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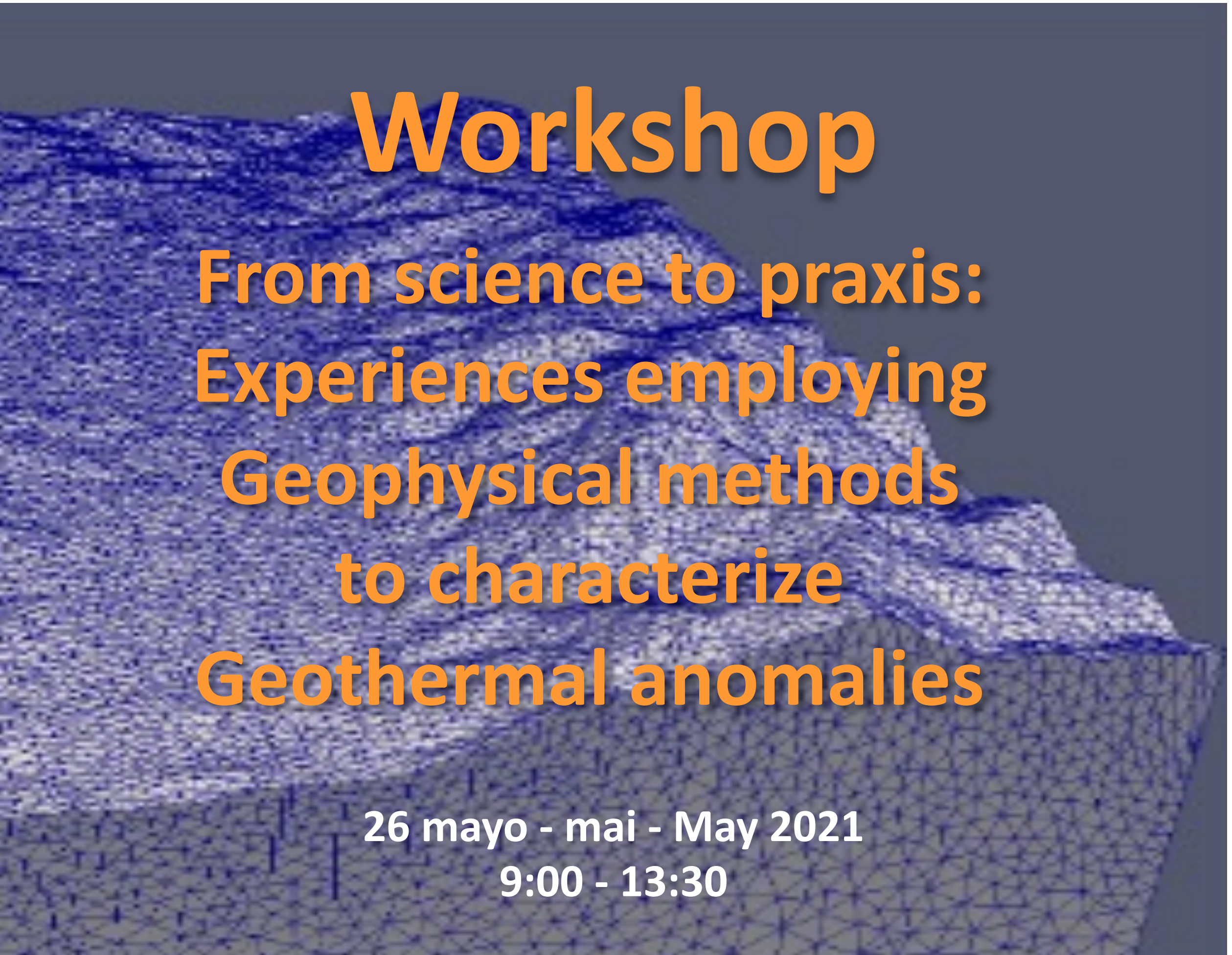

Geophysical data for geothermal resource characterization in the various phases of geothermal development and operation

