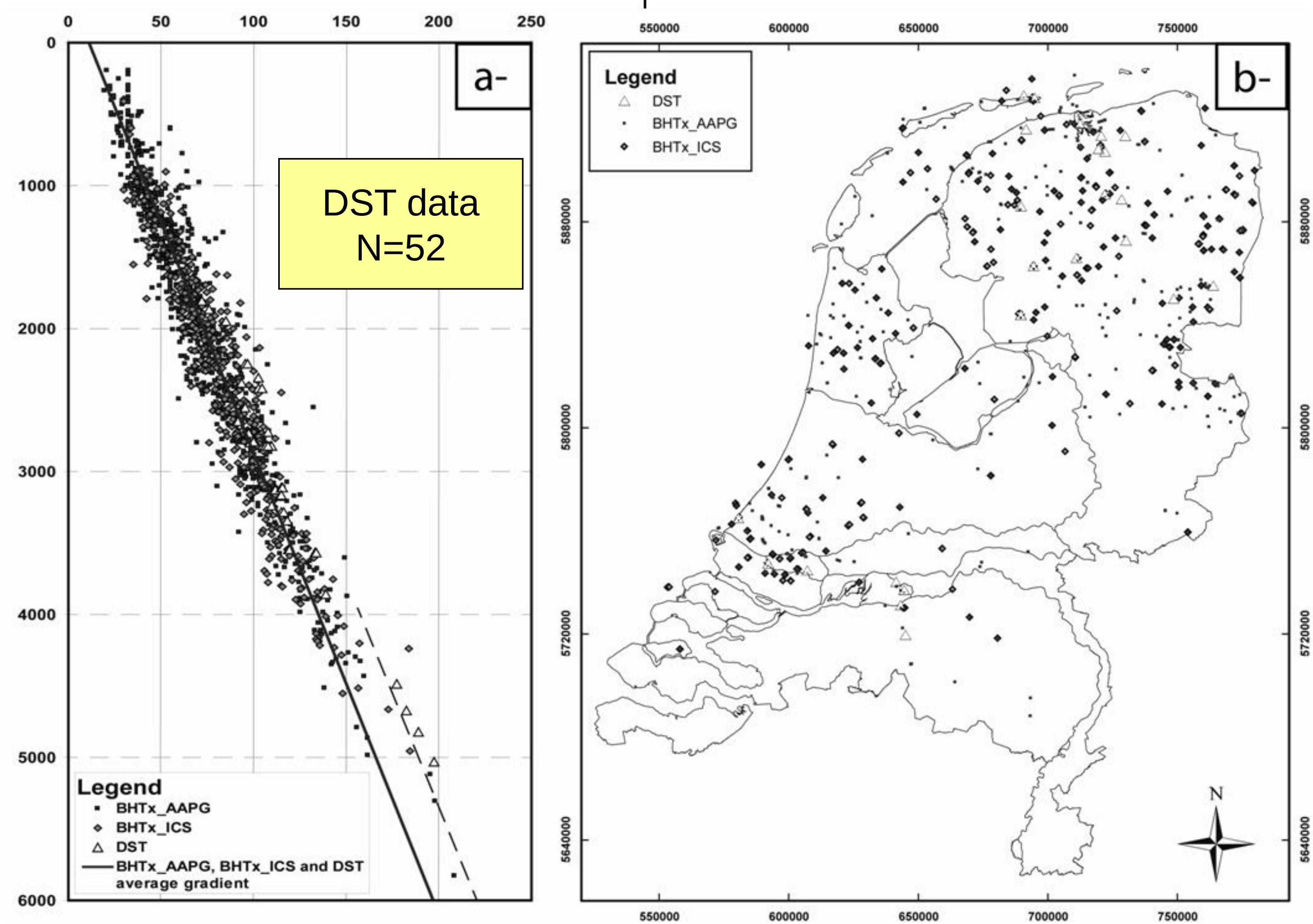
- ICS (n=412)
  - Initial Cylindrical source
  - Used to correct simpler AAPG metho
- AAPG + AAPGcorrected (n=829)



For comparison

DST much less (n=52)

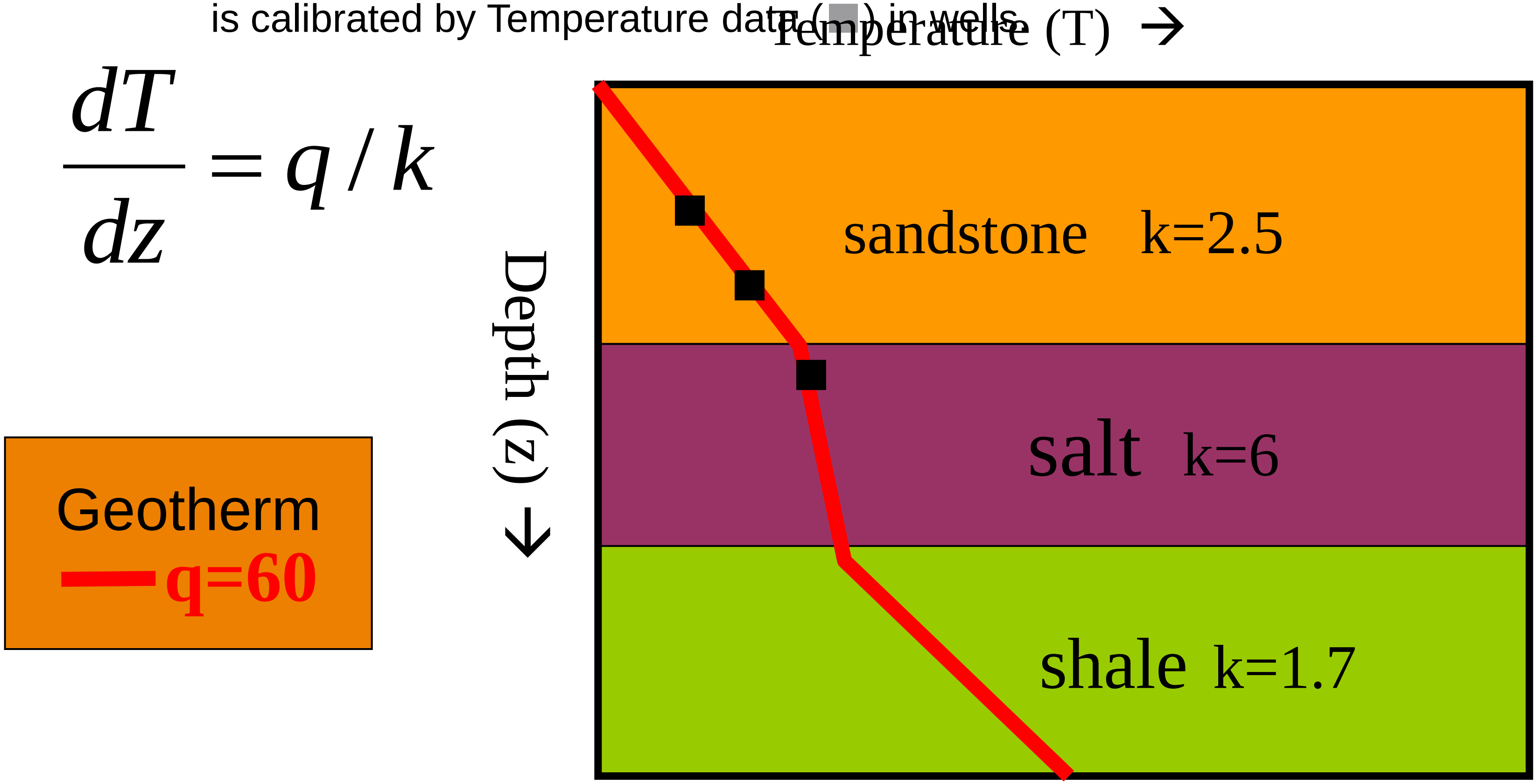
Bonte et al., 2012


a-
DST data
N=52
0
50
100
150
200
250
0
1000
2000
3000
4000
5000
6000
Legend
BHTx_AAPG
BHTx_ICS
DST
BHTx_AAPG, BHTx_ICS and DST average gradient
b-
Legend
DST
BHTx_AAPG
BHTx_ICS
550000
600000
650000
700000
750000
5880000
5800000
5720000
5640000
N

Temperature gradient – heat flow

- **Heat flow q** [mW/m^{-2}] determines the temperature gradient in sediments in conjunction with **rock conductivity k** [W m^{-1} C^{-1}] . Present day (PD) heat flow is calibrated by Temperature data (■) in wells.

$$\frac{dT}{dz} = q / k$$



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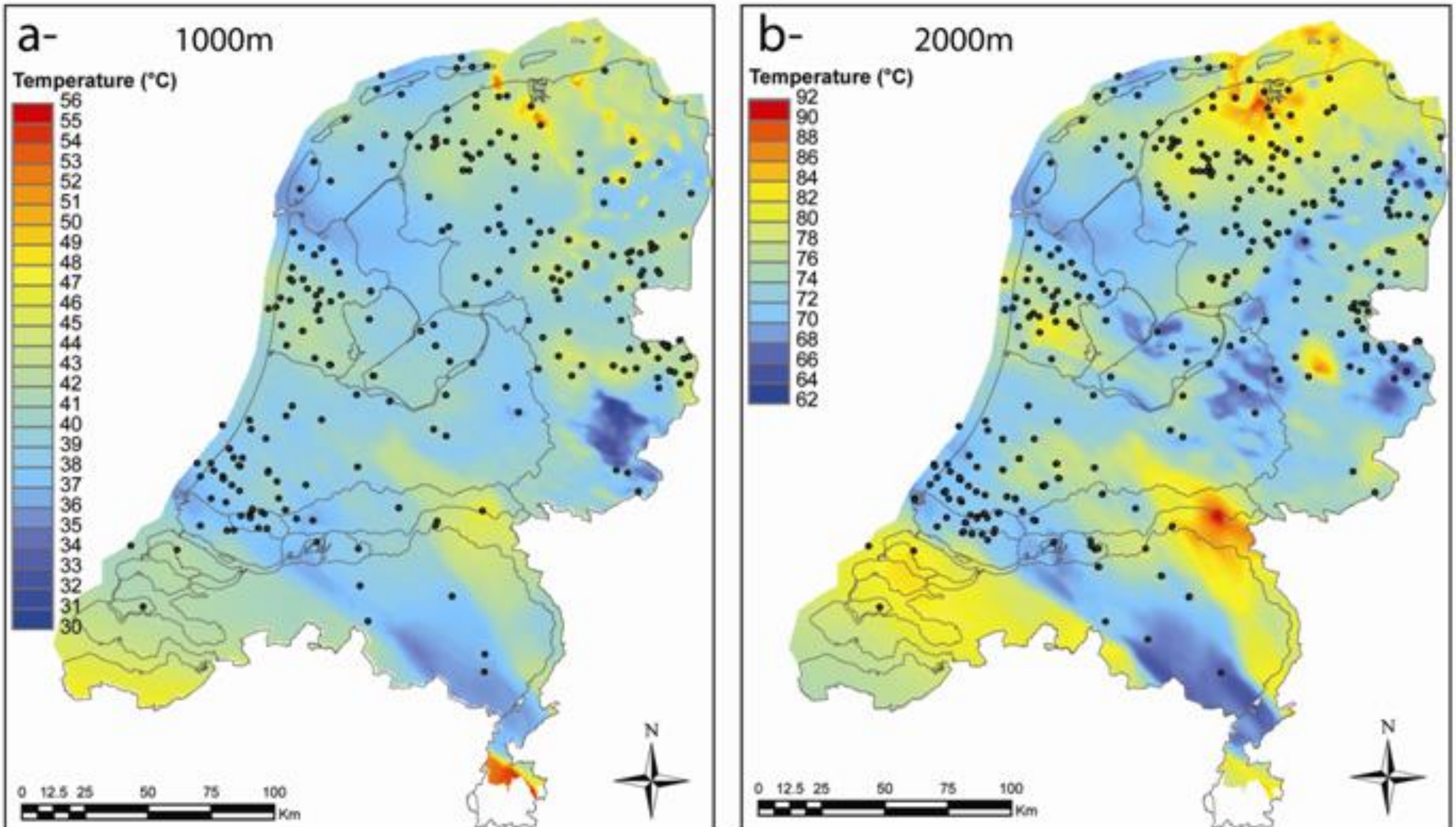
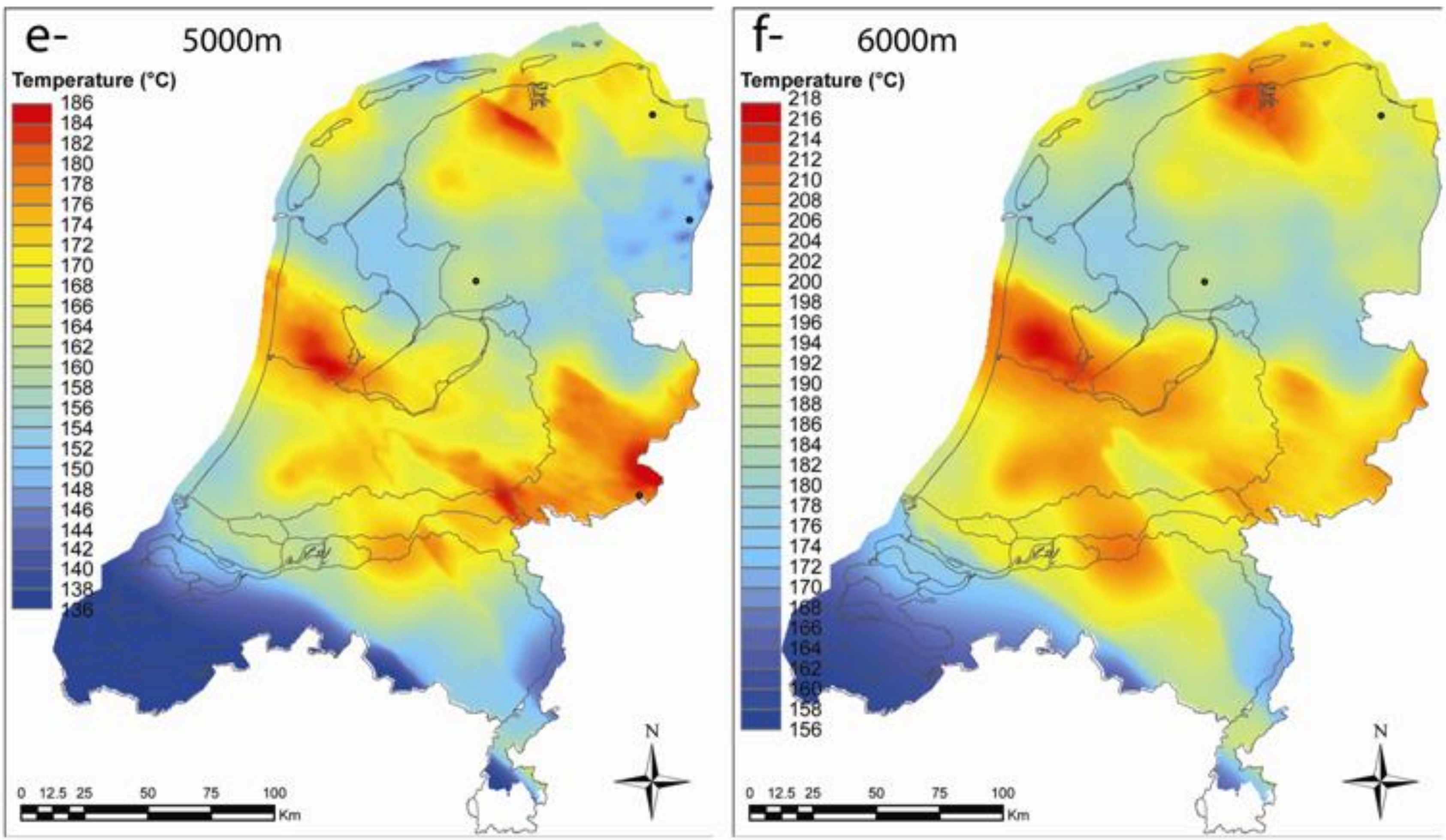
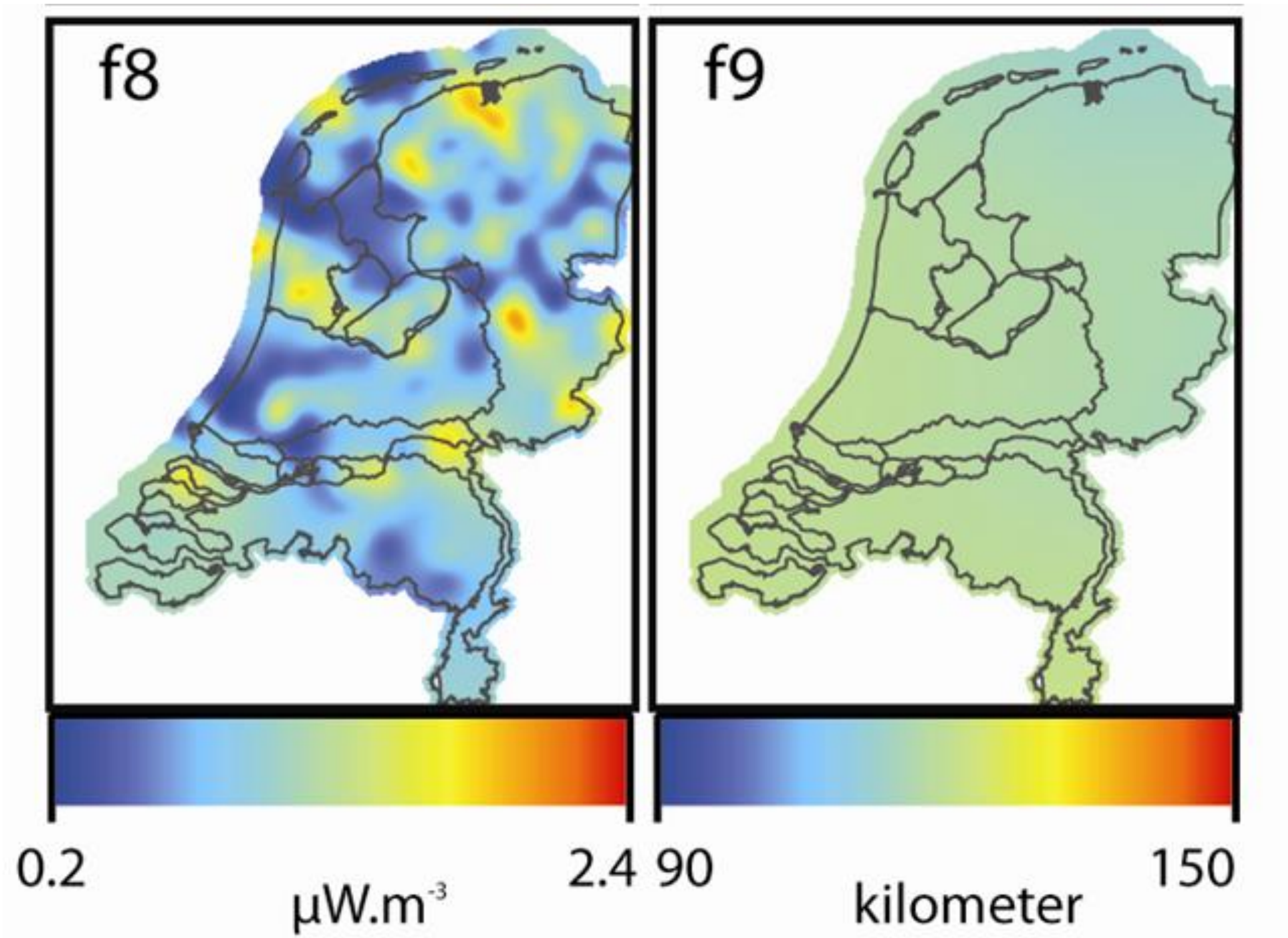
Results - temperature (1)



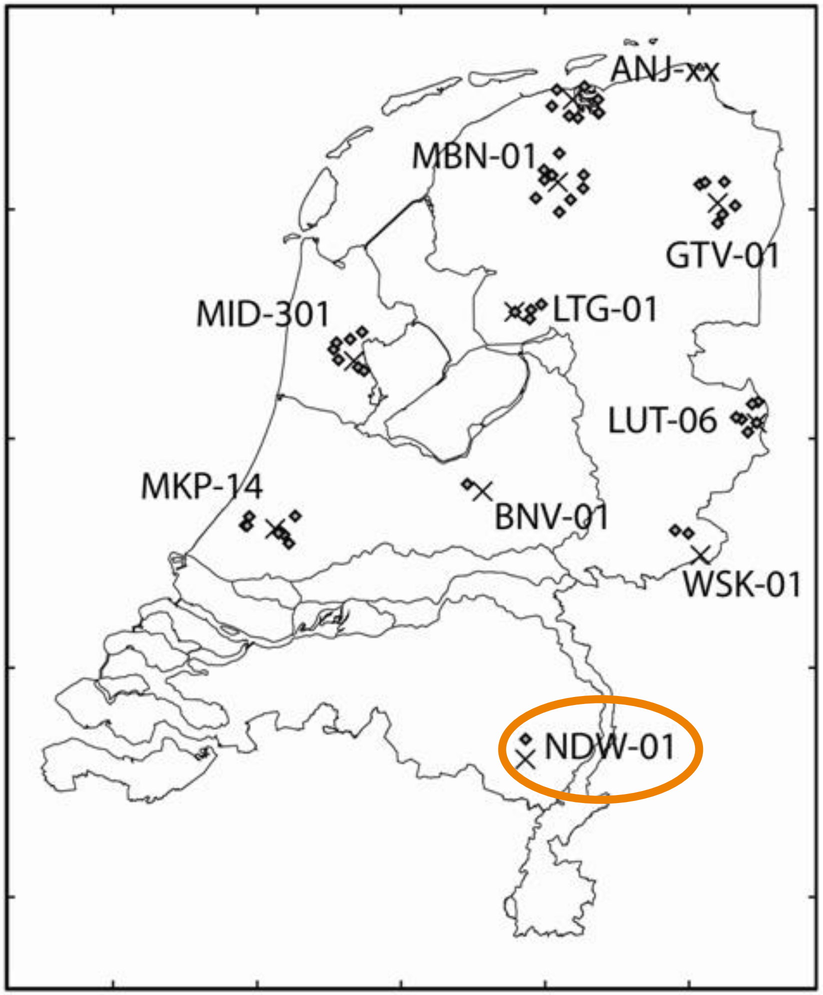
Results - temperature (3)

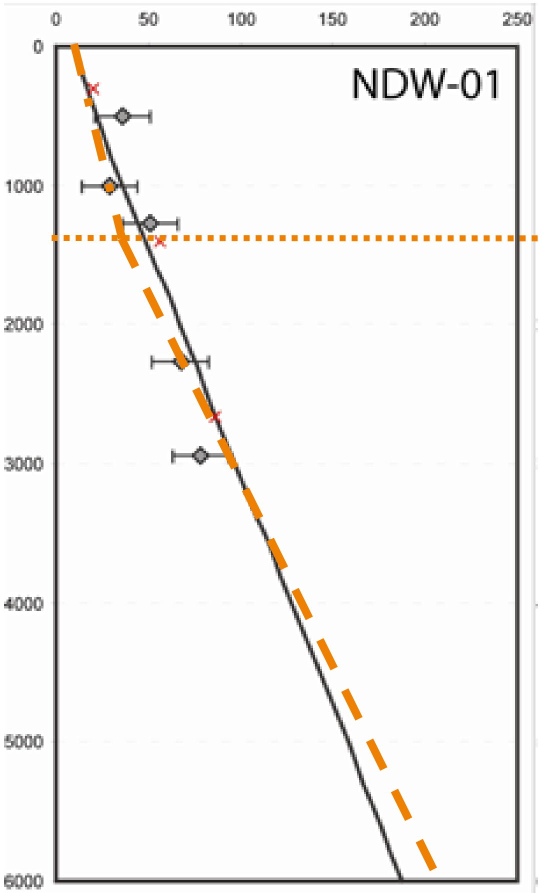


Crustal heat production | Lithosphere thickness

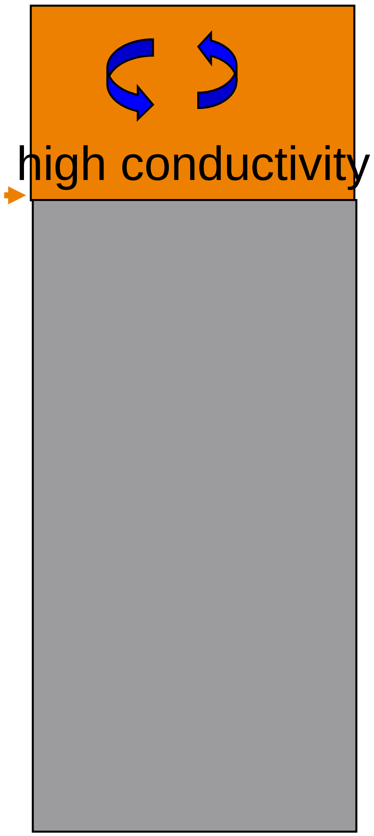


Temperature fit to well data



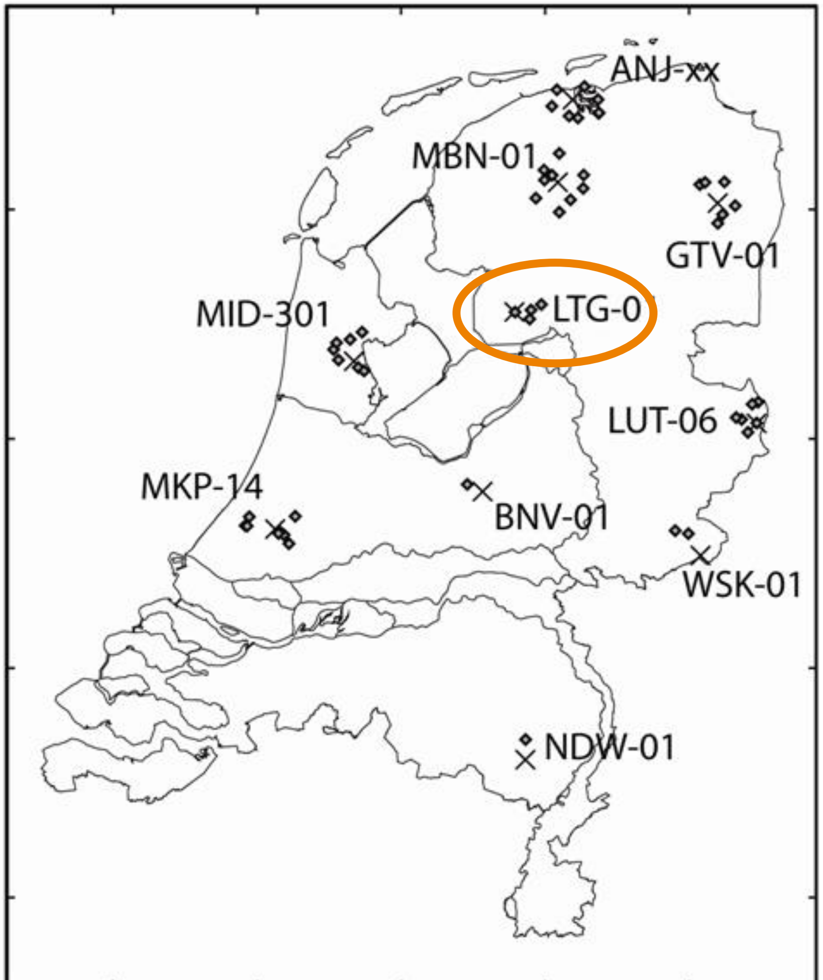


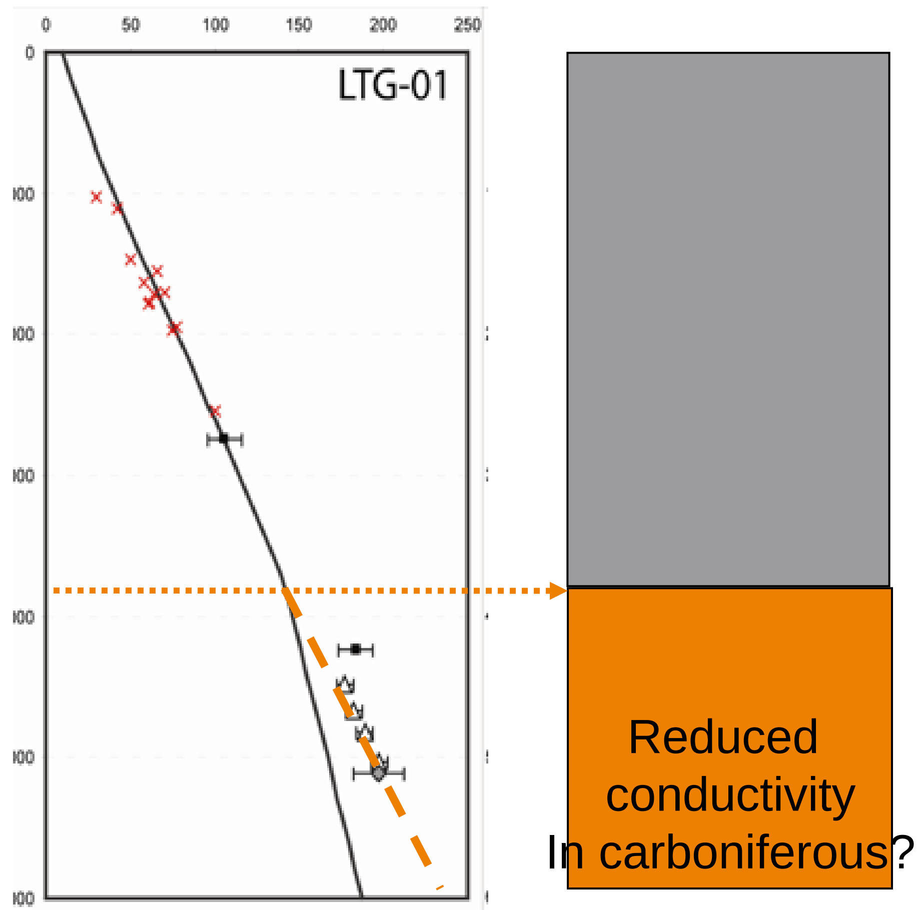
Meteoric water convection



Luijendijk, 2010

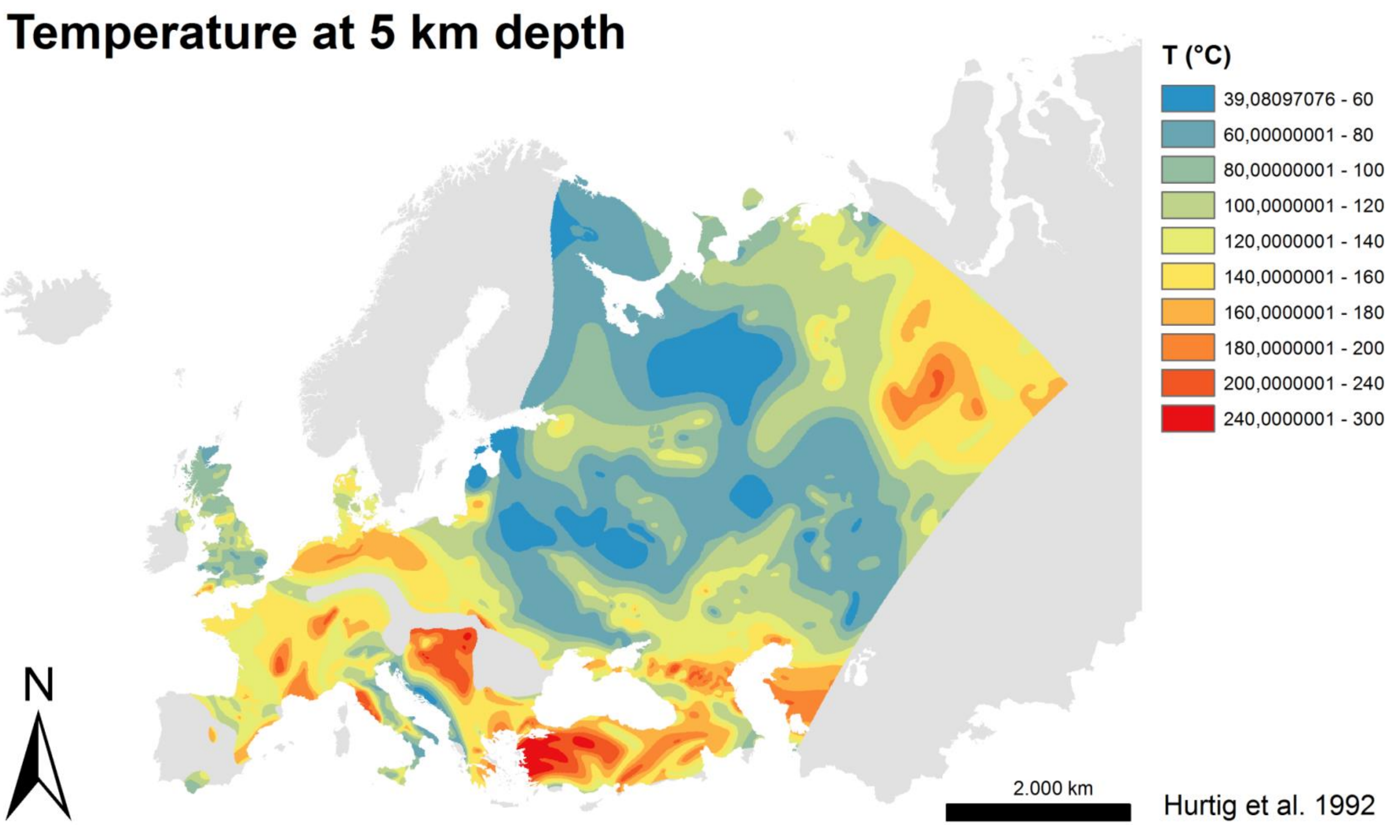
Temperature fit to well data





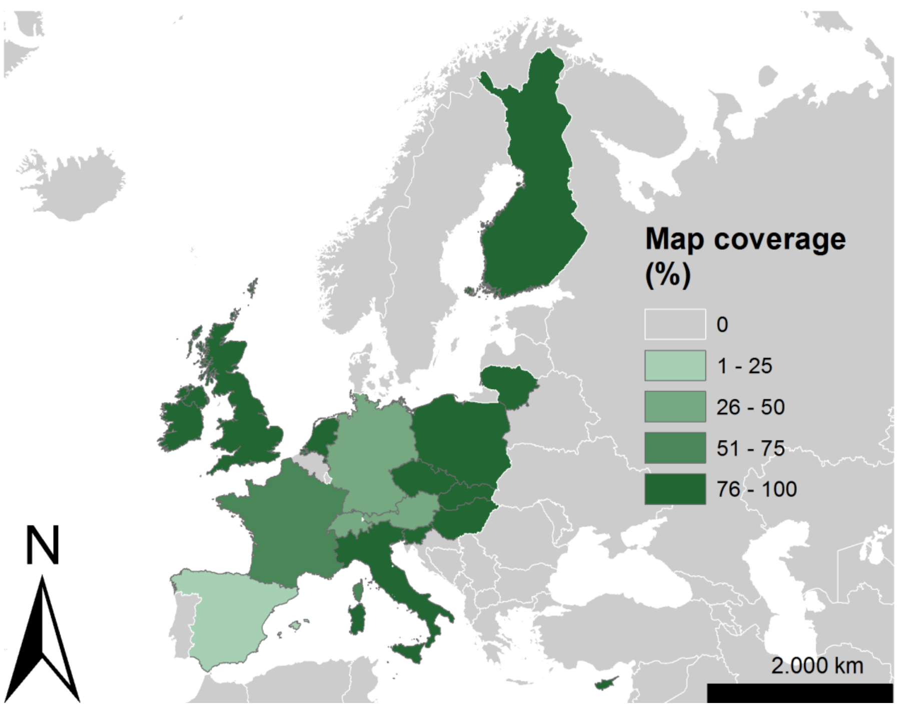
Do we have access to key information?

