Developing Best Practice for Geothermal Exploration and Resource/Reserve Classification Workshop
Essen, Germany, 14 November 2013

Geothermal play types based on geological setting
Convective, Intrusive, Convergent

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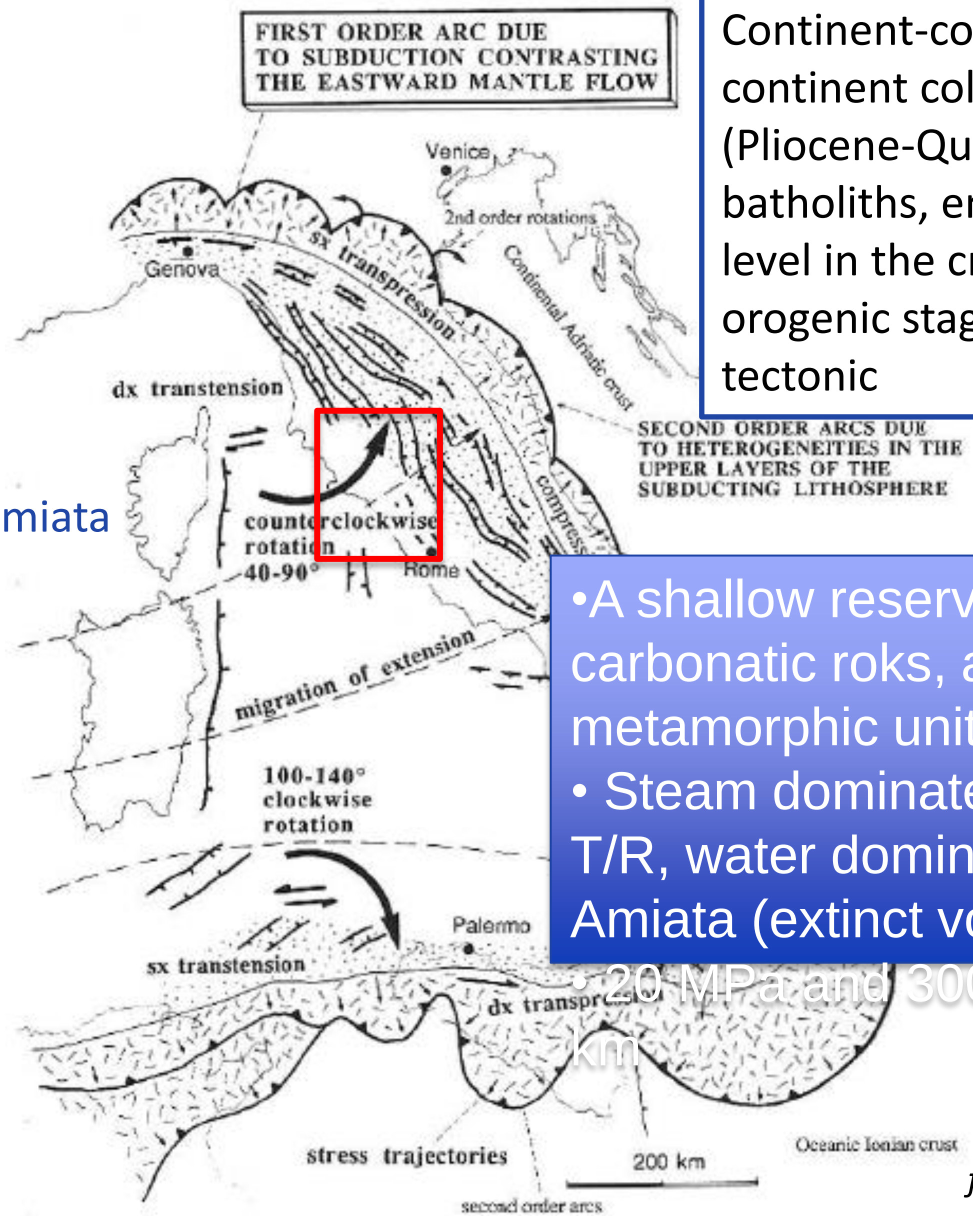
Continent-continent or ocean-continent collision, recent (Pliocene-Quaternary) silicic batholiths, emplaced at shallow level in the crust, during late orogenic stage of extensional tectonic

