Low-temperature deep geothermal systems: an overview

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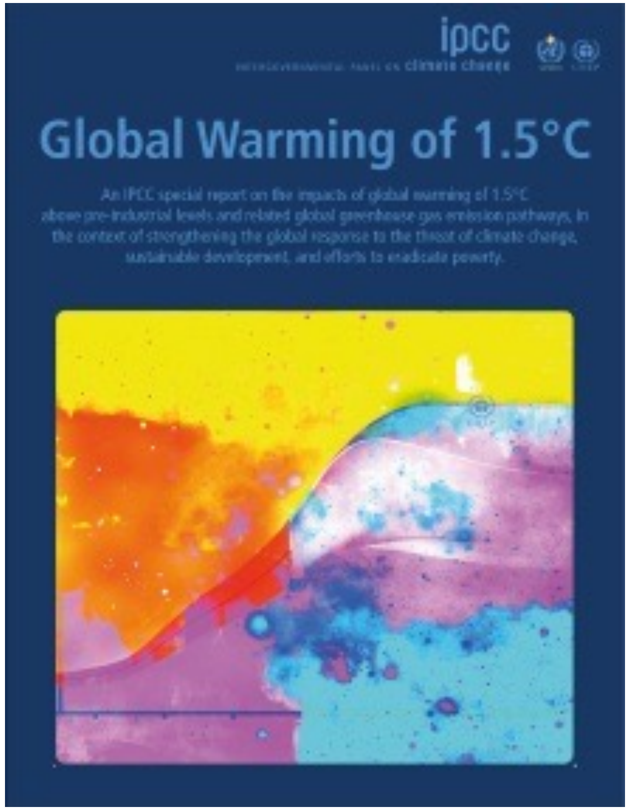
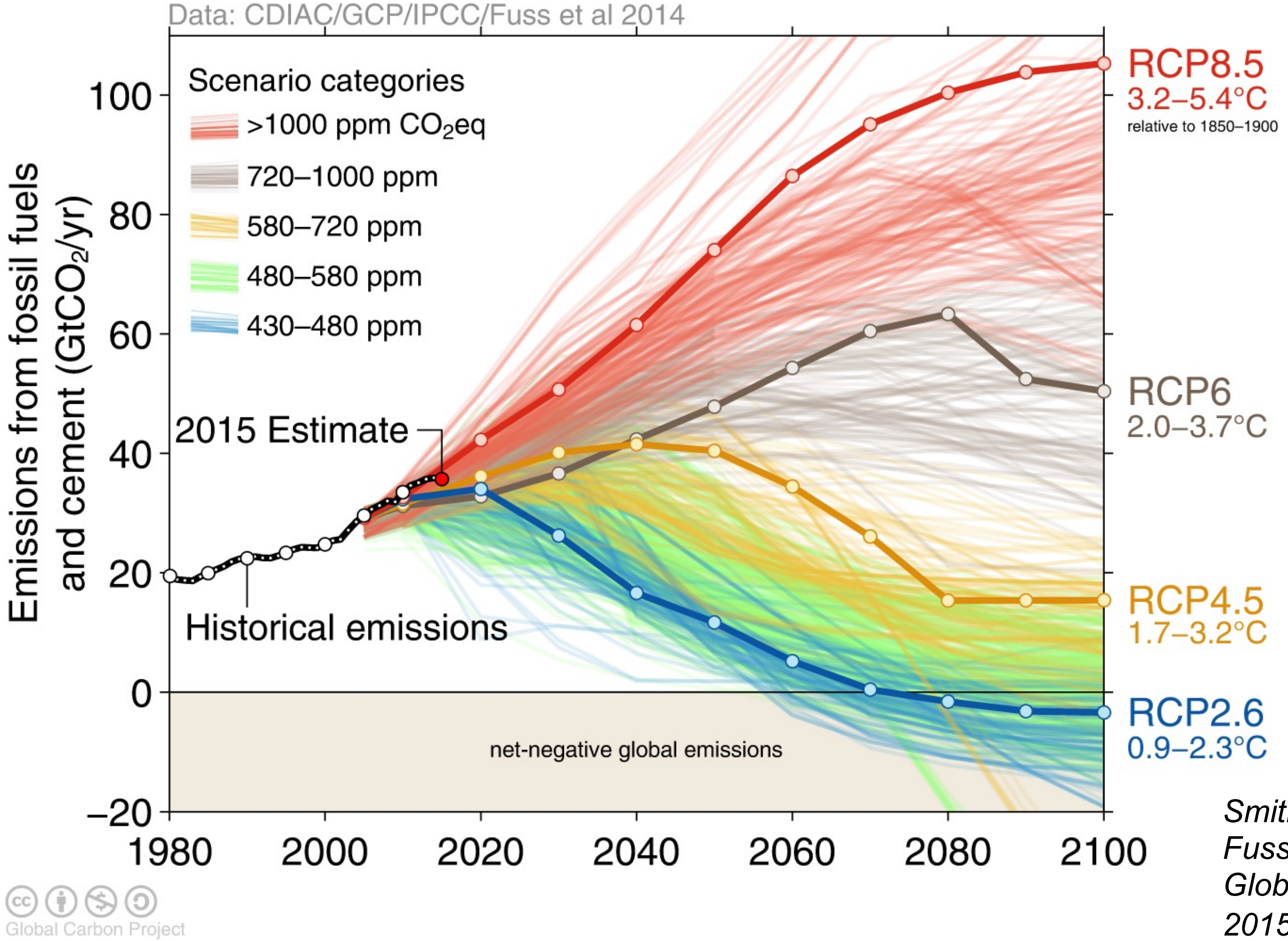
H2020 DEEPEGS project: IDDP-2 well Reykjanes peninsular 4665 m

Intergovernmental panel on climate change: Scenarios to reach COP21 goal

- **IPCC Global Warming report**
  - http://www.ipcc.ch/report/sr15/





Smith, P. et al 2016; Fuss et al 2014; CDIAC; Global Carbon Budget 2015, Leisner 2016

CO_2 emission from reservoir fluids

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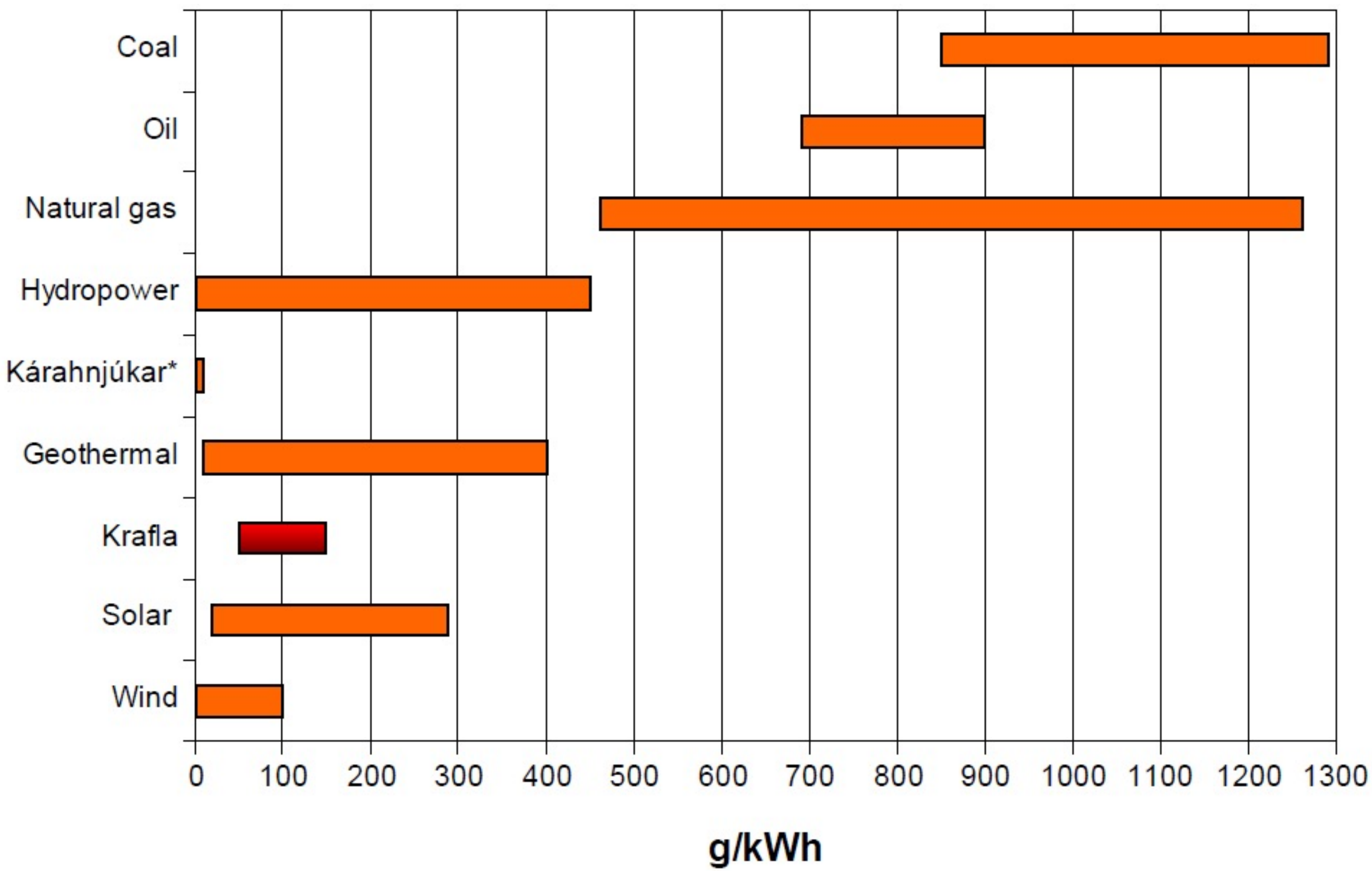
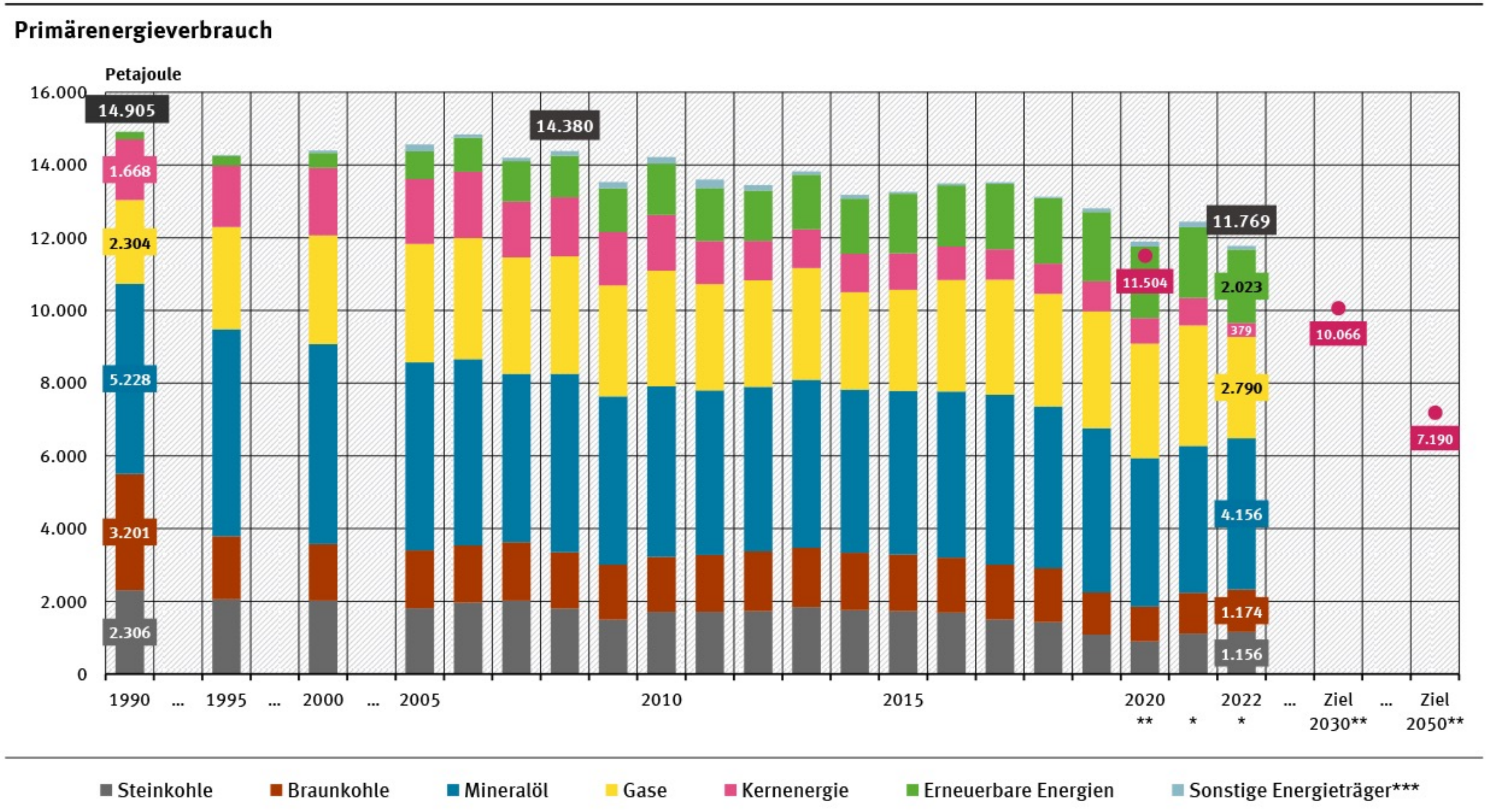


