National Research Council of Italy

Institute of Geosciences and Earth Resources

Geothermal potential and favourability: data integration for resource assessment

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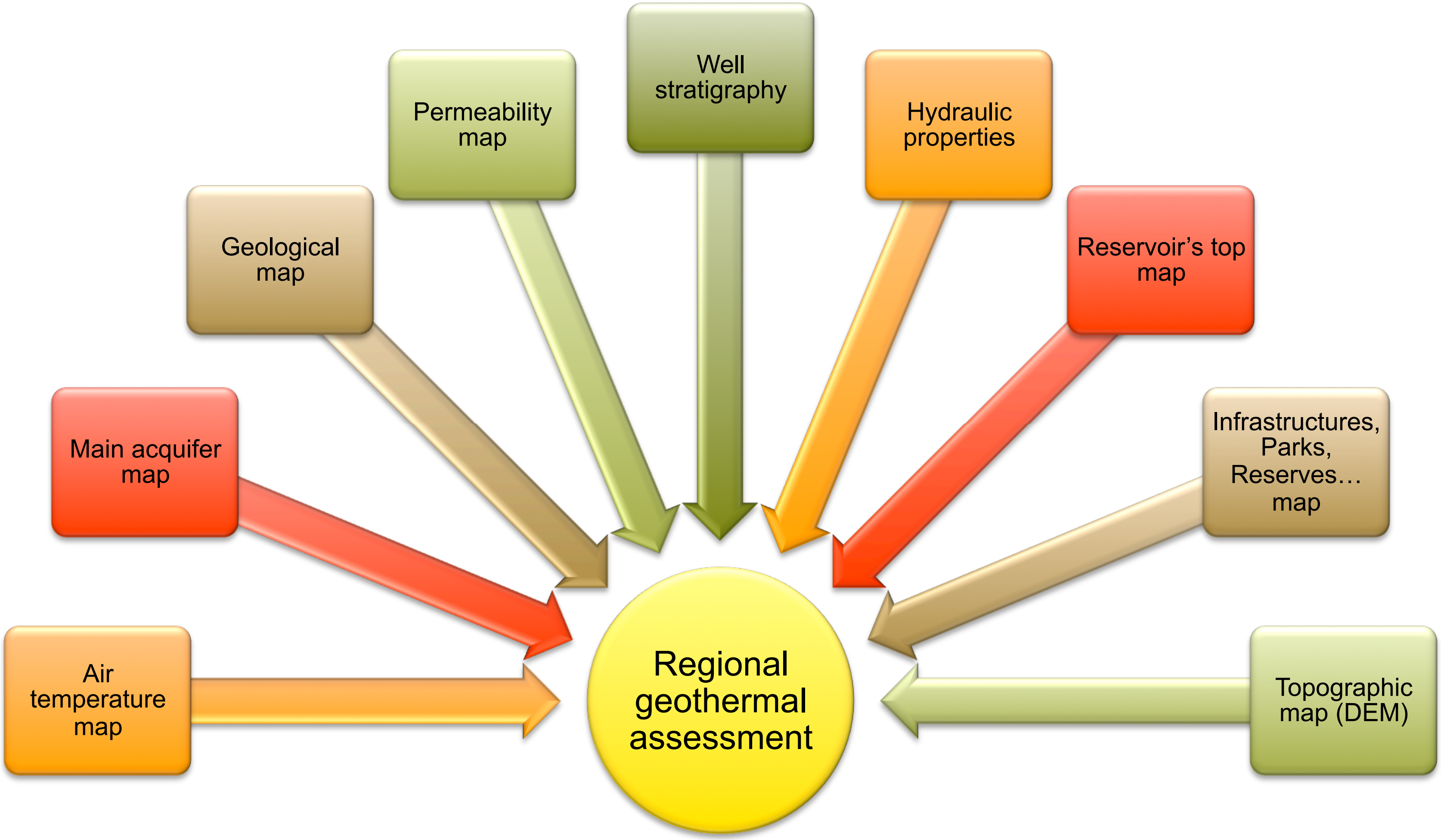
Taking advantage of Geographical Information System (GIS) technology, actual Geothermal Atlases may extrapolate at regional scale the approach used at local scale, providing modern products for evaluating and comparing geothermal resources and imaging semi-quantitative (favourability) and quantitative (potential) assessment of geothermal resources.

The maps are useful for the planning and development of geothermal applications on regional and national scale and represent important tools for all geothermal stakeholders: i) decision makers can use them to establish new policies aimed at fostering geothermal energy, ii) investors can establish where the most promising locations for geothermal exploitation are and calculate the amount of energy available for a specific application.

REGIONAL ASSESSMENT

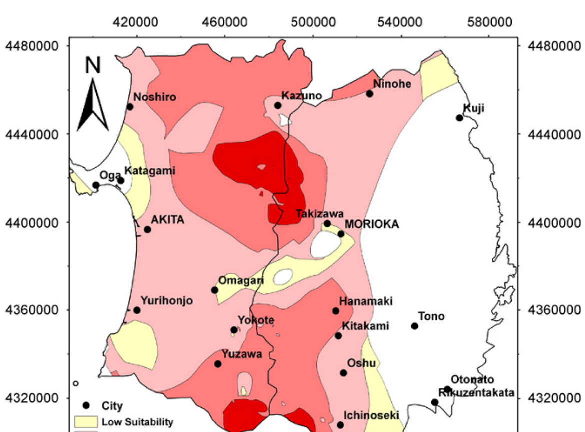


Favourability maps

GIS software provides tools for the spatial analysis of multiple parameters to assist selection of prospective sites, based on pre-defined criteria.

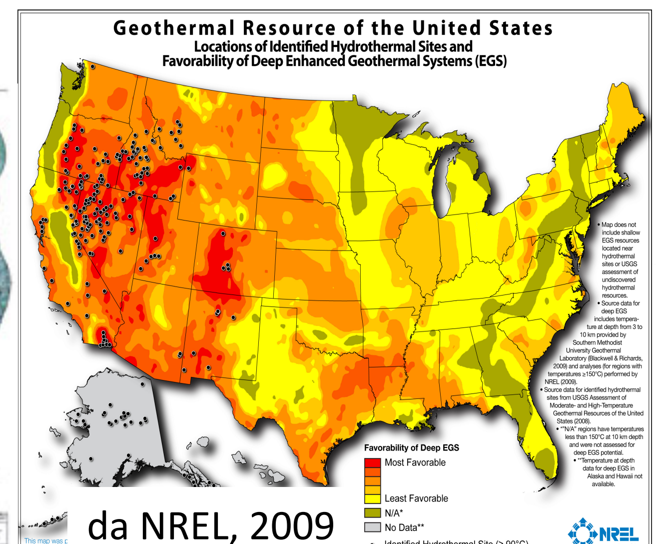
The **favourability** assessment of geothermal resources may focus on conventional and unconventional geothermal systems

- ≠ geothermal potential (energy)
- Geothermal favourability maps relies on available data and refer to a territory favourable and suitable to have the geothermal resource in the underground.
  - In most studies, areas are classified as more or less favourable to the potential use of geothermal resources for **power production**
- Many studies have been carried out in the last 10 years with different approaches



da Noorollahi et al_2007


da Coolbaugh et al., 2005



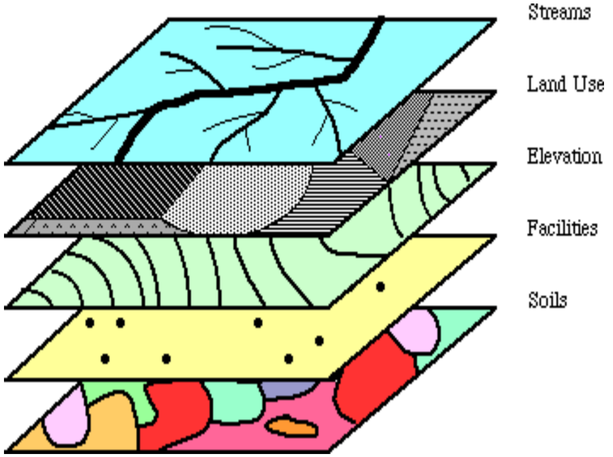
da NREL, 2009

METHODOLOGY

- Geothermal favourability depends on different factors (e.g. geological aspects, temperature distribution etc..)

- Geographical Information System (GIS) allows favourability maps production combining some maps as input

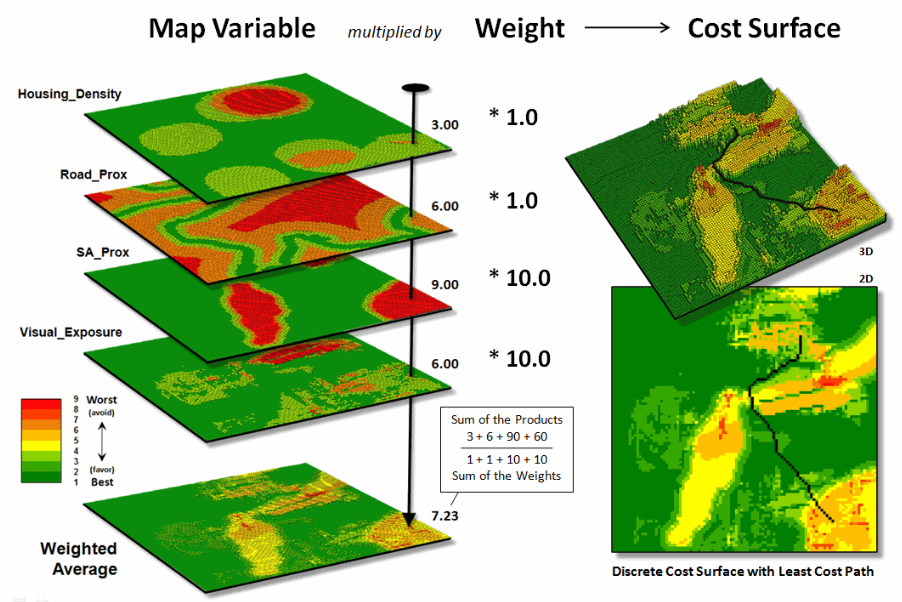
Output map = ***f*** (2 or more input maps)



- The function *f* can be driven by knowledge or data approaches

Index Overlay

- Input data were converted in raster maps
- Each input map is scored and weighted



- where F is the weighted score per area object (pixel)
- Wi is the weight for i-*th* input map
- Sij is the score for j-*th* class of the i-*th* map, the value of j depending on the class actually occurring at the current location

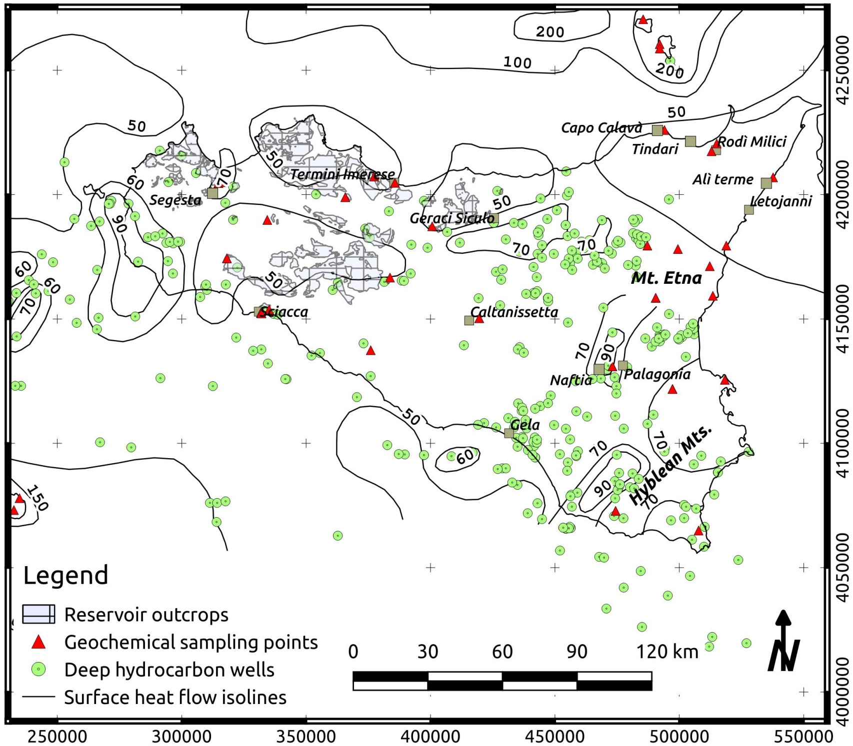
- Allows for a more flexible combination of maps than is possible with a Boolean logic operations
- The scores and map weights can be adjusted to reflect the judgment of an expert in the domain of application under consideration

THERMAL FEATURES IN SICILY

We have proposed an approach for a fully integrated analysis in order to classify the hydrothermal resources hosted by regional reservoirs and suitable for power production and applied it to Sicily.