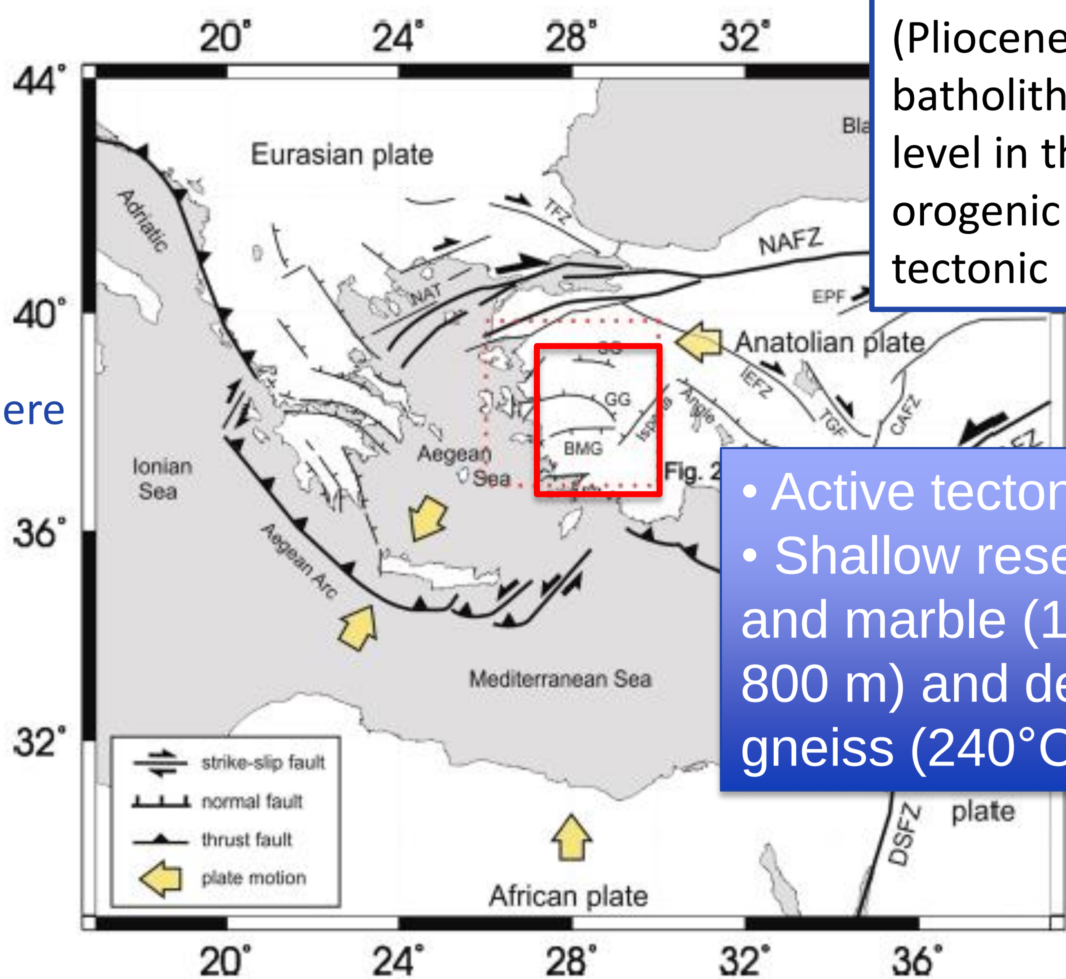
Larderello and Mt. Amiata



- A shallow reservoir in carbonatic roks, a deep in metamorphic units
- Steam dominated in Larderello-T/R, water dominated in Mt. Amiata (extinct volcano)
- 20 MPa and 300-350°C at 3 km

from Doglioni, 1991.

Turkey: Kizildere



Continent-continent or ocean-continent collision, recent (Pliocene-Quaternary) silicic batholiths, emplaced at shallow level in the crust, during late orogenic stage of extensional tectonic

- Active tectonic setting
- Shallow reservoir in limestones and marble (195-205°C at 600-800 m) and deep reservoir in gneiss (240°C at 1.5 km)

from Kurtulmus T. O., Akyol N. (2013).

Figure 1. The major neotectonic structures and plate tectonics of western Turkey. DSFZ, Dead Sea Fault Zone; PFB, Palmyride Fold Bend; EAFZ, East Anatolian Fault Zone; NAFZ, North Anatolian Fault Zone; CAFZ, Central Anatolian Fault Zone; EPF, Ezinepazarı Fault; TGF, Tuzgölü Fault; İEFZ, İnönü-Eskişehir Fault Zone; AFZ, Akşehir Fault Zone; BMG, Büyük Menderes Graben; GG, Gediz Graben; SG, Simav Graben; NAT, North Anatolian Through; TFZ, Thrace Fault Zone. Large arrows indicate relative plate motion directions with respect to Eurasia (after Uzel *et al.* 2012). The area with red dashed lines shows the region of Fig. 2.

USA: The Geysers

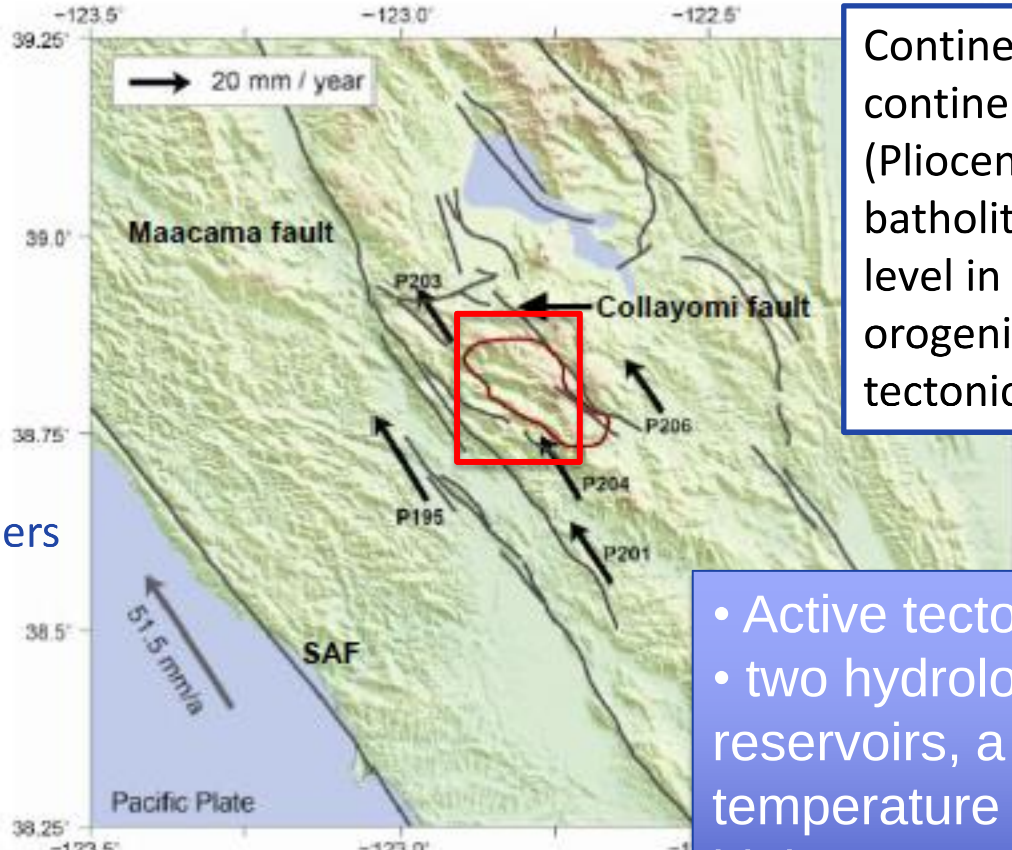


Figure 1: Map of The Geysers g
solid line) within the
fault (SAF) system. Gr
the traces of the major faults. Velocities

Continent-continent or ocean-continent collision, recent (Pliocene-Quaternary) silicic batholiths, emplaced at shallow level in the crust, during late orogenic stage of extensional tectonic

- Active tectonic setting
- two hydrologically connected reservoirs, a “normal” temperature reservoir and a high-temperature reservoir (NTR and HTR) in Meta-Greywacke and felsite rocks (150-342°C at 500-2000 m)

from Altmann et. al 2013.

