Experience and acquired knowledge of Larderello geothermal system (Italy): an overview

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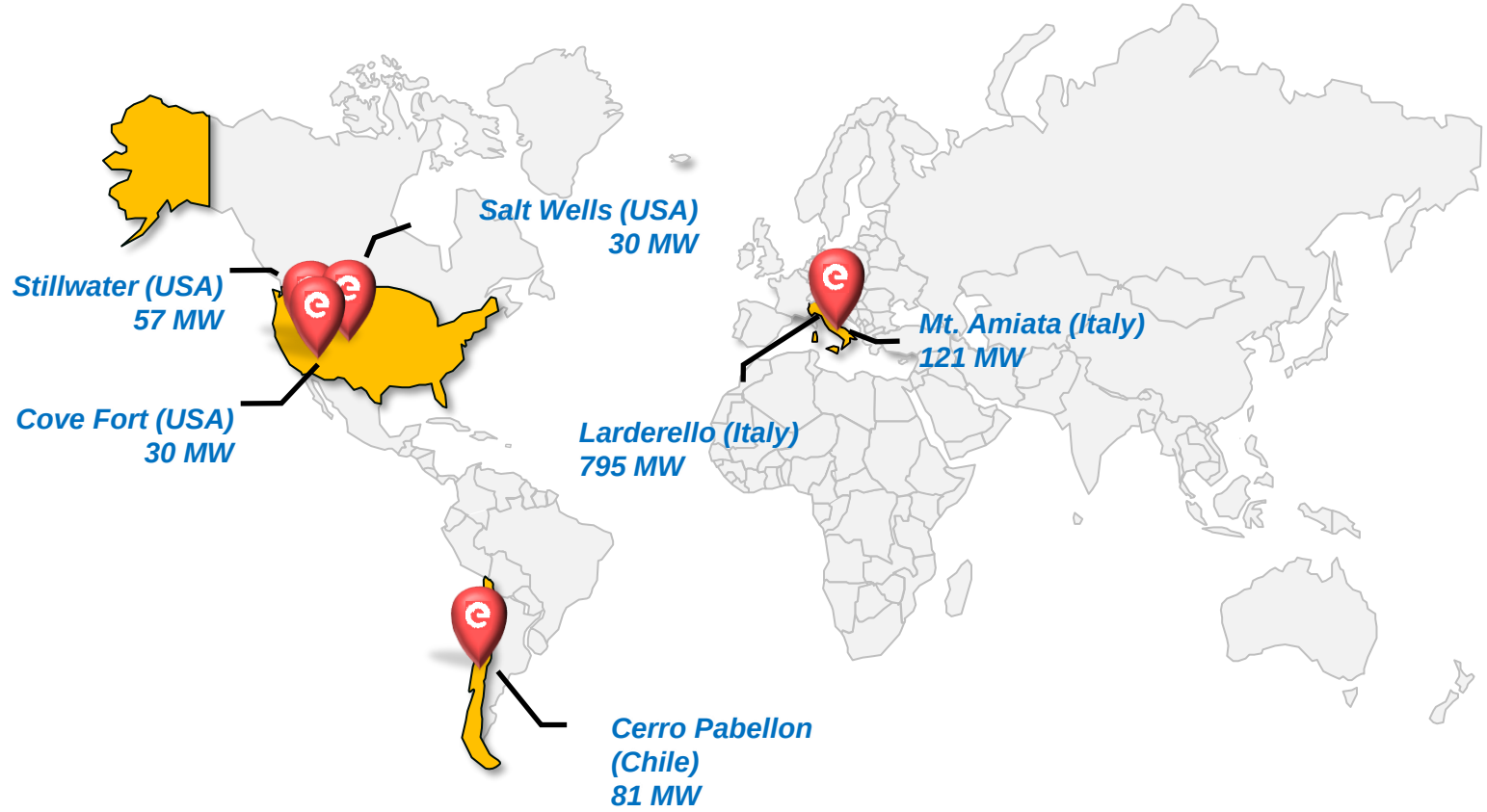
Green Power

Enel Green Power

World geothermal footprint



1114 MWe installed geothermal capacity worldwide

Geothermal Italy Leadership

Assets

Geothermal power production in Italy covers about 30% of Tuscany energy consumption

- The biggest **fully integrated** geothermal operator
- **Pioneer in the use of geothermal resource –** consolidated international experience
- **Culture of field "cultivation" –** reinjection as main strategy to compensate the field decline
- **Performance leadership –** efficiency and availability of power plants.
- **Leadership in environmental protection –** proprietary of patented Technologies (AMIS)

37 generating units
504 Wells in operation
~700Km pipelines
766 MW net capacity (2)
5,7 TWh annual production

1800 employees (3)
86,5% average load factor
4,1 Mt CO_2 emissions avoided
30% of electricity needings in Tuscany
70% of REN power prod. in Tuscany

Source: Company information.
(1) As of 2018
(2) It includes Cornia biomass pp in geothermal areas
(3) It includes direct & indirect employees

Heat supply chain

A CSV[(2)] example

TUSCANY

EMILIA ROMAGNA

100 k tons of CO_2 avoided
>10000 customers
300 Workers from local communities
>170 MWt installed capacity
368 GWht supplied in Tuscany
75 GWht supplied in Emilia Romagna

Direct heat utilizations:

District heating
Brewery
Local products (cheese, meat,…)
Greenhouses (vegetables, flowers,…)

Technology improvement

Digitalization

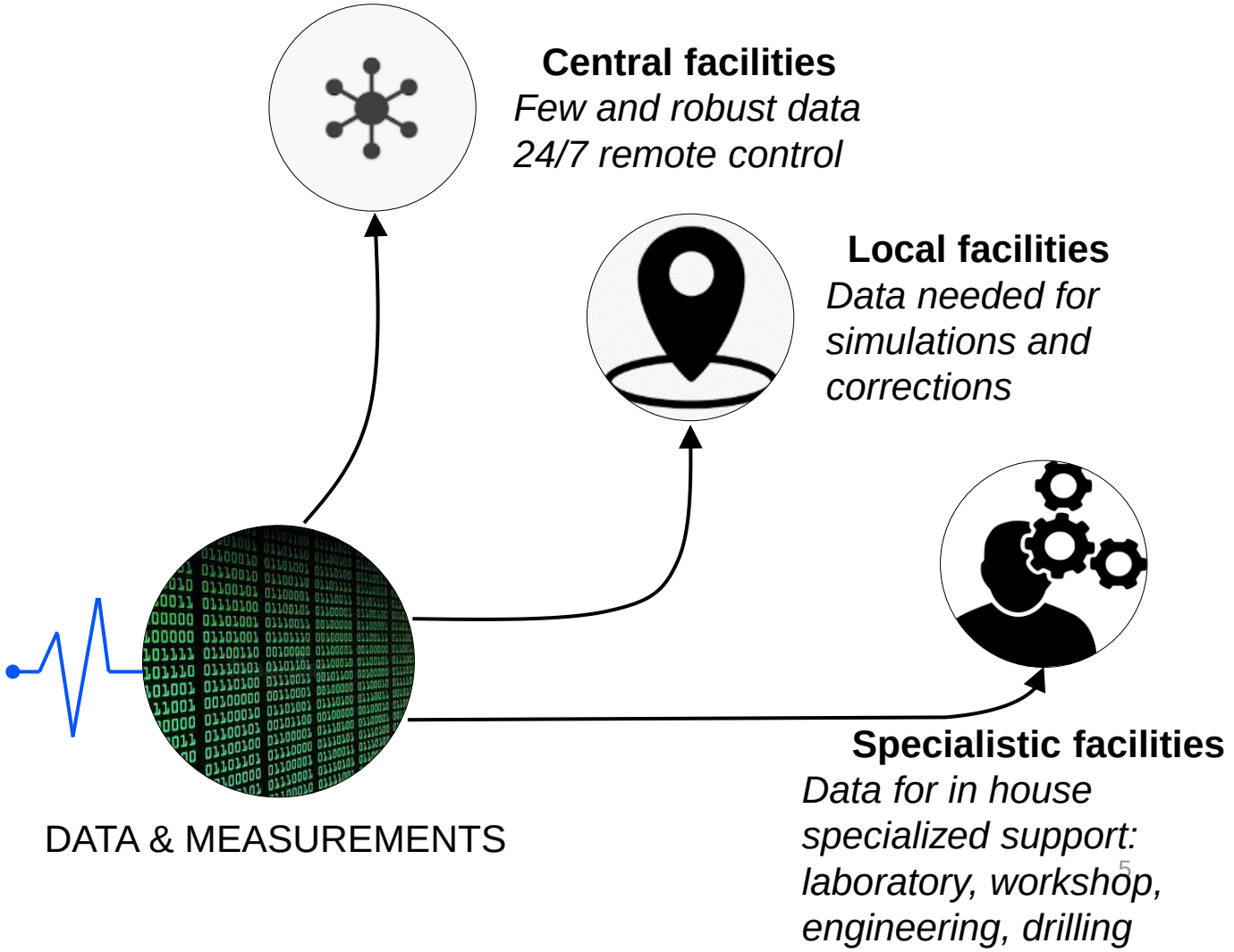
37 remote controlled generating units

120 connected facilities (plants, wells, pipelines, separation platform, etc.)

350km of optical fiber

2000 – 3000 / min measures/data

All IT systems, including acquisition, servers, connectivity is entirely managed & operated by ENEL

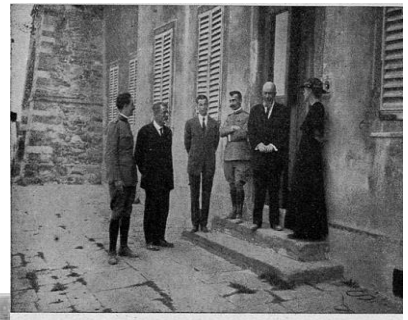


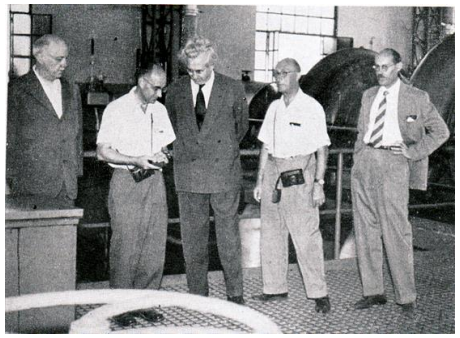
AGENDA

- ***Larderello - Travale system***
- ***Seismic signatures in Travale area and deep reflector in Larderello: what we found***
- ***Microseismic monitoring for the DESCRAMBLE project***
- ***Spectral Gamma Ray log: reconstruction of granitic bodies as reservoir in Travale***

Larderello Travale System

Progress of geothermal production in Italy





New Units in operation
(Nuova Radicondoli 2, Chiusdino)

Repowering
(Rancia 1, Rancia 2, Le Prata, PC3, PC4, PC5)

Nuovo Pignone GE Units
(2x10MW; 2x20MW; 3x40MW)

Ansaldo 2nd Generation Units
(9x20MW; 1x14,5 MW)

2018 Net Production: 5,7 TWh

Valle Secolo 1-2
(2x60MW)

Larderello 3
(3x24MW+1x26MW)

Larderello 2
(6x10MW)

II World War

Larderello 1
(0,25MW) **FIRST GEO PP WORLDWIDE**

New units in operation
(Bagnore 4, Cornia 2 bio)

GWh

Kg/s

Total Gross Production

Steam flow rate

Exploitation of shallow reservoir

- Exploration and development of deep reservoir
- Start of reinjection programme
- Reduction of internal unavailability

CONTINUOUS PRODUCTION GROWTH FOR MORE THAN 100Ys

THANKS TO THE KNOW-HOW IN RESERVOIR MANAGEMENT AND OPERATION EXCELLENCE

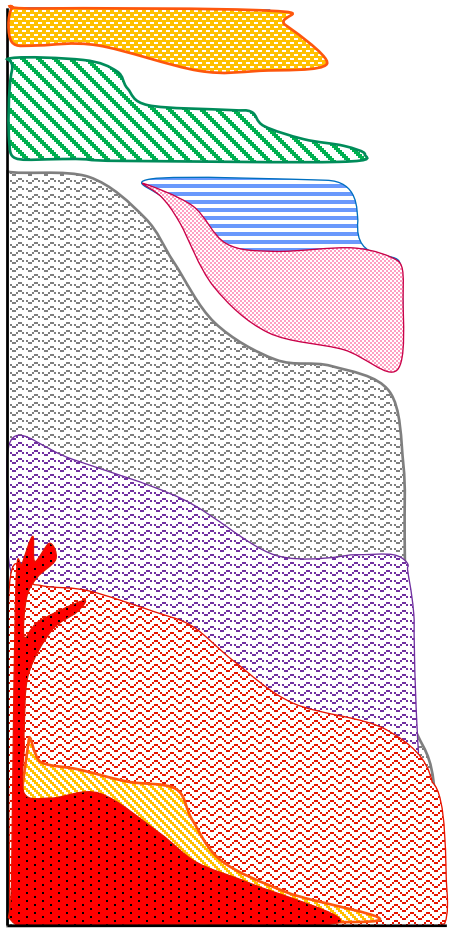
Geothermal areas in Tuscany

Heat flow map

- Two large and intense geothermal anomalies, the result of convective circulation in surface reservoirs, are identified by an isoline of heat flow equal to 200 mW / m2:
  - Larderello-Travale
  - Mt. Amiata
- The heat flow anomaly in the Larderello geothermal field is correlated to the Quaternary granite intrusion;
- Magmatic intrusions in the crust are the cause of the lifting of the neogenic deposits.

Larderello Area

Stratigraphic, tectonic and thermal asset



NEOGENE

LIGURIANS

TUSCAN NAPPE

TECTONIC WEDGES

PHYLLITES

MICASCHISTS

GNEISS

CORNUBIANITES

GRANITE

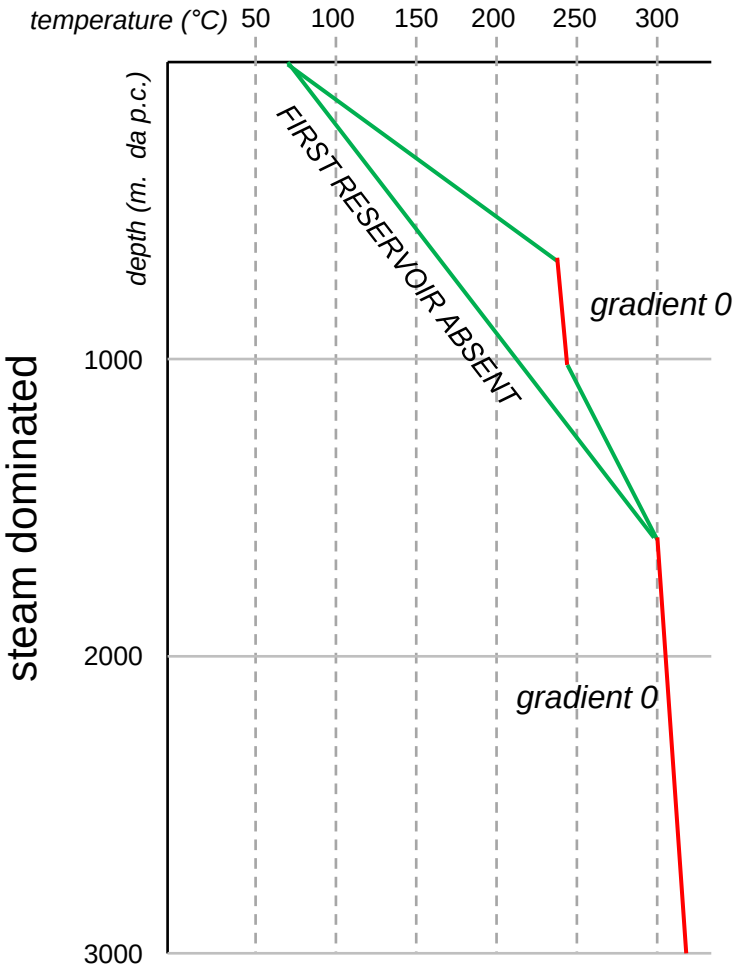
BASAMENT

COVER

FIRST RESERVOIR

SECOND RESERVOIR

GEOTHERMAL SYSTEM
steam dominated

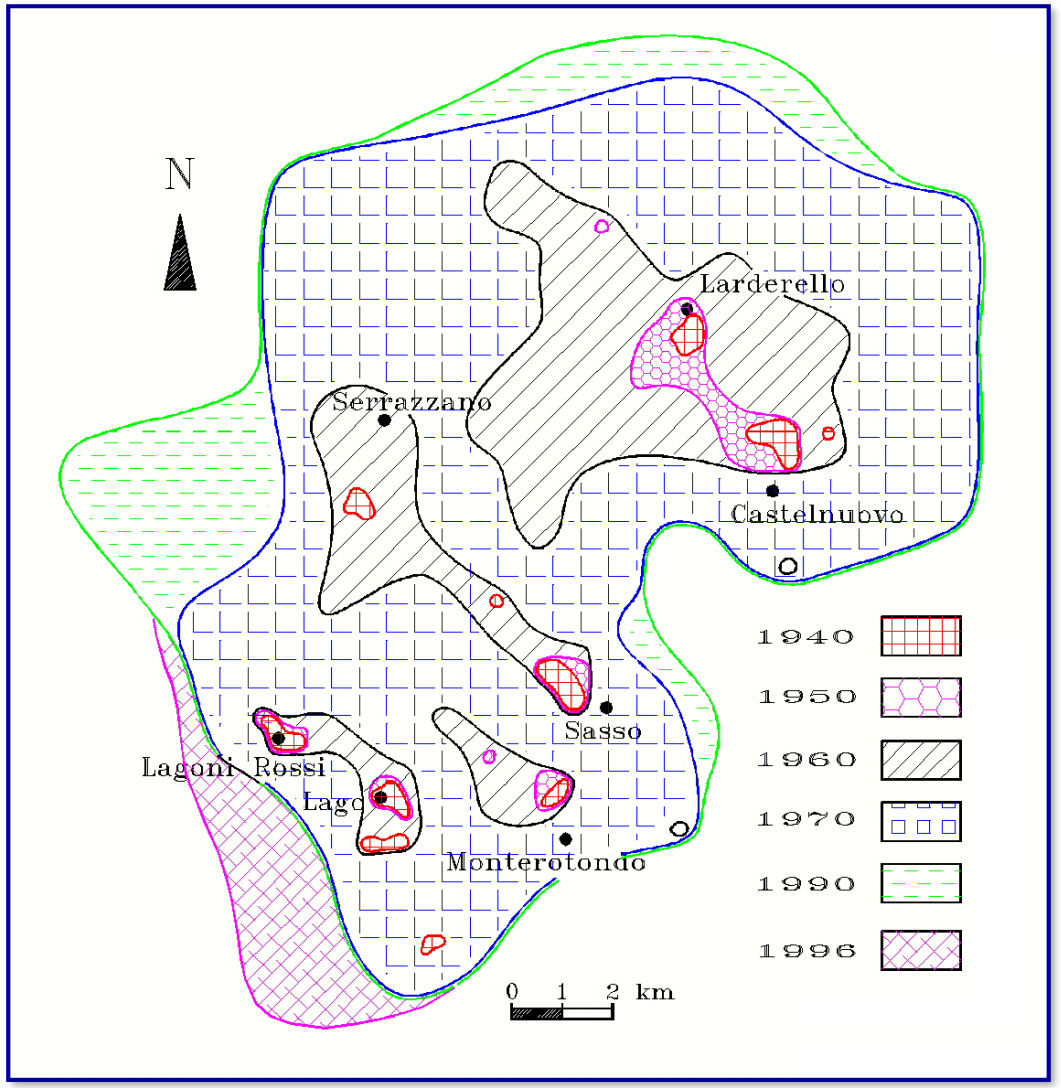


Typical thermal profile in Larderello

Larderello area

Development history

- The explored area is about 250 km^2
- 200 wells produce superheated steam at pressure between 2 and 17 bars
- Temperatures ranging from 150°C to 270°C
- Non-condensible gas content ranges from 1 to 10% by weight
- Some wells producing since 1940s



