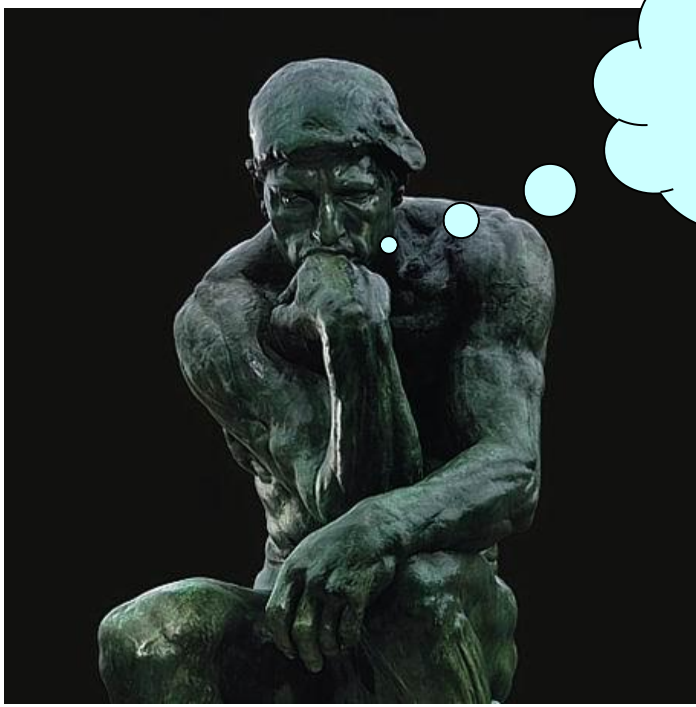
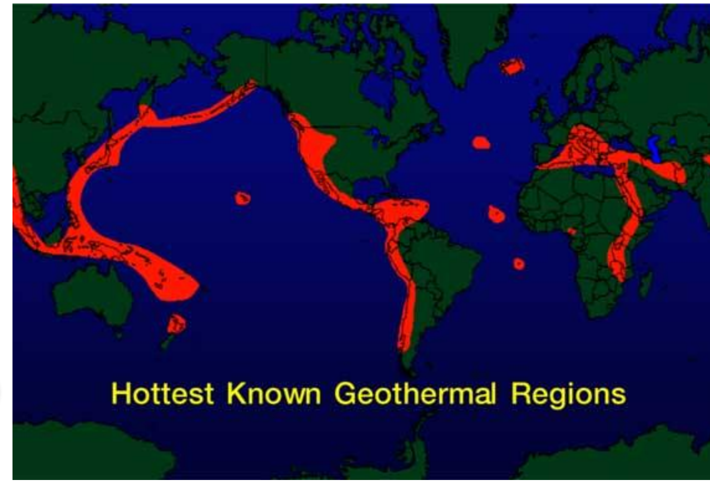
Heat Flow: measurements and significance



What?
Why?
Where?



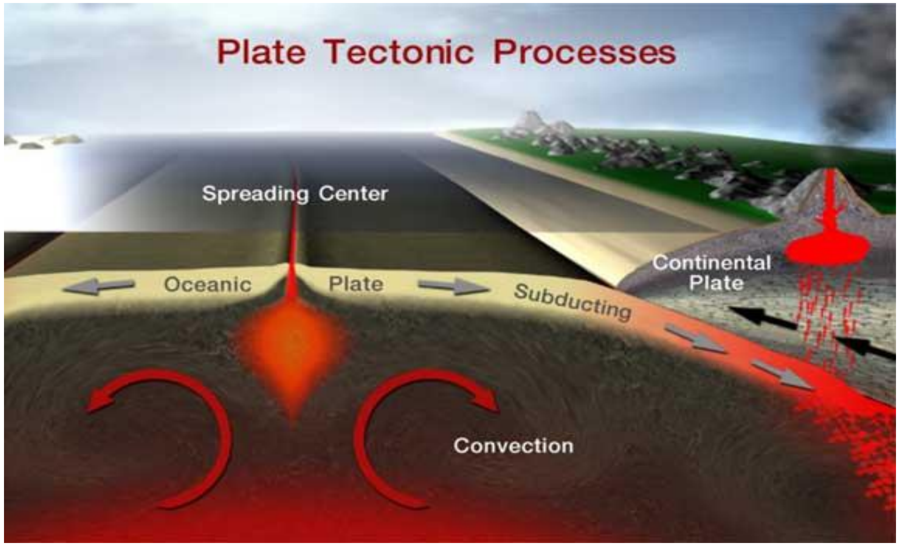
School of Geothermics, ICTP Trieste

Nov. 30, 2011

Summary:

- Heat & heat transfer processes
- Heat flow measurements
- Geologic/Geodynamic significance

The Earth deforms because it is hot inside !



The Earth is a huge heat furnace

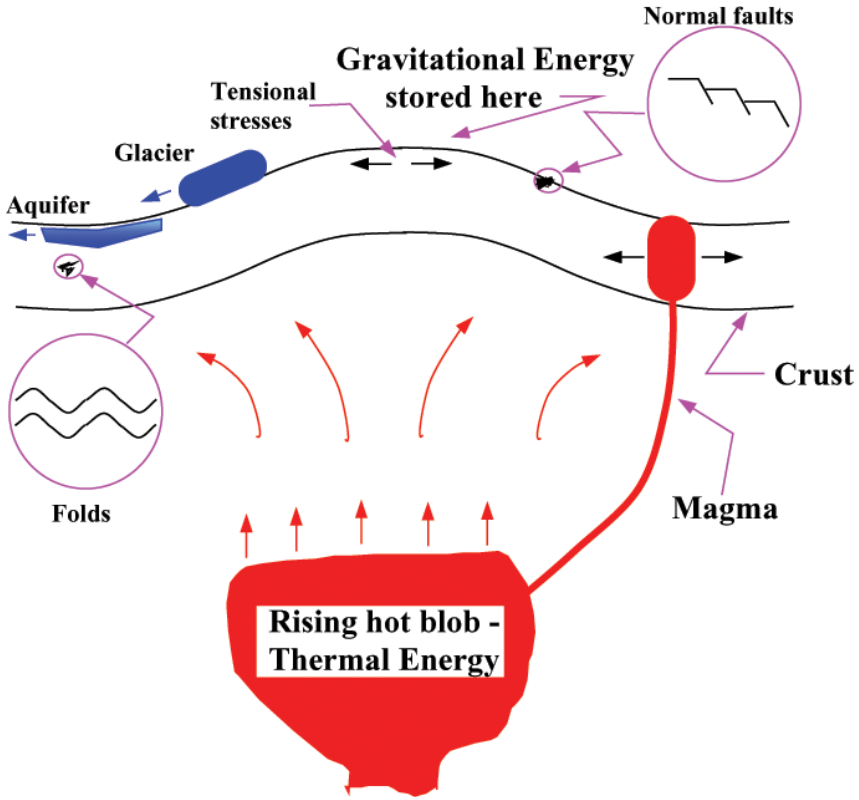
- 99 % T > 1000 °C
- 0.1 % T < 100 °C

- *HF varies in space and time*
- *PLATE TECTONICS is an efficient cooling system for the Earth*

- New lithosphere forms along mid-ocean ridges and continental rifts
- Plumes of magma rise from the edges of sinking plates

Thermal Energy

Heat: spontaneous *flow of energy* caused by T differences; thus, an object cannot possess "*heat*"

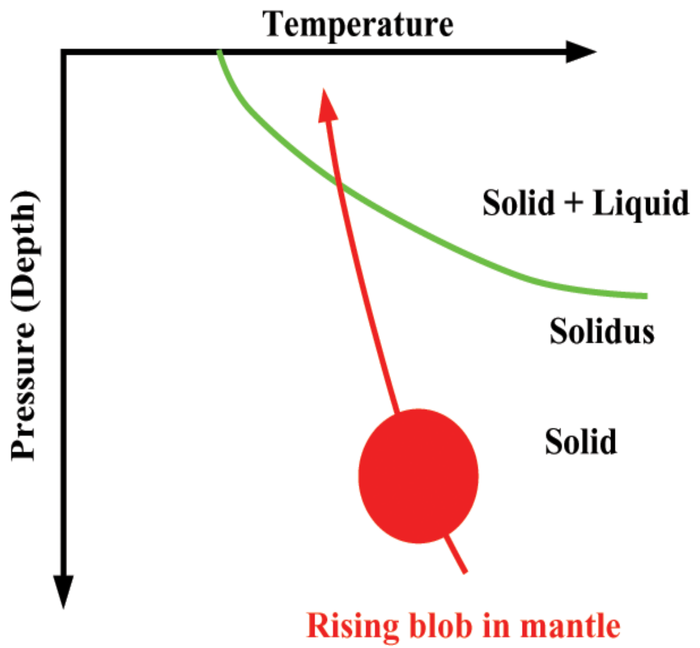


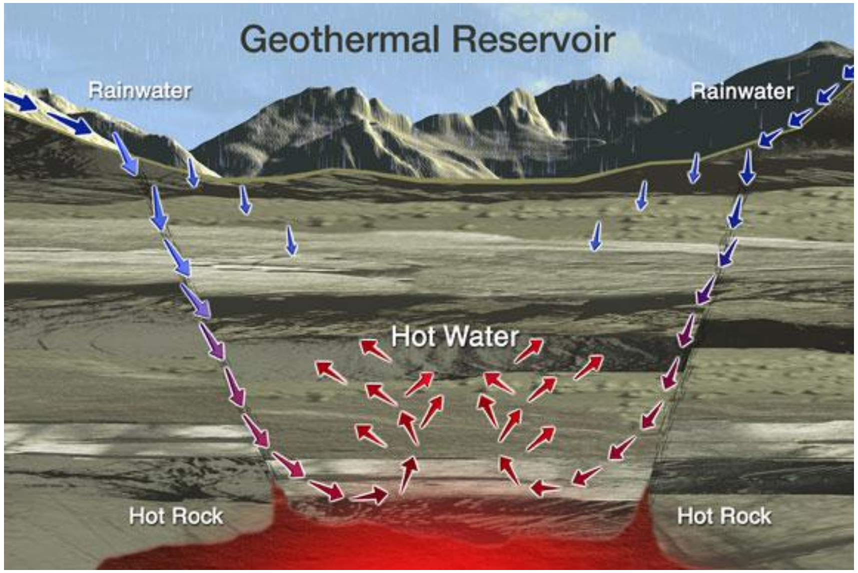
- **Thermal energy:** gives rise to gravitational energy which leads to various geological forces (pressure, gravity, hydraulic head, shear stress...
- **Gravity:** drives almost everything, but heat sources are the ultimate culprits

HEAT SOURCES

- **Radioactive isotopes** (mostly contained in the crust)
- **Mantle plumes** are convecting heat into the lithosphere

Pressure-release Partial Melting

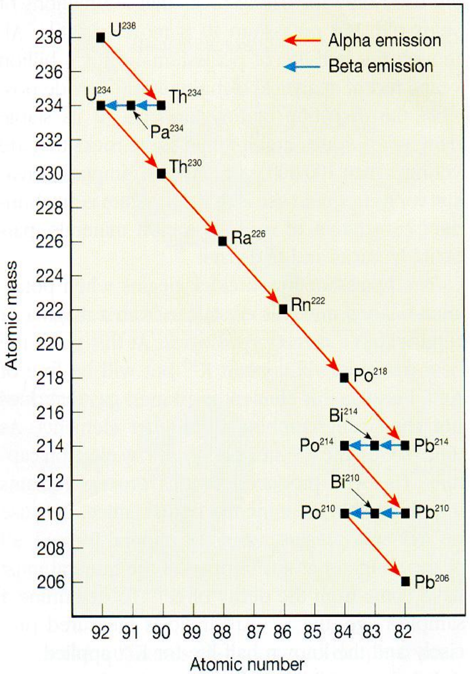




When rising blob crosses the *solidus*, melting can initiate because of P release.
This process is responsible for the creation of **oceanic crust and volcanic arcs**

When hot water and steam are trapped in permeable and porous rocks under an impermeable cap-rock, it can form a **geothermal reservoir**

Radioactive Sources



Typical concentrations of radioactive elements and heat production of some rock types

	Granite	Tholeiitic basalt	Alkali basalt	Peridotite	Average continental upper crust	Average oceanic crust	Undepleted mantle
Concentration by weight							
U (ppm)	4	0.1	0.8	0.006	1.6	0.9	0.02
Th (ppm)	15	0.4	2.5	0.04	5.8	2.7	0.10
K (%)	3.5	0.2	1.2	0.01	2.0	0.4	0.02
Heat generation (10^{-10} W kg^{-1})							
U	3.9	0.1	0.8	0.006	1.6	0.9	0.02
Th	4.1	0.1	0.7	0.010	1.6	0.7	0.03
K	1.3	0.1	0.4	0.004	0.7	0.1	0.007
Total	9.3	0.3	1.9	0.020	3.9	1.7	0.057
Density (10^3 kg m^{-3})	2.7	2.8	2.7	3.2	2.7	2.9	3.2
Heat generation (μW m^{-3})	2.5	0.08	0.5	0.006	1.0	0.5	0.02

(from Fowler, 1990)

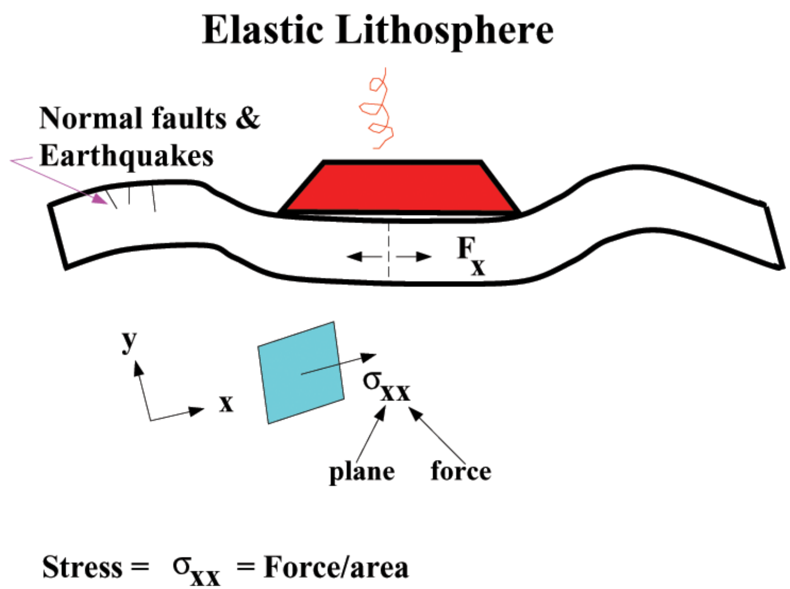
Relative abundance of isotopes and crustal heat generation in the past relative to the present

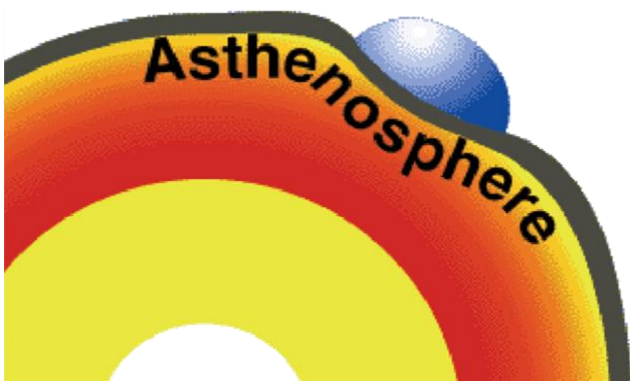
Age (Ma)	Relative abundance ^{238}U	^{235}U	U[a]	Th	K	Heat generation Model A[b]	Model B[c]
Present	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	1.08	1.62	1.10	1.03	1.31	1.13	1.17
1000	1.17	2.64	1.23	1.05	1.70	1.28	1.37
1500	1.26	4.30	1.39	1.08	2.34	1.48	1.64
2000	1.36	6.99	1.59	1.10	2.91	1.74	1.98
2500	1.47	11.4	1.88	1.13	3.79	2.08	2.43
3000	1.59	18.5	2.29	1.16	4.90	2.52	3.01
3500	1.71	29.9	2.88	1.19	6.42	3.13	3.81

Radioactive isotopes: stored in the Crust

Lithosphere: good thermal insulator

How many Lithospheres do we know?





- **Geologic Lithosphere** "thick layer that translates with drifting plates"
- **Mechanical/ Elastic Lithosphere** "strong portion of crust and mantle that deforms in a elastic way up to the point that fails in brittle way"
- **Seismic Lithosphere** "high velocity crust-mantle layer above low velocity zone"
- **Thermal Lithosphere** "thermal boundary layer of the Earth" (~1350 °C melting T at its base)
- Lithosphere is good thermal insulator, low thermal conductivity!

What the T field could tell us?

- provide information on **heat transfer mechanisms**
- unreveal signature of **shallow and deep processes**
- help reconstructing **subsurface T distribution (geotherms)**
- support **processes modelling** in space and time & **applications**

Why do we need reliable geotherms for?

Properties f(T): density, mineral phase boundaries, reaction rates, mechanical, electrical, magnetic, seismic properties

Processes f(T): rheology and deformation, fluid/mass advection, melting + intrusion, tectonic evolution, <u>accumulation of mineral resources and hydrocarbon maturation,</u> ….

Thermal history: space & time change of T field and HF anomalies are important <u>indicators of nature, age and evolution</u>

Geothermal HF: is the surface signature of the T processes at depth; it is a sensitive indicator of the geodynamic evolution and <u>it is critical in the computation of subsurface T</u>

We need deep boreholes to investigate present HF and T

Francis Birch, 1947

(Crustal structure and surface heat flow near the Colorado Front Range. Trans. Am. Geophys. Union, 28 (5), 792-797).