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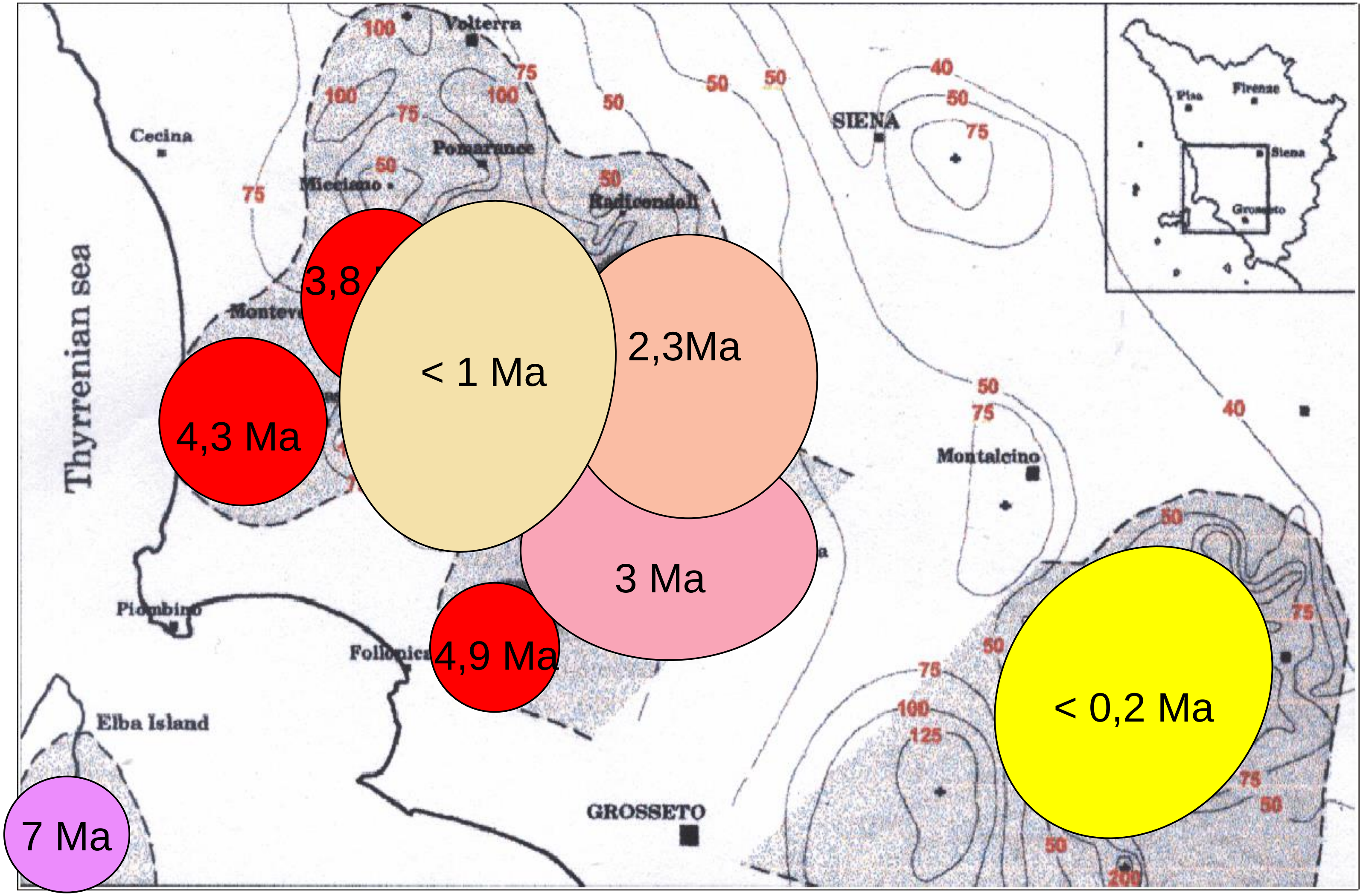
Heat source

Crustal thinning > regional high heat flow

Magma chambers and intrusions with cyclic magma supply (astenosphere or melting of crustal rocks) > local very high heat flow

Intrusions may be composite batholits or complexes of laccoliths with christmas-tree structures (indirect geophysical data, a few direct data from Larderello and The Geysers)

Ages of granitic intrusions



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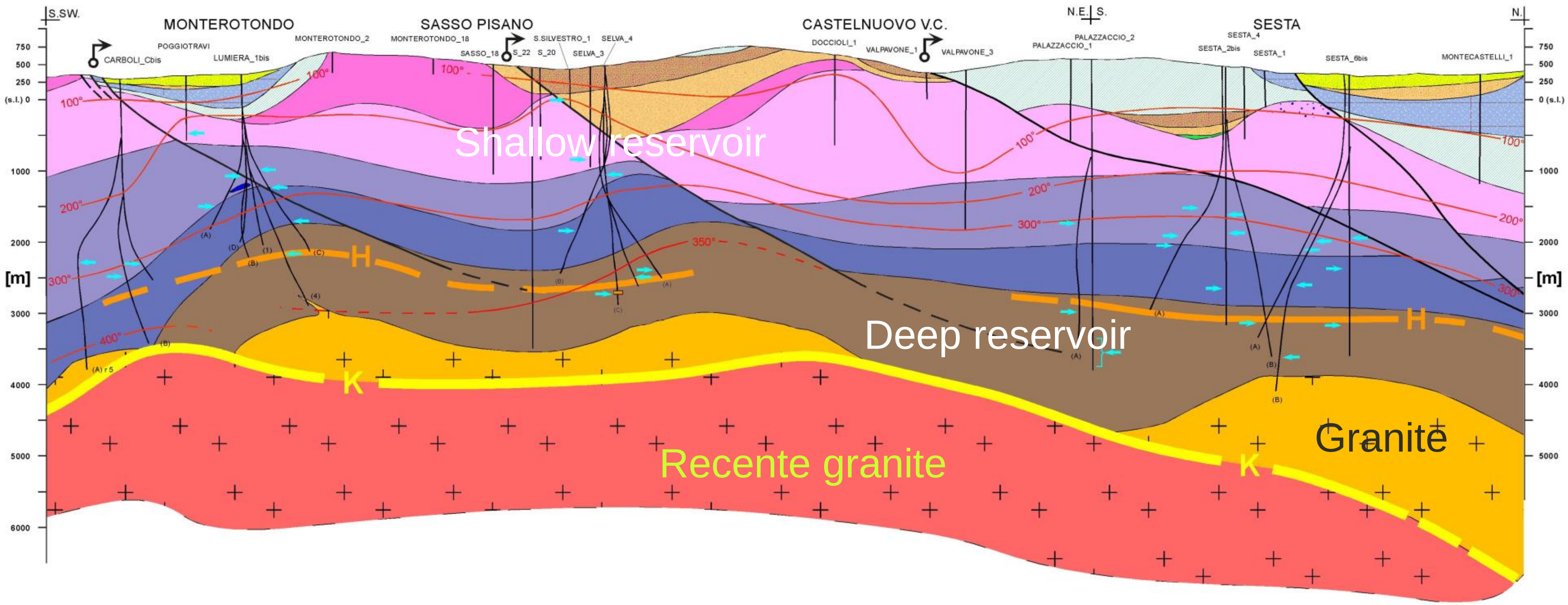
Reservoir's rock types

Variable: sedimentary, intrusive and metamorphic, volcanic

Very complex geological setting, thrust faults and detachment faults, often old fault systems re-activated by recent tectonics. Any kind of rock could be involved.