Travale – Radicondoli area

Main characteristics

The explored area covers approximately 50 km^2;

40 wells produce superheated steam at pressure ranging from 8 to 20 bars

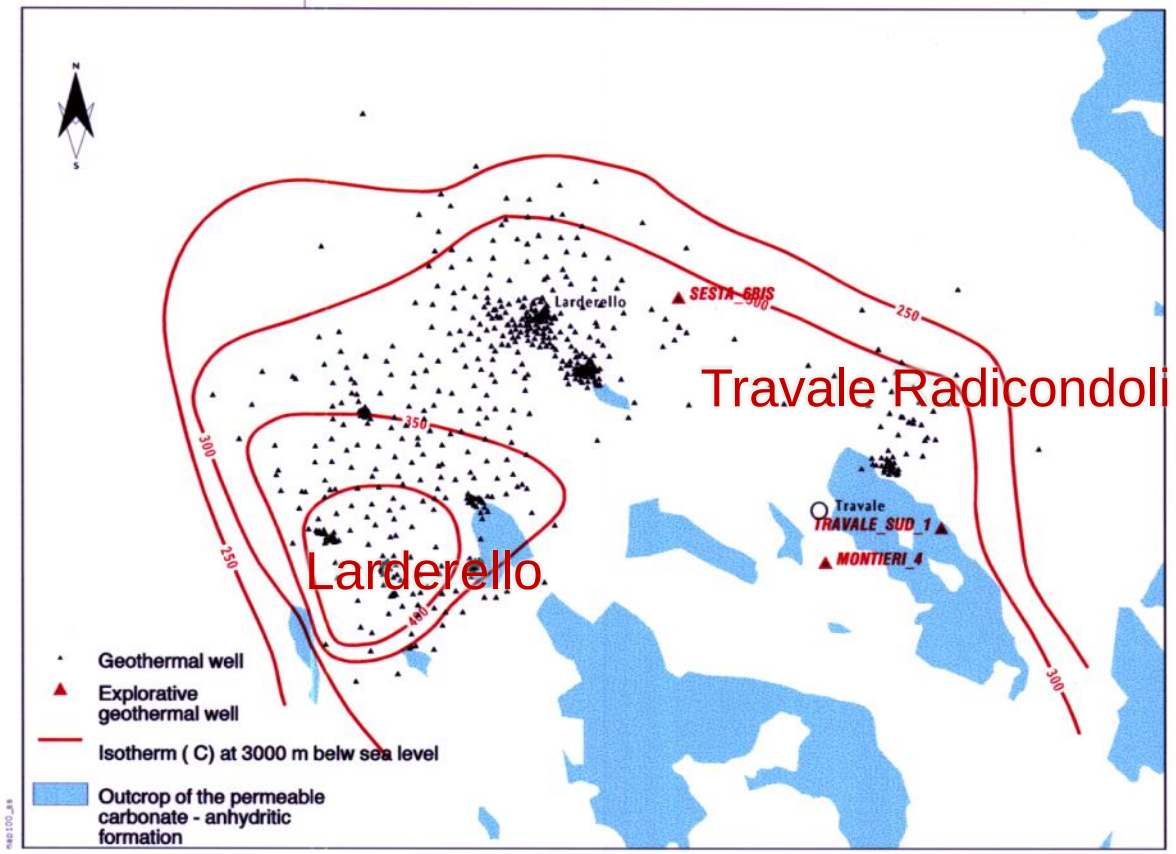
Temperatures range of 190-250° C

Non-condensible gas content is in the range of 5 – 6.5% by weight.

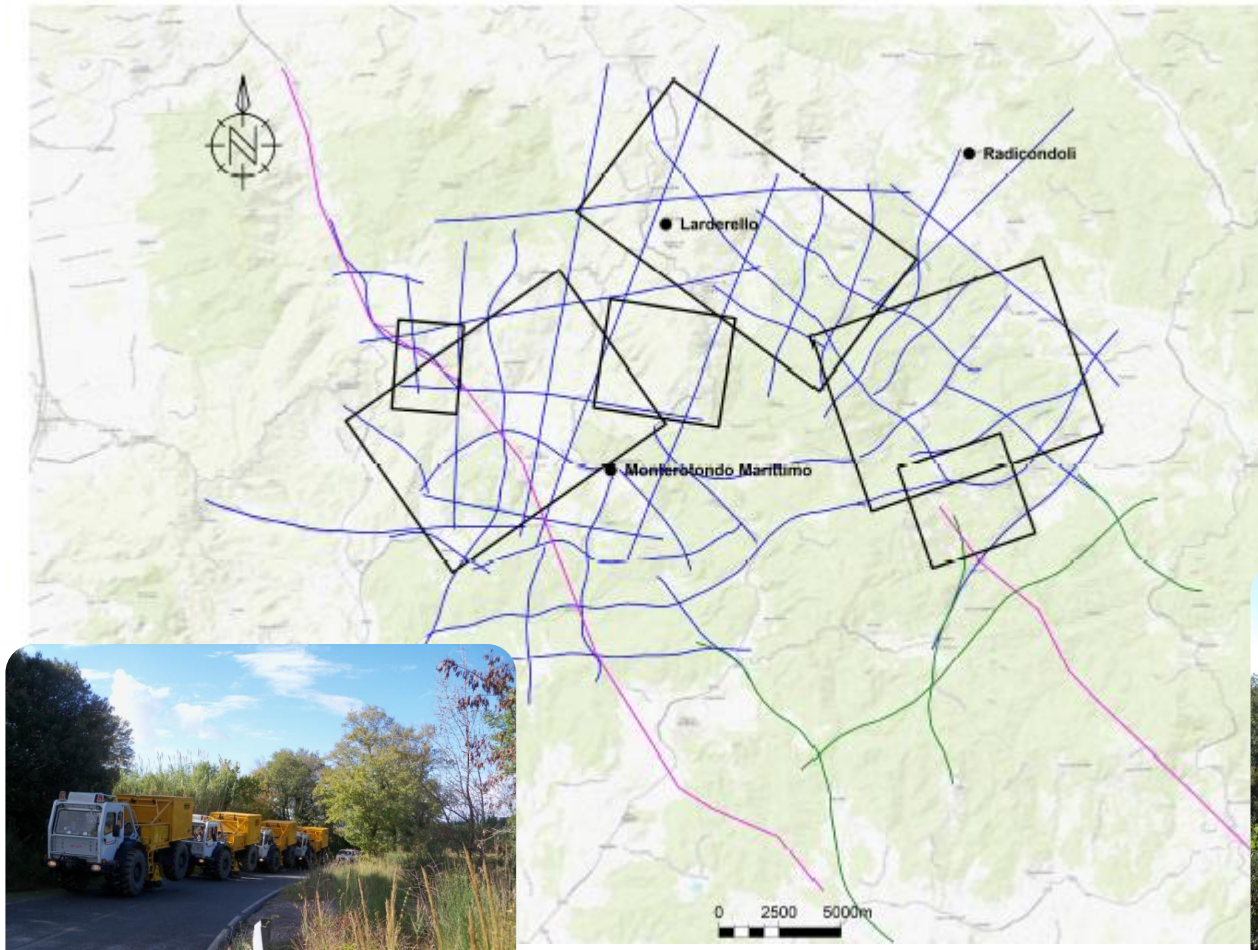
The installed capacity is 200 MWe with 8 units in operation.

40Km of pipelines in 200 branches

ISOTHERMS @ 3000m asl



Seismic lines during years



First line acquired in **1976**:
fold 6
channels 48
group interval 50 m

Last line in **2011**:
fold 40
channels 120
group interval 20 m

Seismic signatures in Travale area and deep reflector in Larderello: what we found

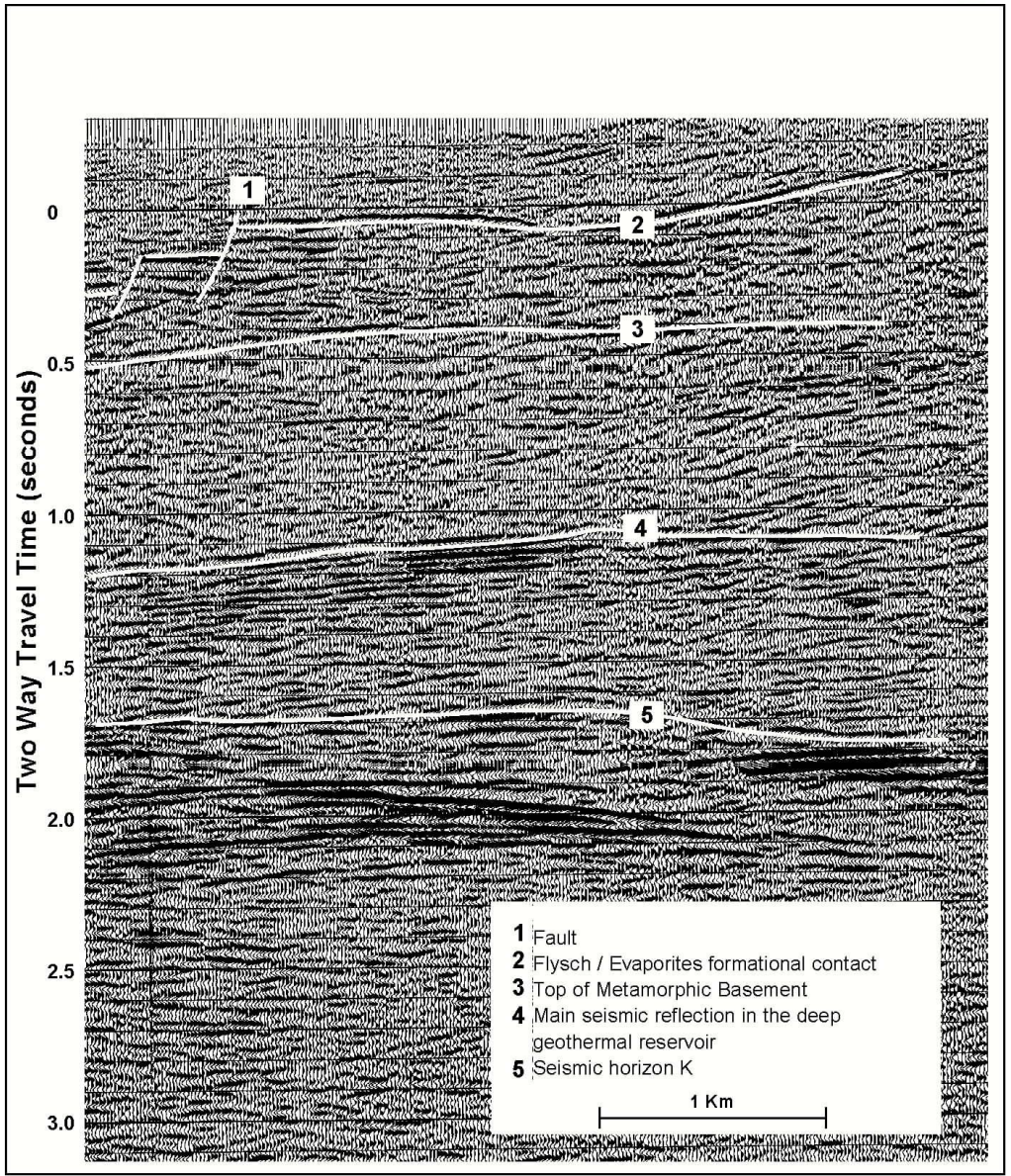
Larderello – Data from seismic lines

TOP OF EVAPORITES → HIGH REFL. COEF.

TOP OF THE METAMORPHIC BASEMENT → MEDIUM REFL. COEF.

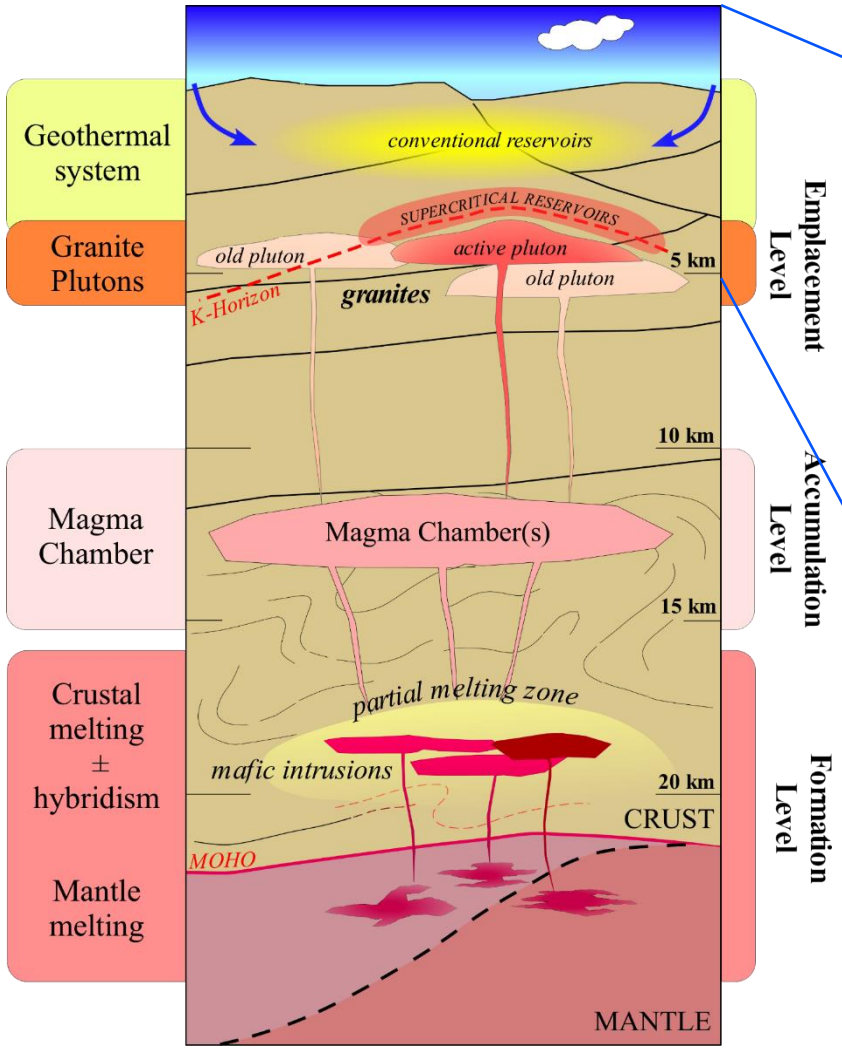
K HORIZON → HIGH REFL. COEF.