The heat flow density shows some anomalies (up to 90 mW/m^2) located in eastern Sicily (south of Mt. Etna) and in south-west Sicily

There are several thermal manifestations in Sicily (temp. up to 56°C)



Input Data

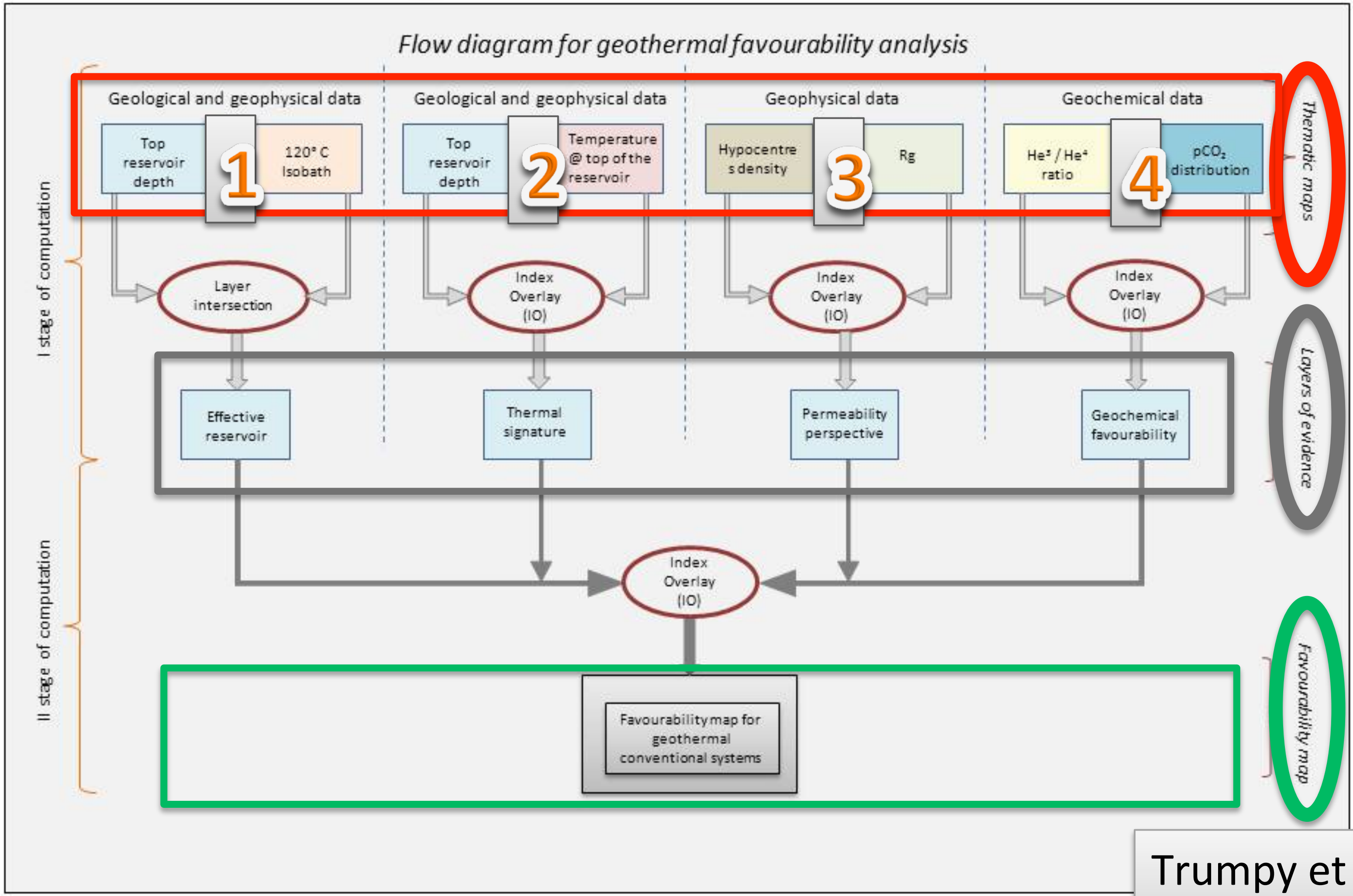
Parameters

- Reservoir
  - **Geometry** of the top of the Geothermal reservoir
  - Petrophysic characteristic of the reservoir
- Underground temperature field
  - Litothermal units definition
  - 3D Temperature distribution
  - Temperature at top surface of the reservoir
- Geochemical indicators
  - Areal distribution of factors indicating the presence of thermal anomaly or specific hydrothermal circulations
- Hydraulic aspects of the reservoir
  - Factors influencing the hydraulic properties of the regional reservoir (seismologic analysis, faults, …)

Thematic maps/layers of evidence

- Effective reservoir
  - Top reservoir depth
  - 120°C isobaths surface
- Thermal signature
  - Temperature at top of the reservoir
- Geochemical favourability
  - $^3He/^4He$ ratio
  - pCO_2 distribution
- Permeability perspective
  - Hypocentre density
  - Cover thermal gradient/reservoir thermal gradient ratio (Rg)

THE APPROACH IN A SHOT



Trumpy et alii, 2015

1 EFFECTIVE RESERVOIR

Intersection between:

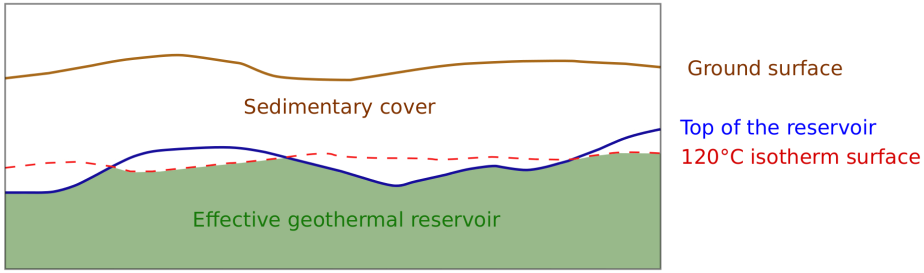
- **Reservoir's top depth map**
- **120°C depth map** (from thermal model)

120° C chosen on the basis of knowledge driven technical and economic factor

Layer of evidence	weight	Thematic map	weight	Score				
				5	4	3	2	1
Effective reservoir	0.4	Effective reservoir surface depth (m)	-	≤ 1500	1500 – 2500	2500 – 3500	3500 – 4500	> 4500

A depth-based scoring of this layer was performed by considering the drilling costs as a function of well length

Cross-section explaining the concept of effective reservoir



2 THERMAL SIGNATURE

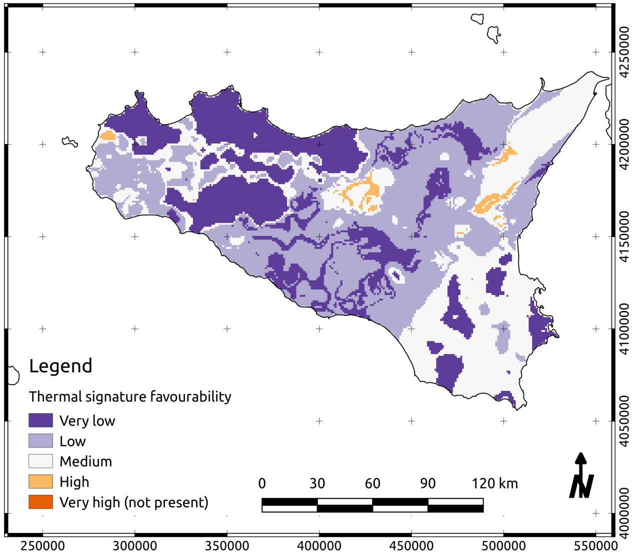
Index Overlay between:

- **Reservoir's top depth map**

  on scoring operation we consider the negative effect of the meteoric water infiltration

- **Temperature map at the top of the reservoir**

  minimum and maximum temperature was chosen on the basis of knowledge driven technical and economic

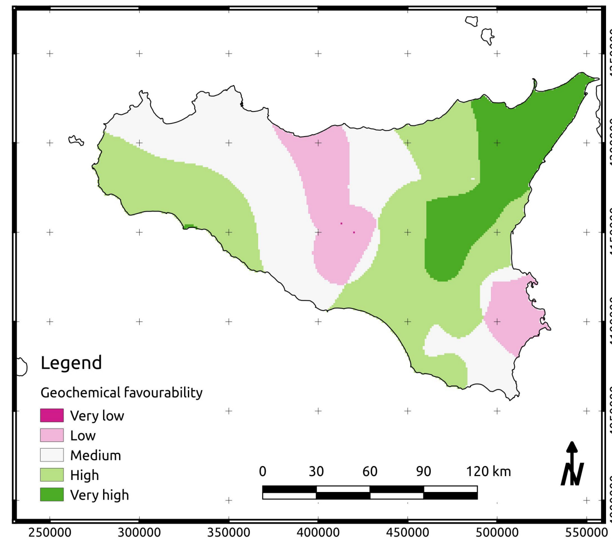


Layer of evidence	weight	Thematic map	weight	Score				
				5	4	3	2	1
Thermal signature	0.3	Temperature at top surface of the reservoir	0.5	≥ 190	160 – 190	140 – 160	120 –140	< 120
		Top of the reservoir depth (m)	0.5	500 – 1500	1500 – 2500	2500 – 3500	3500 – 4500	> 4500 e ≤ 500

3 GEOCHEMICAL FAVOURABILITY

Index Overlay between:

- **R/Ra ratio map**
- **pCO2 map**



- the $^3He/^4He$ ratio is a good indicator of the presence of mantle magmas residing in the crust
- the CO_2 is a good indicator of degassing hydrothermal/metamorphic systems, possibly located around and above the magma chamber itself

Layer of evidence	weight	Thematic map	weight	Score				
				5	4	3	2	1
Geochemical favourability	0.15	He R/Ra	0.5	≥ 5.0	4.0 – 5.0	3.0 – 4.0	1.5 – 3.0	< 1.5
		$\log(pCO_2)$ (atm)	0.5	> 0.0	0.0 – -1.0	-1.0 – -2.5	-2.5 – -3.5	< -3.5

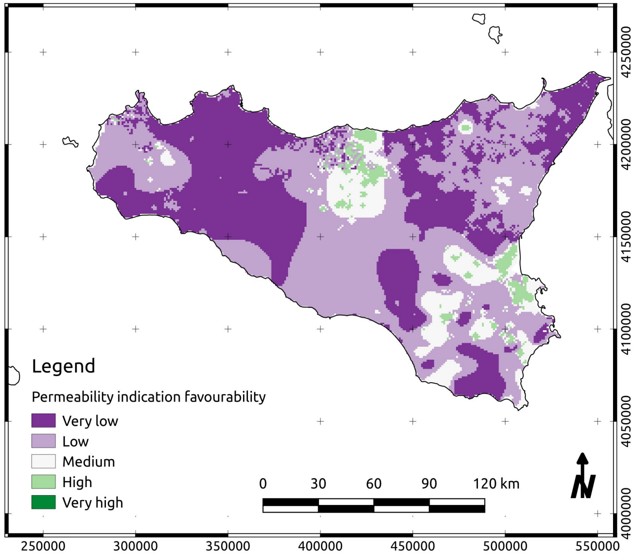
4 Permeability perspective

Index overlay between:

- **Hypocentre density map**
- **cover / reservoir thermal gradient ratio**

$$Rg = \frac{k_2}{k_1} = \frac{G_1}{G_2}$$ for a two layer model

focused our structural interpretation on seismological data as a possible indicator of open fracture systems and high permeability



Layer of evidence	weight	Thematic map	weight	Score				
				5	4	3	2	1
Permeability perspective	0.15	Hypocentre density (number/km^2)	0.5	> 10	3 – 10	1 – 3	0.1 – 1	≤ 0.1
		Rg	0.5	≥ 3.5	2.5 – 3.5	1.8 – 2.5	No cover	< 1.8

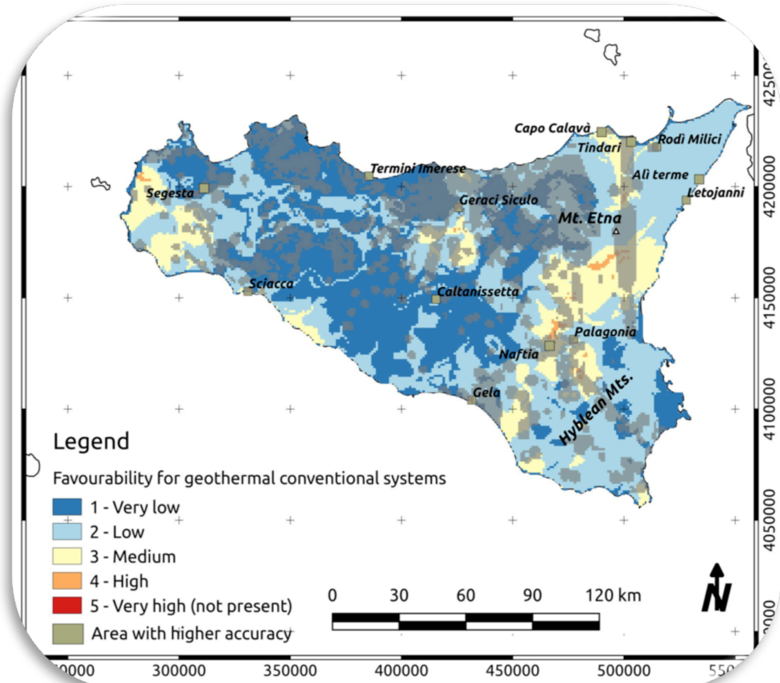
In a conductive steady state layered model without an internal heat source, once we define a basal heat flux, the thermal gradient are inversely proportional to their respective thermal conductivity.

FAVOURABILITY MAP

The map shows the areas of Sicily where geological conditions are likely to host hydrothermal systems at depth, and are thus suitable for a more detailed exploration

The reliability of the favourability map relates mainly to the accuracy of data and the number of measuring sites: unfavourable should not be confused with unknown!

In our study we applied simple spatial operators (i.e., buffer, merge, union) to obtain the accuracy of: (i) geological data, (ii) geochemical data, (iii) seismological data, and (iv) thermal data



Reliable areas > 0.5 – the grey areas in the map

MAIN ADVANTAGES OF FAVOURABILITY CONCEPT

- ❑ Fully integrated approach to rank favourable conditions
- ❑ Highly flexible: with a simple reclassification it can integrate other information, consider different geological conditions and other kind of resources (e.g EGS-conductive)

Favourability maps are useful for highlighting the most interesting areas for detailed assessment. They, however, do NOT provide quantitative values.

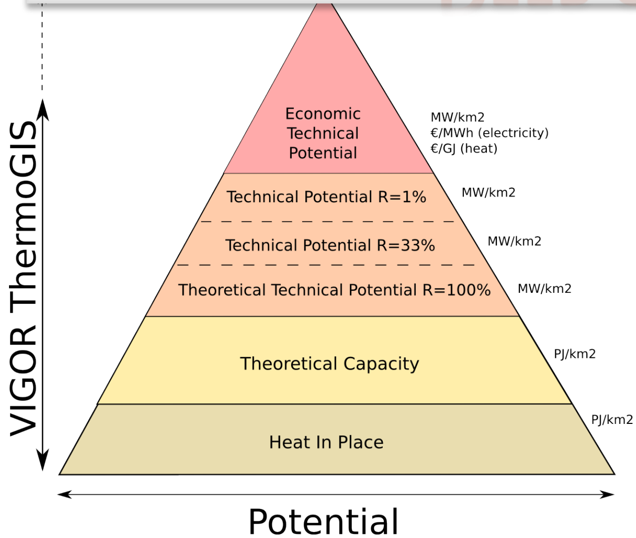
Geothermal potential

As for any form of energy resource, the estimation of energy potential is fundamental to assess the economic benefits and the management plan of its exploitation.

For deep geothermal resources, it provides the thermal energy to be used in various forms of direct uses or the producible geothermal power.

For shallow geothermal energy this requires a reliable quantification of geo-exchange potential of the ground combined with the use of borehole heatexchangers (BHEs) coupled with a heat pump for heating/cooling purposes of residential buildings.

DEEP GEOTHERMAL POTENTIAL



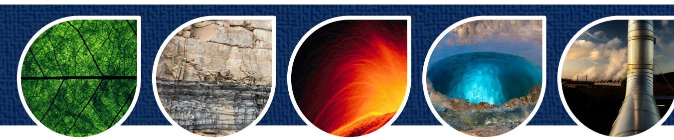
- Progressive filtering approach starting from the total heat stored in the deep-seated reservoirs to the evaluation of the heat which can be extracted from the aquifers
- Volumetric Method
- Energy is extracted by a doublet (production and injection well)
- The subsurface is represented by a 3D voxet with horizontal resolution of 1000 m and vertical resolution of 100 m
- MonteCarlo simulation to incorporate the effects of uncertainty on permeability (P90, P50 and P10 values of transmissivity)

Data input:

- **Geometric** characteristic of the reservoir
- **Temperature** model distribution

Parameters:

- Fluid and Rock-fluid system physical properties
- Technical constraints (e.g. minimum inlet temperature and outlet temperature as a function of application)



Heat In Place [PJ/km^2]

It is the maximum theoretically extractable heat in the reservoir per unit volume (thickness = 100 m)

$H = V \times \boldsymbol{\rho}_{rock} \times cp_{rock} \times (Tx - Ts) \times 10^{-15}$