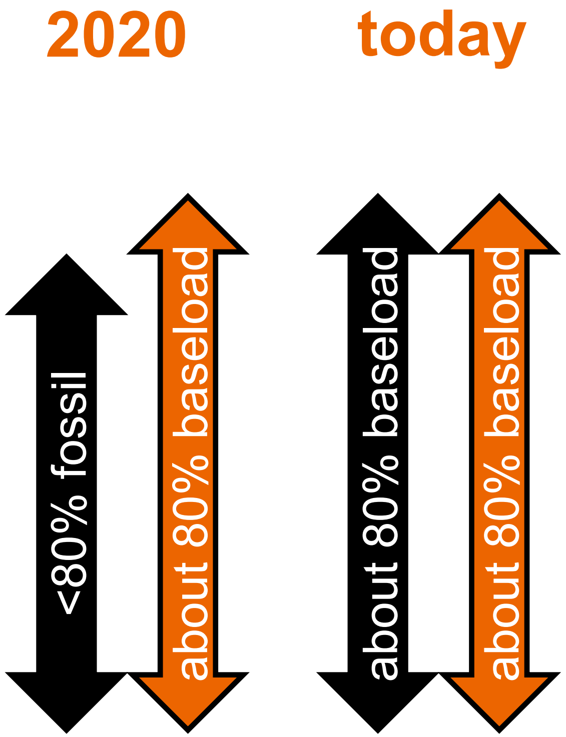
Armannsson, 2003

Share of fossil and baseload energy in the German mix

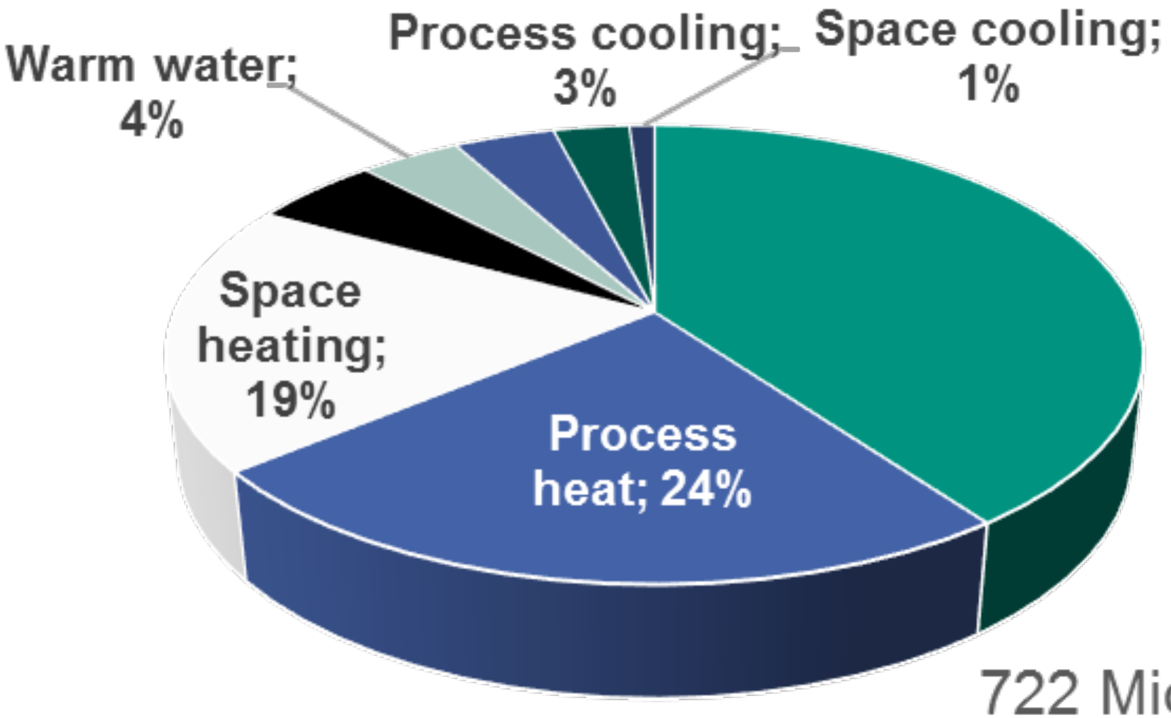


* vorläufig
** Ziele des Energiekonzeptes der Bundesregierung: Senkung des Primärenergieverbrauchs bis 2020 um 20% und bis 2050 um 50% (Basisjahr 2008)
Ziel der Energieeffizienzstrategie 2050: Senkung des Primärenergieverbrauchs bis 2030 um 30% und bis 2050 um 50% (Basisjahr 2008)
*** sonstige Energieträger: Grubengas, nicht-erneuerbare Abfälle und Abwärme sowie der Stromaustauschsaldo

Quelle: Umweltbundesamt auf Basis AG Energiebilanzen: bis 2020: Auswertungstabellen, (Stand 09/2022); 2021: endgültige Energiebilanz 2021 (Stand 03 / 2023); 2022: Primärenergieverbrauch Jahr 2022 (Stand 03 / 2023)



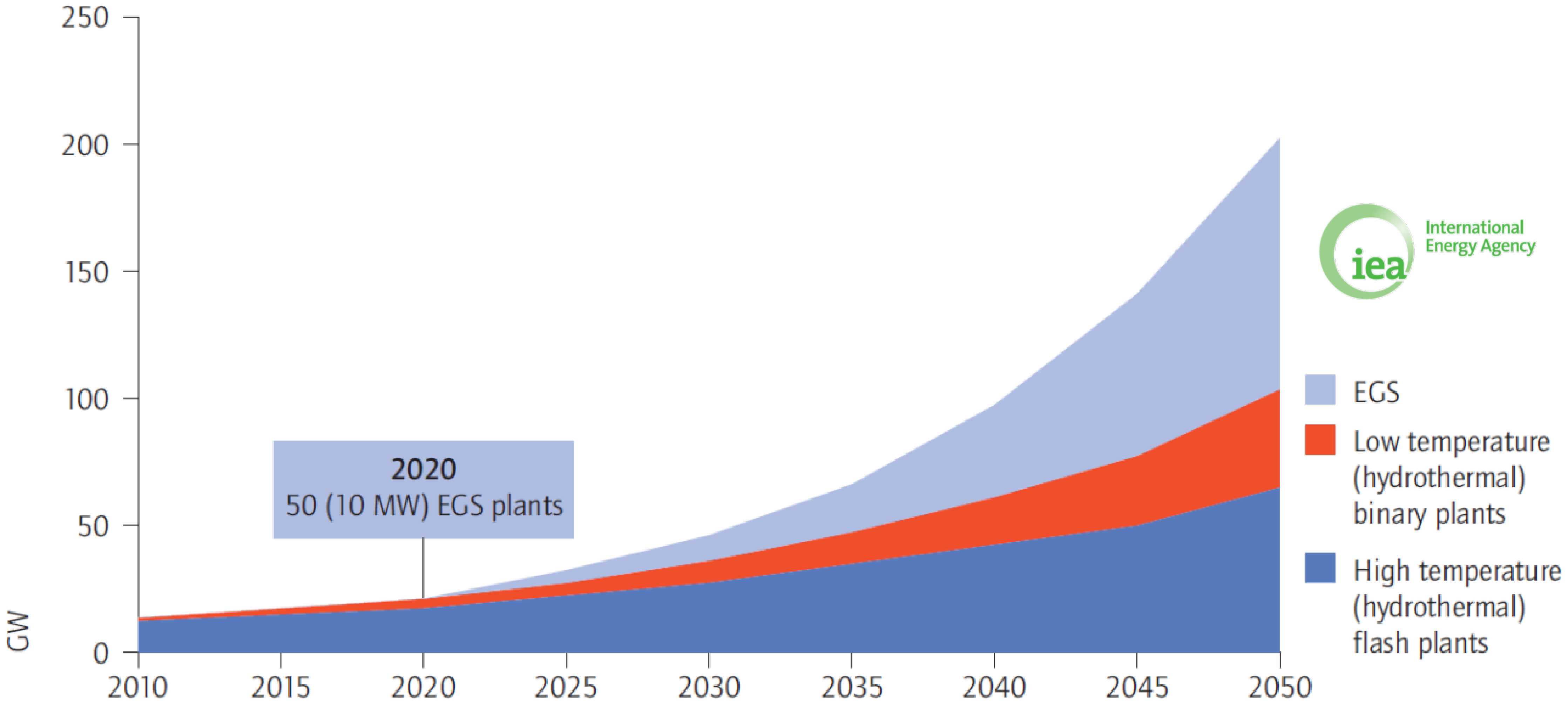
CO_2 emissions in the German energy sector



722 Mio t CO2:
>50% related to heat and cooling

Global geothermal power potential

IEA, 2011



Geothermal energy utilisation in the history

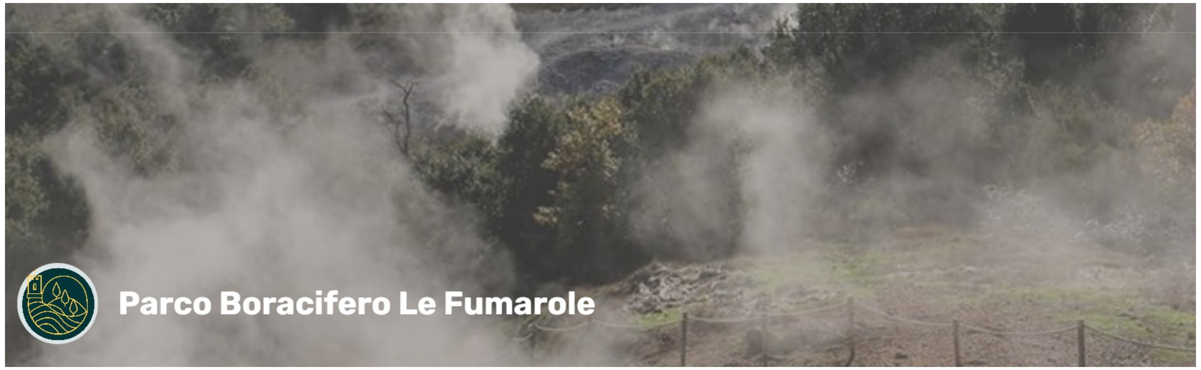
- **6200 BC** Hasan Dag volcano VII level of the Catal Hüyük village in Anatolia (Turkey, Mellaart, 1967)

- **6th century BC** Holy fountain of Giara Santa Vittoria (Sardinia, Italy, www.laghienuraghi.it) sparkling volcanic water

Roman culture to medieval time

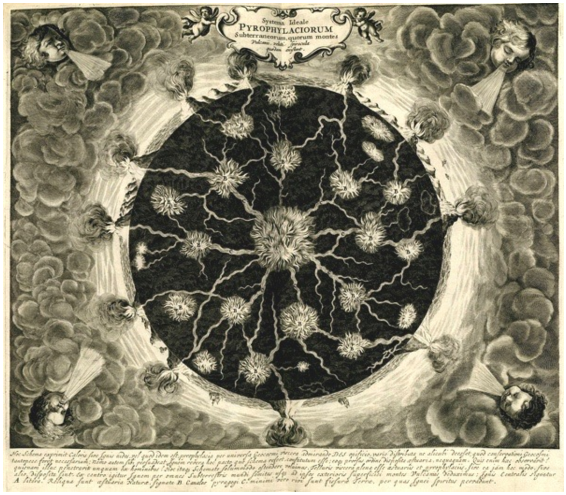
Low temperature

- Thermal spa Wiesbaden (Germany)
  - **77 AD** Naturalis historia (Plinius the Older)
  - **121 AD** Aquae Mattiacorum, Roman settlement
  - **259/260 AD** Destruction by Teutons
  - **306-337 AD** Recapture of the settlement by the Romans (only settlement of Romans Est of the Rhine river)
- Italy after the Roman Empire
  - **1400 AD** Balneotherapy and the use of geothermal products become even more important locally in Tuscany.
  - **1472** End of the "Guerra delle Allumiere" between Volterra and Florence over geothermal manifestations in the "Regione boracifera" (now Larderello). The right of use passes to the Medici family.



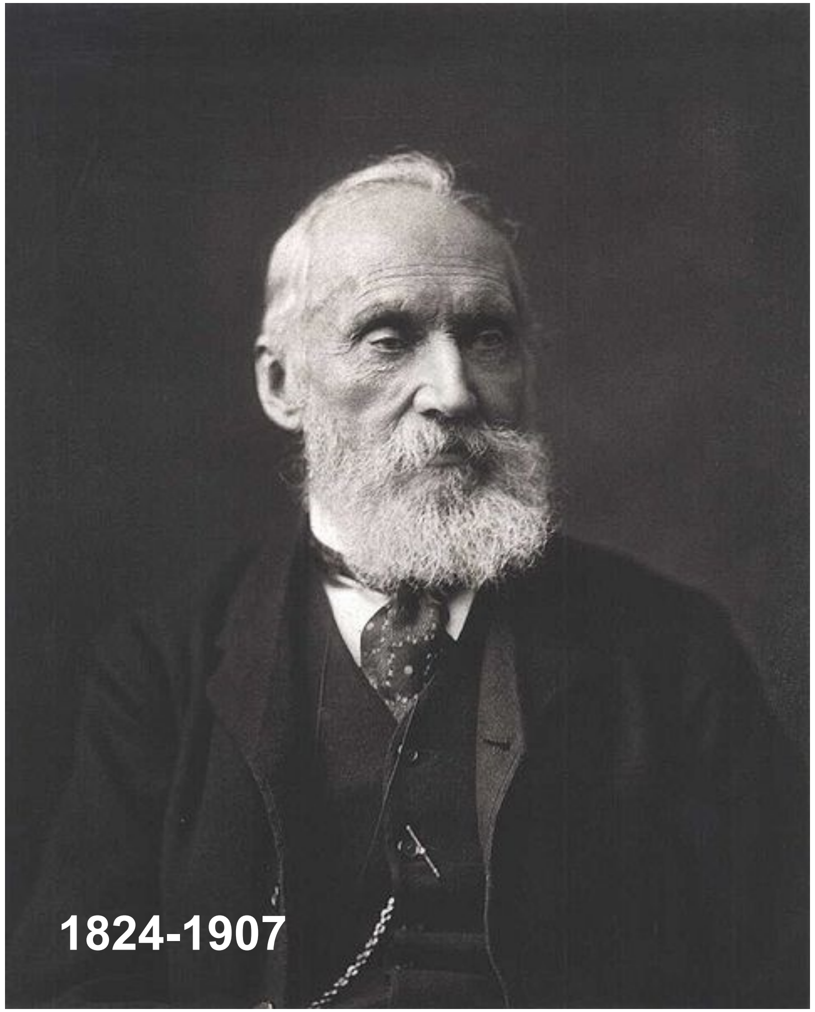
1664-1665 AD during the renaissance
Geocosmus (Athanasius Kircher)

- Hydrophylacia



- Phyrophylacia

1880 AD Lord Kelvin



- **Age of the Earth**
  - Several 100 millions of years
  - His assumption: the **heat flux at the Earth‘s surface** represents the remaining heat from the initial phase of the Earth

$$\frac{1}{A}\frac{dQ}{dt} = \frac{\dot{Q}}{A}$$

- **Fourier‘s Law of Heat Conduction** (1822)

$$T = \frac{q_0}{k} \cdot z + T_0$$

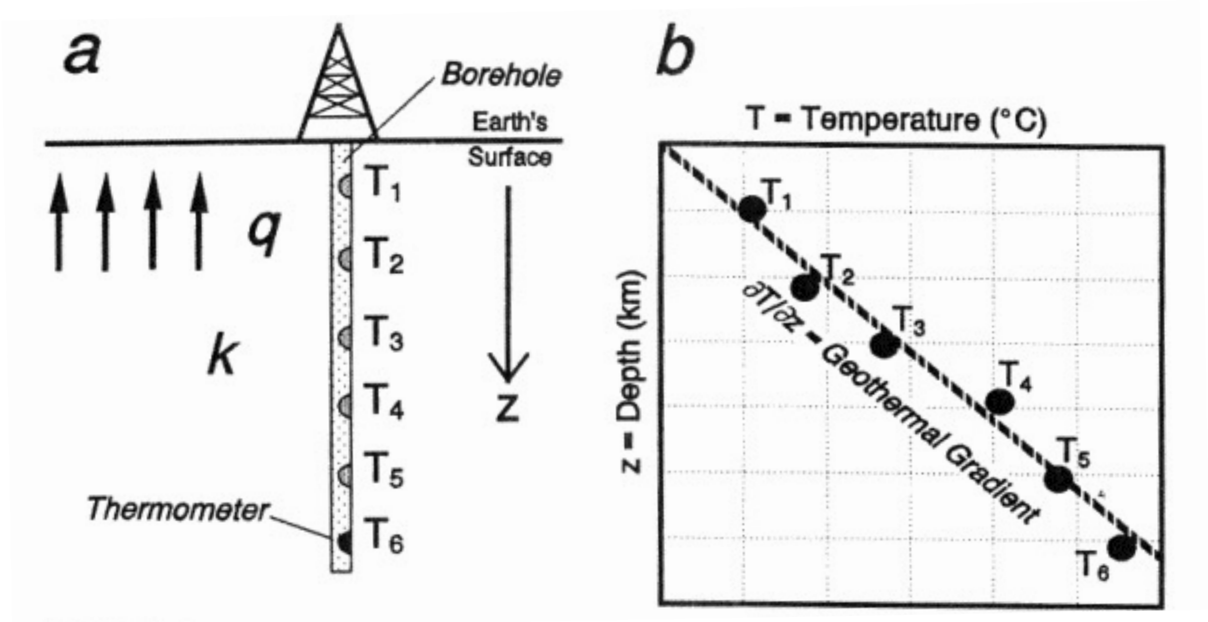
  - Boundary condition
    - surface temperature T_0 and
    - heat flux at the surface q_0

