The Geological Society

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Bryan Lovell Meeting 2019:

Role of geological science in the decarbonisation of power production, heat, transport and industry

21 – 23 January 2019

Deep Geothermal: exploration in Italy, from knowledge to deployment in Europe

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Consiglio Nazionale delle Ricerche

National Research Council of Italy

Istituto di Geoscienze e Georisorse

Institute of Geosciences and Earth Resources

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ETIP-DG

European Technology & Innovation Platform on **Deep Geothermal**

ETIP-DG European Technology&Innovation Platform on Deep Geothermal

The development of low carbon technologies is a key part of the EU strategy.

Geothermal energy, and its generation of electricity, heating and cooling, can contribute to the local, regional and global energy transition toward reliable, clean and affordable energy sources.

To speed up the development and deployment of low-carbon technologies, including geothermal energy, and to strengthen the cooperation with Stakeholders under the Strategic Energy Technology Plan (SET-Plan), the European Commission has introduced Technology and Innovation Platforms (ETIPs).

ETIP-DG European Technology&Innovation Platform on Deep Geothermal

ETIPs are crucial to the SET Plan because:

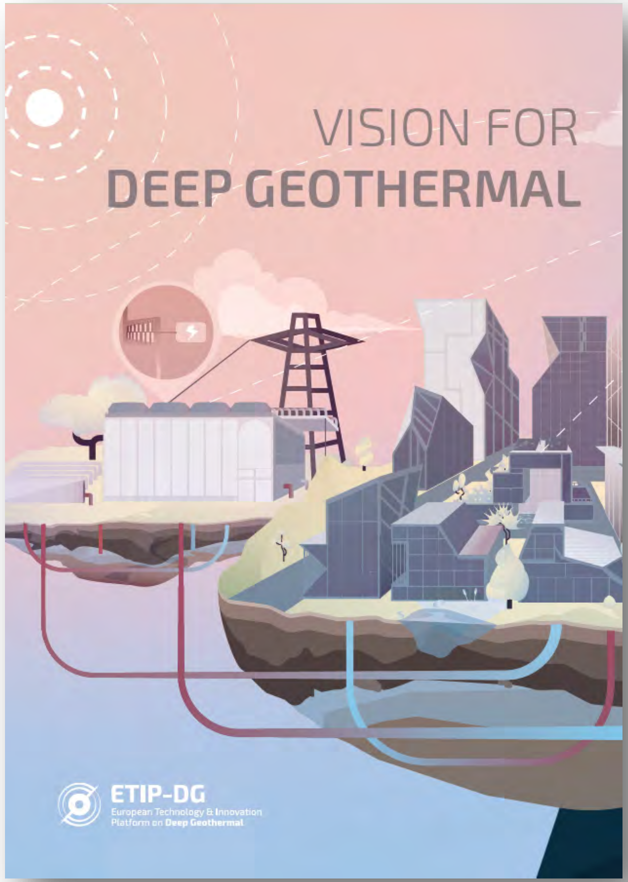
- They support the identification of
  - Additional R&I activities needed to reach the targets (Max. 10 per Implementation Plan)
  - Ongoing R&I activities (When clearly contributing to the targets, ongoing activities (national / EU / industry) need to be identified
  - Non-technological barriers and enablers
  - Monitoring mechanisms
- Cover the whole innovation chain
- Mobilise the relevant stakeholders

ETIP-DG objectives as contribution to RI&D

Develop and implement research pathways towards successful deployment of geothermal technologies

- Set the main targets in the **Vision for Deep Geothermal**
- Define R&D priorities in the **Strategic Research and Innovation Agenda (SRIA)**
- Implementing the priorities in the **Technology Roadmap**

About the Vision



This VISION looks toward **the future of Deep Geothermal energy development** by 2030, 2040, 2050 and beyond, and highlights the great potential of untapped geothermal resources across Europe. After an **Introduction & Overview** the document briefly describes the **Actual Status of geothermal development** and the VISION's aim for

> **> Unlocking geothermal energy**
>
> **> Increasing the Social welfare in Europe**
>
> **> Novel technologies for full and responsible deployment of geothermal potential**

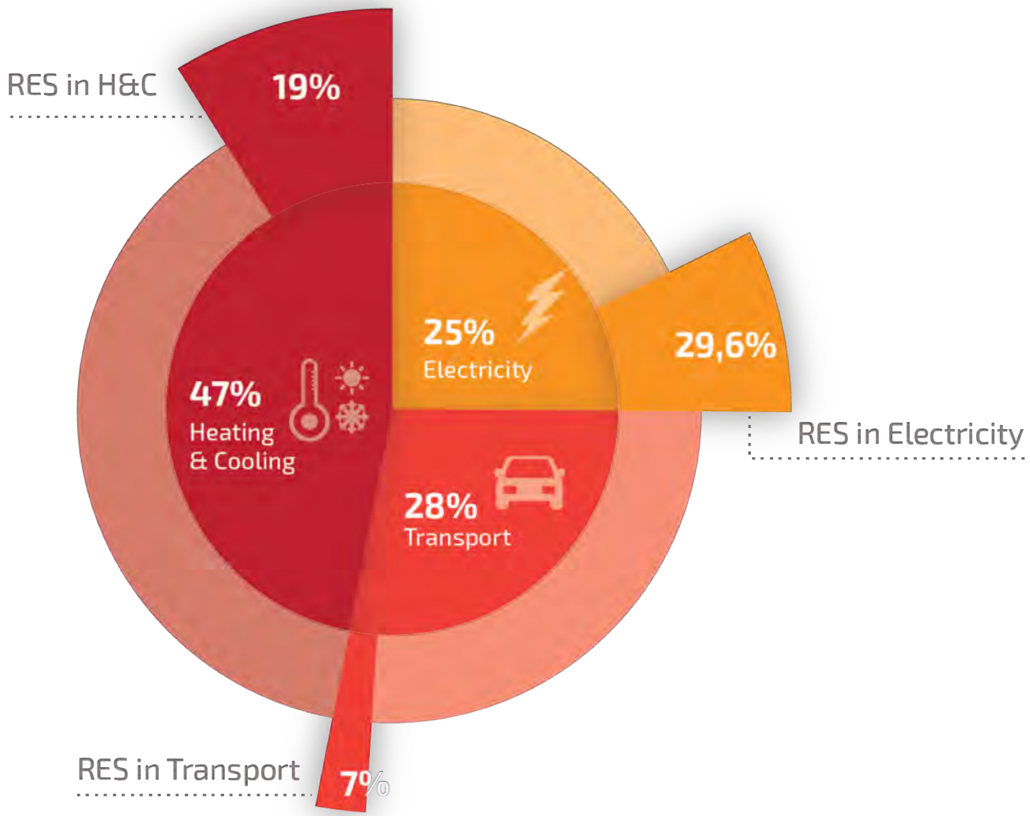
Rising to the Vision

Our VISION is to cover

> A significant part of **domestic heat demand** and

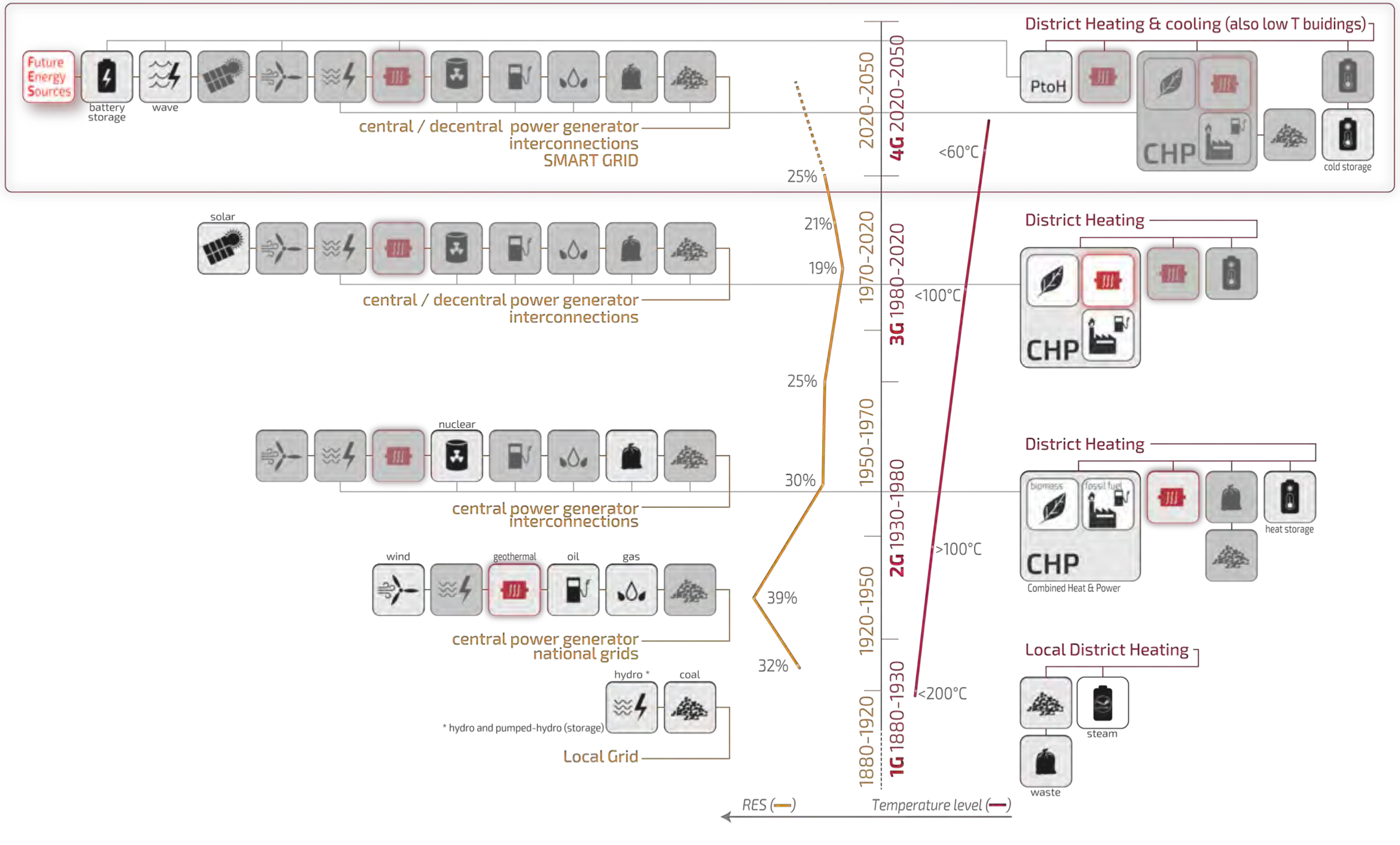
> a large part of **electrical power demand** in Europe by geothermal energy.

This includes taking the maximum advantage offered by the flexibility of geothermal production, providing large **centralized** as well as domestic and **decentralized** small scale options.



Unlocking Geothermal Energy: Heat development

- > Operative temperatures of the DHC network can be reduced
- > By demand site management or by thermal energy storage it will be possible to balance heat demand and supply in a DH network.
- > Cascade applications
- > CHP



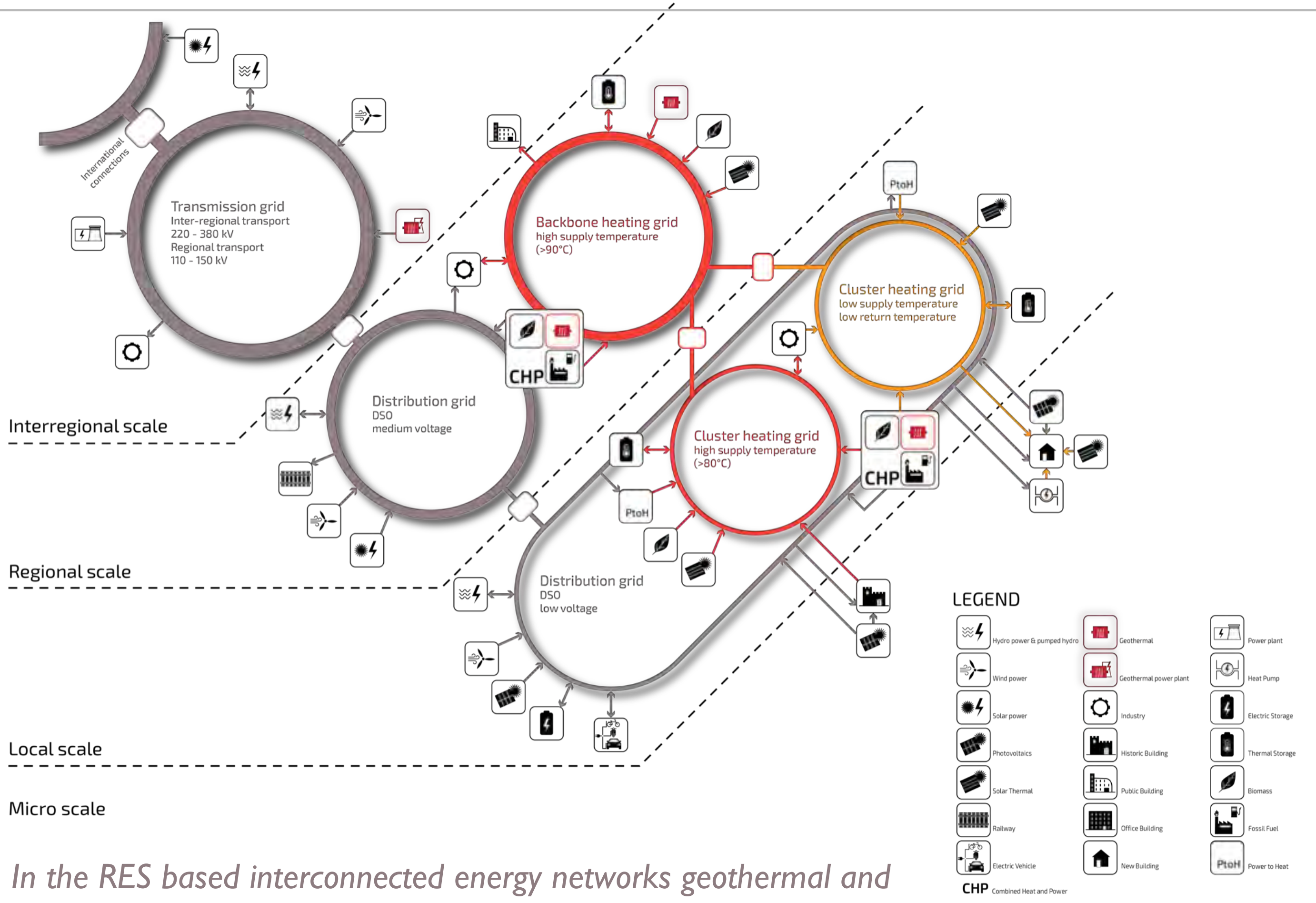
Evolution of power generation and district heating