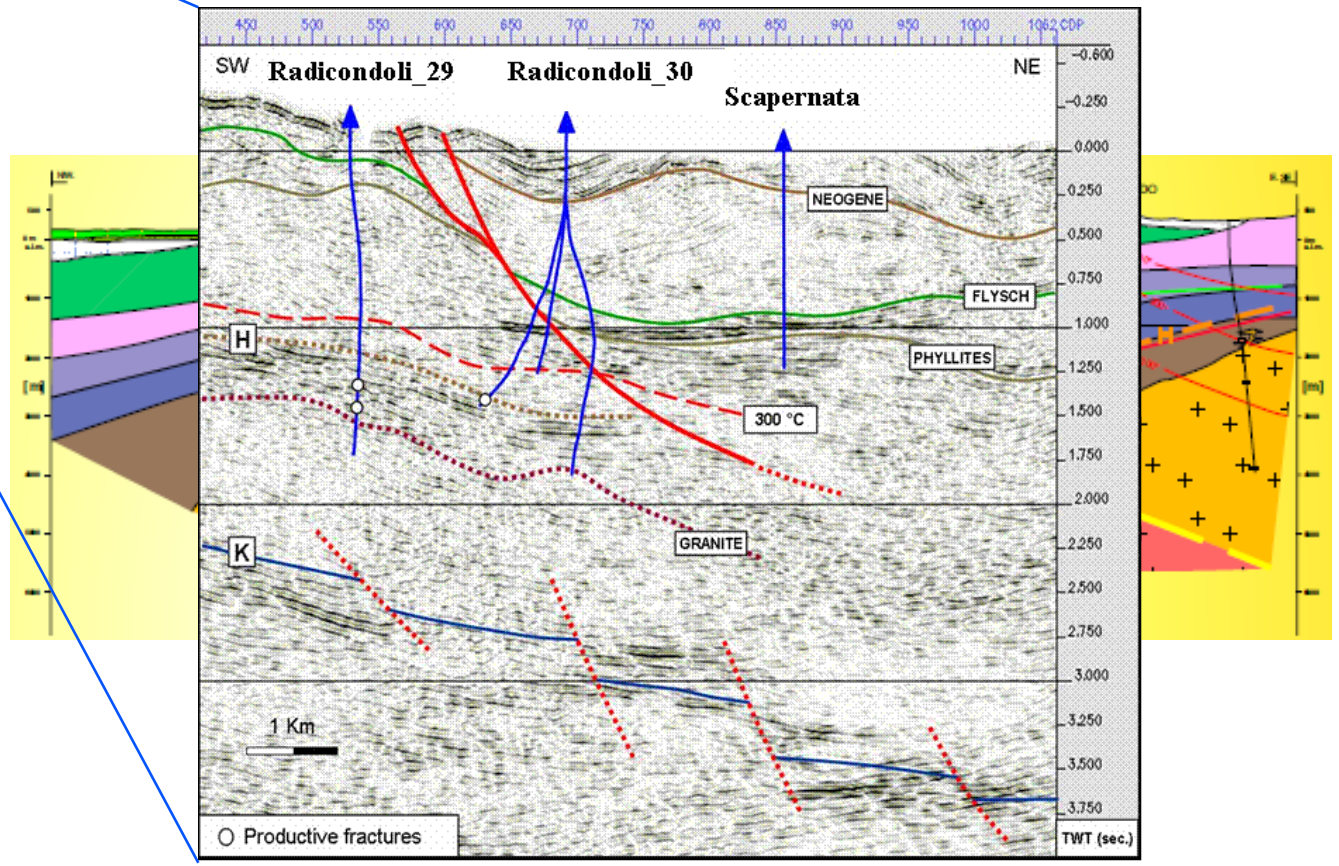
SEISMIC REFLECTIONS ARE OFTEN RECOGNIZED BETWEEN THE TOP OF THE METAMORPHIC BASEMENT AND THE K HORIZON



Travale Area – Deep model from seismic lines

Integrated interpretation of seismic and well data for the reconstruction of the main geological and structural elements

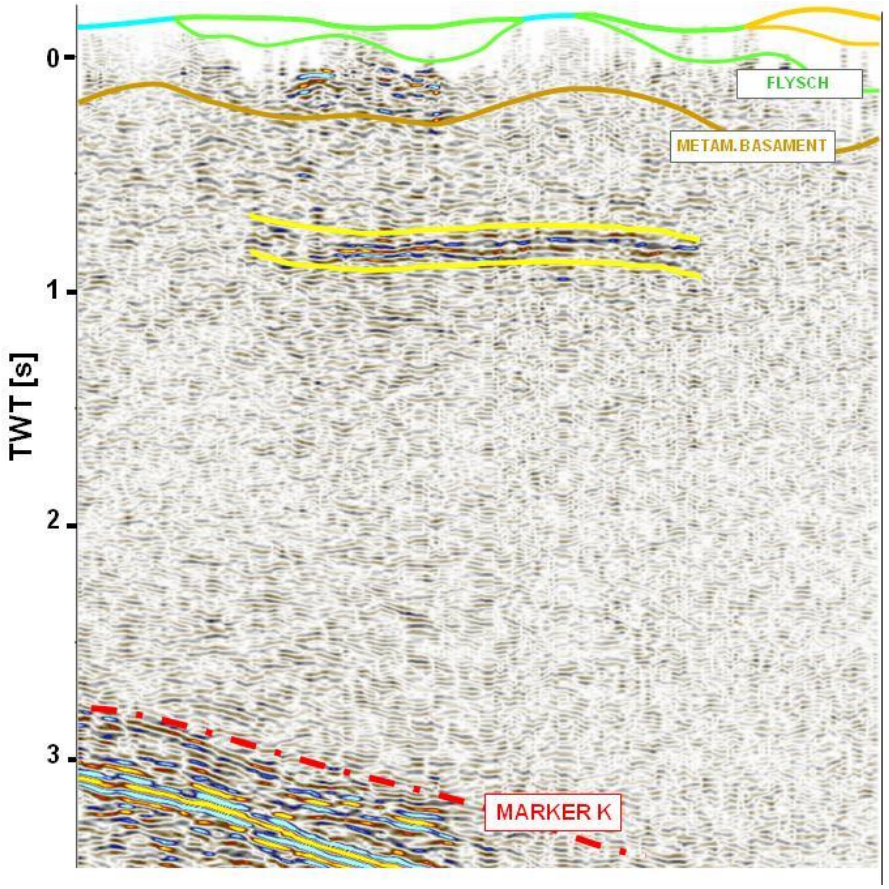




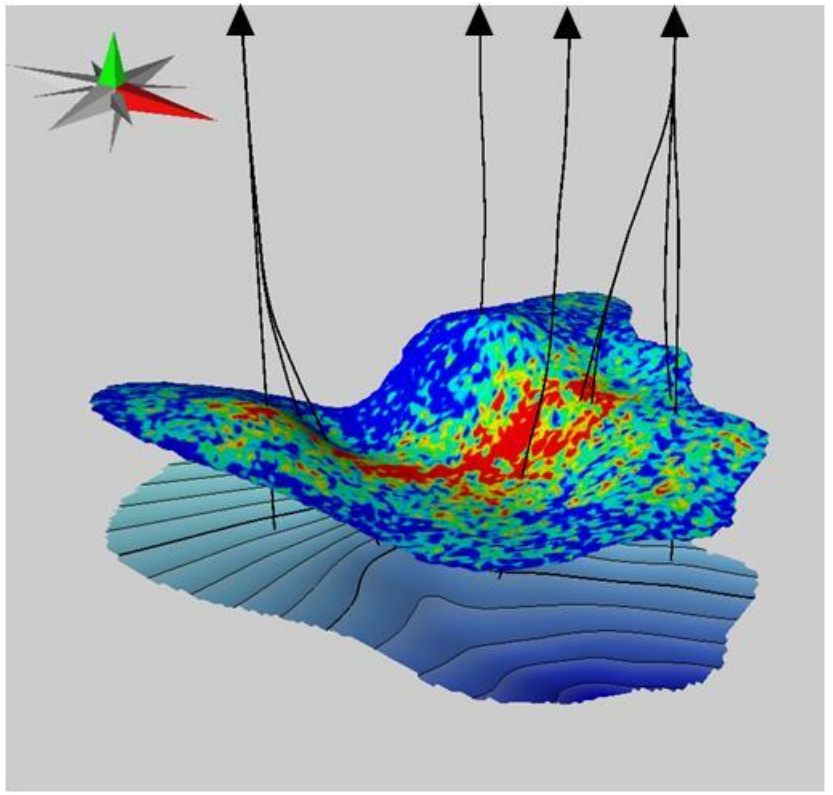
Identification of drilling targets

Amplitude analysis of the H marker (Montieri-Chiusdino)

Dataset processed in an “amplitude preserving” way

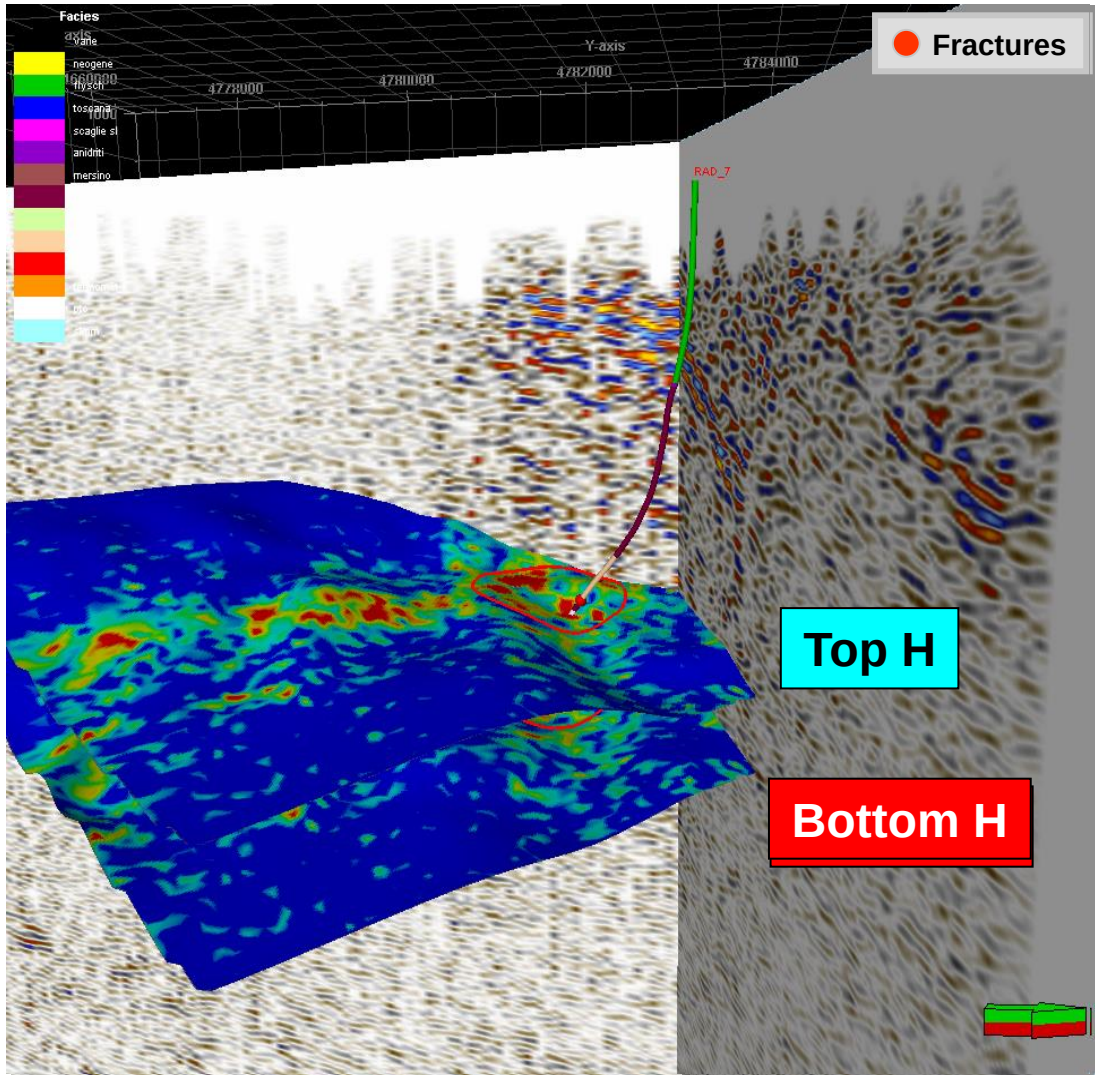


The amplitude analysis carried out on the H horizon allowed the identification of the target for drilling



Seismic target for drilling – 3D applications

An example of the result (Travale area)



Productive fractures

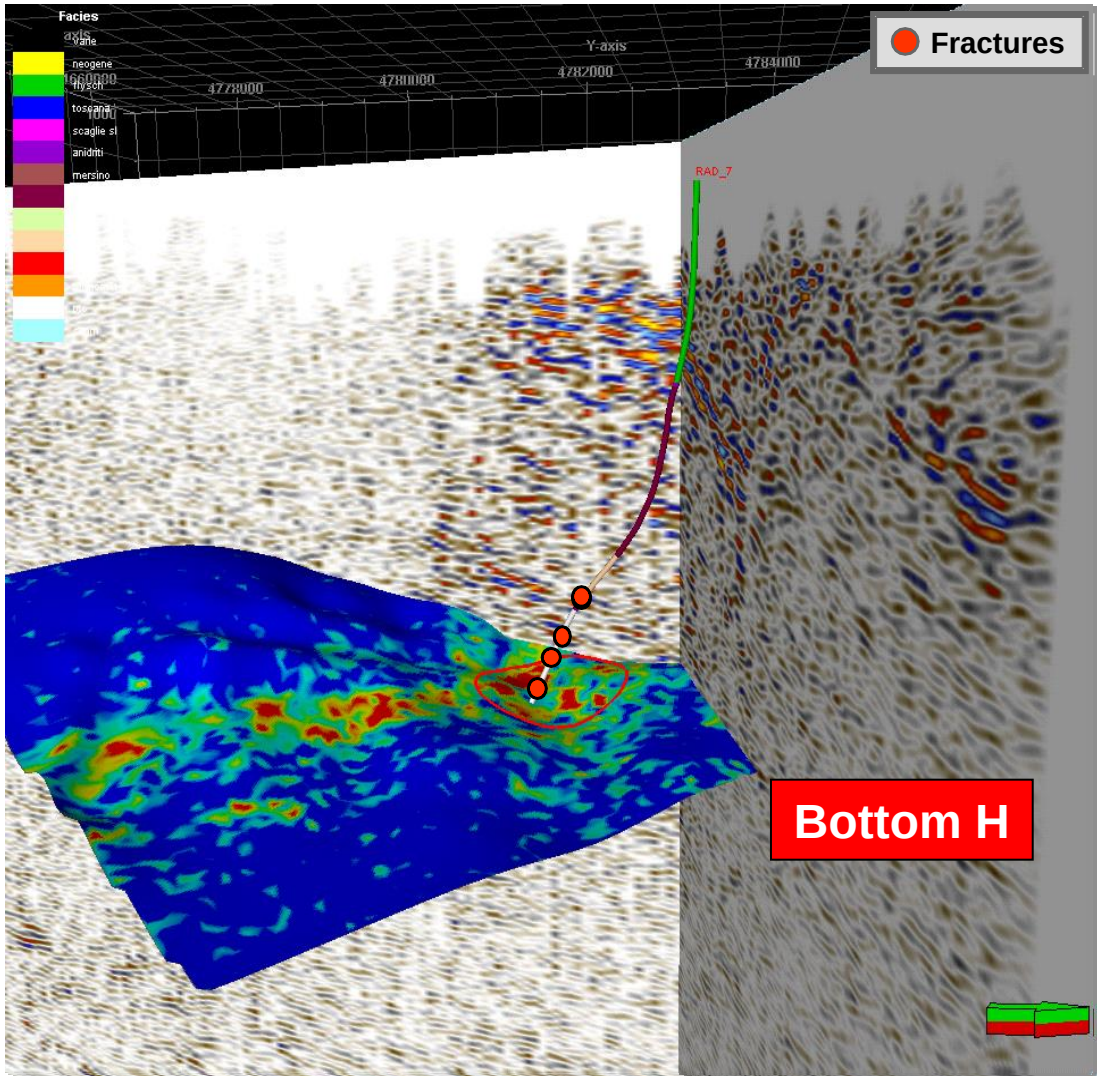
located in the H-horizon

The correspondence between seismic marker and fractured zones is statistically significant

In the Travale area more than 70% of the production comes from the H marker

Seismic target for drilling – 3D applications

An example of the result (Travale area)



Productive fractures

located in the H-horizon

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seismic marker and fractured

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In the Travale area more than

