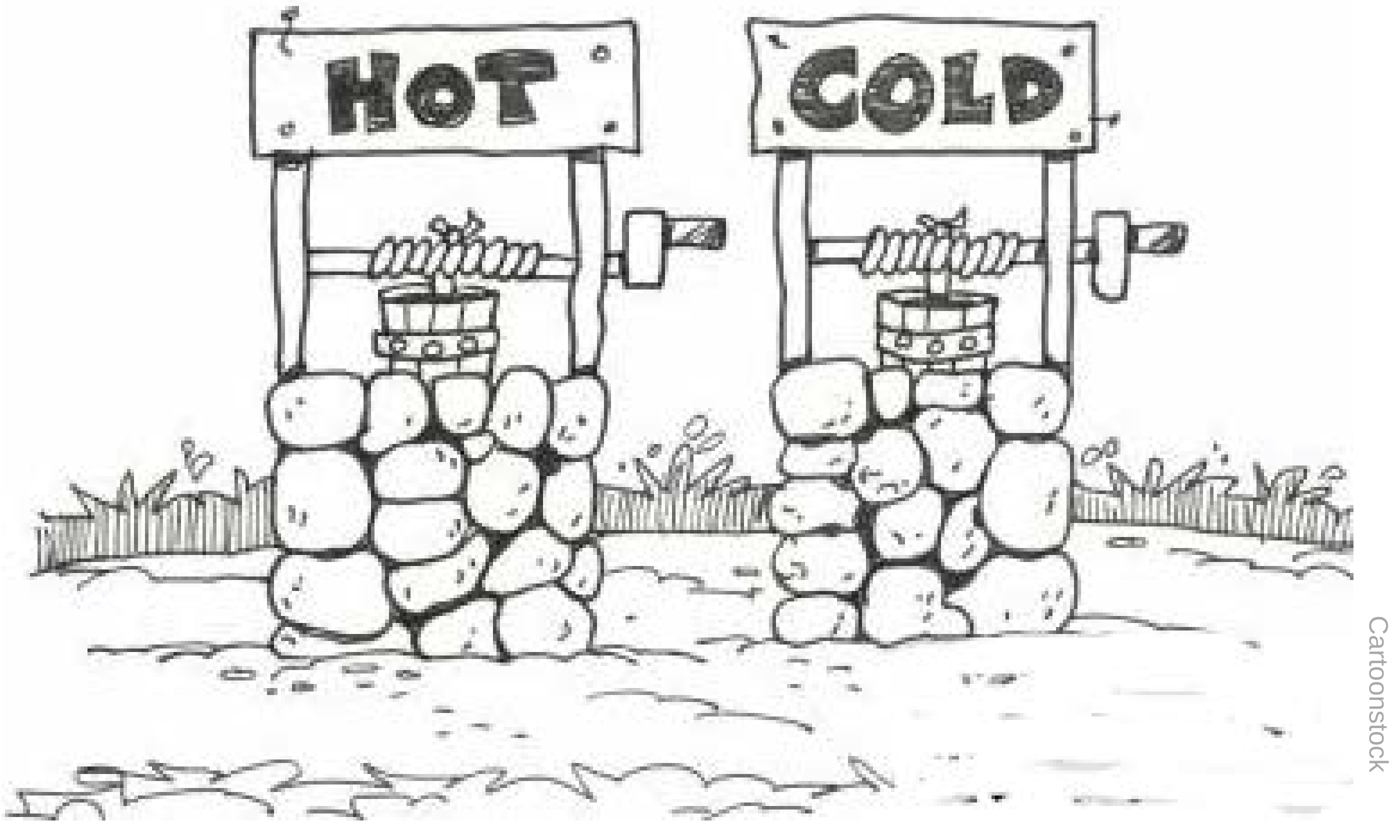
Peter Bayer

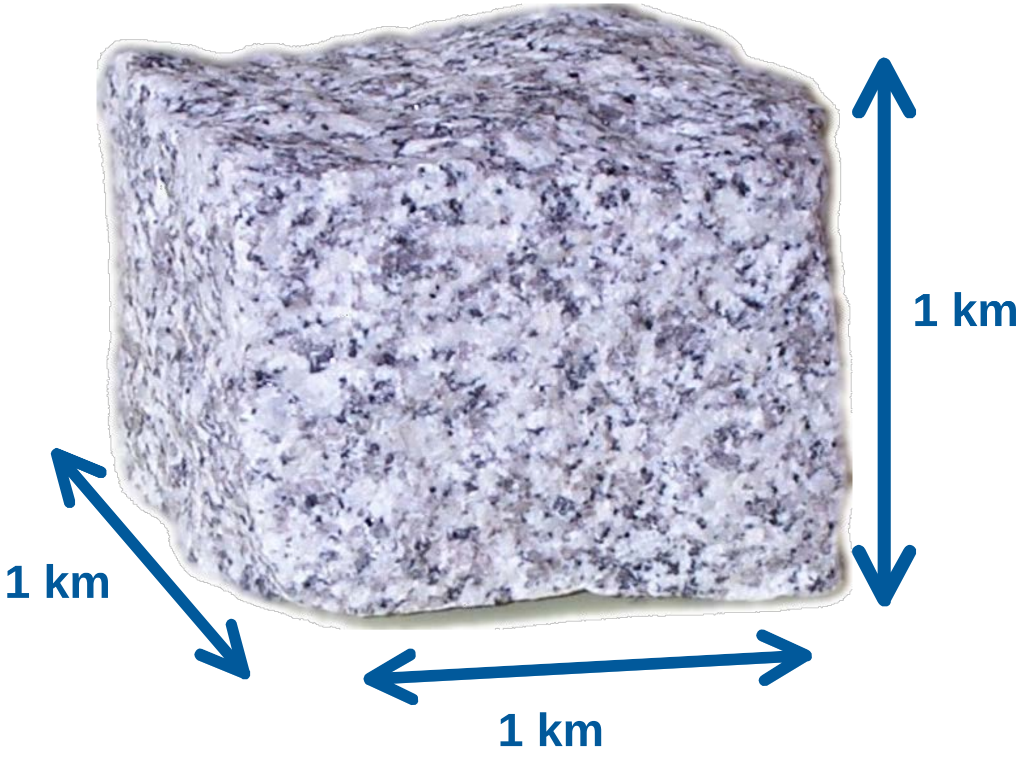
GEOTHERMAL ENERGY



How much energy is in a rock?

1) How much **energy** will 1 km³ of a 200°C hot granite release when cooled by 20 K?
2) If we assume that η=13% of this energy can be **transformed in electrical energy**, what is the capacity of a power plant sustained for 20 years?

$$E = \underbrace{C}_{2.5\ \mathrm{MJ/m^3K}} \cdot \underbrace{V}_{10^9\ \mathrm{m^3}} \cdot \overbrace{\Delta T}^{20\ \mathrm{K}} = 5 \cdot 10^{10}\ \mathrm{MJ}$$



$$P = \eta\, E / 20\ \mathrm{y} = 10.3\ \mathrm{MW_{el}}$$

Availability of geothermal energy

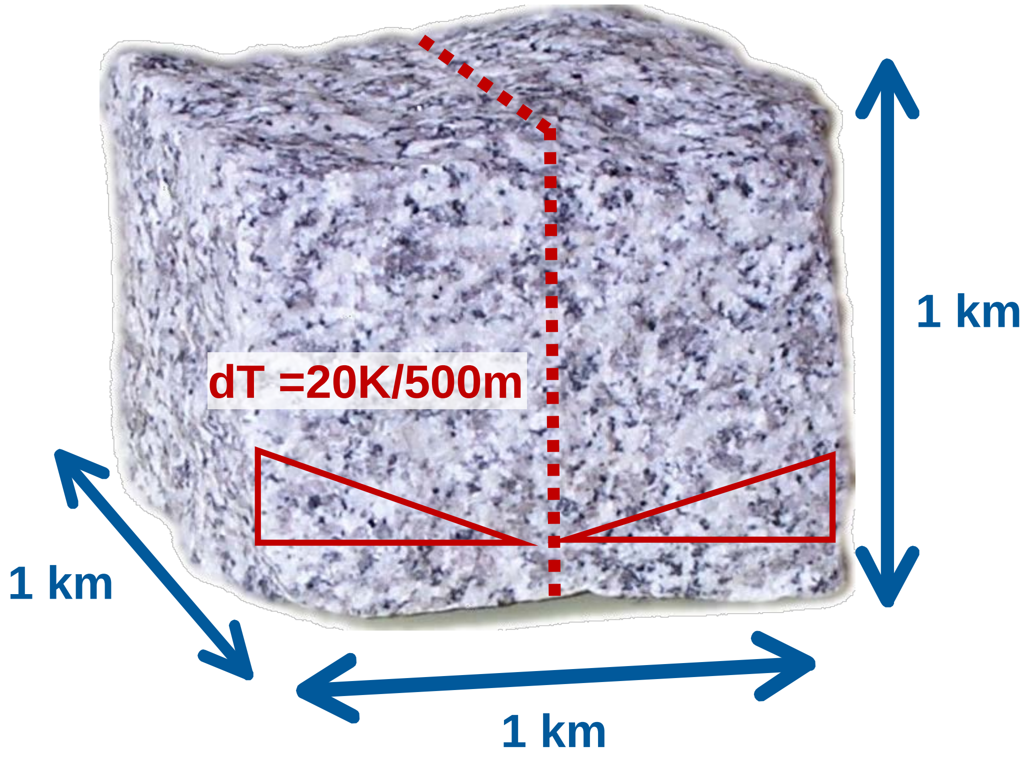
Heat flux into granite cube

What is the thermal power of this cube, if the temperature at a central cross section would be 20 K lower and there exists a linear thermal gradient from the outer cube face (simplified 1-D model)?