Unlocking Geothermal Energy: Power development

Combined biomass and geothermal plant in Cornia, Italy

> Improved efficiency, optimization of material, processes, cycle design
> Hybrid, proper combination
> Cutting edge technologies for any kind of resource (super-hot, off-shore, geopressurized) and any place (from remote islands to urban areas)

Unlocking Geothermal Energy: Combined production



In the RES based interconnected energy networks geothermal and underground thermal storage play an important role

> Coupling renewable heat and electricity sectors and markets for an optimal use of geothermal energy

> Consumer-producer-prosumer perspectives

> Thermal storage to help balance and to optimize production

> Cascade, hybrid, synergy (e.g. geothermal-algae-biofuels-transport)

The City of the Future

Increasing social welfare in Europe

> Achieve lower **environmental footprint**

> Create **wealth**

> Strengthen **dissemination, education and outreach**

> Guarantee **protection and empowerment** of customers

Novel technologies for full and responsible deployment of geothermal potential

> Technologies beyond H2020

> While targeting the EU long-term goal of **reducing costs** and **increase performance** of geothermal technologies and installations, RD&I pursue all opportunities for complete deployment of geothermal resources, aiming at various advancements

1. Prediction, assessment and access to the resource

2. Resource development

3. Heat and electricity generation

4. Assessment and optimization of environmental, social and economic footprints

5. Data and knowledge sharing

FULL AND RESPONSIBLE DEPLOYMENT OF GEOTHERMAL POTENTIAL

A. Prediction and assessment of geothermal resources

B. Resource Access and Development

C. Heat and electricity generation and system integration

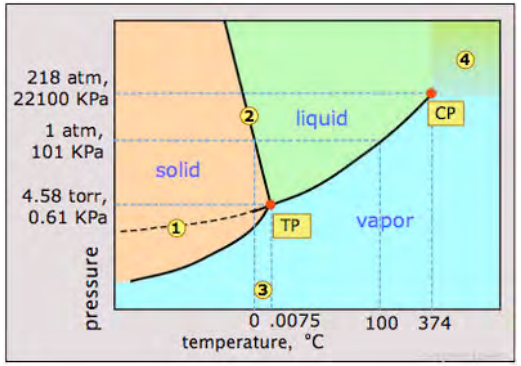
D. From R&I to Deployment

E. Knowledge Sharing

Exploring geothermal supercritical resources: background

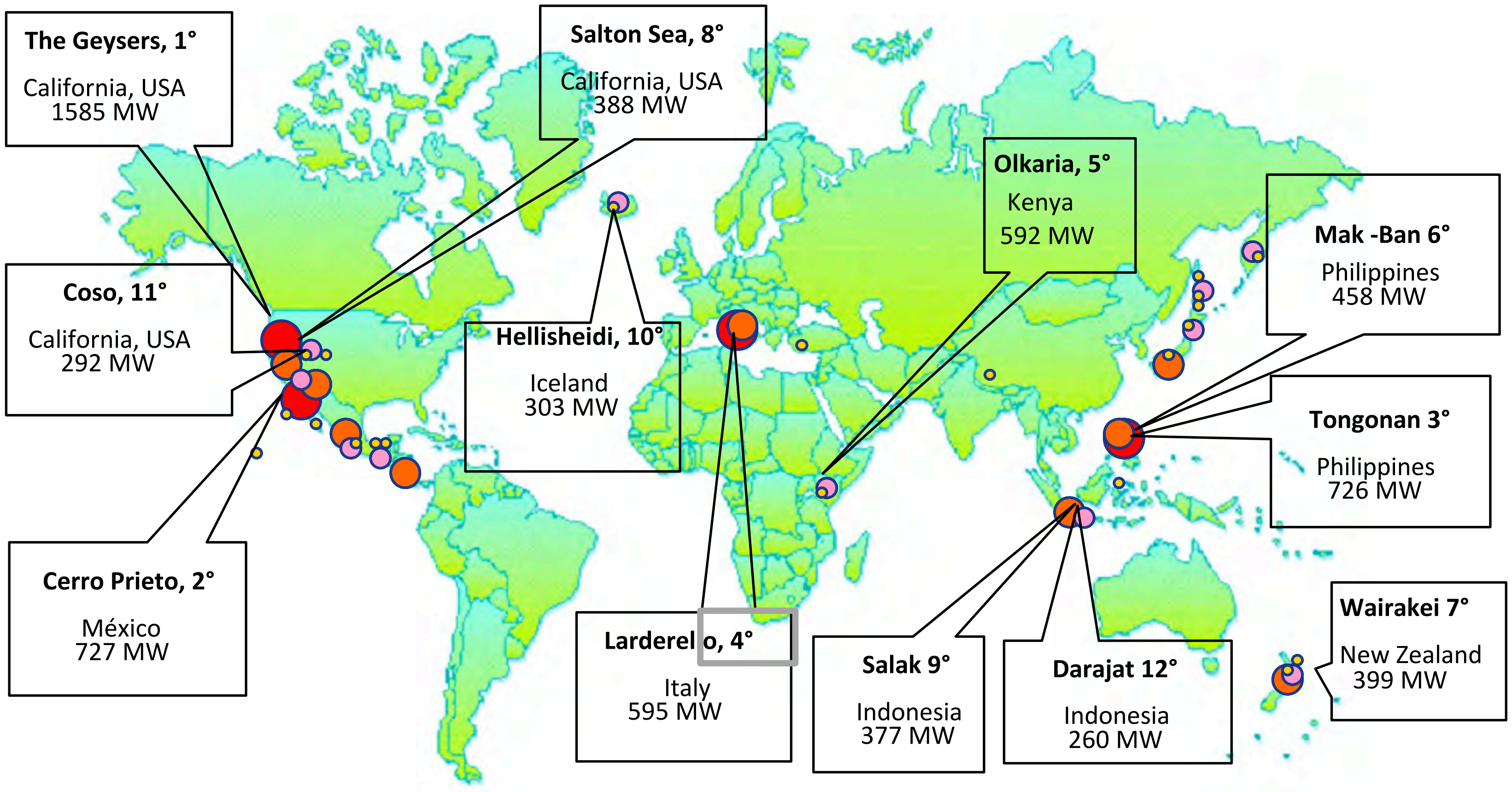
Very high-temperature reservoirs are a possible target for future geothermal exploration either through the direct exploitation of super-critical fluids or as a potential high-temperature reservoir for Enhanced Geothermal Systems.
By exploiting subsurface fluids at very high **temperature the power output per well will increase by a factor of ~10**. This will reduce development costs by decreasing the number of wells needed.

A fluid is called "super-critical" when temperatures and pressures are high enough (for pure water T>374°C and P>22 MPa) that there is no longer any distinction between its liquid and vapour phases. Beyond critical point (the area is marked as 4 in the phase diagram), fluids cannot be liquefied by increasing pressure. Super-critical fluids occurs naturally at depth, but fluid amount, permeability and rheological conditions are still matter of research.

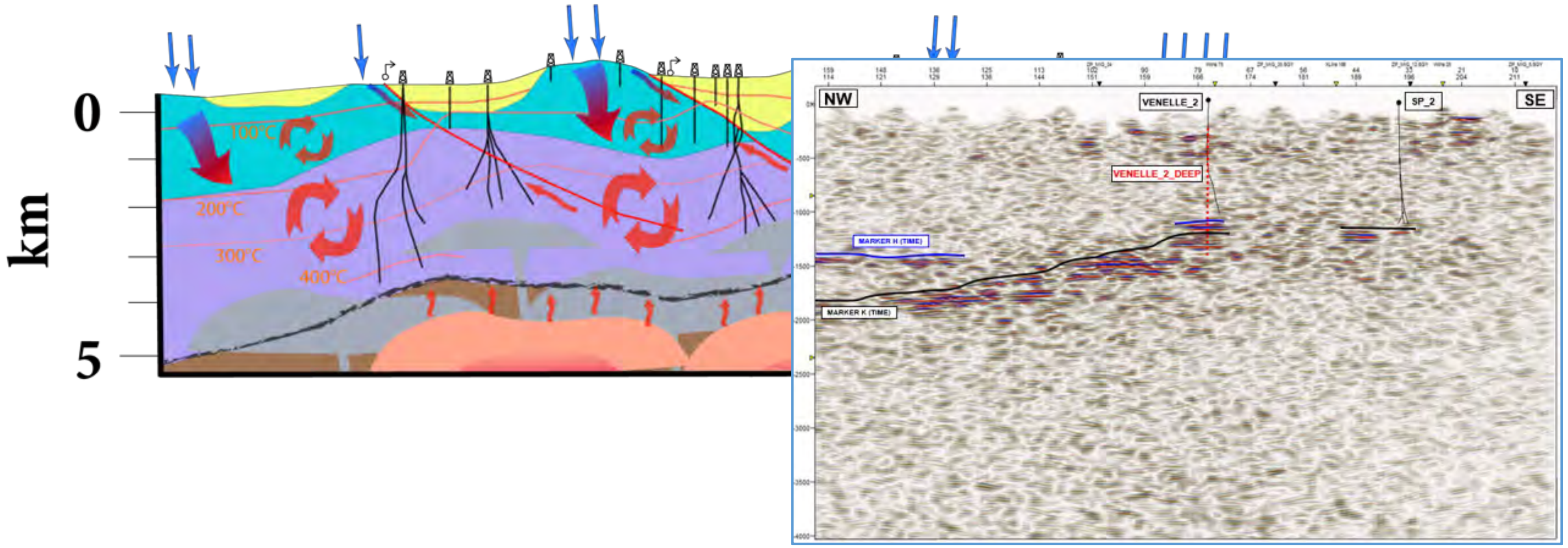


The basic idea of deep well development is to bring water-dominated super-critical fluid to the surface in such a way that it is directly transformed to superheated steam along an adiabatic decompression path.
Another option, wherever natural super-critical fluids are not sufficient or for other practical reasons, is to develop new concepts for performant heat extraction from super-hot subsurface.

The test site: why Larderello?



The test site: why Larderello?



Larderello, Italy, the birthplace of geothermal power production, has been extensively explored and investigated for many decades.

2D and 3D seismic survey data highlighted an important deep seismic marker named “K-horizon” culminating below the currently exploited, vapour-dominated, reservoirs and recognizable throughout southern Tuscany. The high seismic impedance of this seismic marker, even resembling a bright-spot in some areas, has been interpreted as due to **magmatic/metamorphic fluids, possibly in super-critical conditions**. An unexpected over-pressure of a well in the 1970’s when reaching the K-horizon also contributed to this interpretation.

An existing well in the hottest area of Larderello has been used for our testing. The exploration was developed in the frame of two European Projects, IMAGE and DESCRAMBLE

Drilling in dEep Super-CRitical AMBient of continentaL Europe

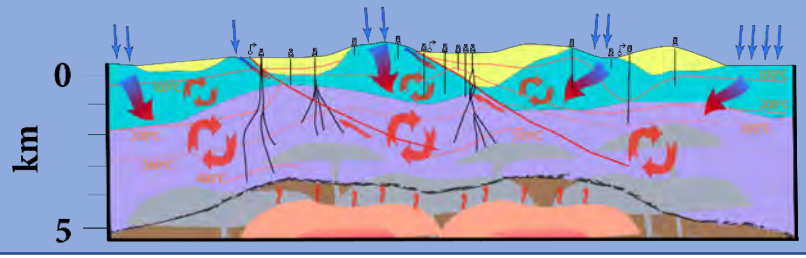
The IMAGE project: objectives

Develop a reliable **exploration** and **resource assessment method** to image geothermal reservoirs (structural and hydrological features as well as the heat source and recharge areas)

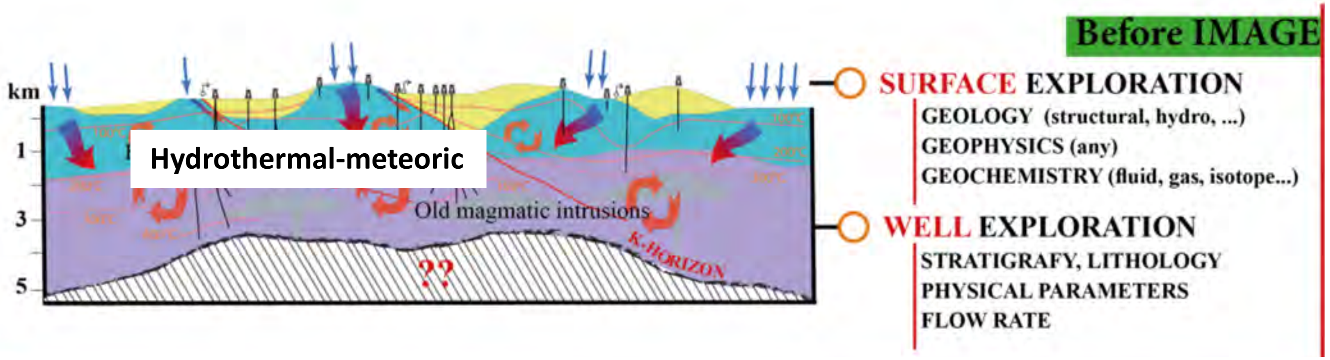
Develop technologies to **exploit unconventional geothermal resources** (e.g. super-critical conditions) in different environments (e.g. deep reservoir hosted in basement rocks in proximity of magmatic bodies)

- Understanding the **physical processes** that control the spatial distribution of critical exploration parameters (e.g. Temperature, Pressure, Permeability, Fluid saturation)
- Improving geo-scientific knowledge for **predicting physical conditions at depth**, which consider geological, petrological, geophysical and geochemical evidences