*To my mind no single outstanding problem is more important for understanding of geological processes than the problem of the distribution of temperature throughout the upper 100km or so, as dependent upon such factors as time, sedimentary cover, and deformation; and probably no geological or geophysical problem has resisted solution more stubbornly. The principal difficulty is our ignorance of the distribution of the radioactive heat producing elements. We have no difficulty in finding possible distributions, consistent with our meagre observational data. But none of the possible distributions really imposes itself as conclusive. The differences between the possible distributions with regard to temperatures are very great, and probably entirely different geological processes would have to be invoked for some of the more extreme types. Thus, every conceivable method of introducing further restrictions on the possible distributions requires careful study.**

Heat Transfer

Kinetic energy is related to motion

Potential energy is related to work

HEAT is energy we relate to temperature

Heat transfer mechanisms:

- **conduction**: through lattice vibration and atoms collisions (e.g. across Lithosphere)
- **convection**: mostly transferred by the movement of material (as in the Mantle and Outer Core)
- **radiation**: by e.m. radiation, significant at high temp.

Thermal regime: is transient by definition

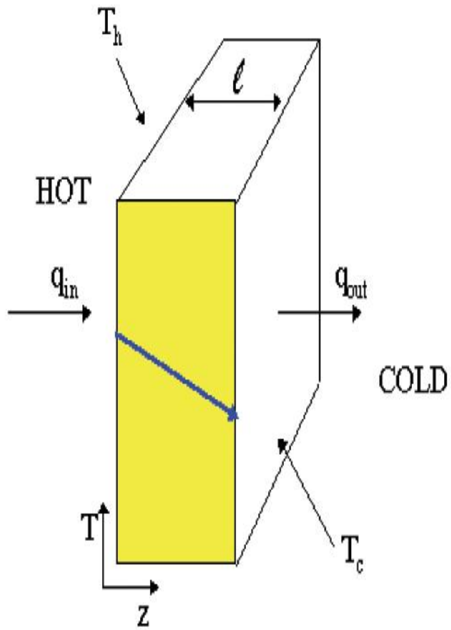
Heat Conduction 1

- **q** is the heat flux
  - The flow of heat energy (Joules, J) across a unit area per unit time (or J/s•m^2 = W/m^2.)
- The heat flux is proportional to the temperature gradient

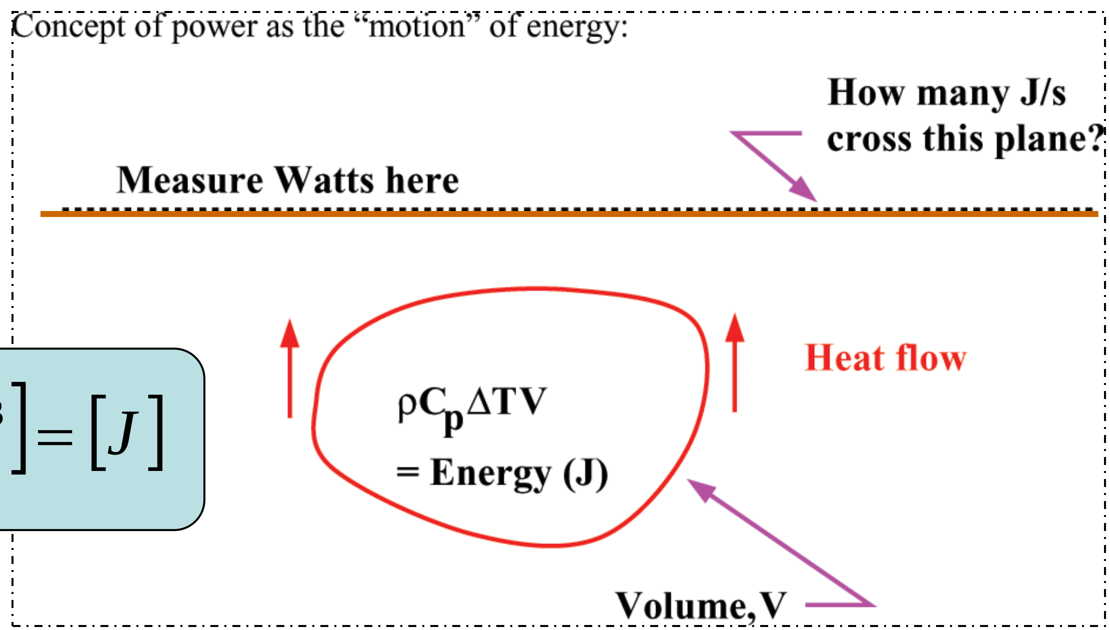
$$q = -K \frac{dT}{dz}$$

- K is the thermal conductivity (units of Wm^{-1}K^{-1}). This relationship holds in a conductive medium.
- The negative sign indicates that the heat is flowing from the hot to cold.
- This equation is known as Fourier's Law of Heat Conduction.

Heat Conduction 2



- Heat flows from hot to cold
- What is the energy balance?
- Heat out – Heat in = change of heat content
- Heat content? = $\rho C_p \Delta T$



$$\frac{[kg]}{[m^3]} \cdot \frac{[J]}{[kg \cdot K]} \cdot [K] \cdot [m^3] = [J]$$

Heat Conduction 3

- **What is Heat Content?**
  - It can be expressed as

$$\rho C_p \Delta T$$

  - ρ is the density
  - C_p is the specific heat with units of J kg^{-1} K^{-1}. It is the amount of energy required to raise 1 kg of material by 1 degree Kelvin.

$$C_p = \frac{dE}{dT}$$

  - The rate of change in heat content over a time interval Δt is

$$\rho C_p \frac{\Delta T}{\Delta t} \rightarrow \rho C_p \frac{\partial T}{\partial t} \longrightarrow \nabla \cdot \mathbf{q} = -\rho C_p \frac{\partial T}{\partial t}$$

$$\nabla \cdot (-K \nabla T) + \rho C_p \frac{\partial T}{\partial t} = 0$$

For K constant this becomes

Heat diffusion Eq. →

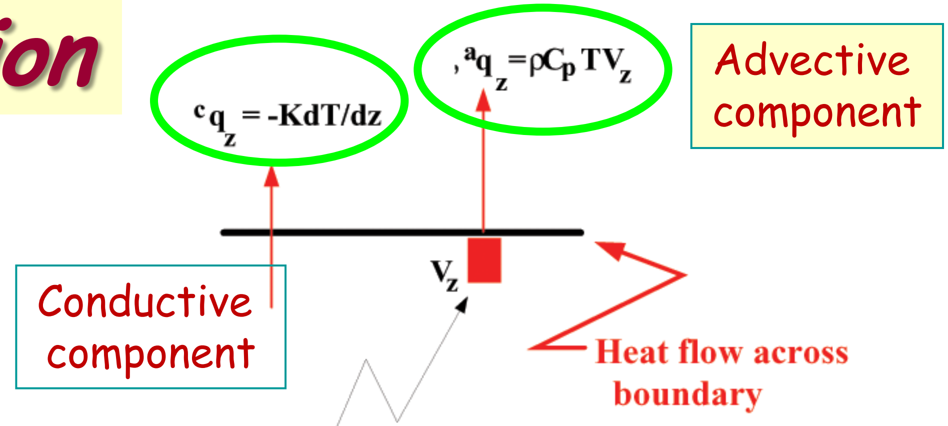
$$\nabla^2 T - \frac{1}{\kappa}\frac{\partial T}{\partial t} = 0$$

Steady-state solution:

$T(z) = Az + B$

$T(z) = (Q/K)\, z + T_0$

Heat Convection



In 1 sec., $V_z$dxdy amount of material crosses the boundary.

So, $^{a}q_{z} = \rho C_p TV_z$ dxdy

amount of heat crosses the boundary.

V_z dx dy = m/s · m · m = m^3/s

$\rho C_p T = J/m^3$

So product = J/s = W

But "per area" gives heat flux

$$^{a}q_{z} = \rho C_p TV_z$$

Figure 4 considers two ways to transport heat. In the *z* direction then

$$q_z = {}^{c}q_z + {}^{a}q_z = -K\frac{dT}{dz} + \rho C_p T V_z$$

Summary:

- Heat & heat transfer processes
- Heat flow measurements
- Geologic/Geodynamic significance

Heat Flow Measurements

Th. Conductivity

T Gradient

[mW m^{-2}]

$$q_z = {}^c q_z + {}^a q_z = -K \frac{dT}{dz} + \rho C_p T V_z$$

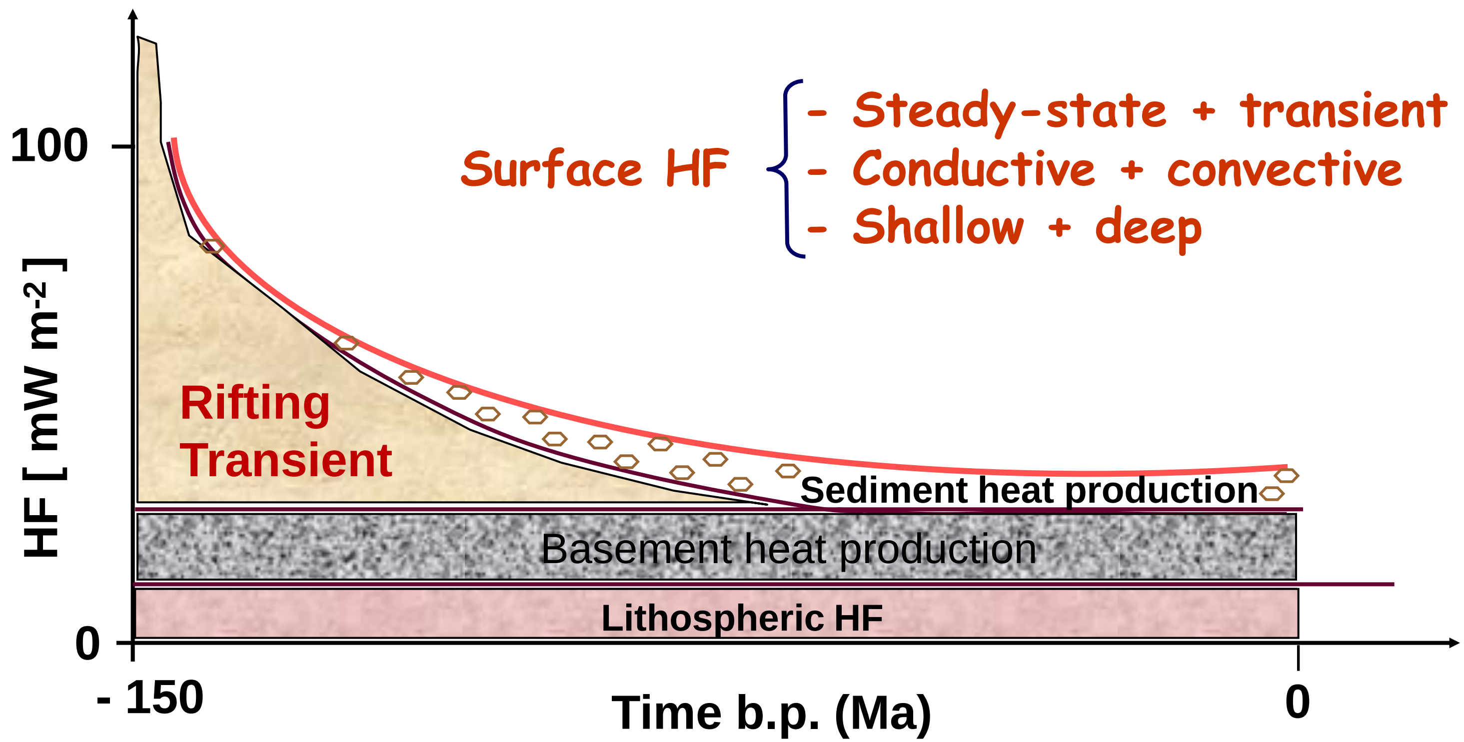
Fluid velocity

- HF is "measured" indirectly, computing T gradient, K and V_z (?)
- in heterogeneous media, horizontal T gradients cannot be neglected
- ${}^a q_z$ is difficult to estimate, because V_z is seldom known
- One approach is to separate contributions and model them separately

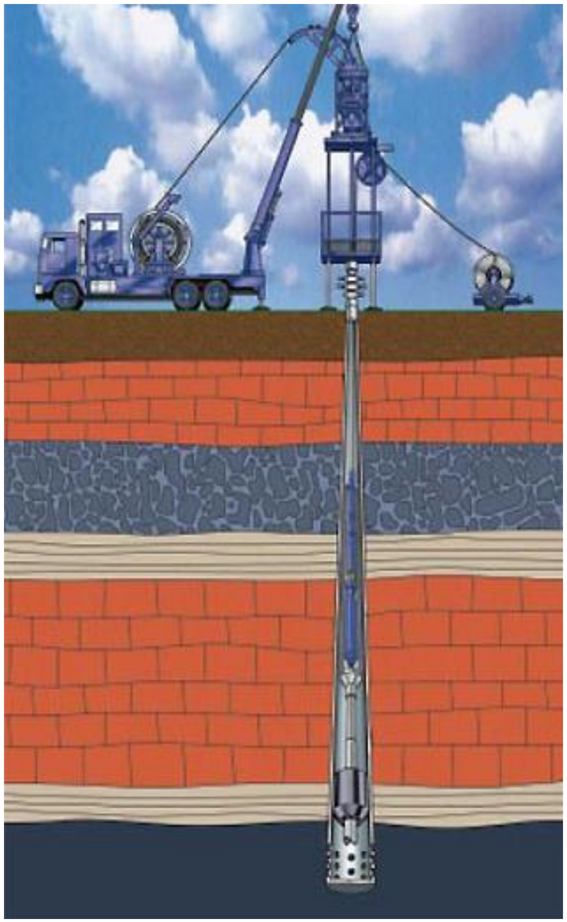
Contributions to surface Heat Flow

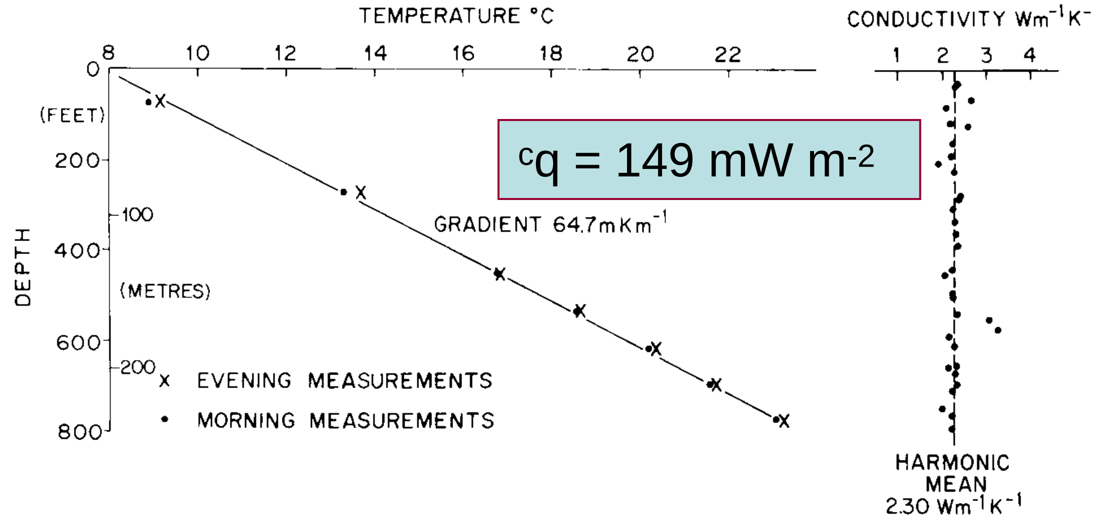
$$q_z = {}^c q_z + {}^a q_z = -K \frac{dT}{dz} + \rho C_p T V_z$$