Determination of heat flux density

Low temperature

- Heat flux density from depth-dependent temperature measurements

$$T = \frac{q_0}{k} \cdot z + T_0$$

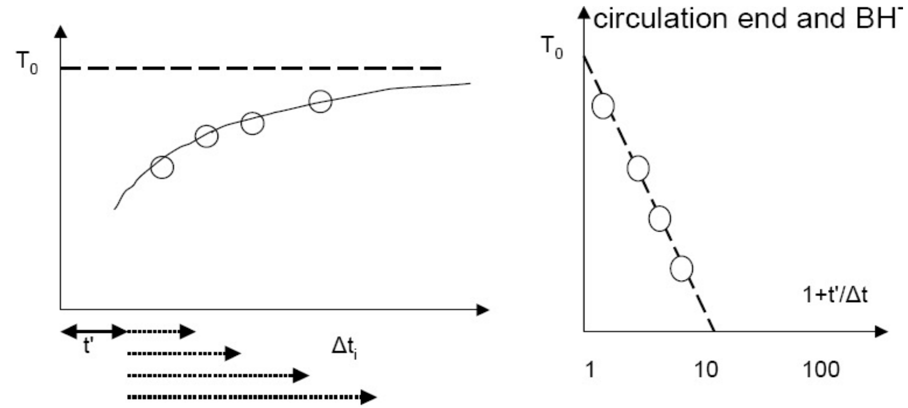


- Determination of […] rock temperatures

$$T(t) = T_0 - k \cdot \log\left(1 + \frac{[\ldots]}{\Delta t}\right)$$

- T0 undisturbed rock temperature
- k constant depending on the λ of mud and surrounding rock
- t' cooling period (duration of circulation at bottom hole)
- Δt recovery period (time between circulation end and BHT measurement)

(Lachenbruch and Brewer, 1959)

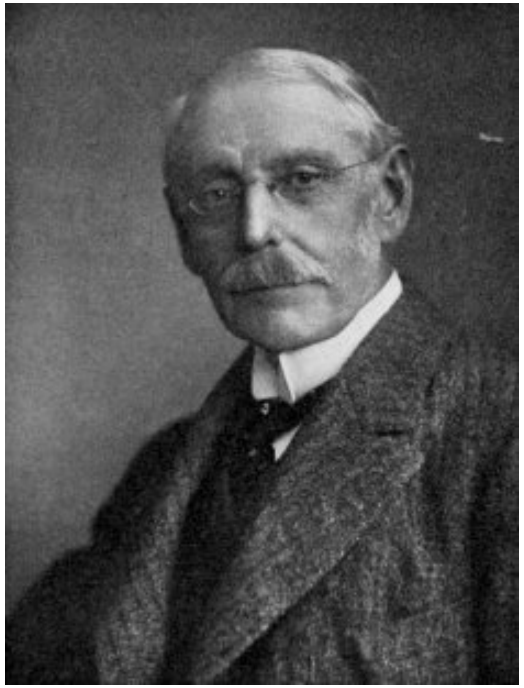


1904 First conversion of geothermal to electric energy

- **1904** First conversion of geothermal to electric energy by Conte Ginorio Conti at Larderello using a heat exchanger. The vapor operated a piston motor that connected to a dynamo of 10 kW lightening five lights.
- **1905** Installation of a piston motor connected to a 20 kW dynamo

1904 « Hellfire Exploration Project »

First idea of EGS



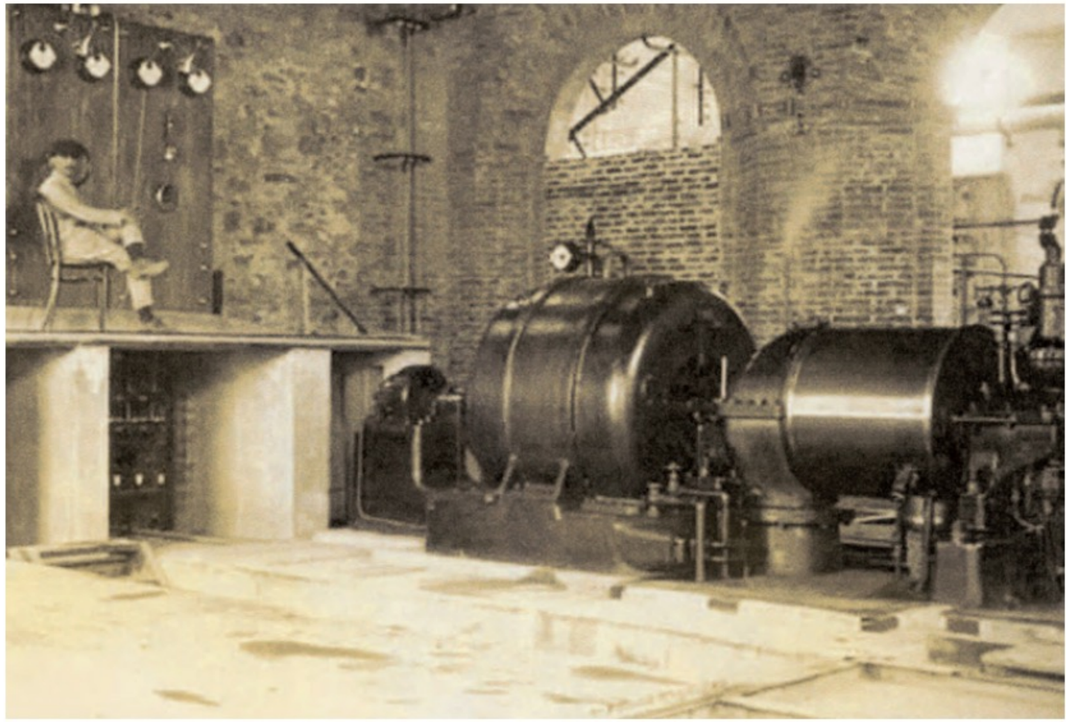
- Sir Charles Parsons published his idea « Hellfire E… Project » as « Presidential Address » in the Annual Report of the B… …ation for the Advancement of Science: Transaction of Section G, En… 667-676):

« The thermal system of the subsurface may be exploited by drilling to a depth of 20km. »

- He estimated
- A duration of construction of 85 years,
- a cost of 5 million pounds and a
- temperature of 600°C (assuming a geothermal gradient of 30°C per km)

Continues development in conventional systems

- **1913** First geothermal plant with a installed capacity of 250kW in La Valle del Diavolo



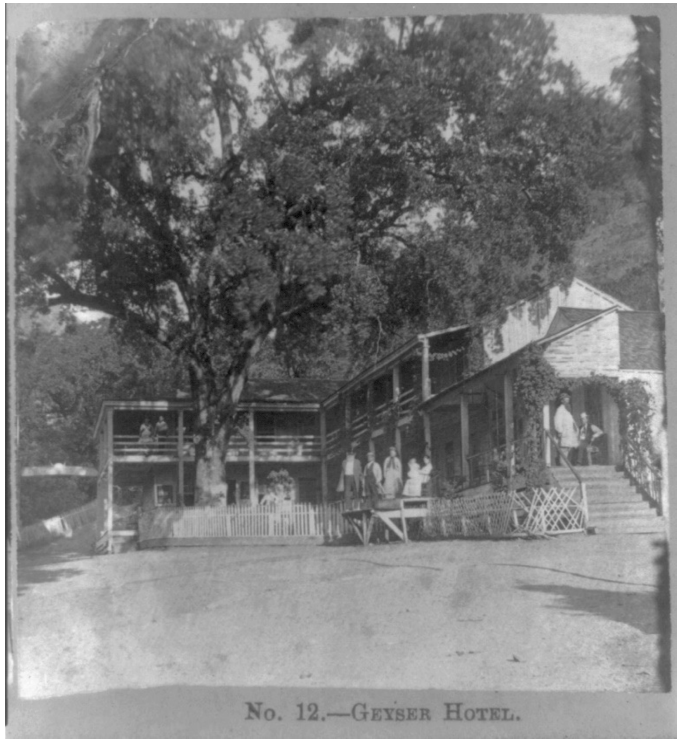
- **Today** about 700 MW installed capacity in 32 plants producing from three productive areas

The Geysers

- The area is noted for numerous geysers and hot springs with surface temperature near 100°C. The area was originally settled by the **Pomos** and **Mayacmas Indians**.
- To the Native Americans this was "Tu-la-ha-lu-si, **the beautiful land**"; and the hot, spongy turf was "Coo-lay-no-maock, **the oven place**", according to a local historian.
- **1862** Samuel Brannan established a resort and spa.

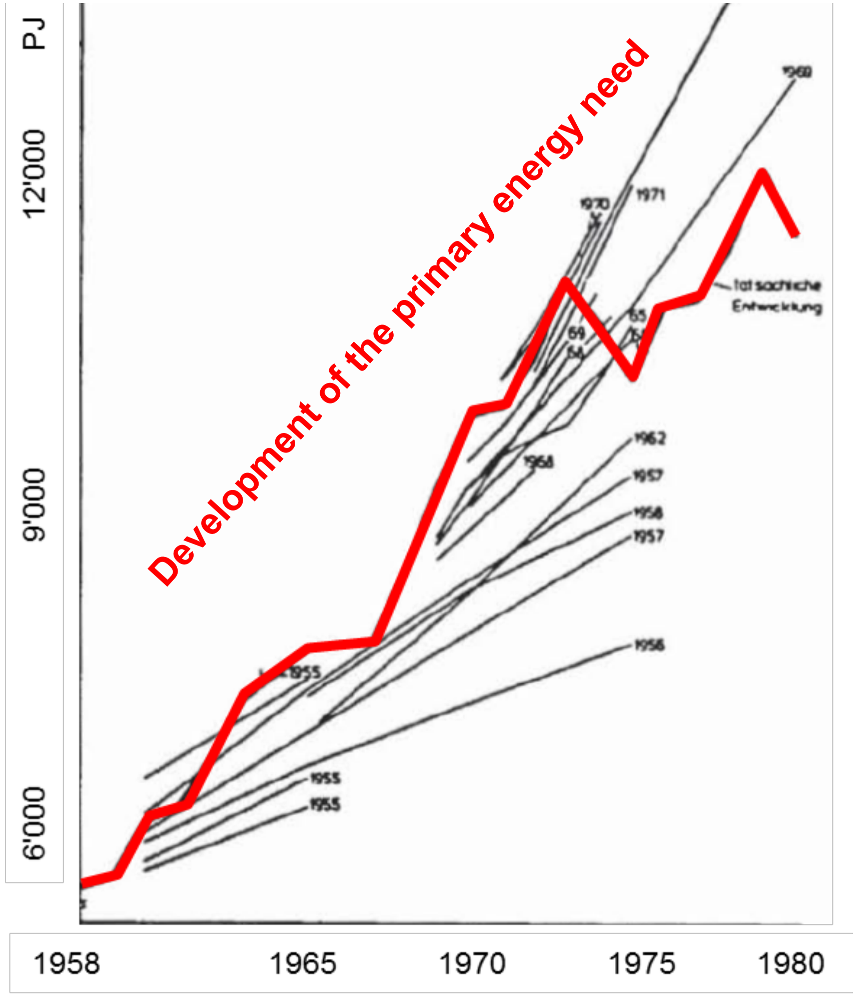
Lund, 1995

- **1960** Pacific Gas and Electric began operation of a 11MW power plant.



Impact of oil crises on geothermal development

- Energy need between 1958-1980
  - Significant increase in the late 1960-ties
  - **1973 oil crisis: price increased 400%**
  - **1979 oil crisis: price increased 100%**



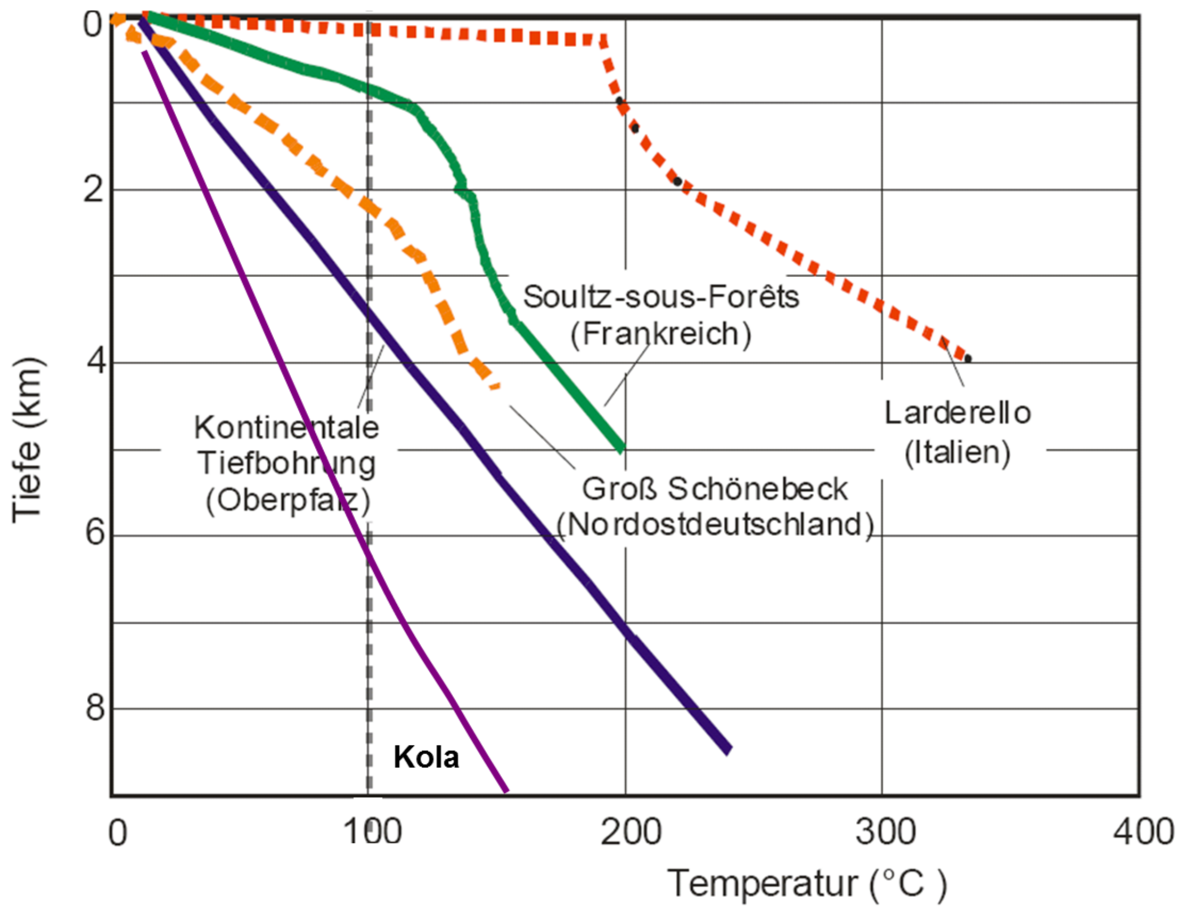
Geothermal energy in Tibet

Yangpachen, 1970

Kola Super-Deep well KSDB-3

- **1970** Start of drilling of KSDB-3 in the northern part of the Pechengsk basin – a thick volcano-sedimentary series of mid-Proterozoic age and a gneissic basement
  - Target depth: 15 km
- **1975** T>120°C at a depth of 7'263m
- **1980** T>180°C in open-hole to a depth of 10'500m bis T>180°C
- **1989** Final depth of 12'261 m