Case studies from Italy and continental Europe

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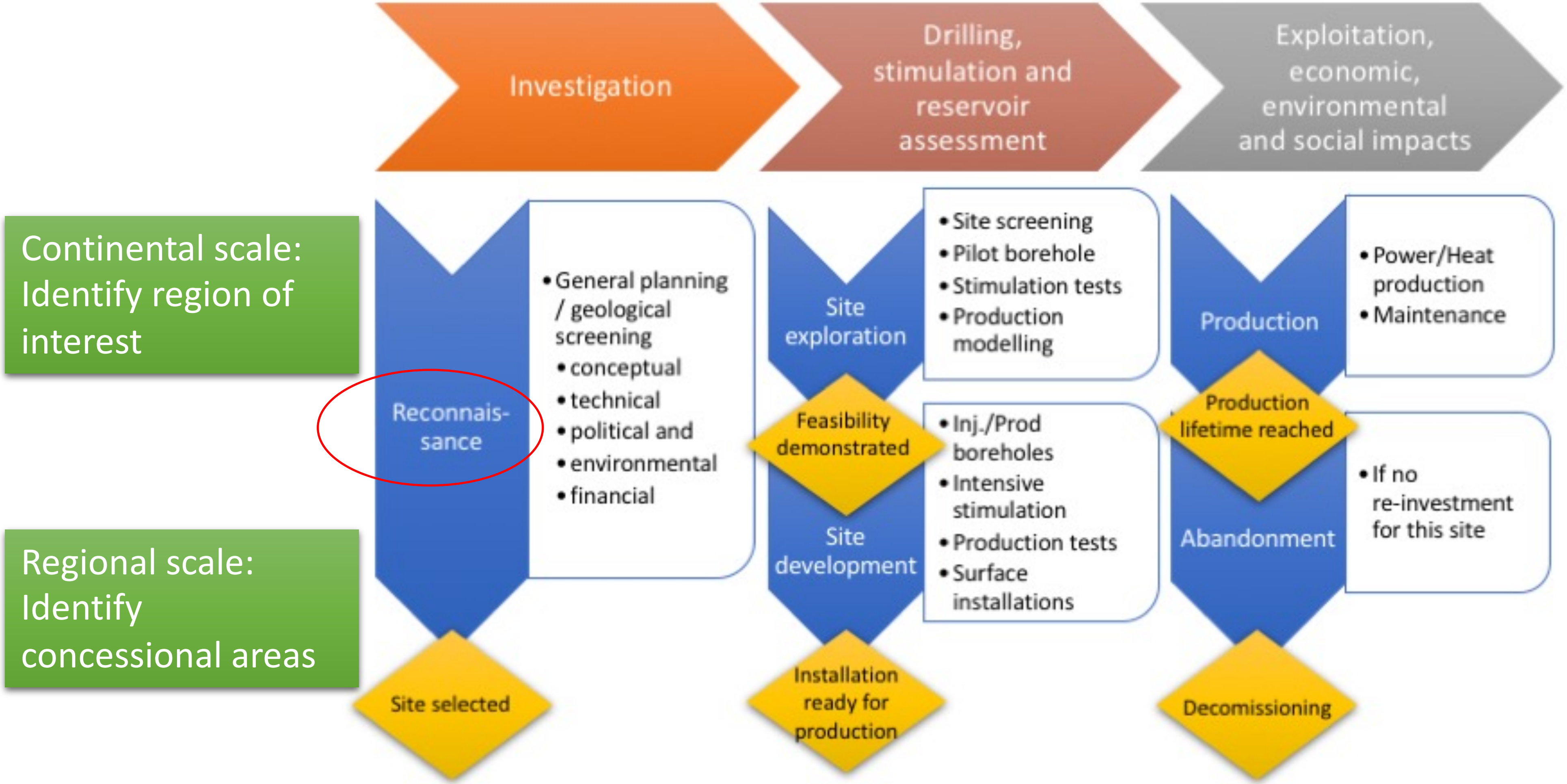
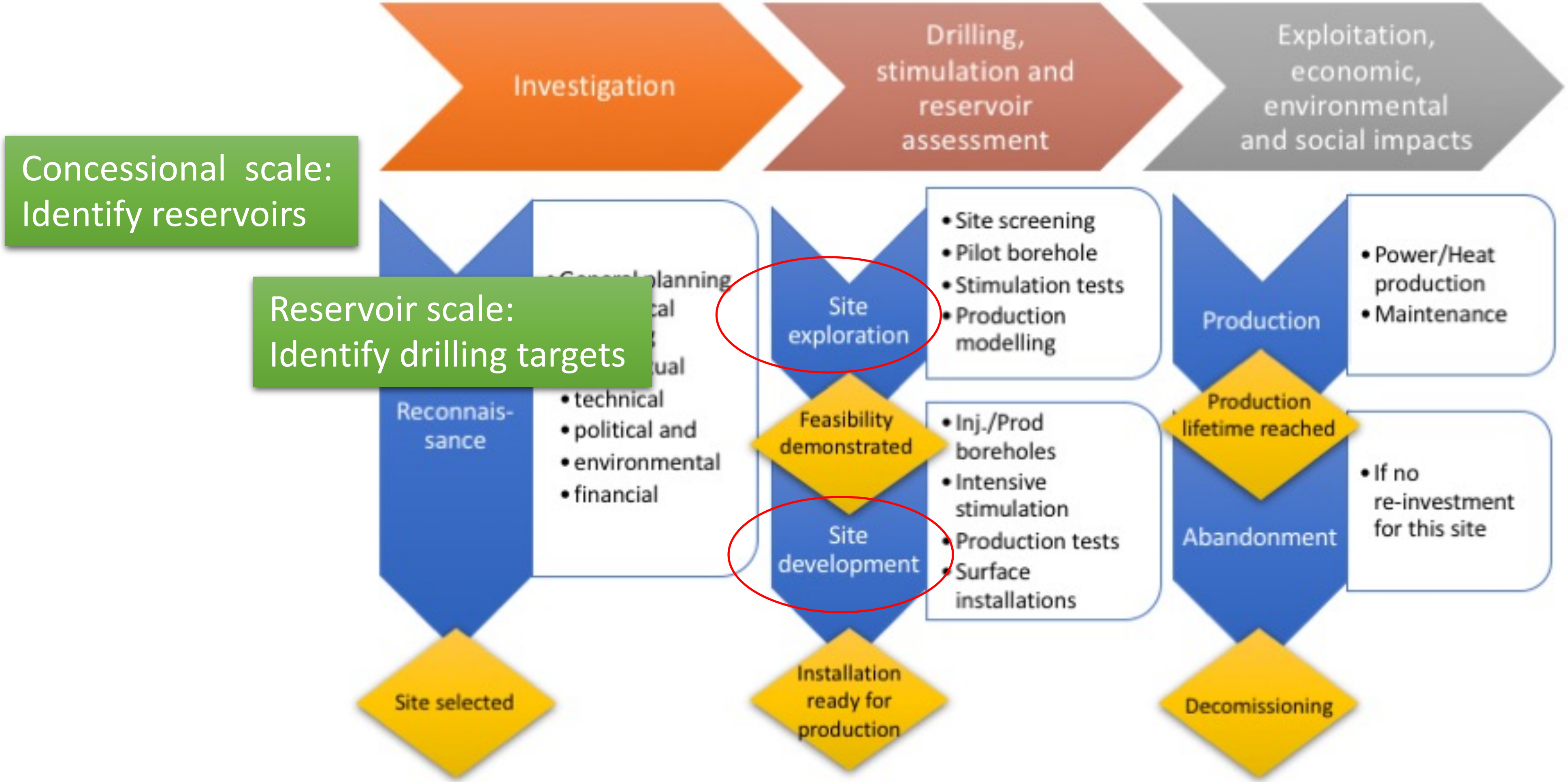
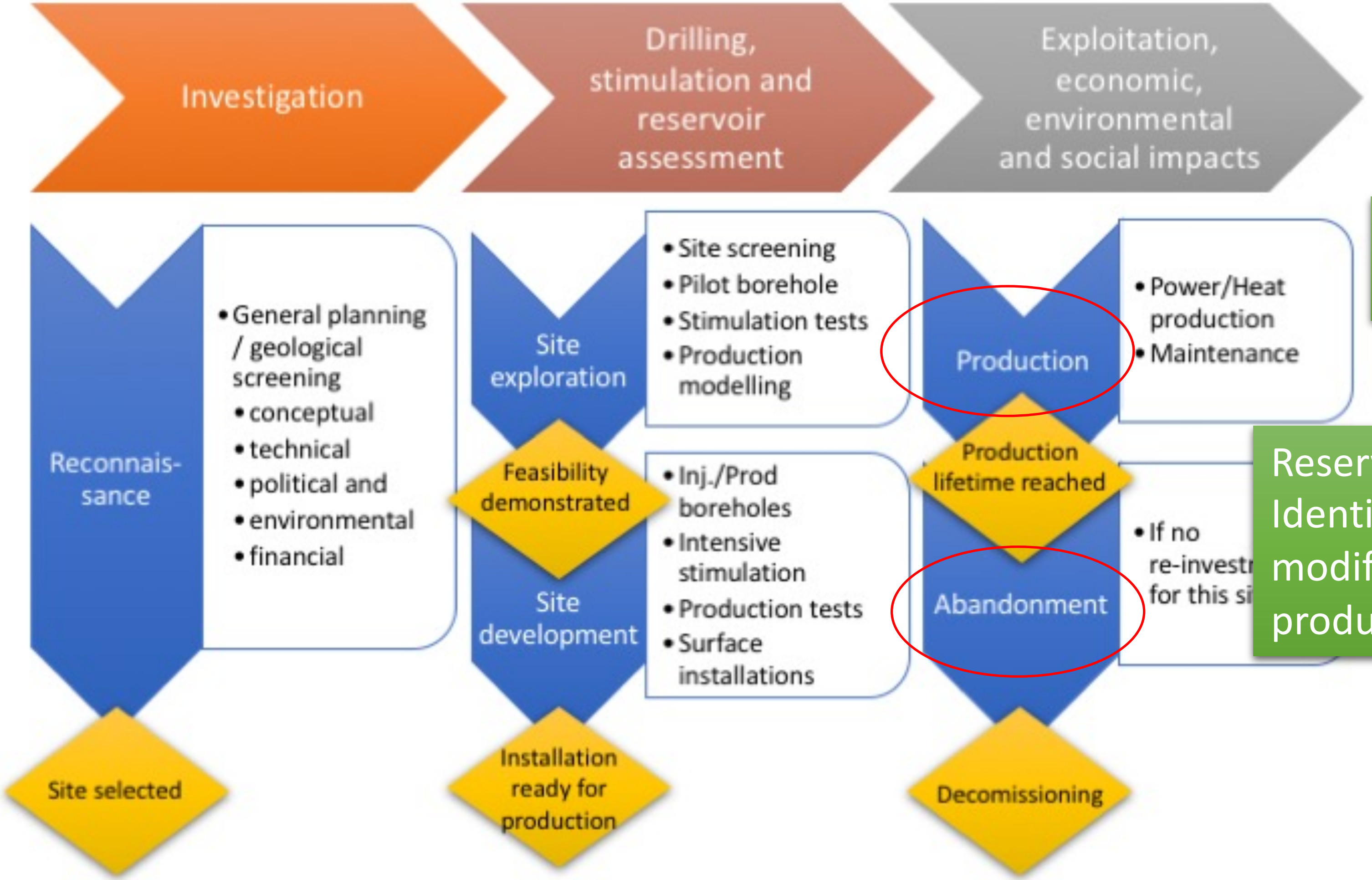


Geophysical methods are used in any phase of a geothermal project



Geophysical methods are used in any phase of a geothermal project



Reservoir scale:
Identify drilling targets

Reservoir scale:
Identify reservoir's modification due to production and injection

Geophysical methods are used in any phase of a geothermal project

A general approach

Two of the largest challenges for increased geothermal deployment are:

- understanding when and how to proceed in an exploration program,
- when to walk away from a site

It is important to build many conceptual models fitting the available data. They should show:

- if and why a resource exists
- size
- permeability and what controls permeability
- reservoir fluid and rock properties (temperature, permeability, volume, pressure, porosity, and chemistry)

(Cumming, 2011).