70% of the production comes from

the H marker

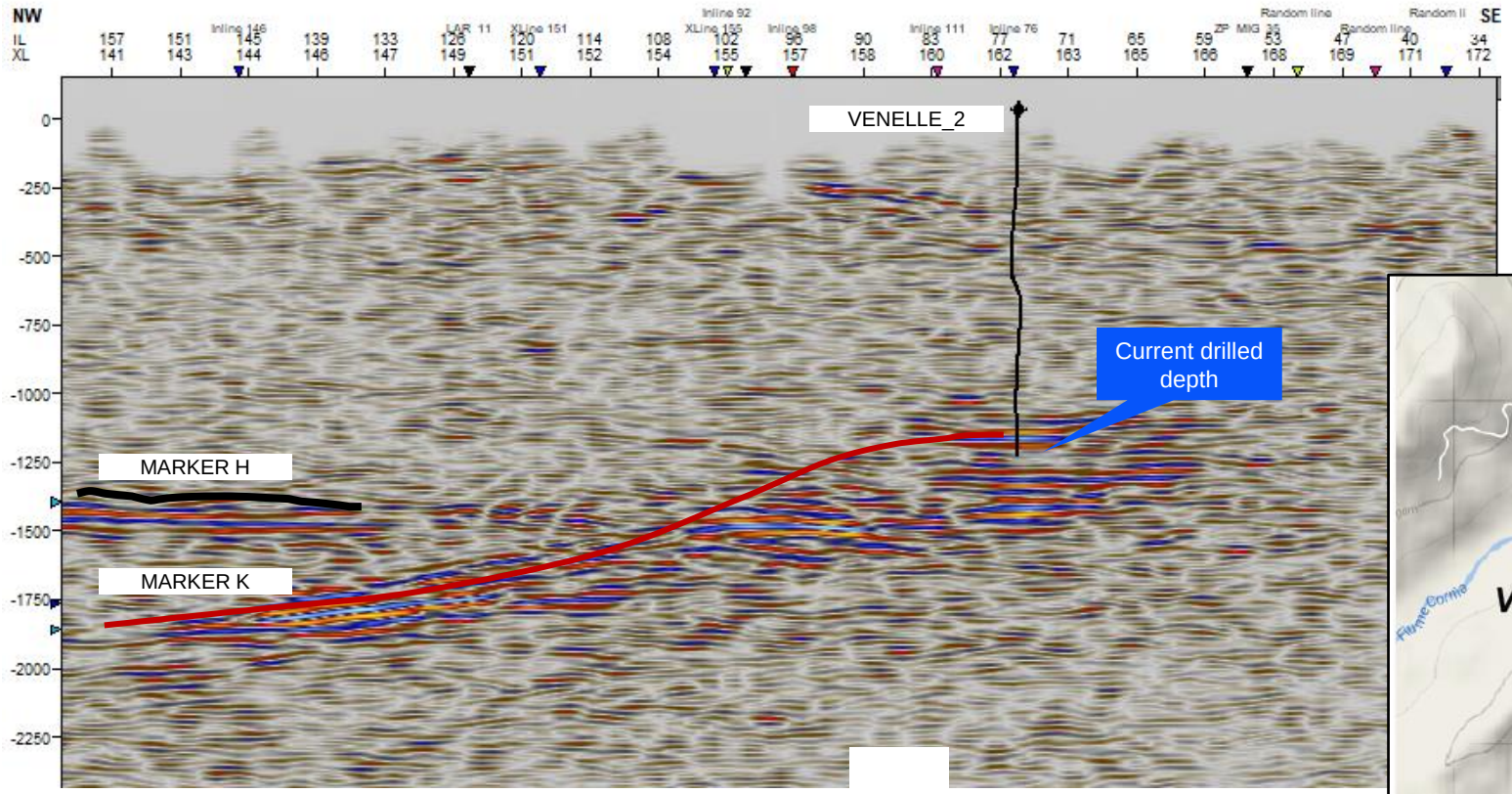
DESCRAMBLE project

Drilling in dEep, Super-CRitical AMBient of continentaL Europe

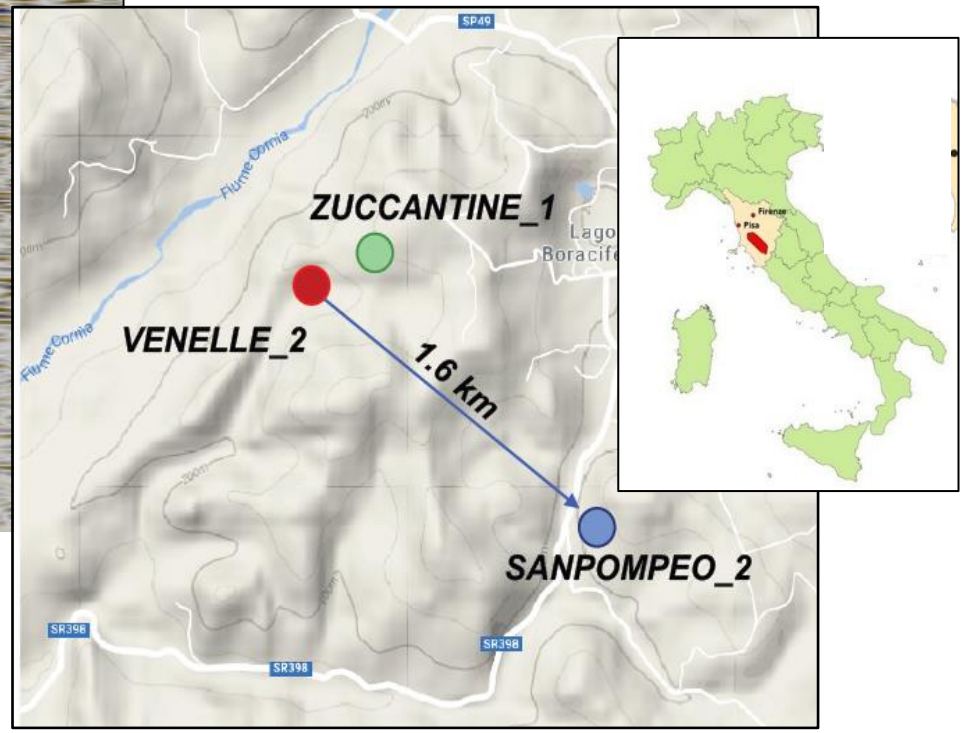
- **Demostrate safe drilling of a deep supercritical geothermal well,** by identifying existing technical problems created by supercritical conditions
- **Reduce the technical and financial risks of drilling and exploiting deep geothermal wells,** by improving knowledge of the physical and chemical conditions in deep geothermal formations
- **Reduce pre-drill uncertainty in the exploration of deep geothermal wells,** by applying the latest seismic processing, imaging and interpretation technology for exploring the supercritical reservoir prior to drilling.
- **Investigate the economic potential of exploiting chemicals and minerals,** by analyzing fluid samples for valuable materials

Seismic signature of K Horizon

DESCRAMBLE PROJECT Target

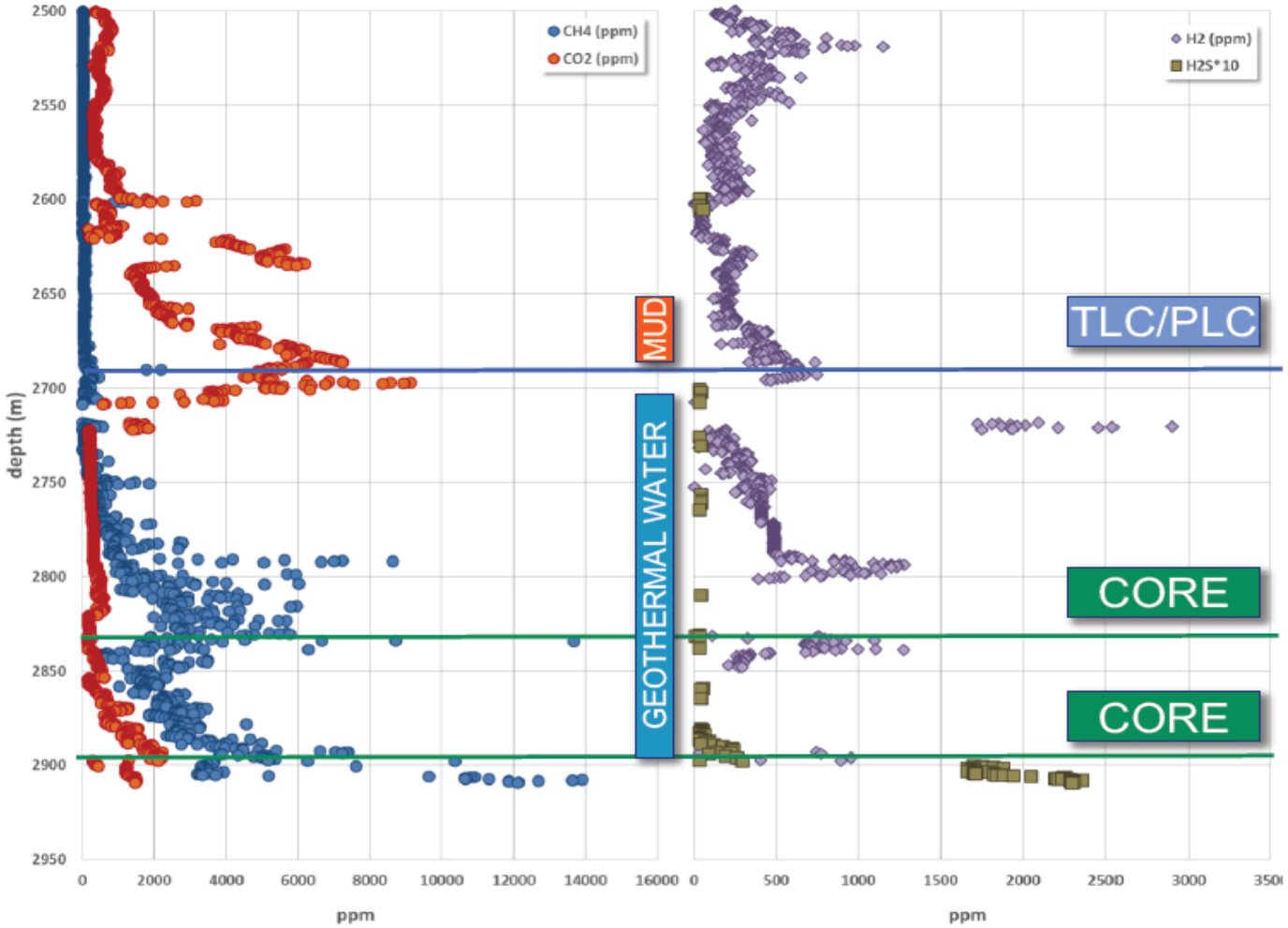


Horizon 2020 EU funded project to drill in superhot systems



Supposed High Pressure **450bar** High Temperature **450°C** conditions

Reactive gases during drilling



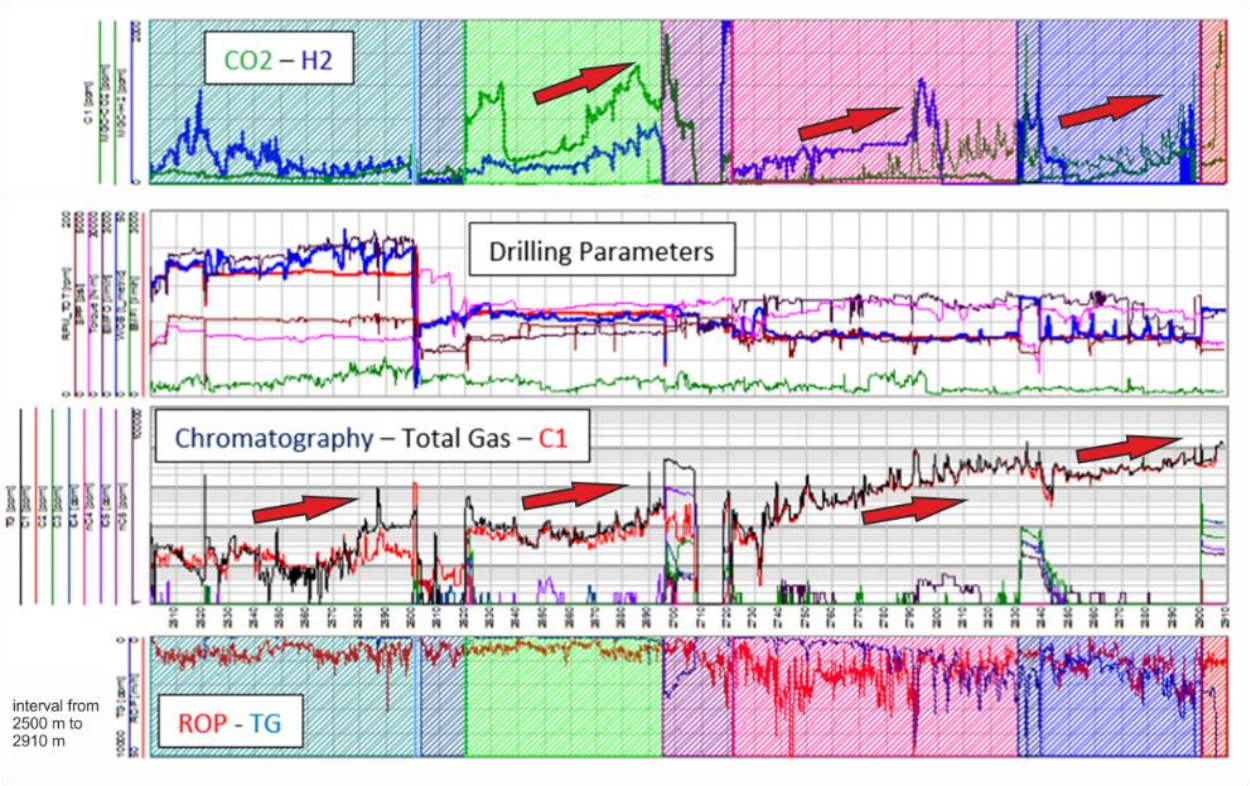
At 2600 m depth: CO_2 and H_2 peaks, other compounds still almost absent

Below 2700 m depth: CH_4 increased (14%v/v), H_2 increased (4%v/v), CO_2 dropped to few ppm (“H” seismic reflector?)

Bottom hole (2909 m depth): CO_2 increased again, H_2S detected in considerable amount, presence of low hydrocarbons

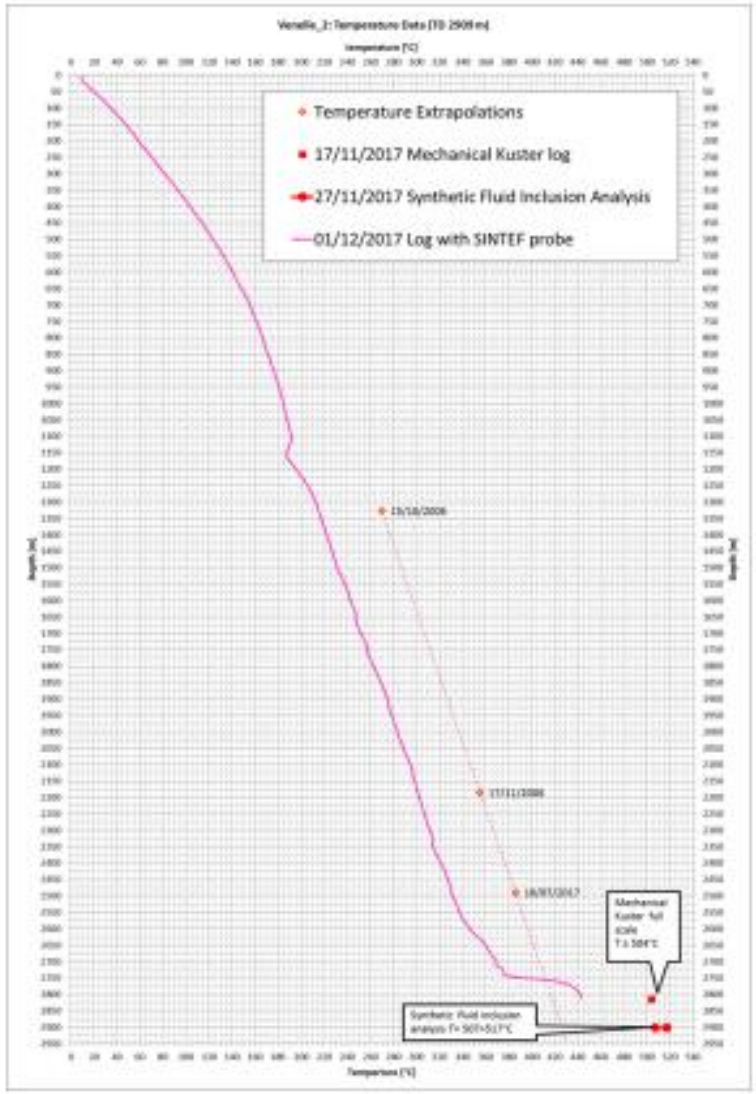
Reactive gases during drilling

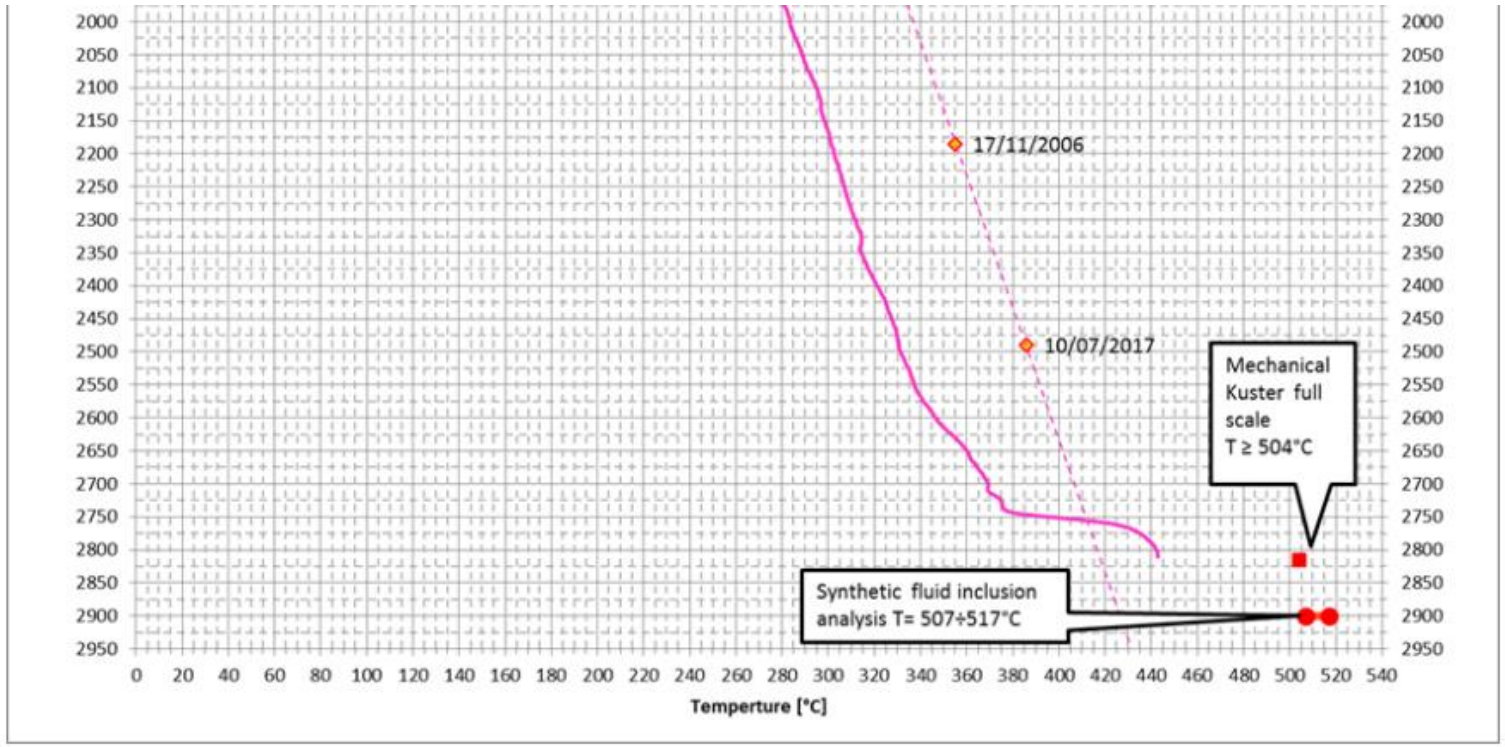
- No positive correlations were observed between gas concentration, rock porosity and the amount of rock crushed in time, as typically reported for oil and geothermal drilling exploration
- A negative correlation among these parameters was observed, along with a series of anomalous increase patterns in CH_4, CO_2 and H_2 concentration
- The chemical signature of Venelle_2 C-bearing gases appeared markedly different from the gases collected at similar depths, from the same lithology (phyllites), in the productive sectors of the Larderello geothermal field



These features were interpreted as an indication of an artificial origin of these gases (ex: thermal cracking of drilled rocks or contamination effect related to the inflow of organic and inorganic additives)