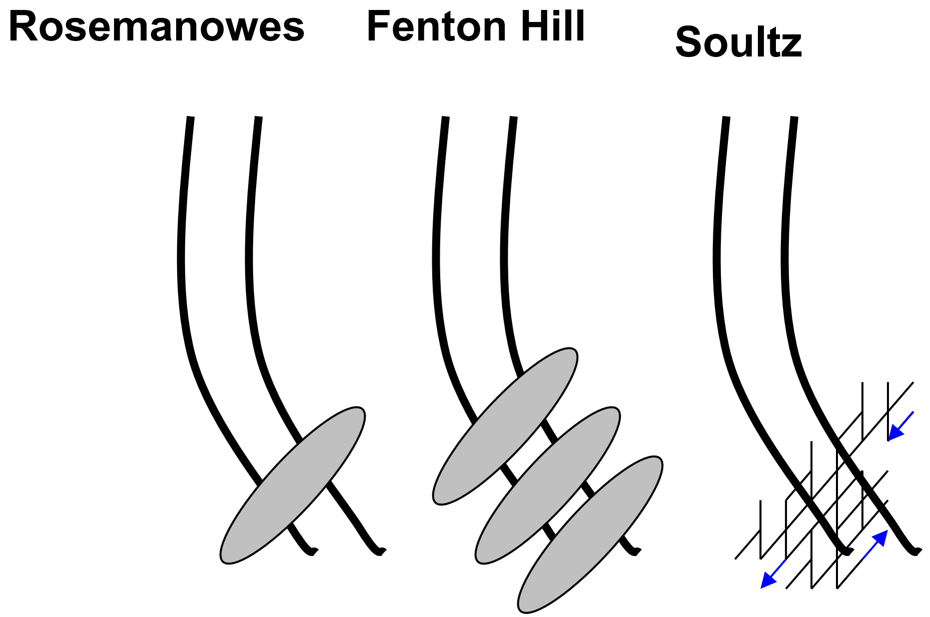
Band width of geothermal wells in 2010

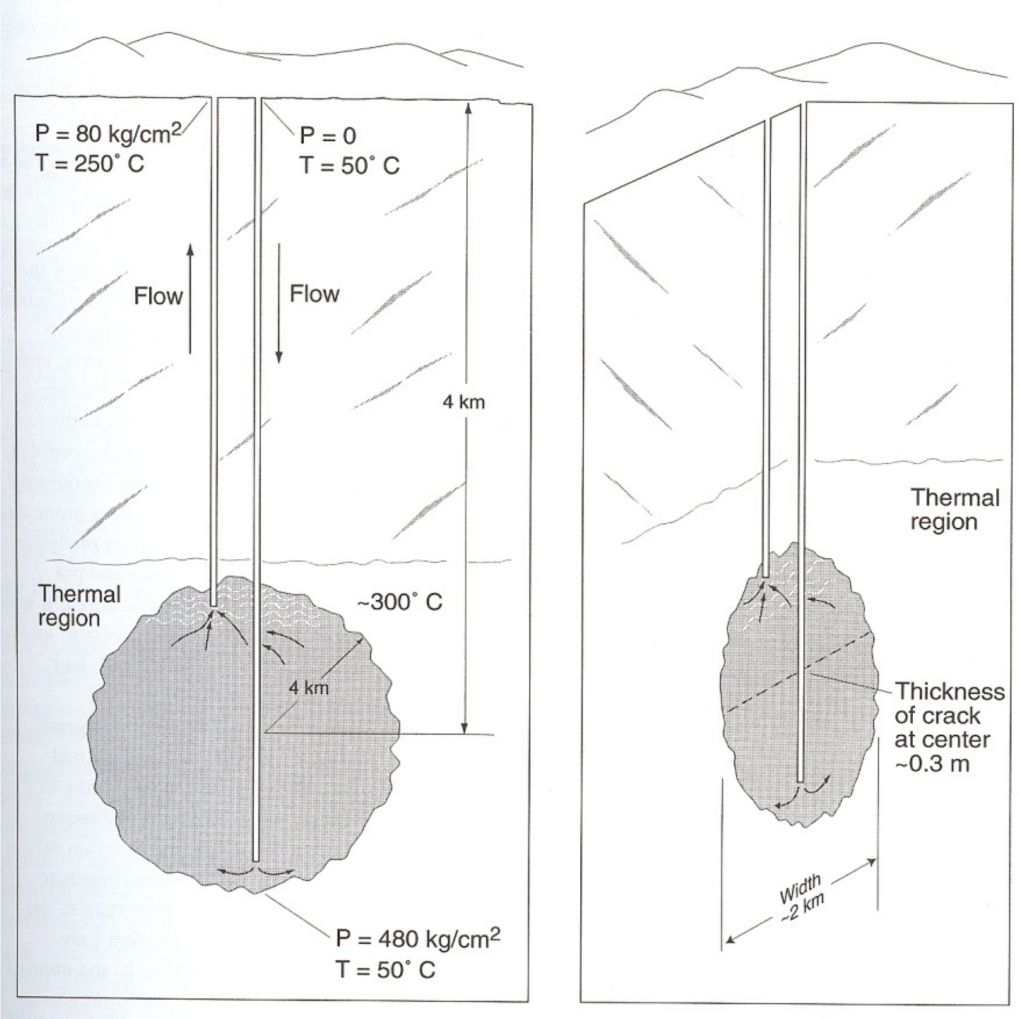


1970 Hot Dry Rock concept

- Hot Dry Rock programme USA
  (Los Alamos, Robinson 1971)

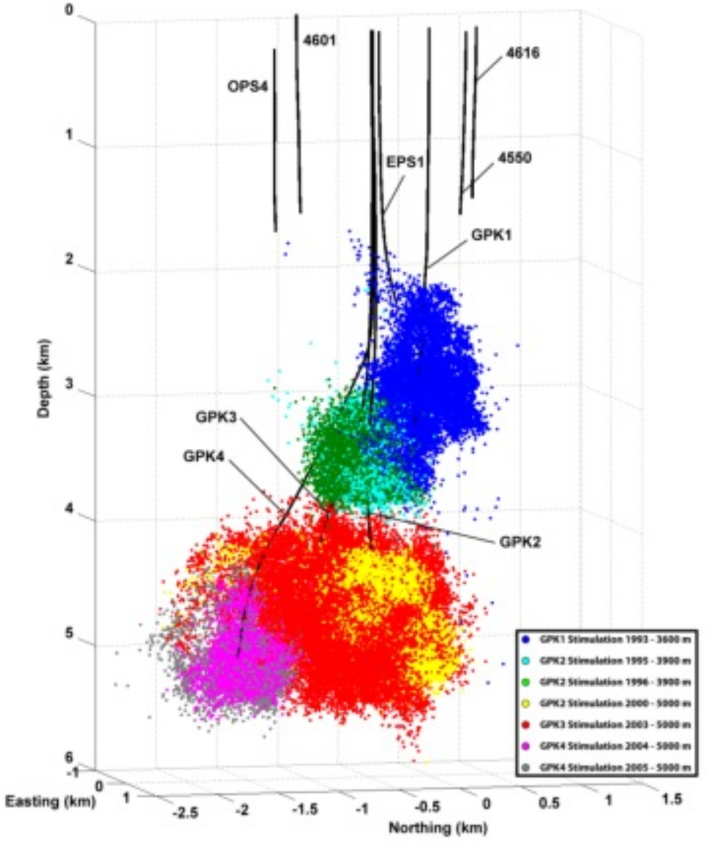
  - **Artificial conductivity by stimulation**





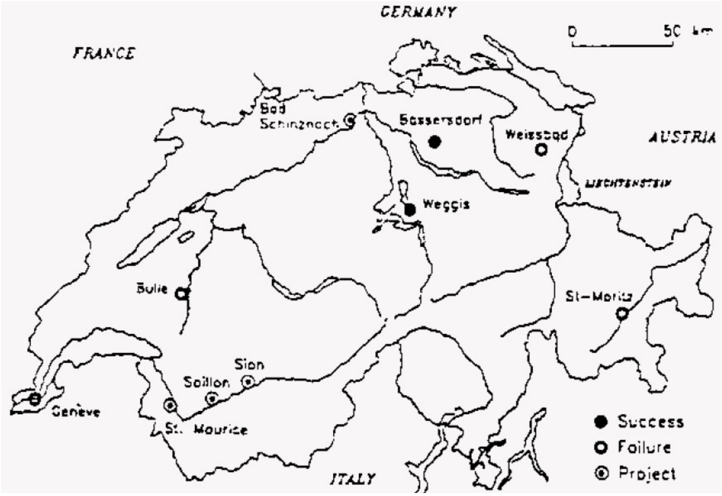
1987 Concepts for non-volcanic, low-temperature zones

HDR to EGS



Low-temperature hydrothermal wells

- Federal programme « Risk guaranty » 1987-1998
- Project « Geothermoval » 1987-1995



Heat transport in low-temperature systems

- Heat transport equation (without adiabatic effect)

$$\rho c_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) + A - [\rho c_p]_f \, v_D \nabla T$$

Energy content of sources from the geosphere

- Heat value
  - Lignite: 1.7×10^{7} J kg^{-1}
  - Black coal: 3.0×10^{7} J kg^{-1}

  - Oil: 3.8×10^{7} J L^{-1}

- Heat capacity
  - Thermal water: 4.2×10^{3} J kg-1 K^{-1}
  - Rock: 2.0×10^{3} J kg-1 K^{-1}

Cooling 1 kg of water or rock by 100K, provides 0.5-1% of the heat that is produced by burning the same amount of fossil oil or coal

$$c_p = \frac{\Delta E}{m \cdot \Delta T}$$

$$\Rightarrow \Delta E = c_p \cdot m \cdot \Delta T$$

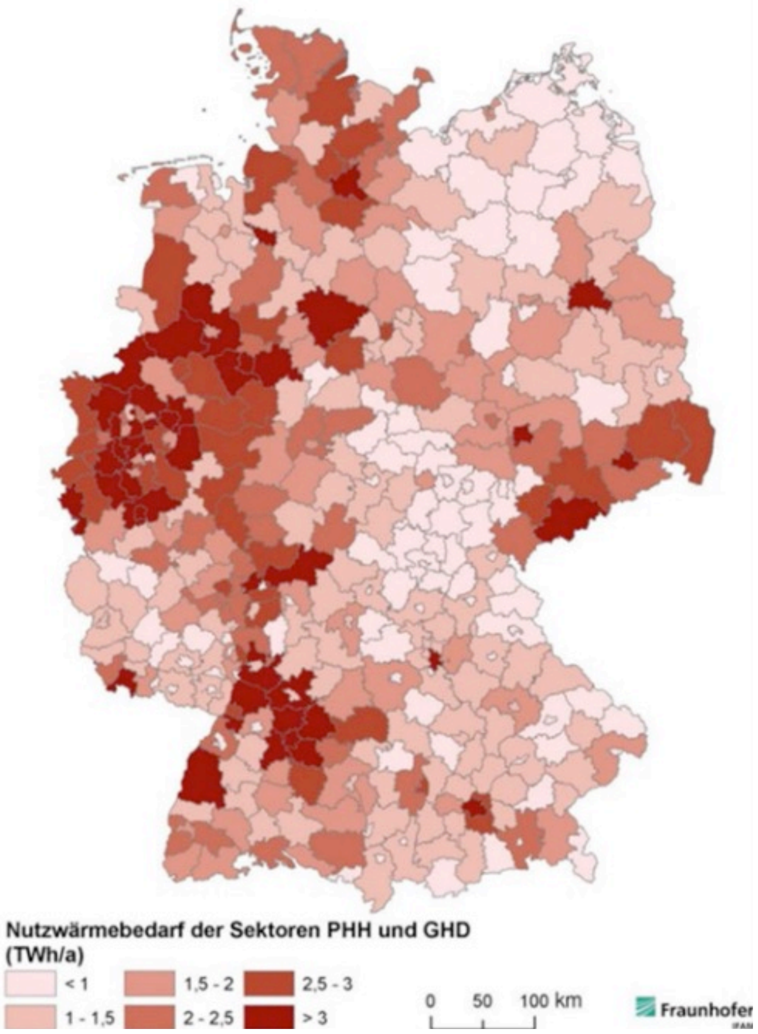
$$\Rightarrow \frac{\Delta E}{t} = \Delta P = c_p \cdot \frac{\rho \cdot V}{t} \cdot \Delta T$$

$$\Rightarrow \Delta P = \rho c_p \cdot Q \cdot (T_{prod} - T_{inj})$$

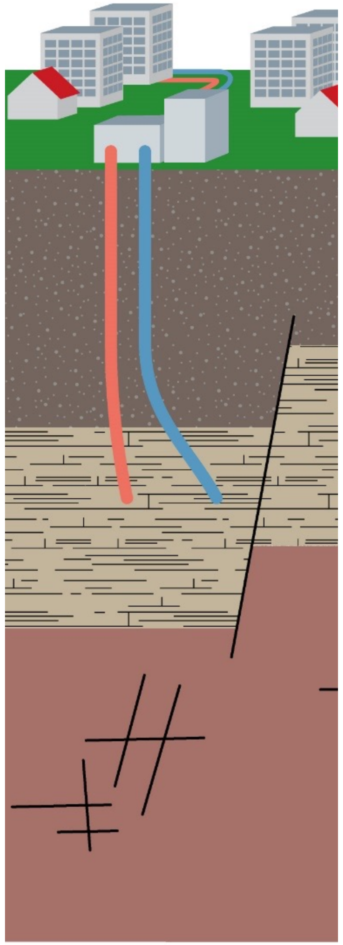
Heat demand in Germany (2019)

- Communities 788 TWh/a
  - Space heating 658 TWh/a (>2100 h/a)
  - Water 130 TWh/a (8600 h/a)

