How to find a geothermal reservoir

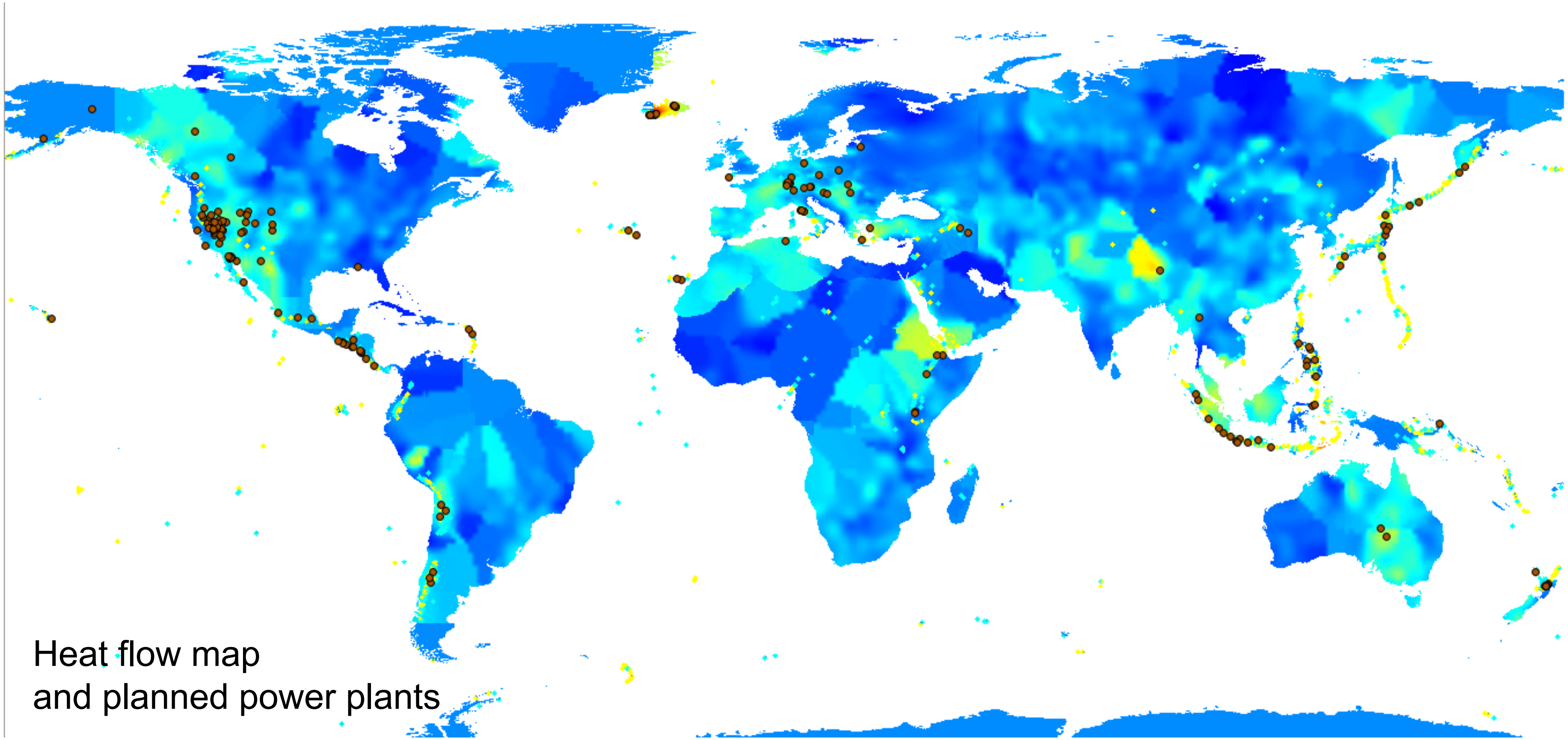
temperature focus – some stress

(modelling and geophysical techniques)

Exploration and Investigation: the quest

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

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



Heat flow map
and planned power plants

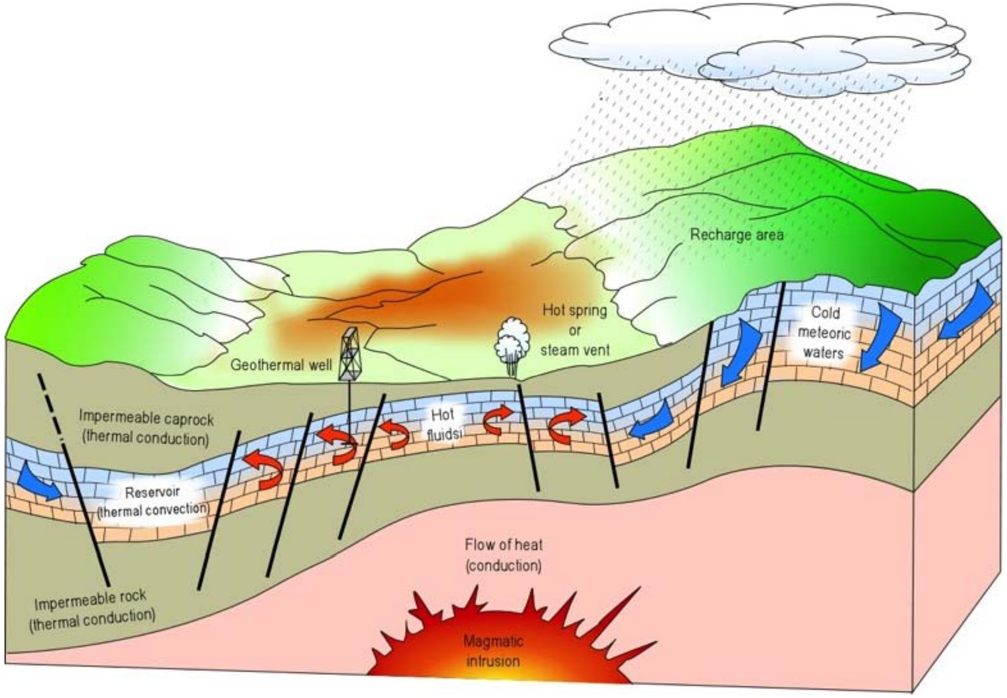
Exploration and Investigation: the quest

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

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

Hydrothermal systems

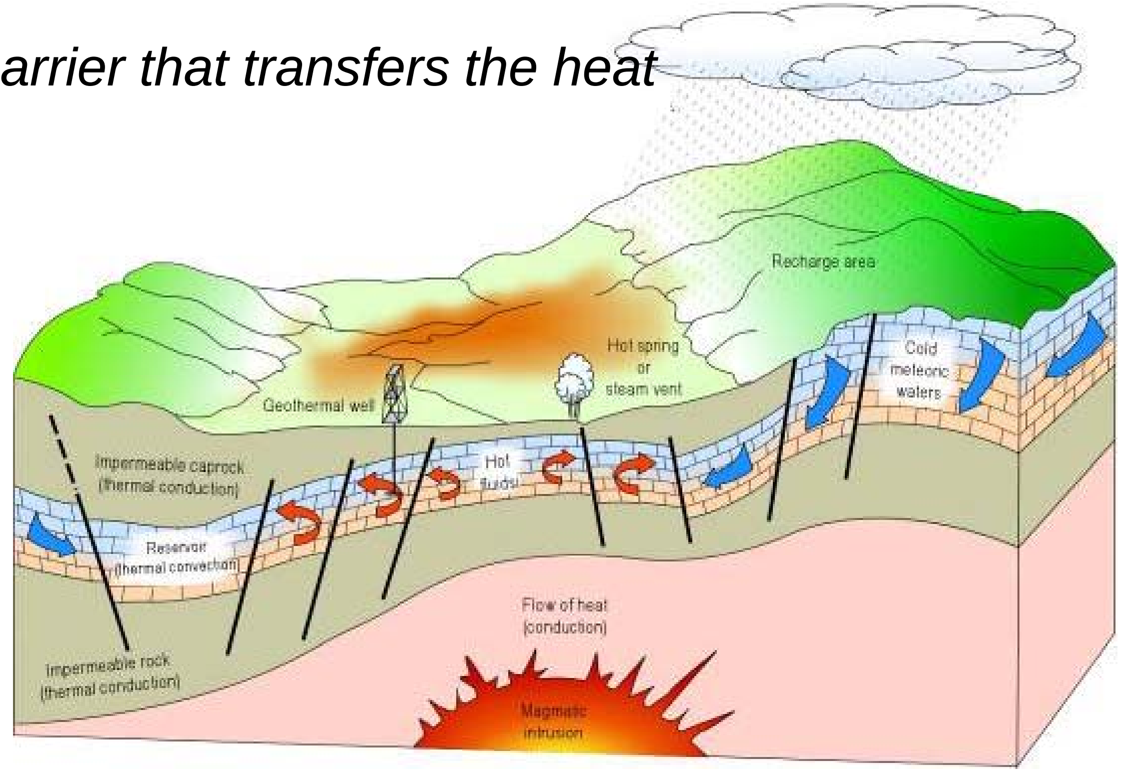
A *geothermal system* can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface".



Hydrothermal systems

Elements of a hydrothermal geothermal system:

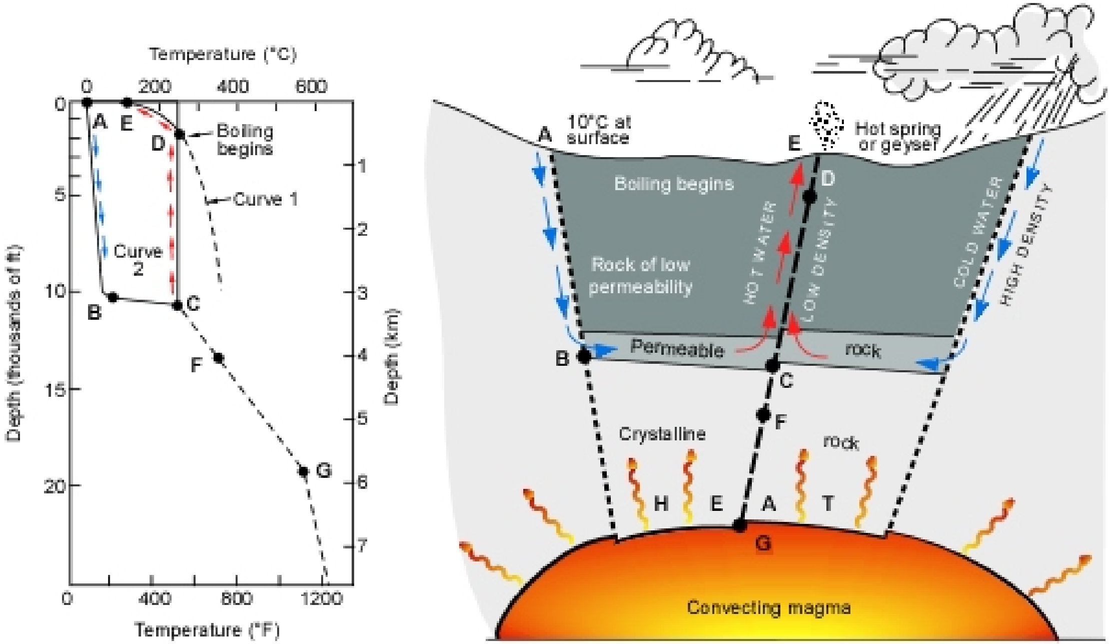
a heat source
a reservoir
a fluid, which is the carrier that transfers the heat
a recharge area



Hydrothermal systems

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

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



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

(From White, 1973).

Hydrothermal systems

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

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

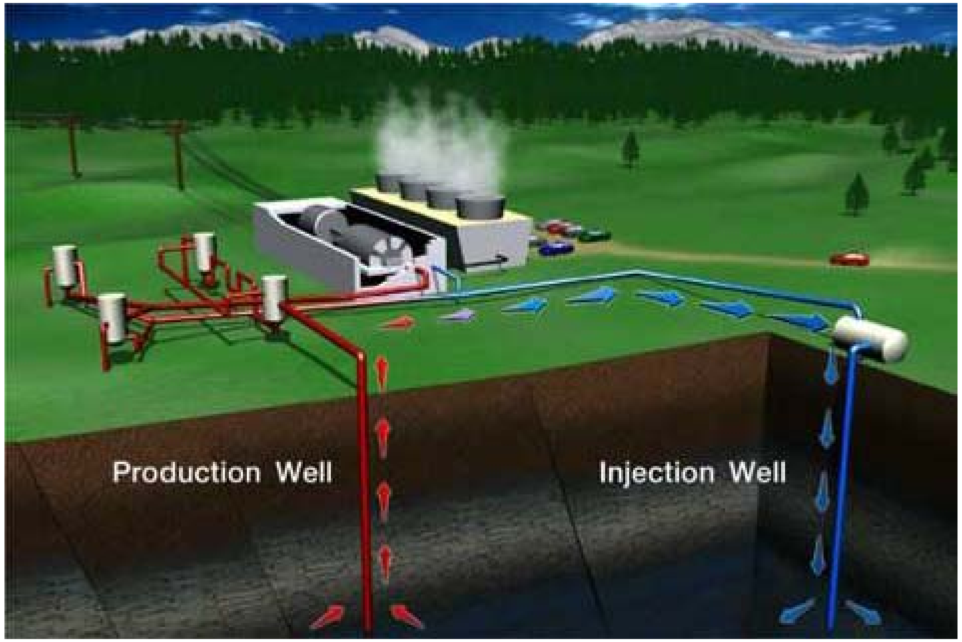
productivity requirement

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

Hydrothermal systems

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

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



Hydrothermal systems

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

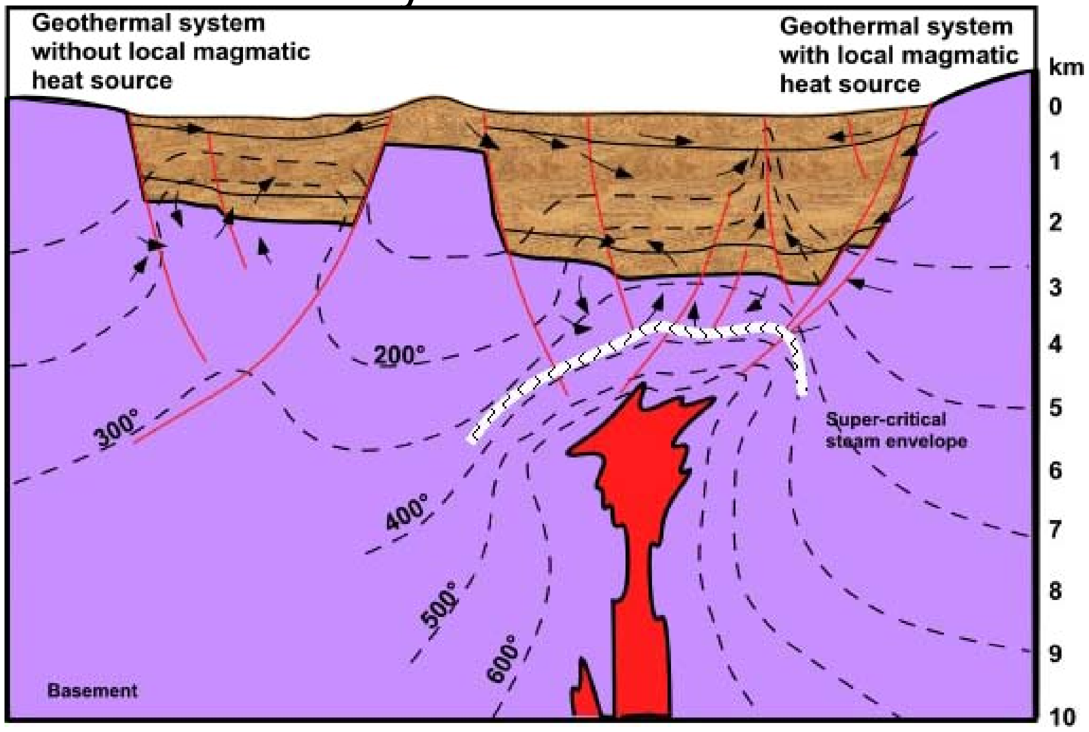
Volcanic rocks are the most common single rock type in which reservoirs occur.

Specific lithology do *not* define geothermal reservoirs

Hydrothermal systems

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

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



Other sources of thermal anomaly:

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

Let us define what we need

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

Example: power production

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

10 MW_t (thermal) → 1MW_e (power)

Let us define what we need

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.

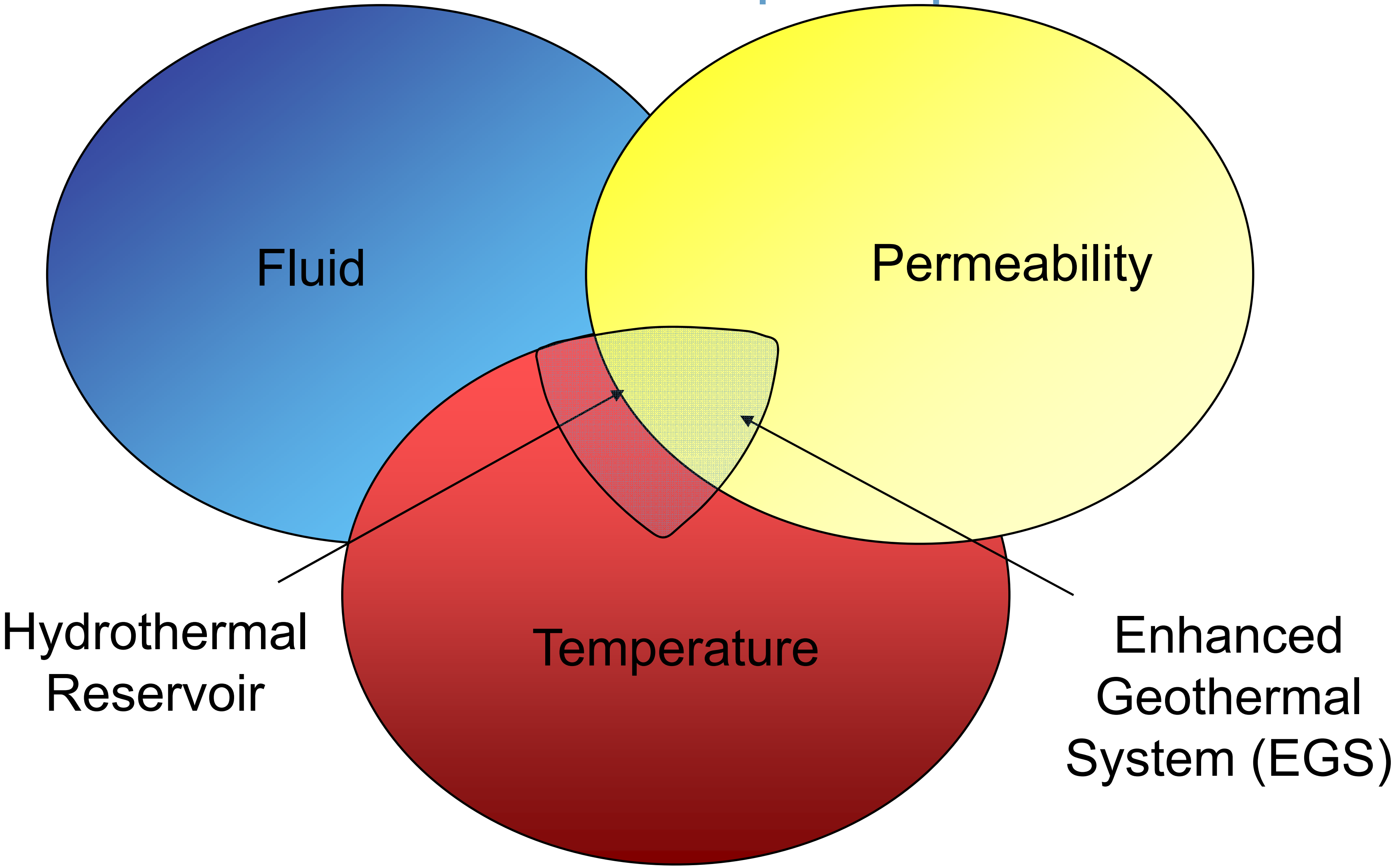
Goal: increase production

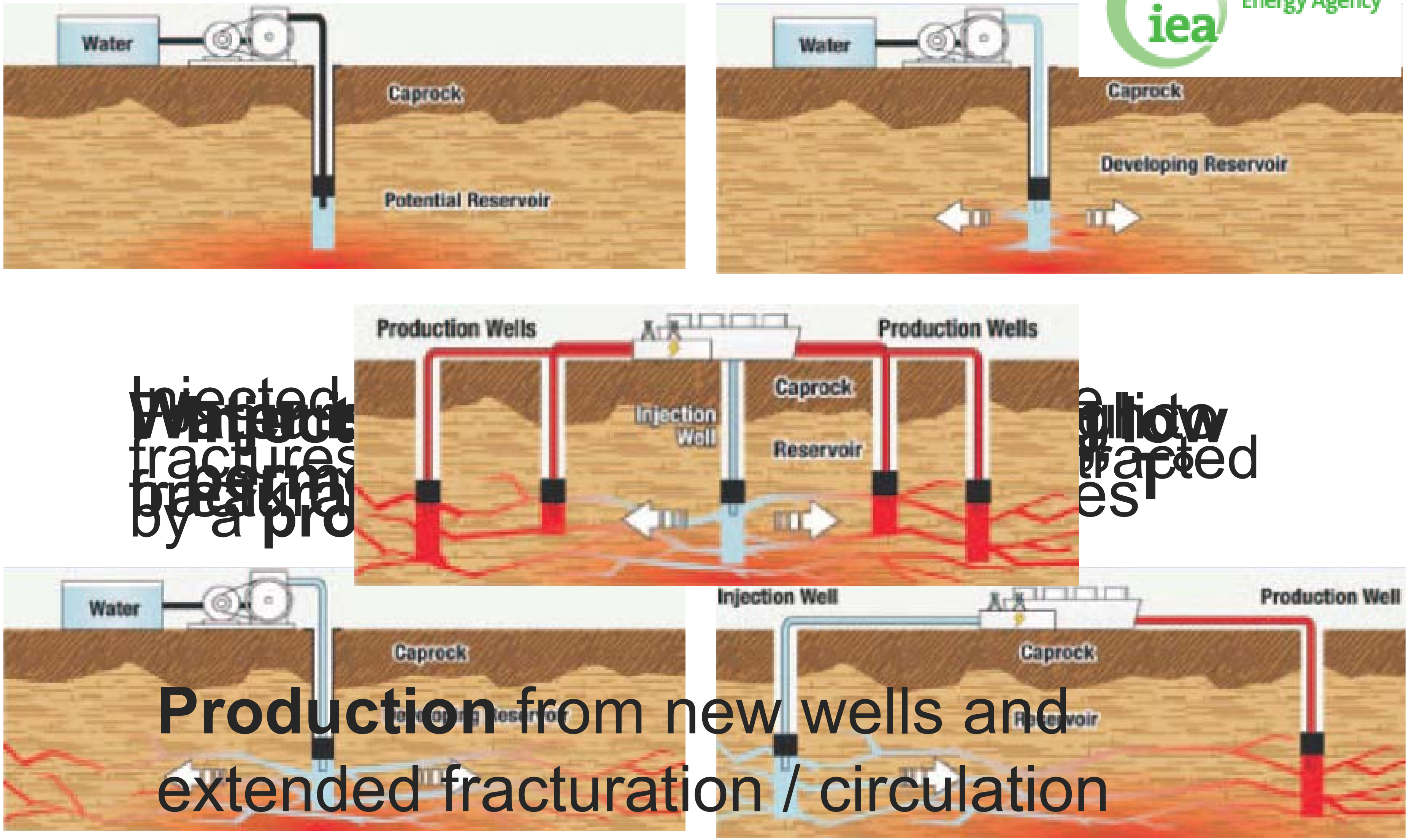
In order to increase geothermal production, we need to increase the amount of fluid heated in the underground.

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

Goal: increase production

The EGS concept is simple





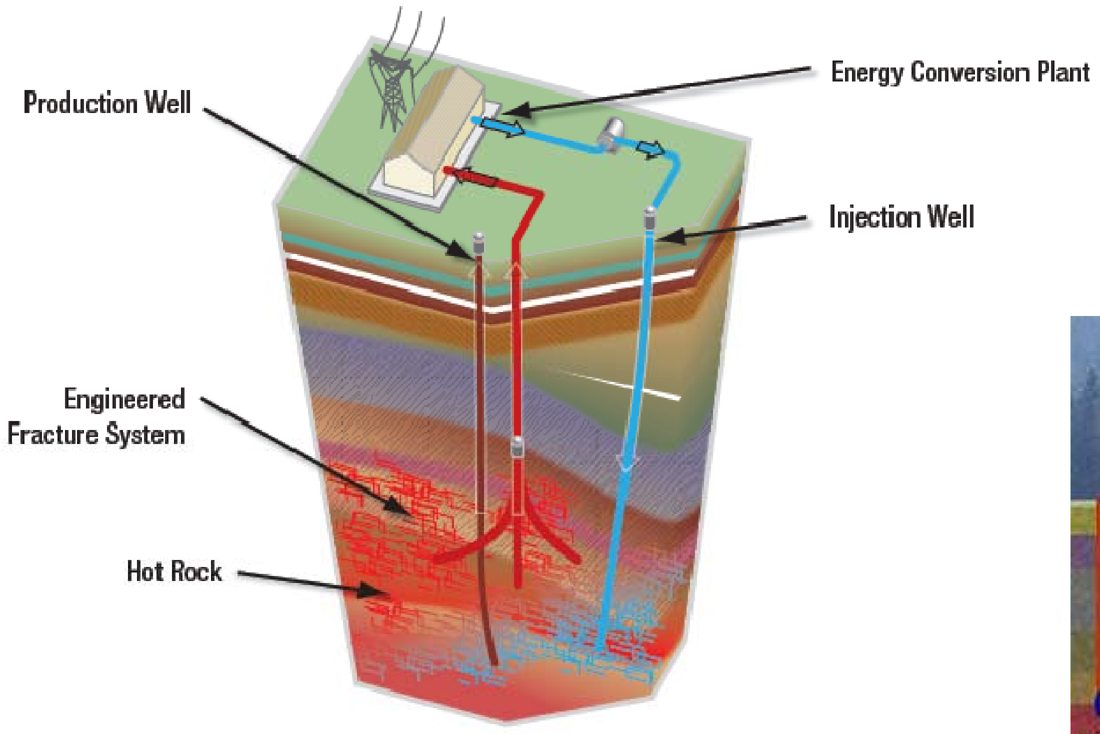
[illegible]

Production from new wells and extended fracturation / circulation

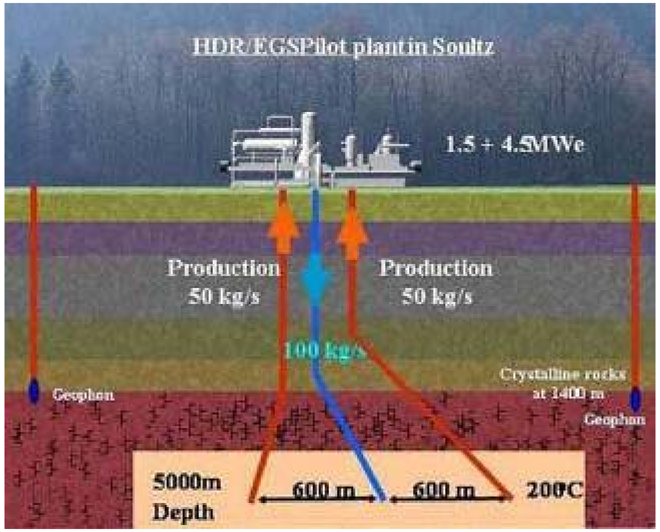
Goal: increase production

The EGS concept is simple

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



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



Goal: increase production

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

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

Exploration and Investigation

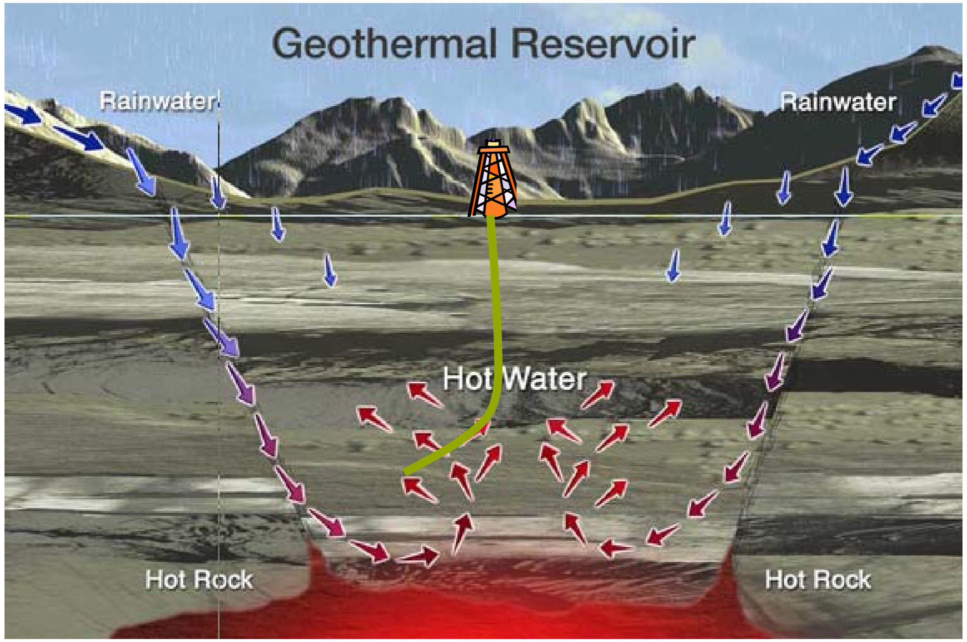
E&I techniques are used in all the geothermal project phases

- *resource characterization*
  - geothermal gradients and heat flow, heat capacity, recoverable heat
  - geological structure, including lithology and hydrogeology
  - Tectonics
  - induced seismicity potentials
- *reservoir design and development*
  - fracture mapping and in-situ stress determination
  - prediction of optimal re/injection and stimulation zones
- *reservoir operation and management*
  - reservoir performance monitoring through the analysis of temporal variation of reservoir properties

Goals to be achieved by E&I

- To provide all necessary *subsurface information* to guarantee the best exploitation efficiency, the sustainability of the resource and the lowest possible environmental impact

- To *reduce the mining risk* by cutting the exploration cost and increasing the probability of success in identification of GS and EGS in prospective areas



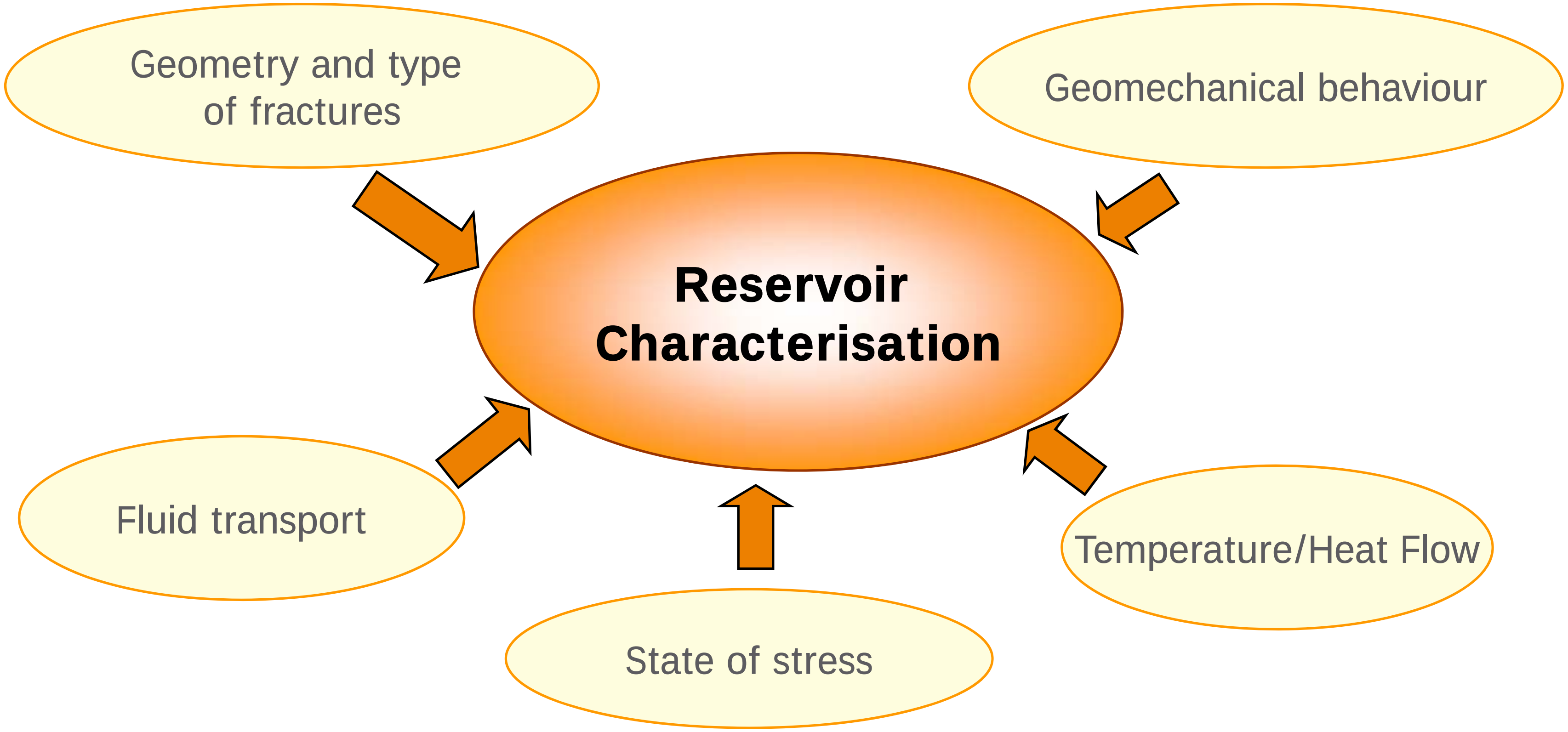
Exploration&Investigation

The objectives of *geothermal E&I* are:

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

Exploration&Investigation

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



Geometry and type of fractures

Geomechanical behaviour

Reservoir Characterisation

Fluid transport

Temperature/Heat Flow

State of stress

Exploration&Investigation

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

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

Exploration&Investigation

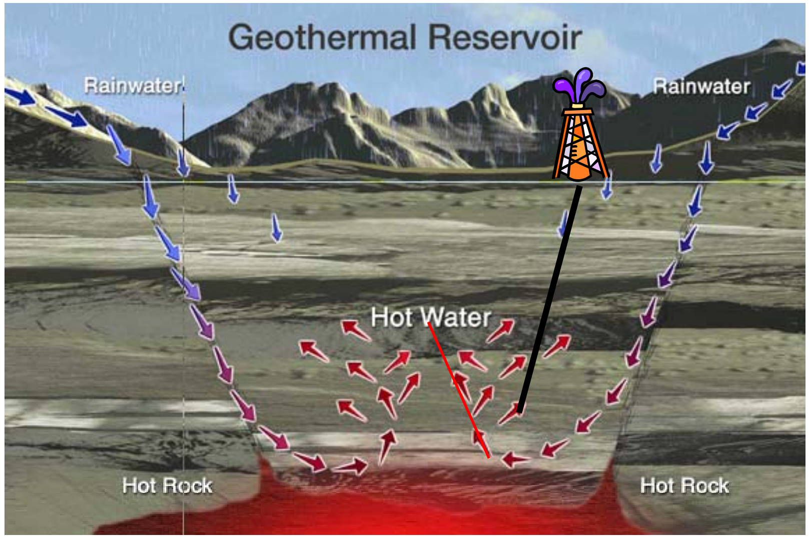
Goals to be achieved by Exploration&Investigation
1: before and during production

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

Main permeability is driven by fracture and faults.

wells $$$

avoid not economic wells



Exploration&Investigation

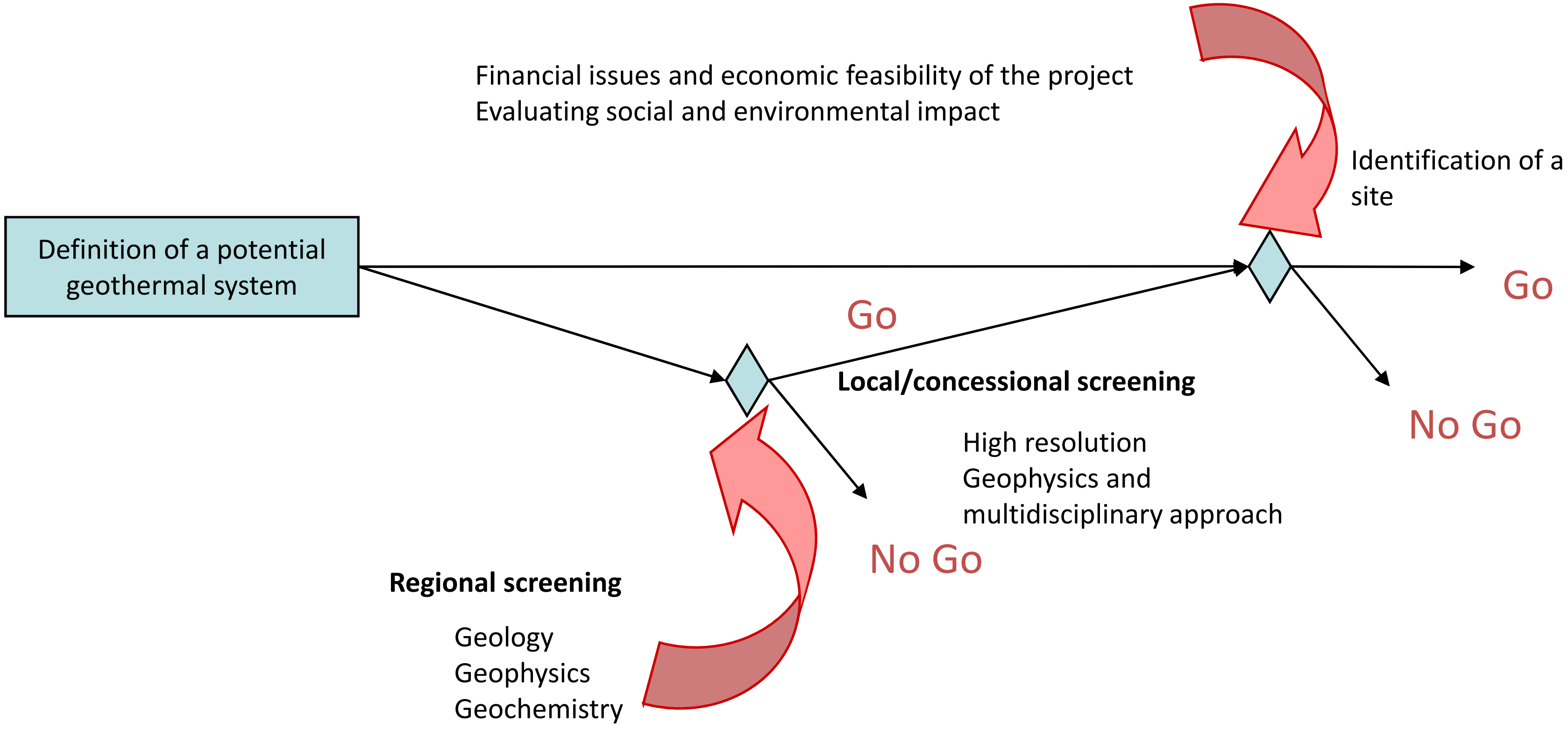
Goals to be achieved by Exploration&Investigation 2: during and after production

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

Exploration&Investigation

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

Choice is also related to cost



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

Identification of a site

Definition of a potential geothermal system

Go

Go

Local/concessional screening

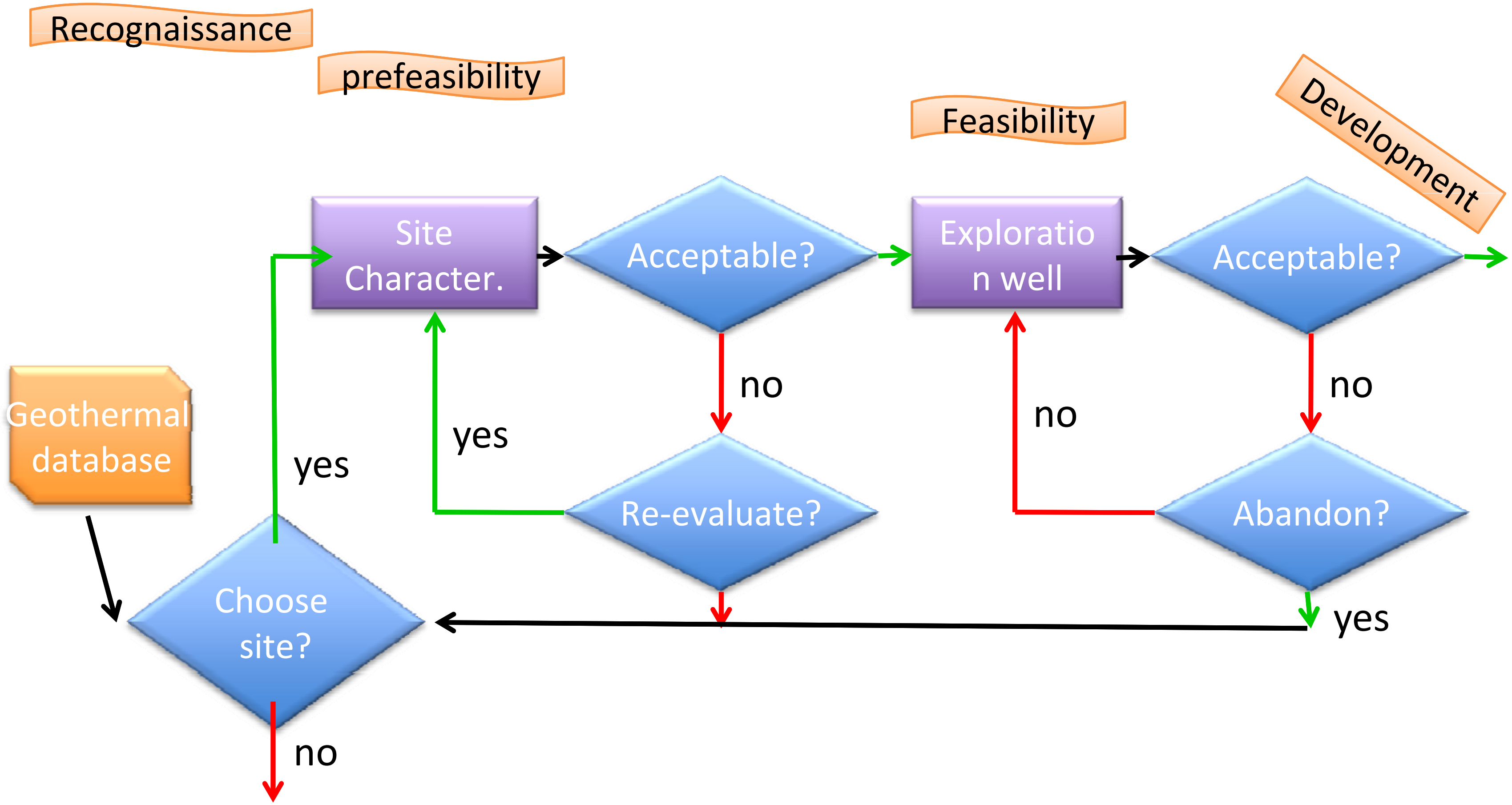
High resolution
Geophysics and
multidisciplinary approach

No Go

No Go

Regional screening

Geology
Geophysics
Geochemistry



Recognaissance

prefeasibility

Feasibility

Development

Site Character.

Acceptable?

Exploration well

Acceptable?

Geothermal database

no

no

yes

yes

no

Re-evaluate?

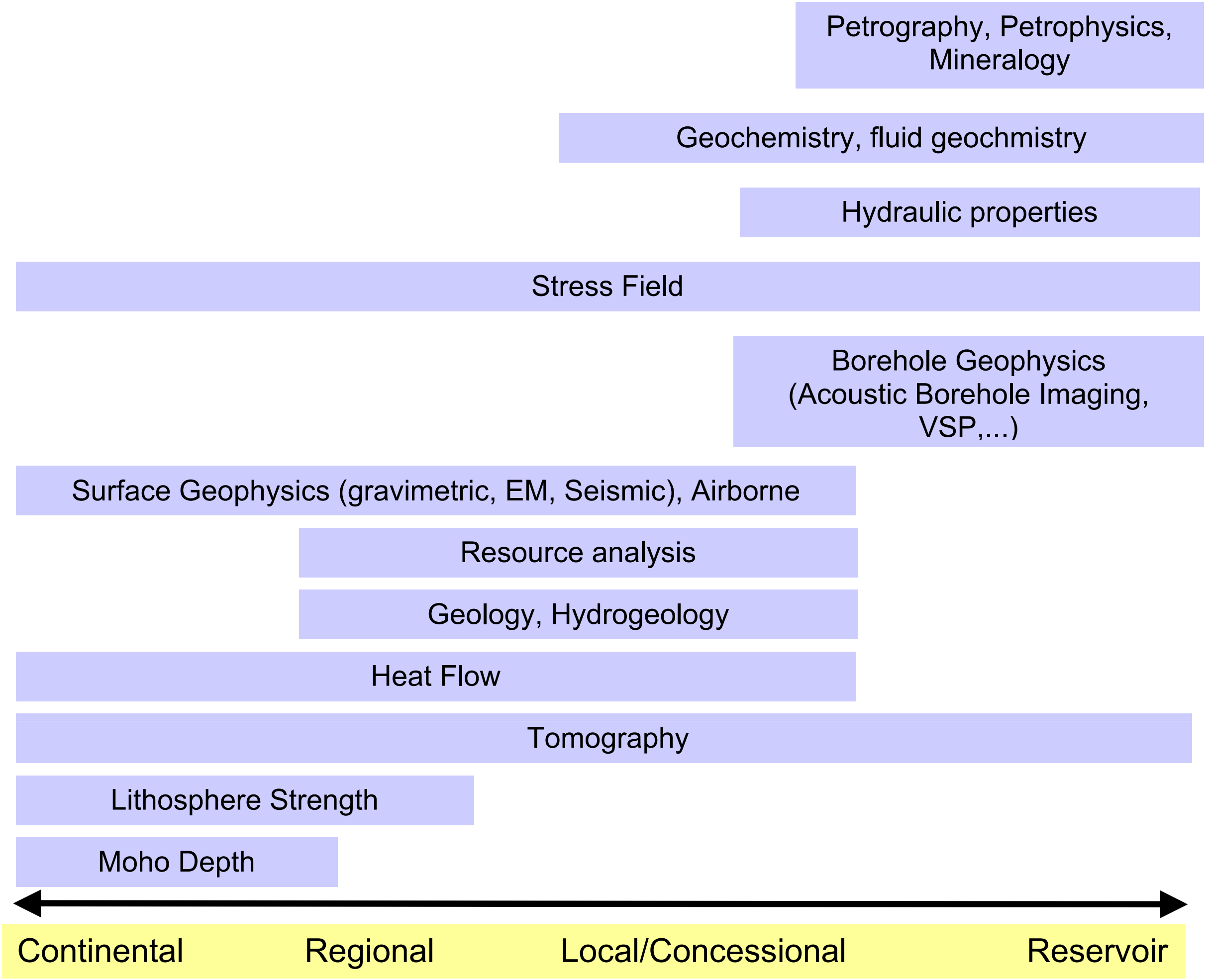
Abandon?

Choose site?

yes

no

A scale dependent approach



Petrography, Petrophysics, Mineralogy

Geochemistry, fluid geochmistry

Hydraulic properties

Stress Field

Borehole Geophysics (Acoustic Borehole Imaging, VSP,...)

Surface Geophysics (gravimetric, EM, Seismic), Airborne

Resource analysis

Geology, Hydrogeology

Heat Flow

Tomography

Lithosphere Strength

Moho Depth

Continental Regional Local/Concessional Reservoir

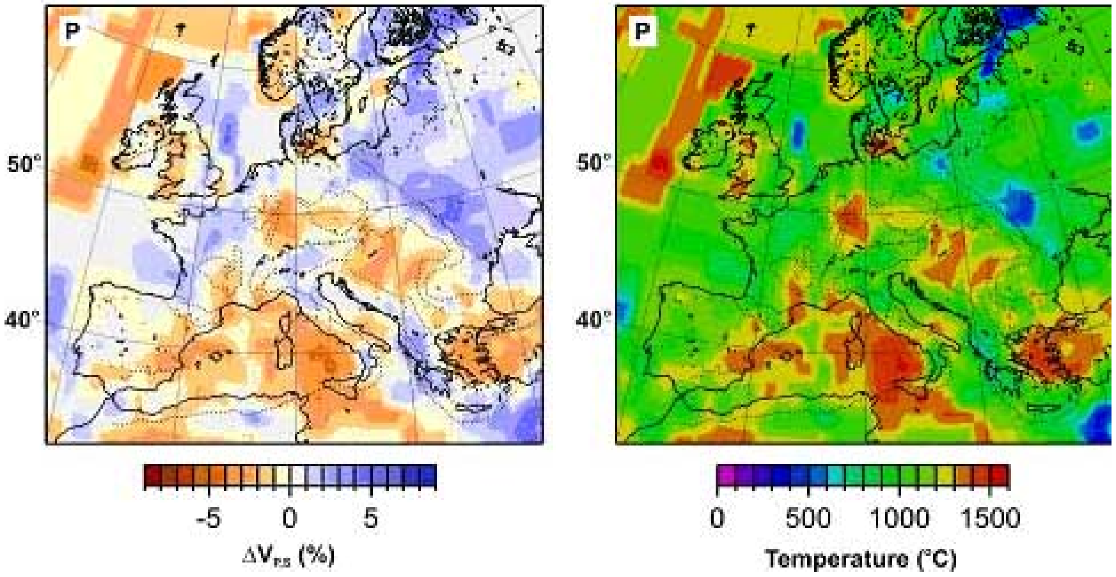
Continental scale E&I

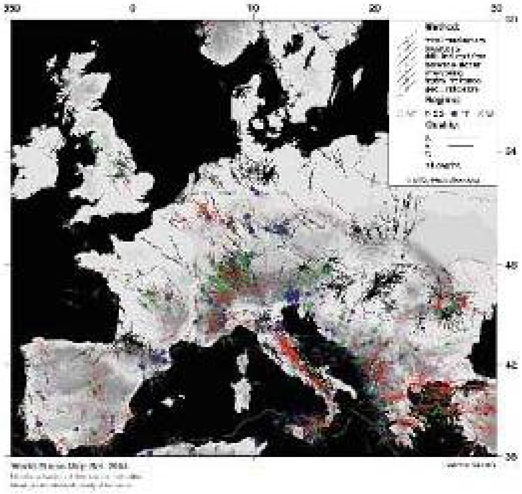
Identification of potentially interesting regions of interest is based on:

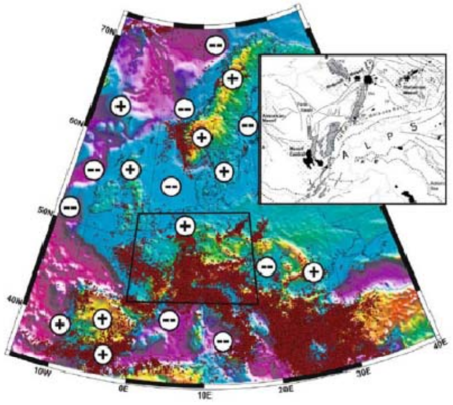
- Task: Identify thermal field at great depths (>10km)
  - from seismic tomography
  - from thermal modeling
- Task: Identify Deformation regime of the crust
  - from passive stretching models
  - Extensional regimes can be of high interest
- Task: Identify Stress regime (neo-tectonics)
  - from data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

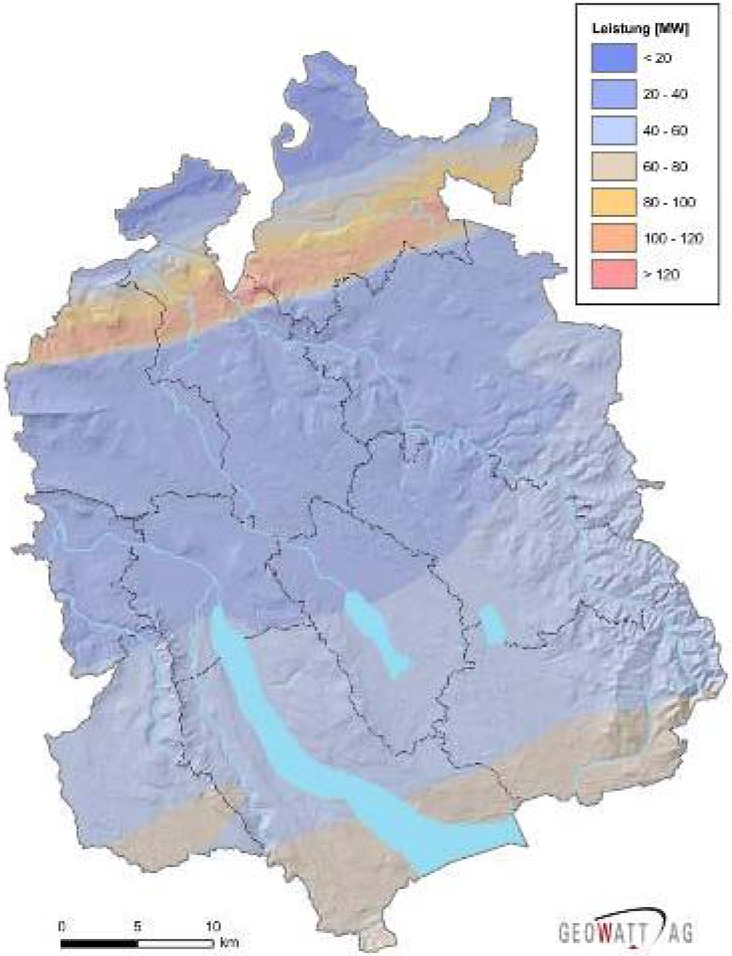
Concessional scale E&I

- 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



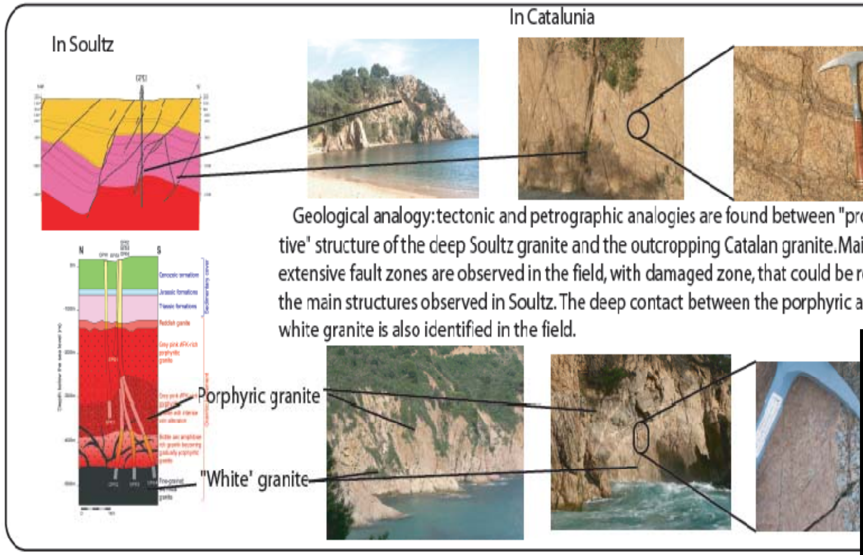
From Kohl et al., ENGINE Mid-Term conference

Reservoir scale E&I

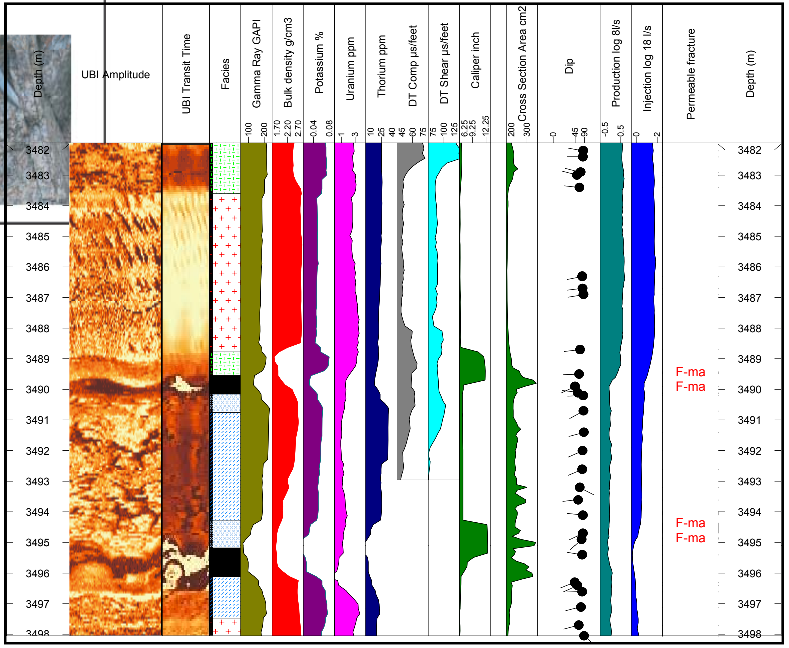
- Well geophysics
  - Vertical seismic profile, allows identification of structures at a distance from the well
  - Borehole acoustic imaging and sonic log provides information about fractures crossing boreholes
  - Borehole gravimetry can help defining conditions into the reservoir
  - Gamma ray and 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.

Reservoir scale E&I

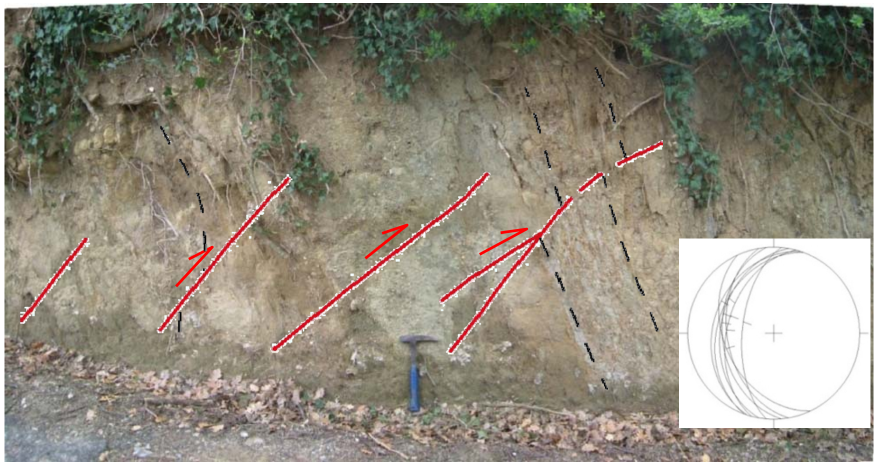
Analogue models

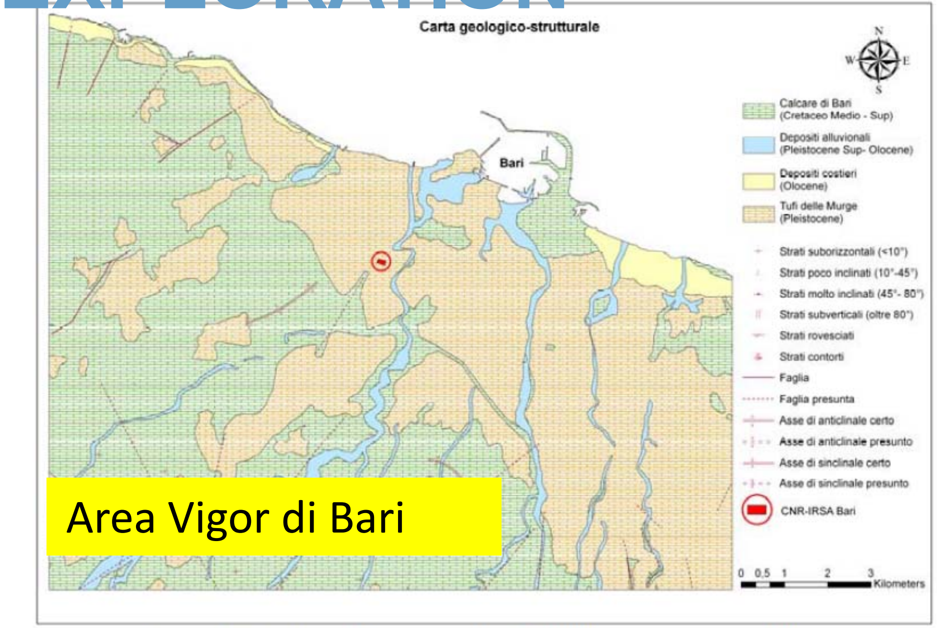


Geological analogy: tectonic and petrographic analogies are found between "prospective" structure of the deep Soultz granite and the outcropping Catalan granite. Main extensive fault zones are observed in the field, with damaged zone, that could be related to the main structures observed in Soultz. The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



GEOLOGICAL EXPLORATION

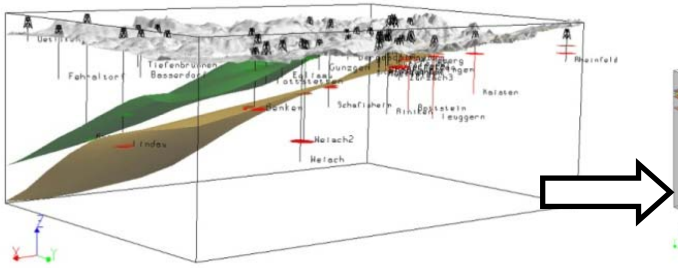




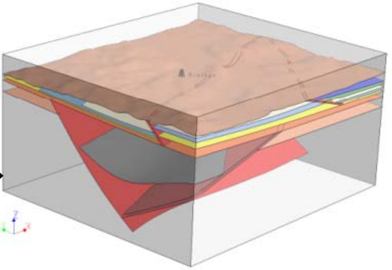
Area Vigor di Bari

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

Data collection

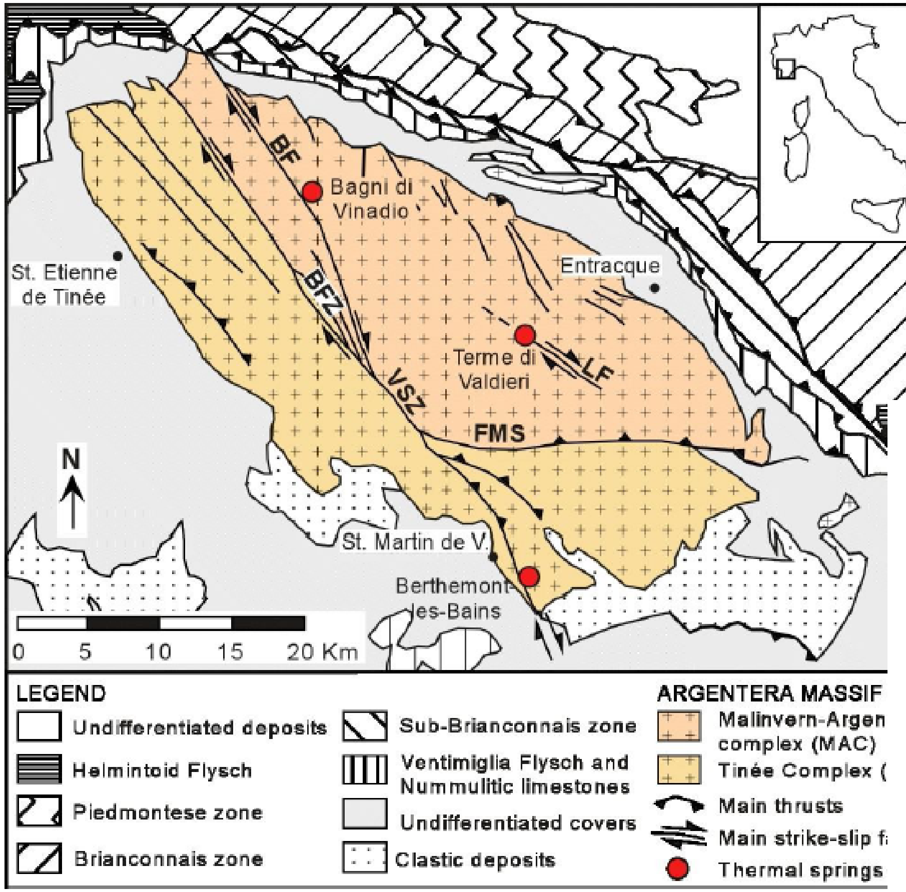


3D geological model

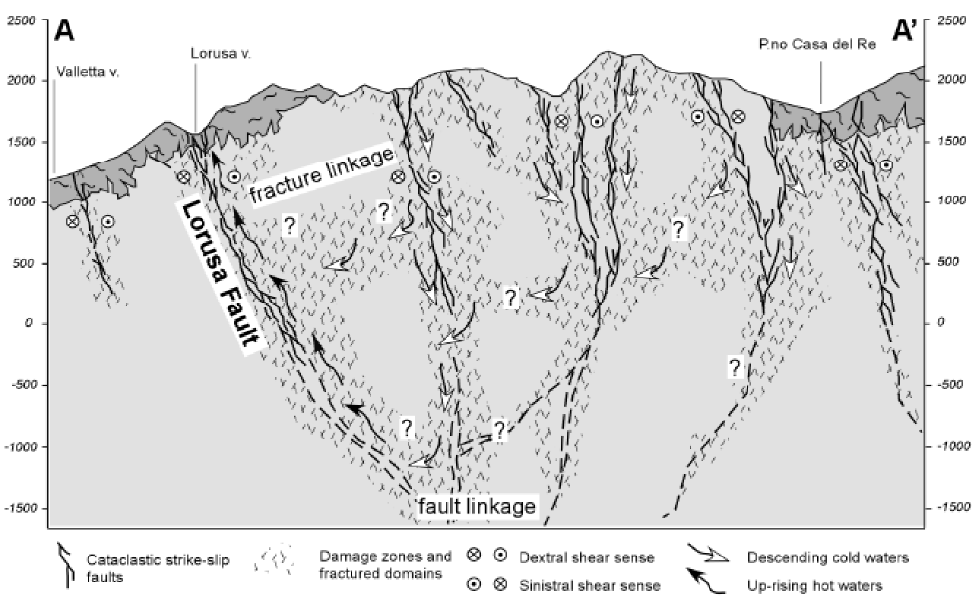


- **Geometry**
- **Fracture field**

GEOLOGICAL EXPLORATION

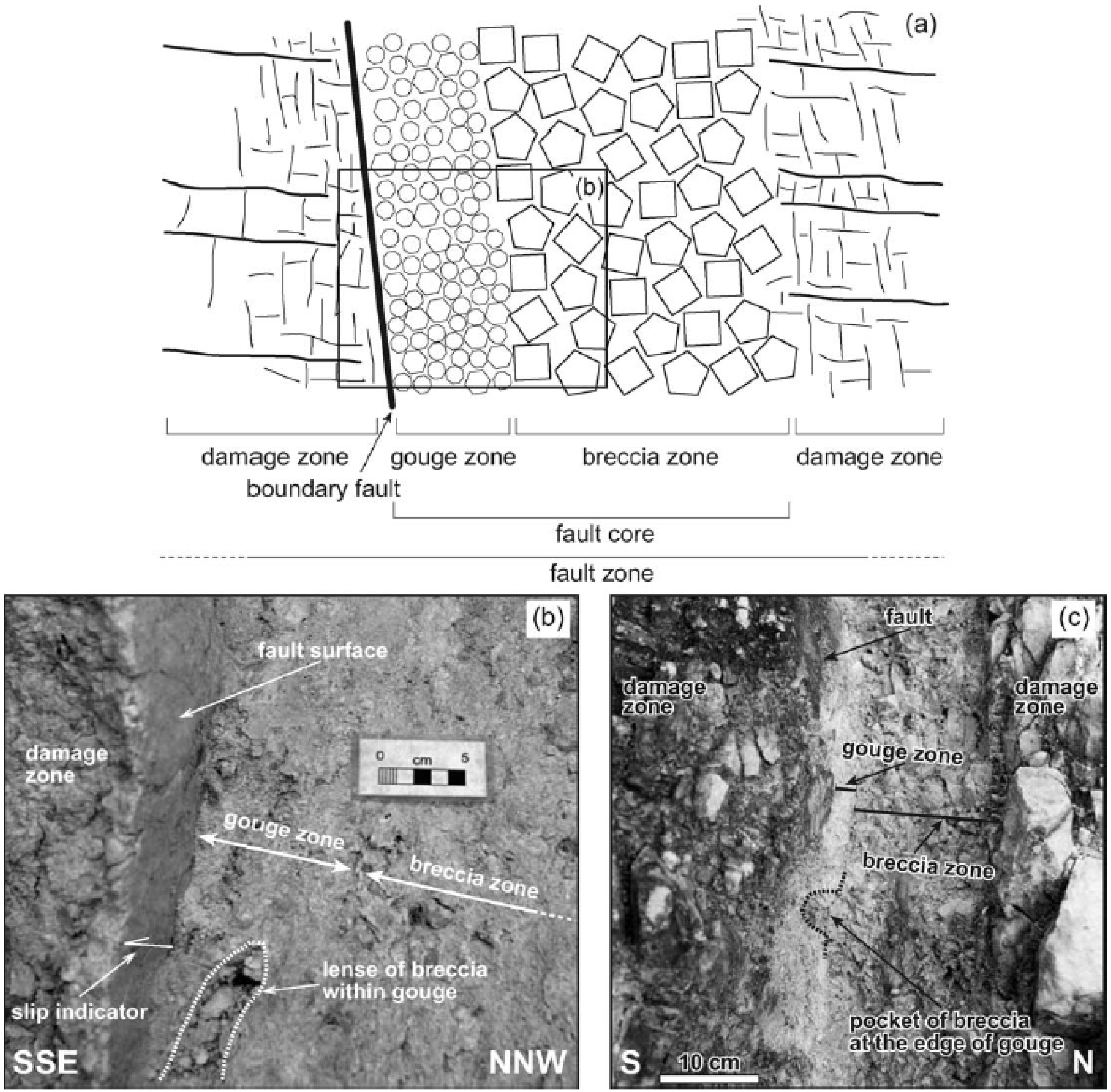


WHAT IS THE REASON OFA FRACTURE FIELD?



It can be

A. Billi / Journal of Structural Geology 27 (2005) 1823–1837



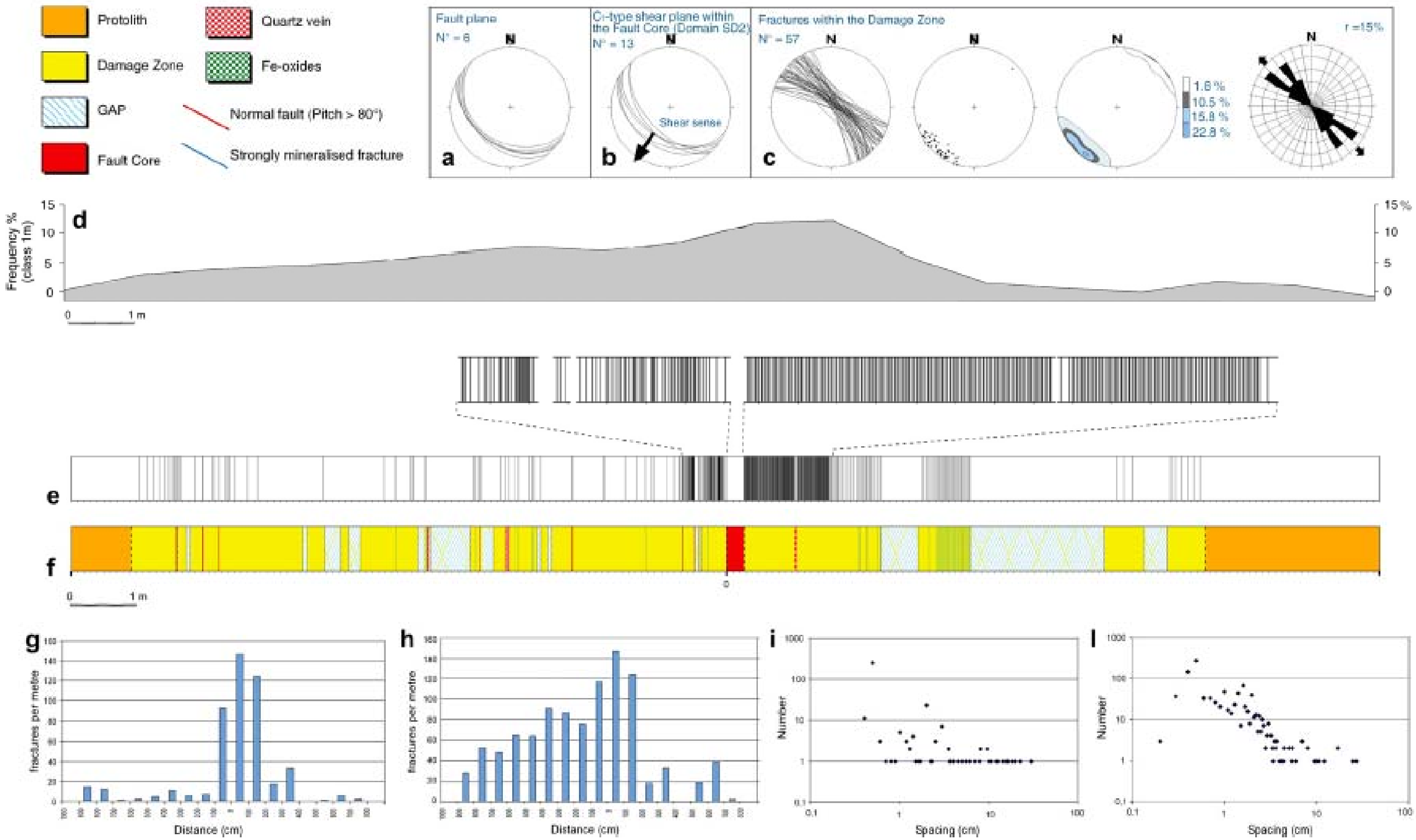


Fig. 9. Scan line across the fault zone exposed in Area 2 shown in Fig. 5. Structural information concerning kinematics, geometry and density of fractures are illustrated in the diagrams a–l: the equal-area plots (Schmidt diagram, lower hemisphere) indicate: (a) the great circles of the fault plane; (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.

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

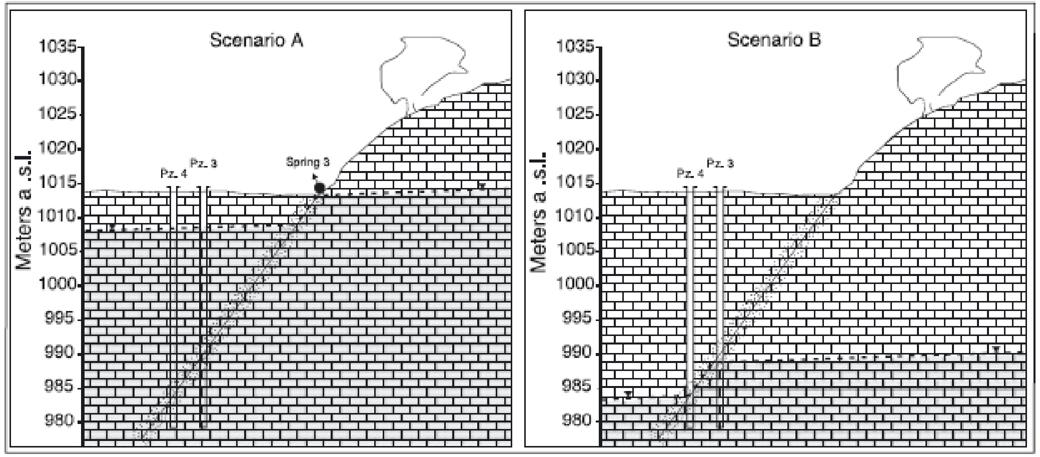


Fig. 8 Evolution of the hydrogeological setting in the fault zone over time (Scenario 'A' – hydraulic gradient monitored in the protolith; Scenario 'B' – hydraulic gradient monitored in the fault core).

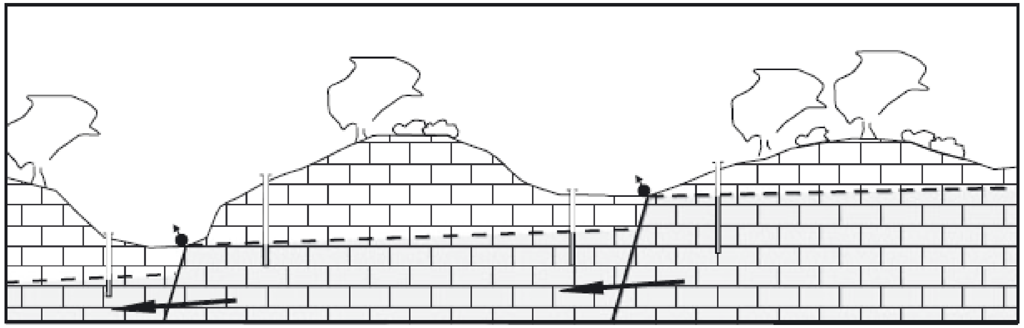
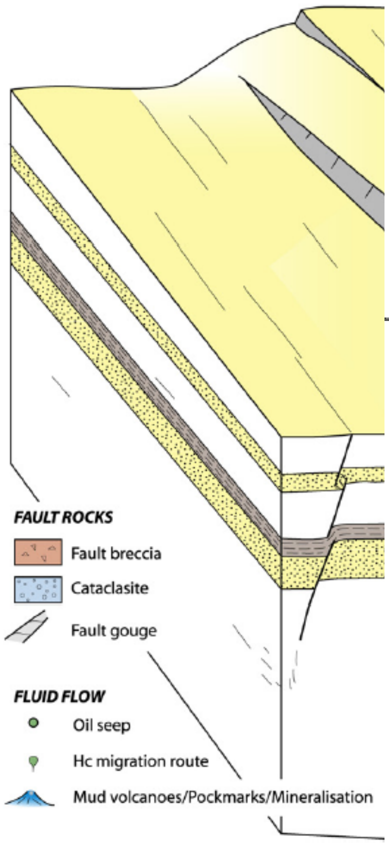


Fig. 9 Schematic representation of a basins-in-series aquifer system (the arrows represent the groundwater flowthrough in fault zones).



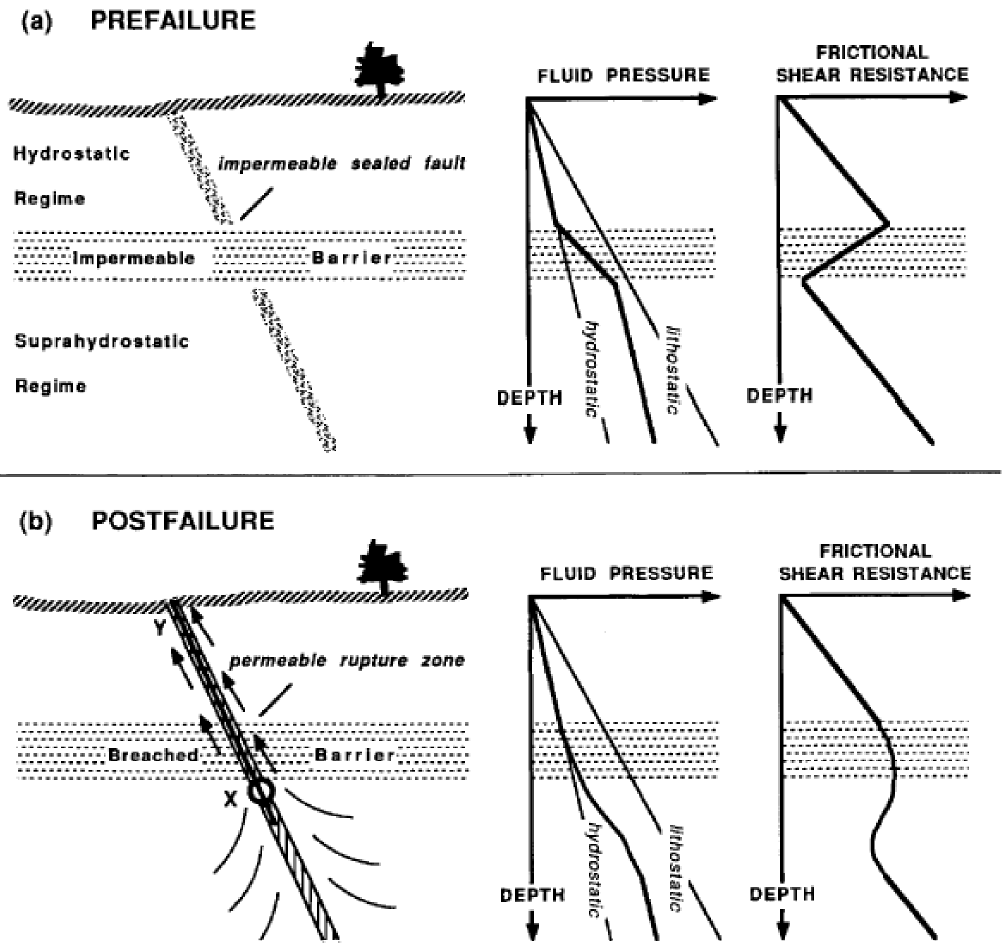
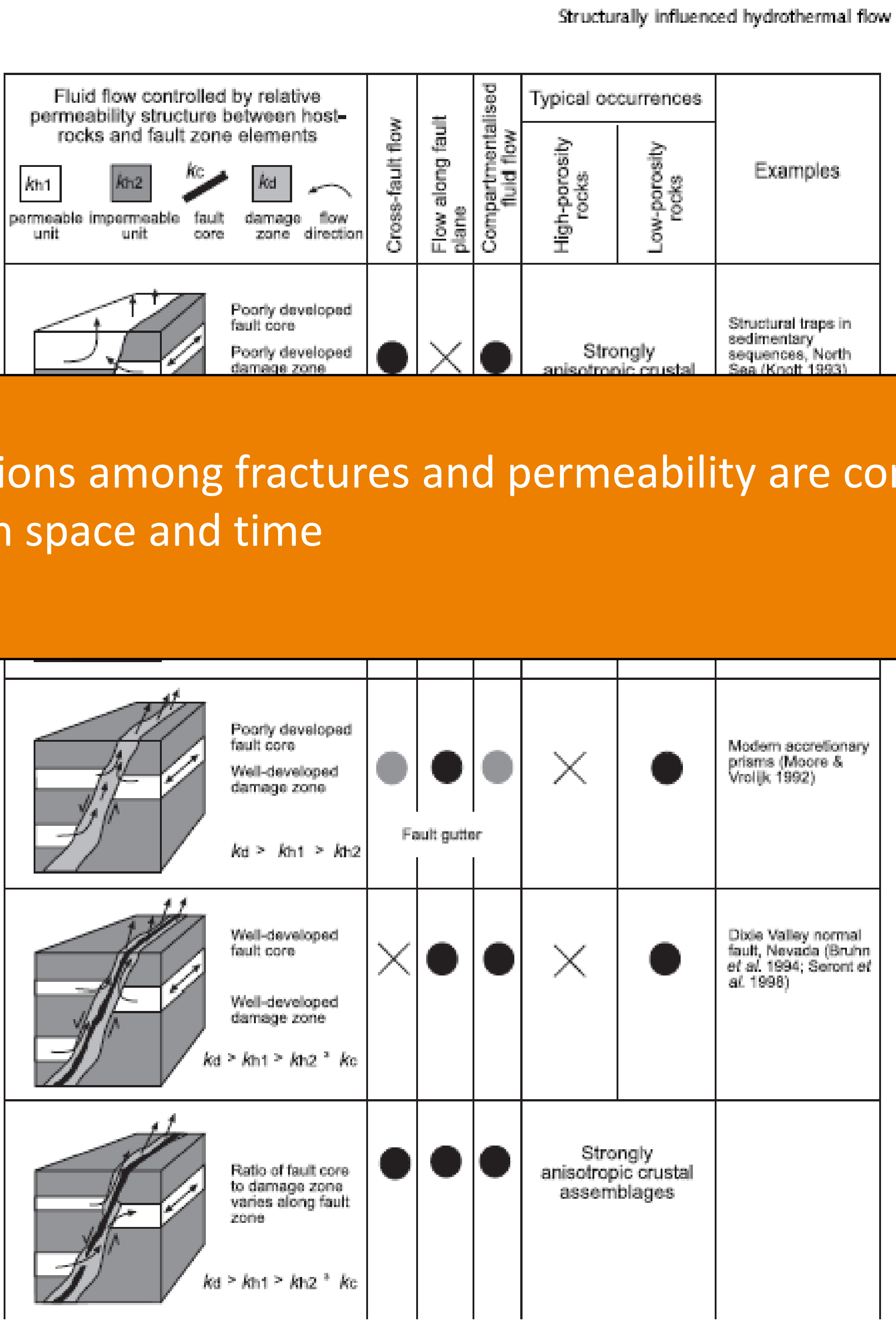


Fig. 5. Potential for fault-valve behaviour (a) Impermeable barrier separating hydrostatic and suprahydrostatic fluid pressure regimes. (b) Breaching of barrier by fault rupture X-Y, leading to an upwards discharge of fluids.