An important step in obtaining useful geophysical data is to have a conceptual understanding of the area before deciding what is the most suitable technique, and how to apply it (e.g. E-W trending aeromagnetic swaths to detect N-S trending dyke swarm; MT for deep seated resources, but also not a direct function of resistivity= fluid-filled rocks if claycaps are involved)

Integration is essential

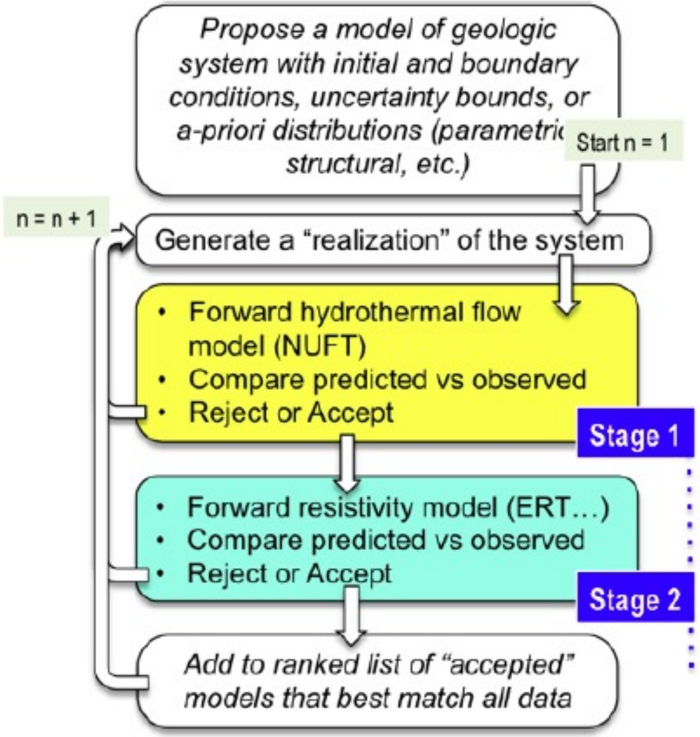
- A single method cannot provide all the necessary information and resolution
- In any case, geophysical data has to be integrated to geological information
- They should also be calibrated

Many options

The most classical is some kind of joint modelling, e.g. constrained modelling, joint inversion

Integrated exploration: stochastic inversion

Geometry, permeability, porosity, heat capacity are modified and compared with T from wells and then with resistivity from MT/ERT/VES data

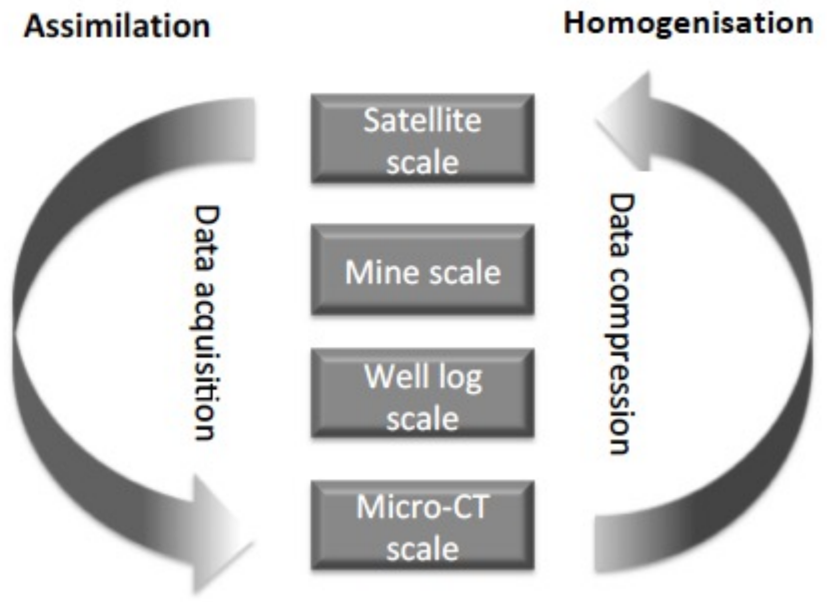


from Mellors et al., Proc. Stanford WS, 2015)

Integration as physics-based big data interpretation

merging the data using the machine learning algorithms requires the full understanding of dominant physics at all scales.
In other sectors (e.g. oil) they are working on a robust multiscale data assimilation workflows for the determination of a common model of physical parameters, geological structure and deformation history

the physical model used in the forward model, used for homogenisation, is interrogated by the data available at both scales through an inversion process. This allows considerations of uncertainty in the data and optimisation of model prediction.

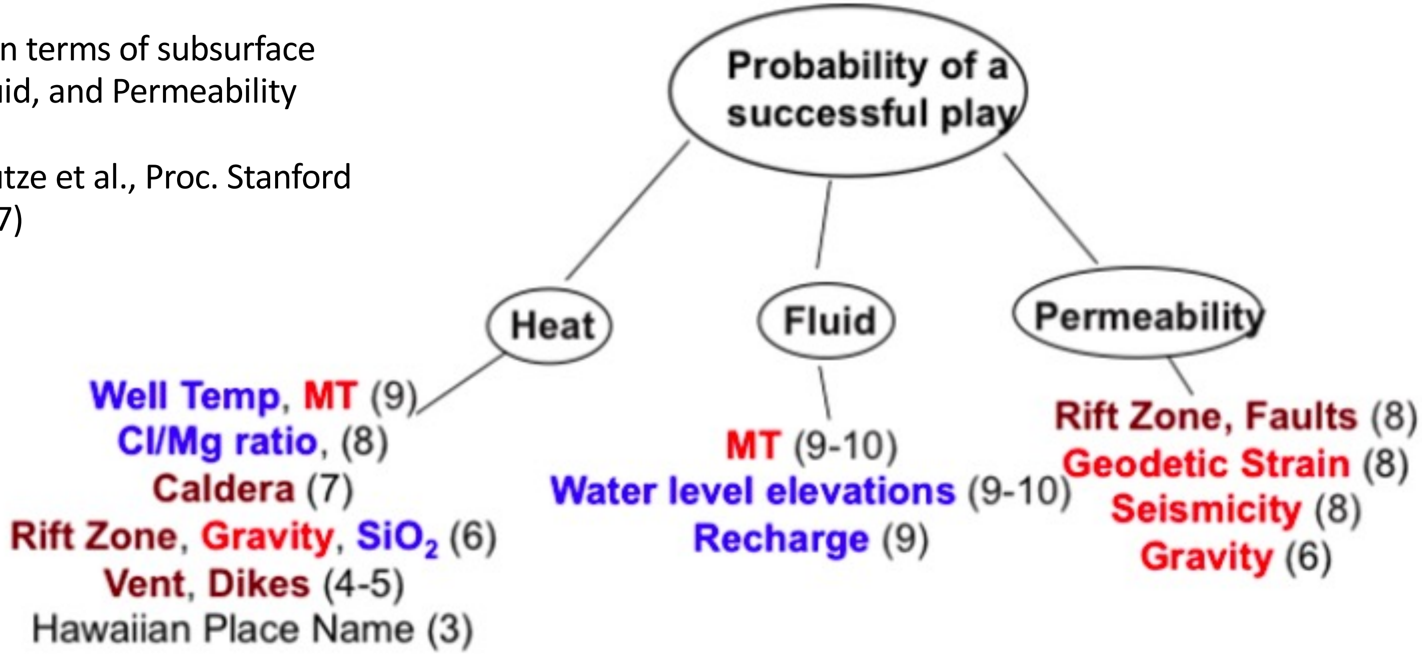


uses knowledge of the physics (and chemistry) of the processes to correctly average the
next scale up using a forward simulation tool