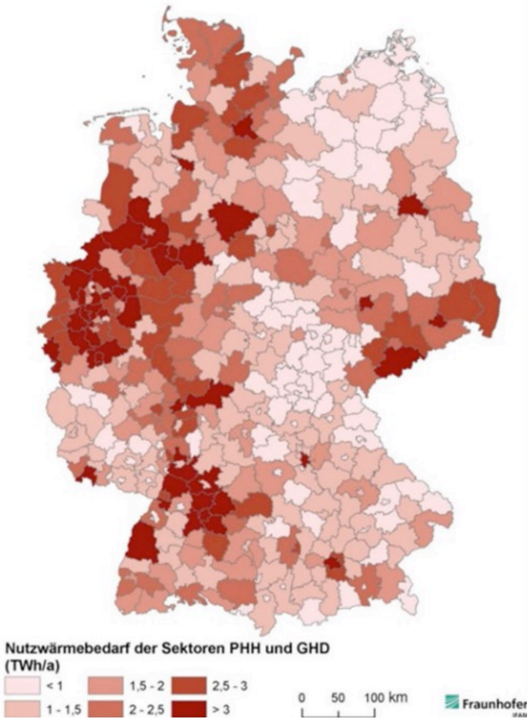
- Industrial demand 604 TWh/a
  - Process heat 541TWh/a 8600 h/a)
  - Space heating 63TWh/a (8600 h/a)

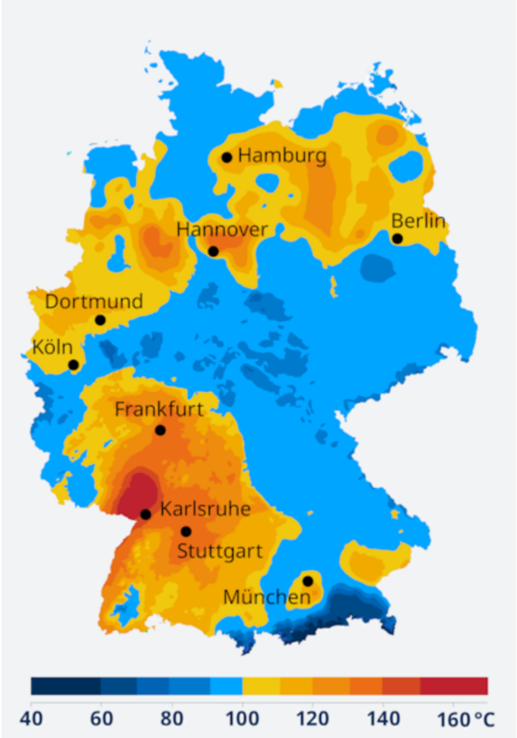


Hydrothermal Potential in Germany



- Goal >2045 for hydrothermal ressources in germany
  - **>300 TWh/a, i.e. 25% of the national heat demand**





Agemar et al. (LIAG)

Geothermal technologies in Germany

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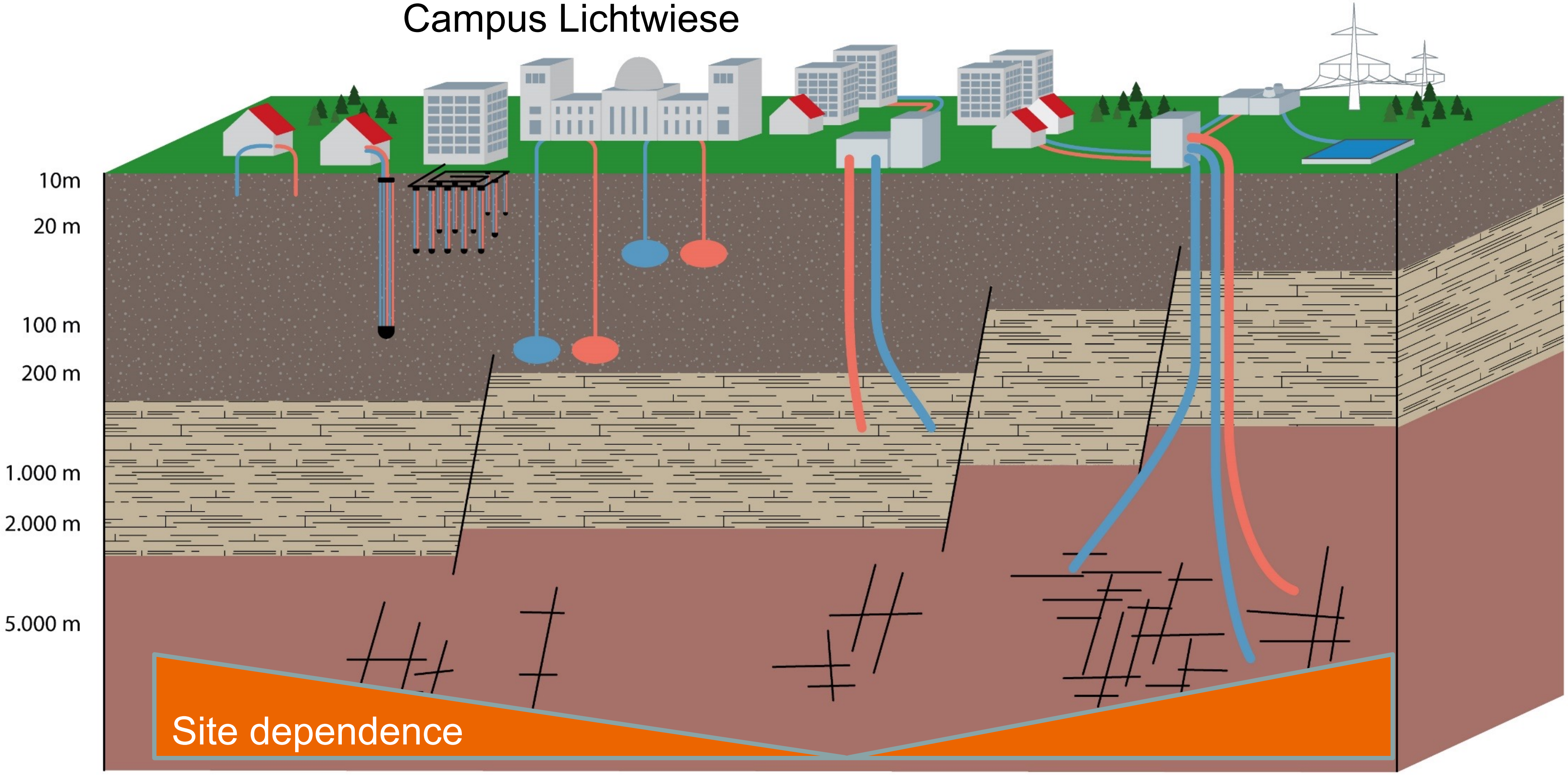
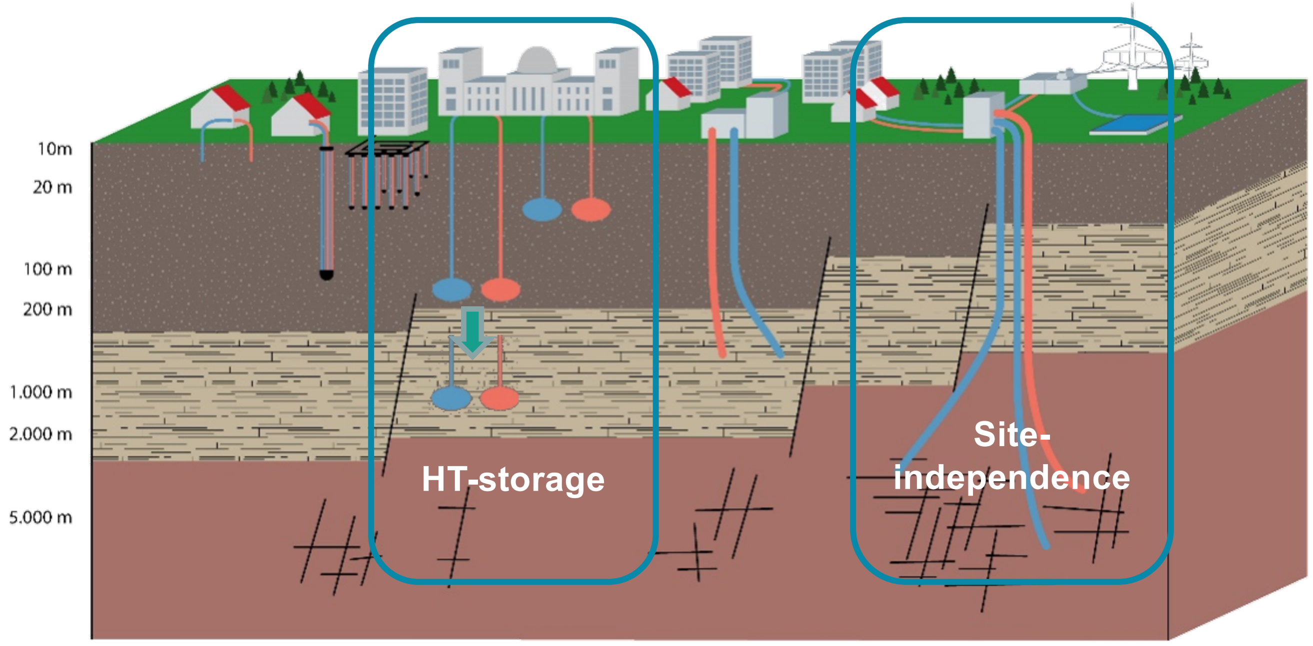
Heat storage at TUDa
Campus Lichtwiese

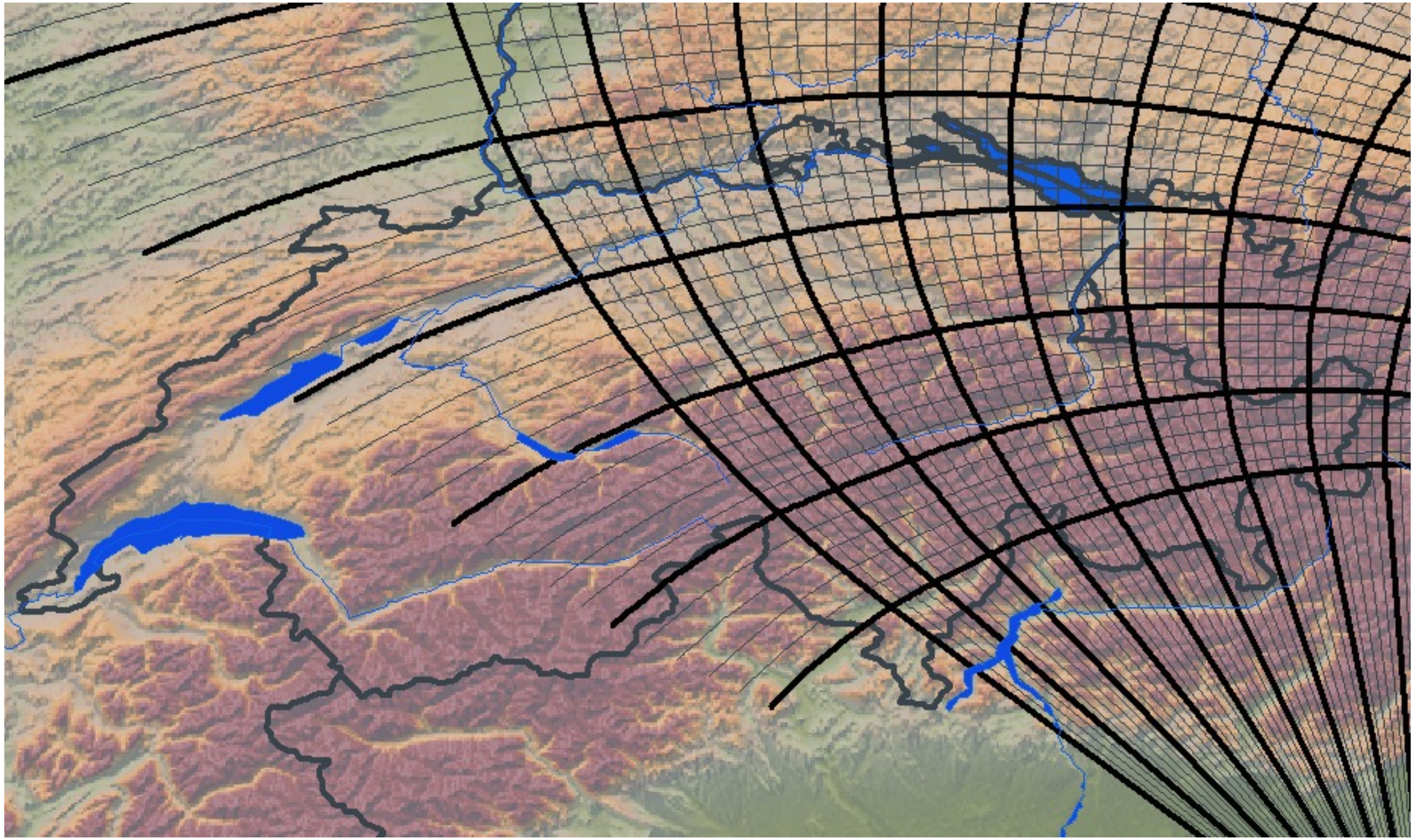


Geothermal potential including new developments

- Large-volume and high-temperature heat storage
- EGS - Enhanced Geothermal Systems technology



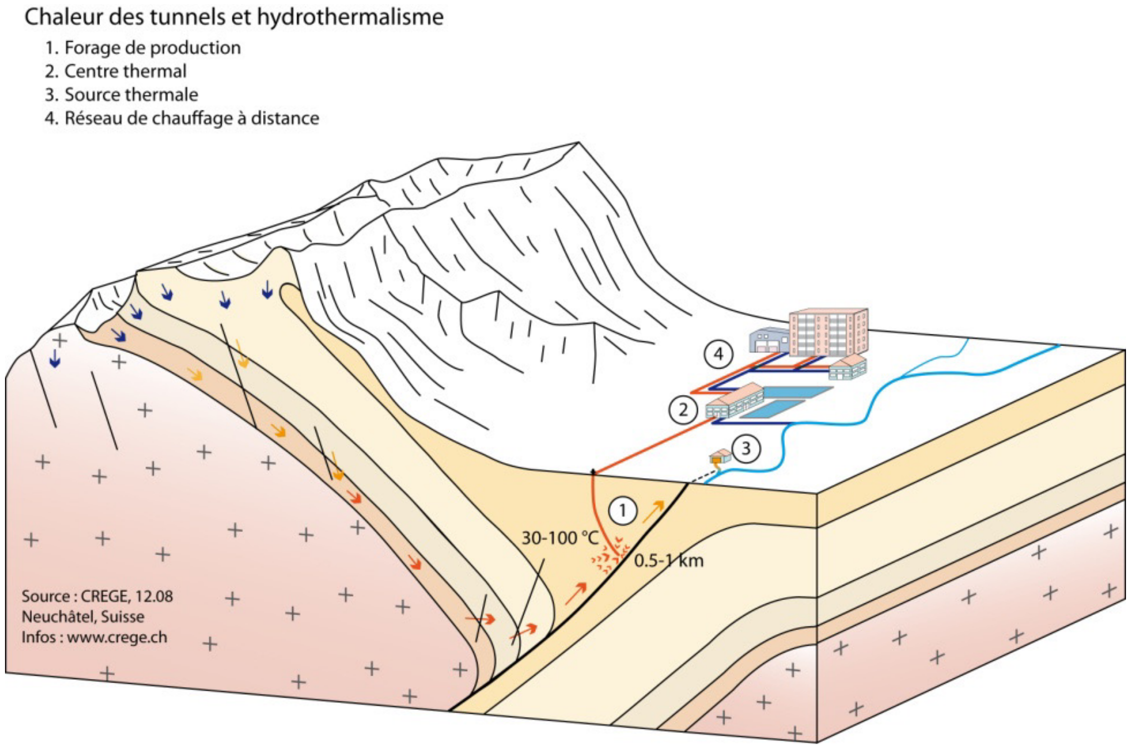
Hydrothermal projects in and near the Alps