Neogene units

Ligurian Flysch

Tuscan Nappe

Metamorphic basement

Granite intrusions

Productive fractures

H - K **Seismic reflectors**

150°C **Isotherm**

Manifestations

from Bertini et al., 2009.

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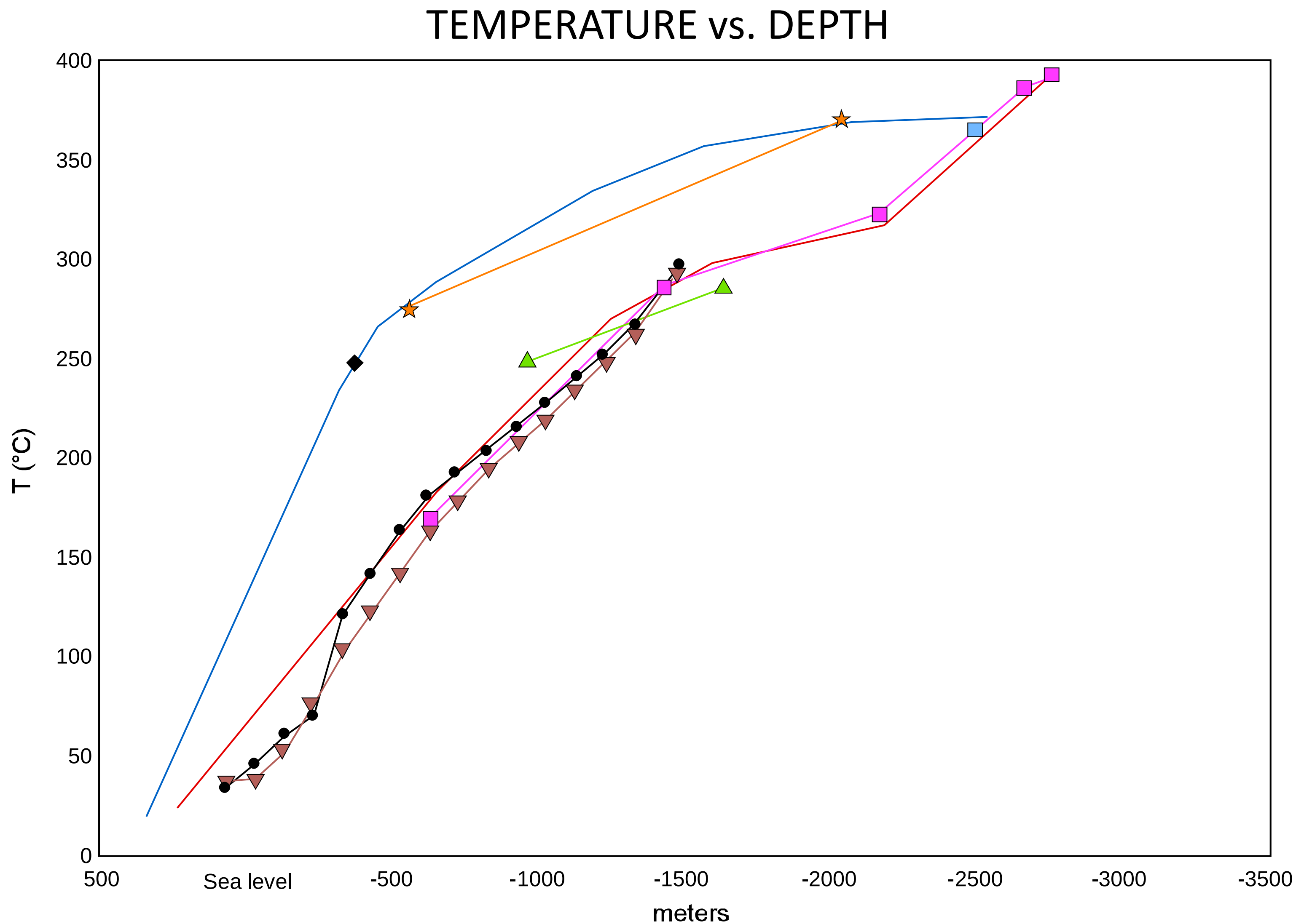
Reservoir’s Temperatures

Usually high at shallow depths

- 150-350 (420°C) in Tuscany
- 150-342°C The Geysers
- Up to 242°C (Kizildere) Turkey



Larderello temperatures

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Reservoir’s depth

Variable

- 400-1500m (shallow) – 1200-4000m (deep) in Tuscany (6-7 MPa)
- 2000m The Geysers
- 600-800m (shallow) – 1500m (deep) in Turkey

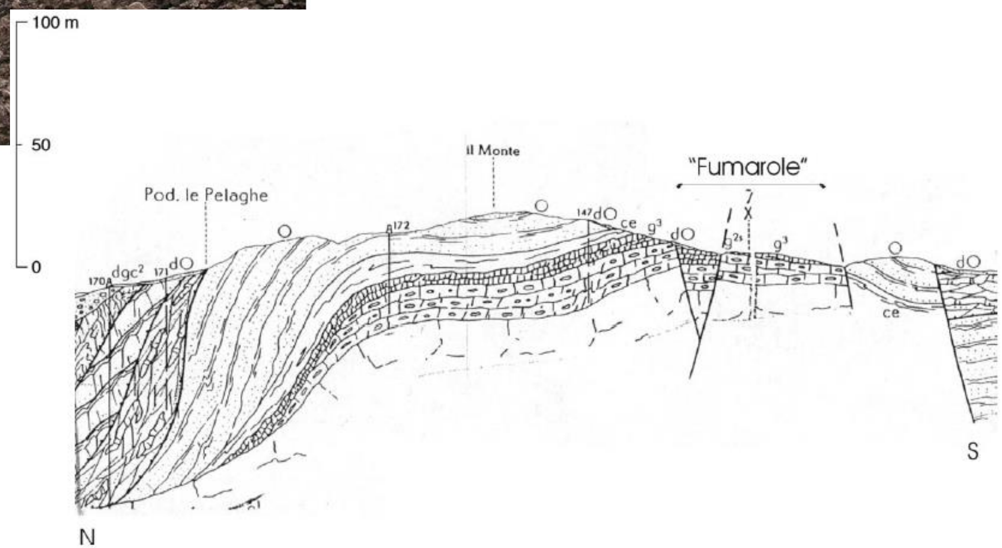
Reservoir's Permeability distribution

Irregular, linked tomain fractures and faults, primary permeability is very low (cristalline rocks)

Larderello: porosity 1.5-3%, matrix permeability 10^{-11} cm^2

Links to tectonic and stress regimes: clearly so, but details are still unclear in most cases

Fig. 5.7 - The fumaroles at Monterotondo Marittimo in the "Biancane" locality.