Temperature compilations date from over 20 years ago, only exists in a paper report

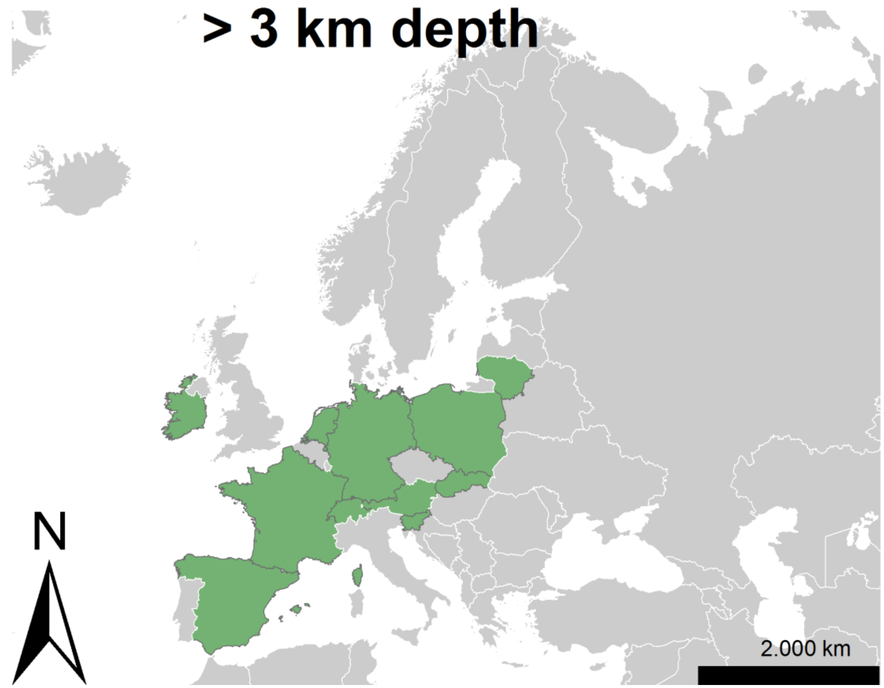


- Map coverage can vary for each country and for each depth interval

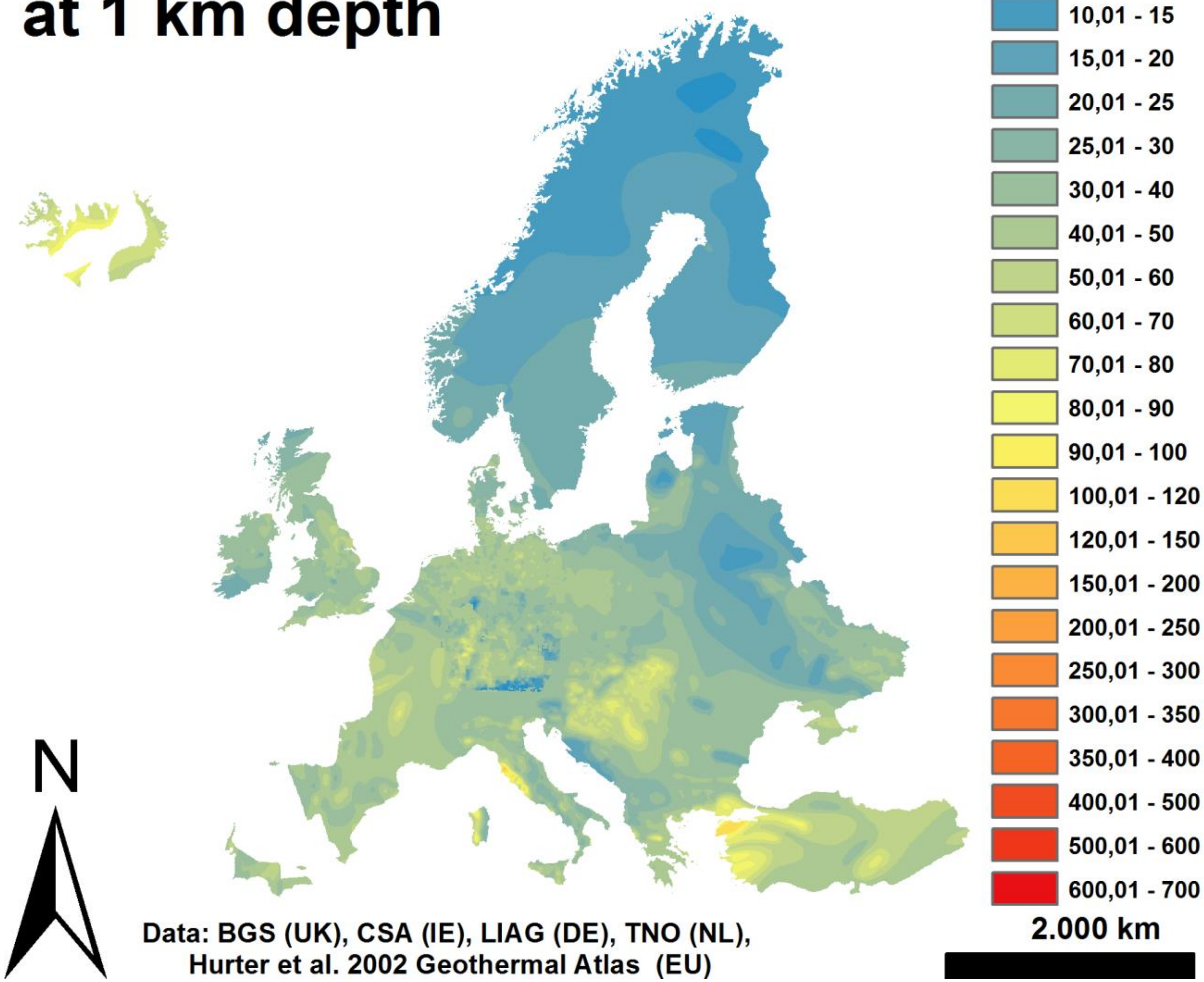
Temperature maps at depth



Temperature maps at depth > 3 km depth

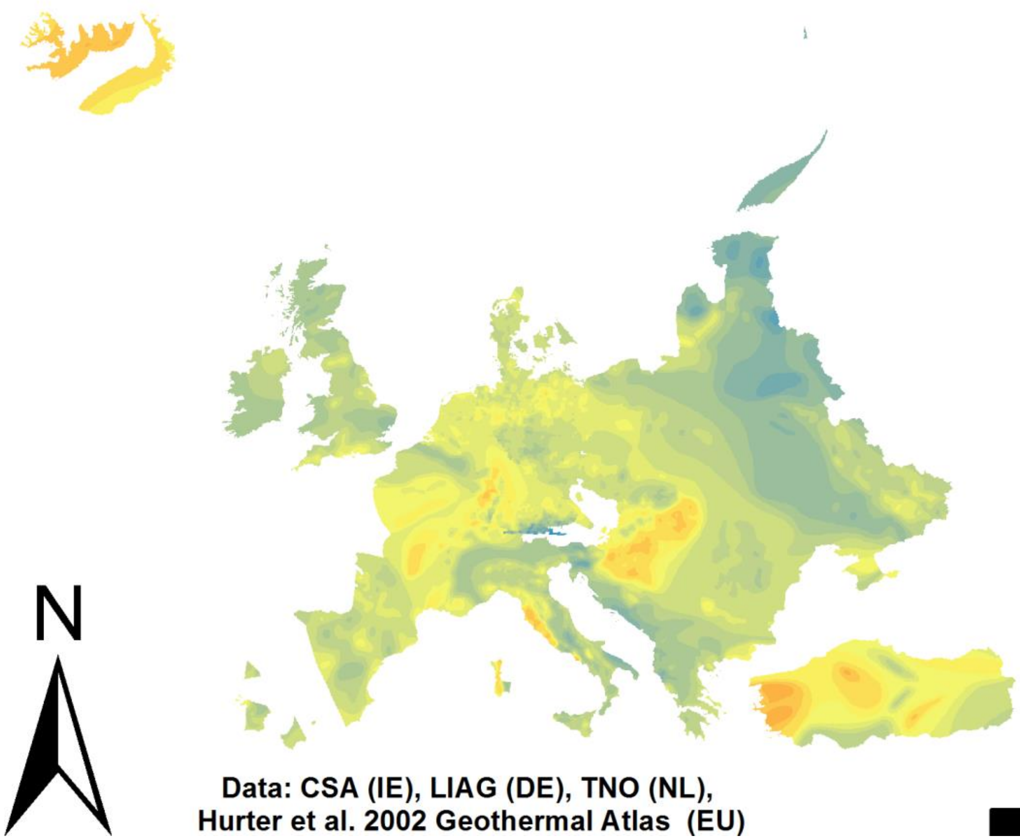


Temperature Constraints at 1 km depth



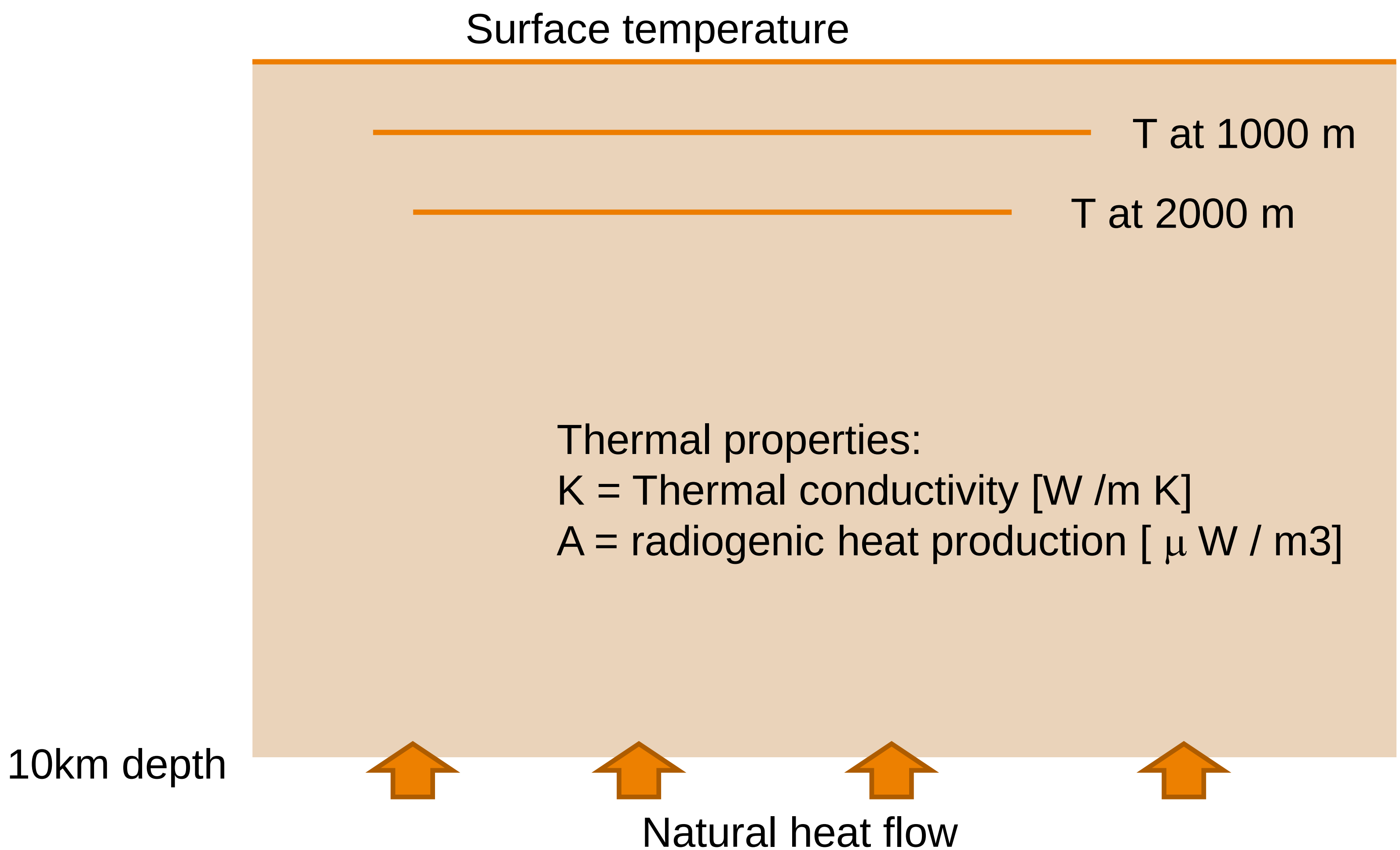
Data: BGS (UK), CSA (IE), LIAG (DE), TNO (NL), Hurter et al. 2002 Geothermal Atlas (EU)

Temperature Constraints at 2 km depth

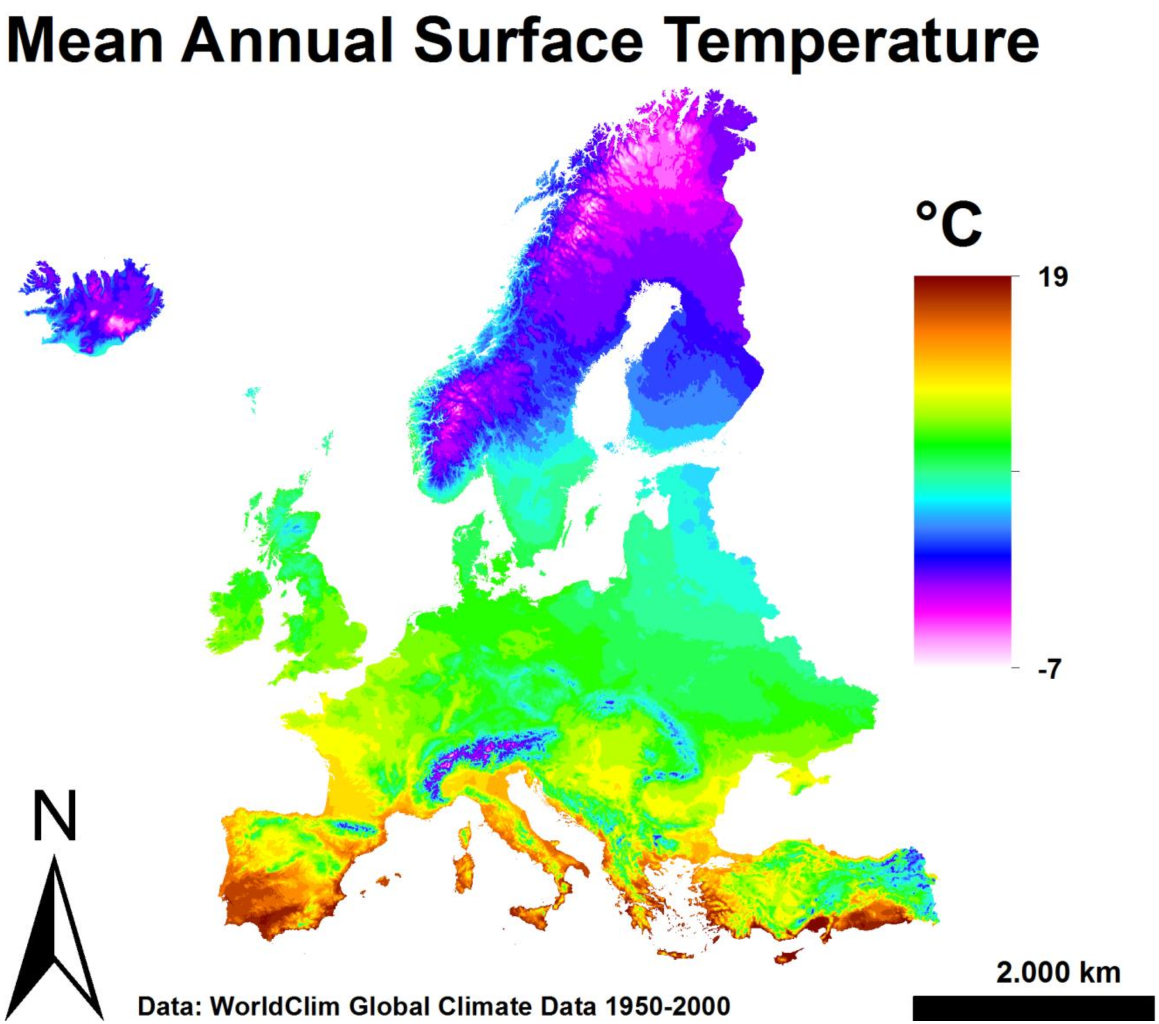


Data: CSA (IE), LIAG (DE), TNO (NL),
Hurter et al. 2002 Geothermal Atlas (EU)

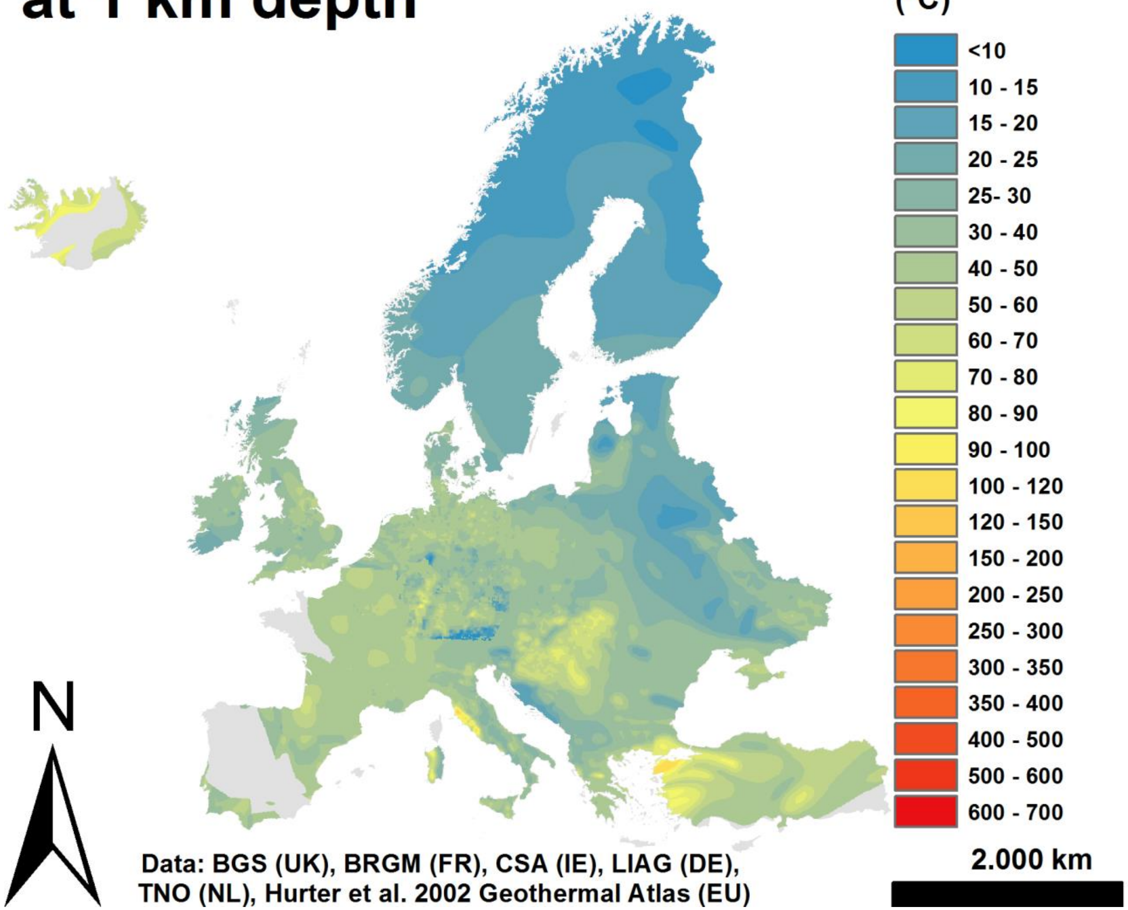
How to construct a temperature model?



Boundary conditions

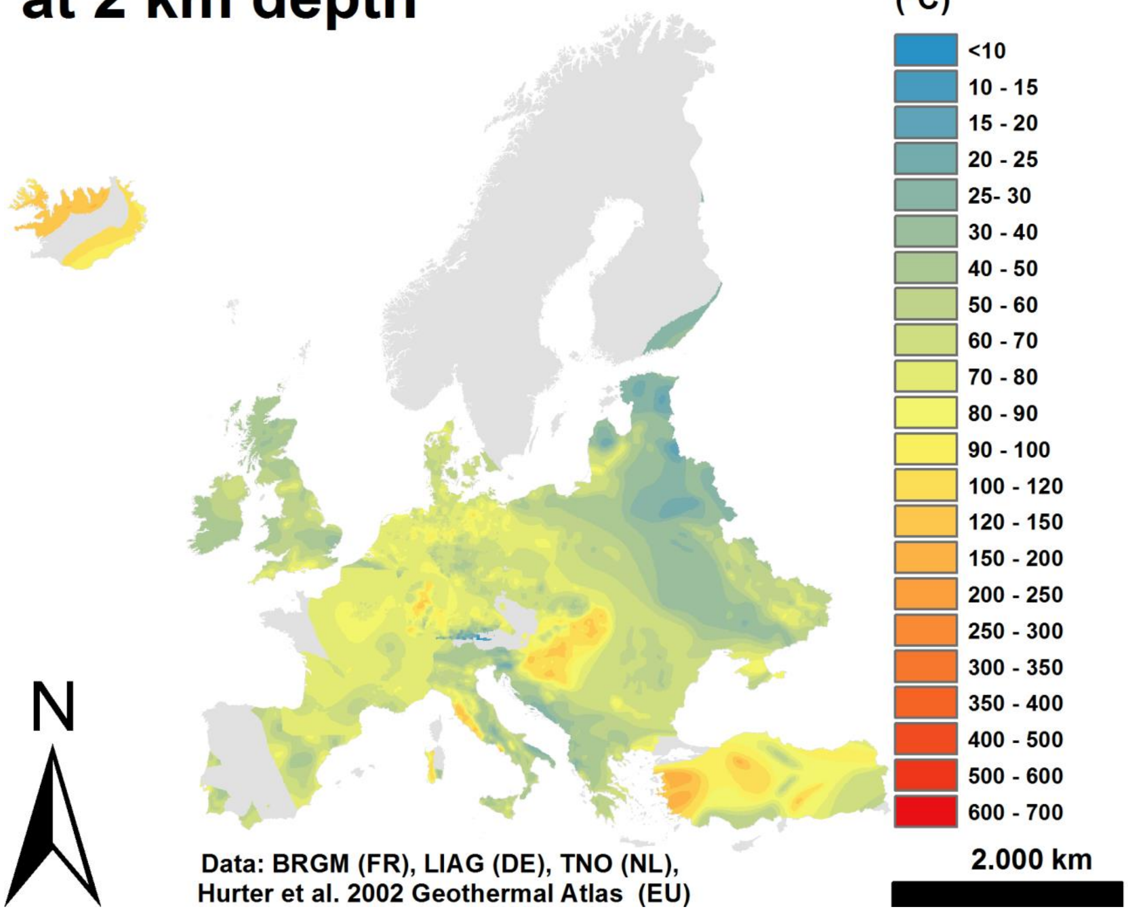


Temperature Constraints at 1 km depth



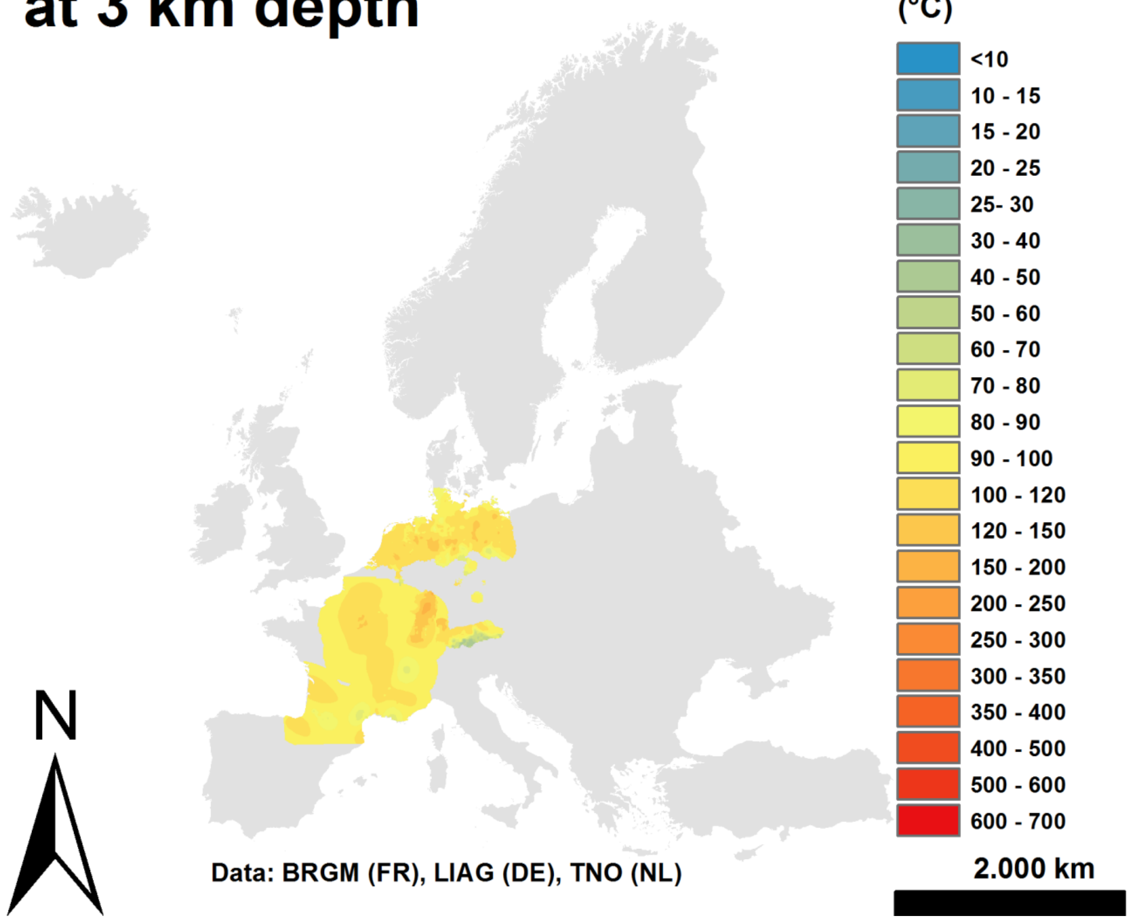
Data: BGS (UK), BRGM (FR), CSA (IE), LIAG (DE), TNO (NL), Hurter et al. 2002 Geothermal Atlas (EU)

Temperature Constraints at 2 km depth

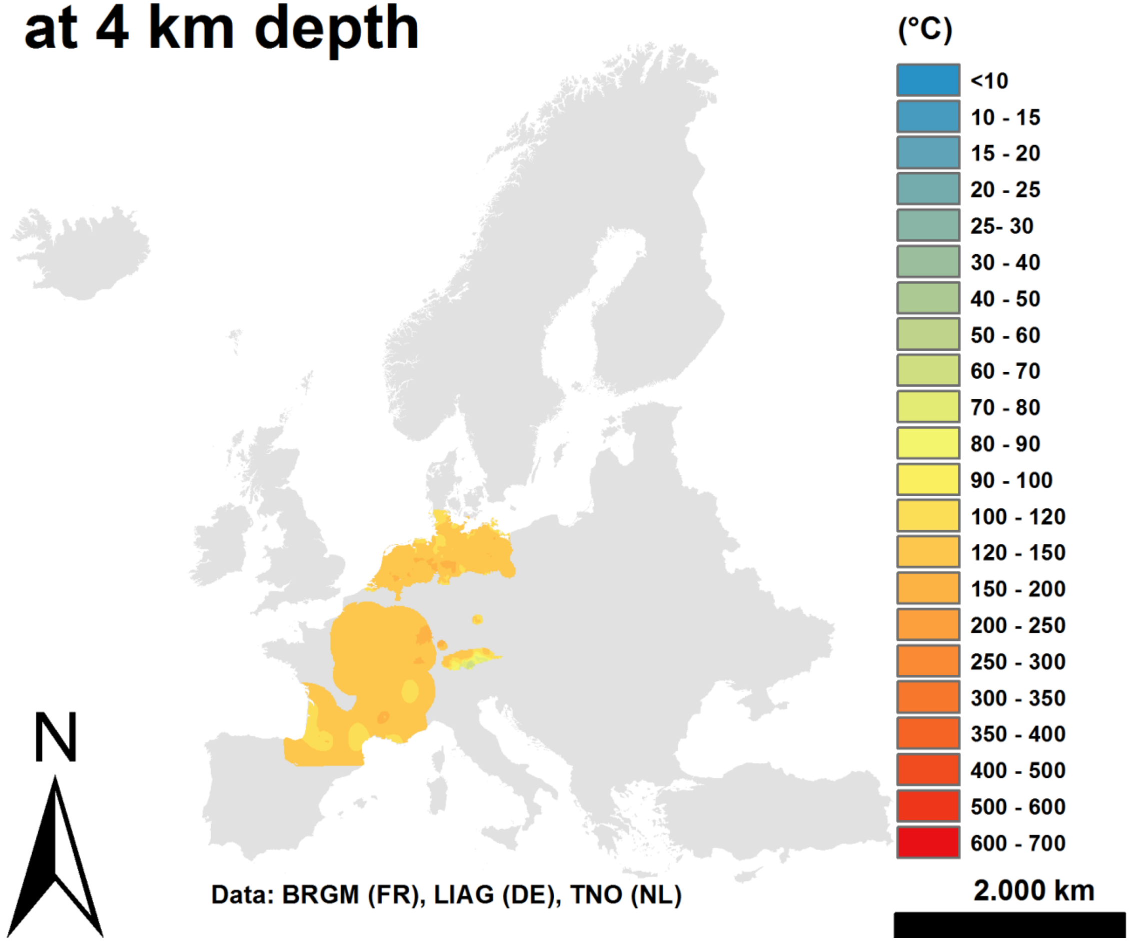


Data: BRGM (FR), LIAG (DE), TNO (NL),
Hurter et al. 2002 Geothermal Atlas (EU)

Temperature Constraints at 3 km depth



Temperature Constraints at 4 km depth



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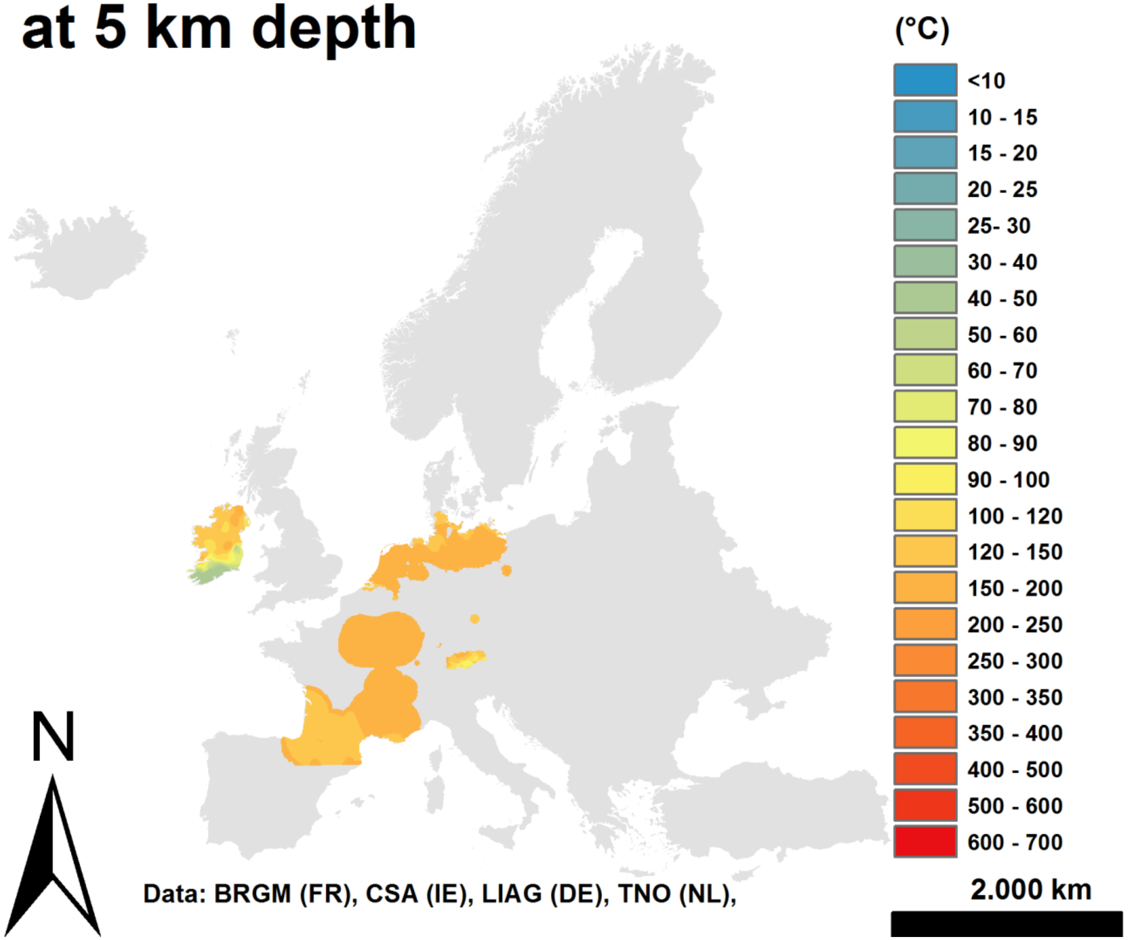
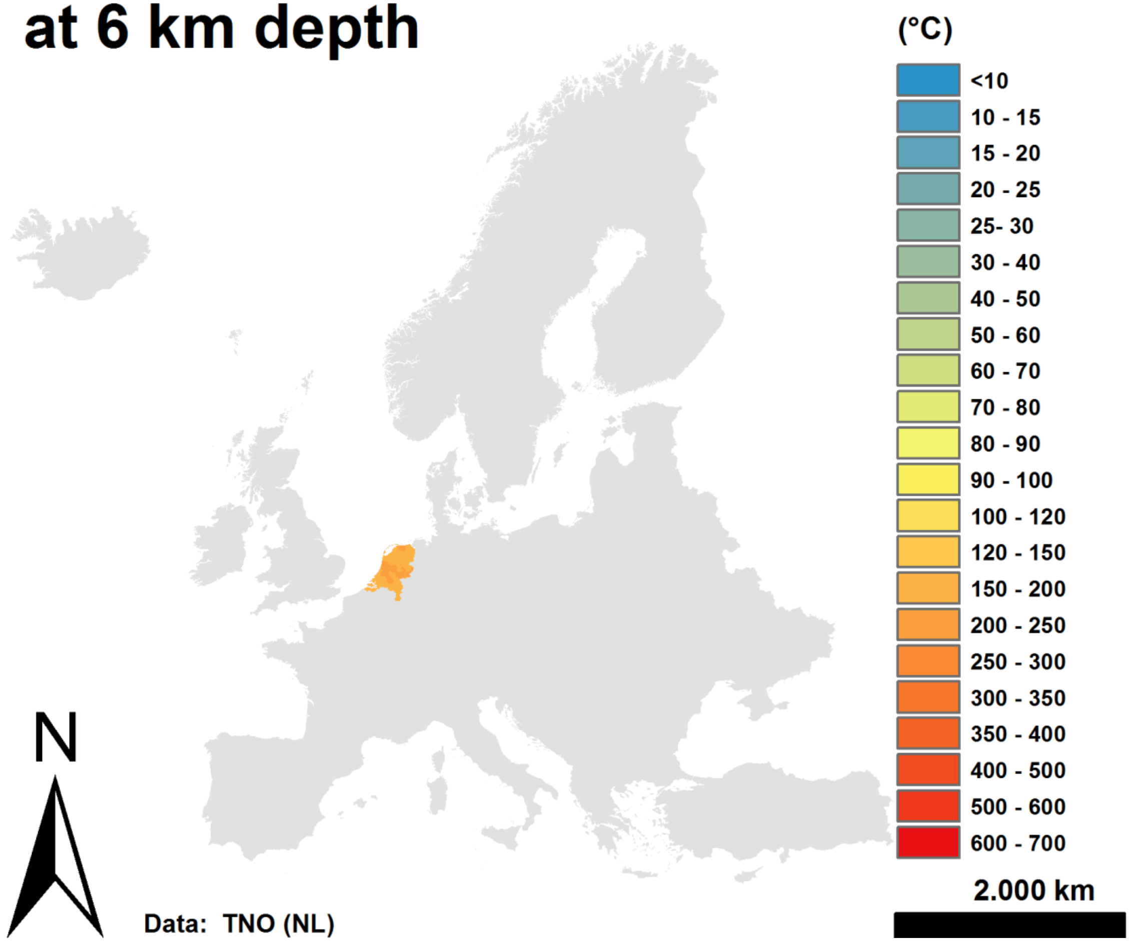
Temperature Constraints at 5 km depth