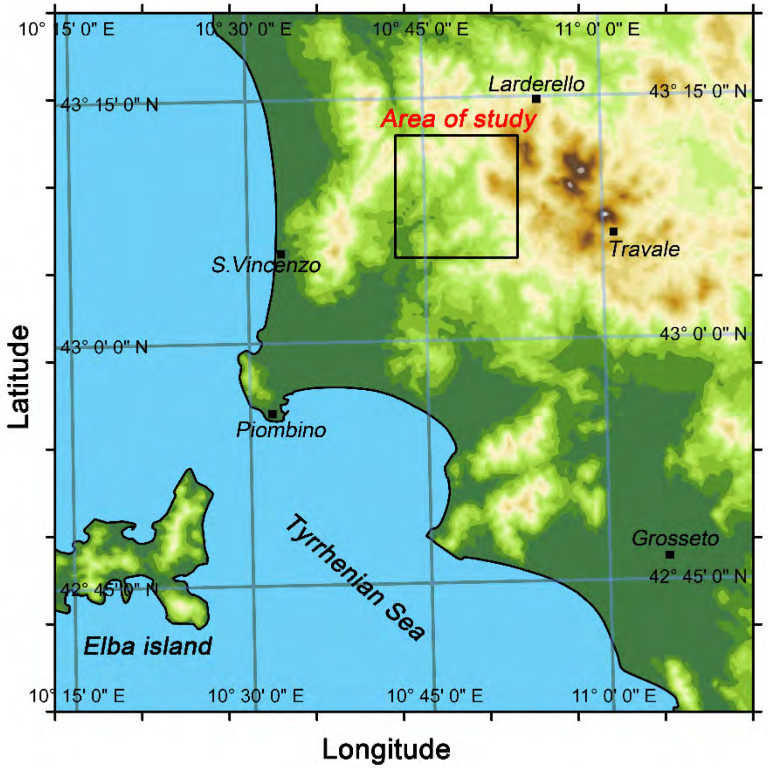
Develop a comprensive **conceptual model** of the geothermal system

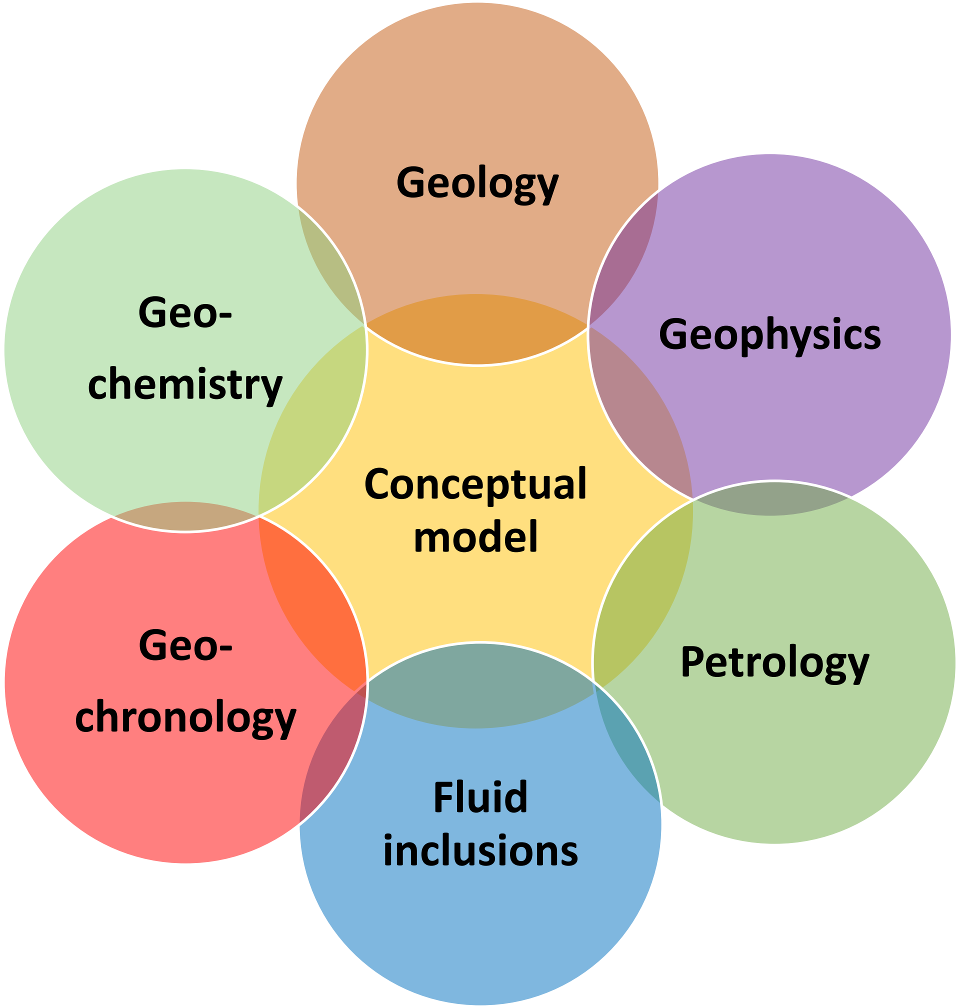


Brownfield



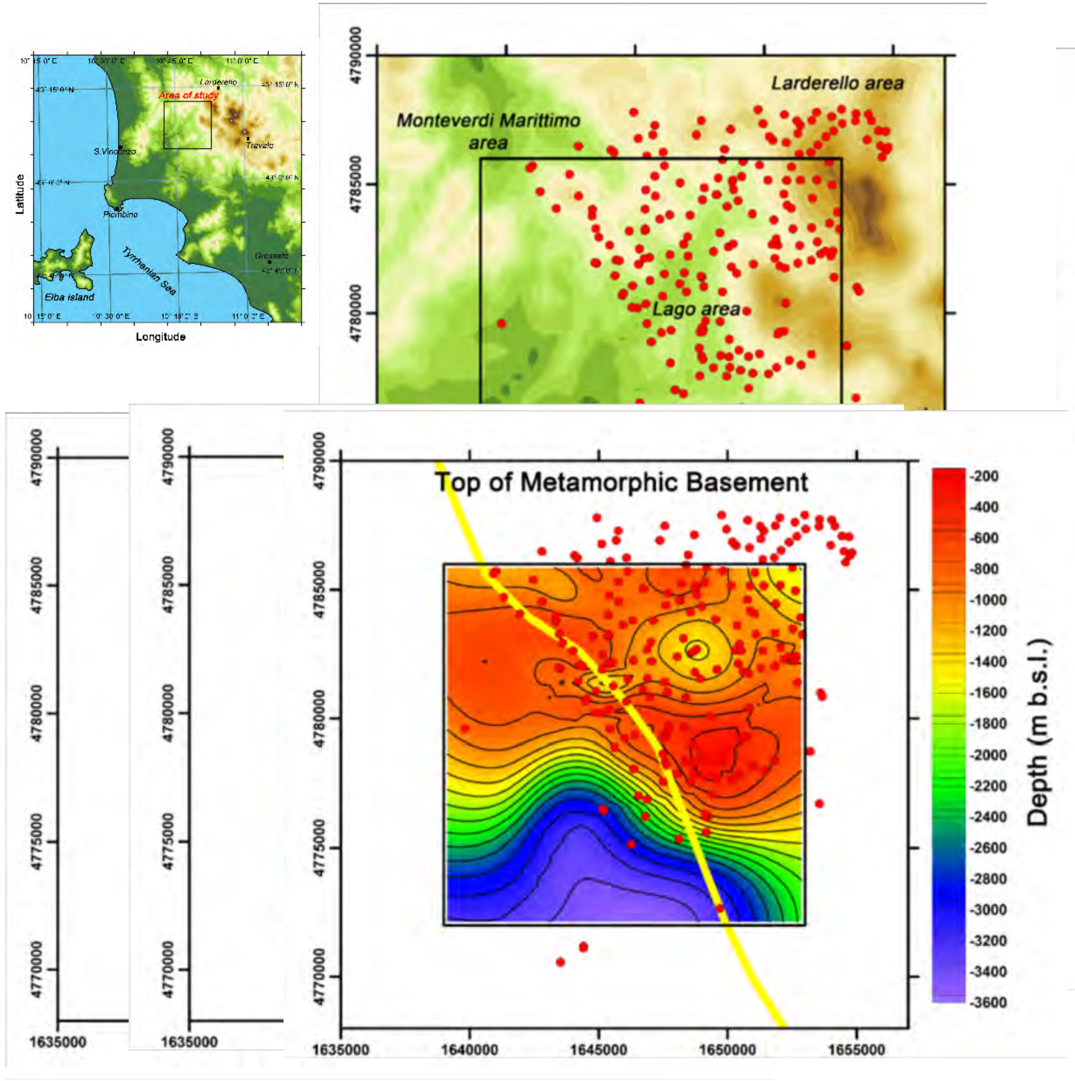
Greenfield

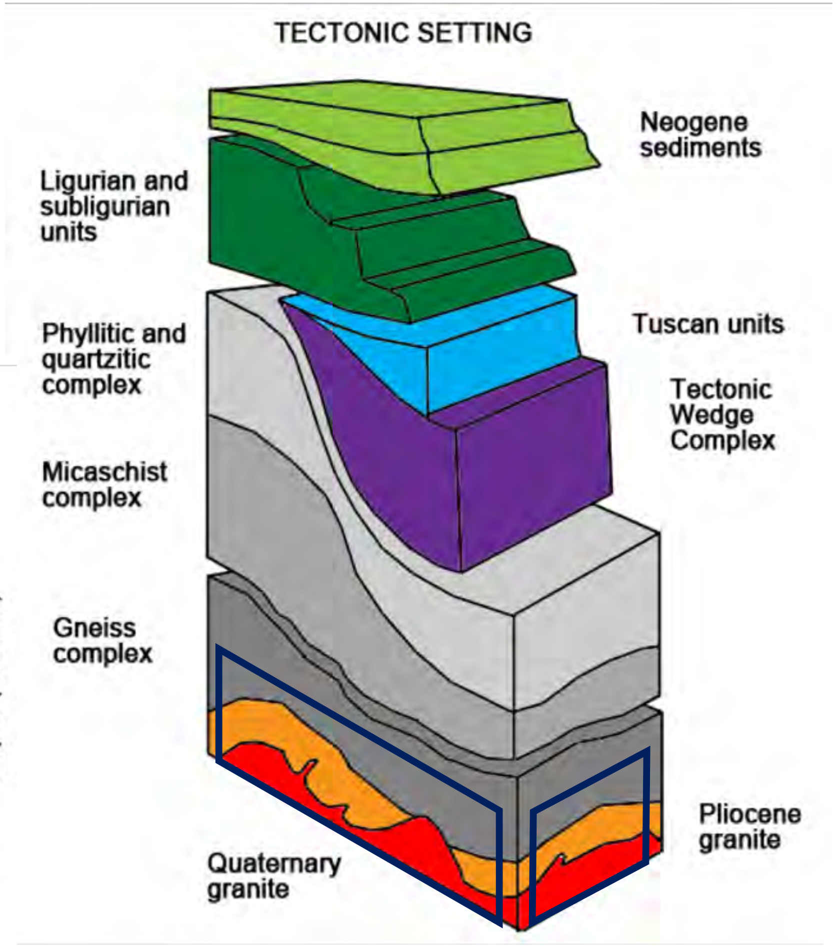




- To understand the **structure** of the **deepest part of the Larderello-Travale Geothermal Field** (**LTGF**).
- To focus on a test site area of 14x14 km^2 in the SW part of **LTGF**, where already drilled **deep geothermal boreholes** and **geophysical surveys** give us a wide dataset.
- To develop 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.

Geological model





The interplay among extensional tectonics, thinning of the previously overthickened crust and lithosphere, and magmatism related to crustal melting and hybridism, controlled the geothermal anomaly occurring in southern Tuscany.

Numerical simulation

IMAGE

3D Numerical Model of Larderello Area

Giordano Montegrossi[1], Marina Agostini[2], Davide Scrocca[3], Giovanni Ruggieri[1], Adele Manzella[4], Alessandro Santilano[4], Lorenzo Petracchini[3], Eugenio Trumpy[4], Roberto De Franco[5], Grazia Caielli[5]

[1]C.N.R. –I.G.G.-U.O.S. Firenze (Italy)
[2]University of Florence, Depth. Earth Sciences, Firenze (Italy)
[3]C.N.R. – I.G.A.G. Roma (Italy)
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National Research Council of Italy

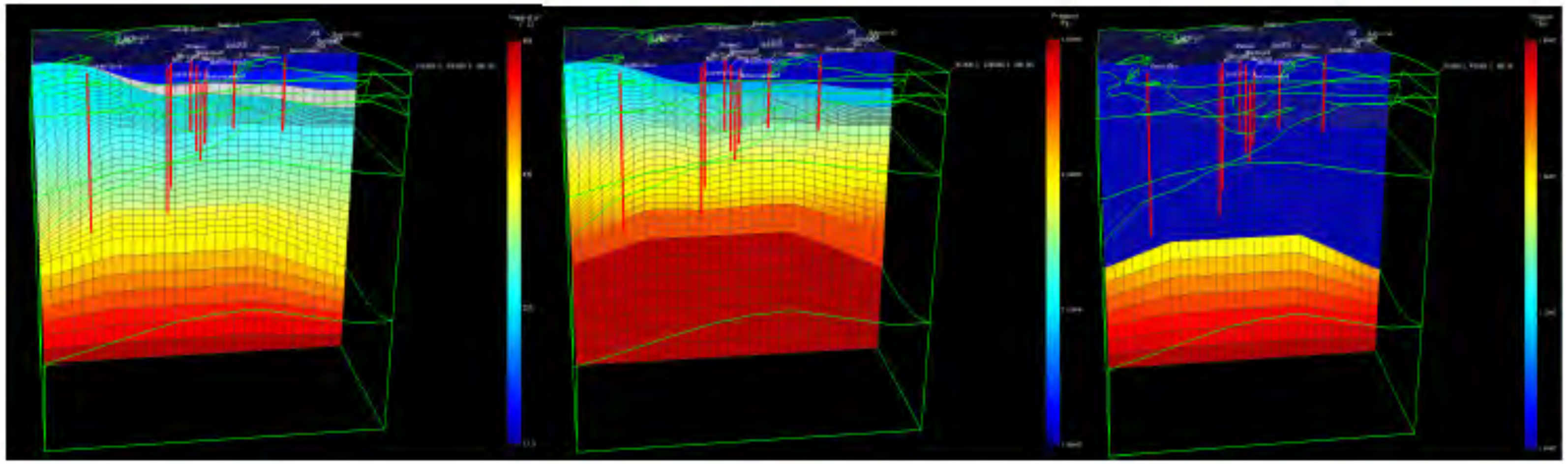


Figure 8 – Temperature distribution, view from east. We can observe an upflow in the central part o the model, use S. Pompeo2 well for reference.