Fluid velocity

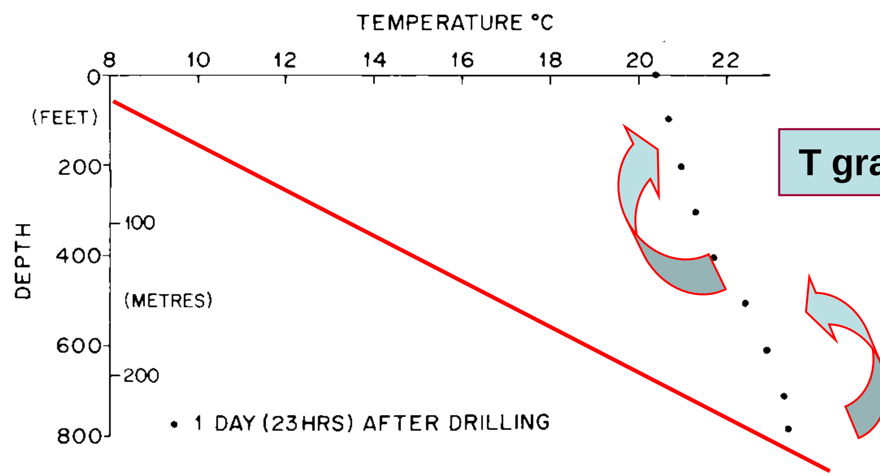


Borehole T and K data





$^{c}q = 149$ mW m^{-2}

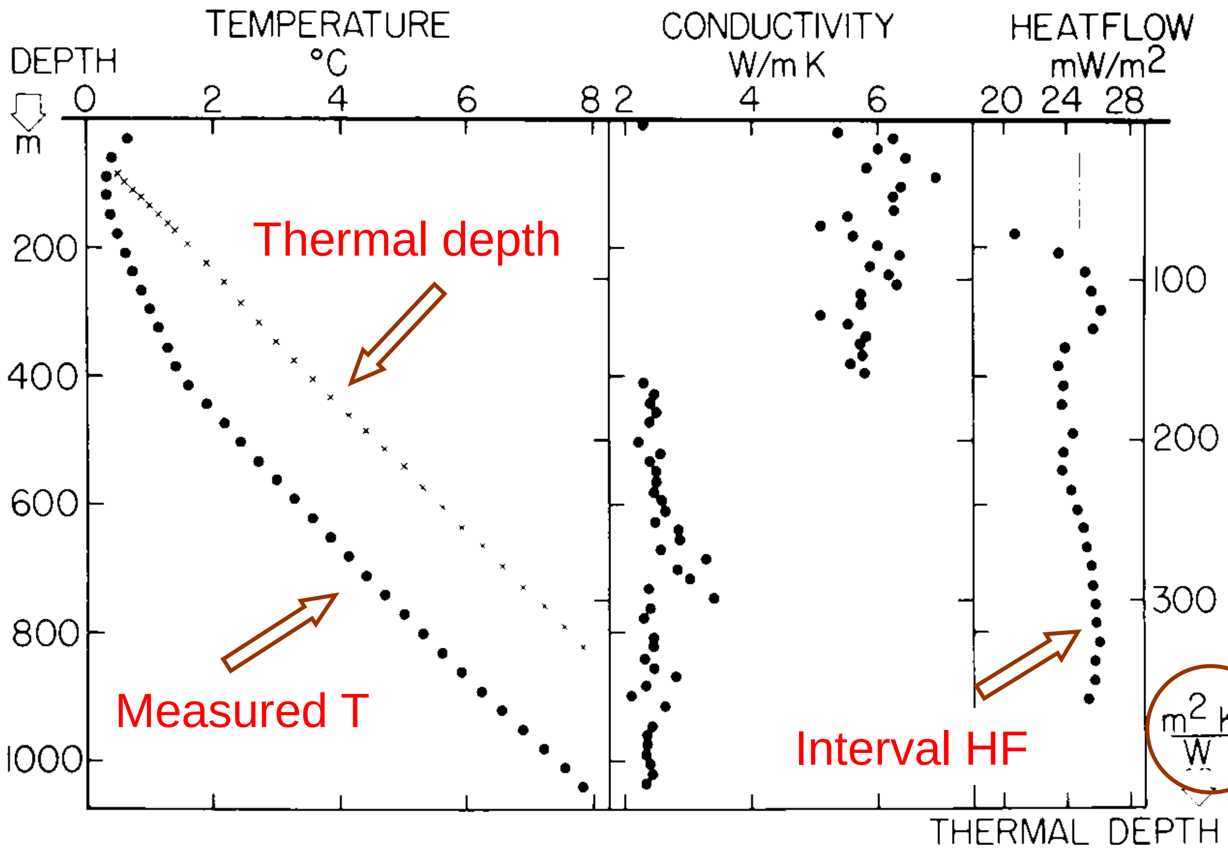


T grad.~12 mK m^{-1}

Groundwater outflow from deep acquifer

After Jessop, 1990

T + K data: accuracy & significance



After Jessop, 1990

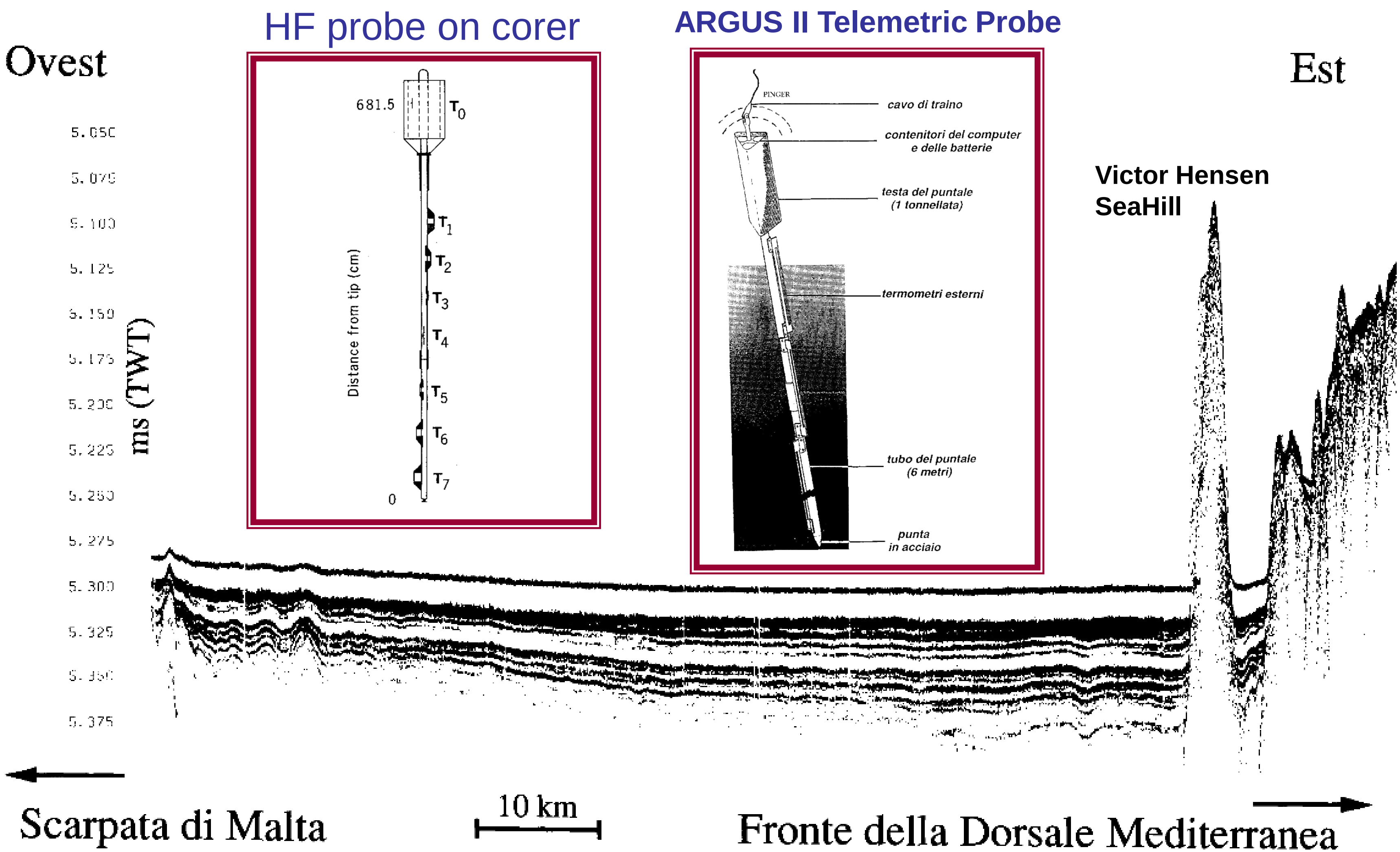
Bullard Plot Method

- no inner sources
- 1D steady-state
- Conduction only

$$T(z) = T_0 + q_0 \sum_{i=1}^{N} (\Delta z_i / K_i)$$

Thermal depth

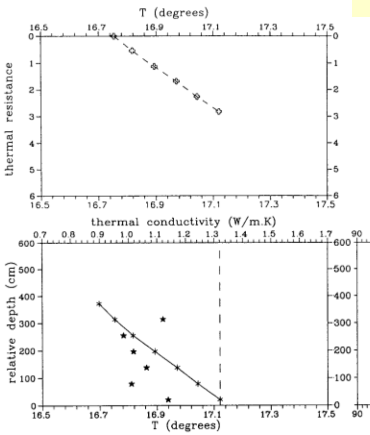
Marine conventional HF Probes



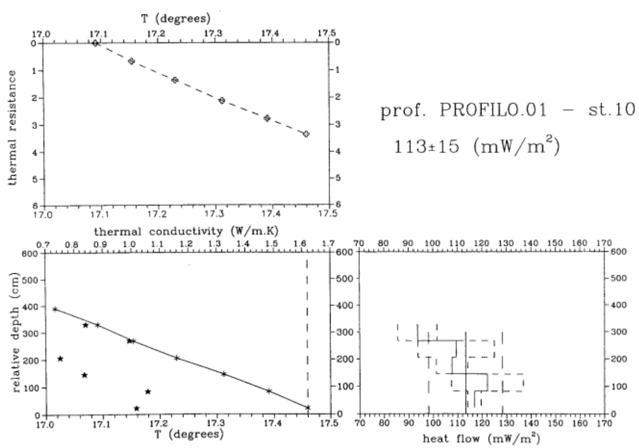
After Della Vedova et al., 2000

Marine HF Measurements

Positive HF



prof. PROFILO.01 – st.9
132±11 (mW/m²)



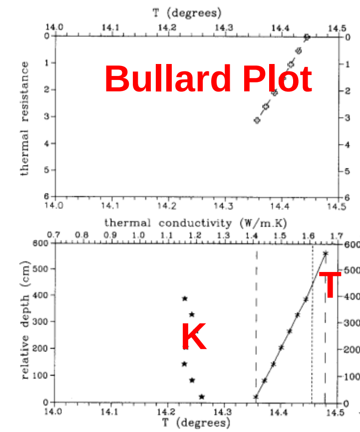
prof. PROFILO.01 – st.10
113±15 (mW/m²)

MEDRIFF dataset, Ionian Sea 1993

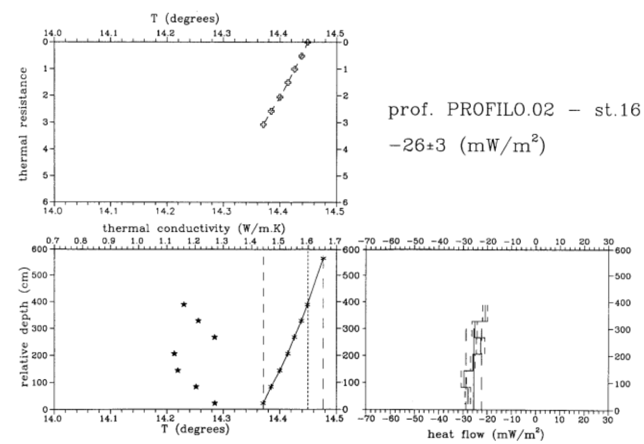
Effect of the Eastern Mediterranean Transient

(After Della Vedova et al., 1998)

Negative HF



prof. PROFILO.02 – st.15
−27±2 (mW/m²)



prof. PROFILO.02 – st.16
−26±3 (mW/m²)

Environmental Disturbances to HF

- Topography
- **Vertical** and Lateral **heterogeneities**

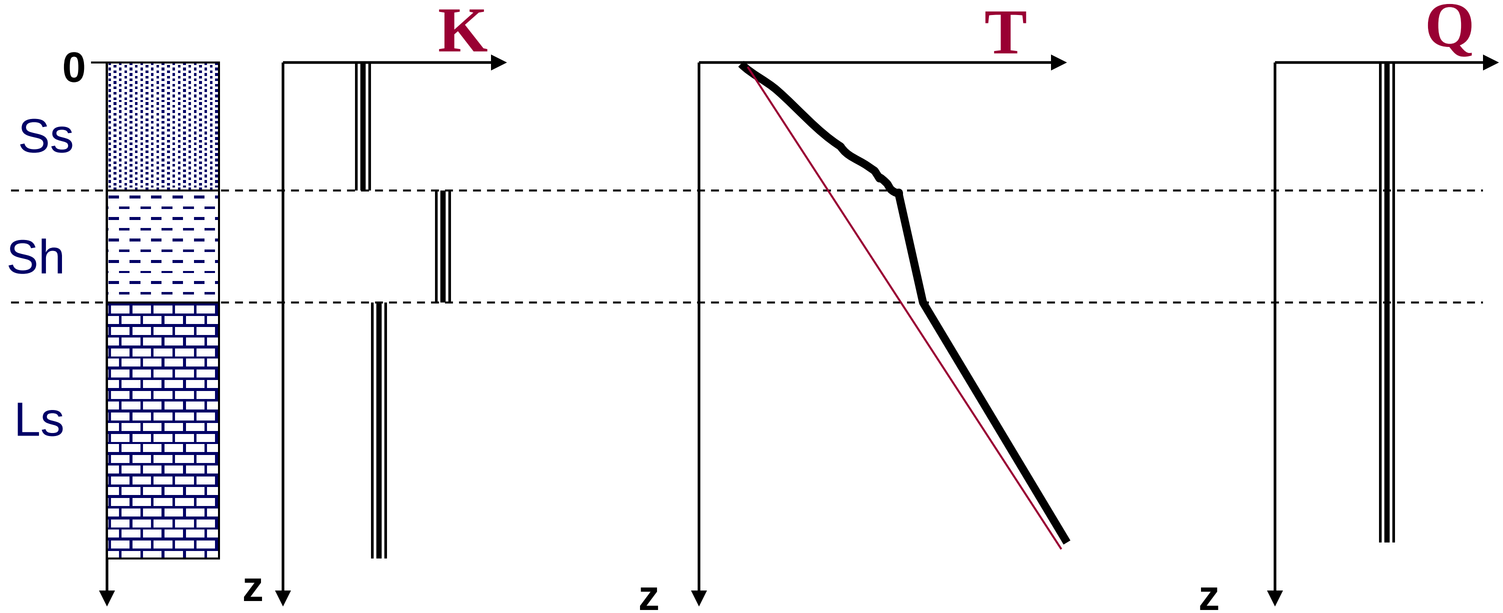
  (lithology, salt domes, intrusions, faults, valleys, horsts, Φ and K changes, basement top.)
- Volcanic intrusions
- Sedimentation
- Erosion
- Uplift
- **Fluid circulation**
- **Surface T changes (Climatic effects)**

Most of these disturbances are confined in the upper 10 km of the Crust

HF signature in the upper few km:

Crustal heterogeneity and steady-state heat conduction

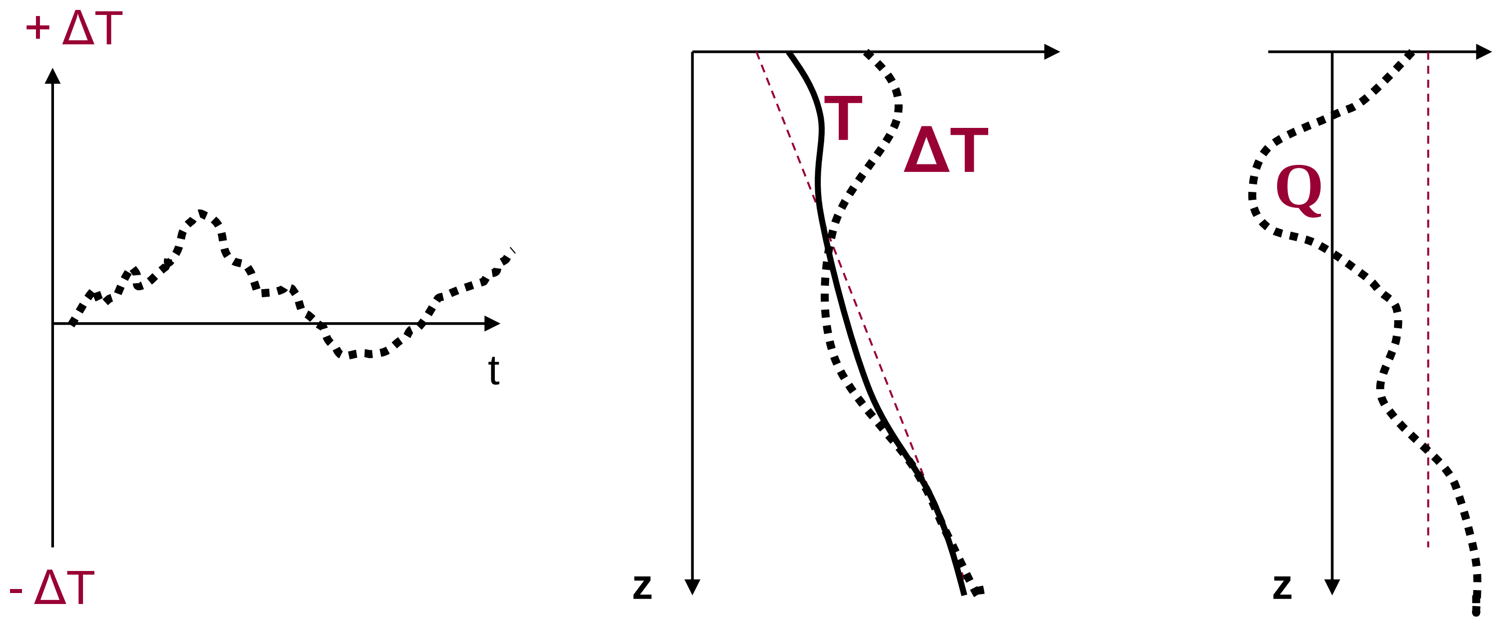
- **TERRAIN HETEROGENEITY** (*steady state*)
  - layering, anisotropy, intrusions, faults, Φ + K changes
  - near-borehole & 3-D effects, topography, …
  - sedimentation, erosion, uplift, subsidence, …



HF signature in the upper few km:

Surface T changes and transient heat diffusion

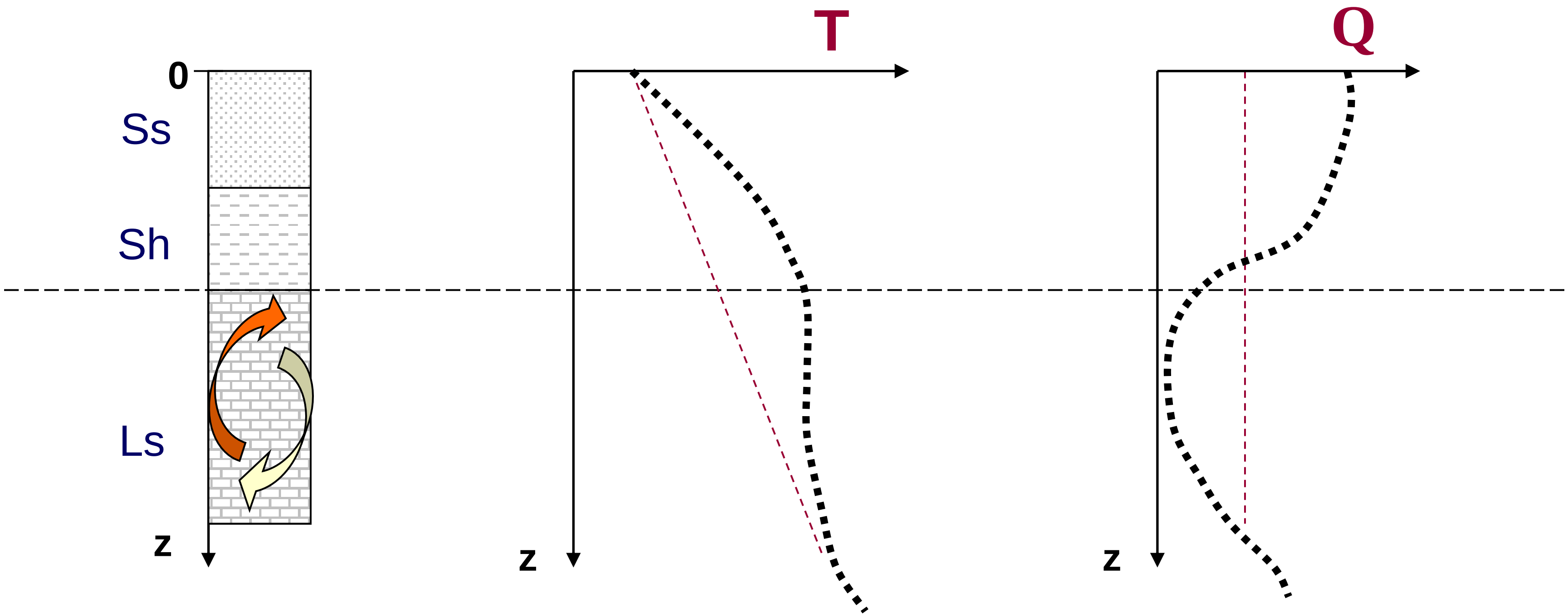
- **SURFACE T CHANGES** (*transient*)
  - periodic changes (day, season, multiannual & climatic cycles)
  - sudden changes (sedimentation, erosion, uplift & denudation)