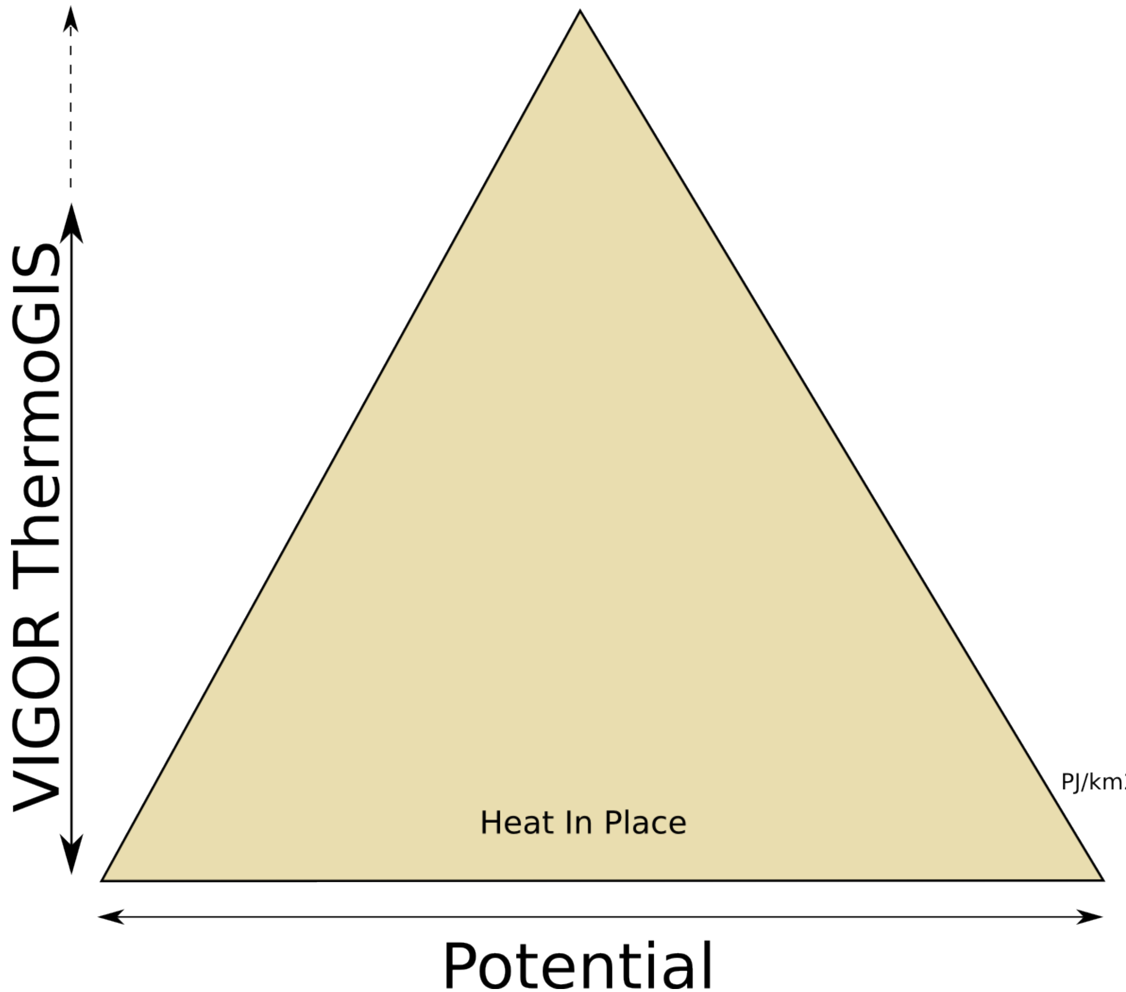
Tx = Temperature @ depth

Ts = Temperature @ surface

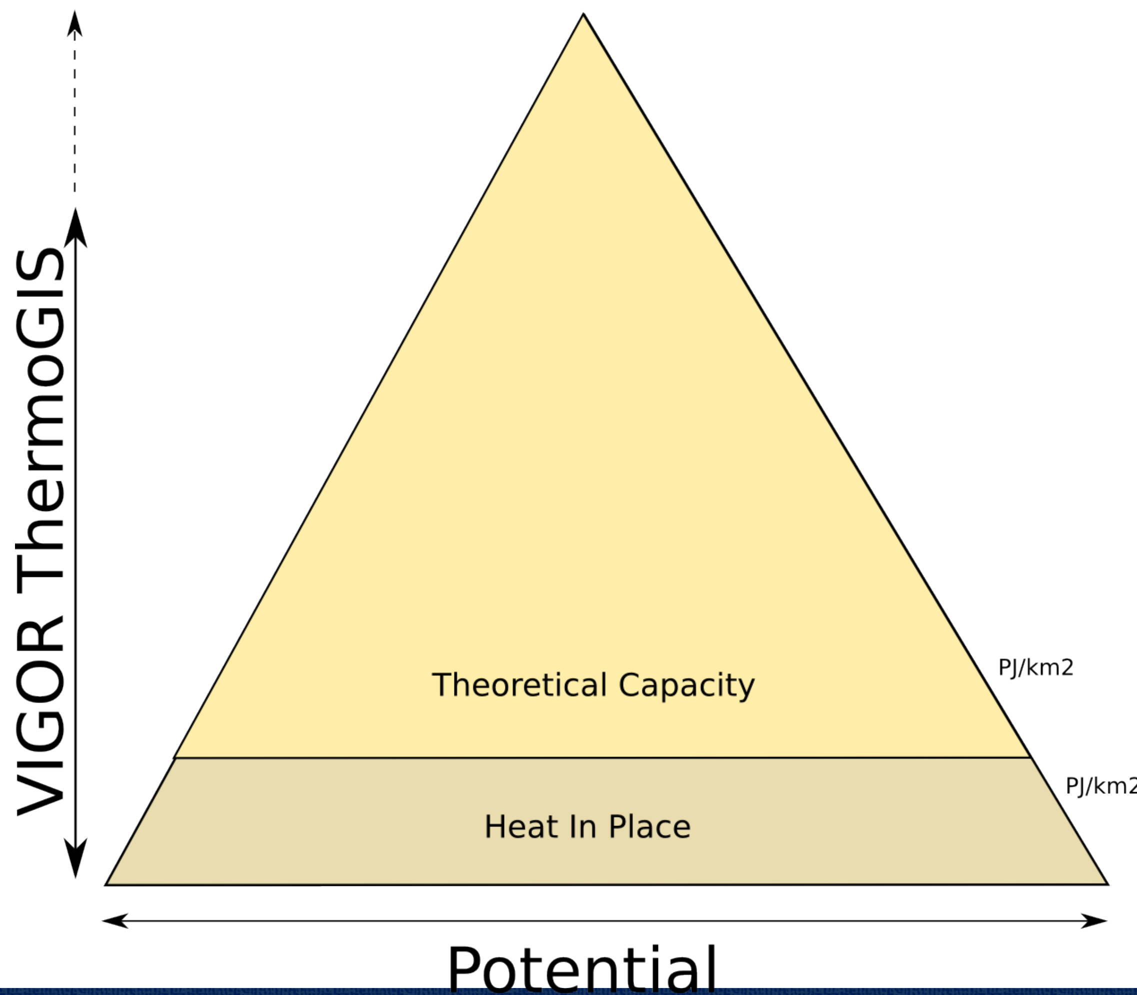
$\boldsymbol{\rho}_{rock}$ = 2700 kg/m^3 is density

cp_{rock}= 1000 J/kg k is specific heat

The map of H is calculated as the vertical sum of H in the grid cells belonging to the reservoir, divided over the surface area of the voxels (in our case 1 km^2)



Theoretical Capacity [PJ/km^2]



Thermal Energy produced by a technology per unit volume (TC=H x technology efficiency)

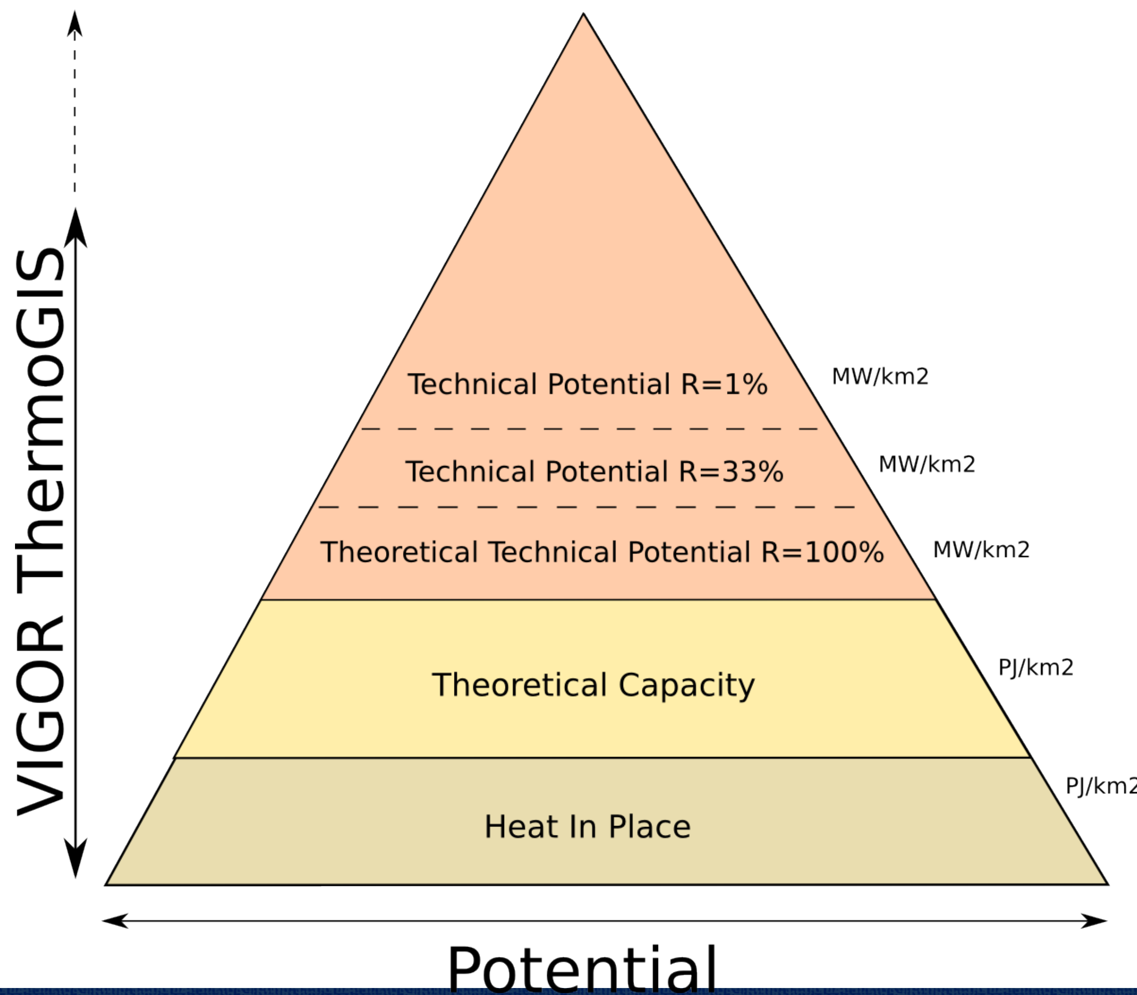
H is the maximum theoretically extractable heat in the reservoir per unit volume (thickness = 100 m)

Theoretical and Technical Potential [MW/km^2]

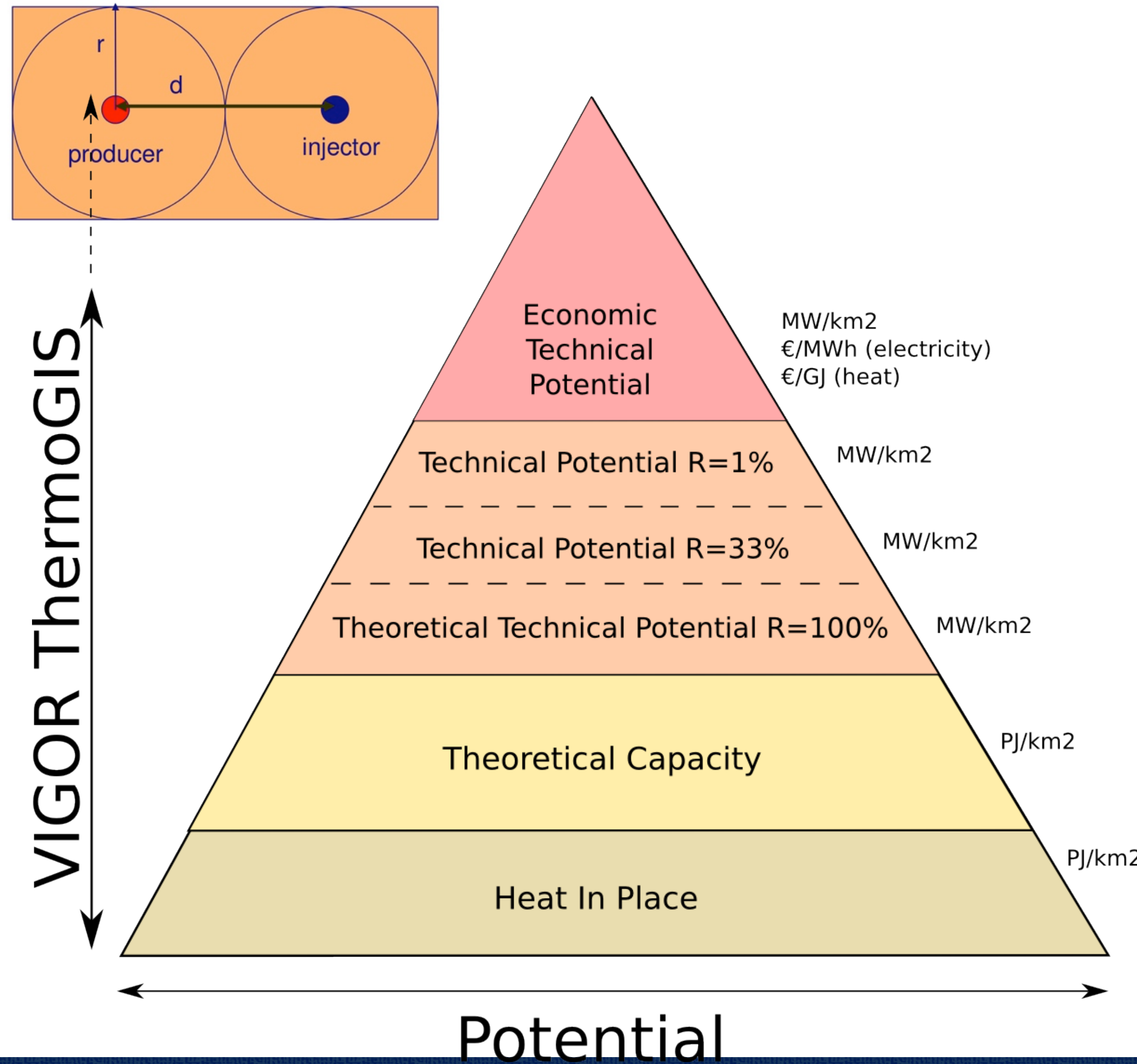
Geothermal Potentials for a lifecycle of 30 years and different Recovery Factors
(GP=TC x R / 30 years)

Thermal Energy produced by a technology (TC=H x technology efficiency) per unit volume

H is the maximum theoretically extractable heat in the reservoir per unit volume (thickness = 100 m)



Economic Technical Potential [MW/km²]



Technical Potential for LCOE < threshold (200 €/MWh power, 9 €/GJ heat) and using expected flowrate from a doublet system

Geothermal Potentials for a lifecycle of 30 years and different Recovery Factors (GP=TC x R / 30 years)

Thermal Energy produced by a technology (TC=H x technology efficiency) per unit volume

H is the maximum theoretically extractable heat in the reservoir per unit volume (thickness = 100 m)

The **Heat in Place** for each cell, H*i* , of the 3D grid results from the equation (Muffler and Cataldi [1978]):

$$H_i[PJ] = V_i * \rho rock_i * Cprock_i * (T_i - Ts) * 10^{-15}$$

The heat that can be extracted and used (**Theoretical capacity**) depends on the technology. Each application is characterized by technical parameters, such as the **efficiency of the thermodynamic cycle** (η), the **minimum operating temperature** (production temperature T*x*) and the output temperature (**re-injection temperature** Tr). In this case the reference temperature is not, any more, the surface air temperature but the re-injection temperature and the equation of the theoretical capacity becomes:

$$TC_i[PJ] = \eta * V_i * \rho rock_i * Cprock_i * (T_i - Tr) * 10^{-15}$$

At this stage of computation, those voxets that did not meet the minimum required temperature were rejected.