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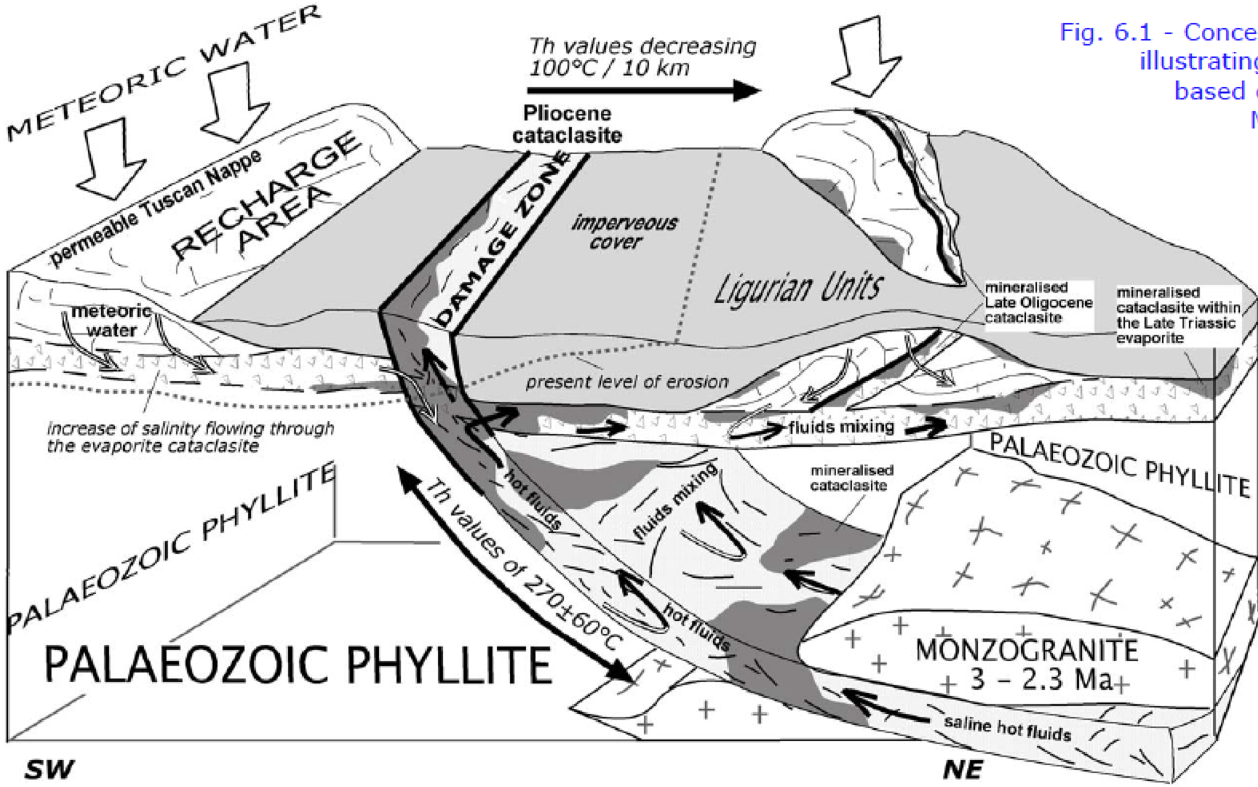

Fig. 6.1 - Conceptual cartoon, not to scale, illustrating the path of the fluid flow, based on the results of our study. Meteoric water infiltrated to depth through the damage zone of the Boccheggiano fault and trough the permeable Tuscan Nappe fractured and porous rocks. At depth, down to the monzogranite, heating and mixing with deep fluids originated hydrothermal mineralizing fluids, upflowing toward the surface and pervading the existing cataclasites and locally mixing with meteoric water (From Liotta et al., 2010).

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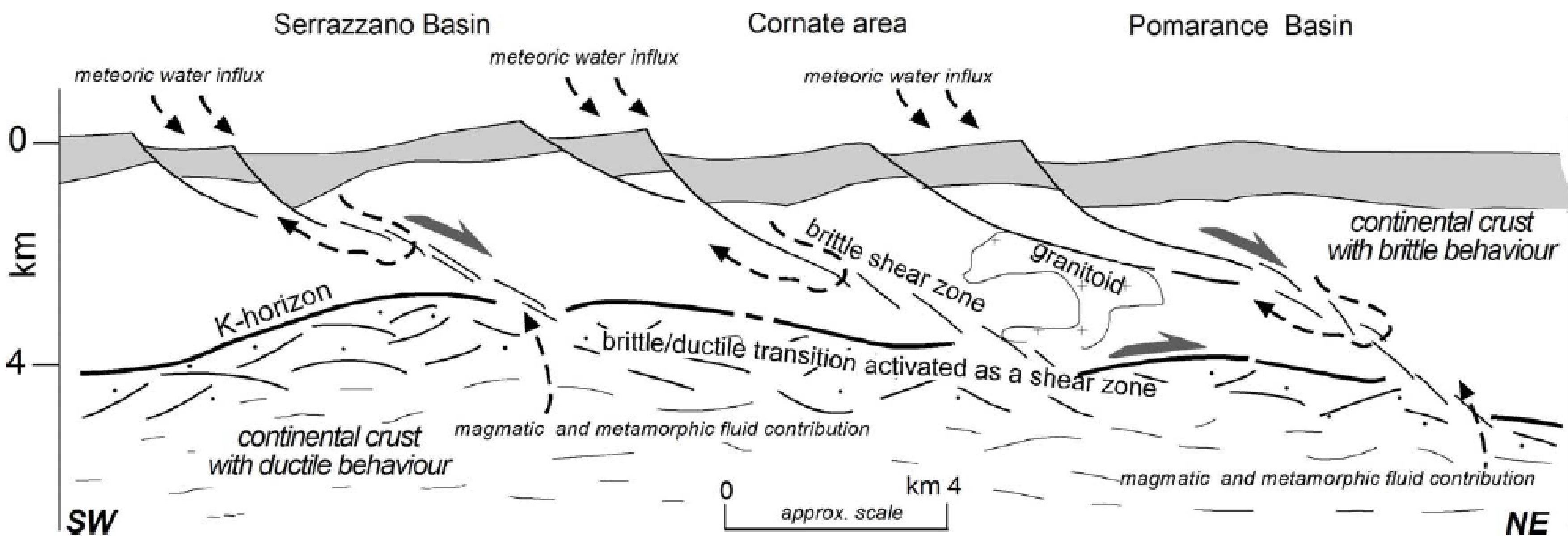

Fig. 6.2 - Geological interpretation of the Larderello geothermal area. The extensional shear zones and the top of the brittle-ductile transition are shown (thick arrows indicate the sense of shear). The shear zones act as hydraulic channels where geothermal fluid circulation is enhanced (dashed arrows). These shear zones are exploited and named as deeper reservoir. Light grey: sedimentary cover; the Calcare Cavernoso Fm. is located at the base of the sedimentary cover including the Upper Triassic evaporites at its base. In this level structural traps hosting geothermal fluids are located. An already cooled granitoid is delimited at the top by extensional structures.

from Bellani et al., 2004.