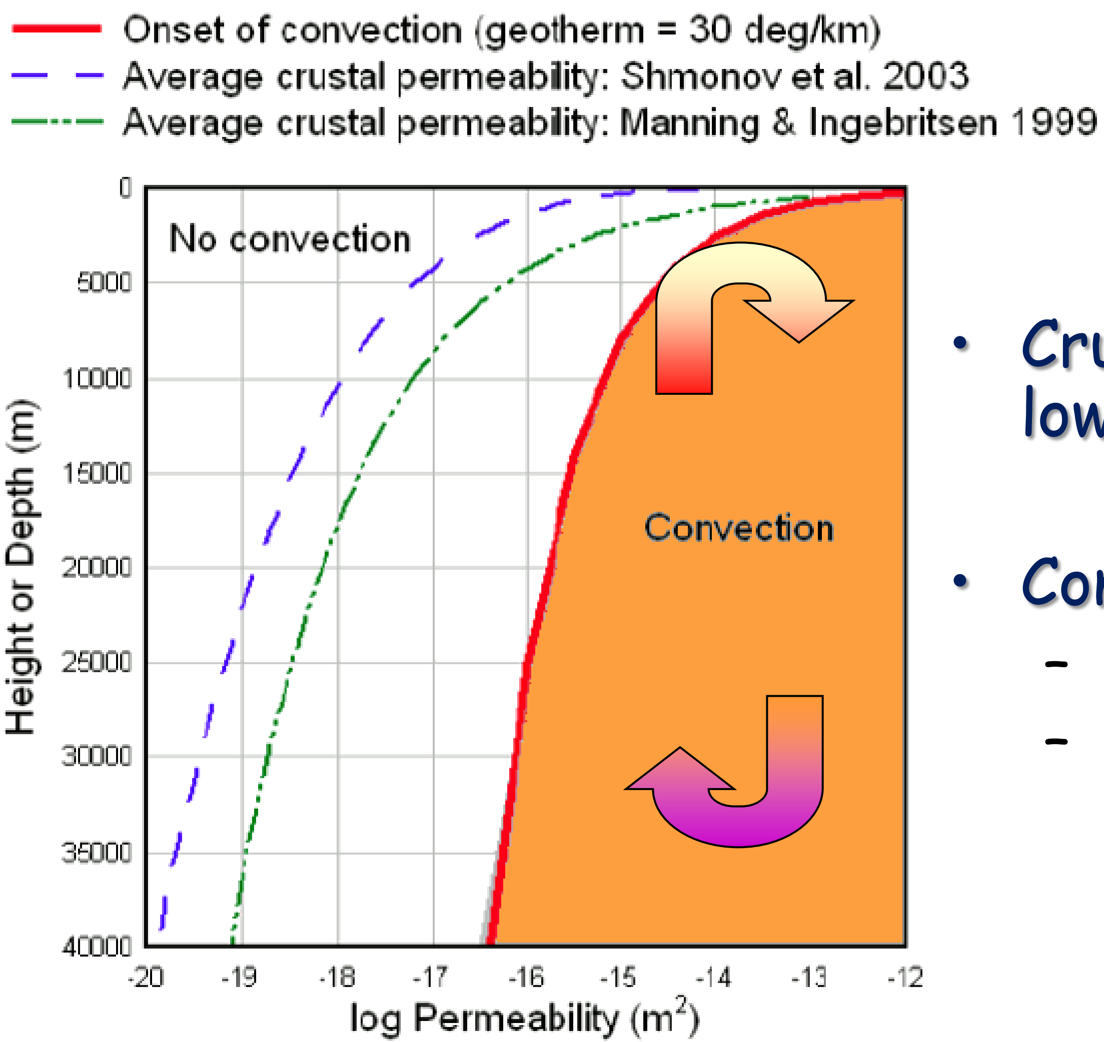
HF signature in the upper few km:

Pore water flow and heat advection

- **CONVECTIVE TRANSFER BY MASS FLOW** (*transient*)
  - Groundwater flow and deep fluid circulation
  - igneous intrusions, eruptions, salt diapirism, mud volcanoes,...

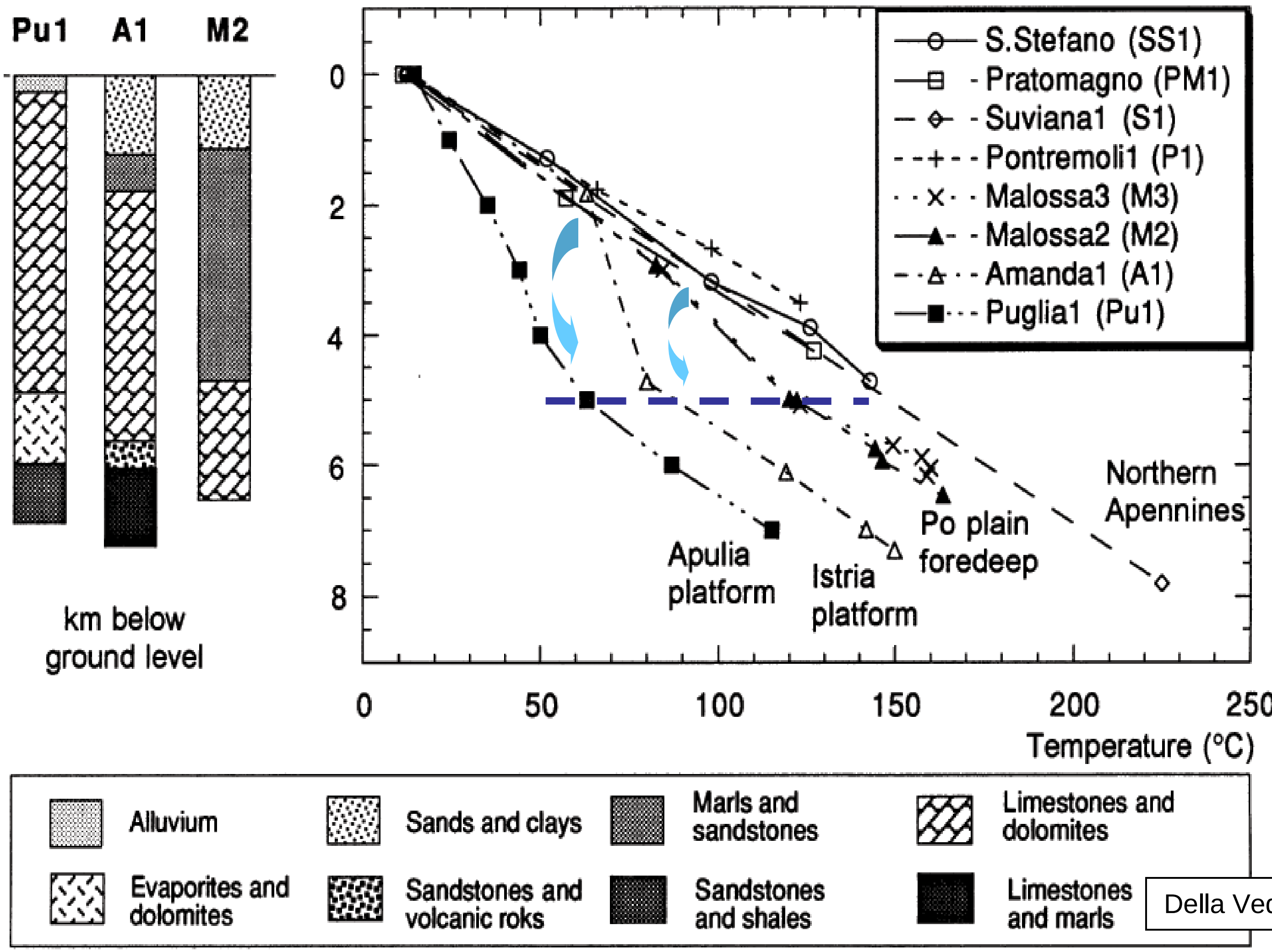


Hydraulic permeability controls convection



- Crustal permeability is too low for fluid convection
- Convection can develop:
  - Along faults and fractures
  - Where T gradient is high enough (dike intrusions, magma chambers, …)

Groundwater circulation in Mesozoic Platforms

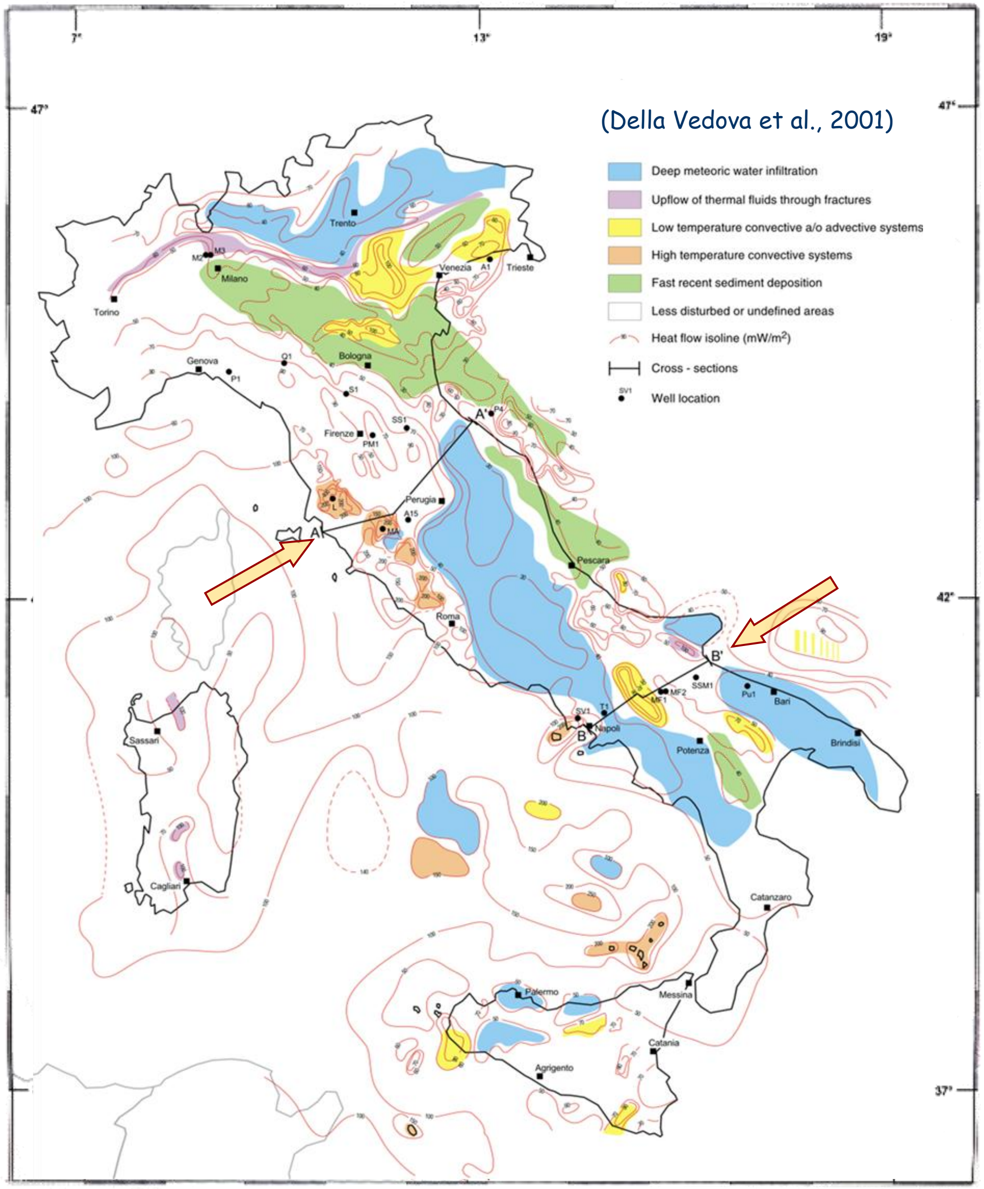


Della Vedova et al., 2001

Summary:

- Heat & heat transfer processes
- Heat flow measurements
- Geologic/Geodynamic significance

HF Map & disturbances in upper 10 km



- high sedimentation rate (green)
- meteoric water infiltration (azur)
- geothermal low T convective systems (yellow and violet)
- volcanic areas and high T systems (pink)

They induce strong lateral T changes at shallow depths

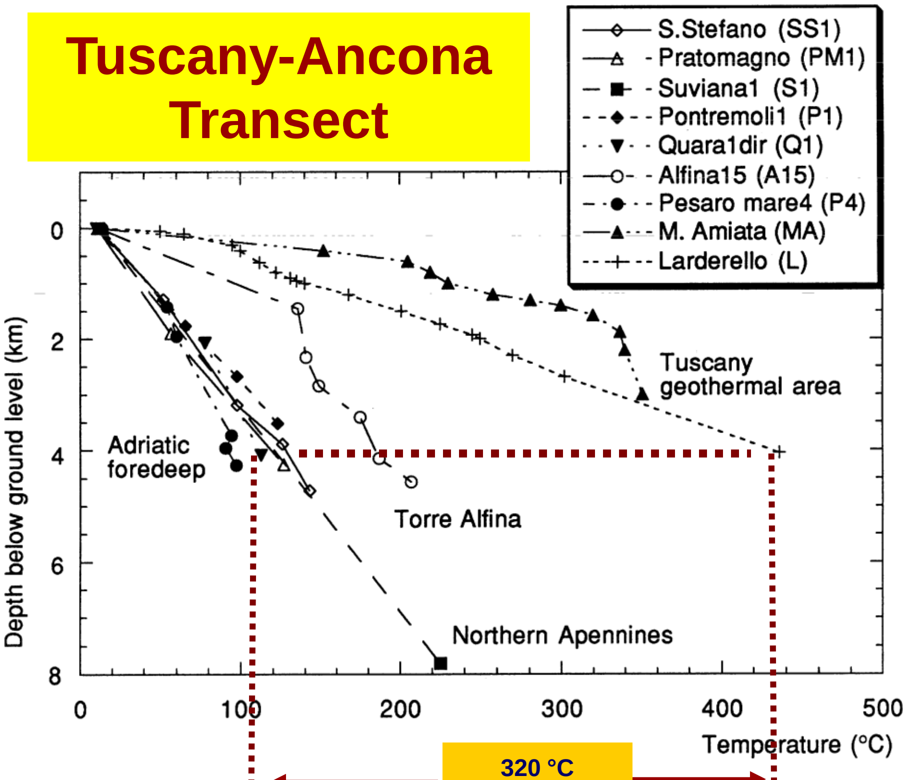
DATASET:

- 2700 T grad. meas. (700 HF offshore),
- 255 new ENI boreholes (1980-96)