K-Horizon Looking for supercritical conditions





No permeability
Hot Dry rock system

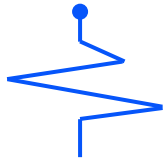
T = 515°C @ 2909m
LOP = 300 bar

Microseismic monitoring for the Venelle project

High resolution microseismic monitoring

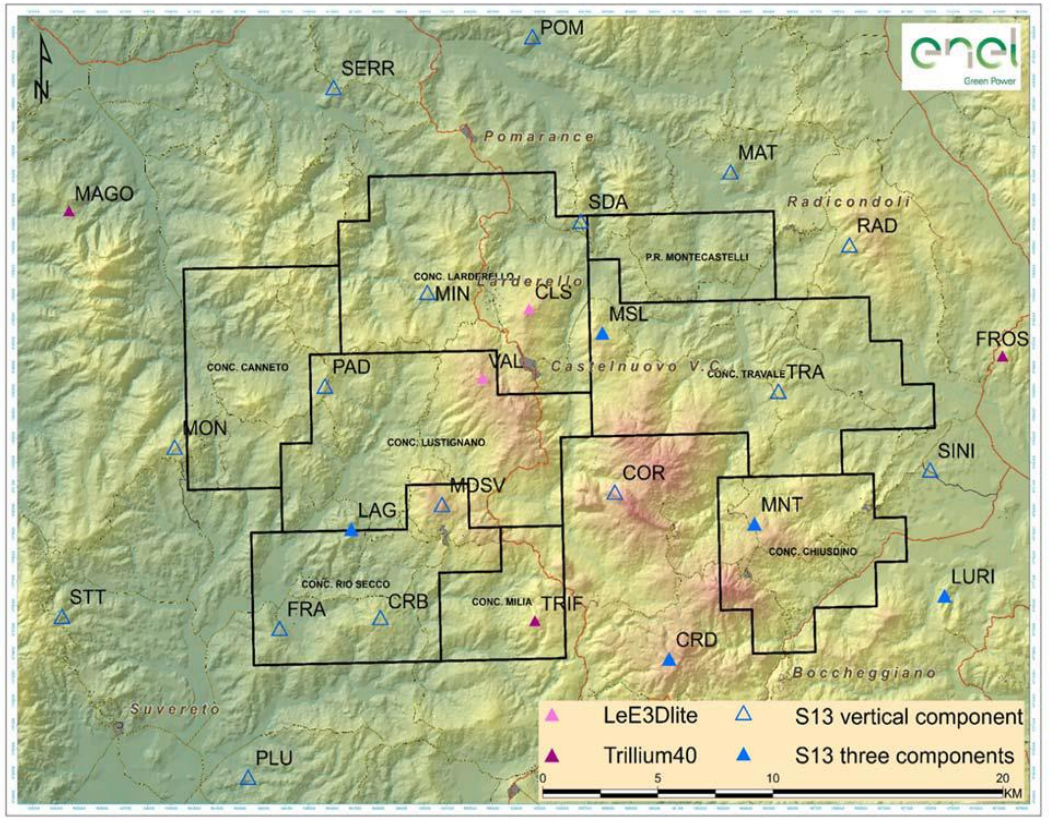
Seismographic coverage of the area - Larderello Travale Seismic Network (LTSN)

- The LTSN is in operation since 1976
- 26 Seismic Stations (SS), with spacing varying from 3 to 9 Km
- 820 km^2 covered area
- detection of close to 0 magnitude microseismic events (catalogue completeness of 0.7 in Magnitude)
- Real time connected to the Larderello seismological datacenter.



The signals coming from the stations are scanned through the automatic acquisition system

Hypocentral and magnitude determinations are provided automatically .



Alert sent to the seismologist and to the plant operators in case events detected close to drilling site or power plant

Seismic monitoring

Four Additional Temporary Seismic Stations (ATSS) at 1.5 to 2 km distance from the VENELLE_2 installed from the beginning of 2016

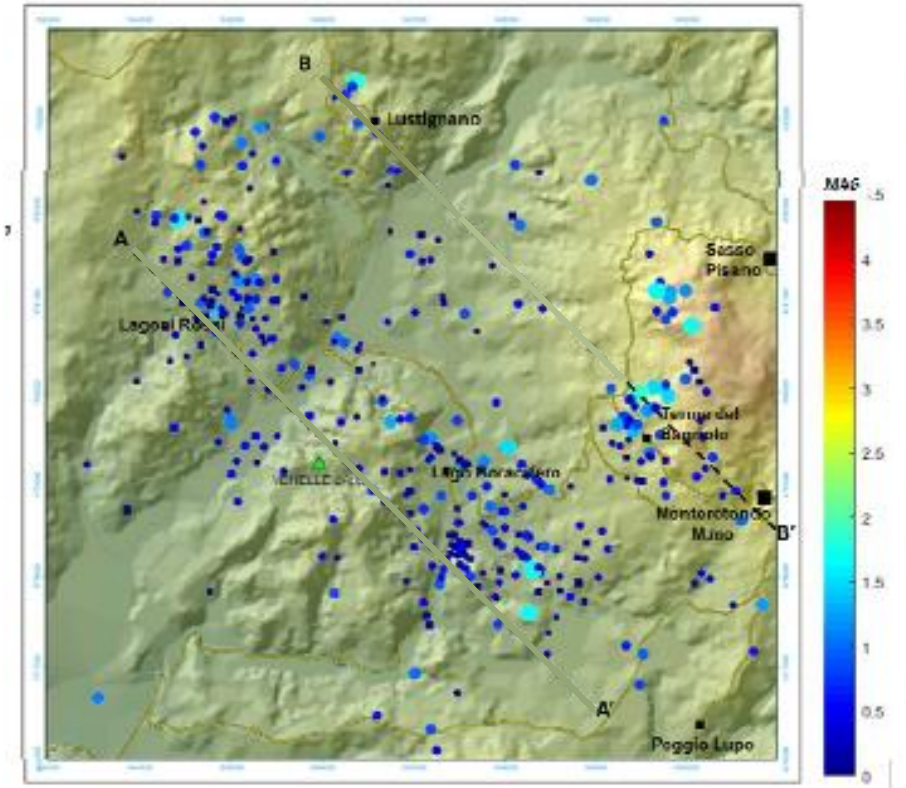
The two years period of observation covers:

• blank measurement, 15 months duration, before the start of VENELLE_2 deepening operation,

• The drilling period from April 28, 2017 to November 12, 2017

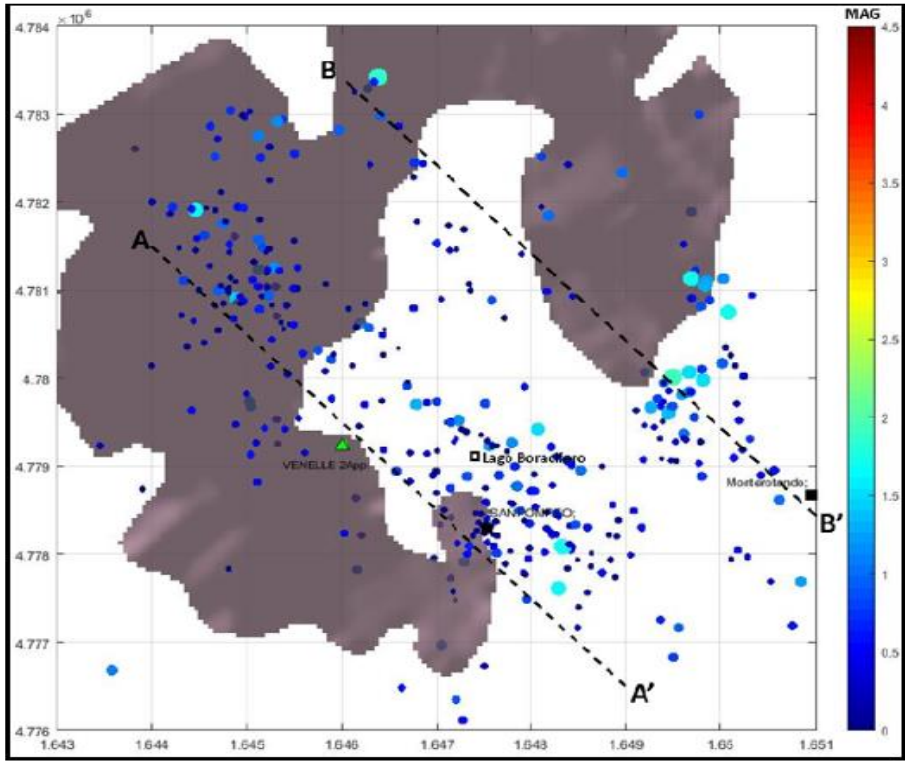
373 events with magnitude ranging from -1.04 to 1.92 were detected.

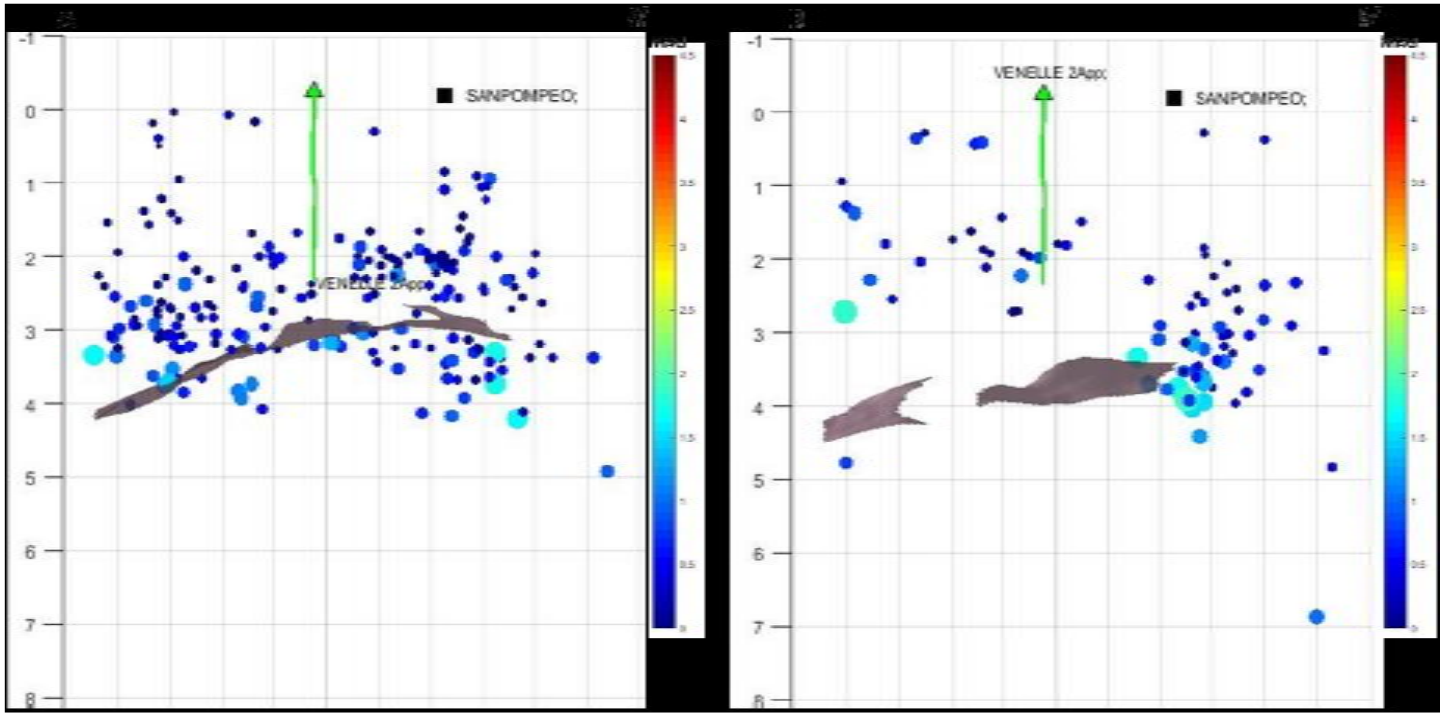
Seismic activity is present more or less over the entire area



High resolution microseismic monitoring

Seismicity of the area – Depth distribution





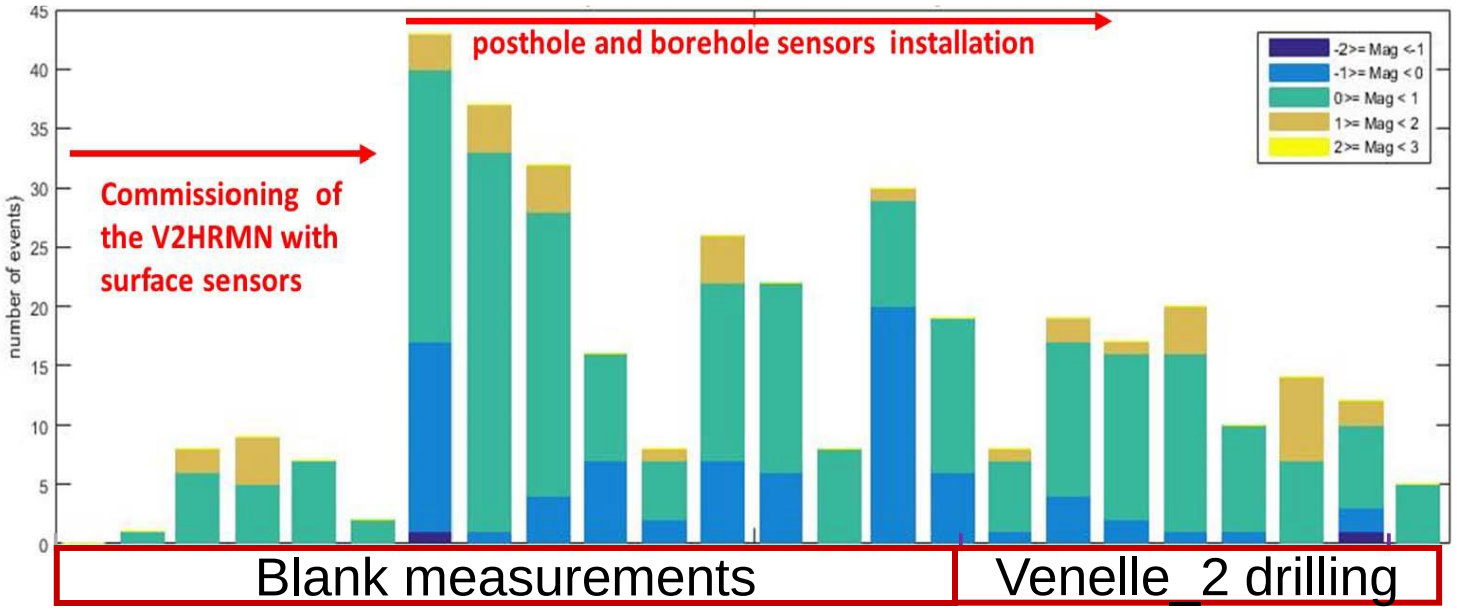
High resolution microseismic monitoring

Seismicity of the area – Frequency distribution

On July 2016, a strong variation of the earthquakes occurrence is observed.

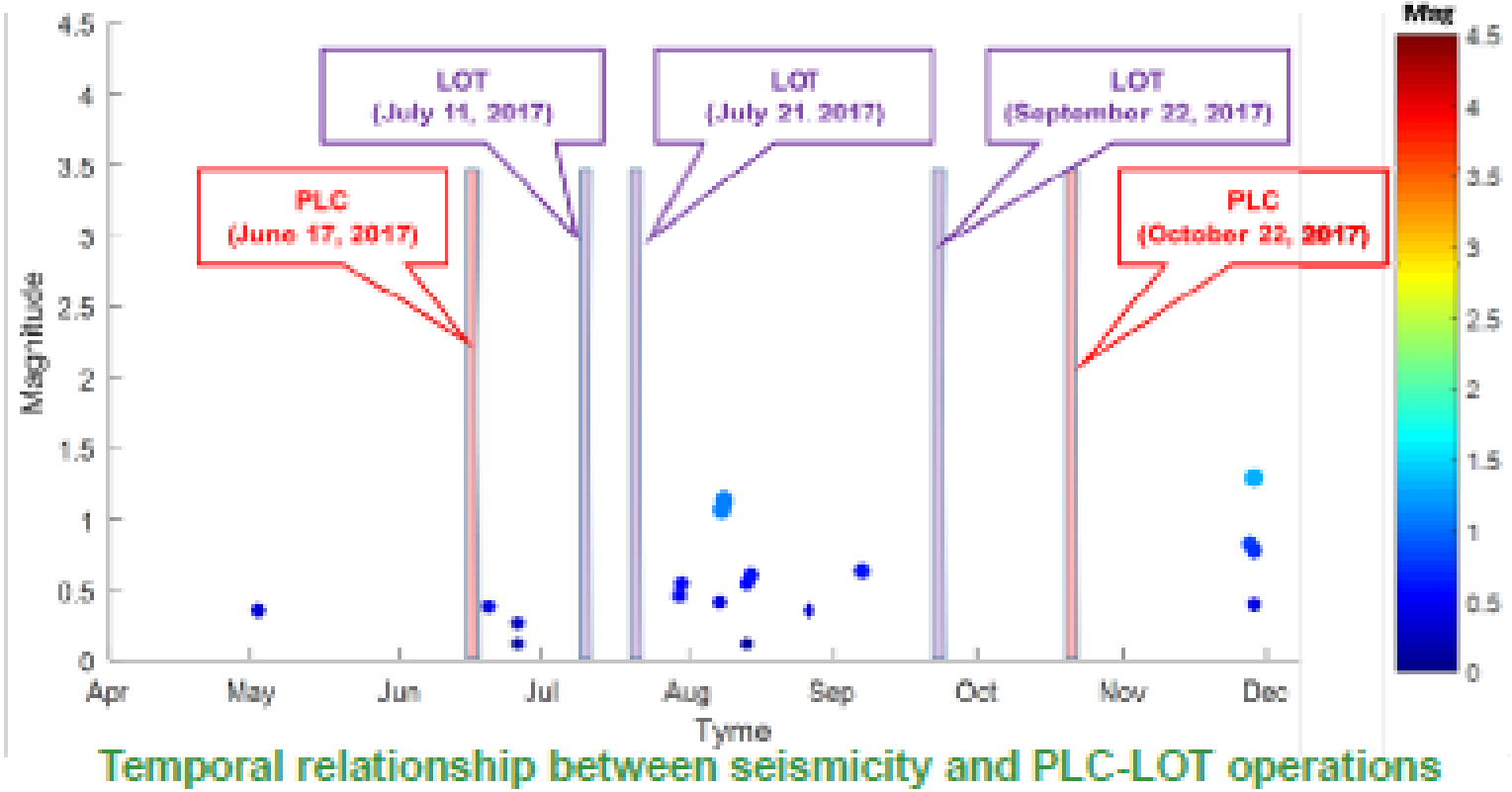
The apparent increase in seismicity is mainly due to the contribution of the events with magnitude < 0.5, and especially with magnitude < 0