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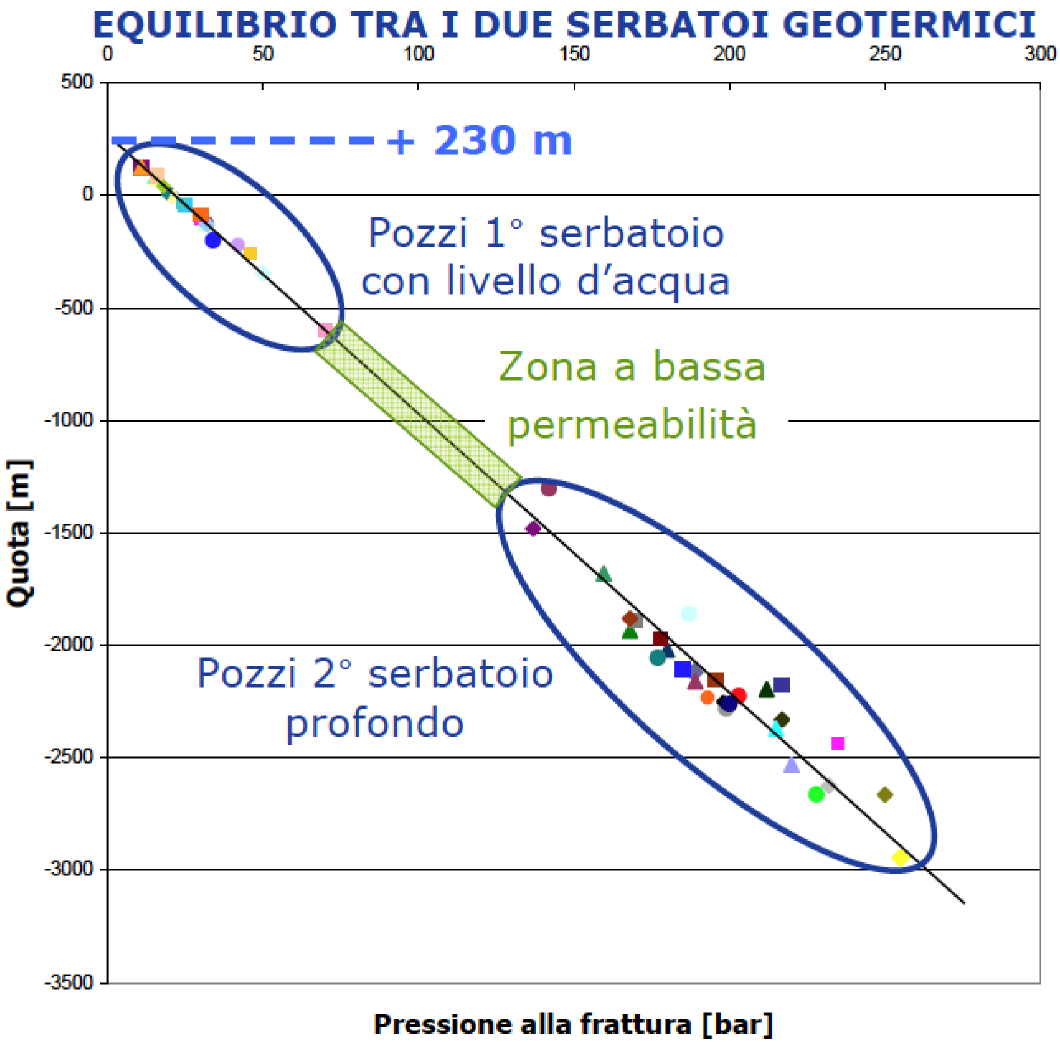
Same Fluid from the Shallow and Deep Reservoir Rocks

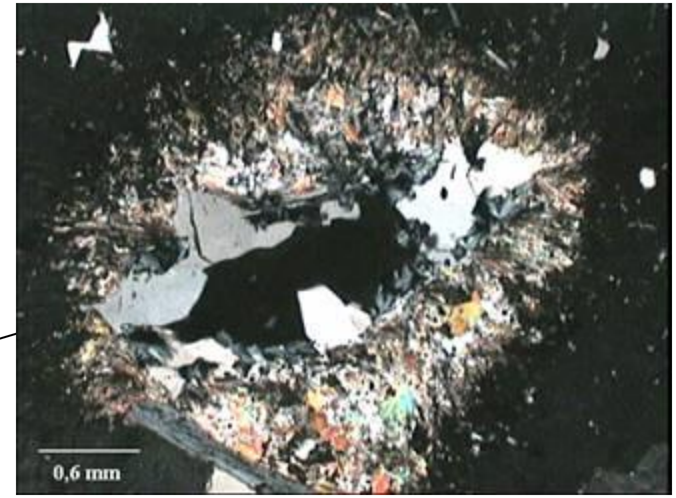
The composition of the geothermal fluid is remarkably constant: isotopic imprint characteristic of a meteoric origin, same gas/steam ratio (5wt% of gas, mostly CO_2) in all drillholes and different reservoir composition (from Mesozoic dolostone to granite).

This almost constant composition of the fluid, over a drilled area of approximately 400 km^2, supports the hypothesis of the presence of a giant reservoir.



from ENEL, 2008.