The **Technical Potential** (TP) returns the producible thermal energy during the mean plant lifespan, here considered as 30 years. The TP depends on the actual recoverable thermal energy from the reservoir. The recovery factor (R) denotes the practical efficiency of the thermal exchange between rocks and fluid.

$$TP_i \left[\frac{MW}{km^2}\right] = \frac{H_i * \eta * R * 10^{15}}{30\ year * (seconds\ per\ year) * 10^6} = 1.057 * H_i * \eta * R$$

where η is the efficiency.

Following (Di Pippo, 2007) $$\eta = \frac{T_i - Ts}{T_i + Ts + 2 * 273.15K} * 0.6$$

R, the recovery, is a key factor, and ranges from 0.01 for an Enhanced Geothermal System (EGS) (IPCC, 2011) to the theoretical maximum value of 0.5 for a hydrothermal reservoir (van Wees et al, 2013). Without any direct geothermal production information in the studied areas, the use of a mean value comprised between 0.02 and 0.20 was suggested by Beardsmore [et al, 2010].

Levelized Cost Of Energy [LCOE, €/MWe, €/JG]

Calculated for power, district heating and direct heat uses.
The LCoE is computed as the ratio of the accumulated discounted cost over the lifetime of the doublet (30 years) and the accumulated discounted energy [Van Wees et al., 2012].

Depends on:

- Drilling cost (depth, stimulation, pump, ...)
- Economic lifetime
- ***Flowrate*** & temperature
- Power surface facilities (O&M, plant investiment, ...)
- Complementary electricity/heat sales
- Economic factors (inflation, interest rate on debit, tax)

Flowrate depends on transmissivity, delta pressure applied at reservoir level and viscosity

Specific routines redistributes the permeability according to Montecarlo simulation

From transmissivity average on drilled interval, cumulative probability of expected flowrate is considered

In our work it is assumed that the geothermal plant consists of a doublet system, where the production well and the re-injection well are 1000m from each other, and the flow rate Q is given by (Van Wees et al., 2012):

$$Q = \Delta p \left(\frac{2\pi\, k\, h}{\mu_{inj}\left(\ln\left(\frac{L}{r_w}\right)\right)} + \frac{2\pi\, k\, h}{\mu_{prod}\left(\ln\left(\frac{L}{r_w}\right)\right)}\right)$$

Δp = pressure to drive the flow at the reservoir level (max 10% of the hydrostatic pressure)
k = permeability,
L = injector-producer distance
r_w = well radius
μ = viscosity
h = thickness of the reservoir

Flowrate depends on transmissivity, delta pressure applied at reservoir level and viscosity

Q is assigned to each reservoir voxet on the basis of the expected transmissivity for a certain cumulative probability computed by the Monte Carlo Simulation

In order to compute the LCoE, the energy available in each volumetric cell is derived as:

$$Energy\ [MW] = Q * \rho water * Cpwater * (Tx - Tr) * \eta * 10^{-6}$$

$\rho water$ = fluid density (kg m^{-3})
$Cpwater$ = fluid specific heat (J kg^{-1} K^{-1})
Tx = temperature at depth x
Tr is the re-injection temperature

The Economic Technical Potential is extracted from the TP (with R=0.1), accepting only those cells of the 3D grid where the Levelized Cost of Energy (LCoE) is less than a given threshold.

	Power product.	**District heating**	**District heating&cooling**
Tmin	120	80	60
T-reinject	107	44	33
Efficiency	0.6	1	0.7
Economic Model	power	heat	heat
Recovery factor	0.1	0.1	0.1
LCOE <	200 €/MWe	9 €/GJ	9 €/GJ

Currently, there is no well-defined and unique methodology in the literature that determines the installable electrical power from the geothermal potential.
We proposed a post-processing analysis of the Economic Technical Potential map for power production in order to estimate which part of the geothermal potential could be used by geothermal binary plants at the regional scale. We called this geothermal potential, the **Installable Electrical Capacity** (IEC).

We estimate the potential annual regional **power production** as product of the Total IEC and the annual load hours of the plant.

From this value, it is also possible to estimate the GreenHouse Gas **GHG emission reduction** that would be obtained by developing the estimated power production.

A GOOD APPLICATION

Match Resource to energy demand

Technical Potential for LCOE < threshold and expected flowrate from a doublet system

Geothermal Potentials for a lifecycle of 30 years and different Recovery Factors (GP=TC x R / 30 years)

Thermal Energy produced by a technology (TC=H x technology efficiency) per unit volume

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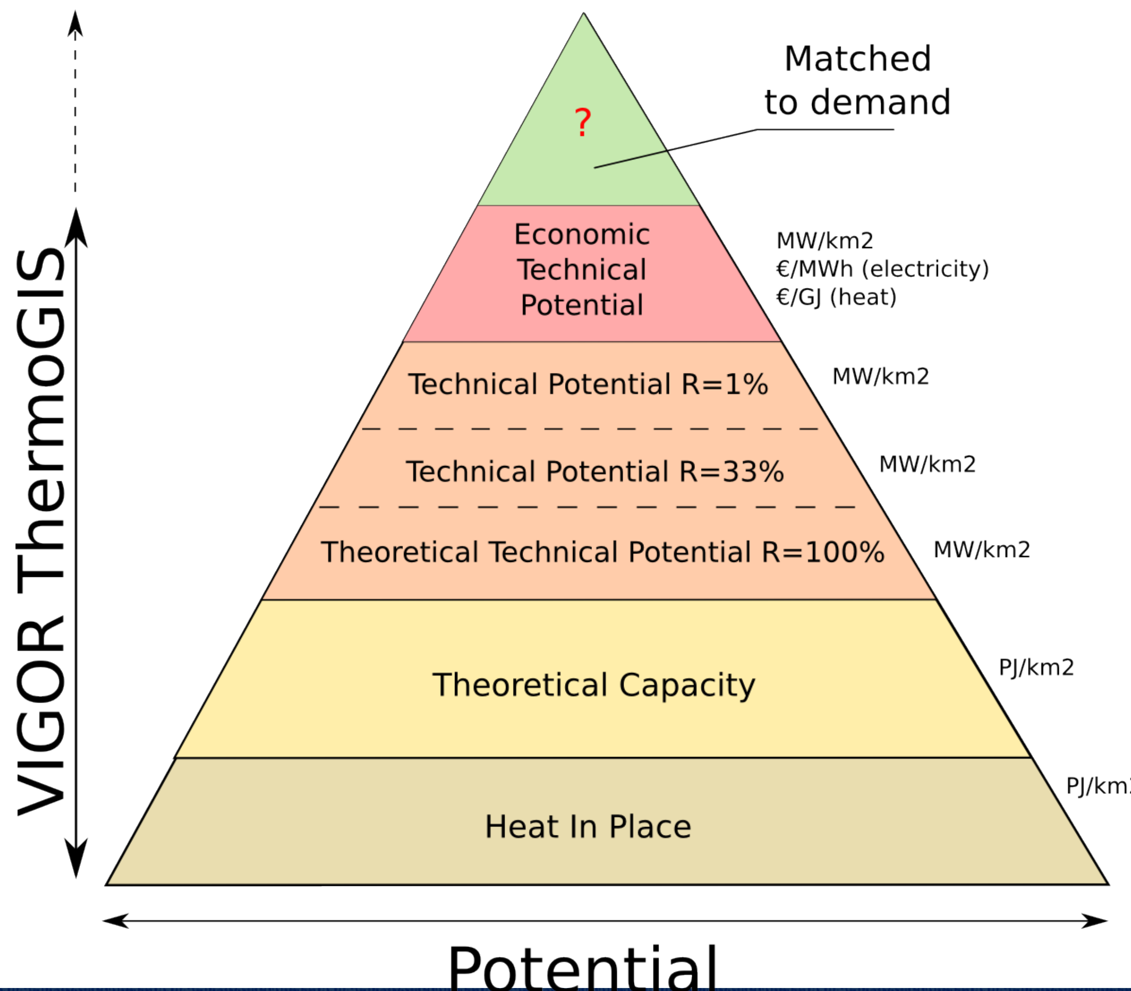
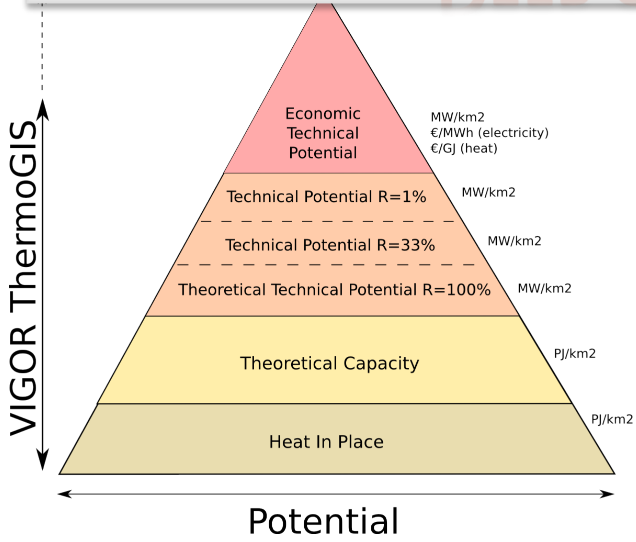


DEEP GEOTHERMAL POTENTIAL



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Data input:

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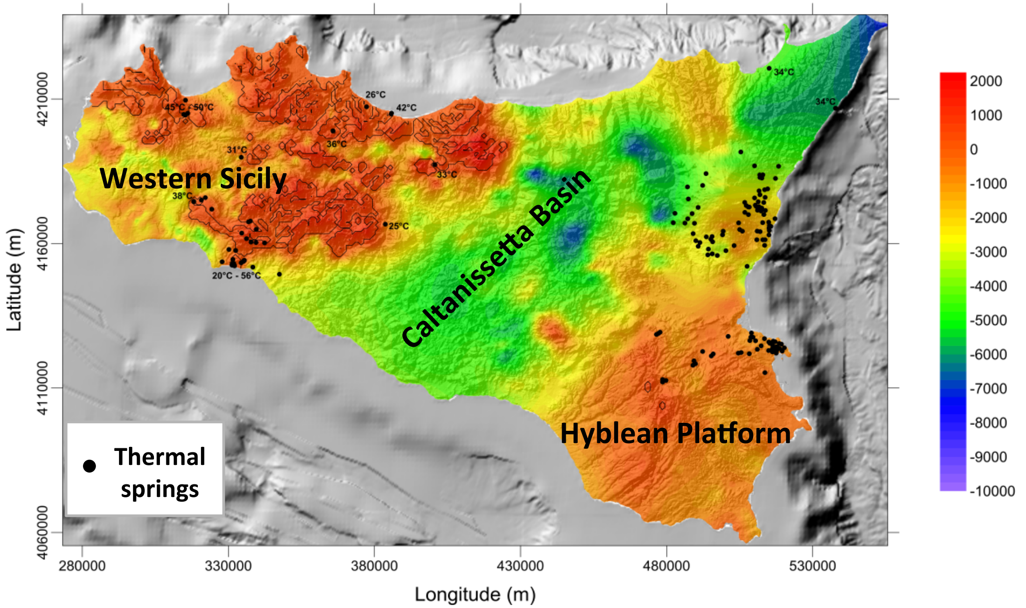
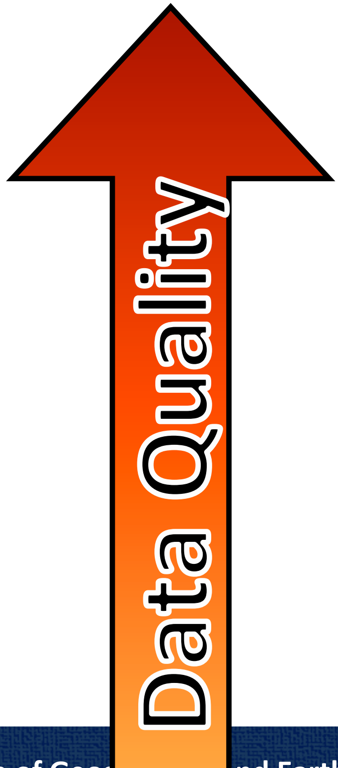
Geometric characteristic: Top of the reservoir

- We focused on the evaluation of the deep-seated geothermal resources (hydrothermal systems) **down to 5 km depth**
- Mesozoic Carbonate Units host the main regional aquifer
- Well data and interpreted seismic profiles allowed to define at regional scale the top of the reservoir



Temperature model distribution: Temperature database

Due to the different conditions under which the temperatures are measured and to the purposes for which they are used, these data constitute an heterogeneous database with different degree of accuracy and spatial distribution.