Integration as probability

ranking in terms of subsurface Heat, Fluid, and Permeability

from Lautze et al., Proc. Stanford WS, 2017)



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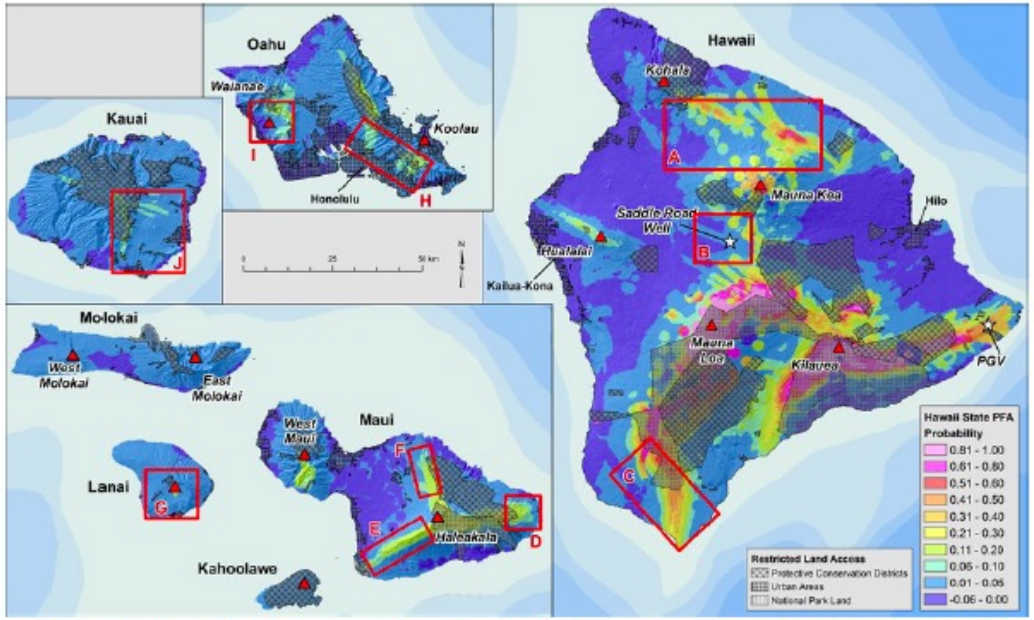


Figure 2: Results of the DOE Phase 1 geothermal play fairway probability analysis for the State of Hawaii. Probabilities of a geothermal resource are colored. Areas with restricted land access are shown in stippled and crosshatch patterns (e.g., National Park lands, protective conservation districts, and urban areas). Red boxes outline areas proposed for Phase 2 study. Red triangles indicate the calderas of the main shield volcanoes. White stars mark the locations of the Saddle Road well and Puna Geothermal Ventures (PGV).

Reconnaissance: an example for Supercritical resources

European DB and favourability map

We exploited GIS spatial analysis for mapping the favourable areas. The information does not allow to carry out a statistical analysis, and we applied a knowledge-driven method using the Index Overlay (IO) technique to combine geological and geophysical information. The resulting map is obtained from equation, where F is the favourability for each pixel, Wi is the weight for the ith map, and Sij is the score for the jth class of the ith map (Bonham-Carter, 1994):

$$F = \frac{\sum_{i=1}^{n} S_{ij}\, W_i}{\sum_{i=1}^{n} W_i}$$

Each map is classified, scored and weighted.

Classification: five ranges of values (classes), from “Very low” (least favourable area, class 1) to “Very high“. The thre maps are then combined by IO computation to produce the final map.

Thematic map	Weight	Score				
		5 (Very high)	4 (High)	3 (Medium)	2 (Low)	1 (Very low)
Depth of 400 °C isotherm	0.5	0-3500 m	3500-5000 m	5000-10000 m	10000-15000 m	15000-53037 m
Depth of MOHO	0.2	0-10000 m	10000-25000 m	25000-35000 m	35000-40000 m	40000-58491 m
Filtered earthquake density	0.3	30-112	10-30	5-10	0.9-5	0-0.9

Thematic map	Score				
	5 (Very high)	4 (High)	3 (Medium)	2 (Low)	1 (Very low)
Favourability map of supercritical resources in Europe	4.2-5	3.4-4.2	2.6-3.4	1.8-2.6	0-1.8

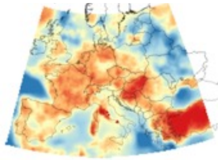
Reconnaissance: an example for Supercritical resources

European DB and favourability map

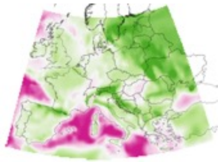
Indicators
applicable over broad areas

Classification (5 classes)

Score

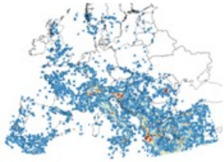


0.5



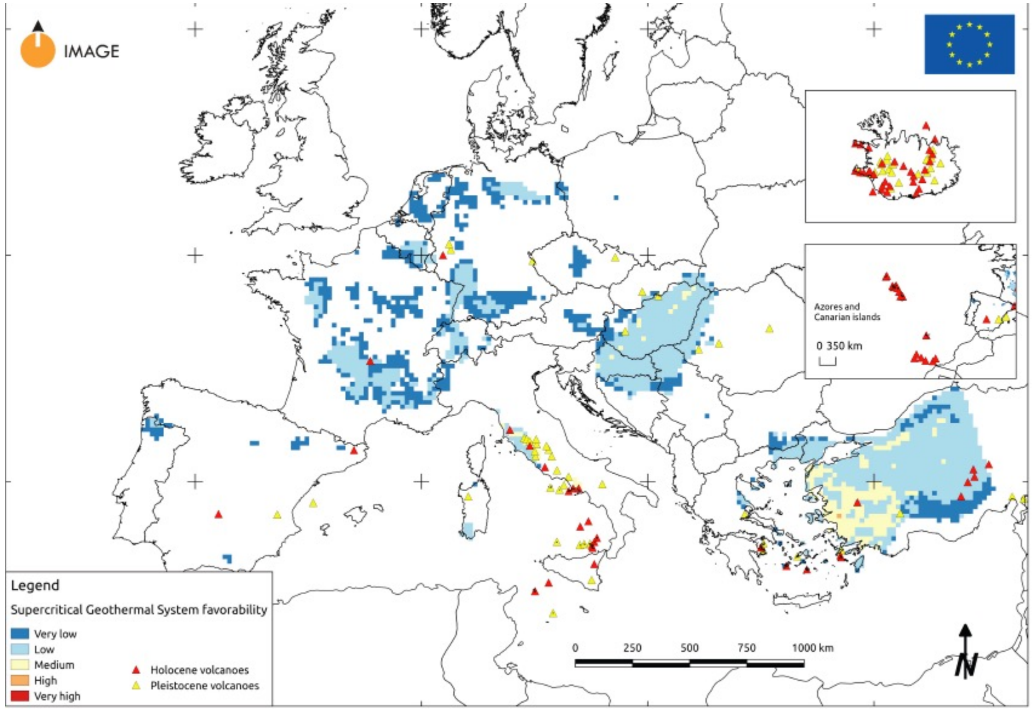
0.2

0.3



Isotherm 400 °C depth, crustal thickness, brittle-ductile transition depth, earthquake density
Recent volcanic activity centres were also mapped