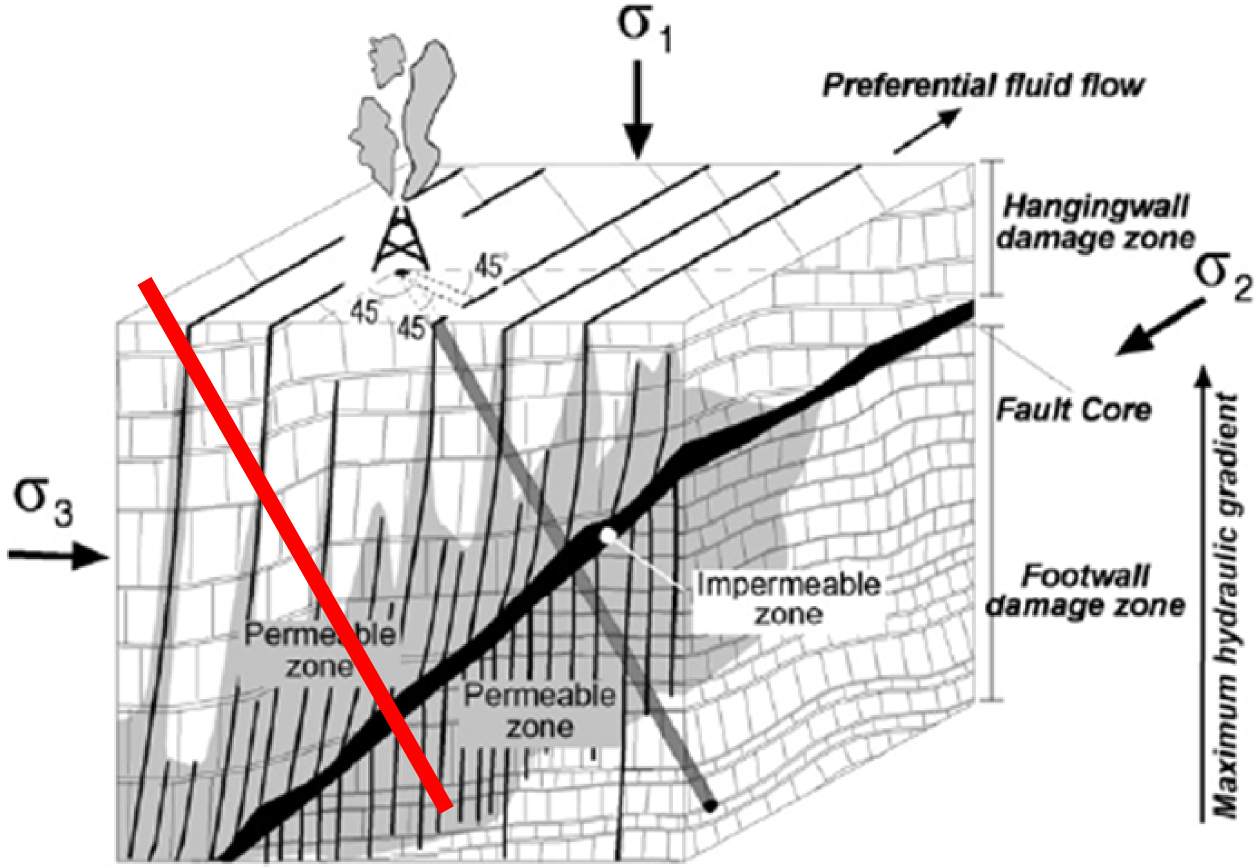
Fig. 2. Block diagram showing the evolution, from left to
linkage of the individual faults, incorporating the slices o
which then gets "eaten up" as the fault continues to grow. A few simple fluid trapping and migration pathways are also shown for illustration.



Structurally influenced hydrothermal flow

Fluid flow controlled by relative permeability structure between host-rocks and fault zone elements kh1 permeable unit kh2 impermeable unit kc fault core kd damage zone flow direction	Cross-fault flow	Flow along fault plane	Compartmentalised fluid flow	Typical occurrences: High-porosity rocks	Typical occurrences: Low-porosity rocks	Examples
Poorly developed fault core Poorly developed damage zone	●	✕	●	Strongly anisotropic crustal		Structural traps in sedimentary sequences, North Sea (Knott 1993)
Poorly developed fault core Well-developed damage zone kd > kh1 > kh2	◍	● Fault gutter	◍	✕	●	Modern accretionary prisms (Moore & Vrolijk 1992)
Well-developed fault core Well-developed damage zone kd > kh1 > kh2 ³ kc	✕	●	●	✕	●	Dixie Valley normal fault, Nevada (Bruhn *et al.* 1994; Seront *et al.* 1998)
Ratio of fault core to damage zone varies along fault zone kd > kh1 > kh2 ³ kc	●	●	●	Strongly anisotropic crustal assemblages		

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


σ1
Preferential fluid flow
Hangingwall damage zone
σ2
45°
45
45
Fault Core
σ3
Footwall damage zone
Impermeable zone
Permeable zone
Permeable zone
Maximum hydraulic gradient

GEOPHYSICAL EXPLORATION

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.

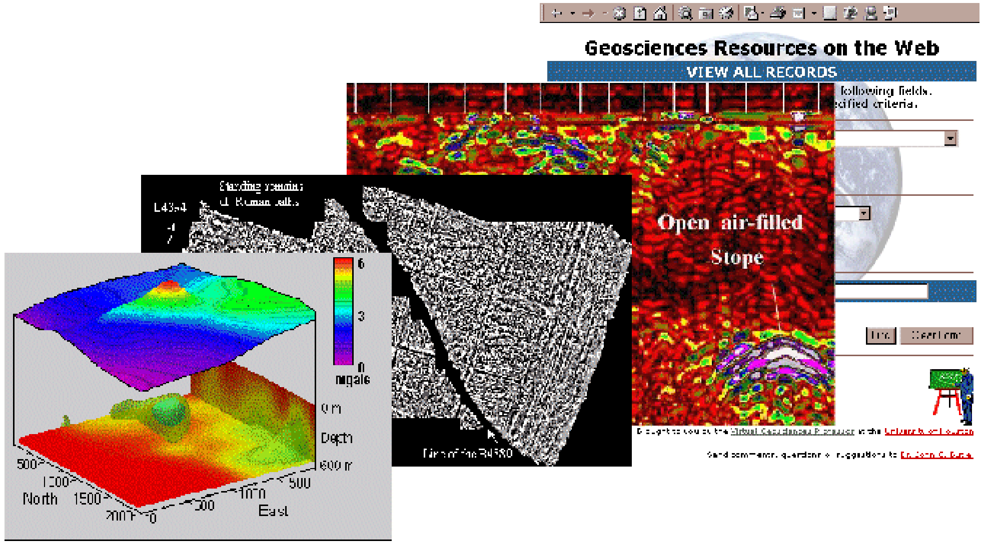
Geophysical techniques are indirect investigation surveys (from the surface or in hole) which allow to evaluate the distribution of some physical parameter:

- 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.

GEOPHYSICAL EXPLORATION

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

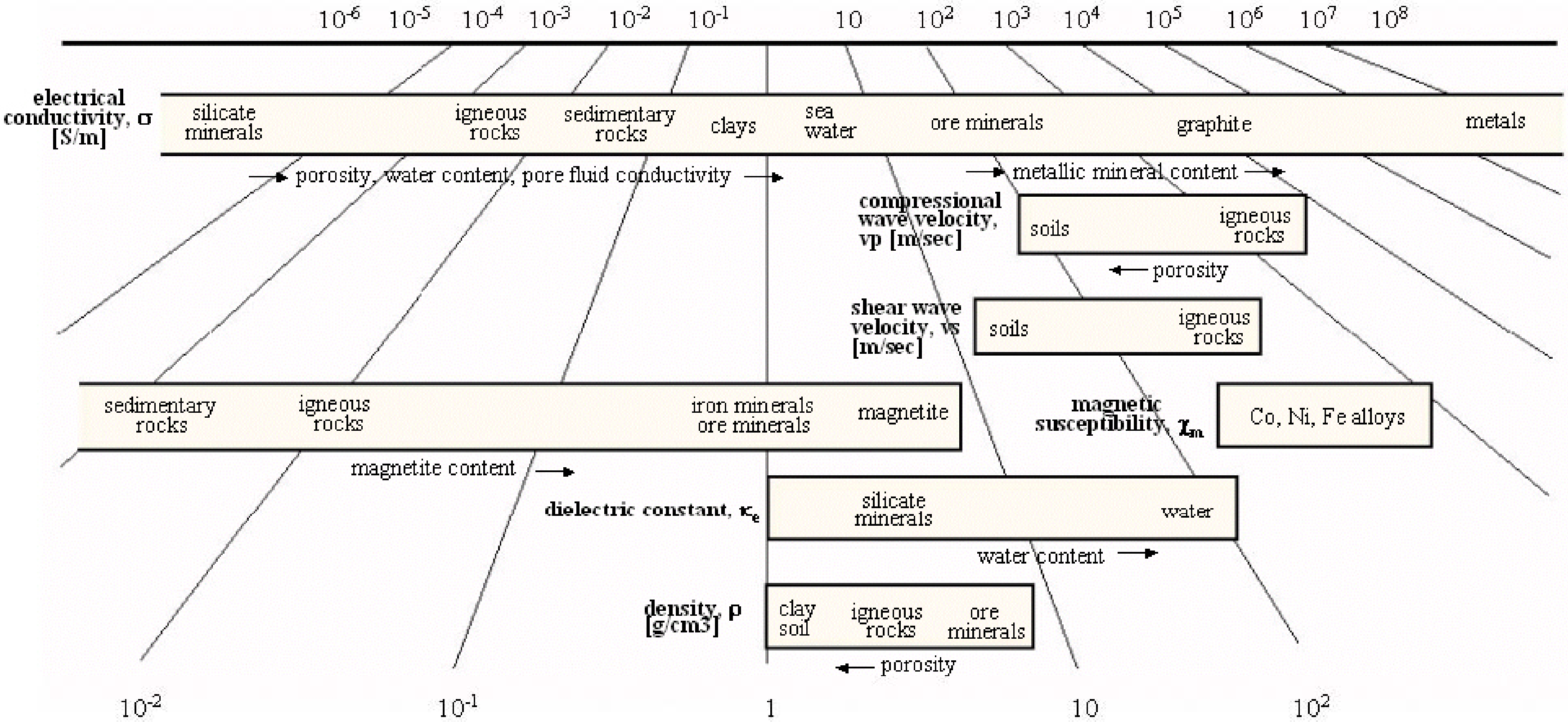


This is obtained by measuring the response of the medium under investigation to the passage of a certain “energy field”:

natural → passive tests or artificially induced → active tests

GEOPHYSICAL EXPLORATION

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



GEOPHYSICAL EXPLORATION

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
Porosoty	🟥	⬜	🟥	🟩	🟩
Permeability	⬜	⬜	🟦	🟦	🟦
Water content	🟩	⬜	🟥	🟥	🟩
Water quality	⬜	⬜	🟥	⬜	⬜
Clay content	🟦	⬜	🟥	🟦	🟩
Magnetic mineral content	🟩	🟥	🟦	⬜	⬜
Metallic mineral content	🟥	⬜	🟥	⬜	🟩
Mechanical properties	🟩	⬜	🟩	🟦	🟥
Subsurface structure	🟩	🟩	🟩	🟥	🟥

🟥 **Strong**	🟩 **Moderate**	🟦 **Weak**	⬜ **None**

Degree of reletionship

GEOPHYSICAL EXPLORATION

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*).

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

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)

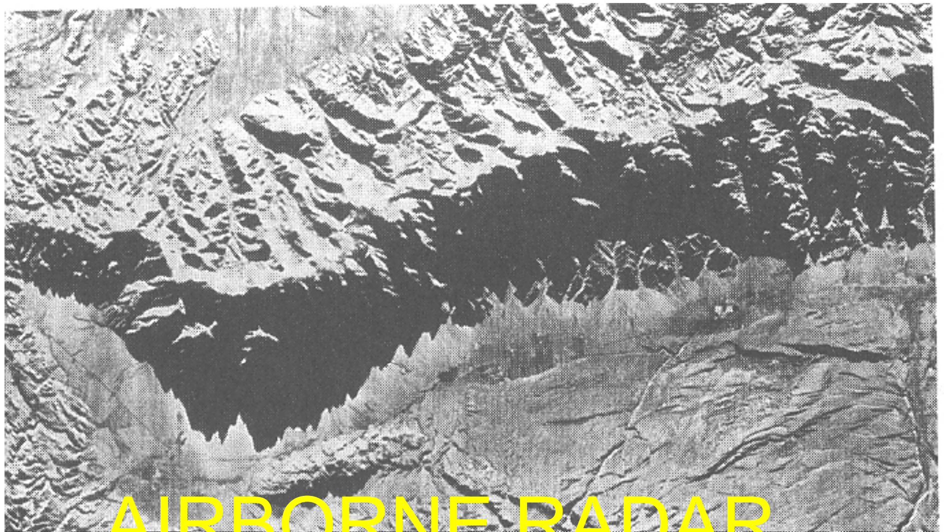
EM radiation/matter interactions of interest:

Transmission > refraction ($n=c_a/c_s$)

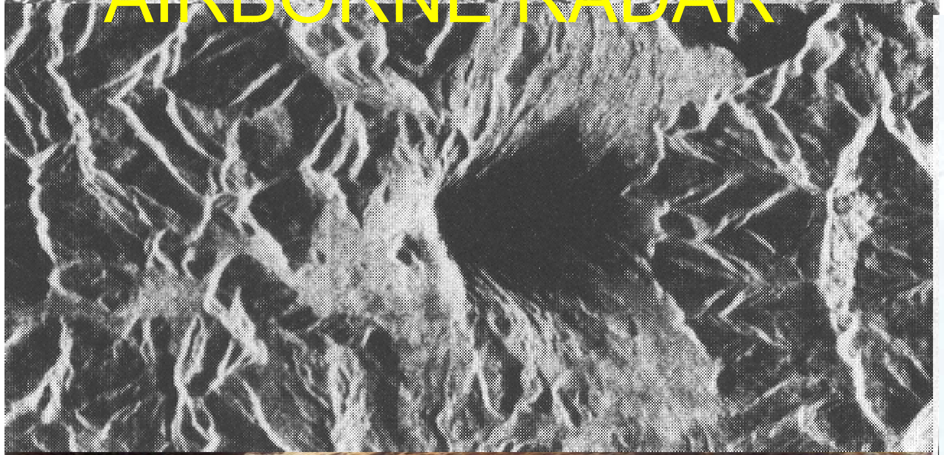
Absorption > largely heating Surface phenomena

Emission > f(structure, temperature of material)

Scattering, Reflection, Polarization Volume phenomena



AIRBORNE RADAR



LANDSAT

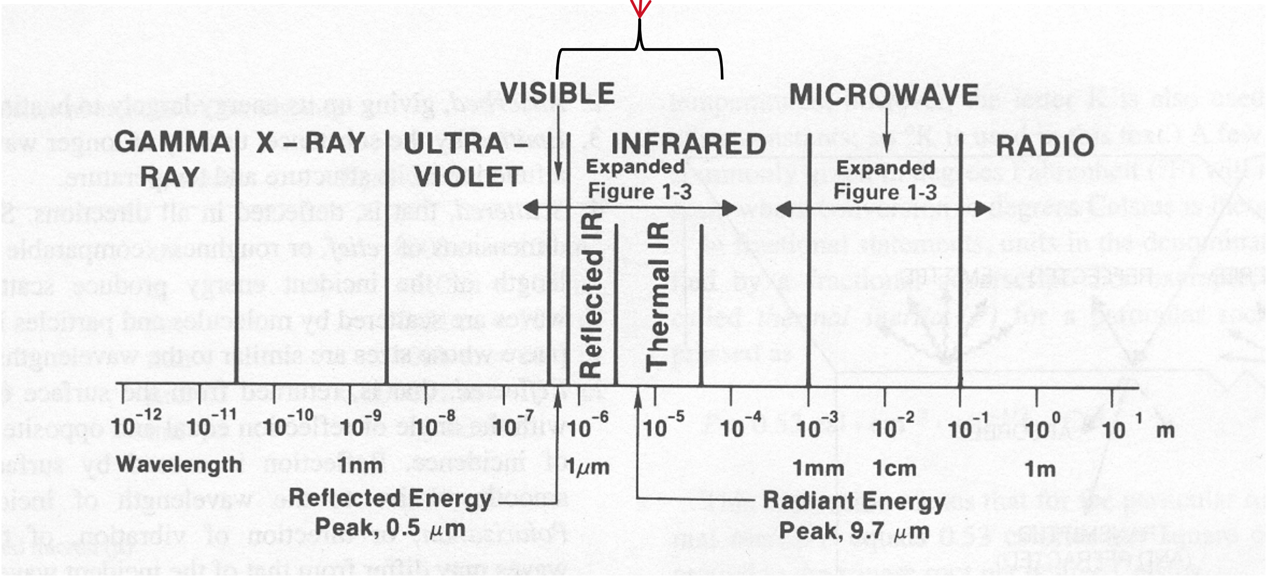
Applications to geothermal exploration

Optical

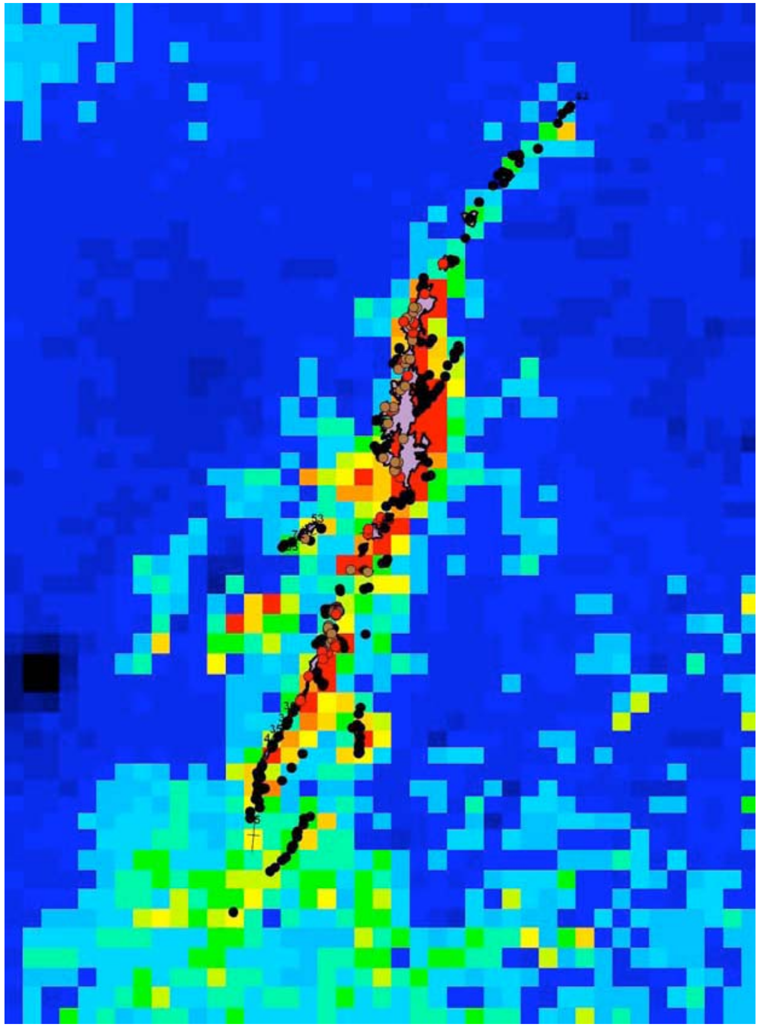
Near-Infrared

Thermal-Infrared

imagery can be used to identify surface expressions of geothermal resources

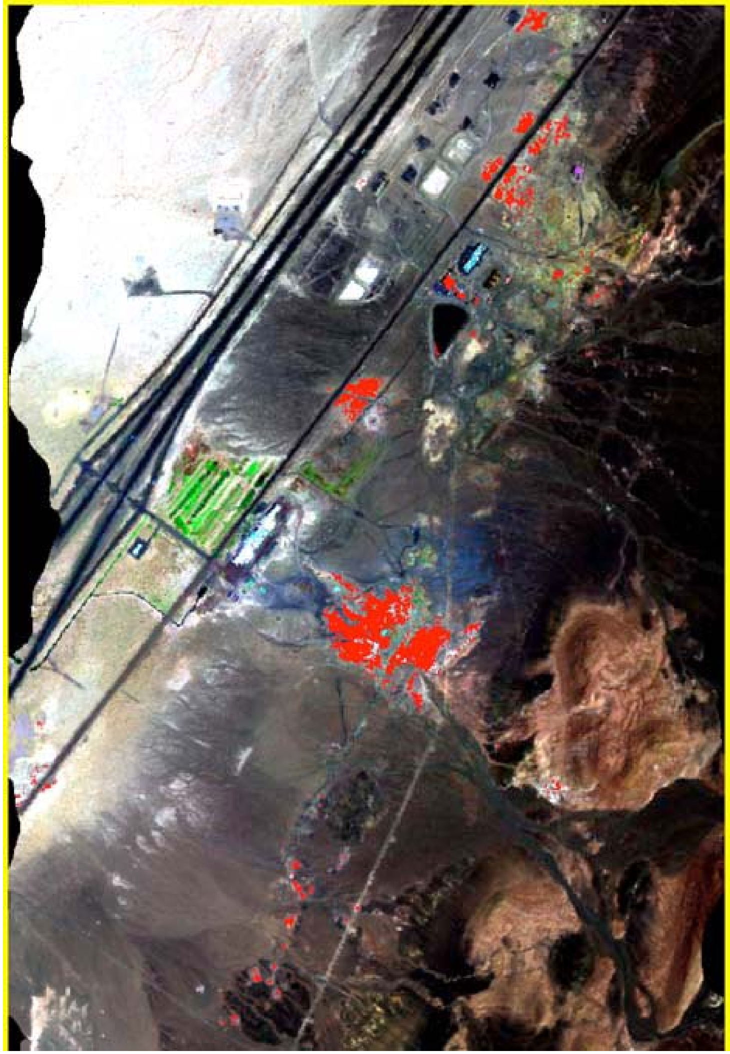


Example



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)

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 $g=GM_E/R^2$

GRAVITY SURVEYS

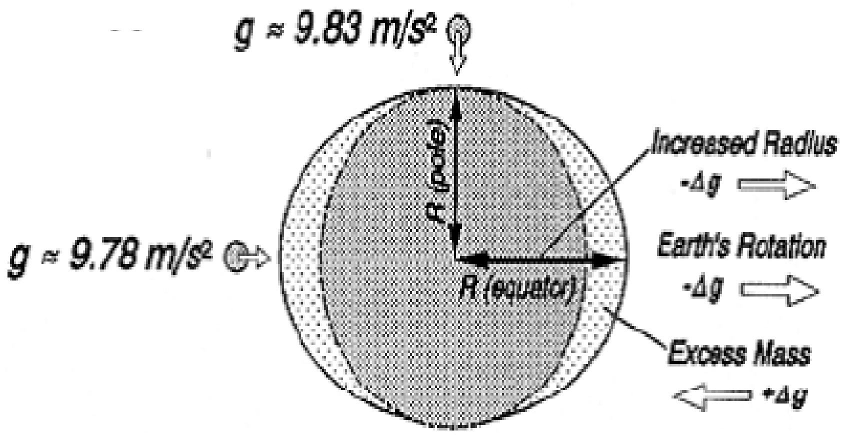
- 1 gal = 10^{-2} m/s^2
- 1 mgal = 10^{-3} gal = 10^{-5} m/s^2
- 1 µgal = 10^{-6} gal = 10^{-8} m/s^2 (precision of a gravimeter for geotechnical surveys)

- Gravity Unit: 10 gu = 1 mgal

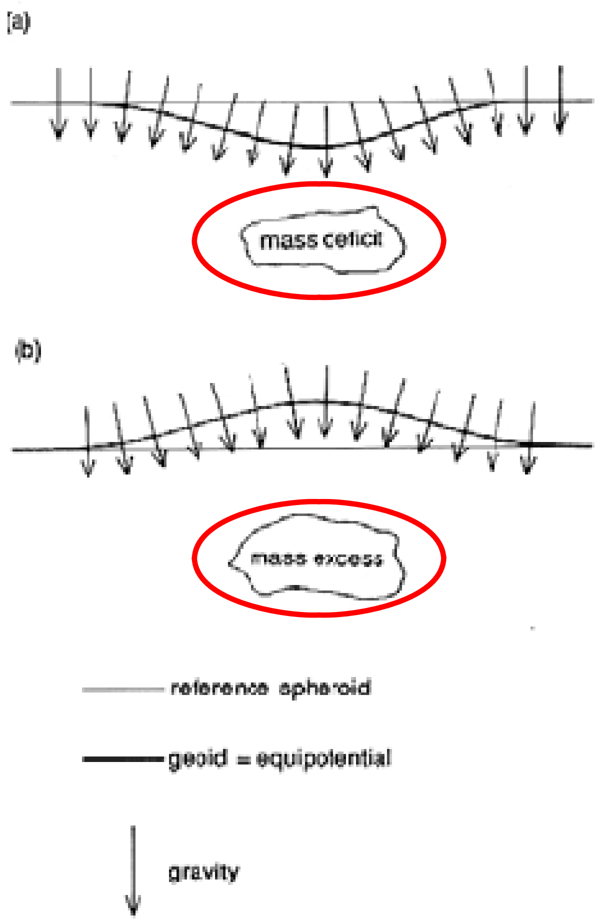
- Mean gravity around the Earth: 9.81 m/s^2 or 981000 mgal

GRAVITY SURVEYS

The mean value of the field at a point on the earth's surface is mostly determined by the mass of the earth but small local variations in mass perturb this mean value.



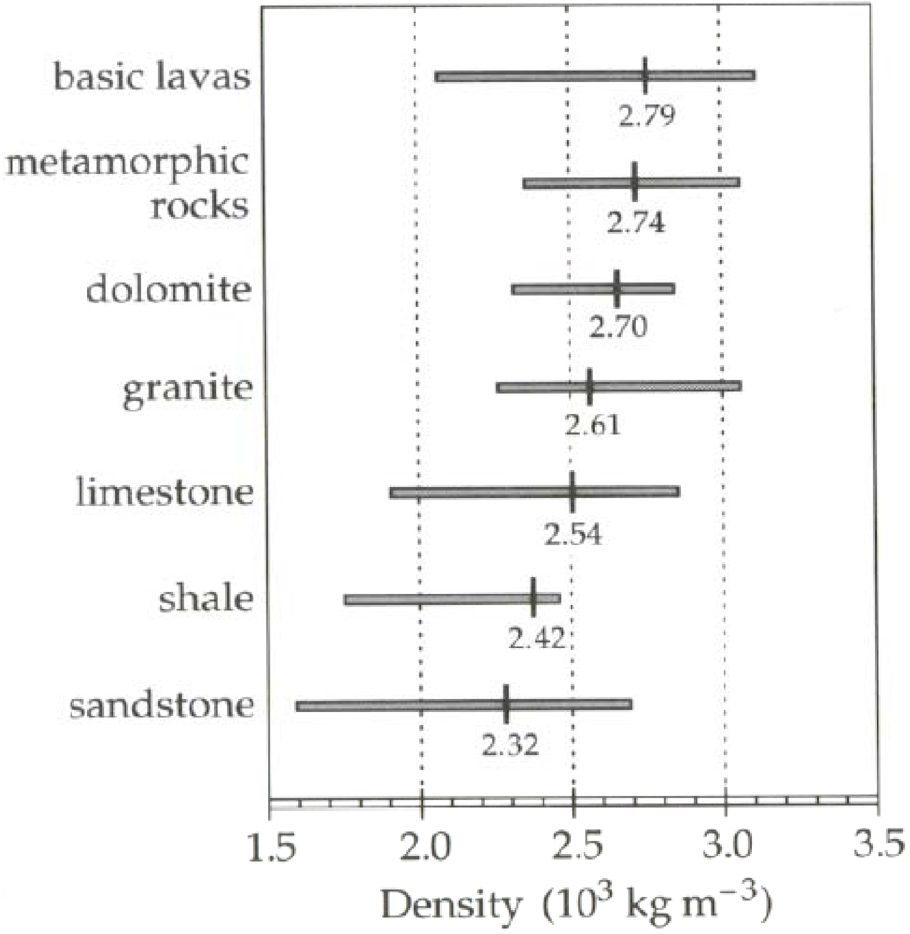
Large scale variations: global or regions



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



GRAVITY SURVEYS

Absolute measurements

- Large pendulums

$$T = 2\pi \sqrt{L/g}$$

- Falling body techniques

$$z = \frac{1}{2} g t^2$$

For a precision of 1 mgal

Distance for measurement 1 to 2 m

z known at 0.5 µm

t known at 10^{-8} s

Relative measurements

- Gravimeters
- Use spring techniques
- Precision: 0.01 to 0.001 mgal

Relative measurements are used since absolute gravity determination is complex and long!

AUTOGRAV:

Rapid (6 mas/sec)

Autoleveling

Filtering

Datastorage

GRAVITY SURVEYS

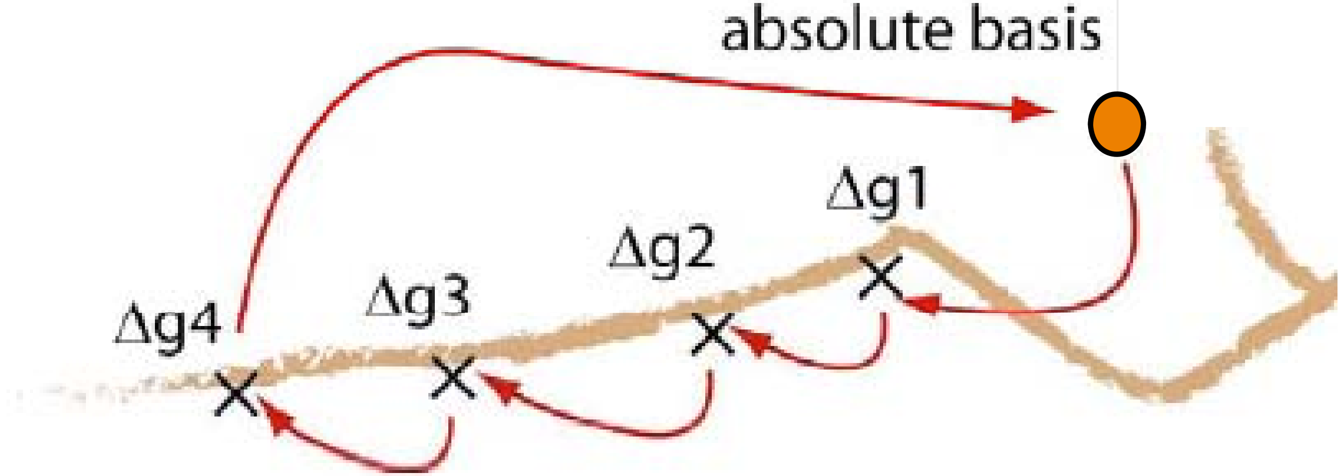
The magnitude of gravity depends on 5 factors:

- Latitude
- Elevation
- Topography of the surrounding terrains
- Earth tides
- Density variations in the subsurface:

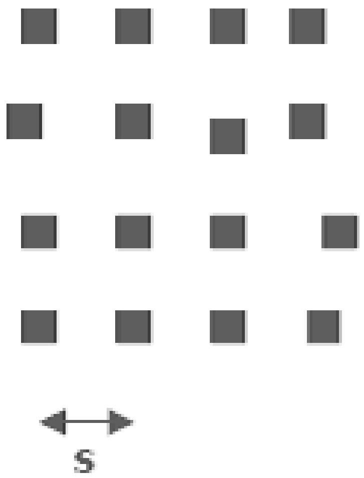
  this is the factor of interest in gravity exploration, but it is much smaller than latitude or elevation effects!

GRAVITY SURVEYS

- Good location is required (about 10m)
- Uncertainties in elevations of gravity stations account for the greatest errors in reduced gravity values (precision required about 1 cm) (use dGPS)
- Frequently read gravity at a base station (looping) needed



GRAVITY SURVEYS



Survey design considerations

- **Uniform grid – for easier interpretation**
- **Station spacing: s < h**

  h is the depth of the body of interest
- **Avoid steep tomographic gradients**
- **Absolute and relative station locations are needed** …how accurate?

Typical station spacing

Regional geologic studies: km to 10s of km

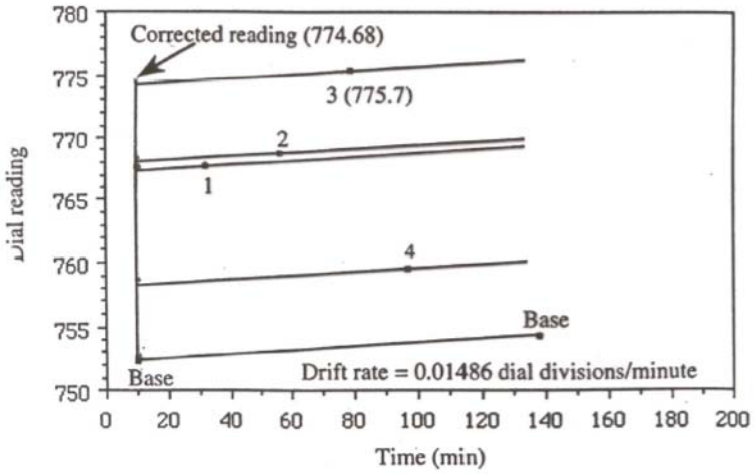
Local structure/Engineering/Environmental: 10s to 100s m

Near surface e.g. archeology: few meters

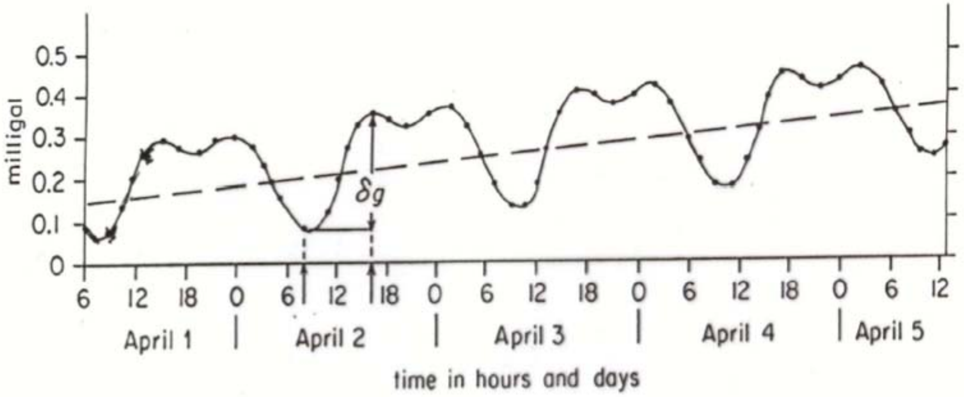
GRAVITY SURVEYS

g_{obs} can be computed for the stations using Δg only after the following corrections:

- Drift correction



- Tidal correction



Effect of the Moon: about 0.1 mgal

Effect of the Sun: about 0.05 mgal

GRAVITY SURVEYS

$$BA = g_{obs} - g_{model}$$

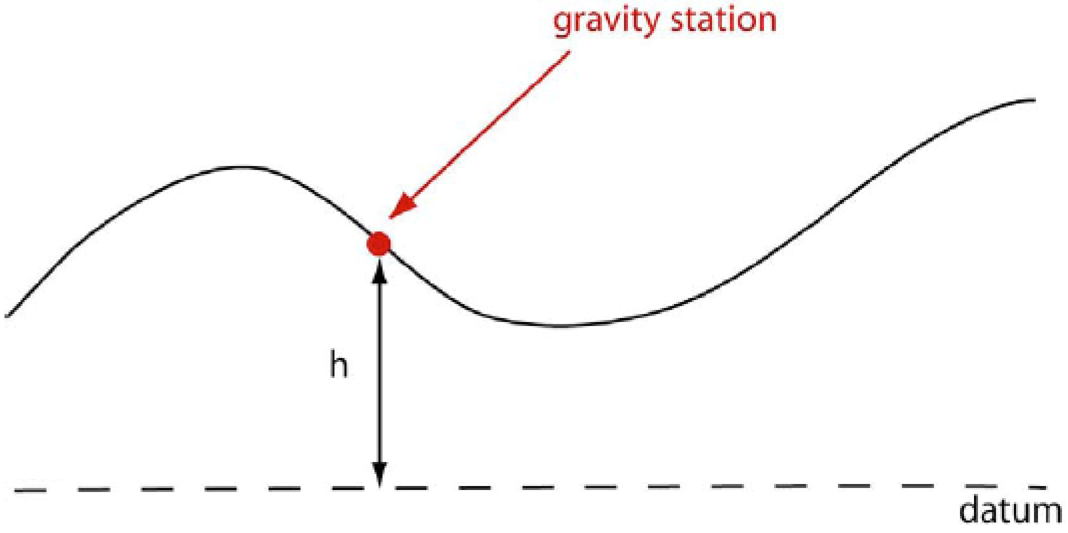
$$g_{model} = g_{\phi} - FAC + BC - TC$$

g_{model}	model for an on-land gravity survey
g_{ϕ}	gravity at latitude ϕ (latitude correction)
FAC	free air correction
BC	Bouguer correction
TC	terrain correction

GRAVITY SURVEYS

The *FAC* accounts for variation in the distance of the observation point from the centre of the Earth.

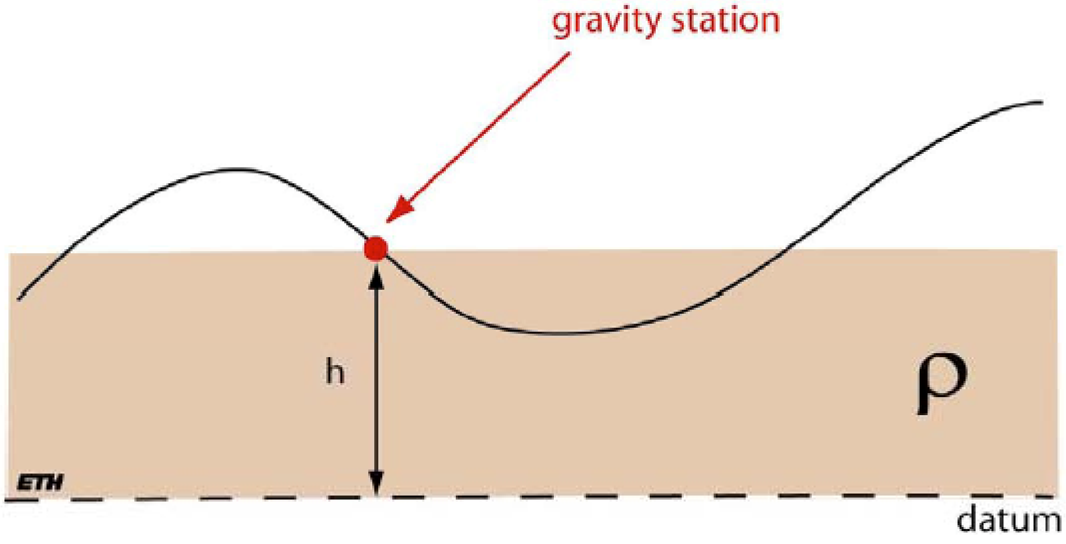
This equation must also be used to account for the distance ground/gravimeter.



GRAVITY SURVEYS

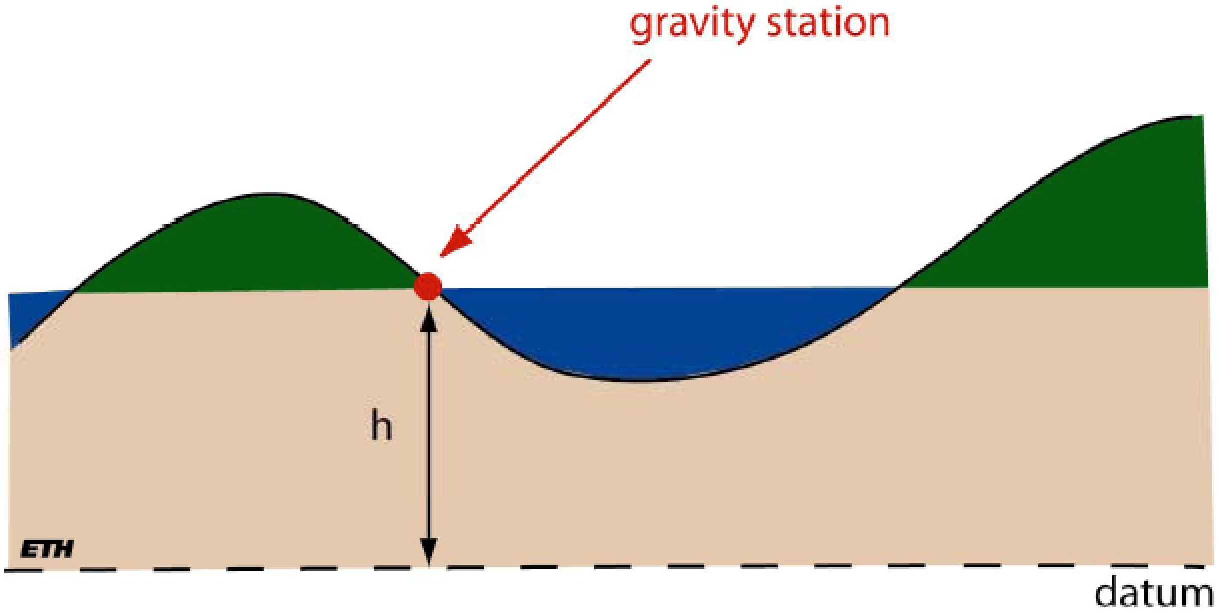
- The *BC* accounts for the gravitational effect of the rocks present between the observation point and the datum
- Typical reduction density for the crust is ρ =2.67 g/cm^3

$$BC = 2\pi\, G\, \rho\, h$$



GRAVITY SURVEYS

The *TC* accounts for the effect of topography.



GRAVITY SURVEYS

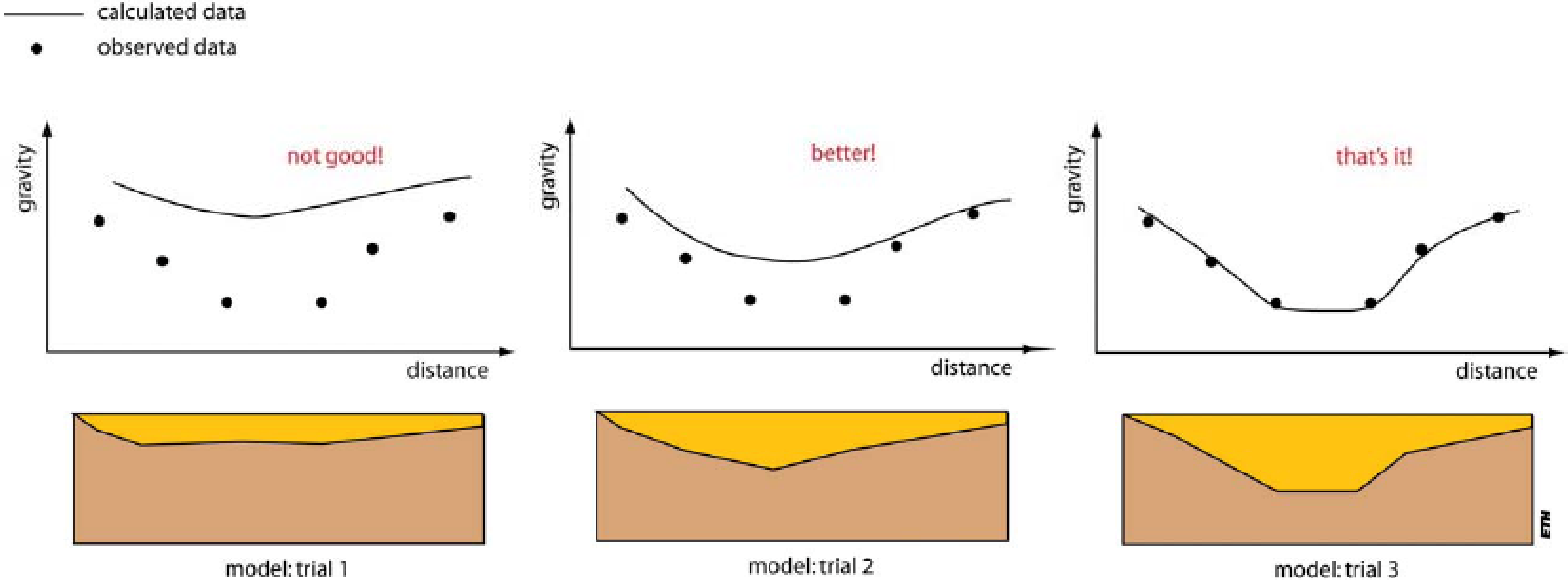
Inverse Problem!!!

(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)



GRAVITY SURVEYS

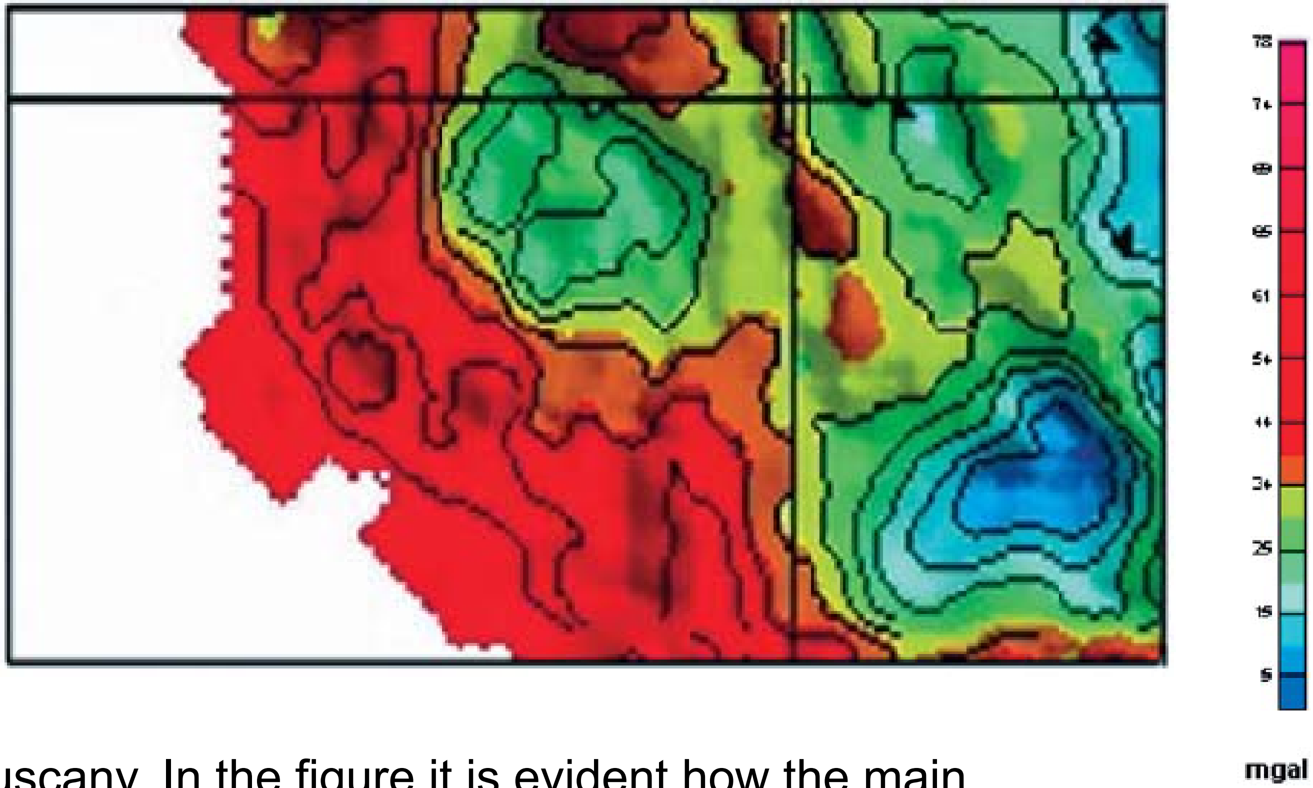
The primary use of gravimetric measurements today is to help constrain the structural context of an area, outline trends of faults or the depth of the basement. They are often used for this purpose as one of the first steps to characterise a region of interest and to help constrain areas for further inspection.

The long-wavelength components reflect large-scale structural heterogeneities of the lithosphere, supposedly related to its thermal regime. The regional relatively short-wavelength components (L <2000 km) correlate with specific tectonic structures, which in turn may be related to geothermal conditions.

When regional seismic reflection and tomography data are available it is possible to separate gravity effect of the Moho variations and density variations within the crust and the mantle. When large-scale density distribution is available, and shallow formation are known, it is possible to define anomalous areas which could be possibly related to geothermal conditions.

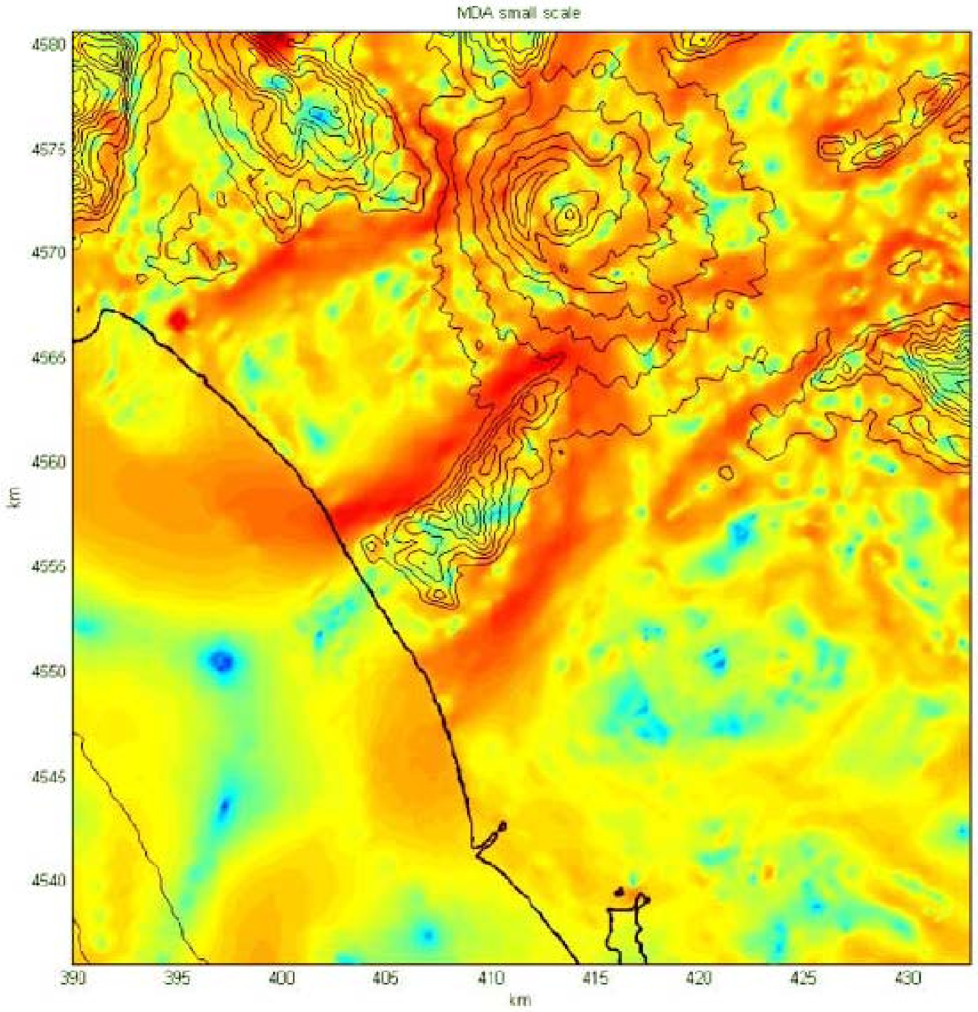
GRAVITY SURVEYS

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).

GRAVITY SURVEYS

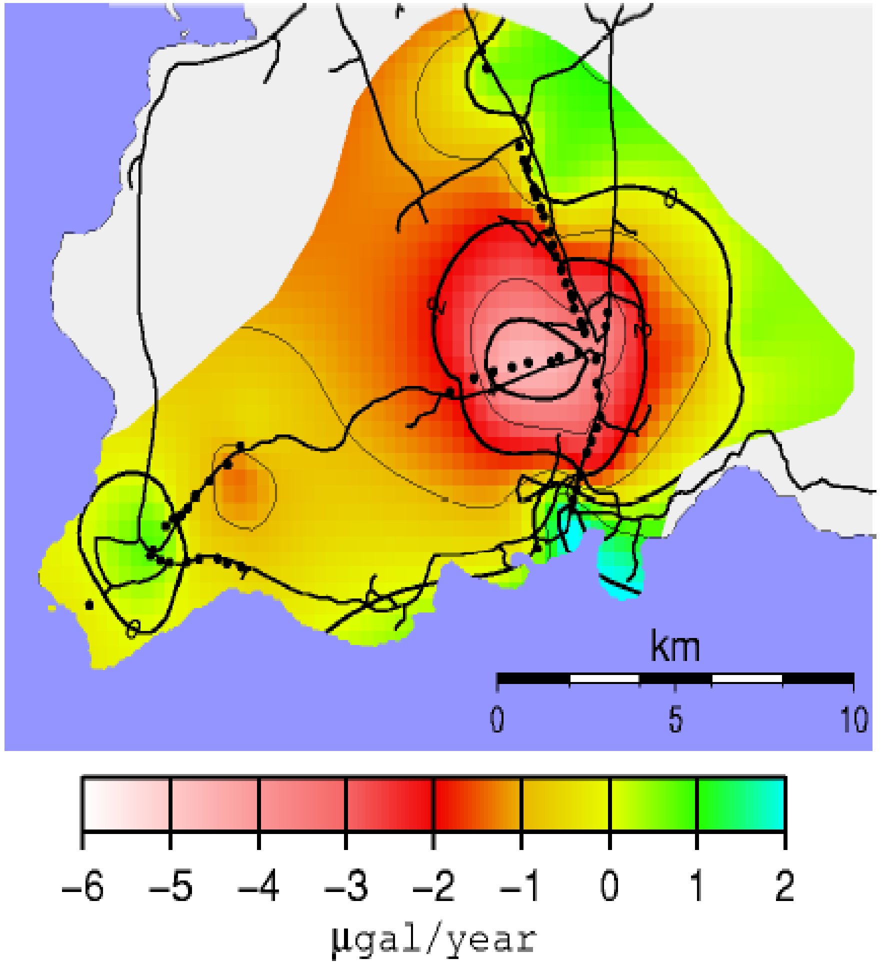


Mappa dei lineamenti strutturali
del Mte.Massico
da dati gravimetrici

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.



GRAVITY SURVEYS

gravity monitoring - weather monitoring

⇓

relationship between gravity and precipitation

⇓

shallow ground water level change

Gravity is then corrected by this effect, and its changes show the fluid recharge in geothermal systems and the need of reinjection

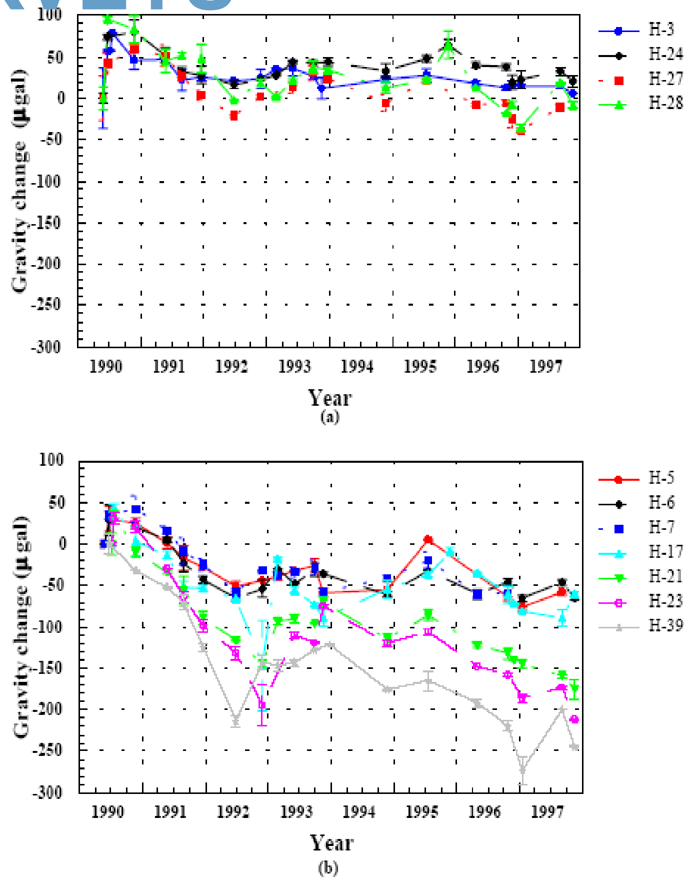


Figure 4. Examples of gravity change at Hatchobaru geothermal field. (a): in the reinjection zone, (b):in the production zone.

GRAVITY SURVEYS

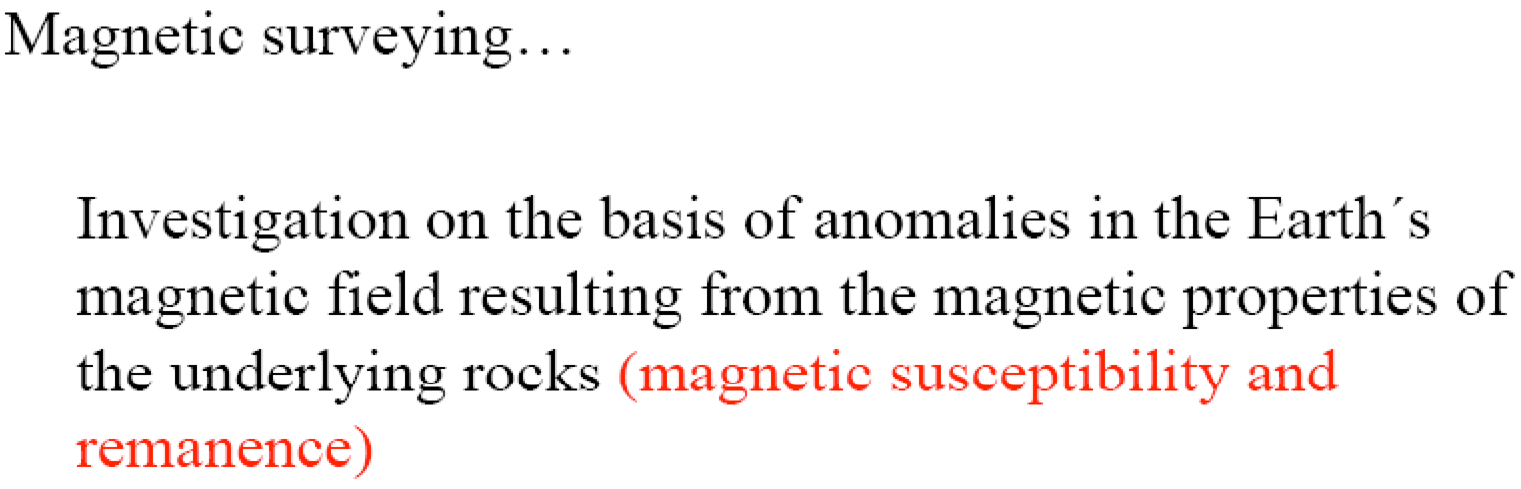
The advantages of gravimetric methods over other geophysical methods are that they are comparatively easy to use and fairly economical as far as their absolute cost is concerned.

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.

MAGNETIC SURVEYS

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.



Magnetic surveying…

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

MAGNETIC SURVEYS

Definitions: Magnetic potential

- Remember that the ‘potential’ is defined as the ‘potential to do work’.
- Magnetic Potential: $W = \frac{\mu_o}{4\pi}\frac{p}{r} = c\frac{p}{r}\left[\frac{Wb}{m}\right]$

where $\mu_o = 4\pi\ 10^{-7}$ [H/m] is the *magnetic permeability of free space* and p [A/m] is *magnetic pole strength*

- Gravitational Potential: $U = G\frac{m}{r}$

$\mu_o/4\pi$ is equivalent to G

p is equivalent to m

MAGNETIC SURVEYS

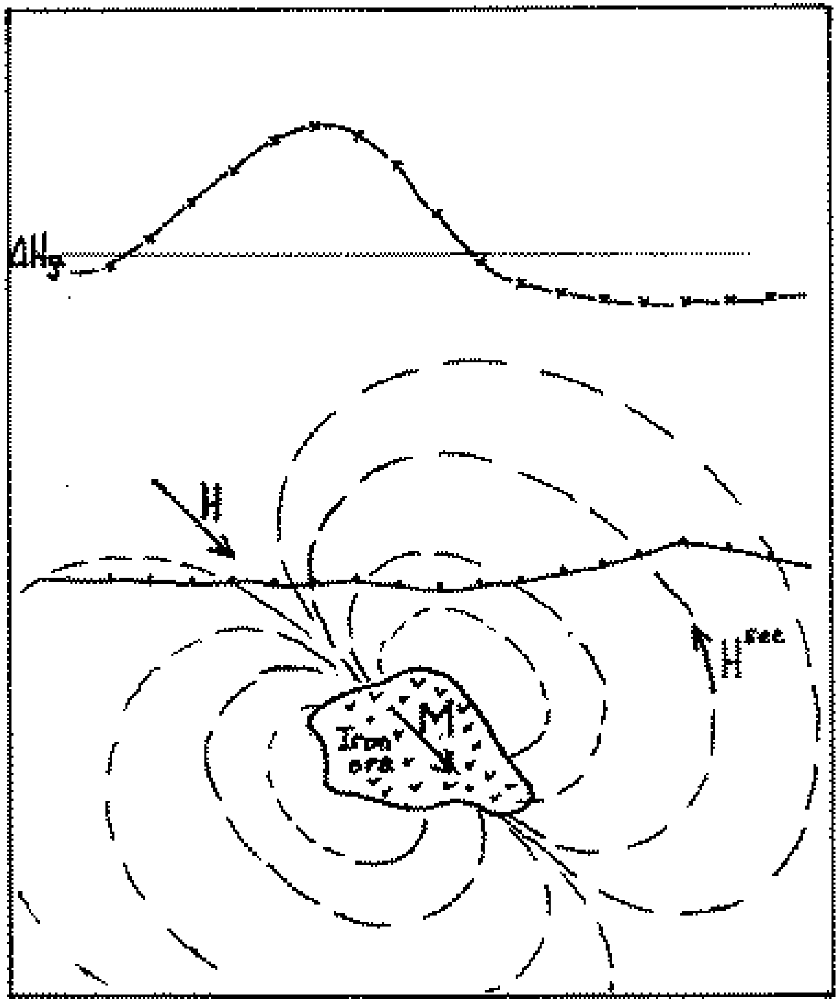
Definitions: Magnetic field or flux density

- Definition: Vector quantity defining the magnetic flux/unit area; i.e., the density of the magnetic field lines. Thus often called *Flux Density*
- Mathematical Definitions:
  - Air: $B = -\nabla W = \frac{\mu_o}{4\pi}\frac{p}{r^2}\hat{r} = c\frac{p}{r^2}\hat{r}\left[\frac{Wb}{m^2} = Tesla\right]$
  - Magnetic materials: $B = -\nabla W = \frac{\mu}{4\pi}\frac{p}{r^2}\hat{r}$

$$= \frac{\mu_r\mu_0}{4\pi}\frac{p}{r^2}\hat{r} = \mu_r c\frac{p}{r^2}\hat{r}$$

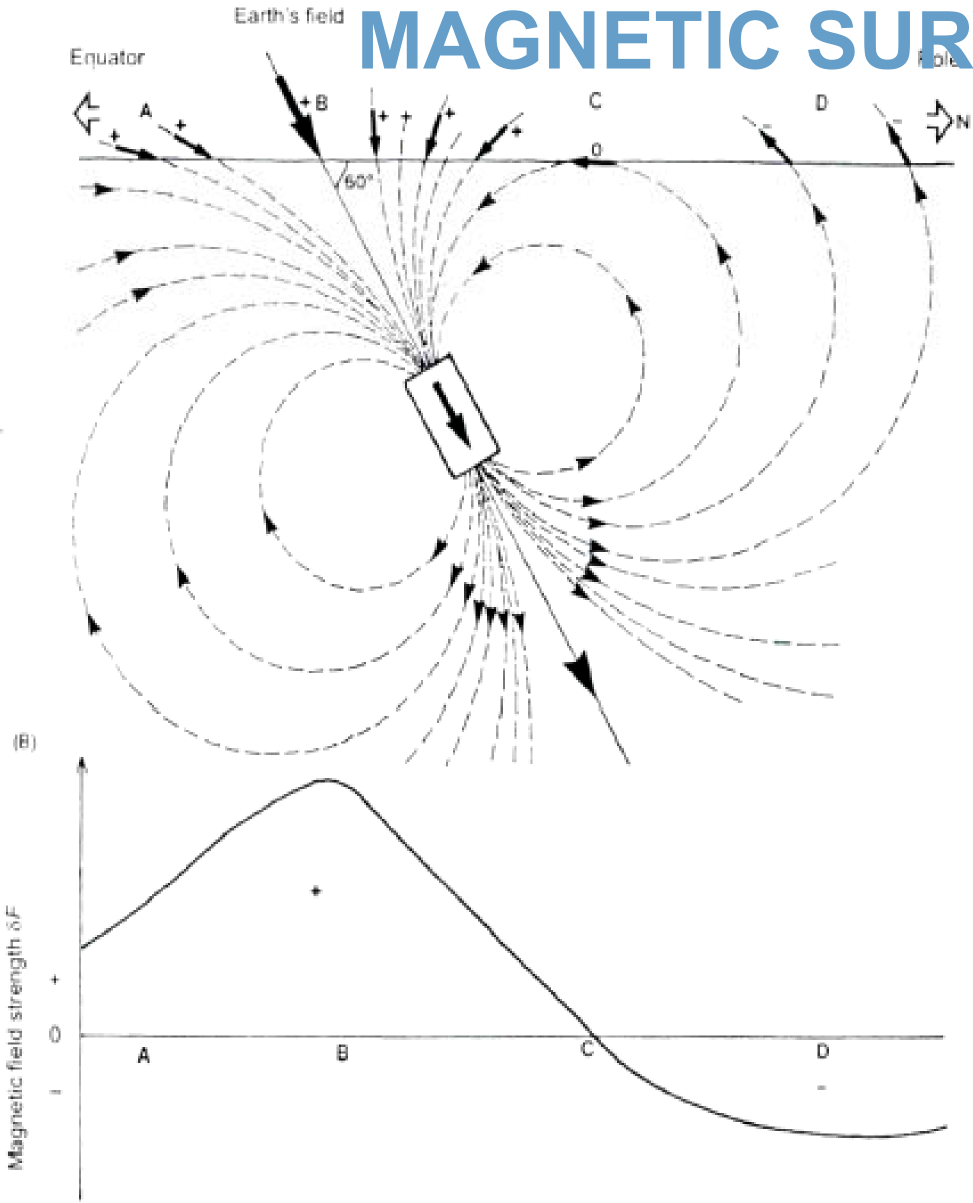
- μ is the *magnetic permeability* of the material
- μ_r is the *relative magnetic permeability* of the material
- $\check{r}$ is a unit vector pointing from the magnetic pole to the measurement point.

MAGNETIC SURVEYS



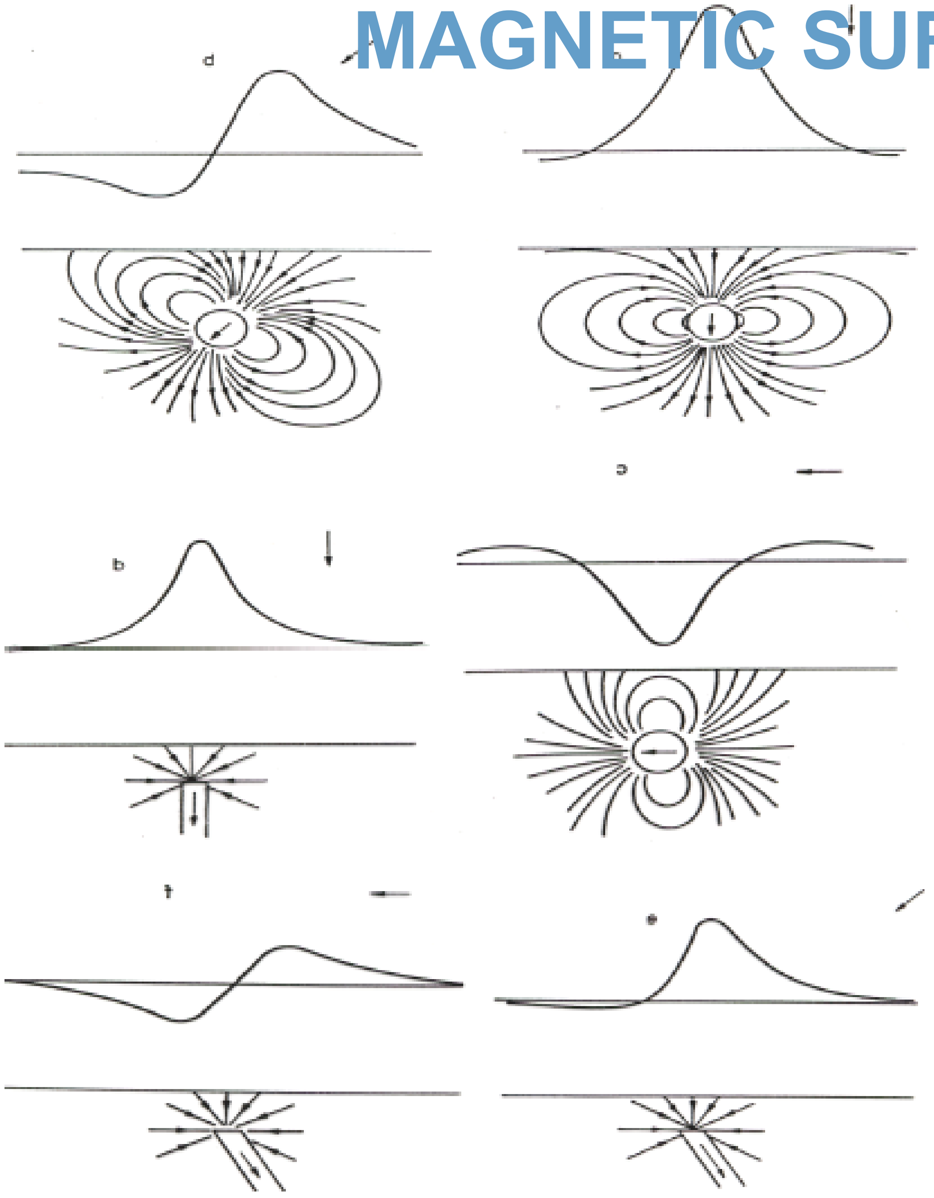
An object in this case, an iron ore deposit, has been magnetized with a magnetization **M** in the direction of the earth's field **H**. The magnetized body has its own magnetic field **H**^{sec}, which for this body has the roughly dipolar form shown by the dashed lines in the figure. These secondary fields add vectorally to the inducing (Earth's) field. Accurate measurements of the magnetic field along a profile over the body will reveal a characteristic pattern or anomaly caused by the body.

MAGNETIC SURVEYS



More complex than gravity anomalies (vary not only in amplitude but also in direction)

MAGNETIC SURVEYS

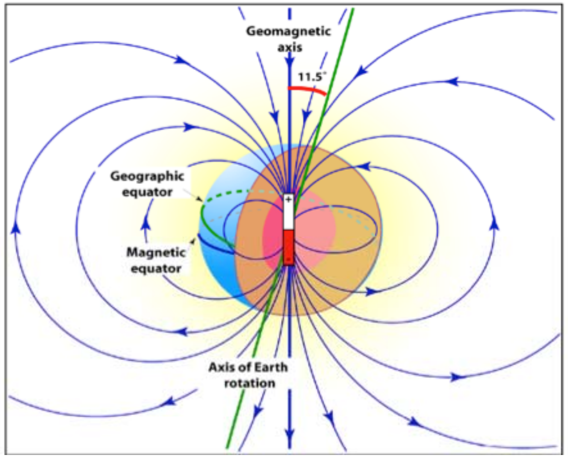


Bodies with identical shapes and intensity of magnetization can give rise to very different magnetic anomalies depending their latitude

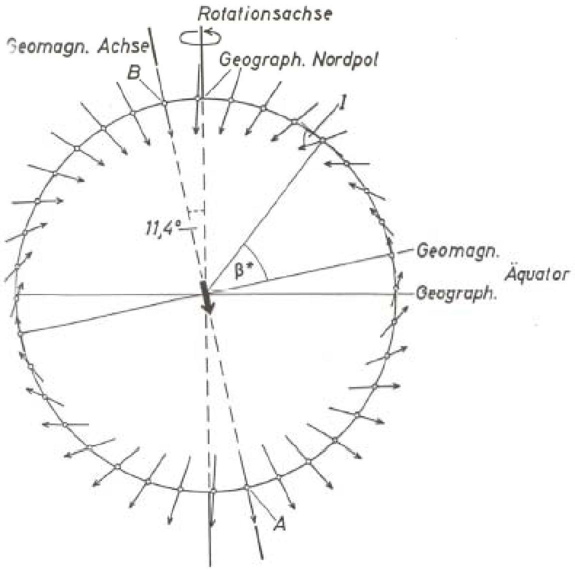
MAGNETIC SURVEYS

The shape and magnitude of a magnetic anomaly depends primarily on two factors:

- The shape and orientation/position of the magnetic body and
- The latitude of the location.



This factor is important because of the dipolarity of Earth’s magnetic field. The inducing magnetic field has a dip angle that varies from place to place over the surface of the earth: At the magnetic North pole, it is vertical, and the pattern of magnetic anomalies is symmetrical, while the patterns of anomalies that are recorded become more complex away from the pole.