Est. Error: 5-20 mW m^{-2}

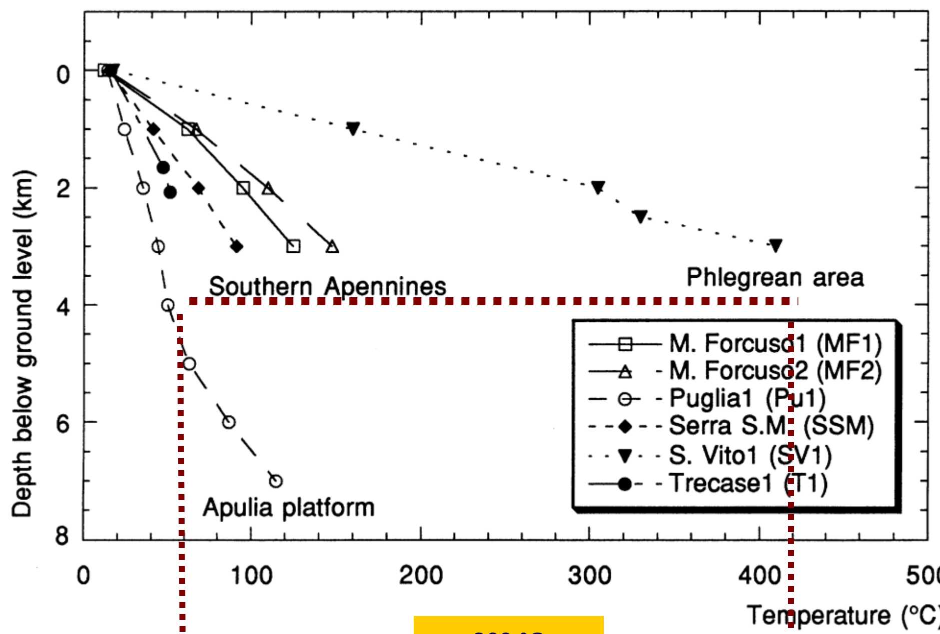
Hot Tyrrhenian vs. cold Adriatic side

Tuscany-Ancona Transect



320 °C

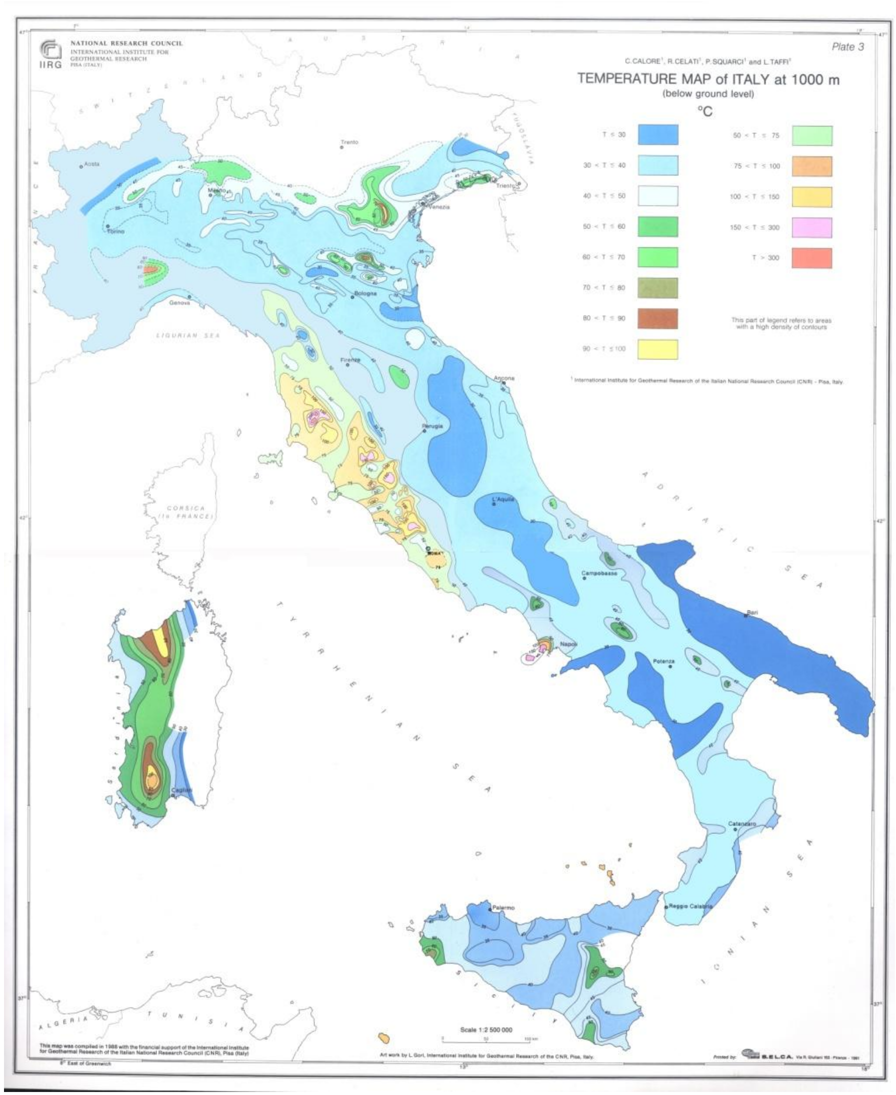
Naples-Gargano Transect

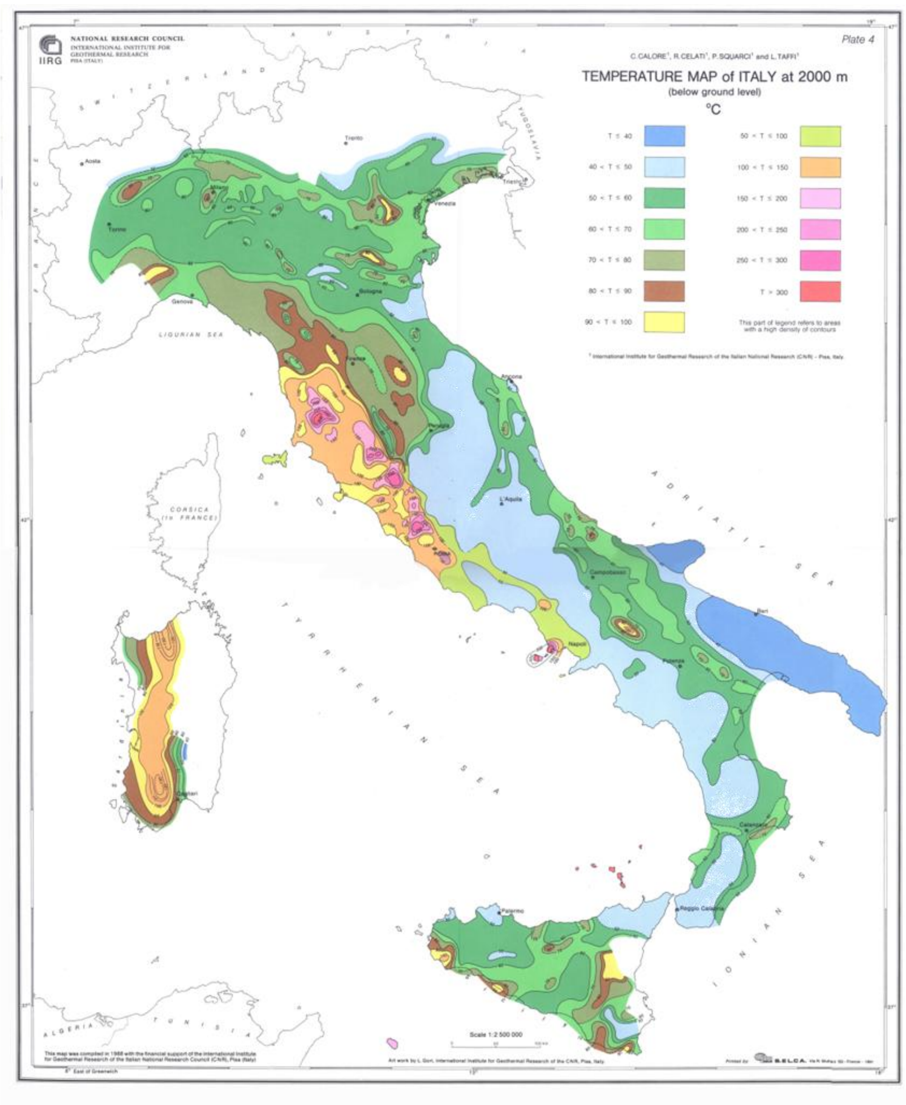


360 °C

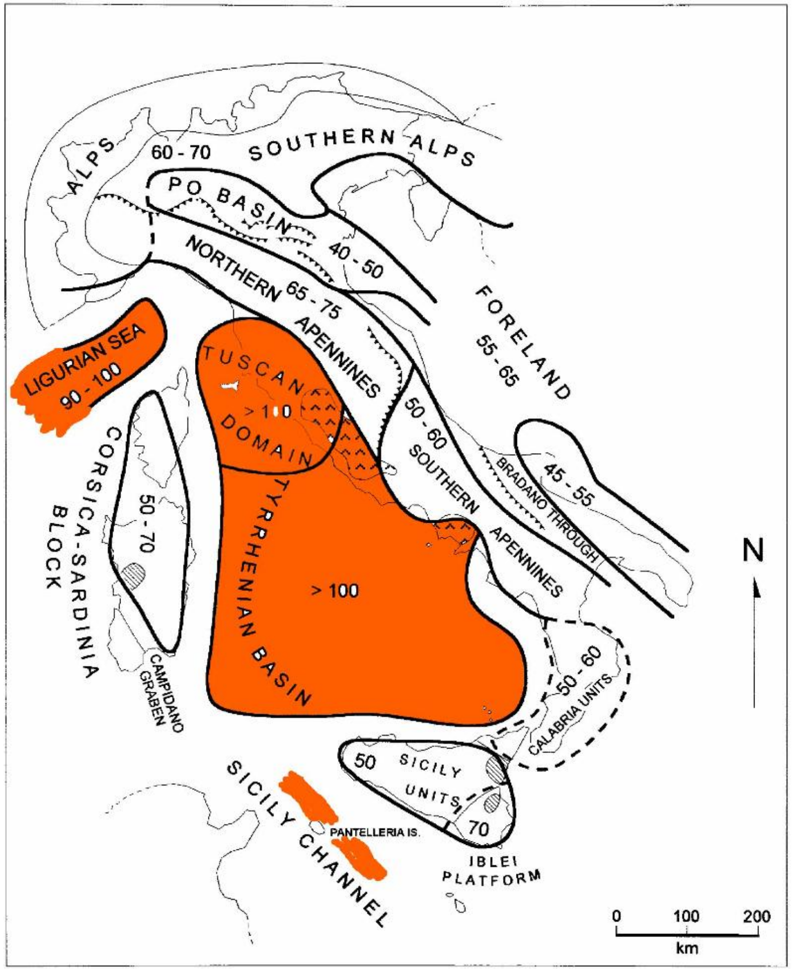
Large Q_b difference!

T at 1000 & 2000 m depth



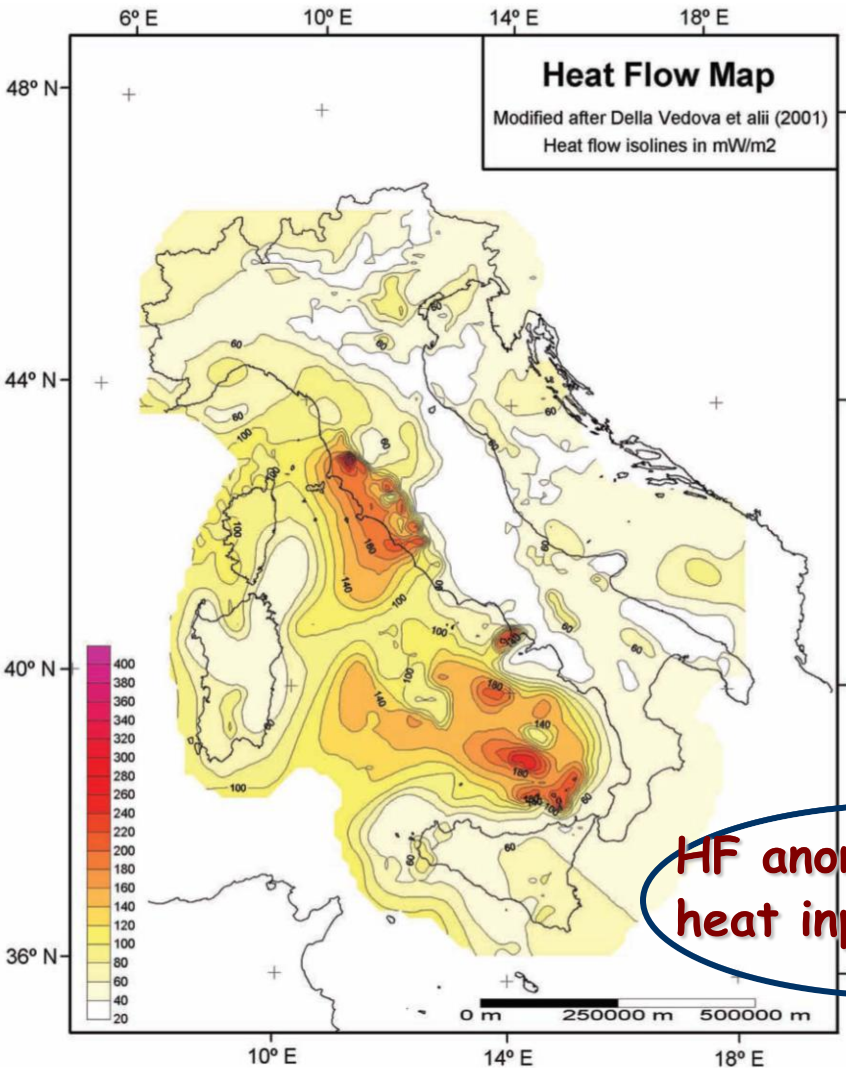


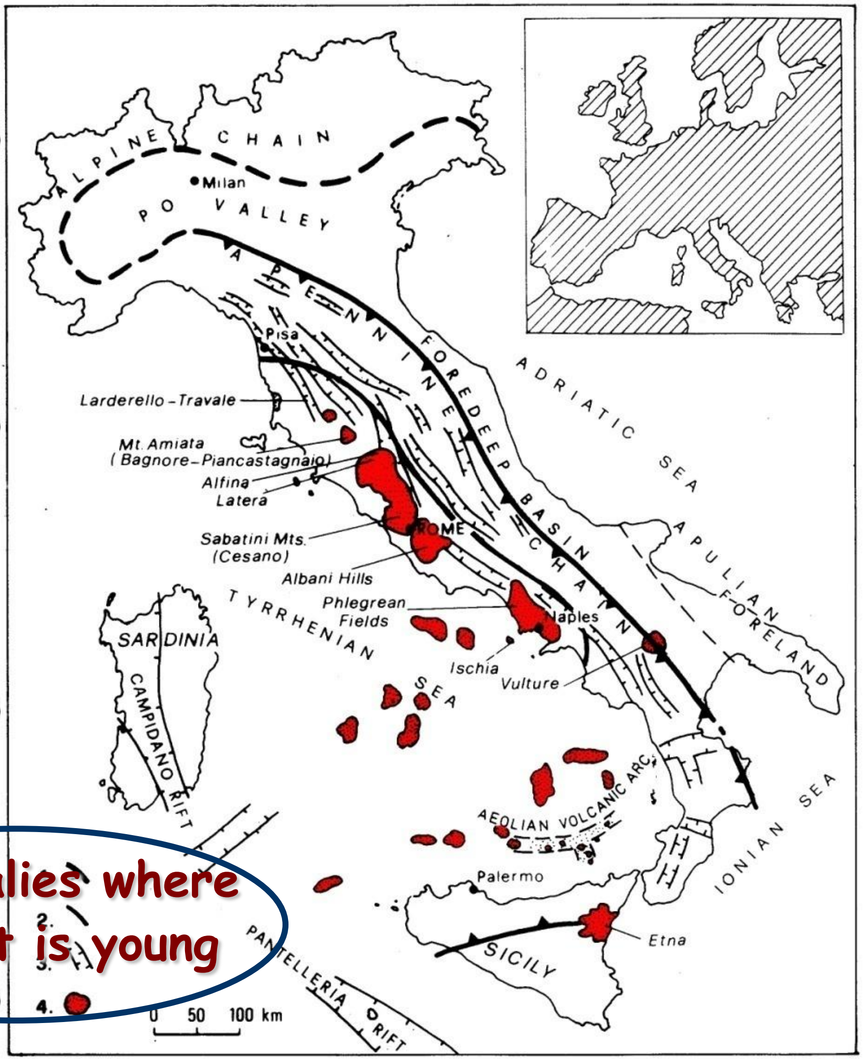
HF Provinces: basement HF



- Predicted HF is significantly higher in South Apennines, Po basin, foreland areas
- Undisturbed HF in foreland is 45-55 mW m^{-2}, compared to obs. 30-40 mW m^{-2}
- This implies higher deep contributions and transient components in these areas, suggesting younger tectonic ages
- The difference between N and S Apennines is less pronounced
- The deep thermal regime of Tuscany, Tyrrhenian Sea, Apennines and foredeep areas has not yet reached equilibrium

