

Exploring for geothermal energy

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Module 3 - geothermal energy



Conceptual model of a high temperature

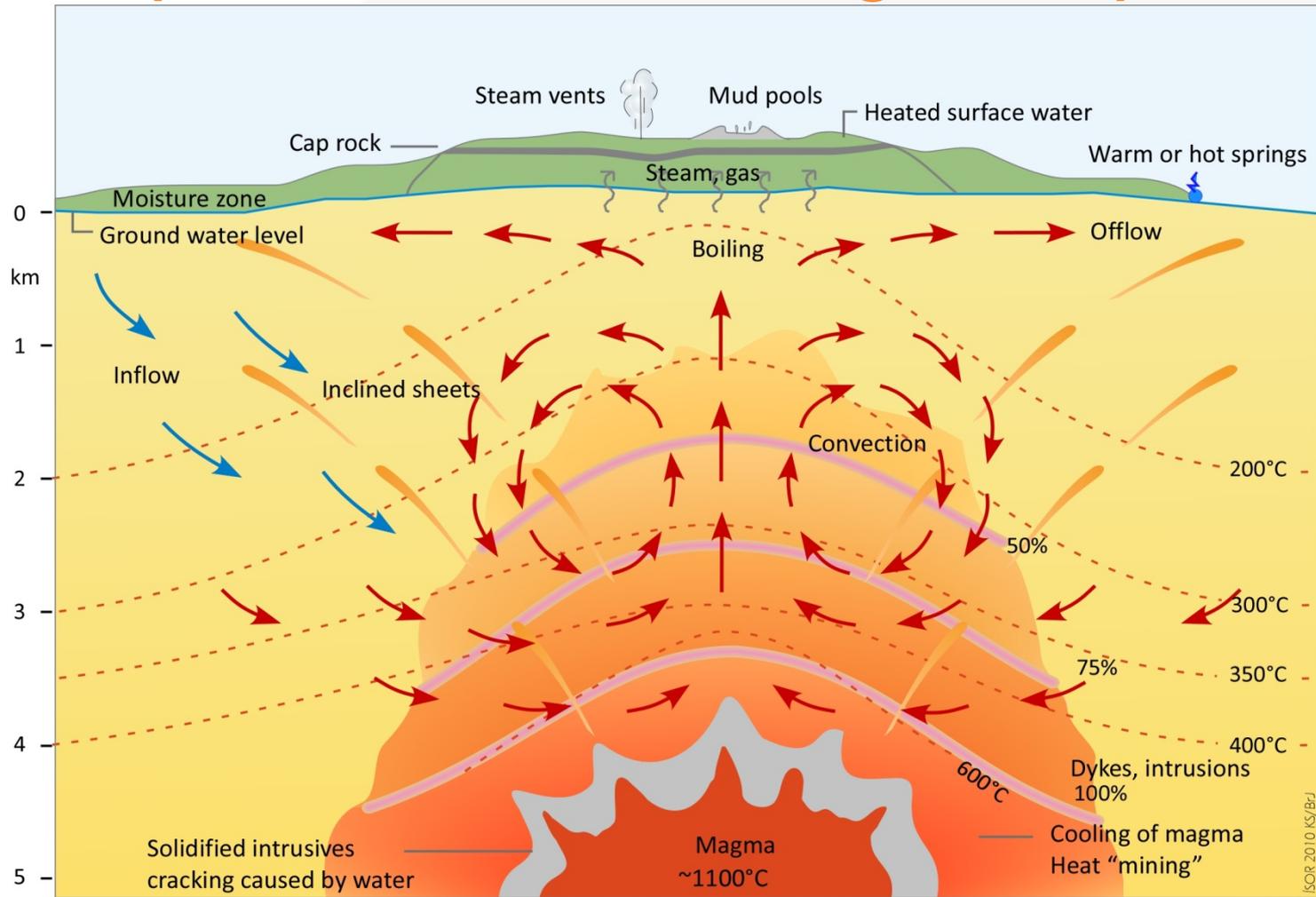


Figure: Kristján Sæmundsson, ÍSOR ©

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We need careful exploration:

- A deep exploration borehole in a high temperature field can cost several million USD.
- The total cost of geo-scientific exploration is only a part of the cost of one such well.
- However, exploration requires considerable up-front cost prior to exploration drilling. Therefore:
 - Exploration methods must be selected with respect to the site
 - Exploration must be carried out in professional manner
 - Stepwise approach is recommended, i.e. the strategy must be revised as the results appear.

Scales of Exploration:

- **Regional exploration:** Exploration covering large area in order to identify possible geothermal resources and roughly assess their size.
- **Local exploration:** Exploration that concentrates on the interior of a known geothermal field in order to identify the best production sites and target for drilling to obtain maximum energy output with minimum cost.

The selection of exploration methods

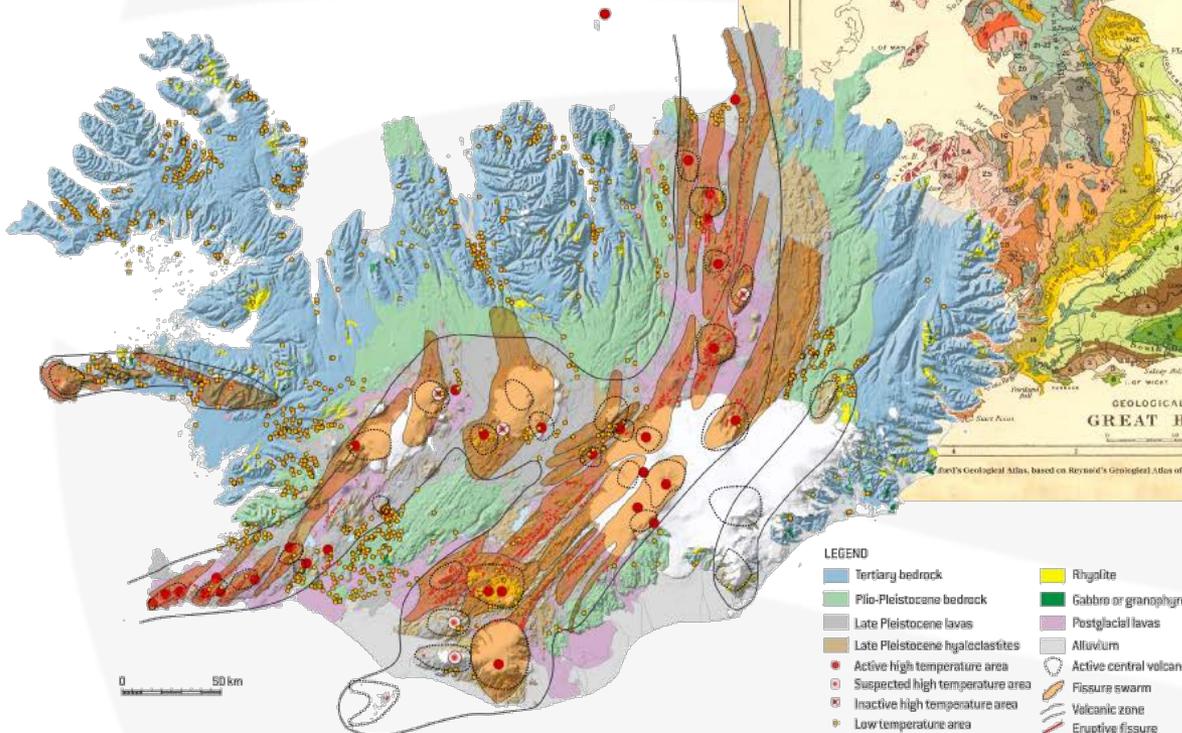
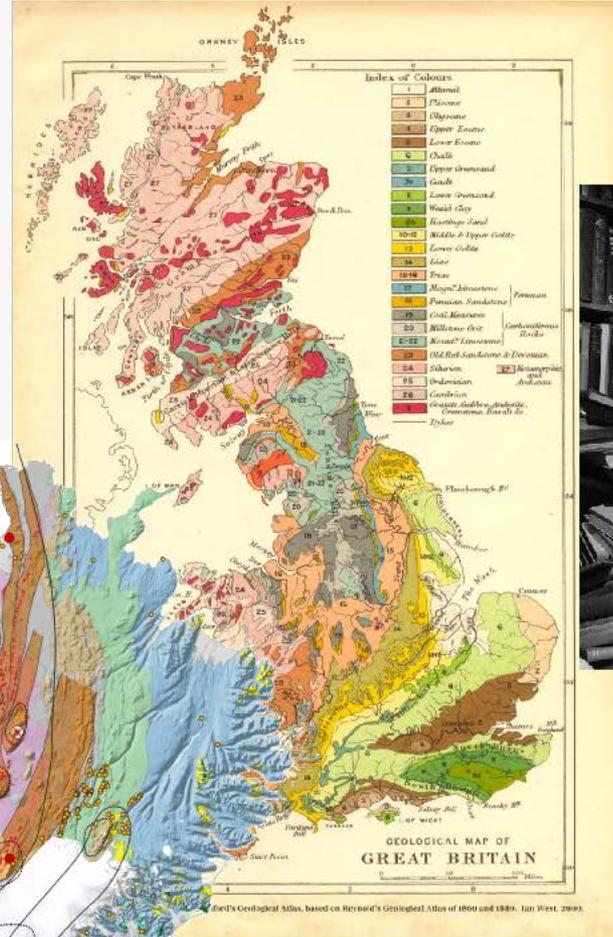
- The geology of geothermal fields are quite variable from one place to another.
- There is no single exploration procedure that can be applied universally to all geothermal fields.
- The selection of exploration methods must be tailor-made for each field.
- But we have guidelines to form suitable exploration strategy for each field.