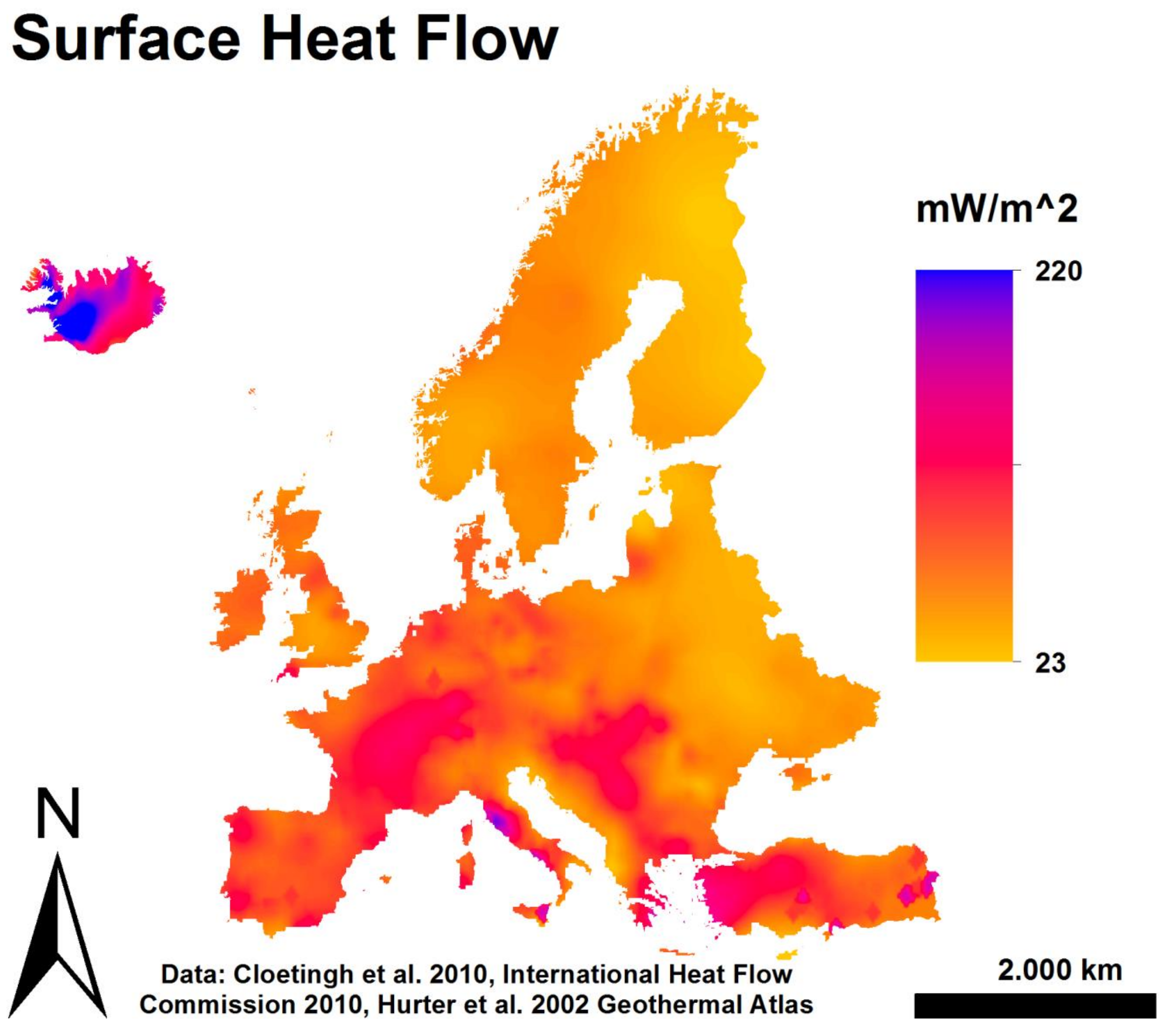


Data: BRGM (FR), CSA (IE), LIAG (DE), TNO (NL),

Temperature Constraints at 6 km depth

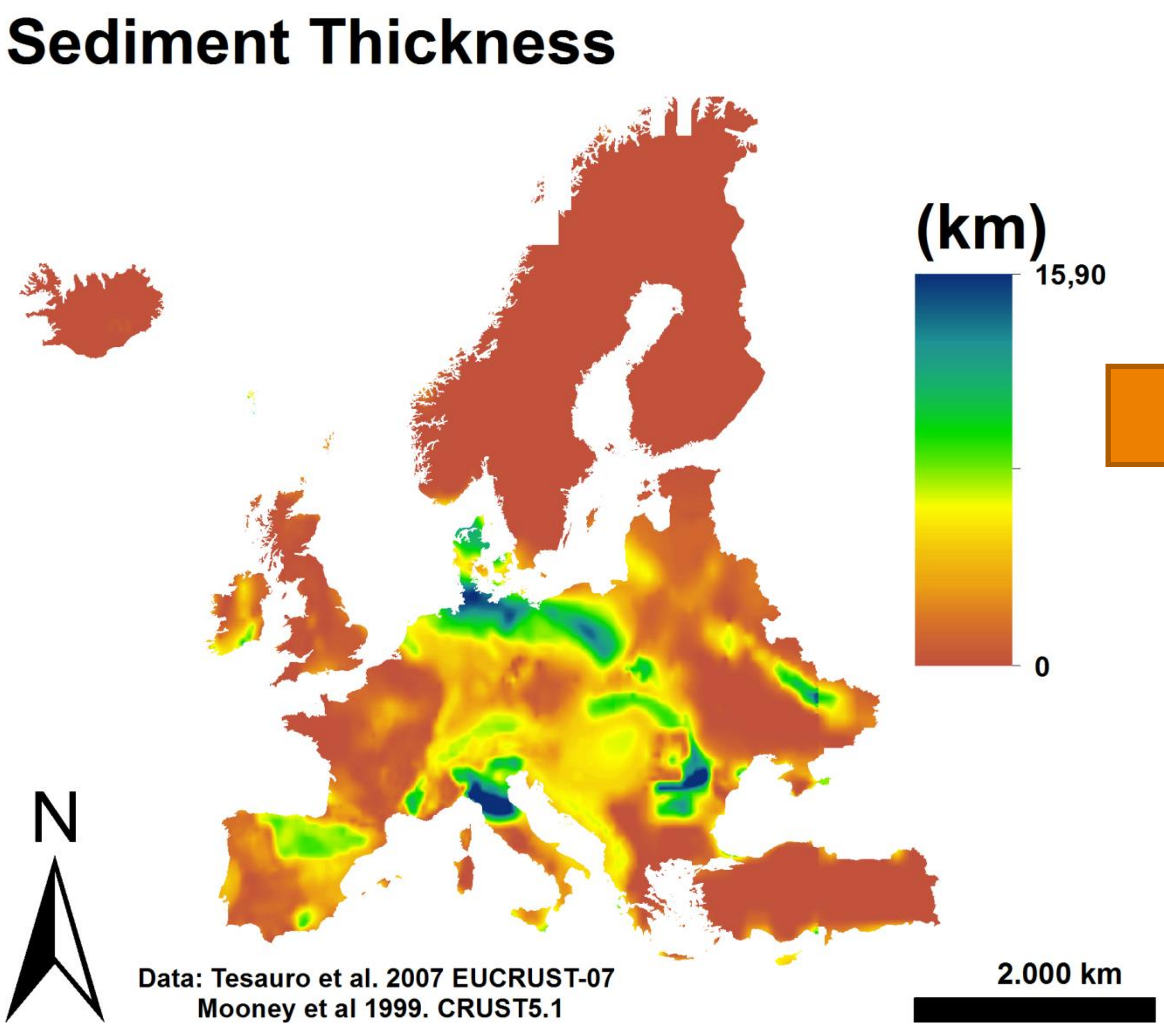


Boundary condition at Base -->



Data: Cloetingh et al. 2010, International Heat Flow Commission 2010, Hurter et al. 2002 Geothermal Atlas

Populating model with thermal properties (cf. beardsmore, 2011)



$K_{sed} = 2.5$

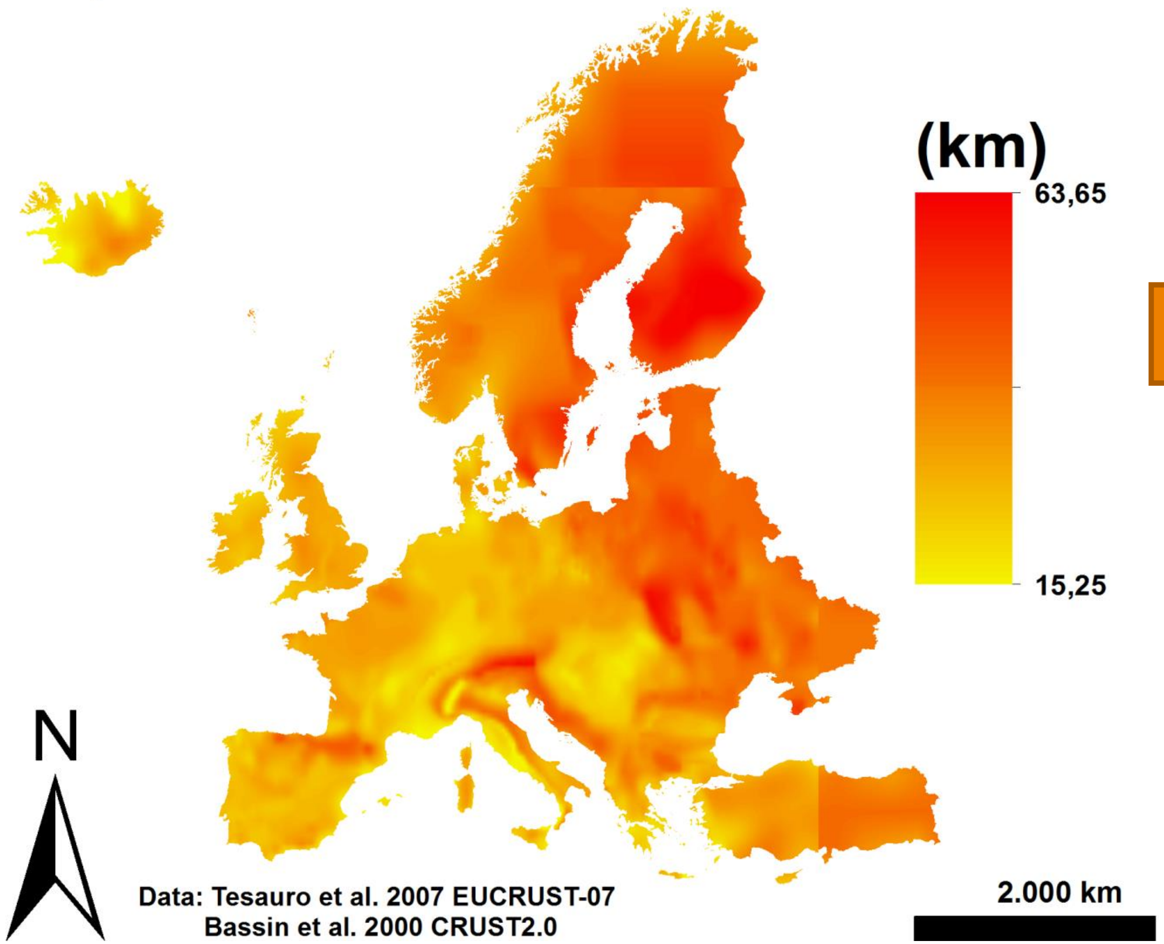
$K_{bsmt} = 2.14$

$A_{sed} = 1$

$A_{bsmt} = 2.65$

Populating model with thermal properties (cf. Cloetingh et al., 2012)

Depth of the Moho



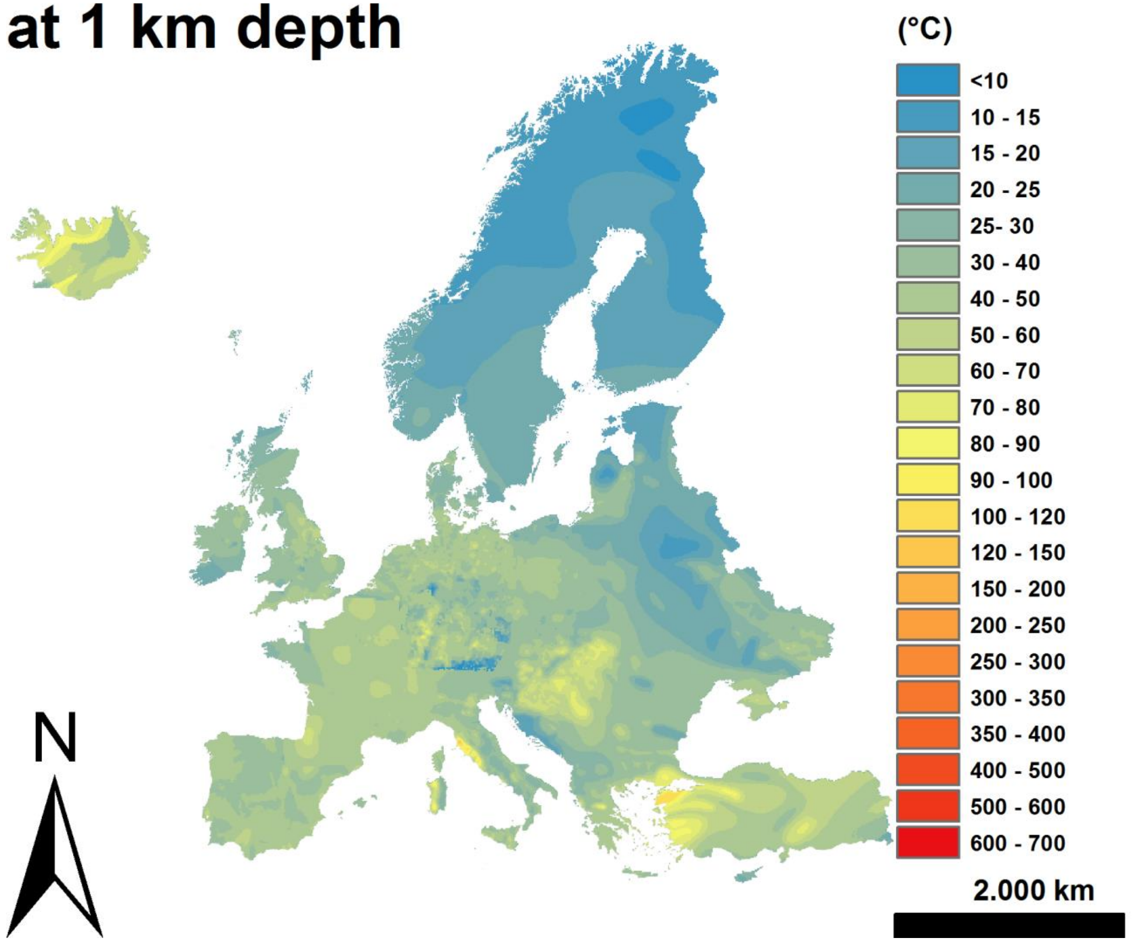
$K_{sed} = 2$

$K_{bsmt} = 2.6$

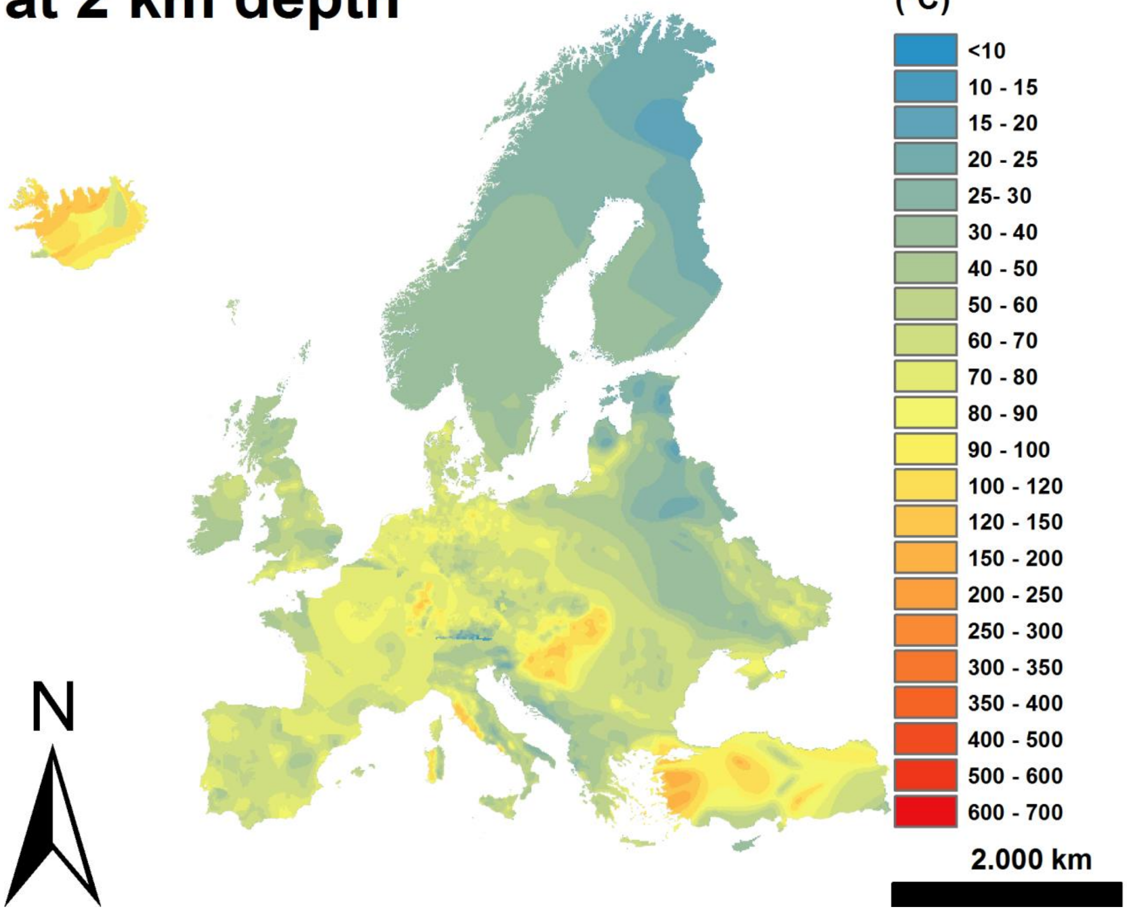
A_{sed} = 40% HF

A_{bsmt} = 40% HF

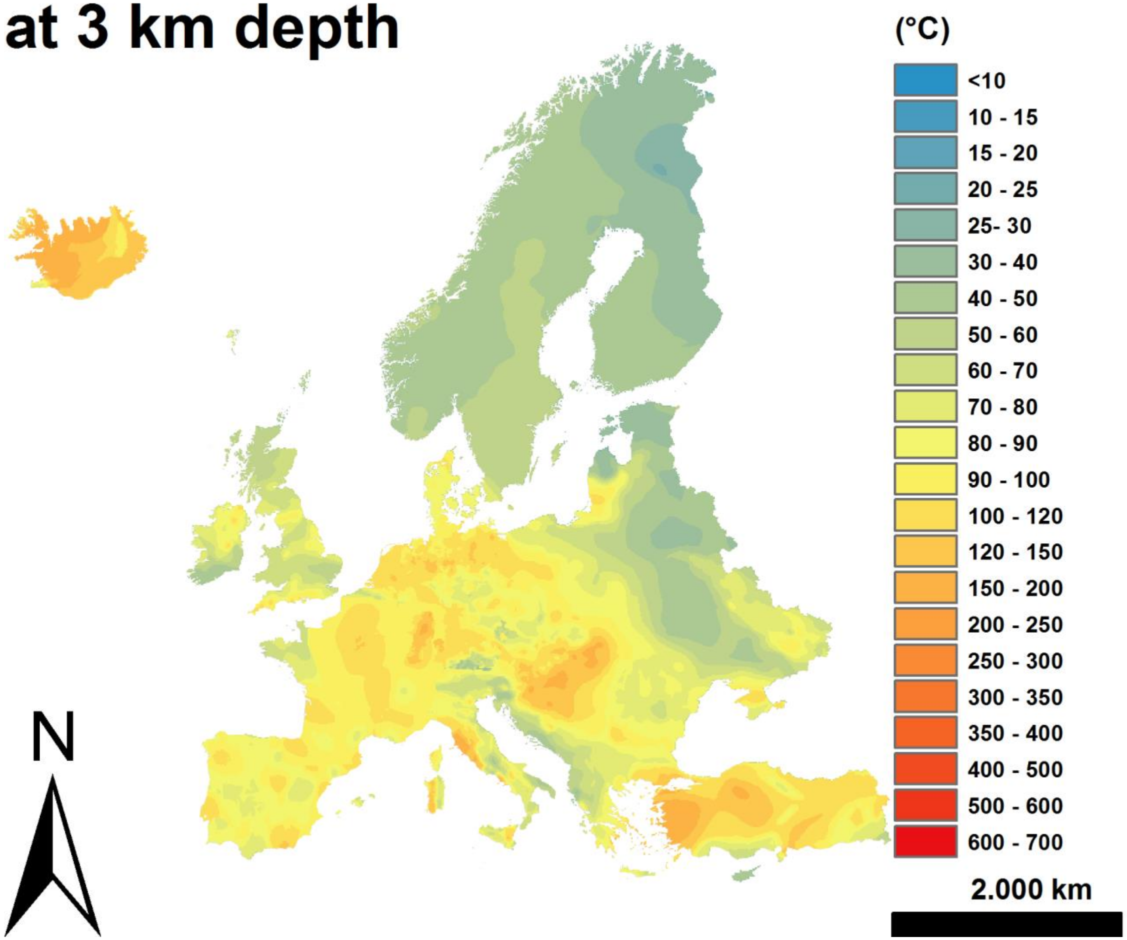
Modeled Temperature at 1 km depth



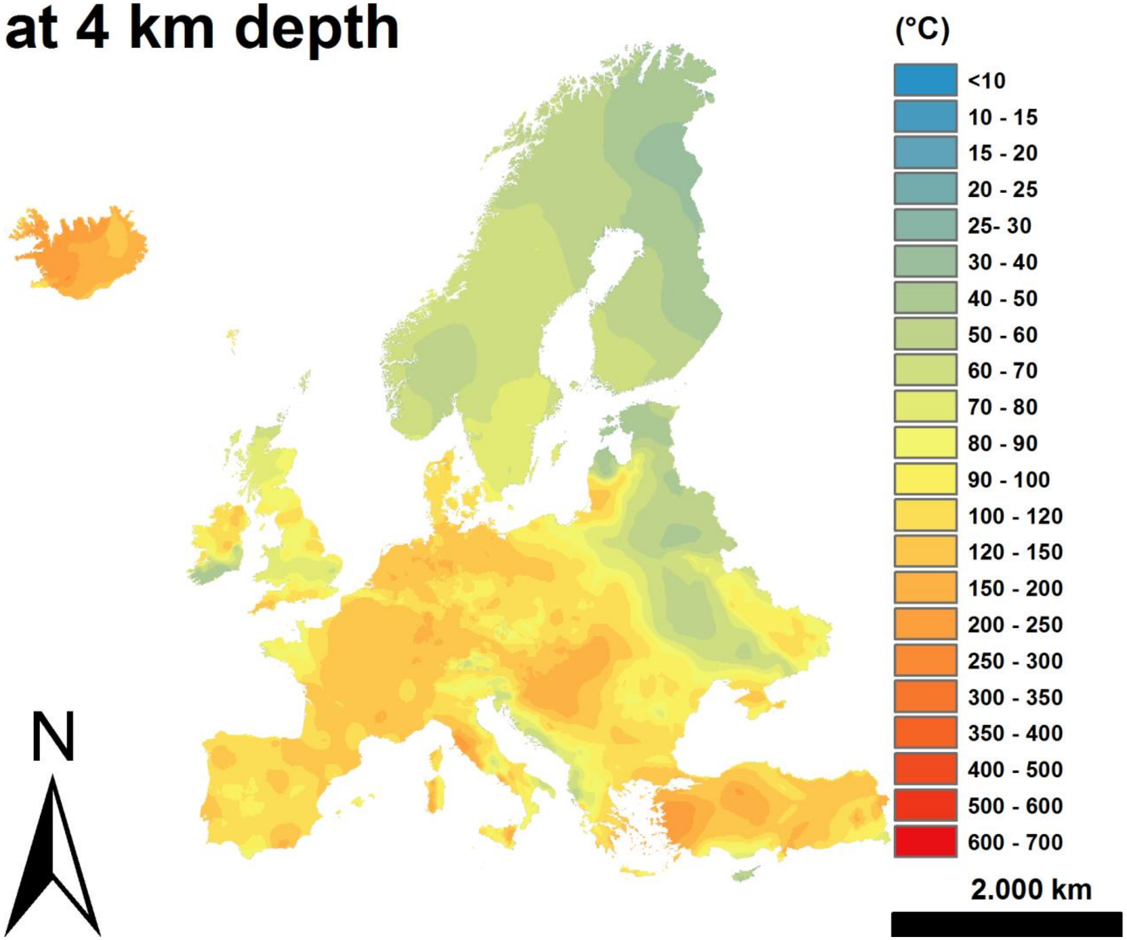
Modeled Temperature at 2 km depth



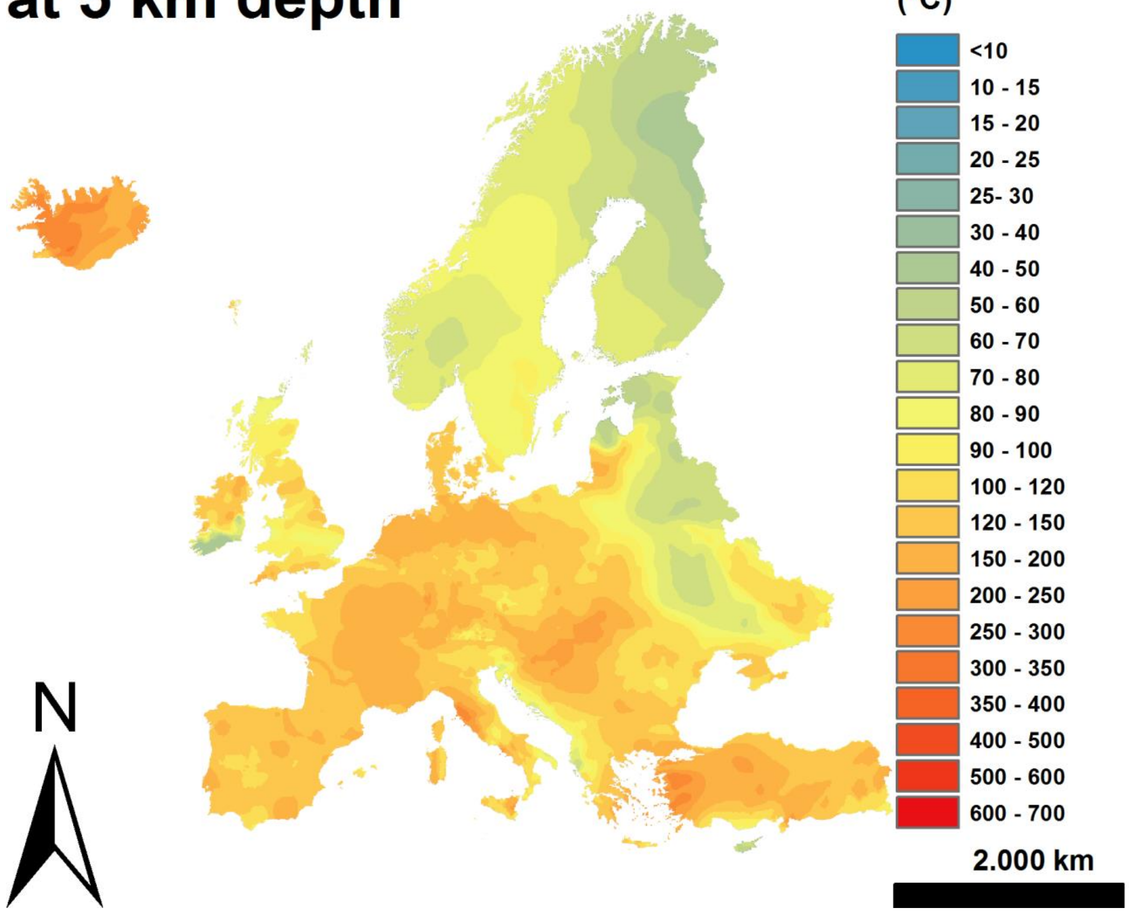
Modeled Temperature at 3 km depth



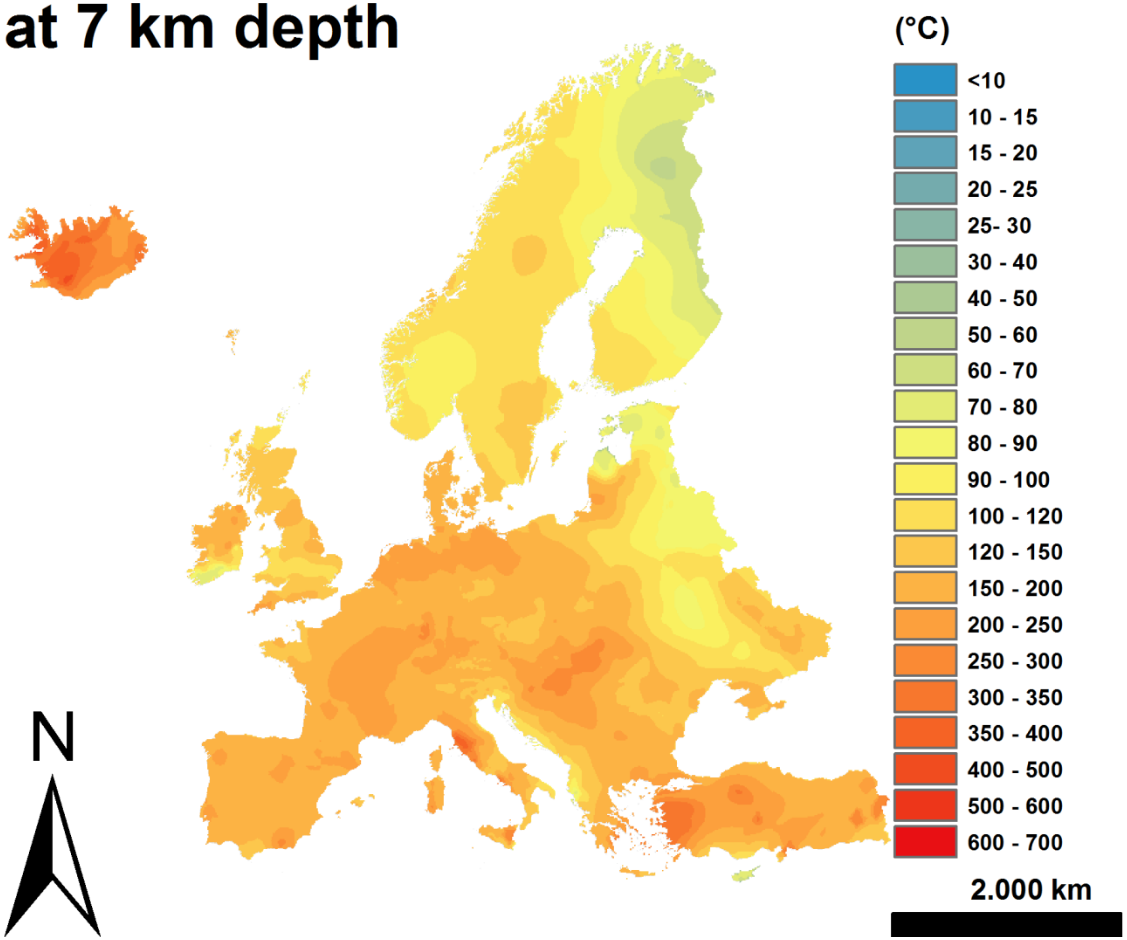
Modeled Temperature at 4 km depth



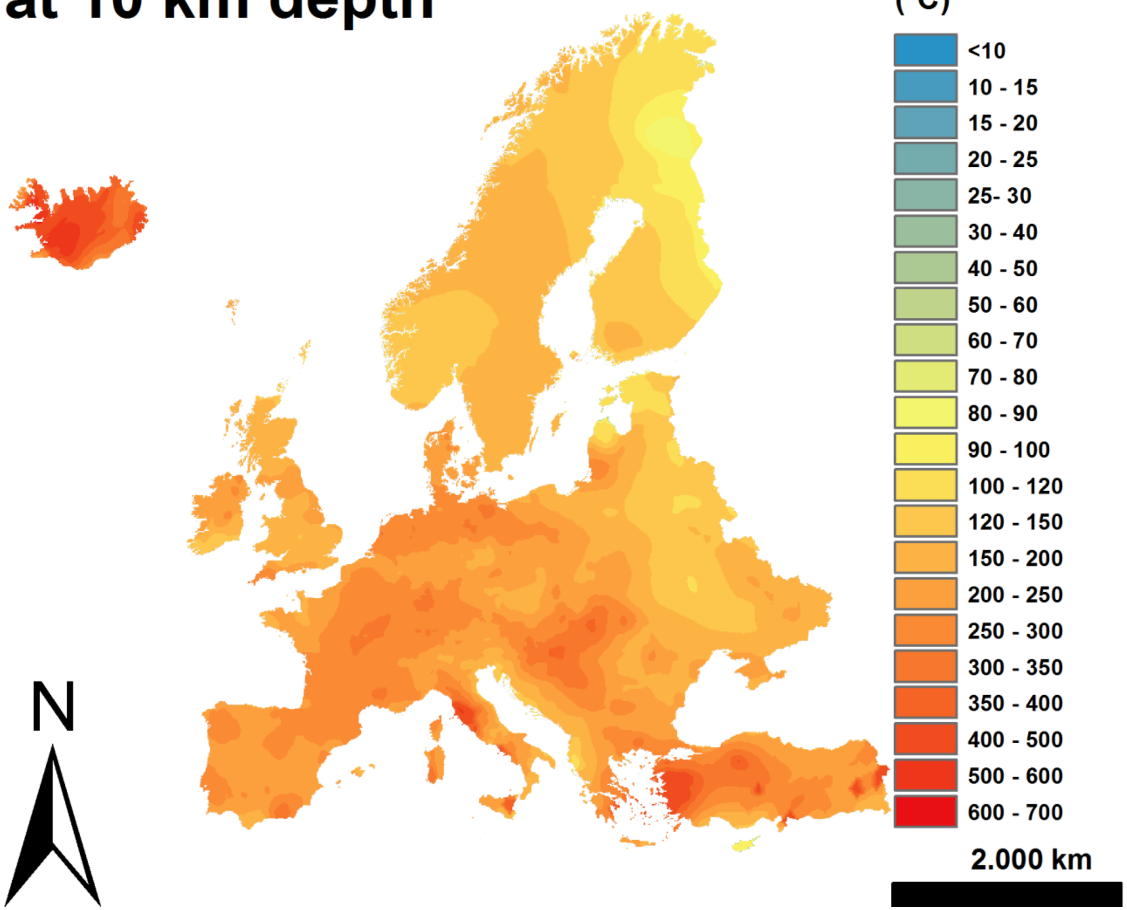
Modeled Temperature at 5 km depth

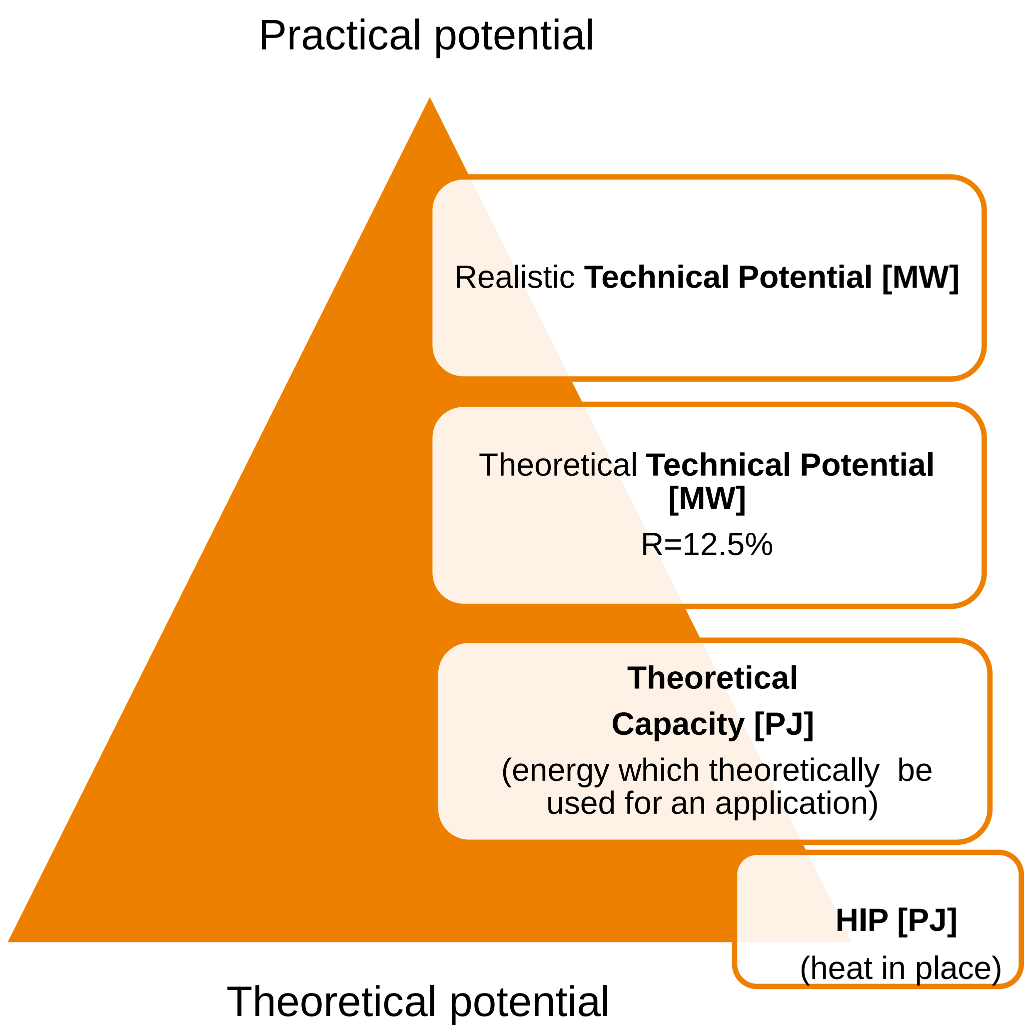


Modeled Temperature at 7 km depth



Modeled Temperature at 10 km depth





Economic potential

Tplcoe_c [MW/km2] = TP, if LCOE<c

TP[MW/km2] = 1.057* TC* R

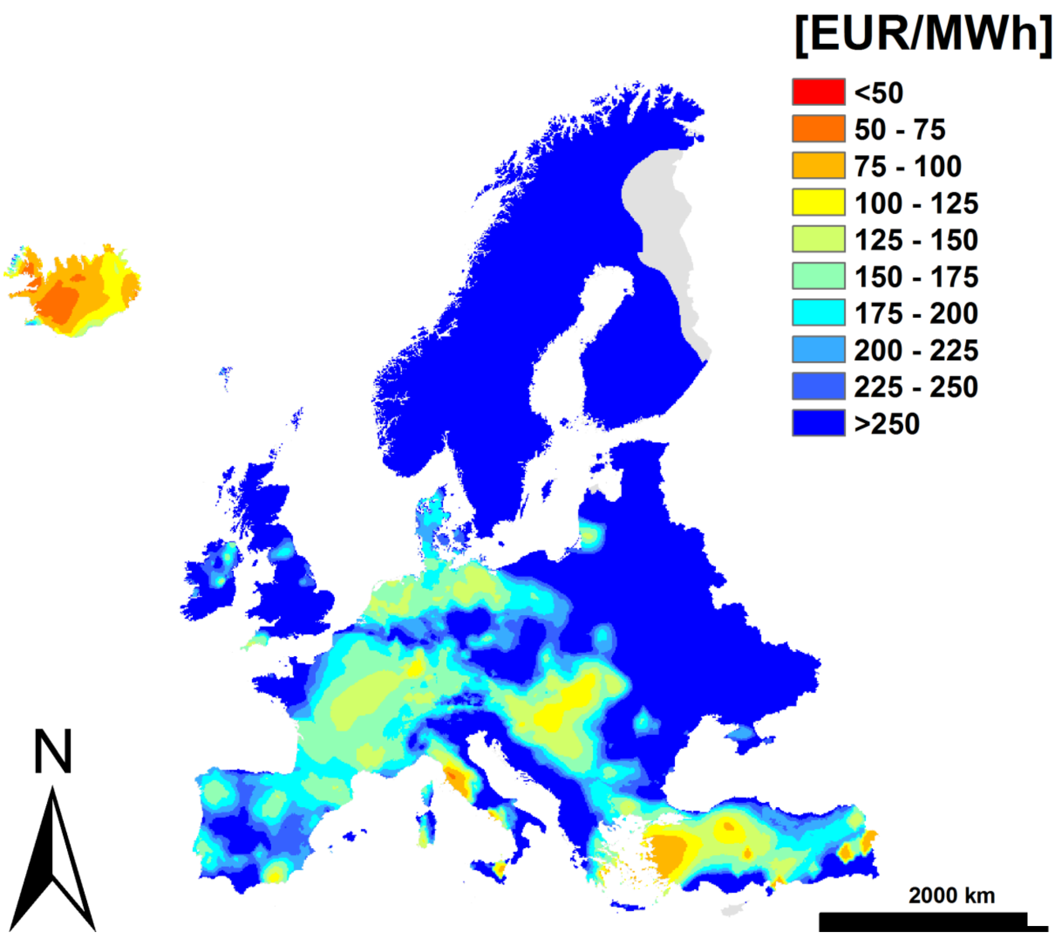
$$TC\ [PJ/km2] = z\rho_{rock} C_{rock} (T_x - Tr)\eta\ 10^{-9}$$