Monthly frequency histograms of the recorded seismic events

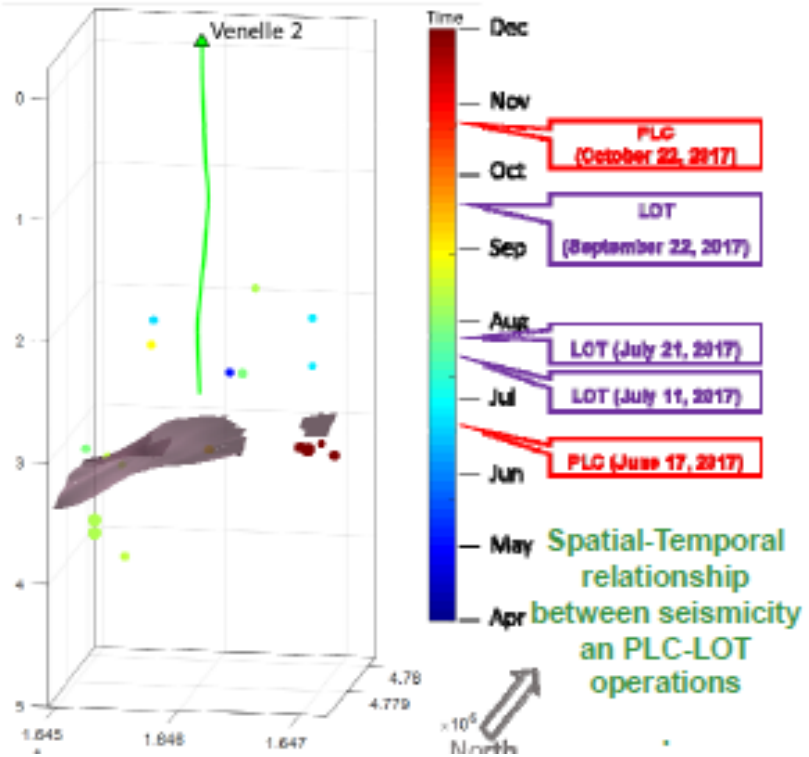


This is not a real increase in seismicity, but it is the improvement of seismic network detection capability due to posthole and borehole sensors installation.

Seismicity during VENELLE drilling



Temporal relationship between seismicity and PLC-LOT operations



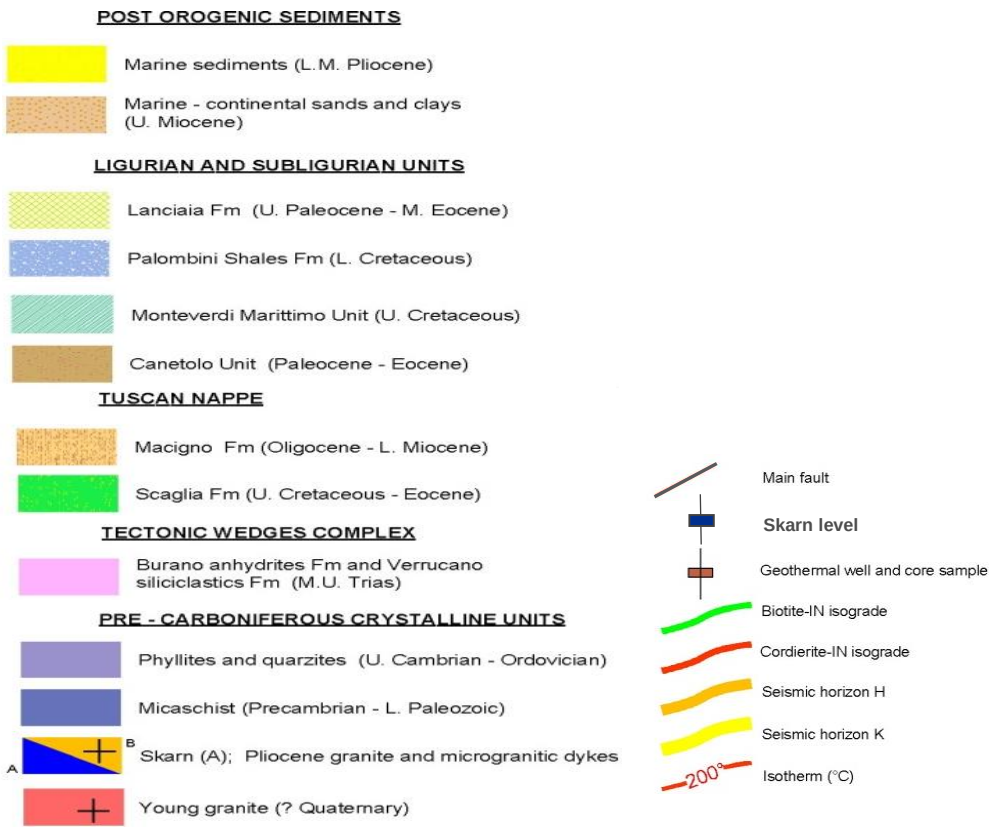
No temporal and spatial correlation seems to exist between the seismicity and drilling operations.

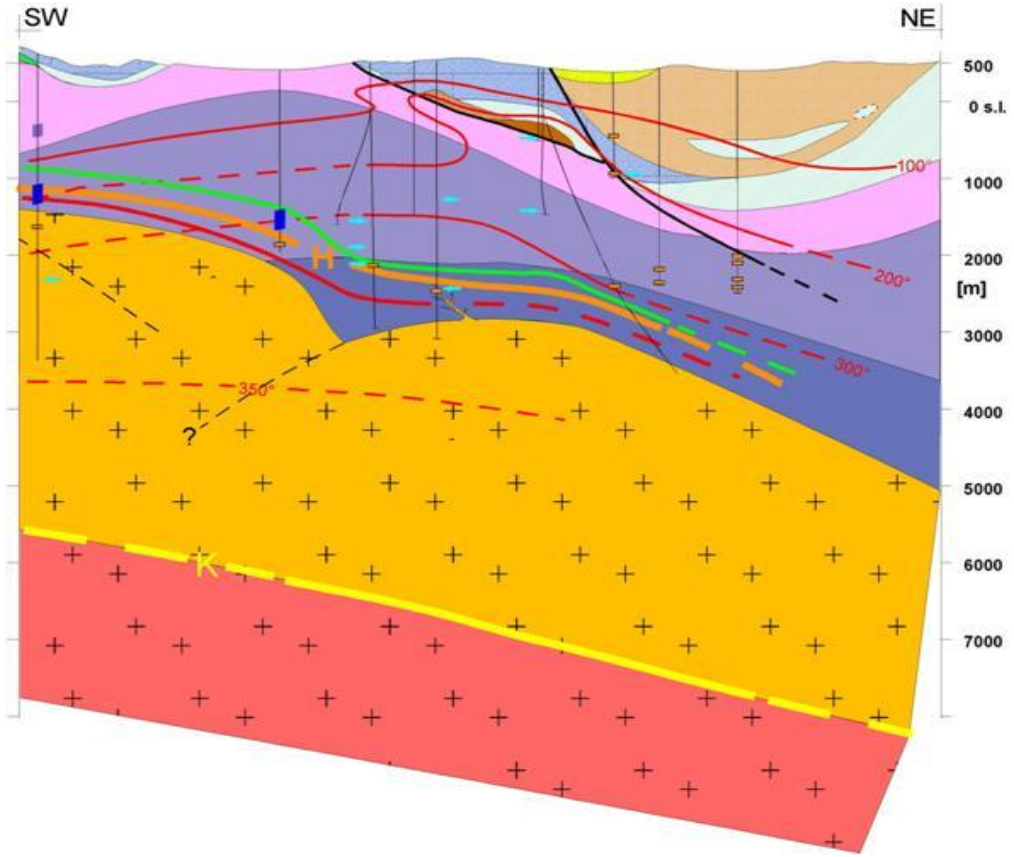
Spectral Gamma Ray log: reconstruction of granitic bodies as reservoir in Travale

Area of interest

Geology of the area and Plutonic complex

Deeper part of the system (below ca. 2500-4000 m) constituted by a plutonic complex built up (between 3.8 and 1.3 Ma) by progressive stacking of several different granite magma batches.





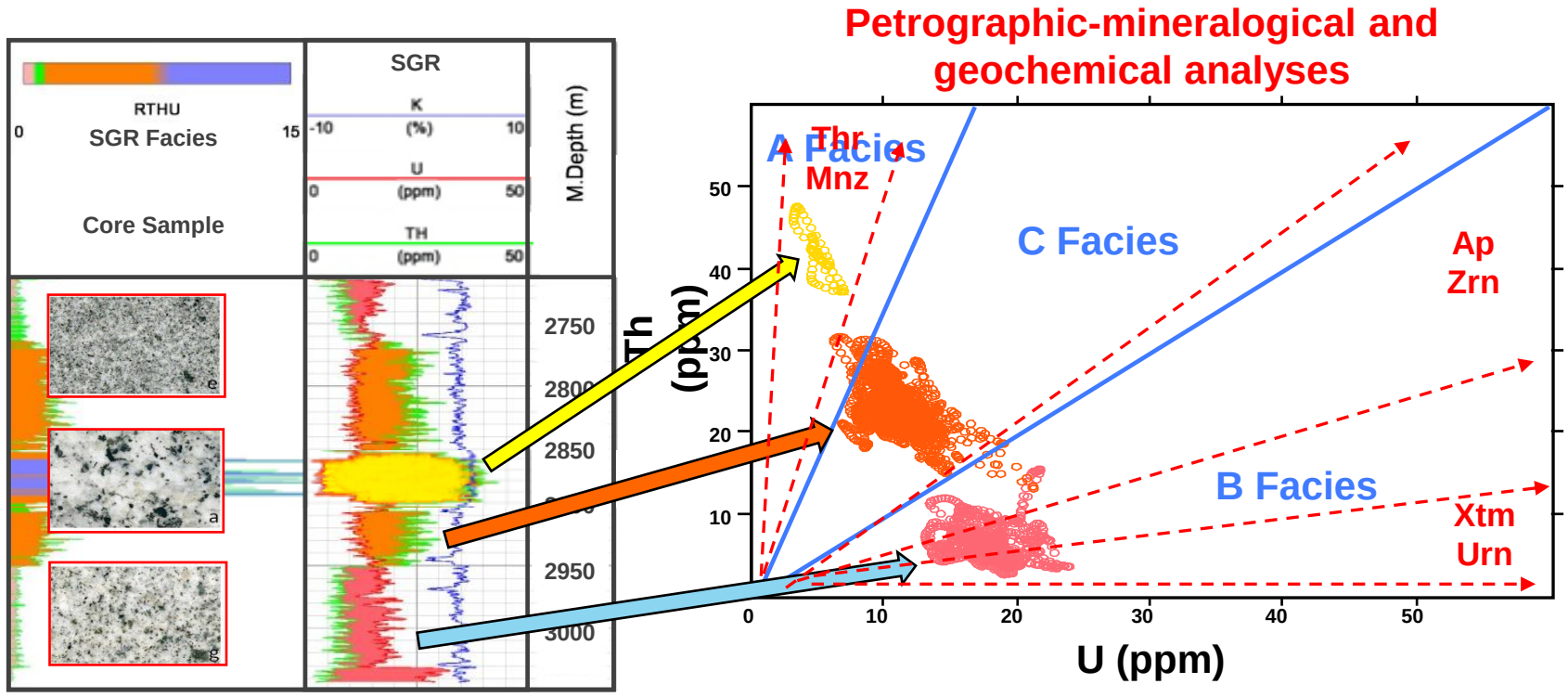
Aim of work

SGR test as a tool to the identification of the granite types

Possibility to unravel internal units and structures of Travale granite intrusions by application of Spectral Gamma Ray analyses.

Geochemical comparison and characterization of U and Th mineral carriers

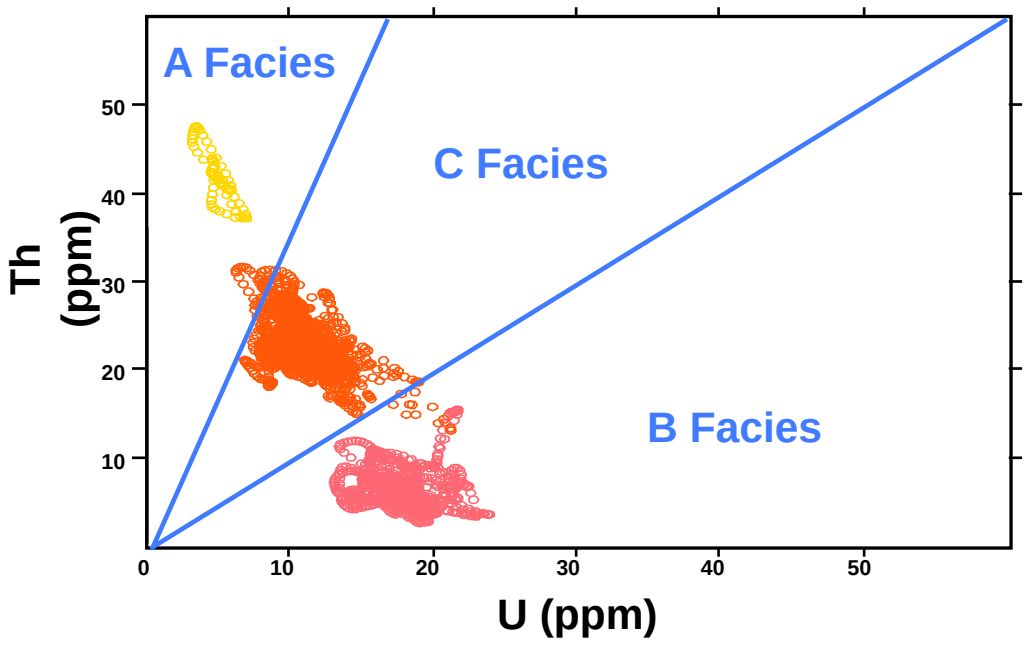
Petrographic, mineralogical (SEM-EDS) and geochemical analyses on core and cutting samples are compared with SGR data available.

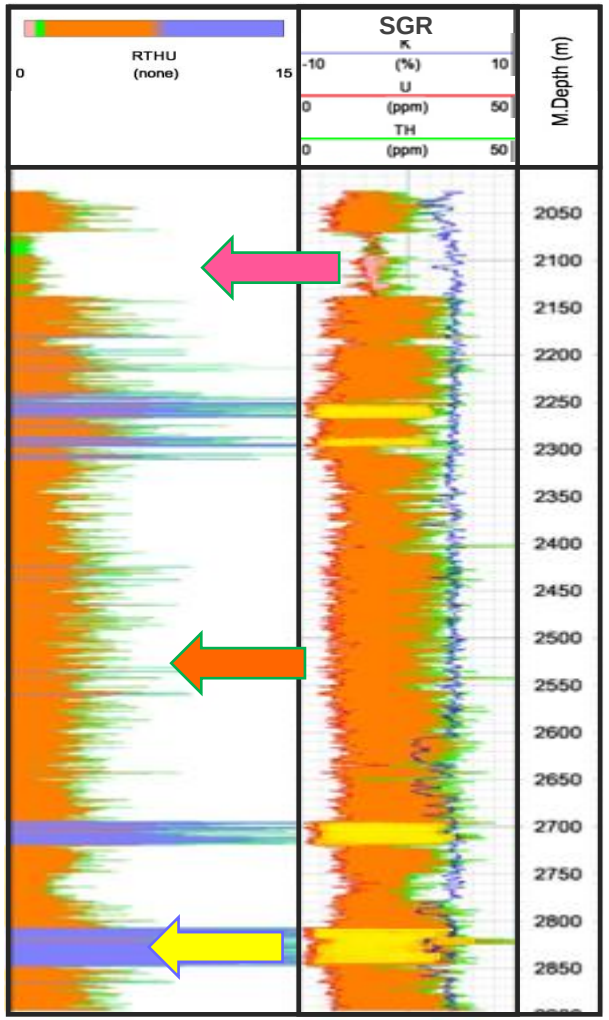


SGR test as a tool to the identification of granite types

The calibrated sections were used for comparison with other granite intersections drilled and sampled during last decade.

Thanks to the larger dataset, the classification of Larderello-Travale granites proposed by Dini el al. (2005) was significantly improved.