Regional exploration – The first 3 phases of geothermal development

1. Review of existing data
2. Reconnaissance
3. Geological Exploration
4. Geophysical Exploration
5. Exploration Drilling
6. Preliminary Resource Estimate

These studies end in a pre-feasibility report

Step 1. Review and study available data



Step 2: Reconnaissance

- Desktop study of all available data
- Field studies:
 - Visual studies, maps, photographs (infra red)
 - Mapping of the manifestations
 - Temperatures and flow rate
 - Mapping of soil temperatures
 - **Fluid sampling and analyses (geo-thermometers, fluid chemistry)**
 - Historical data on activity and utilization
- Ownership and rights (licensing)
- Environmental aspects (EIA)
- Social aspects
- Market possibilities

Are there market opportunities in developing the area?



Mapping of manifestations,
temperature and flow-rate.

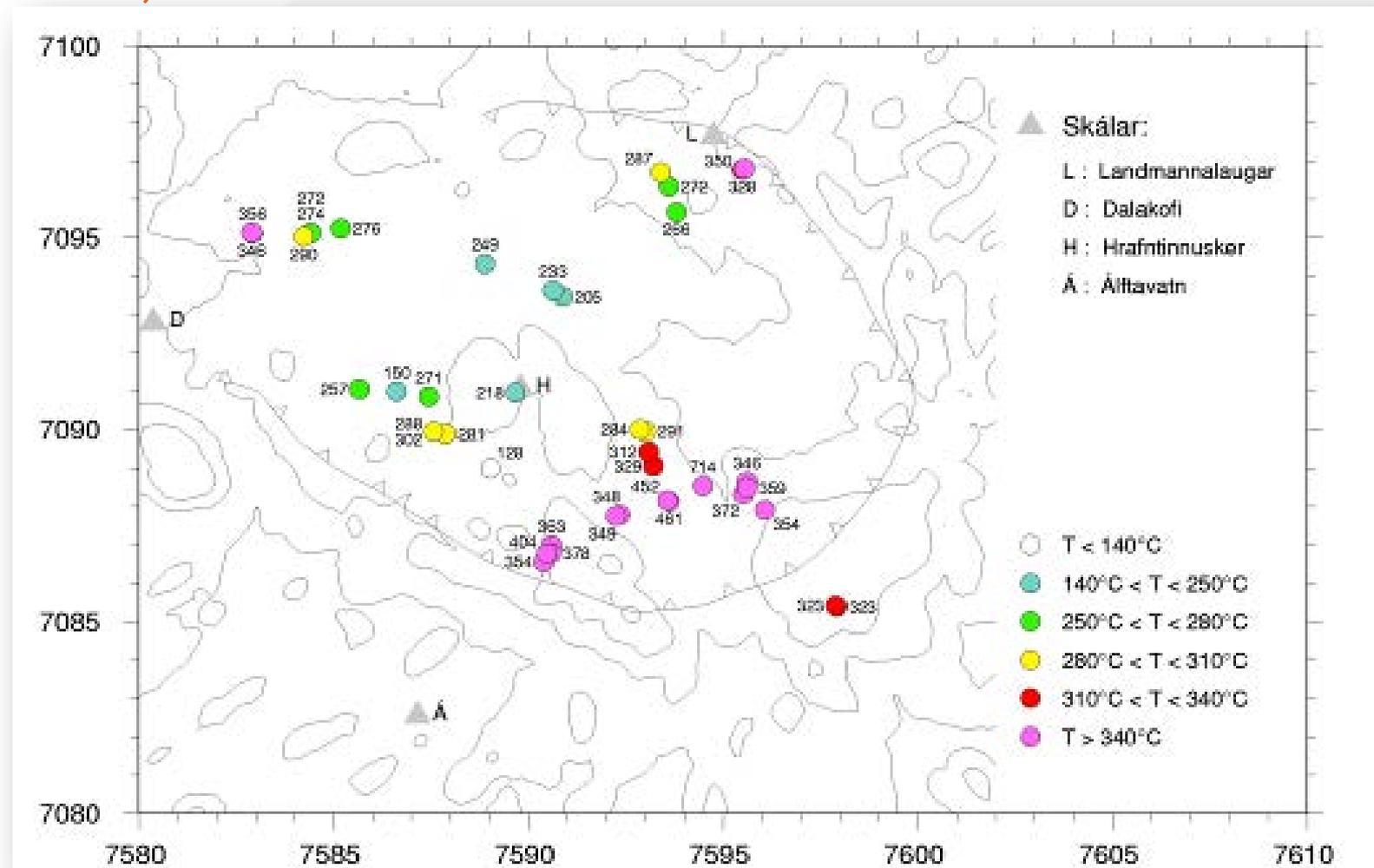
Mapping of soil temperatures

Chemical analysis of springs and
gas from steam vents gives
information on reservoir
temperatures.

Geothermometers:

- If we have access to the geothermal fluid through hot springs, steam vents or borehole we can take samples for chemical analysis
- From the results of the analysis we can calculate and estimate the likely temperature in the underlying reservoir.

Geothermometers: CO₂-temperature map of Torfajökull geothermal system, Central Iceland



Step 3: Geological Exploration

- Geological mapping (lithology).
- Structural geology (faults, fractures, dykes).
- Volcanology and volcanic history.
- Hydrogeology.
- Geo-hazards and environmental geology.