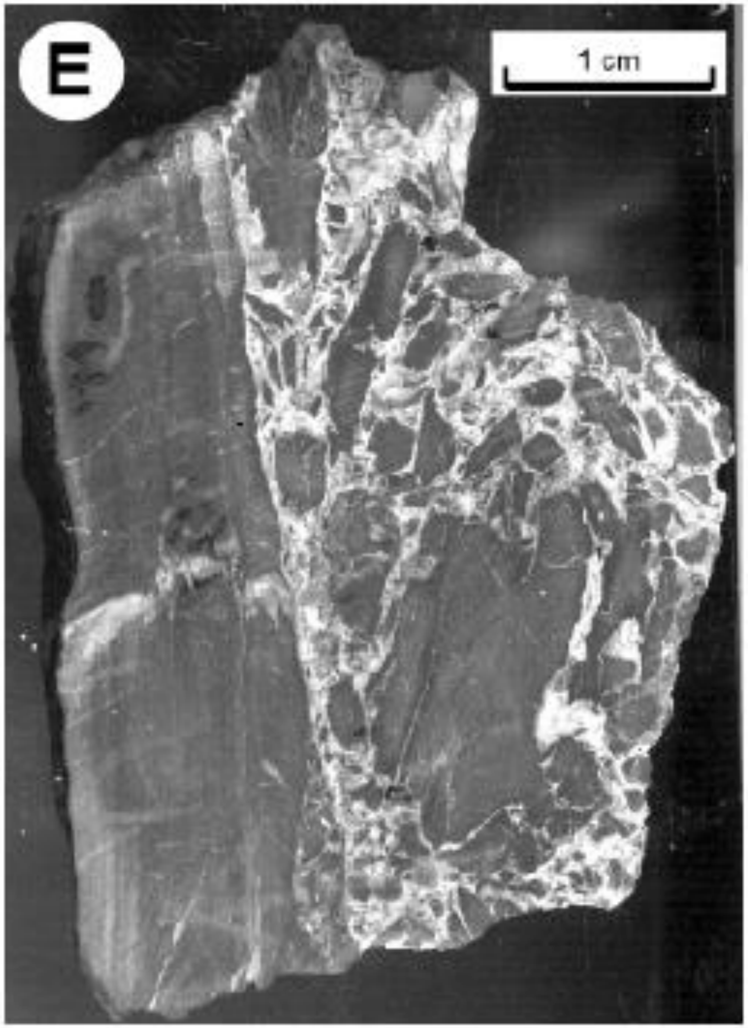
GRANITE AS A GEOTHERMAL RESERVOIR



from Gianelli, 2008.

PERMEABILITY

Hydraulic and tectonic fracturing can enhance permeability of rocks with very low porosity



from Gianelli, 2008.

Differences and similarities

- How does your play differ or have similarities to other plays?

The scenario is tectonically so complex that similarities are possible with other settings. Permeability is usually different (linked to fractures and faults)

Exploration methods

- Geological: structural geology for regional tectonic features
- Geochemical: geothermometers, fluid origin
- Geophysical: heat flow, gravimetry, resistivity methods, **seismic**
- others remote sensing

At what stage do you see drilling be introduced as an exploration tool? Late stage

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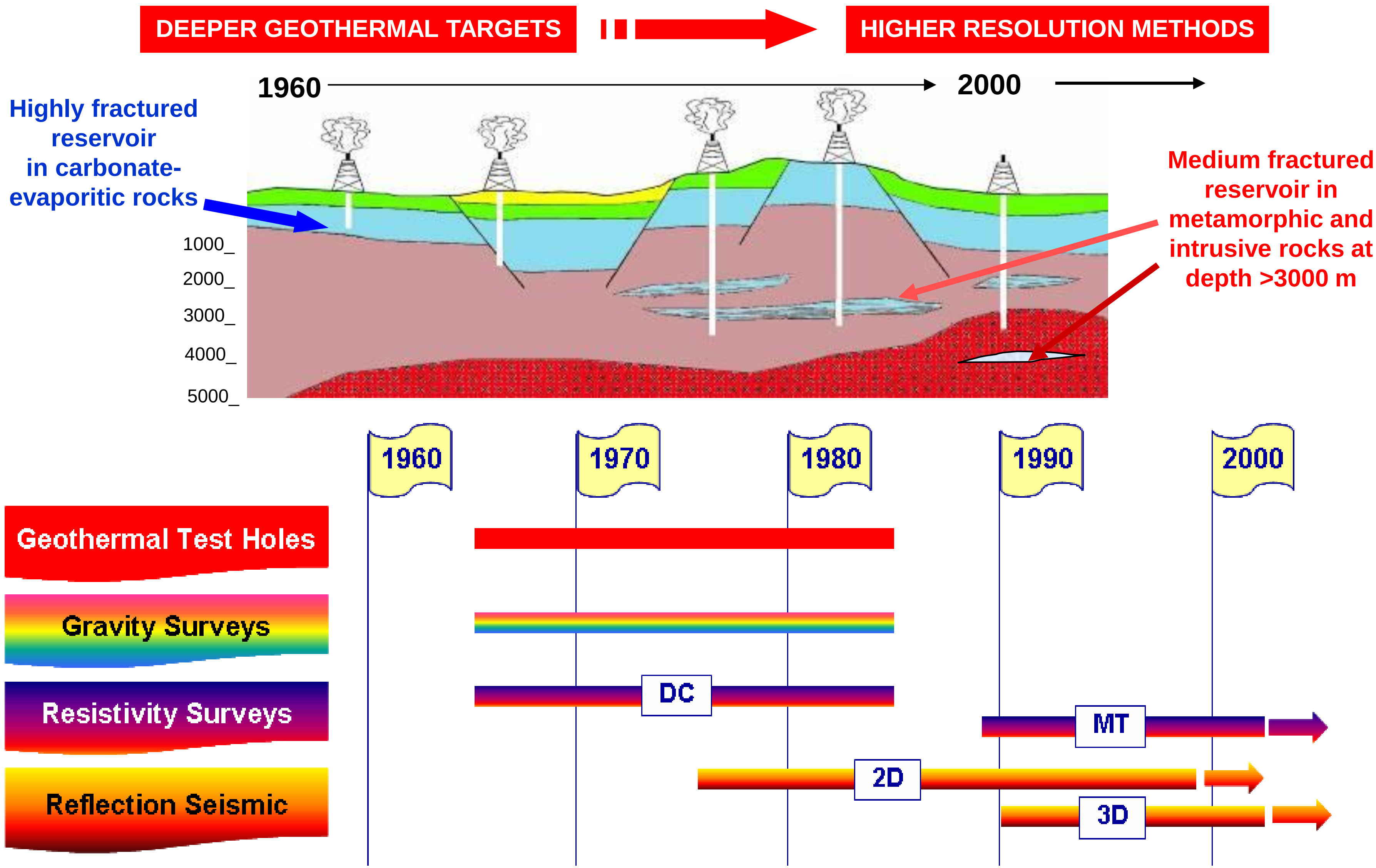
Geophysical Exploration Methods – Time evolution