Favourability map of geothermal resources at supercritical condition In Europe



The map highlights areas where investment in knowledge has the highest probability of being productive, as in Iceland and Italy, where supercritical resources have been reached. Supercritical potential in Iceland is within a drillable depth of 4-5 km in the 32,000 km^2 volcanic rift zone where temperature above 400 °C and adequate pressure are expected

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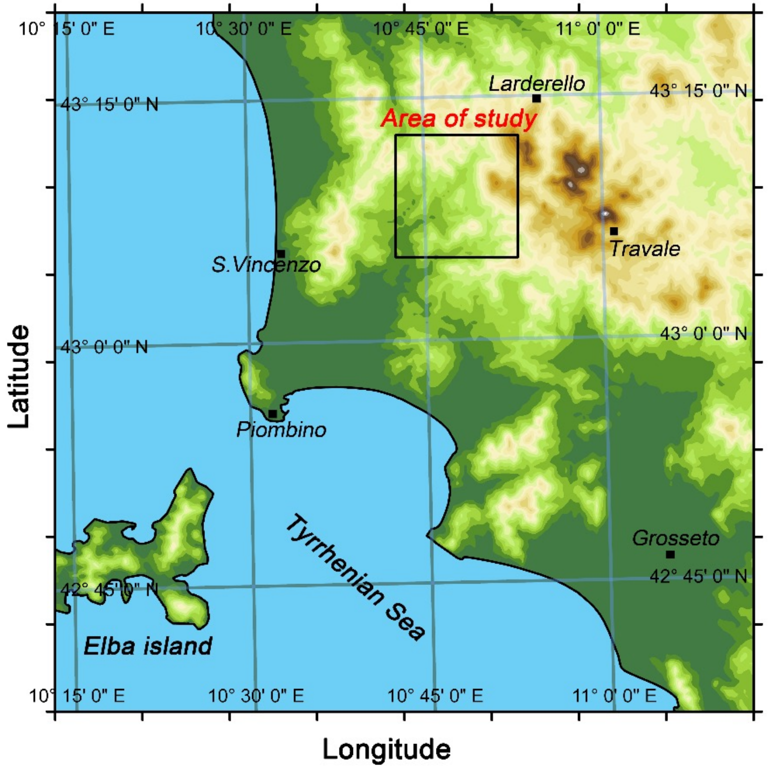
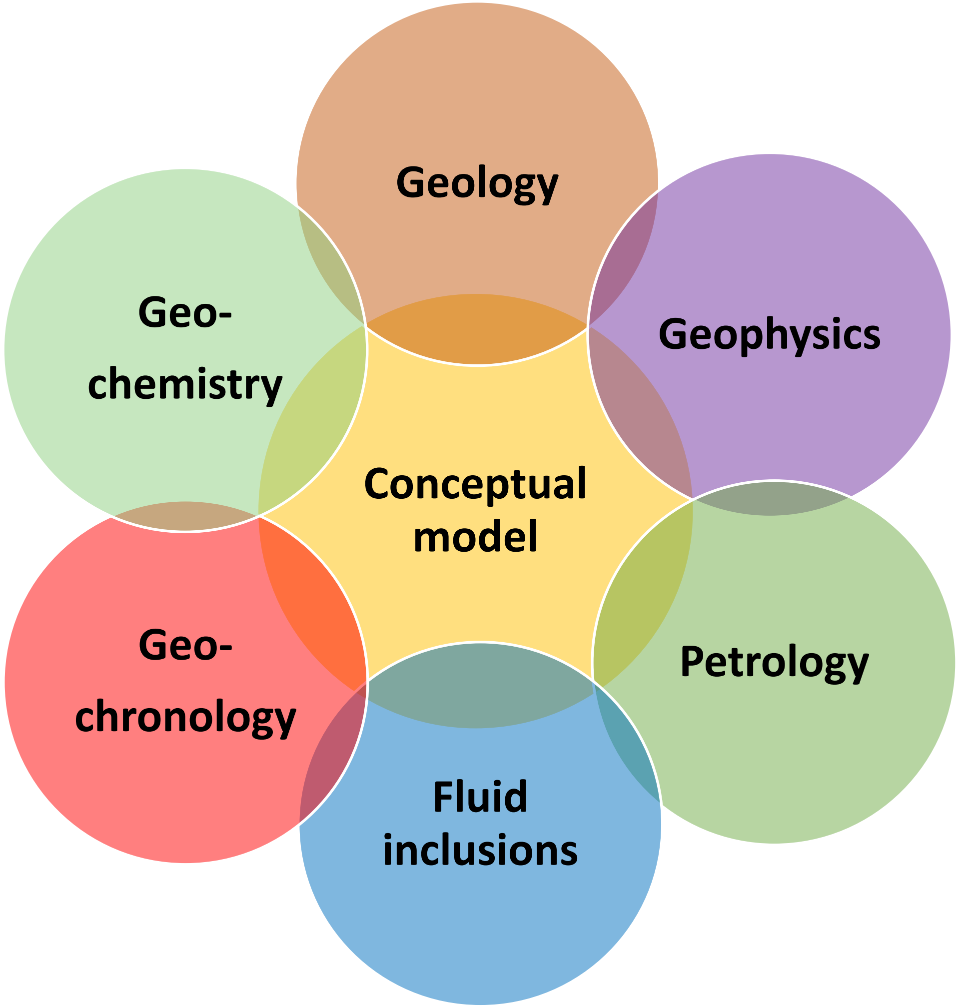
Site exploration: an example for Supercritical resources

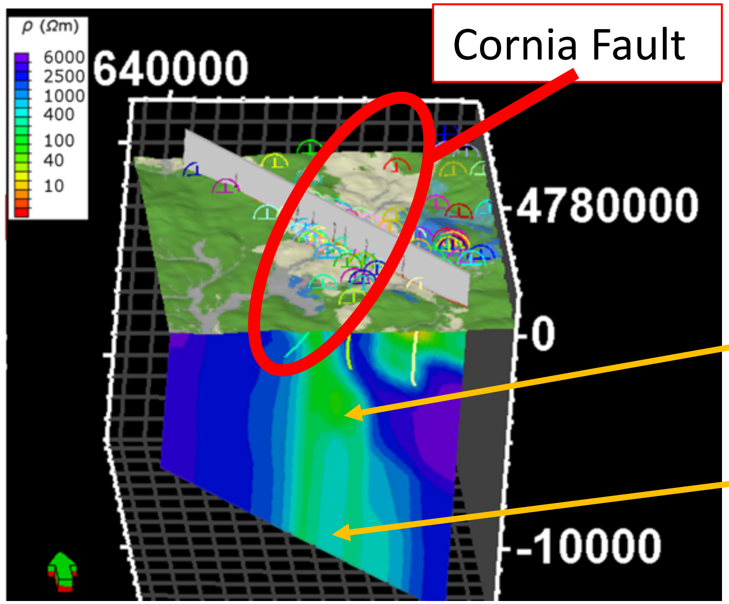
Exploration in Tuscany, Italy

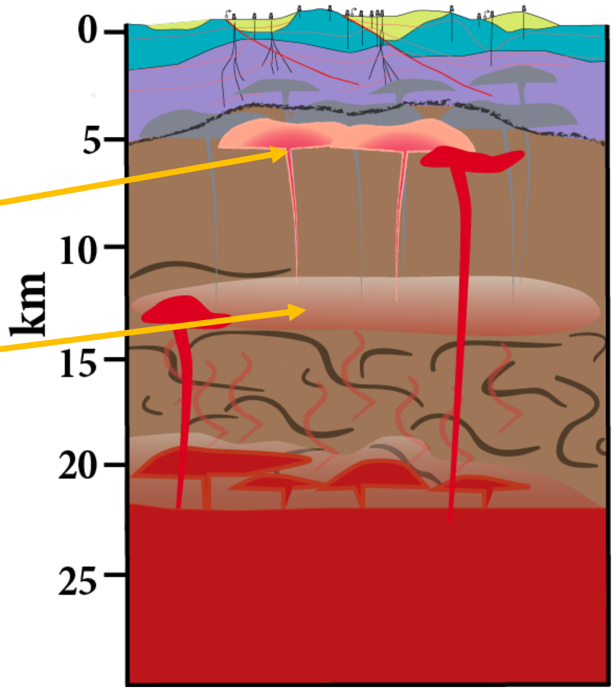




- To understand the **structure** of the **deepest part of the Larderello-Travale Geothermal Field** (**LTGF**).
- To focus on a test site area of 14x14 km^2 in the SW part of **LTGF**, where already drilled **deep geothermal boreholes** and **geophysical surveys** give us a wide dataset.
- To develop a **multidisciplinary conceptual model** in order to characterize the deep geothermal resources where the occurrence of super-hot fluids, possibly in supercritical conditions, are envisaged.