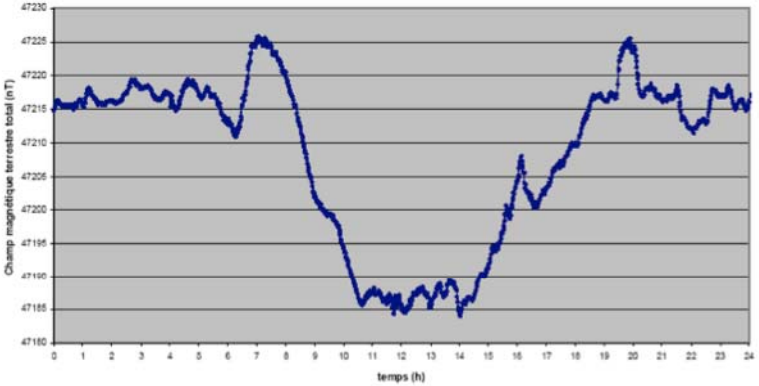
MAGNETIC SURVEYS

Diurnal variations

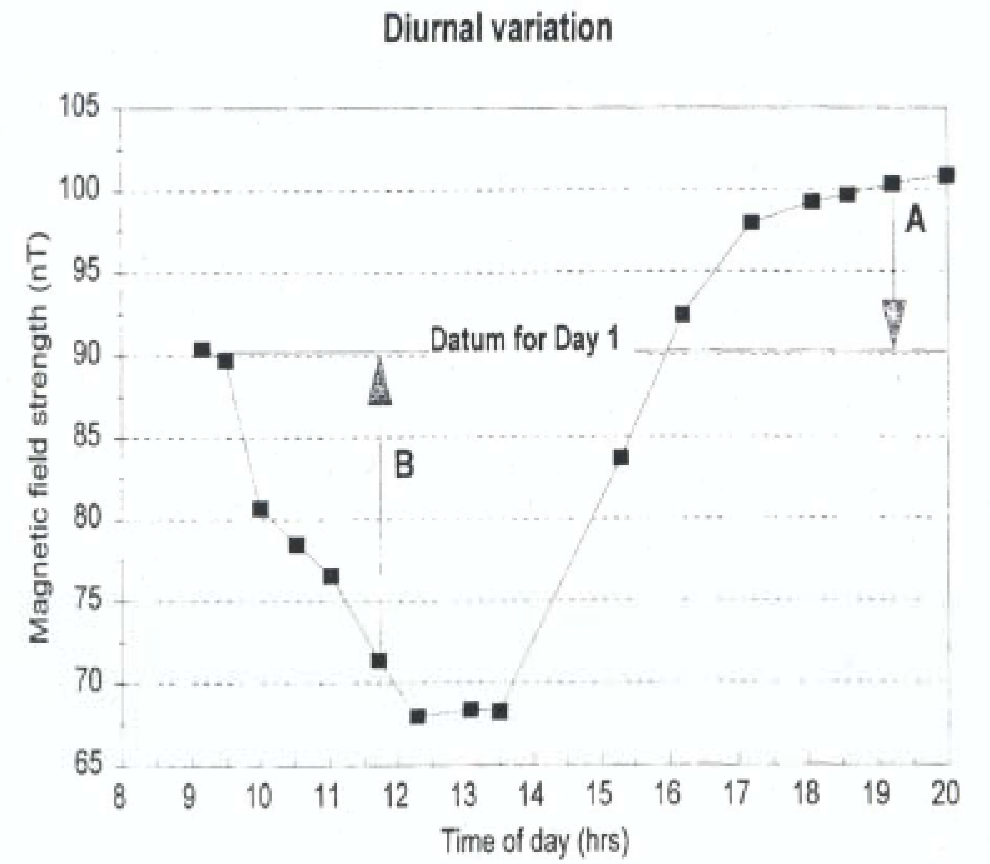
- Variations of external origin. Results from the magnetic field induced by the flow of charged particles within the ionized ionosphere towards the poles
- Movements in ionosphere:

  Difference in temperature in atmosphere

  Sun-Moon attraction
- Varies with latitude and seasons (max. in summer, max in polar regions)
- Smooth variations. Amplitude 20-80 nT



MAGNETIC SURVEYS

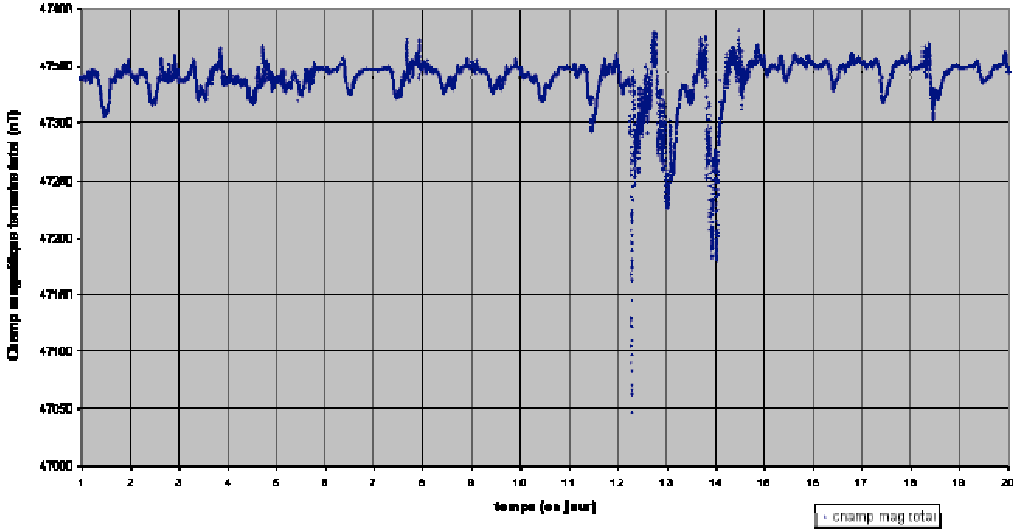


- Loop to a reference basis (tedious…)
- Use a fixed magnetometer located at the basis to correct the data collected with a second magnetometer
- Use the record of a regional magnetic observatory

MAGNETIC SURVEYS

Magnetic storms

- Associated with intense solar activity, results from the arrival in ionosphere of charged solar particles
- Less regular than diurnal variations. Amplitude up to 1000 nT!
- No magnetic surveys during storms (impossibility of correcting the data)



MAGNETIC SURVEYS

Two types of magnetometers are frequently used in magnetic surveying:

- Proton magnetometer
- Optically pumped magnetometer
- Other device: fluxgate magnetometer

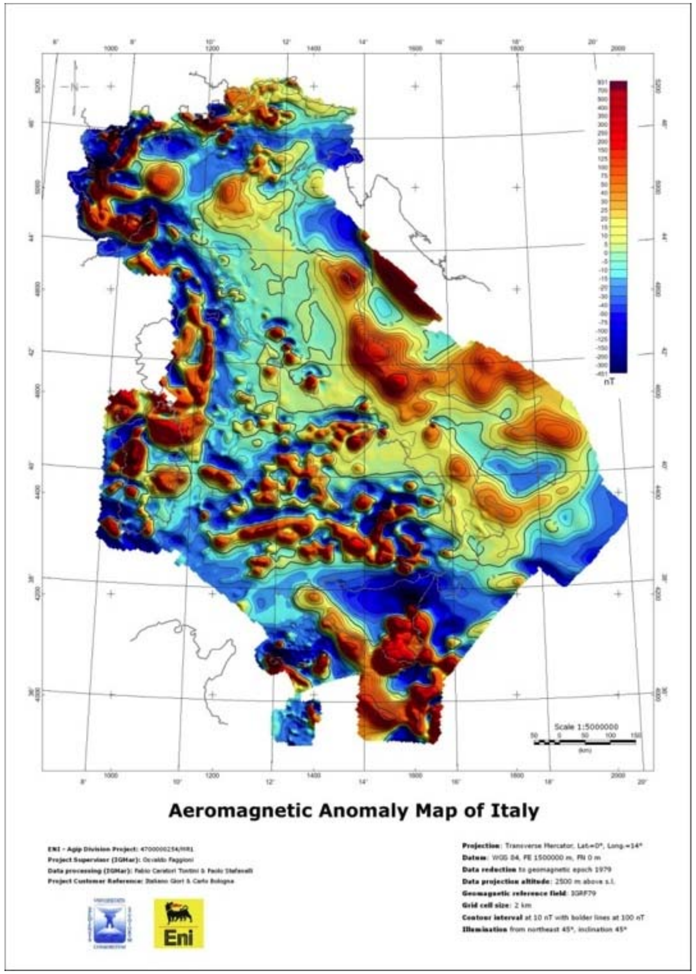
MAGNETIC SURVEYS

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

ENI - Agip Division Project: 4700000154/MR1
Project Supervisor (IGMar): Osvaldo Faggioni
Data processing (IGMar): Fabio Caratori Tontini & Paolo Stefanelli
Project Customer Reference: Italiano Giori & Carlo Bologna

Projection: Transverse Mercator, Lat.=0°, Long.=14°
Datum: WGS 84, FE 1500000 m, FN 0 m
Data reduction to geomagnetic epoch 1979
Data projection altitude: 2500 m above s.l.
Geomagnetic reference field: IGRF79
Grid cell size: 2 km
Contour interval at 10 nT with bolder lines at 100 nT
Illumination from northeast 45°, inclination 45°

MAGNETIC SURVEYS

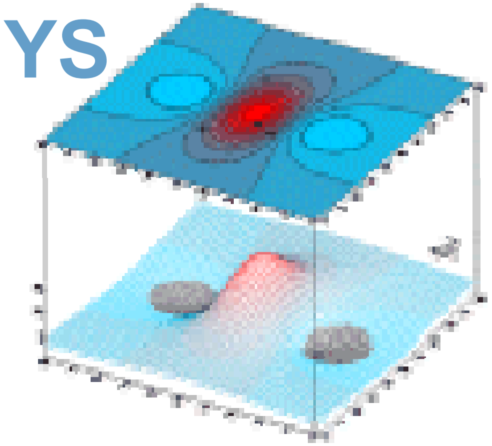
Curie temperature is in the range of a few hundred to 570°C for titano-magnetite, the most common magnetic mineral in igneous rocks

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.

MAGNETIC SURVEYS



A correction *to the pole* recomputes the magnetic profile map for a vertical inducing field using the actual observed magnetic map

Since the magnetic anomaly depends, in a complicated way, on the size and shape of the magnetic bodies, the magnetic anomaly can be computed numerically for various models and depths.

The most straightforward procedure is to select a relatively simple magnetic anomaly on the map that can be represented by a body of simple geometric shape. A series of spectra is computed for various depths to the Curie point, and the spectra computed from the field data are compared with these to reach an estimate of the depth to the Curie point.

MAGNETIC SURVEYS

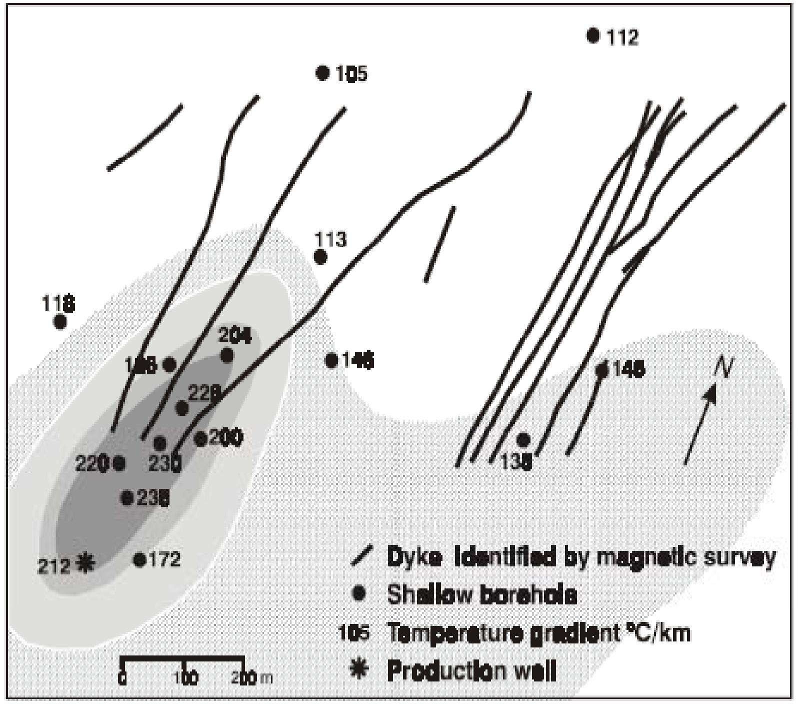


Figure 5. An area outlined in figure 1. Dykes mapped by ground magnetic surveys emplaced on a temperature gradient map. The production well ARS-29 is marked by a star. Note the two dyke swarms and that the main anomaly in the gradient is located, where three dykes are converging.

The presence of dykes is revealed by high susceptibility. On the other end circulation of hydrothermal fluids causes alterations in the rock which lead to a reduction in susceptibility. This reduction is a consequence of the destruction of the magnetite contained in the rocks. That way, units of volcanic rocks and lava flows can easily be distinguished from hydrothermally altered rock units, which makes geomagnetic surveys a useful tool for geothermal prospecting at high enthalpy volcanic reservoirs.

An example of the result of a ground magnetic survey in Iceland, which has defined a map of the main dykes in the area
(from Flovenz et al, WGC2000)

ELECTRICAL AND EM METHODS

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.

ELECTRICAL AND EM METHODS

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

Main propagation mechanisms are:

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

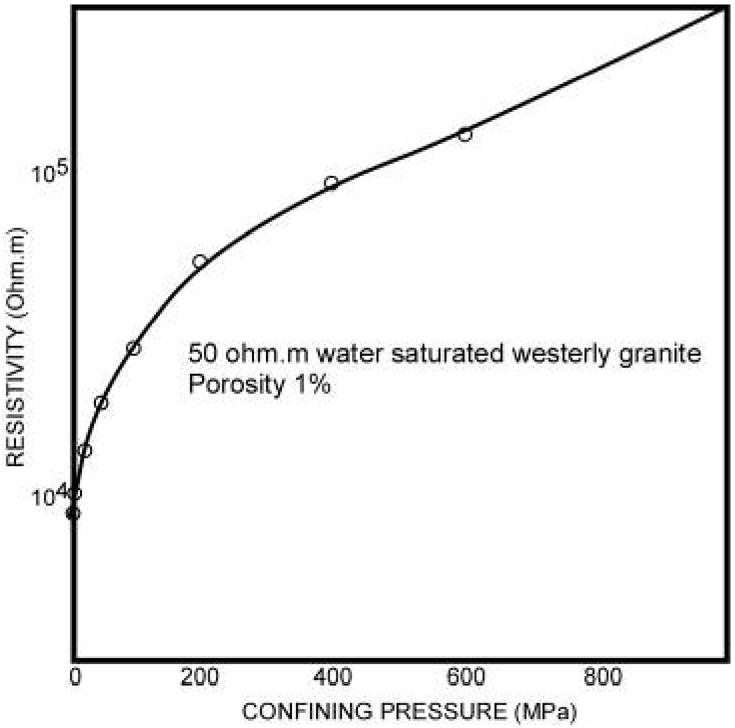
ELECTRICAL AND EM METHODS

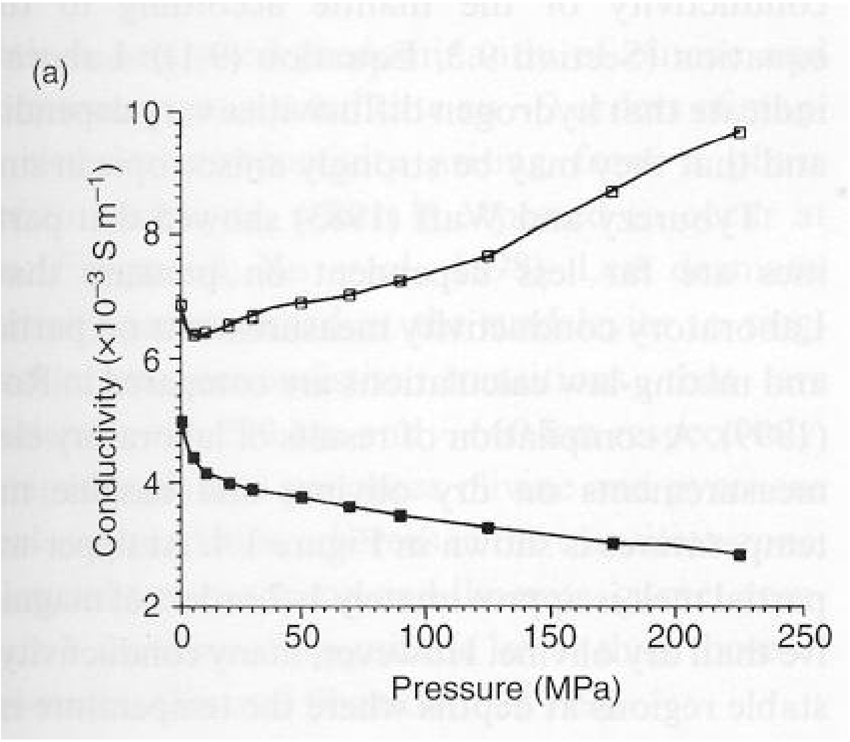
Resistivity depends on of both host rocks and pore fluid properties

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

ELECTRICAL AND EM METHODS

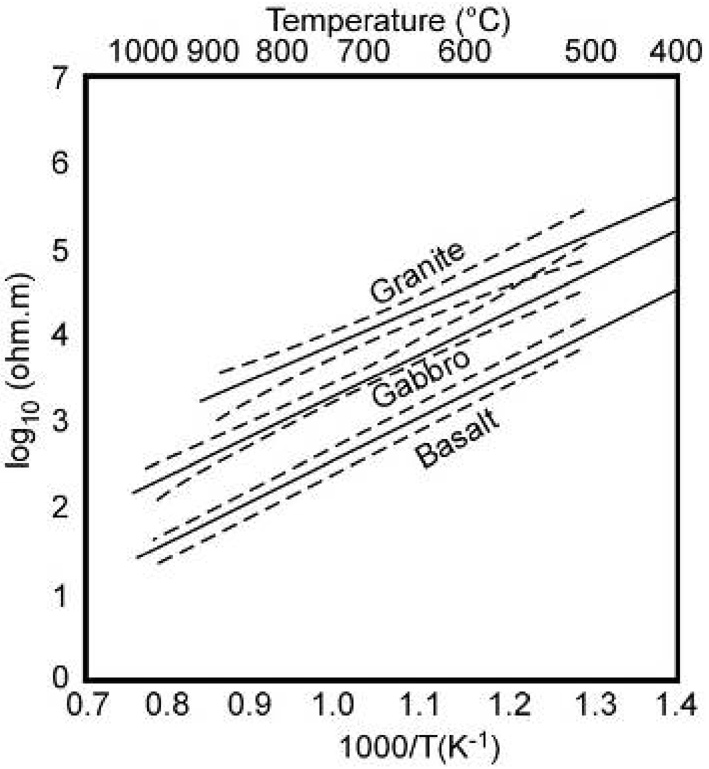
Confining Pressure Dependance





Confining pressure influences electrical resistivity improving the fluid pathway interconnection and, in a reduced percentage, improving the soild particles interconnection.

ELECTRICAL AND EM METHODS



From Karya and Shankland, 1983

Temperature dependance

At normal temperature at the earth surface, silicate minerals have very high resistivity.

The higher the temperature, the lower the resistivity.

Approaching the melting point of a rock the resistivity becomes low enough to become comparable with resistivities in water-saturated rocks

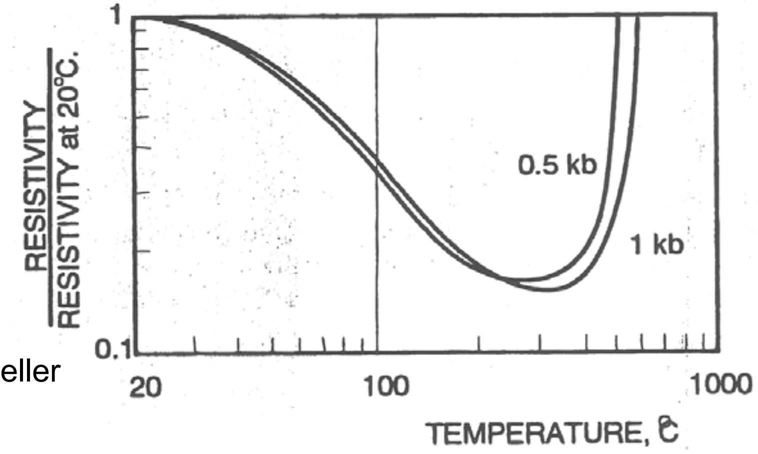
ELECTRICAL AND EM METHODS

Temperature dependance

When rocks contain fluids, electrical conduction takes place mainly by passage of current through the fluid in the pores, since almost all rock-forming minerals are almost insulators at low-medium temperatures.

The conductivities of both the electrolytes and the rock matrix are temperature dependent in a manner that causes a large reduction of the bulk resistivity with increasing temperature.

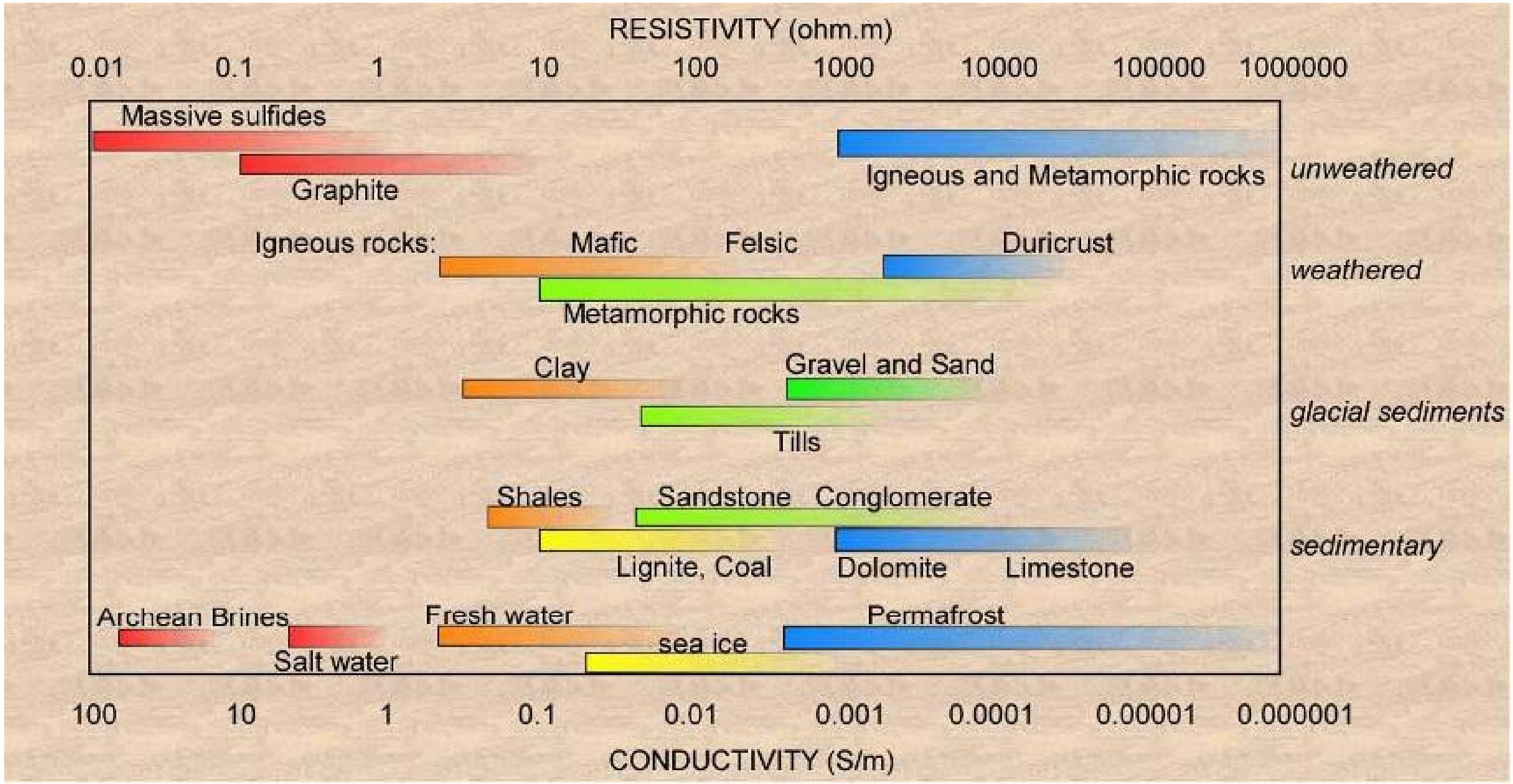
The maximum enhancement in conductivity is approximately sevenfold between 350°C and 20°C for most electrolytes



From Keller

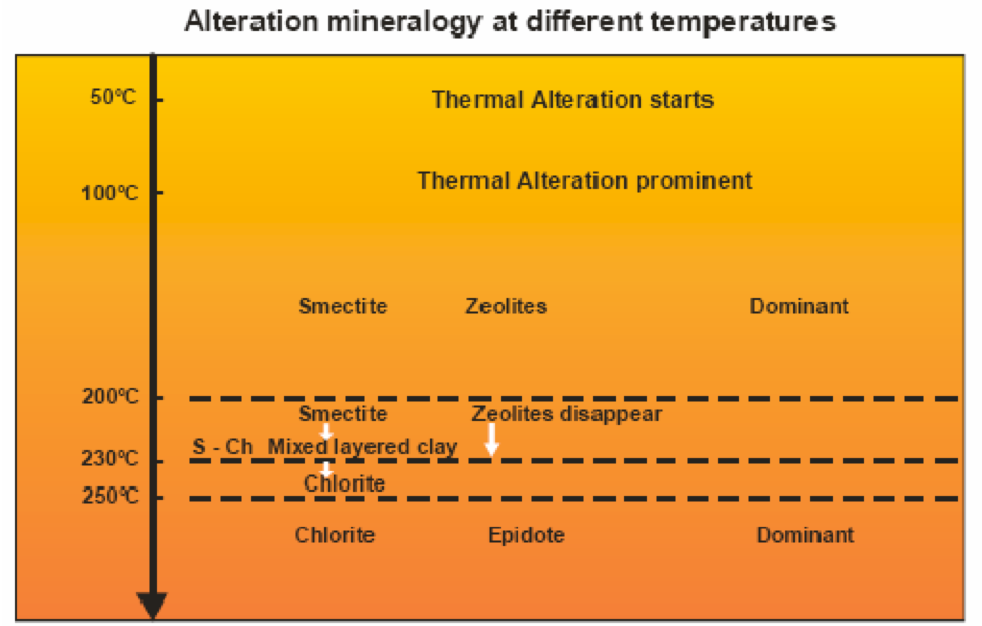
ELECTRICAL AND EM METHODS

Lithology dependance



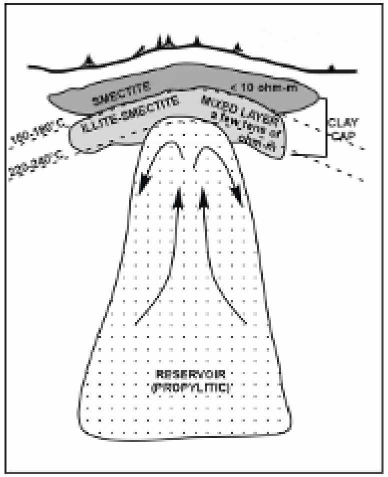
ELECTRICAL AND EM METHODS

Clay content dependance



Clays not only decrease the resistivity by themselves, but also increase the surface effect (frequency-dependent IP)

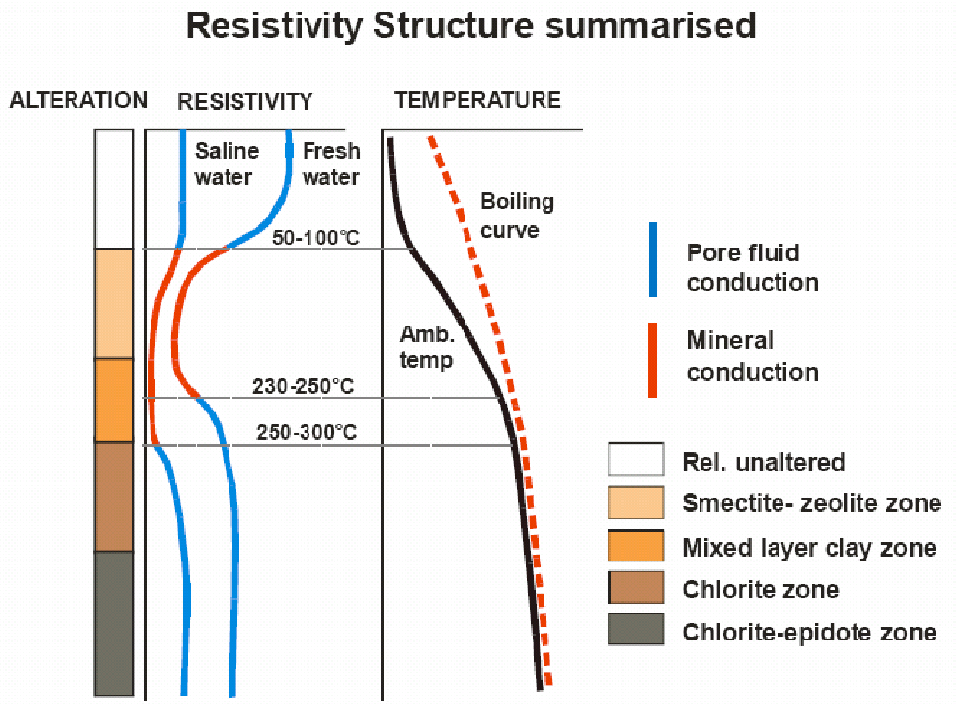
The resulting resistivity is also related to the presence of clay minerals, and can be reduced considerably when the clay minerals are broadly distributed.



From Pellerin et al., 1996

ELECTRICAL AND EM METHODS

Resistivity should be always considered with care. Experience has shown that the apparent one-to-one correlation between low resistivity and the presence of fluids is not correct, since alteration minerals produce comparable, and often higher reduction of resistivity with respect to fluid flow.

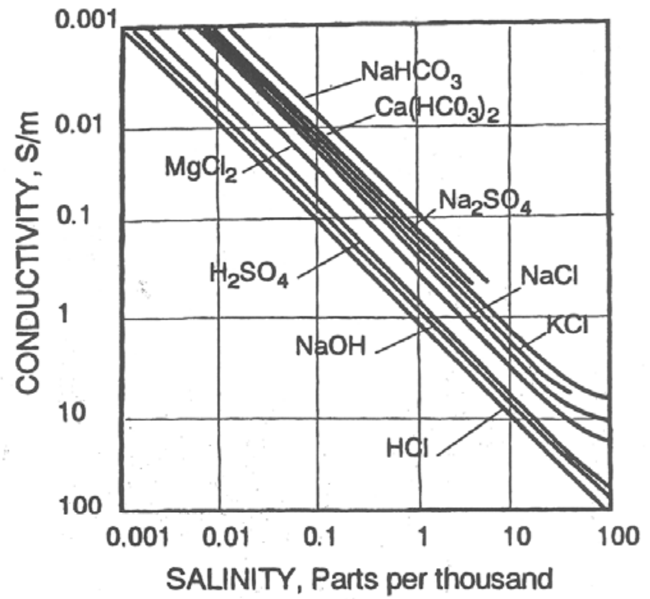


Moreover, although the hydrothermal systems in volcanic rocks have an associated low-resistivity signature, the converse is not true.

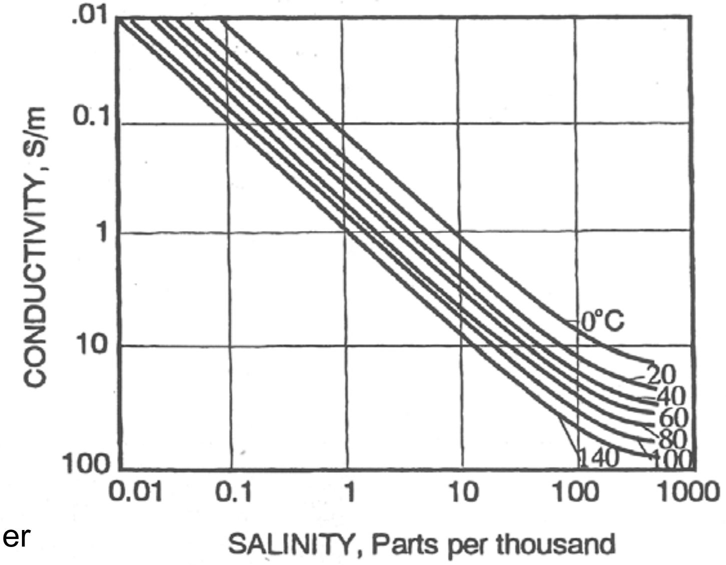
ELECTRICAL AND EM METHODS

Salinity dependance

Geothermal waters have high concentrations of dissolved salts which provide conducting electrolytes within a rock matrix



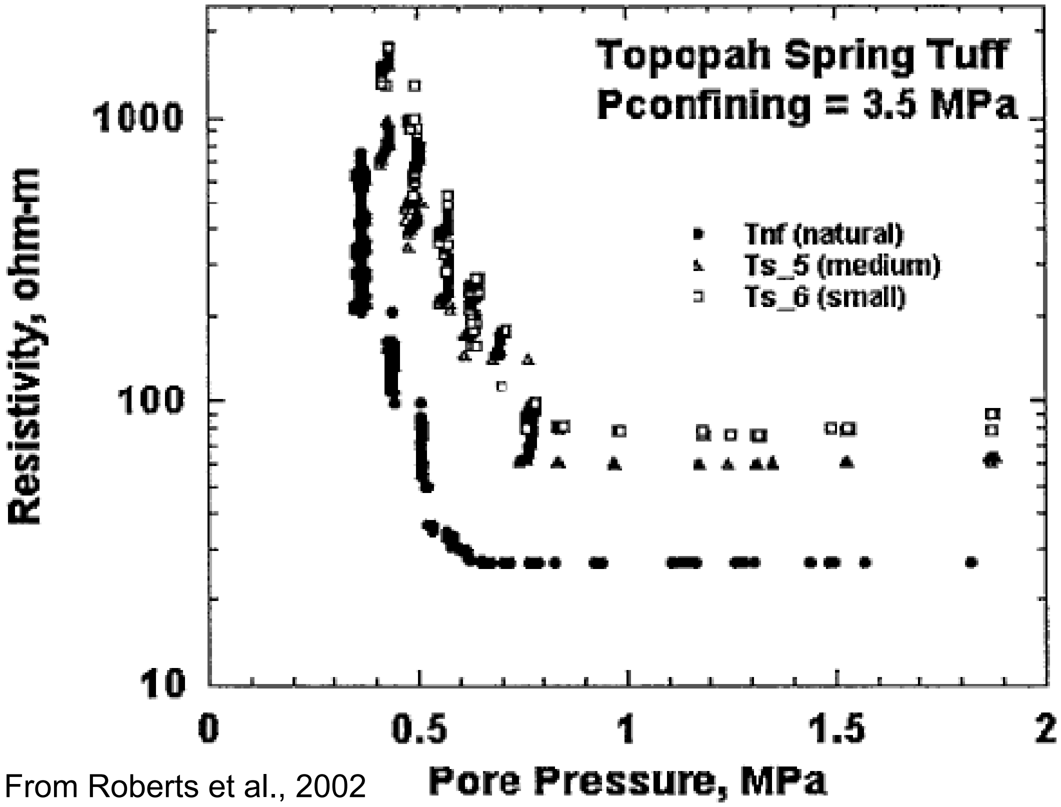
From Keller



As a result, it is not unusual to see an increase in conductivity by an order of magnitude or more in a geothermal reservoir compared with rocks at normal temperatures removed from the reservoir.

ELECTRICAL AND EM METHODS

Fluid phase dependance



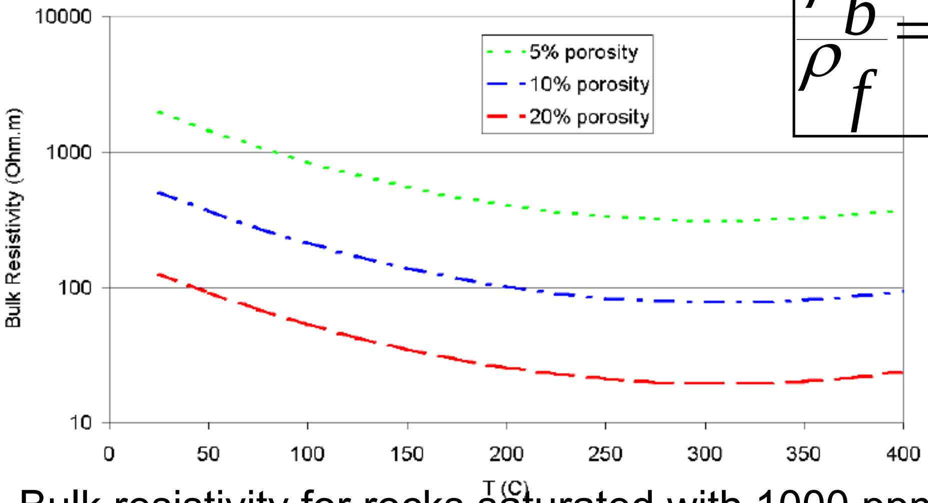
From Roberts et al., 2002

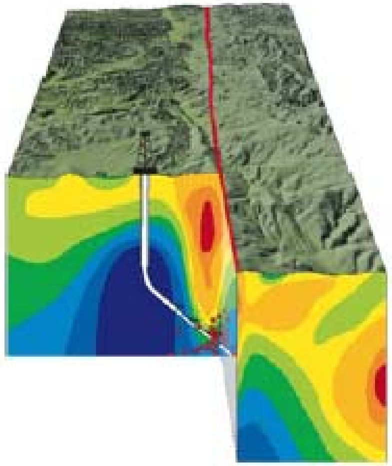
ELECTRICAL AND EM METHODS

Hydraulic property dependance

In most rocks there is an empirical relationship, established by *Archie (1942)*, between the ratio of the bulk rock resistivity, ρ_b, to the pore fluid resistivity, ρ_f, called the formation factor, F, and the volume fraction porosity, φ. The relationship, now called Archie's law, is:

$$\boxed{\frac{\rho_b}{\rho_f} = F = a\phi^{-m}}$$





Bulk resistivity for rocks saturated with 1000 ppm NaCl solutions, using Archie's law.
From Ussher et al., WGC2000.

ELECTRICAL AND EM METHODS

Hydraulic property dependance

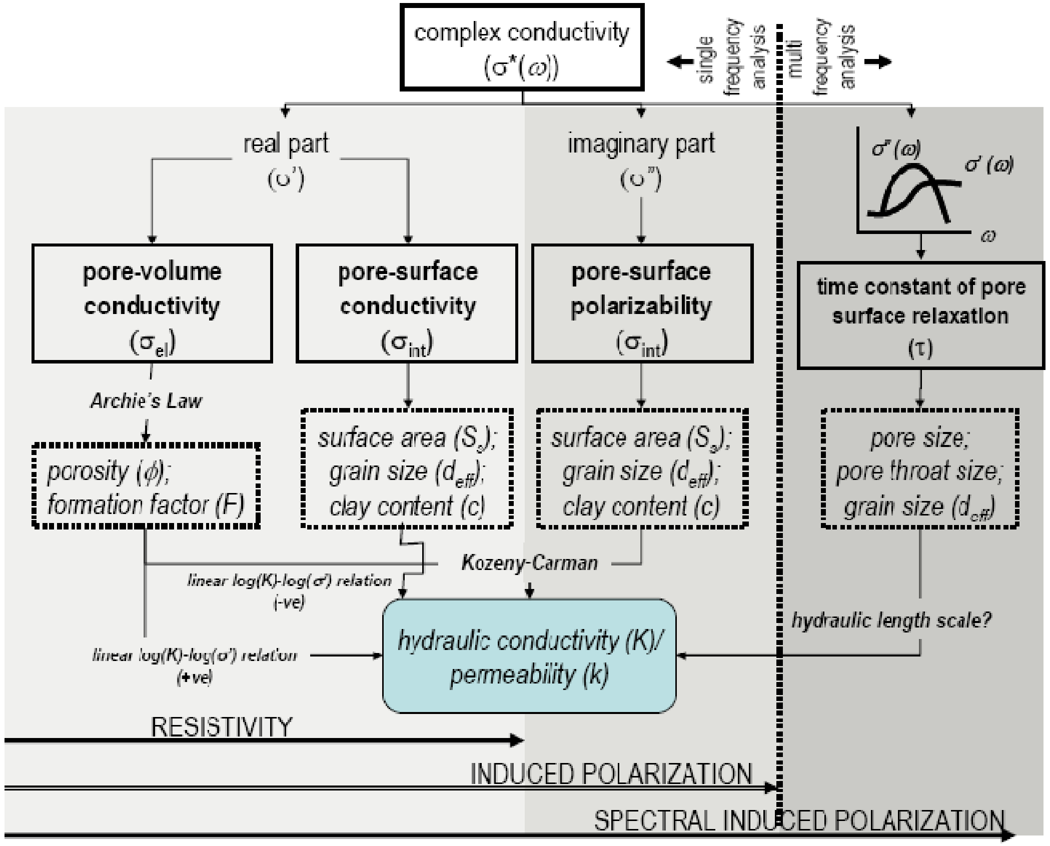


Figure 1. Flowchart summarizing efforts to predict hydraulic conductivity (*K*) from petrophysical relationships established for electrical measurements.

ELECTRICAL AND EM METHODS

natural-source induction methods
(magnetotellurics, audiomagnetotellurics and self-potential)

controlled-source induction methods
(TDM, VLF)

direct current methods
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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 reservoir rocks, and several tens of kilometres when seeking the thermally excited conductive zone associated with the source of a geothermal system.

ELECTRICAL AND EM METHODS

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

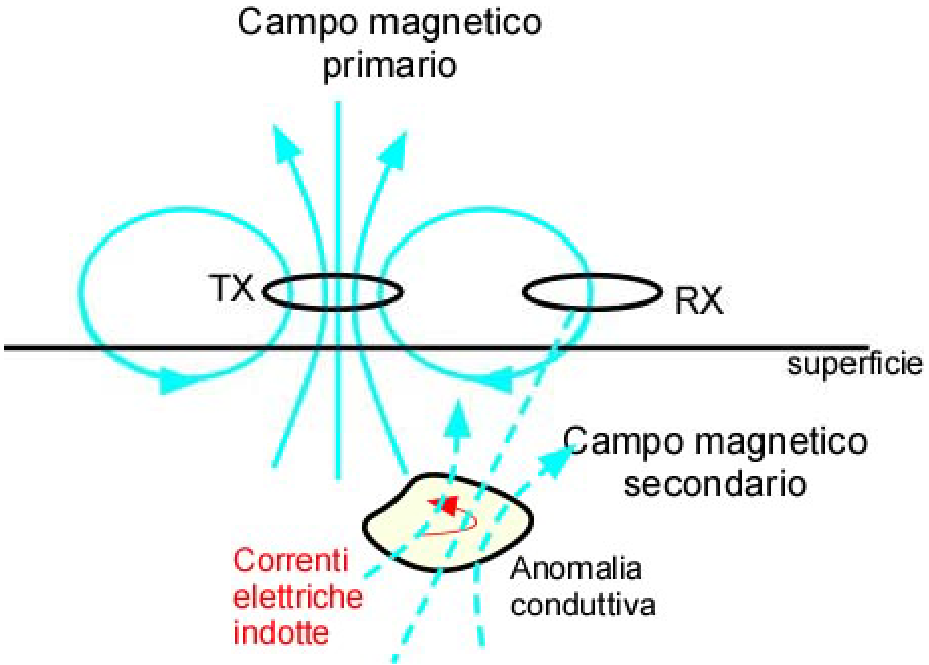
On the contrary, resistivity techniques usually provide information on resistivity-thickness products for resistive layers and conductivity-thickness products for conductive layers.

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

ELECTRICAL AND EM METHODS

The **total** EM field measured at the surface (receiver Rx) is the sum of the primary and the secondary field.

Measuring E and H field at the surface we can retrieve information regarding the underground resistivity structure



Any EM inductive method follows this scheme.
Depending on the method, the fields can be measured as a function of time or of frequency

MAGNETOTELLURIC METHOD

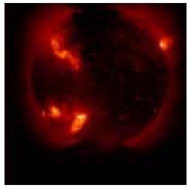
Magnetotellurics (MT for short) is a technique which utilizes the earth's naturally occurring electromagnetic field to image the subsurface's electrical resistivity structure.

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

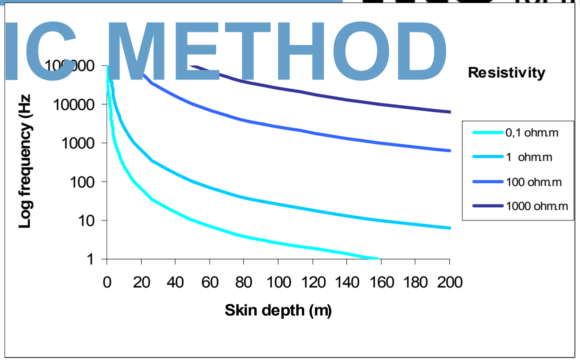
Low frequency signals are generated by sun-spots



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.

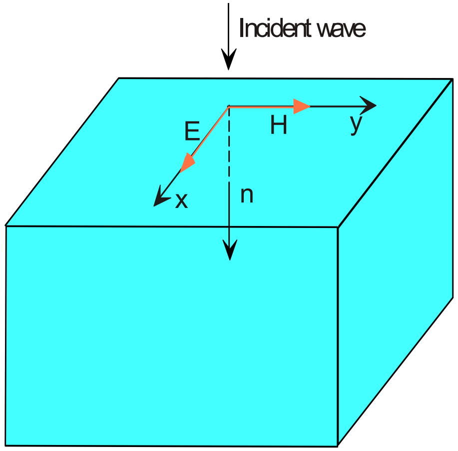
MAGNETOTELLURIC METHOD

As these waves travel into the Earth's interior they decay at a rate dependent upon their wavelengths.



These electromagnetic waves penetrate the earth and return to the surface bearing information on its electrical resistivity structure.

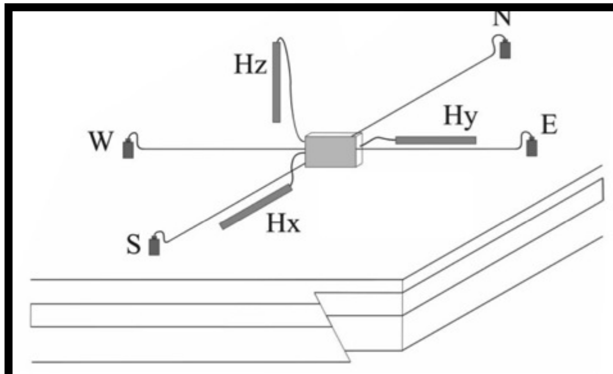
By some tortuous mathematics it is possible to demonstrate that the ratio between electric (E) and magnetic (H) fields at the earth's surface is independent from the source electromagnetic field, but depends only on the electrical resistivity structure of the subsurface.



By measuring E and H at the surface we can generate electrical resistivity models of the earth. Electrical resistivity can then be interpreted, guided by other fields observations, such geological and other geophysical constraints.

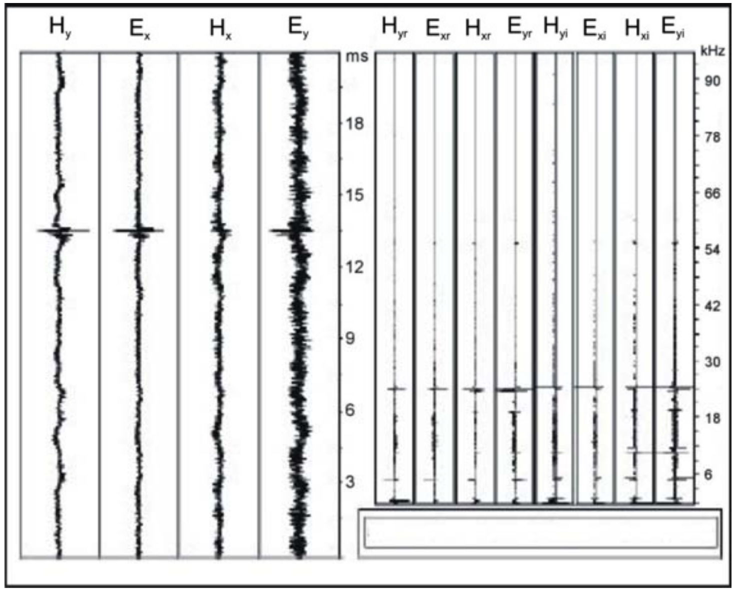
MAGNETOTELLURIC METHOD

We therefore measure the variation of E and H in time over the sounding spot:



Array geometry

Time-series **FFT**



Transfer function Z impedance tensor

$$\begin{pmatrix} E_i(\omega) \\ E_j(\omega) \end{pmatrix} = \begin{pmatrix} Z_{ii}(\omega) & Z_{ij}(\omega) \\ Z_{ji}(\omega) & Z_{jj}(\omega) \end{pmatrix} \begin{pmatrix} H_i(\omega) \\ H_j(\omega) \end{pmatrix}$$

i,j, two perpendicular directions

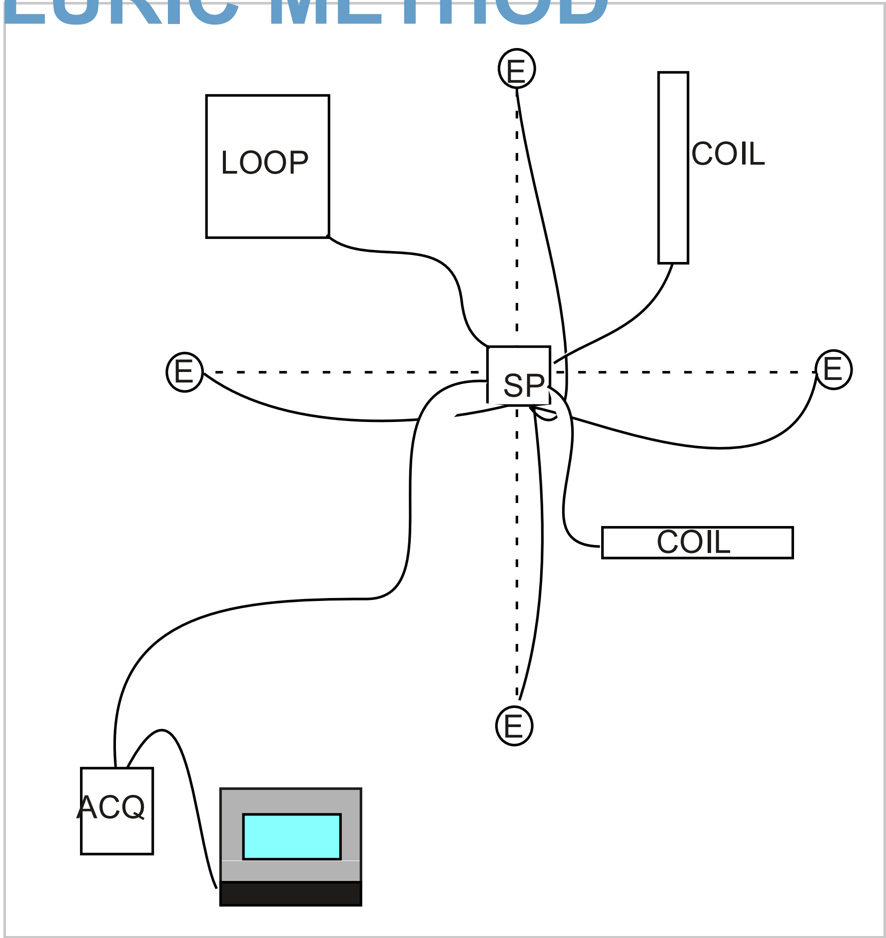
MAGNETOTELLURIC METHOD

MT data are acquired in the field, as measurements of electric and magnetic fields with time

$E_x(t)$, $E_y(t)$, $H_x(t)$, $H_y(t)$, $H_z(t)$

Timing is obtained from GPS time signals.

Care must be put on the choice of the site, trying to avoid possible noise sources, such as power lines, electrified railways, pipelines.



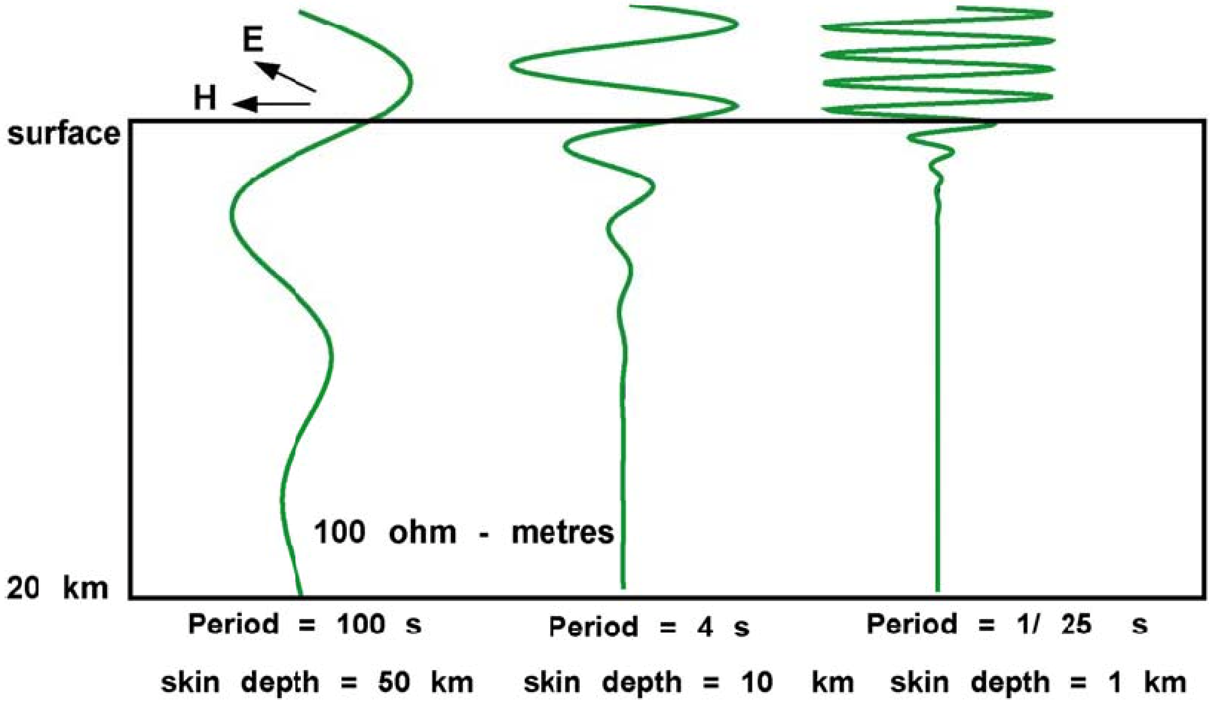
MAGNETOTELLURIC METHOD

As these waves travel into the Earth's interior they decay at a rate dependent upon their wavelengths.

This is the main advantage of MT: large depths can be reached by using a low frequency, without the need of an artificial source

Depth of penetration α **sqrt (period x resistivity)**

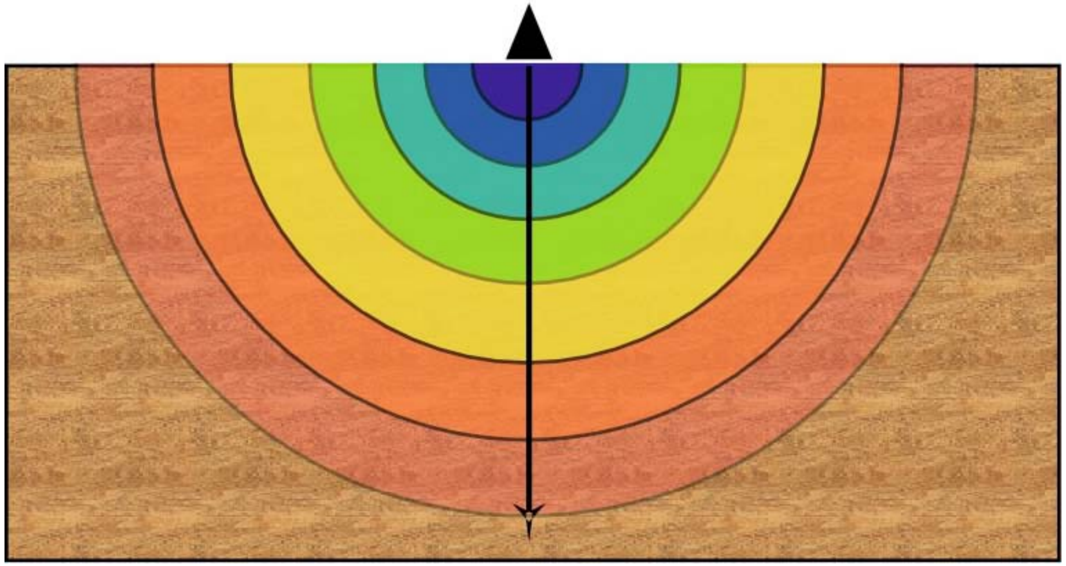
Resistivity of ground $\alpha \left(\frac{E}{H}\right)^2$



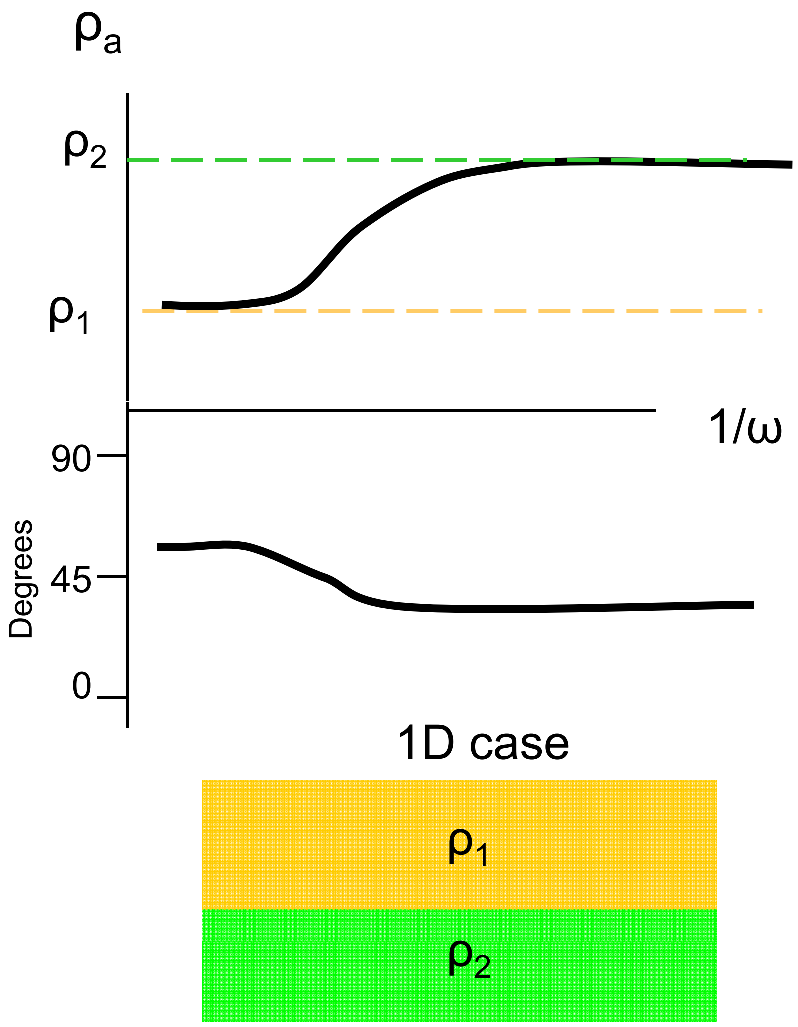
MAGNETOTELLURIC METHOD

It is important to consider which part of the Earth is being sampled in such a measurement. Since the EM fields attenuate in the Earth with a length scale of a skin depth (δ), this measurement samples a **hemisphere around the observation site, radius δ.**

Data derive not only from the geometrical-physical features on the vertical of the recording site, but depends also on the later features: this lateral dimension increases with depth (decreases with frequency)



MAGNETOTELLURIC METHOD



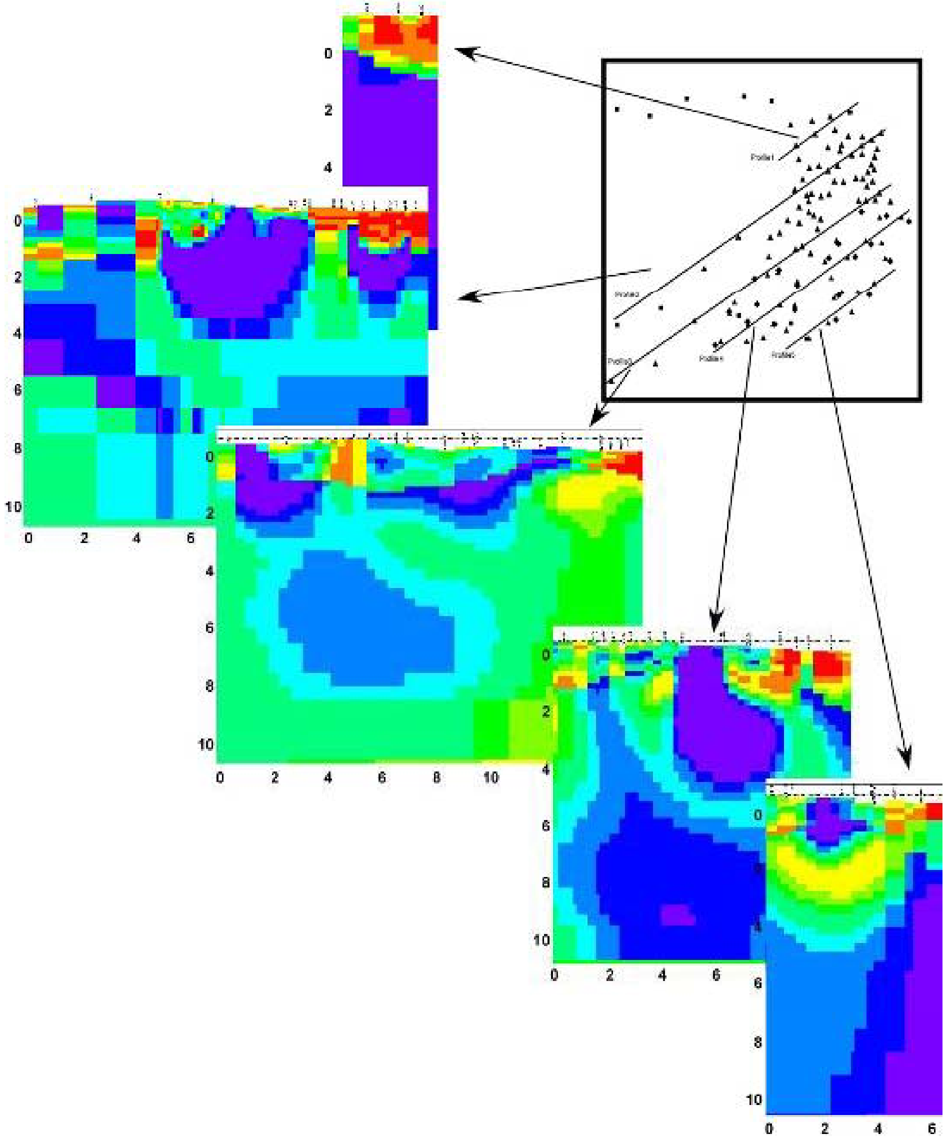
Apparent resistivity

$$\rho_{a,ij}(\omega) = \frac{1}{\omega\mu}\left|Z_{ij}(\omega)\right|^2$$

Phase

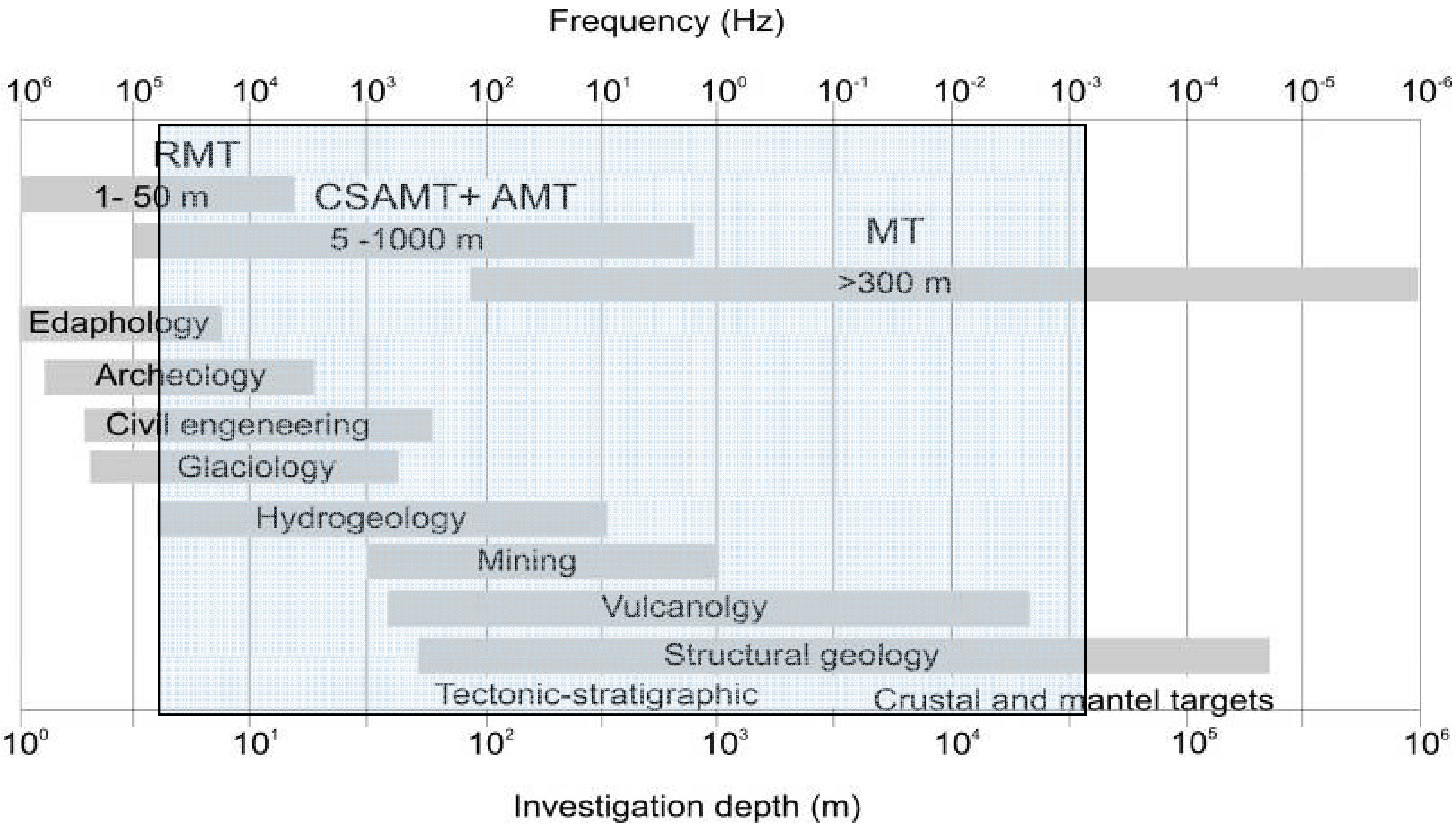
$$\varphi_{ij}(\omega) = \tan^{-1}\left(\frac{Z_{ij}^{I}(\omega)}{Z_{ij}^{R}(\omega)}\right)$$

MAGNETOTELLURIC METHOD



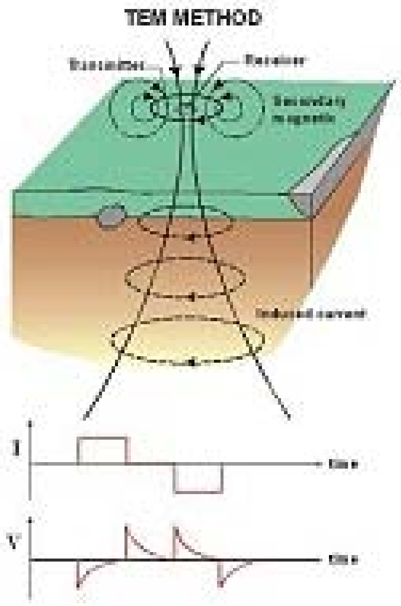
Magnetotelluric data, after processing and modelling, provide the resistivity distribution at depth of various km.

Example: 2D inversion models in Larderello, Italy

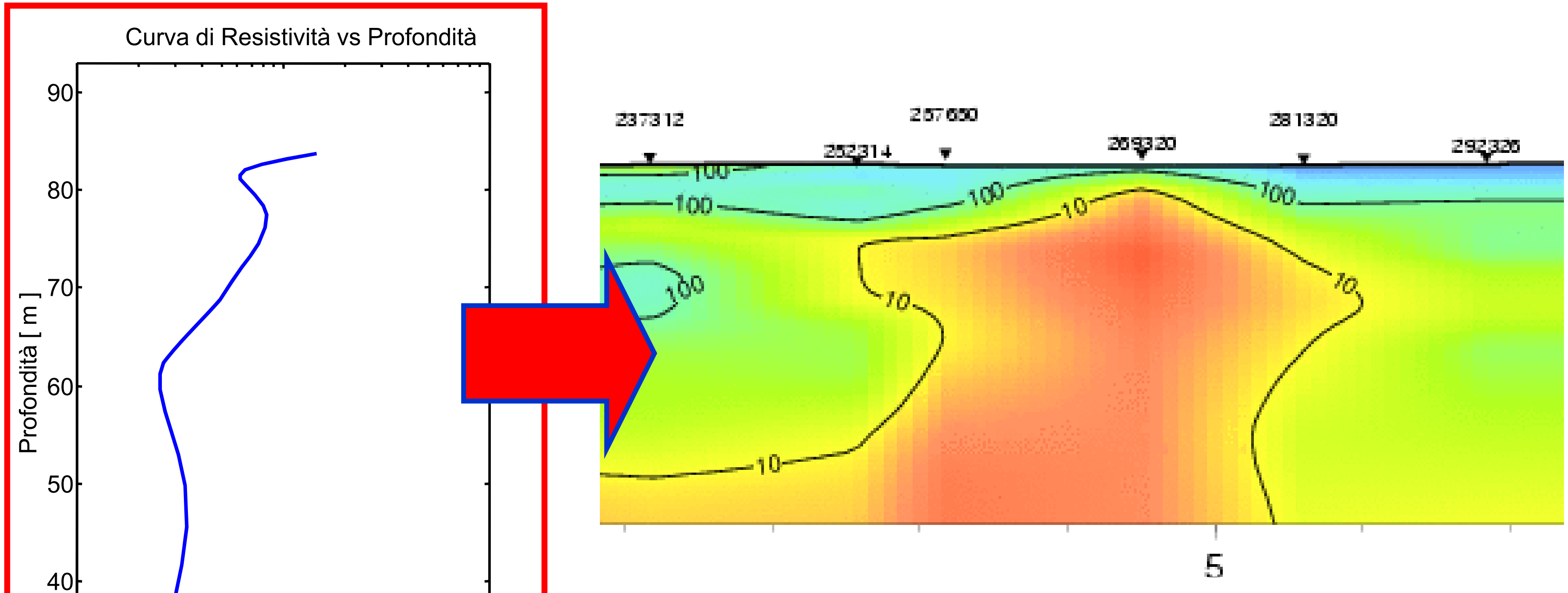

Frequency (Hz)
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
RMT
1- 50 m
CSAMT+ AMT
5 -1000 m
MT
>300 m
Edaphology
Archeology
Civil engeneering
Glaciology
Hydrogeology
Mining
Vulcanolgy
Structural geology
Tectonic-stratigraphic
Crustal and mantel targets
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
Investigation depth (m)

ACTIVE EM METHODS - TEM

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.

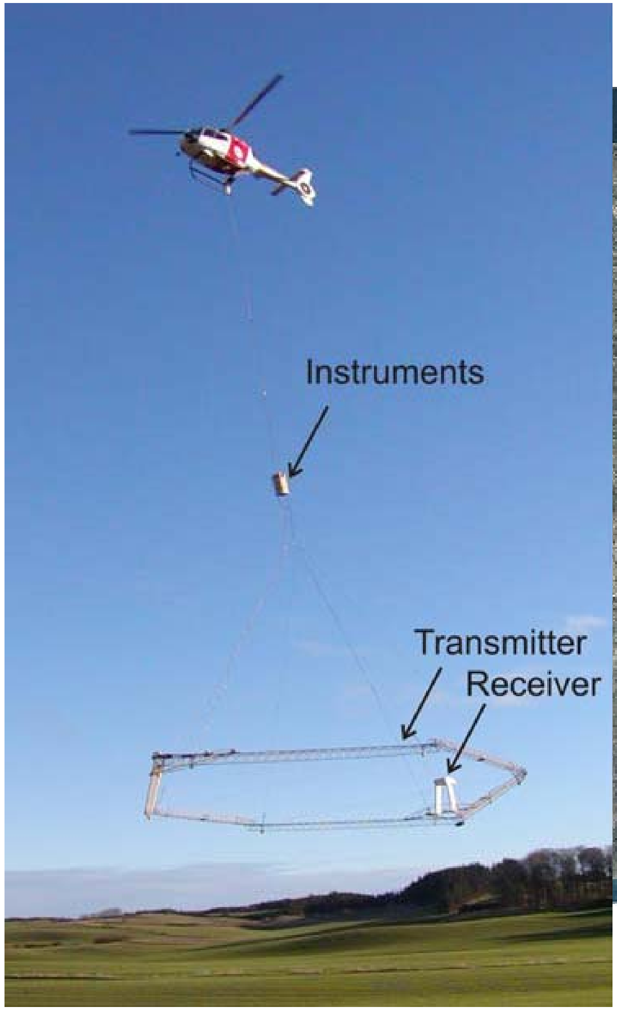


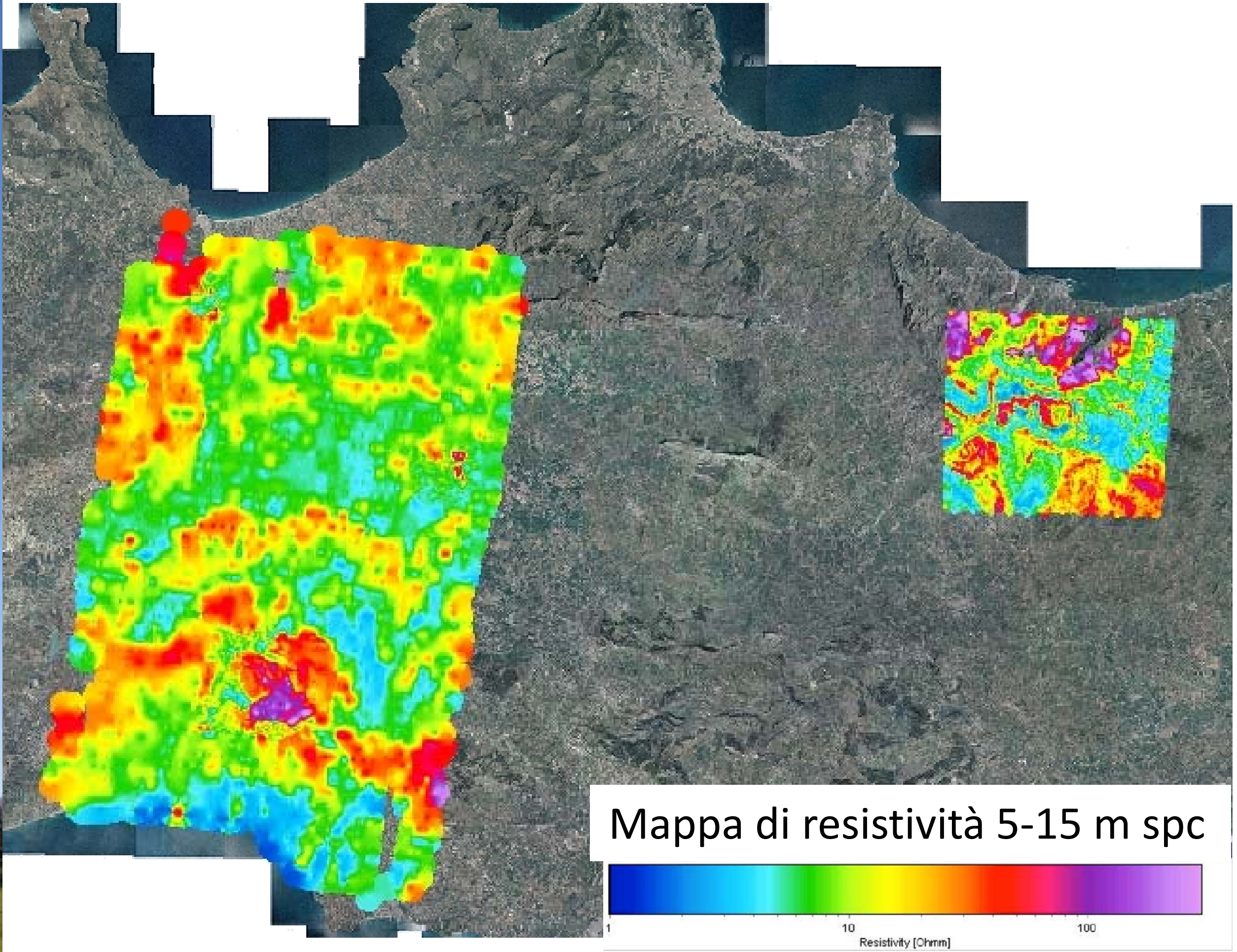
ACTIVE EM METHODS - TEM



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.

SkyTEM: metodo elettromagnetico elitrasportato
Sicilia-Progetto Vigor





ACTIVE EM METHODS - TEM

Advantages
over DC methods:

- less expensive
- interpretation is less time consuming
- more downward focused
- excellent resolution
- requires significantly less area than other electric methods
- MT Static shift correction
- in DC sounding, the monitored signal is low when subsurface resistivity is low, as in geothermal areas, whereas in TEM soundings the situation is the reverse, the lower the resistivity the stronger the signal

Over MT method:

- cheaper and has a much higher resolution at lower depths.

Disadvantage:
Limited depth of penetration (similar to most electrical methods)
1D models

ELECTRICAL (DC) METHODS

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.

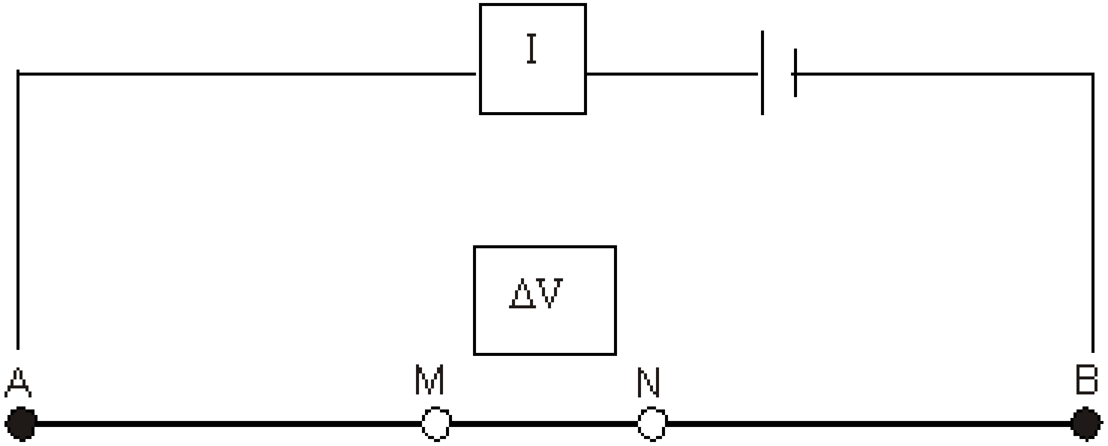
The direct current methods achieve control of the depth of the penetration by regulating the geometry of the array of equipment used.

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.

ELECTRICAL (DC) METHODS

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.



ELECTRICAL (DC) METHODS

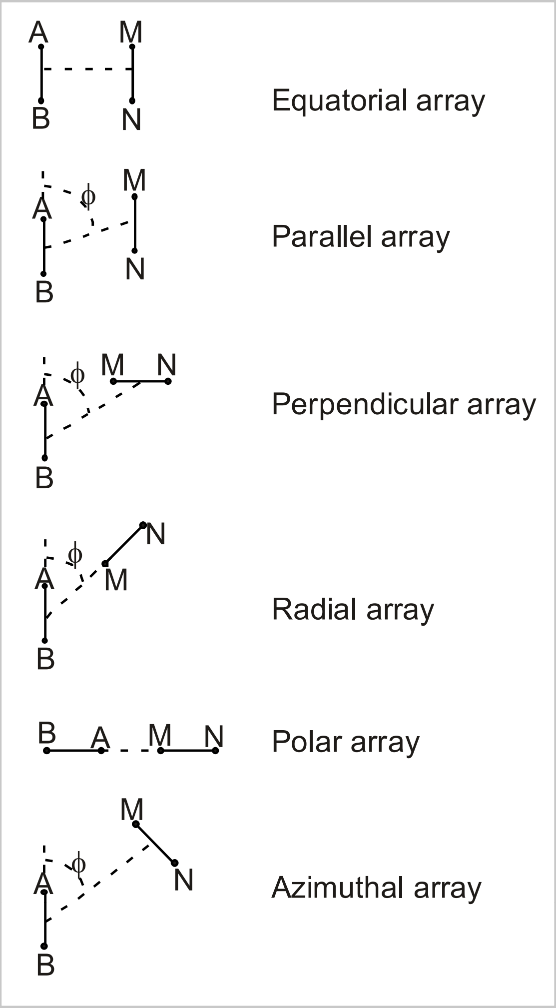
Also with the **Wenner** array electrodes are placed along a common line and separated by a distance, which is used to control the depth of penetration.

A couple of electrodes drive current into the ground, while the other couple is used to detect the electric field caused by the transmitted current.

The two couples of electrodes are separated by progressively greater distances as a sounding survey is carried out, so that information from progressively greater depths is obtained.

This method is particularly influenced by vertical structures

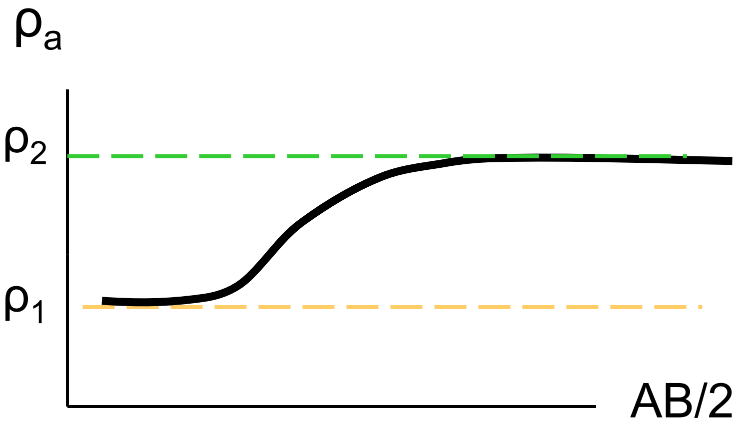
ELECTRICAL (DC) METHODS

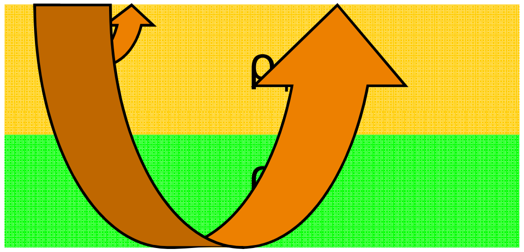


In order to detect the presence of lateral discontinuities in resistivity, the **bipole–dipole** and **dipole–dipole** techniques have come into use. In the **dipole–dipole** technique, four electrodes arrayed along a common line are used, but in this case the outer two electrodes at one end of the line provide current to the ground while the outer two electrodes at the other end of the line are used to measure the voltage caused by that current.

In a survey, the receiving electrodes and transmitting electrodes are separated progressively by increments equal to the separation between one of the pairs, in the direction along which they are placed.