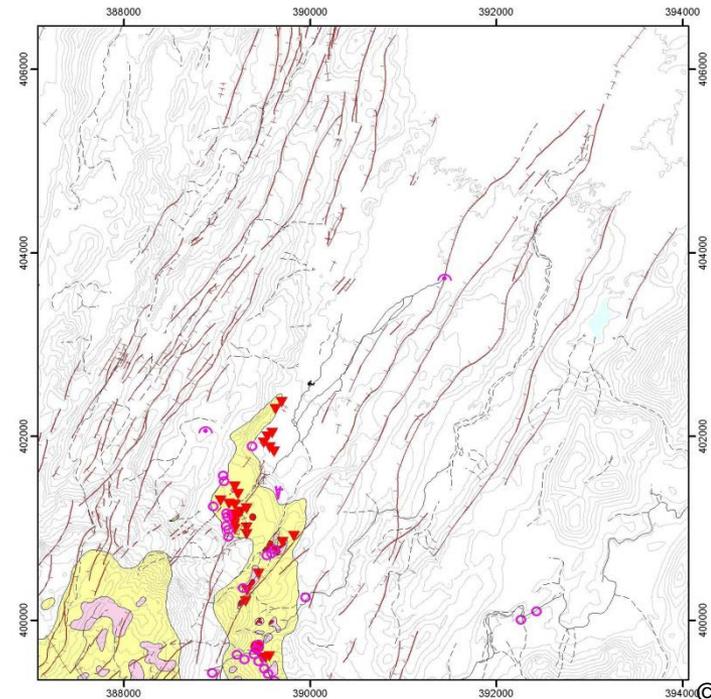
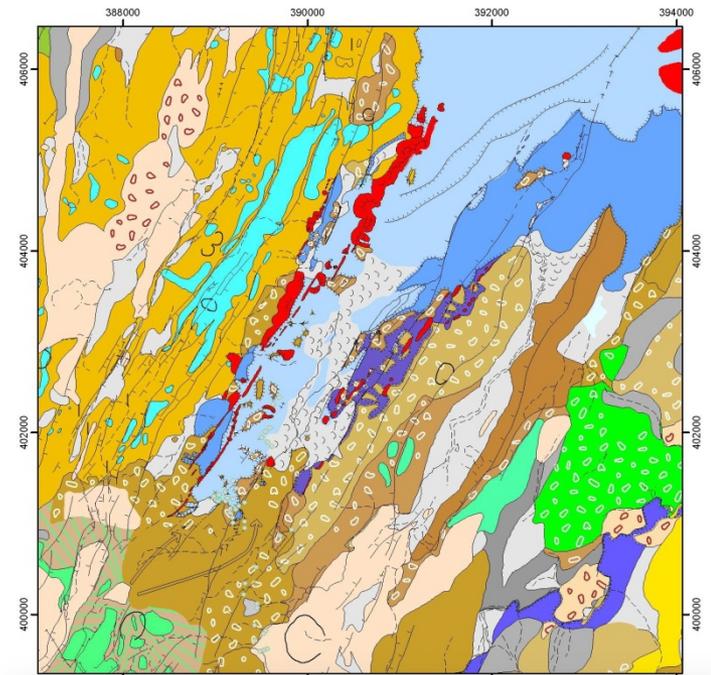


Does the surface activity relate to geological structures ?

Geological maps:



The Nesjavellir field (above).
Lithological units (right corner).
Geothermal map: Tectonic fractures, surface manifestations and alteration (to the right)



Geological maps are basis for environmental assessment:



Special geological phenomena that must be protected

The risk for geological hazards like eruptions and earthquakes is based on evidence of these events in the field, estimate of their timing and frequency, seriousness and likely effects on power plants.



Step 4: Geophysical Exploration

- **Resistivity** – TEM (0 -1 km) & MT (0-25 km)
- Micro seismicity (2 - 10 km)
- Heat flow
- Gravity
- Magnetics (dykes, faults)
- Seismic reflection (only in sedimentary rock)

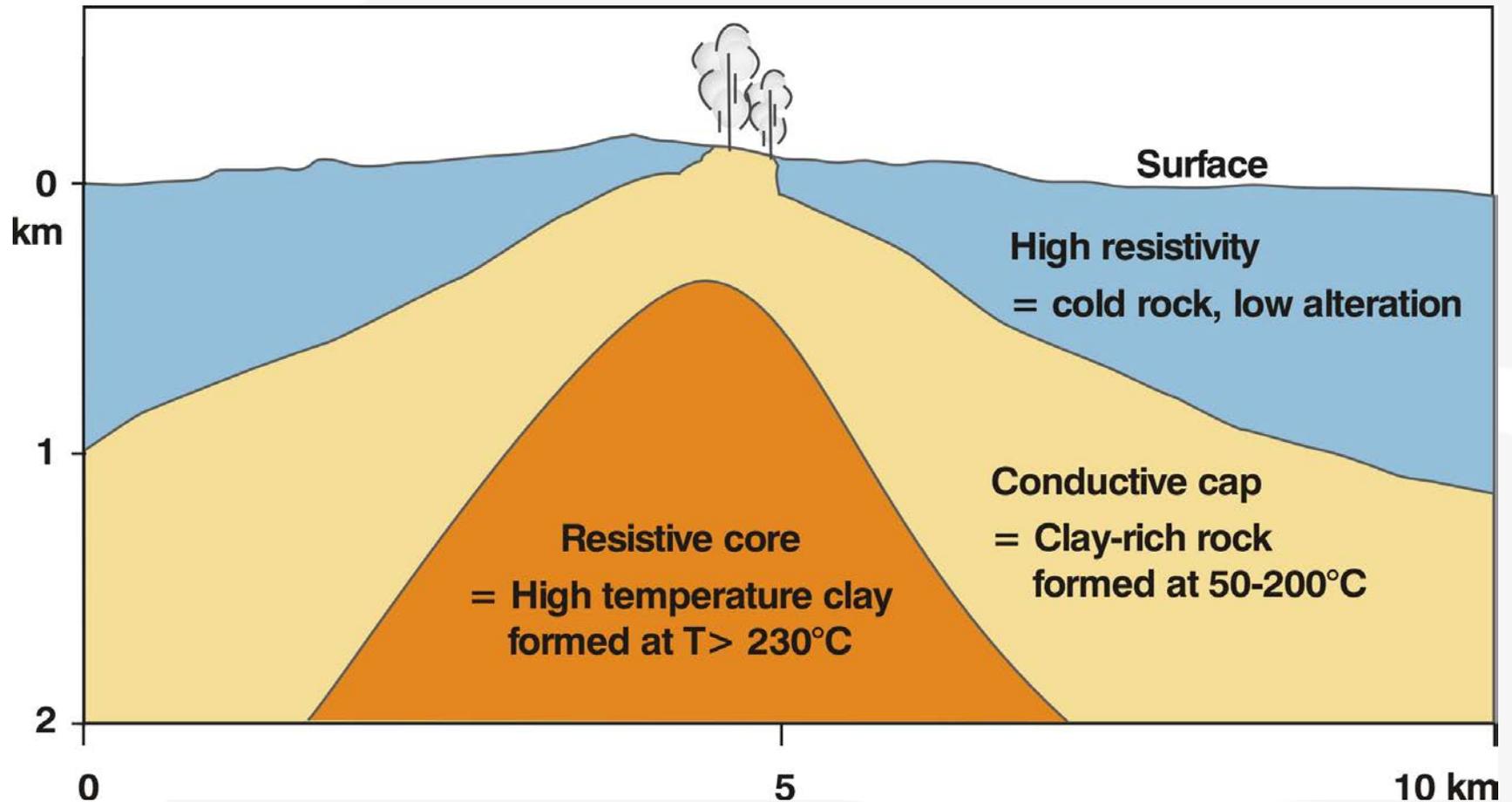
How big is the active resource and selecting the drilling targets.