Figure 9 – Pressure distribution, view from east. Left figure is focused on pressure distribution above K-Horizon, right figure is focused on pressure distribution below K-Horizon

Analogue modelling

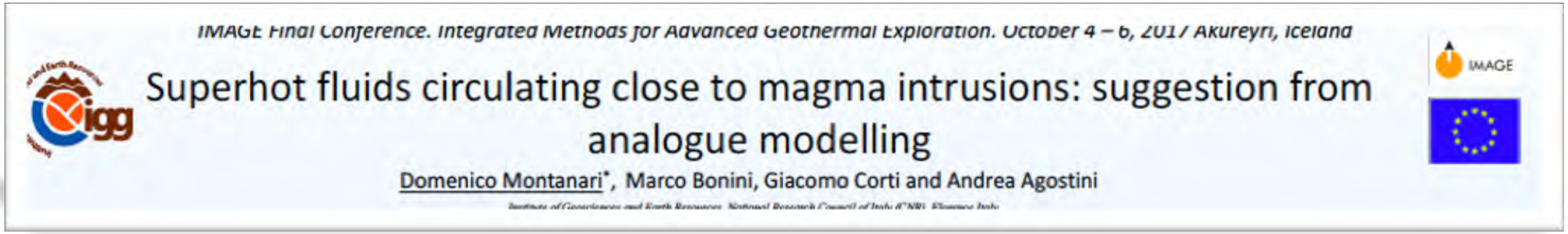
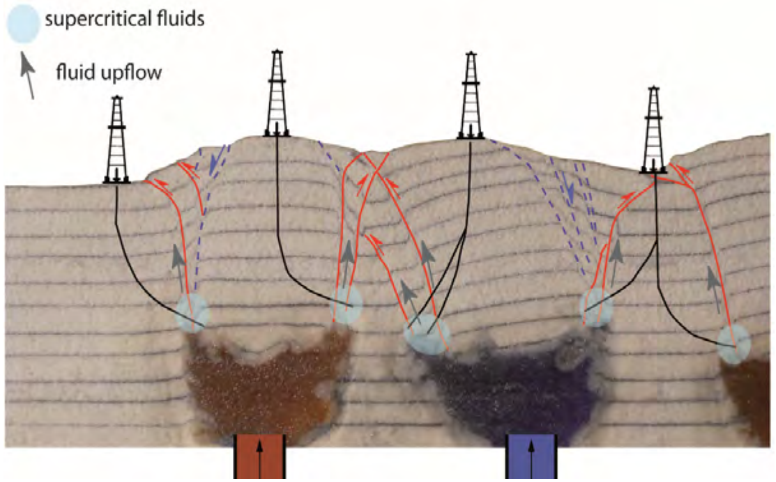


IMAGE Final Conference. Integrated Methods for Advanced Geothermal Exploration. October 4 – 6, 2017 Akureyri, Iceland

Superhot fluids circulating close to magma intrusions: suggestion from analogue modelling

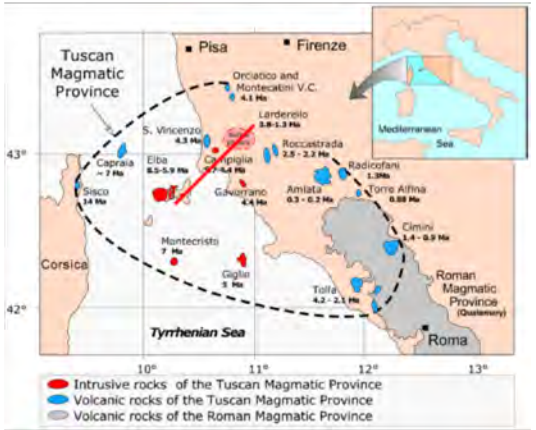
Domenico Montanari*, Marco Bonini, Giacomo Corti and Andrea Agostini

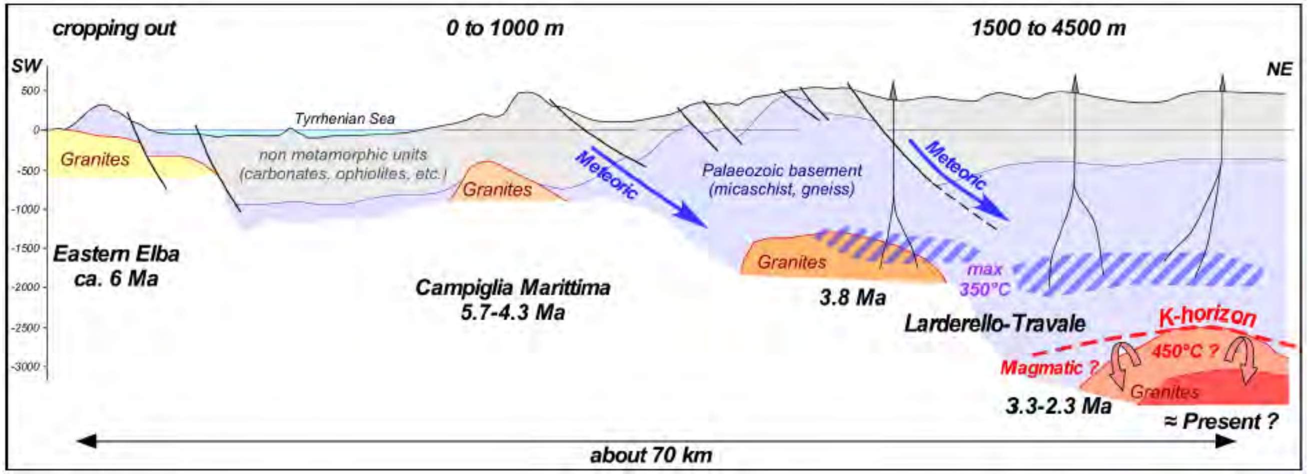


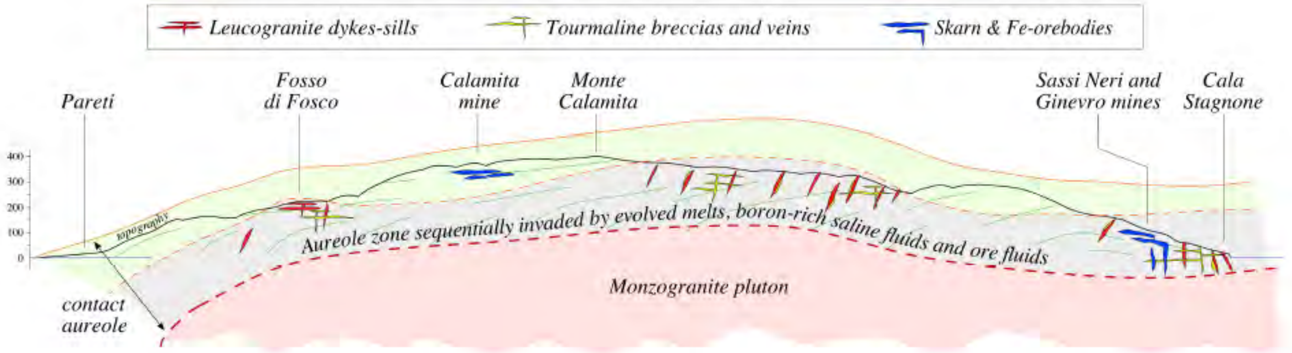
To get insights into this process, analogue modelling reproduced and analyzed the fracture/fault network associated with the emplacement of magma at shallow crustal levels, which are indeed expected to significantly influence the distribution and migration of superhot geothermal fluids near the edge of the magma intrusion.

Elba as "proxy" of Larderello deep zone

To study the past to understand the present: we can retrieve useful information about the K-horizon by the study of exhumed fossil geothermal systems







WP3 activity

- Similar emplacement depth, around 4-6 km.
- Progressive eastward younging.
- Differential exhumation

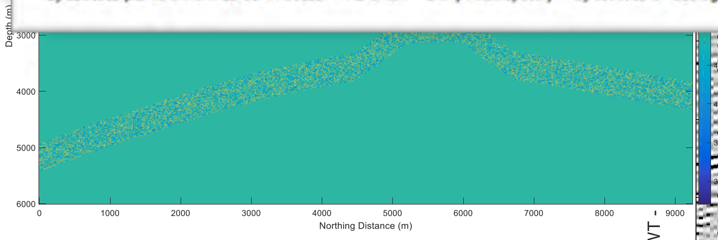
Seismic modelling

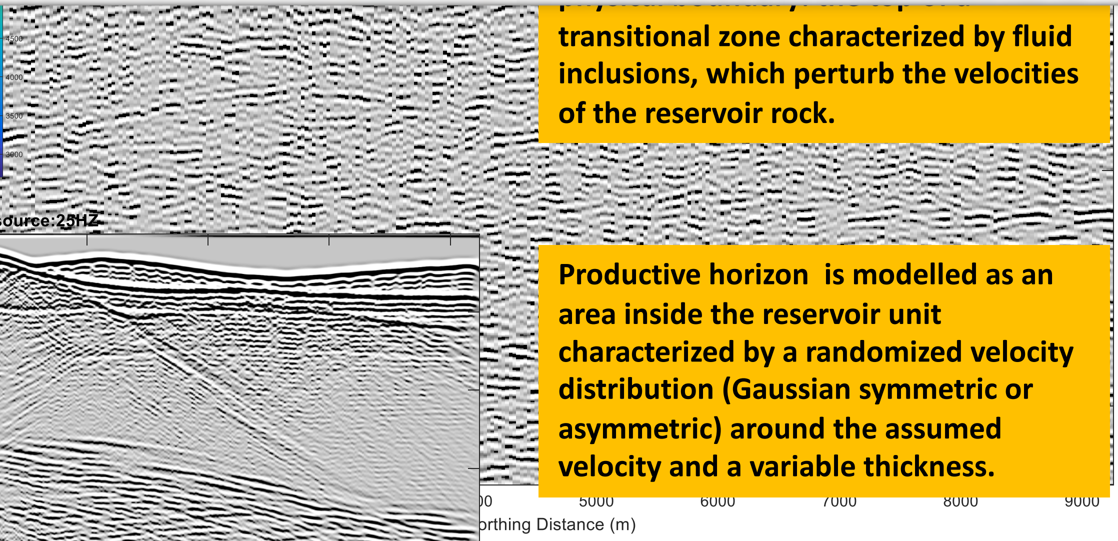
IMAGE

3-D geological-geophysical model and synthetic seismic reflection modelling along CROP18A line in the Larderello area

R. de Franco[1], L. Petracchini[2], G. Caielli[1], D. Scrocca[2], A. Santilano[3-4], A. Manzella[3], G. Montegrossi[3] , G. Norini[1], G. Groppelli[1]

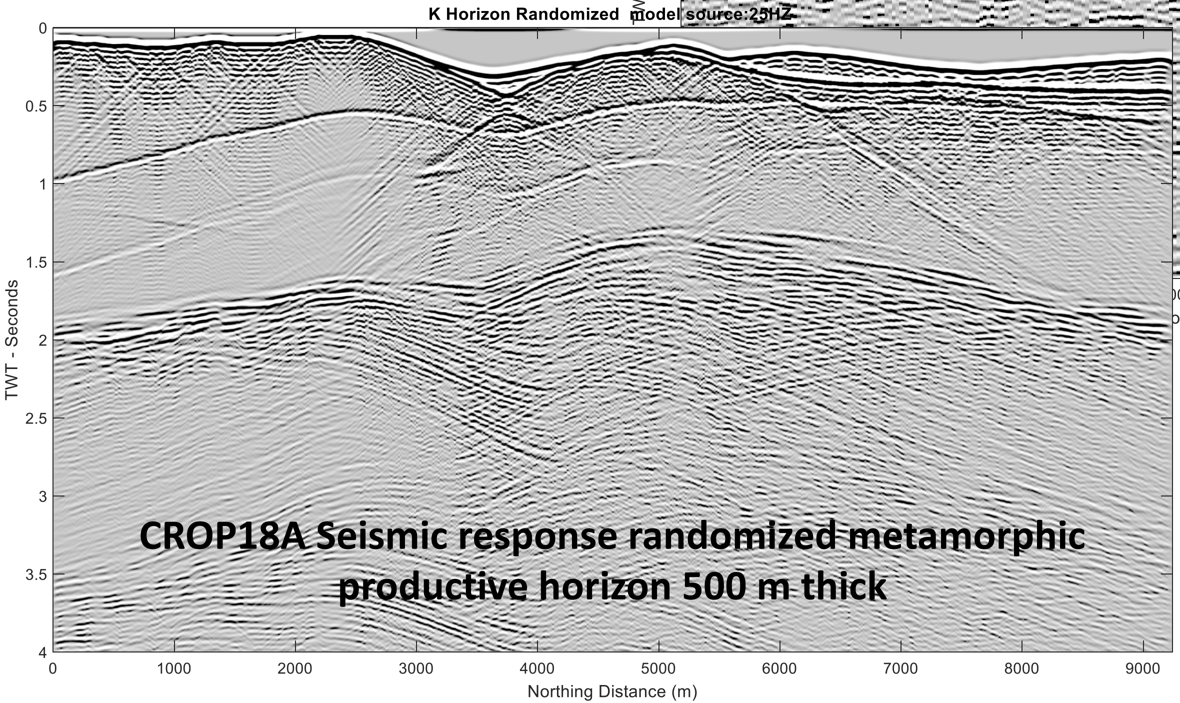
1) Istituto per la Dinamica dei Processi Ambientali - CNR, Milano, Italy – 2) Istituto di Geologia Ambientale e Geoingegneria – CNR, Roma, Italy – 3) Istituto di Geoscienze e Georisorse – CNR, Pisa, Italy – 4 DIATI - Politecnico di Torino, Italy

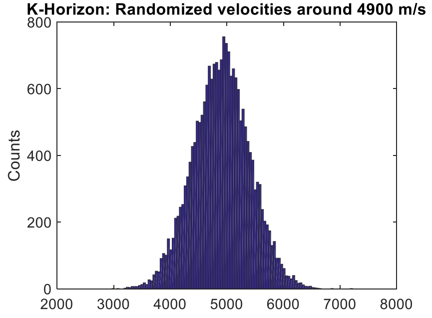




transitional zone characterized by fluid inclusions, which perturb the velocities of the reservoir rock.

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.