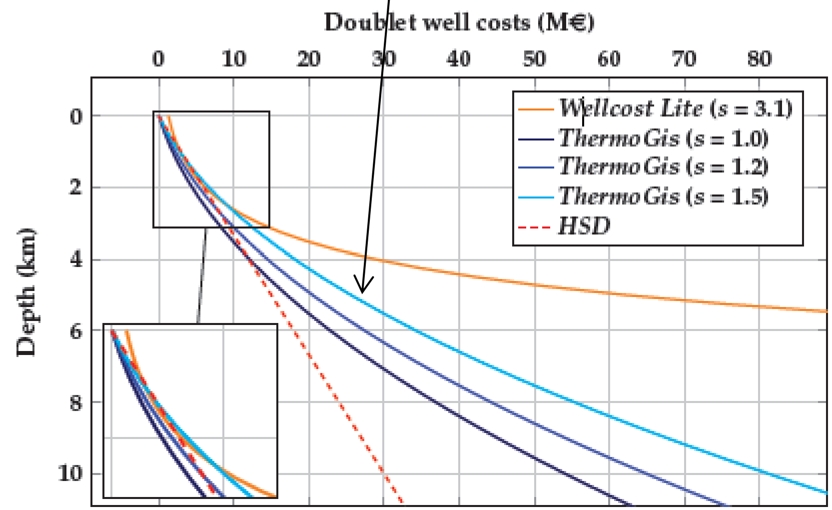
$$\text{HIP}\ [PJ/km2] = z\rho_{rock} C_{rock} (T_x - Ts)\ 10^{-9}$$

Modified from beardsmore et al., 2011

Assumptions:

- Doublet
- COP = 50
- Tmin = 100°C
- Flow rate = 70 l/s
- Welcost scaling = 1.5
- Zmax = 7km
- Stimulation costs = 20M euro

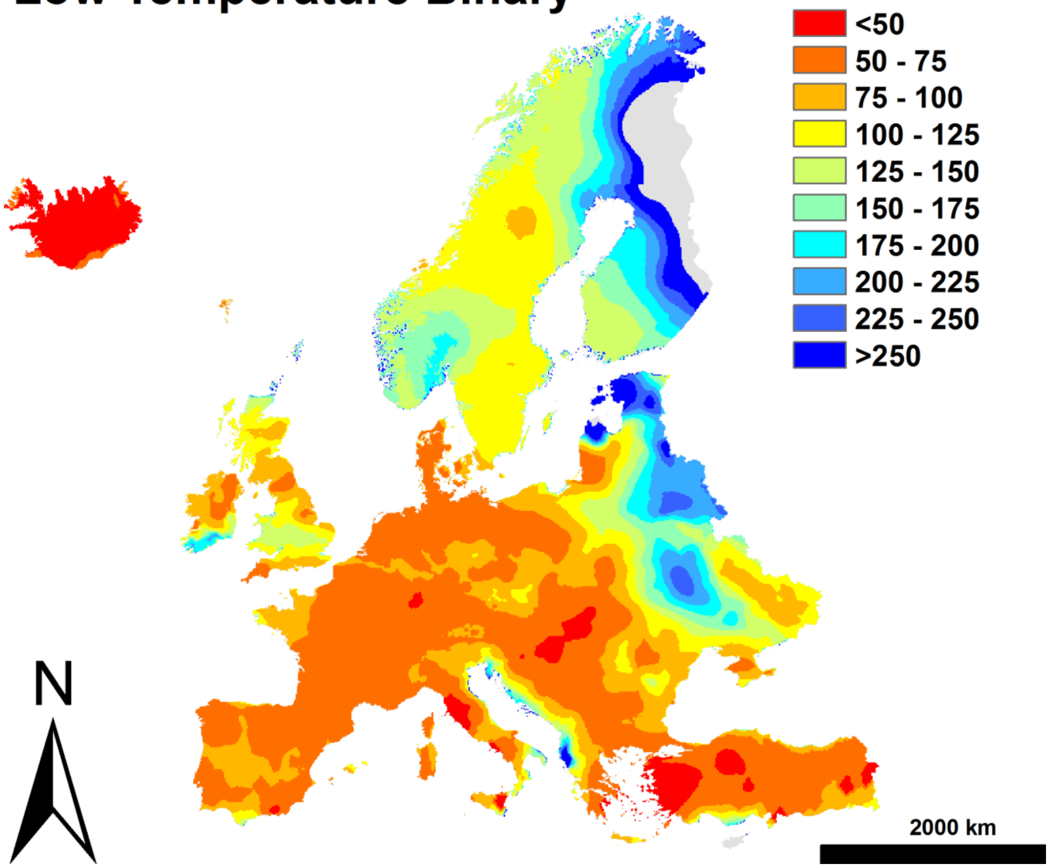




+20mln stimulation

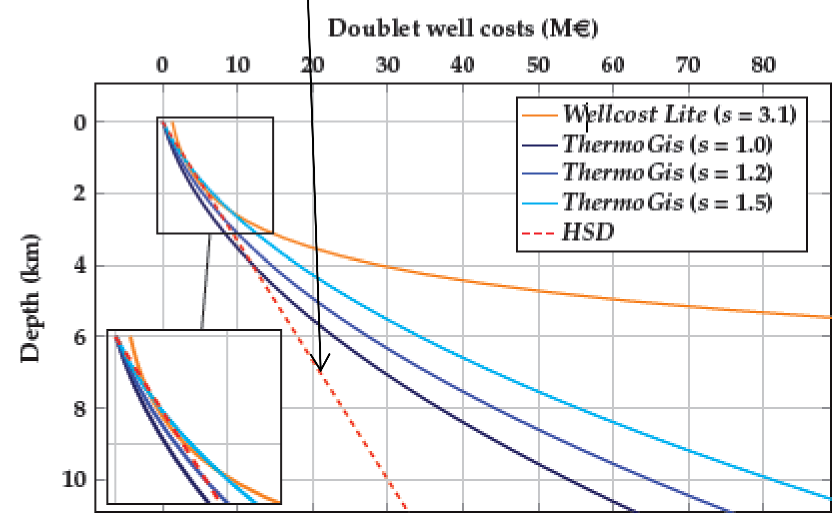
Minimal LCOE EGS 2050: Flame Drilling and Low Temperature Binary

[EUR/MWh]

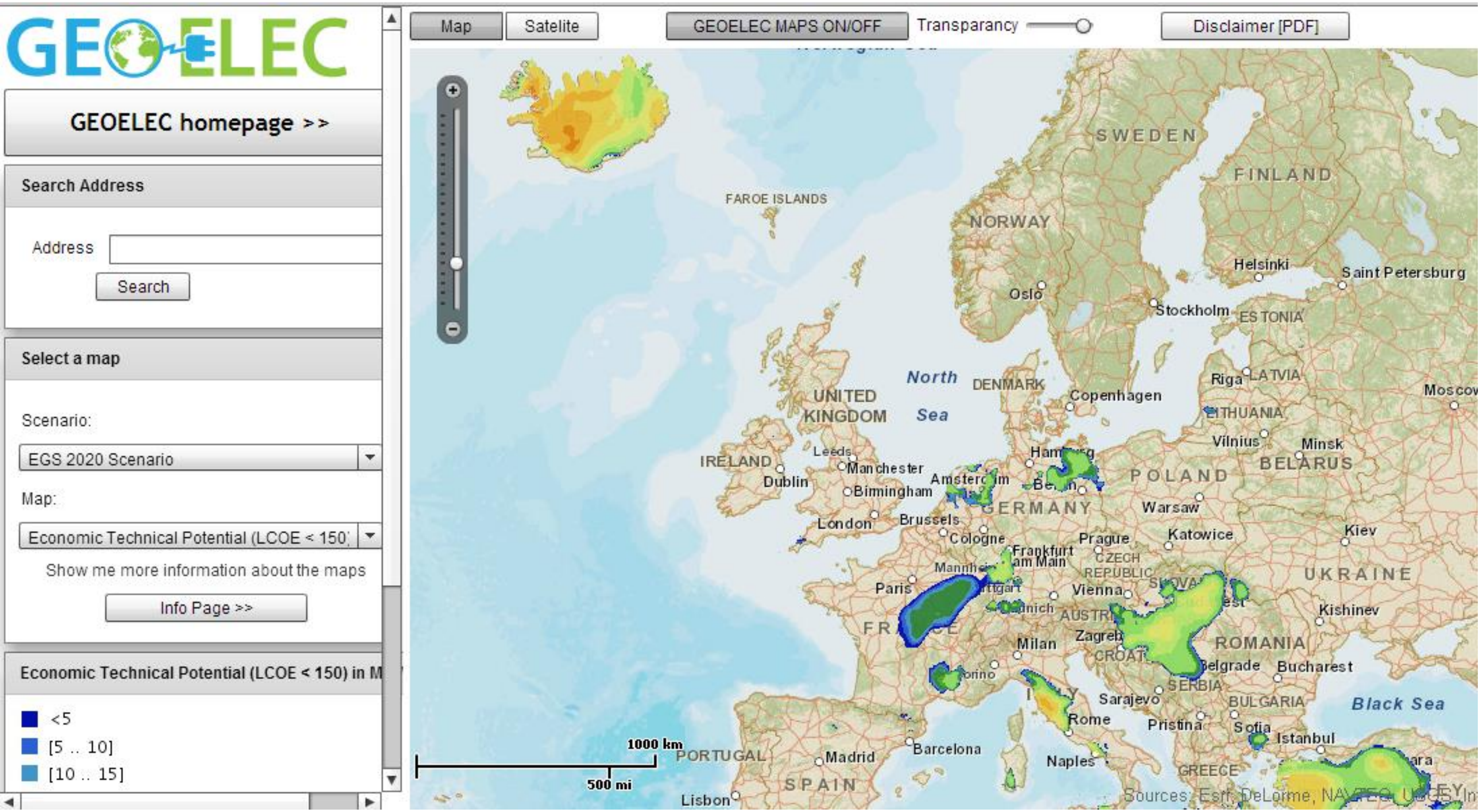


Assumptions:

- Doublet
- COP = 1000
- Tmin = 100°C
- Flow rate = 100 l/s
- Welcosts = €1.500/m
- Zmax = 10km
- Stimulation costs = 20M euro
- Carnot efficiency = 70%



http://test.thermogis.nl/geoelec



Resource assessment: targets and tools

Remote Sensing
for geothermal exploration

Remote sensing: airborne and satellite imagery

- Preliminary, low-cost exploration for geothermal resources
- Mapping of geothermal indicators in large regions
- Mapping of faults and geological features of interest
- Easy access to inaccessible/unexplored areas

Remote sensing: airborne and satellite imagery

Geothermal indicators

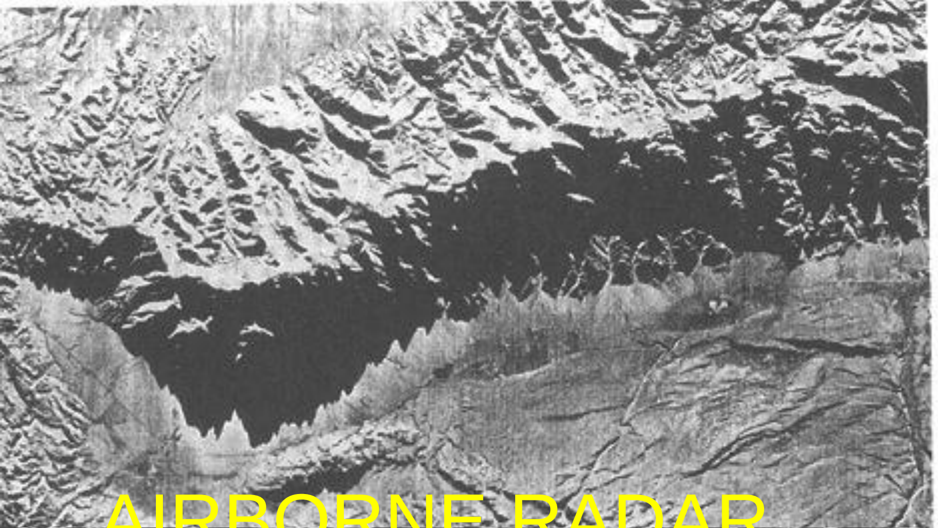
- Sinter/tufa
- Hydrothermal alteration products (clays, sulfates)
- Thermal anomalies
- Vegetation anomalies

Remote sensing: airborne and satellite imagery

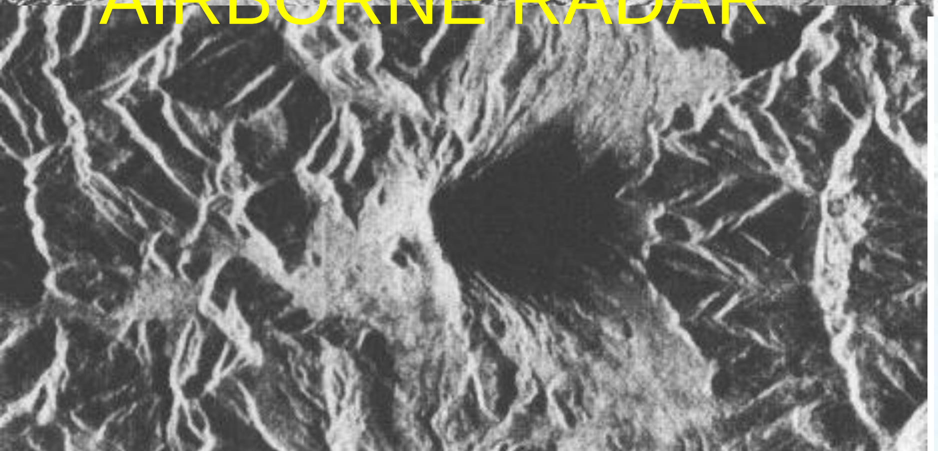
Fundamentals: active/passive methods

- Passive systems: record energy naturally radiated or reflected by objects at the Earth's surface
- Active systems: supply their own source of energy, measure the returned energy (e.g. radar, laser)

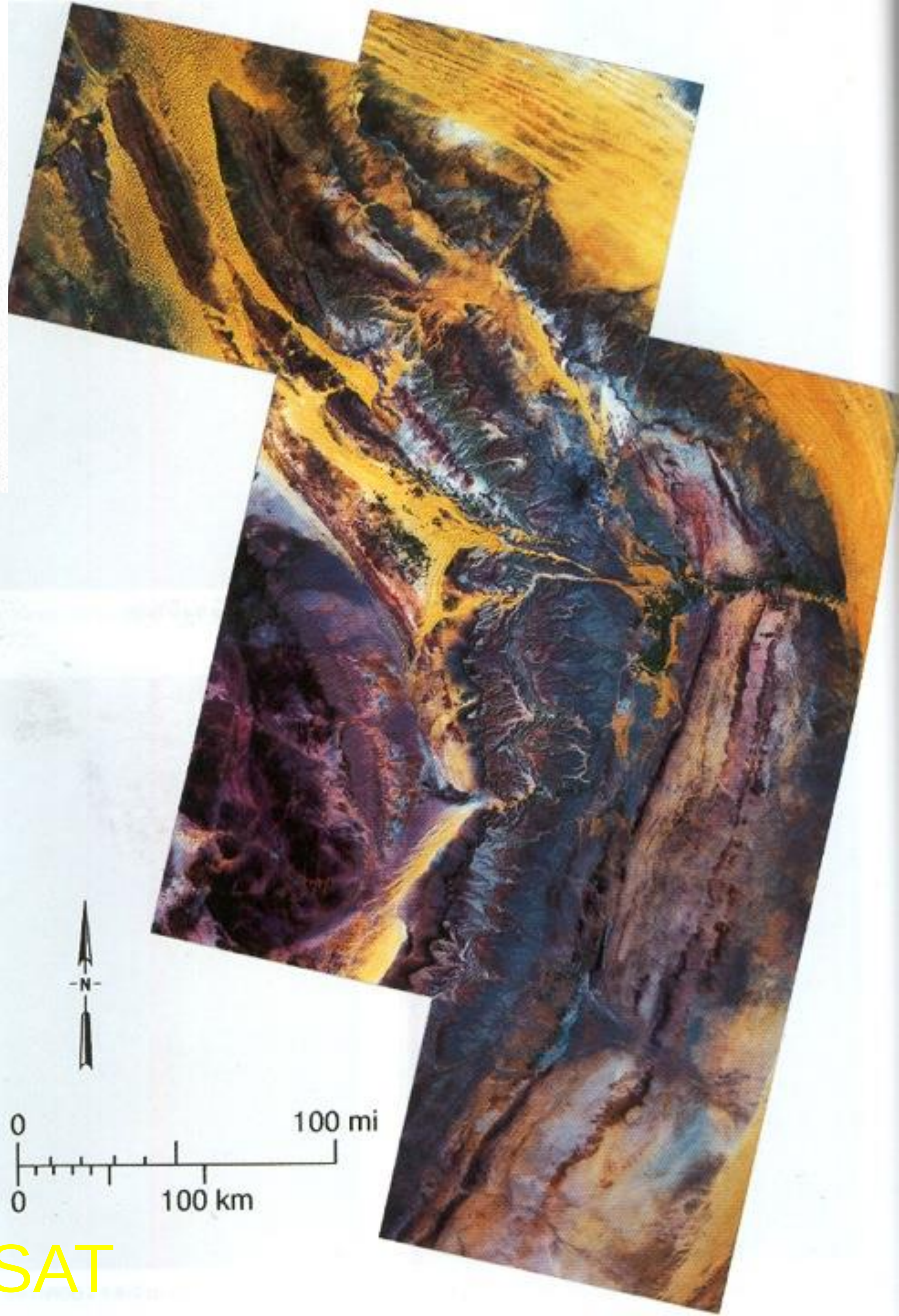
EM radiation/matter interactions of interest:
Transmission > refraction ($n=c_a/c_s$)
Absorption > largely heating *Surface phenomena*
Emission > f(structure, temperature of material)
Scattering, Reflection, Polarization *Volume phenomena*



AIRBORNE RADAR



LANDSAT



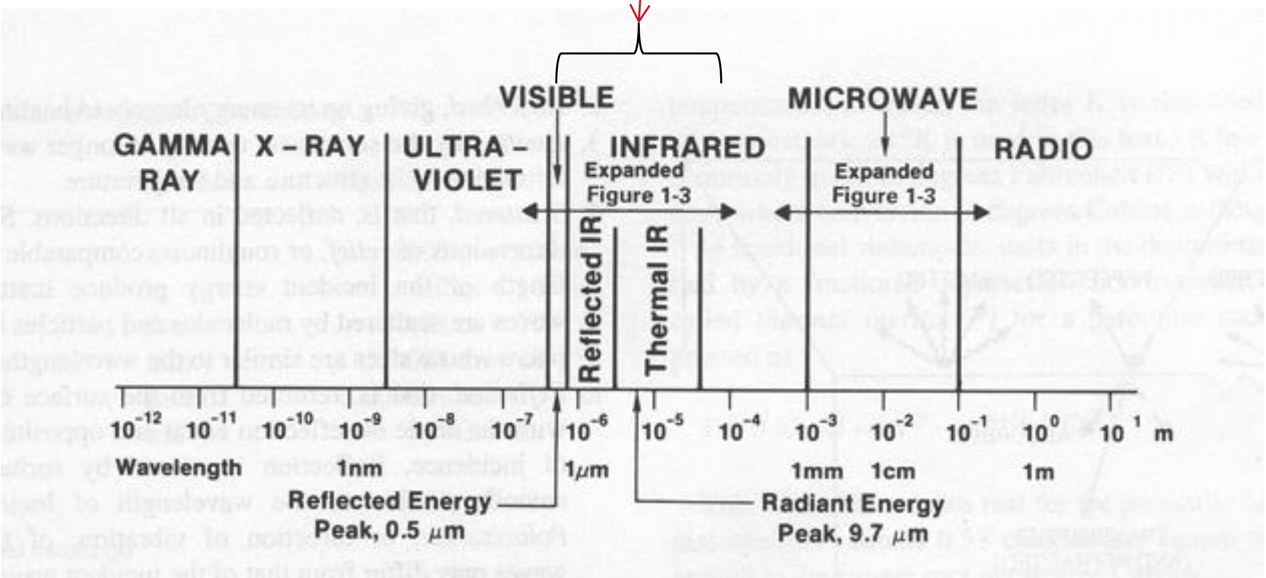
Applications to geothermal exploration

Optical

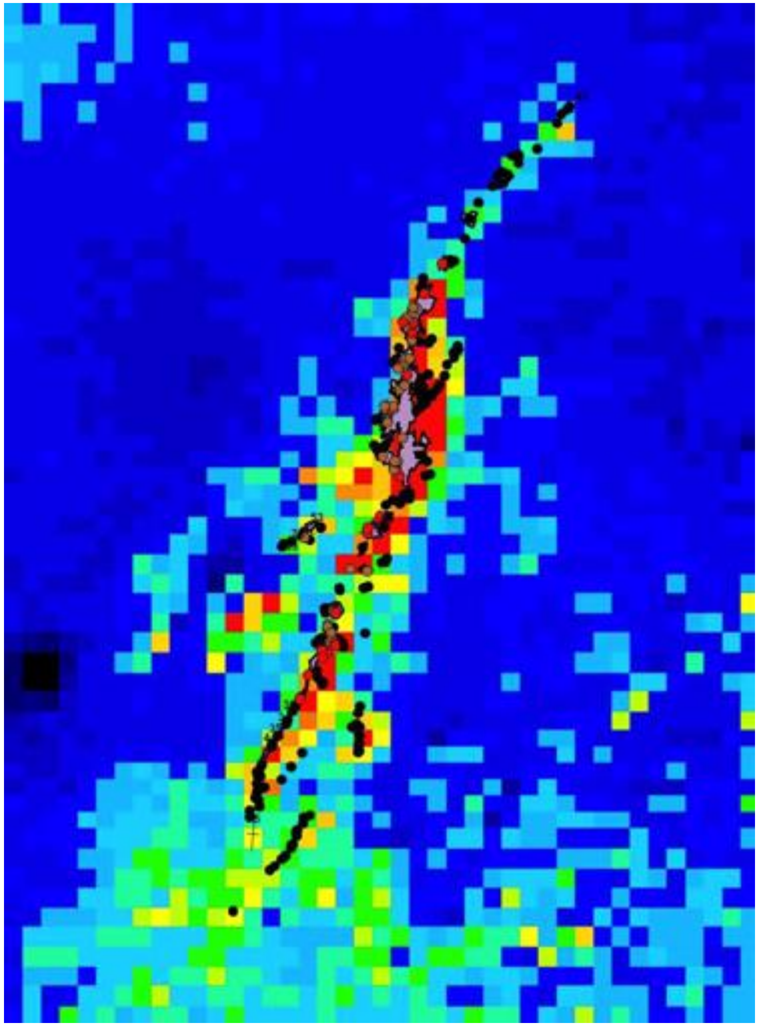
Near-Infrared

Thermal-Infrared

imagery can be used to identify surface expressions of geothermal resources



Example



Remote sensed thermal anomaly vs. warm ground/fumaroles location at Brady Hot Springs (USA) *(from Calvin et al., 2002)*

Example

Remote sensed sinter map at Brady Hot Springs (USA)
(from Calvin et al., 2002)

Conclusions

Thermal anomalies

+

Band center position

Band shape

Band width

CAN BE USED in geothermal exploration to identify resources and map minerals.

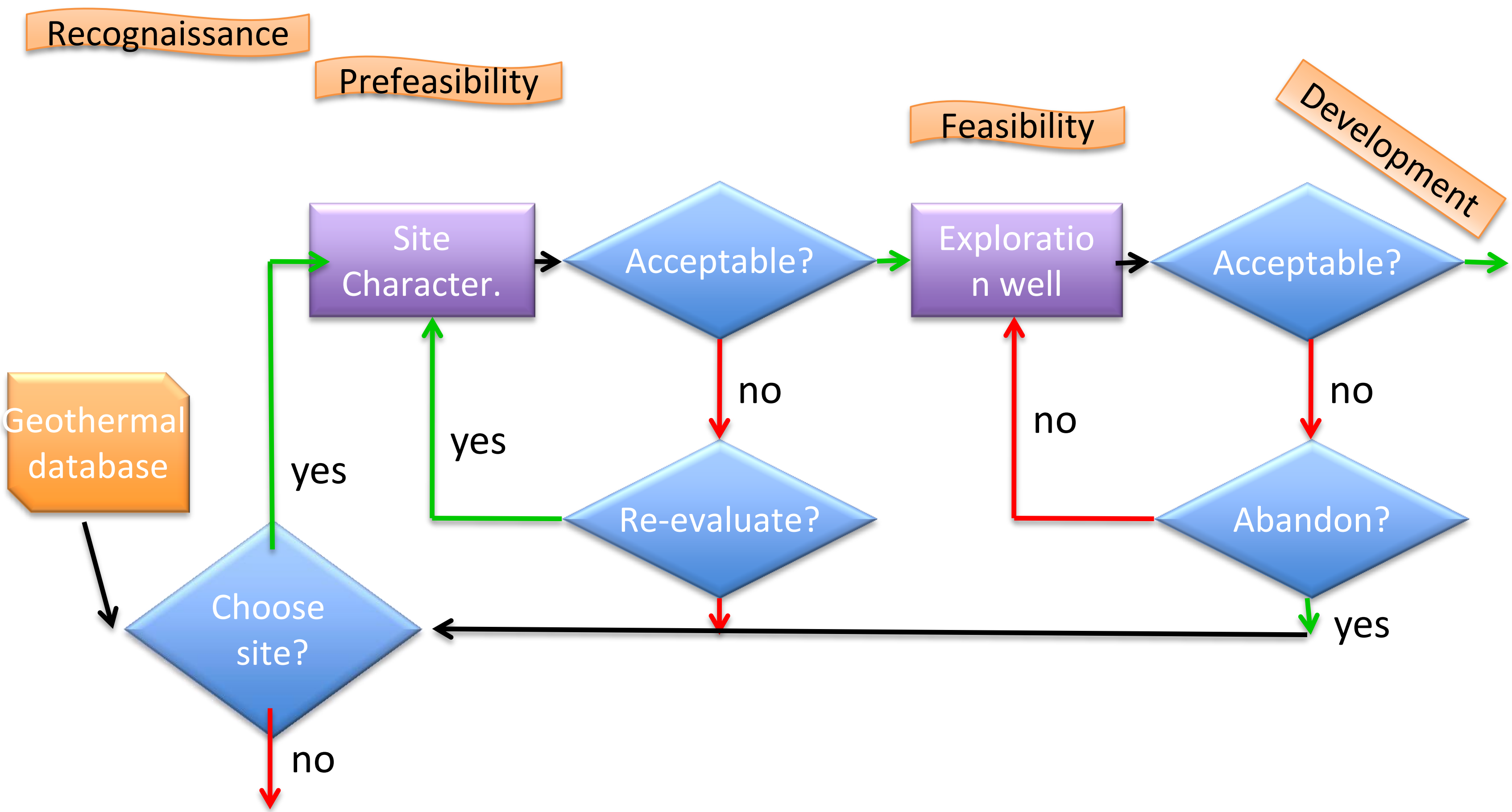
Basic methods:

a. Night/day imagery to identify thermal anomalies

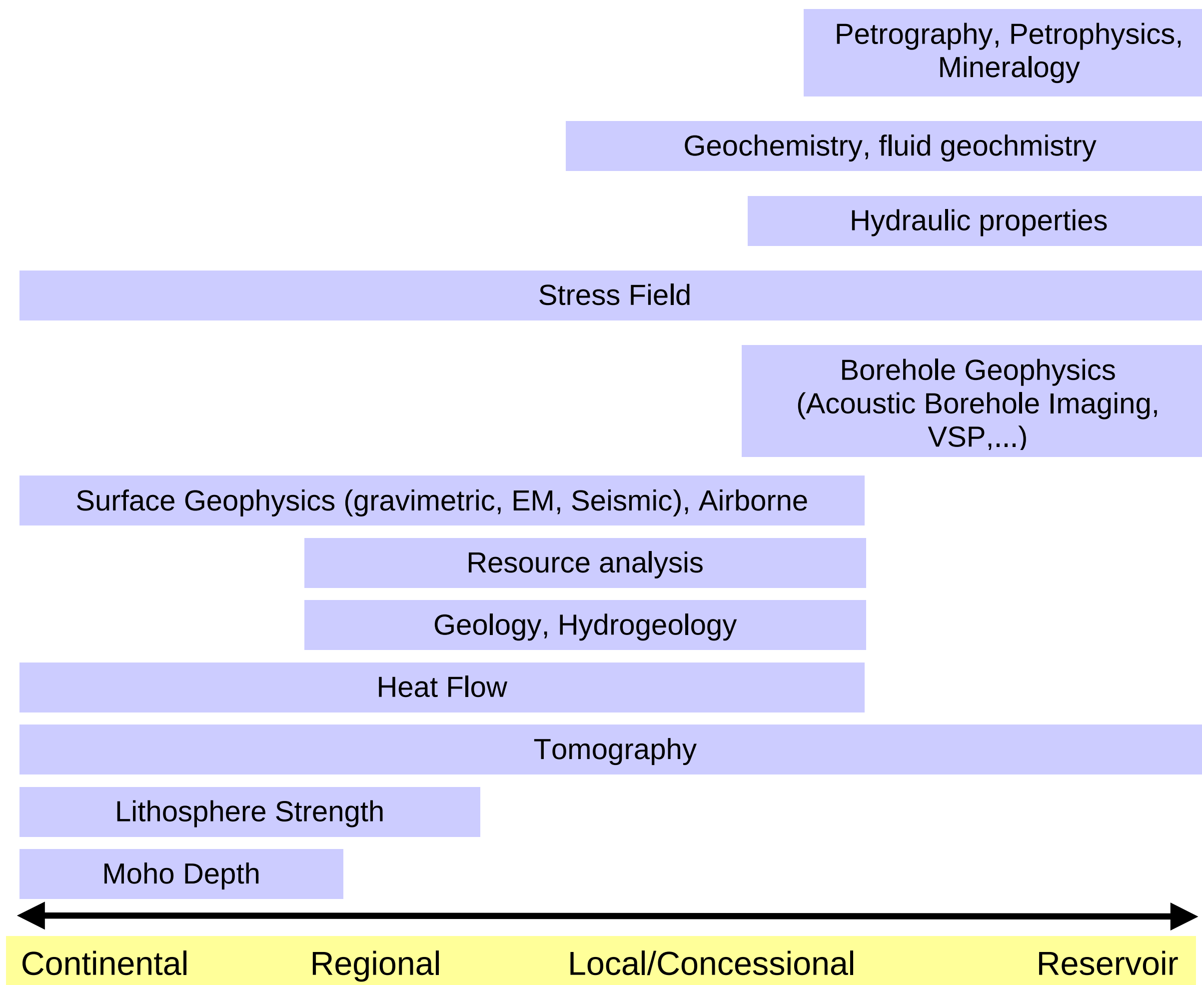
b. Spectral analysis to identify characteristic mineral signatures (absorption)

Resource assessment: targets and tools

Site screening:
Best practice to localize a geothermal site


Recognaissance
Prefeasibility
Feasibility
Development
Site Character.
Acceptable?
Exploratio n well
Acceptable?
Geothermal database
no
yes
yes
no
no
Re-evaluate?
Abandon?
Choose site?
yes
no

A scale dependent approach



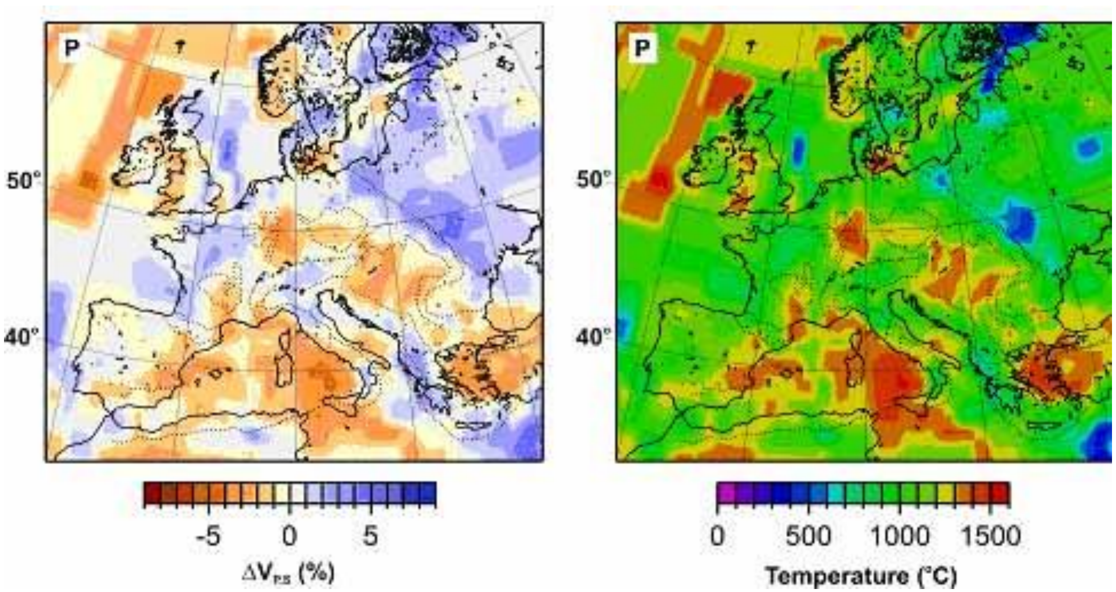
Continental scale E&I

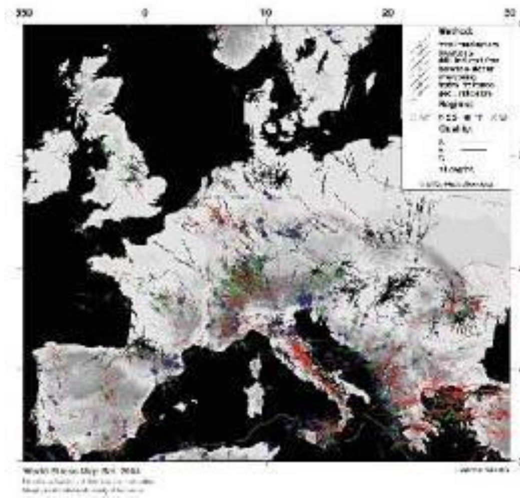
Identification of potentially interesting regions of interest is based on:

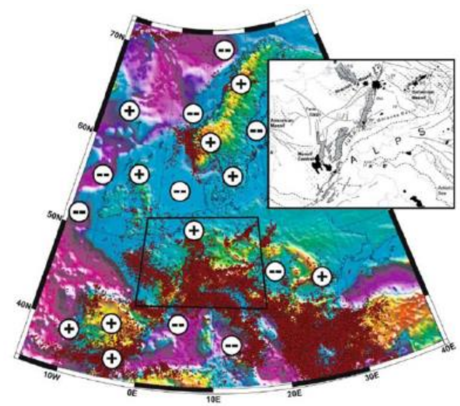
- Task: Identify thermal field at great depths (>10km)
  - from seismic tomography
  - from thermal modeling
- Task: Identify Deformation regime of the crust
  - from passive stretching models
  - Extensional regimes can be of high interest
- Task: Identify Stress regime (neo-tectonics)
  - from data 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

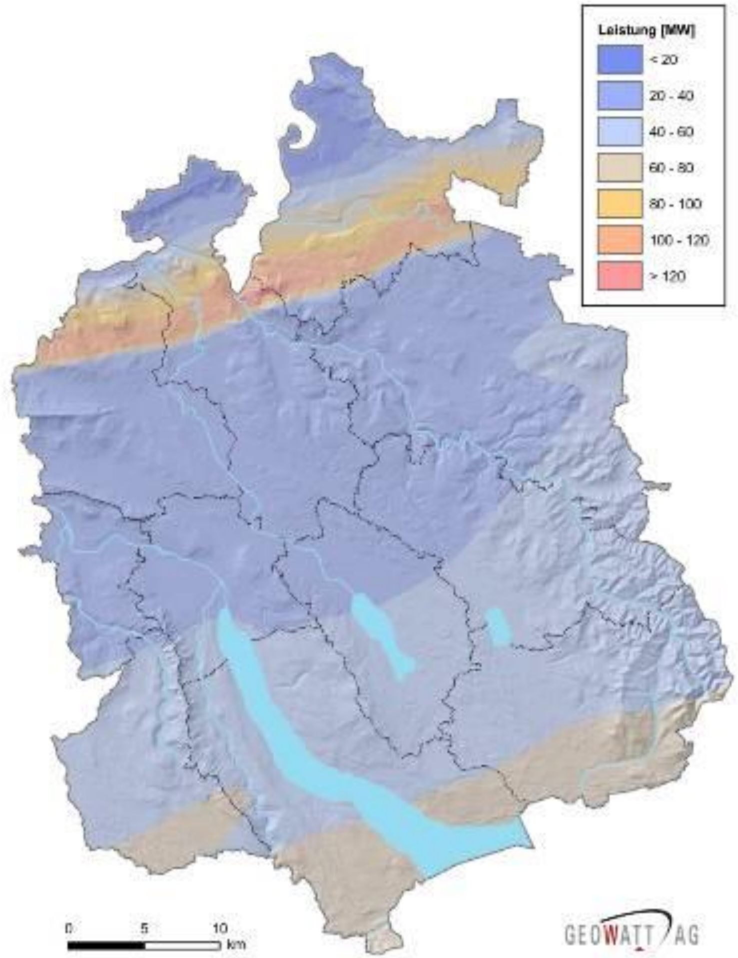
Concessional scale E&I

- 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
  - Economic viability of the system.