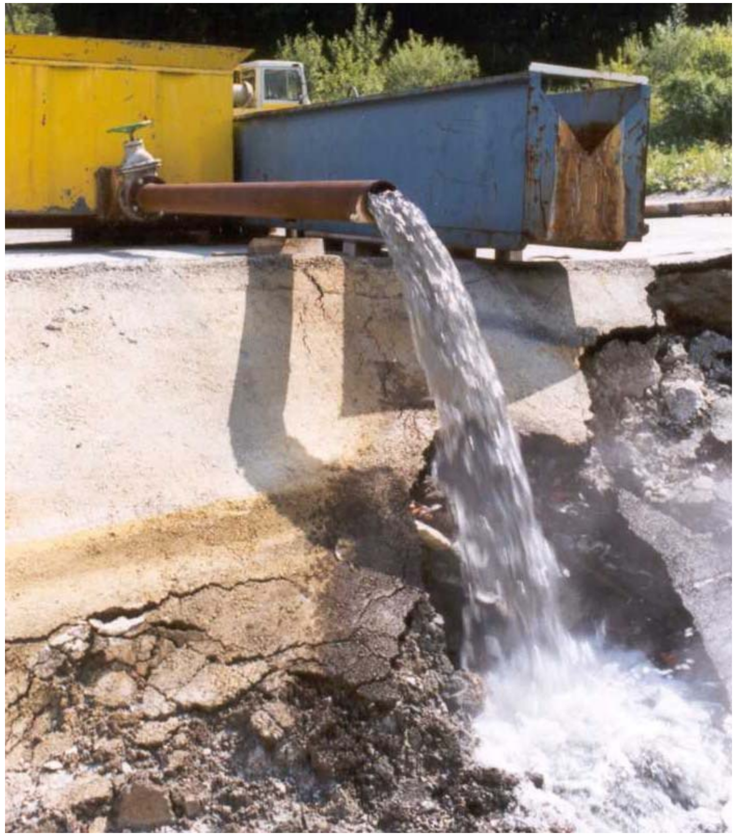
Schill, Wellmann and Regenauer-Lieb (2007)

Alpine systems

- Typical concept of thermal utilisation



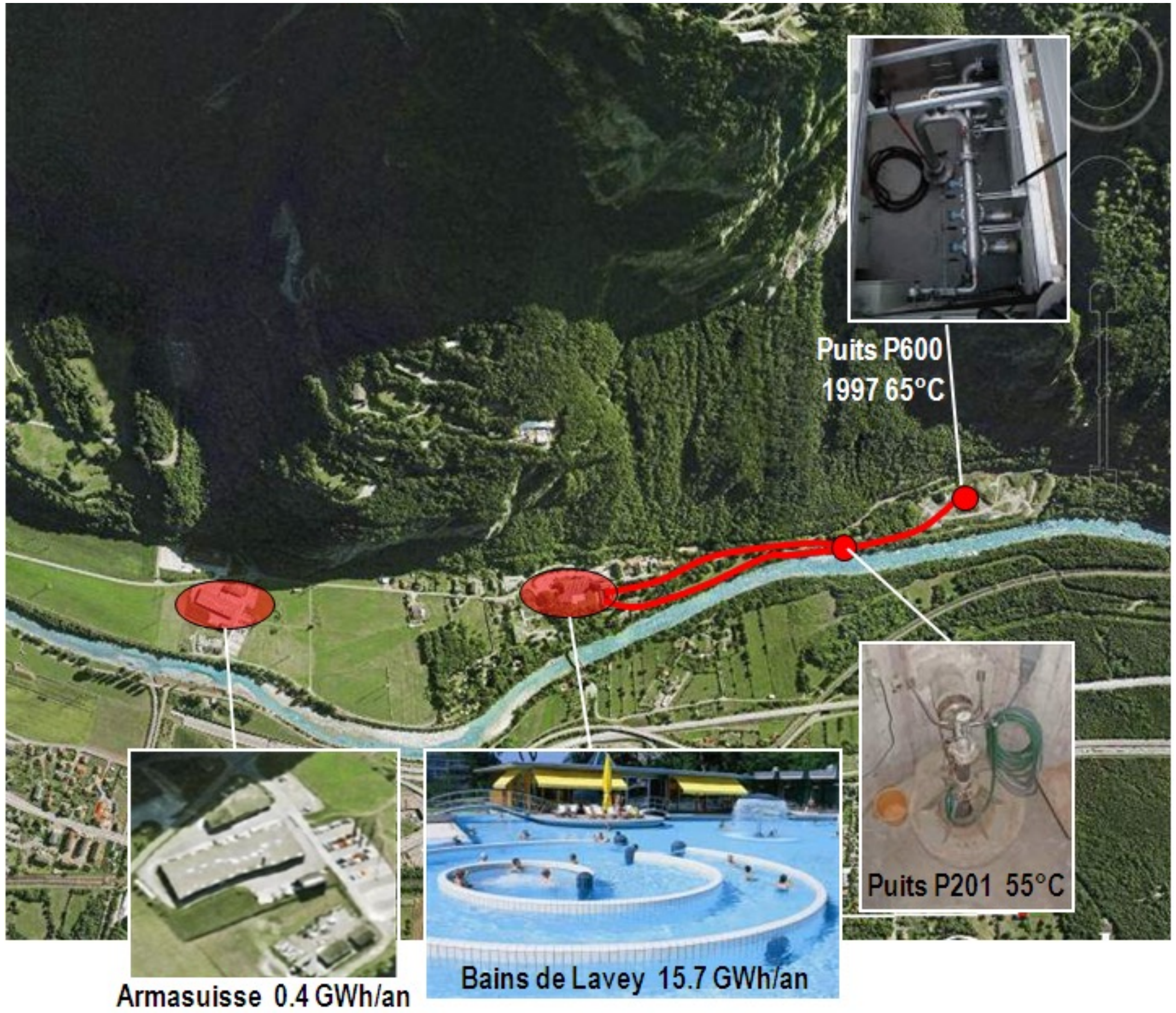
- Production test Lavey-les-Bains (P600)



Spa / direct heat utilisation

- P201 (201 m, 1973)
- P600 (600 m, 1997)

- Total flow rate 27 l/s
- Maximum temperature of 67°C



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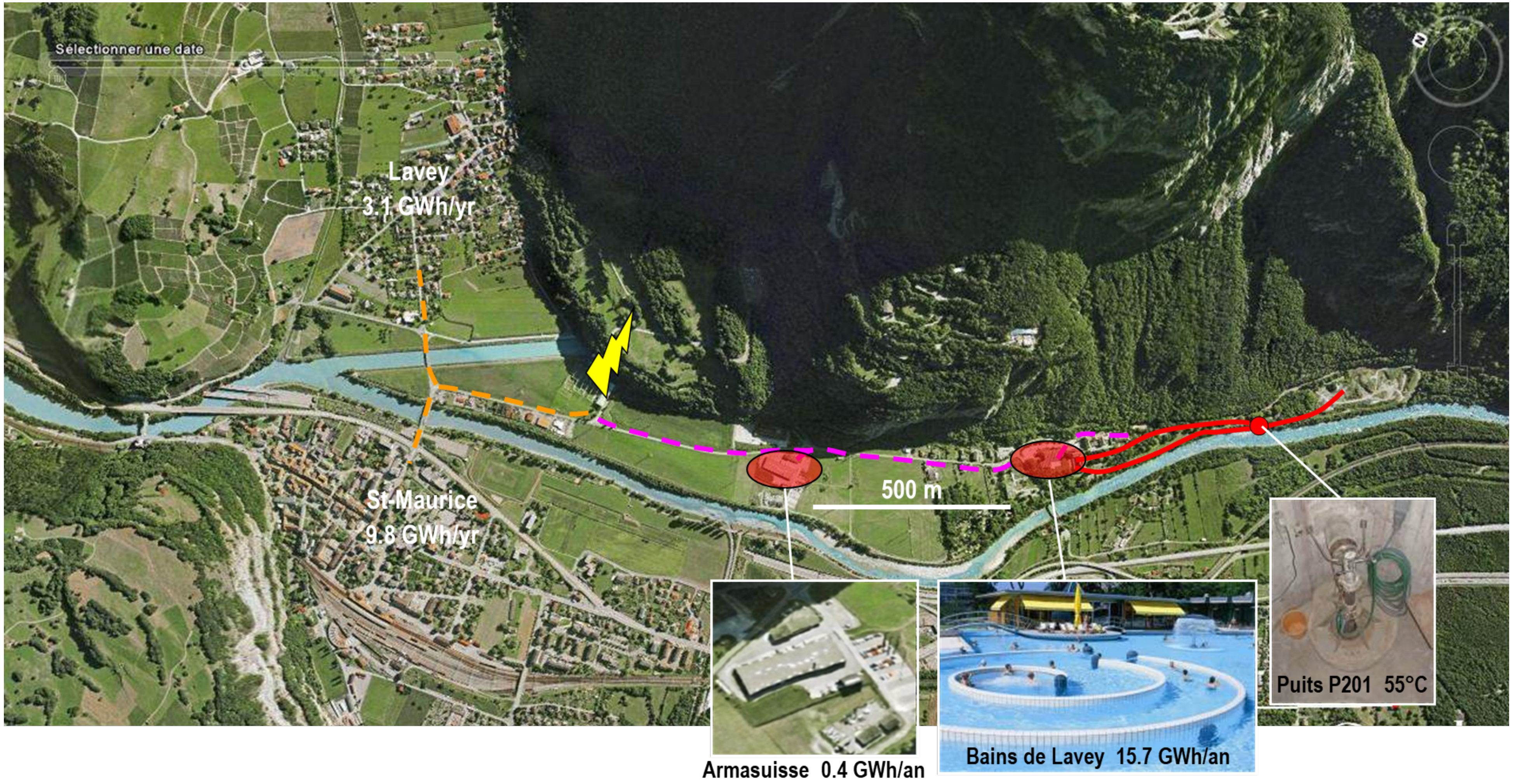


Simplified Darcy's experiment

- **Steady state production rate**

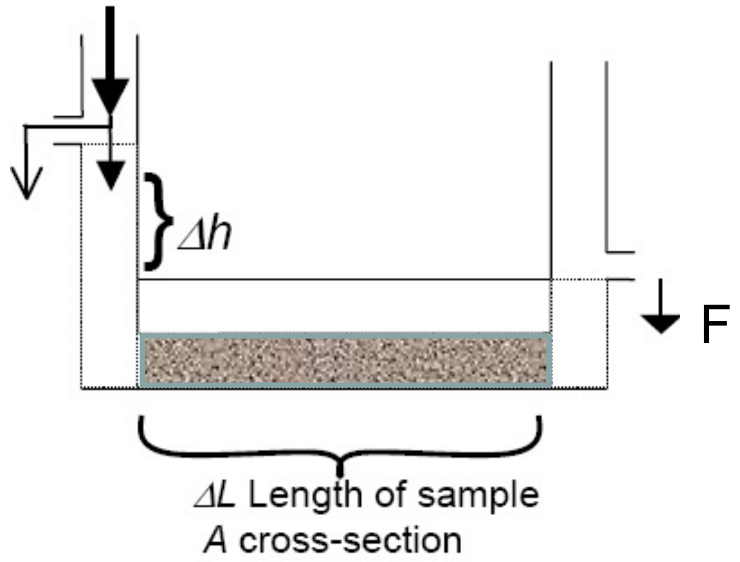
$$F = \frac{K \cdot A \cdot (h_1 - h_2)}{L}$$

- **Volumetric flow rate:**
  steady state flow rate per cross-sectional area

$$q = \frac{F}{A} = \frac{k \cdot \rho \cdot g}{\mu} \cdot \frac{dh}{dL} = K \cdot \frac{dh}{dL} = \nu_D \left[\frac{m}{s}\right]$$

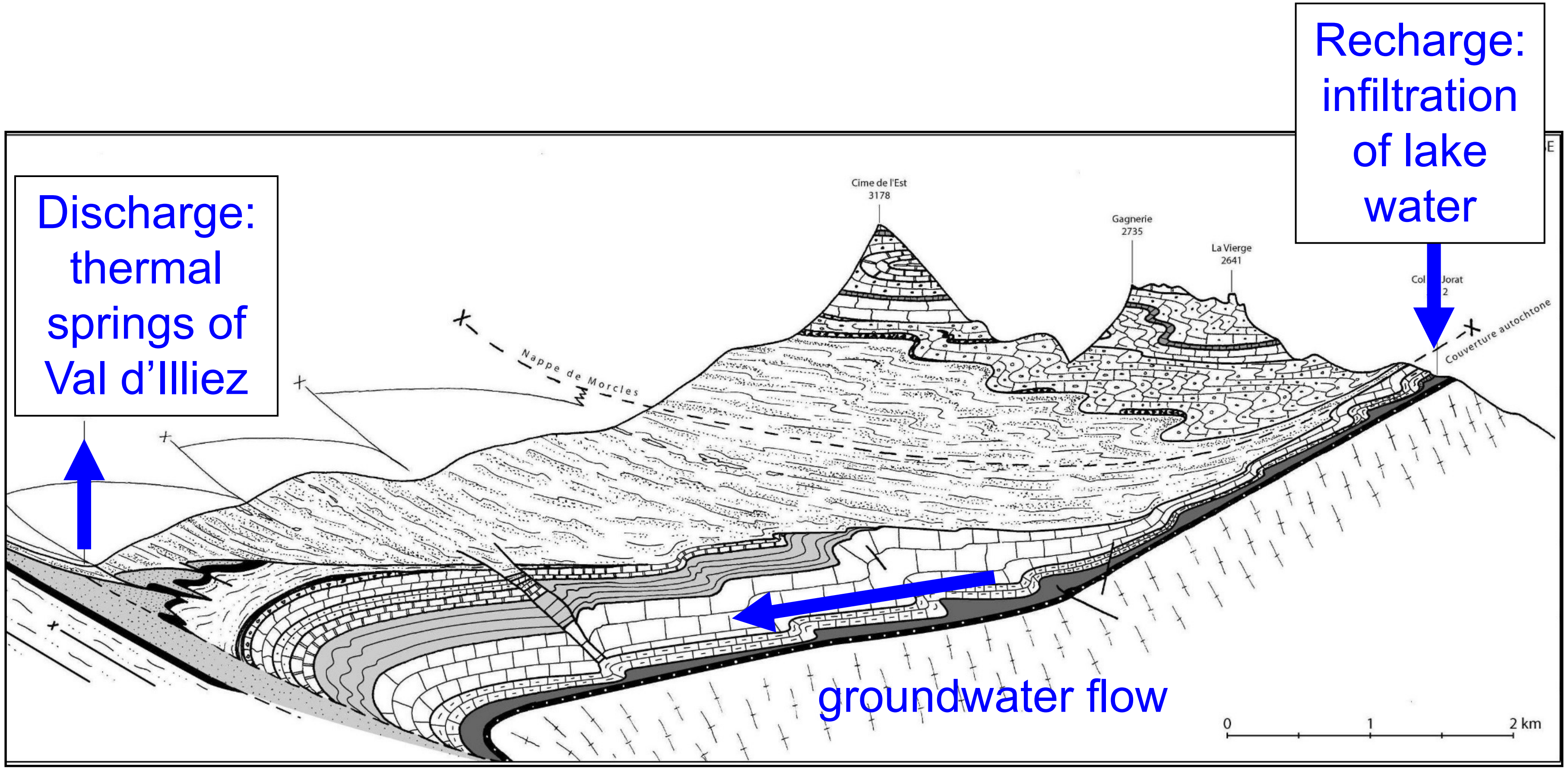
- **Note:**

$$\nu = \frac{\nu_D}{\frac{V_{connected\ void\ space}}{V_{total}}} = \frac{\nu_D}{\eta_{e\ (effective\ porosity)}}$$