The important resistivity measurements

- The best available geophysical method.
- The only method that is sensitive to geothermal properties of rock.
- Two main types, TEM and MT, should be used together.
- Has limitations and pitfalls must be avoided



Resistivity structure of a typical simple high temperature field:



Important to know:

The resistive core shows a volume where temperature has reached at least 230°C for some period of time during the geological history of the geothermal field.

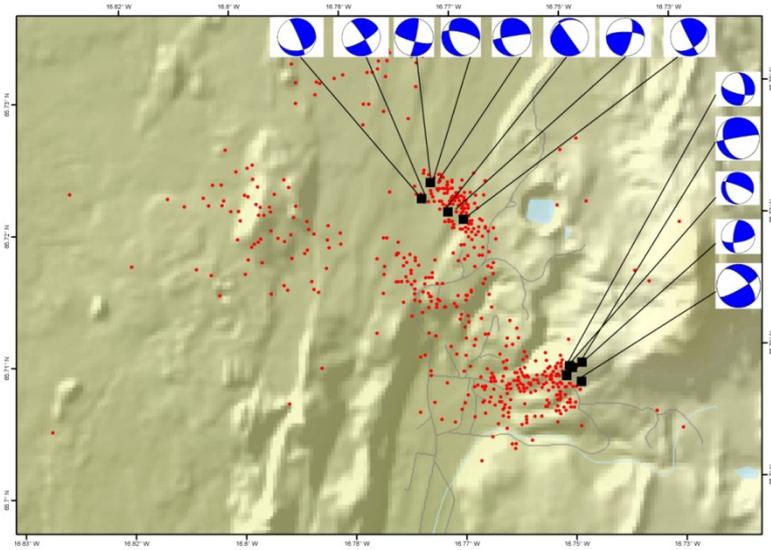
It is not necessarily so hot to-day: If the hot resistive core cools down the resistivity will not lower correspondingly. This must be tested by drilling.

Hence the resistivity do not tell us where to drill to obtain 230°C – but it tells us definitely where not to drill.

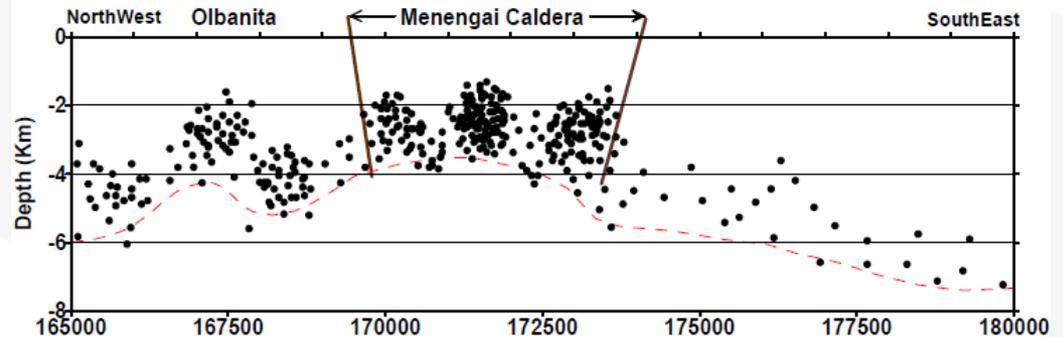
New or improved exploration methods are needed to predict temperature variations within the resistive core.

Micro-seismicity

- Gives information about location of active faults.
- Helps to define drilling targets.
- Can show location of magma bodies.
- Can give information on the elastic crust.
- Can show fluid flow in fractures.



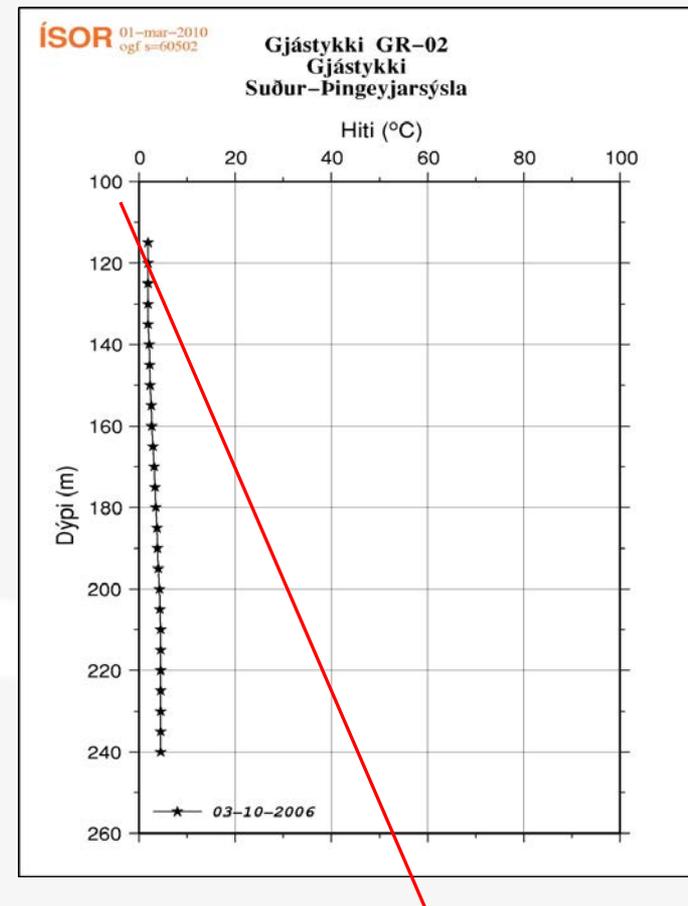
Distribution of microearthquakes and focal planes in Krafla geothermal field, Iceland



Earthquake section through Menengai, Kenya

Heat flow

- Measurement or temperature gradient in shallow boreholes.
- The heat flow must be conductive not convective
- Most high temperature fields are covered by thick permeable formation that make heat flow studies impossible or expensive.

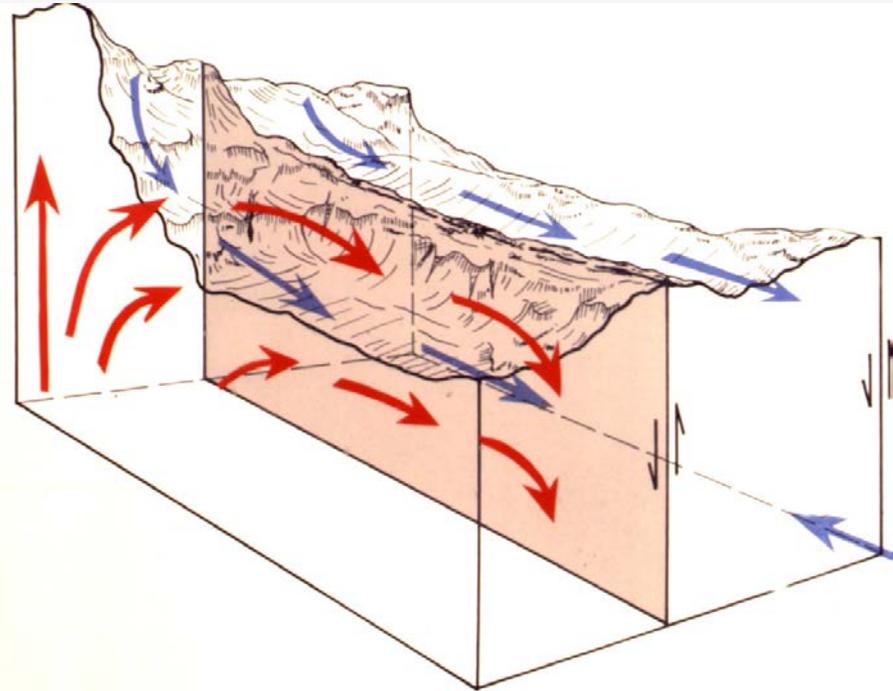


Temperature logs from a high temperature reflecting fluid flow in permeable rock. The red line show the expected conductive heat flow if 240°C is expected at 1 km depth

Information gained from Surface Exploration

(Preliminary geothermal model)

- Estimation of the size of the geothermal resource and its exploitable thickness:
- Estimation of the reservoir temperature
- Expected reservoir fluid chemistry
- Definition of drilling targets and type of exploration wells to be drilled
- The information should be incorporated into a preliminary conceptual model of the field.
- Volumetric assessment made to get a first estimate of the power potential of the resource.