Task: Identify reservoirs

Concessional scale E&I

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



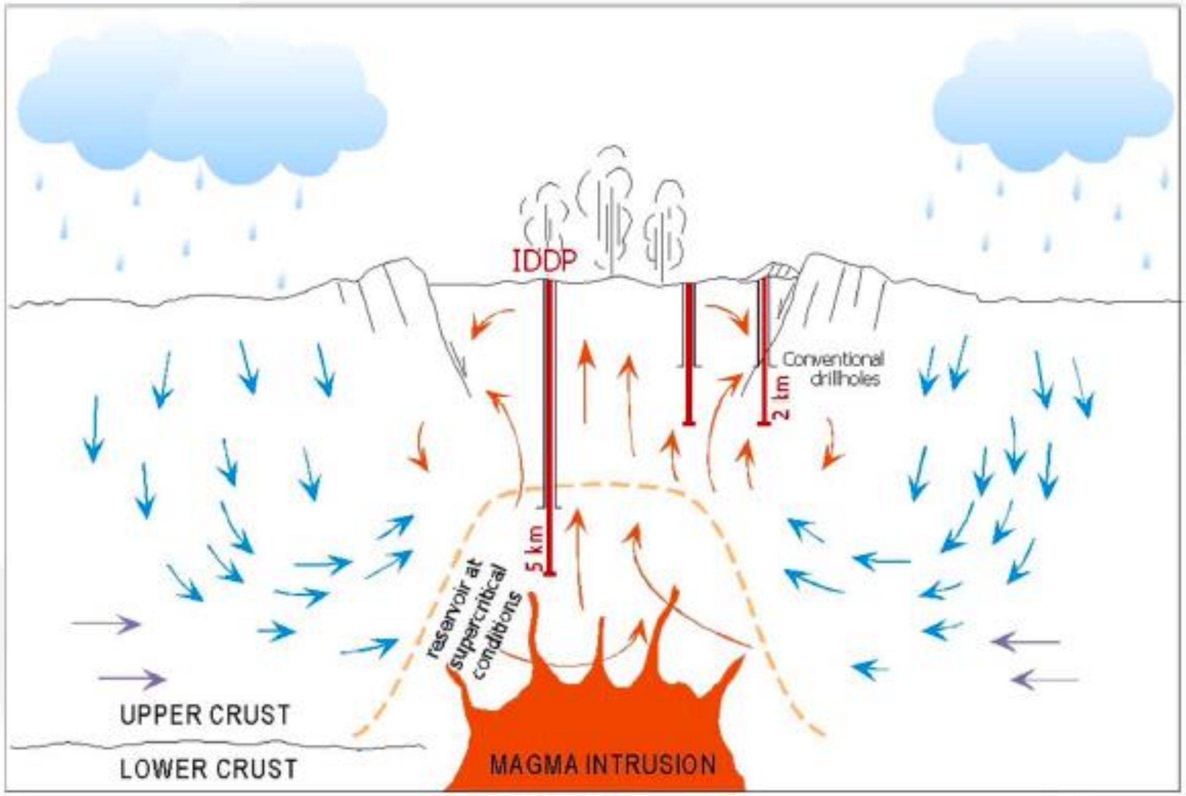
From Kohl et al., ENGINE Mid-Term conference

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.

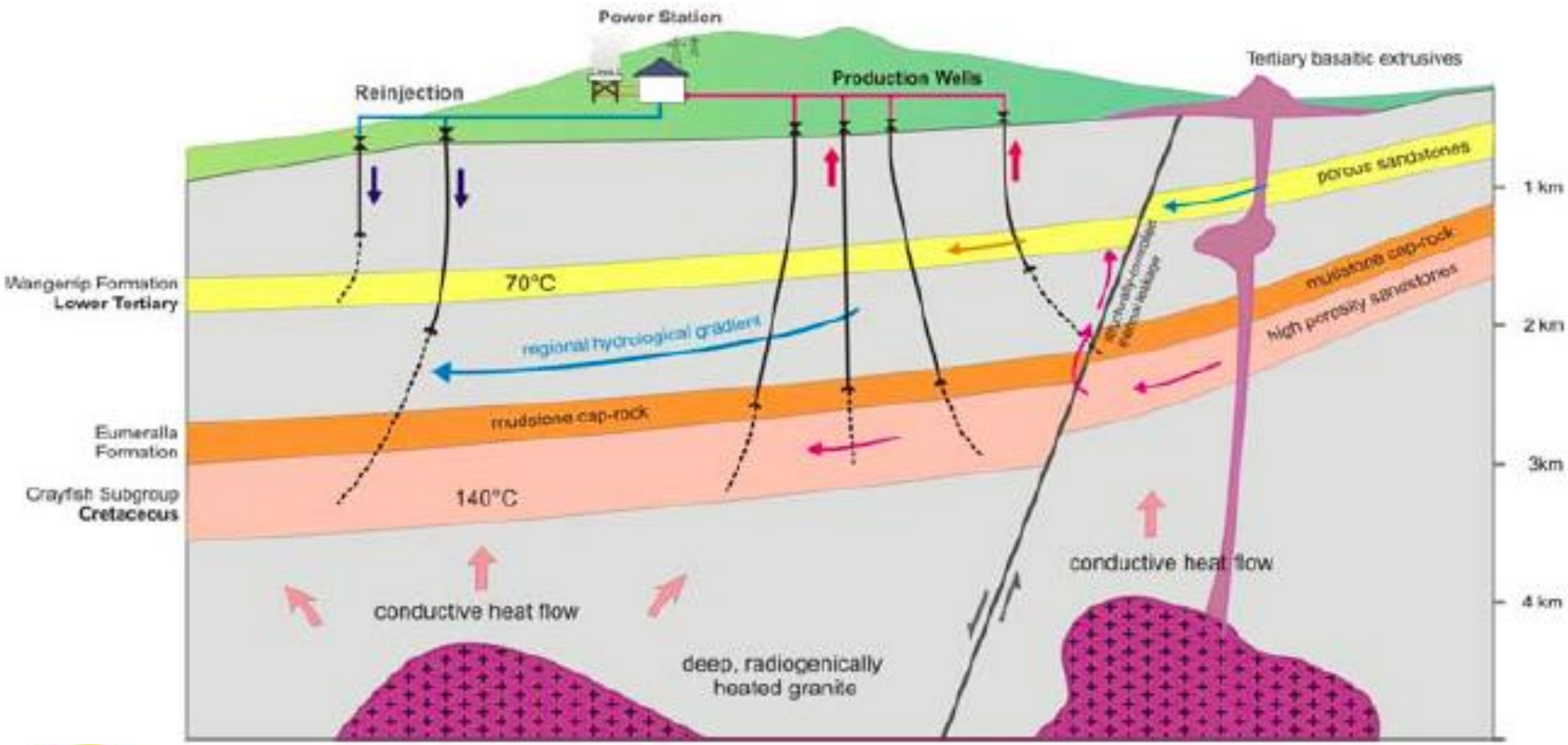
Task: Identify drilling targets

Conceptual model



The most important element of an analysis to target a geothermal well or assess resource capacity is a resource conceptual model consistent with the available information.

Conceptual model



Schematic hydrogeological/geothermal production model

hotrock

Assessment Report, 2009

Conceptual model

The first step in geothermal resource assessment is usually based on either an analogy or an assumed correlation (anomaly hunting, following Cummings, 2009)

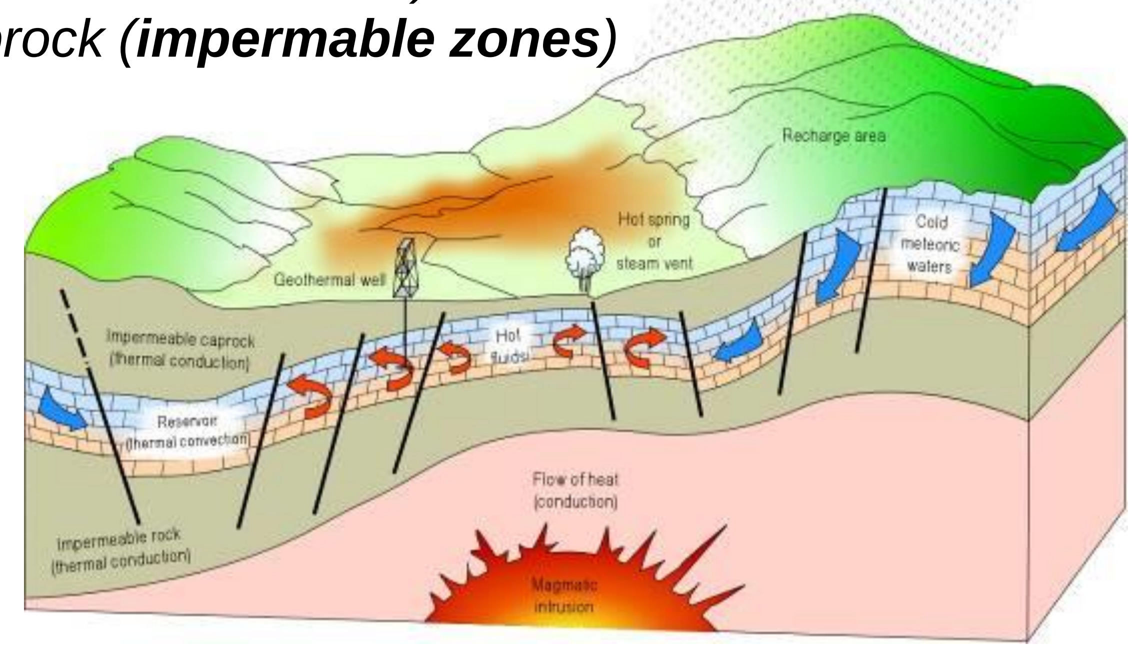
In the second step a number of roughly coincident anomalies are considered together (anomaly stacking, following Cummings, 2009)

A conceptual model approach integrates data sets across all disciplines in the context of a physical model and constrains geothermal target parameters

Hydrothermal systems

Elements of a hydrothermal geothermal system:

*a heat source (**thermal modelling**)*
*a reservoir (**permeable zones**)*
a fluid, which is the carrier that transfers the heat
*a recharge area (**upflow and outflow**)*
*an impermeable caprock (**impermable zones**)*



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Final Report
Geothermal Exploration in Montserrat, Caribbean

Prepared for

Minister of Communications and Works
Government of Montserrat, Caribbean

January 2010

By
EGS Inc.
Santa Rosa, California

Contents

FINAL REPORT: GEOTHERMAL EXPLORATION IN MONTSERRAT, CARIBBEAN

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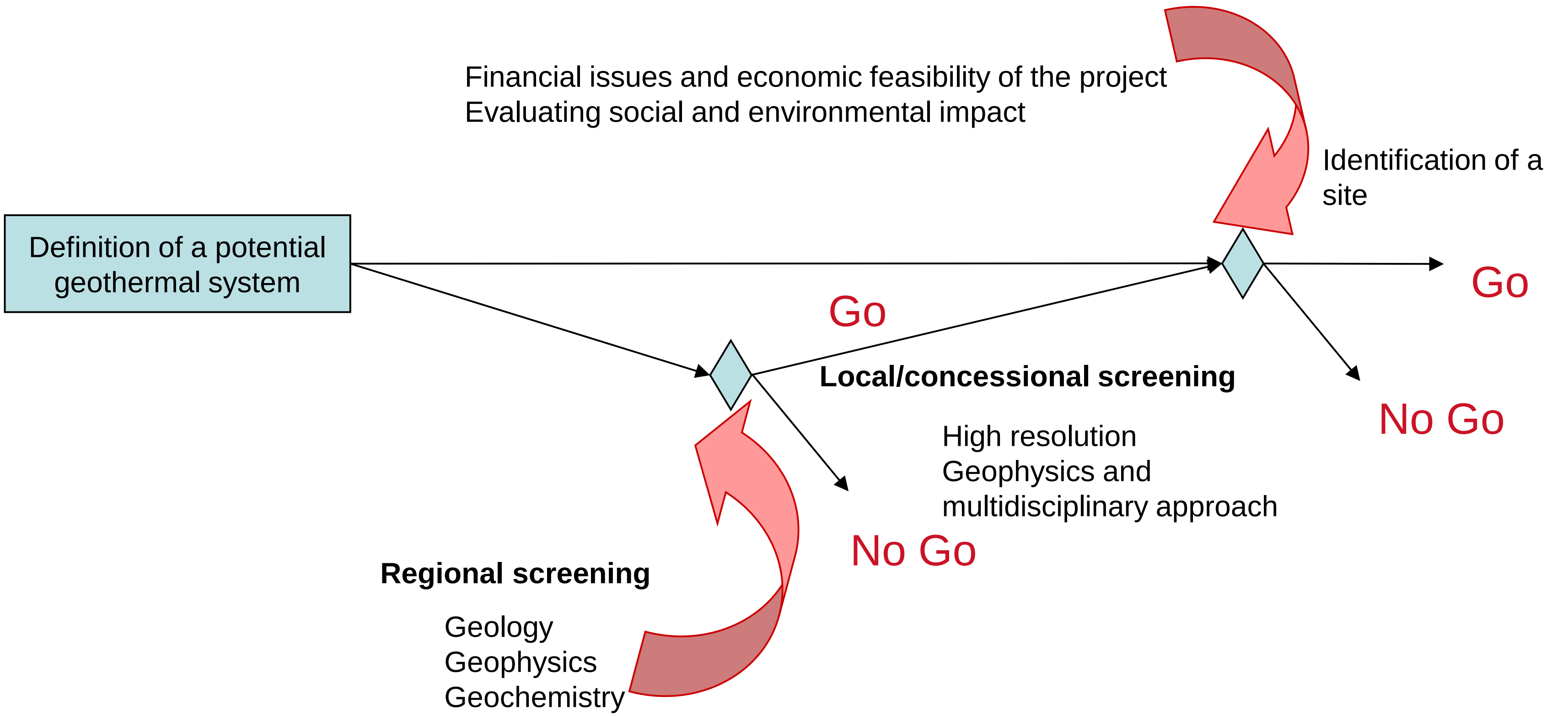
EGS

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



Geothermal Potential Assessment Goals

- Assess nature and extension of the geothermal system
- Assess reservoir porosity, permeability and recharge
- Evaluate fluid characteristics
- Assess energy production capacity (surf. exploration + wells)

Geothermal Potential Assessment Goals

- Integrate available data & produce best conceptual model
- Evaluate the energy production potential, through Monte Carlo model
- Model the geothermal system to simulate production response and to estimate the system energy production potential
- Estimate effects of reinjection by numerical modelling
- Evaluate the production characteristics of reservoir fluids based on chemical characteristics and prevailing reservoir conditions.

…Rendering Geological Risk structure

- Exploration and Drilling is predominant in the early exploration phases
- Reservoir state and response to production is preliminary new and unknown
- main Reservoir responses are hydraulic welltests

Geological Risk Factors

- **Exploration Factors**
  - Resource Existence
  - Reservoir Temperature
  - Reservoir Size
  - Reservoir Permeability
  - Dissolved Gases
  - Fluid Scaling & Corrosion
  - Fluid or Steam Acidity
- **Drilling**
  - Unstable Formations
  - Unexpected Geology
  - Technical Problems
  - Equipment Failure Operator Failure
- **Reservoir Decline**
  - Pressure Drawdown low flow rate
  - Temperature decline
  - - inadequate fluid composition
    - long time changes of fluid
    - current gas dissolution or scaling
- **Geological Hazard**
  - Volcanic Risk
  - Seismic Risk
  - Hydrothermal eruption
  - Landslides
  - Flooding

Resource assessment: targets and tools

Case Studies:
Examples from known geothermal systems

Medium enthalpy geothermal systems in carbonate reservoirs, the Western Sicily example

DOMENICO MONTANARI(1), G. BERTINI(1),S. BOTTEGHI(1), G. CAIELLI (3), F. CAIOZZI(1), R. CATALANO(2), R. DE FRANCO(3), M. DOVERI(1), G. GIANELLI(1), G. GOLA(1), A. MANZELLA(1), A. MINISSALE(1), G. MONTEGROSSI(1), S. MONTELEONE(2), G. NORINI(3), G. TRANCHIDA(4), E. TRUMPY(1)

[1] Institute of Geosciences and Earth Resources, National Research Council of Italy (CNR), Via Moruzzi 1, 56124 Pisa, Italy

[2] Dipartimento Scienze della Terra e del Mare, University of Palermo, Via Archirafi 2°, 90100 Palermo, Italy

[3] Institute for the Dynamics of Environmental Processes, National Research Council of Italy (CNR), Via Mario Bianco, 9 - 20131 Milano, Italy

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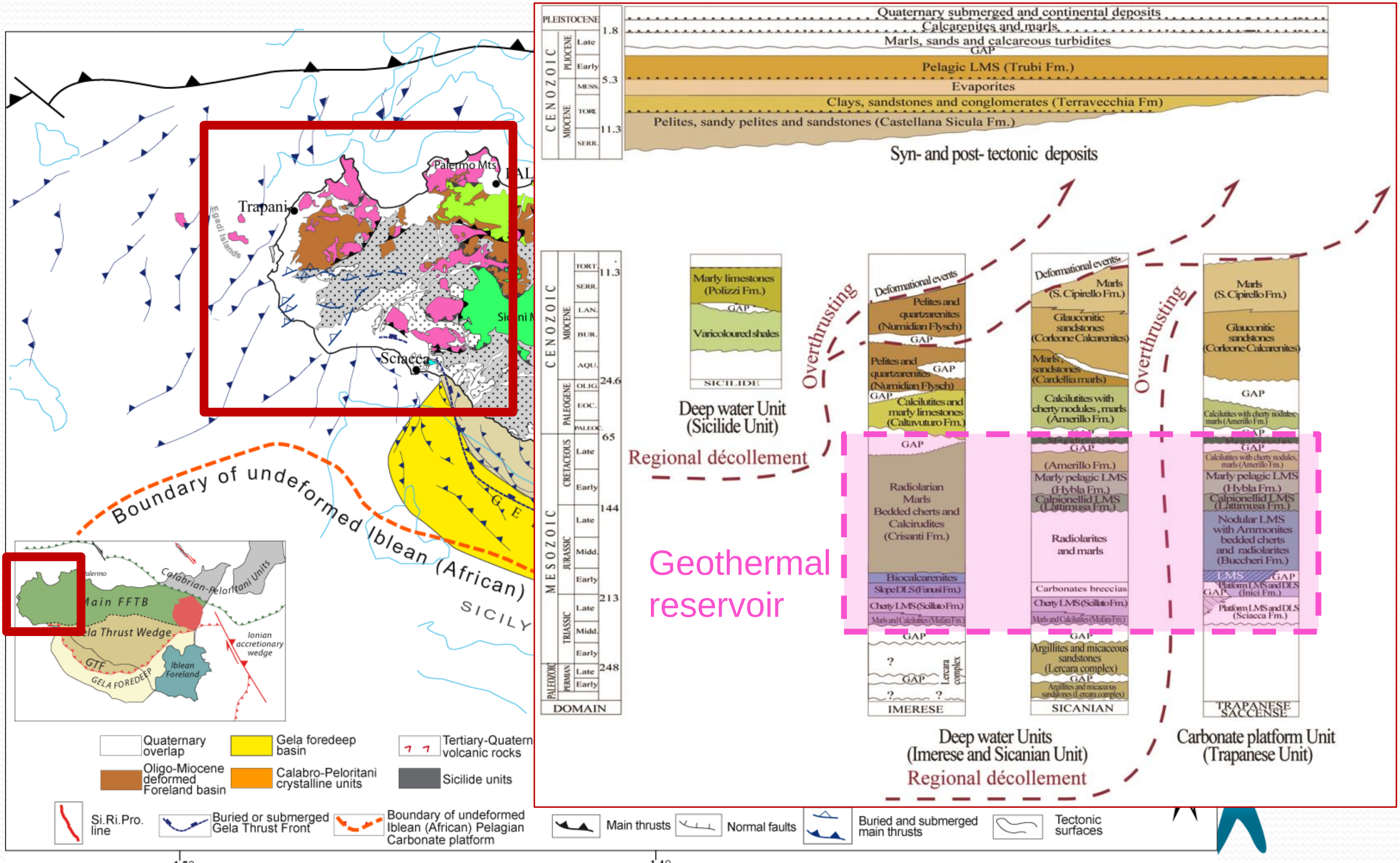
Resource Assessment – Italy [HS1]

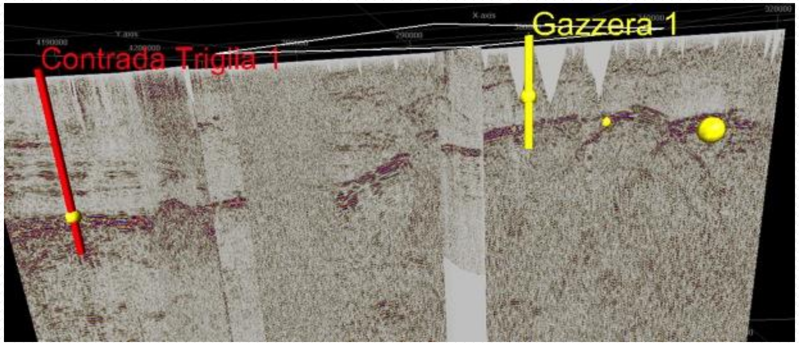
Regional geological setting

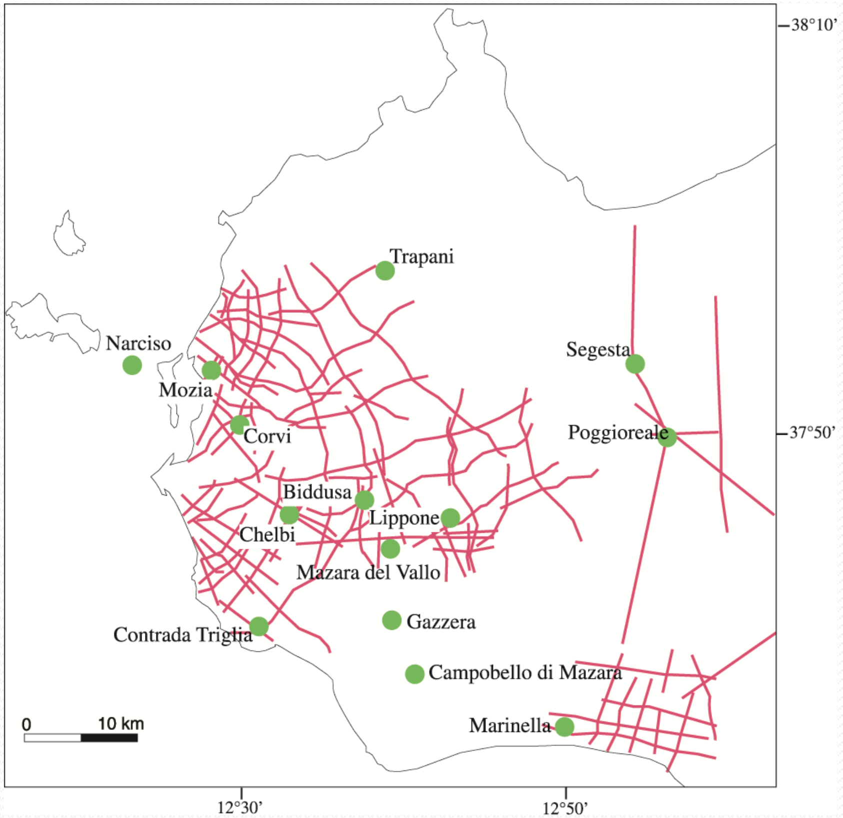


Available data at depth

Oil exploration in western Sicily started in the late 1950s when several exploration wells were drilled, and continued with the acquisition of many seismic reflection profiles and the drilling of new wells in the1980s

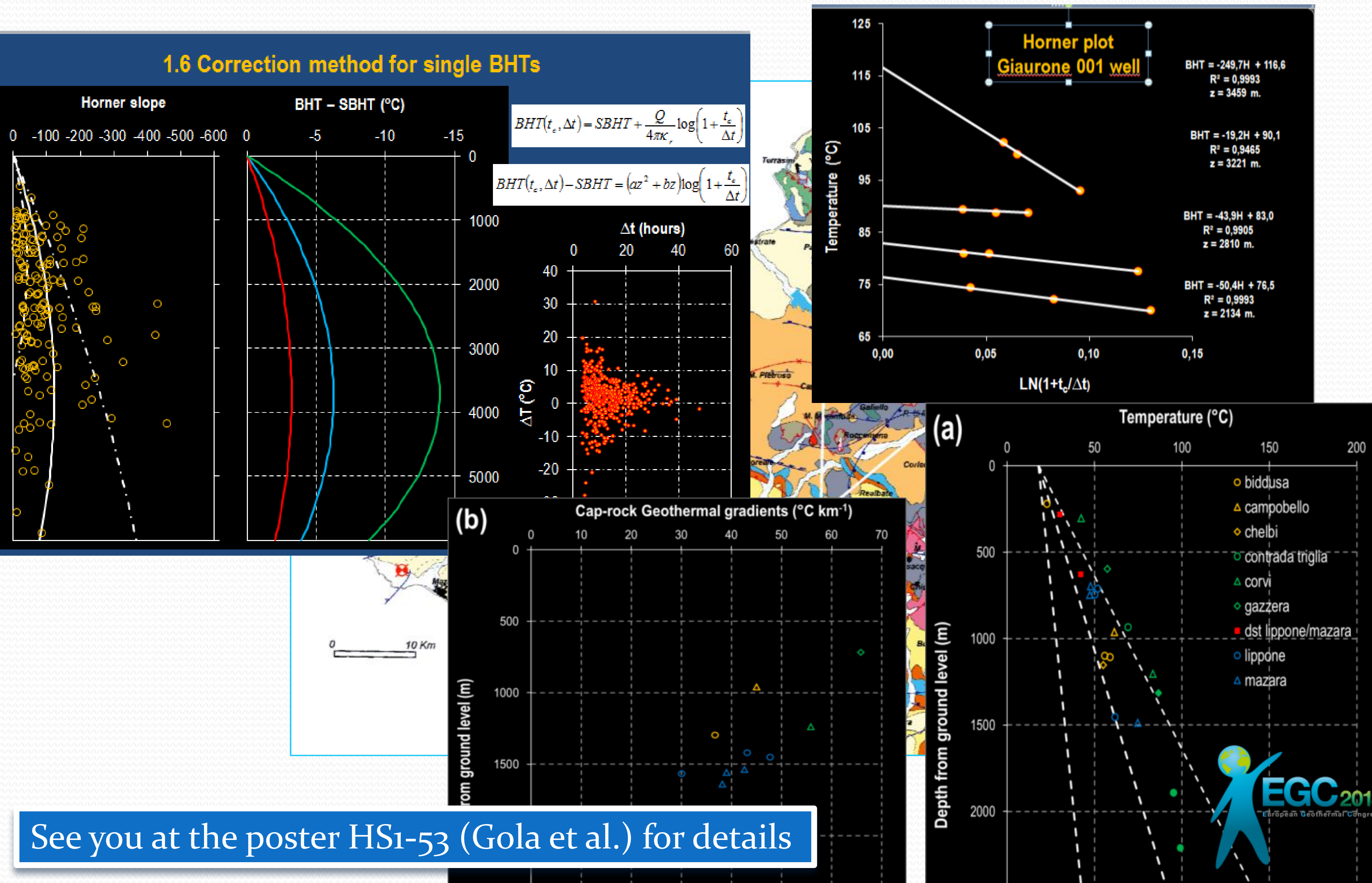
Although it has not produced completely satisfactory results for oil industry, this hydrocarbon exploration provided a great amount of data, resulting very suitable for geothermal resource assessment.





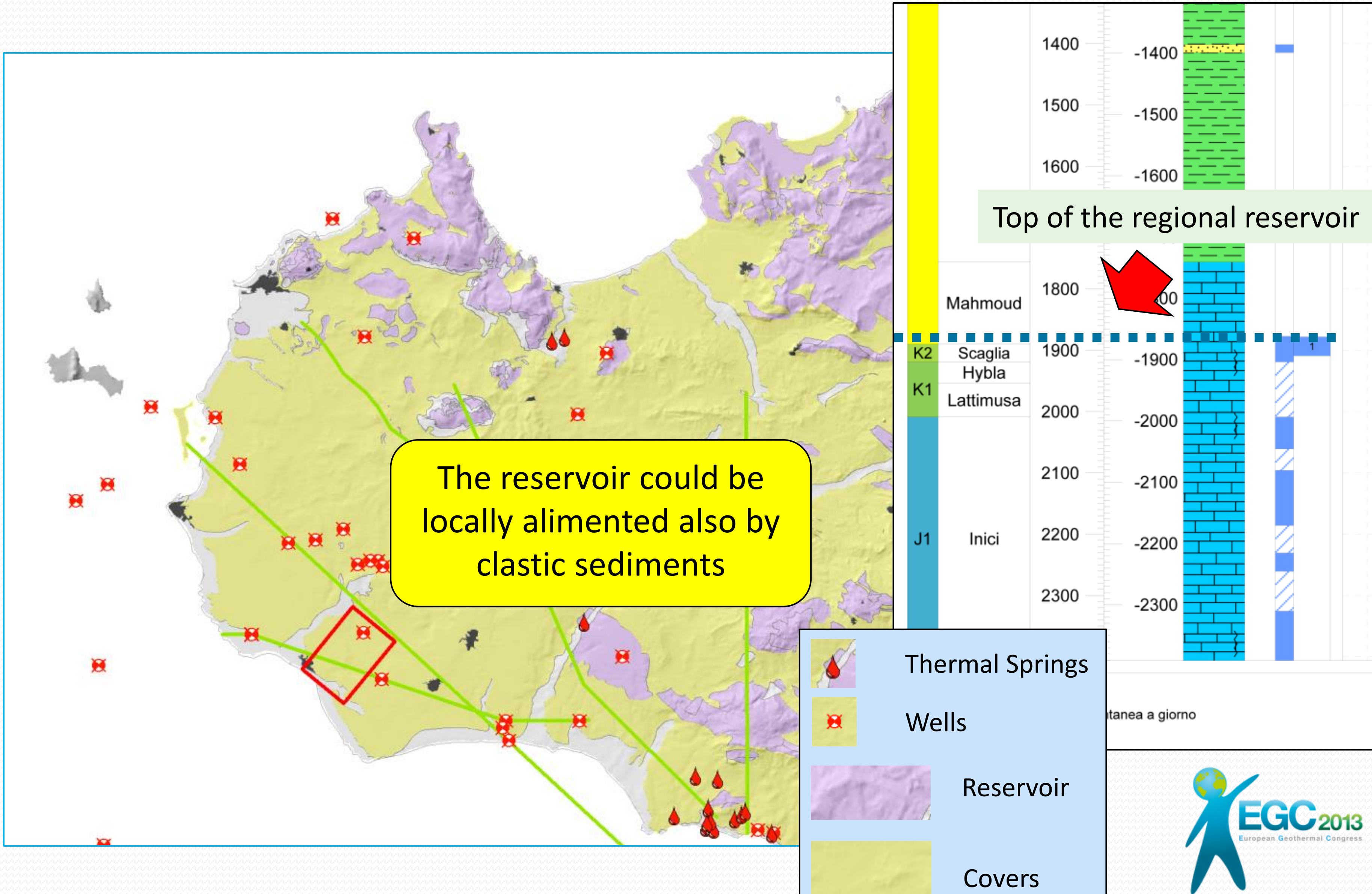
Location map of wells and seismic reflection profile grid acquired by AGIP (1979–1987).

Surface geology and well-Log data analysis

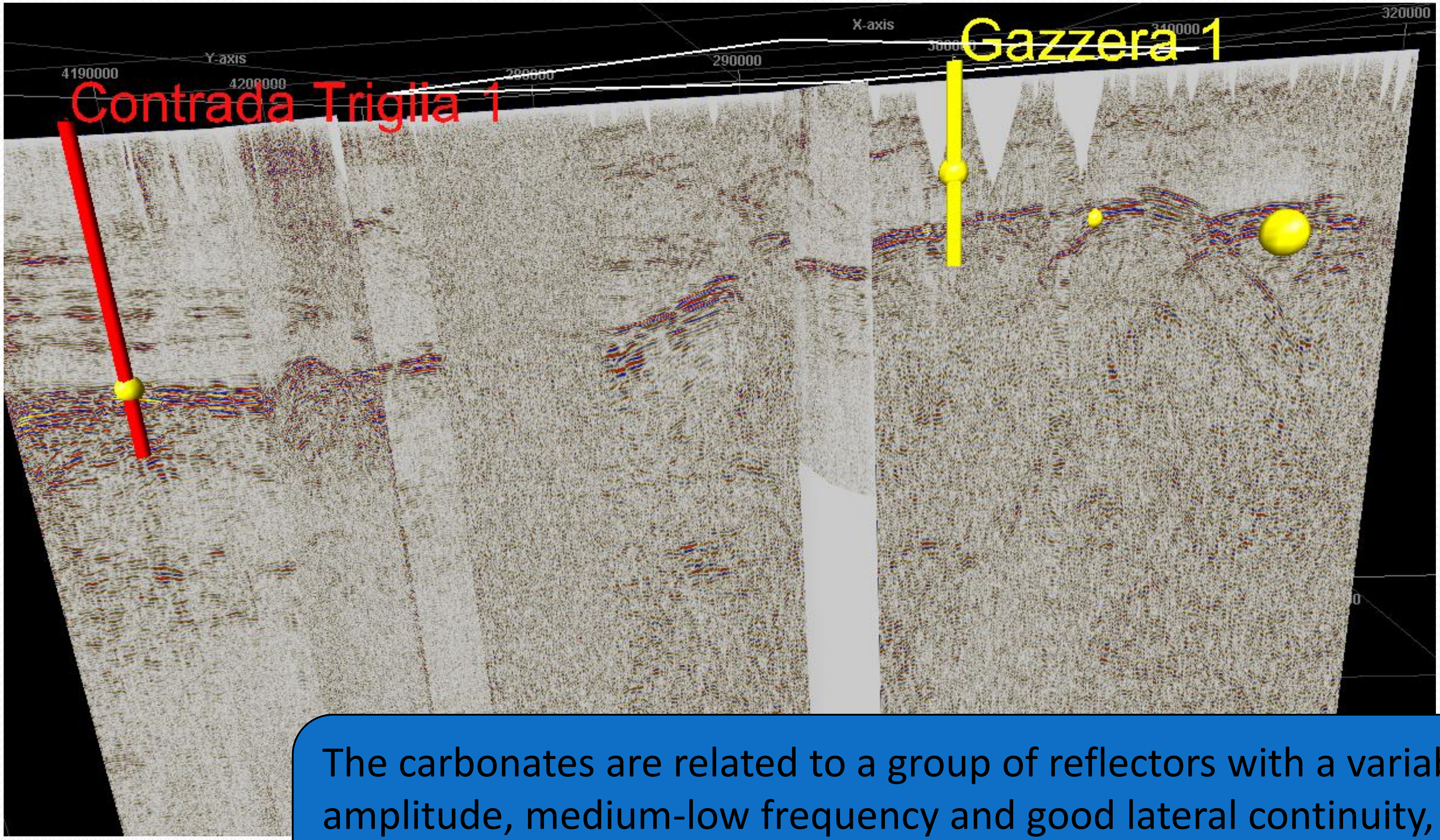


See you at the poster HS1-53 (Gola et al.) for details

finition of the potential geothermal reservoir



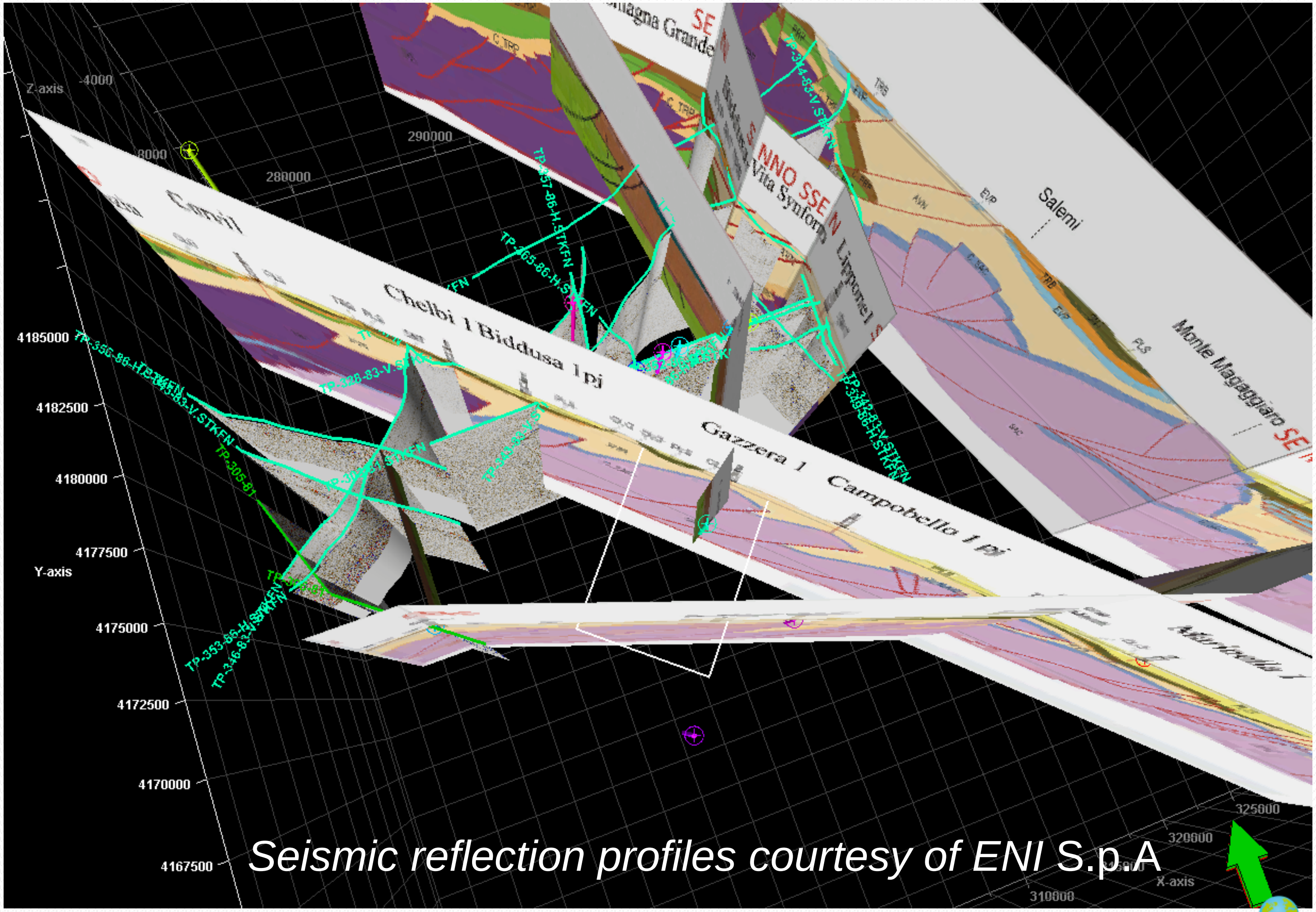
Seismic data



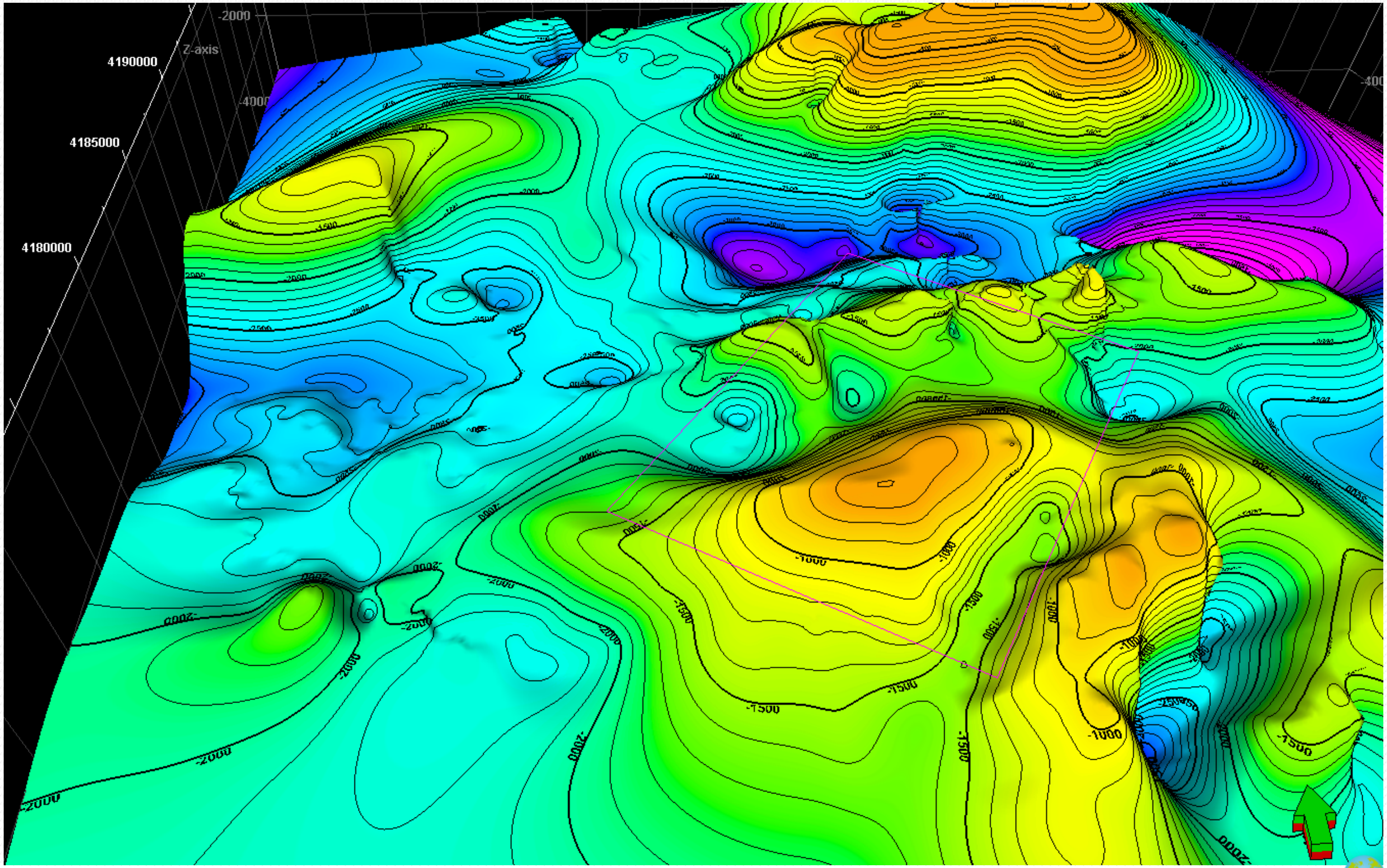
The carbonates are related to a group of reflectors with a variable amplitude, medium-low frequency and good lateral continuity, alternating with transparent zones, **topped by a high amplitude, good lateral continuity reflector**