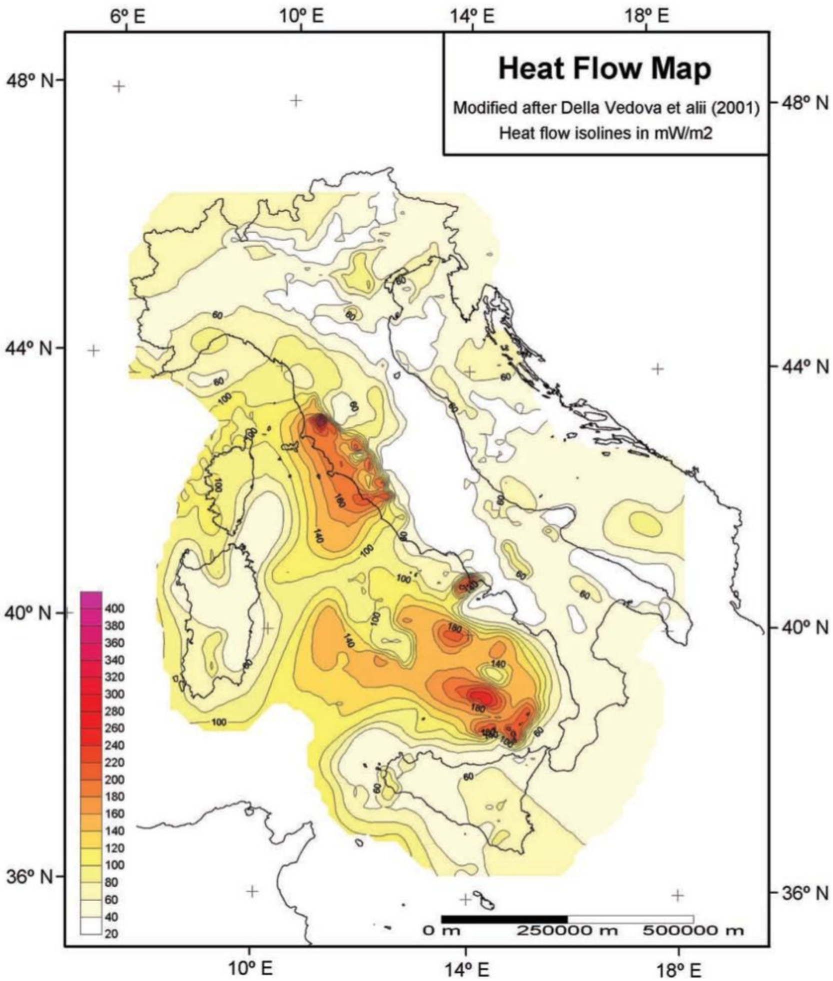
HF map & young magmatic provinces

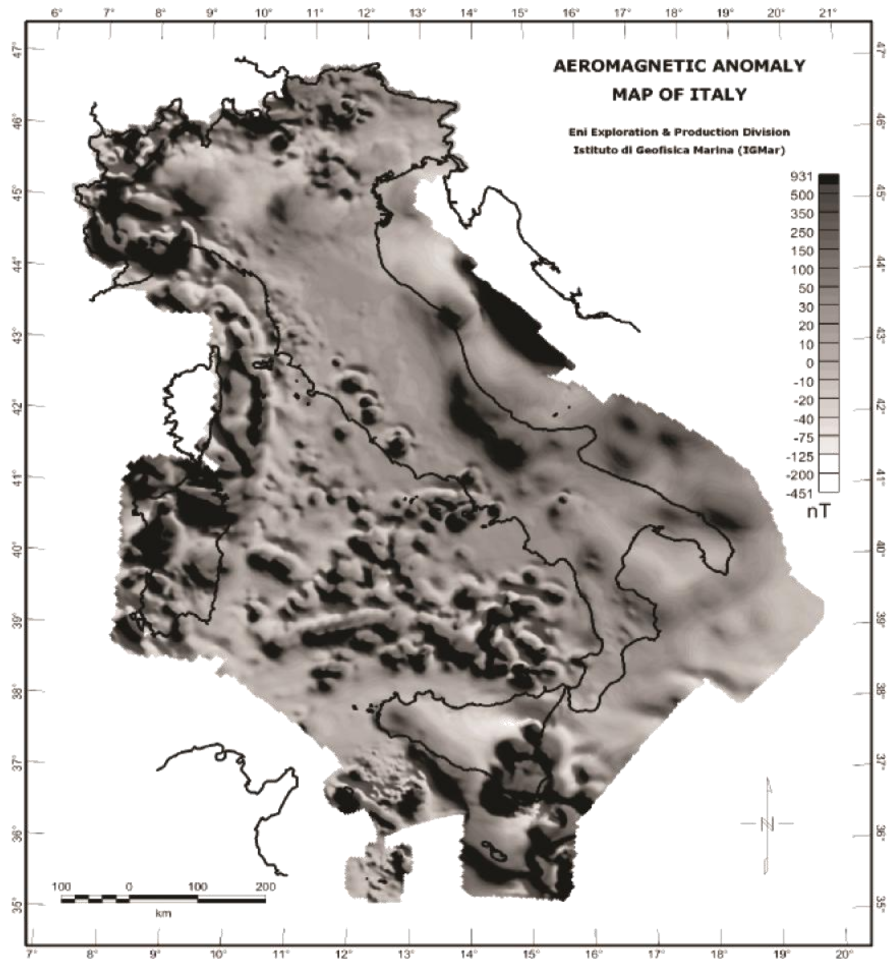




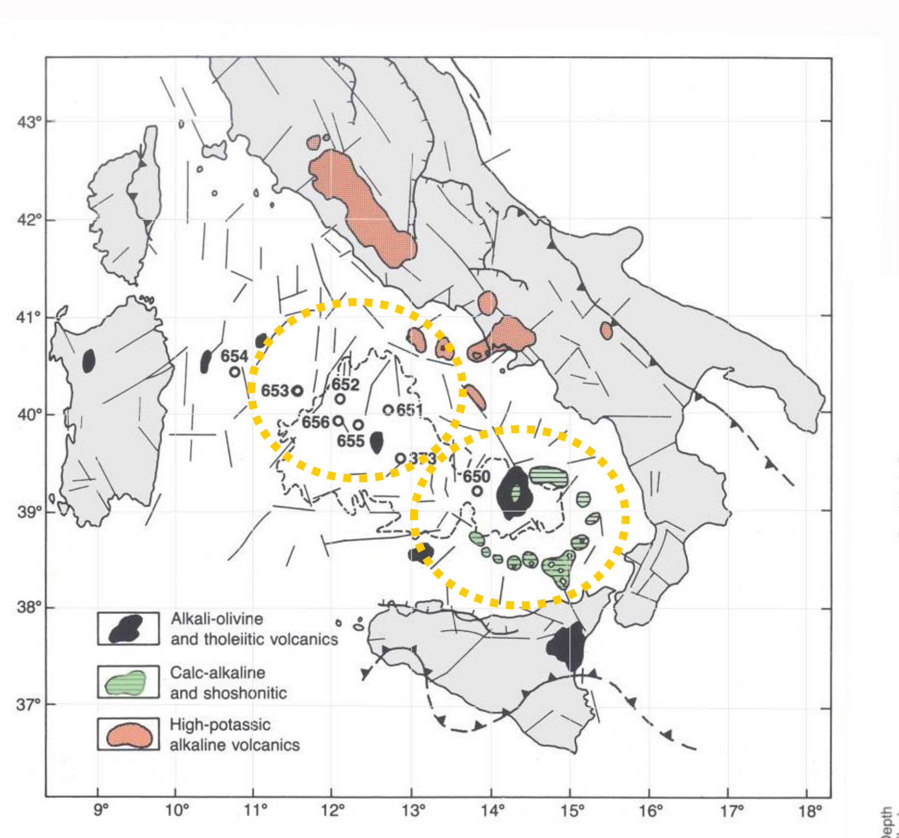
HF anomalies where heat input is young

HF vs. aeromag anomalies

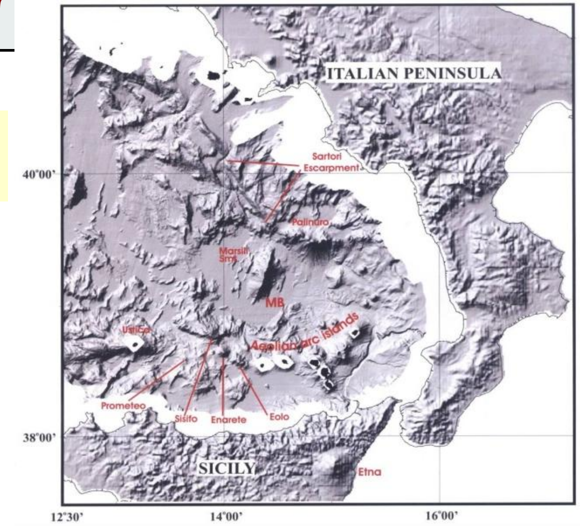




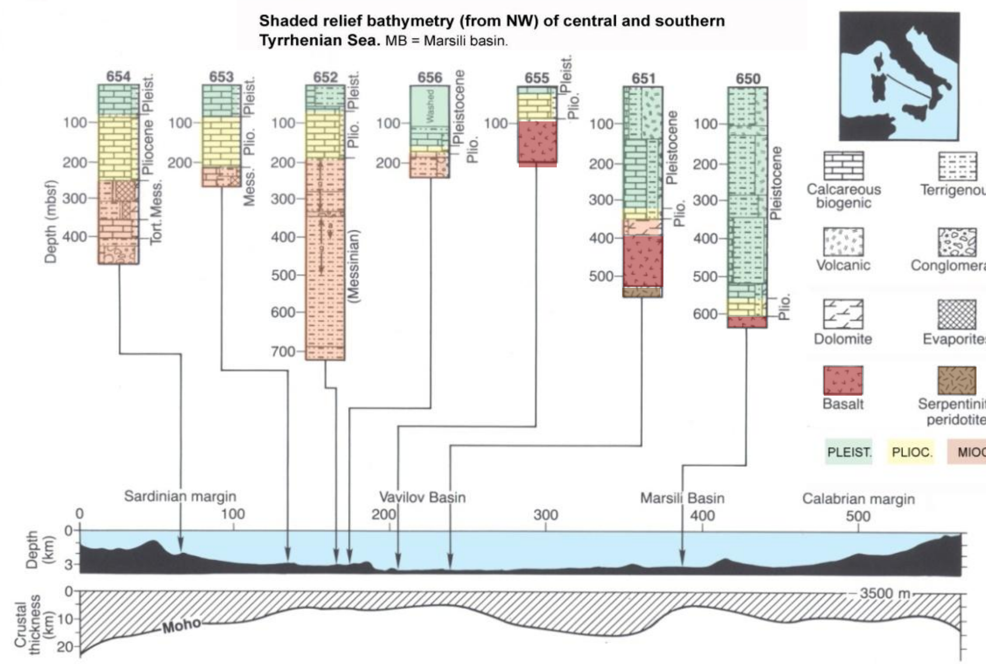
DSDP e ODP borehole data



Pleistocene volcanism in and around the Tyrrhenian Sea. After Sartori (1986).

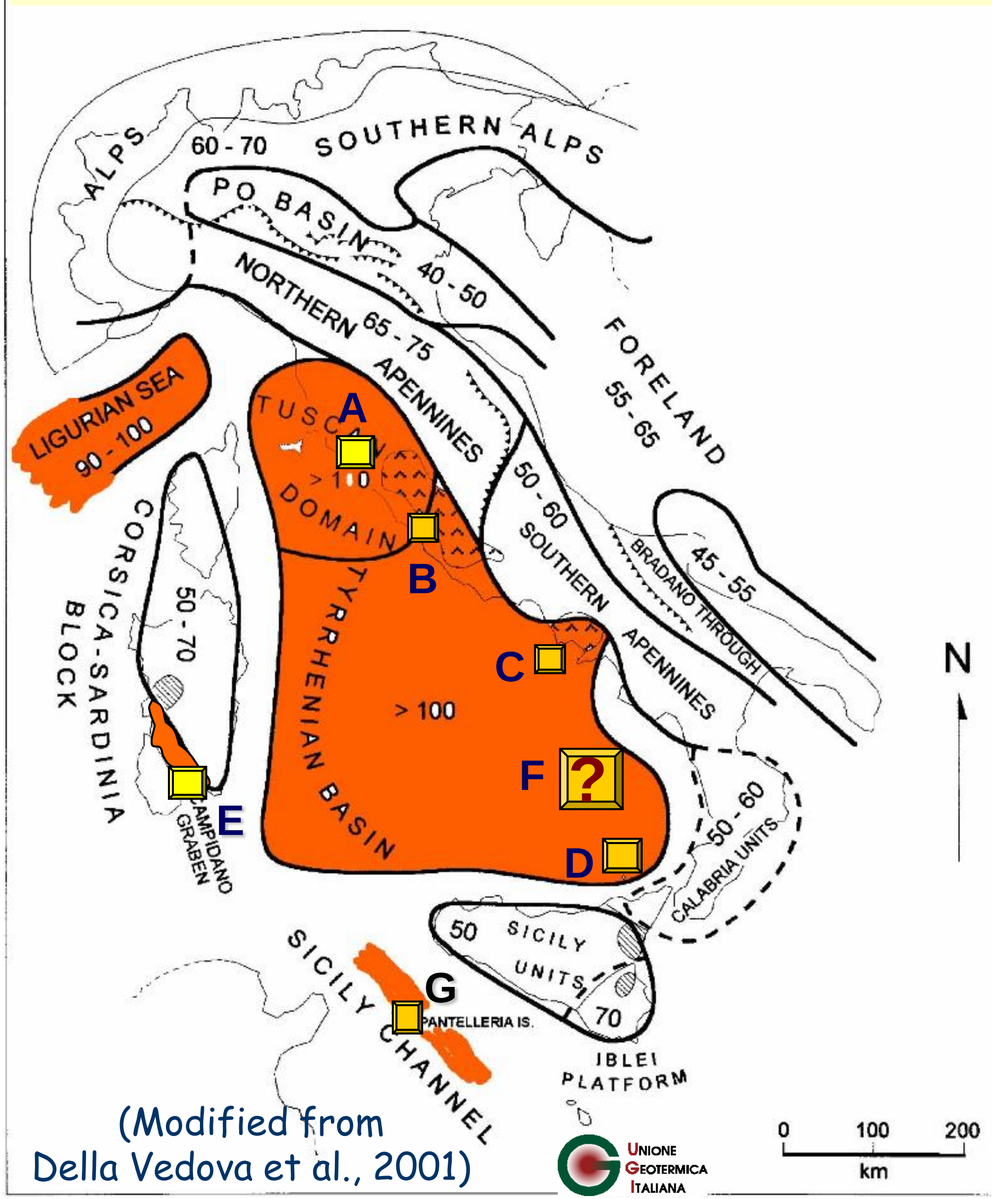


Shaded relief bathymetry (from NW) of central and southern Tyrrhenian Sea. MB = Marsili basin.



Max. T gradient in boreholes: 100-150 °C/km

Offshore, Islands and Coastal Areas Potential



(Modified from
Della Vedova et al., 2001)

A.) **Coastal areas of Toscany**
T≥ 150 °C at ~ 2 km

B.) **Latium Province**
T≥ 150 °C at ~ 2 km

C.) **Flegrean Province**
T≥ 200 °C at ~ 2 km

D.) **Eolian Is.**
T≥ 200 °C at ~ 2 km

E.) **Sardinia (Campidano Graben)**
T≥ 150 °C at ~ 2 km

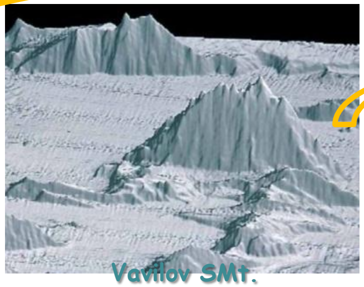
F.) **Submarine volcanoes Palinuro, Marsili**
T≥ 200 °C at ~ 1,5-2 km below sea floor

G.) **Sicily Channel (Pantelleria Is.)**
T≥ 250 °C at ~ 2 km

Shallow water resources <200 m (red and orange patterns)

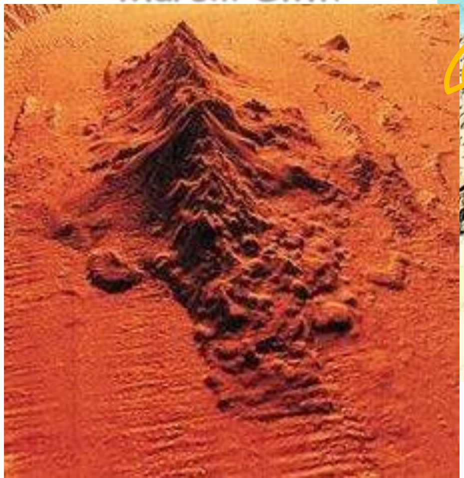
Deep resources (circles)

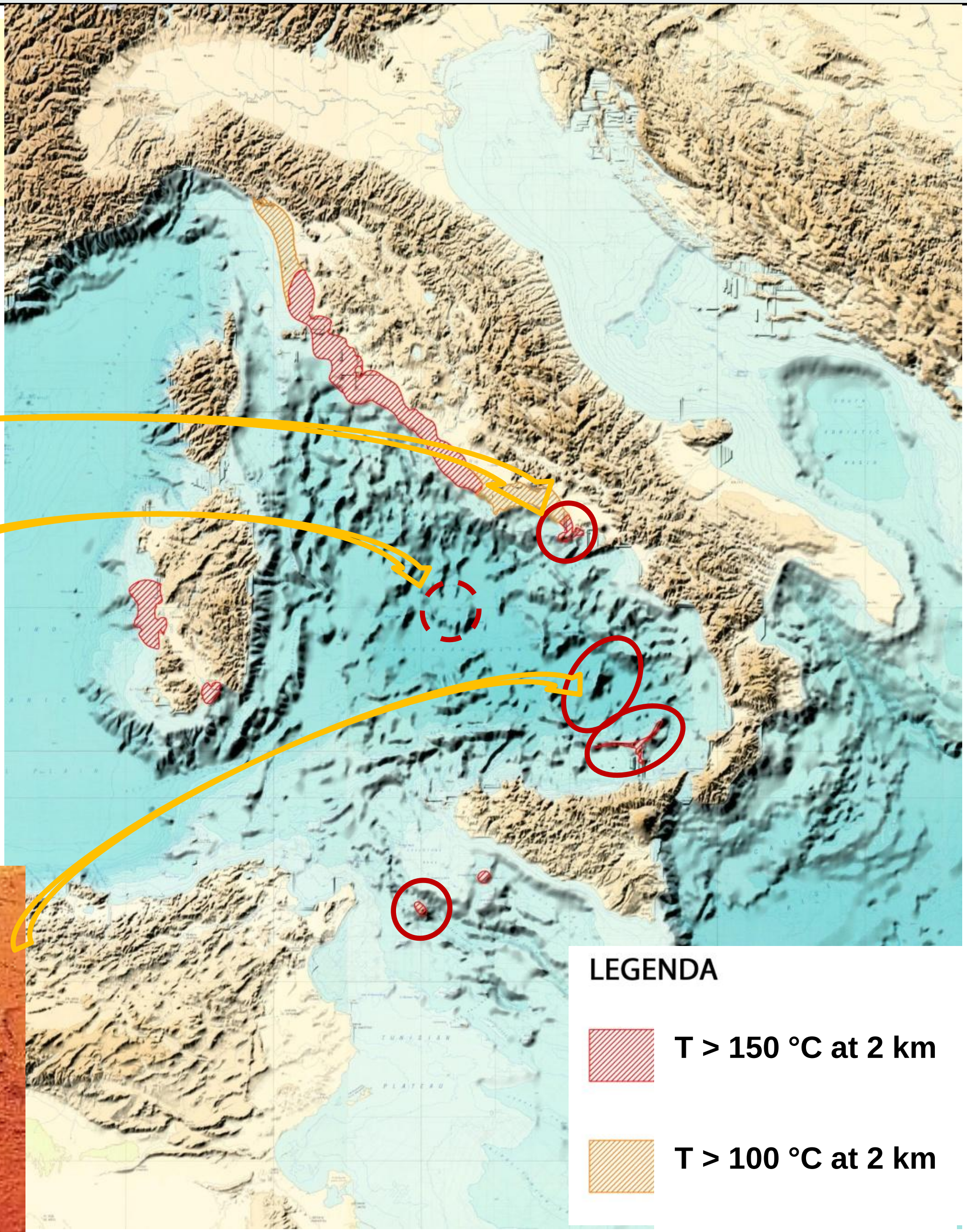
Campi Flegrei Deep Drilling Project



Vavilov SMt.