ELECTRICAL (DC) METHODS

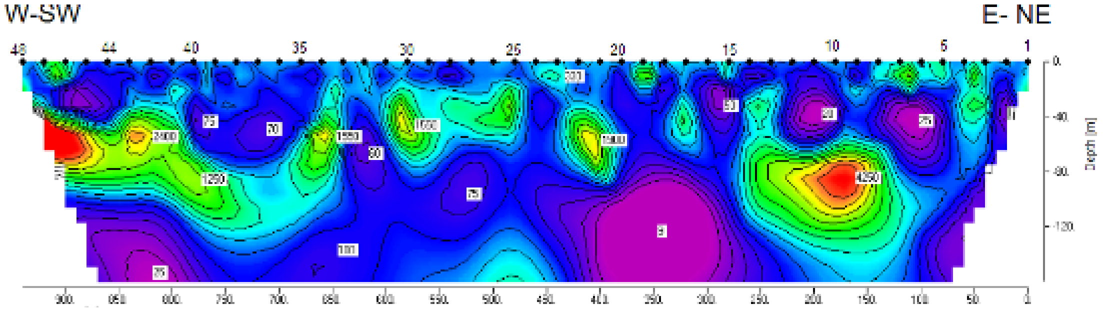




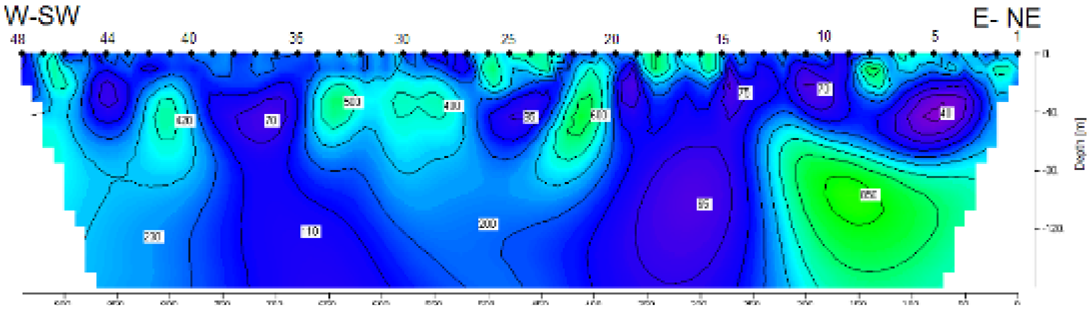
Data are represented as an “apparent resistivity”, defined as the resistivity of the homogeneous earth which would produce the measured response at a certain distance between transmitter electrodes

ELECTRICAL (DC) METHODS

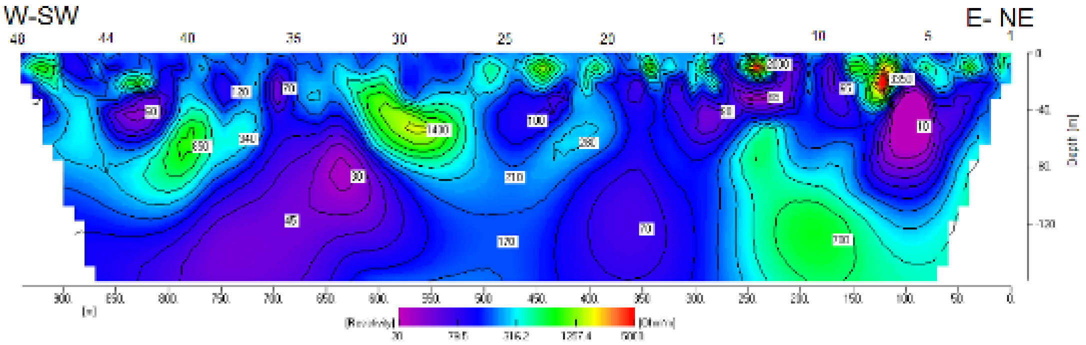
dipole-dipole



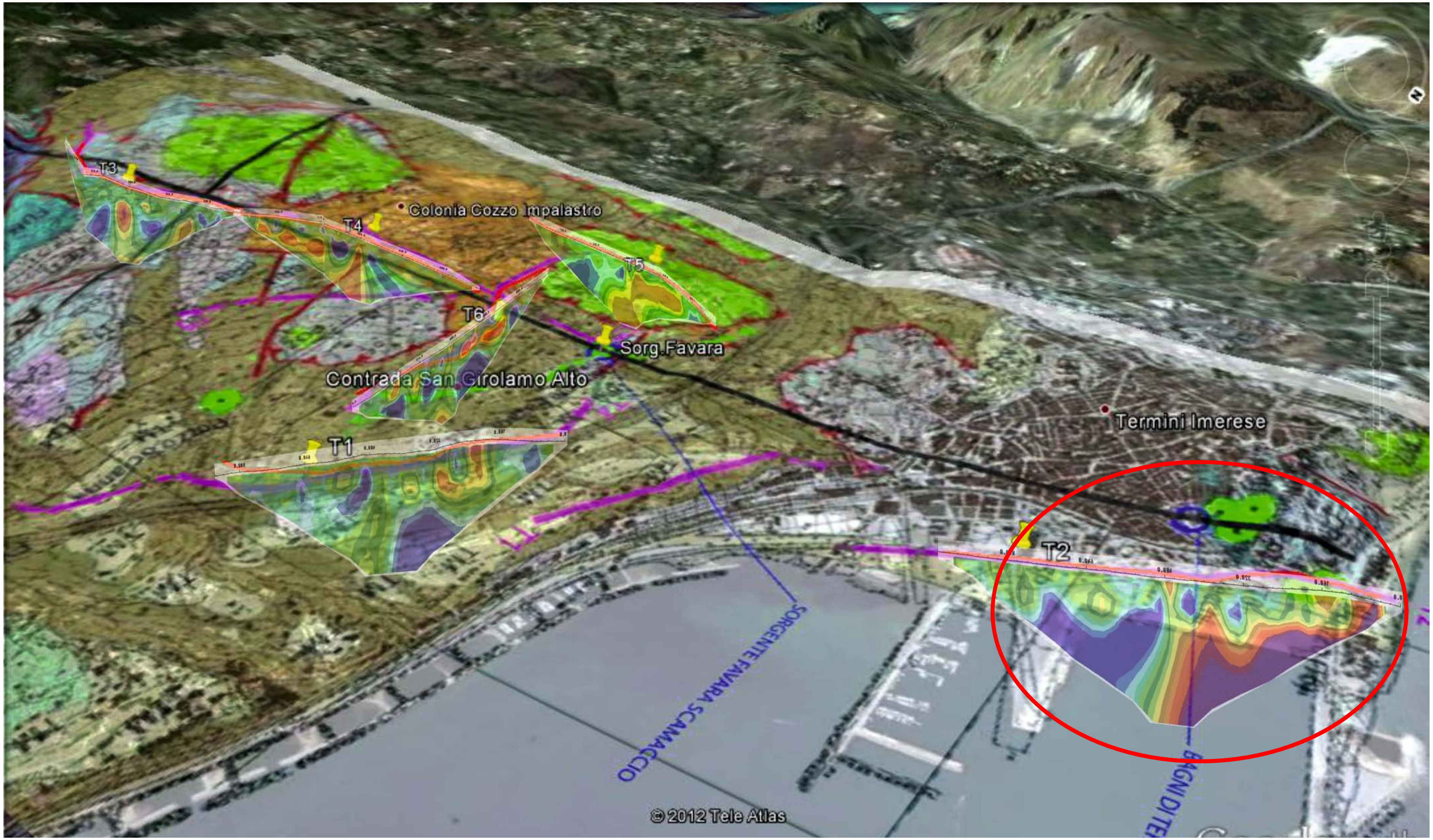
Wenner



Schlumberger



ELECTRICAL (DC) METHODS



ELECTRICAL (DC) METHODS

ELECTRICAL (DC) METHODS

Used in areas where the geothermal circulation and related alteration take place at shallow depths (<2 km)

Long electric arrays (Schlumberger and dipole-dipole) used in the 70’s and 80’s for resistivity imaging

2 D and 3 D inversion softwares available “off the shelf”

Advantages : source controlled, resolution

Disadvantages :

Implementation very heavy compared with MT and TDEM

equivalences (non unique solution),

“Blackbox”software could drive very easily to erroneous interpretations

SEISMIC METHODS

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.

SEISMIC METHODS

Elastic waves

When a stress is applied (or released) the corresponding strain propagates out from the source.

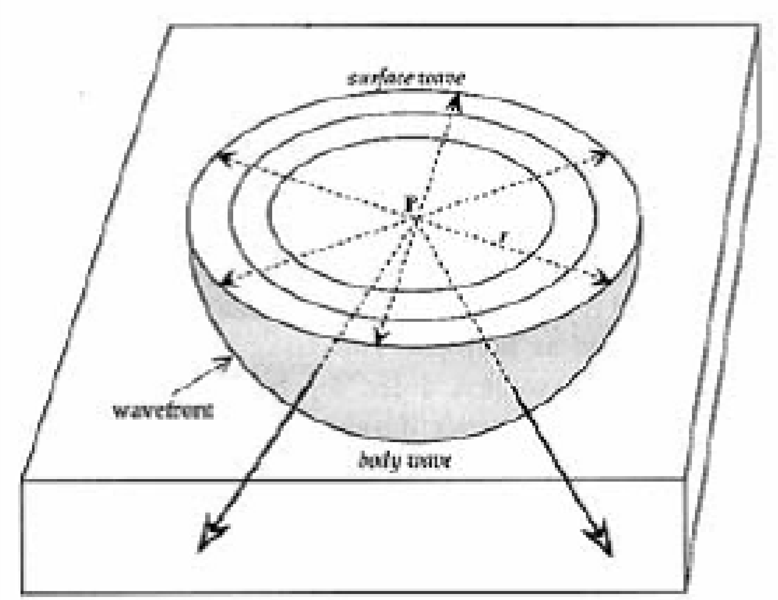


Fig. 3.9 Propagation of a seismic disturbance from a point source P near the surface of a homogeneous medium; the disturbance travels as a body wave through the medium and as a surface wave along the free surface.

Point source seismic disturbance:

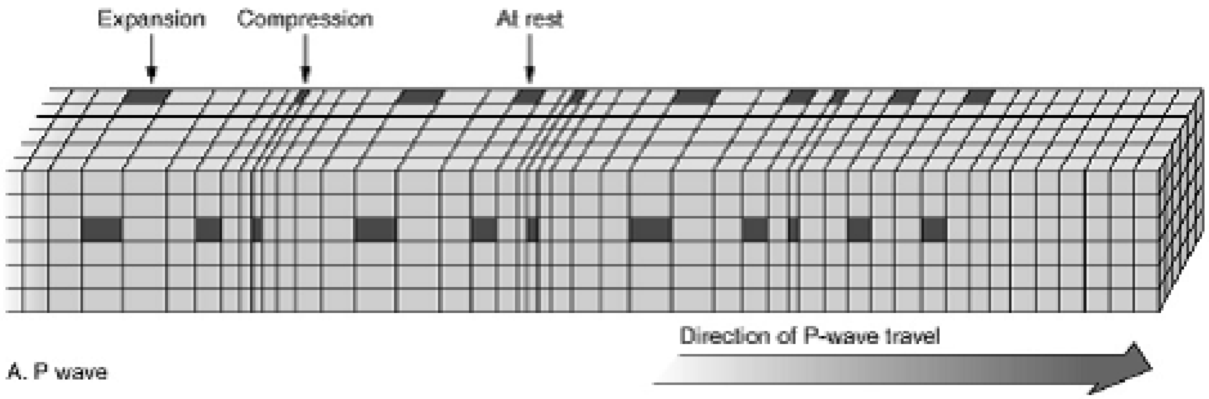
- Wavefront expands out from the point: **Huygen's Principle**
- Body waves: sphere
- Surface waves: circle
- **Rays:** perpendicular to wavefront

SEISMIC METHODS

Body waves

P-waves

- P for "primary" or "push-pull"
- Compression and rarefaction, no rotation
- Causes volume change as the wave propagates
- Similar to sound waves traveling through air



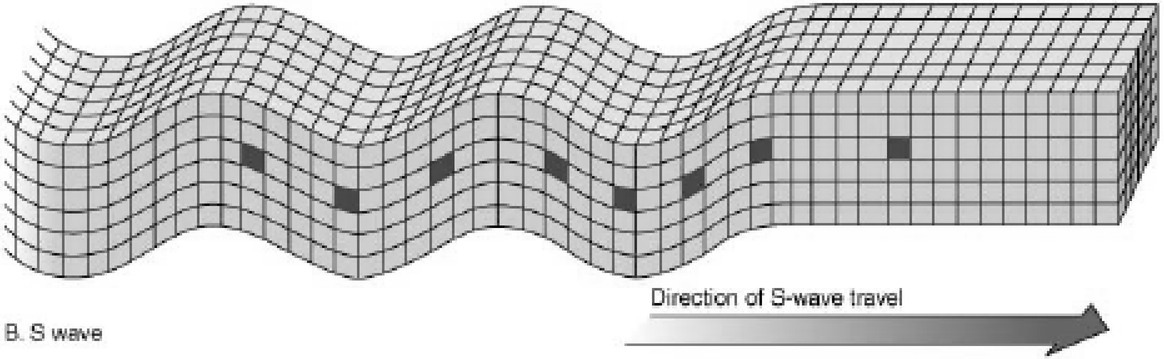
A. P wave

SEISMIC METHODS

Body waves

S-waves

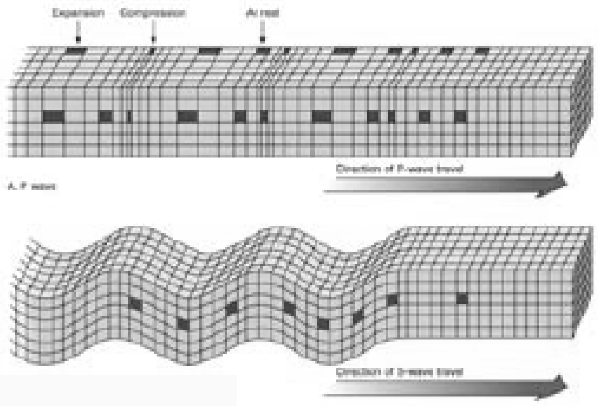
- S for "secondary" or "shear" and "shake"
- Shearing and rotation
- No volume change as the wave propagates

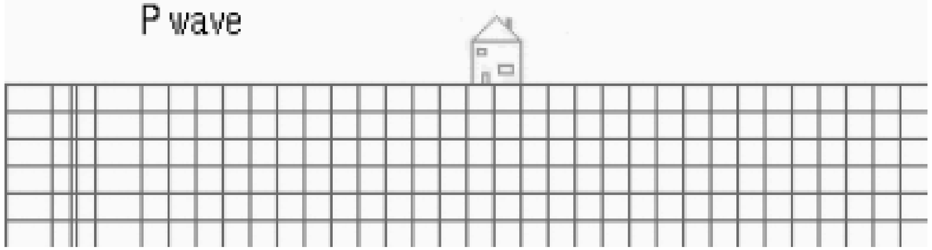


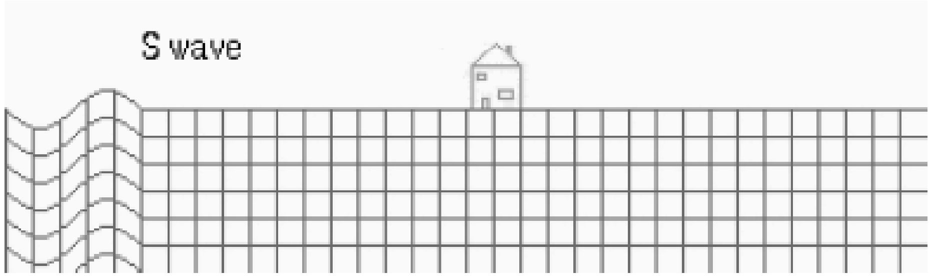
B. S wave

SEISMIC METHODS

Body waves
P and S-waves







SEISMIC METHODS

Elastic moduli

describe the physical properties of the rock
...and determine the seismic velocity

Young's modulus

Poisson's ratio

Shear modulus, μ

- Force per unit area to change the shape of the material

Bulk modulus, κ

- Ratio of increase in pressure to associated volume change
- Always positive

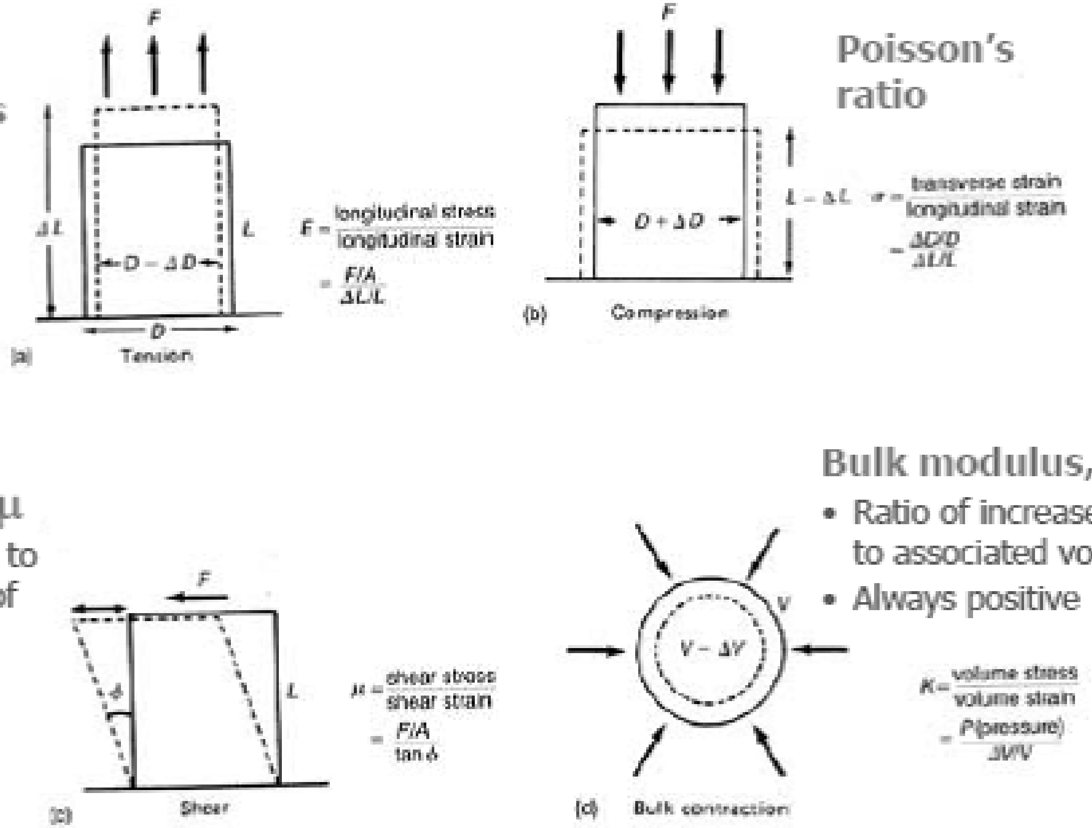


Fig. 4.2 Common types of elastic stress and strain. Cross-sections of bodies shown before strain (solid line) and after strain (dashed line). Directions of stress are shown by thick arrows. The related elastic moduli are defined. (a,b) Young's modulus, E, and Poisson's ratio, σ. (c) shear (or rigidity) modulus, μ; (d) bulk modulus, K: application of uniform pressure shown by thick arrows around the body. Poisson's ratio is a measure of the relative deformation of the body in two perpendicular directions. F denotes the force acting on a cross-sectional area A.

SEISMIC METHODS

P and S-velocities

P-velocity

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

change of shape and volume

S-velocity

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

change of shape only

For liquids and gases $\mu = 0$, therefore

➔ $V_S = 0$ and V_P is reduced in liquids and gases

➔ Highly fractured or porous rocks have significantly reduced V_P

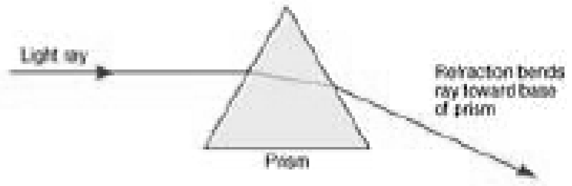
The bulk modulus, κ is always positive, therefore $V_S < V_P$ always

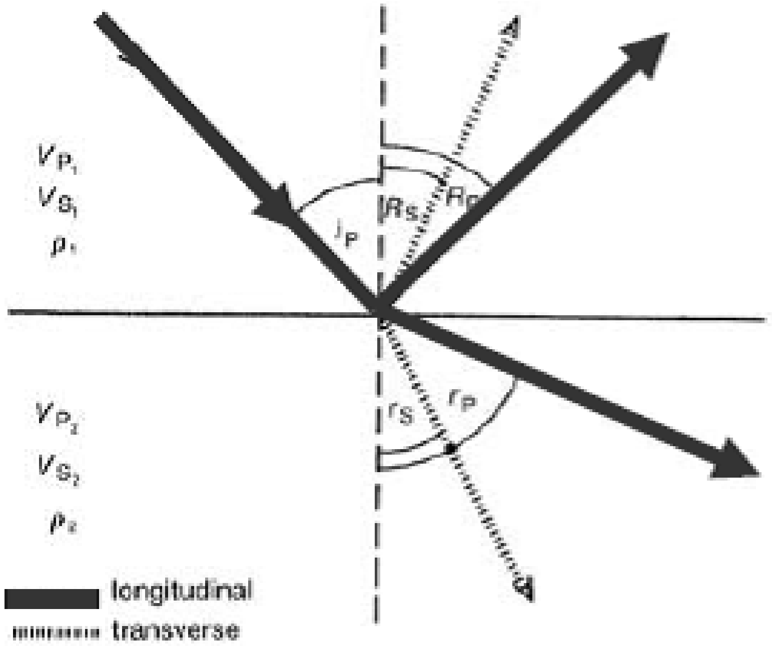
P-waves are the most important for controlled source seismology

- They arrive first making them easier to observe
- It is difficult to create a shear source, explosions are compressional

SEISMIC METHODS

Reflection and transmission





Seismic rays obey Snell's Law

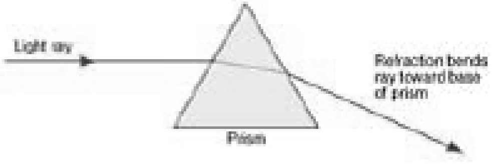
(just like in optics)

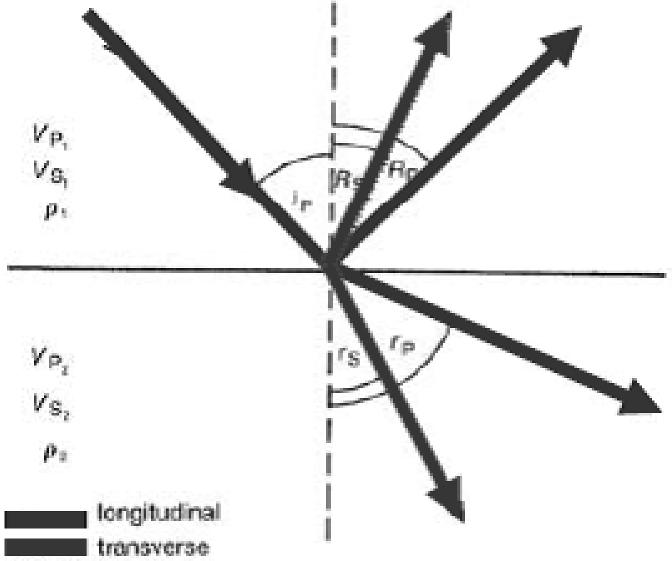
The angle of incidence equals the angle of reflection, and the angle of transmission is related to the angle of incidence through the velocity ratio.

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin R_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}}$$

SEISMIC METHODS

Reflection and transmission





Seismic rays obey Snell's Law

(just like in optics)

The angle of incidence equals the angle of reflection, and the angle of transmission is related to the angle of incidence through the velocity ratio.

But a conversion from P to S or vice versa can also occur. Still, the angles are determined by the velocity ratios.

$$\frac{\sin i_P}{V_{P1}} = \frac{\sin R_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}} = \frac{\sin R_S}{V_{S1}} = \frac{\sin r_S}{V_{S2}} = p$$

where p is the ray parameter and is constant along each ray.

SEISMIC METHODS

Amplitudes reflected and transmitted

The amplitude of the reflected, transmitted and converted phases can be calculated as a function of the incidence angle using **Zoeppritz's equations**.

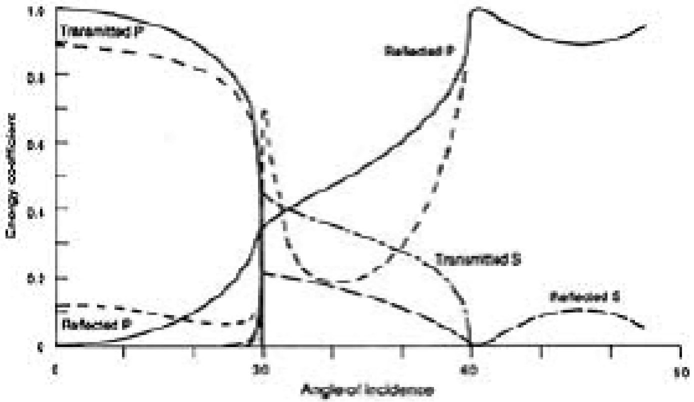
Simple case: **Normal incidence**

Reflection coefficient

$$R_C = \frac{A_R}{A_i} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

Transmission coefficient

$$T_C = \frac{A_T}{A_i} = 1 - R_C = \frac{2\rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$



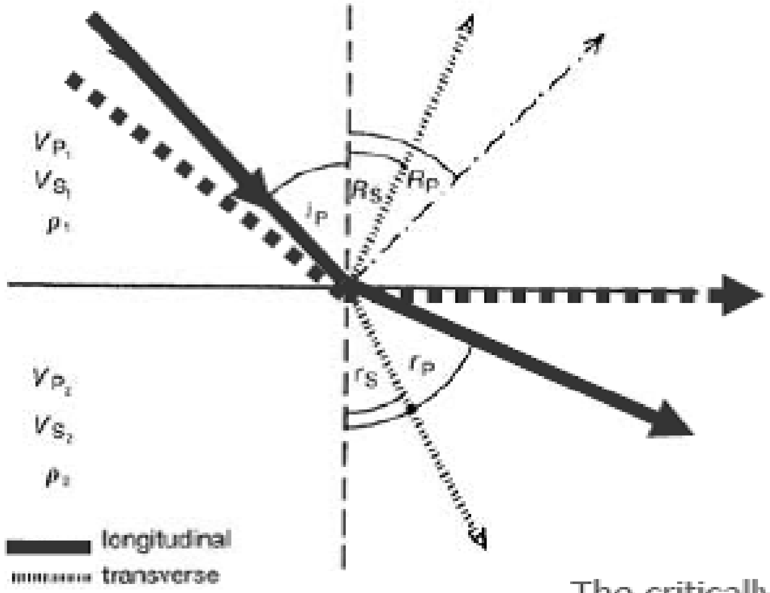
Reflection and transmission coefficients
for a specific impedance contrast

These coefficients are determined by from the product of velocity and density – the **impedance** of the material.

R_C usually small – typically 1% of energy is reflected.

SEISMIC METHODS

Critical incidence



$$\frac{\sin i_P}{V_{P1}} = \frac{\sin r_P}{V_{P2}}$$

when $V_2 > V_1$, $r_P > i_P$

therefore, we can increase i_P until $r_P = 90°$

When $r_P = 90°$ $i_P = i_C$ the critical angle

$$\sin i_C = \frac{V_{P1}}{V_{P2}}$$

The critically refracted energy travels along the velocity interface at V_2 continually refracting energy back into the upper medium at an angle i_C

→ **a head wave**

ACTIVE SEISMIC METHODS

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.

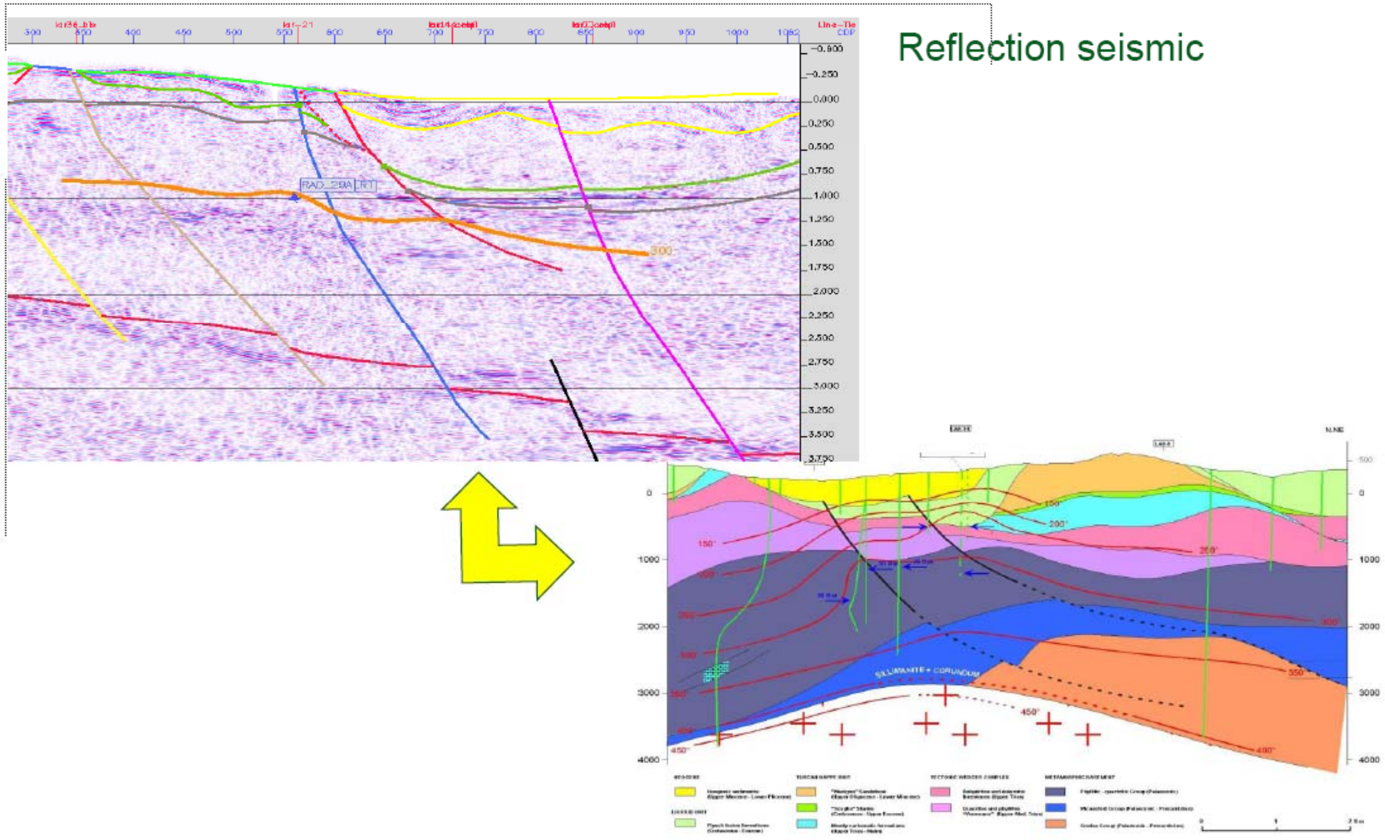
Seismic refraction is normally restricted to cases where the densities of the rocks and thus seismic **velocities increase** with depth. In addition, geophone arrays for refraction measurements need a **length of at least 4-** to 5 times (sometimes even 8 times) the sampling depth because of the very 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.

ACTIVE SEISMIC METHODS

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.

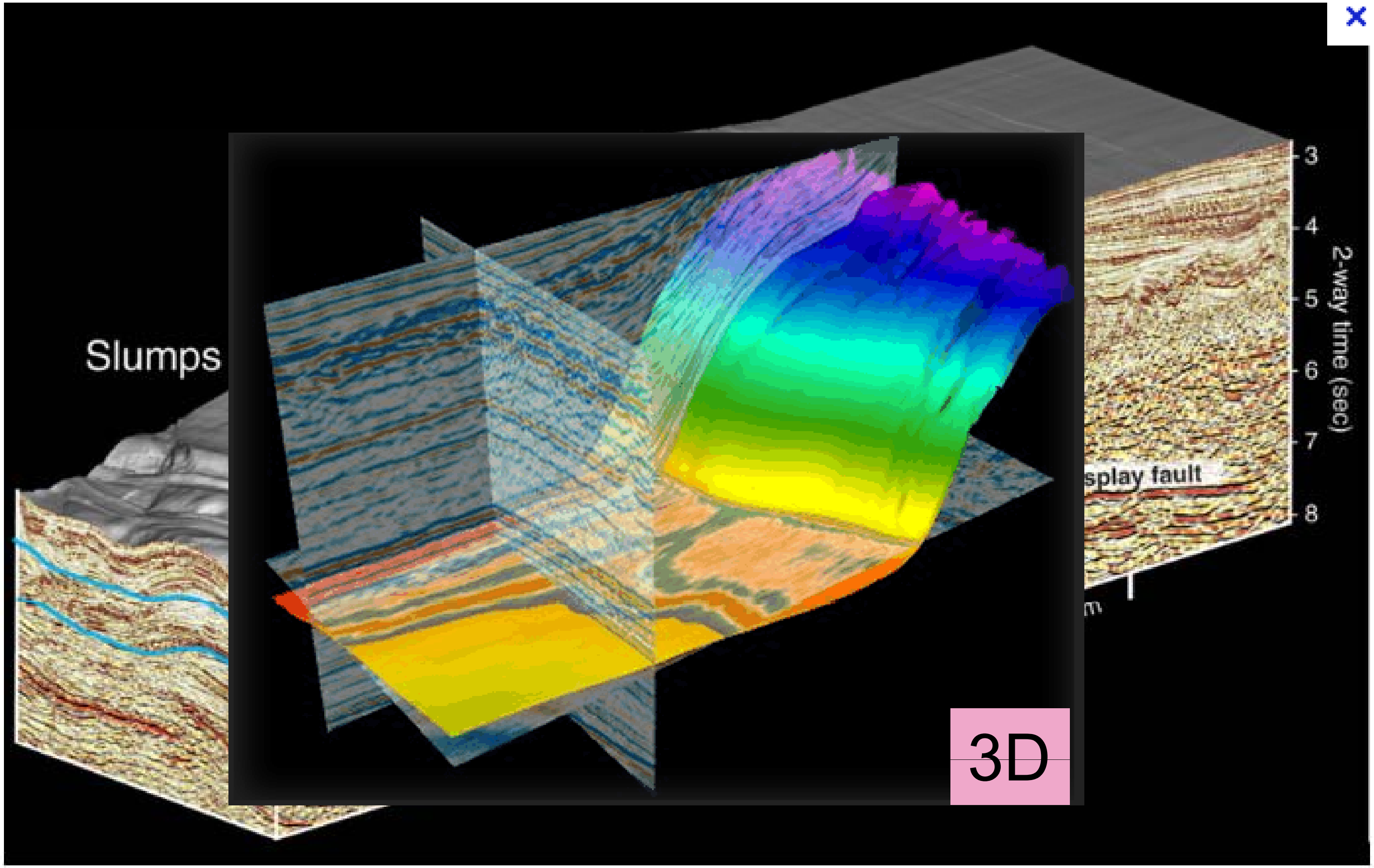
However, reflection signals are much more complex to detect and to analyse than refraction signals as they never arrive first, which implies time and labour intensive filtering and detection from a multitude of overlapping data. Moreover, the specific setup for reflection measurements requires more logistic 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.

ACTIVE SEISMIC METHODS

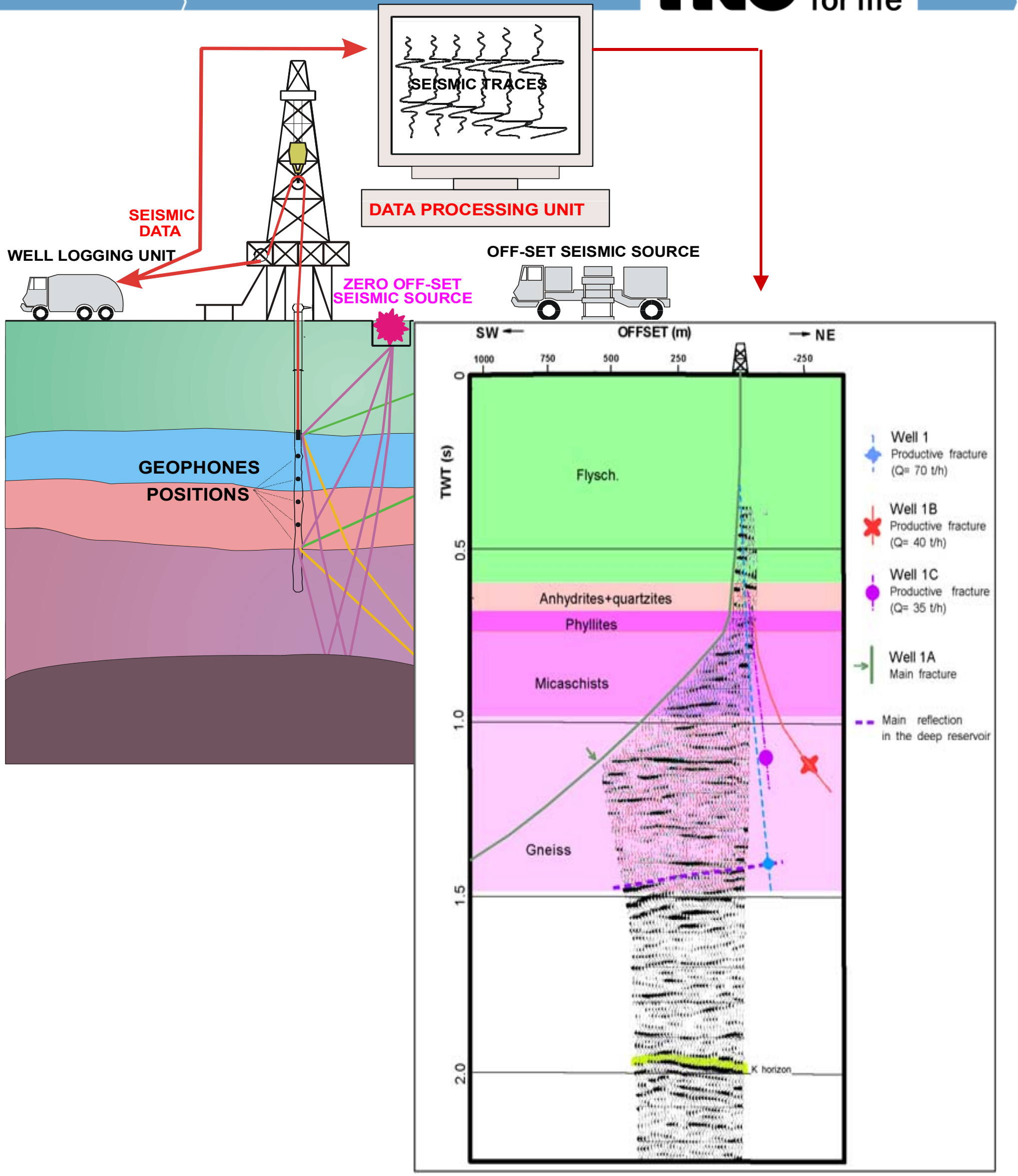


Reflection seismic

ACTIVE SEISMIC METHODS



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.



ACTIVE SEISMIC METHODS

Despite their clear advantages, especially resolution with depth, active seismic methods are not very common in geothermal exploration. One of the reasons why there are not widely used is that their cost often makes them difficult to fund for tight-budgeted geothermal projects especially where the geological complexity requires 3D arrays.

In volcanic environment they are seldom used due to the too high noise and strong attenuation.

PASSIVE SEISMIC METHODS

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.

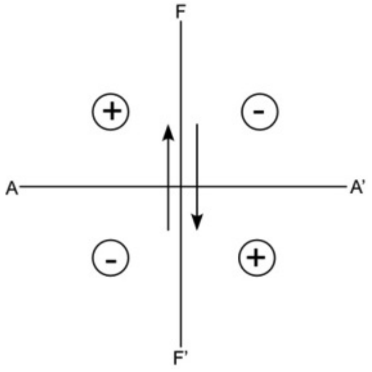
PASSIVE SEISMIC METHODS

Seismic surveys of microseismicity require a sufficiently dense network of recording stations placed around the potential reservoir and an extended period of recording time, usually several months. Several well-located events are necessary to reliably characterise an active fault. If these active faults are located, sophisticated use of recording and the recorded data can help to construct a three-dimensional image of fluid flow in the reservoir, as fluid circulation occurs in open faults and fracture systems, which are often responsible for the observed microseismicity.

The frequencies associated with fluid circulation in open fractures are usually at the lower limit of the recording spectrum. This problem can be solved by the use of broadband stations that record a much broader spectrum of frequencies than standard seismometers.

PASSIVE SEISMIC METHODS

The first target of passive seismic method is to determine hypocenters, whose location is directly linked to those of faults – including those created by stimulation and hydrofracturing - and to the tectonic signature of the area. In addition, information about the geology and tectonics can be obtained from fault plane solutions and first motion studies of these earthquakes, which are valuable in determining whether the earthquake activity in a prospect area is anomalous or typical of the region.



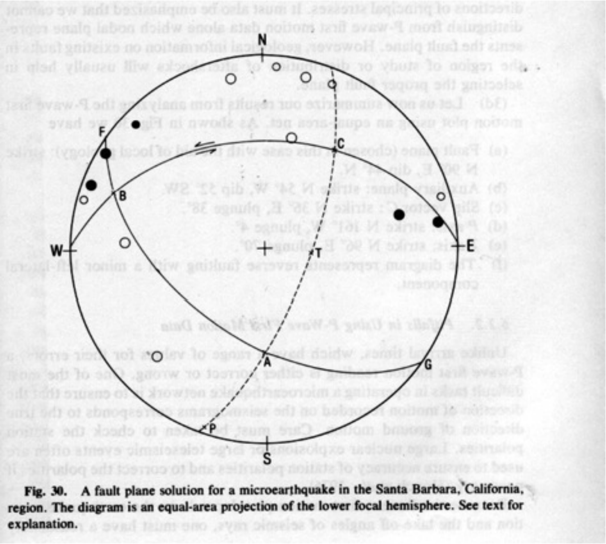
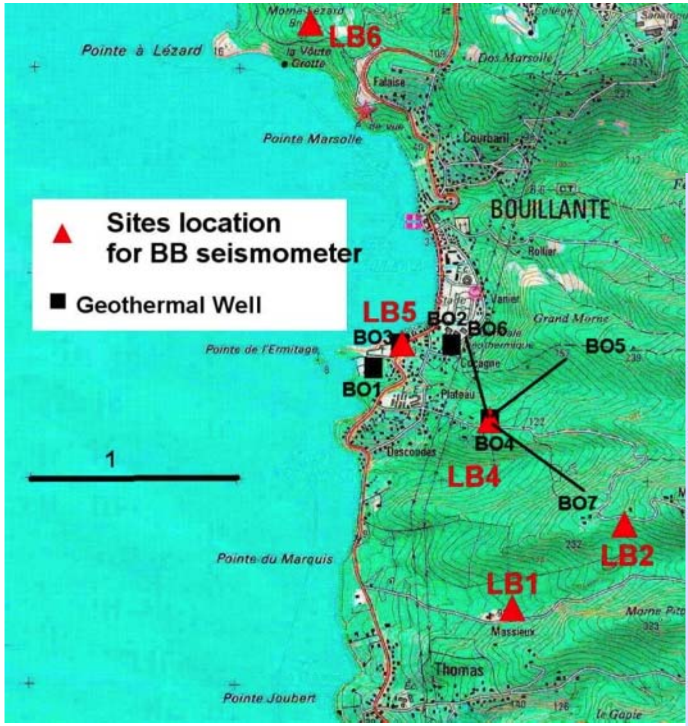
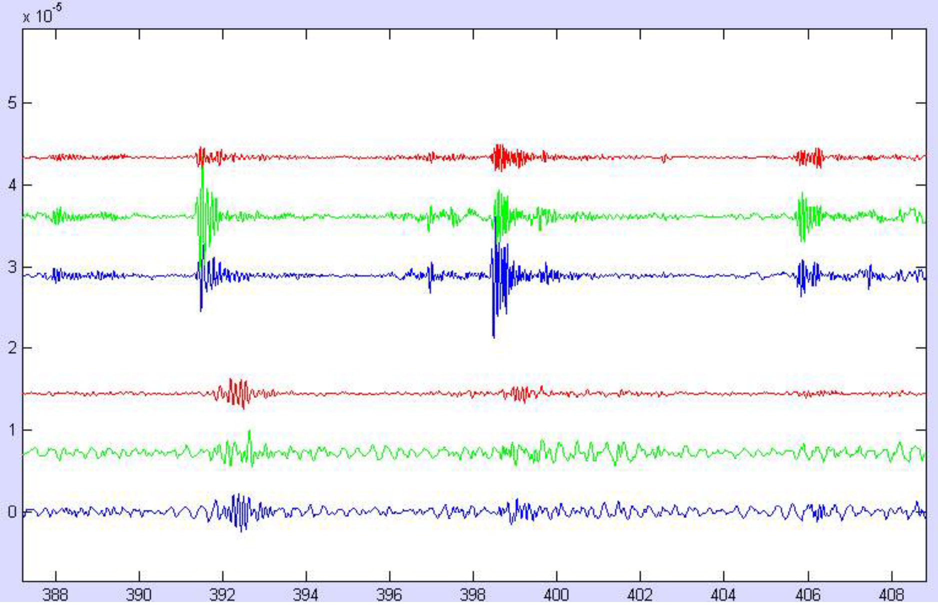


Fig. 30. A fault plane solution for a microearthquake in the Santa Barbara, California, region. The diagram is an equal-area projection of the lower focal hemisphere. See text for explanation.

PASSIVE SEISMIC METHODS

Detection of long period (LP) signals related to hydrothermal manifestations (bubbling of gas in a fracture close to the surface)





PASSIVE SEISMIC METHODS

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.

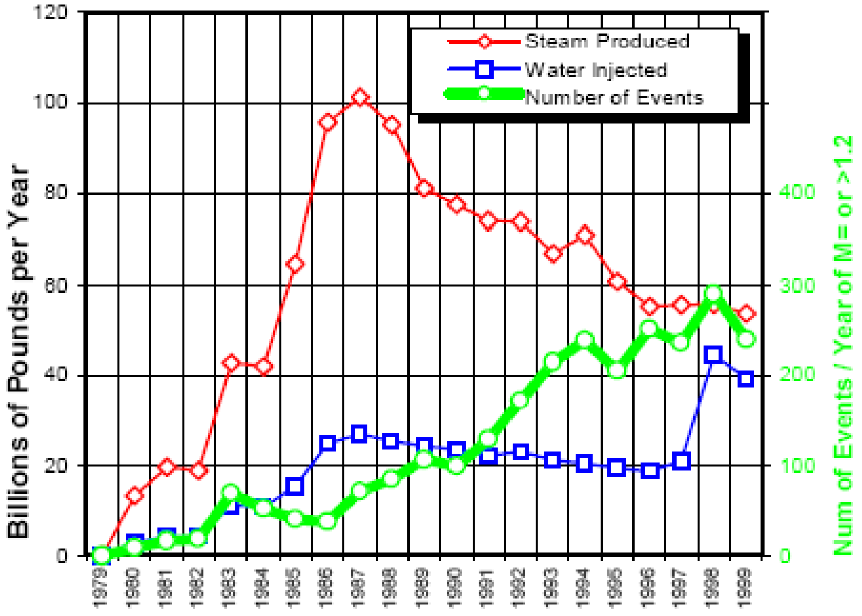
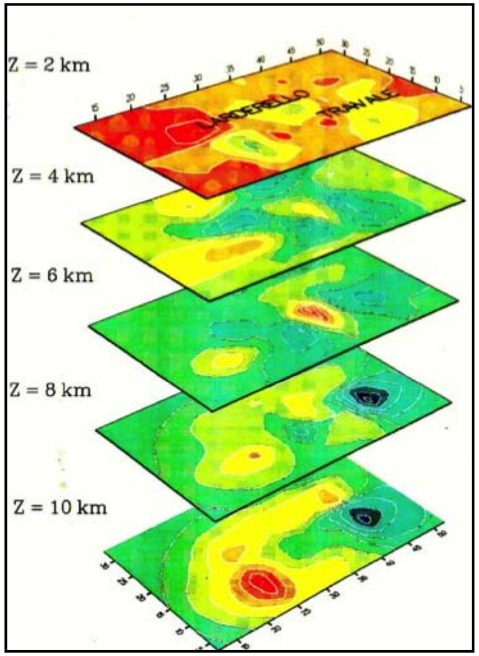
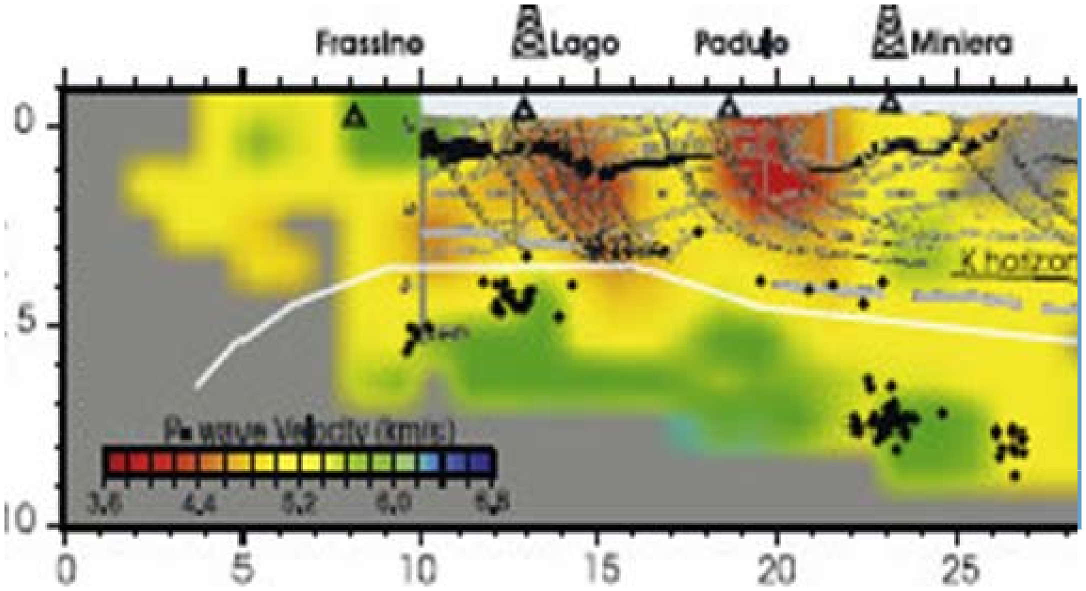


Fig.4 Annual Production, Injection & Seismicity, SE Geysers

PASSIVE SEISMIC METHODS

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





SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

Measurements are made in holes of at least 100 m deep

The diurnal temperature cycle penetrate only a few tens of centimetres into soils

The annual temperature cycle penetrate many metres into soils

Long-term climatic changes produce effects in temperature barely detectable at depths of 100 m

Objectives of thermal gradient measurements in boreholes:

- detection of areas of unusually high temperature
- quantitative determination of the component of heat flow along the direction of the borehole

SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

To eliminate the dependence on the thermal conductivity of the rock type, temperature gradients are converted to heat flow values (Fourier's equation)

$$\text{grad}\ T = \Phi/K$$

or

$$\Delta T/\Delta z = \Phi_z/K$$

$\Delta T/\Delta z$ = vertical gradient in temperature
K = thermal conductivity
Φ_z = thermal flux in the z (vertical) direction

Thermal conductivity is measured in lab over rock samples, whereas temperature is measured in the well.

SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

To reach a temperatures within 10 % of its undisturbed state it should be necessary to wait a period of time comparable to that involved in drilling the well. It may take day for wells of several hundreds m

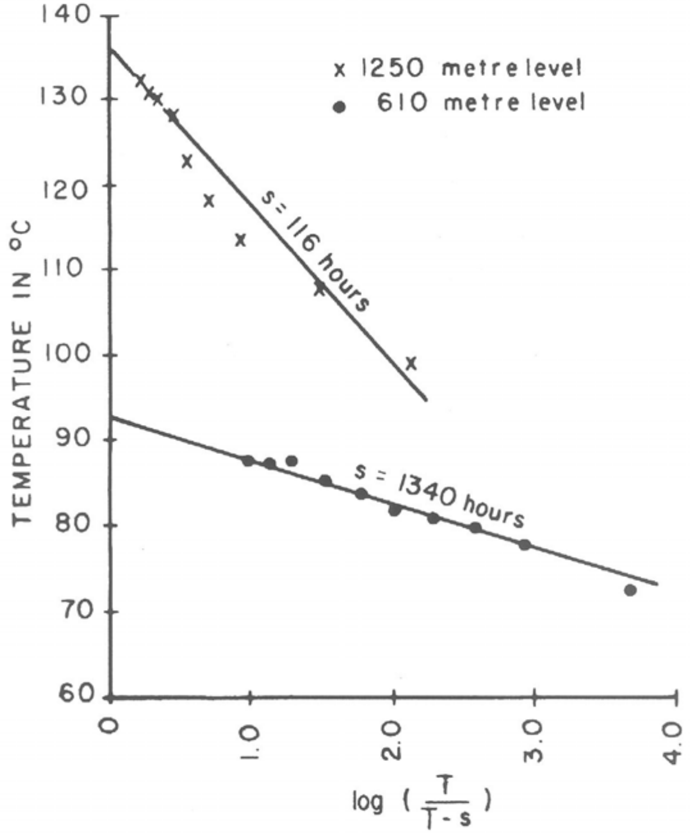
Stabilisation temperatures obtained by plotting Temp. against log *T/(T – s)*

T = total time since the drill first opened the borehole at the depth where the temperature is being measured

s is the time since circulation in the well was halted.

If the solution of Fourier's equation are valid (linear rate of drilling and consistent removal of heat by the drilling mud from the bottom of the hole), results are approximately linear.

By extrapolating to zero, the temperature after an infinitely long re-equilibration process is obtained.



SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

Corrections

- *topographic* correction (the reference plane is the horizontal one at the measuring site and crossing topography). When changes are rapid and isotherms are not in equilibrium, it is not enough, and other corrections should be taken into account

- *paleoclimatic* correction (continuous climatic variations are taken into account and surface temperature is assumed constant in the last 10000 years)

- correction due to changes of ground surface due to rapid sedimentation or erosion

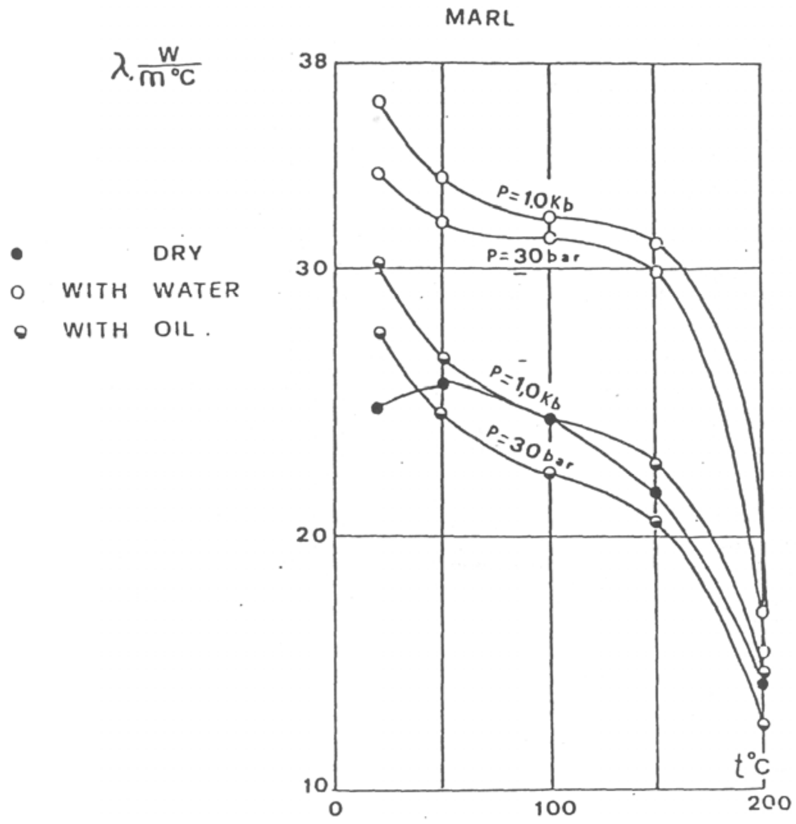
When convection is rapid, Fourier's simple equation cannot be used to compute heat flow, and hydrogeological knowledge becomes of main importance.

SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

Thermal conductivity measured on samples should always be averaged. Moreover, it decreases with temperature and increases with pressure.

Pressure variation can be neglected, whereas temperature variation can not be neglected and depends also on the saturation level.

Usually conductivity increases with depth, due to compaction of rock at increasing pressures and to alignment of clay minerals and anisotropy effects.



SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS

Thermal conductivity depend also on the porosity of the formation. The following example show the relation for Hawaian basalt, as defined in laboratory measurements (*from Morita et al.,*

WGC 1995).

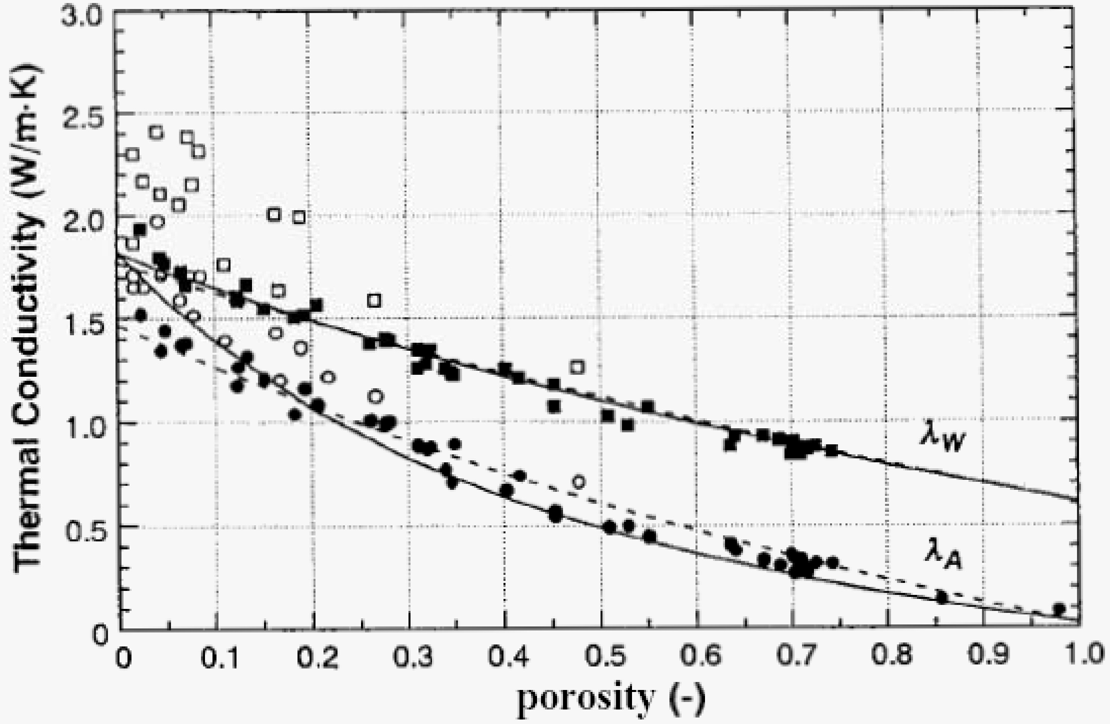
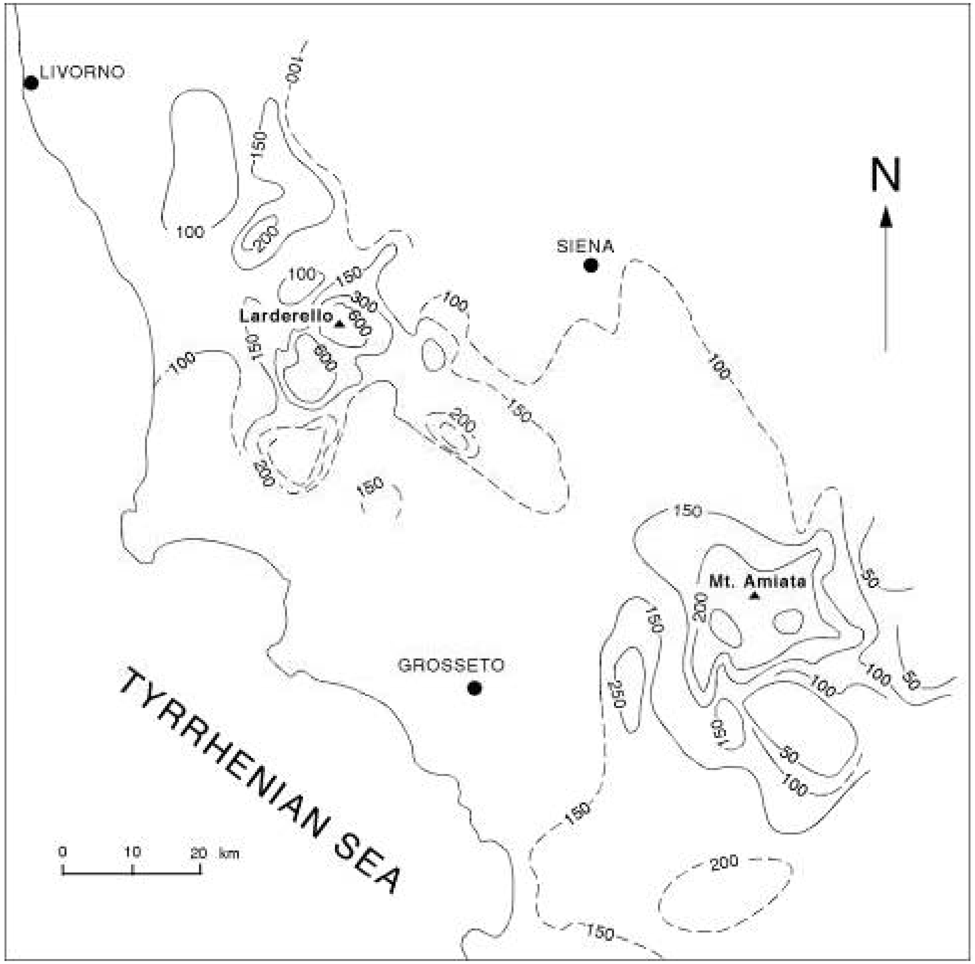


Fig. 10 The relationship between porosity and the thermal conductivity of Hawaiian basalt correlated by Horai (1991). Solid and open symbols denote that the values for the modal content of olivine are less than 5% and greater than 5%, respectively. "λ_A" and "λ_W" in the figure denote the thermal conductivities in air-saturated or water-saturated states, respectively.

SUBSURFACE TEMPERATURE AND THERMAL GRADIENT SURVEYS



When thermal conductivity and temperature gradients are known, heat flow is mapped and anomalous areas are detected.

Anomalies are linked to any heat source: however, those due to hot fluid circulation affect large areas. This way the most interesting areas can be defined and application of more expensive geophysical methods are limited.

Heat Flow map (units in mW/m^2) in the geothermal areas, southern Tuscany, Italy

OVERALL GEOLOGICAL FEATURES

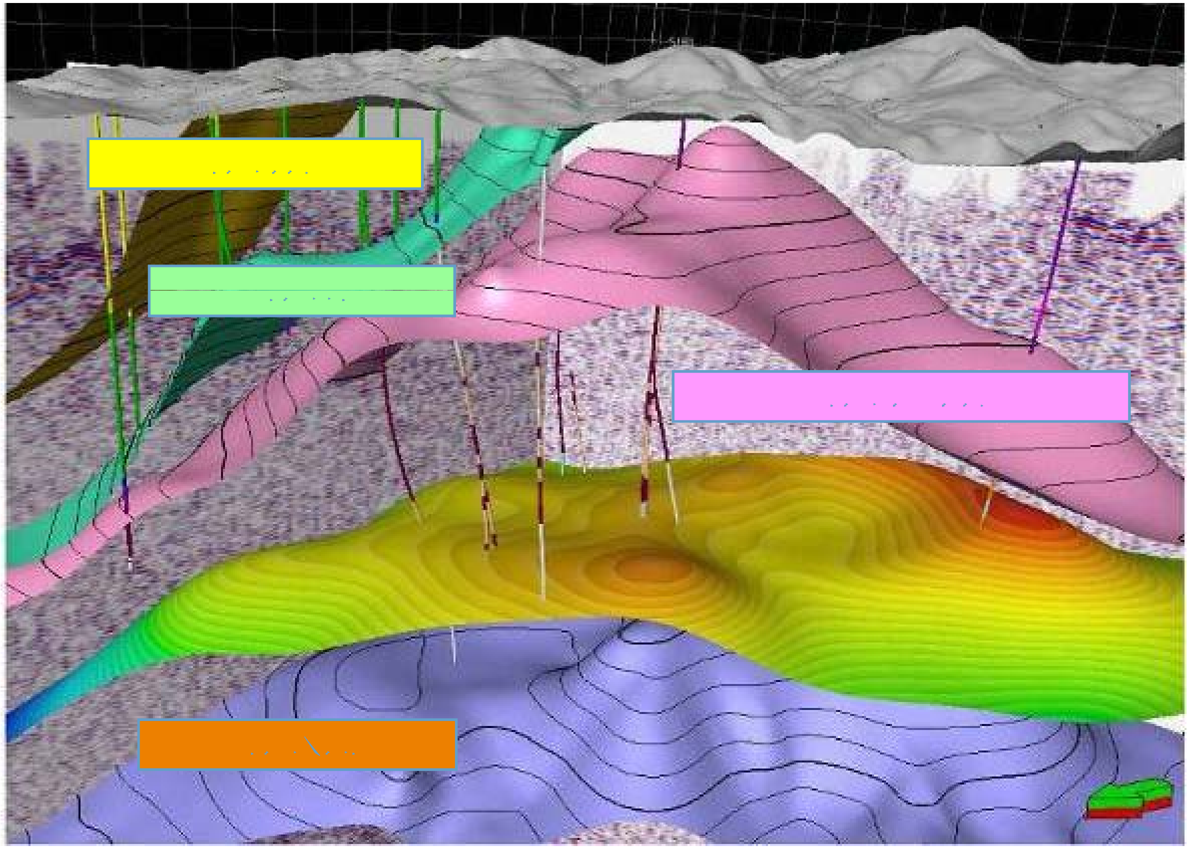
The best suited method in sedimentary and crystalline geological scenarios to extrapolate borehole information and to define and image the geological structure is the active seismic.

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

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

Expensive → Cost reduction

OVERALL GEOLOGICAL FEATURES

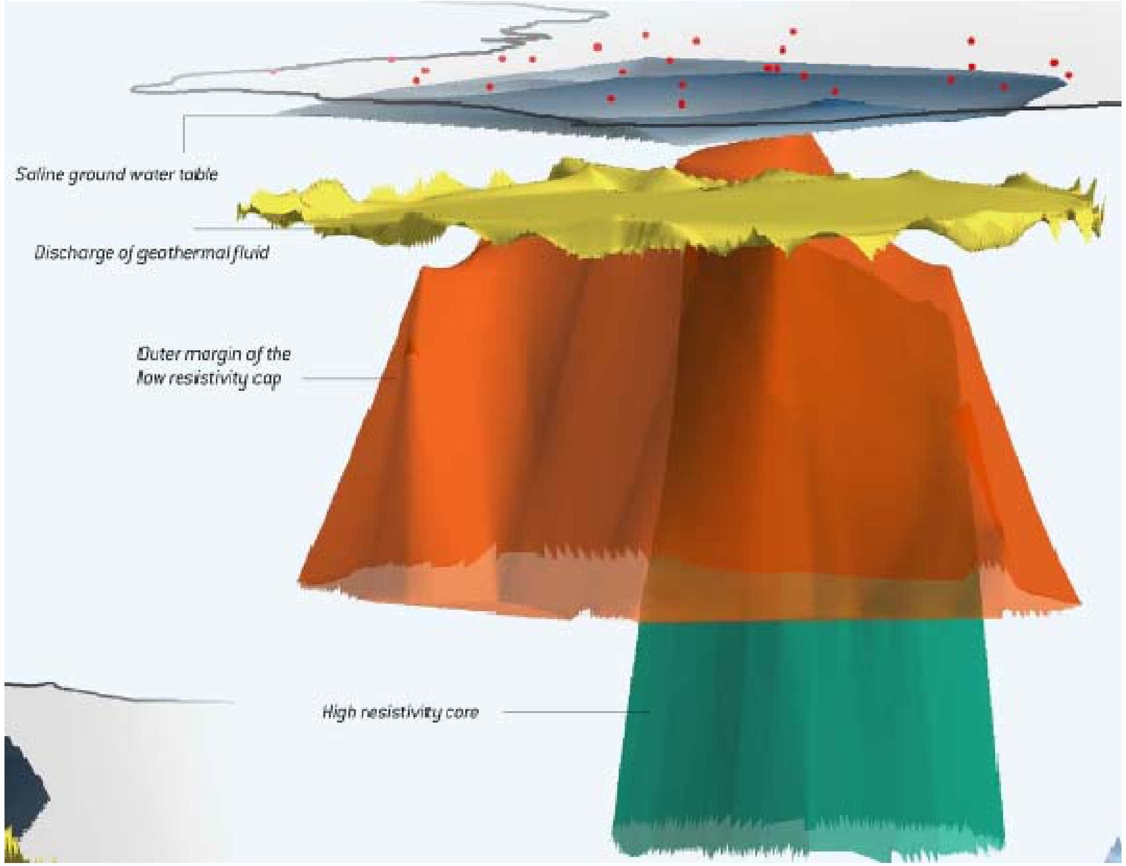


From ENEL, ENGINE Worhshop1

STRUCTURAL INTERPRETATION

OVERALL GEOLOGICAL FEATURES

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



From Karlsdottir, ENGINE Worhshop1

OVERALL GEOLOGICAL FEATURES

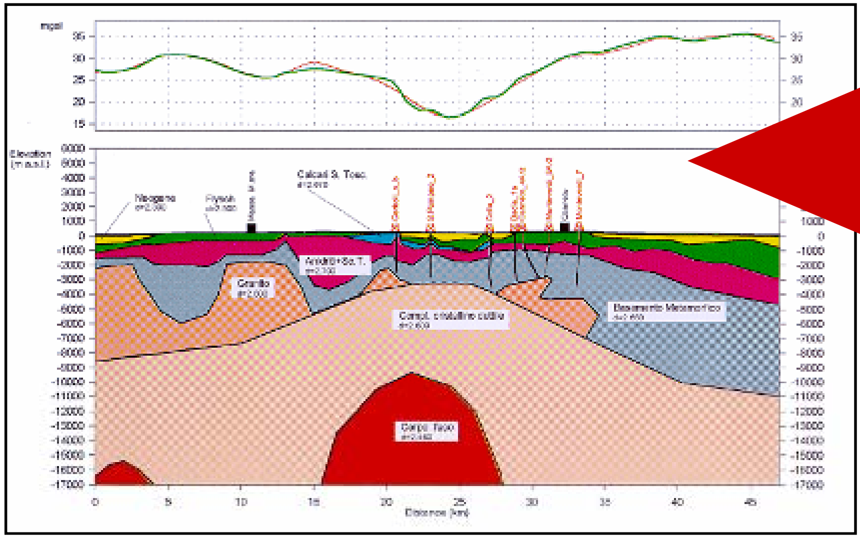
Partially molten intrusives, representing the heat source in most of geothermal fields, at depths as shallow as 10 to 20 km produce thermally excited rocks which define high regional heat flow

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

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

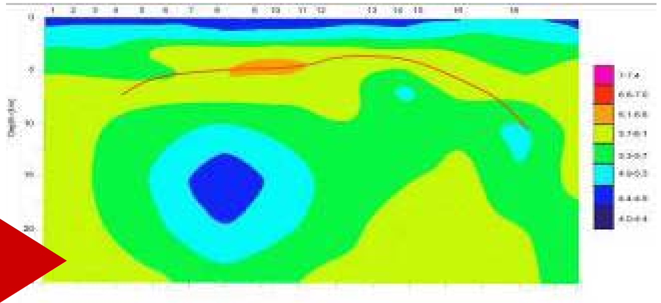
Density reduction due to partial melts may also be detected by gravity anomalies.

OVERALL GEOLOGICAL FEATURES

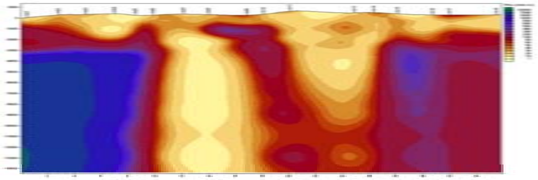


2/3D Modeling, properly balanced with experimental density data, pointed out deep low density bodies to be related to molten intrusions

From ENEL, ENGINE Worhshop1

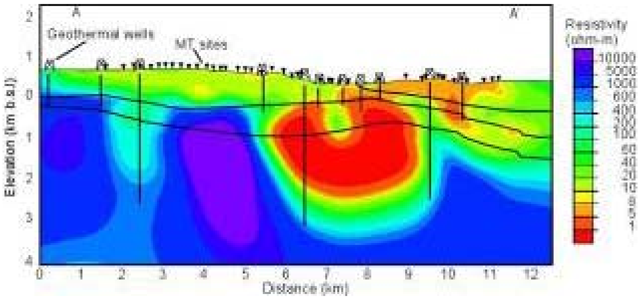


Low velocity bodies defined by teleseismic tomography and corresponding low resistivity bodies

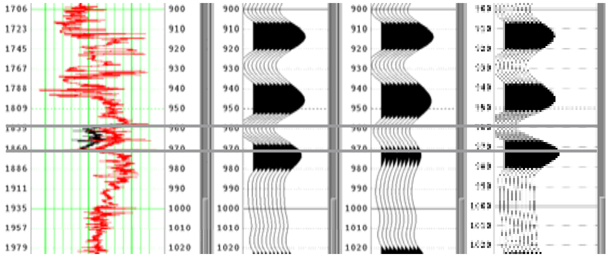


OVERALL GEOLOGICAL FEATURES

Resistivity decreases with increasing porosity and increasing saturation.



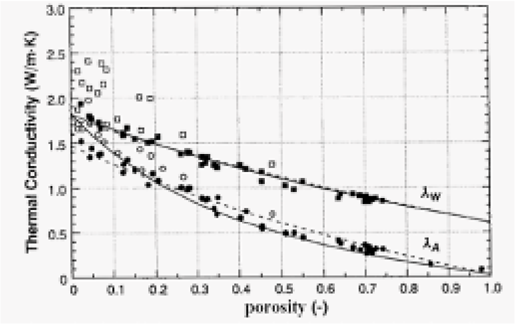
Wave velocity is reduced by increasing porosity but shows different behaviour for different saturation, with an inverse relationship when saturation is high (100/85%) and a direct relationship when saturation is low, being constant for saturation of 15-85%.



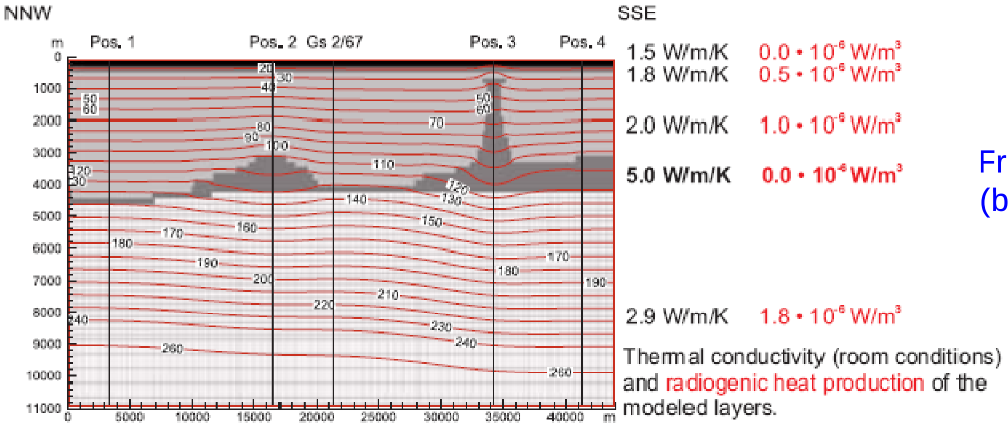
From Trappe,

ENGINE Worhshop1

Thermal conductivity depends also on the porosity of the formation.

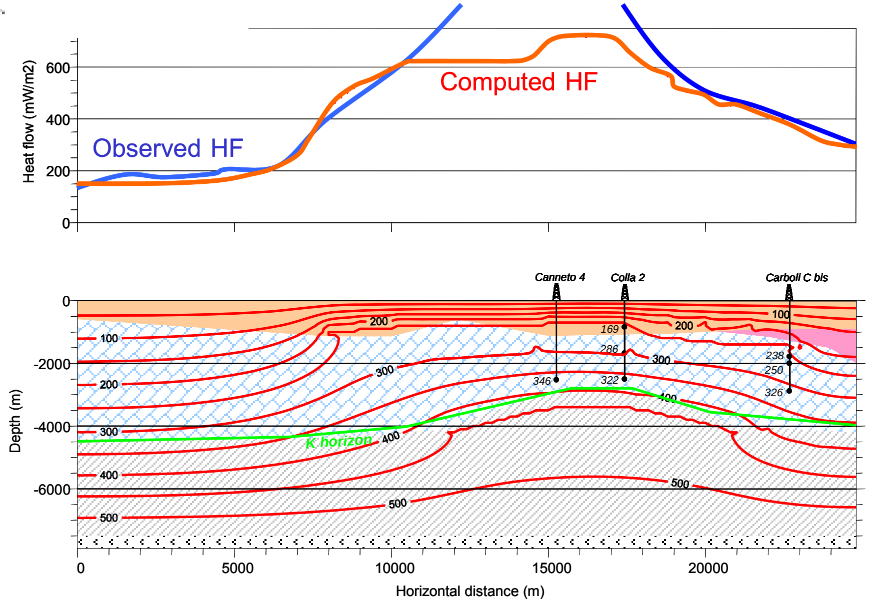


SUBSURFACE TEMPERATURE



Thermal conductivity (room conditions) and radiogenic heat production of the modeled layers.

From Norden (left) and Bellani (below), ENGINE Worhshop1



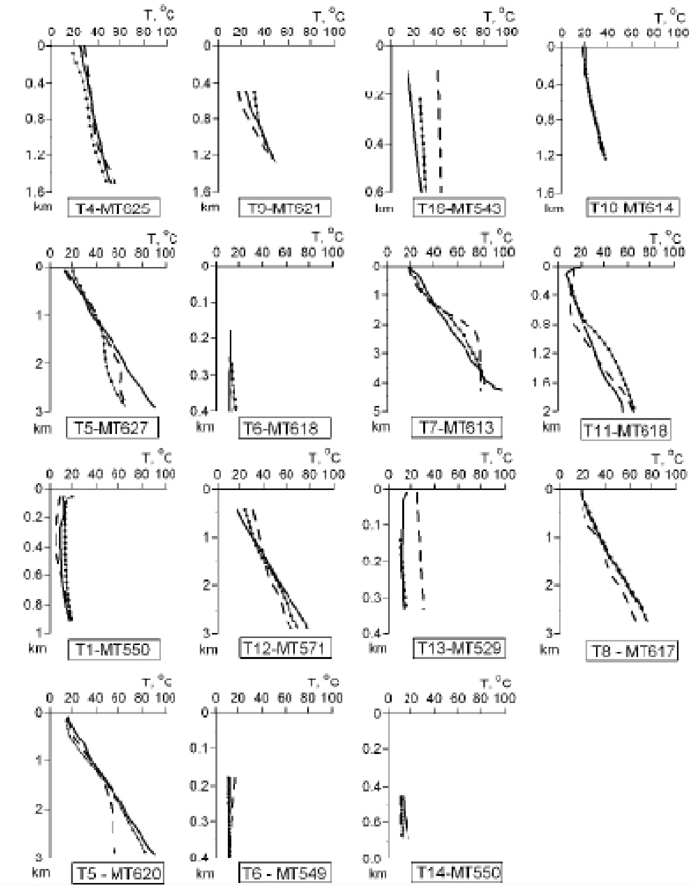
With proper care, heat flow and gradient data are able to define T° distribution at depth

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

SUBSURFACE TEMPERATURE

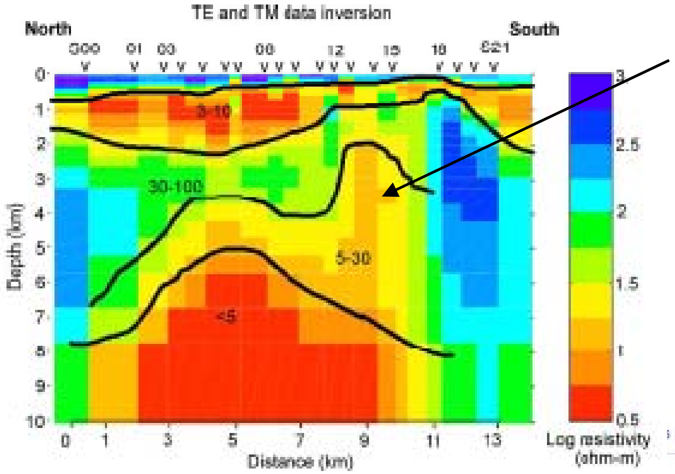
Through a neuronet analysis of MT and T° data, incorporating also geological information, electromagnetic data may be used as geothermometers.

An example is shown for Bishkek site in Tien Shan (Spichak, ENGINE Worhshop1). Measured and modeled T° distribution in wells. Solid line: measured T°; dashed line: modelled T° based on T° data only; modelled T° based on T° and MT data.