ν_D = Darcy Fluid velocity [m s^{-1}]
μ = Dynamic viscosity (fluid) [Pa s]
ρ = Density (fluid) [kg m^{-3}]
g = Gravity [m s^{-2}]
k = Permeability [m^2] or [1 Darcy D = $10^{-12} m^2$]
K = Hydraulic conductivity [m s^{-1}]
F = Steady state production rate [m^3 s^{-1}]

Hydrogeological interpretation of the geological profile Val d'Illiez



Pantet (2004)

Heat transport in low-temperature systems

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- Heat transport equation (without adiabatic effect)

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Hydrothermal projects in and near the Alps

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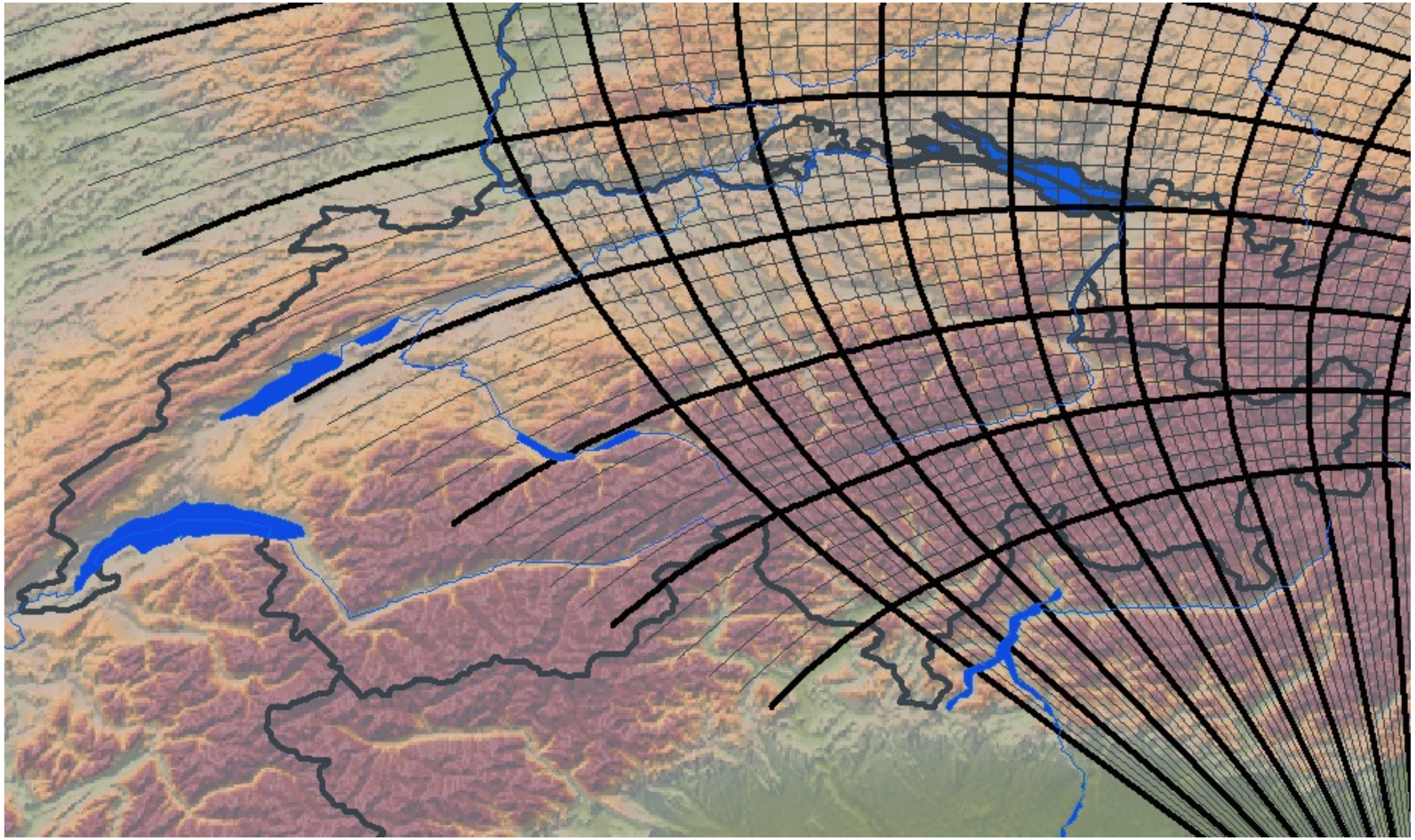
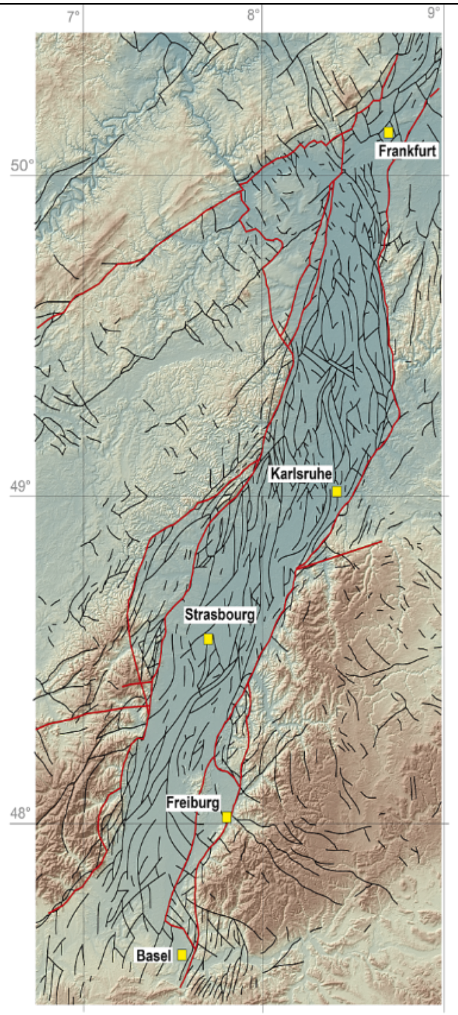
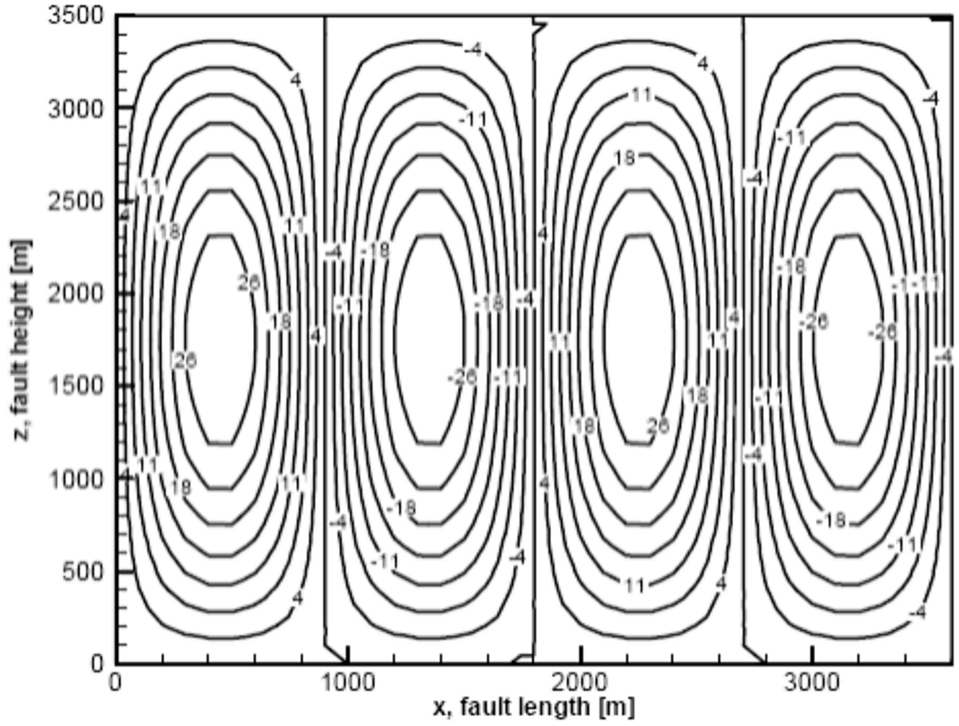


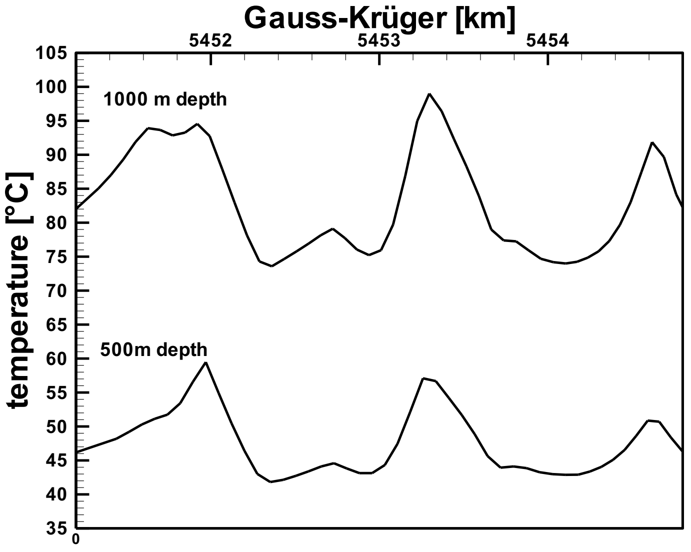


Schill, Wellmann and Regenauer-Lieb (2007)

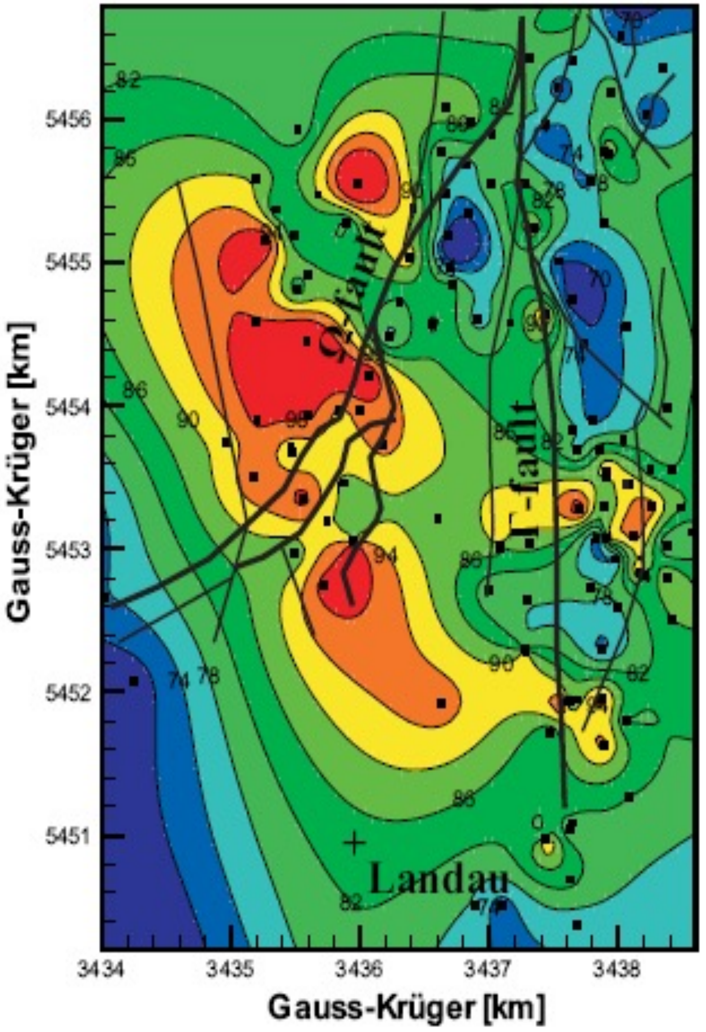
Indication for free (gravity-driven) convection in the URG

- Temperature distribution along fault zones at Landau in 1000m depth
  - Systematic temperature differences along Γ-fault
  - Analytical calculated temperature disturbance in the Γ-fault of about 15-20°C between lows and highs





Bachler, 2003



(Critical) Rayleigh number

- Ratio between hydraulic permeability and heat conductivity

$$Ra = \frac{\boldsymbol{k} \cdot \alpha \cdot \rho^2 c_p \cdot g \cdot \Delta T \cdot \Delta z}{\mu \cdot \boldsymbol{\lambda}}$$

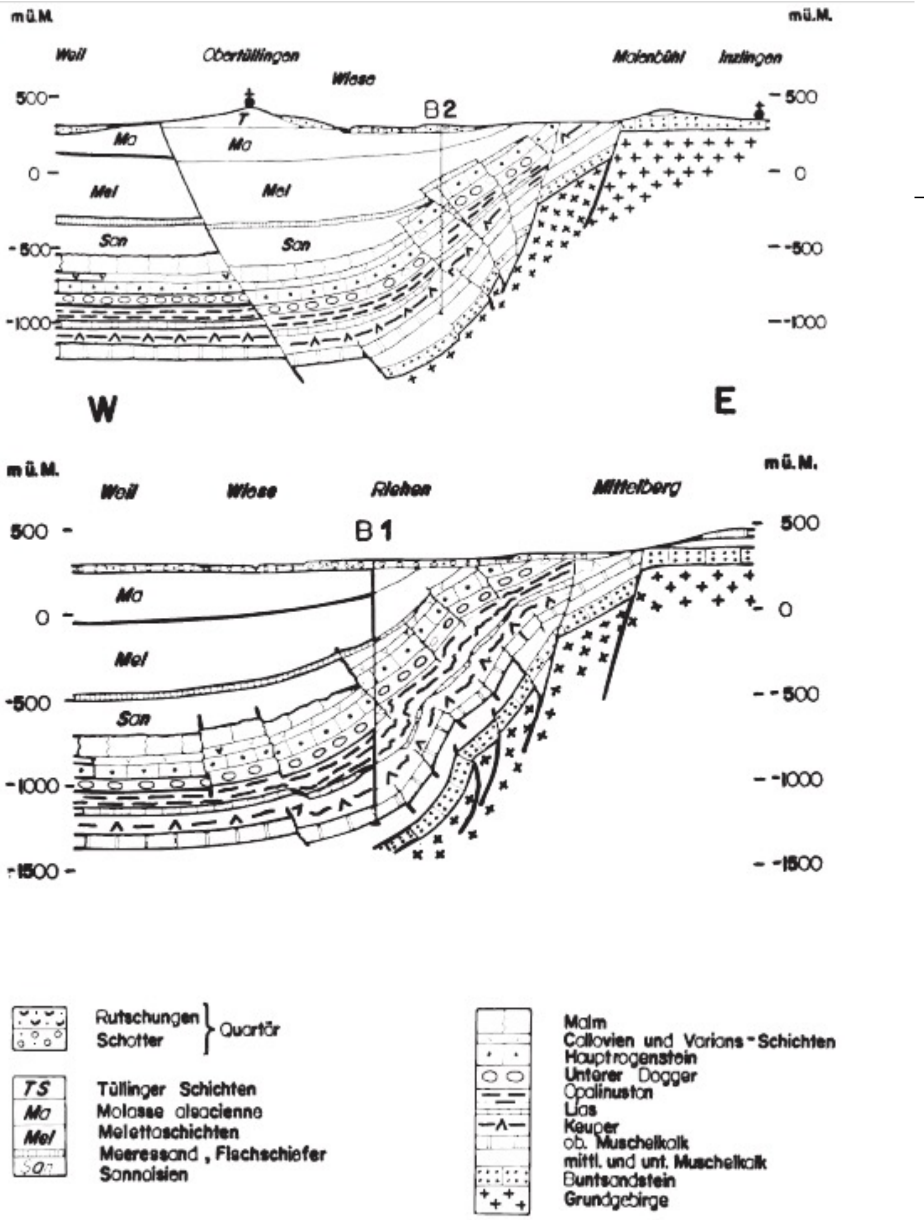
- Critical Rayleigh numbers
  - Free surfaces: Ra = $^{27}/_{4}\, \pi^4 \approx 657.51$ (Lord Kelvin, 1916)
  - Rigid lower boundary: Ra = 1100.65
  - Rigid lower and upper boundaries: Ra = 39.48

k = hydraulic permeability
α = thermal expansion
ρ = density
c_p = heat capacity of the fluid
g = gravitational acceleration
μ = fluid viscosity
λ = heat conductivity