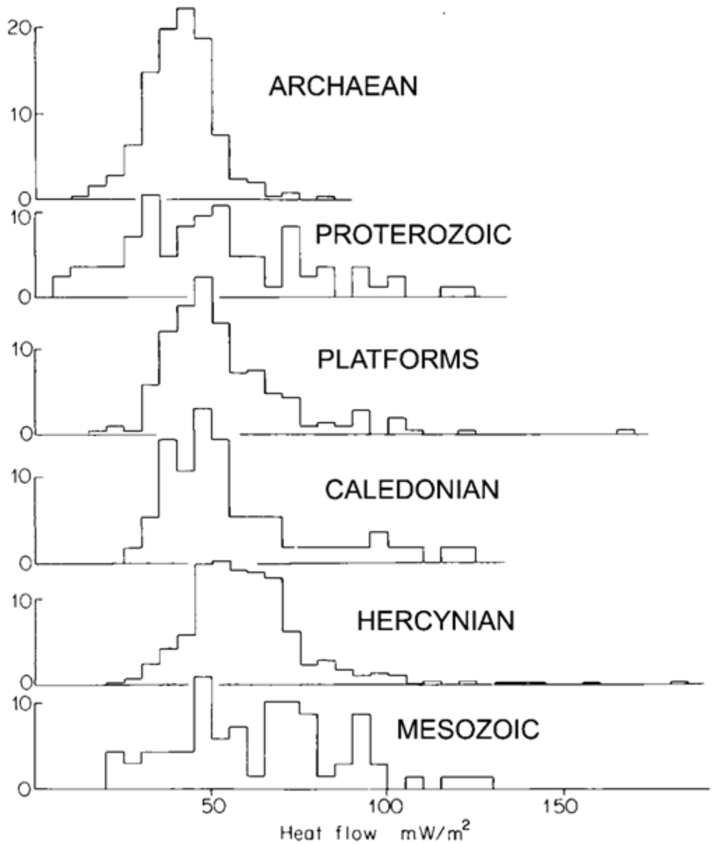
Marsili SMt.



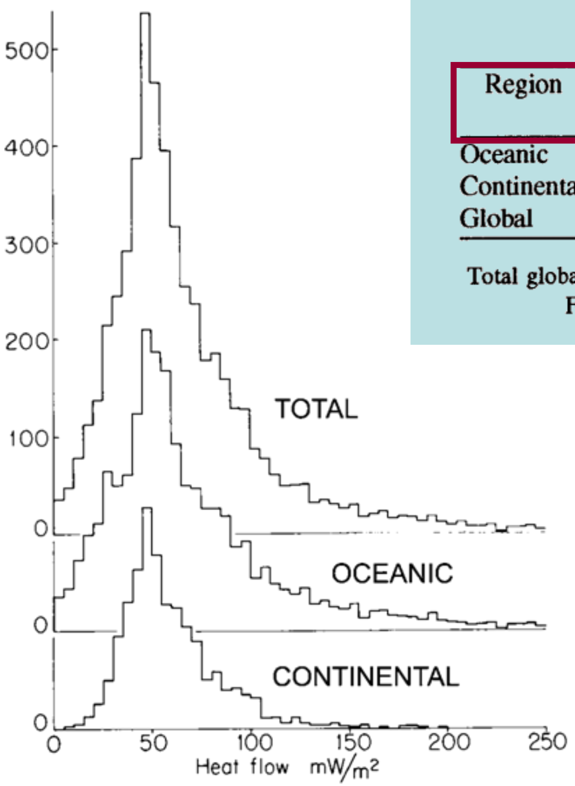


HF in different structural settings

CONTINENTS



CONT. vs. OCEANS



Global Heat Flow

Region	Mean heat flow ($mW\ m^{-2}$)	No. Data
Oceanic	101 ± 2.2	9864
Continental	65 ± 1.6	10337
Global	87 ± 2.0	20201

Total global heat loss= $4.42 \pm 0.10 \times 10^{13}$ W
From Pollack et al. [88].

(Stein, 1995)

Jessop, 1990

HF: clock of thermotectonic events

- **Lithosphere is cooling**: HF decays with *t*
- **Transient HF component**: clock of thermotectonic events
- **Substantial difference between oceans and continents**:
  - **oceanic HF** is a function of age: $q(t) = A \cdot t^{-1/2}$
  - **continental HF** is proportional to the radioactive heat production within the crust and decreases with *t*

Continental HF $q = q_r + DA_0$

$A(z) = A_0 e^{-(z/D)}$

Time-dependent solution

Consider the one dimensional heat diffusion equation with zero fluid velocity and no heat sources:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\kappa}\frac{\partial T}{\partial t} = 0$$

Writing out the heat equation in dimensional form:

$$\frac{T}{L^2} = \frac{T}{\kappa\tau}$$

where L is a lenght scale and τ is a time scale.

$$\frac{L^2}{\kappa} = \tau$$

Characteristic time

A 100 km thick slab with $\kappa = 10^{-6}$ m^2 s^{-1} would cool (or heat) in more than 50 Ma

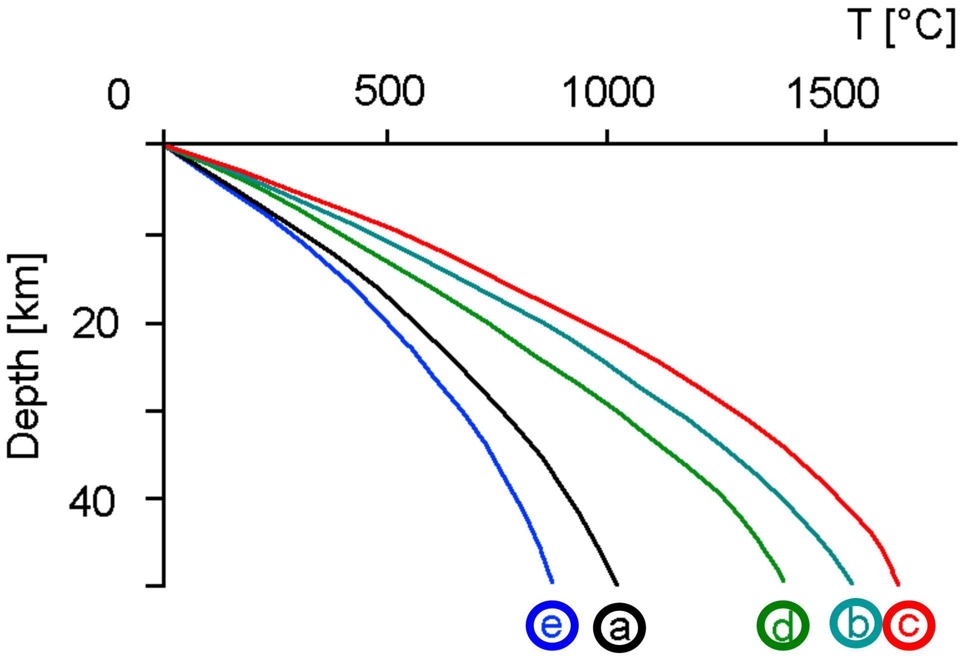
Steady state equilibrium geotherms

1-D Heat conduction Eq.

$$\partial^2 T/\partial z^2 = - A/K$$

$$T(z) = (A/2K)\, z^2 + (Q_b/K)\, z$$

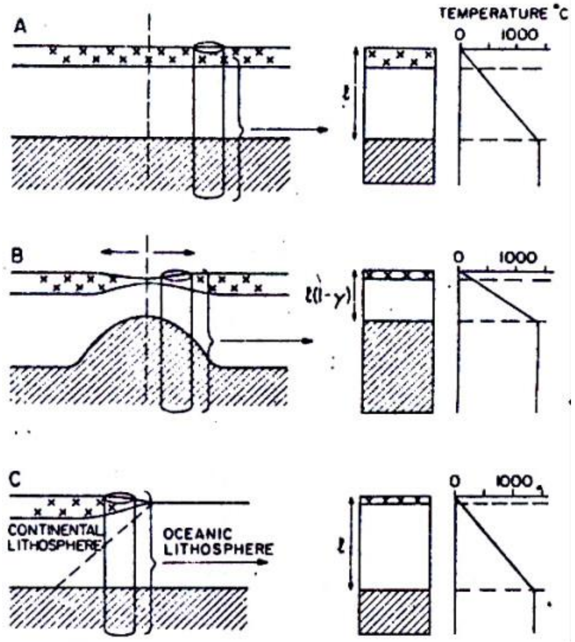
#	K (W/m·K)	A (μW/m³)	Q_b (mW/m²)	G (mK/m) Sh	G (mK/m) Deep
ASM	2.5	1.25	21	30	~15
B	**1.7**	1.25	21	45	~20
C	2.5	**2.5**	21	50	~20
D	2.5	1.25	**42**	40	~15
E	2.5	1.25	**10.5**	27	~10



Continental Rifting Models

Transient heating by extension, thinning, intrusion, faulting

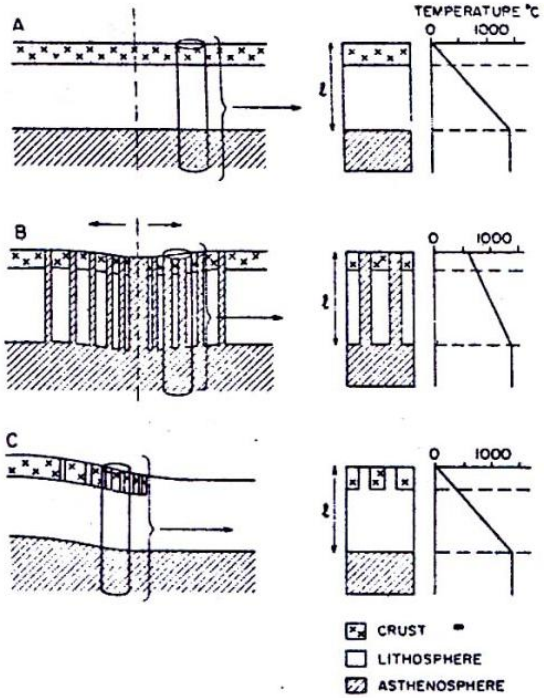
Pure shear model (McKenzie, 1978)



We need good data to:

- model steady-state & transient heat transfer, conduction & convection
- reconstruct tectonic history

Dike intrusion model (Royden et al. 1980)



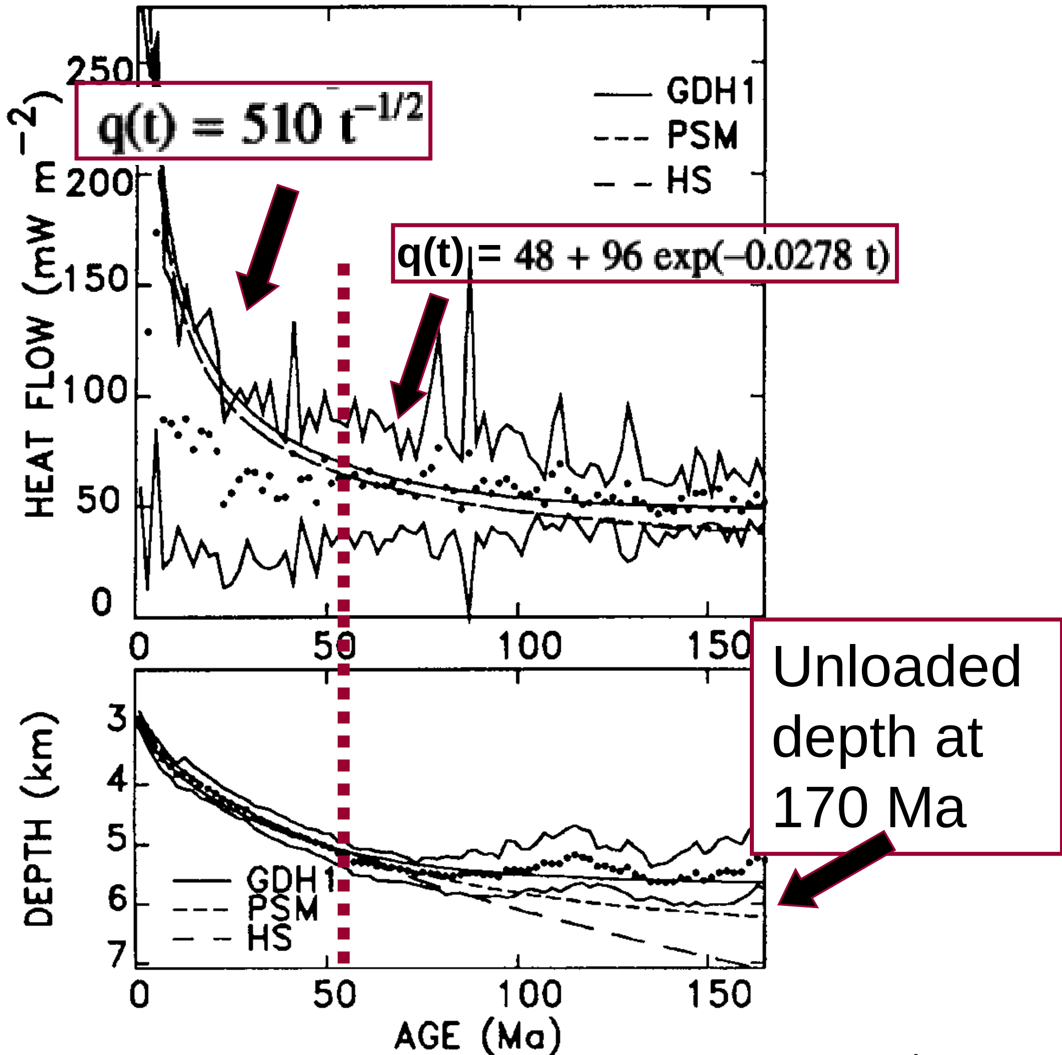
- HF anomalies inversely related to streching factor ß
- Rifting HF anomalies dissipate in less than 100 Ma

Localized HF anomalies over shallow/recent convective sources

Oceanic Data and Models

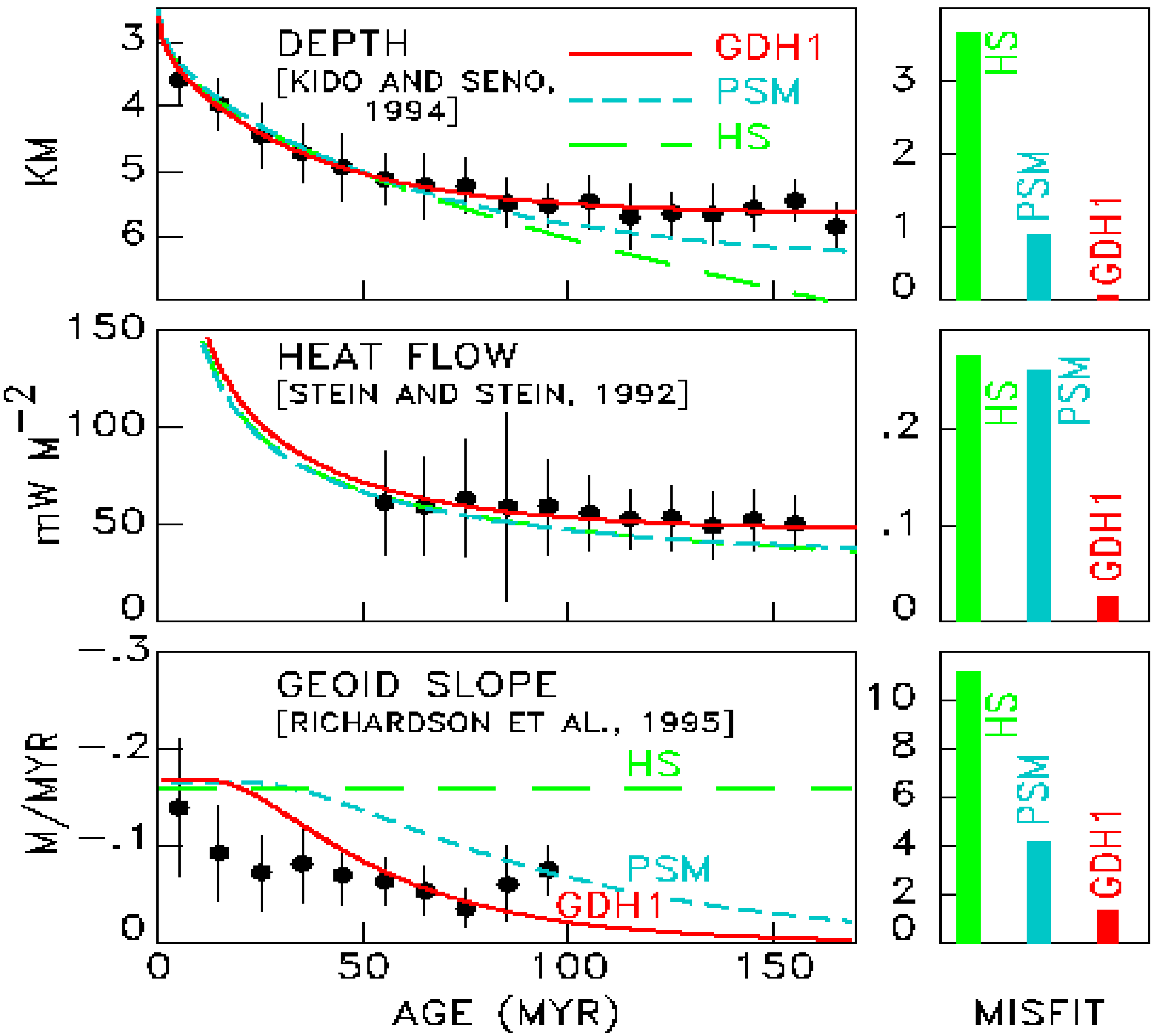
Mean HF = 100 mW^{-2}

- Depth and HF anomalies reflect thermal state of the lithosphere
- Advection dominates for t<55 Ma
- Conduction dominates for t>55 Ma
- Oceanic cycle is a primary mode of heat transfer: the crust loses heat and contracts with time