FLUID PATHWAY

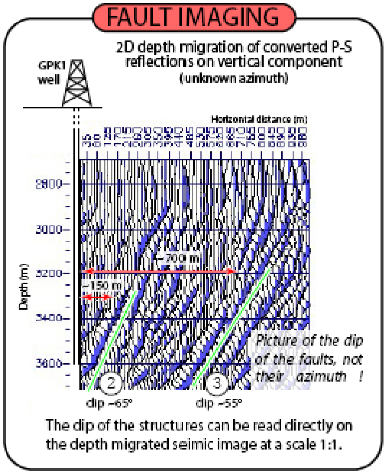
Many geophysical methods are able to map main lineaments and faults



Inferred fault

Oskooi et al., 2005

From Place, ENGINE Worhshop1

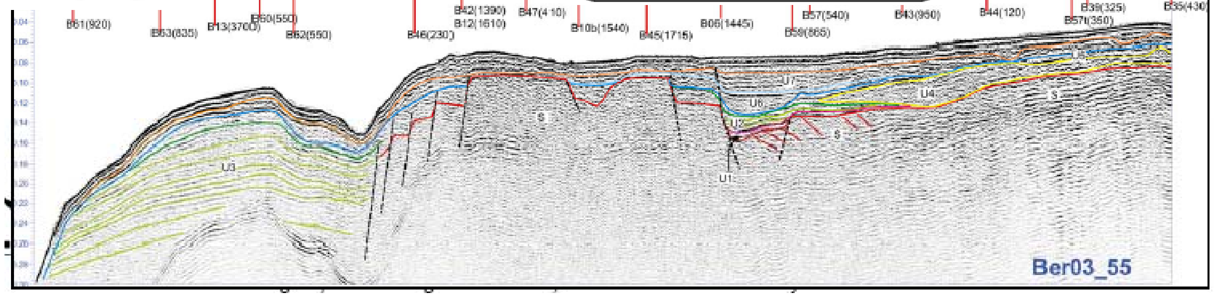


FAULT IMAGING

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

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

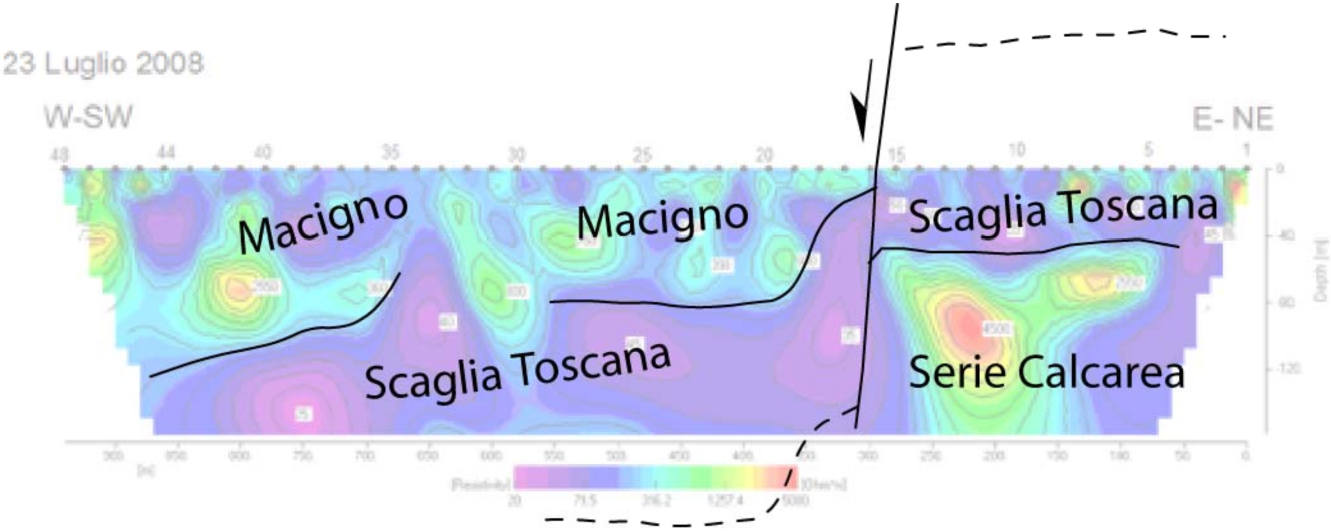
The dip of the structures can be read directly on the depth migrated seimic image at a scale 1:1.

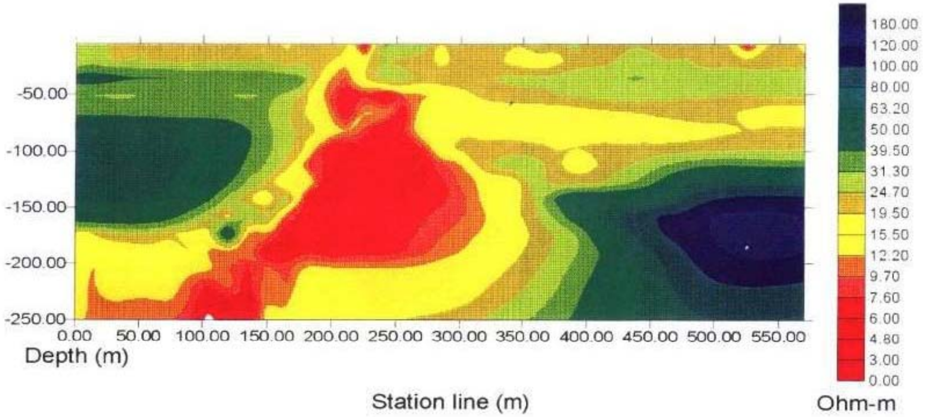


But this is not enough since there is still no direct evidence of fluid circulation

FLUID PATHWAY

Geothermal exploration at a low enthalpy field using ERT. The low resistivity zone is coincident with a known fault.





Geothermal exploration at a hot spring area near Beijing using AMT. The low resistivity zone is coincident with a known fault.

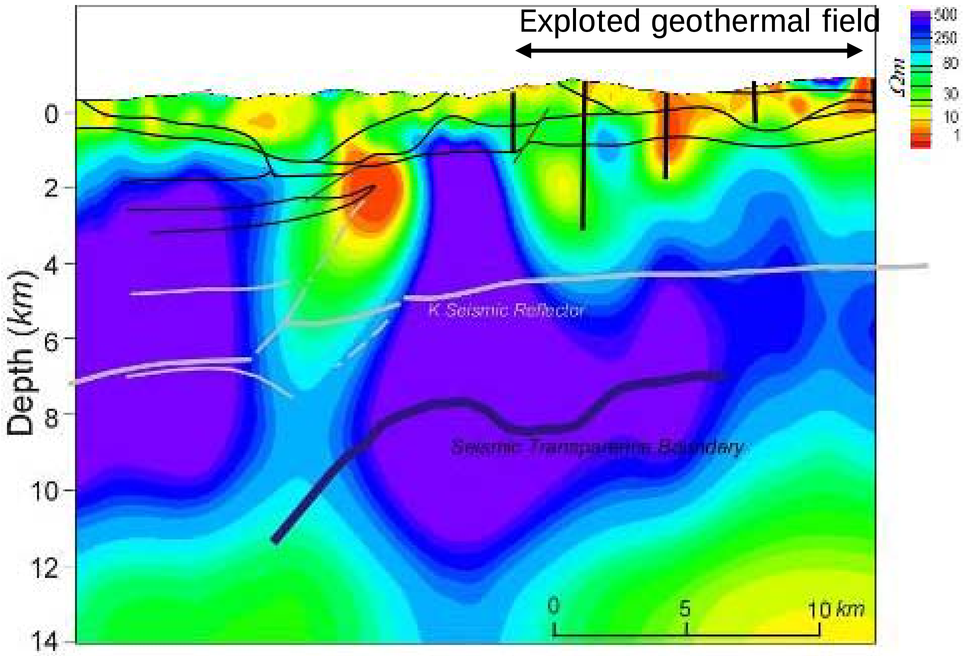
Consiglio Nazionale delle Ricerche, Dipartimento Terra e Ambiente, Istituto di Geoscienze e Georisorse

FLUID PATHWAY

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

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

Heat flow provide extra data



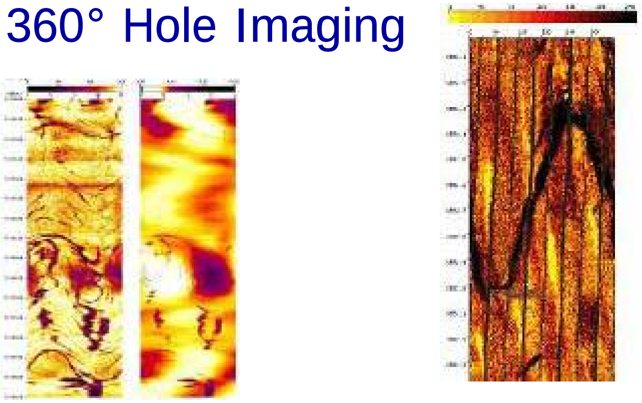
FLUID PATHWAY

Geophysical well logging by means of:

Elastic/Acoustic and resistivity parameters

Waveform analysis

360° Hole Imaging

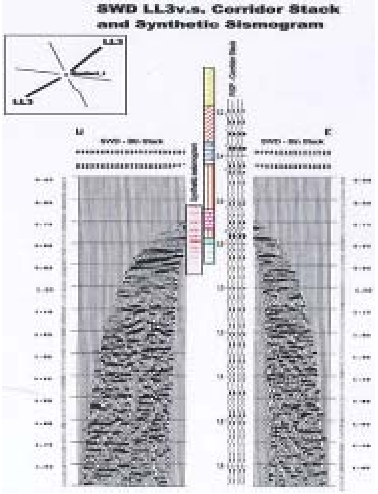


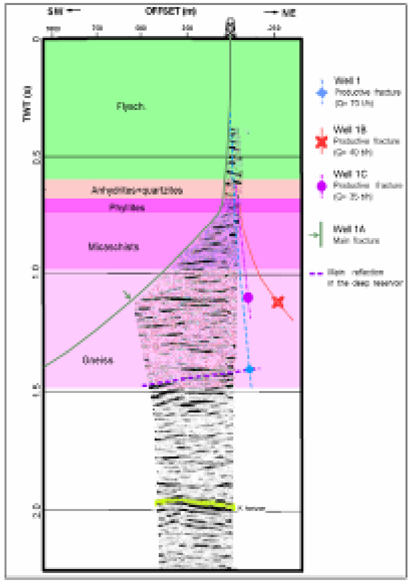
From Dezayes, ENGINE Worhshop1

WSP (Well Seismic Profiling):

VSP

SWD



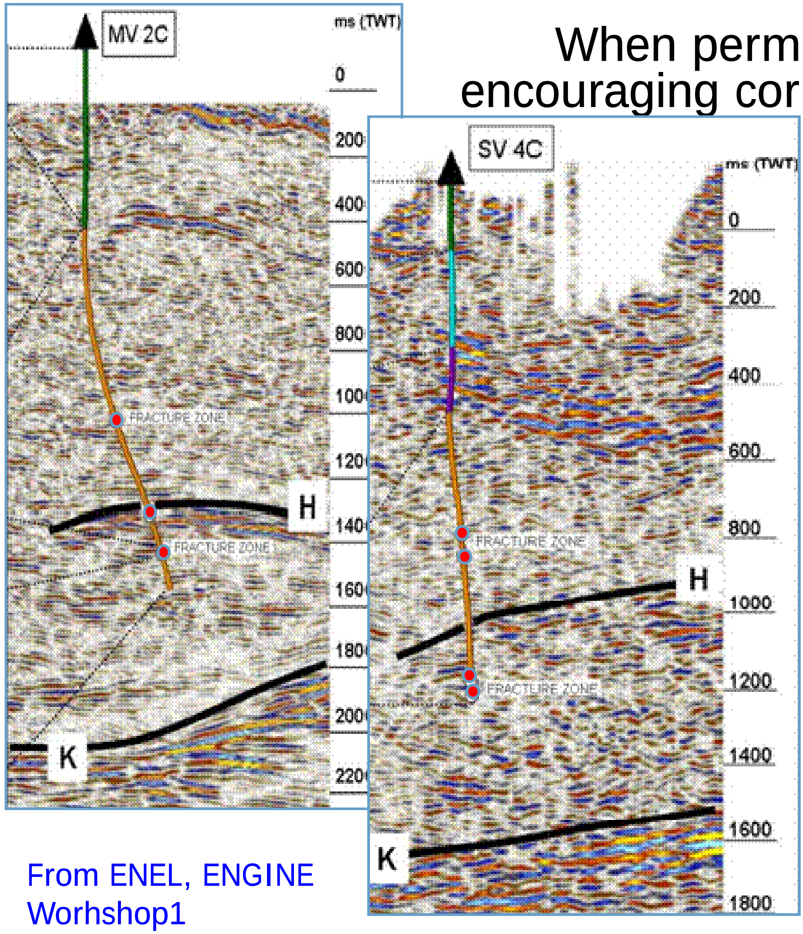


From ENEL, ENGINE Worhshop1

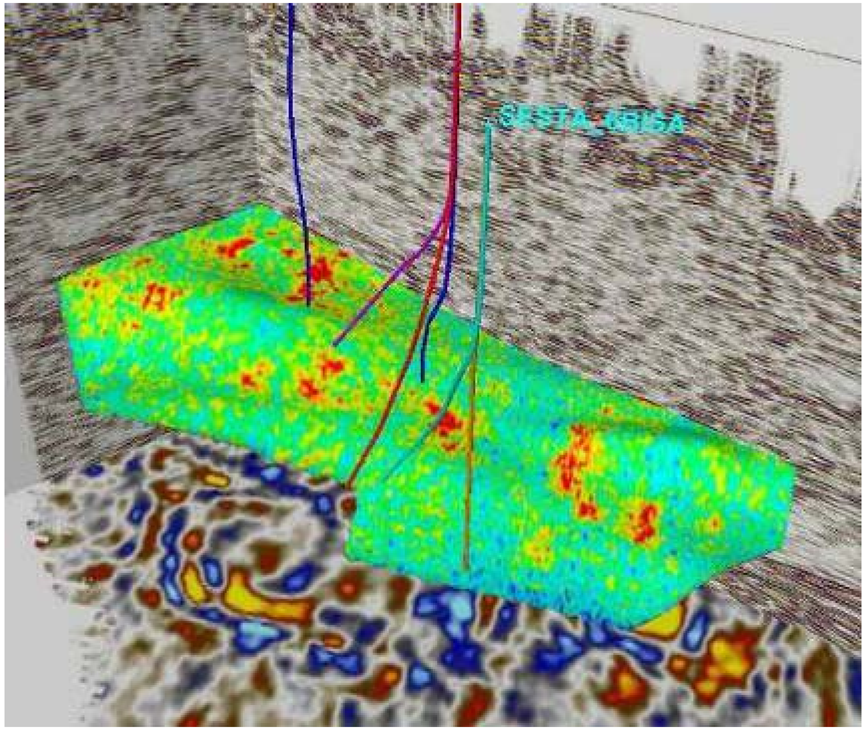
These data contrains seismic and MT, which are necessary for 3D extrapolation

FLUID PATHWAY

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

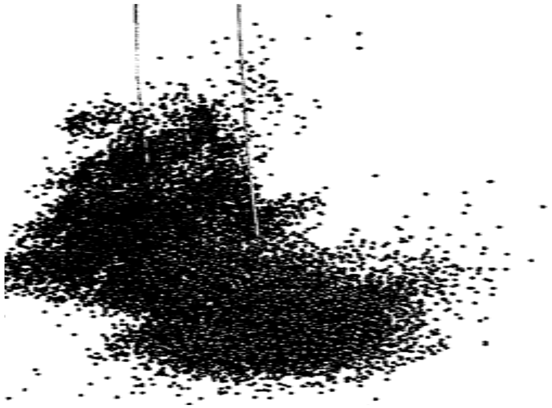


From ENEL, ENGINE Worhshop1



FLUID PATHWAY

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

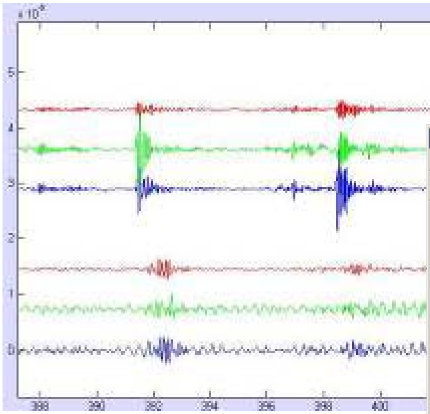


FLUID PATHWAY

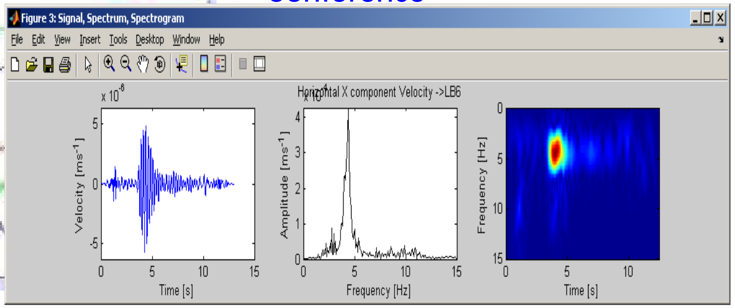
By full wave 3D modelling of broadband seismological data it is possible to detect the formation of gas bubbles in the fluid due to pressure decrease.

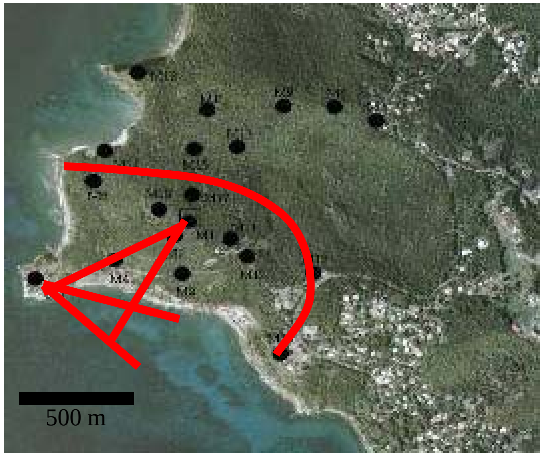
Definition of:

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



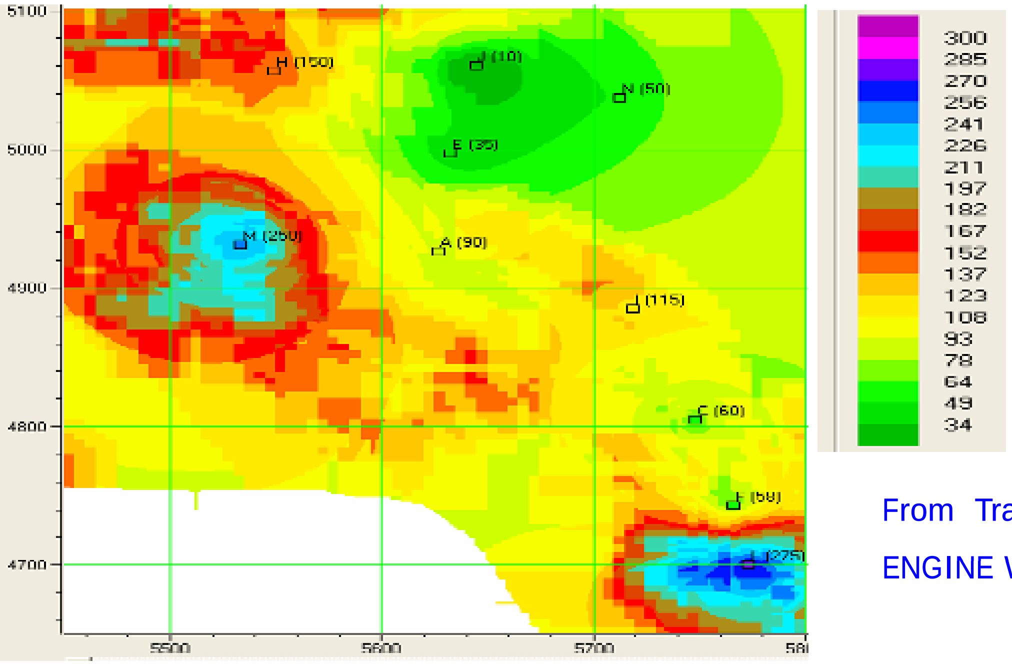
From Manzella et al, ENGINE Launching Conference





FLUID PATHWAY

Quantitative fracture prediction is made possible by modern reflection seismic concepts



From Trappe,

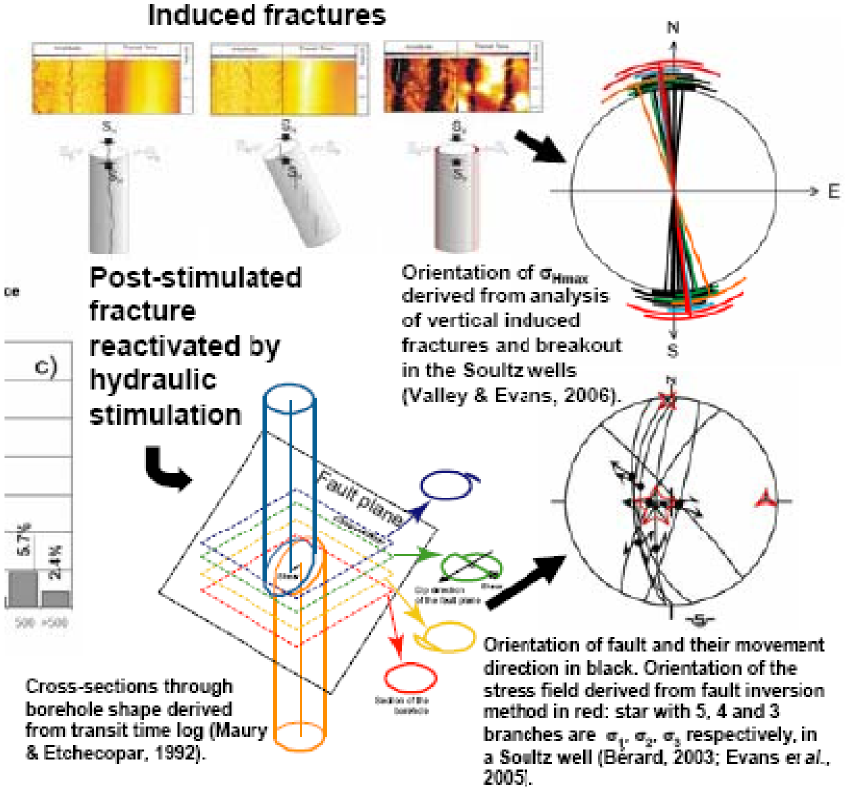
ENGINE Worhshop1

STRESS FIELD

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

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

Their geometrical relationship with the present-day stress field could be derived or computed. From Dezayes, ENGINE Worhshop1



Induced fractures

Post-stimulated fracture reactivated by hydraulic stimulation

Orientation of σ_{Hmax} derived from analysis of vertical induced fractures and breakout in the Soultz wells (Valley & Evans, 2006).

Cross-sections through borehole shape derived from transit time log (Maury & Etchecopar, 1992).

Orientation of fault and their movement direction in black. Orientation of the stress field derived from fault inversion method in red: star with 5, 4 and 3 branches are σ_1, σ_2, σ_3 respectively, in a Soultz well (Bérard, 2003; Evans et al., 2005).

MONITORING

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

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

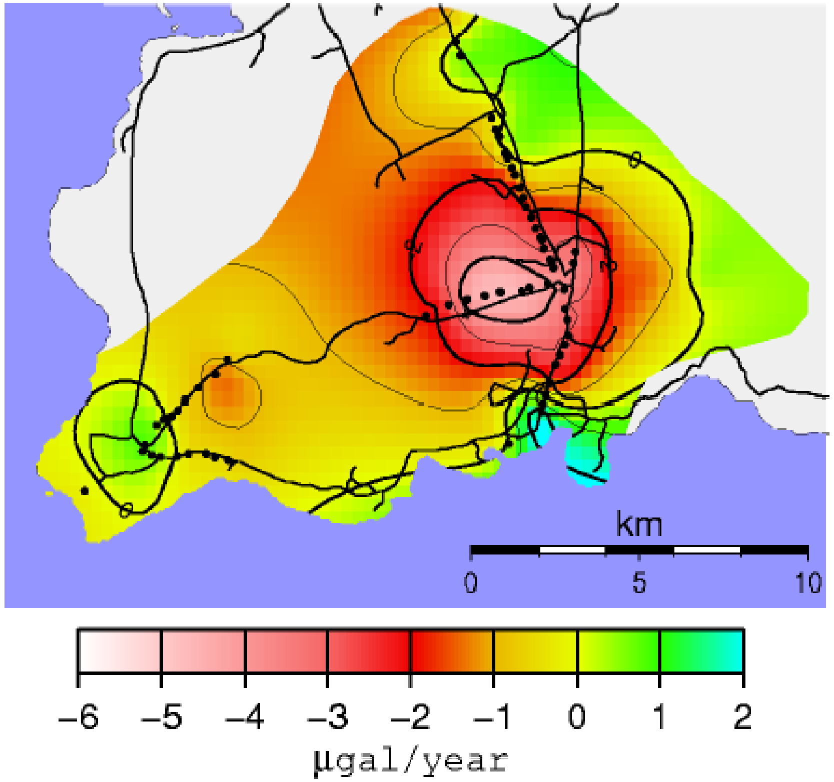


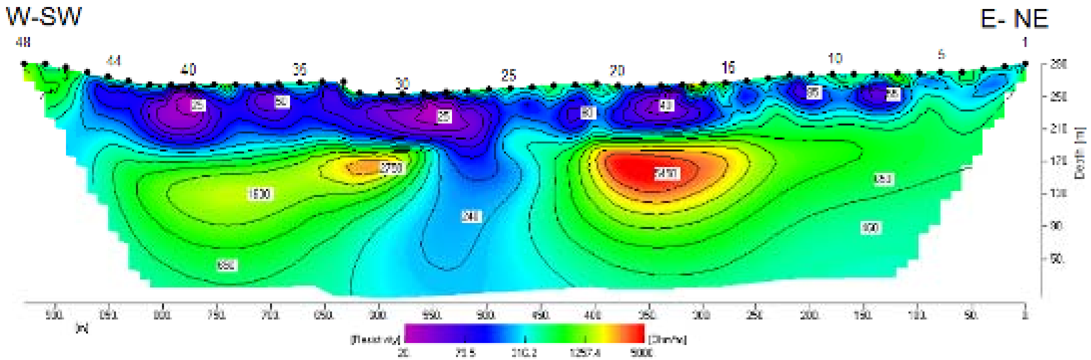
Figure 8. Mean gravity variation (µgal/year) from 1975 to 1999. Only points measured in 1999 and at least two times earlier are used.

MONITORING

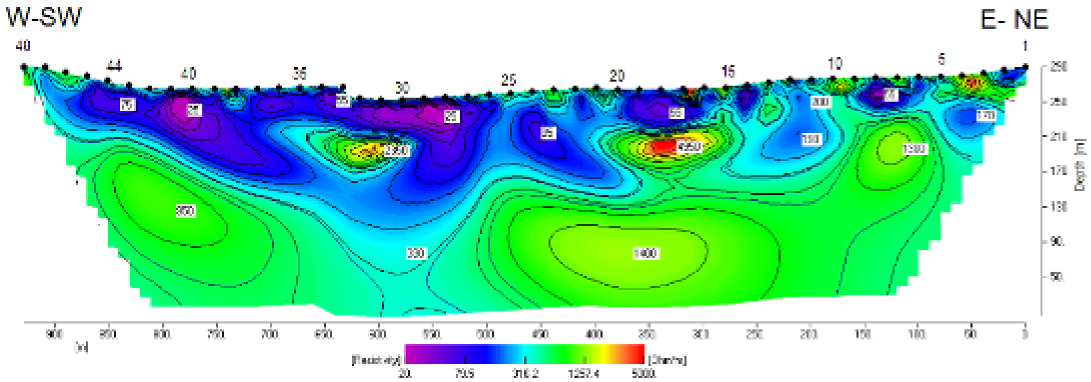
Geothermal exploration at a low enthalpy field using ERT. The low resistivity zone is coincident with a known fault where warm and saline fluids mix with surface and fresh water. An example of monitoring the effect on resistivity change when fresh water is pumped out from a well at the center of profile: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

25 Novembre 2008

Polo-Dipolo-rho



26 Novembre 2008

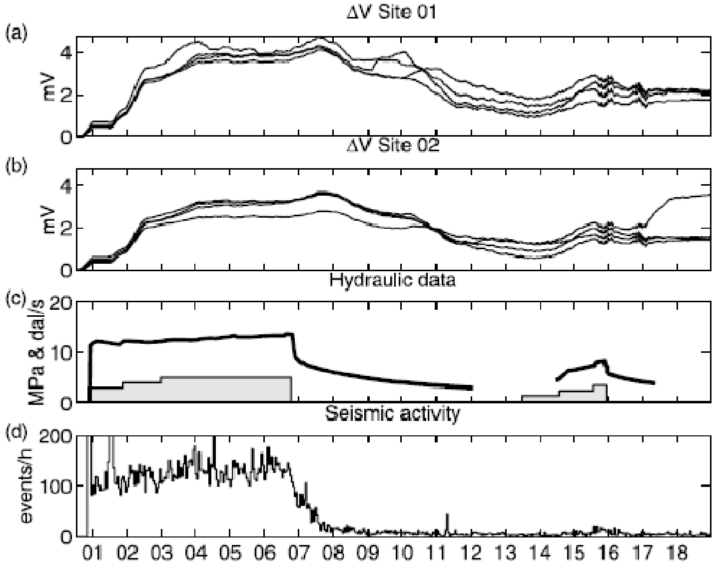


MONITORING

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

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

No examples or applications found in literature
Some examples from SP (electric field) showing interesting results: is it possible to use the same kind of information in MT? To be defined



How to find a geothermal reservoir

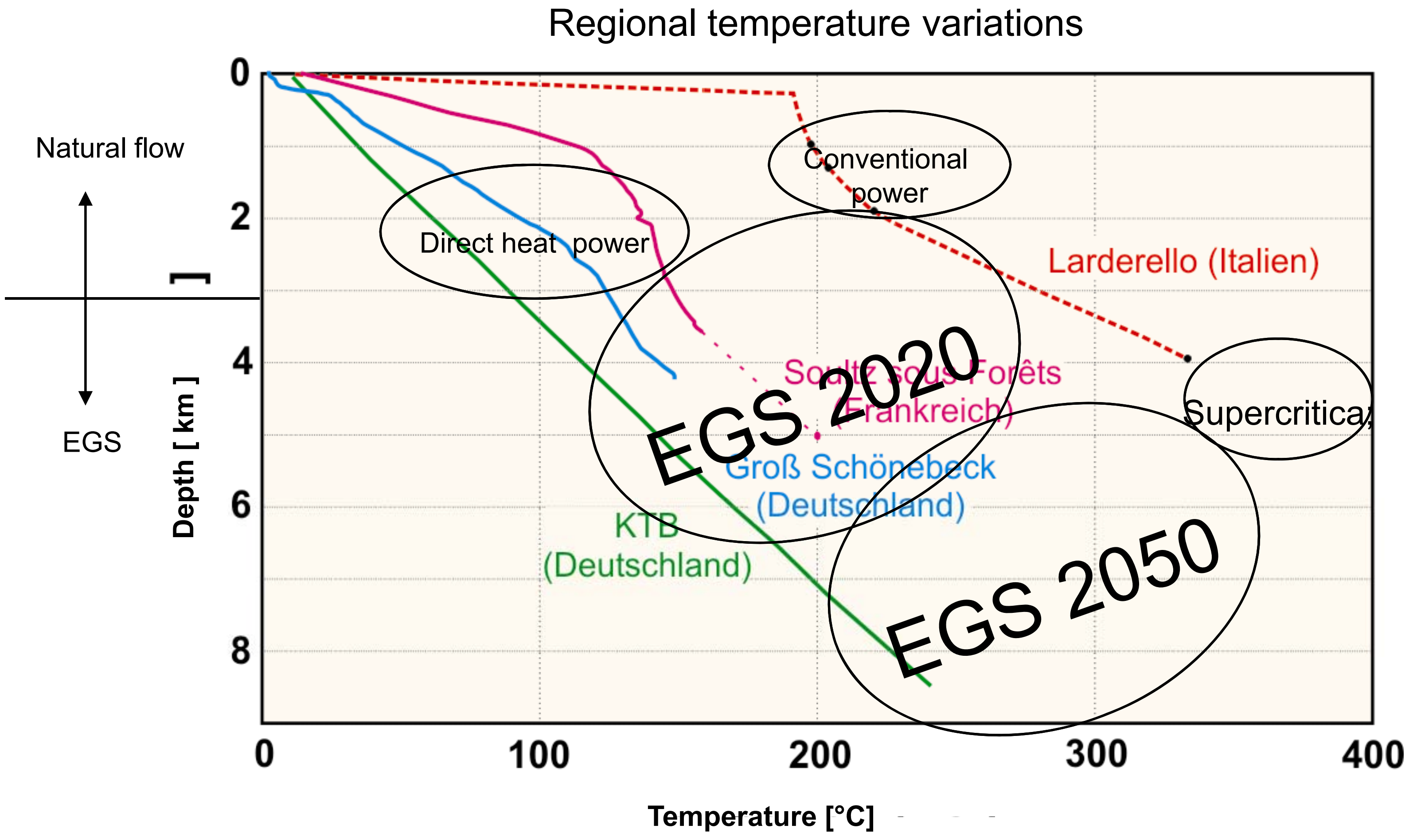
temperature focus – some stress

(modelling and geophysical techniques)

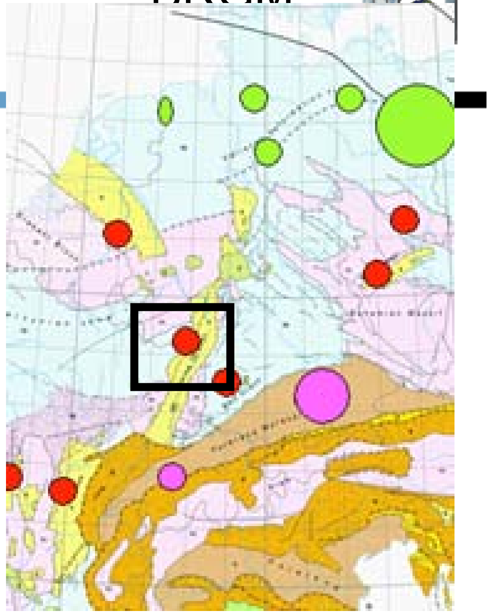
Content

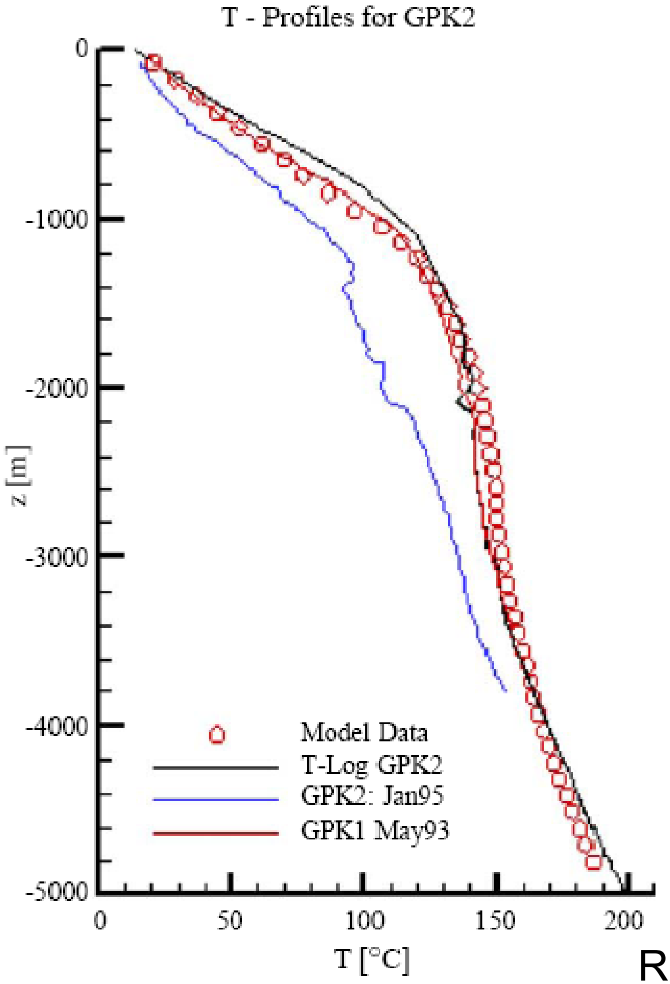
- Geothermal gradients – introduced by Pierre
- Plate tectonics – covered by Pierre
- Convective controls: A closer look at Mantle dynamics
- Conductive controls: Lithosphere composition and differentiation
- Regional and local temperature assessment
  - Conductive (predictable →
      - **Use temperature data and models**
  - vs advective (magmatic, partially predictable)
    - Global (heat flow –tectonic analysis)
    - Local (**geophsyical exploration techniques** probing deeper temperature)

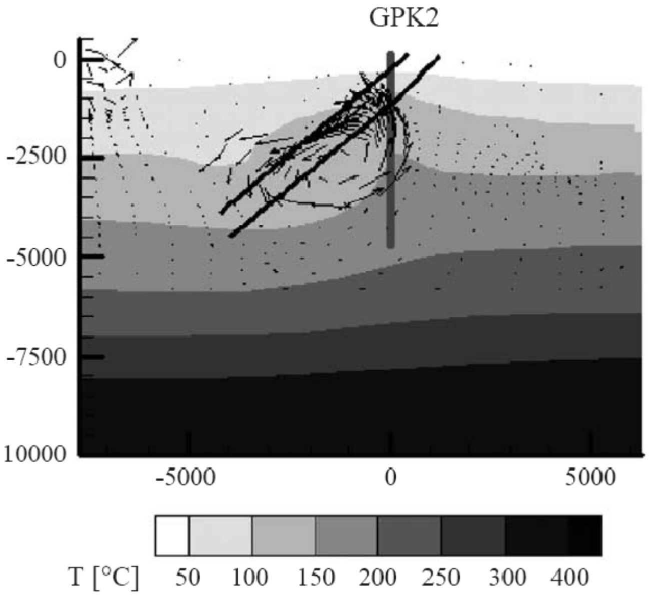
Temperature gradients in the upper crust



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





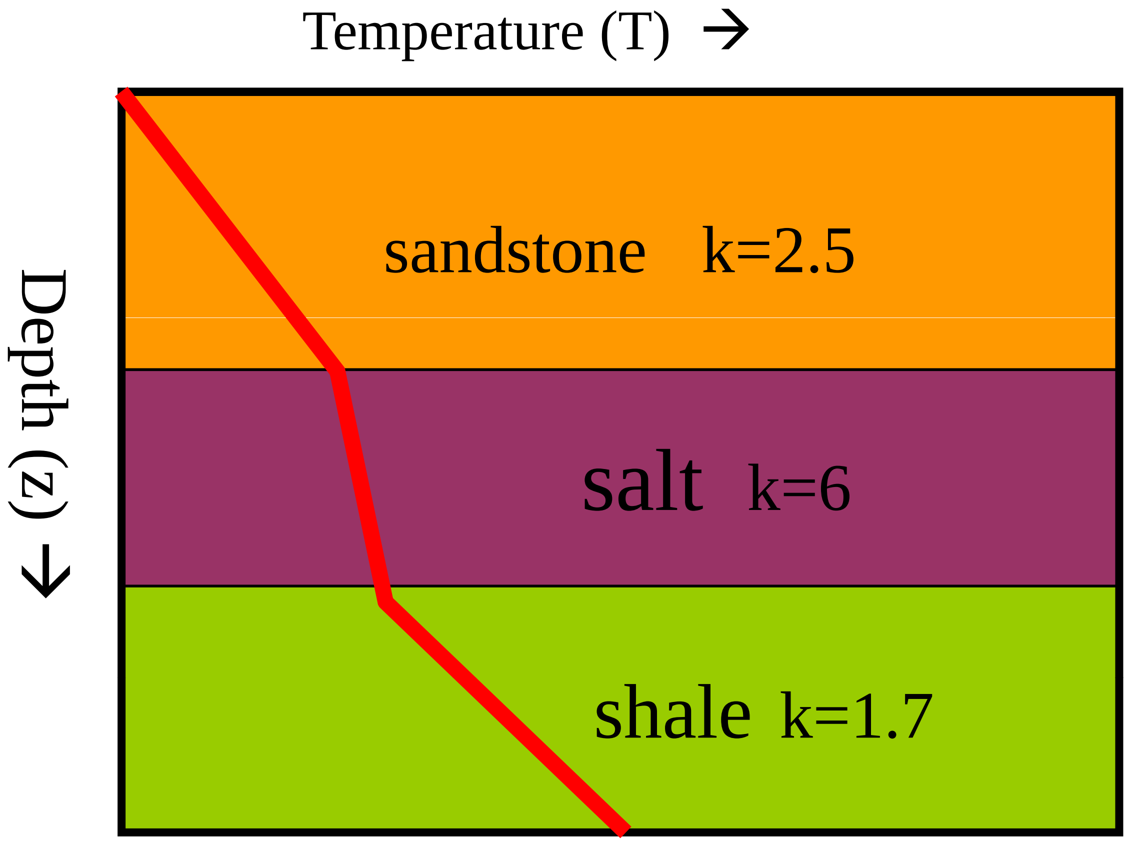


Ranalli and Rybach, 2005

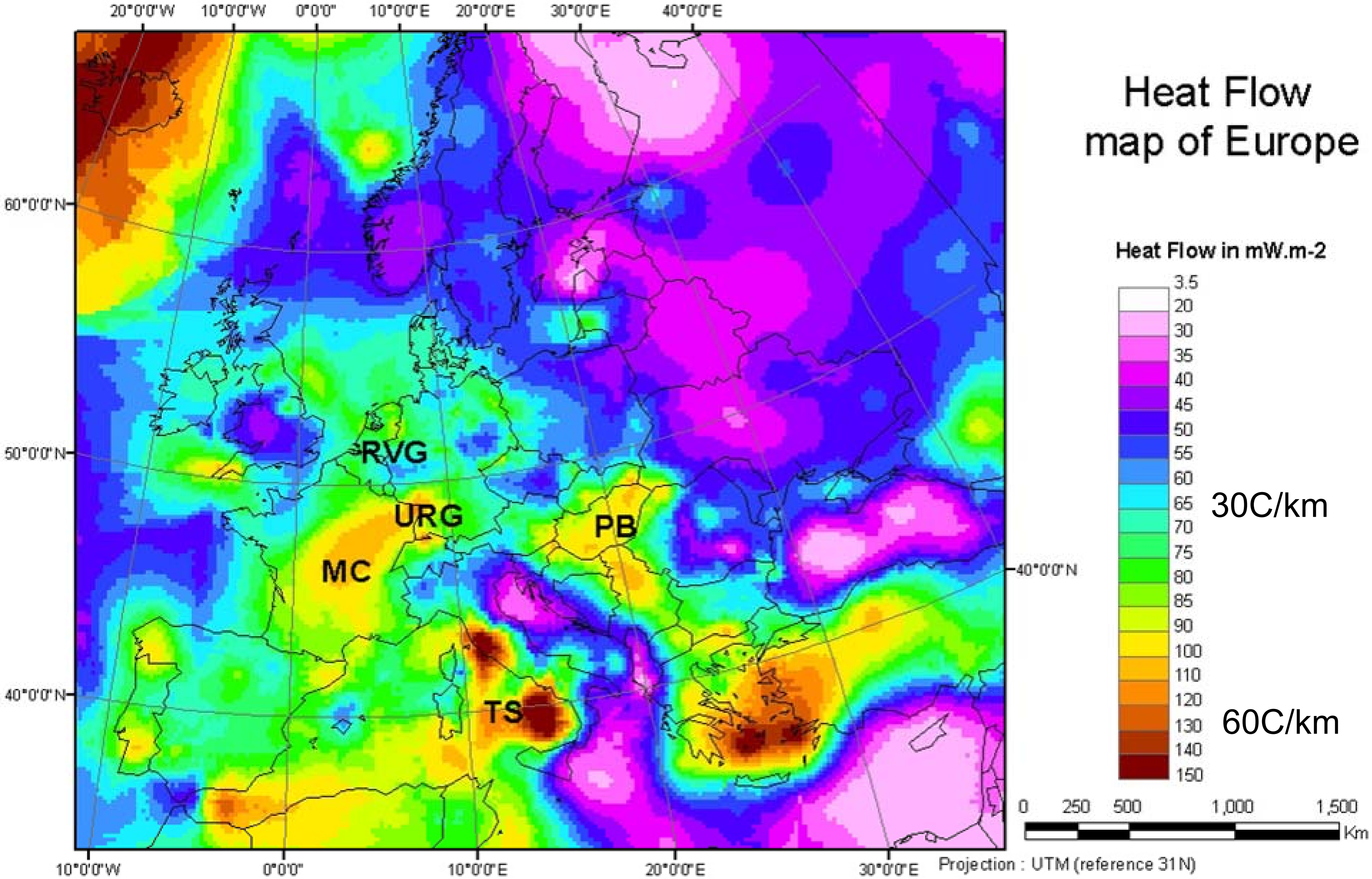
Temperature is reconstructed using a steady state geotherm (conductive approach)

- **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}]

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



Heat Flow map of Europe



30C/km

60C/km

Cloetingh et al., 2010, Earth Science Reviews, in press

Content

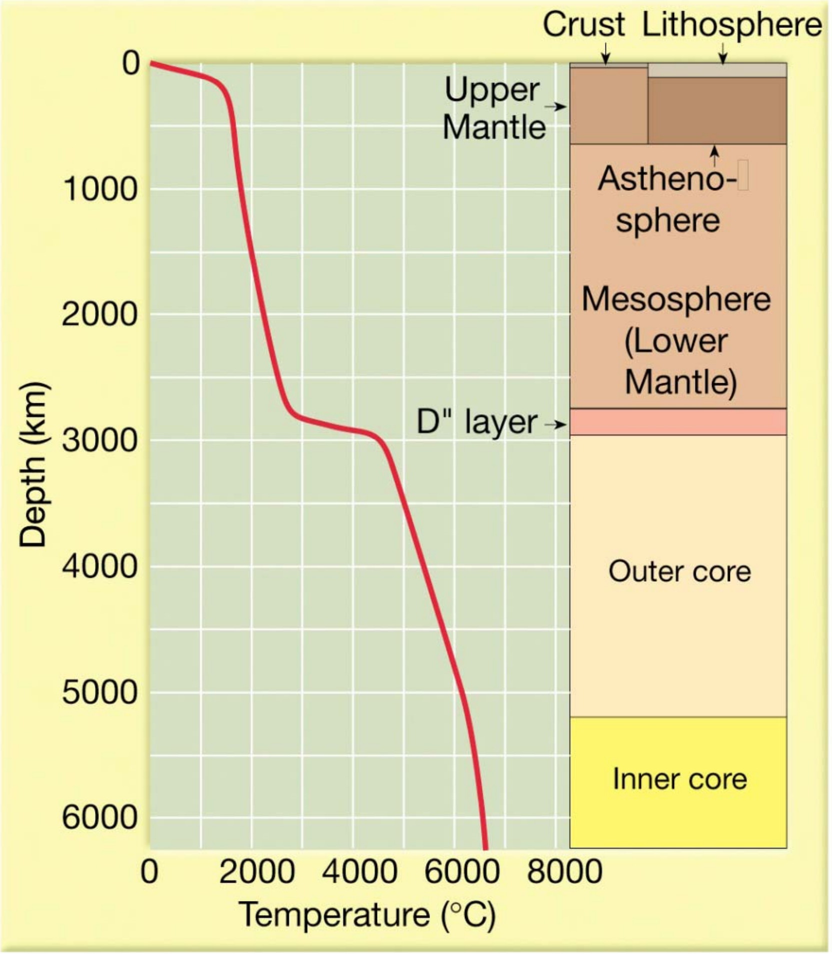
- **Convective controls: A closer look at Mantle dynamics**
  - Lithosphere vs astenosphere
  - Cooling plate
  - Not so simple
  - Phase transitions
  - Smaller scale phenomena
- Conductive controls: Lithosphere composition and differentiation

Geotherm and geothermal gradient

Geotherm = temperature as a function of depth

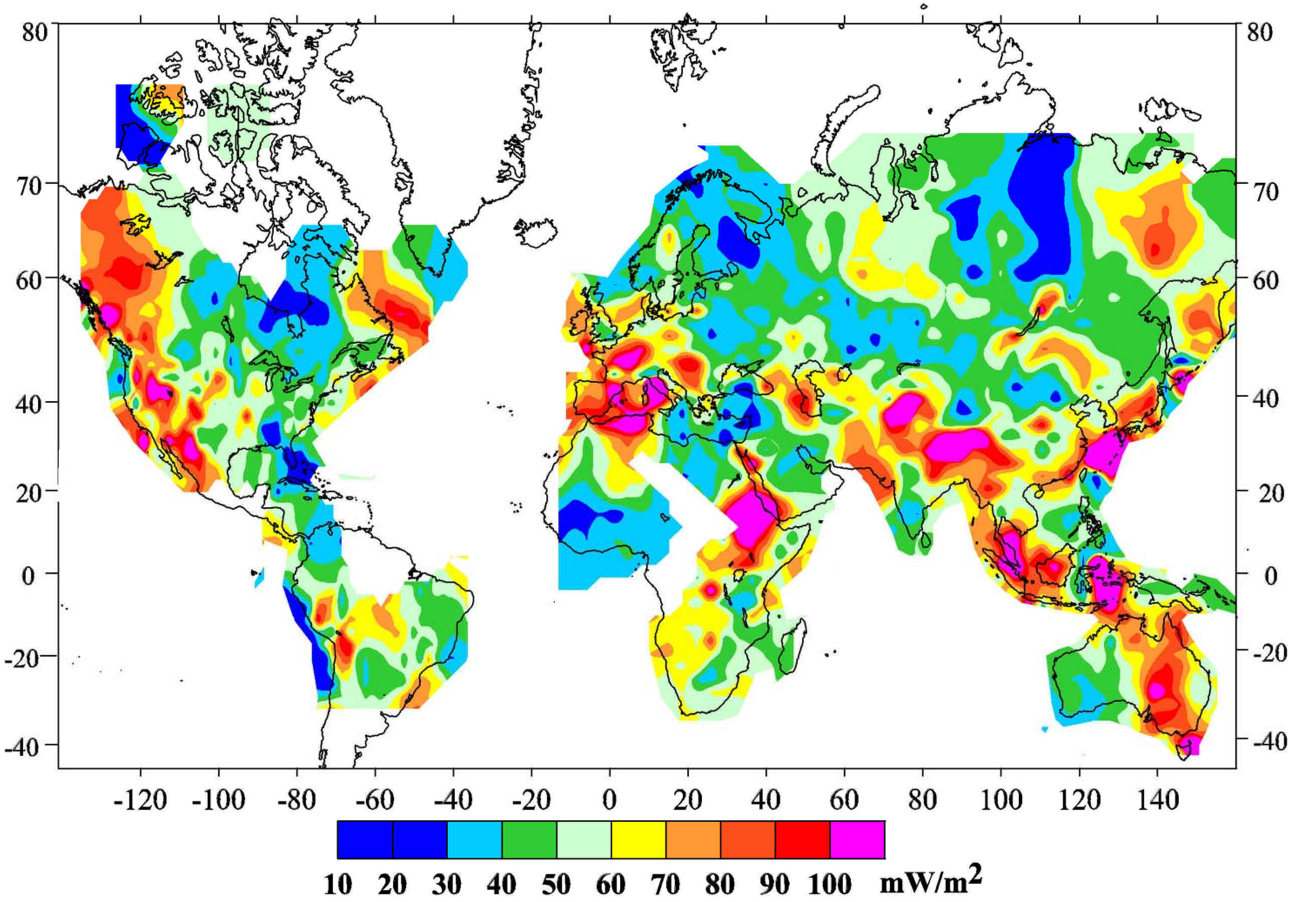
Geothermic gradient = rate of change in temperature with increasing depth

- gradient varies depending on location
- surface gradient is average 20-30 oC/km
- Surface gradient is much higher than in mantle and core

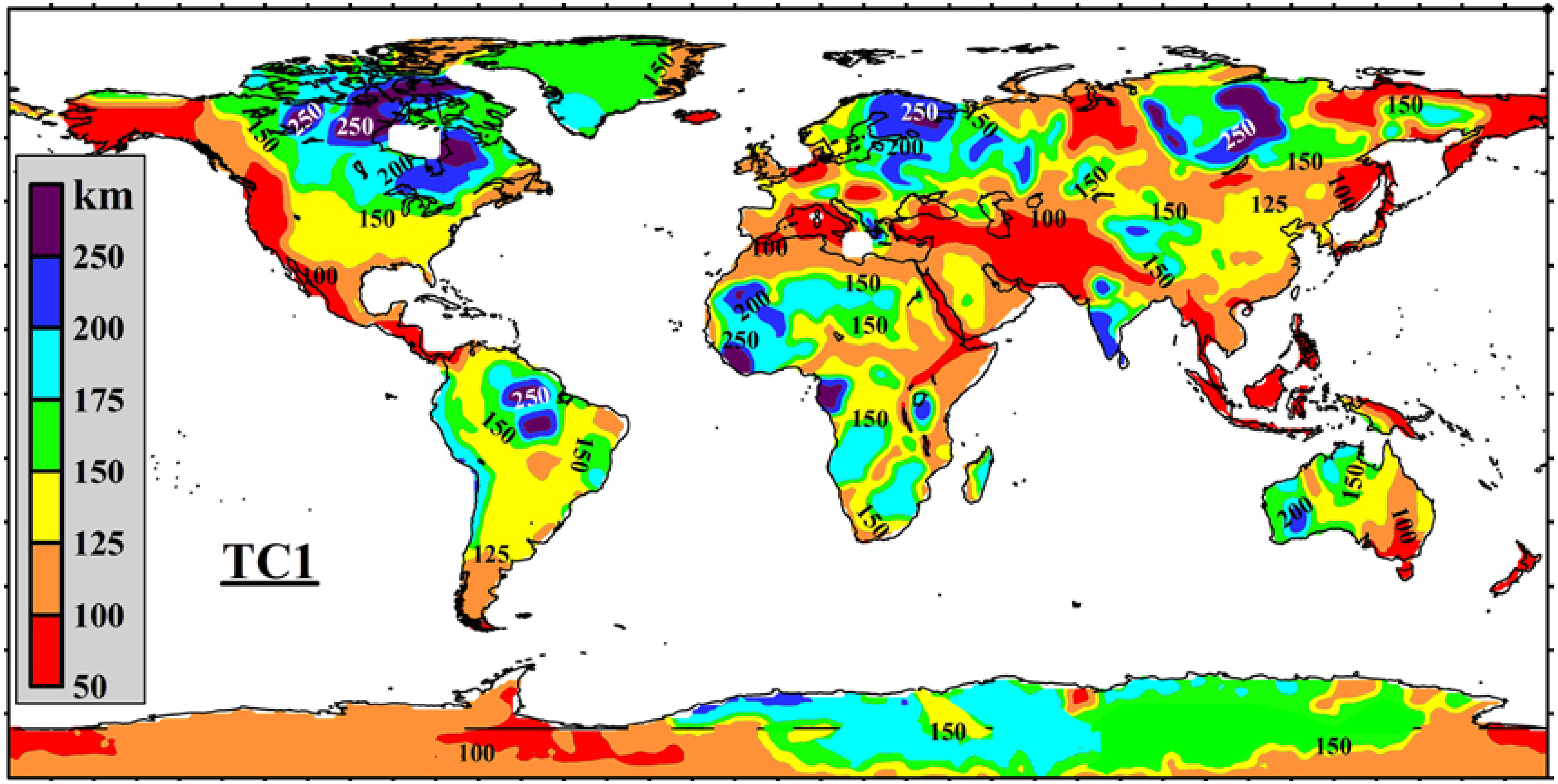


Heat flow at Earth's surface

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



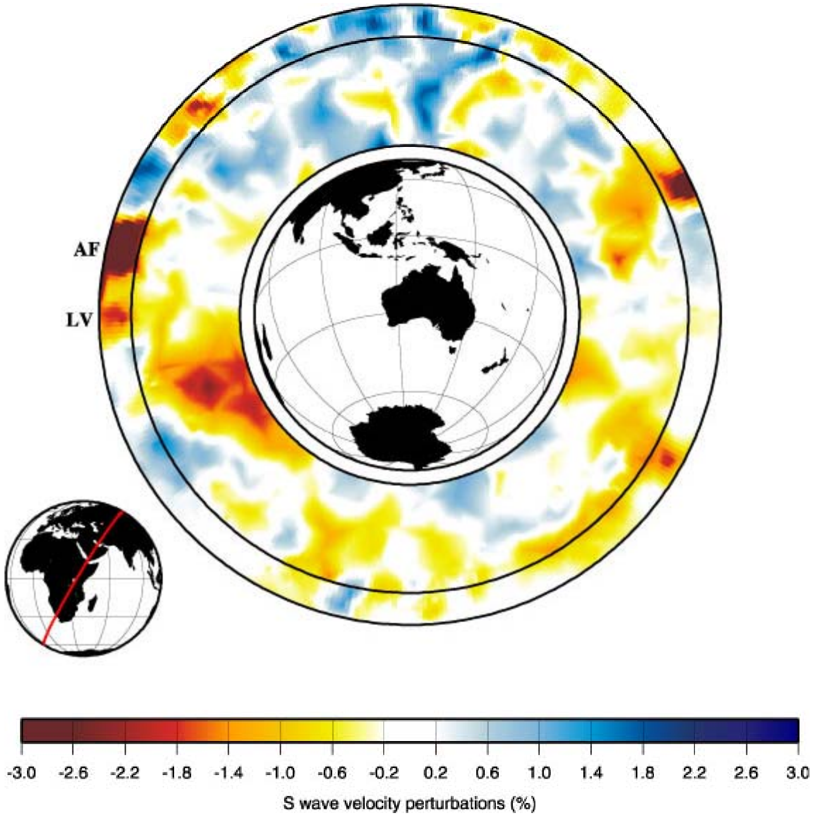
Lithosphere thickness

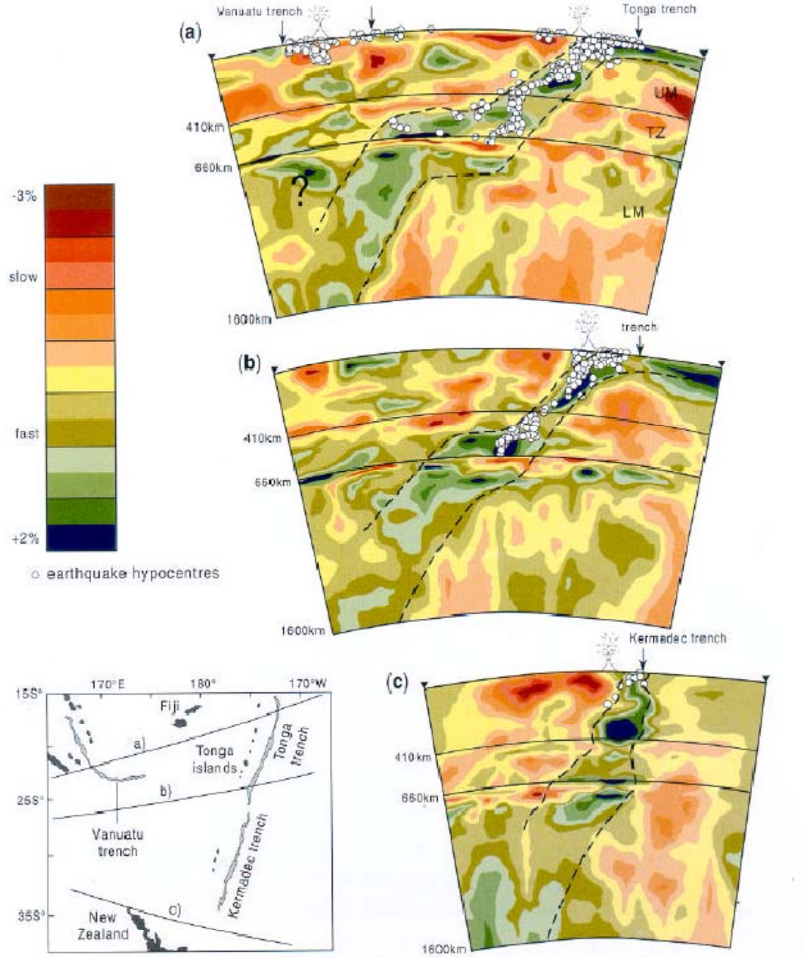


Seismic tomography

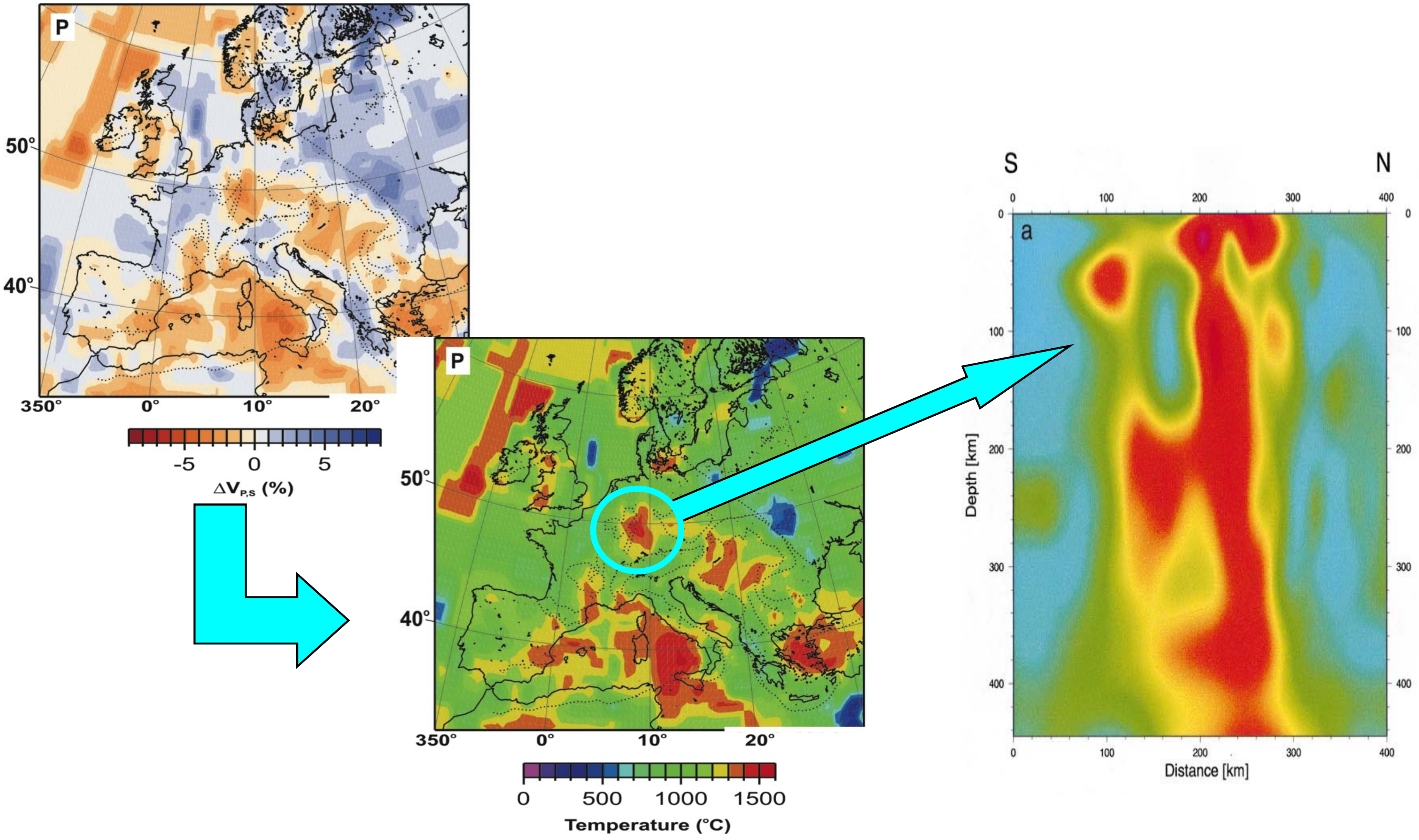
Seismic wave velocity is a function of temperature:

- Warm → slower
- Cold → faster





Seismic tomography



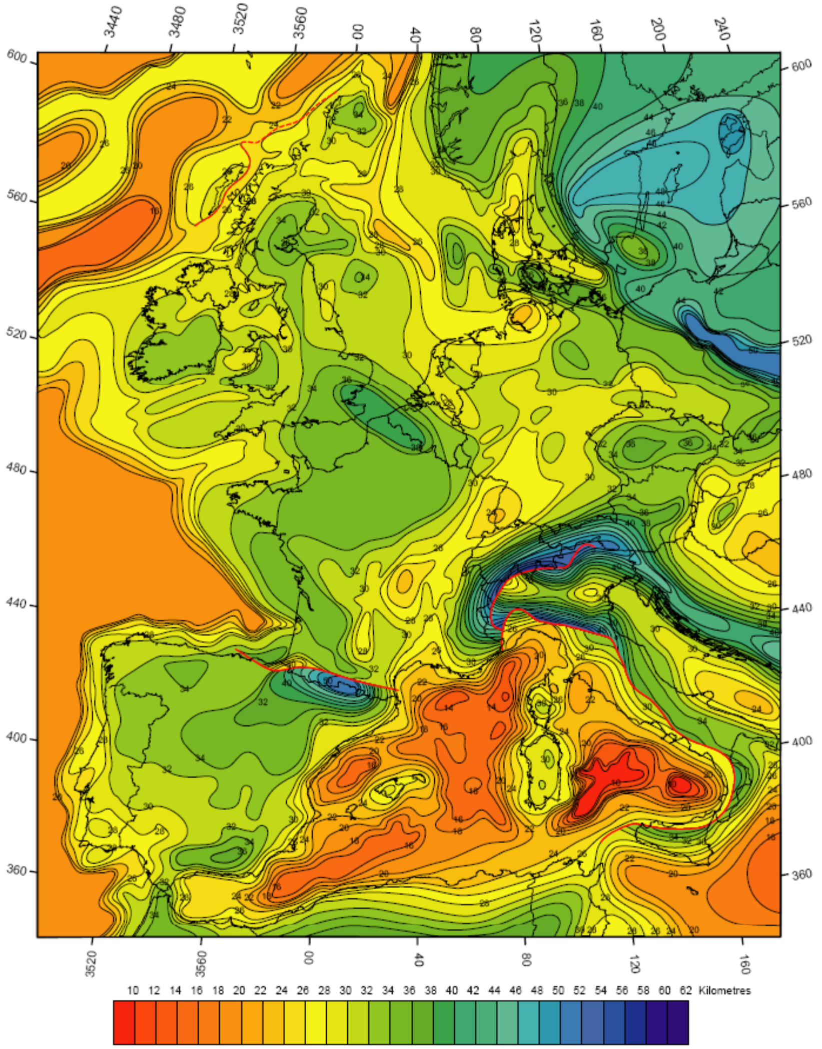
Conclusions

- Strong differentiation in heat flow at base of the lithosphere due to convection/advection
- Can explain heat flow variations to some degree
- Kinematic response at surface convective forcing more

Content

- Geothermal gradients, power-EGS and the conductive earth
- Plate tectonics
- Convective controls: A closer look at Mantle dynamics
- **Conductive controls: Lithosphere composition and differentiation**

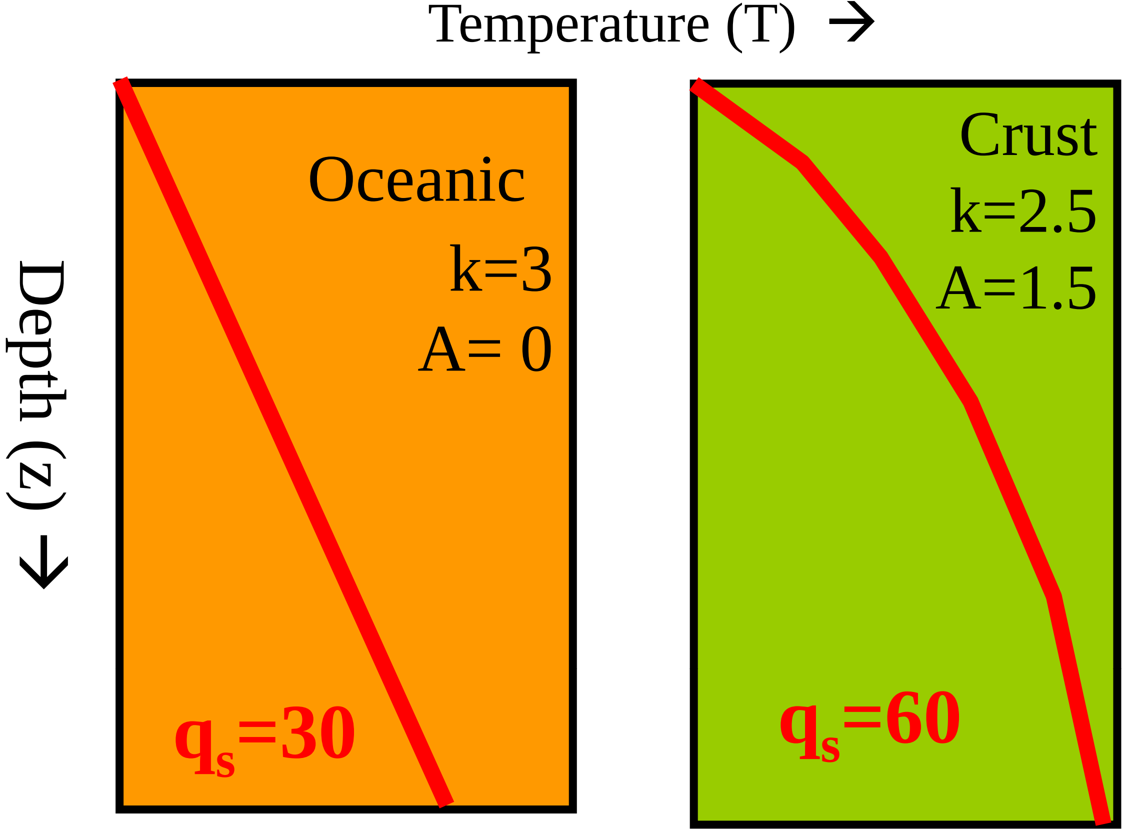
Crustal thickness



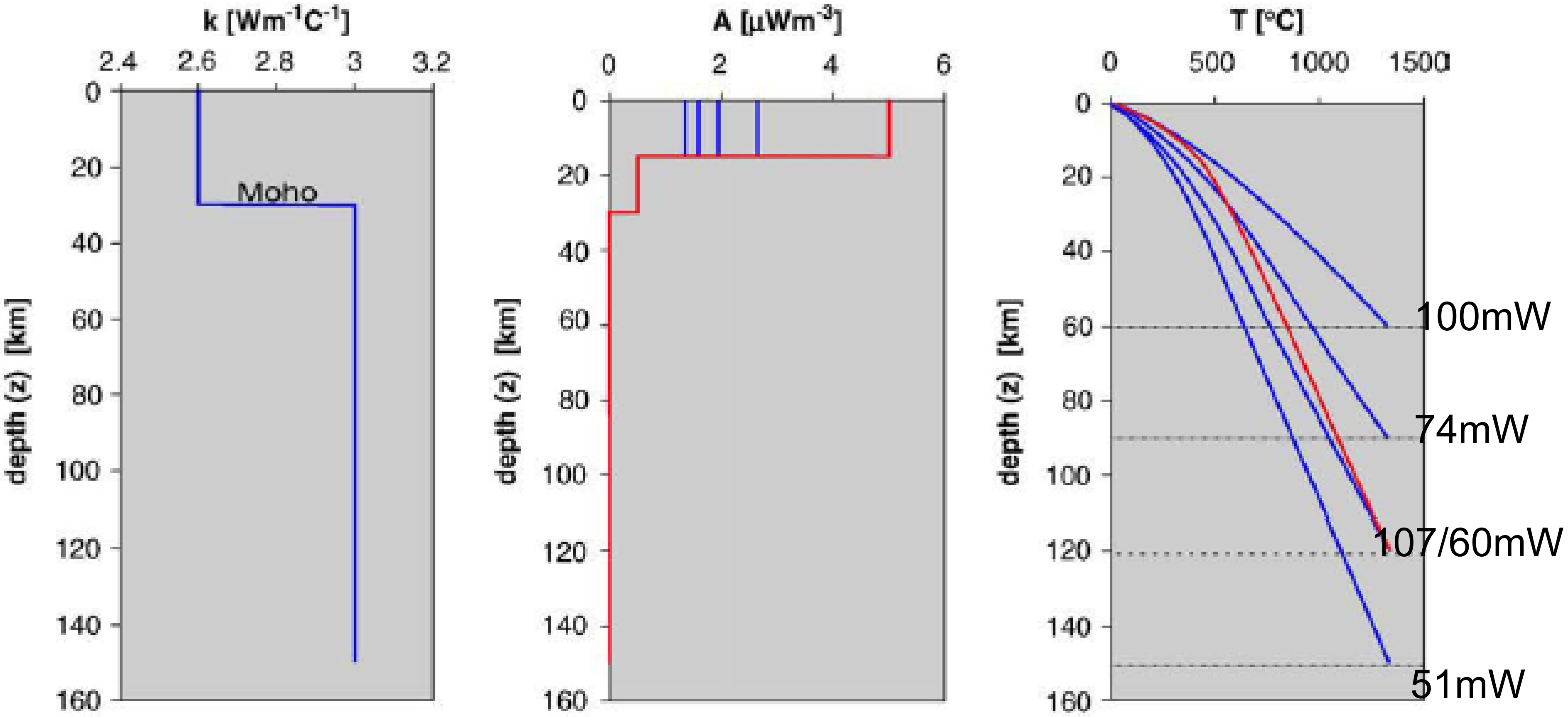
Projection: Lambert Azimuthal Equal Area; Centre: 04¡.00"/48¡.00"; Region : W/E/N/S = 350¡/28¡/62¡/34¡; Ellipsoide wgs-84

Radiogenic heat generation A **[μW m^3] is a function of relative abundance of radiogenic minerals in rock. It influences the steady state geotherm**

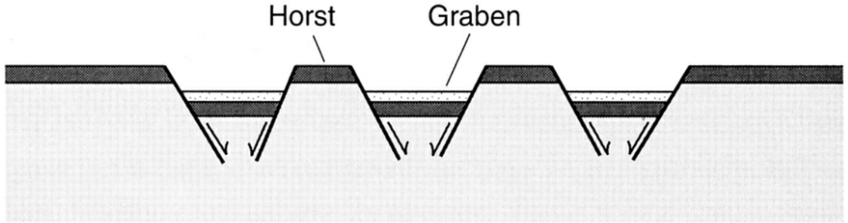
$$\frac{dT}{dz}(z) = q_s / k - Az / k$$



Crustal heat production and geothermal gradients

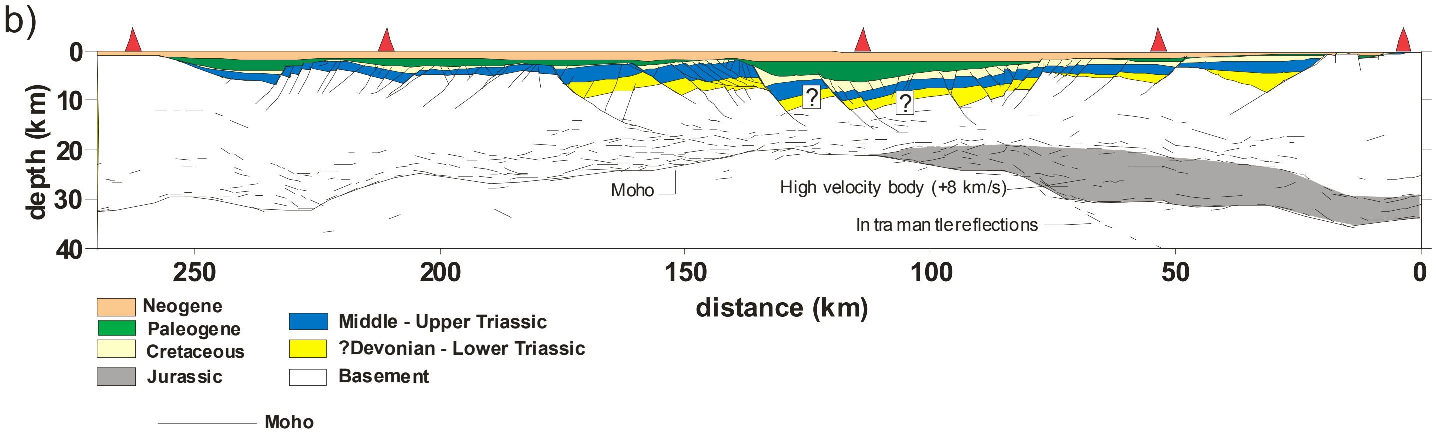


FAULT SYSTEMS

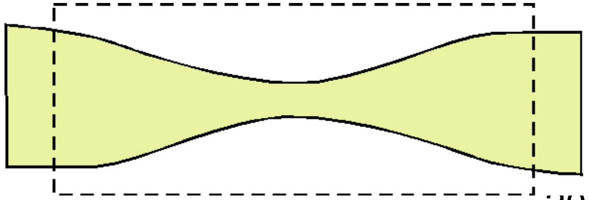


Assemblage of planar faults

Assemblage of listric faults

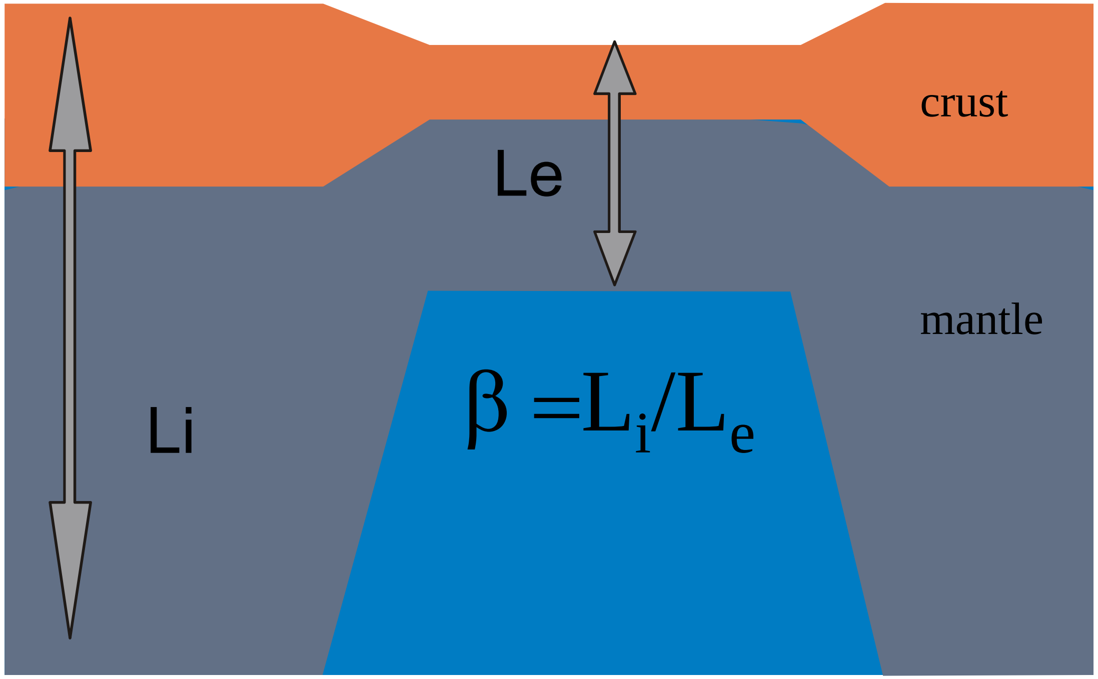


Note: these faults accommodate a pure shear deformation (also called non rotational

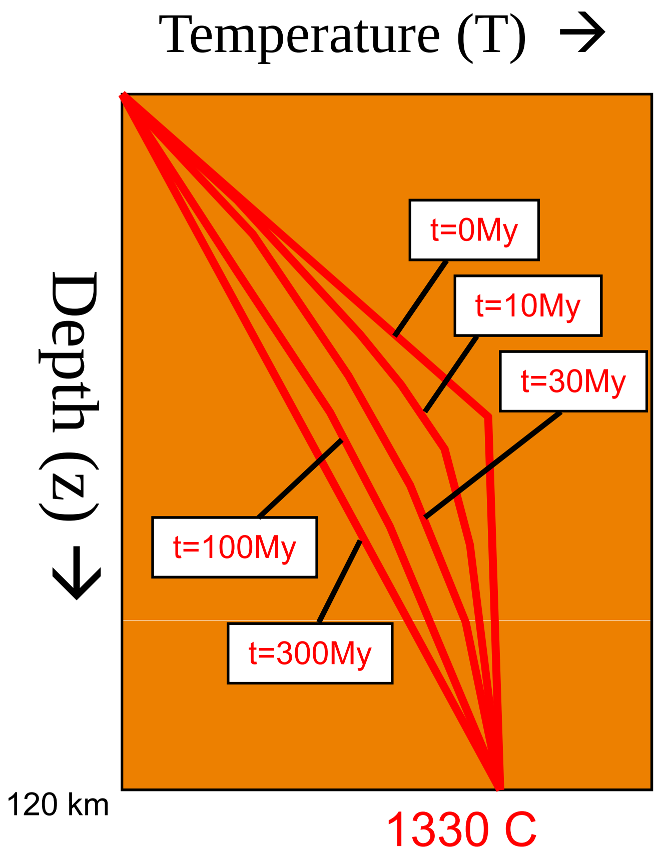


Tectonic Numerical kinematic models predict temperature effects of lithosphere deformation. The 1D McKenzie Model (1978) is a classic for continental lithosphere extension (rifting)

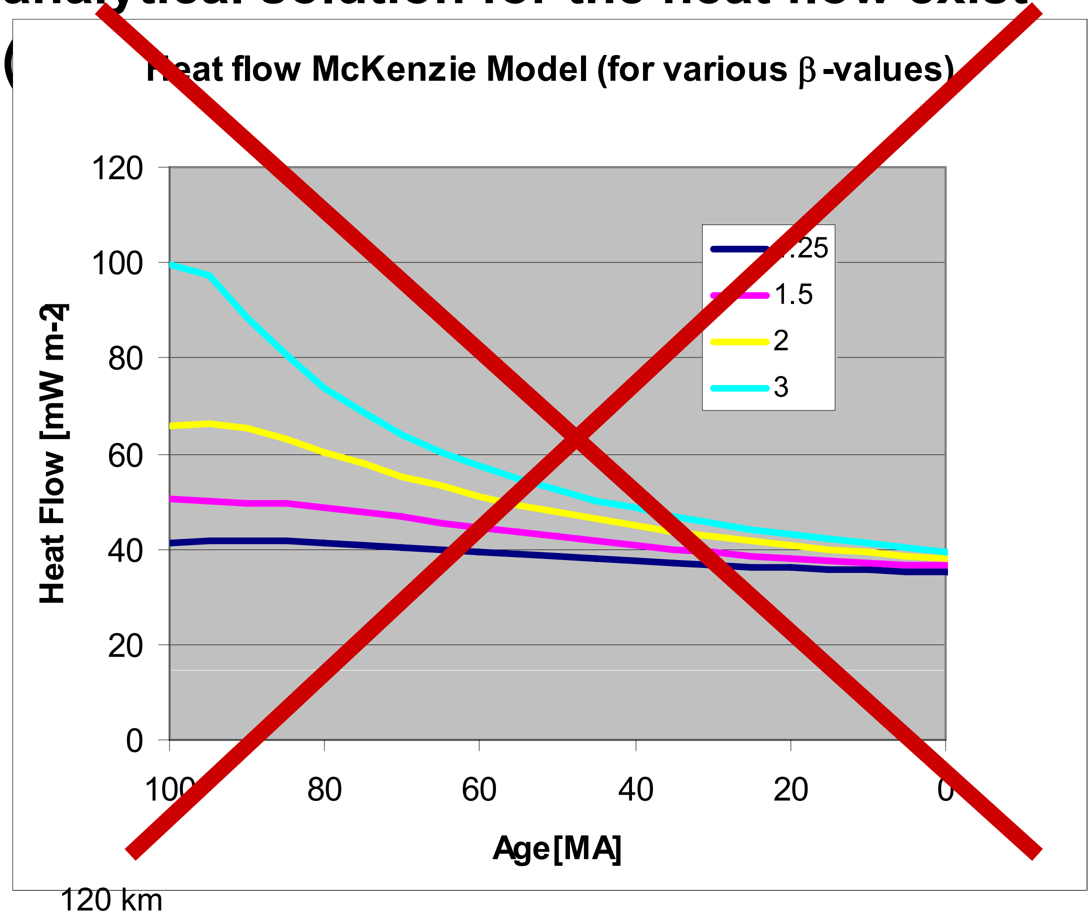
Numerical Temperature Model. t=time after rifting Temperature at surface and bottom are fixed (Mckenzie, 1978)