From the exploration results we can make rough assessment of the size of the resource

The surface exploration can give the maximum volume of the geothermal reservoir.

The first approach to evaluate the resource is to carry out a volumetric assessment of it.

It can be done by applying rules of thumb or by more precise volumetric assessment based on statistical methods.

If all results are positive we go for the next step, the exploration drilling.

Result from the first four steps:

Preliminary conceptual model.

Selected site and design of exploration wells (shallow, intermediate or deep wells).

Step 5: Exploration Drilling (sub-surface exploration)

- Testing the results of the resistivity exploration
- Confirming/updating the conceptual model
- Confirming the temperature estimation of surface sampling
- Confirming the chemical composition of the brine
- Confirming the existence of a geothermal resource
- Flow-testing the reservoir
- Update the reservoir model

Is it likely that the geothermal resource is exploitable, and what kind of power plant is viable?

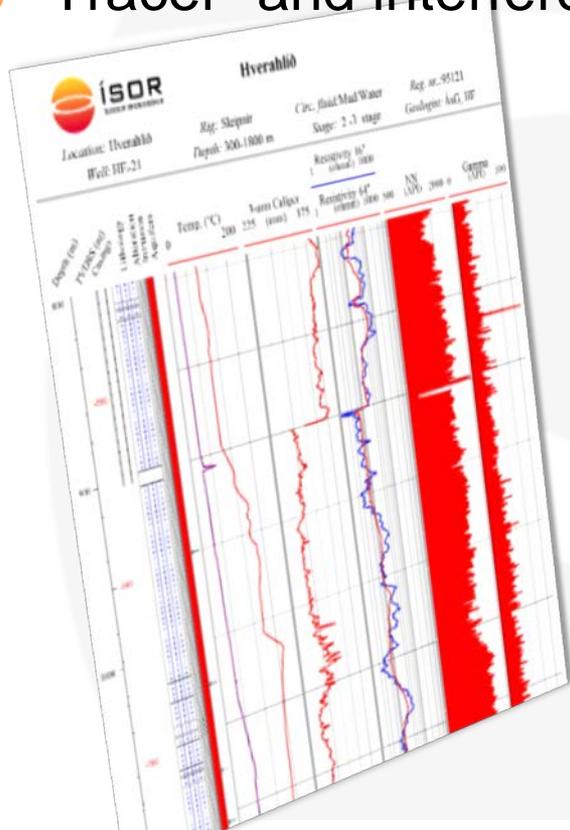
Additionally to drilling

- Well siting
- Well design
- Drilling supervision
- Mud logging
- Borehole logging
- On site geological consultancy

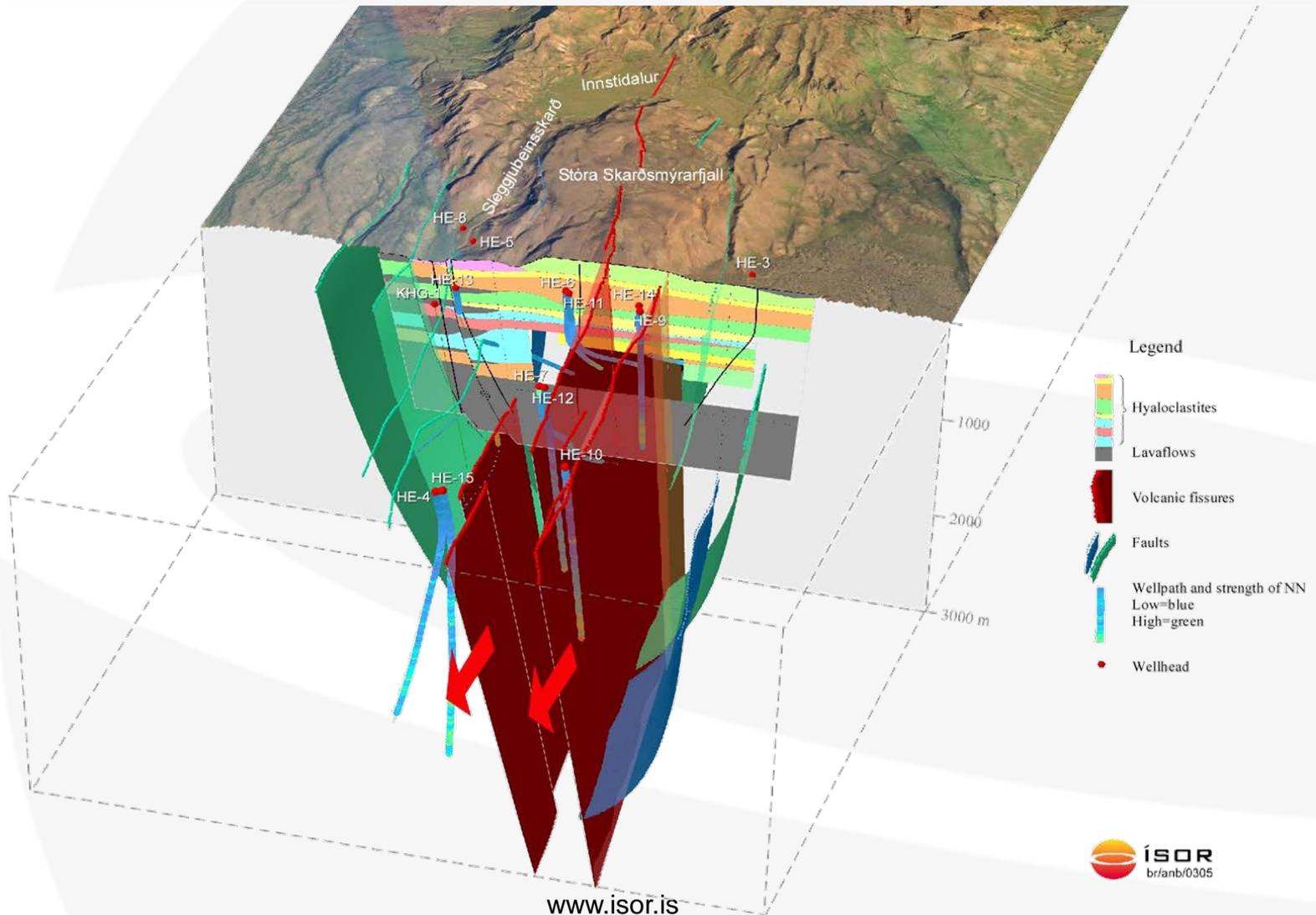


Well testing of exploration wells

- Temperature- and pressure logging
- Injection- and flow testing
- Well stimulations
- Tracer- and interference testing