MT data integrated interpretation

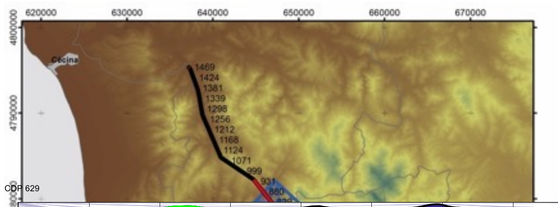




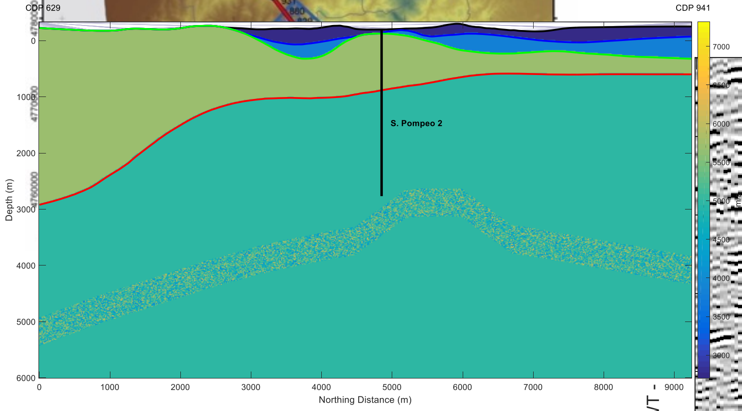
Low resistivity data are located in an area of high Vp/Vs (at 5 km) and low Vp, extremely high heat flow, low density: magmatic intrusions and partial melts.

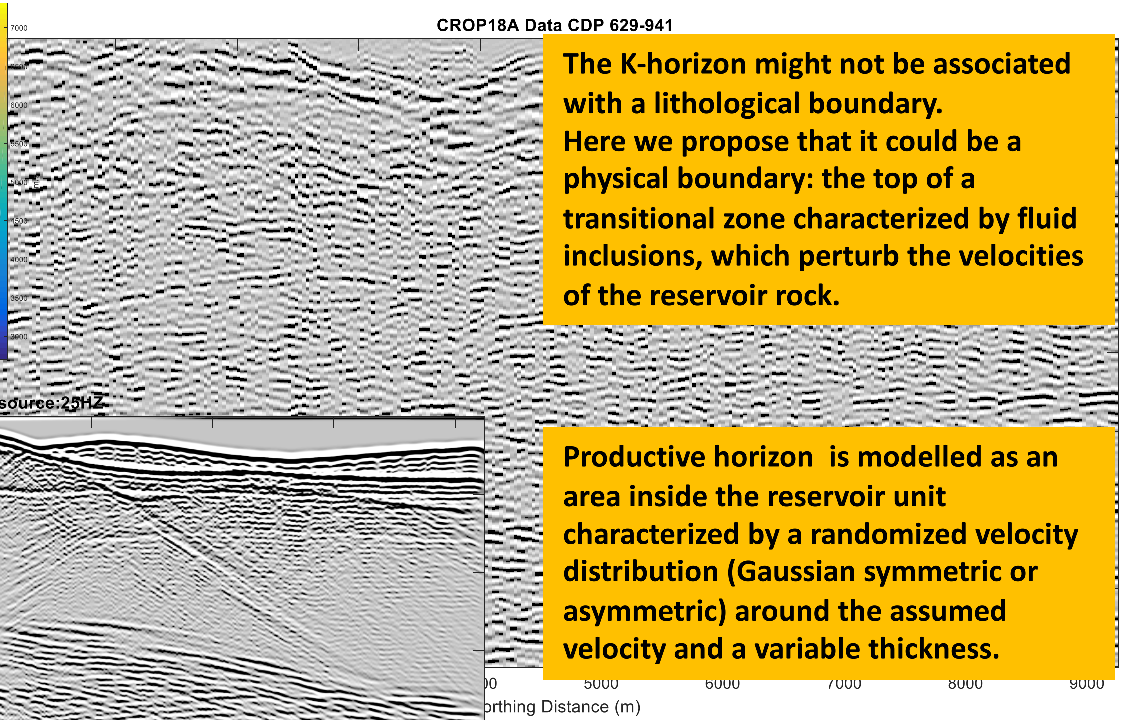
A main tectonic structure favored both fluid circulation (in the liquid-dominated ancient system, then increasing alteration??) and magma emplacement.

Seismic modelling

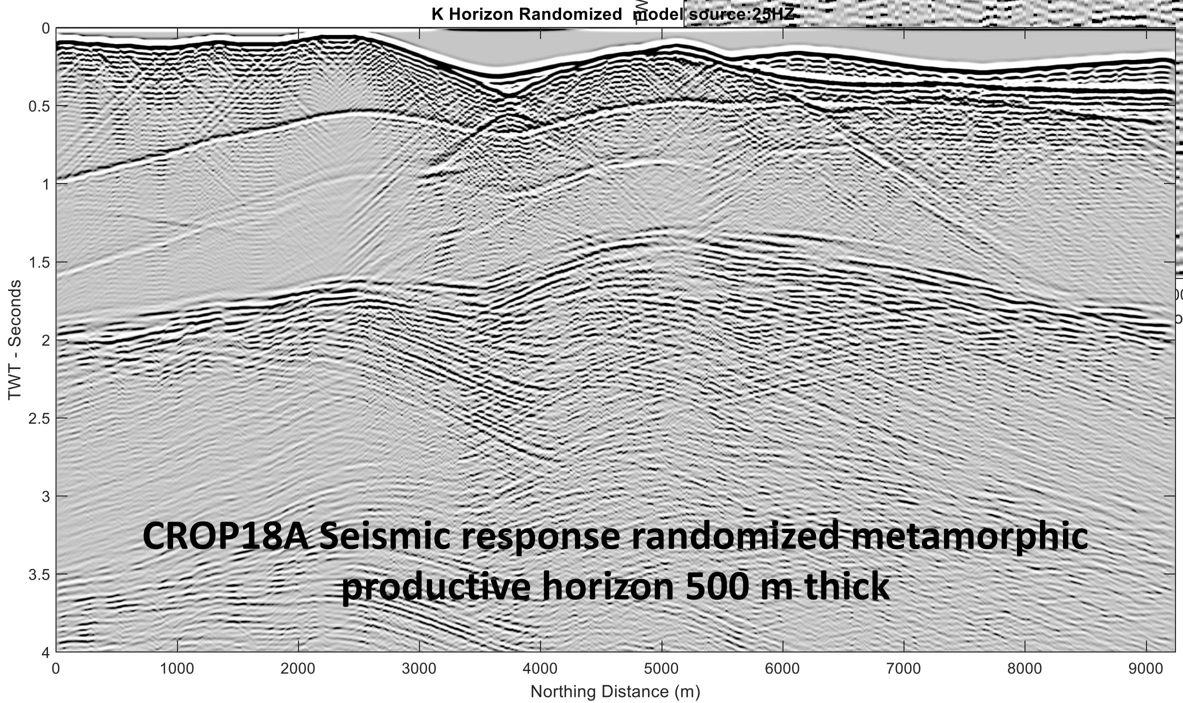


Public 2D seismic data (CROP 18A), recorded for deep crustal investigation, is compared with several synthetic seismic sections computed by the Finite difference exploding reflector acoustic approach and assuming different velocity values.