Stein and Stein, 1992
Parsons and Sclater, 1977
Half-space model

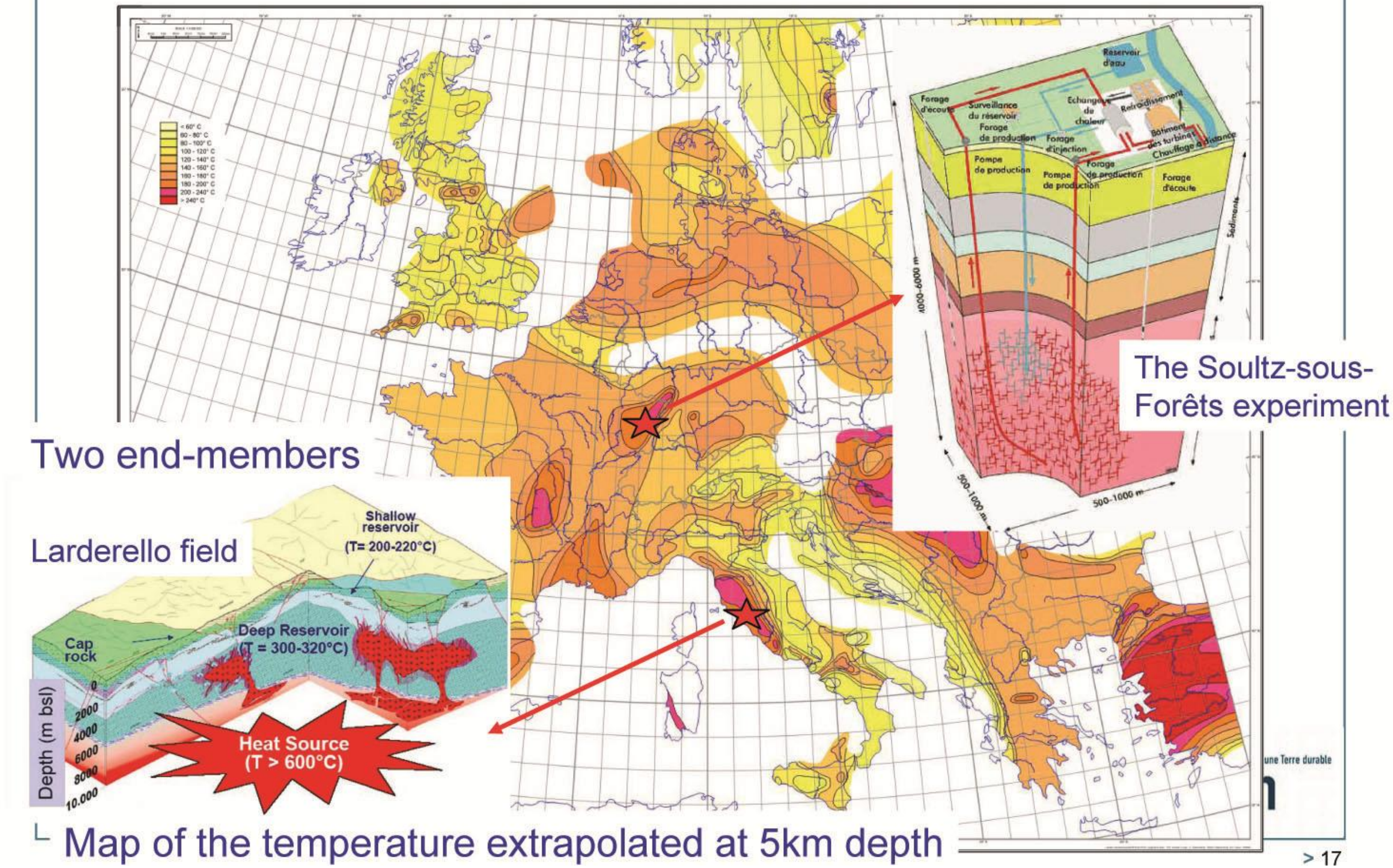
Comparison among different Models



Summary:

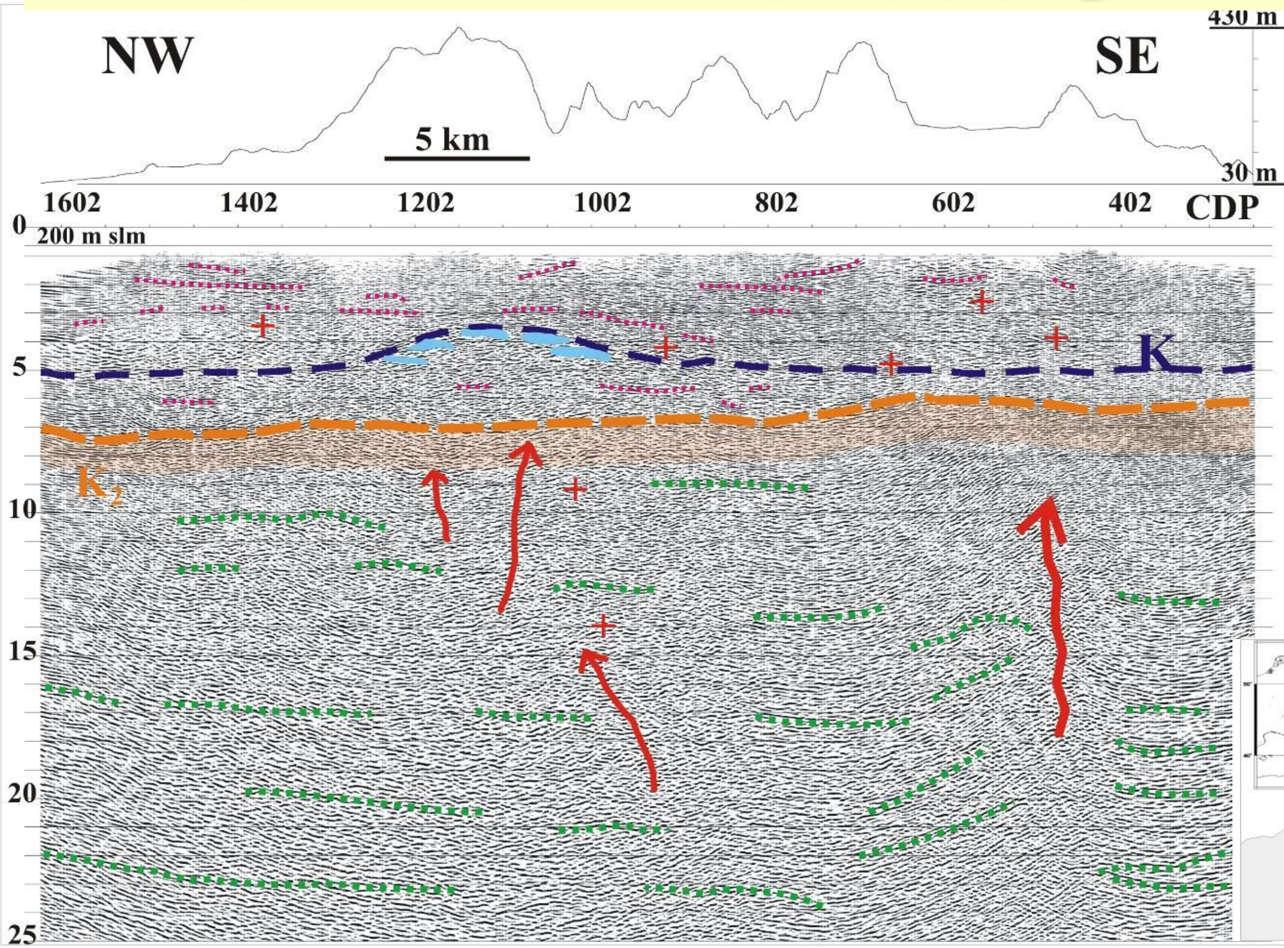
- Heat & heat transfer processes
- Heat flow measurements
- Geologic/Geodynamic significance
- An example: Lardarello ......

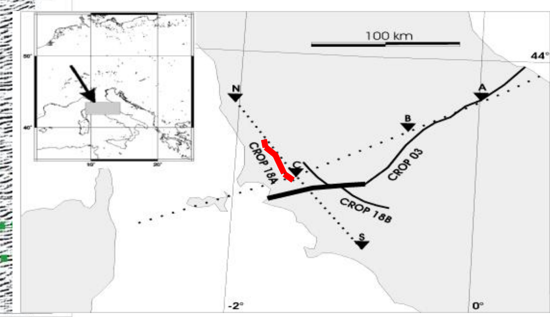
The Enhanced Geothermal System concept, a perspective for continuous base load-power generation in 20/30 years ?



(after Genter, Huenges, 2006)

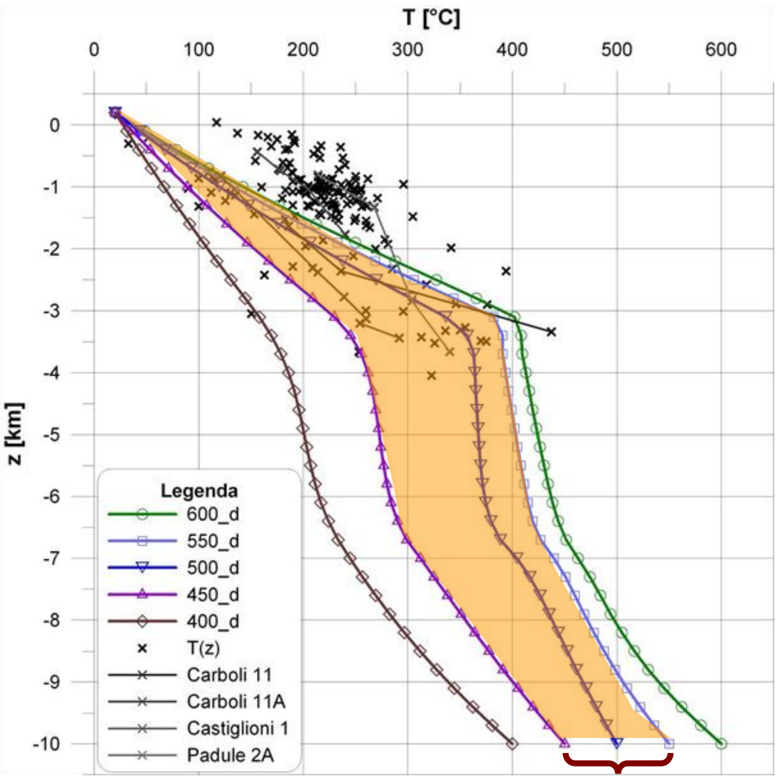
CROP 18-A across Larderello

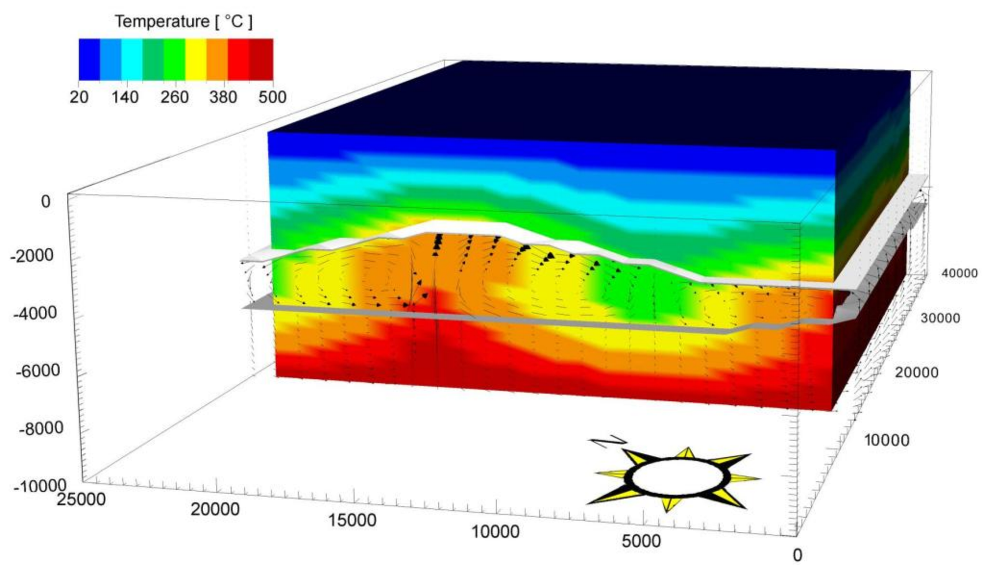




(modified from Accaino et al., 2005)

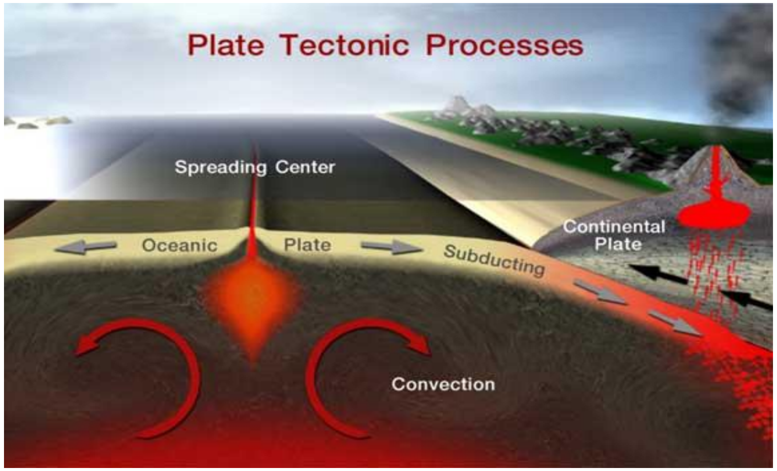
Larderello geothermal field T modelling
(Della Vedova et al., 2007)



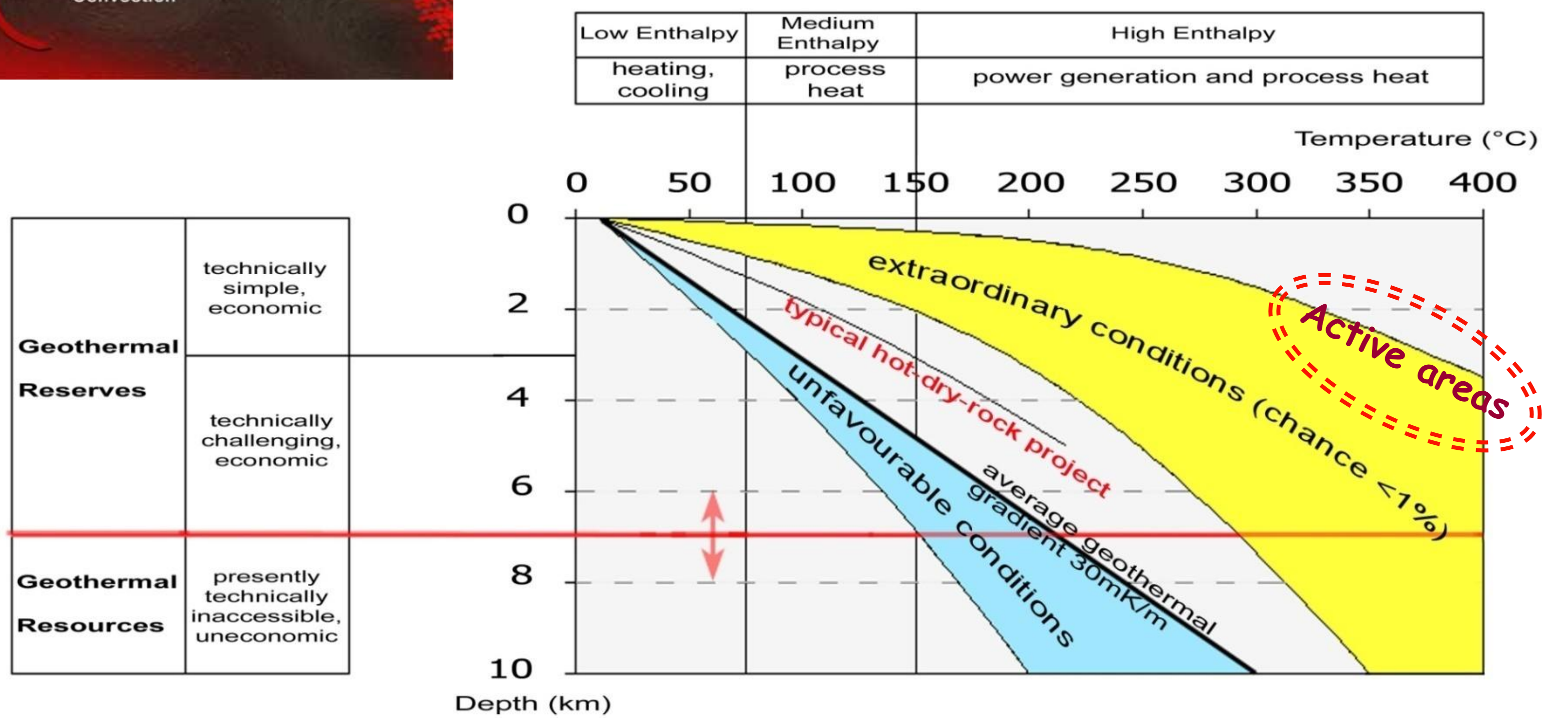


500 ± 50 °C

Geothermal Resources & Reserves



- Heat potential is enormous
- Present at shallow depth in active areas
- Better resources Atlas needed

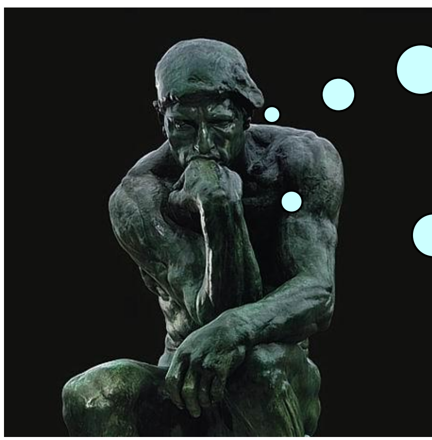


(Modified after B. Cociancig)

THANKS FOR YOUR ATTENTION

PLEASE VISIT THE UGI WEB SITE

http://www.unionegeotermica.it/



What?
Where?
Why?

- T(z) is crucial indicator
- HF controls geodynamics
- Heat is a huge resource

School of Geothermics, ICTP Trieste

Nov. 30, 2011