Seismic profiles were kindly provided by ENI s.p.a

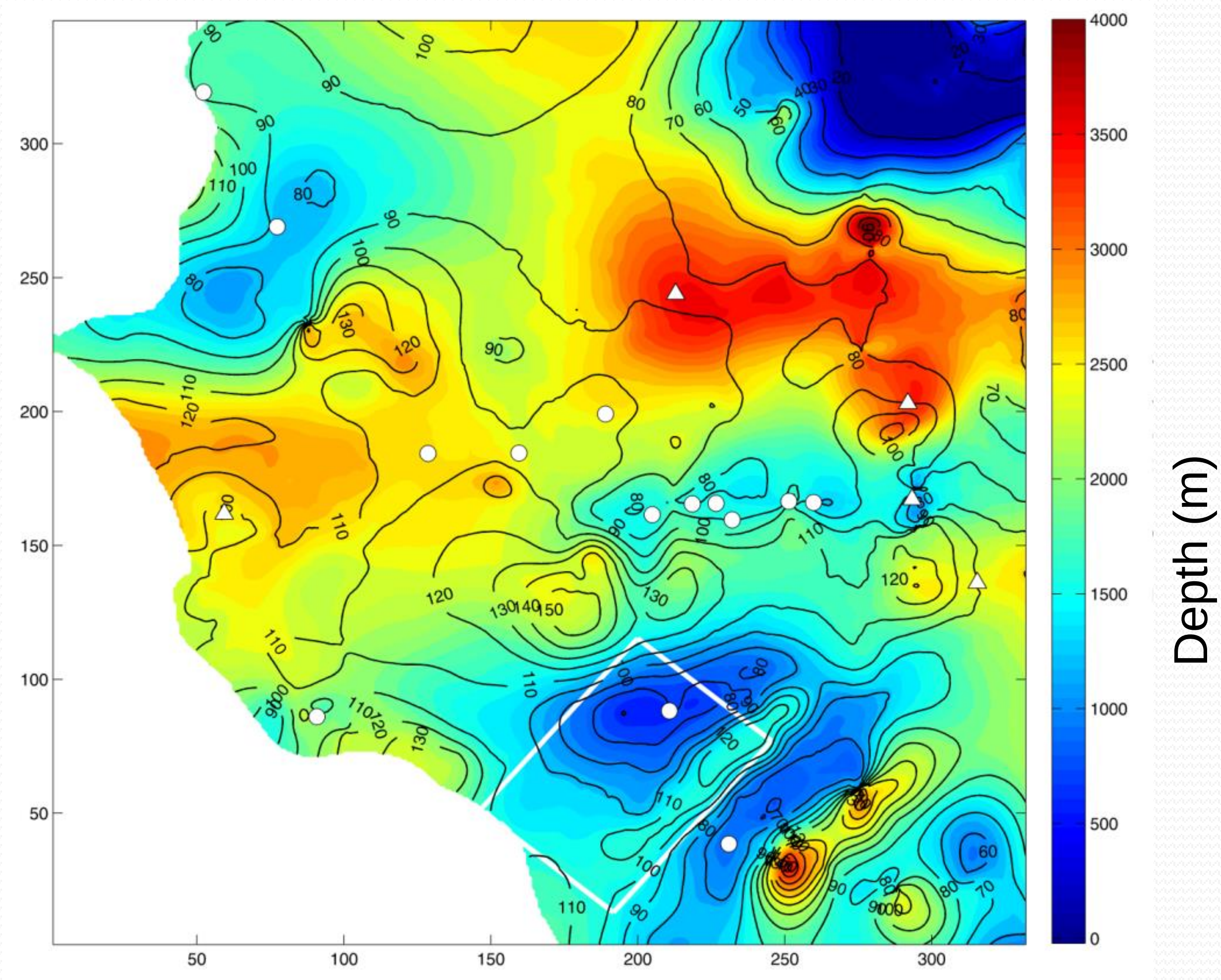
3D geological model



Top of the carbonate reservoir

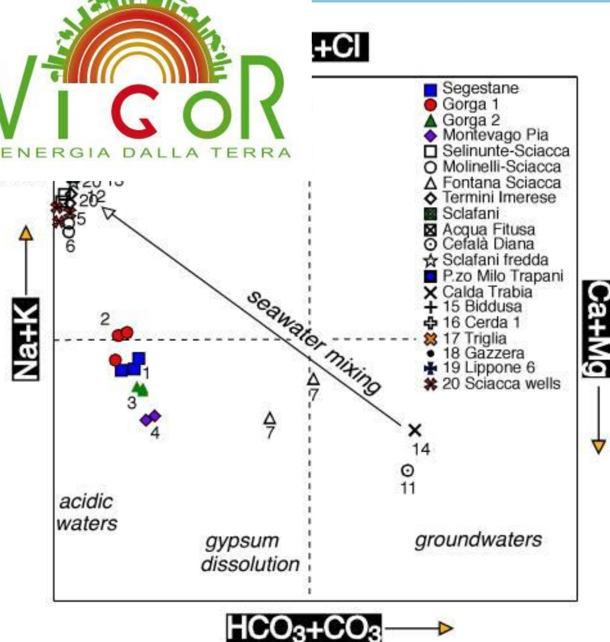


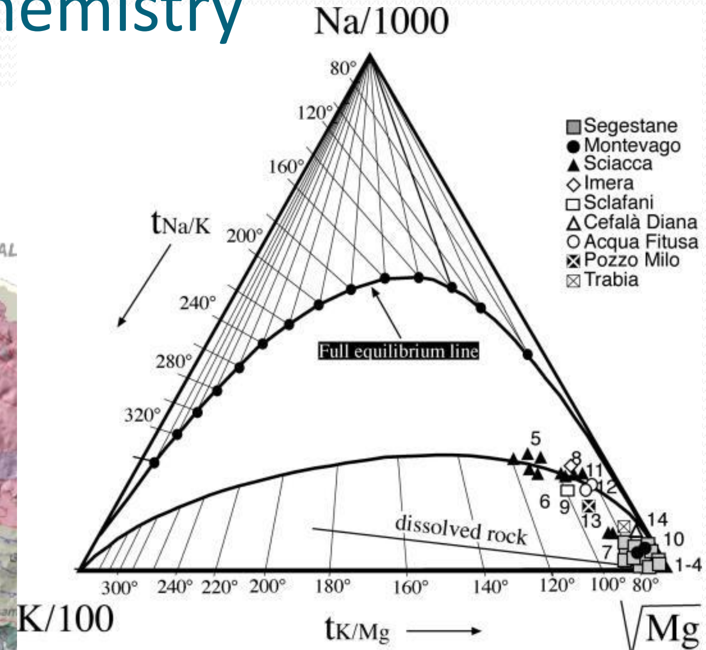
T map at the top of the reservoir

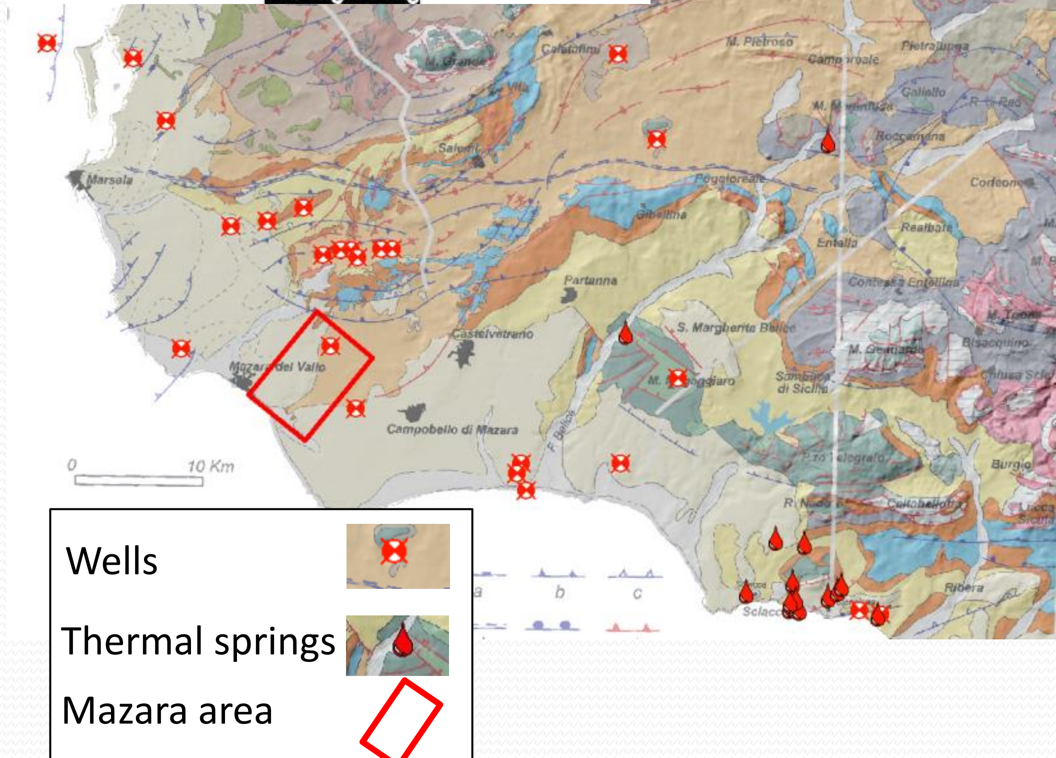


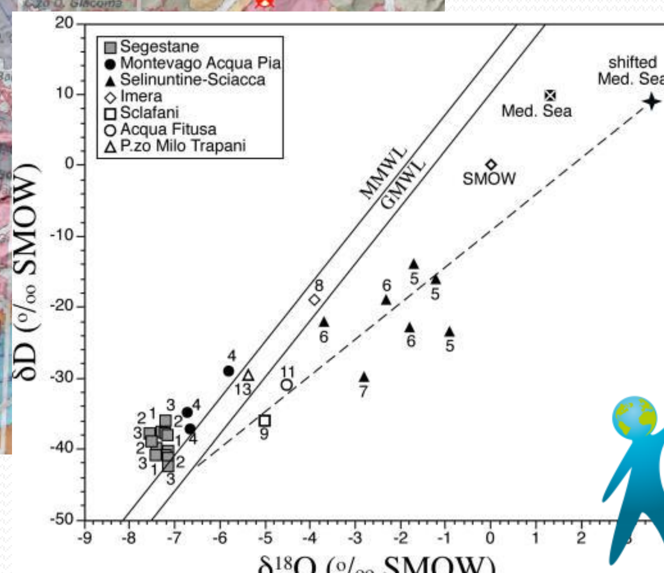
See you at the poster HS1-53 (Gola et al.) for details

Fluid geochemistry





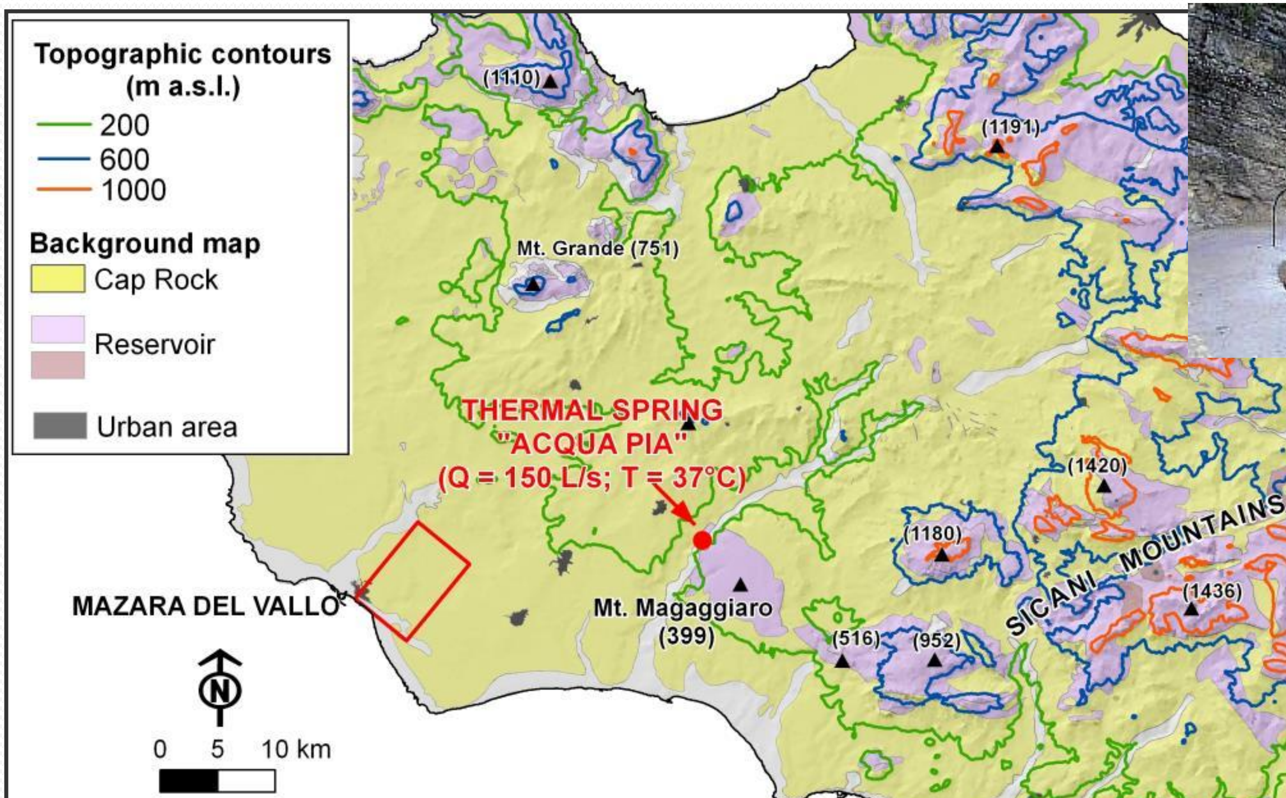




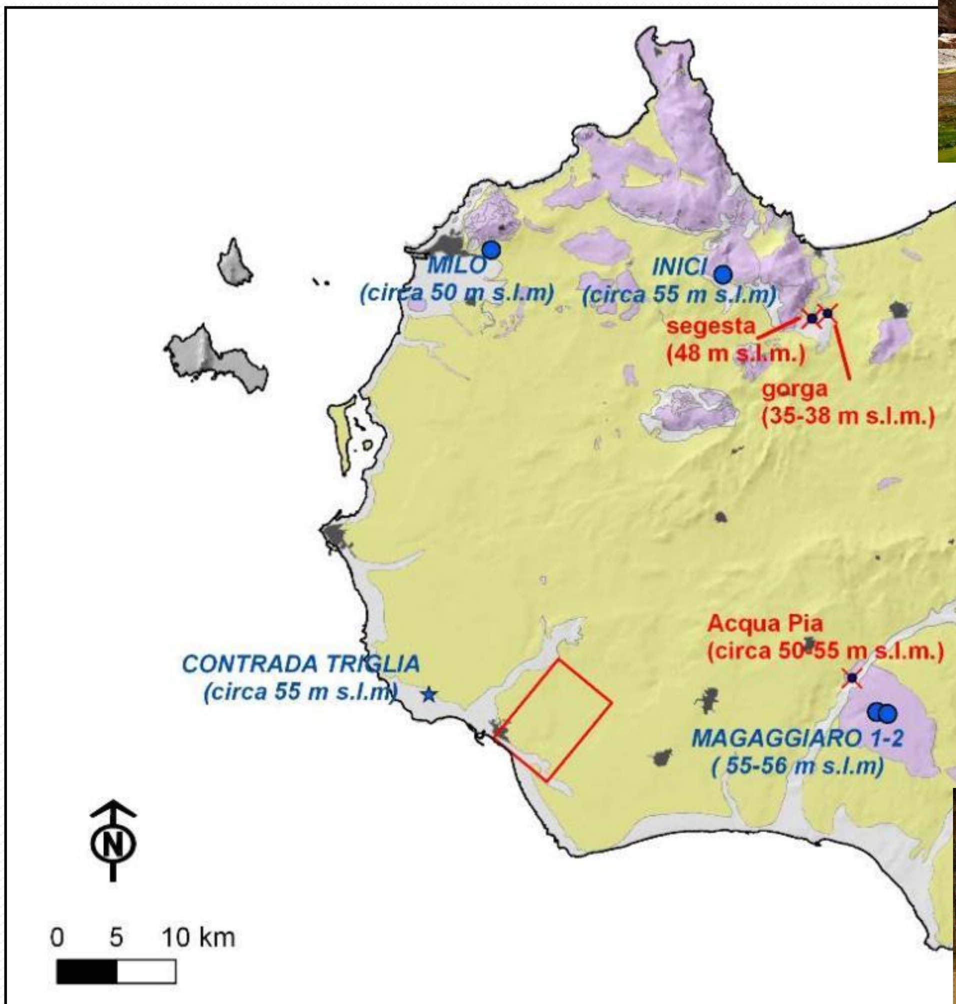
Isotopic evidences of regional circulation systems

$\delta^{18}O$ of “Acqua Pia” thermal spring is about -6.7 ‰.
Based on the local “$\delta^{18}O$‰ – altitude” relationship such value indicate an **average altitude of infiltration higher than 600 m a.s.l.**

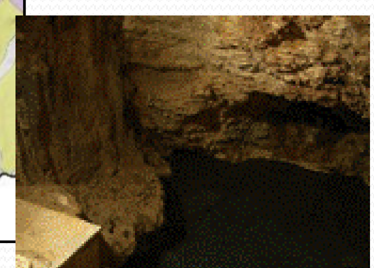
Moreover the tritium value of 0.0 TU (err. ± 0.4) analyzed by Fancelli et al. (1991) indicates an **average residence time of groundwater longer than 50 years**



Water levels

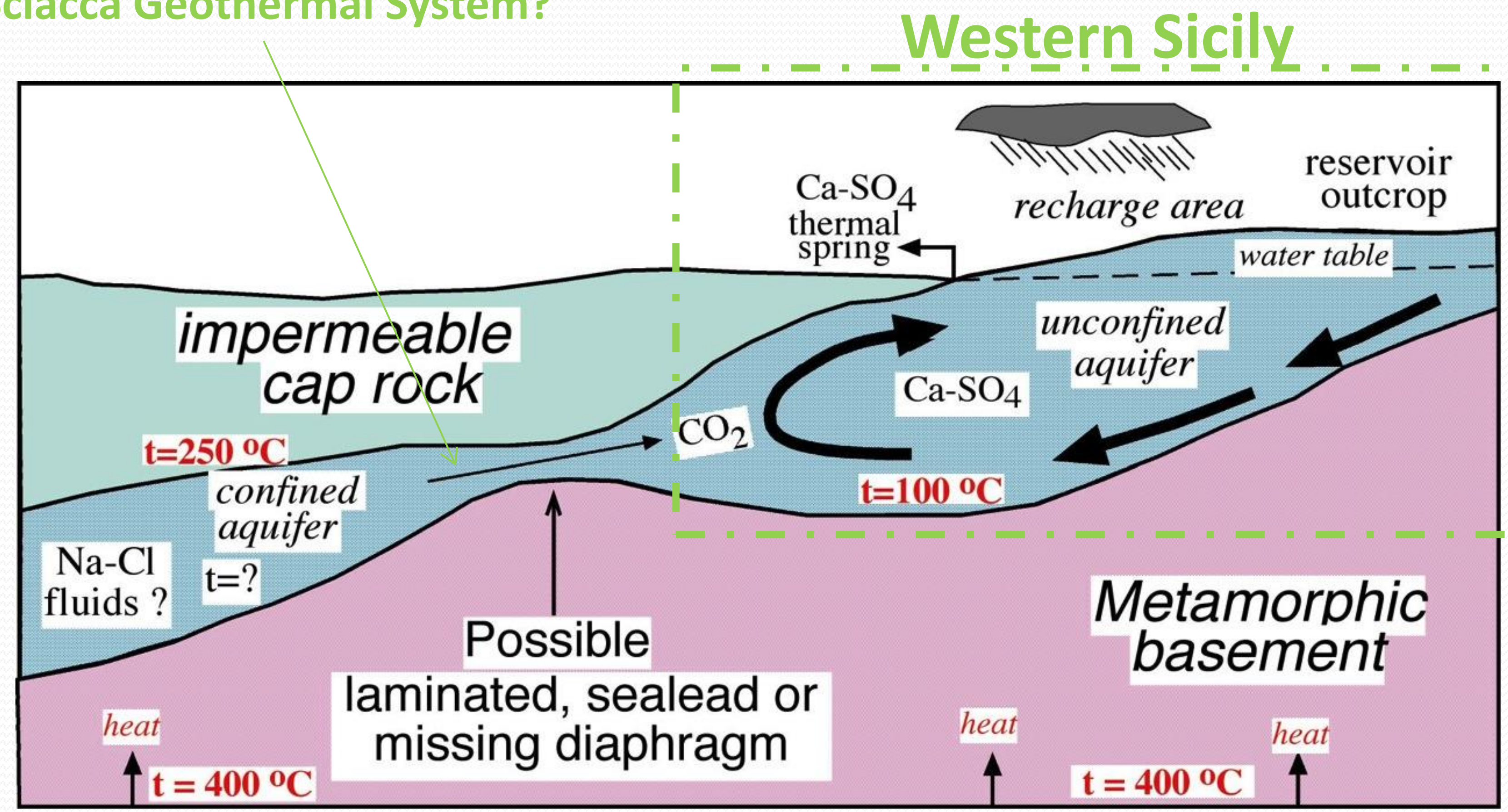


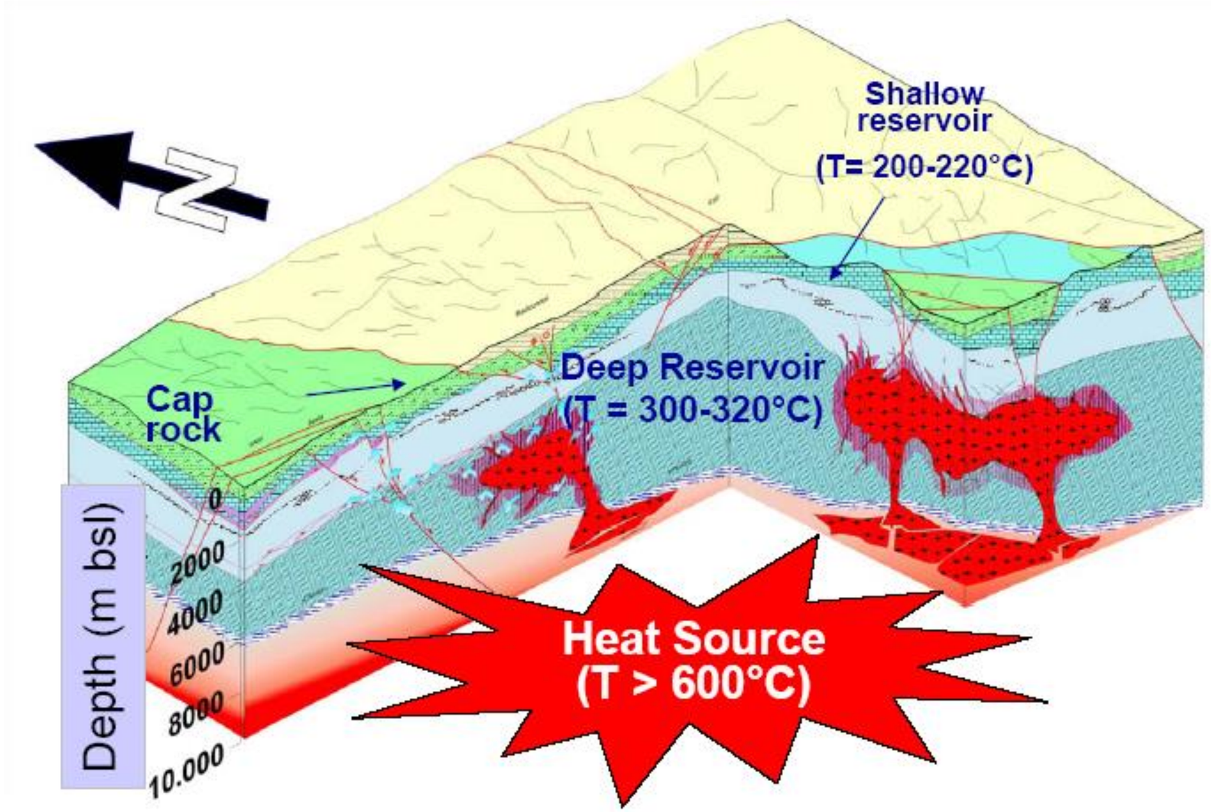
Thermal springs altitudes together with the water levels, achieved from direct measurements into the wells or by layer pressures data, highlight that the **hydraulic head** values of thermal groundwater cover a limited range between 40 and 60 m a.s.l.



Conceptual model

Sciacca Geothermal System?





Courtesy of Enel

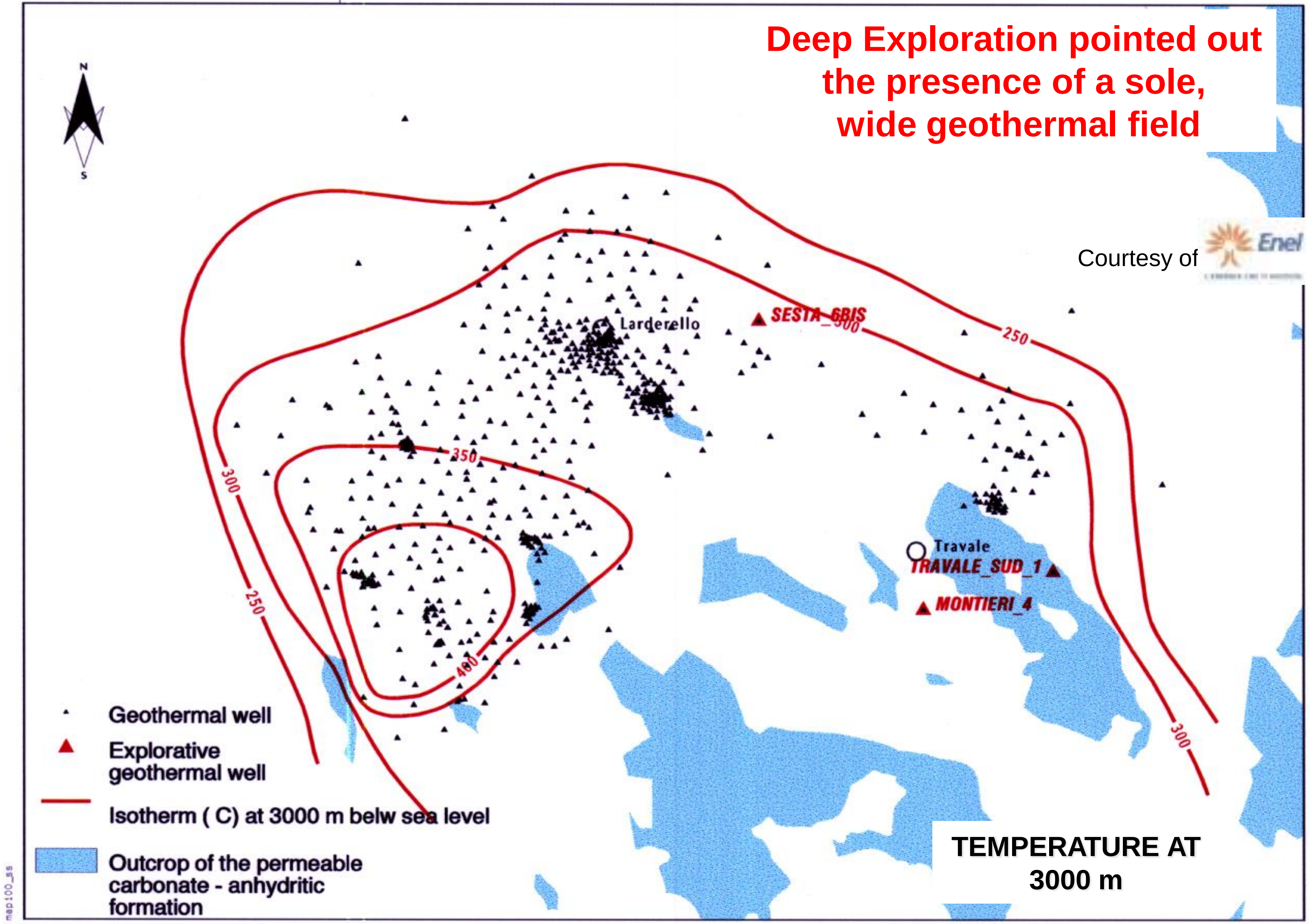
Very high temperatures characterize the two geothermal reservoirs in Larderello.

The geothermal exploration targets are mainly located in metamorphic and granitic rocks down to 4700 m depth

Shallow and deep exploration of the Larderello-Travale field

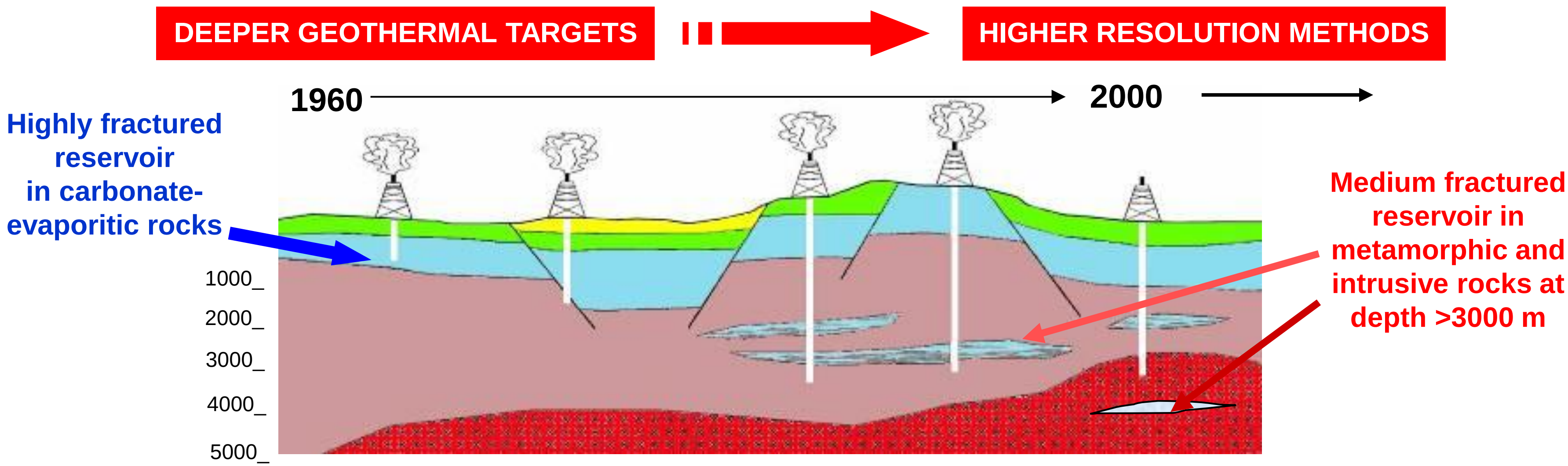
Deep Exploration pointed out the presence of a sole, wide geothermal field