Fluid inclusions

Characterization of the early stage magmatic fluids circulation at/just after the granite emplacement
Fluid inclusion analyses in Larderello refer to the surrounding of the “shallow”, old and cold granite

e

Thermo-metamorphic carbonic fluids

Magmatic hypersaline fluids

Coexistence of hypersaline and carbonic fluids

Fluid-rock interaction

IMAGE

Geochemical model of high temperature gas-water-rock interaction

Giordano Montegrossi[1], Giovanni Ruggieri[1], Barbara Cantucci[2]

[1]CNR -IGG, Institute of Geosciences and Earth Resources, Via La Pira 4, 50121 Florence, Italy
[2]INGV, Fluid Geochemistry Lab. Rome 1 Section, Via di Vigna Murata 605, Rome, 00143, Italy

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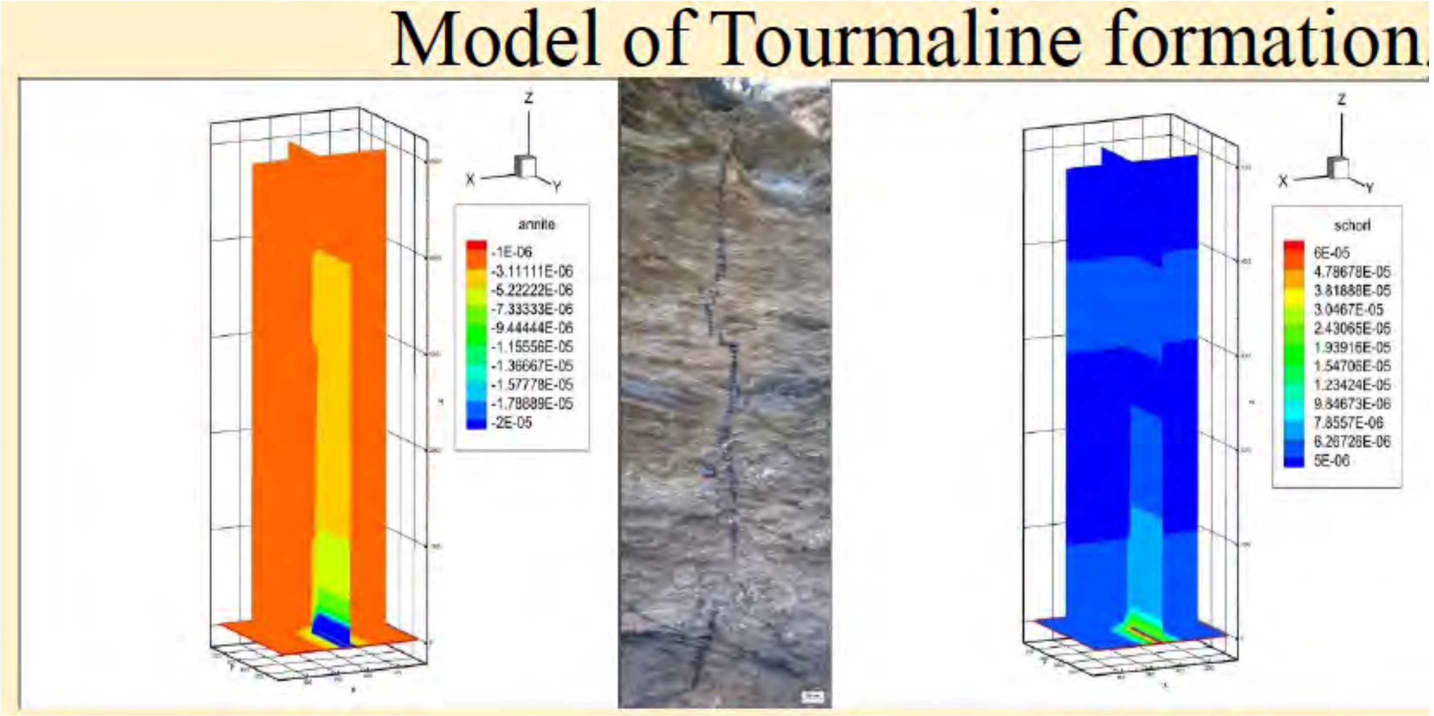
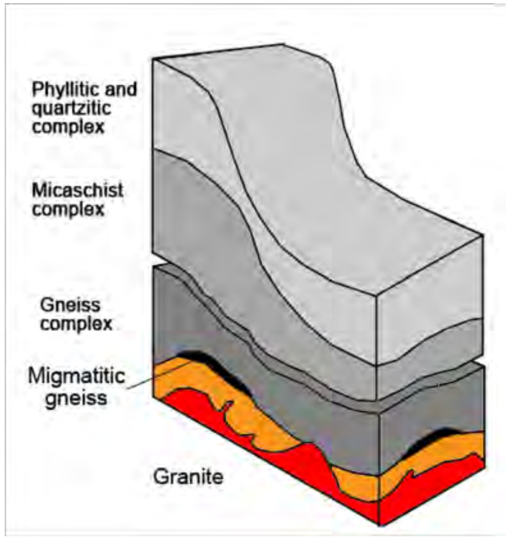
National Research Council of Italy



Metamorphic Basement

Thermal metamorphism (HT-LP)



Bt in
(~400°C)

Crd in
Chl-Mus out
(T>500°C)

Cor in
(T>600°C)

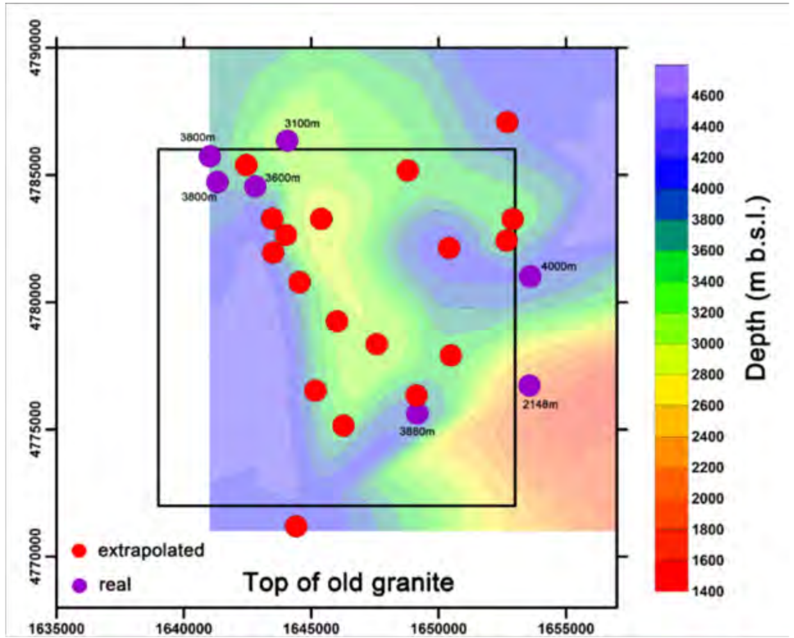
melt
(T>650°C)

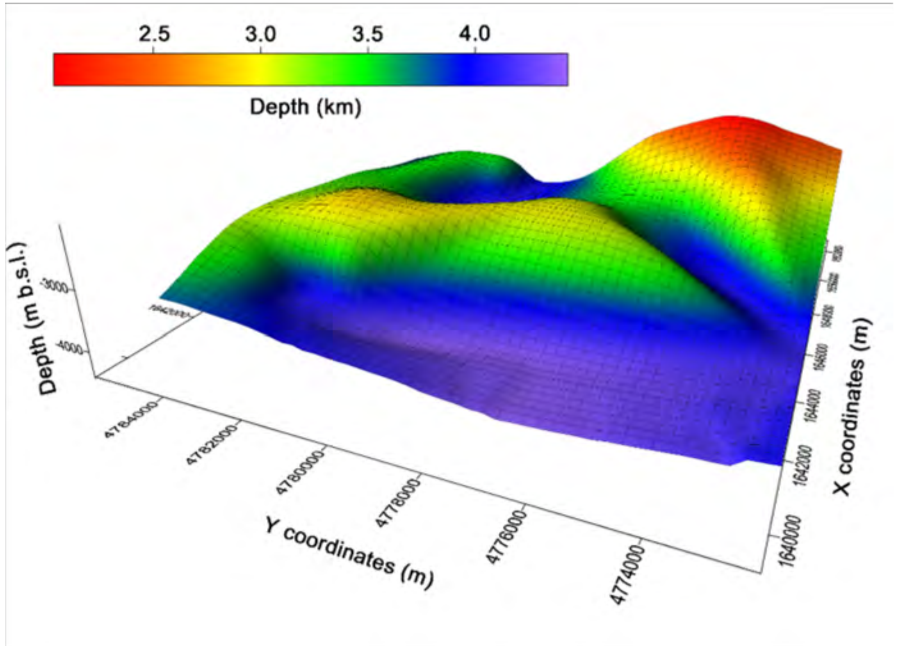
Andalusite-Cordierite Micaschist
Chl + Mus + Qtz -> Crd + And + Bt + H_2O — P = 100-150 MPa, T = 500-520°C
Chl + Mus + Qtz -> Crd + Bt + H_2O — P = 100-150 MPa, T = 520-560°C

Andalusite-Cordierite Gneiss
Ms + Qtz -> And + K-f + H_2O — P = 100-150 MPa, T = 540-560°C

Corundum Gneiss
Ms -> Cor + K-f + H_2O — P = 100-150 MPa, T = 590-620°C

Migmatitic gneiss
K-f + Qtz + Pl + H_2O (magmatic) + Bt + Cor -> melt — P = 150-200 MPa, T = 650-680°C

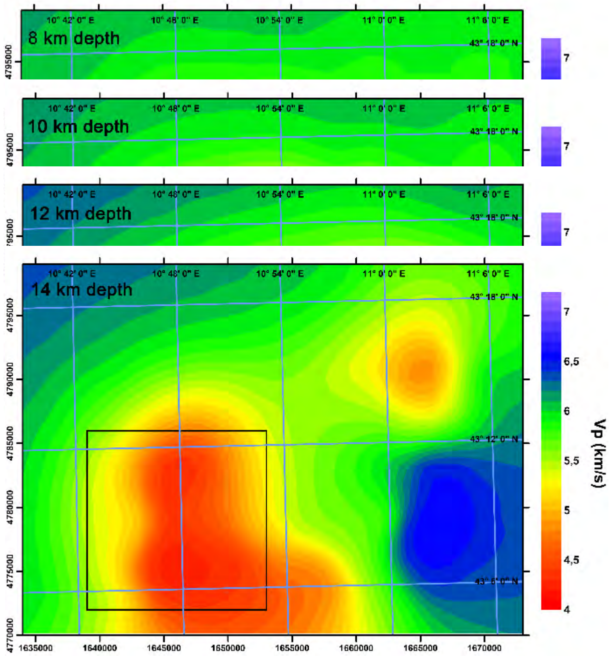




Geophysical evidences

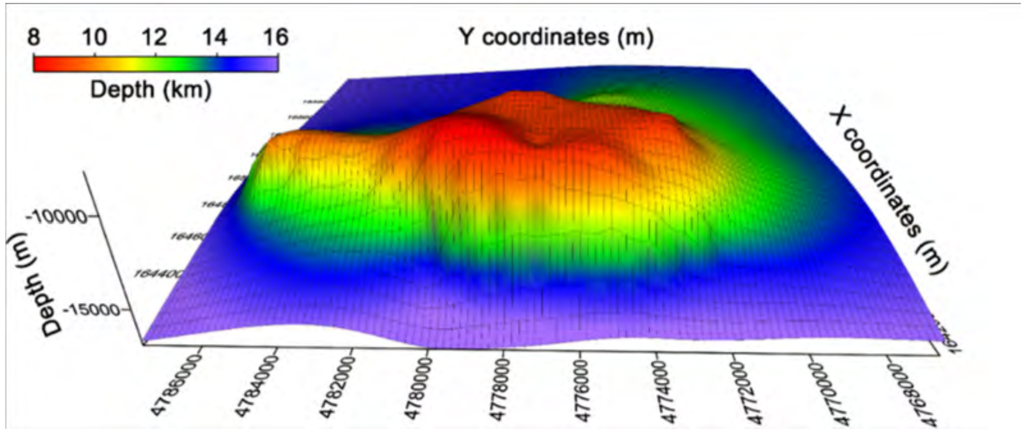
Earthquakes tomography

Batini/Toksoz et al. 1995

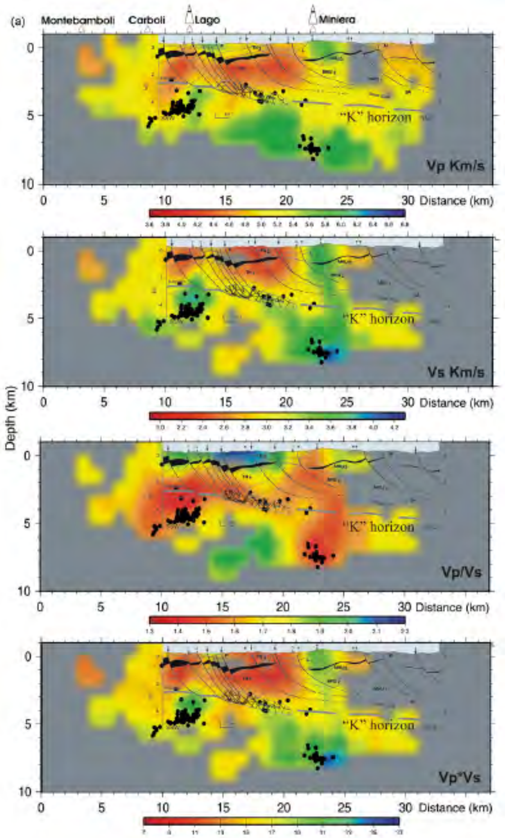


Shallow seismic tomography evidences strong lateral variations, possibly due to the interplay of the petrophysical characteristics of the basement rocks (e.g. porosity, fluid saturation and state) and the presence of upper-crust, partially molten, intrusions.