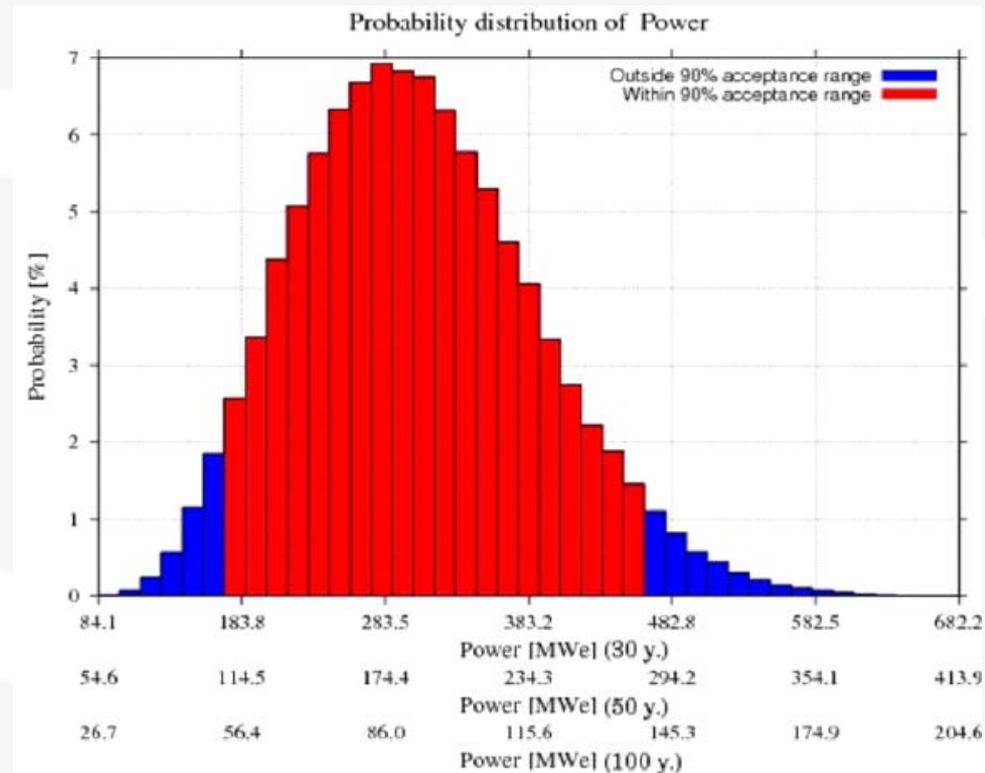
Step 6. Preliminary Resource Estimate and updating the conceptual model.



Volumetric assessment

The first approach to evaluate the resource up on completing the surface exploration is to carry out a volumetric assessment of the resource. This assessment is improved by the information gained from the exploration drilling, often by applying Monte Carlo statistics to the volumetric assessment.

Statistical sizes	Values [MWe] (30 y.)	Values [MWe] (50 y.)	Values [MWe] (100 y.)
Most probable value (with 7% probability)	275-290	165-175	85-90
90% confidence interval	170-460	100-270	50-140
Mean	300	180	90
Median	300	180	90
Standard deviation	80	50	20



Regional exploration - concluding remarks

- It is our experience that the investment in executing a thorough surface exploration program is money well spent
- One failed well due to negligence in exploration can cost several times the cost of the surface explorations
- Surface studies should therefore have high priority in all geothermal exploration programs
- **Regional exploration and exploration drilling ends in a pre-feasibility report, with some preliminary power plant designs.**

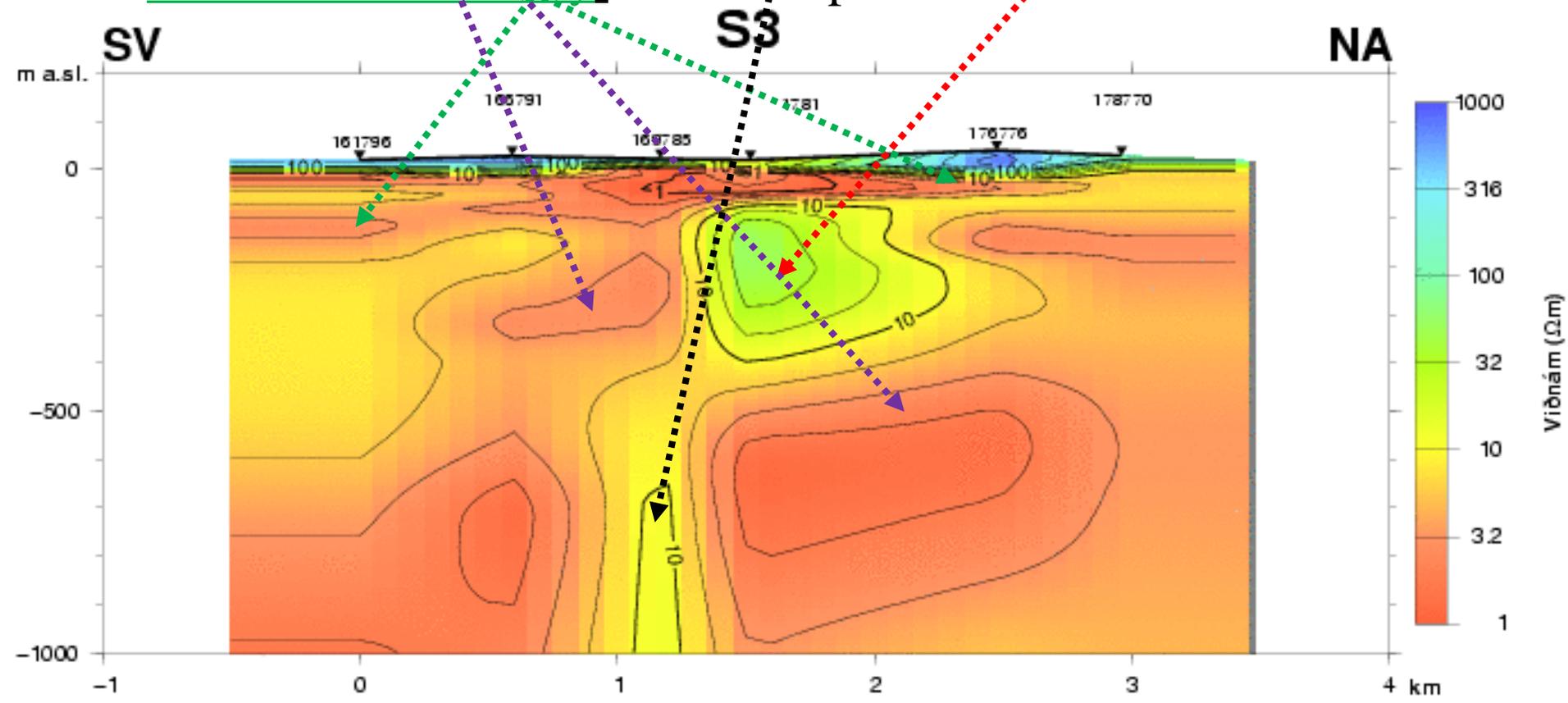
Local exploration:

- If regional exploration is successful further development takes place.
- Local exploration is necessary to define drilling targets in order to maximize the energy output from new wells:
 - Find the up-flow zones of the
 - Find permeable fractures
 - Find fault zones and intrusions
 - Find cooling magma bodies