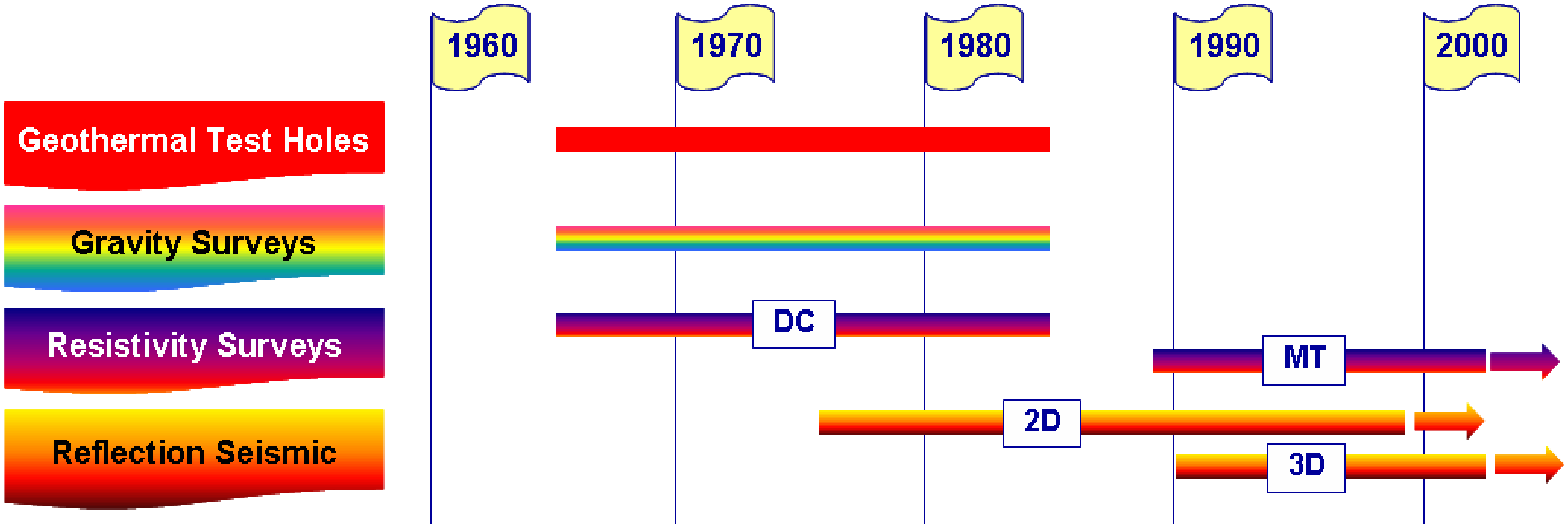
Courtesy of Enel



TEMPERATURE AT 3000 m

Geophysical Exploration Methods – Time evolution

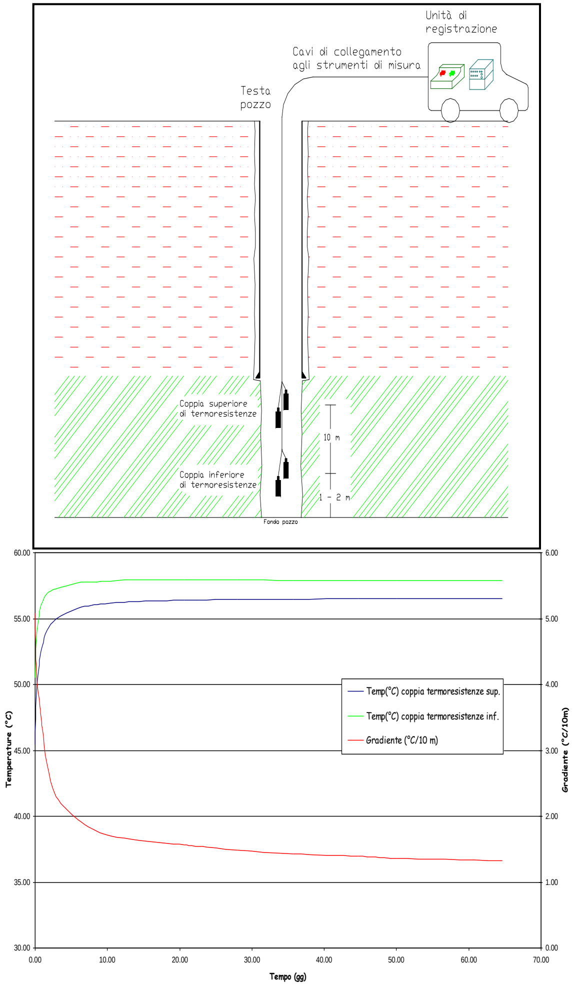




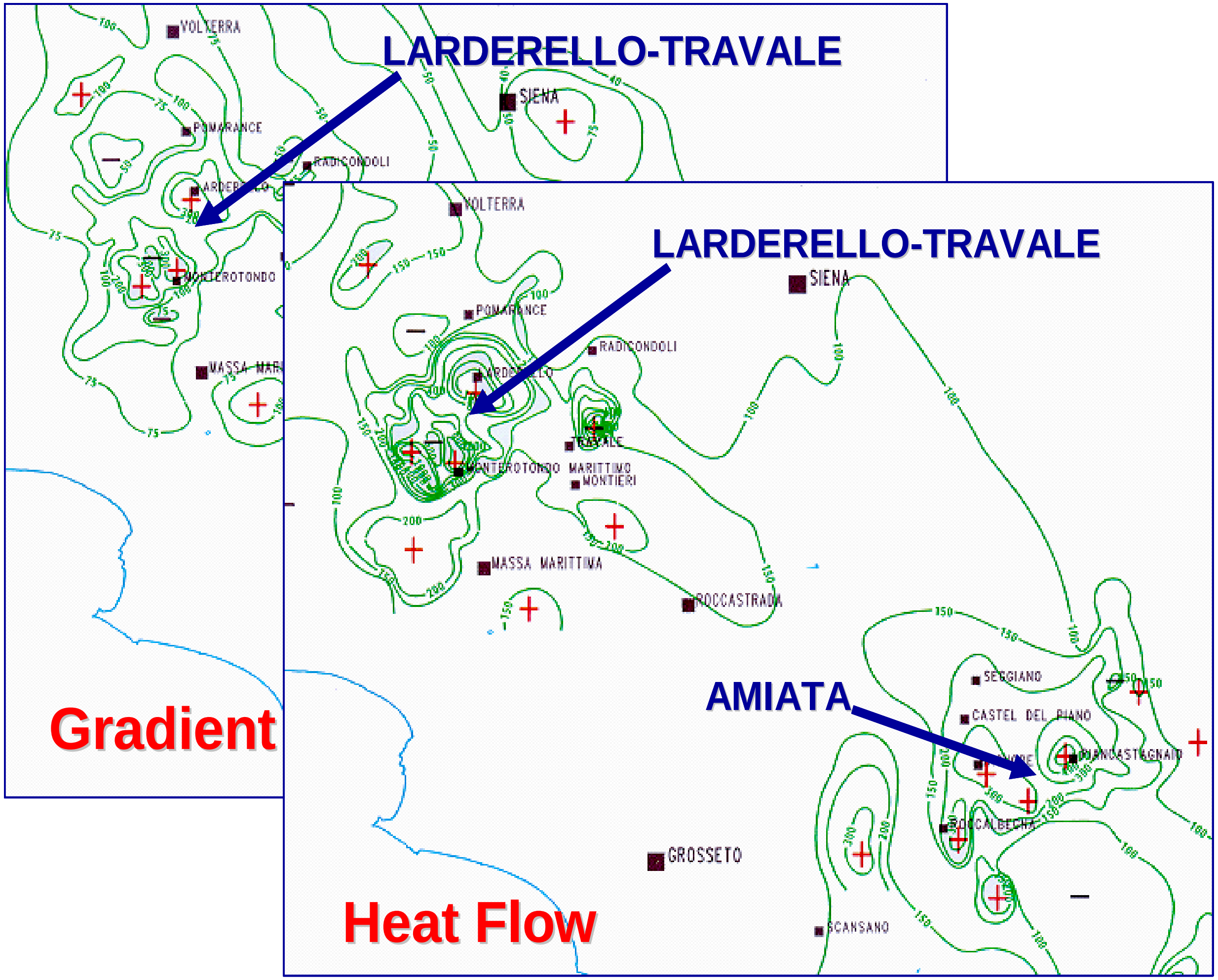
Courtesy of Enel

Exploration Methods – Gradient holes

Temperature measurements in holes at 30 - 300 m (400 in Tuscany, 200 in Latium)



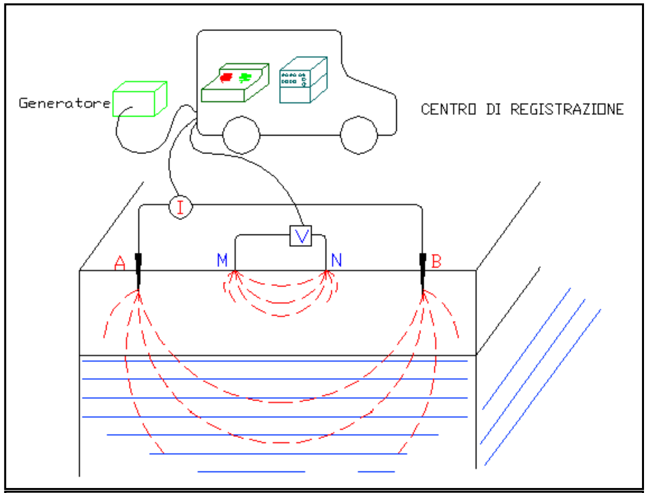
Reconstruction of Geothermal gradient and heat flow maps for the definition of zones with thermal anomaly, to be merged with structural high of the SHALLOW RESERVOIR

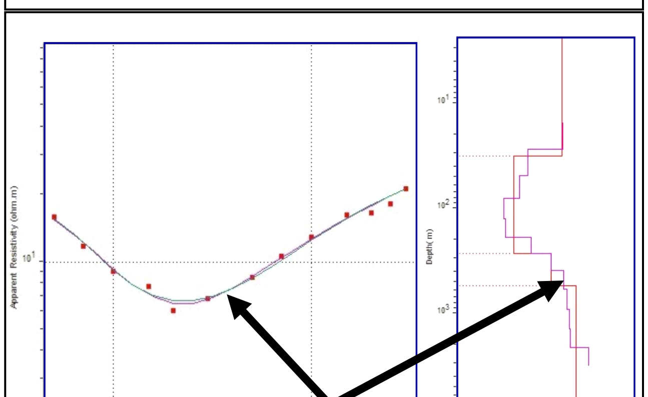


Courtesy of Enel

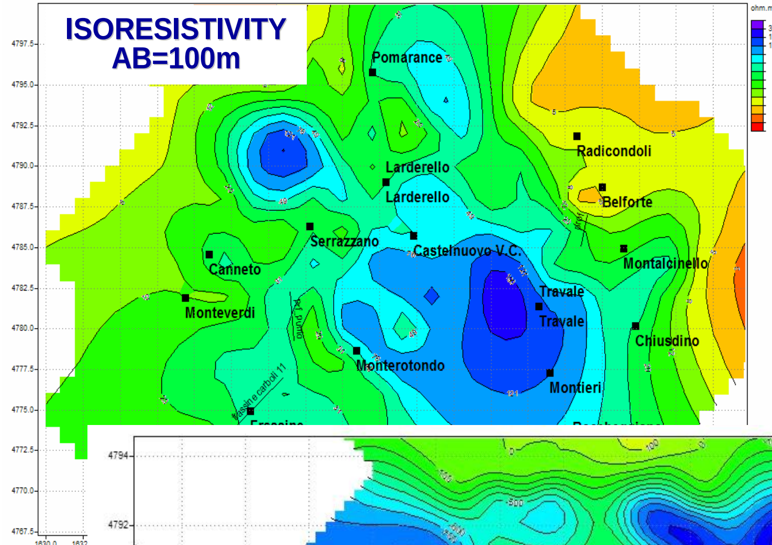
Exploration Methods – DC Soundings

Schlumberger VES
with AB range of 2- 8 km
(5500 in Tuscany, 2500 in Latium)

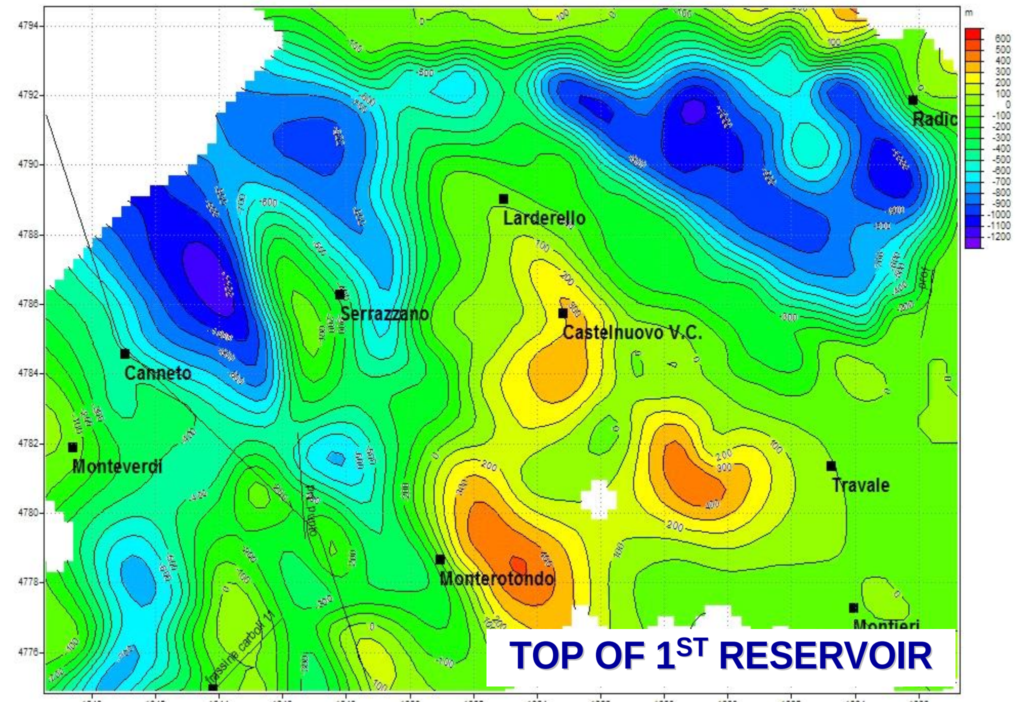




Resistive Substratum Corresponds to Carbonate Reservoir



Qualitative mapping of conductive anomalies

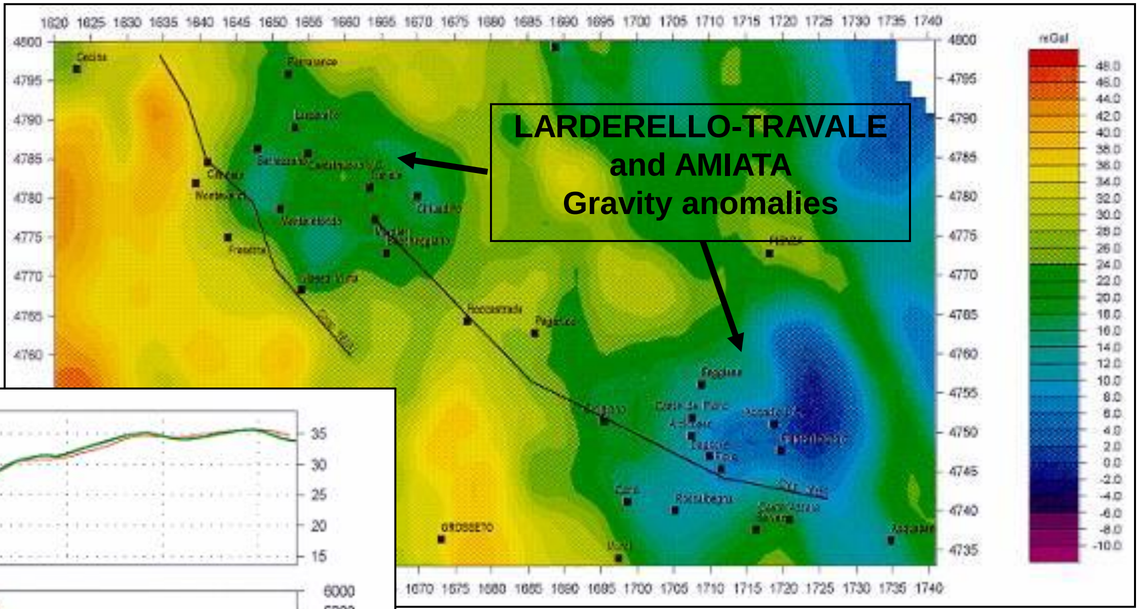


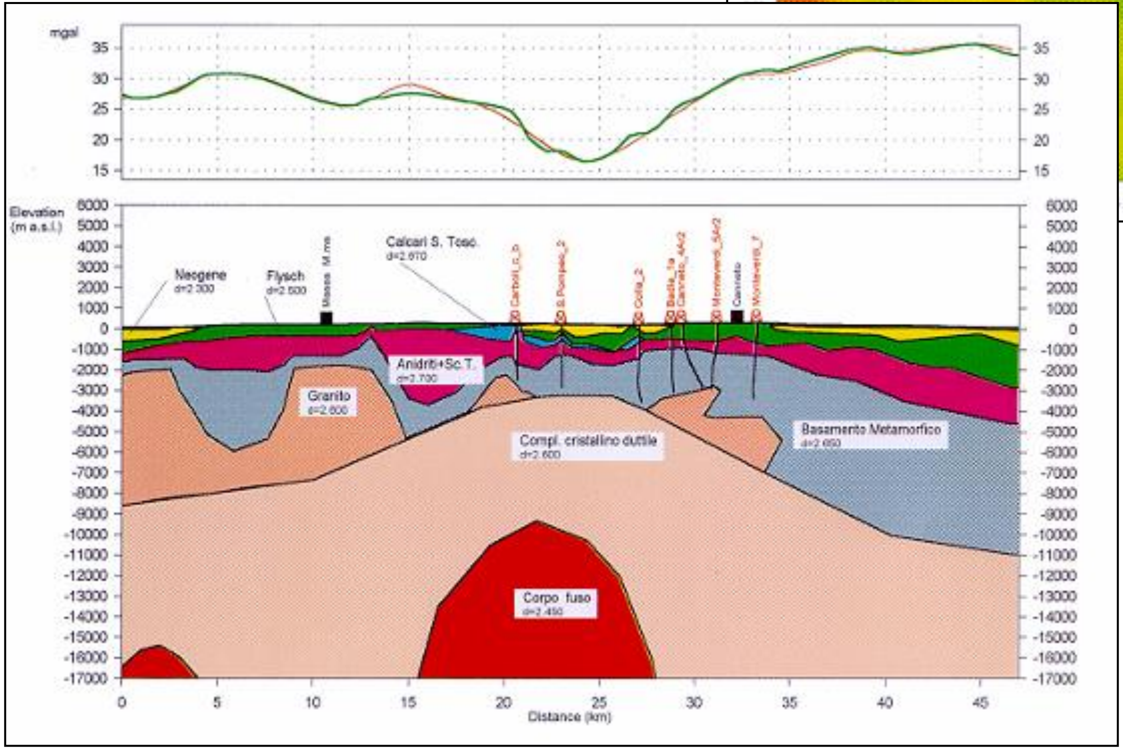
Courtesy of Enel

Exploration Methods – Gravimetric surveys

More than 23000 gravity stations in the geothermal regions
(average density higher than 1 st/km^2)

Anomaly Maps pointed out regional structures and GEOTHERMAL SIGNATURES



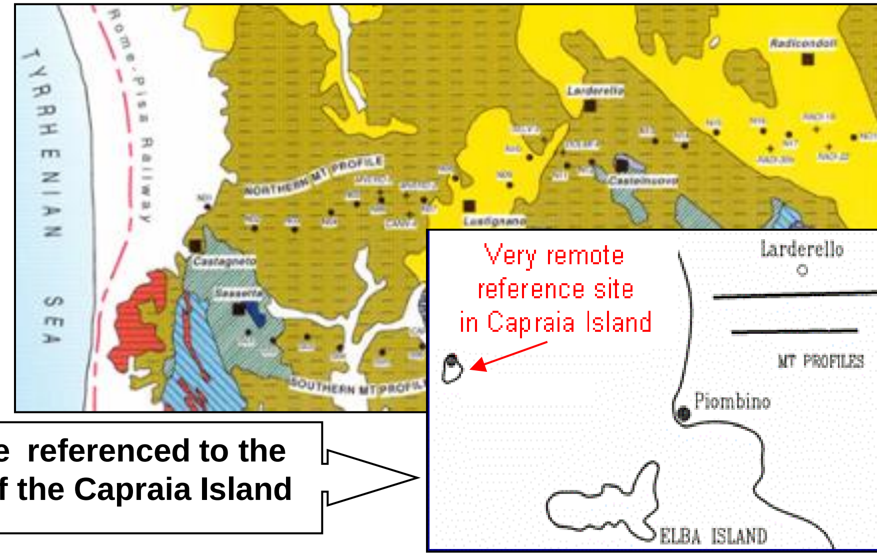


2/3D Modeling, properly balanced with experimental density data, pointed out deep low density bodies to be related to molten intrusions
(HEAT SOURCE)

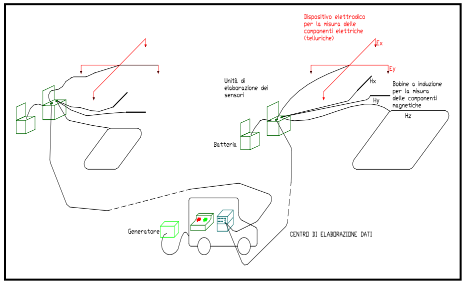
Courtesy of Enel

Exploration Methods – MT Tests

Remote-Remote-Reference methodology (cooperation with MIT and IGG-CNR) to remove noise of large electromagnetic sources



34 MT sites in the Larderello-Travale Area

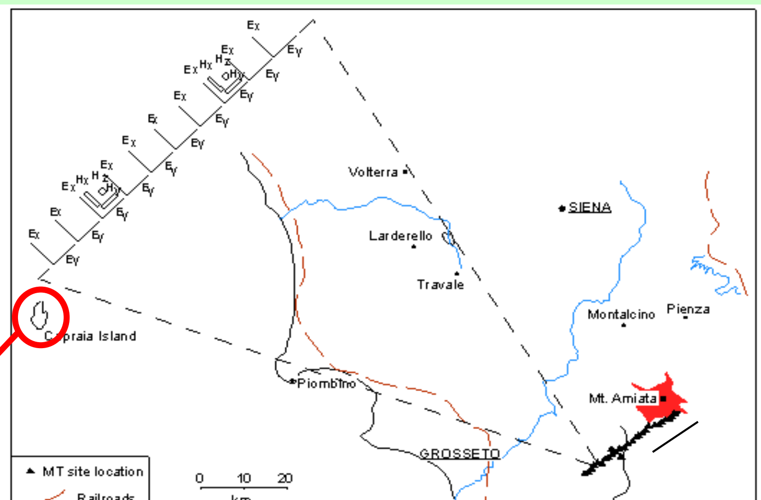


2 local referenced signals were referenced to the very remote, undisturbed site of the Capraia Island

This methodology allowed to evaluate and remove the noise due to the electric railway

36 sites in the Amiata Area

with additional dipoles between MT sites to record electric field data in the high frequency band and enhance shallow structures resolution



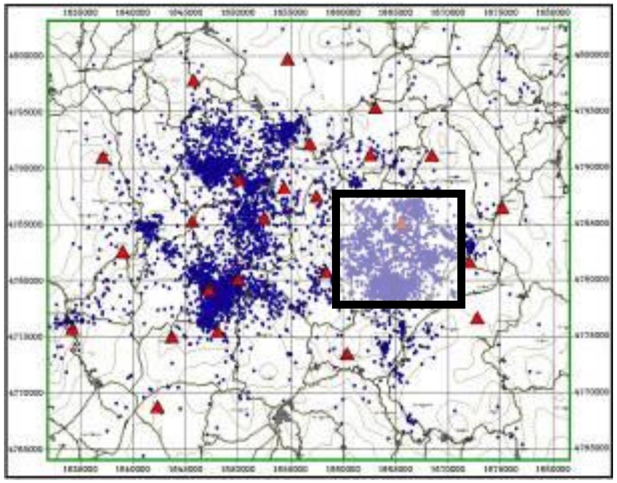
Low frequency data were acquired simultaneously on two main MT sites and on Capraia island

Courtesy of Enel

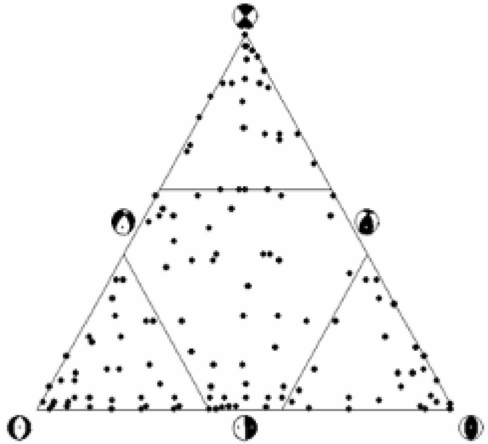
In both cases 2D modeling pointed out deep conductive anomalies mainly interpreted as the effect of geothermal fluid circulation and magmatic bodies

Exploration Methods – Microseismic monitoring

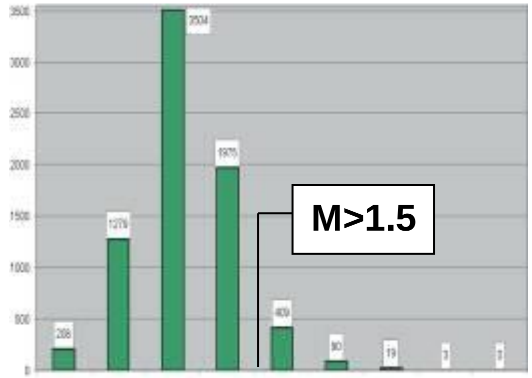
Since 1977 Monitoring networks
Installed for environmental monitoring



FOC MEC analysis
(stress field reconstruction)

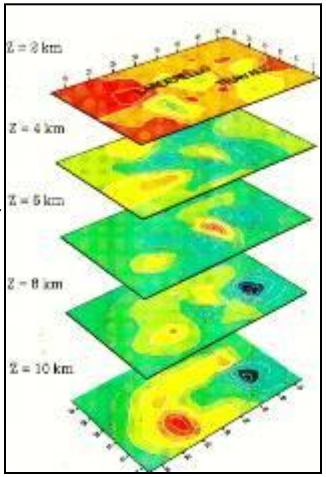


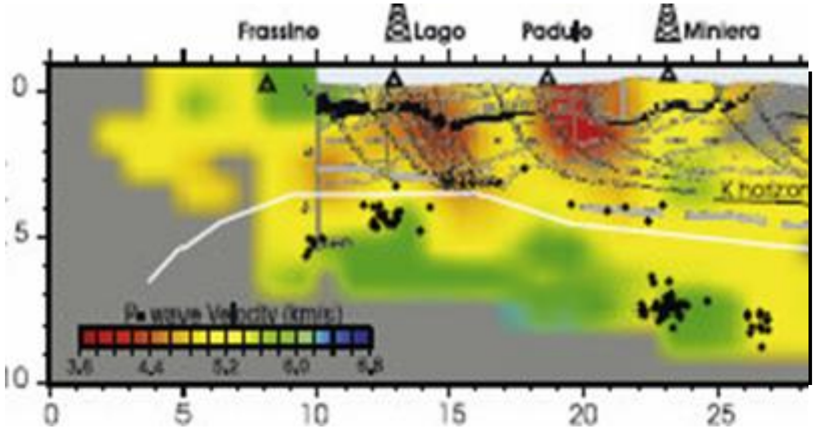
Disperse FOCMEC also in small area



Prevailing Micro-earthquakes
Few phase data

EARTHQUAKE TOMOGRAPHY ATTEMPTS



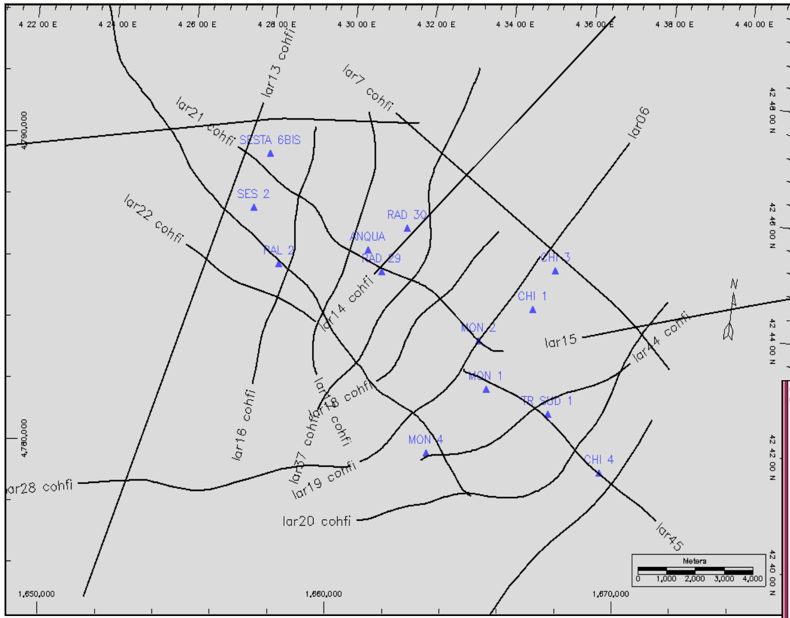


DIFFERENT VELOCITY ANOMALIES DISTRIBUTION DIFFERENT STRUCTURAL AND GEOTHERMAL CHARACTERIZATION

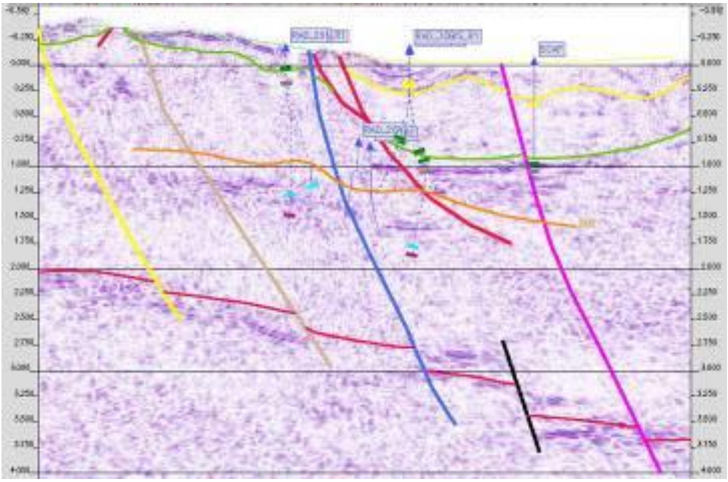
Courtesy of Enel

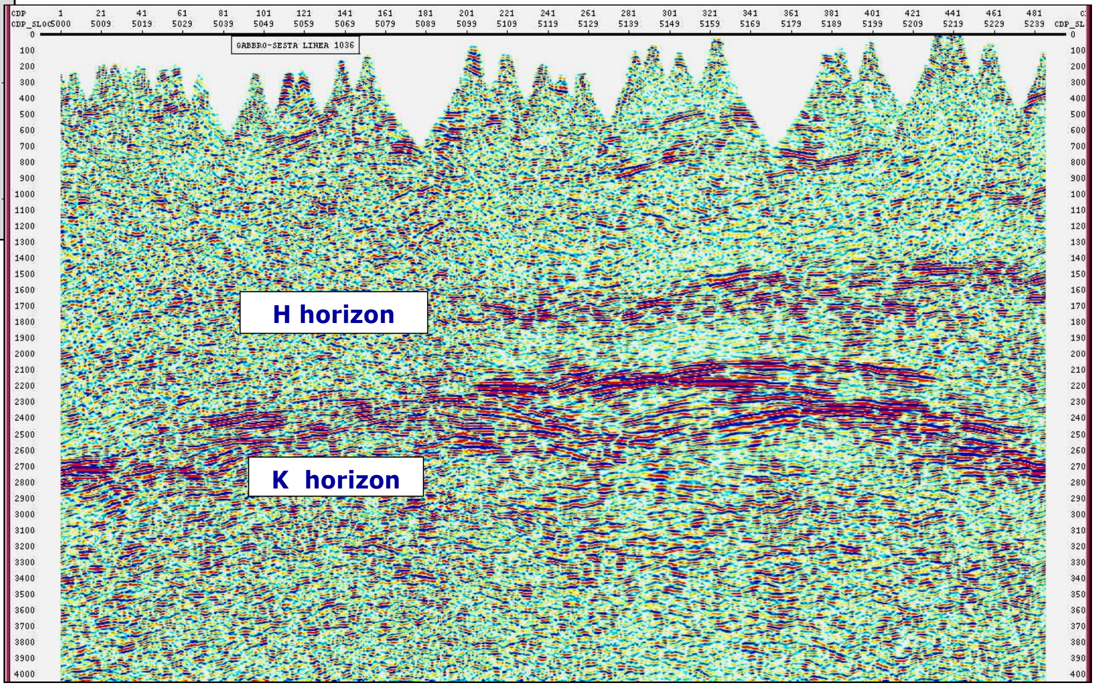
Exploration Methods – Seismic surveys

More than 250 km of 2D Seismic Profiles in the Larderello-Travale area



Geological and structural Interpretation to locate first deep wells





Potential tool for the individuation of fractured and productive deep levels.

These are often in correlation with a seismic marker (H) that runs discontinuously above the deeper and continuous marker K.

Courtesy of Enel

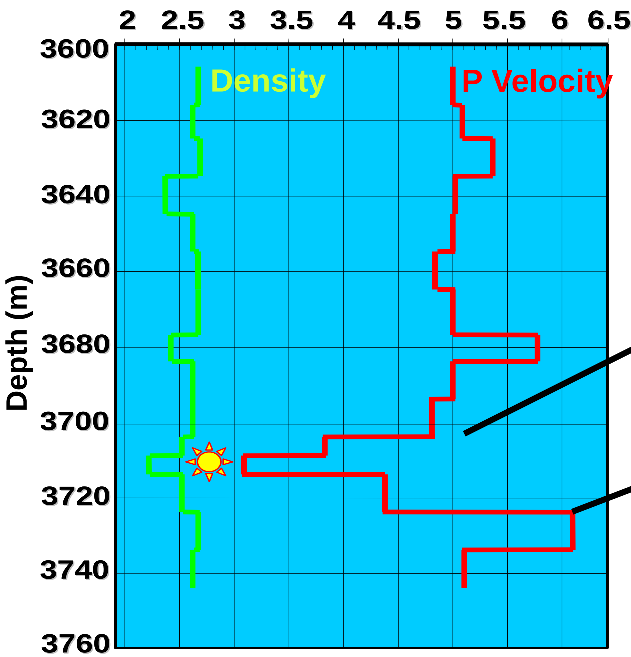
Exploration Methods – Seismic surveys

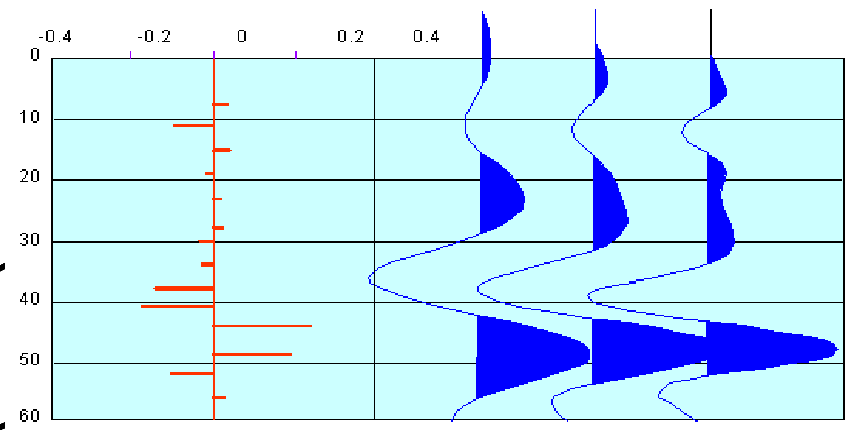
Seismic reflections result from variations of the elastic characteristics:
- **lithological-structural factors**
- **variations in porosity/permeability due to fractures**

Fractured levels are often marked by sharp reductions of velocity and density

Acoustic Impedance Variation

Higher is the acoustic impedance contrast
Higher are reflection coefficient values
And higher is the AMPLITUDE of the reflected signal





Coefficient of Reflectivity

Synthetic seismogram (Ricker zero-phase)

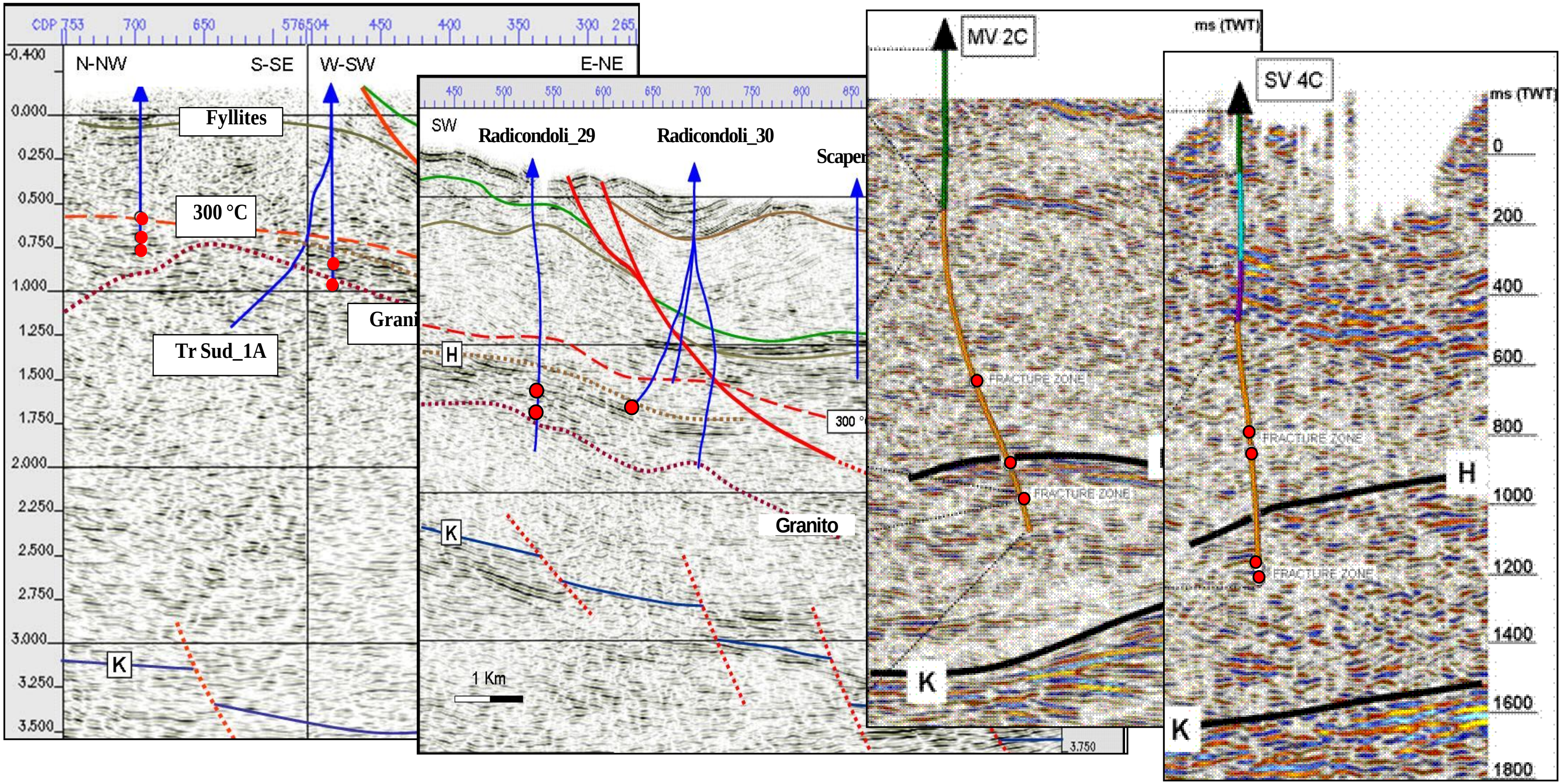
$$CR = \frac{Vp_2\delta_2 - Vp_1\delta_1}{Vp_2\delta_2 + Vp_1\delta_1}$$

The correlation seismic reflections/fractures is as likely as much the reflections occur within homogeneous geological formations (Metamorphic Basement)

Courtesy of Enel

Exploration Methods – Seismic surveys & mining risk reduction

Encouraging correlation between seismic reflections (H marker) and fractures (red dots)