McKenzie model: lithosphere is instantaneously thinned by factor β



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

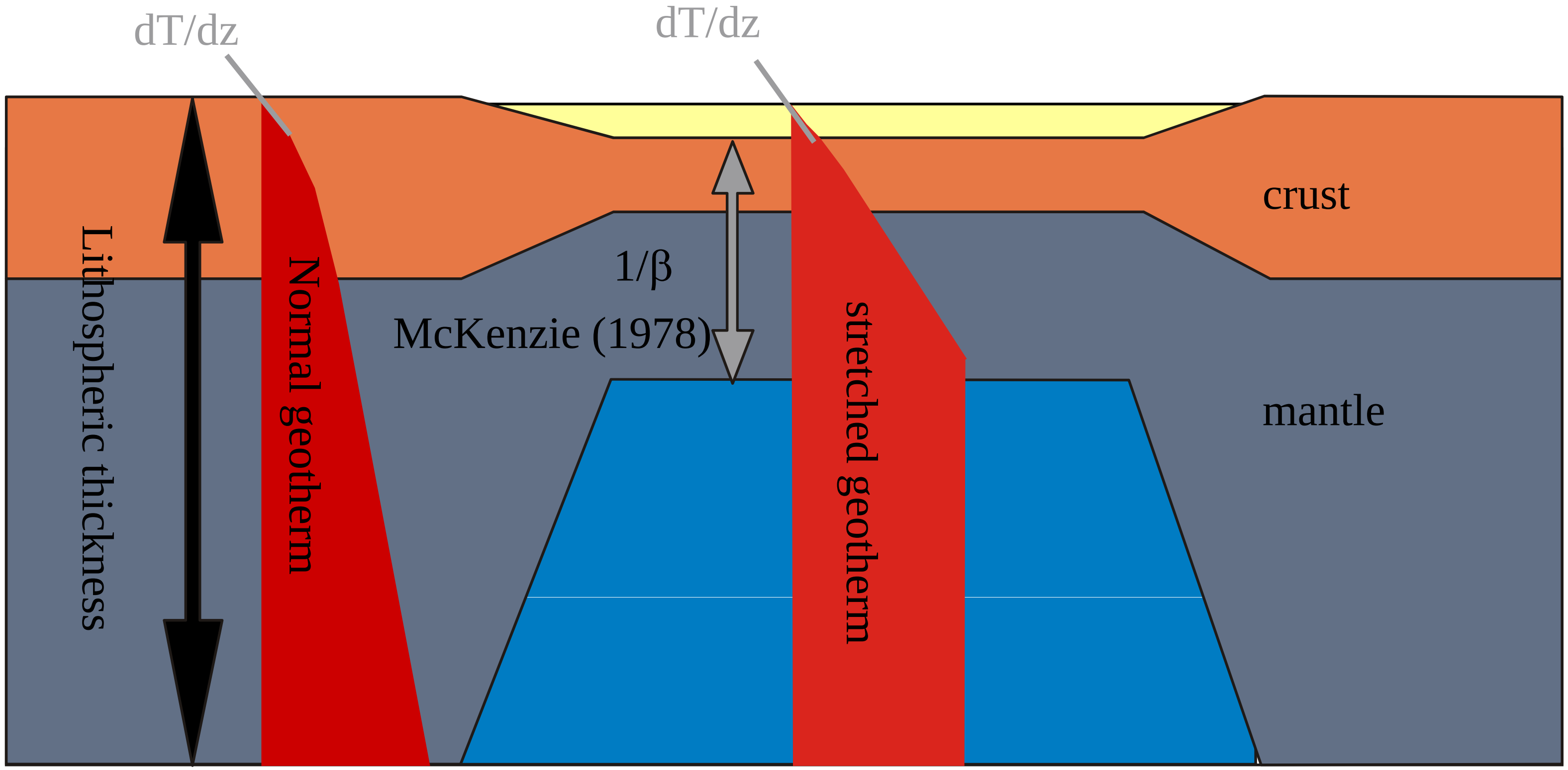


120 km

McKenzie heat flow
No Good:

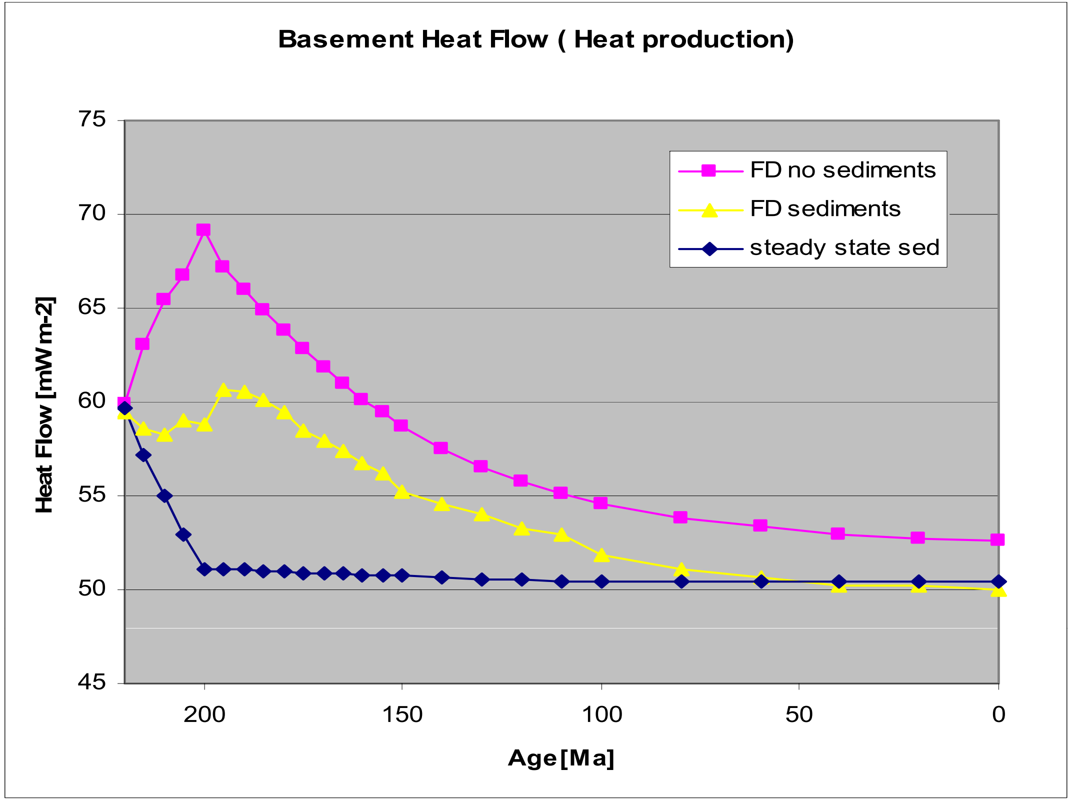
- No crustal heat production
- No sediment infill

- **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

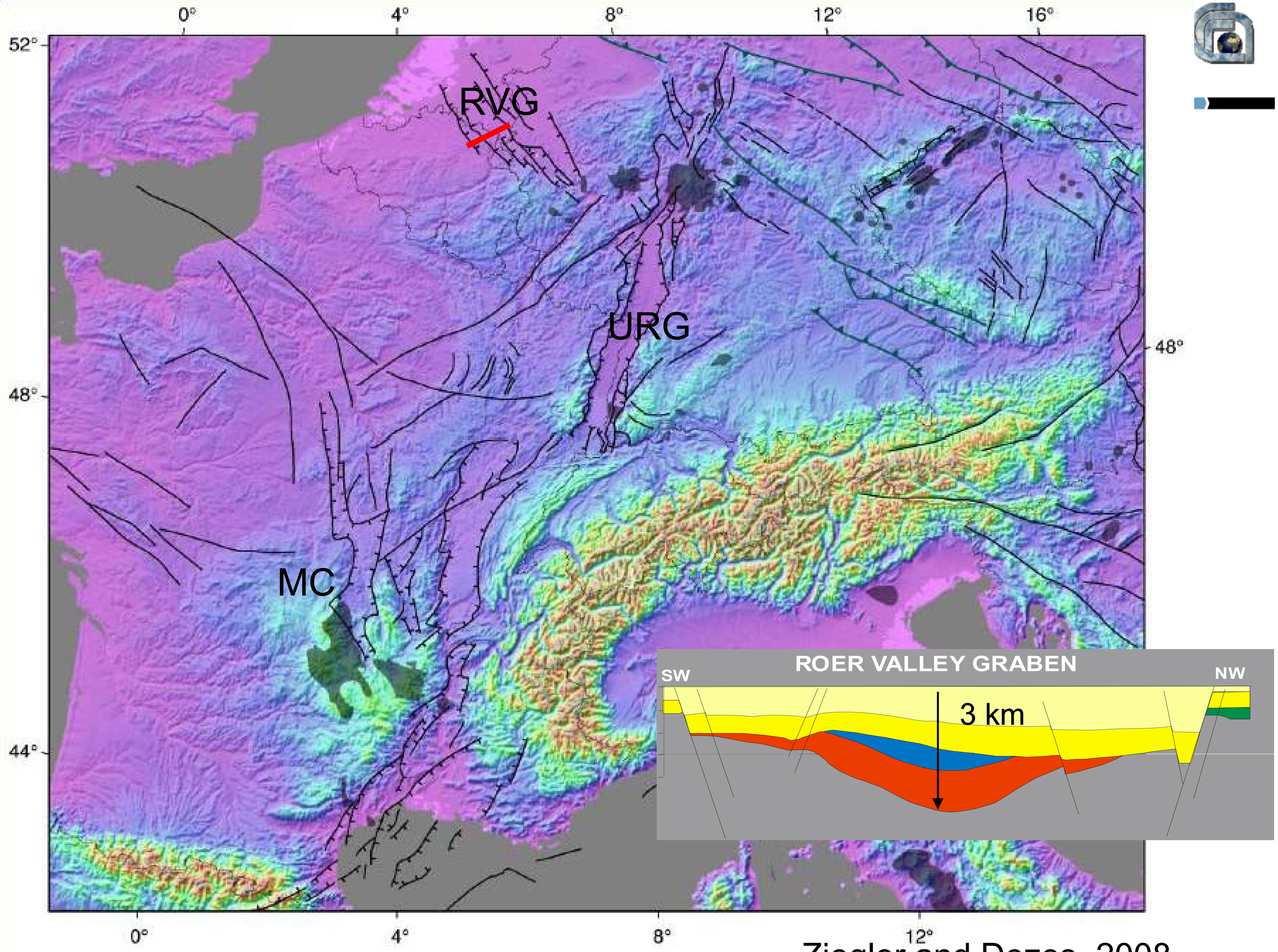
- Classis models such as Mckenzie, neglect effects of crustal heat production. Crustal heat production accounts to ca 50% of the surface heat flow, however it diminishes as a result of crustal thinning during extension and is not fully compensated by heat production of sediment replacing crust. The net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

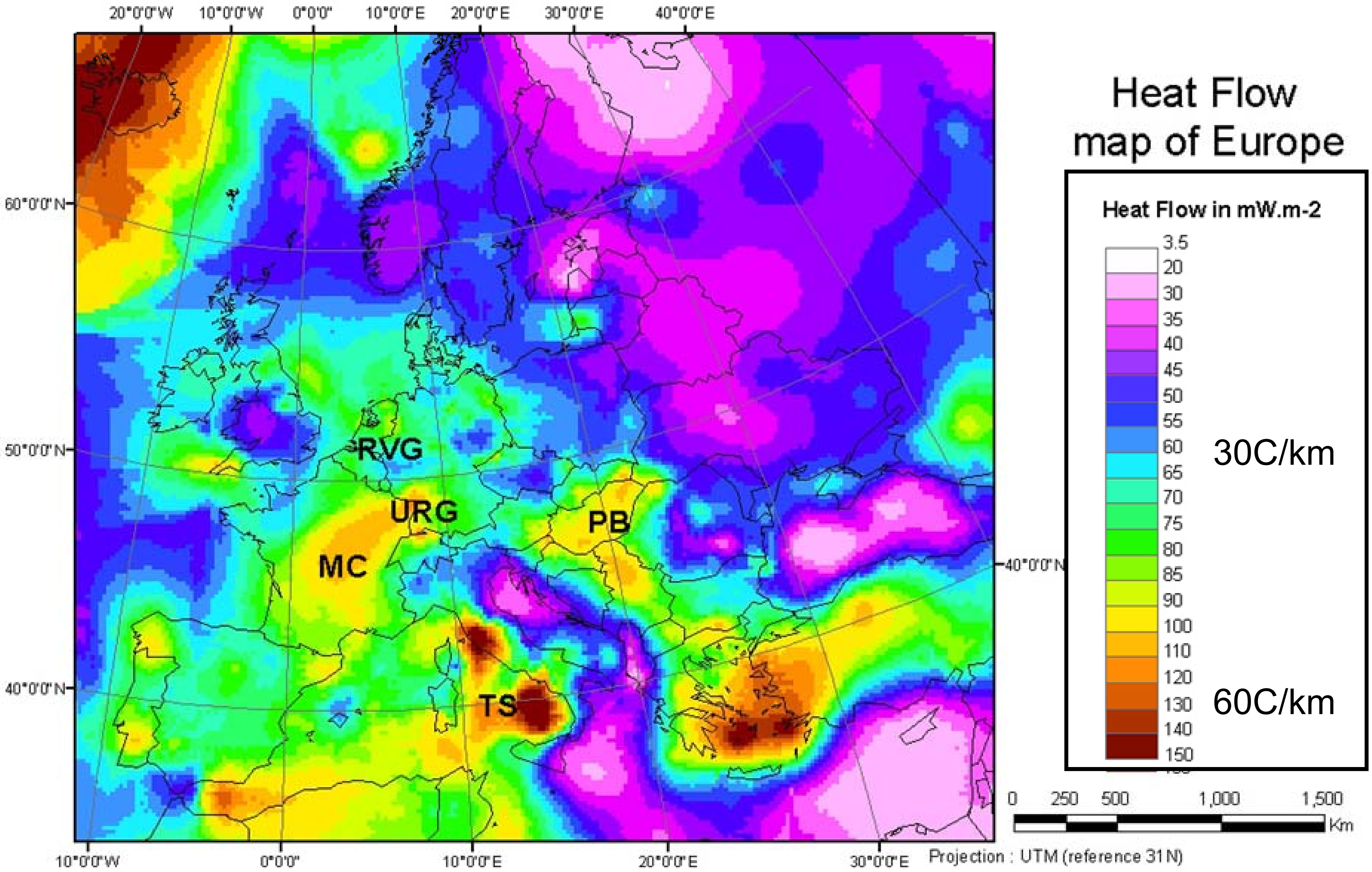


Ziegler and Dezes, 2008

Supported by INTELLIGENT ENERGY

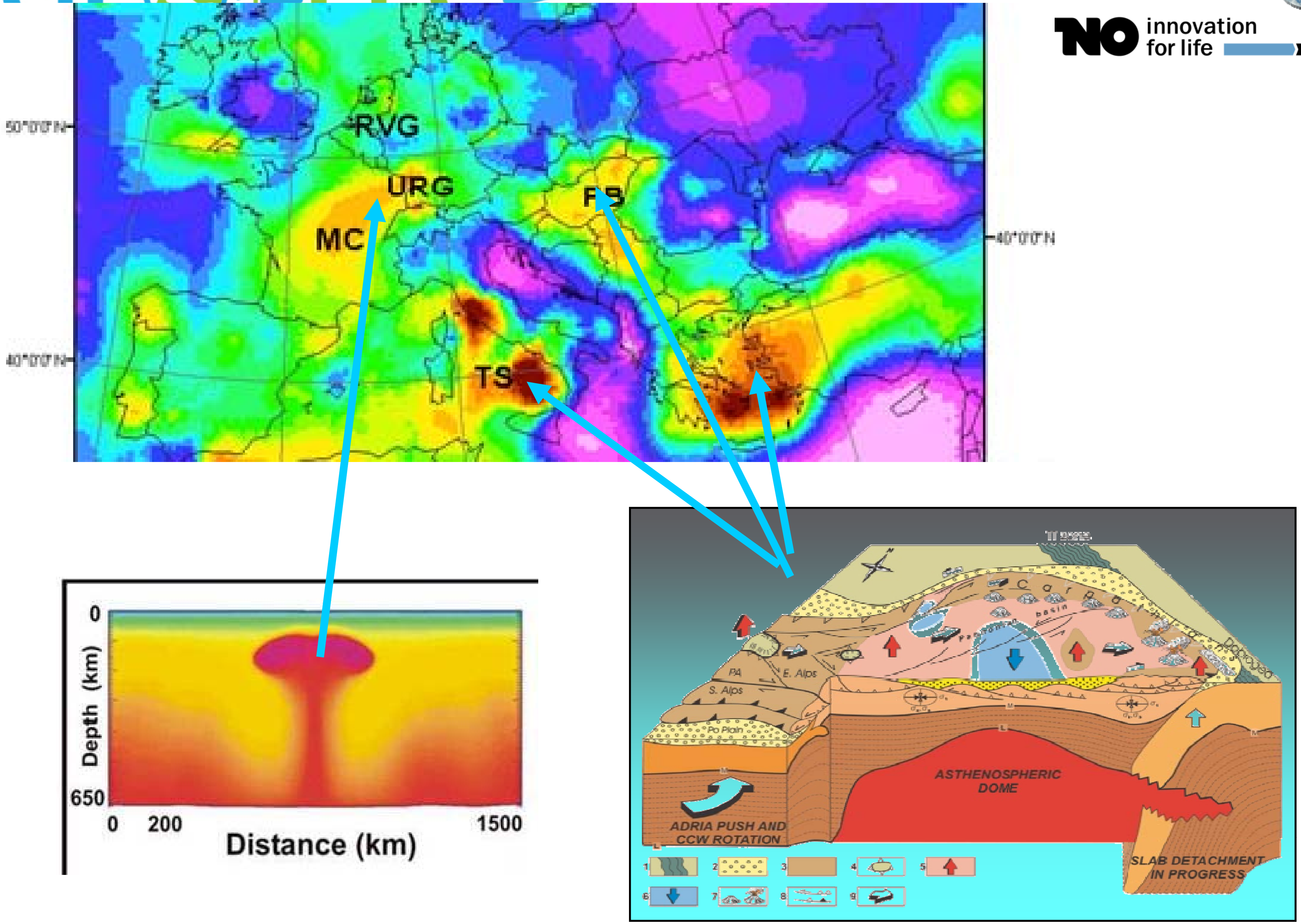
BRGM

Heat Flow map of Europe



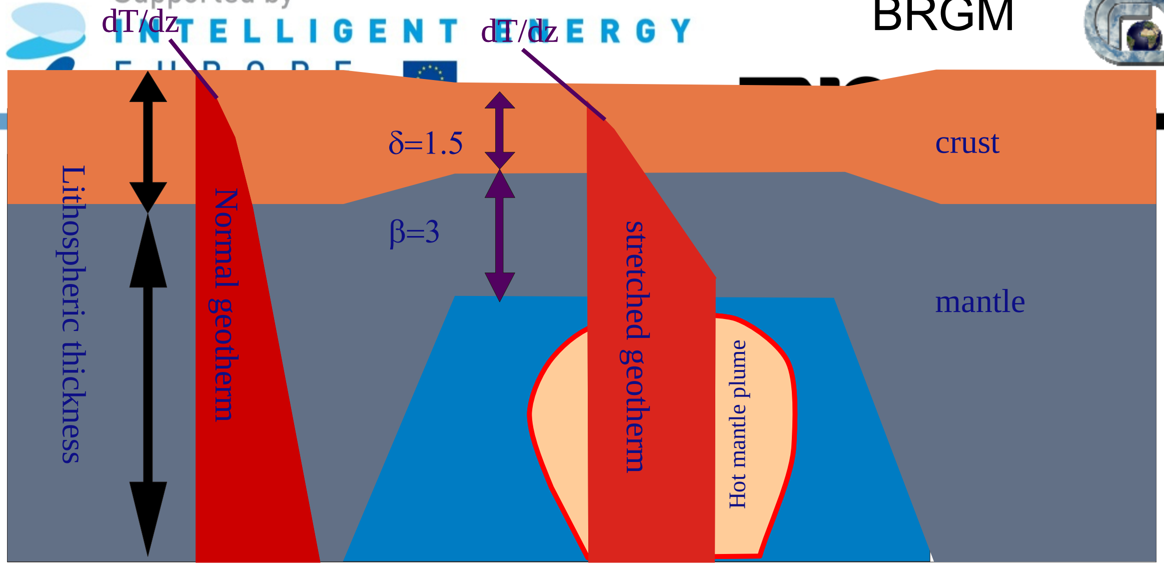
30C/km

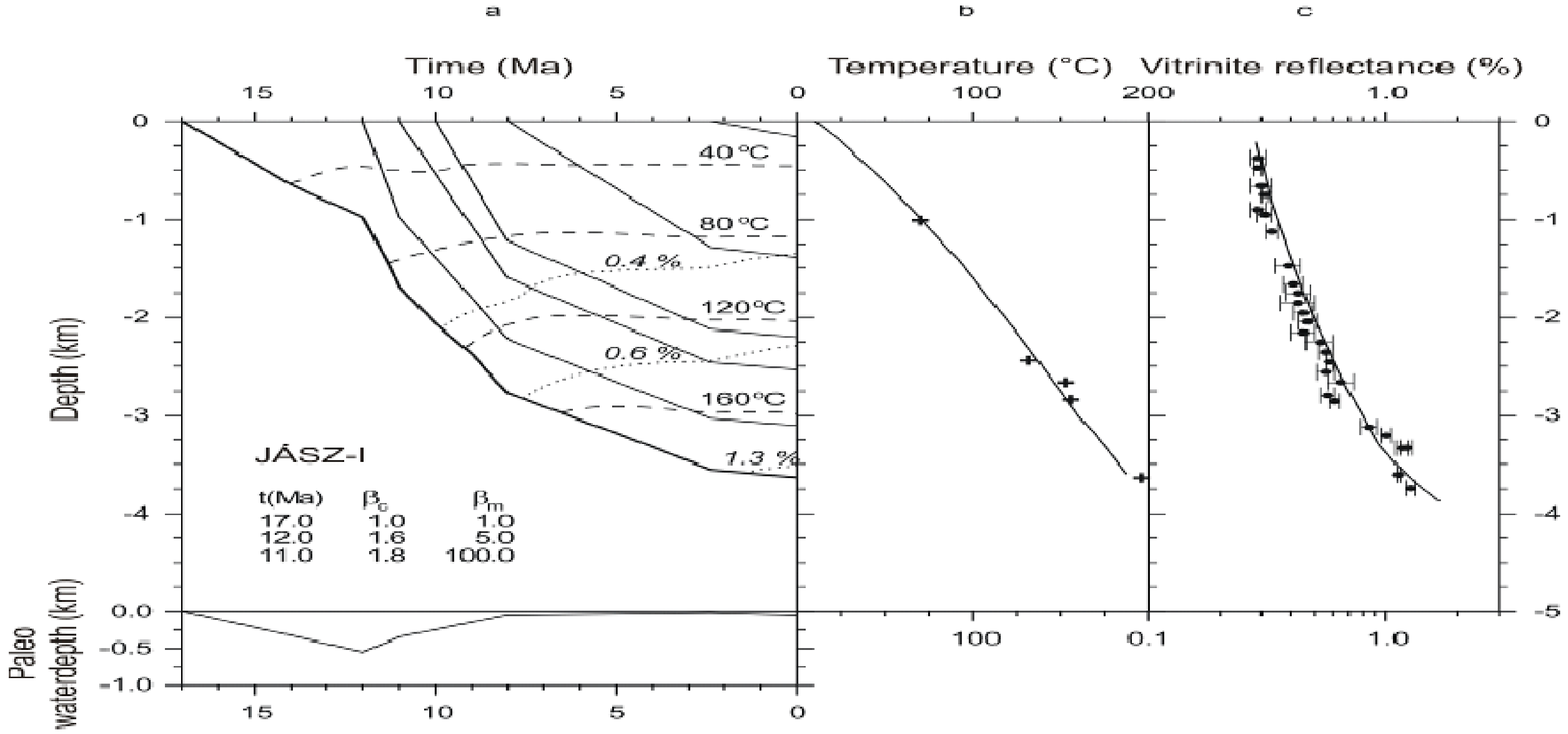
60C/km

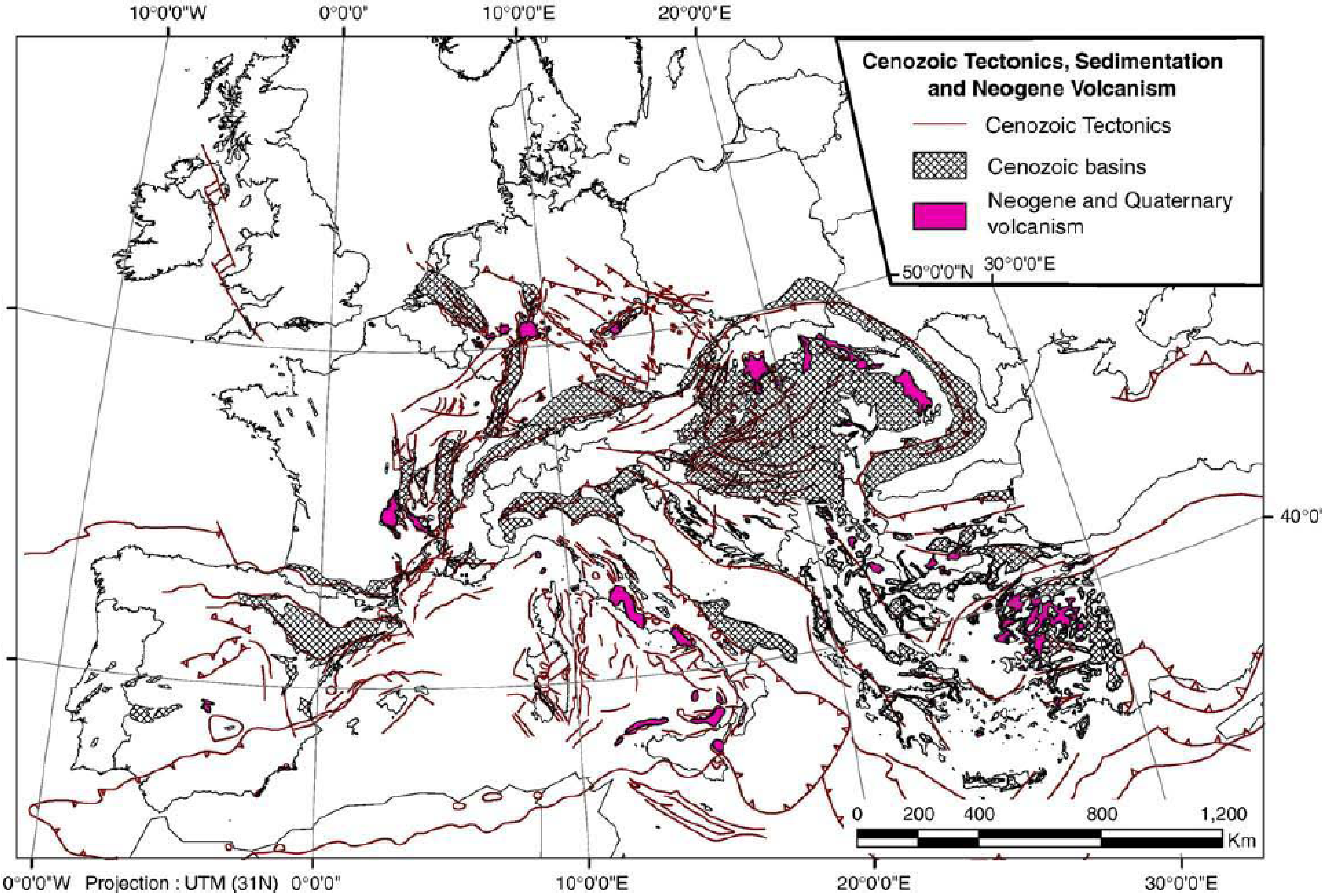


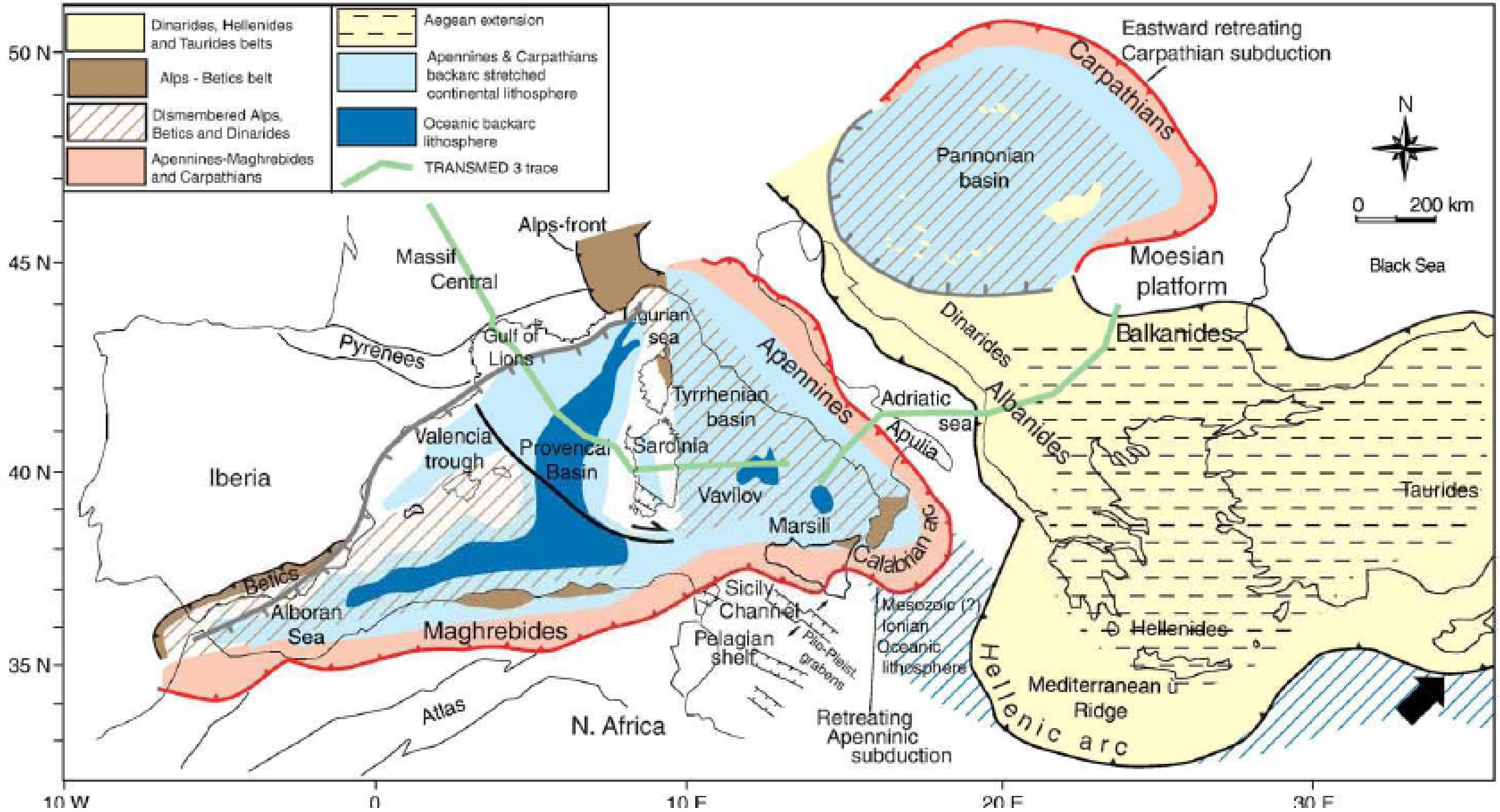
Cloetingh et al., 2006

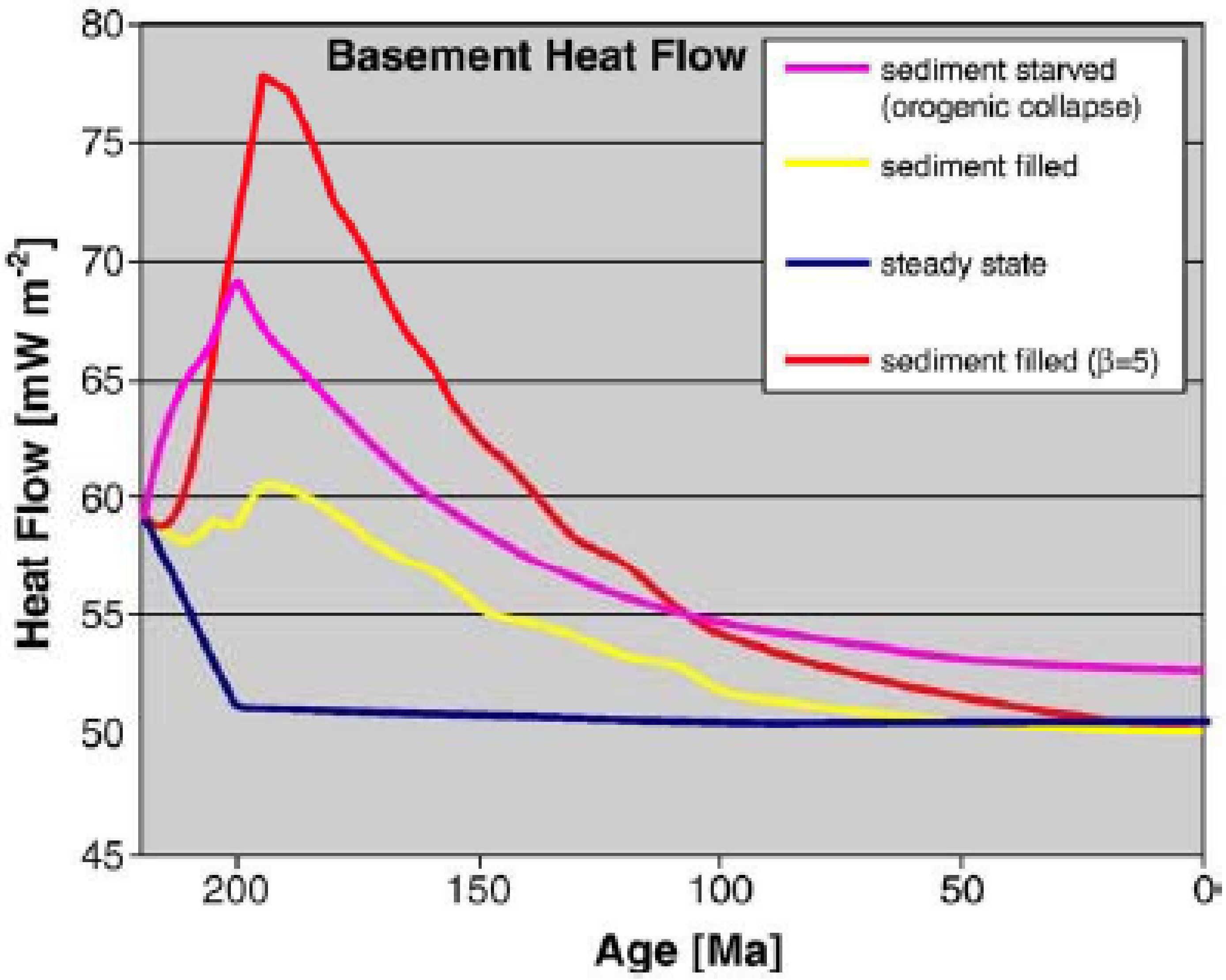
Panonian Basin



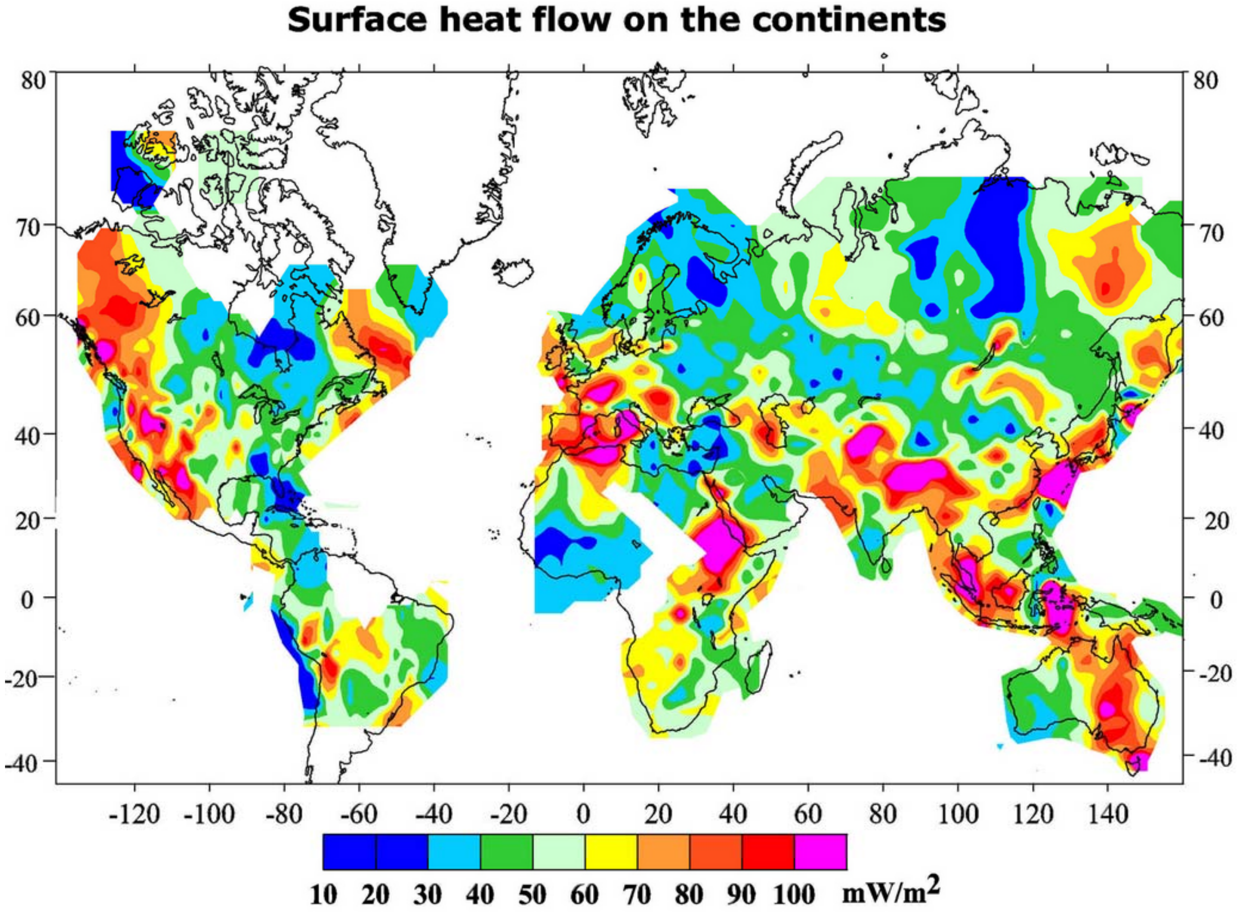



Cenozoic Tectonics, Sedimentation and Neogene Volcanism
Cenozoic Tectonics
▨ Cenozoic basins
Neogene and Quaternary volcanism
10°0'0"W
0°0'0"
10°0'0"E
20°0'0"E
50°0'0"N
30°0'0"E
40°0'
0 200 400 800 1,200 Km
0°0'0"W
Projection : UTM (31N)
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E


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
Dinarides
Balkanides
Apennines
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]

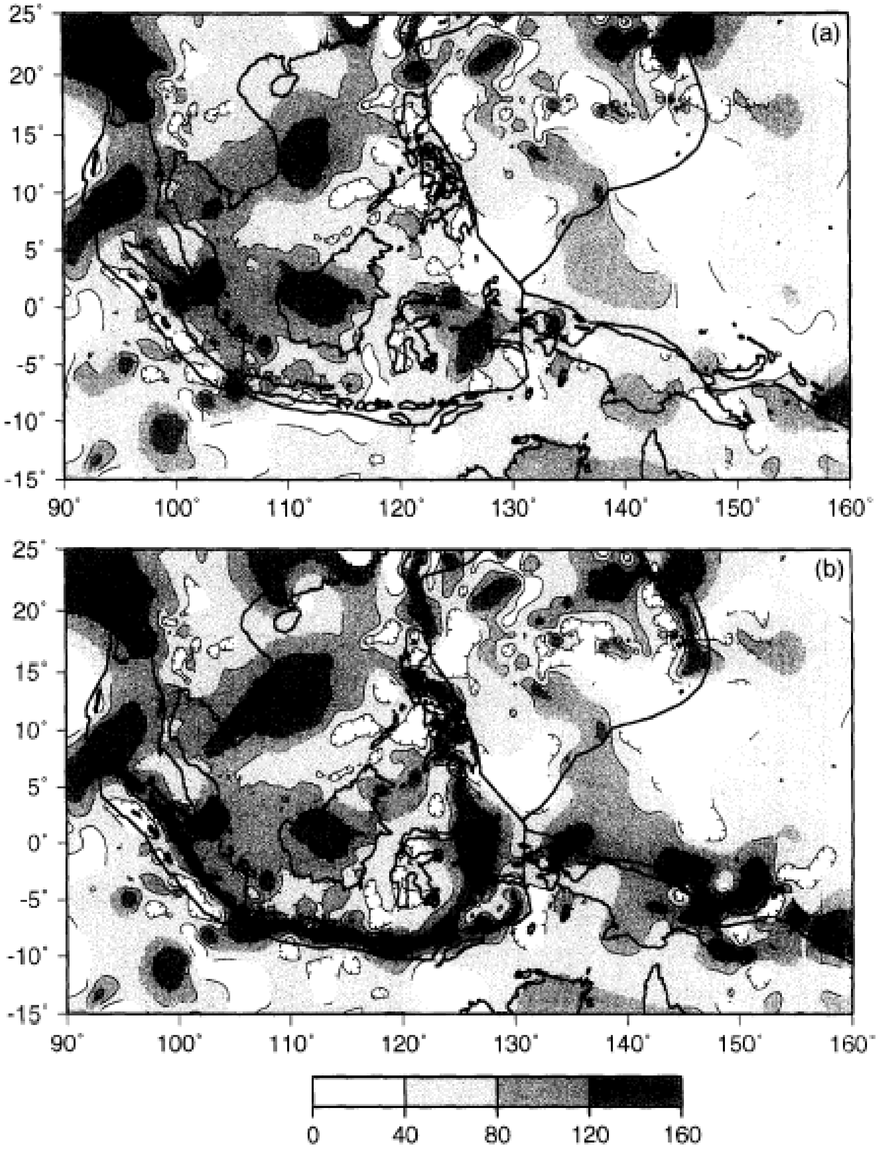
Interpolation using all datapoints



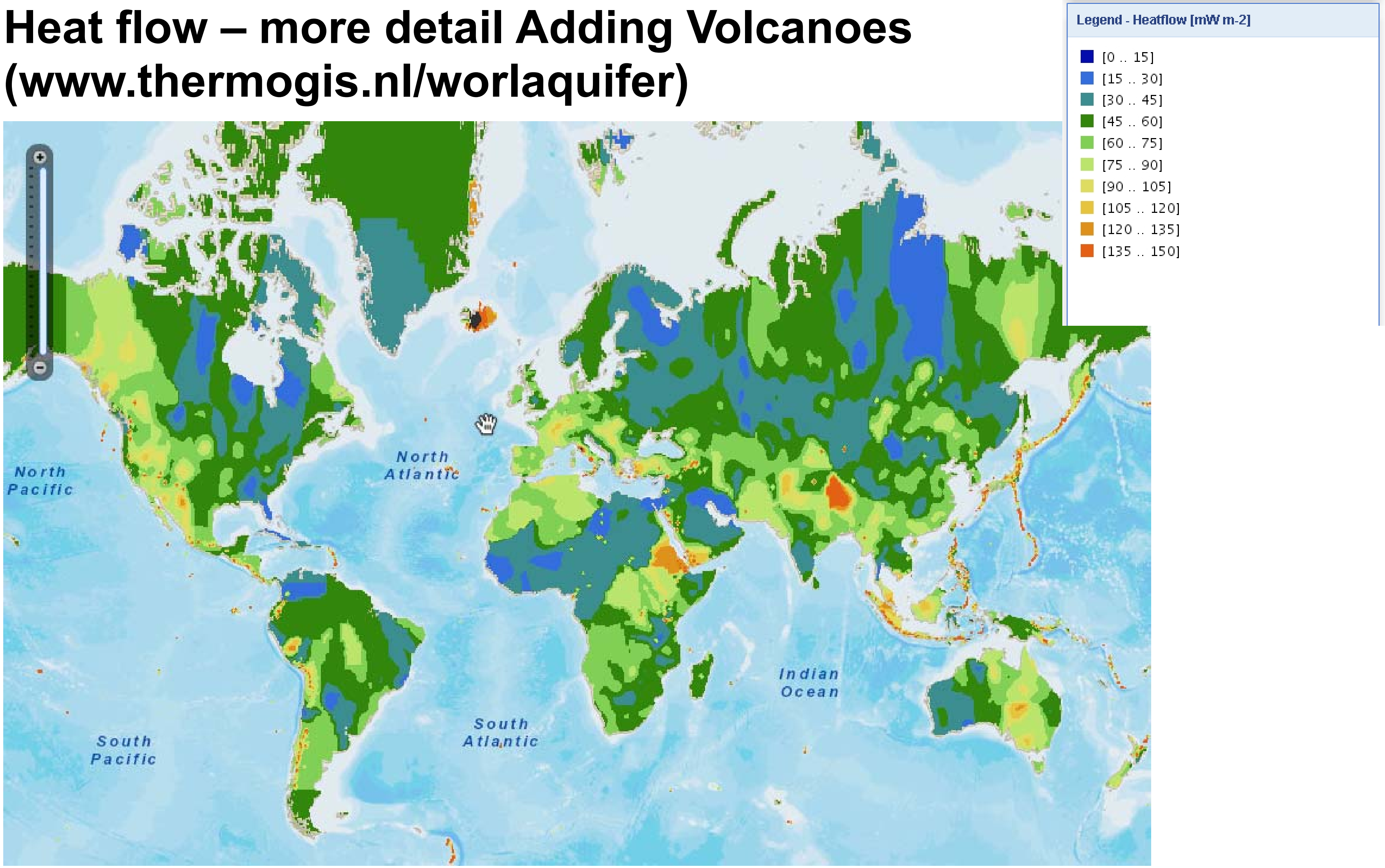
Artimieva et al,2001 and 2006

Adding volcanoe

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



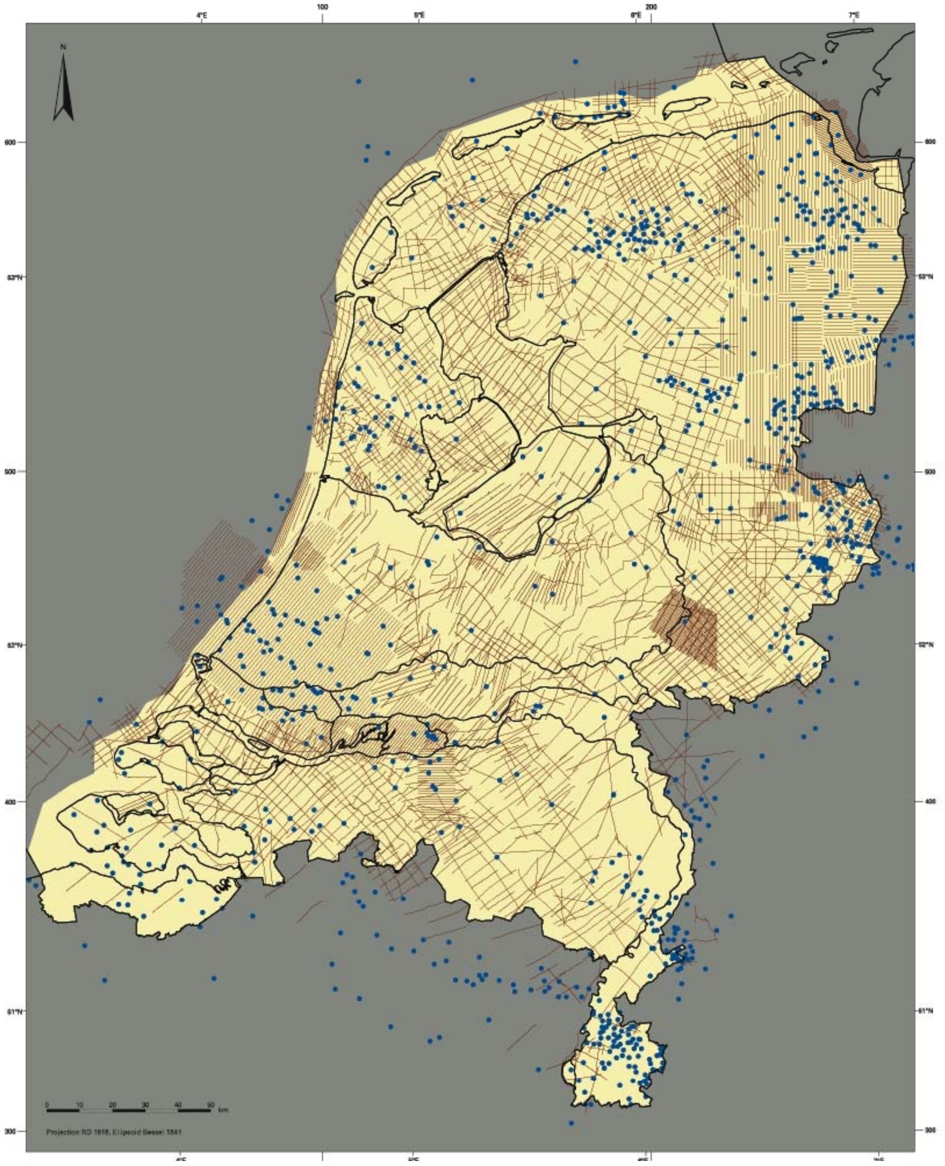
Heat flow – more detail Adding Volcanoes (www.thermogis.nl/worlaquifer)

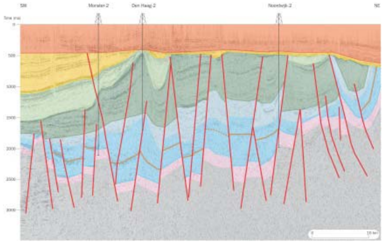


A closer look at europe – active volcanoes – holocene and younger

Magmatism

- Plate tectonics related
  - Mid oceanic ridge (e.g. iceland) and rift (east africa)
  - Subducting plate (e.g. indonesia)
- Mantle plume (core-mantle boundary, e.g. geysers, hawaii, canary islands)
- Orogenic collapse

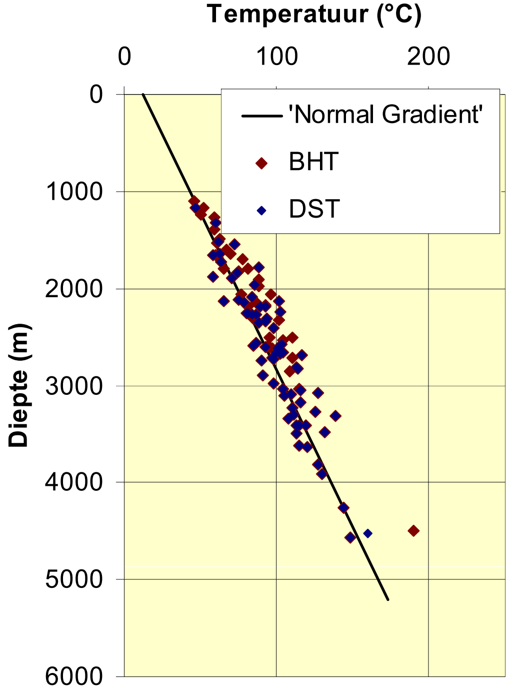




Well & Seismic Data

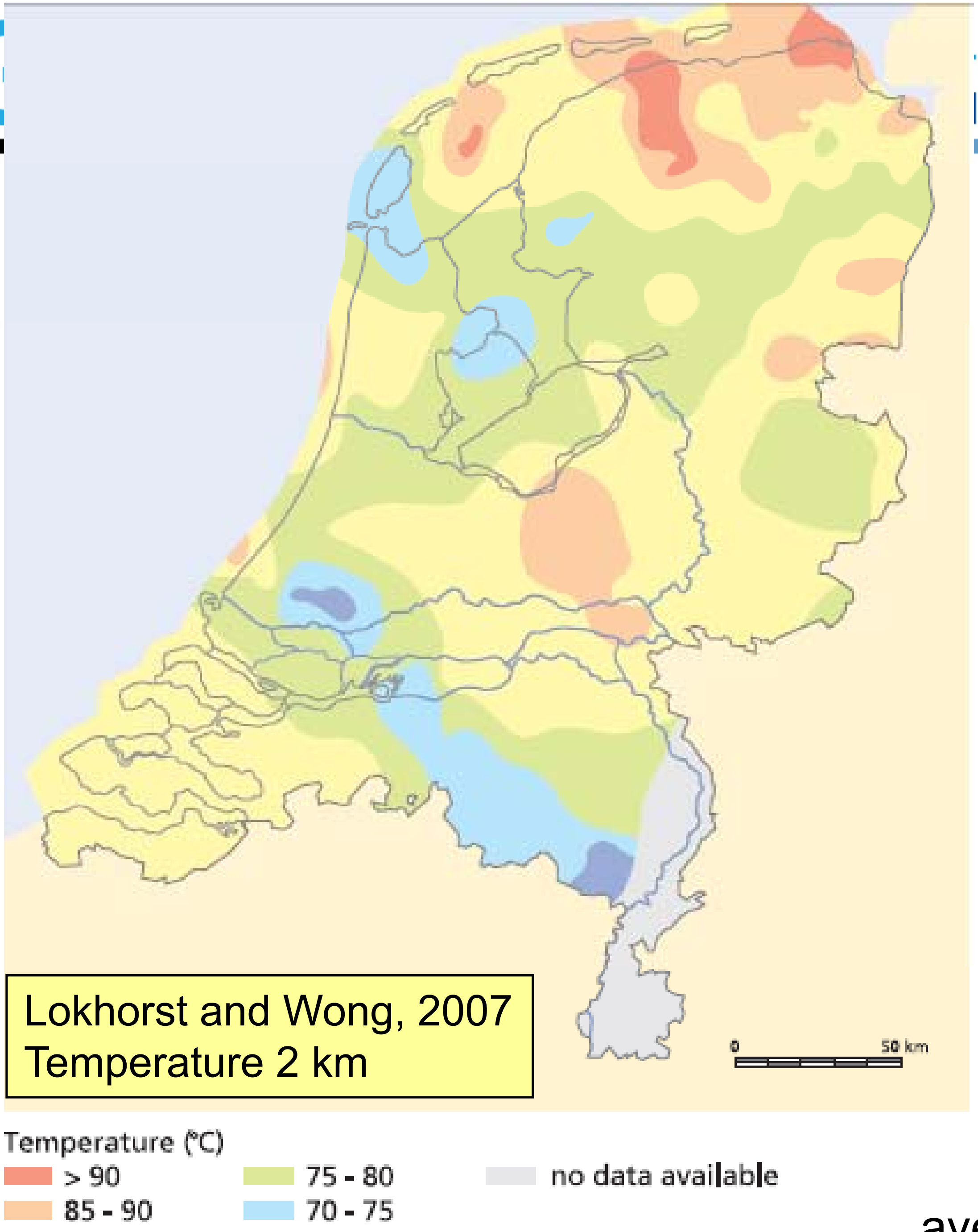
Wells: 5876 (onshore/offshore)

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

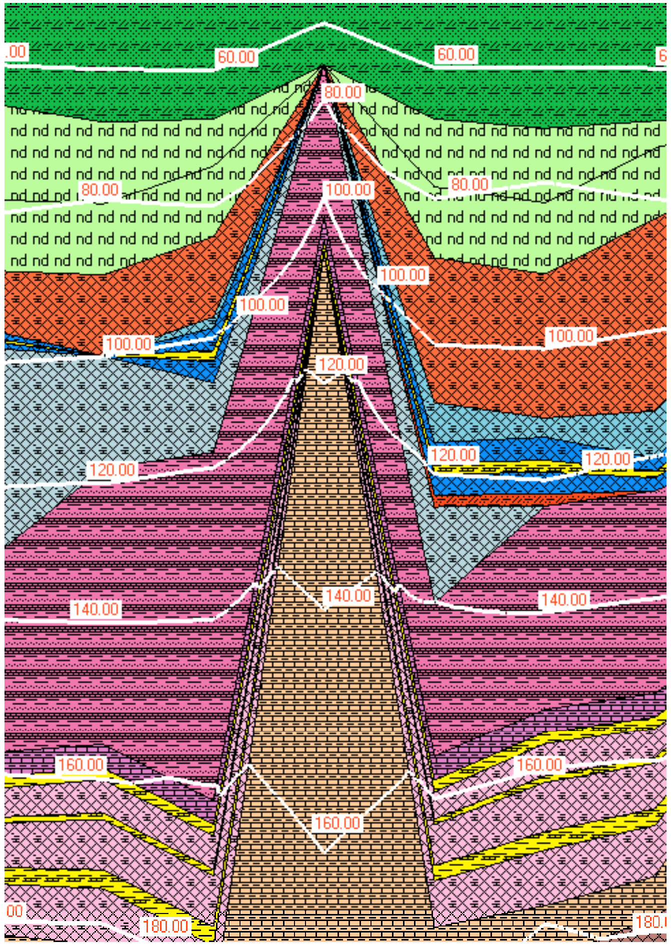


Over 1000 BHT and DST data

Deeper/lateral
Requires better
models



Lokhorst and Wong, 2007
Temperature 2 km

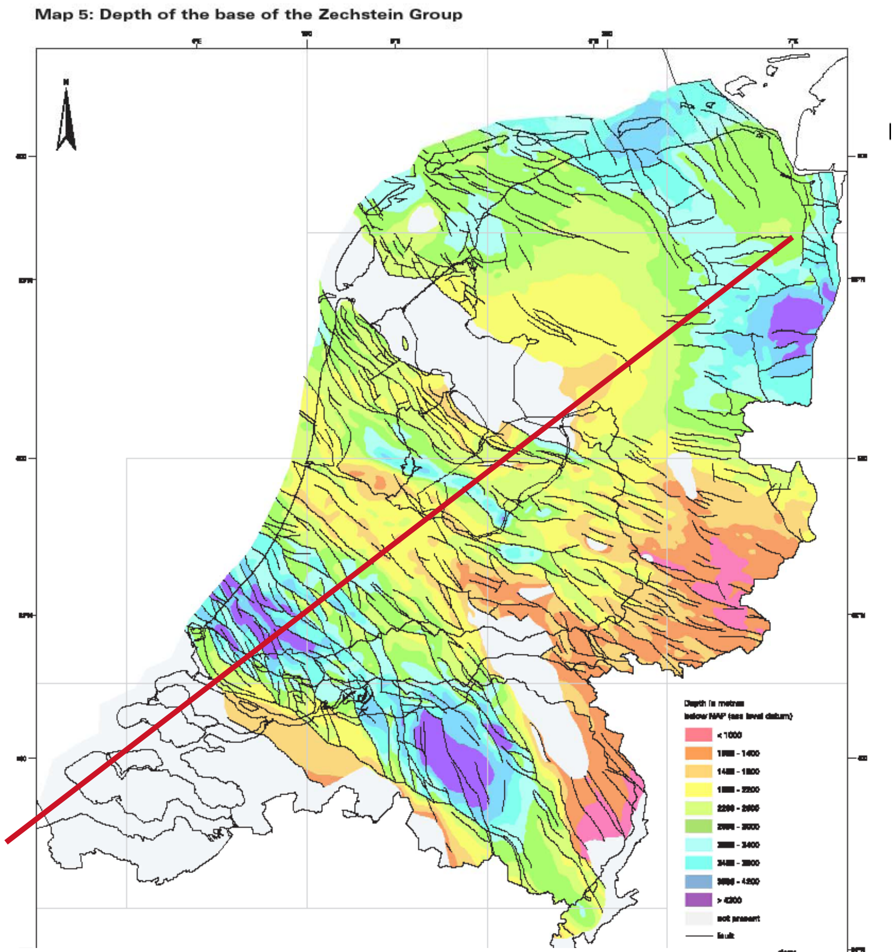


average ca 30C/km

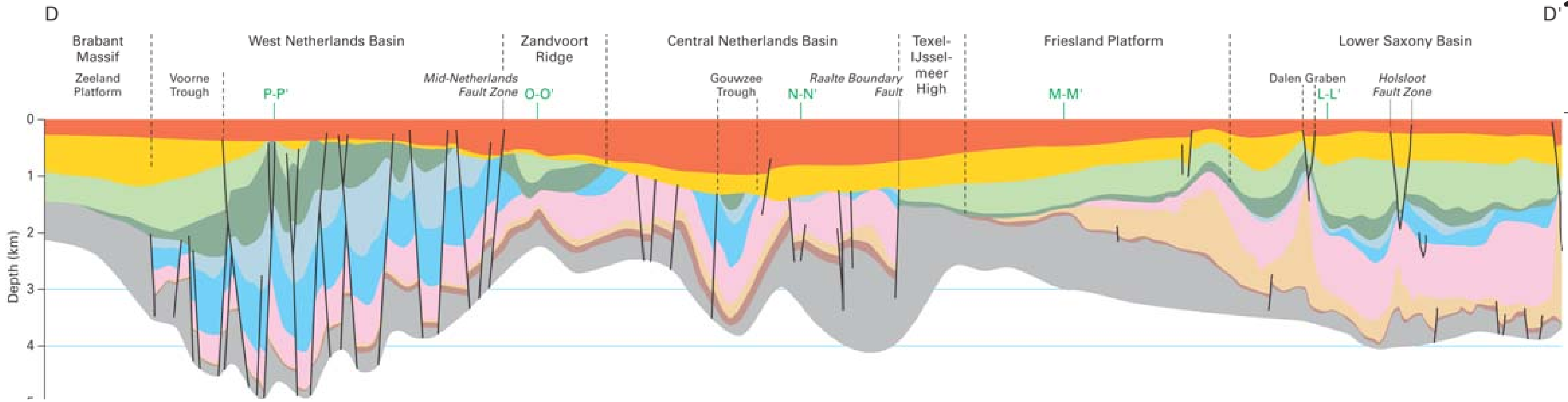
Supported by INTELLI
EUROP

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

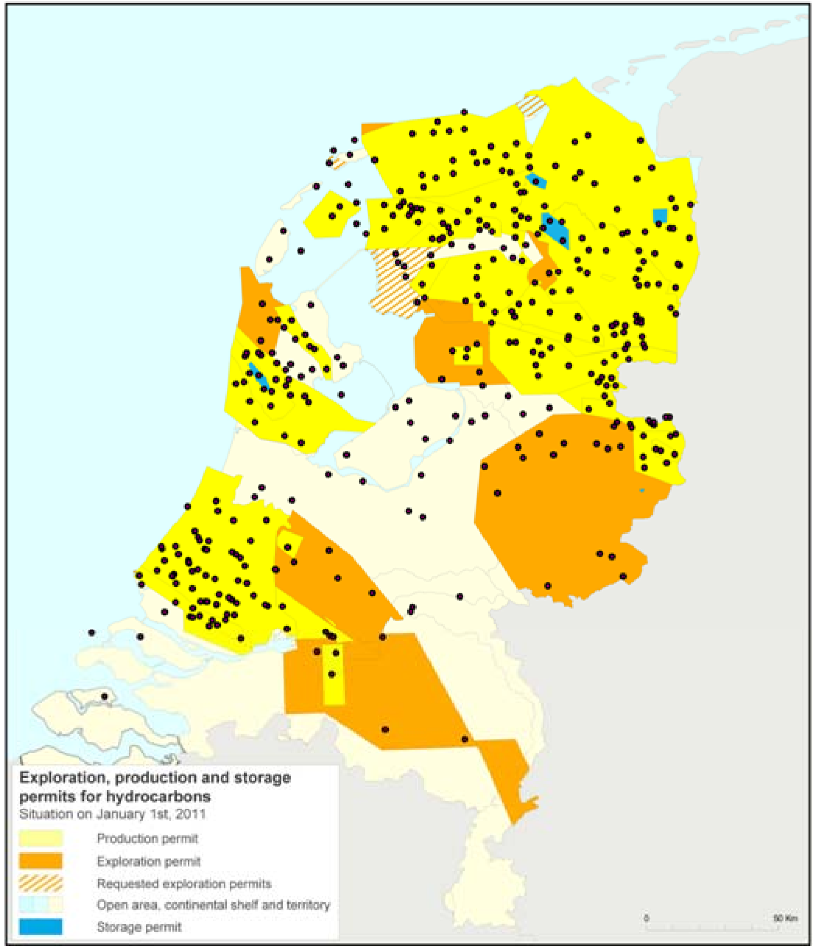


Map 5: Depth of the base of the Zechstein Group



BHT data (n=1241)

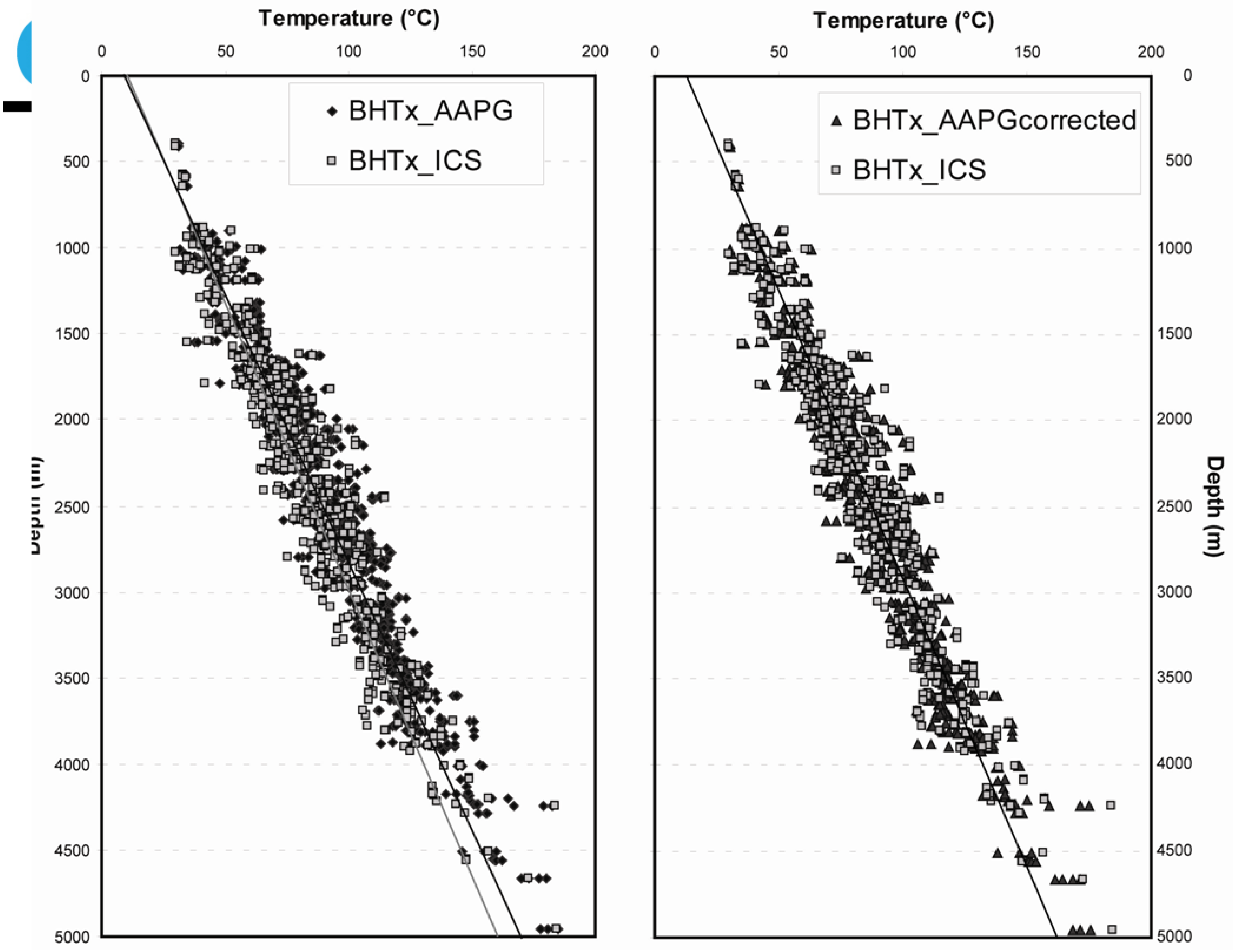
BHT wells and
E&P licenses

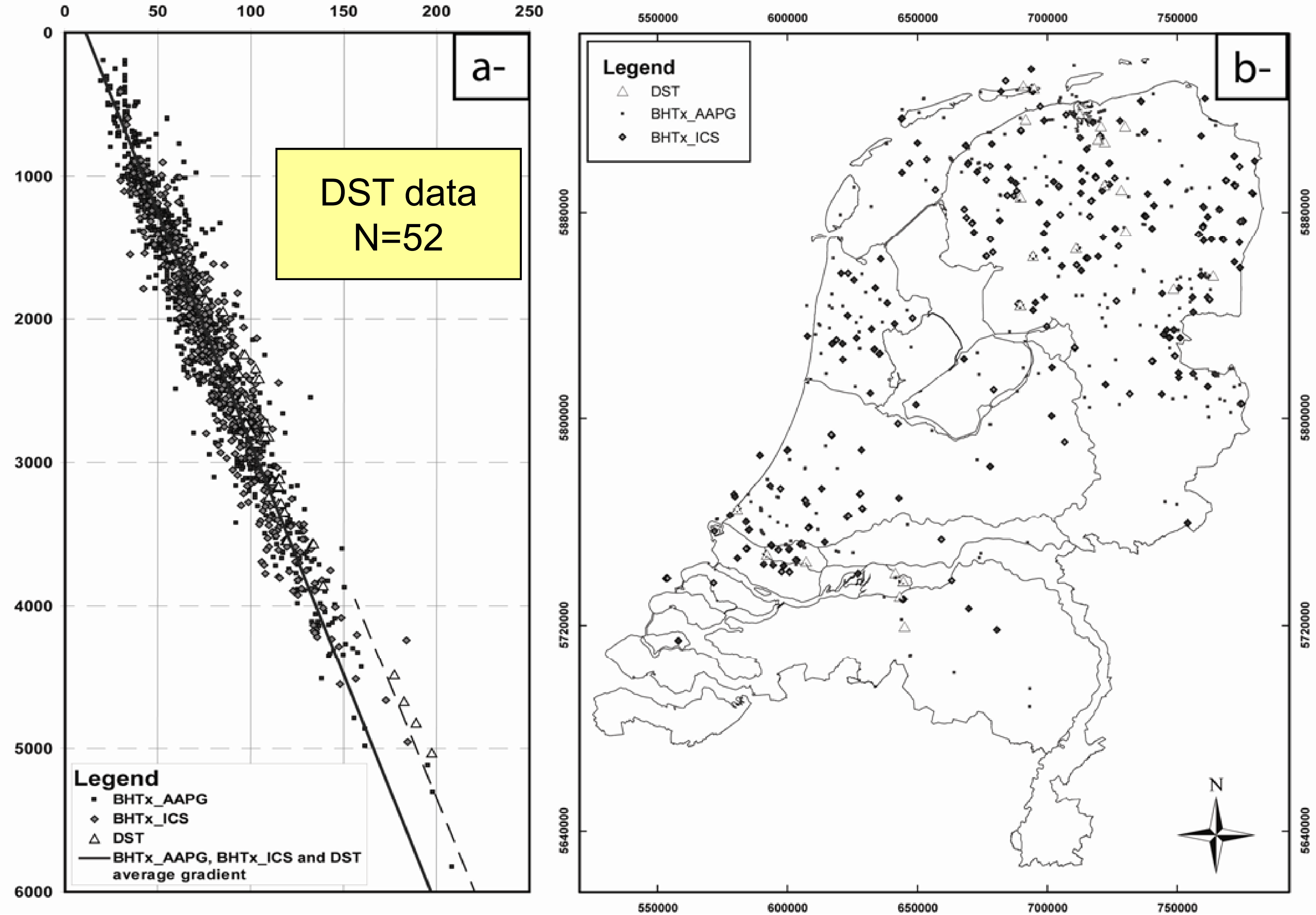


- ICS (n=412)
  - Initial Cylindrical source
  - Used to correct simpler AAPG methods
- AAPG + AAPGcorrected (n=829)

For comparison

DST much less (n=52)