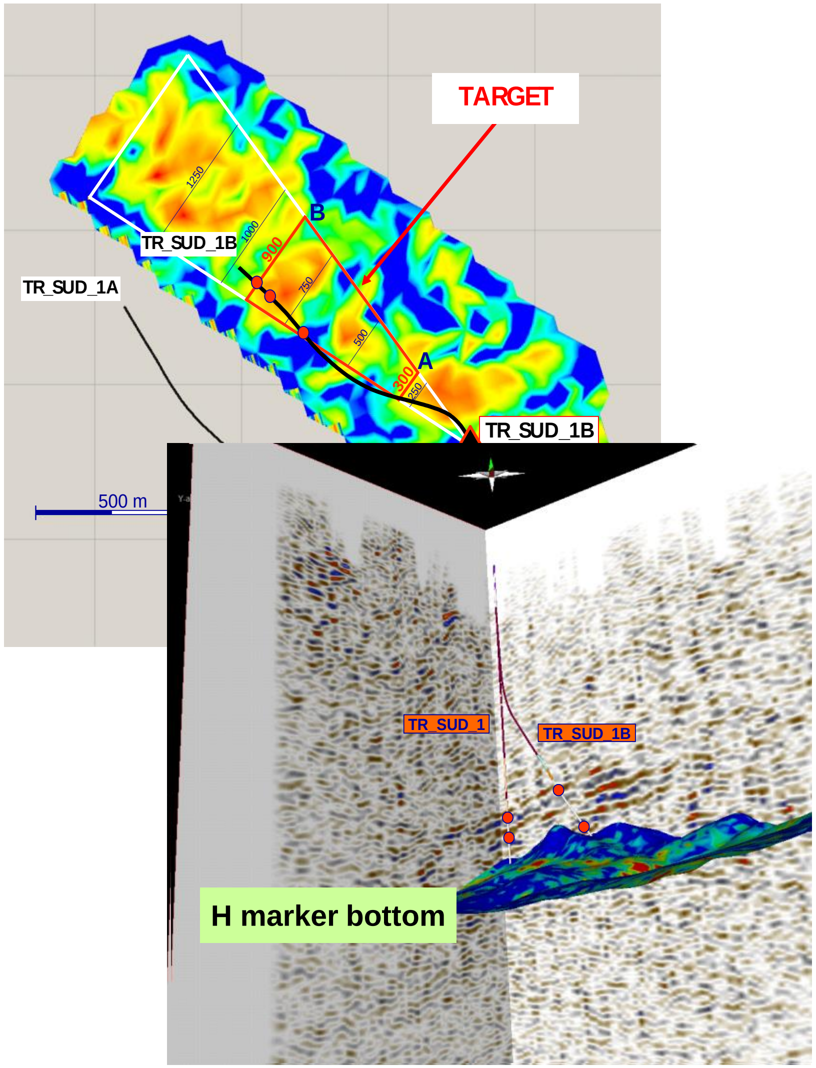


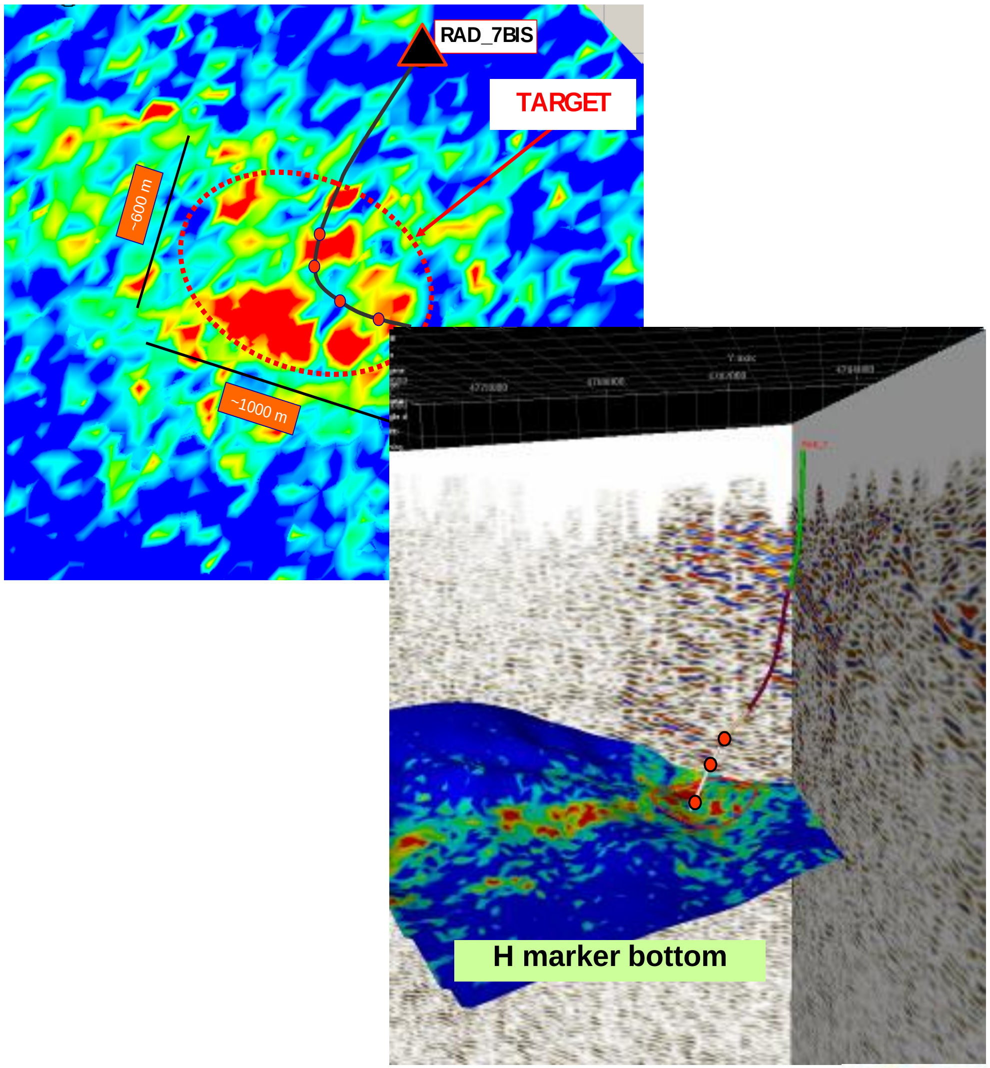
Courtesy of Enel

Exploration Methods – 3D Seismic surveys (first results)

Well target - Drilling Project – Drilling Execution – Drilling Result

Fractured levels





Courtesy of Enel

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