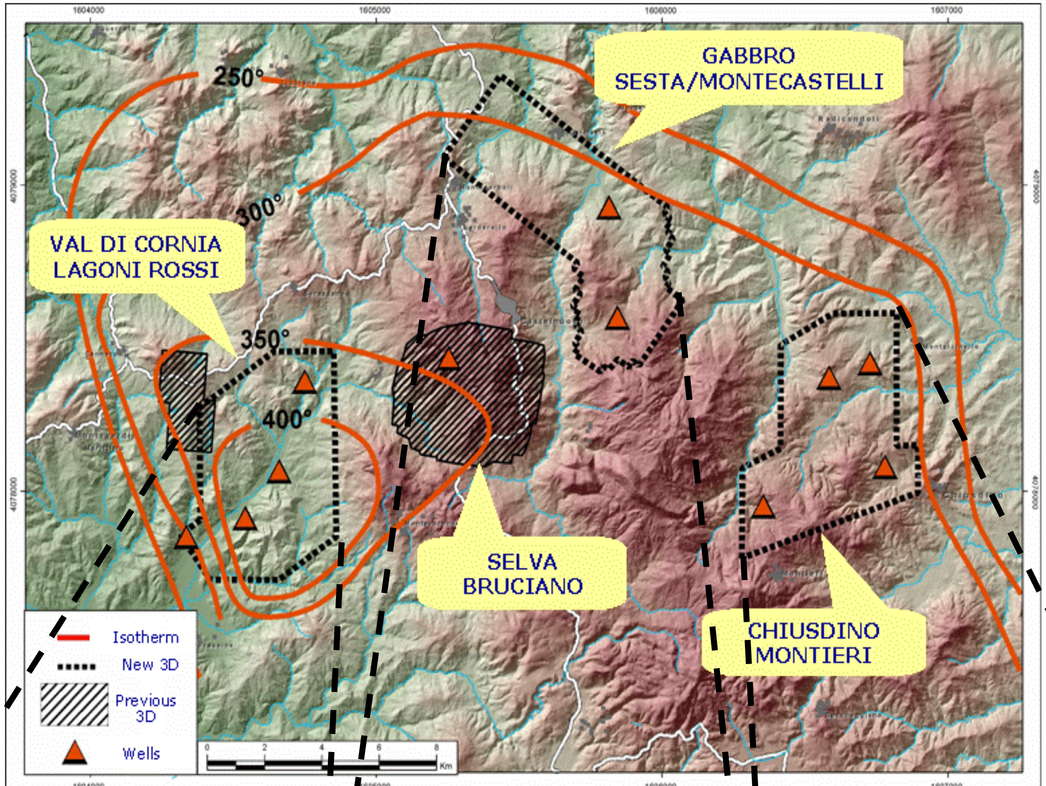
Seismic surveys can significantly help the detection of productive levels representing the targets for deep wells

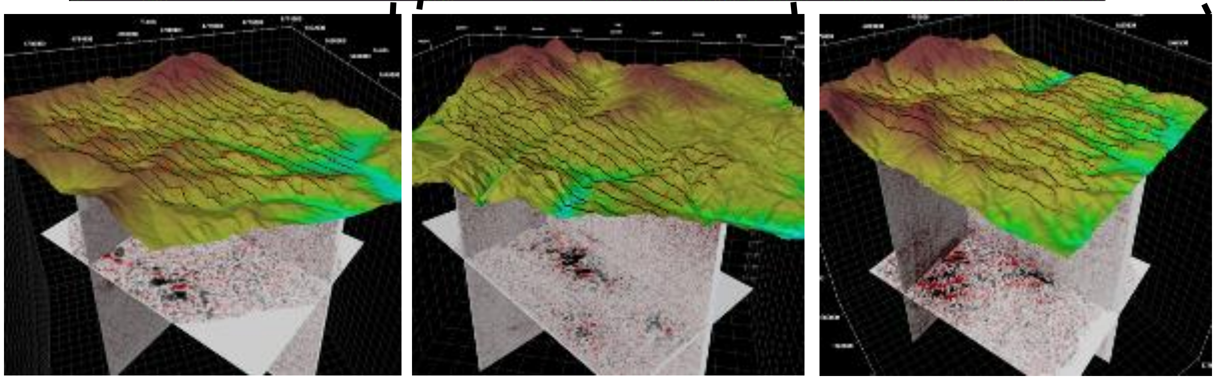
MINING RISK REDUCTION

3D SEISMIC

Courtesy of Enel

Exploration Methods – 3D Seismic surveys





DEEP EXPLORATION PROGRAM

2003 - 2007

ACTIVITIES

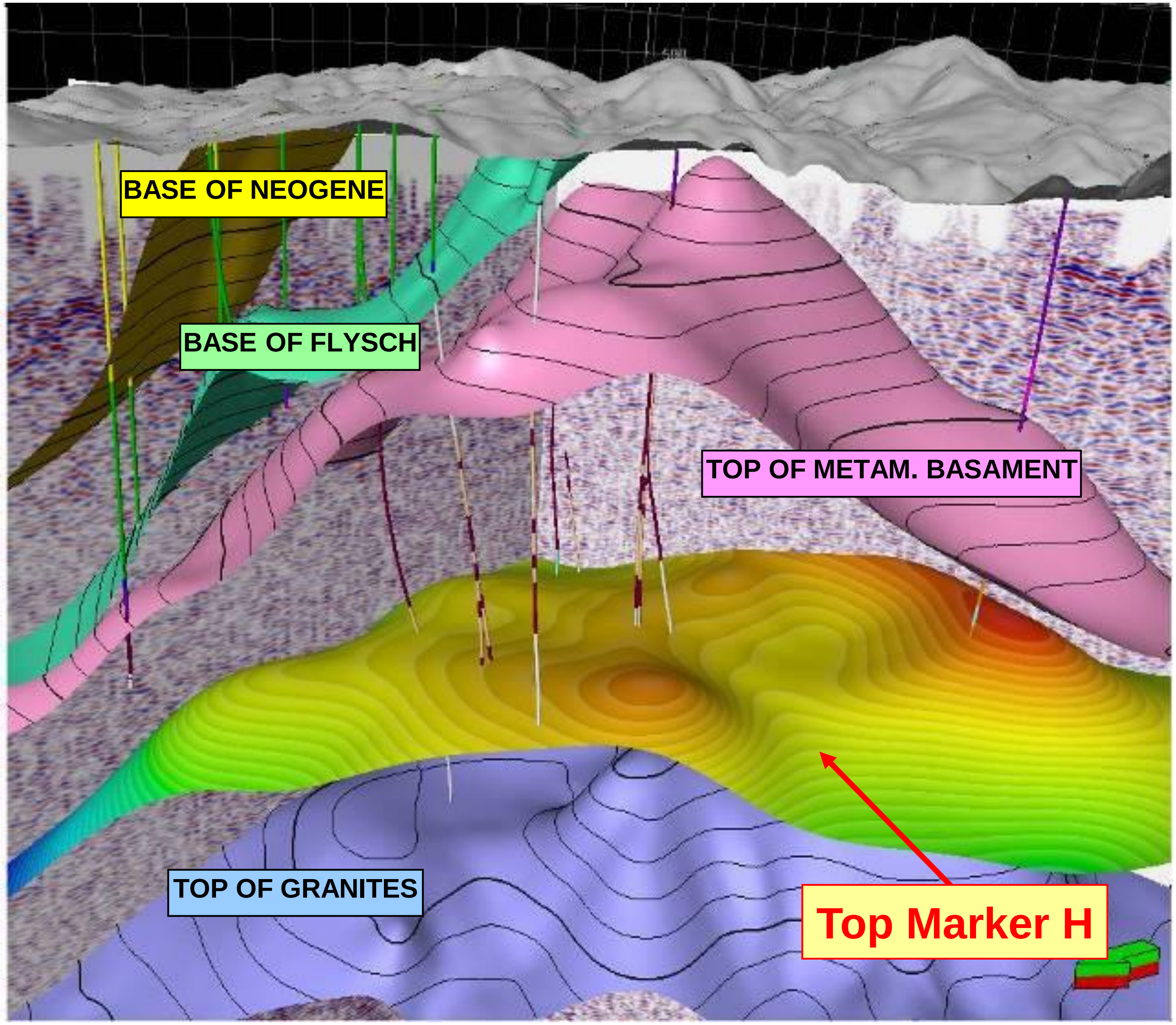
- **3D Seismic surveys**
- **Drilling of 11 deep exploration wells (3.5-4 k m)**

Main acquisition parameters

- Fold ≥ 1600%
- Full fold area 33-34 Km^2
- Bin Size 25x 40 m
- Source lines distance 500 m
- S.P. distance 80 m
- Receivers line distance 480 m
- Receivers distance 50 m
- Hole depth 10-12 m
- Charge size per hole 3 kg
- Average shot holes 1550

Courtesy of Enel

Exploration Methods – 3D Seismic surveys



INTERPRETATION

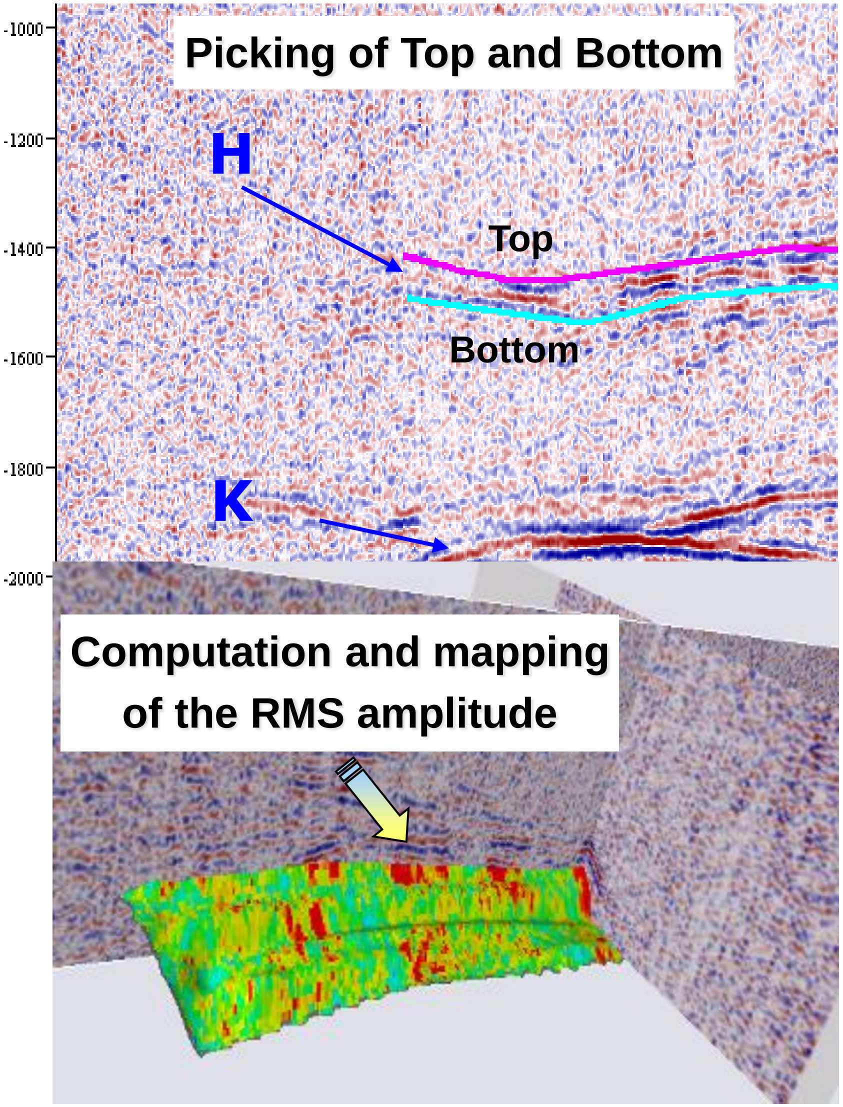
- **3D Seismic data**
- **Geological well data**
- **Geophysical well data**

STRUCTURAL INTERPRETATION

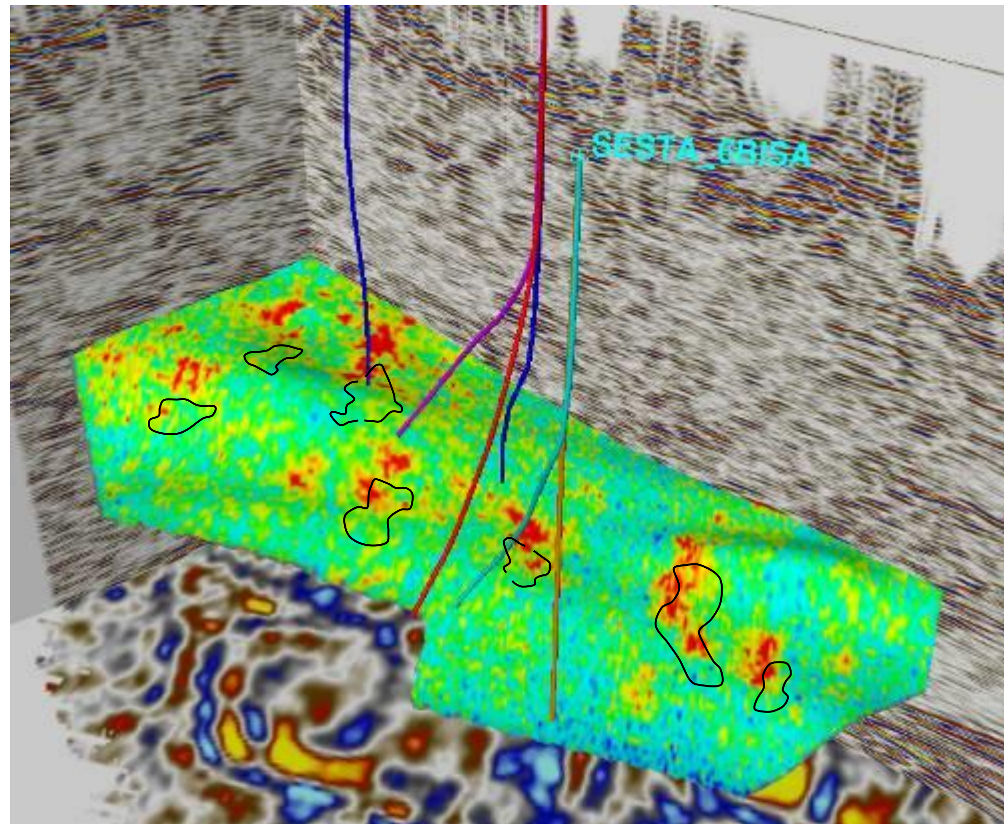
POTENTIAL TARGET

Courtesy of Enel

Exploration Methods – 3D Seismic surveys



INTERPRETATION OF THE H MARKER AND POTENTIAL DRILLING TARGET INDIVIDUATION



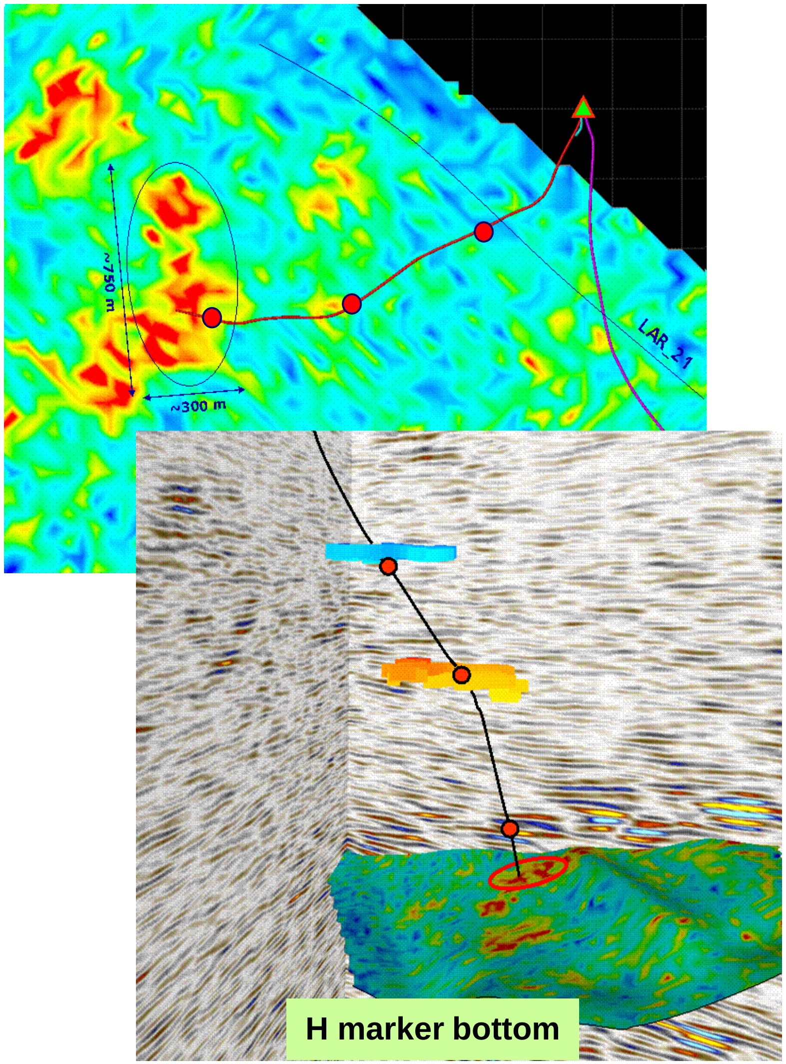
Areas with the highest RMS amplitude values

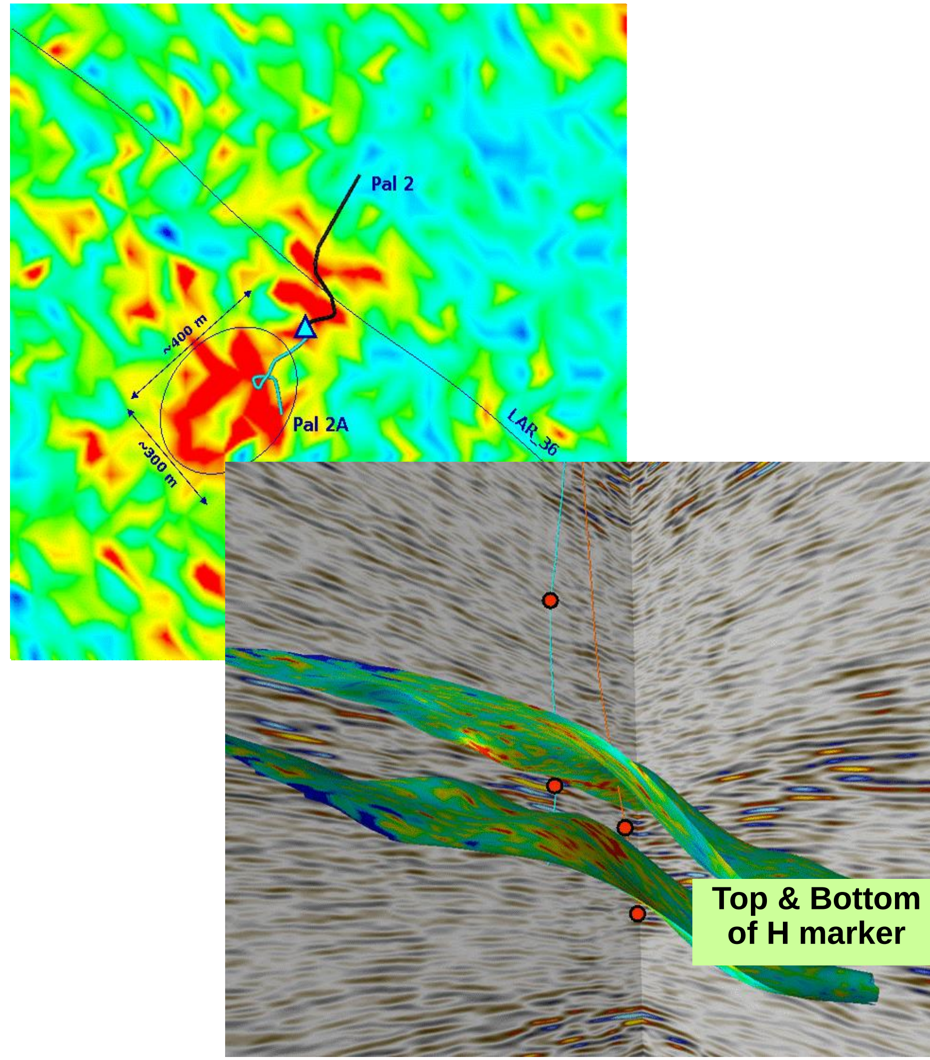
Courtesy of Enel

Exploration Methods – 3D Seismic surveys (first results)

Well target - Drilling Project – Drilling Execution – Drilling Result

● Fractured levels



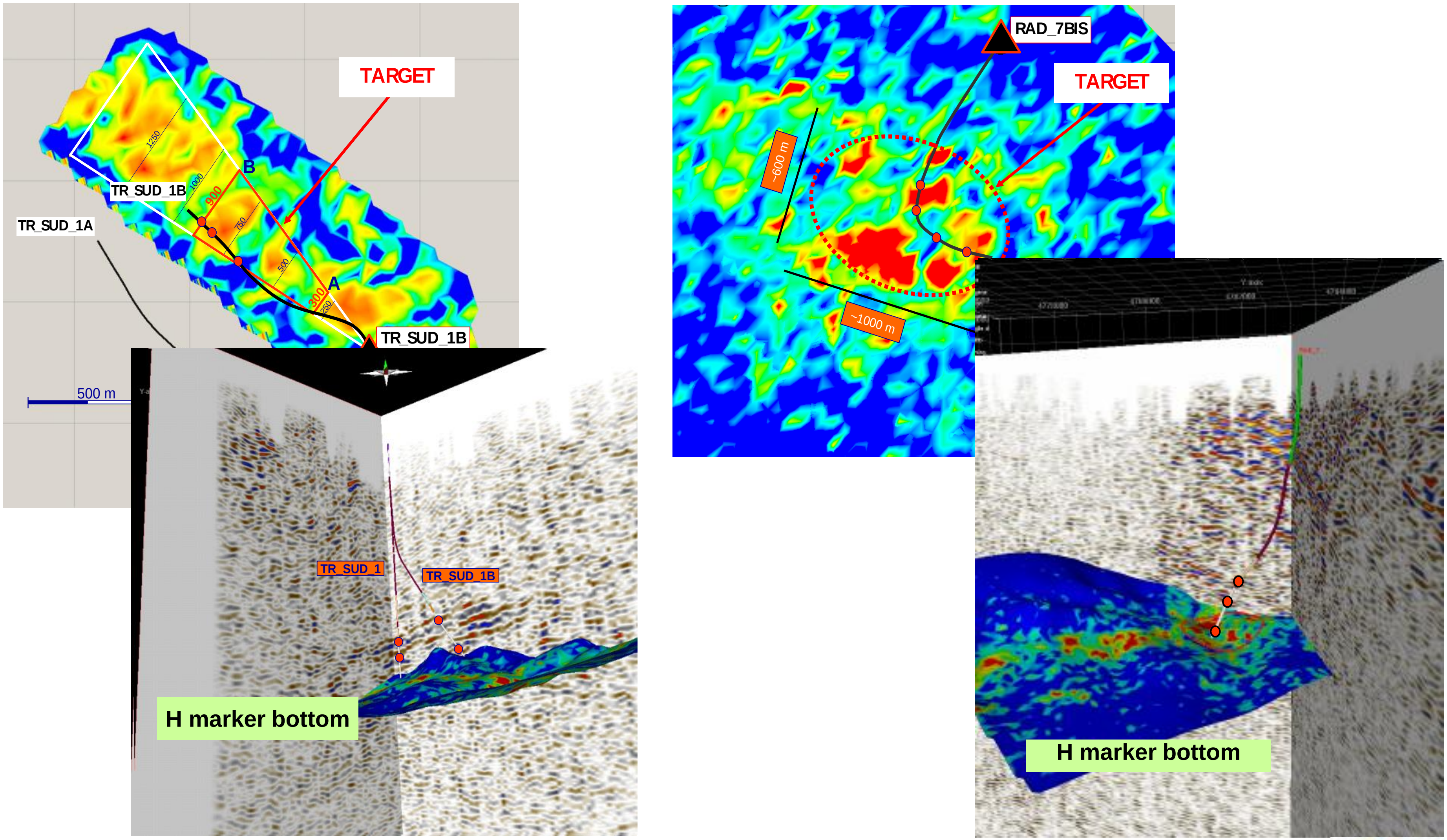


Courtesy of Enel

Exploration Methods – 3D Seismic surveys (first results)

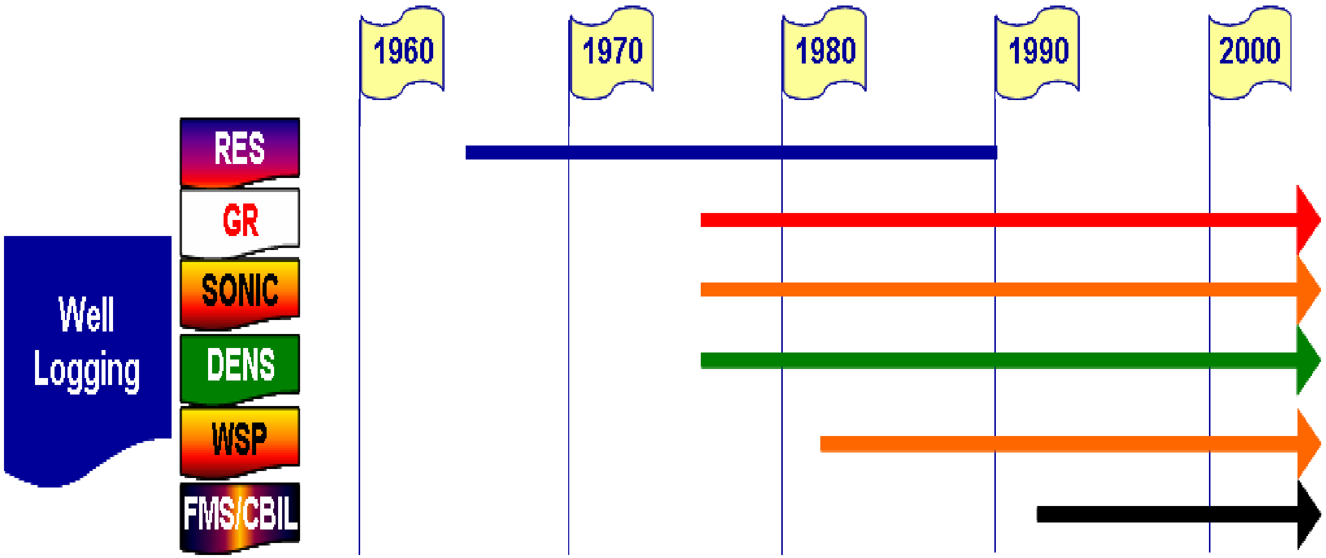
Well target - Drilling Project – Drilling Execution – Drilling Result

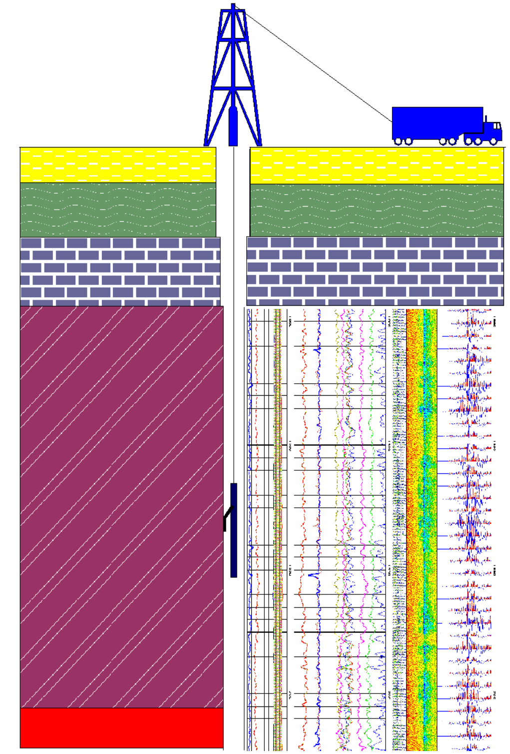
Fractured levels



Courtesy of Enel

Exploration Methods – Geophysical well logging





NOT ONLY

- **Stratigraphic and Structural reconstruction**
- **Geophysical Modeling Calibration (gravity, resistivity, seismic)**

BUT ALSO AND MAINLY

DETECTION AND CHARACTERIZATION OF FRACTURES

BY MEANS OF

- **Elastic/Acoustic parameters**
- **Waveform analysis**
- **360° Hole Imaging**

Courtesy of Enel

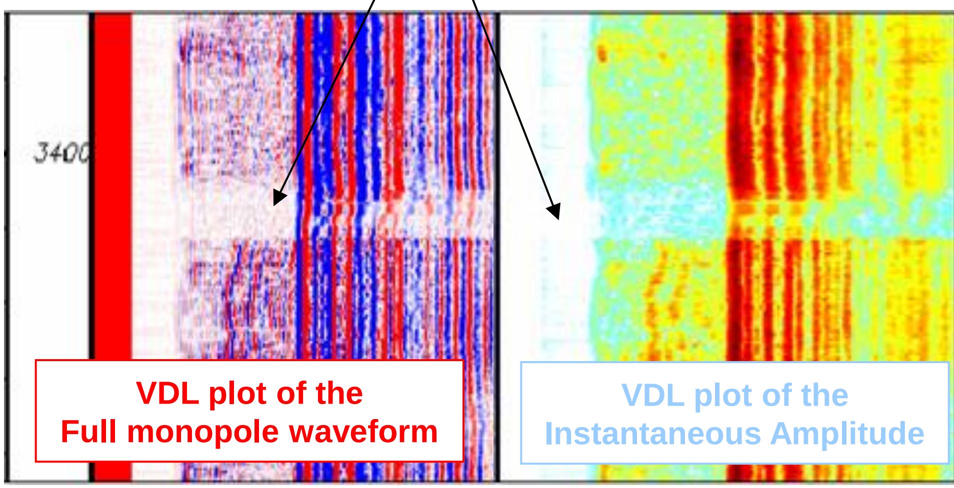
Exploration Methods – Geophysical well logging

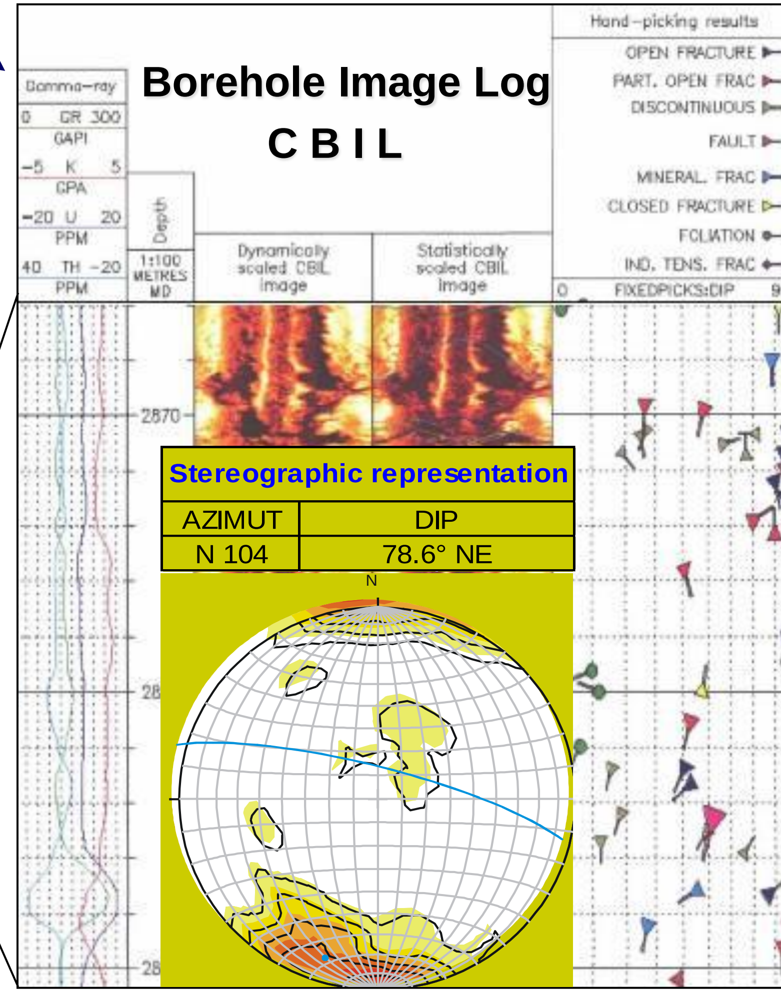
FRACTURES DETECTION AND CHARACTERIZATION

GEOMETRY RECONSTRUCTION
OF VARIOUS TYPES OF LINEAMENTS
(Strike, Plunge, Dip)

Waveforms Analysis

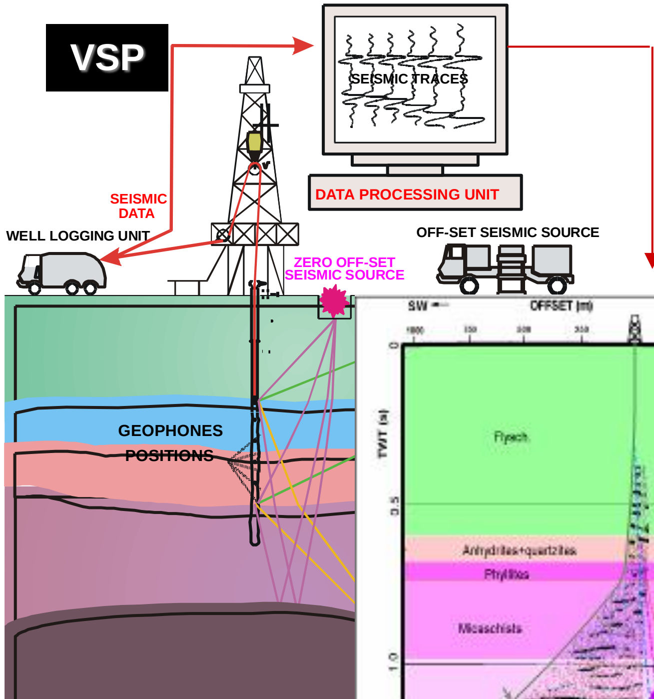
Fractured zones show strong attenuation of the acoustic signal

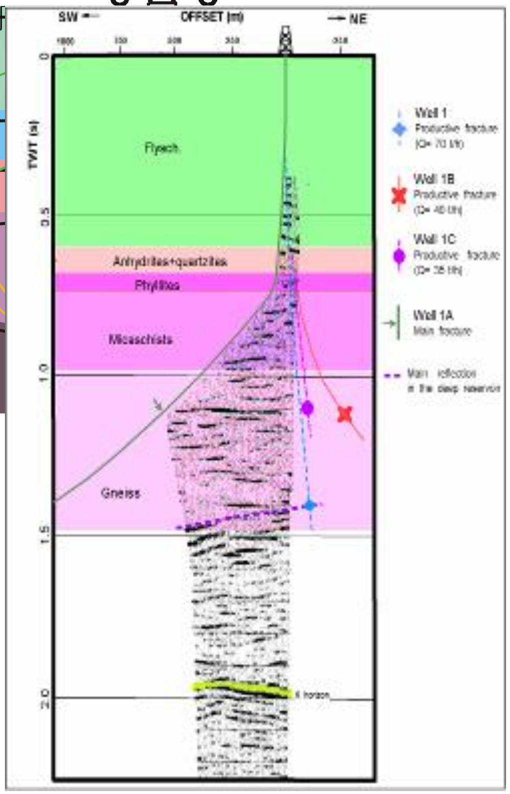




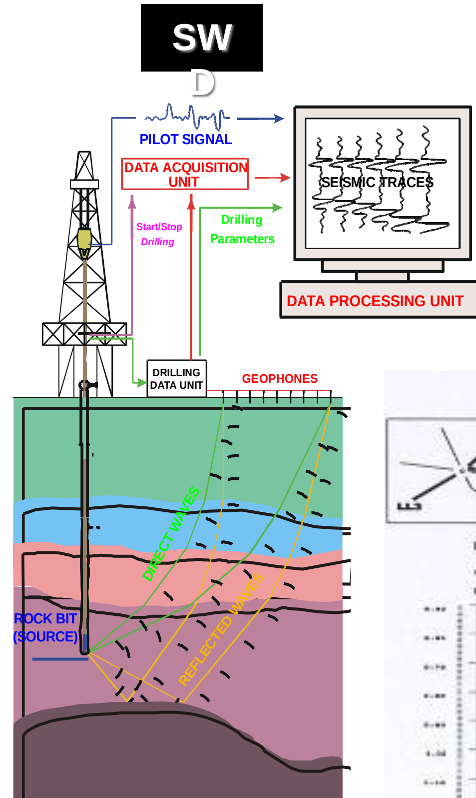
Courtesy of Enel

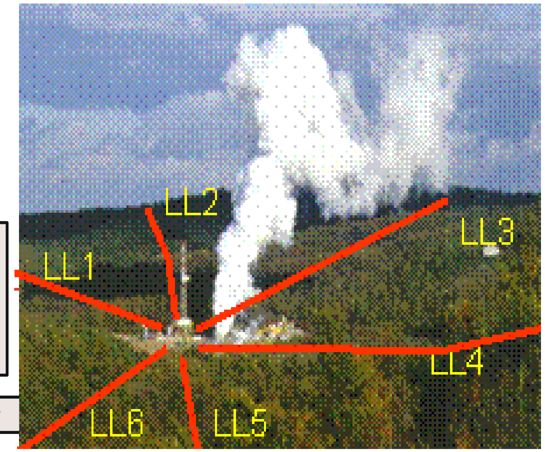
Exploration Methods – WSP (Well Seismic Profile)

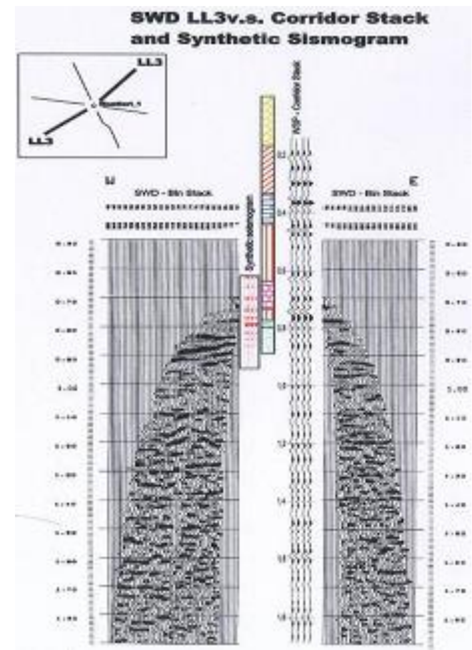




More than 50 VSP (mainly 0-offset)







Many tests and 2 surveys in the framework of EU projects

Courtesy of