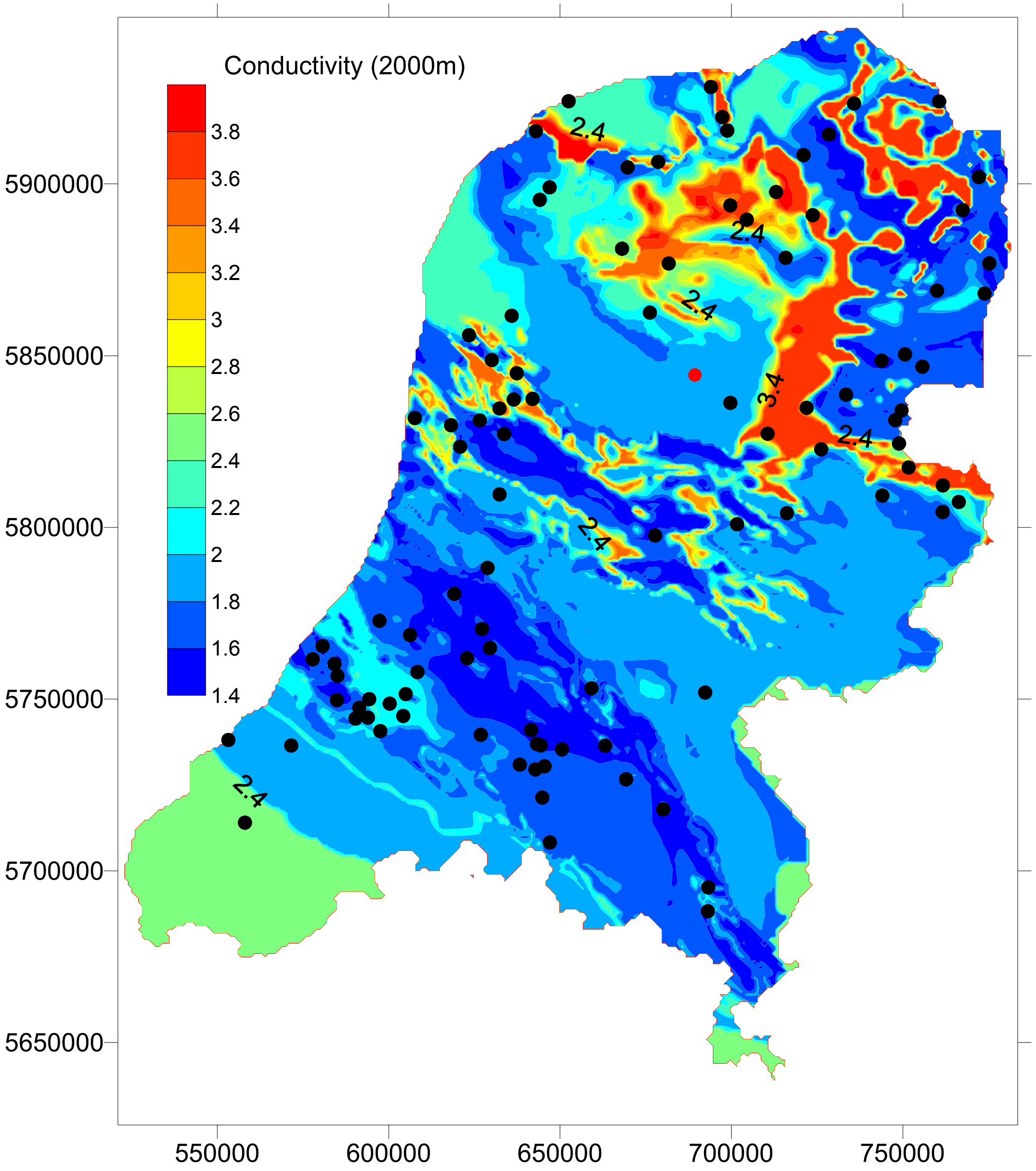

Temperature (°C)
0
50
100
150
200
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
◆ BHTx_AAPG
▫ BHTx_ICS
Temperature (°C)
0
50
100
150
200
▲ BHTx_AAPGcorrected
▫ BHTx_ICS
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Depth (m)


a-
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

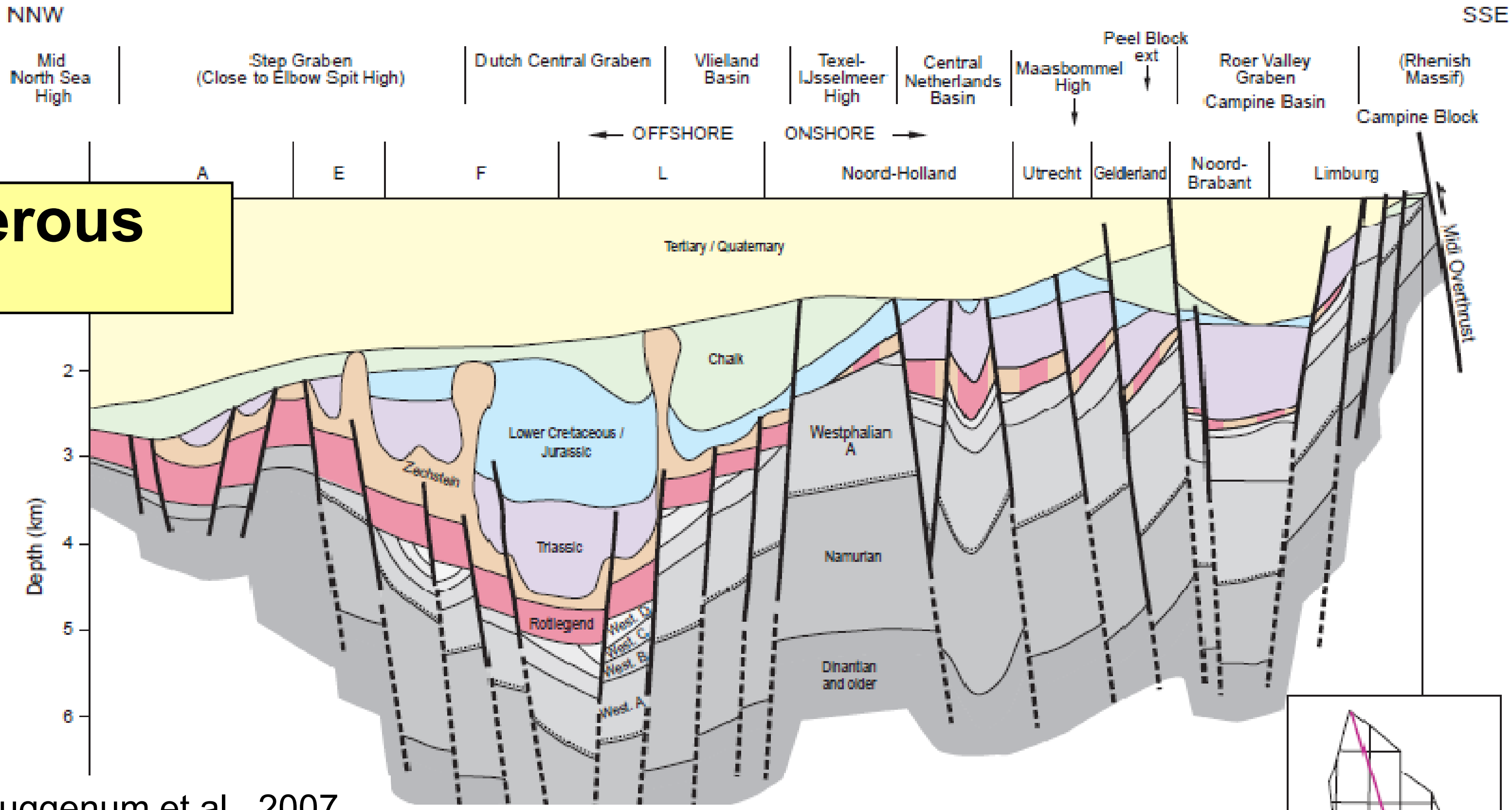
DST data
N=52

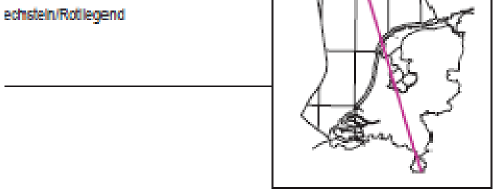
conductivity

- Strong spatial variation

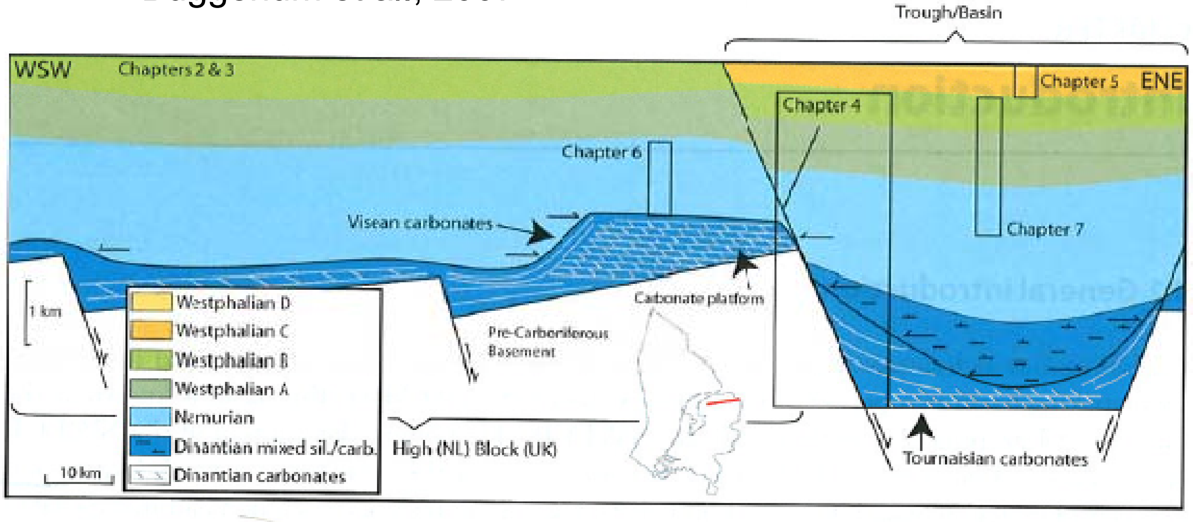


Carboniferous





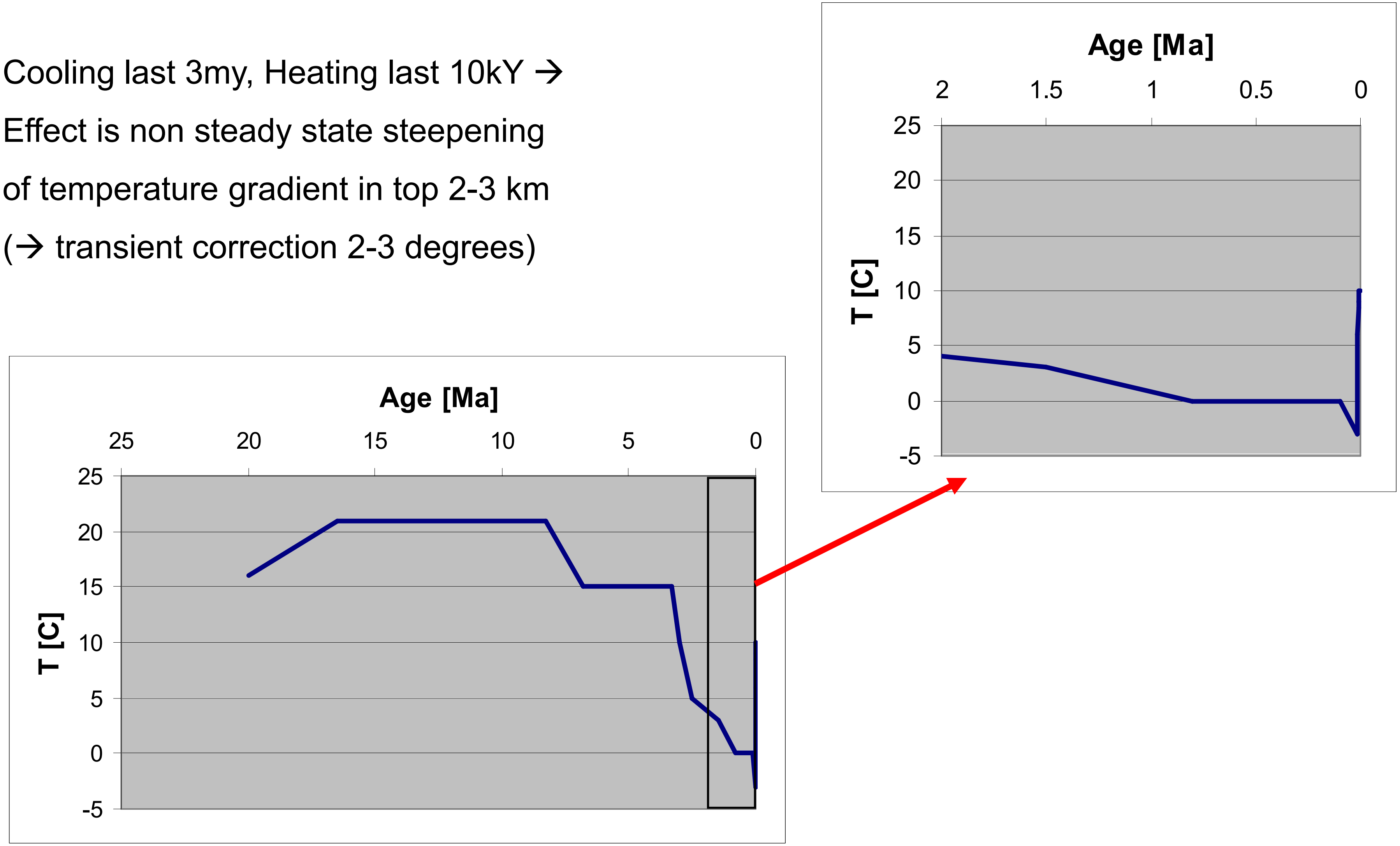
Buggenum et al., 2007



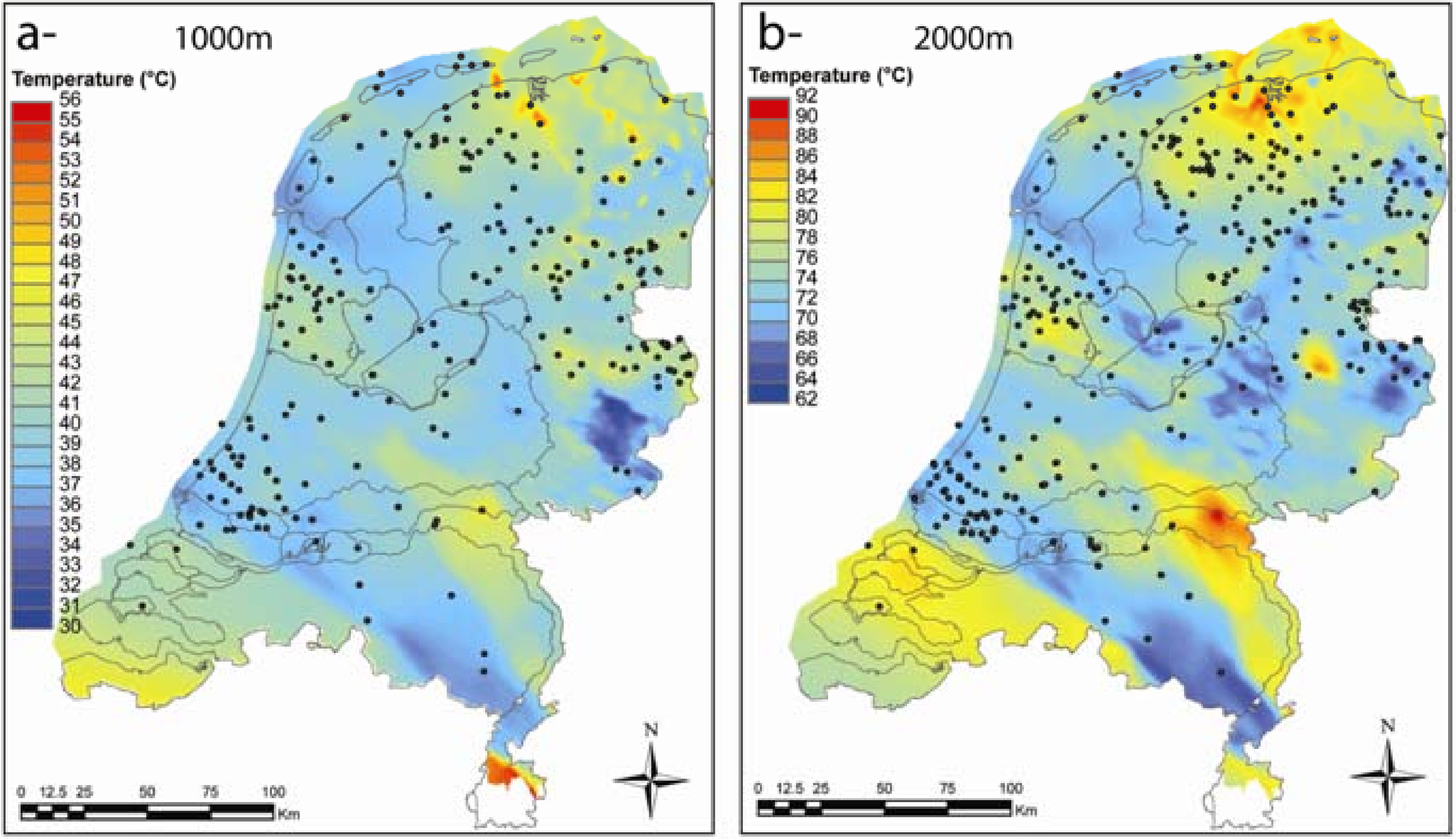
Kombrink, 2008

Surface Temperature

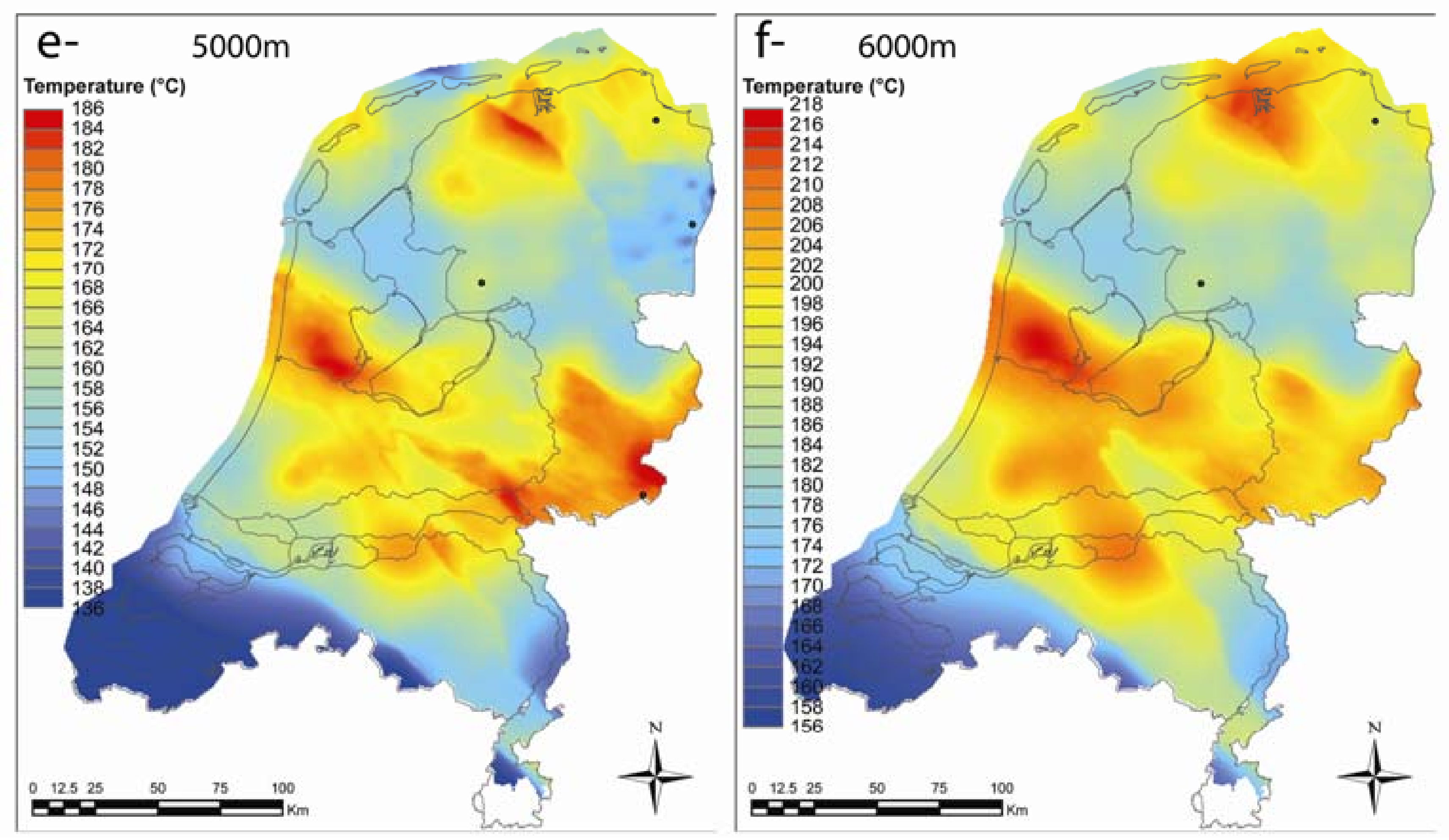
- Cooling last 3my, Heating last 10kY → Effect is non steady state steepening of temperature gradient in top 2-3 km (→ transient correction 2-3 degrees)



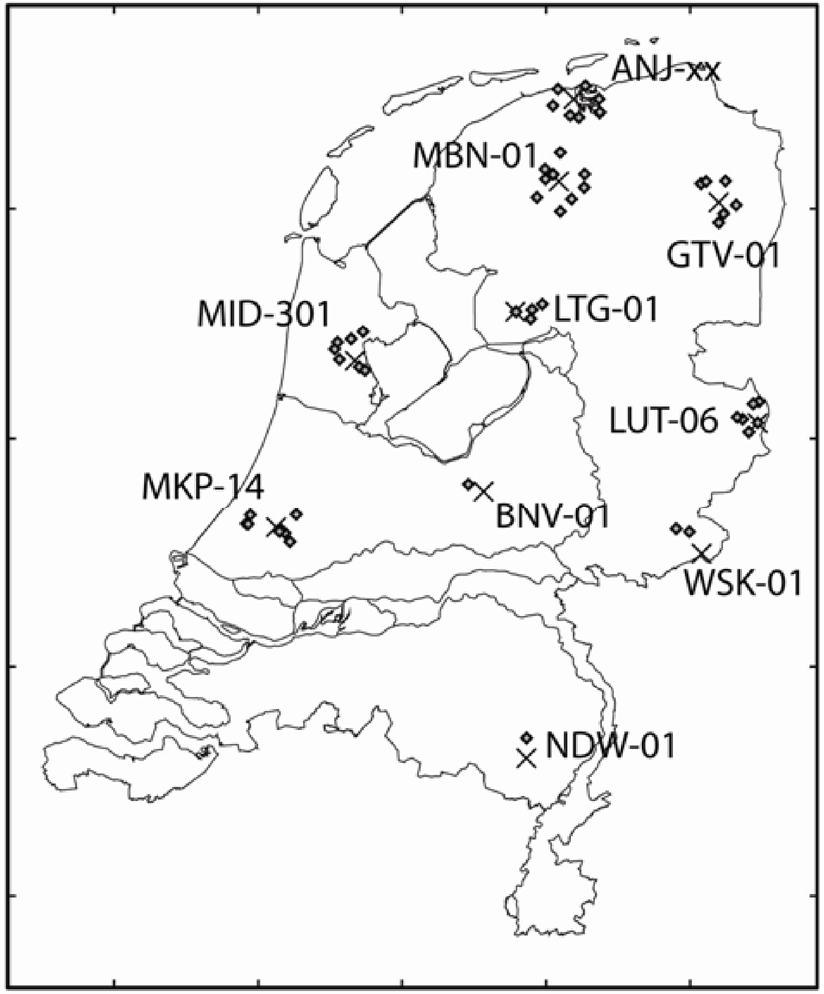
Results - temperature (1)

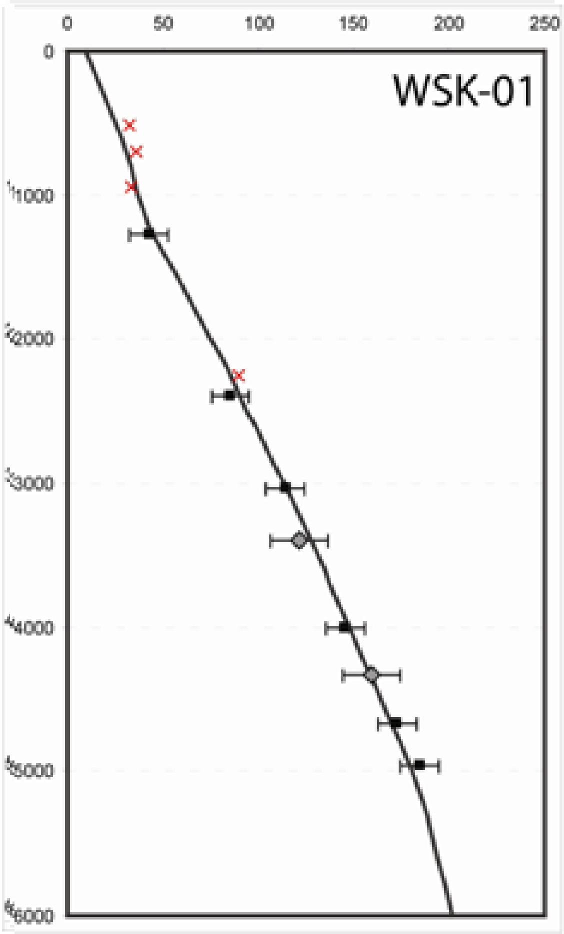


Results - temperature (3)

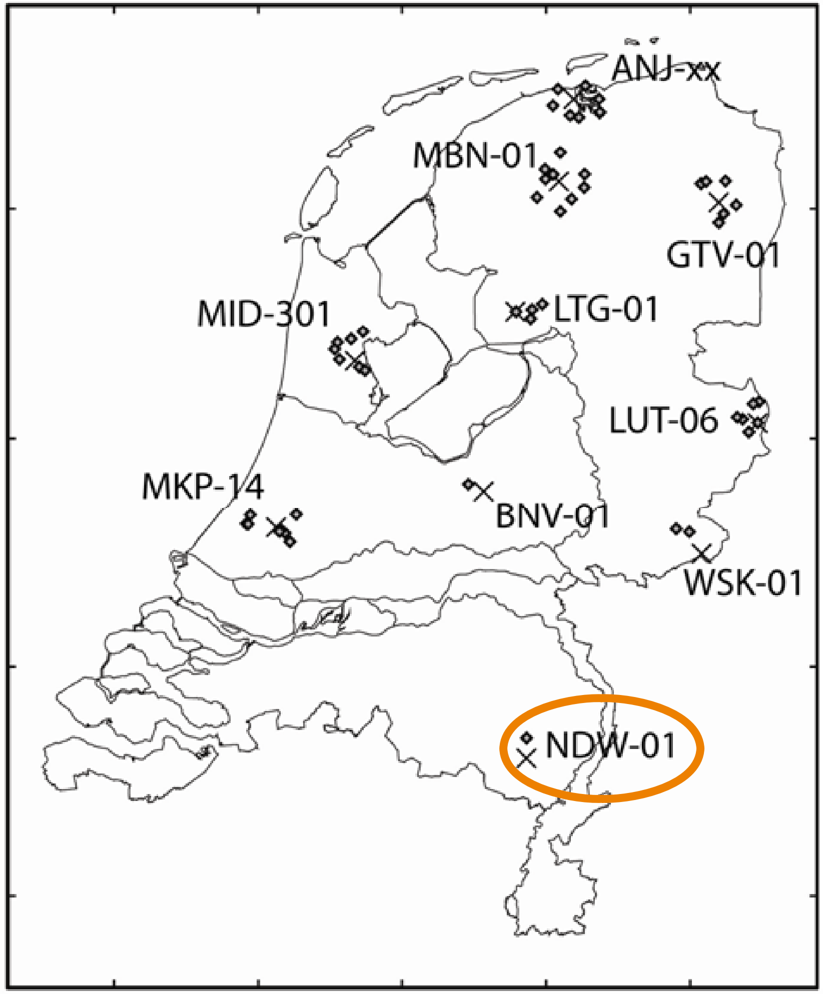


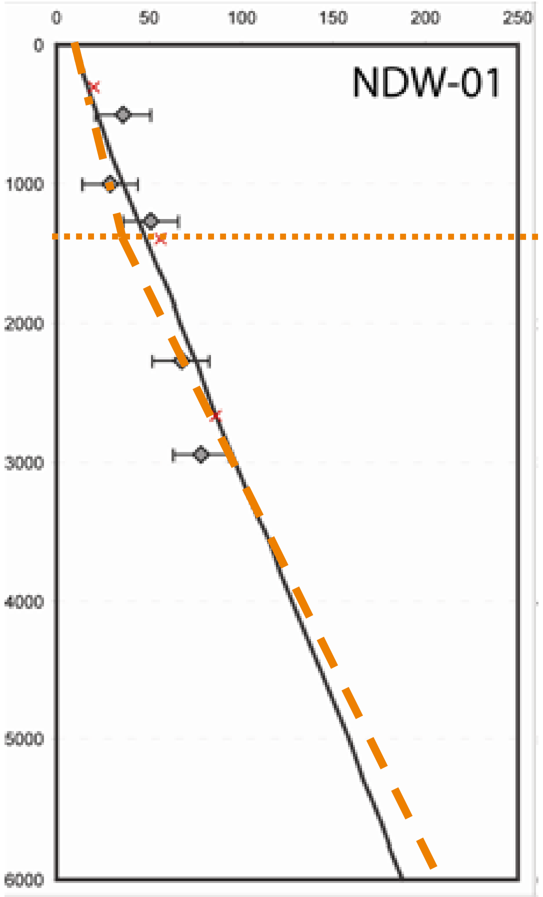
Temperature fit to well data



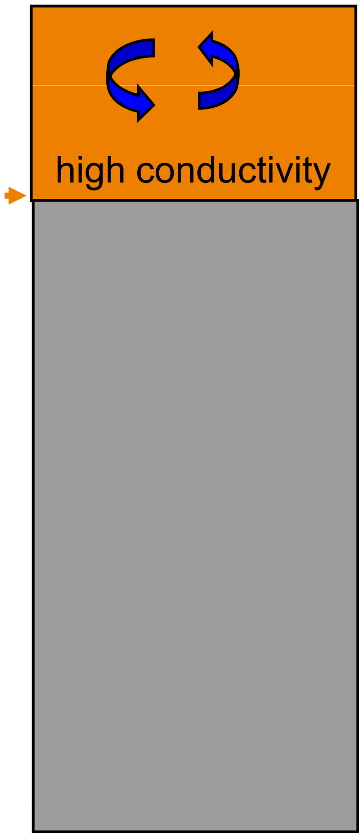


Temperature fit to well data



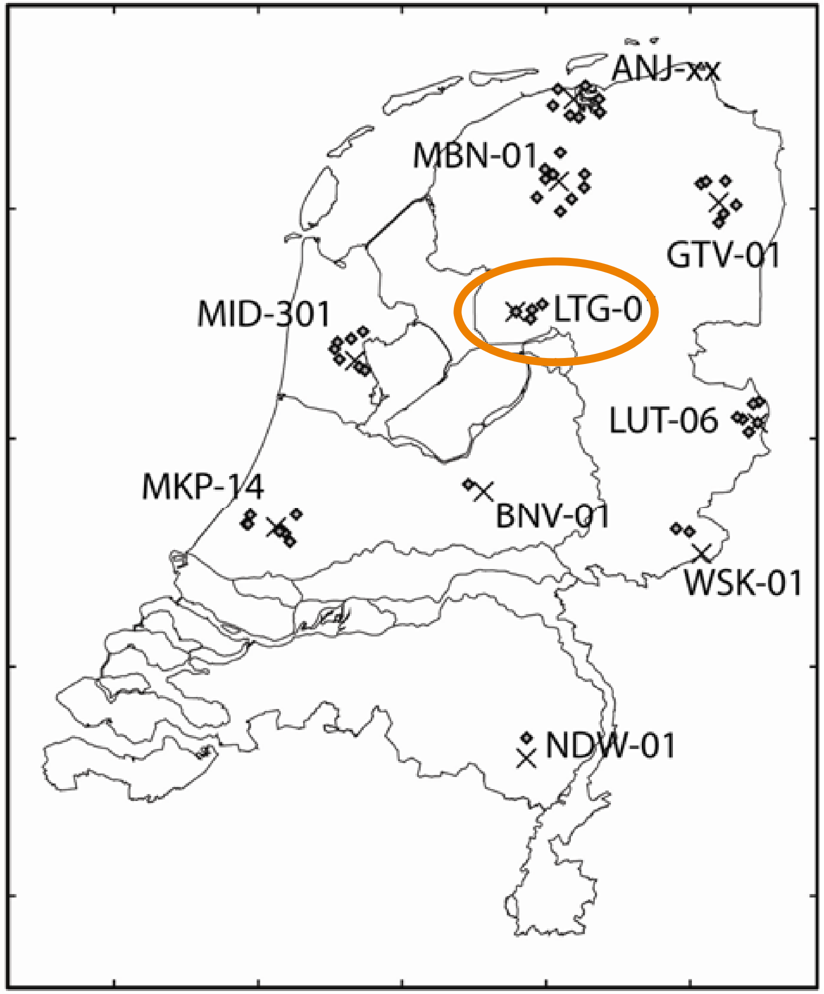


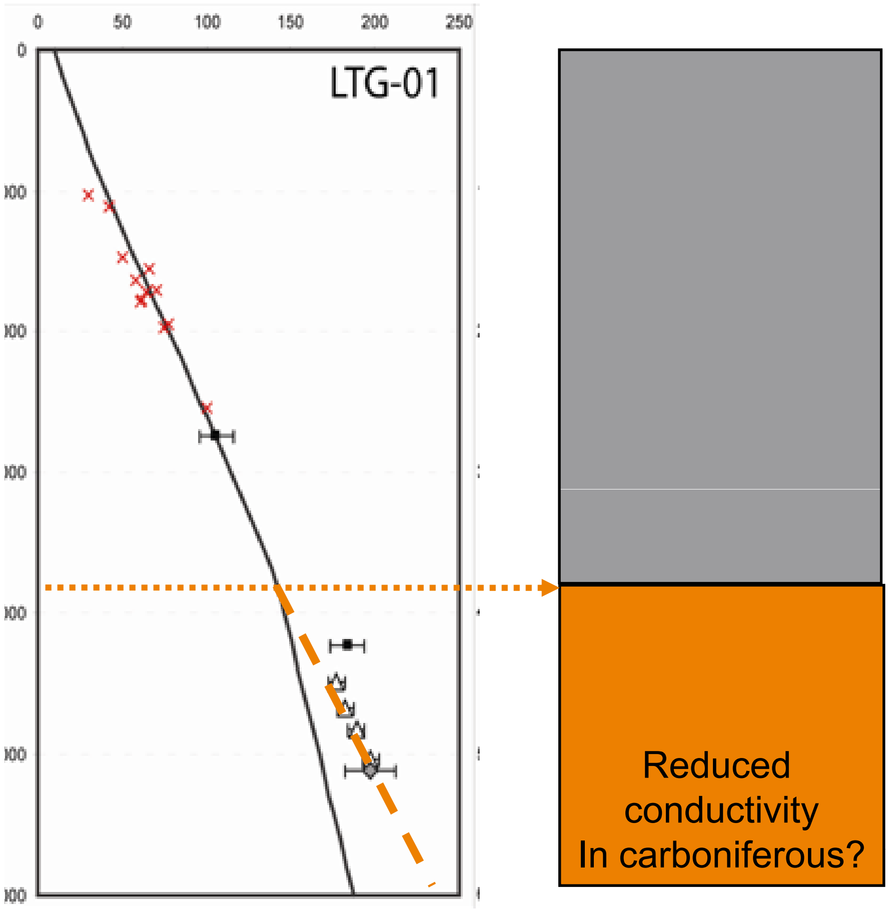
Meteoric water convection



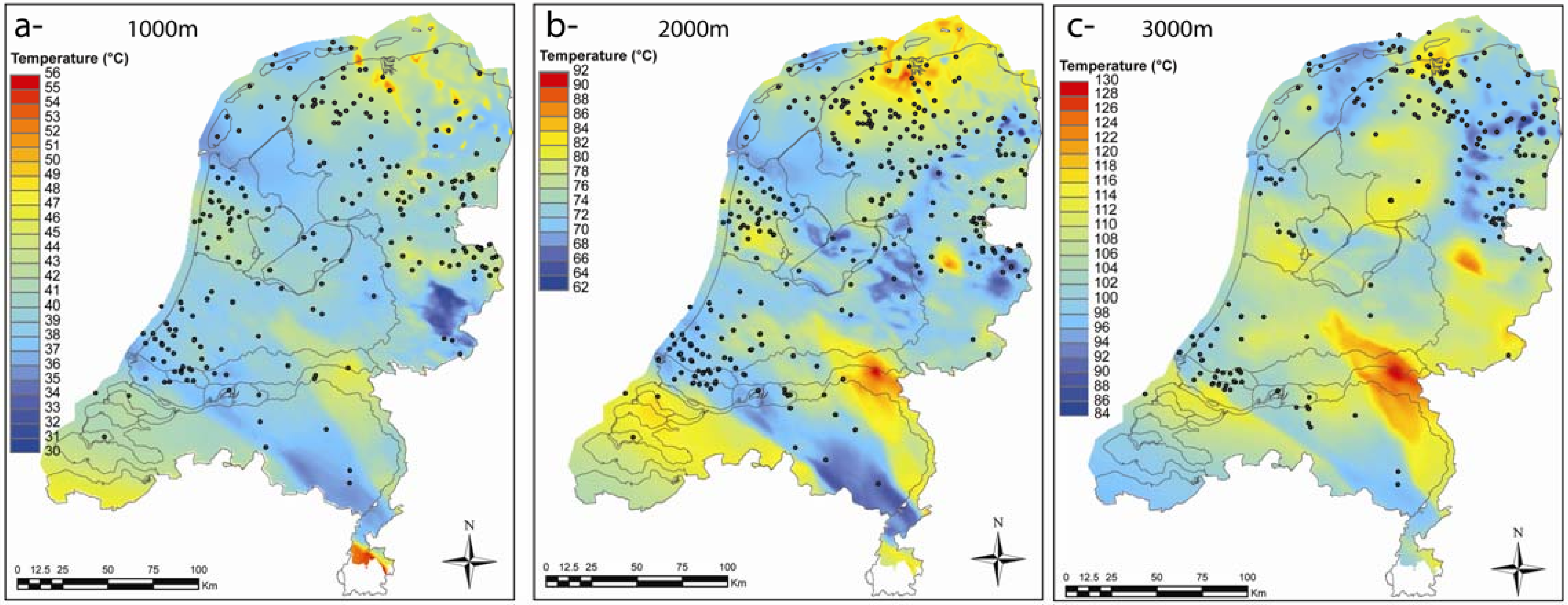
Luijendijk, 2010

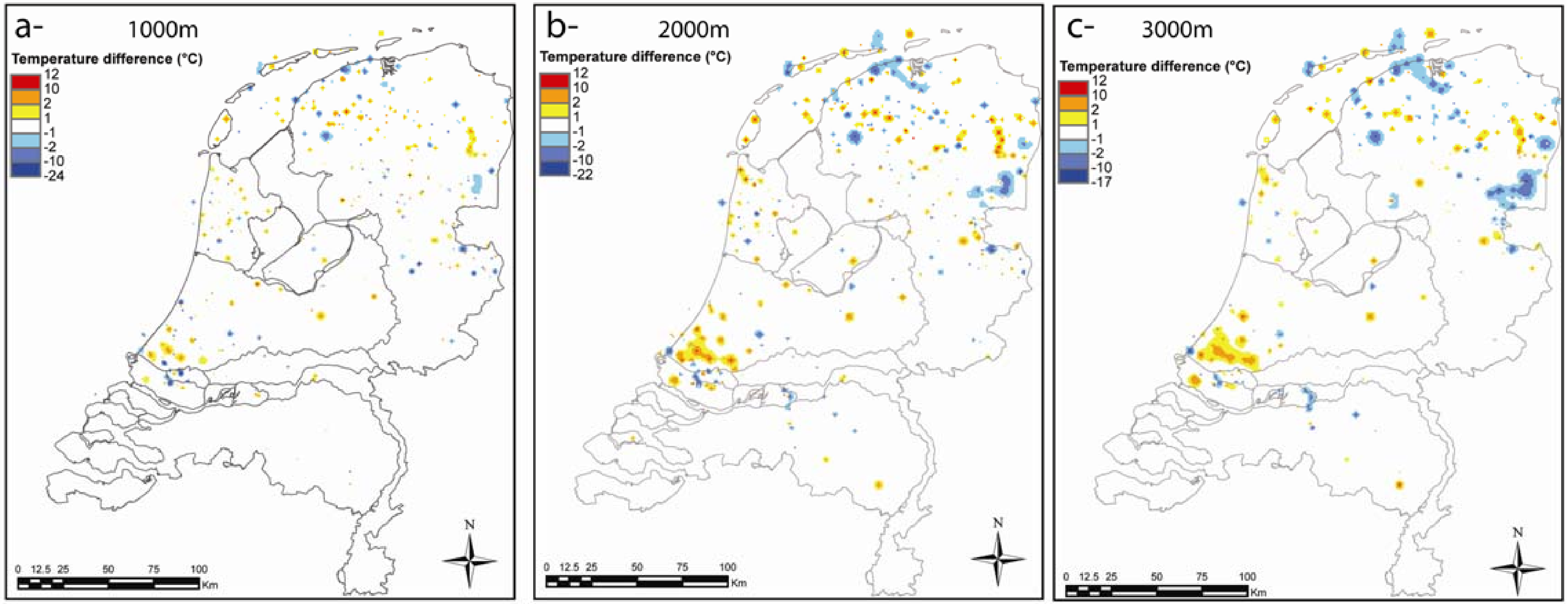
Temperature fit to well data



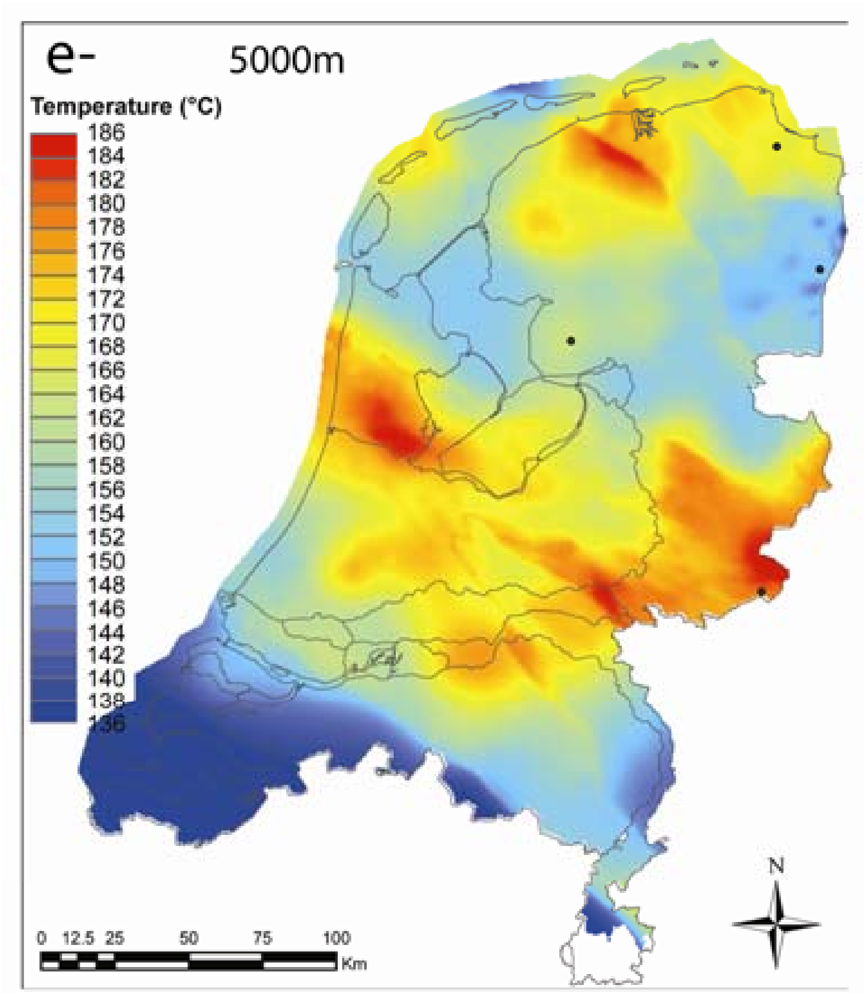


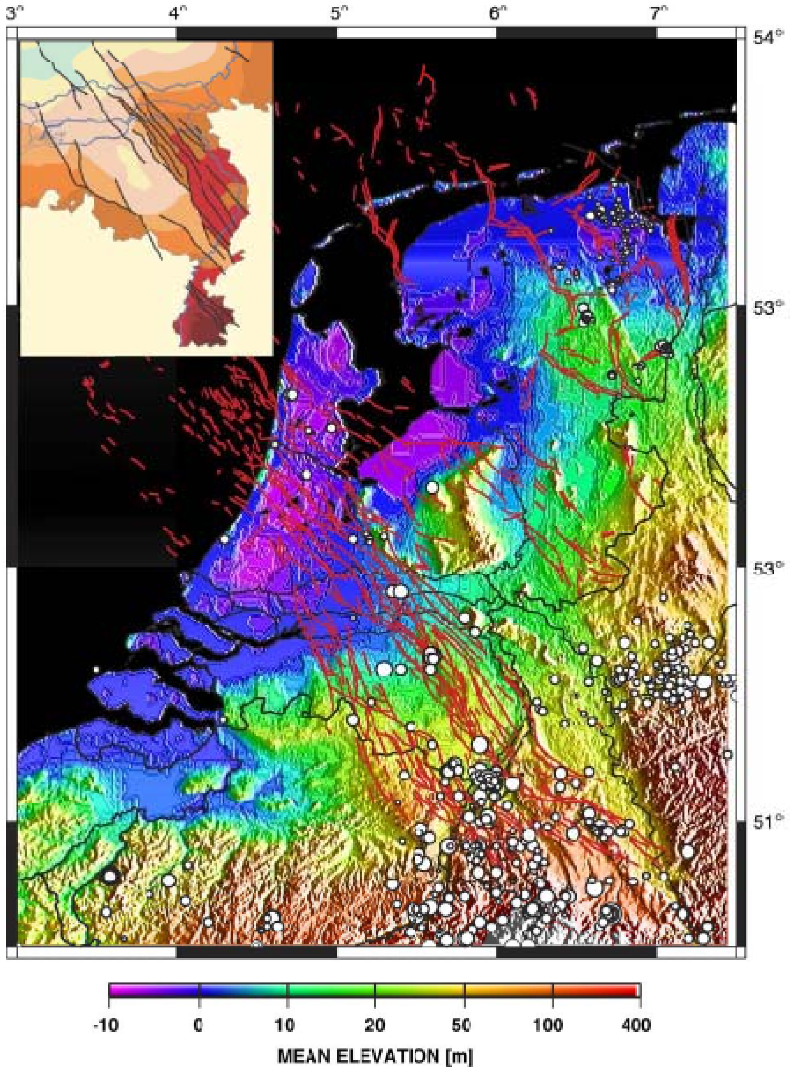
Reduced conductivity
In carboniferous?

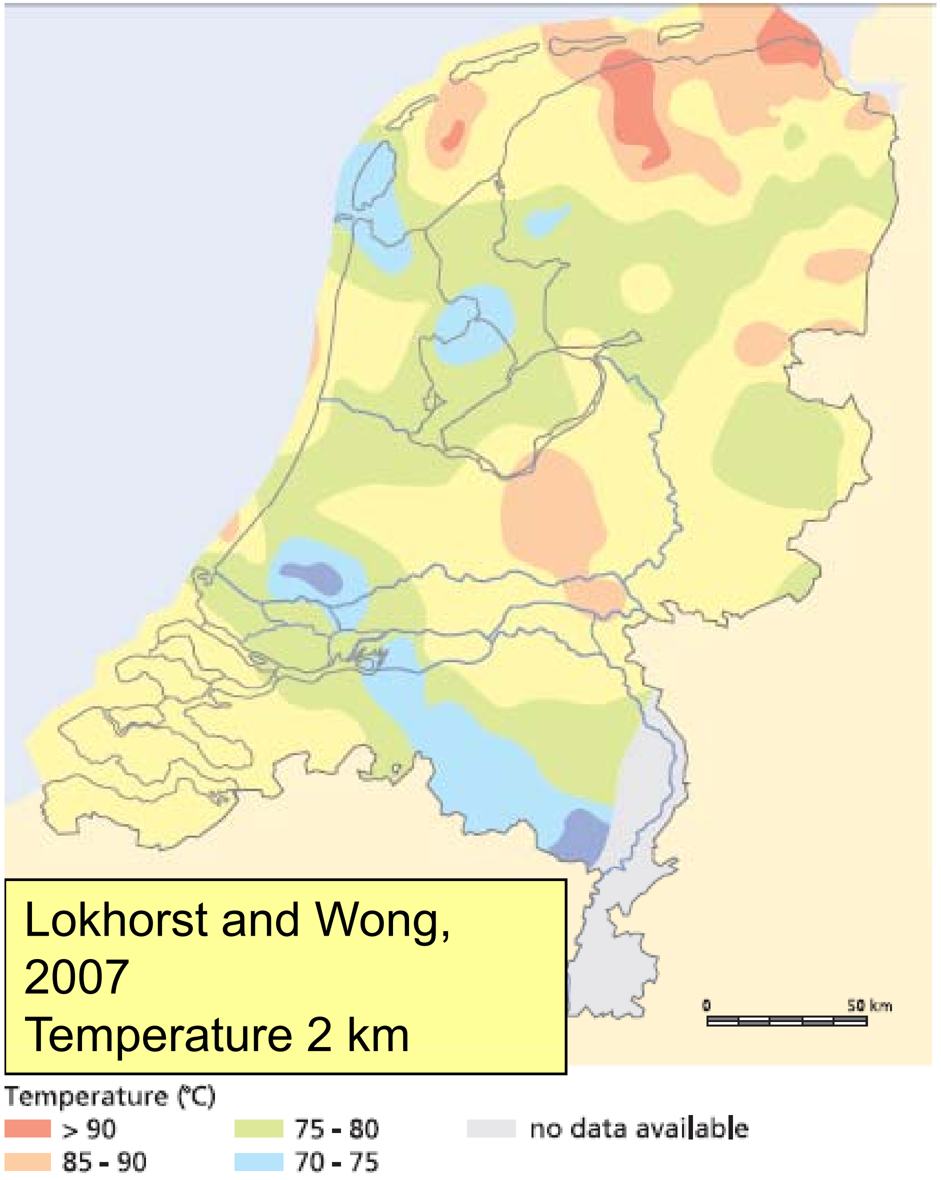

a-
1000m
Temperature (°C)
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
0
12.5
25
50
75
100
Km
N
b-
2000m
Temperature (°C)
92
90
88
86
84
82
80
78
76
74
72
70
68
66
64
62
0
12.5
25
50
75
100
Km
N
c-
3000m
Temperature (°C)
130
128
126
124
122
120
118
116
114
112
110
108
106
104
102
100
98
96
94
92
90
88
86
84
0
12.5
25
50
75
100
Km
N


a-
1000m
Temperature difference (°C)
12
10
2
1
-1
-2
-10
-24
0
12.5
25
50
75
100
Km
N
b-
2000m
Temperature difference (°C)
12
10
2
1
-1
-2
-10
-22
0
12.5
25
50
75
100
Km
N
c-
3000m
Temperature difference (°C)
12
10
2
1
-1
-2
-10
-17
0
12.5
25
50
75
100
Km
N

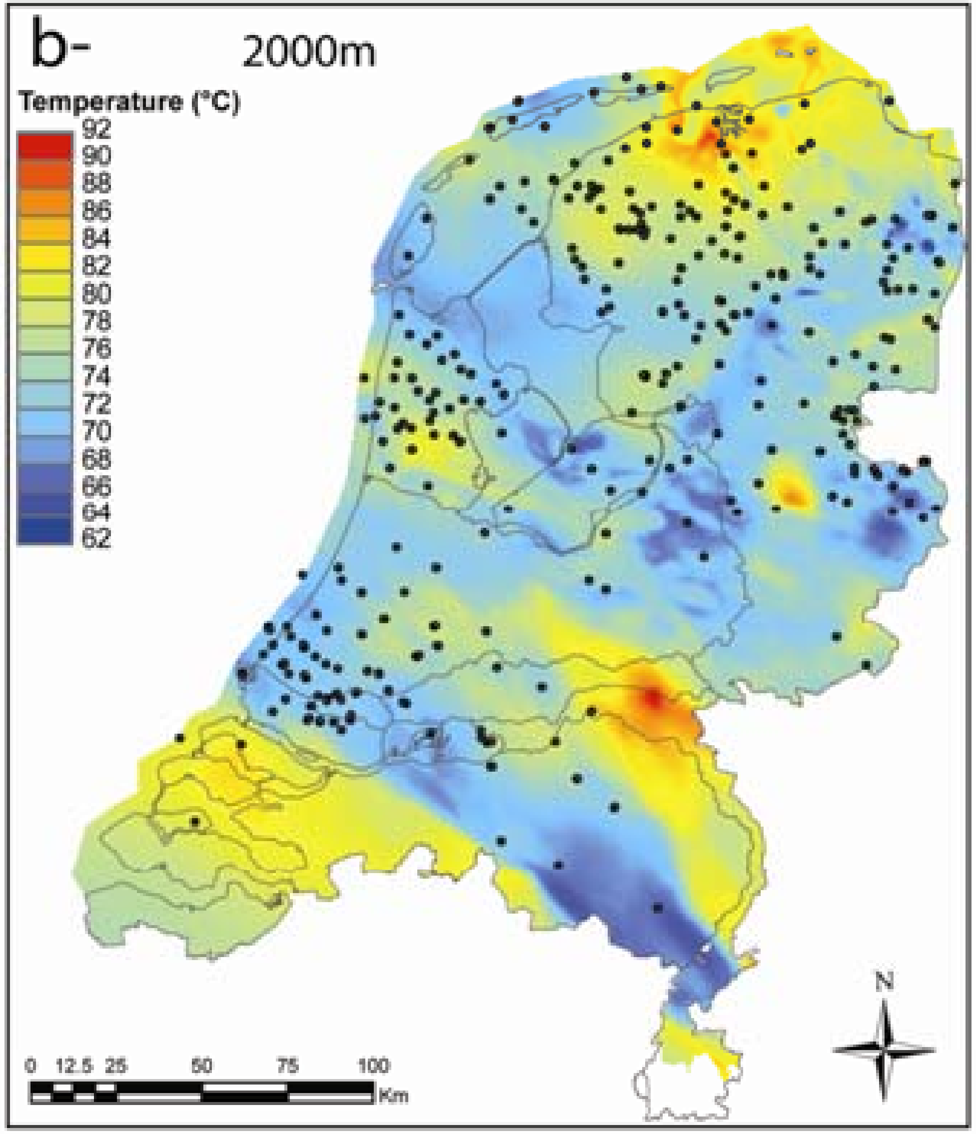
Implications for EGS



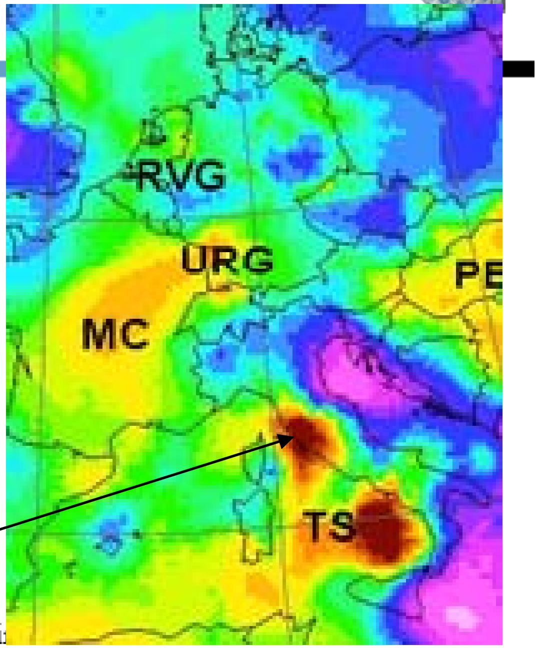


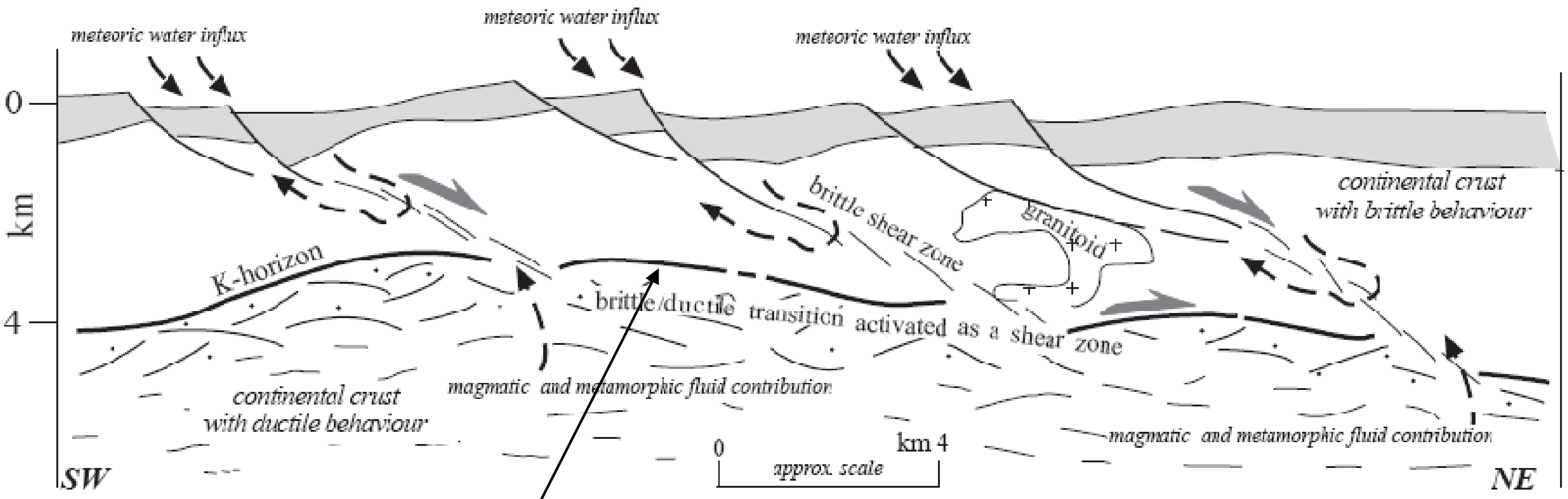


Lokhorst and Wong, 2007
Temperature 2 km



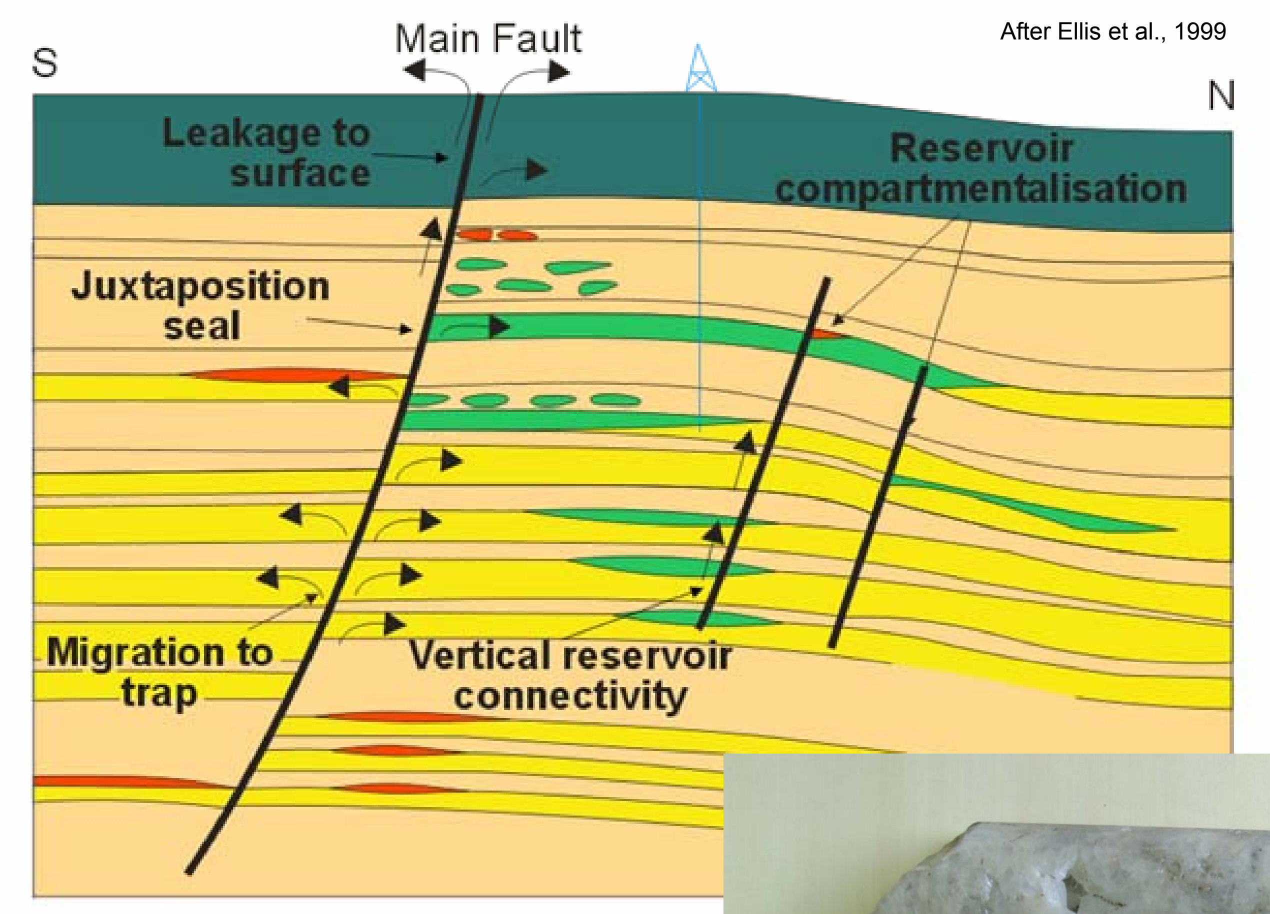
Geothermal fields Larderello **(Italy)**
→ ca 800 MWe





400 C

Ranalli and Rybach, 2005

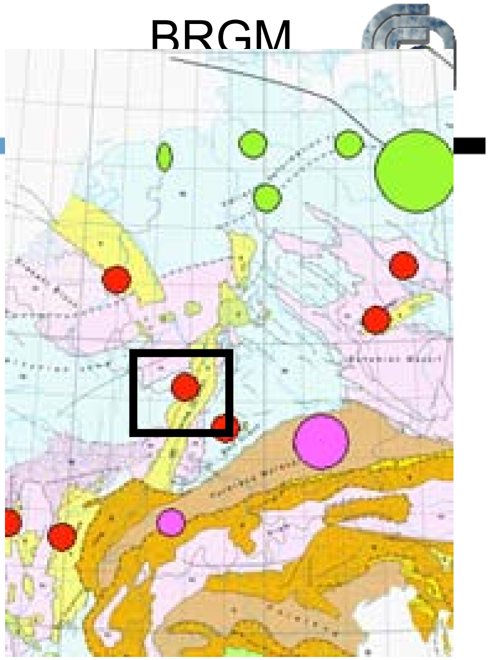


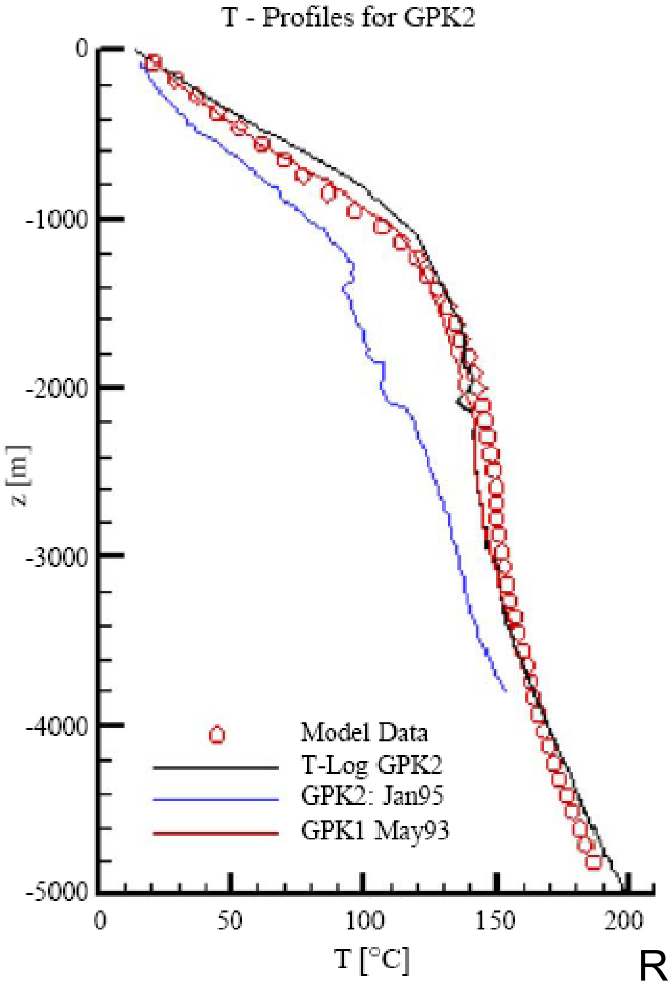
After Ellis et al., 1999

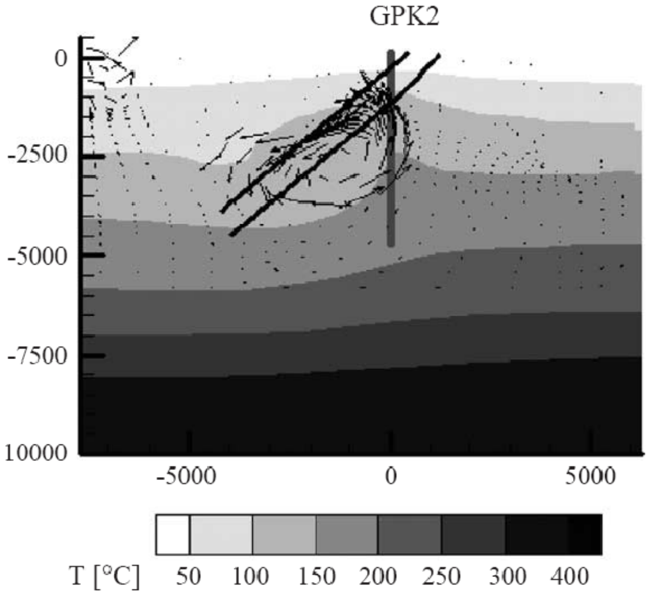
Soultz, core of fault zone
4 km depth (HAFZ)

Active faults allow hydro-thermal conduit zones

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

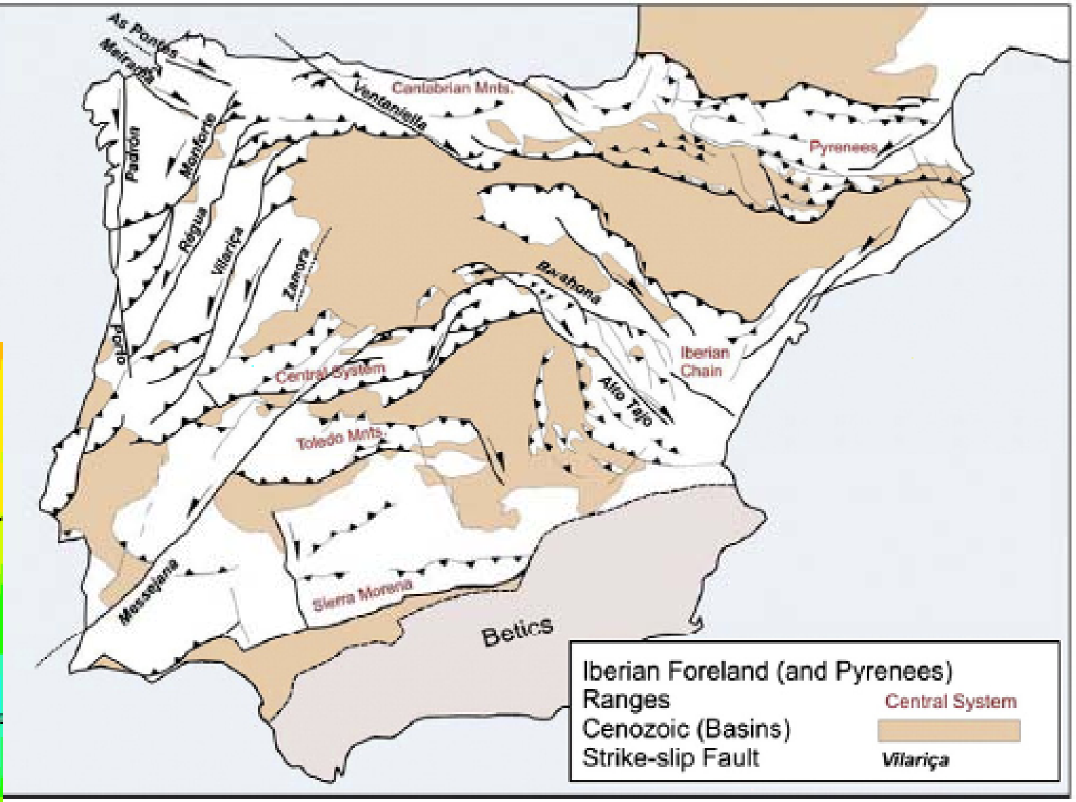


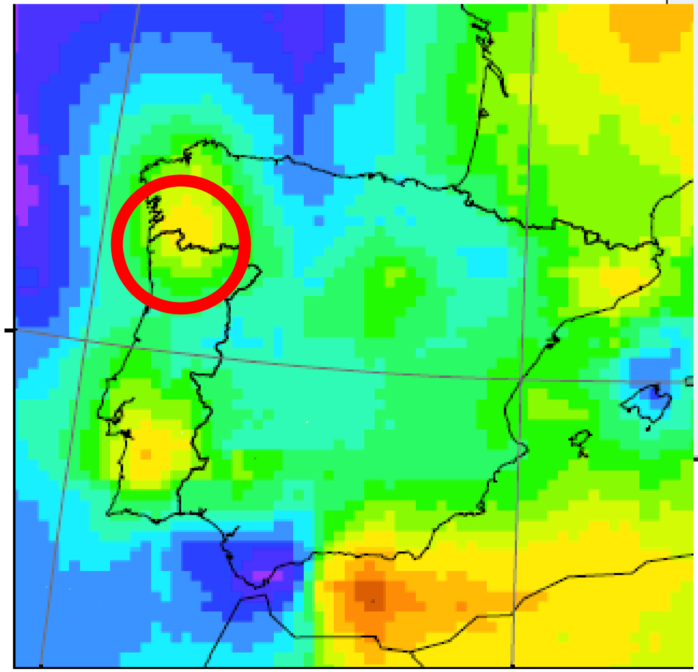




Ranalli and Rybach, 2005

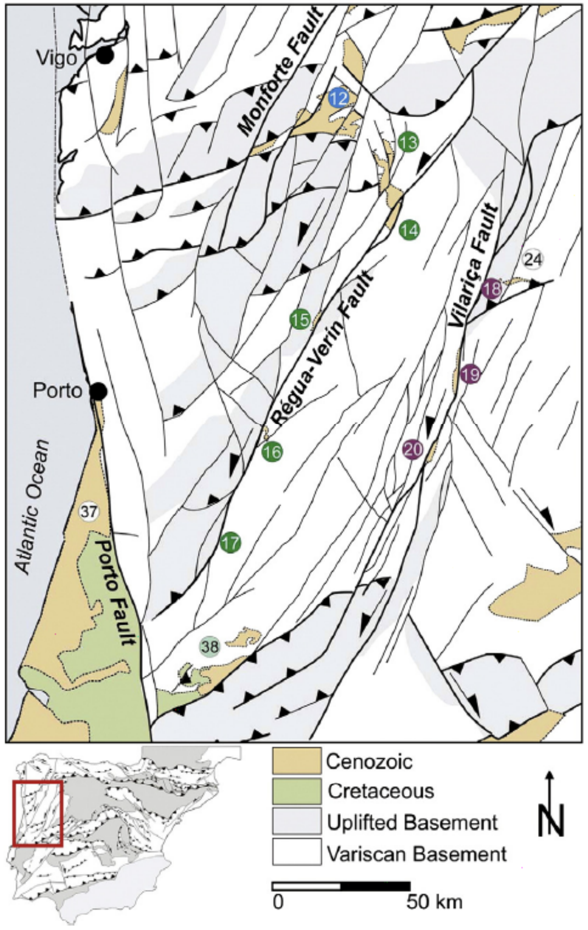
IBERIA: intrap



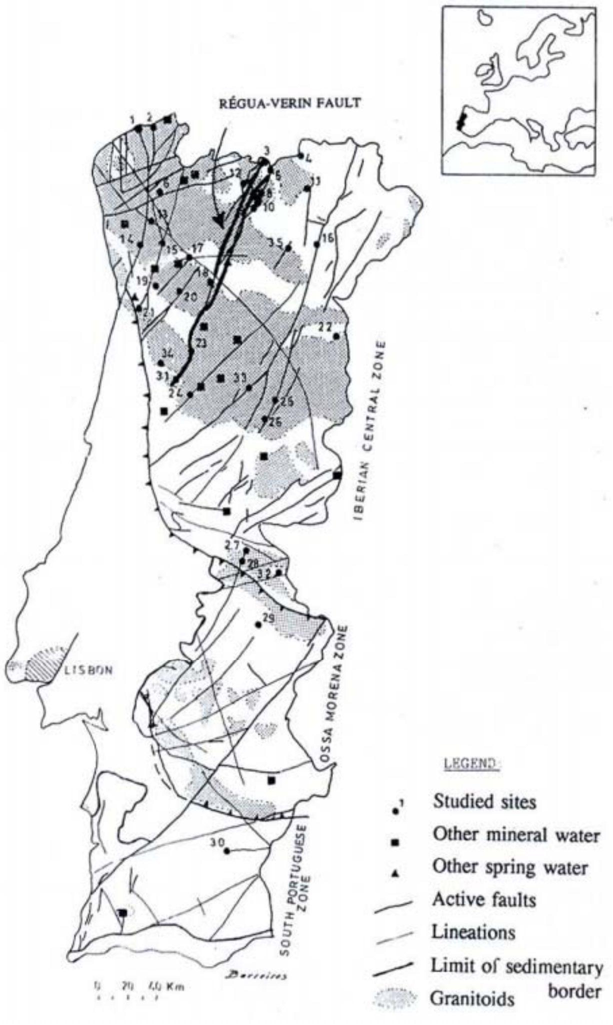


deVicente et al. 2011 (Tectonophysics)

ive faults, fault g fluid-path ways



deVicente et al. 2011 (Tectonophysics)



Carvalho 1993

Combination with other techniques

- Seismic structure and velocities
  - Assumption: correlations (e.g. salt high velocity, low resistivity), starting point model boundaries
  - Pitfalls: assumptions (high sensitivity to salt content in pores)
- Gravity
  - Assumptions: Correlations (crustal density, resistive core), flexural isostacy
  - Pitfalls: non-uniqueness
- Microseismicity at above magma chambers
  - Assumptions: occur rheological boundary viscous-brittle)
- Satelite information
  - Vertical movements, temperature

Iceland - Hengill

MT – inversion

(Arnason, 2010)

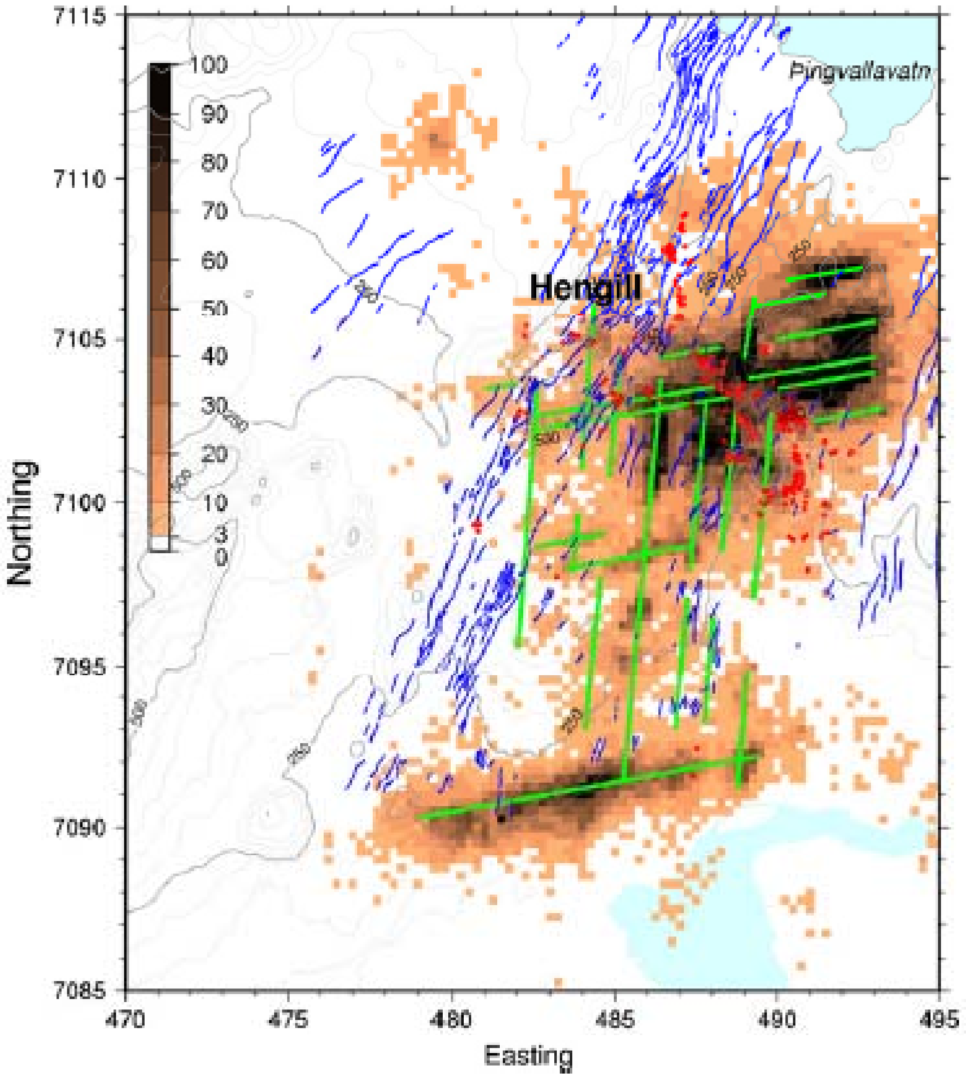
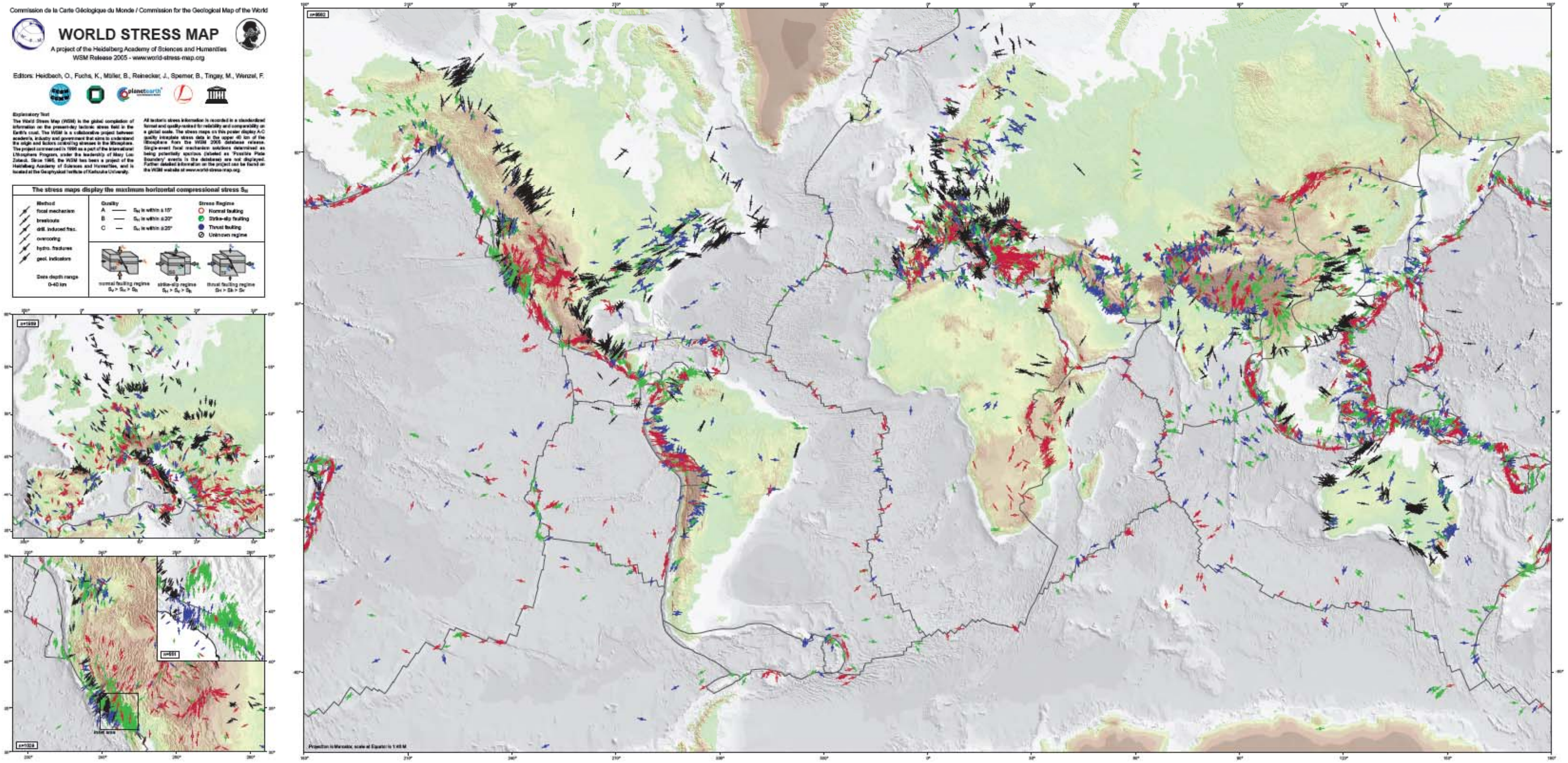


Fig. 3. Density of seismic epicentres (number within 250 m × 250 m bins) from 1991 to 2001 and inferred transform tectonic lineaments (green lines). The lineaments are based on the overall distribution of the seismicity as well as more focused analyses of individual episodes (earthquake swarms). Blue lines: faults and fissures mapped on the surface; red dots: geothermal surface manifestations (Sæmundsson, 1995). Thin black lines: topographic contour lines in m a.s.l. Distances are given in km. Modified from Árnason and Magnússon (2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Intra-plate-stresses

World Stress Map project



Commission de la Carte Géologique du Monde / Commission for the Geological Map of the World

WORLD STRESS MAP

A project of the Heidelberg Academy of Sciences and Humanities
WSM Release 2005 - www.world-stress-map.org

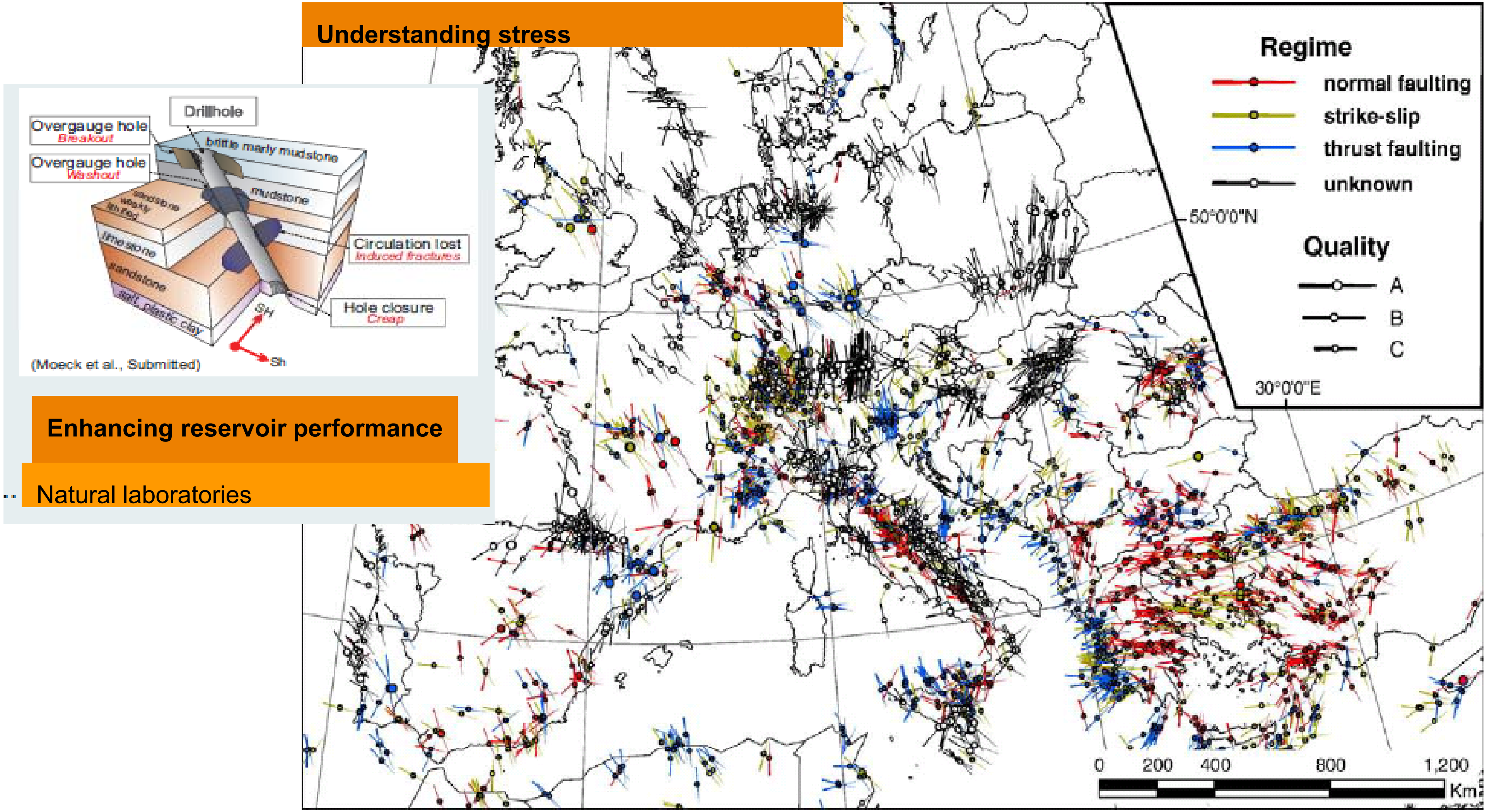
Editors: Heidbach, O., Fuchs, K., Müller, B., Reinecker, J., Sperner, B., Tingay, M., Wenzel, F.