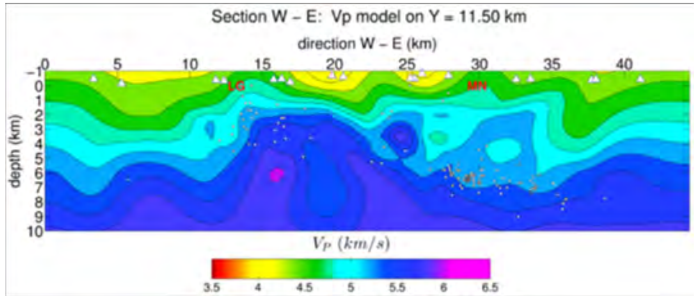
The velocity field derived from deep seismic tomography is dominated by a low velocity body (Vp < 5 km/s) which mimics a middle-crust magmatic chamber



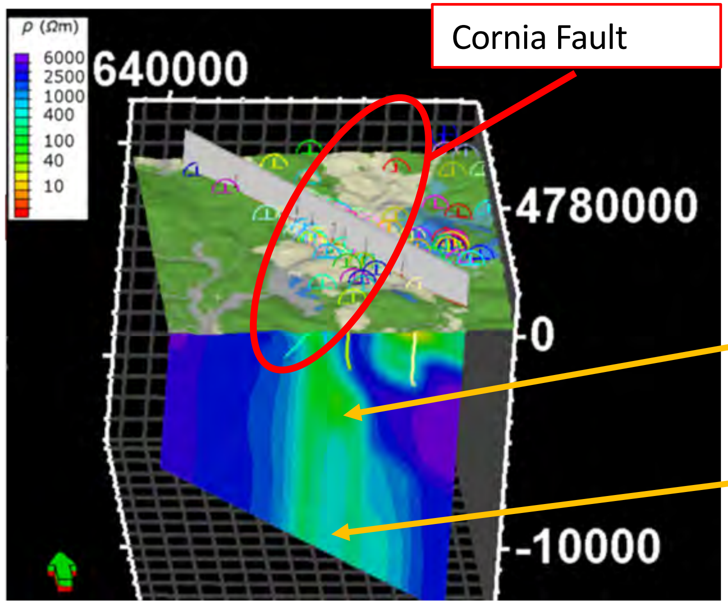
De Matteis et al. 2008

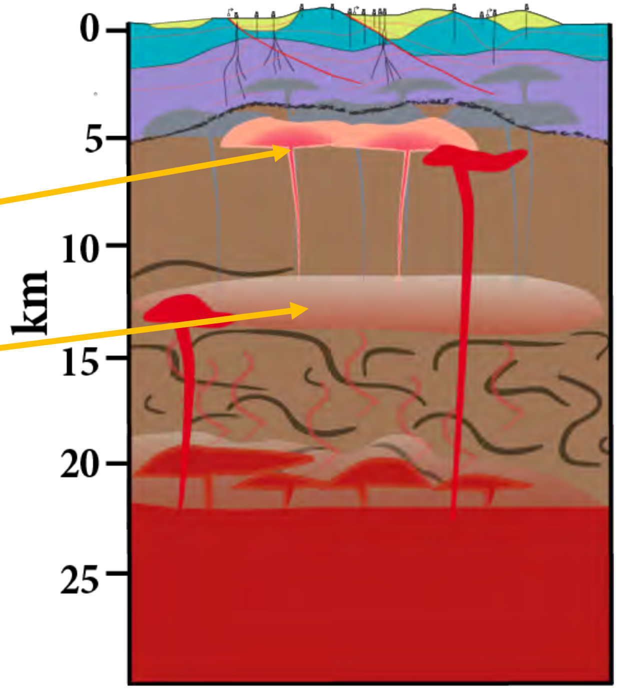


Saccarotti et al. 2014



MT data integrated interpretation





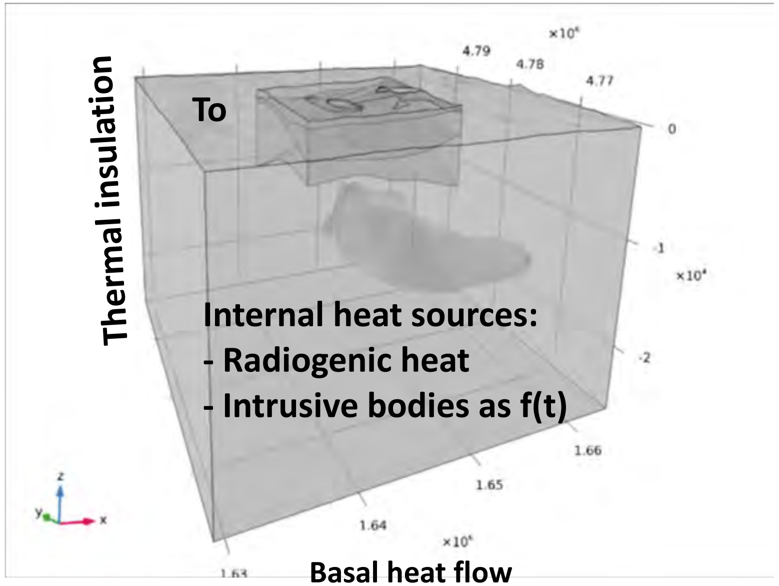
Low resistivity data are located in an area of high Vp/Vs (at 5 km) and low Vp, extremely high heat flow, low density: magmatic intrusions and partial melts.

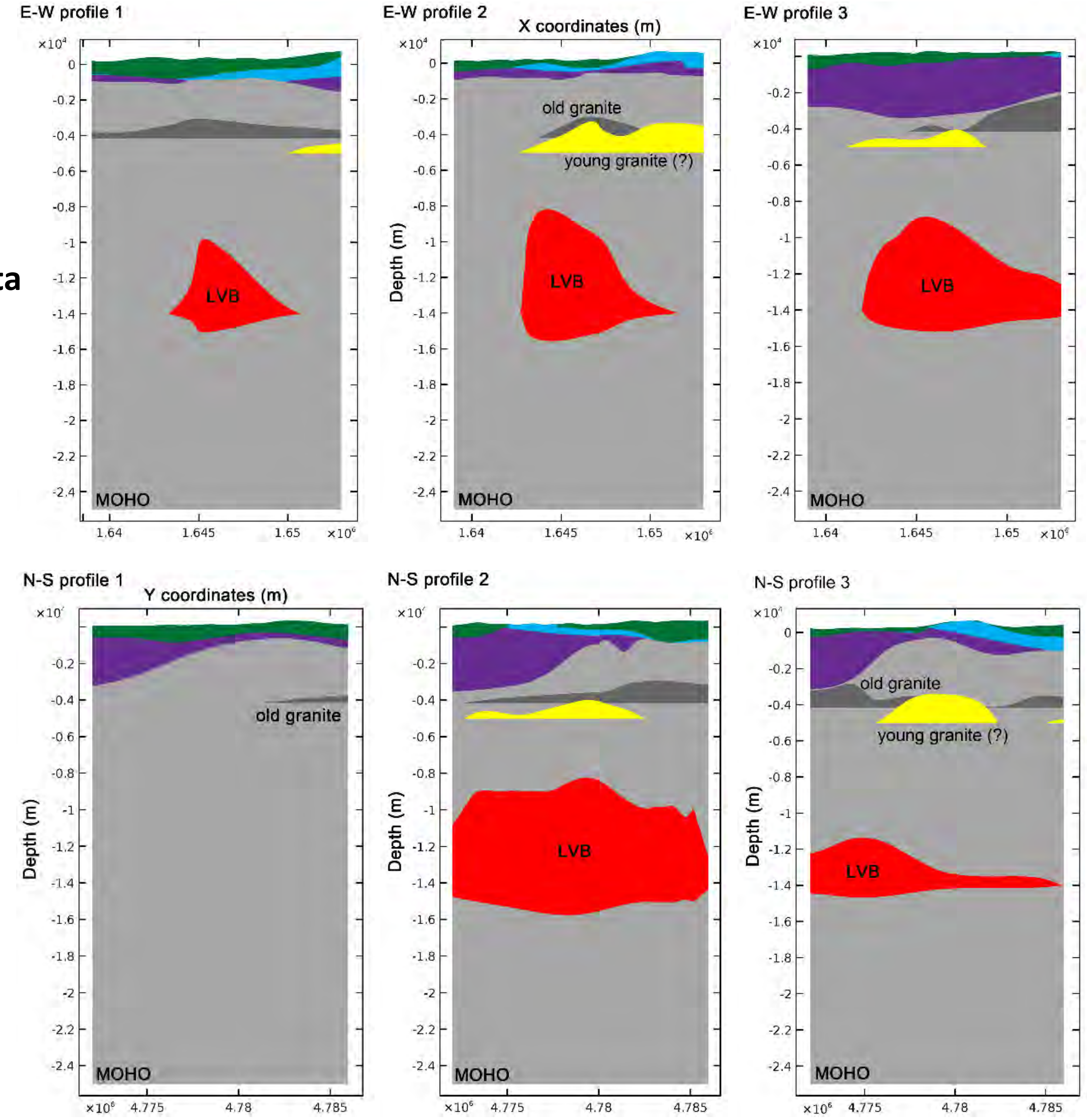
A main tectonic structure favored both fluid circulation (in the liquid-dominated ancient system, then increasing alteration??) and magma emplacement.

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





DESCRAMBLE Project Outline

The "**D**rilling in d**E**ep, **S**uper-**C**Ritical AMBient of continenta**L** **E**urope" (DESCRAMBLE) project has drilled in continental-crust, super-critical geothermal conditions, to:

1) **Demonstrate safe drilling** able to control gas emissions, the aggressive environment and the high temperature/pressure expected from super-hot, supercritical condition by
   - combining geothermal and oil&gas techniques, testing and choosing materials, equipment, components able to resist high temperature and pressure, aggressive conditions
2) **Reduce pre-drilling uncertainties** by
   - adapting Real-time well control simulators from oil&gas to geothermal conditions
   - improving 3D seismic images of drilling target
   - characterizing deep physico-chemical conditions
   - simulations of conventional and supercritical reservoir conditions
3) **Improve in-situ characterization**, by
   - developing a special tool for super-high T and P measurements
   - analysing fluid and rocks samples of deep, supercritical conditions

An existing well in Larderello (Tuscany, Italy), has been deepened from its original depth of 2.2 km down to 2.9 km to reach the K horizon.

The shallow depth of the chosen resource has reduced costs for this test, whose results will open new market frontiers for exploiting similar resources at deeper depth.

DESCRAMBLE results

On 20 October 2017 a loss of circulation has been identified at depth of 2,7 km, with temperature >400° and pressure about 300 bar. It was a first evidence of the existence of supercritical conditions in our deep system.

Further drilling confirmed the supercritical PT condition. At the final depth of 2,9 km, in the middle of the seismic reflections, a steep increase of temperature has been measured, reaching 507-517°C , with a leakoff pressure of about 300 bar.

There has been no evidence of a commercially exploitable super-critical reservoir and fluids. High seismic impedance/fluid correlation was not proved (up to the drilled depth).

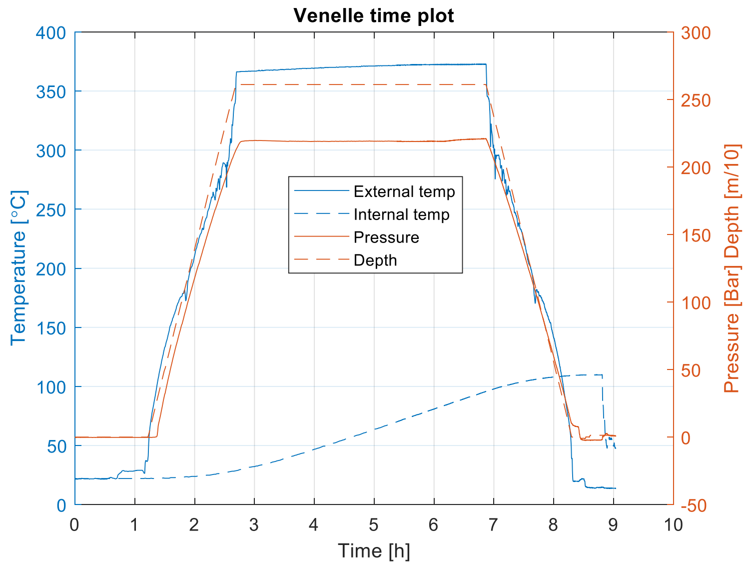
Development of a Novel Logging Tool for 450°C Geothermal Wells

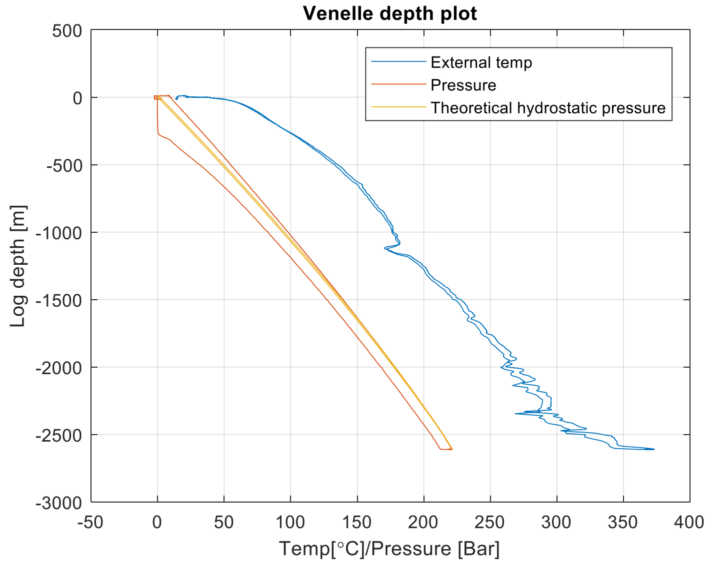
- Not possible to design electronics for operating at this temperature, practical limit today is 200 – 250°C.
- Traditional cooling of the electronics impossible – nowhere to get rid of the heat.
- Electric wireline cables can be used up to ≈350°C only, therefore limited power available from batteries.

Only viable alternative:

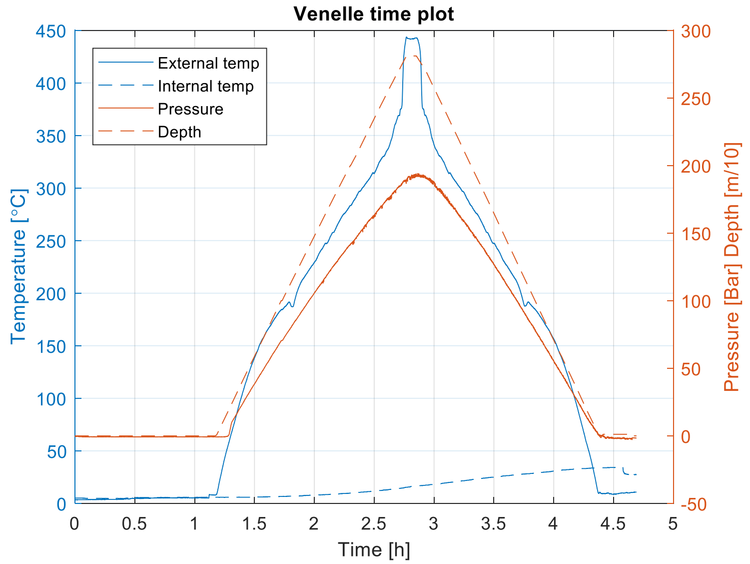
- Protect the electronics & batteries from the heat by a thermal shield (dewar).
- Use internal heat-sink with high heat capacity to delay heating.
- Remove the tool from the well before critical temperature is reached inside the thermal shield.
- Log data to internal memory and read out afterwards, communication to topside is complicated without electrical cable.