Temperature Log

- Continuous log
- Accuracy of ± 0.05°C
- Static conditions
- Few logged wells
- Shallow depth

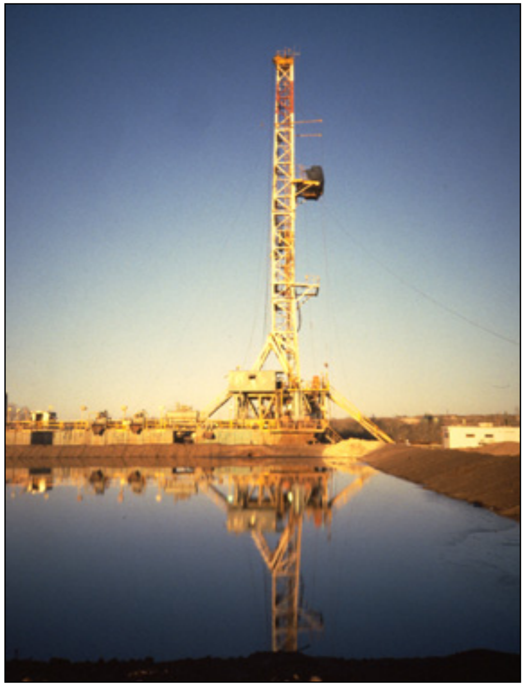
Drill Stem Test Temperature

- Referred to the productive interval
- Accuracy of ± 2°C
- Flowing fluid temperature
- Industrial confidential data
- High depth

Bottom Hole Temperature

- Punctual measurements
- Accuracy of ± 2°C
- Dynamic conditions
- Many available wells
- High depth

BHT Correction to Static Conditions
Time temperature series



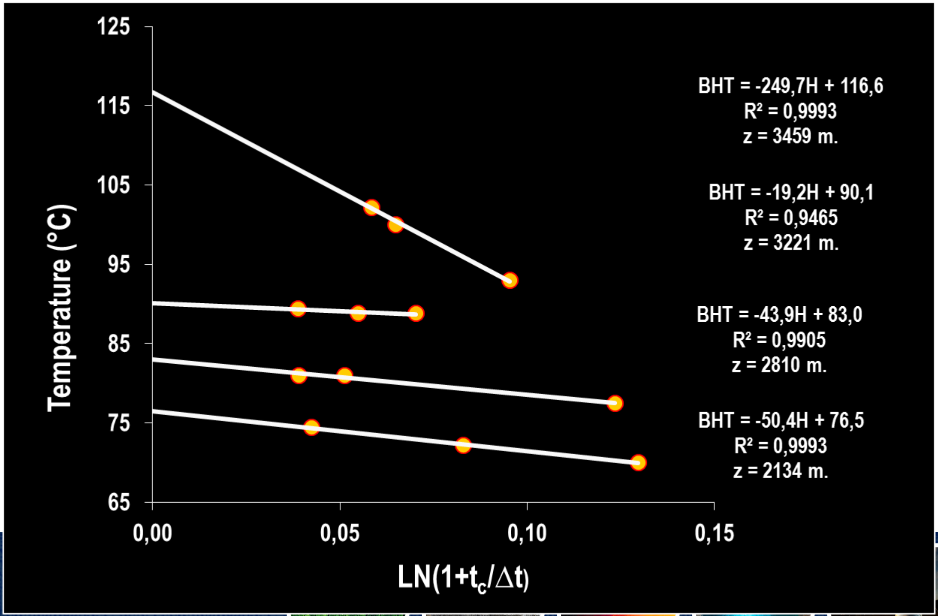
Bottom Hole Temperatures (**BHT**) reflect the thermal conditions of the drilling mud, not those of the undisturbed rock.

Most correction techniques treat temperatures as a transient function, i.e. they involve progressive measurements after drilling operation, to extrapolate the temperature to static conditions (**SBHT**).

The line source model assumes that the mud circulation acts as a heat sink

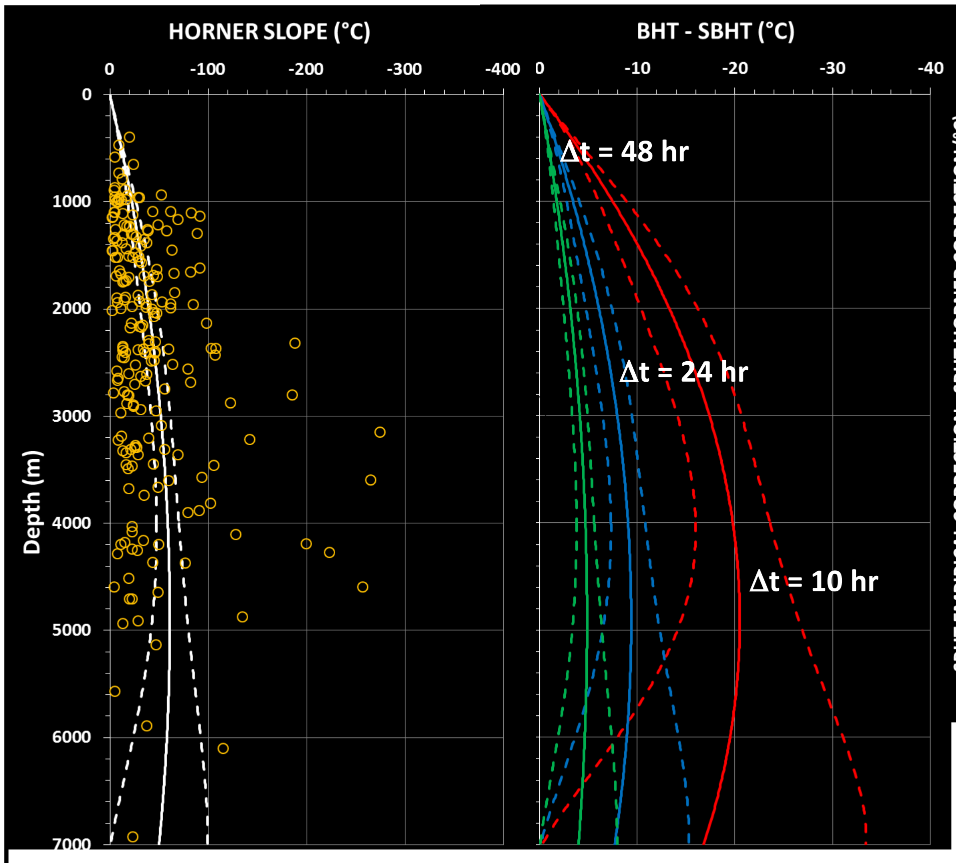
$$BHT(t_c, \Delta t) = SBHT + \frac{Q}{4\pi\kappa_r}\log\left(1 + \frac{t_c}{\Delta t}\right)$$