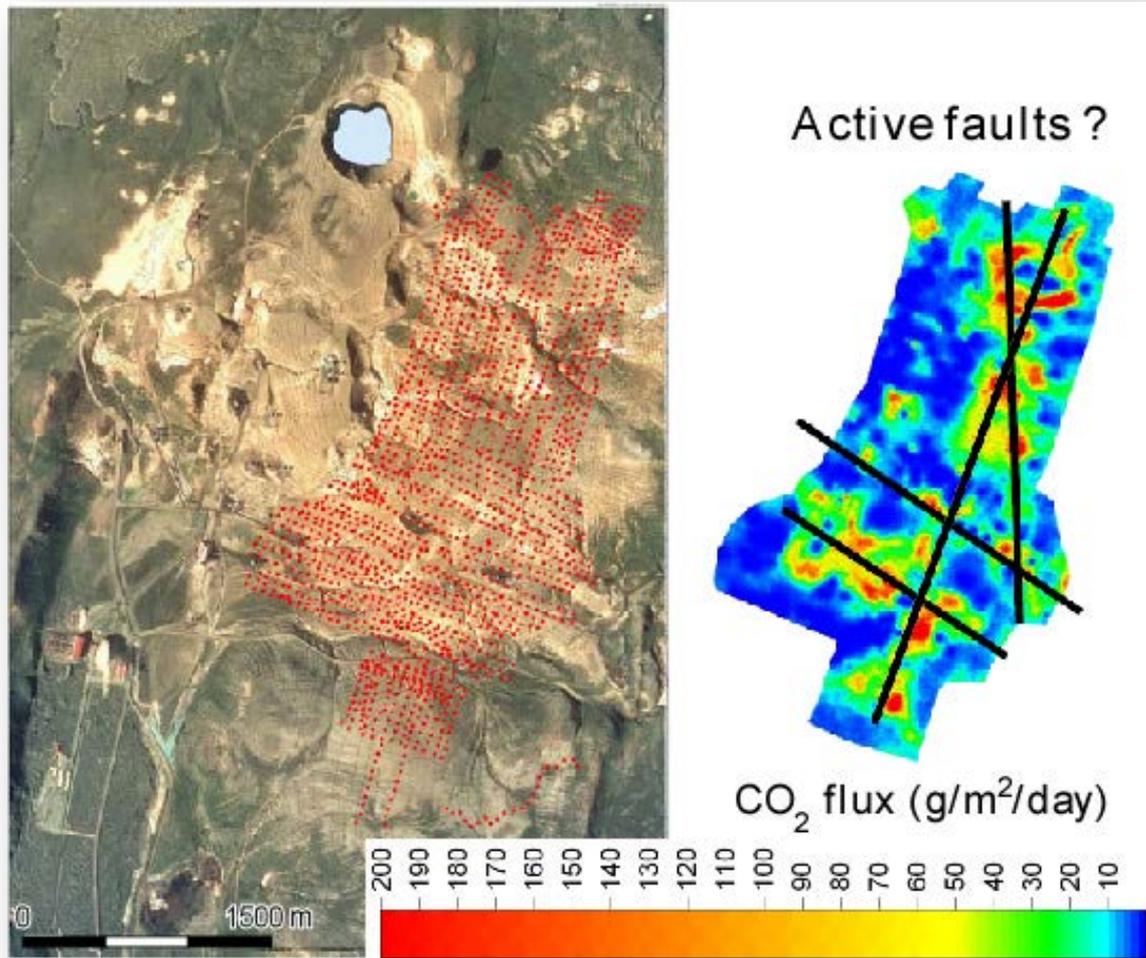
Local exploration requires several methods:

- Densely spaced resistivity soundings, preferably three dimensional interpretation.
- Detailed fracture mapping close to the drill site.
- Micro-seismic studies, before drilling, and during drilling and well tests or stimulation.
- Well logging and borehole geological data.
- Gravity or magnetic studies.

Resistivity section from Reykjanes high temperature field showing a conductive cap, a resistive core, shallow high resistivity below the steam vent area (boiling?) and possible horizontal flow away from the up-flow zone.

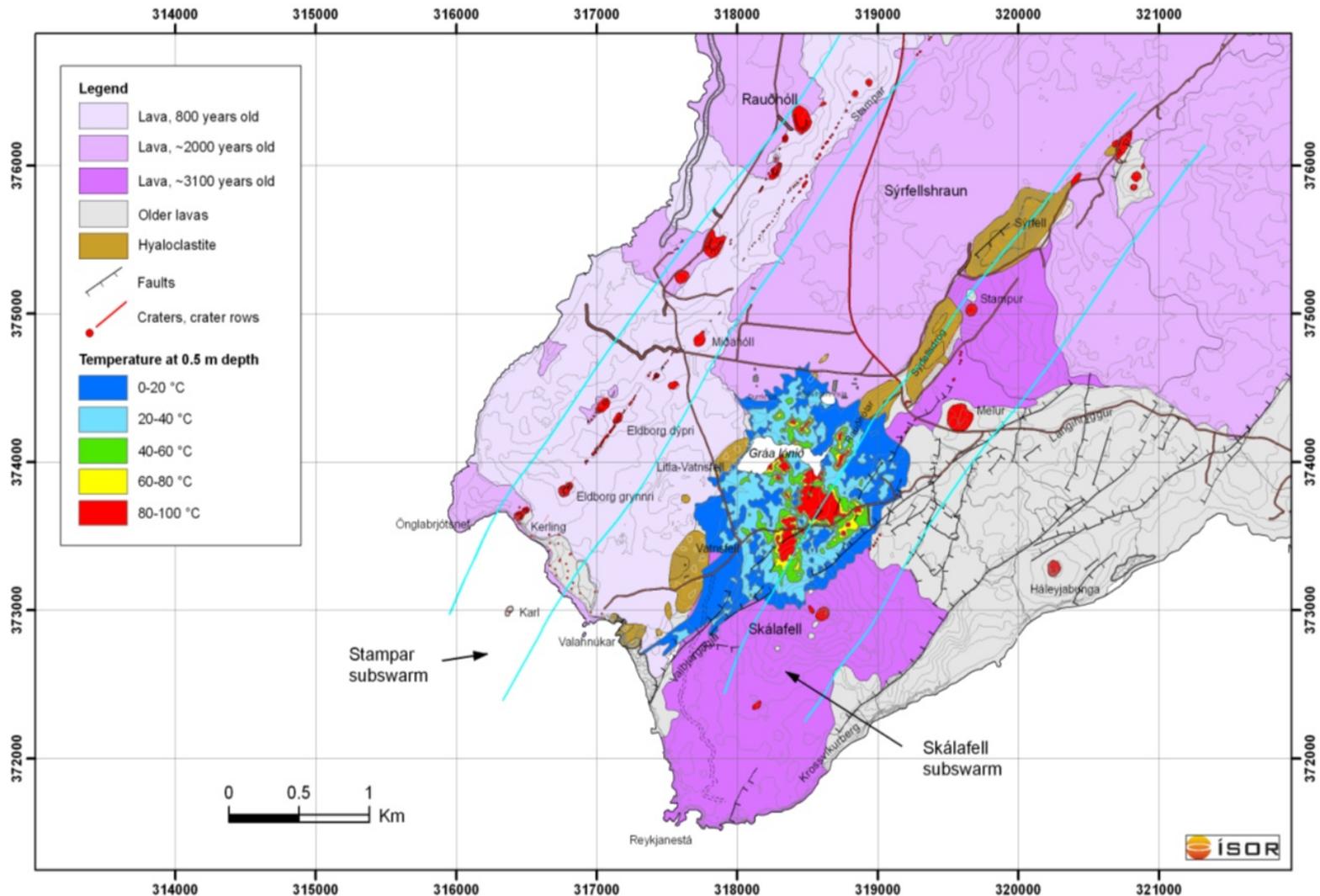


Detailed fracture mapping



Gas flux measurements in the field showing underlying fractures.