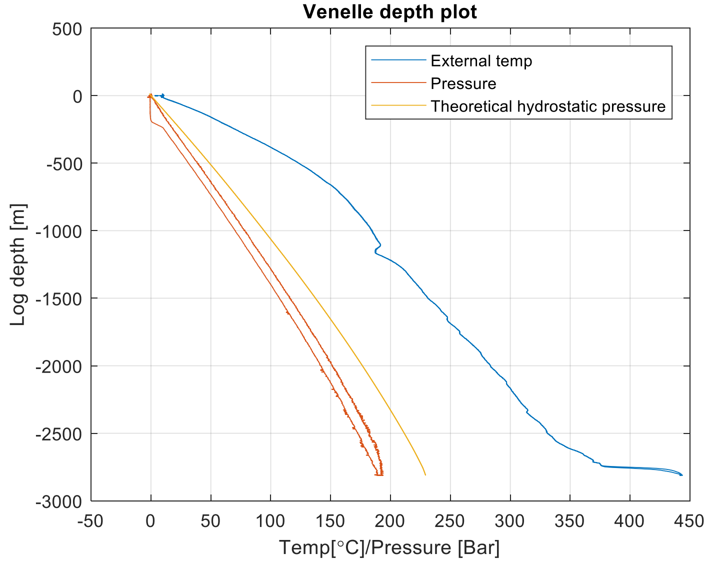
SINTEF PT tool - Field test





run1
d= 2620 m
(Sept 2017)
Max T°: 372.9°C
Max P: 219 bar
Max int T°: 110.0°C



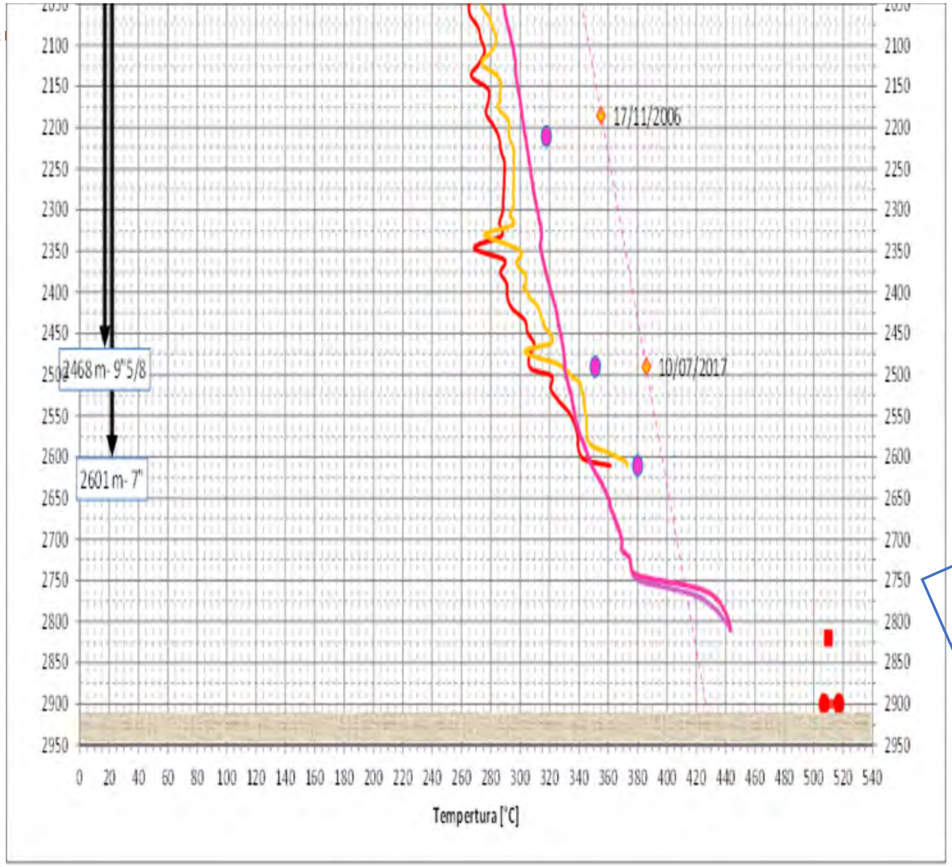


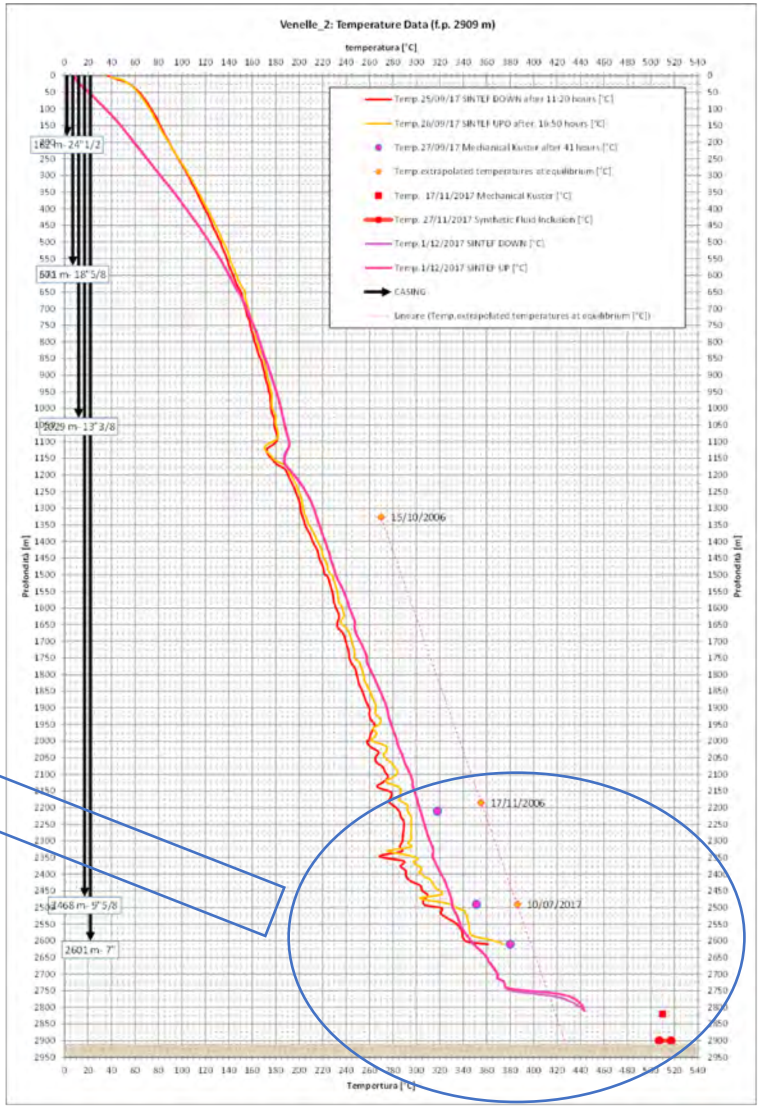
run2
d= 2810 m
(Dec 2017)
Max T°: 443.6 °C
Max P: -
Max int T°: 34.7 °C

Temperature data

Temperature was also estimated by producing synthetic fluid inclusions at the depth of 2.9 km

Project

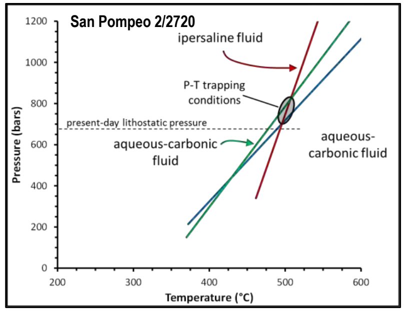


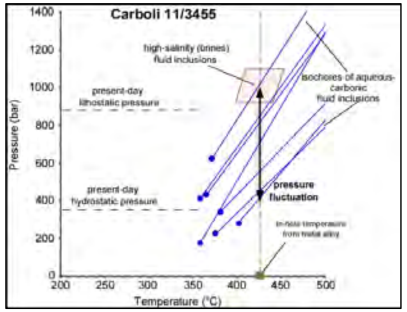


Reservoir Characterization

An Interdisciplinary Study:
just few examples

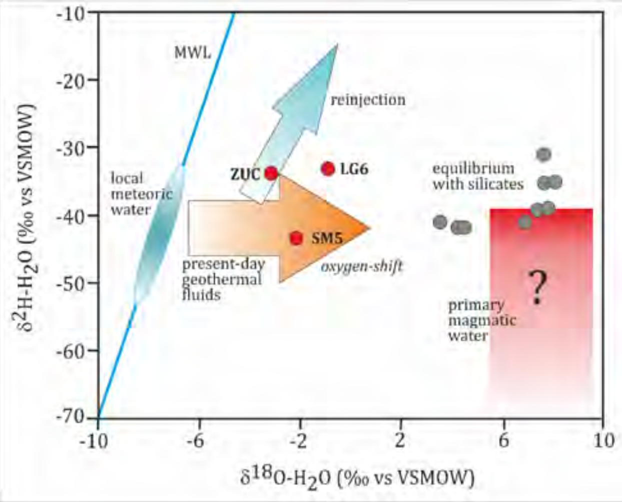
Fluid Inclusions

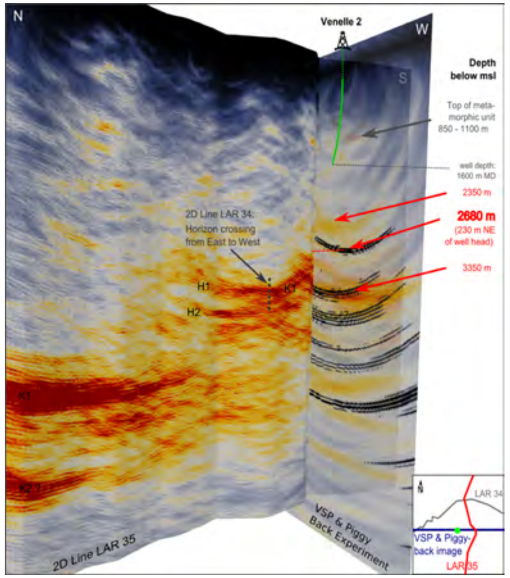




Petrology

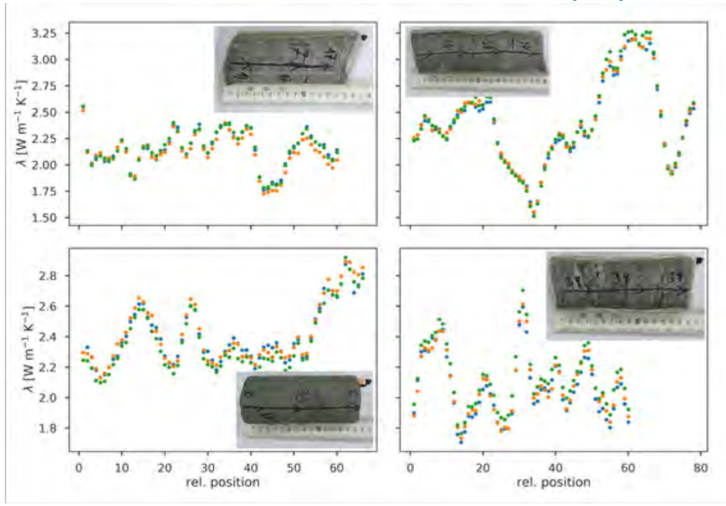
Fluid geochemistry



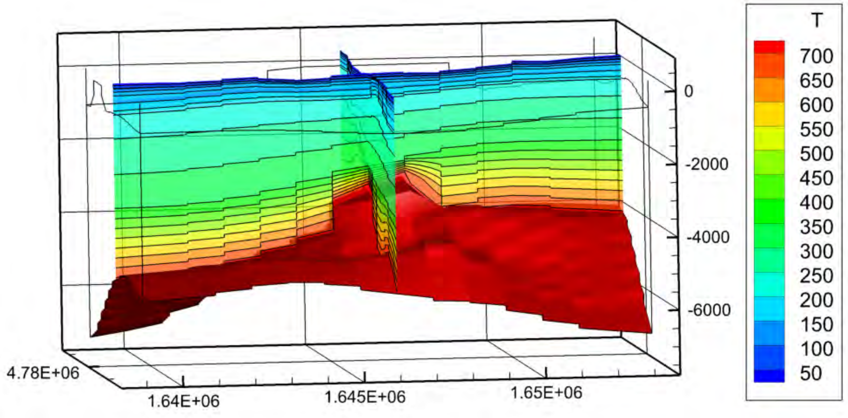


Geophysics

Petrophysics



Simulations with TOUGH2

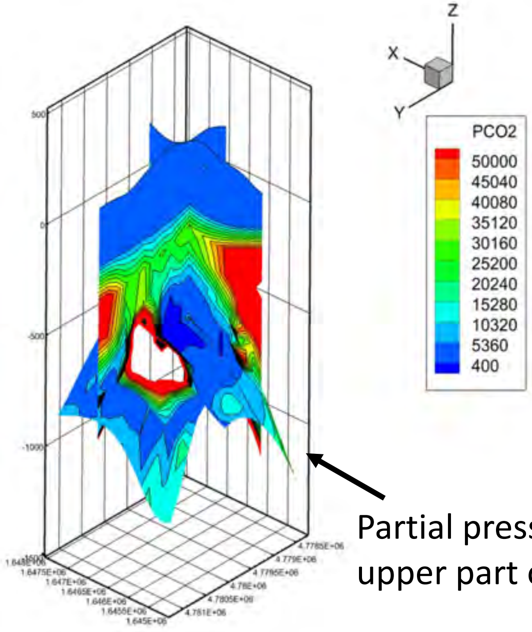


Temperature distribution, view from south

EOS-SC for supercritical water in collaboration with John Burnell, GNS

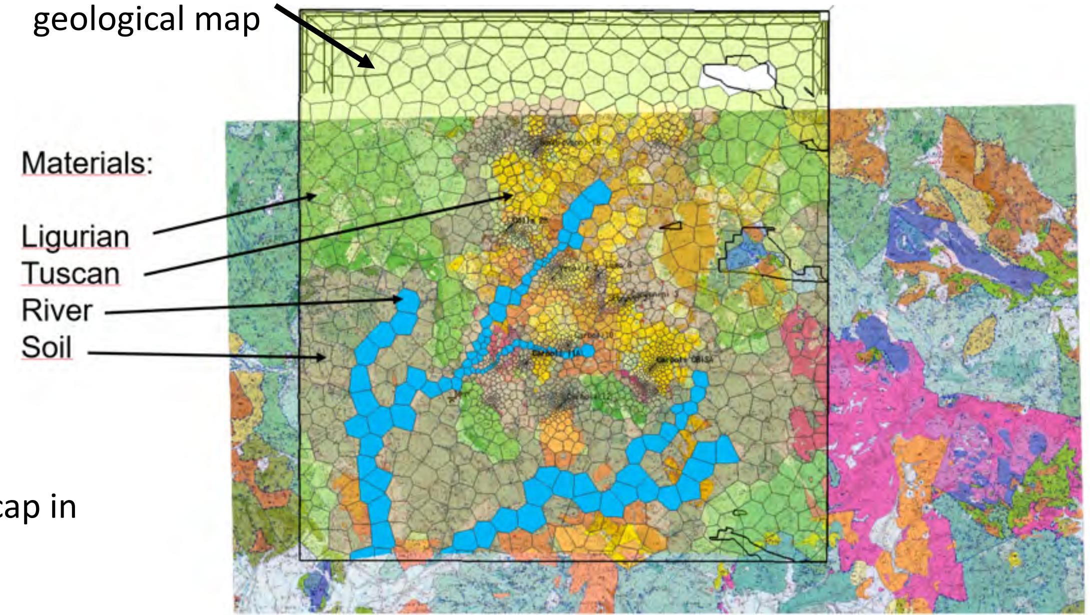
EOS_CO2_SC for supercritical water and CO_2