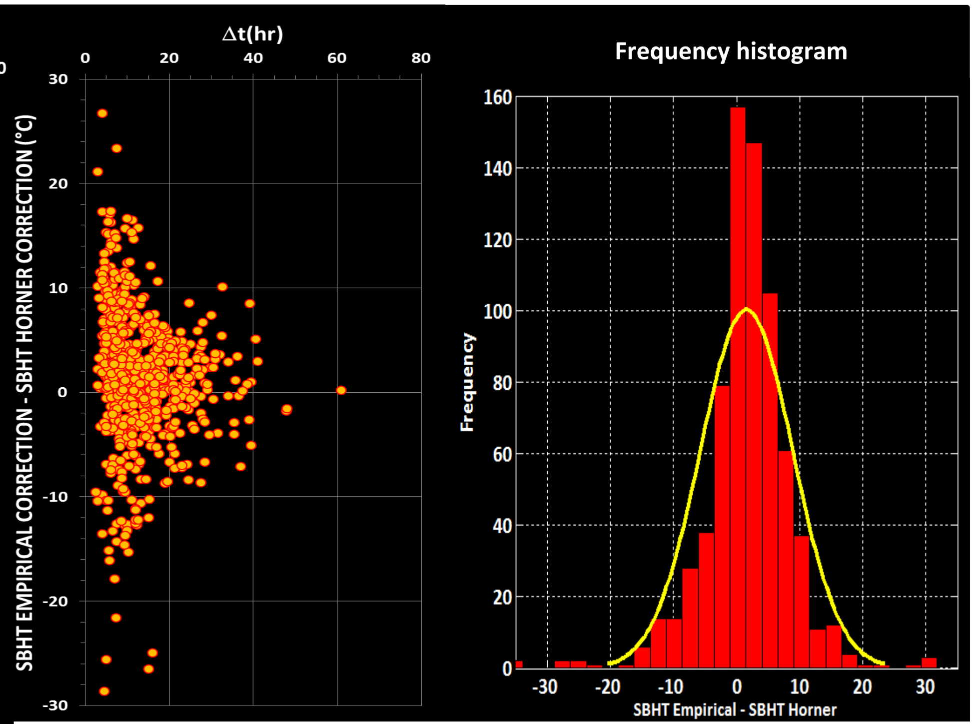
HORNER PLOT METHOD



BHT Correction to Static Conditions

Single temperature measurements



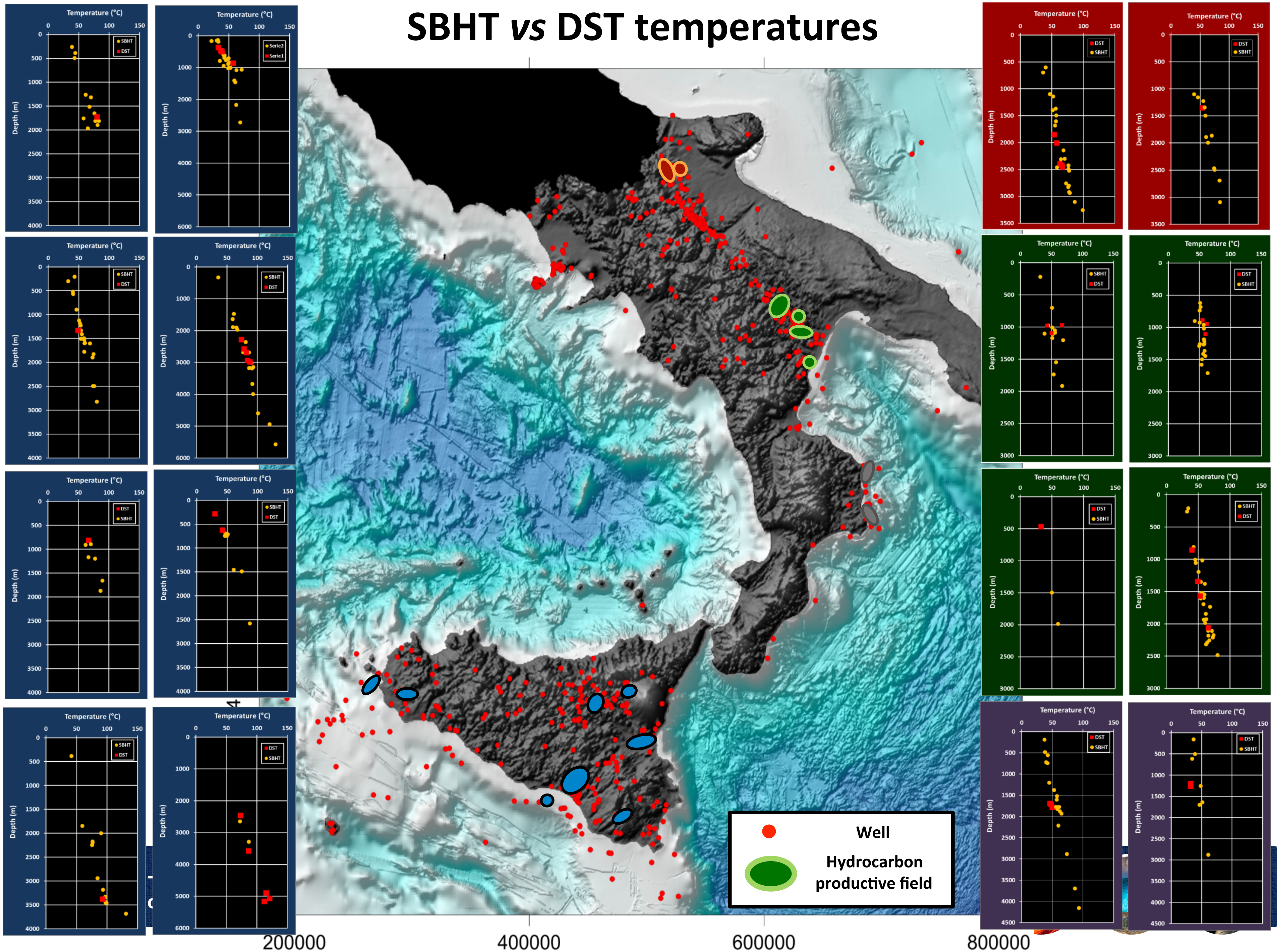


$$BHT(t_c, \Delta t) - SBHT = \left(a z^2 + b z\right)\log\left(1 + \frac{t_c}{\Delta t}\right)$$

A technique that enables to correct **single BHTs** is based on the correlation between the Horner slope and depth.

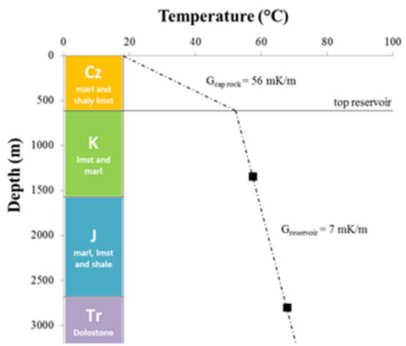
A comparison of the corrected temperatures (**SBHT**) from the same dataset obtained by means of: 1) the depth-time function, 2) the Horner method, shows a decrease of the differences with the increase of the shut-in time.

SBHT vs DST temperatures



Geothermal Gradients inferred by well data

Temperature data, analysed well-by-well together with lithostratigraphic information, allowed to describe the temperature increase with depth both in the impermeable cap-rock units and in the potential reservoir units

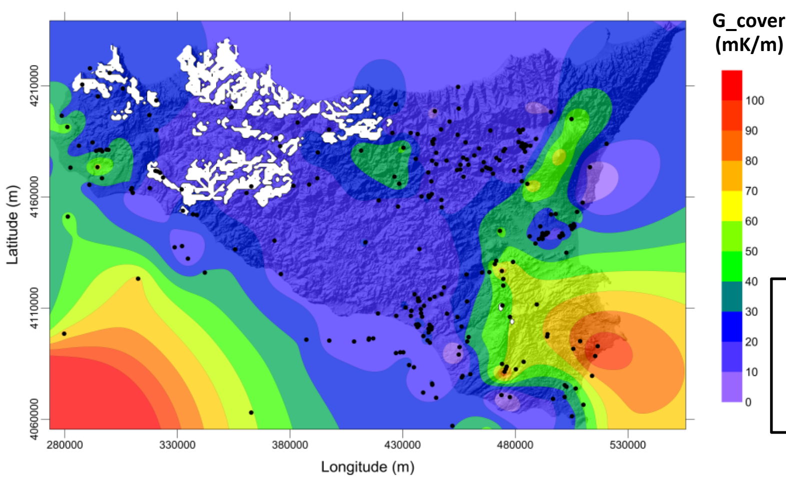


Example: Segesta 1 well (Sicily)

Focusing on conventional hydrothermal systems:

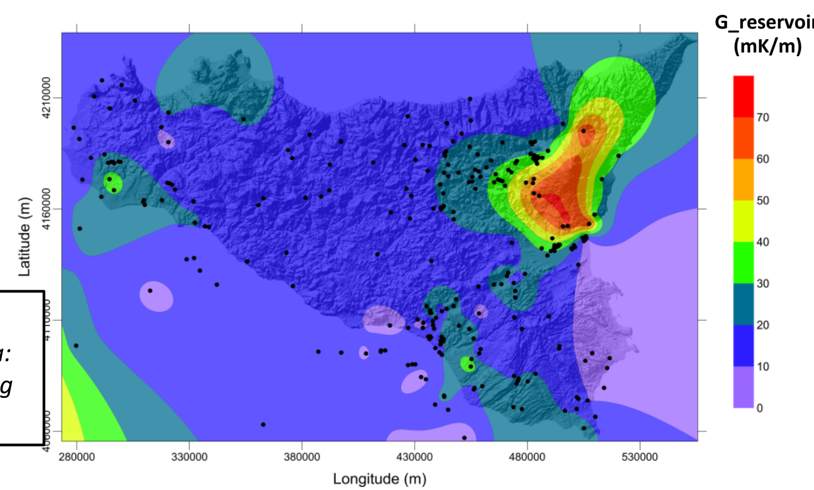
- In the **<u>cap rock</u>** the **high** temperature **gradients** imply a predominance of conductive heat transfer. Geothermal gradients mimic the underlying geometries of the potential reservoir
- The temperatures in the carbonatic **<u>reservoir</u>** reveal very **low** geothermal **gradients** where the component of convective heat transfer is not negligible

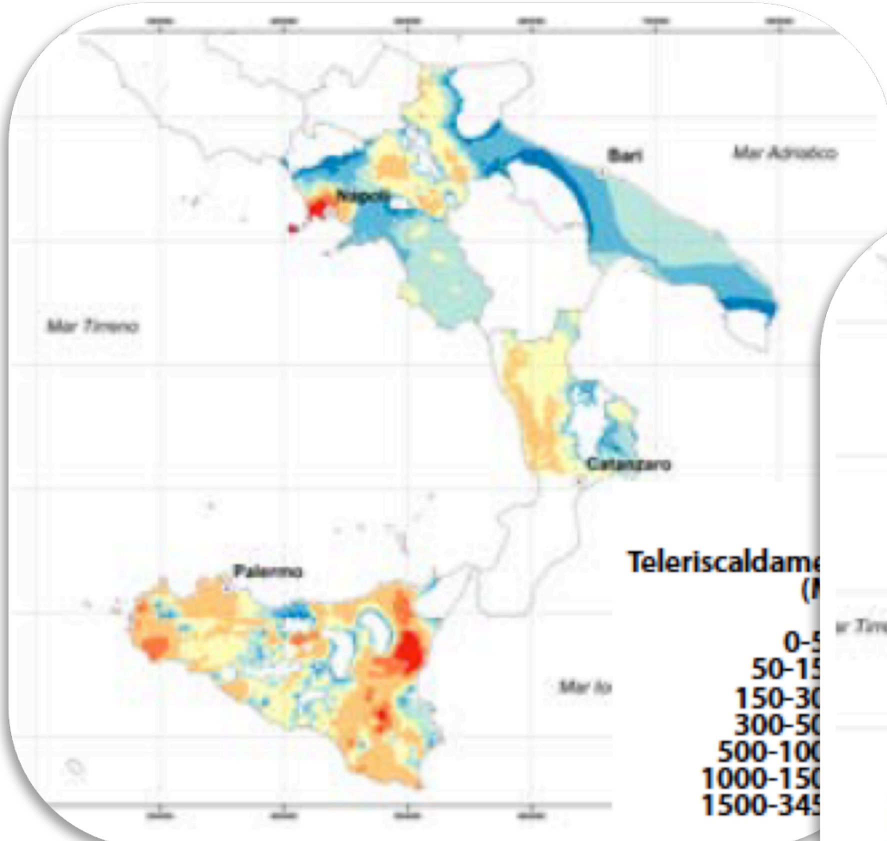
COVER

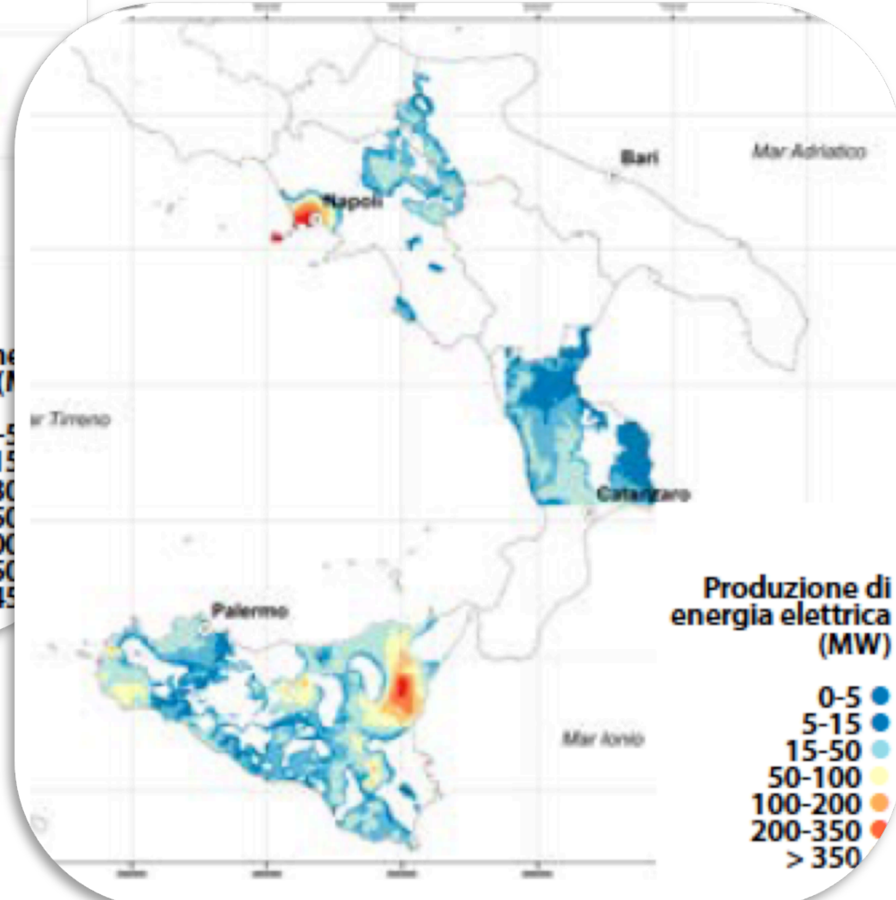


- • Well
- *White area: outcropping reservoir*

RESERVOIR




Bari
Mar Adriatico
Napoli
Mar Tirreno
Catanzaro
Palermo
Mar Io
Teleriscaldame
0-5
50-15
150-30
300-50
500-100
1000-150
1500-345


Bari
Mar Adriatico
Napoli
r Tirreno
Catanzaro
Palermo
Mar Ionio
Produzione di energia elettrica (MW)
0-5
5-15
15-50
50-100
100-200
200-350
> 350

SHALLOW GEOTHERMAL POTENTIAL

A GIS-based approach able to generate thematic maps of geothermal energy exchanged potential by vertical boreholes for Closed-Loop System (Borehole Heat Exchangers, BHEs).