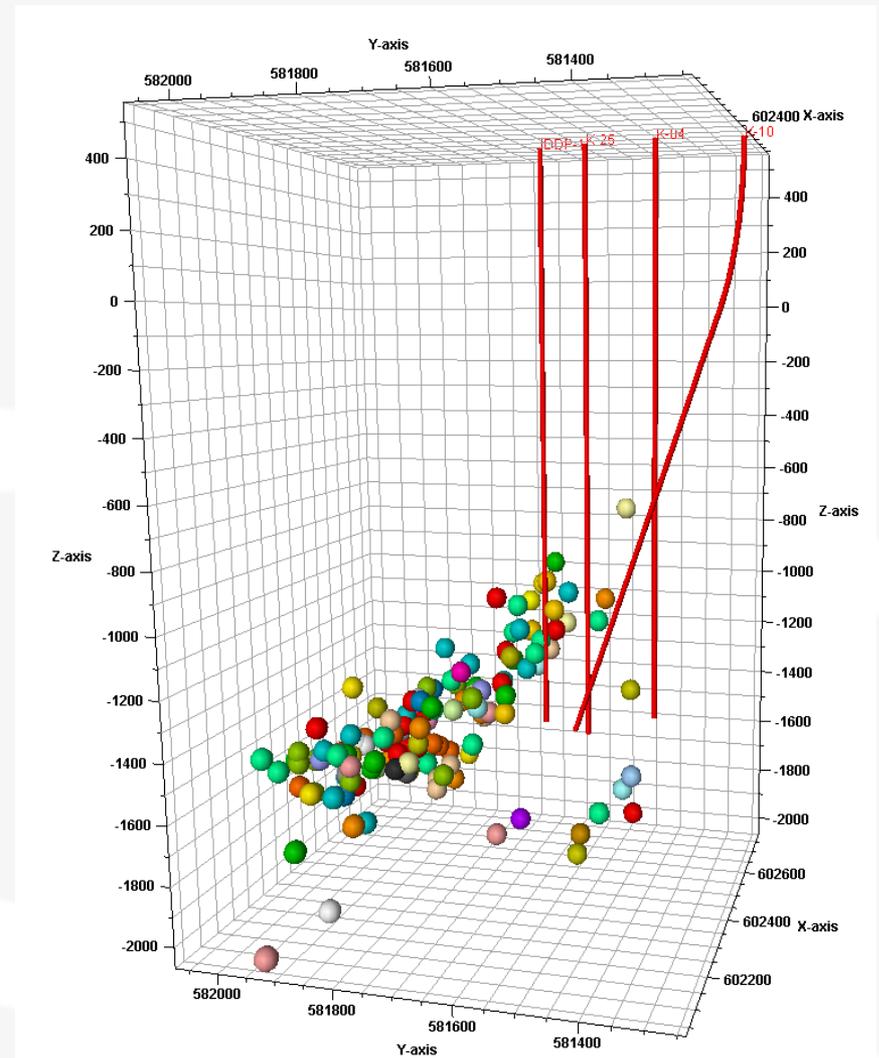
Detailed tectonic and geothermal map



Micro-seismic studies for fractures

Example showing how distribution of micro-earthquakes fall on a straight line during injection test.

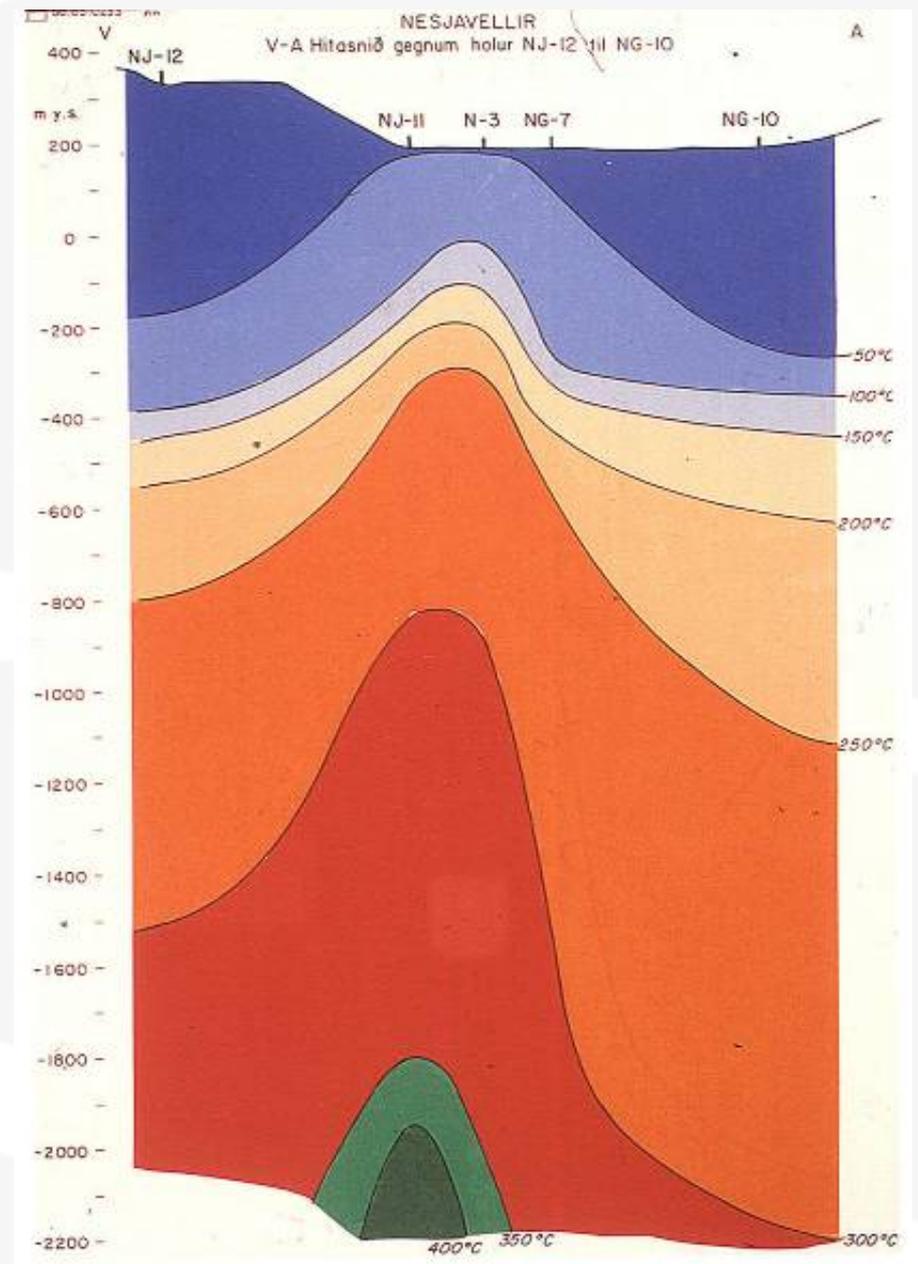
The line denotes a permeable fault that is target in drilling



Application of well logging data

Temperature cross section based on temperature logging in boreholes.

It shows clearly the up-flow zone of the geothermal water.



We need to improve the exploration tools:

- Better tools for data processing and interpretation
- Joint interpretation or processing of resistivity and seismic data.
- Devices for laboratory measurements of rock samples at 200-600°C that can handle fluid filled porous rock.

Concluding comment:



Well organized and professional exploration is the basis for successful and viable geothermal projects.

The end