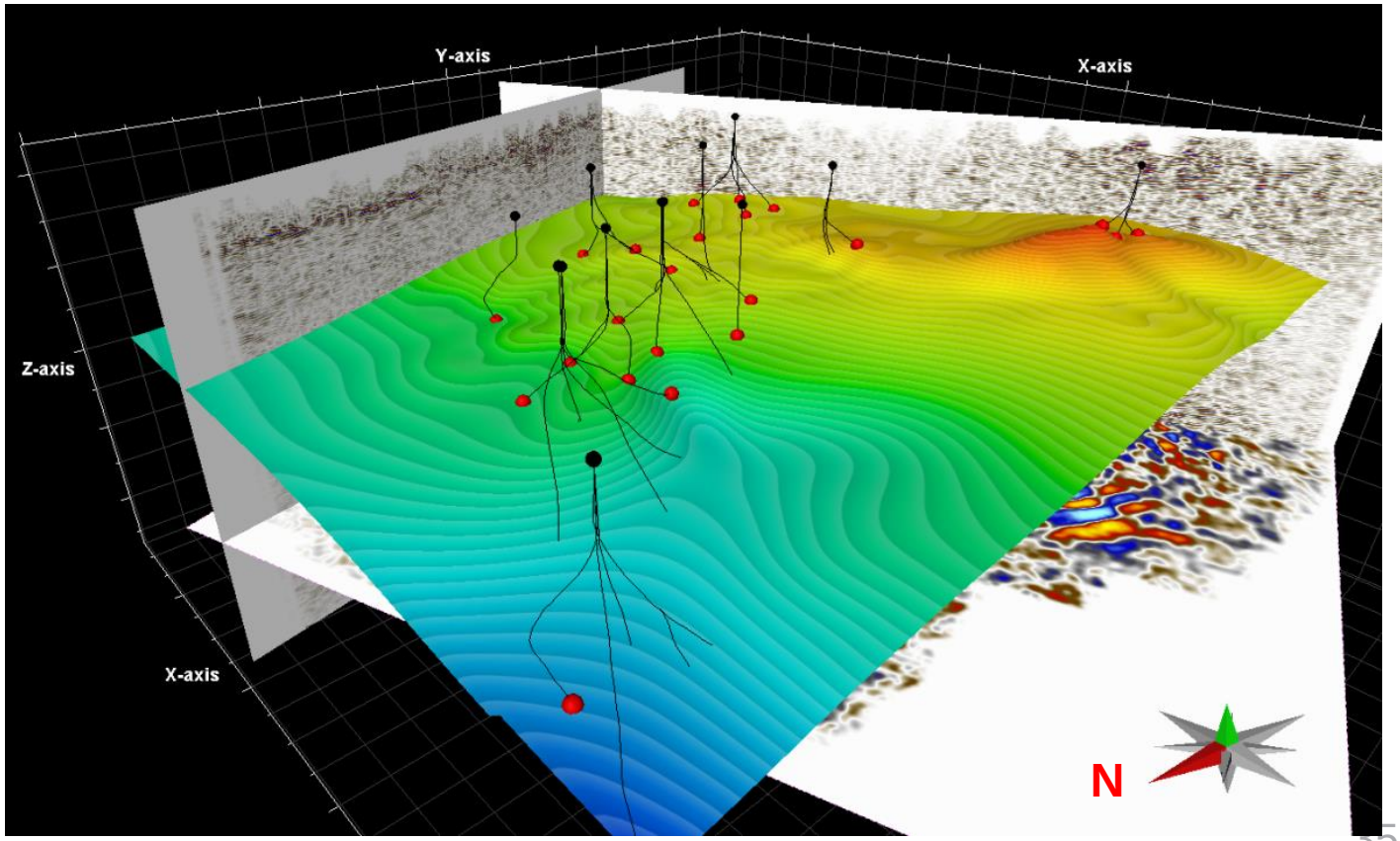


Analyzed data

Top of the granite intrusion

A detailed 3D reconstruction of the top of the granite intrusion was reconstructed by means of:

- ✓ Well logs (SGR Spectral Gamma Ray Log).
- ✓ 3D and 2D reflection seismic prospection.
- ✓ Observation of cutting.
- ✓ Observation of cores sample.

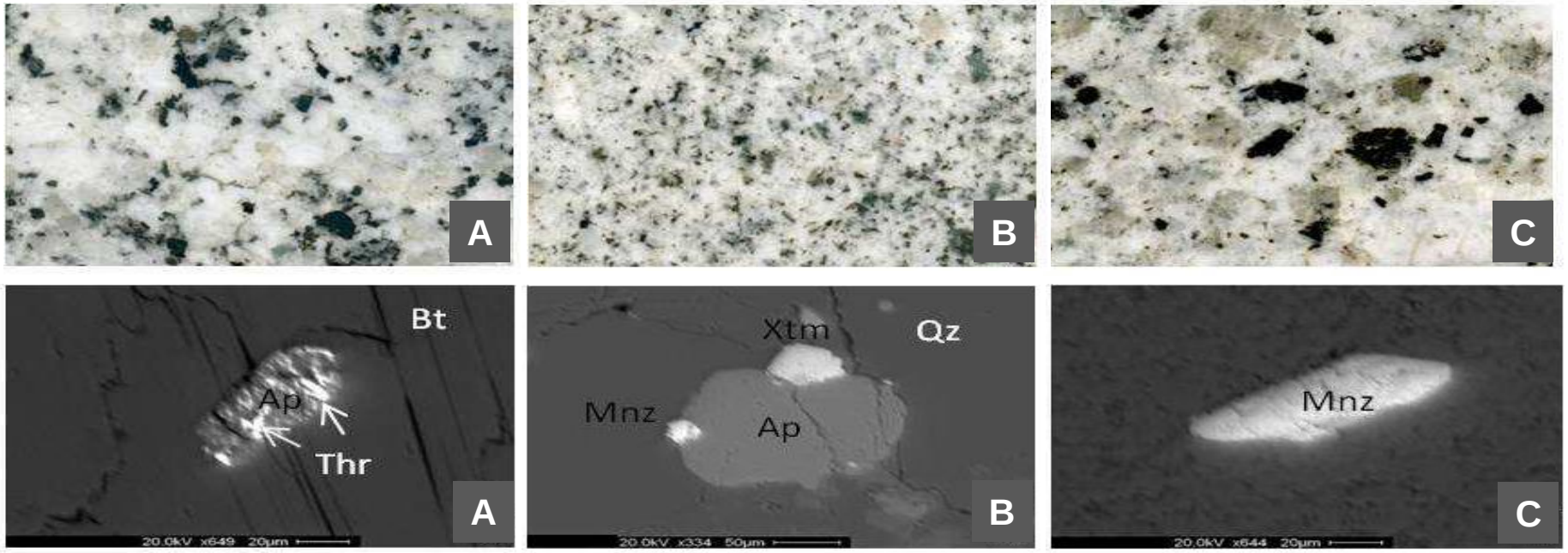


Petrography

Lithological Log, petrographic and SEM analysis

Travale granites display significant textural and mineralogical variation, easily recognizable in the hand specimens and under the microscope. They can be classified in 3 petrofacies on the base of their Th/U ratio.

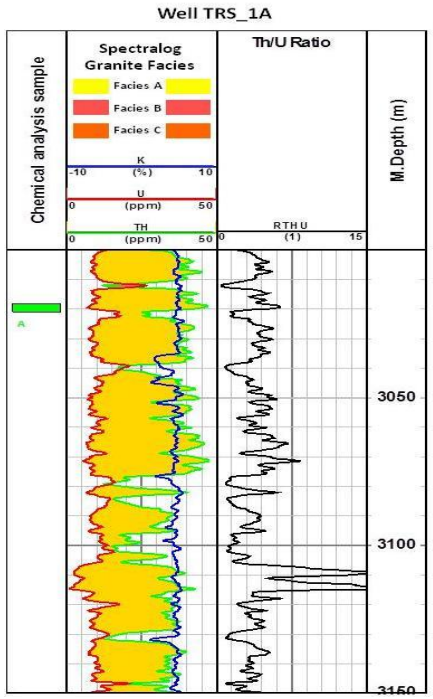
Petrofacies A: **Petrofacies B:** **Petrofacies C:**



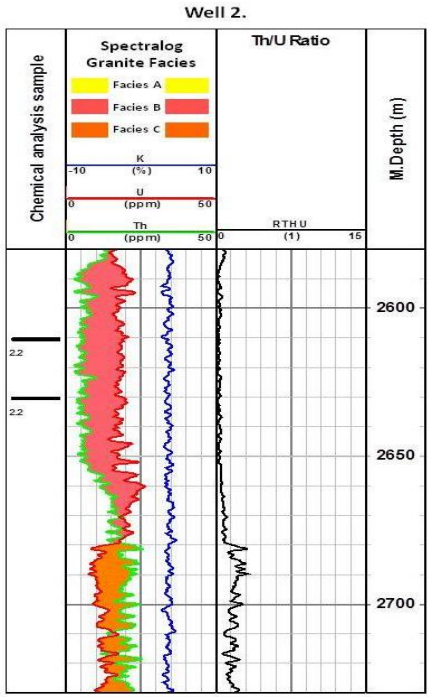
Spectral Log Analyses

SGR Facies identification

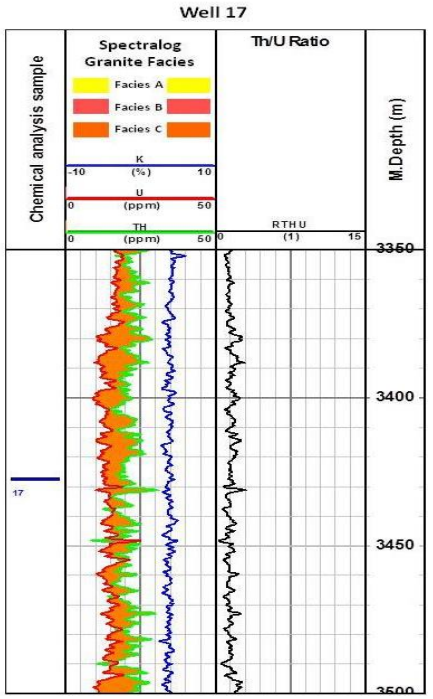
Facies A
high Th content and high Th/U ratios (>4)



Facies B
Granite uranium-enriched high U content,Th/U ratios <1



Facies C
similar U and Th content, with Th/U ratio from 1 to 4.



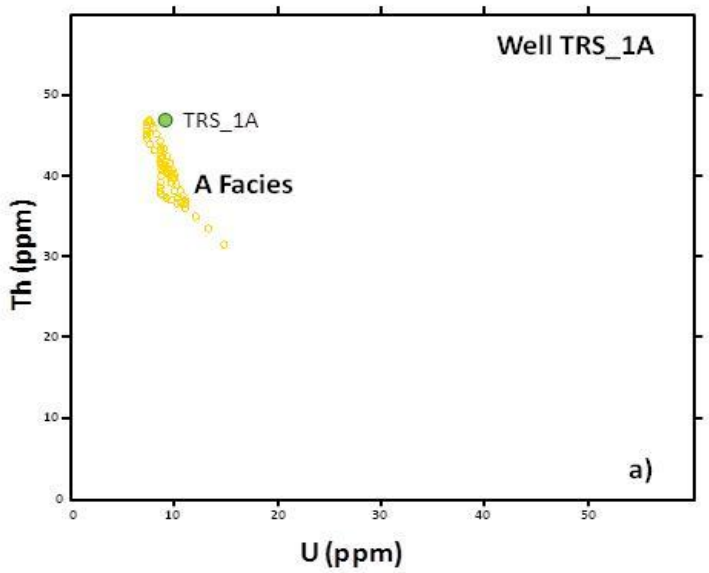
K content is the same in all the A, B and C facies and ranges around 5%.

Spectral Log Analyses

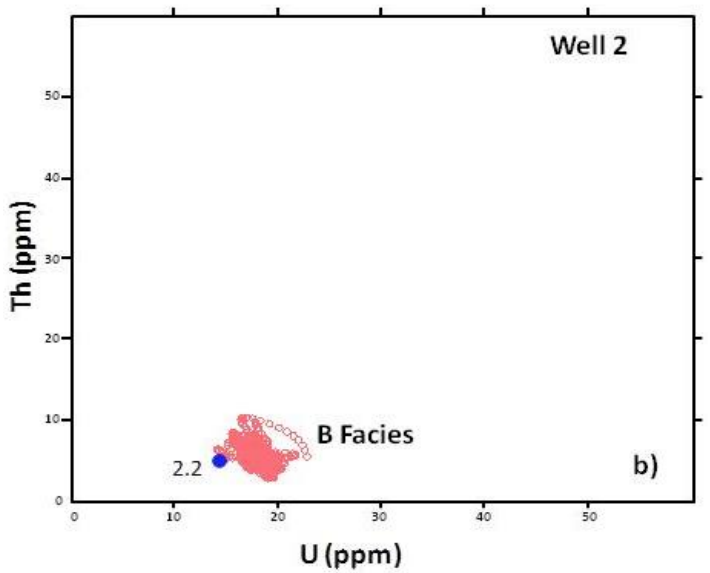
SGR Facies and U-Th content from chemical analysis

For the wells in which both SGR and chemical analysis on core/cuttings are available, the cross-plots U vs Th, have been compared with U and Th content determined by chemical analysis (solid points).

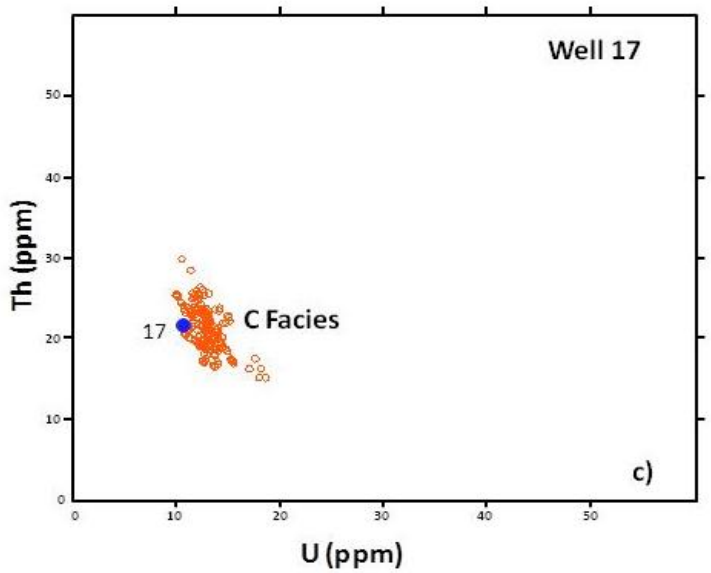
Facies A
high Th content
high Th/U ratios (>4),



Facies B
high U content
low Th/U ratios <1



Facies C
similar U and Th content
Th/U ratio ranges from 1 to 4.



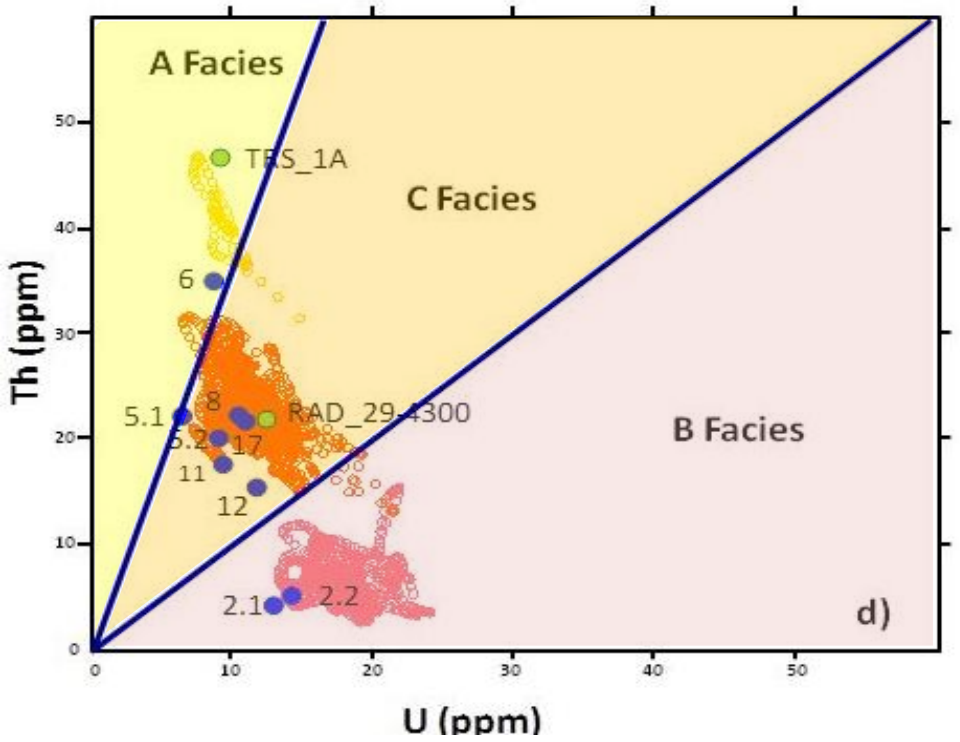
Spectral Log Analyses

SGR Facies and U-Th content from chemical analysis

3 granite facies strongly correlated with petrofacies distinguished by the petrographic observation and chemical analyses.