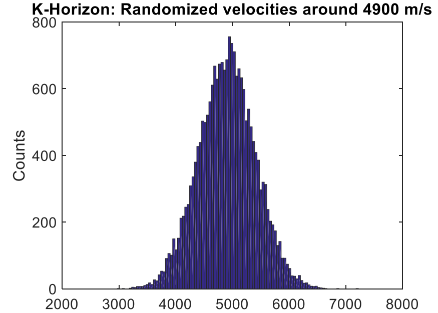


The K-horizon might not be associated with a lithological boundary.
Here we propose that it could be a physical boundary: the top of a transitional zone characterized by fluid inclusions, which perturb the velocities of the reservoir rock.



CROP18A Seismic response randomized metamorphic productive horizon 500 m thick

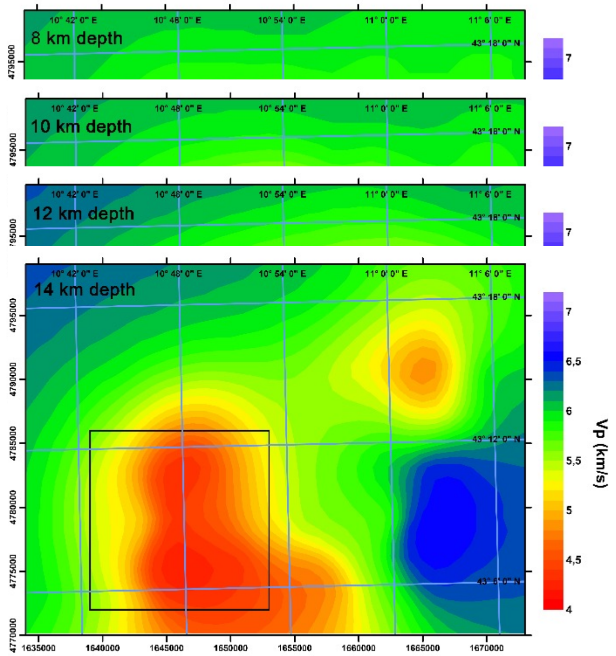
Productive horizon is modelled as an area inside the reservoir unit characterized by a randomized velocity distribution (Gaussian symmetric or asymmetric) around the assumed velocity and a variable thickness.



Geophysical evidences

Earthquakes tomography

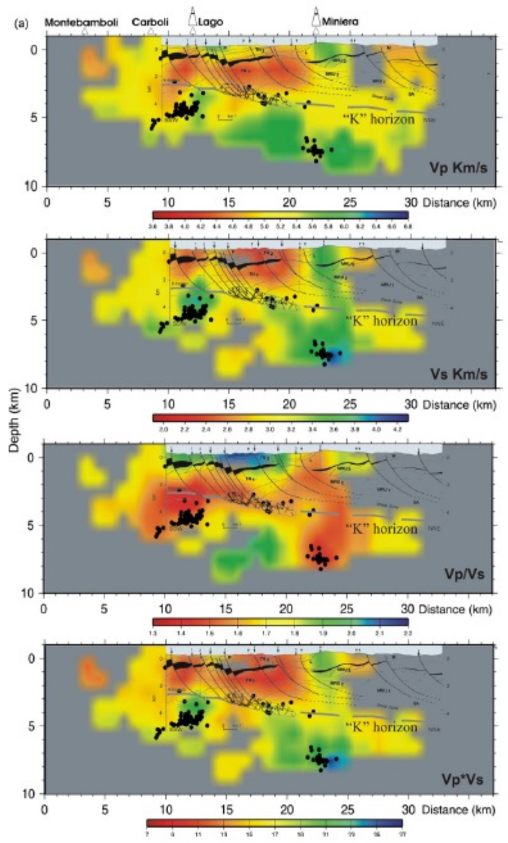
Batini/Toksoz et al. 1995

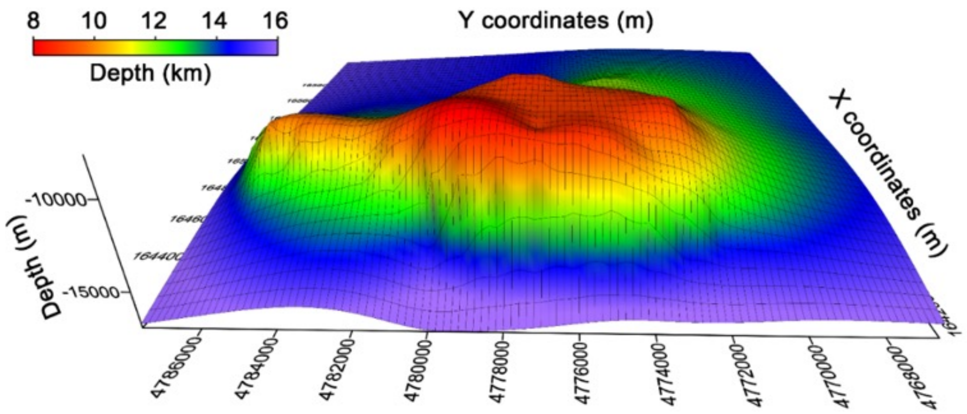


Shallow seismic tomography evidences strong lateral variations, possibly due to the interplay of the petrophysical characteristics of the basement rocks (e.g. porosity, fluid saturation and state) and the presence of upper-crust, partially molten, intrusions.

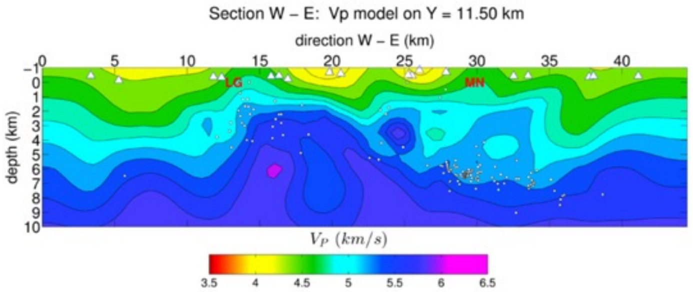
The velocity field derived from deep seismic tomography is dominated by a low velocity body (Vp < 5 km/s) which mimics a middle-crust magmatic chamber