The approach provides the map of maximum ground heat exchangeable through the unit area, evaluated on the basis of local geological and climatic conditions, energy requirements for a typical reference residential building and energy requirements on heat pump efficiency.

Temperature distribution at surface

Air temperature data, topography, latitude

Thermal conductivity distributions

Geological maps, hydraulic and stratigraphic well data, conductivity from literature and lab analyses

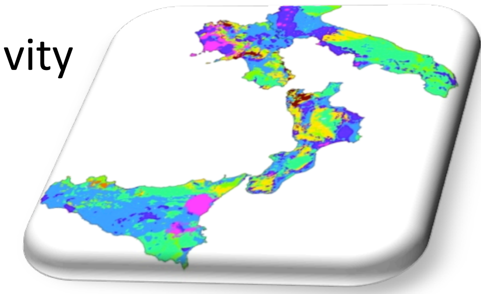
Exchange energy

Ground Temperature, reference volume to be heated-cooled –energy demand

SHALLOW GEOTHERMAL POTENTIAL

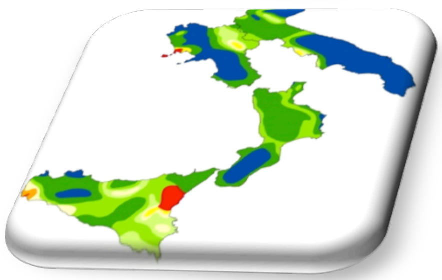
Thermal conductivity

λ



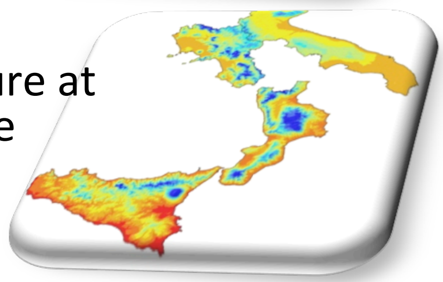
Heat flow

Φ



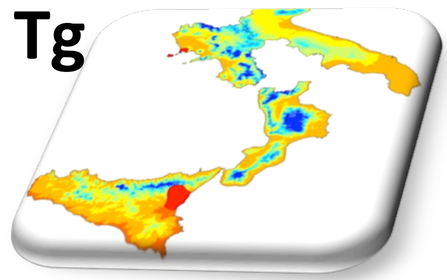
Average temperature at the surface

Tm



Ground temperature at 50 m depth

Tg



$$Tg = Tm + \frac{\Phi}{\lambda} * L/2$$

Fourier's Law

L = 100 m

Total length of the group of BHEs (field) required to satisfy the energy need

Ltot

SHALLOW GEOTHERMAL POTENTIAL

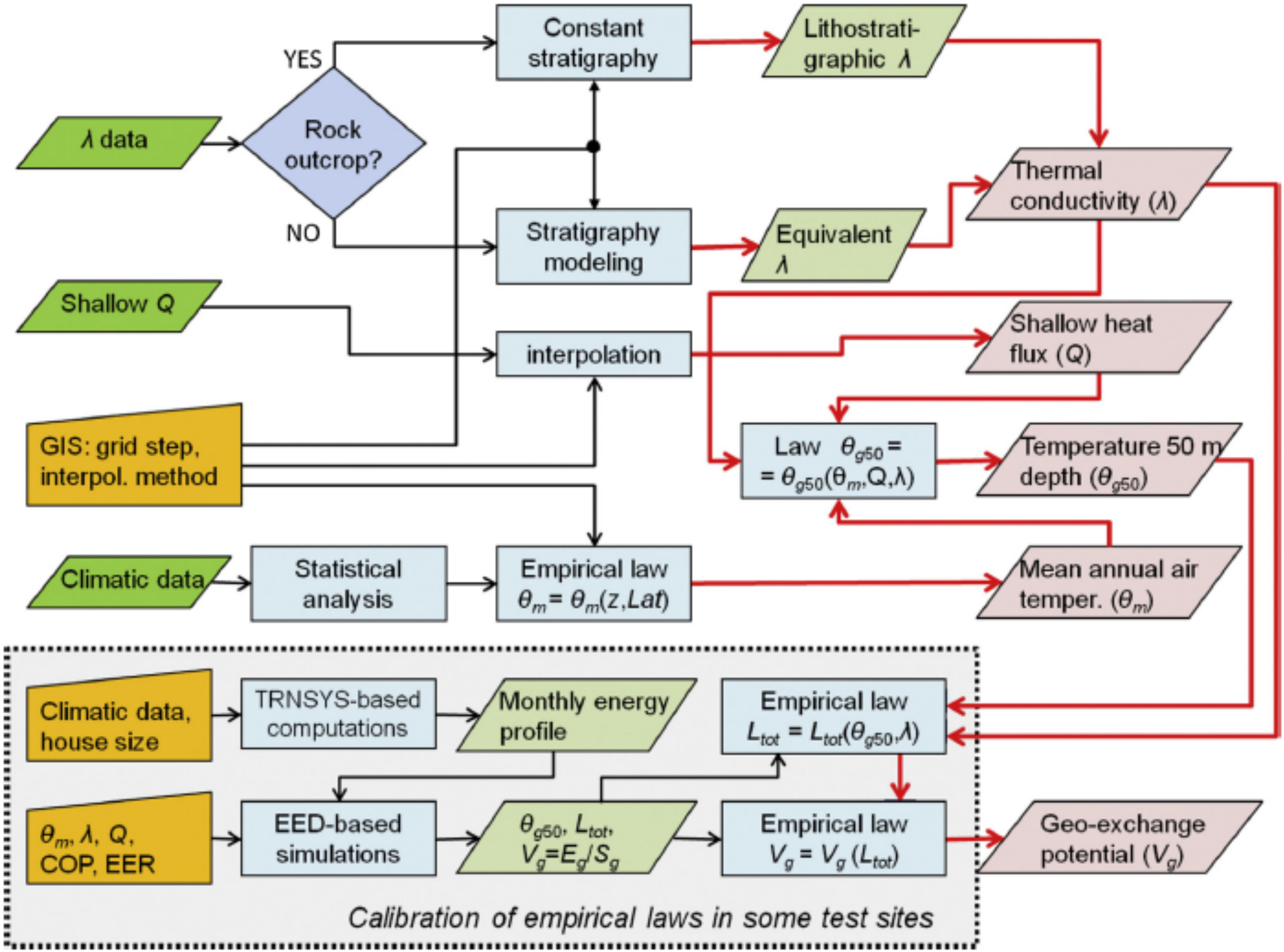
The surface area through which the geothermal energy is exchanged assuming a regular BHE field of 100 m long vertical probes spaced 7 m is

$$S_g = Ltot/100\ S_{single} = Ltot/100\ (49\ m^2)$$

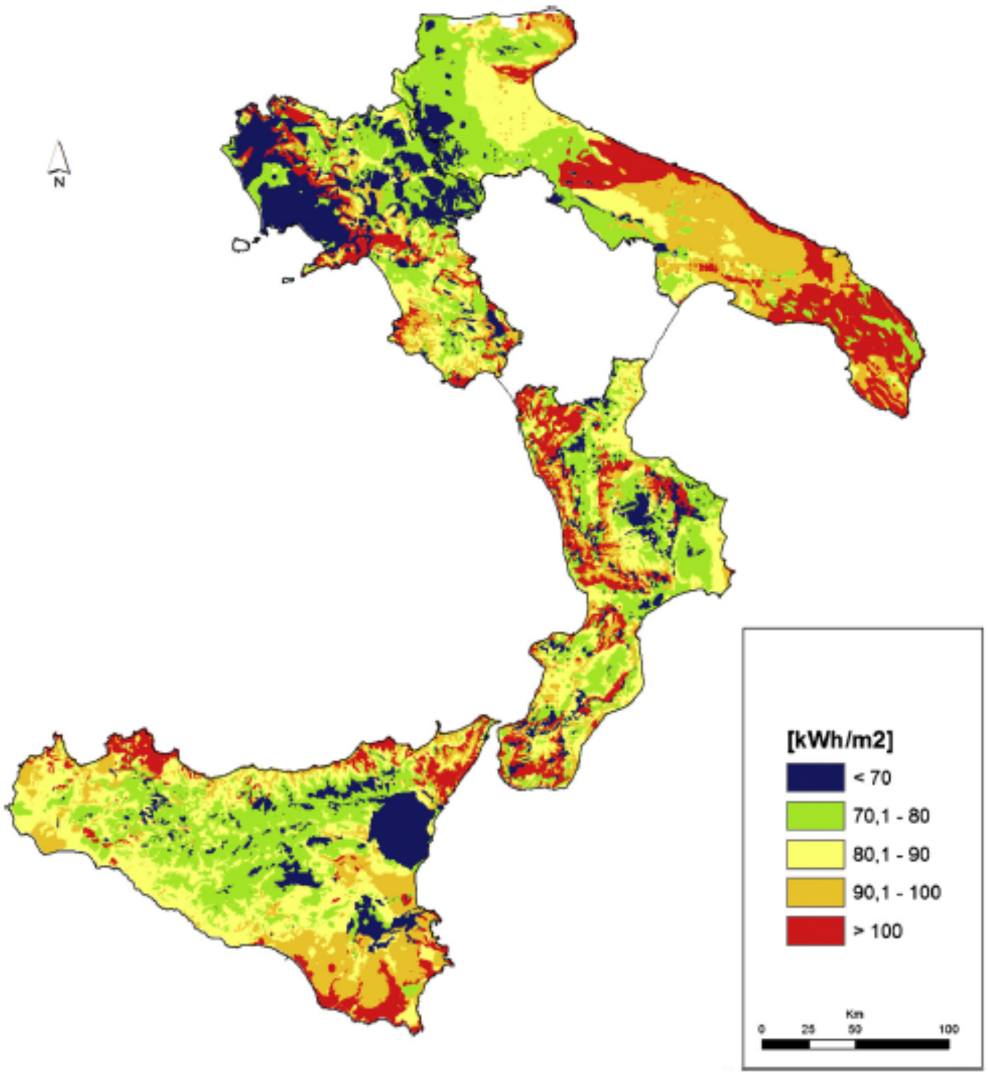
where S_{single} is the area of a single grid square.

The annual balance of thermal energy request E_g is the sum of the total annual heating energy E_h and the total annual cooling energy E_c

The ratio $V_g = E_g/S_g$, is the geothermal energy exchangeable through the unit area, can be mapped using GIS, and was used as geo-exchange potential. It represent the thermal energy that can be exchanged by a unit volume of ground for a reference GSHP plant



λ data
Rock outcrop?
YES
NO
Constant stratigraphy
Stratigraphy modeling
Lithostrati-graphic λ
Equivalent λ
Thermal conductivity (λ)
Shallow Q
interpolation
Shallow heat flux (Q)
GIS: grid step, interpol. method
Law θg50 = = θg50(θm,Q,λ)
Temperature 50 m depth (θg50)
Climatic data
Statistical analysis
Empirical law θm = θm(z,Lat)
Mean annual air temper. (θm)
Climatic data, house size
TRNSYS-based computations
Monthly energy profile
Empirical law Ltot = Ltot(θg50,λ)
θm, λ, Q, COP, EER
EED-based simulations
θg50, Ltot, Vg=Eg/Sg
Empirical law Vg = Vg (Ltot)
Geo-exchange potential (Vg)
Calibration of empirical laws in some test sites


N
[kWh/m2]
< 70
70,1 - 80
80,1 - 90
90,1 - 100
> 100
Km
0
25
50
100

Jigokudani Hot Springs – Japan