Green and blue solid dots are Th and U content obtained from chemical analyses

Empty circles are Th and U content obtained from SGR analyses

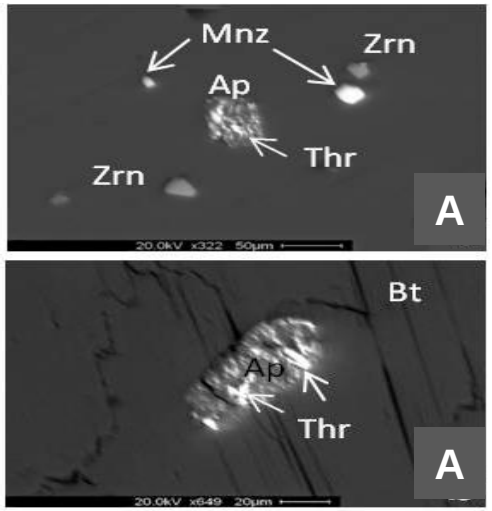


Petrography - SGR Facies matching

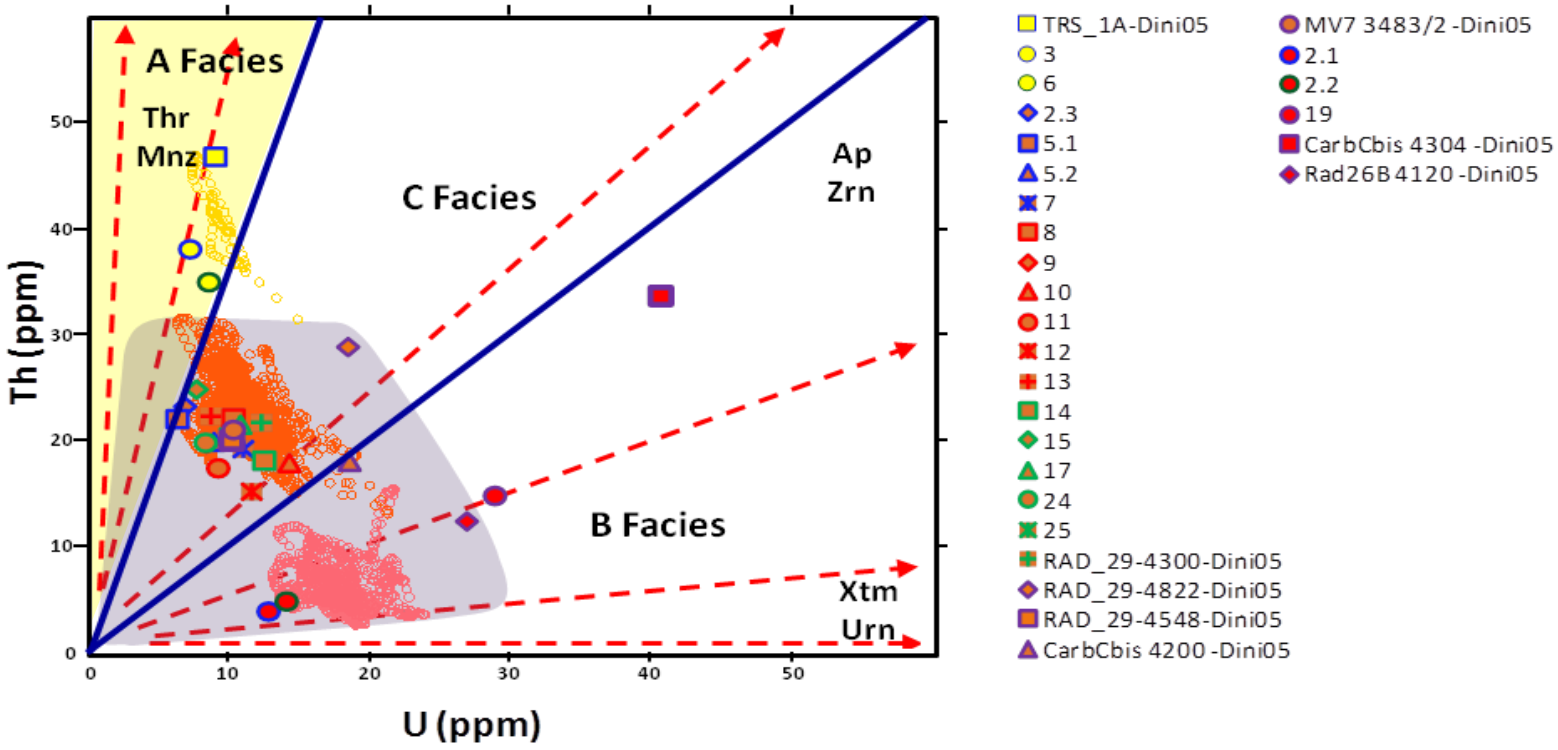
Facies A

A Facies corresponds to K-feldspar megacryst-rich coarse-grained monzogranite.

The high Th content and Th/U ratio is controlled by the common occurrence of thorite and monazite.



Backscattered SEM
Thr and Mnz

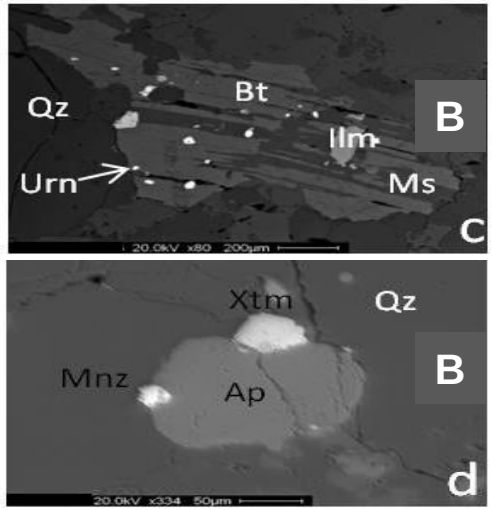


Petrography - SGR Facies matching

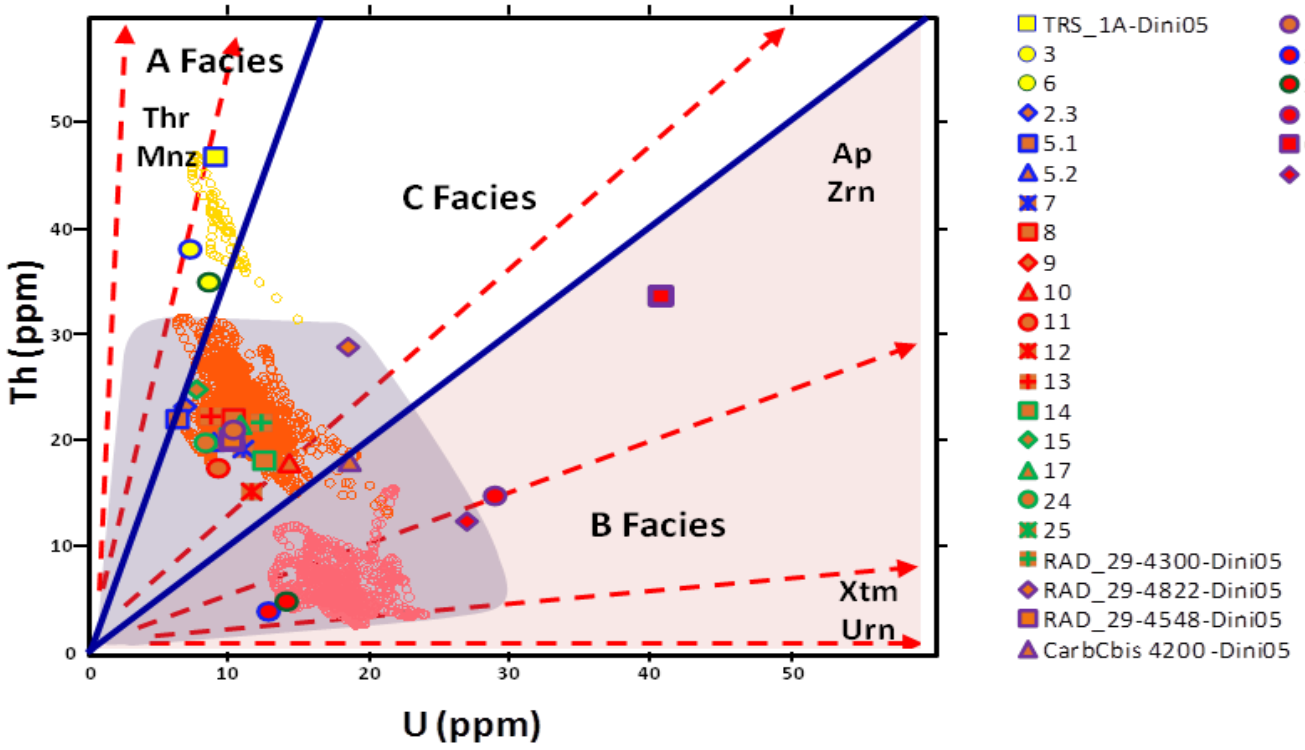
Facies B

B Facies includes the most silicic, medium-grained, monzo-syenogranites.

The characteristic high U enrichment (very low Th/U ratio) is mainly due to the presence of uraninite and thorite coupled with the ubiquitous occurrence of xenotime.



Urn and Xtm as accessory minerals

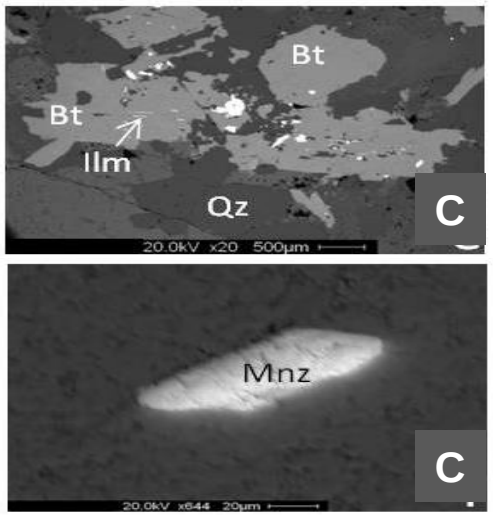


Petrography - SGR Facies matching

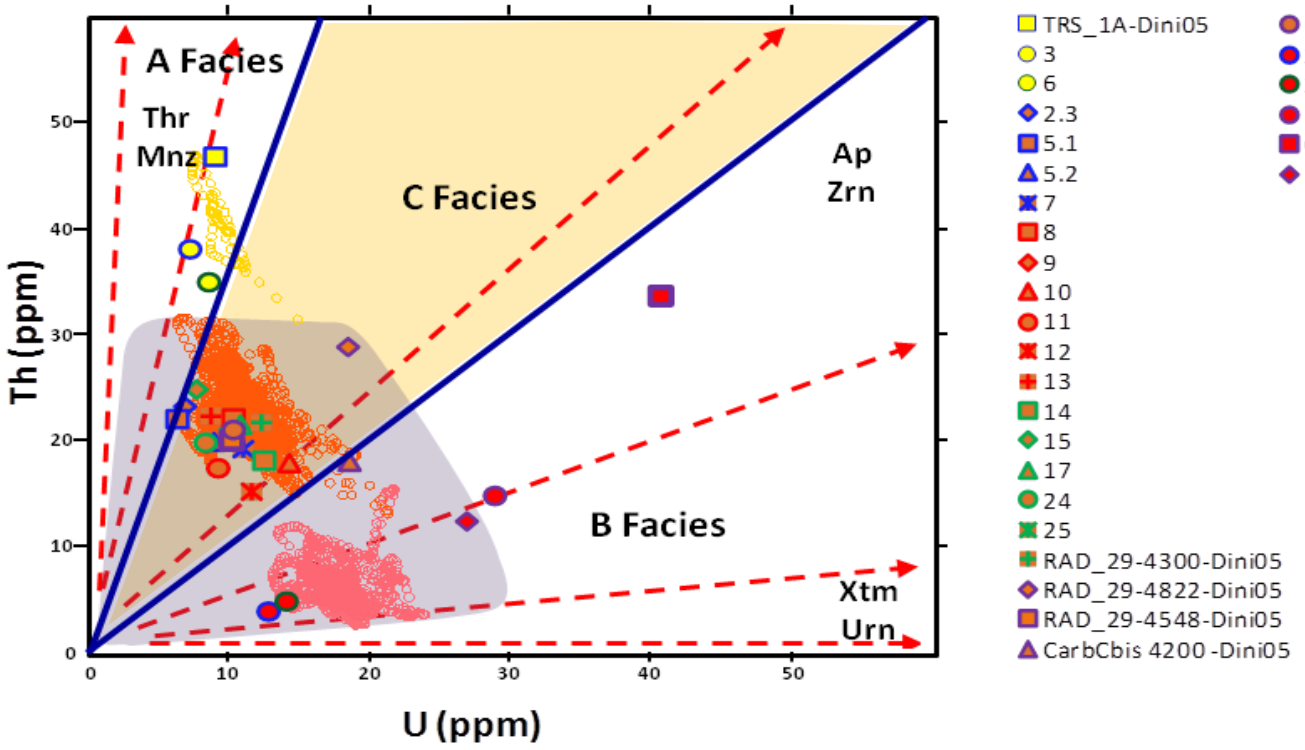
Facies C

C Facies includes two textural types (porphyritic and microgranitic) showing monzogranite composition.

The Th and U contents are comparable with the values already measured in other granites from the TMP.



Mineral paragenesis with Bt, Ilm, Qz and Mnz



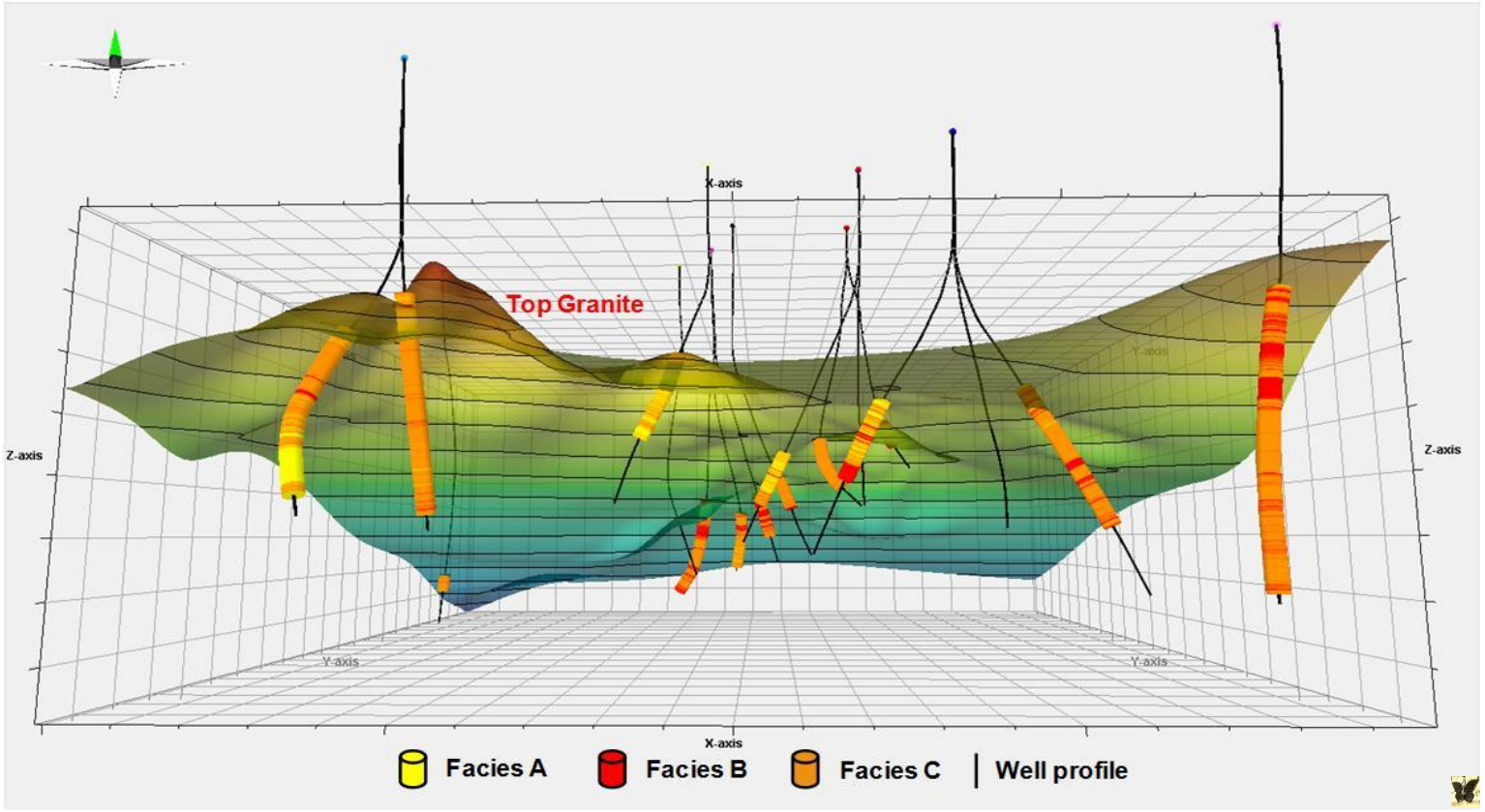
SGR FACIES: 3D spatial distribution

3D spatial distribution of the three facies show the complexity of their geometric relationships

C Facies is the most widespread and is found in almost all the wells.

B Facies thickness is up to 250m, but without a preferential spatial distribution.

A Facies thickness, ranging from 50 to 600m, is mainly found in the southwestern area

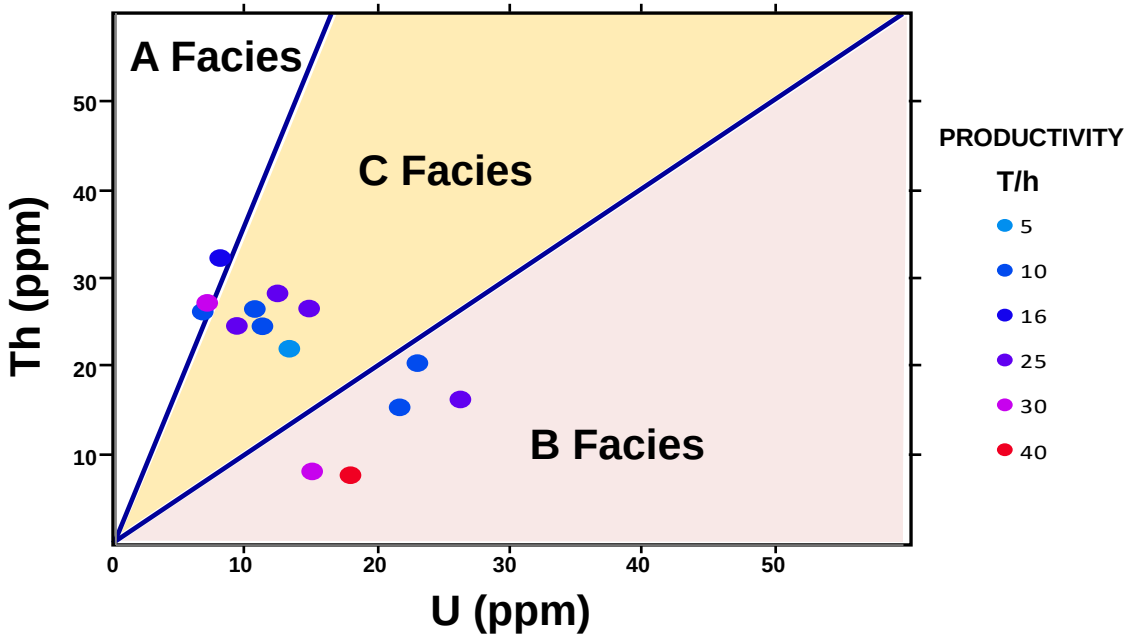


Application of Spectral Log Analyses

For the wells in which both SGR and productive fractures are recognized, for each fracture and/or permeable zone the relative U and Th values are obtained.

These values, ranked by production in t/h, are compared with the cumulative cross-plot U vs Th from SGR.

The largest number of fractures with the highest productivity fall in in the diagram areas relative to C and B Facies



Final remarks

- Geothermal systems are a fascinating very complex subjects depending on geological setting
- Data means value
- Different methodologies to understand the subsurface
- Modern technologies should be used as far as they become accessible


Green Power