Deep geothermal project at Riehen, Switzerland

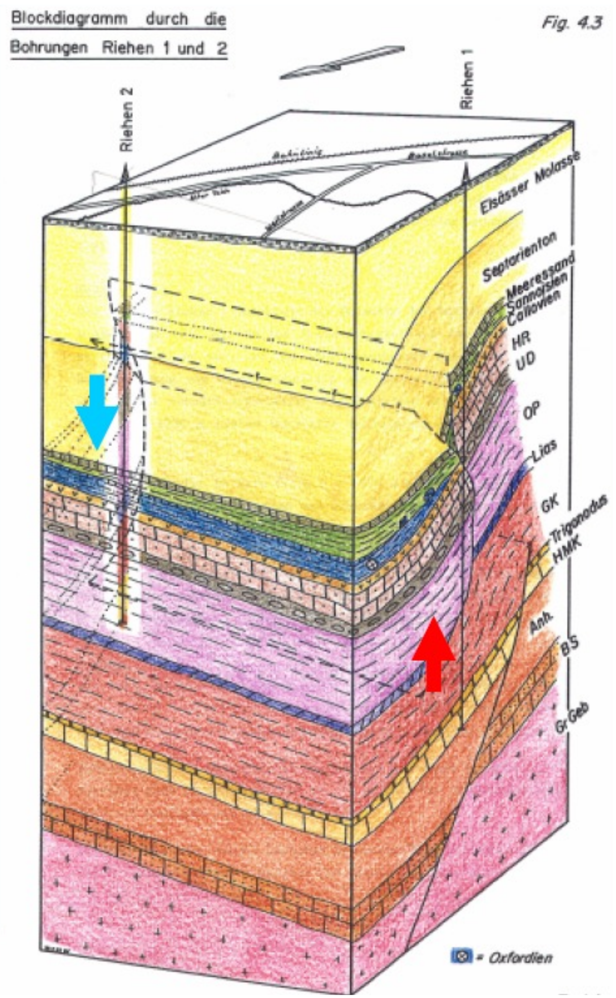
- The sediments in the vicinity of the URG boundary fault
- highly factured
- small tectonic units [Gürler et al., 1987].

- The productive formation is the Upper Muschelkalk.
- In order to obtain maximum production, the highly fractured zones near the boundary fault were selected for the doublet system [Boissavy & Hauber, 1994].



[Baudepartement Basel-Stadt 1989]

Naturally fractured reservoir Riehen (Switzerland)

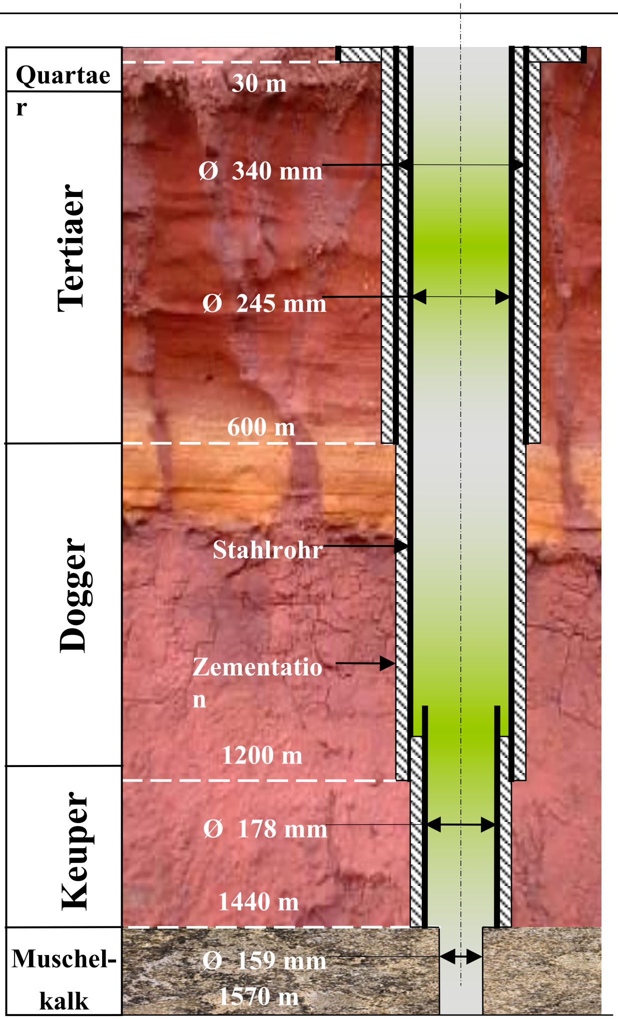


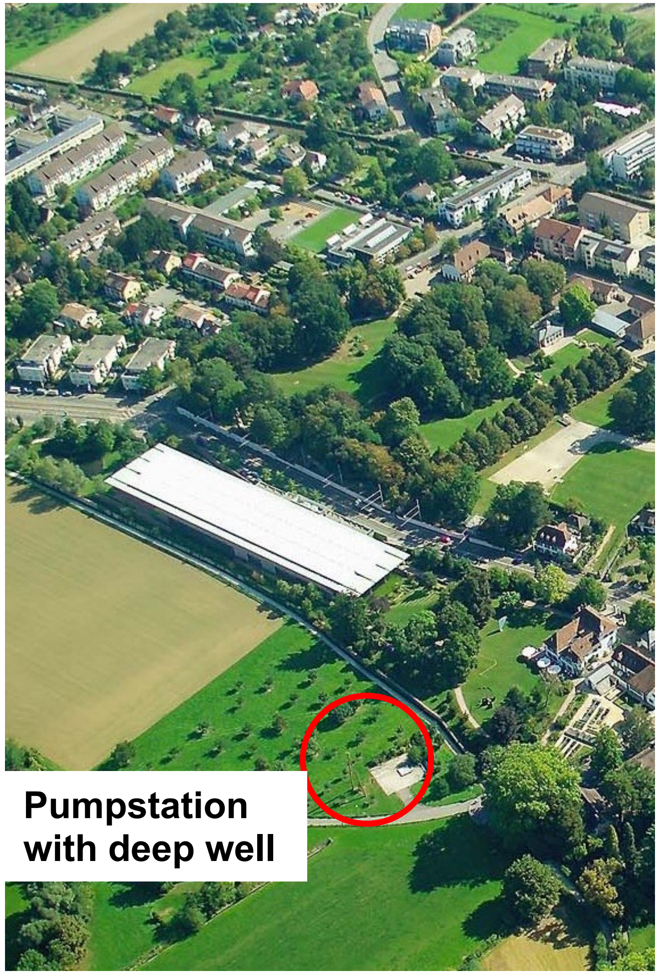
- **1988** Well RB1 (producer) and RB2 (injector)
- **1997** First trans-border heating system between Germany and Switzerland
- **2006** Riehen-Plus:
  Enhancement of the production rate from 18 to 23 L/s

- Production from the Upper Muschelkalk using a doublet system. Strong mineralisation of the brine impedes a singlet system. The well Riehen1 is deeper and thus warmer as Riehen 2.
- The reinjection guarantees the maintainance of the pressure (sustainable reservoir management)

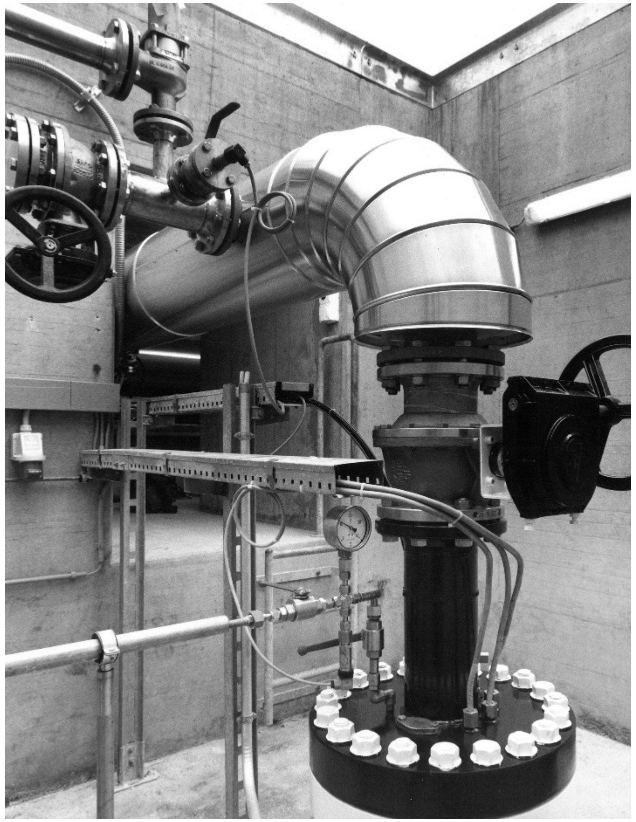
Production well RB1 (Bachtelenweg)

gruneko
a Gruner company





Wellhead
under construction and in use



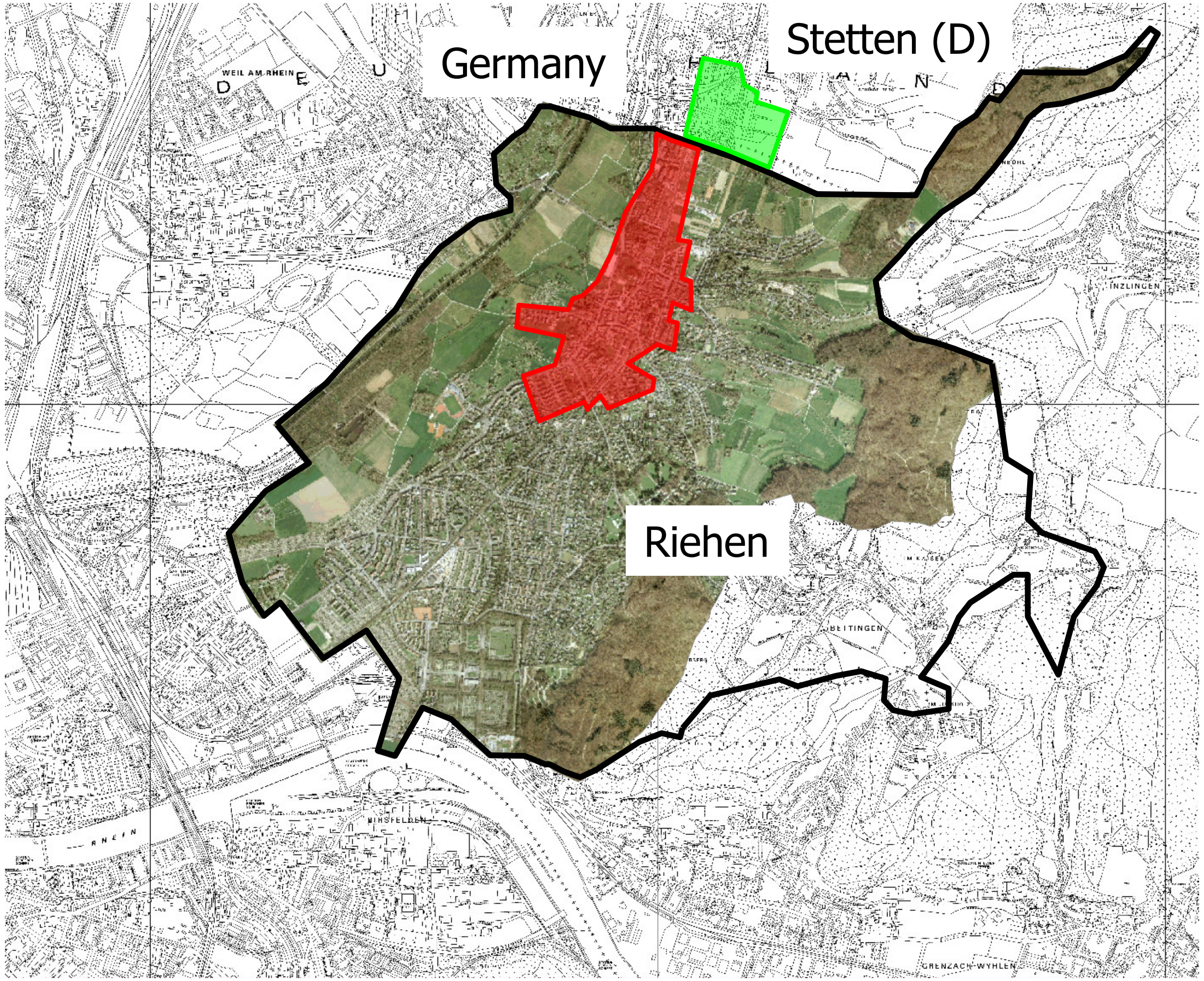
gruneko
a Gruner company

Deep geothermal project at Riehen

	Riehen 1	**Riehen 2**
Depth of Upper Muschelkalkes:		
Trigonodusdolomit	1444 - 1464 m	1123 - 1158 m
Hauptmuschelkalk	1464 - 1536 m	1158 - 1223 m
	2 m (1 fracture)	9 m (3-4 fractures)
Pressure:		
	300m a.s.l. + 25 m artesic	300m a.s.l. + 15 m artesic
Temperature in the Aquifer:		
	66,4 °C	52,2 °C
Distance between wells:		
	960 m	

Direct use

- Service aera as per 2009
  - Production rate 18'300 kW
  - Customers 202
  - Production temperature 65°C
  - Injection temperature 29°C
  - Production 18 l/s (~65 m^3/hr)
  - Sales of heat 26'000 MWh/a
  - Heating district 21.4 km
  - The sales of geothermal heat corresponds to the use of 3'000'000 liters of oil



Concept of district heating at Riehen