De Matteis et al. 2008





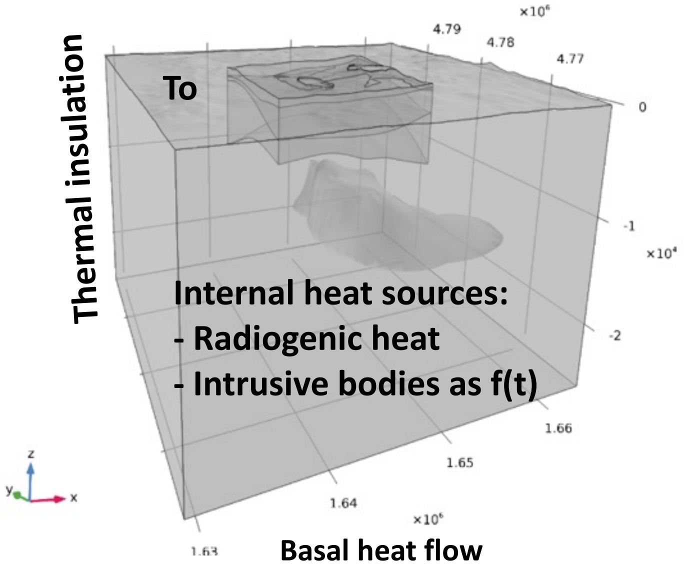
Saccarotti et al. 2014

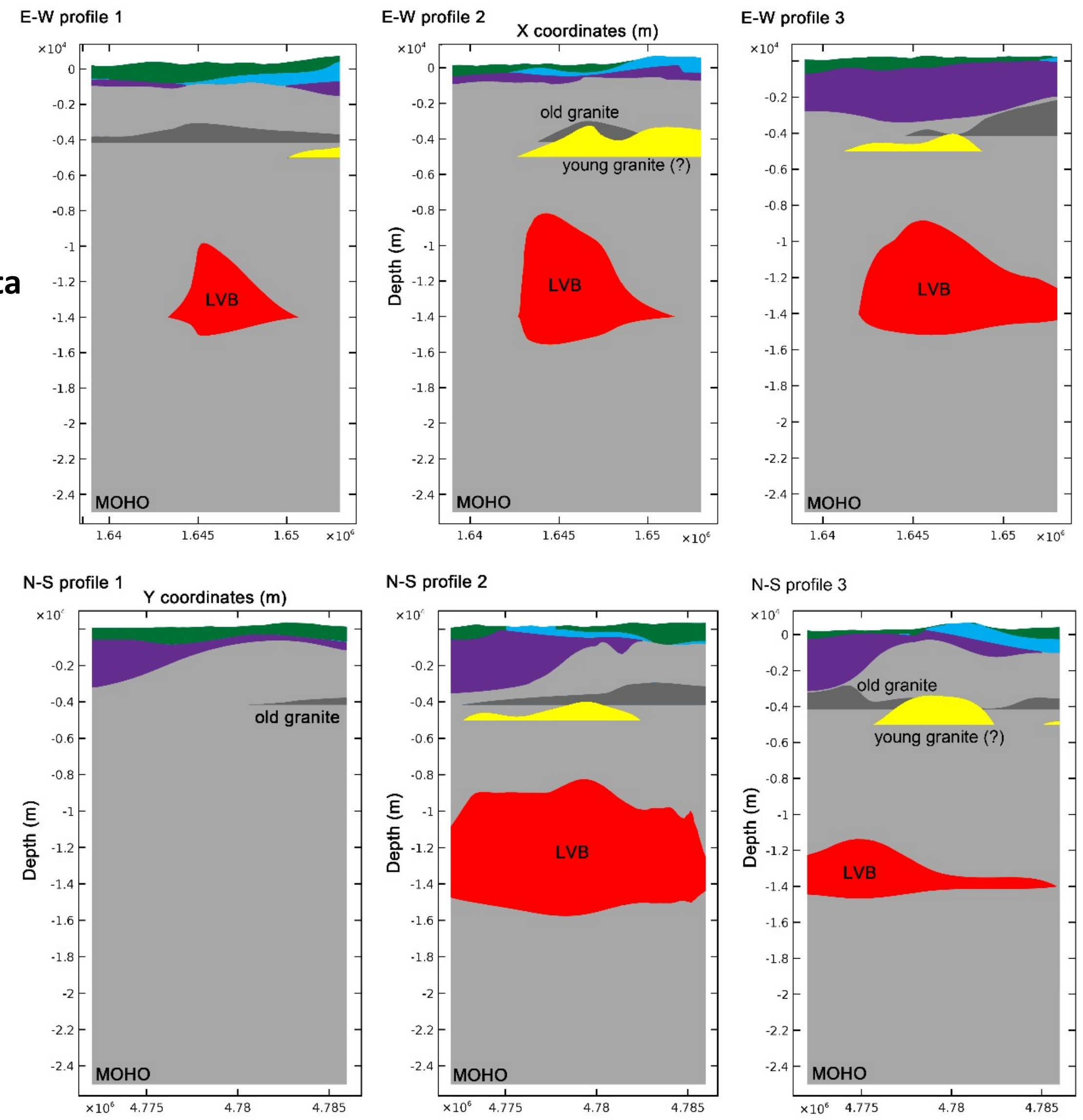


Thermal modelling

Input geometry and boundary conditions

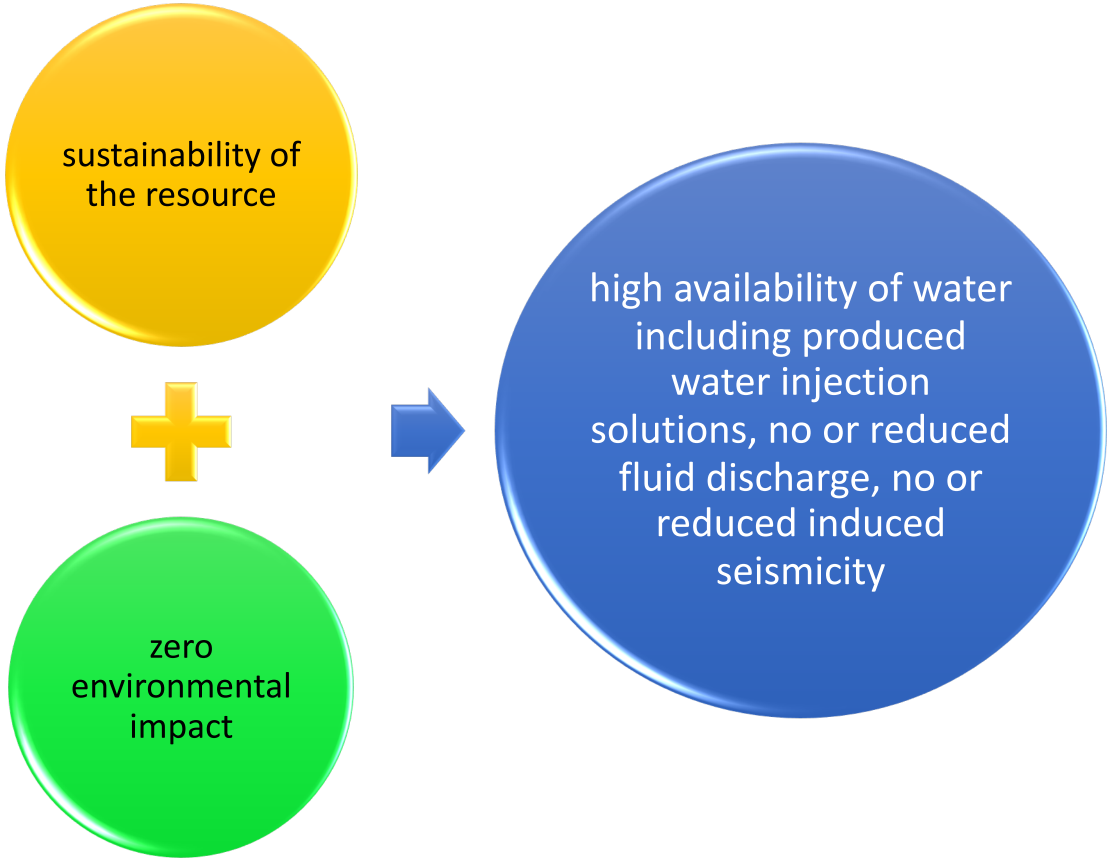
- Lithothermal units from 3D geological model
- Deep heat source
  - LVB from Vp anomaly (Vp < 5 km/s)
- Shallow heat sources
  - Old granite (3.8 – 1.3 Ma) from well data
  - Young granite (1.3 – present) from K-horizon shifted 500 m downward
- Latent heat of crystallization
- Temp. dependent thermal properties of rocks





Development and production: beyond drilling targets

A multi-scale process: Imaging at wells, concession and reservoir area; realtime monitoring



- Mapping of environmental condition before entering new areas: baseline
- Monitoring before and during operational, stimulation and production phases
- Understanding micro and macro processes
- **Predicting the effects of activity** (risk and impact based evaluations)

Thank you

If you want to be in touch

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