EOS_CO2_salt_SC for supercritical water, CO_2 and NaCl

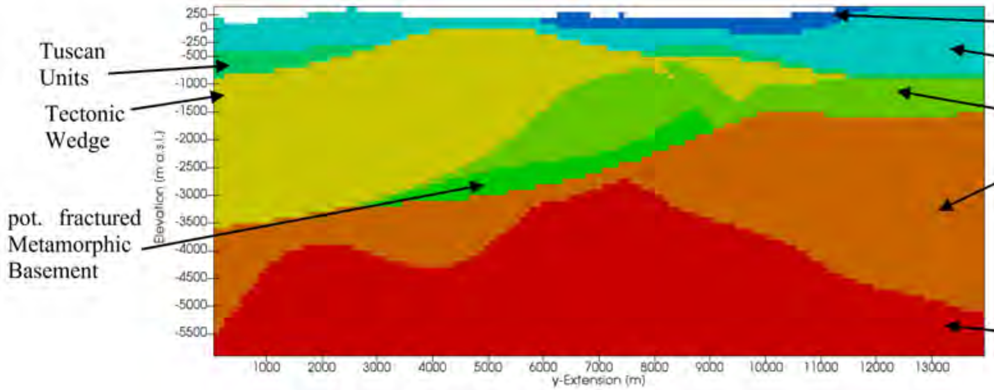


Partial pressure of CO_2 cap in upper part of model

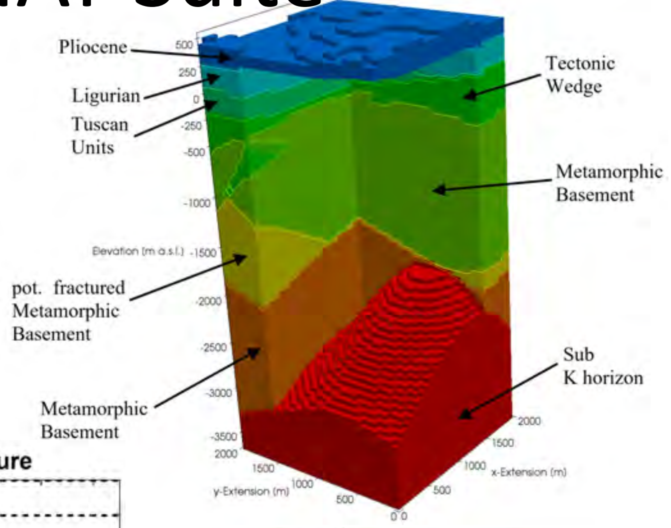
Surface layer with geological map

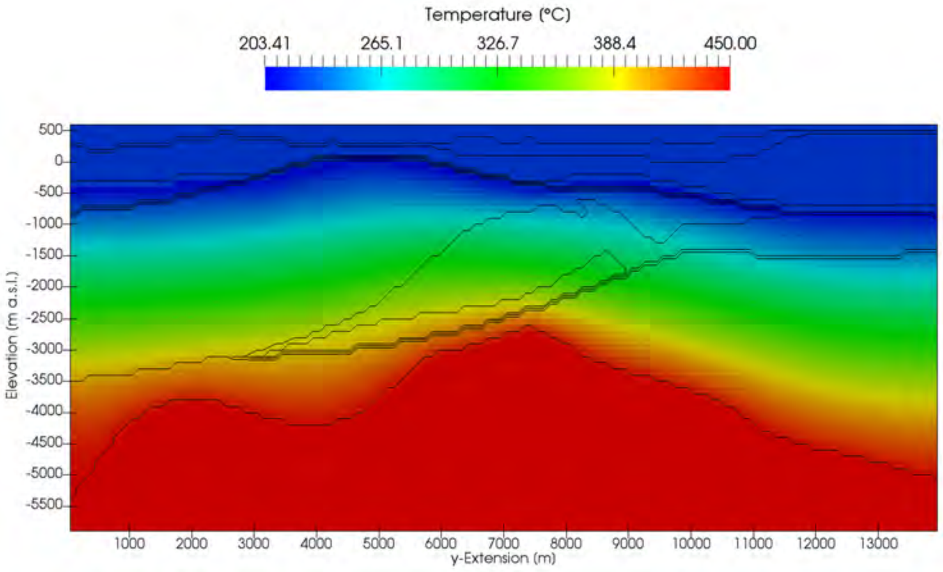


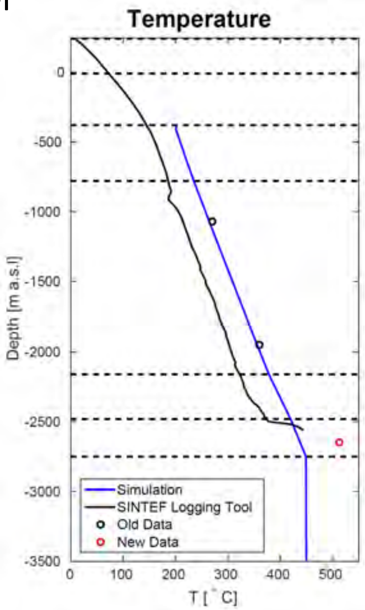
Supercritical Two-Phase Simulations with SHEMAT-Suite

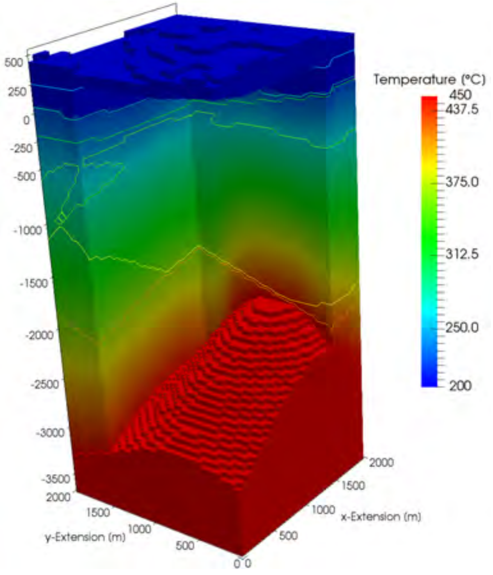


Layering of two-dimensional slice through regional model



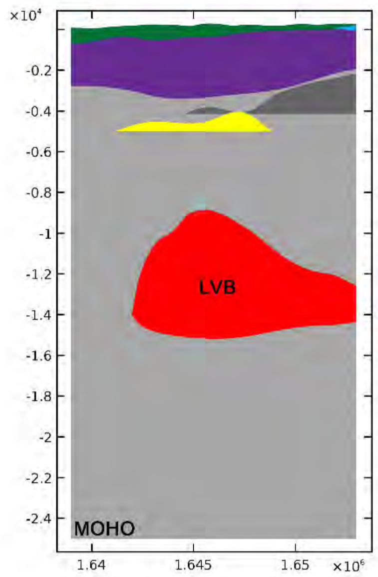






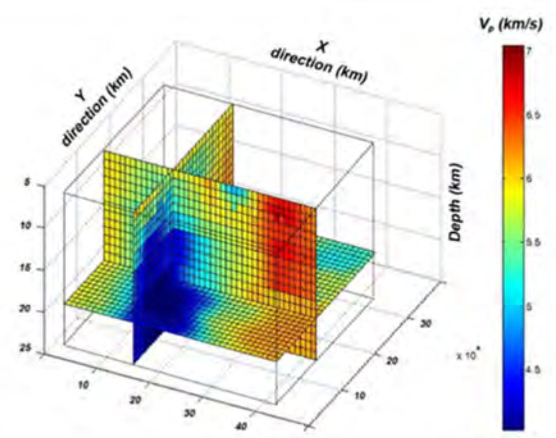
Temperature distribution after simulation of 1 Ma

Transient, thermal modelling of a deep-seated magmatic system

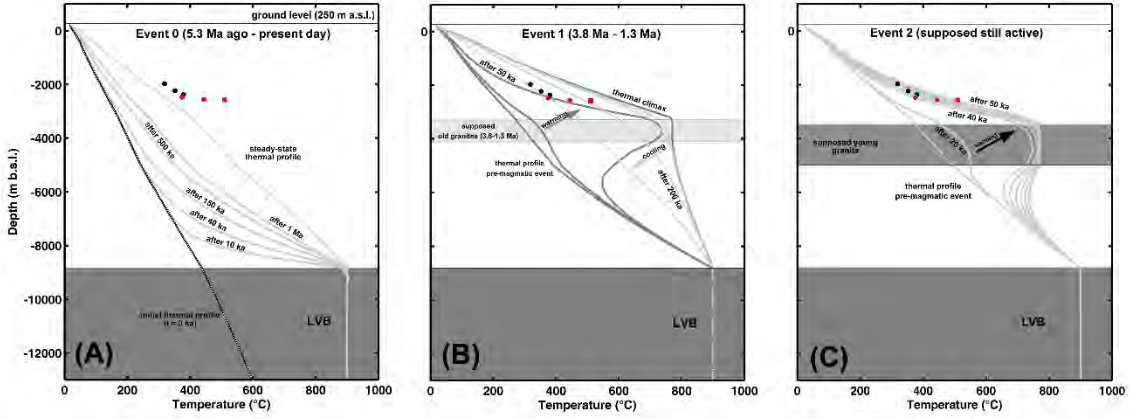


Geometrical features of the magmatic system

- Low-velocity anomalies from seismic tomography (Batini et al., 1995; Foley et al., 1992)
- Occurrence of thermal metamorphic rim in deep boreholes (Franceschini 1995, Musumeci et al. 2002) and direct evidences of drilled dikes and/or laccolites
- Geophysical (MT, passive seismic) data anomalies interpreted as due to shallow Neogene-Pleistocene composite granitoids



Conductive thermal evolution of the magmatic system

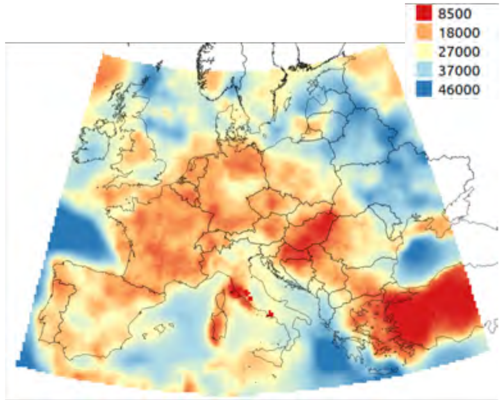


- Various magmatic sources (middle-crustal and shallow) supplied discontinuously the thermal load during the last 5 Ma
- Heat transfer by conduction
- Temperature dependent on petrophysical properties and latent heat during magma crystallization
- Geochronological and petrographic data integrated in the model calibration
- The age of the youngest shallow magmatic event is estimated of the order of 50 ka

Highlights

When technology will be proven to utilize this super-critical resource at shallow depth, and figures will be available for business planning, a new market frontiers will open for commercial development of similar resources in continental crust at deeper depth.

- **Increased power output per well (possibly 5-10 fold)**
- **Production of a higher value steam (higher P-T)**
- **Extending the resource base and lifetime of existing fields**
- **Knowledge of resource characteristics at large depths**
- **Advancing techniques of UGR (Unconventional Geothermal Resources)**
- **Development of an environmentally benign resource**
- **Development of high-temp. instruments and drilling technology**
- **Application to high-temp. geothermal systems world wide**
- **Educational, industrial and economic spin offs**



Depth of isotherm 400 °C

Role of geological science in the decarbonisation of power production, heat, transport and industry

- It is immense in the geothermal sector
- Geological science provide data in every phase of a geothermal project (exploration and investigation, well design and drilling , monitoring of subsurface changes due to production and injection for sustainable management, monitor and mitigate environmental impacts)
- It is not straightforward: various challenges
  - The technical challenge is to create the systems and technologies that will streamline and optimise a sophisticated and complex workflow.
  - The logistical and organisational challenge is to create the units and the processes within the geothermal community.

A. Prediction and assessment of geothermal resources

B. Resource Access and Development

C. Heat and electricity generation and system integration

D. From R&I to Deployment

E. Knowledge Sharing

From R&I to Deployment: topics

- Set the right policies
- Public and other stakeholders' engagement
- Reinforce competitiveness
- Establish Financial Risk Management schemes
- Support schemes to deploy geothermal
- Establish legal and regulatory framework
- Embedding geothermal energy in the circular economy
- Harmonised protocols for defining environmental and health impacts of geothermal energy and mitigation planning
- Human deployment

Knowledge sharing: topics

- Underground data sharing - unlocking existing subsurface information
- Organization and sharing of geothermal information
- Shared Research Infrastructures (includes large labs and well access for experimenting)

https://www.etip-dg.eu/publication/strategic-research-and-innovation-agenda-for-deep-geothermal-first-draft-for-publication-consultation/

Thank you for your kind attention

The research leading to scientific results in Larderello, Italy, has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE) and from Horizon2020 Research and Innovation Programme under grant agreement No. 640573 (Project DESCRAMBLE)

ETIP-DG is supported by DG-ETIP, a H2020 project (GA 773392)

www.image-fp7.eu
www.descramble-h2020.eu
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