Enhancing reservoir performance →Stress is critical

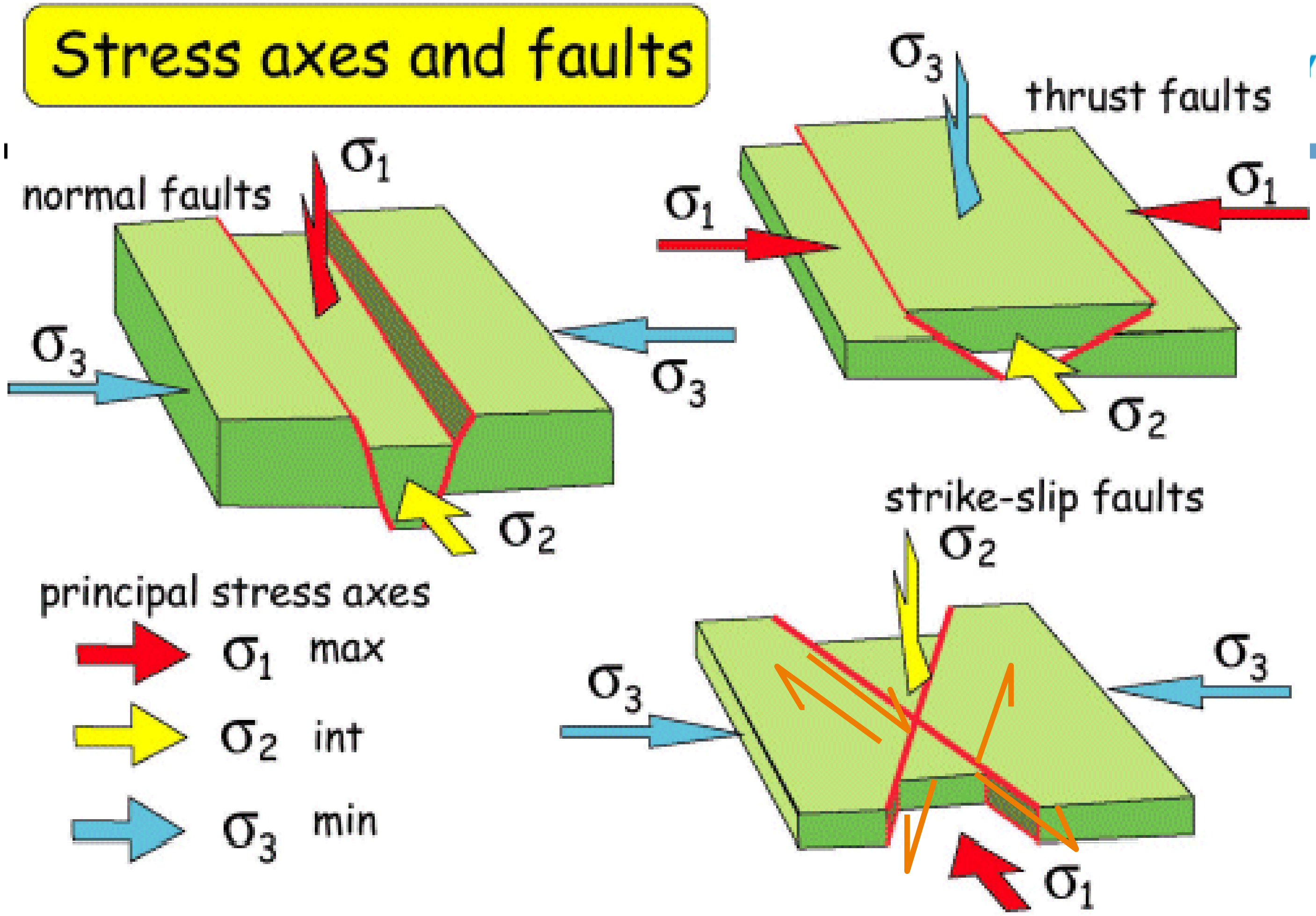
Understanding stress

Enhancing reservoir performance

Natural laboratories



Cloetingh et al., 2010



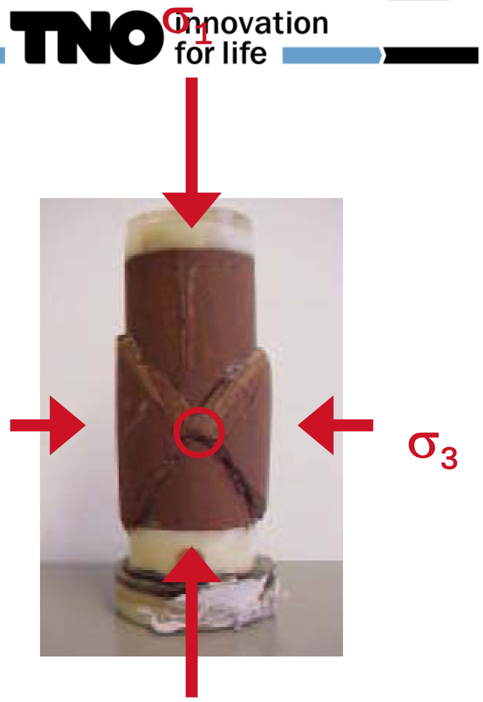
FAULT SYSTEMS

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**

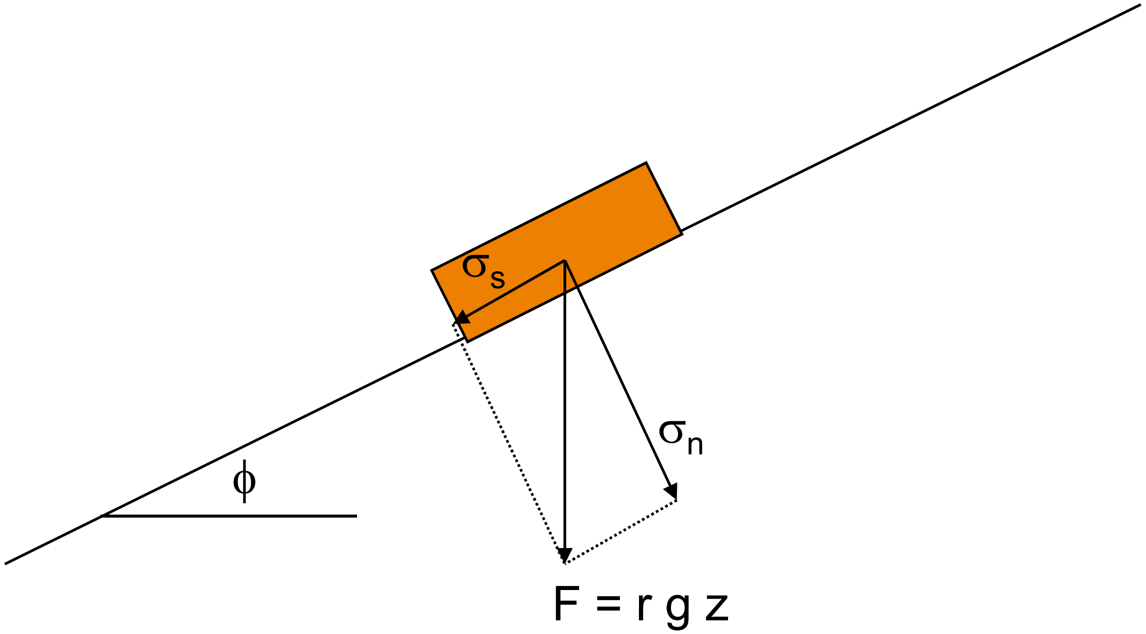


Conjugate faults are excellent indicators of stress directions

Mohr Coulomb

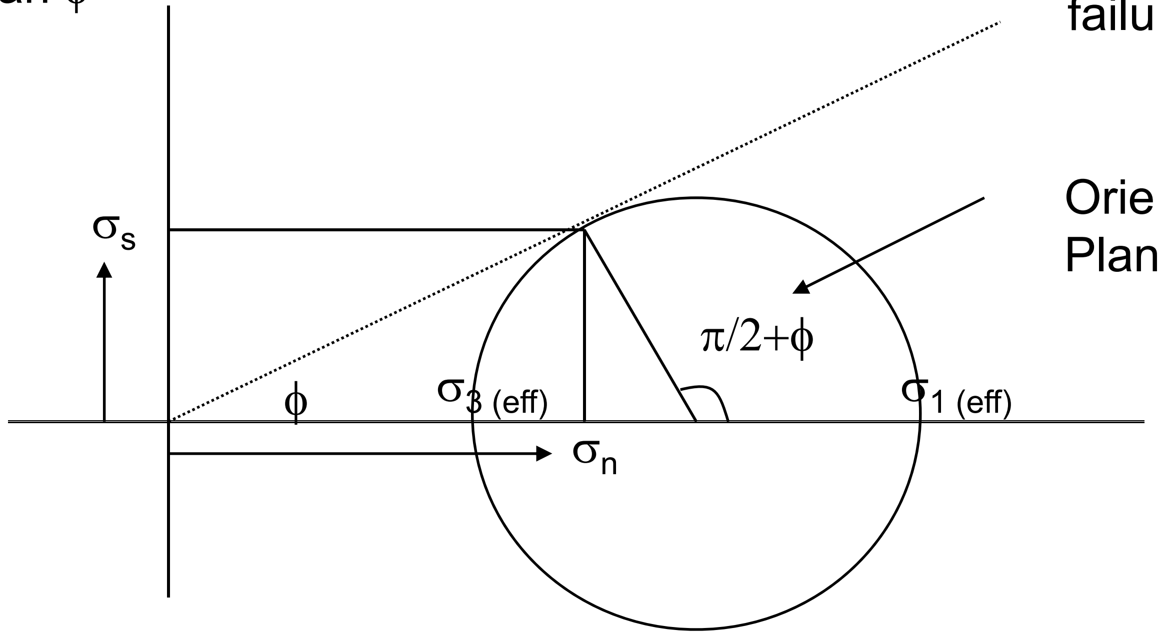
- Slip along a fault occurs if

  $\sigma_s/\sigma_n > \tan \phi$



- Slip along a fault plane occurs if

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



failure envelope

Orientation of fault
Plane (next slide)

Mohr circle (touching failure envelope)

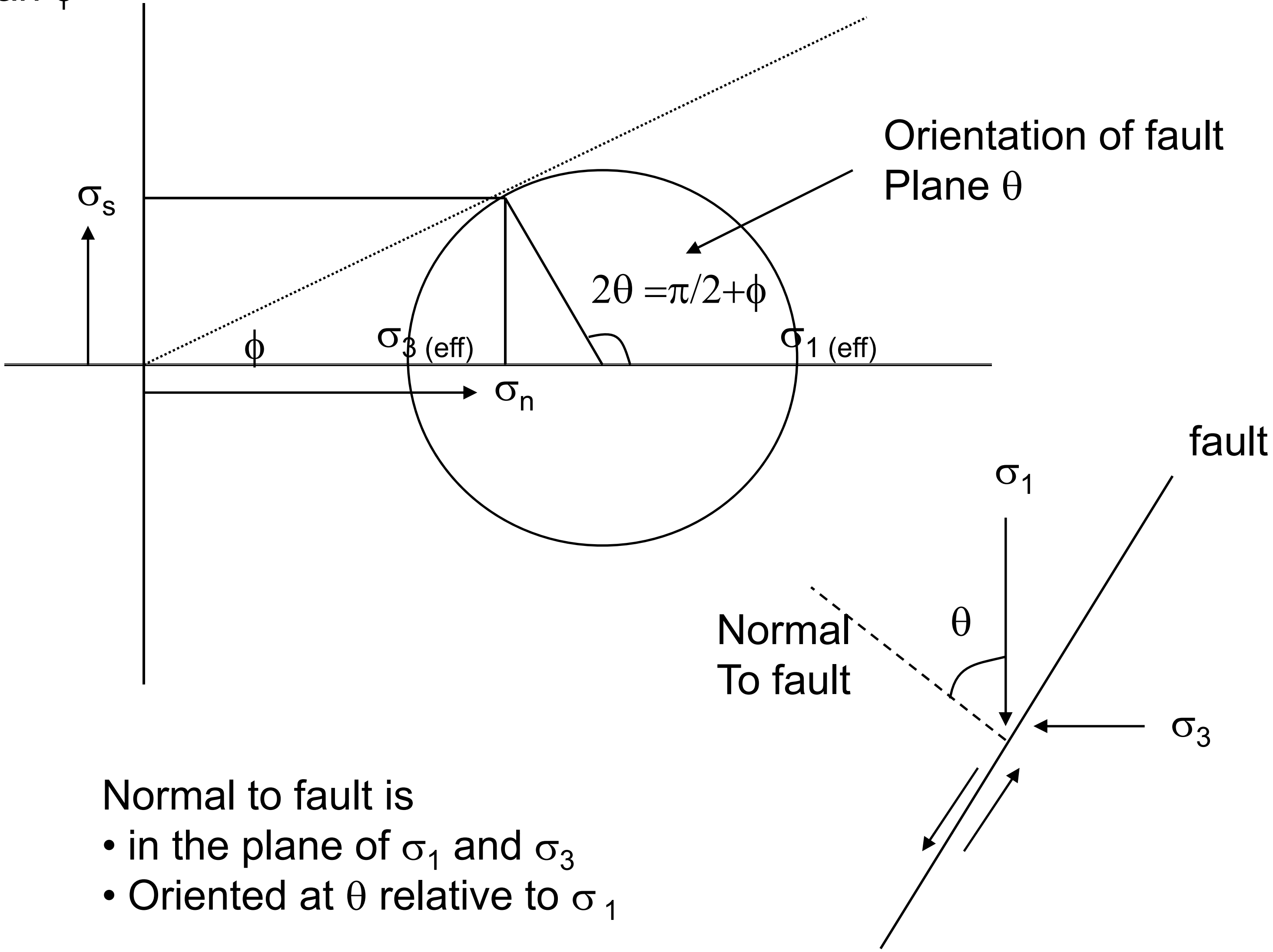
$\sigma_{3\ (eff)}$ = minimum principal effective stress = $\sigma_3 - P_f$

$\sigma_{1\ (eff)}$ = maximum principal effective stress = $\sigma_1 - P_f$

P_f = fluid pressure is typically $\rho_w g z$ (assuming connected pore space) which is ca one third of total vertical stress $\sigma_z = (\rho g z)$

- Slip along a fault plane occurs if

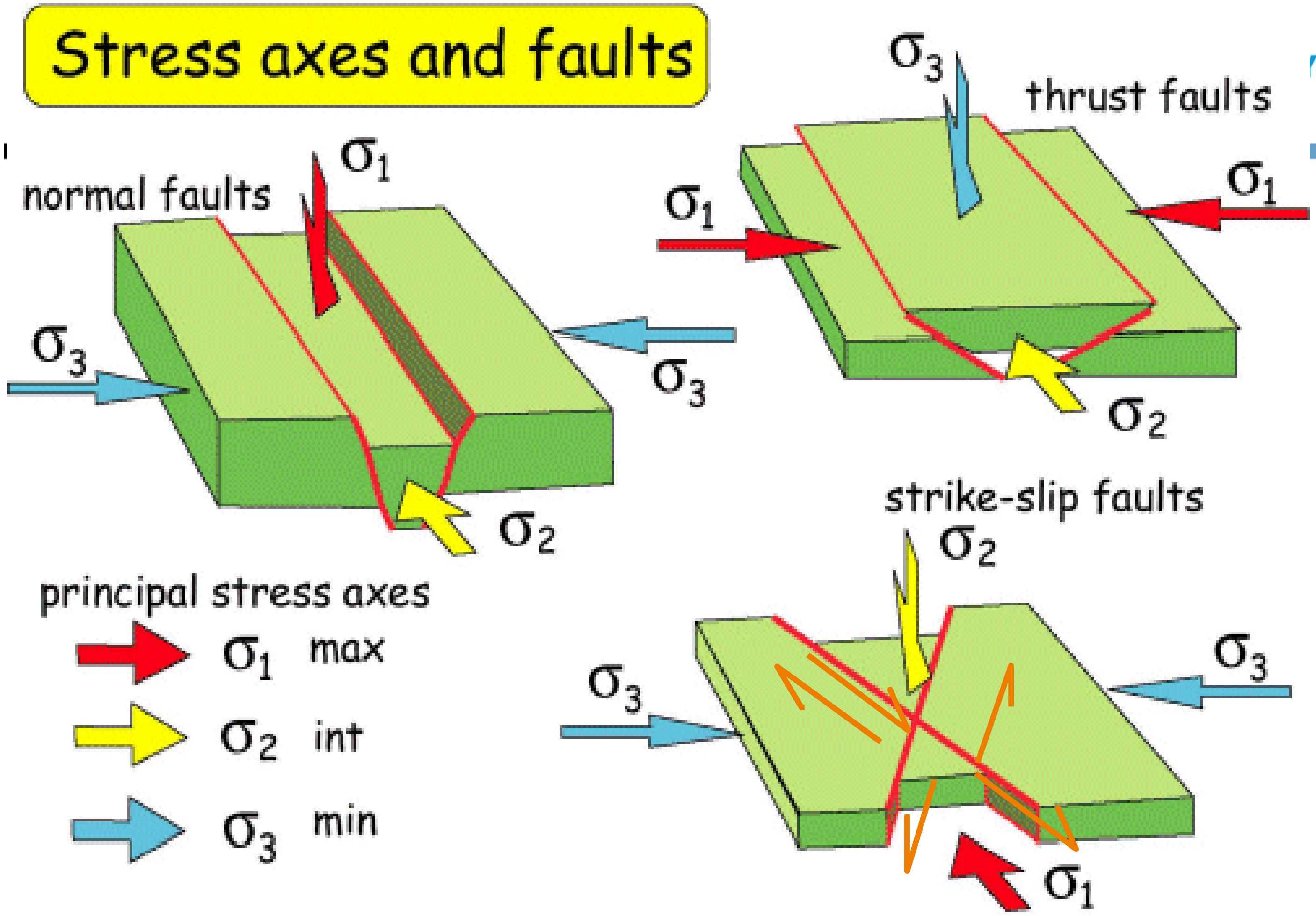
$\sigma_s/\sigma_n \geq \tan\phi$

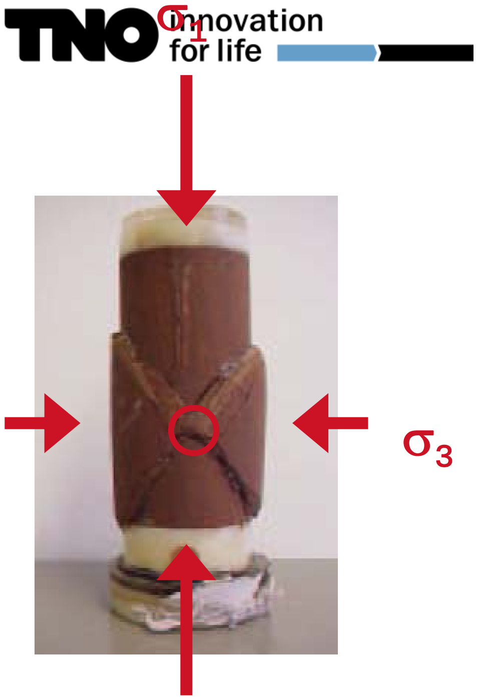


Orientation of fault Plane θ

Normal To fault

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





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

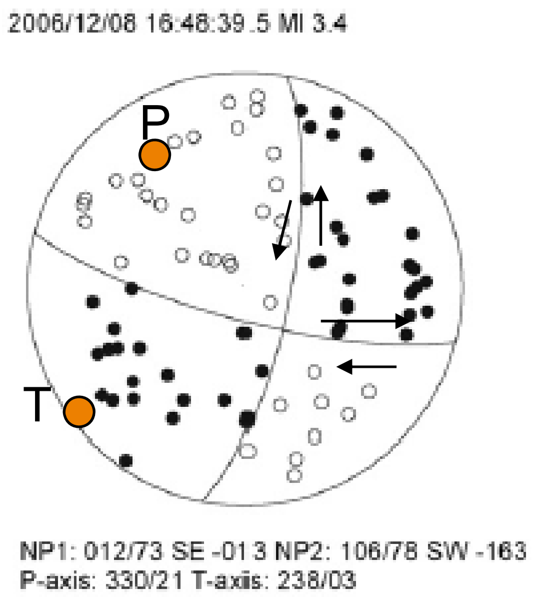
They

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

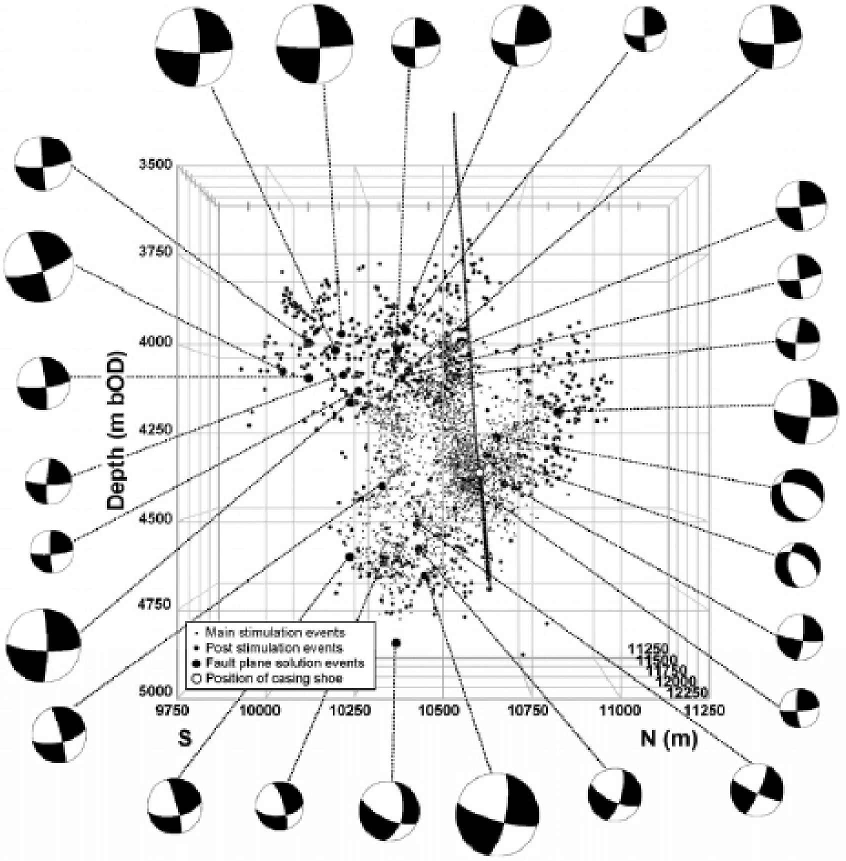
Measurements of stress

- Stress estimation
  - Well data (tommorow)
    - Break-out data
    - LOP
    - Minifrac tests
  - *Earth quakes*
    - *moment tensor*
    - *Maximum depth as indicator for Brittle-ductile transition*
  - *Fault and fracture analysis*
    - *Slip tendency (stress which fits with fractures/faults)*

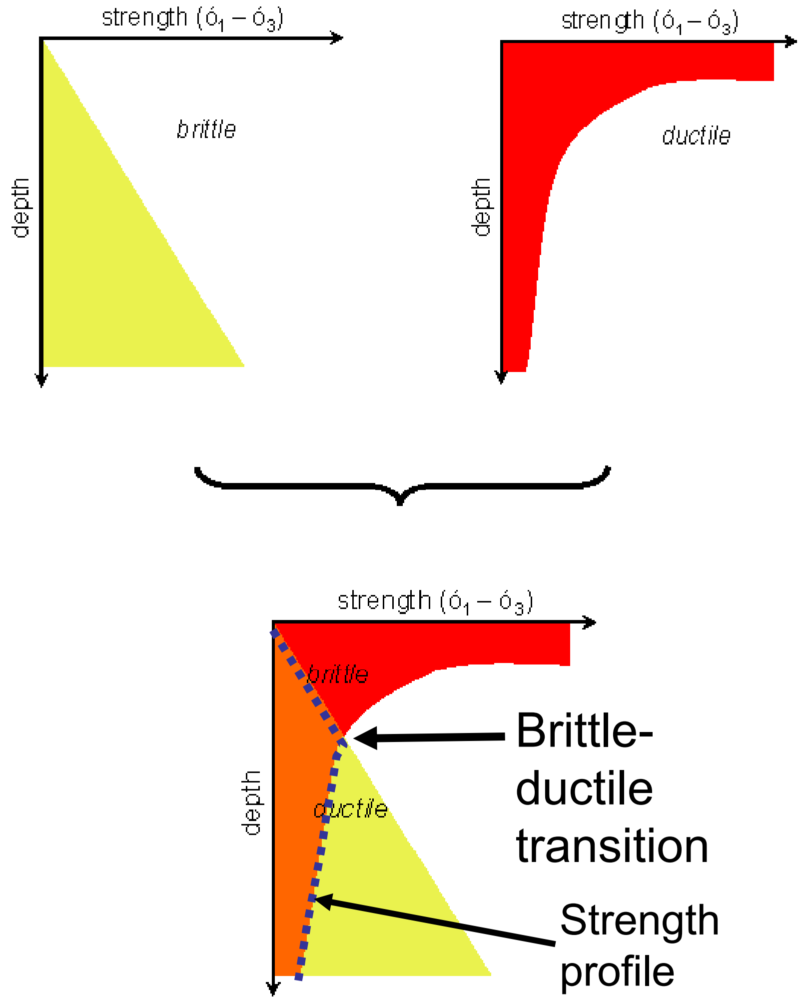
P-wave first arrivals polarity (up-P, down-T) → beach balls



- Compressional arrival (P) → σ1
- Tensional arrival (T) → σ3



Beach balls



Brittle-ductile transition

Strength profile

Rheology of the lithosphere → maximum depth of earthquakes

Combining brittle and ductile laws results in a rheological strength profile, showing the change of rock strength as a function of depth.

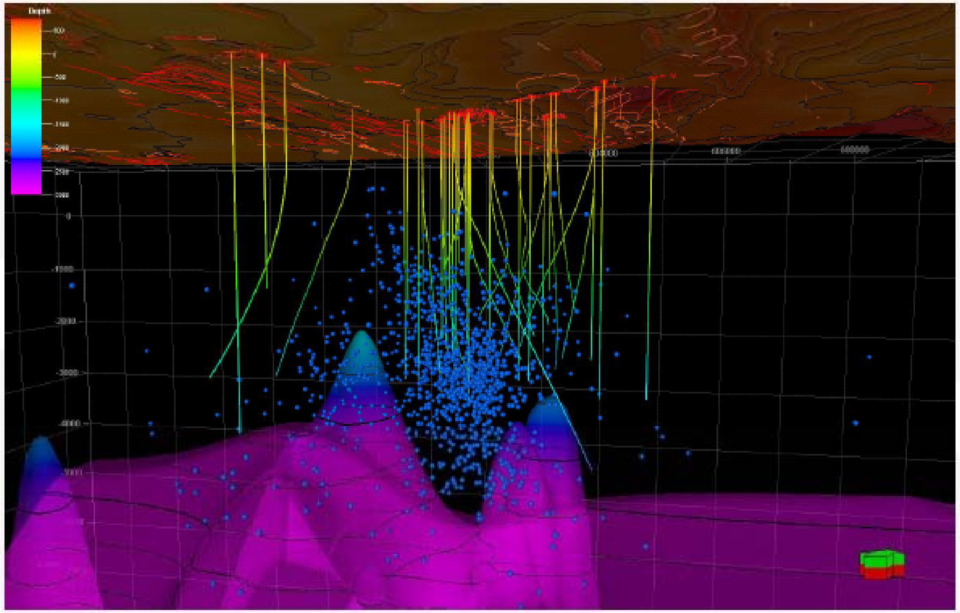
Data from Krafla where a magma was recently met during drilling

Prior to drilling of the IDDP well:

- The resistivity surveys shows a conductive body mostly staring at 4-5 km depth but with spikes up to 2km depth.
- The micro-earthquake-studies shows that all micro-earthquakes occur above the conductive body indicating more than 700°C

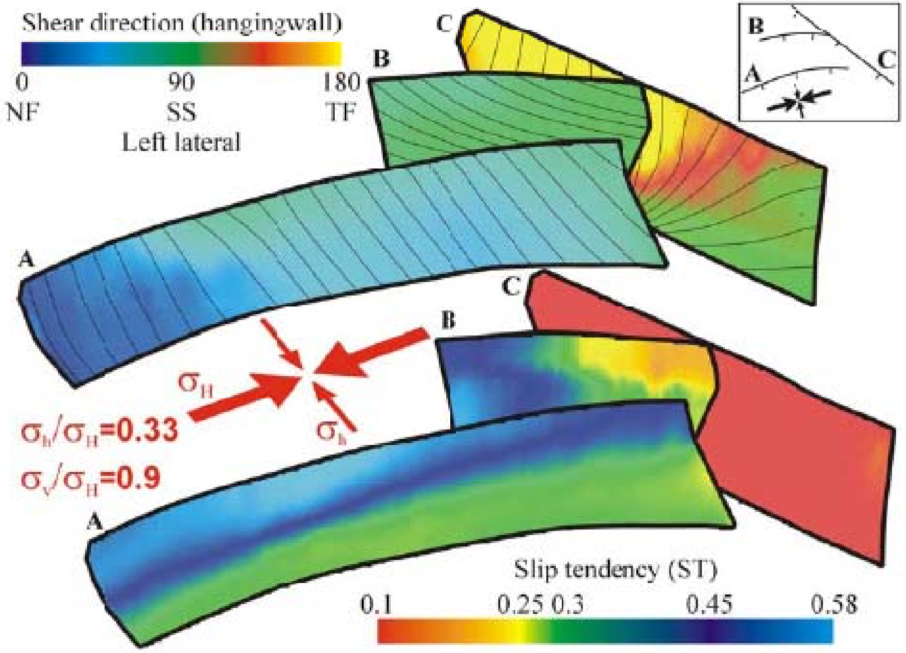
The IDDP well drilled in 2009:

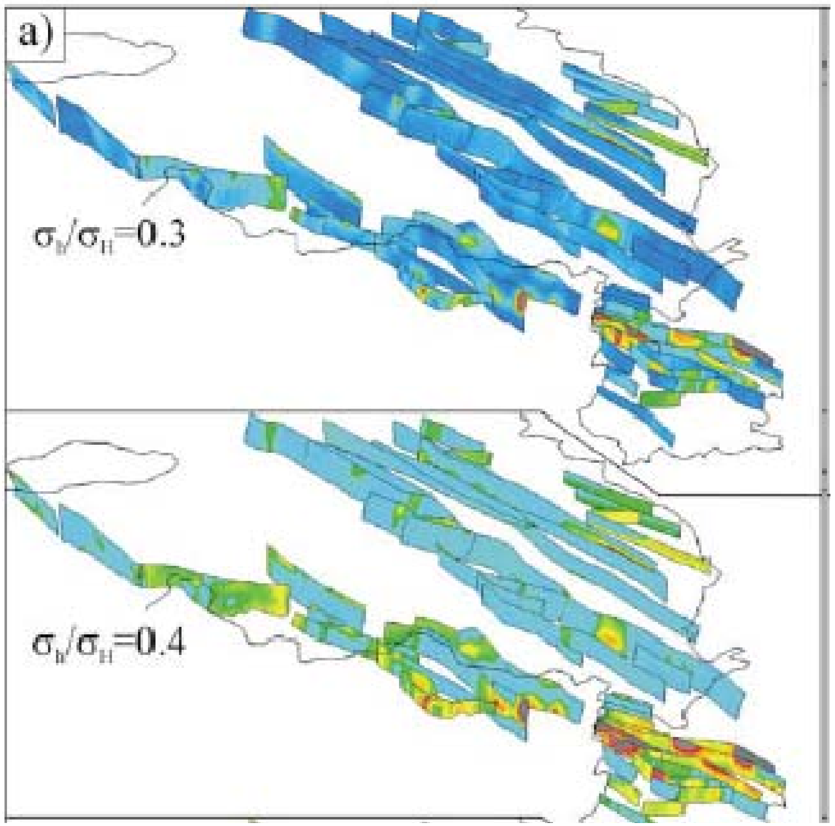
- Drilled close to one of the spikes but was not intended to enter it.
- Acidic magma was found at 2,1 km depth preventing further drilling and <u>underlining the needs for more accurate exploration methods</u>



Combined results of resistivity soundings (TEM/MT) and micro-seismicity analysis

Slip tendency → criticallity of stress & fluid flow potential





Slip Tendency (Worum et al., 2004)

Geochemical exploration in geothermal research: Introduction

(Minissale, CNR-IGG)

types of fluid emission

1 - overheated (over the critical point of water = 371°C) fumaroles (T up to 1150 °C)

2 - saturated fumarole along the water boiling curve (generally up to 160°C steam)

3 - boiling fumaroles at atmospheric pressure (90-100 °C)

4 - boiling mud pool containing steam condensate at 90-100°C, generally very acidic (up to pH=0)

5 - boiling springs (>90°C, high flow rate)

6 - thermal springs (>20-90 °C)

7 - cold gas bubbling pool (cold stagnant water, sometimes very acidic)

8 - dry gas vent

Geodynamic environments

- **-subduction zone**
  - back arc
  - main thrust
  - foredeep

-accretionary complexes

-rift areas (intraplate)

-cratonic areas (stable)

-strike-slip faults (San Andreas-type)

cratons

-no active volcanism
-thermal springs along regional faults
-gases N_2-and ^4He-rich; low $^3He/^4He$
-low fluid pressure along faults

strike-slip faults (San Andreas)

-N_2 (CO_2 e CH_4)-rich thermal springs
-variable $^3He/^4He$ ratio (sometimes high)
-high fluid pressure in faults

accretionary complex

-sediments loading (subsidence)
-formation of hydrocarbons (CH_4)
-saline diapirs, connate waters, mud volcanoes

intraplate rift

-fluids similar to orogenic areas since they are activated by subcrustal magmas (CO_2, ^3He)

subduction zones

back arc areas

-crust in extension
-mantle magma intrusions (^{3}He)
-granites
-metamorfism and metasomatism (skarns)
-hydrothermal (geothermal) systems
-condensazion zones (CO_2, H_2S, H_2 escape)
-water-rock interaction (t-dependent)
-fumaroles, thermal springs, CO_2

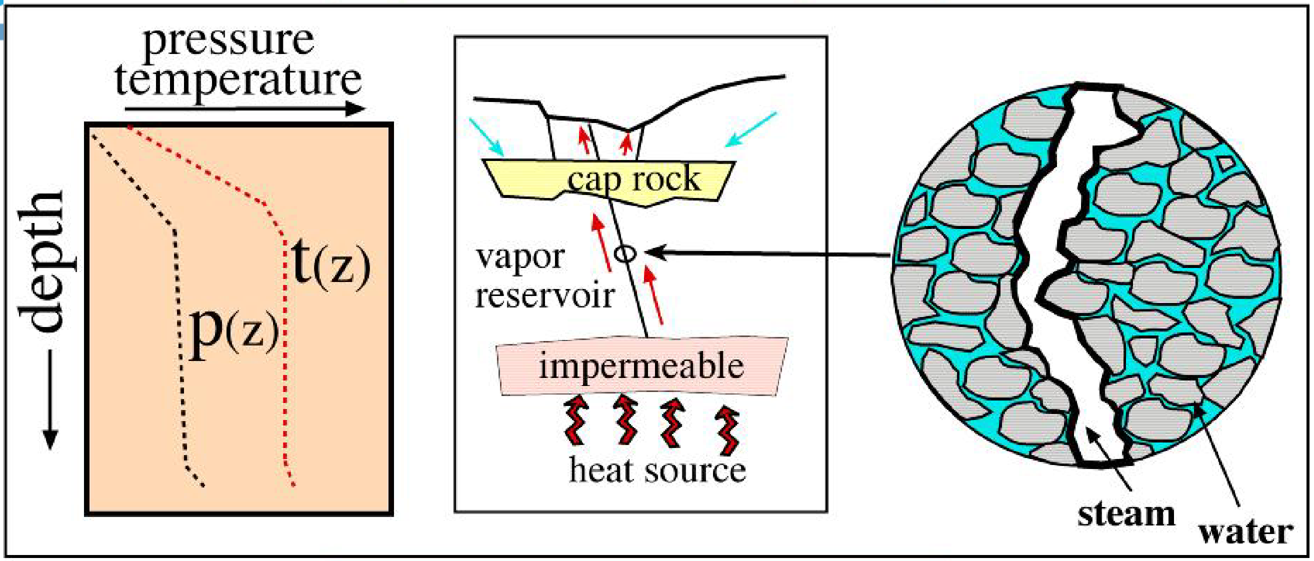
main thrust

-compression (^{4}He)
-fluids squeezing (CH_4)
-thermal springs (N_2 e/o CH_4)

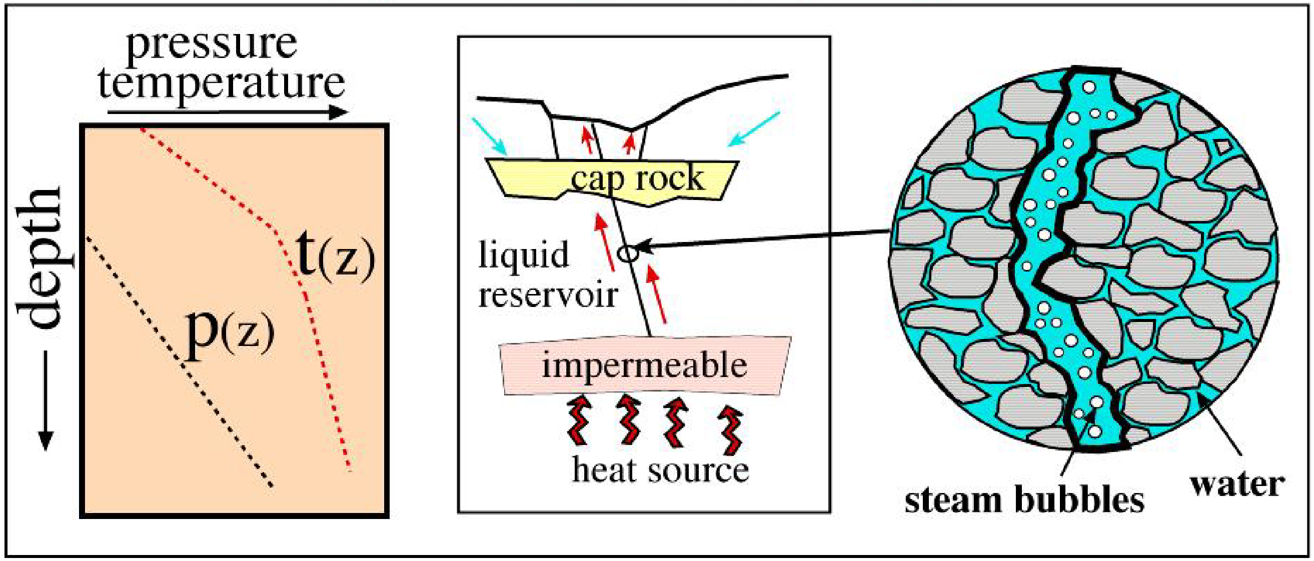
foredeep

-compression
-sediments accumulation
-CH_4 formation (saline domes)
-mud volcanoes

vapor-dominated system



liquid-dominated system



Promising surface features

1) Steam fumaroles at T~ 160 °C

2) Steam emission at boiling temp.
(very high local thermal gradient)

3) Thermal springs with high P_{CO_2}

4) Gas CO_2 emissions (rich in H_2)

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

5) Hydrothermal alterations
(ore deposits)

<u>Steam fumaroles at 160°C</u> at atmospheric pressure means that underground there is a hydrothermal system at the maximum enthalpic point (236 °C and 32 bars) whose abiabatic expansion at atmospheric pressure generates fumaroles at 160 °C (typical of volcanic environment, but e.g. present at Larderello in Tuscany)

Steam at surface at **boiling temperature** (no matter the flow rate) always meens high thermal gradient where steam derives by secondary boiling of aquifers located at “intermediate” depth between a deep hydrothermal reservoir and the surface.

If steam temperature is much **lower than boiling temperature** it may derive by the boiling of a convective aquifer whoose depth can be high.

Promising thermal springs have the following characteristics:

1) Relatively low temperature ($30<T<70°C$)

2) Low-to-very low flow rate (~ 1 L/sec)

3) Low salinity (shallow circulation and/or steam condensation)

4) Neutral to slightly acidic *p*H (CO_2)

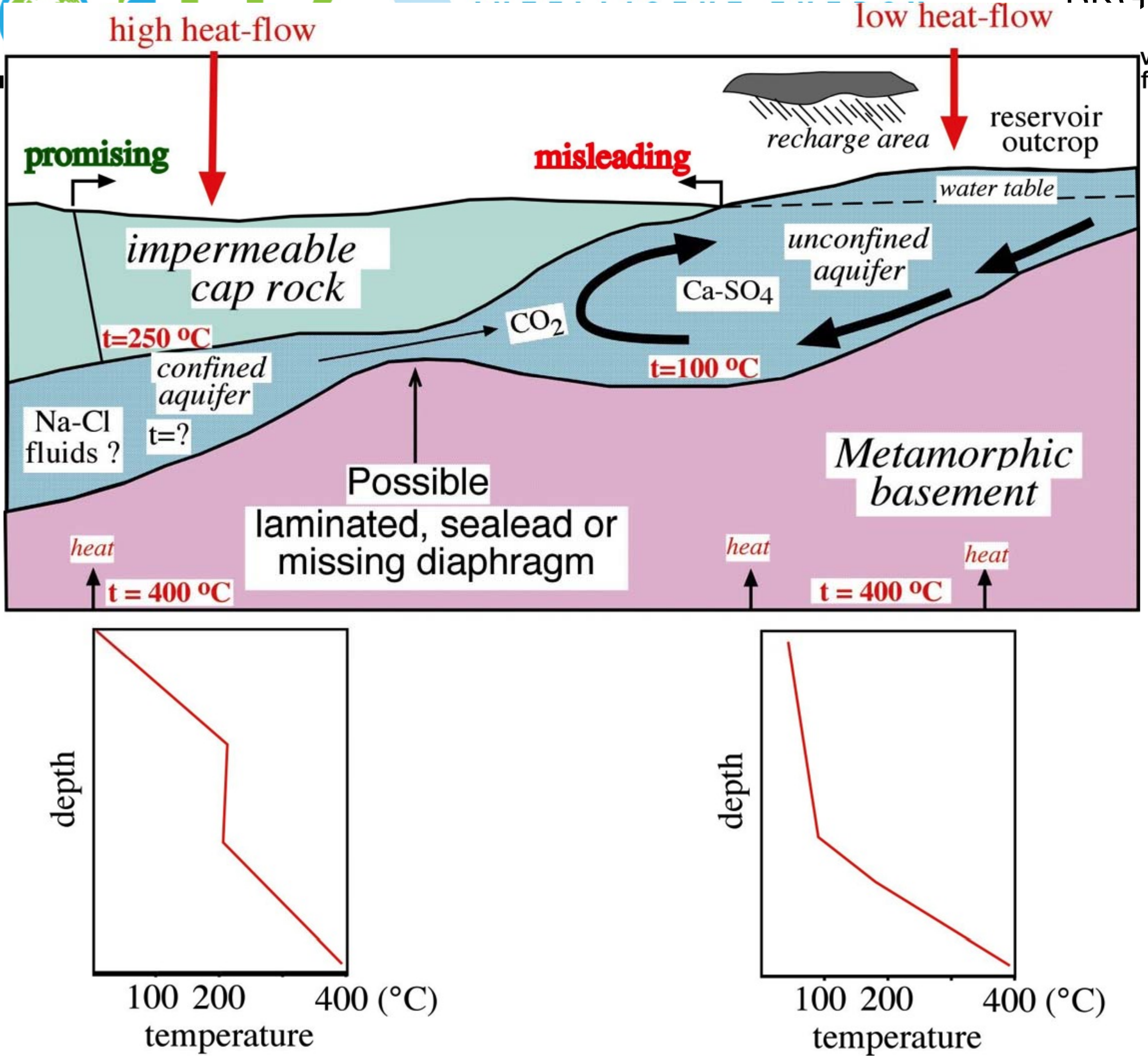
5) CO_2 (H_2S) as main associated gas phase

6) Low He (diluted by hydrothermal CO_2)

7) High $^3He/^4He$ ratio (mantle magmas)

Misleading thermal springs have the following characteristics:

1) Near boiling temperature (85<T<99 °C)
2) High flow rate (up to 1 t/sec)
3) High salinity (deep, long circulation)
4) Neutral to highly basic *p*H (up to 12)
5) N_2 gas phase (up to 99 %)
6) High He (up to 10% of total volume)
7) Low ^{3}He/^{4}He ratio (^{4}He in the crust)


high heat-flow
low heat-flow
promising
misleading
recharge area
reservoir outcrop
water table
impermeable cap rock
unconfined aquifer
Ca-SO4
CO2
t=250 °C
t=100 °C
confined aquifer
Na-Cl fluids ?
t=?
Possible
laminated, sealead or missing diaphragm
Metamorphic basement
heat
heat
heat
t = 400 °C
t = 400 °C
depth
100 200 400 (°C)
temperature
depth
100 200 400 (°C)
temperature

Sampling fumaroles, springs and gases

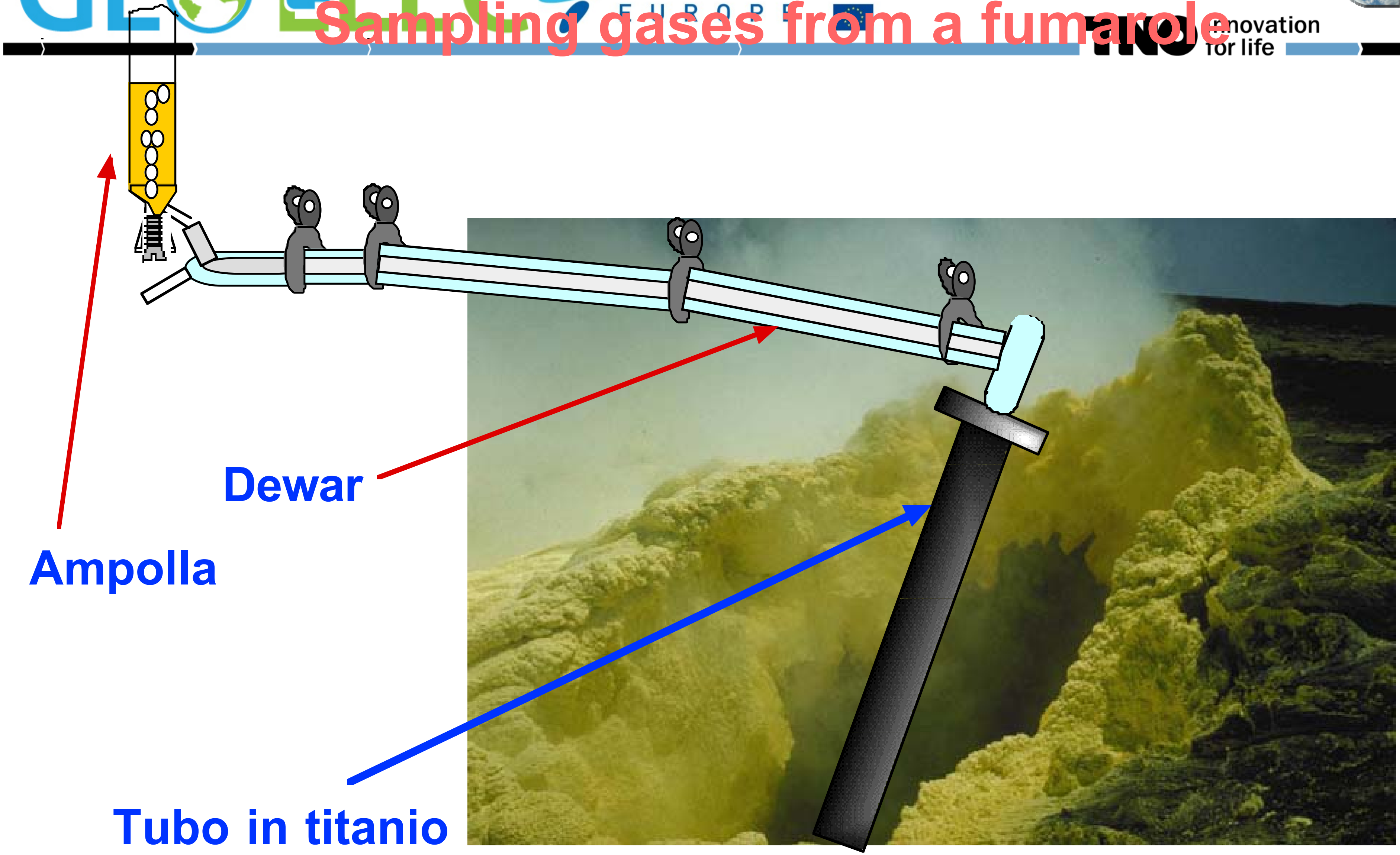
The main gol of Fluid Geochemistry during the exploration phase is to understand the relation between the fluids emerging at the surface with the “*parent*” fluid in depth (reservoir ?).

In particular, in case of springs, if they can be considered:

1) promising *or*

2) measleading

Sampling gases from a fumarole



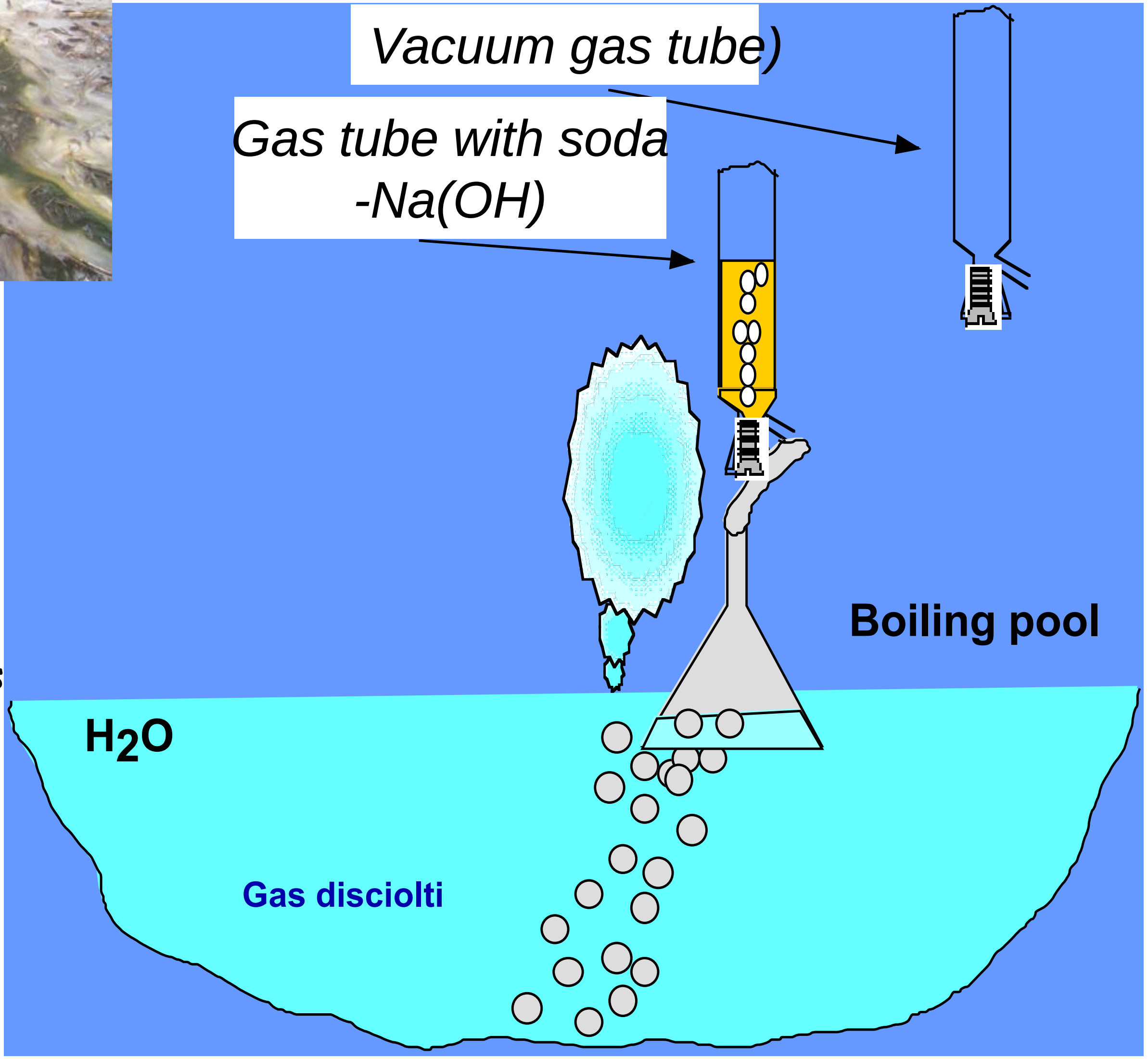
Sampling gases from a gas vent

What to sample for components in the gas phase:

1) A pre-evaquated and pre-weighted gas tube for main (CO_2, N_2, H_2S, CH_4…etc) and trace (He, Ar, CO…etc) components, and $^{13}C/^{12}C$ in CO_2

2) A pre-evaquated and pre-weighted gas for the determination of the $^3He/^4He$ ratio

3) A gas tube for hydrocarbons (ethane, buthane, benzene…etc.)



Acidic gases react with the soda

Steam => condensation

$2Na^+ + CO_2 + 2(OH)^- = 2Na^+ + CO_3^{2-}{}_{(aq)} + H_2O$

$7Na^+ + 4SO_2 + 7(OH)^- = 7\ Na^+ + 3SO_4^{2-}{}_{(aq)} + HS^-{}_{(aq)} + 3H_2O$

$Na^+ + H_2S + (OH)^- = Na^+ + HS^-{}_{(aq)} + H_2O$

$2Na^+ + 2HCl + 2(OH)^- = 2Na^+ + 2Cl^- + 2H_2O$

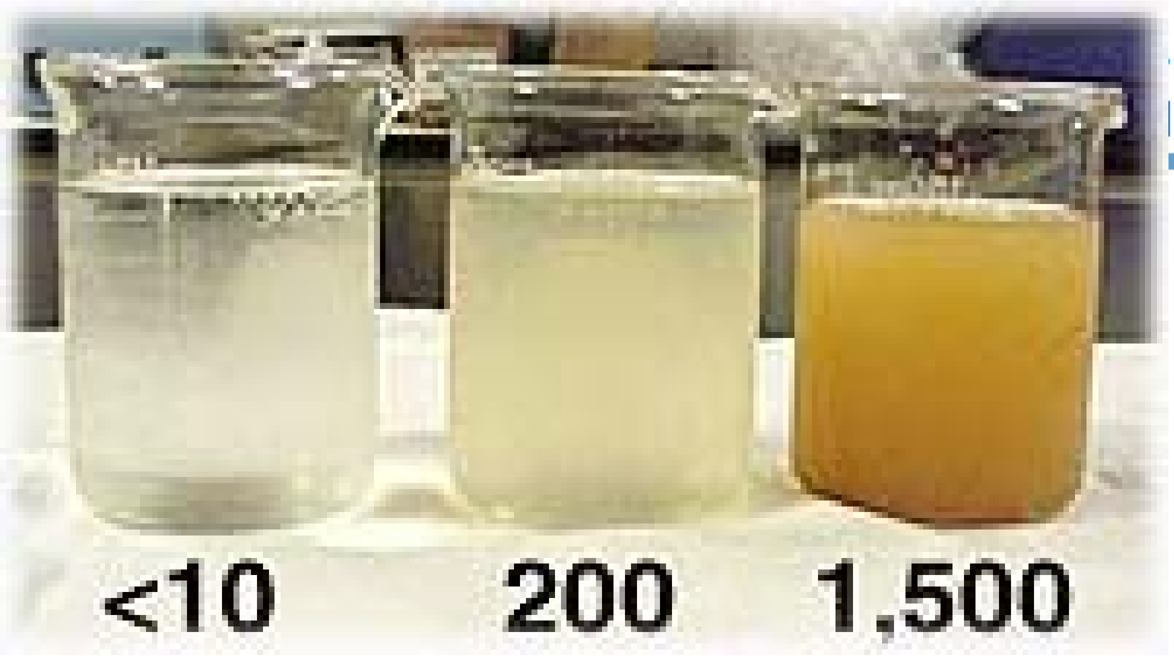
(analysis of Cl, S species, F…etc. with chemical procedures)

Inert gases (He, Ar, N_2..etc) concentrate in the vacuum up to 100 times

(analysis with gas chromatography)

Organic gases (ethane, propane…benzene..etc)

(analysis with a Gas-Mass)



After filtering

What to sample for components in liquid phase?

1) 250 ml of water in plastic bottle (for main components and some trace elements)
2) 50 ml of water in a plastic bottle acidified with a few drops of concentrated HNO_3 for Ca and metal cations
3) 25-50 ml of water (as fast as possible, eventually usings gloves if too hot) in a glass bottle for isotopes
4) Aliquotes of stabilized free CO_2 and H_2S for isotopes

Types of waters:

Juvenile (very rare)
Hydrothermal (hot springs)
Fossil (in the sediment pores since the beginning)
Formation (filling the pores)
Brines (hyper-saline waters)

Temperature (temperate latitude)

- ✓Cold waters (T<20 °C)
- ✓Hypothermal (20<T<30 °C)
- ✓Thermal (30<T<40 °C)
- ✓Hyperthermal (T>40 °C)

Salinity (Total Dissolved Solids)

Fresh waters: TDS<1000 ppm
Brackish waters: 1000<TDS<20000 ppm
Salt (marine) water: ≈35000 ppm
brines: >35000 ppm

Measurements in the field on spring water samples:

1) Temperature
2) *p*H
3) Electrical conductivity
4) Ammonia (NH_4)
5) Silica (SiO_2)
6) Elevation
7) Coordinates

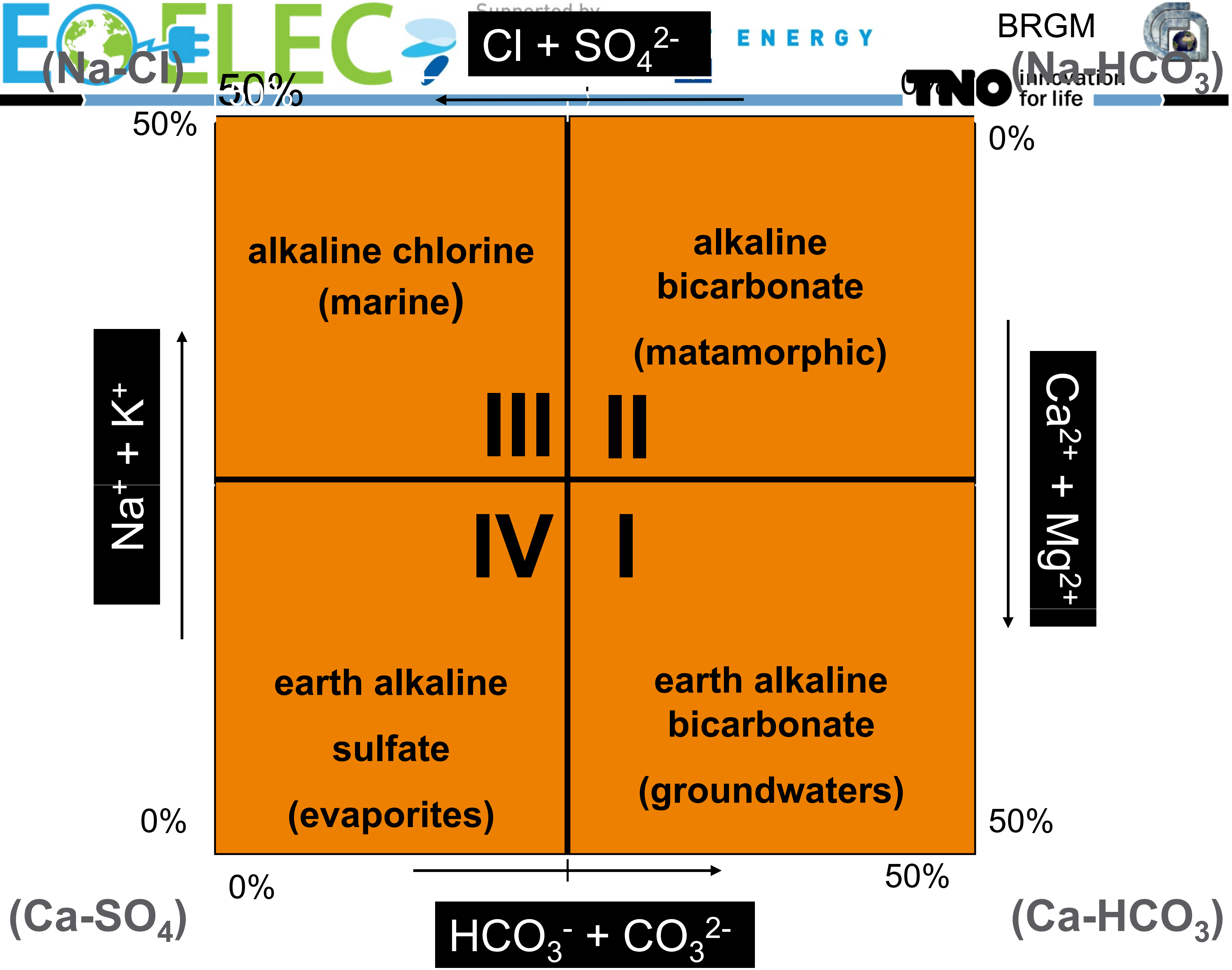
Measurements in the laboratory:

1) Main components (Na,K,Mg,Ca,HCO_3,SO_4,Cl)
2) Some trace elements (B, Br, Sr, NO_3, Li, F)
3) $^{18}O/^{16}O$ and $^{2}H/H$ ratios in water
4) $^{13}C/^{12}C$ in DIC (dissolved inorganic carbon)
5) $^{35}S/^{34}S$ in sulfur species

Minimum data set necessary for the elaboration of liquid and gas phase:

Spring water: Ca, Mg, Na, K, HCO_3, SO_4, Cl (main)
SiO_2, NH_4, B, NO_3 (minor)
Li, Br, Sr, F (trace)
$\delta^{18}O$ and $\delta^{2}H$
$\delta^{13}C$ in DIC (Dissolved Inorganic Carbon)

Gas phase (either exolved from water or as dry emission):
CO_2, H_2S, CH_4, N_2, O_2,
Ar, He, Ne
$\delta^{13}C$ in CO_2
$^{3}He/^{4}He$



(Na-Cl)

50%

$Cl + SO_4^{2-}$

0%

$(Na\text{-}HCO_3)$

50%

0%

$Na^+ + K^+$

$Ca^{2+} + Mg^{2+}$

alkaline chlorine (marine)

III

alkaline bicarbonate (matamorphic)

II

IV

earth alkaline sulfate (evaporites)

I

earth alkaline bicarbonate (groundwaters)

0%

50%

0%

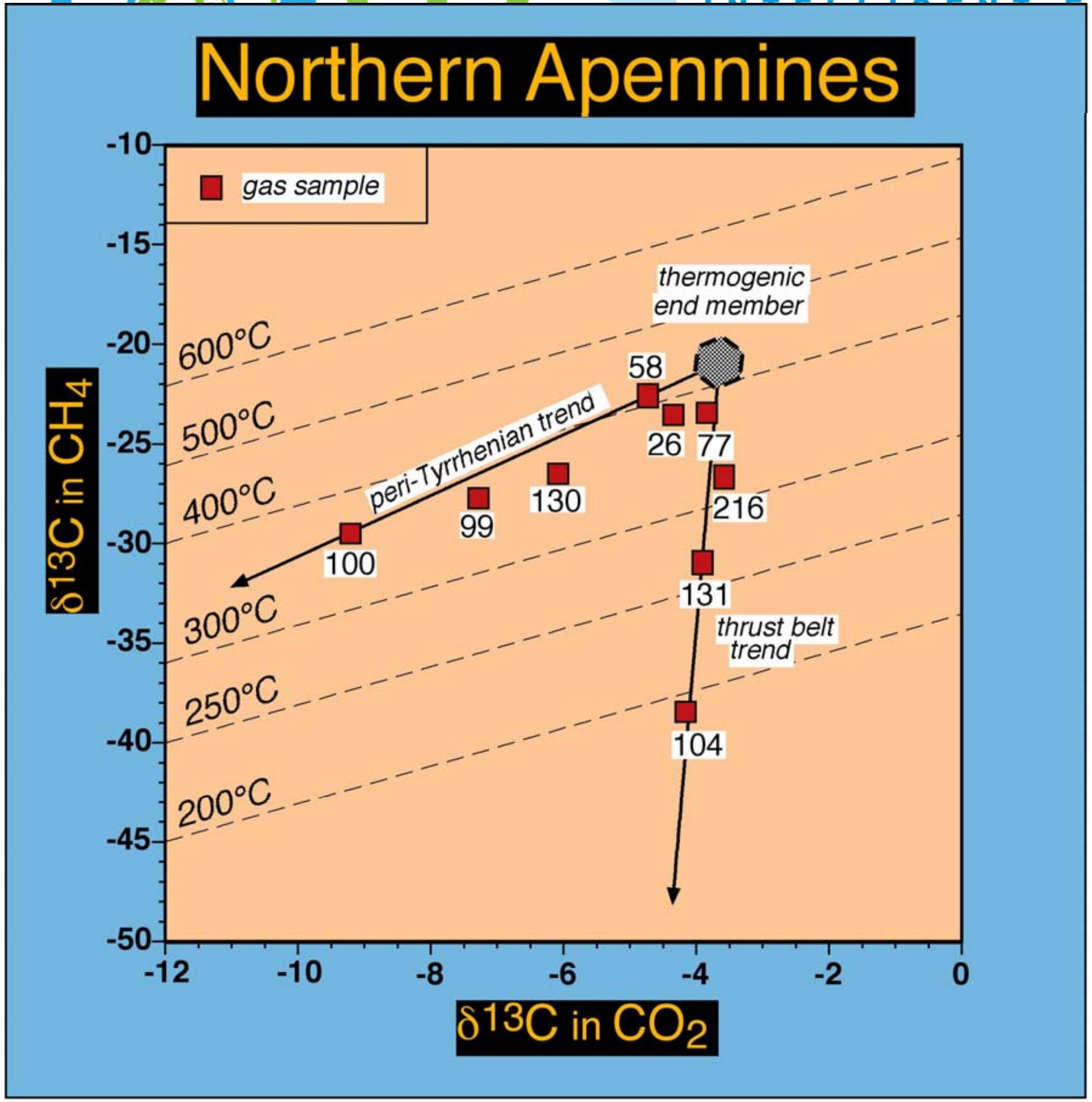
50%

$(Ca\text{-}SO_4)$

$HCO_3^- + CO_3^{2-}$

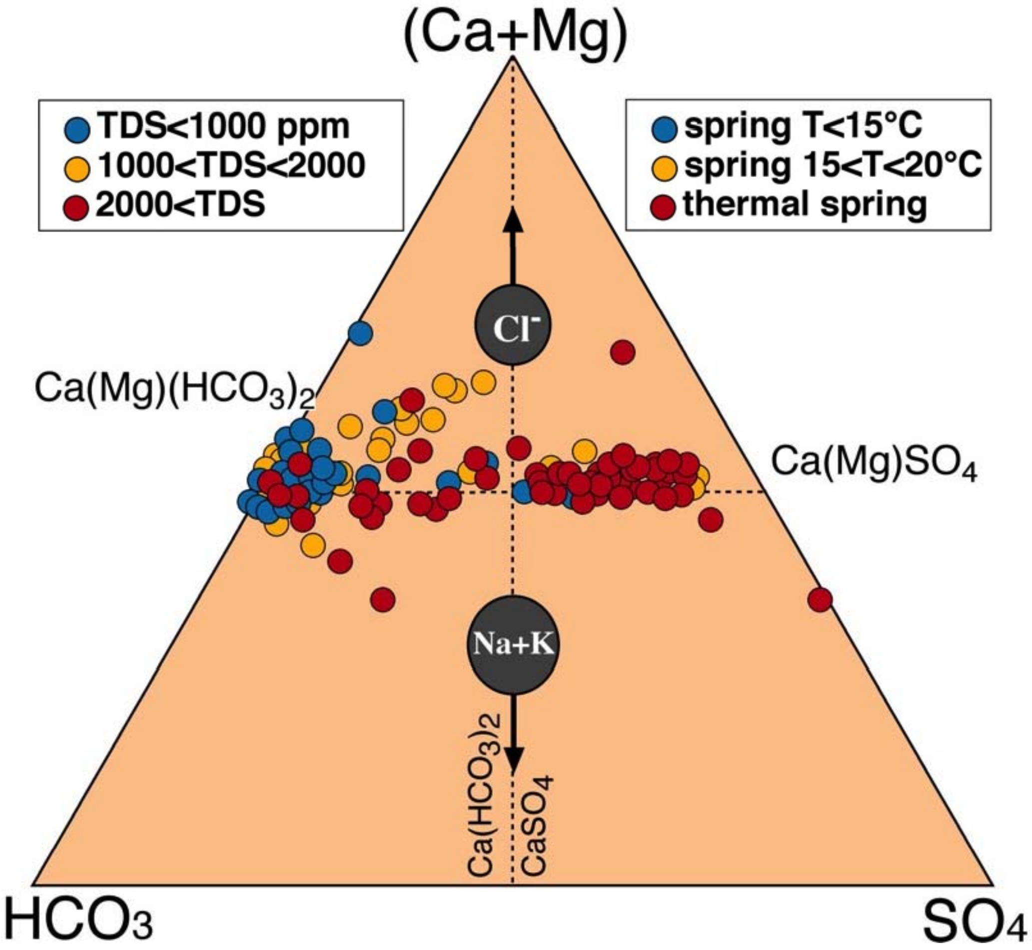
$(Ca\text{-}HCO_3)$

Binary diagrams



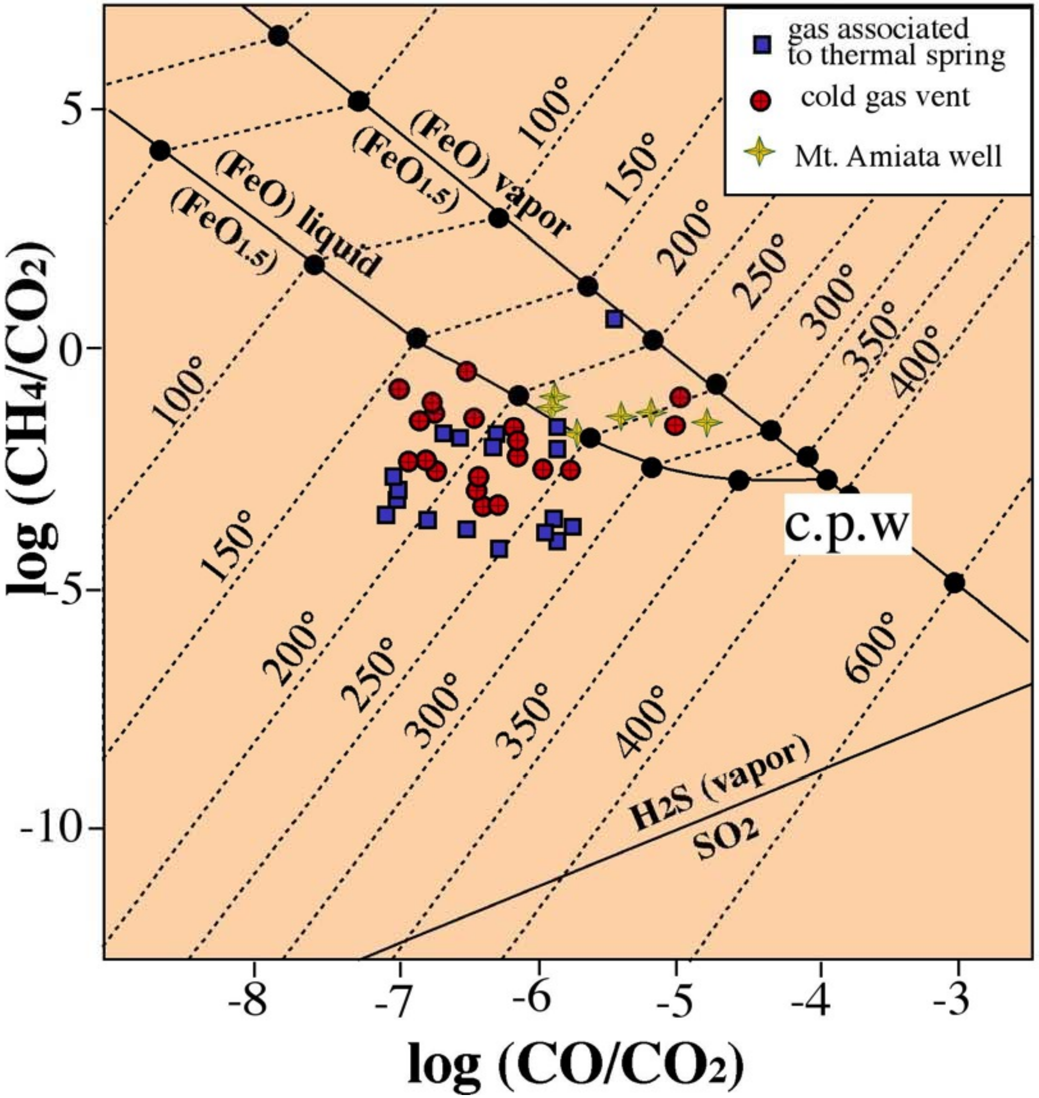
Minissale, Magro, Martinelli, Vaselli, Tassi (2000) **A fluid geochemical transect in the Northern Apennines: fluid genesis and migration and tectonic implications**. *Tectonophys. 319*, 199-222

Springs circulating in Mesozoic limestone in central Italy



Ternary diagrams

geothermometry in the gas phase



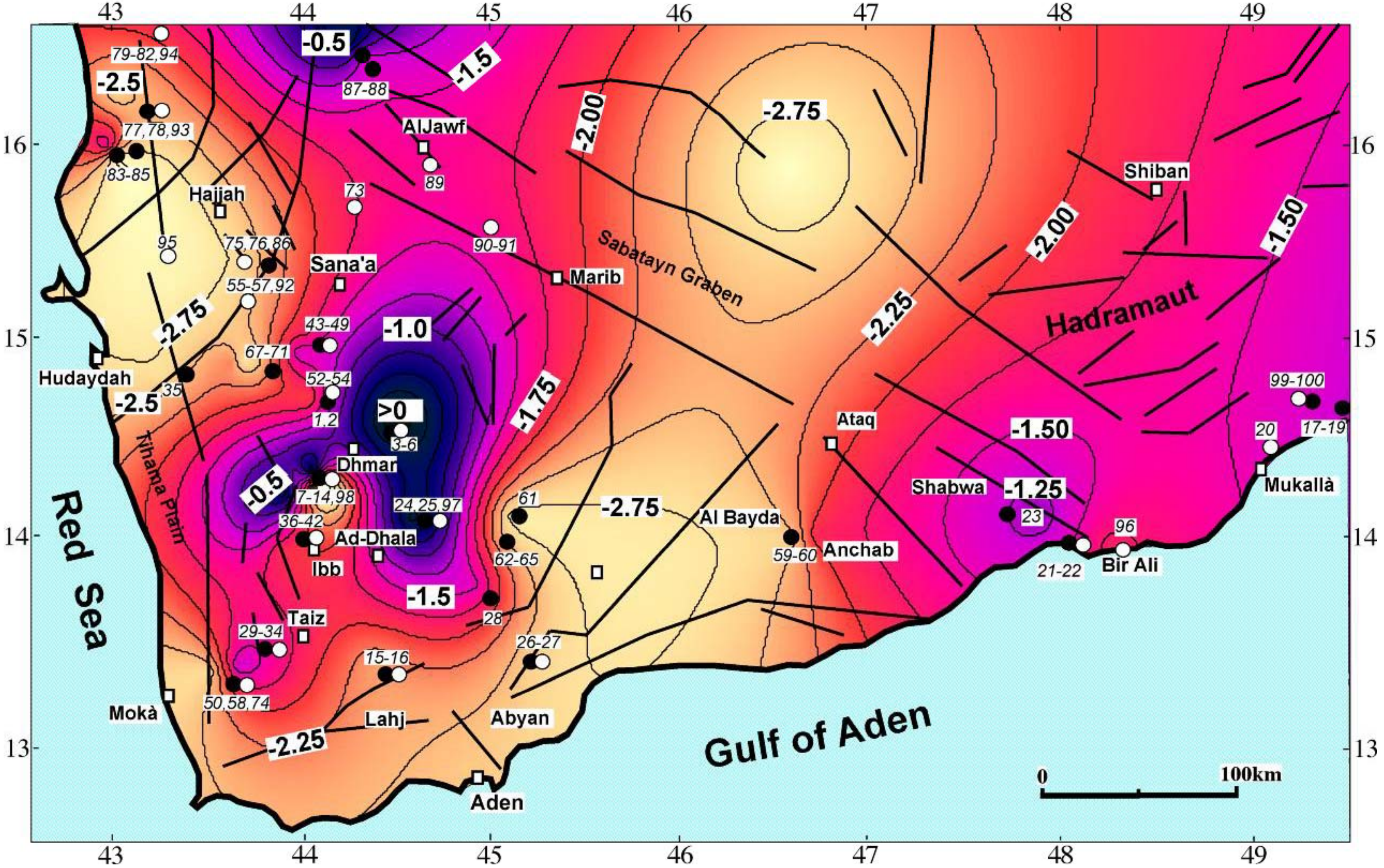
$CH_4 + 2H_2O \Longleftrightarrow CO_2 + 3H_2$

$CO + 0{,}5O_2 \Longleftrightarrow CO_2$

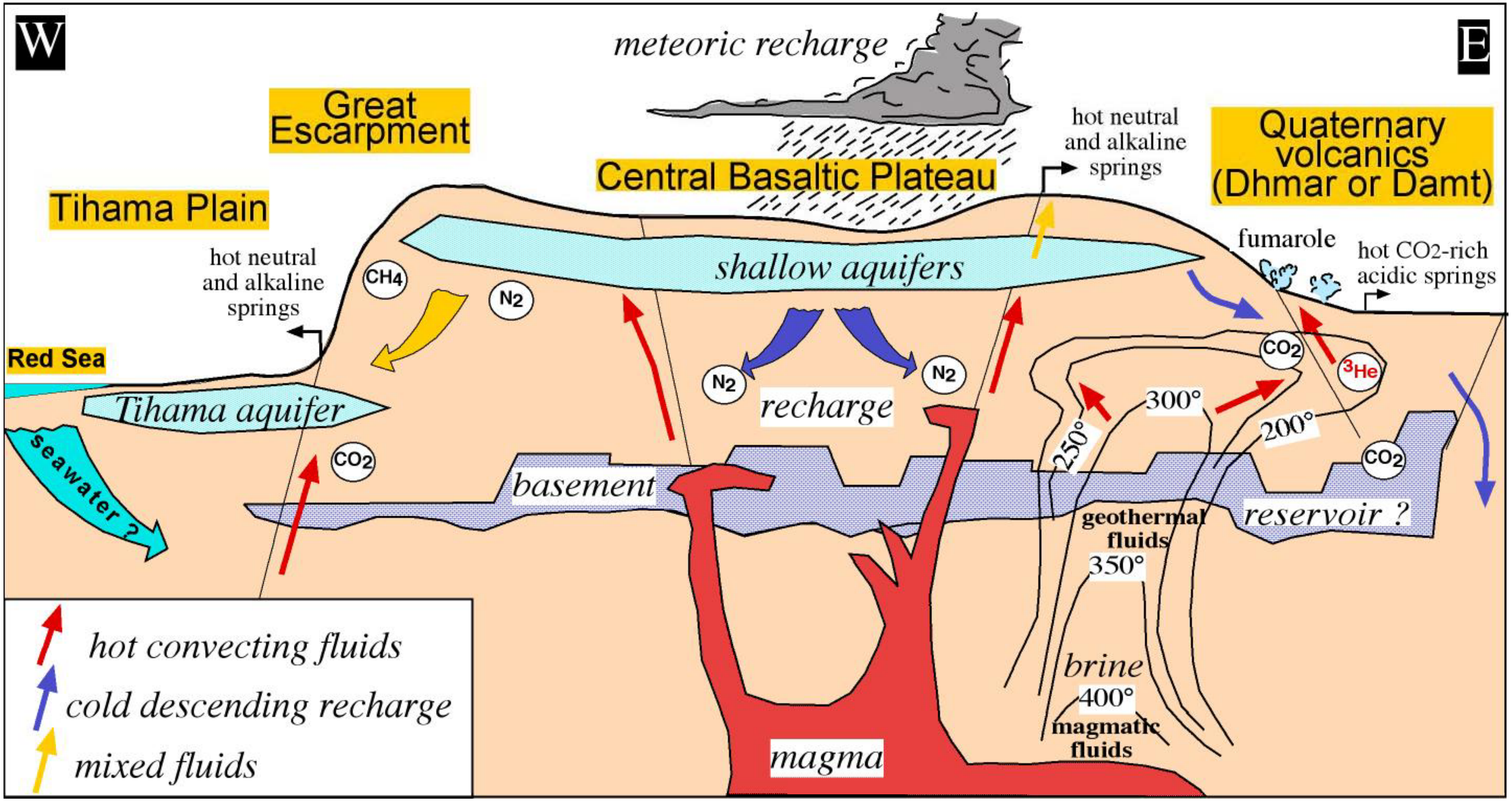
$FeO + 0.25\ O_2 \Longleftrightarrow FeO_{1.5} + 0.25\ e^-$

$H_2S + 2H_2O \Longleftrightarrow SO_2 + 6H^+ + 6e^-$

Distribution map of calculated *p*CO2 in thermal springs

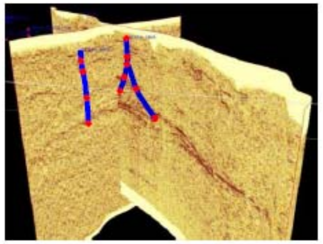


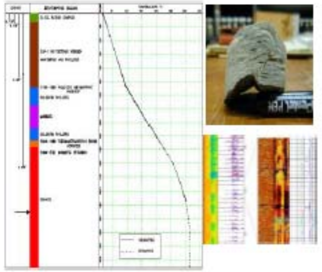
West-East 100 *km* section across Yemen



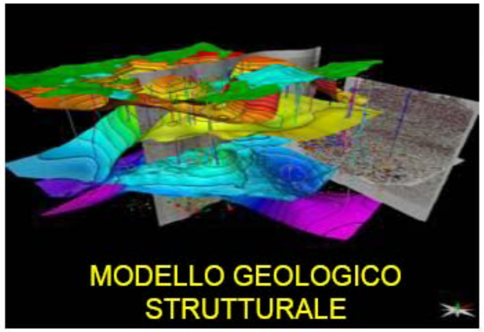
RESERVOIR MODELLING

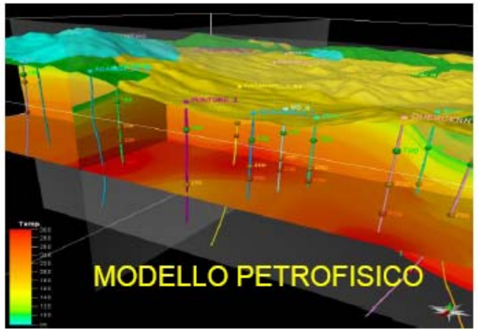
INPUT



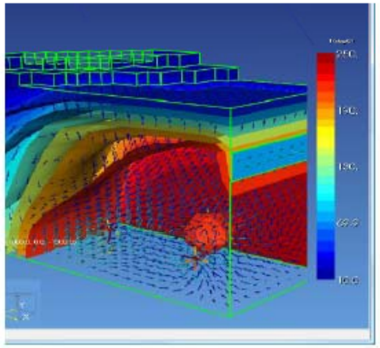


STATIC MODEL





TERMO-FLUIDO -DYNAMIC MODEL



SIMULATED RESULTS