20 K   500 m

$$P = \lambda \cdot A \cdot \Delta T / \Delta x = 0.12\ \text{MW}$$

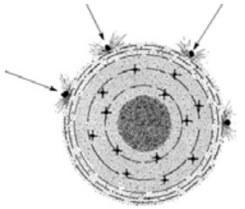
3 W/mK $10^6\ m^2$



What we know today:

The **flow of heat from Earth's interior to the surface** is estimated at 47 TW (heat loss). The heat emerges at the surface at volcanoes and mainly heat conducted through the crust. This heat is radiated into space, primarily at infra-red wavelengths.

50% of the Earth's underground heat is from radioactive elements. This heating is caused by the decay of elements such as potassium, uranium and thorium.



50% of the Earth's heat, with the other heat coming from the primordial heat of the Earth (heat from the Earth's formation).

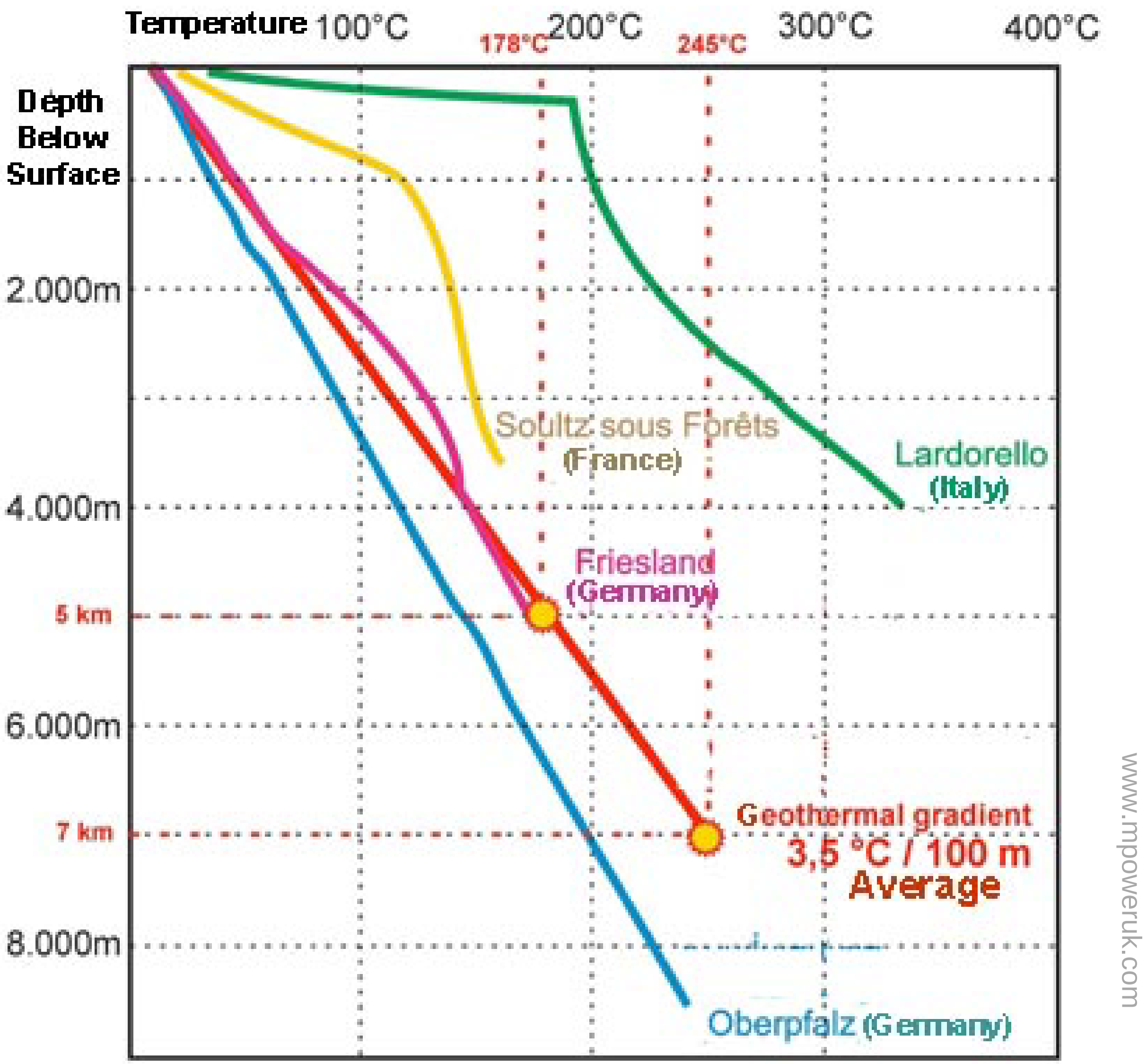
+ **at the surface**: absorption/emission of heat, interaction with atmosphere
→ Local heat gain during last century due to climate change

<u>Note</u>: heat energy coming from Earth's interior is actually only 0.03% of Earth's total energy budget at the surface, which is dominated by 173,000 TW of incoming solar radiation.

→ Thus, it is solar energy that drives weather, climate, and erosion. But it is geothermal energy that powers plate tectonics and mountain building.

Availability of geothermal energy

Geothermal gradient



30 °C/km - average

10 °C/km - on old continents

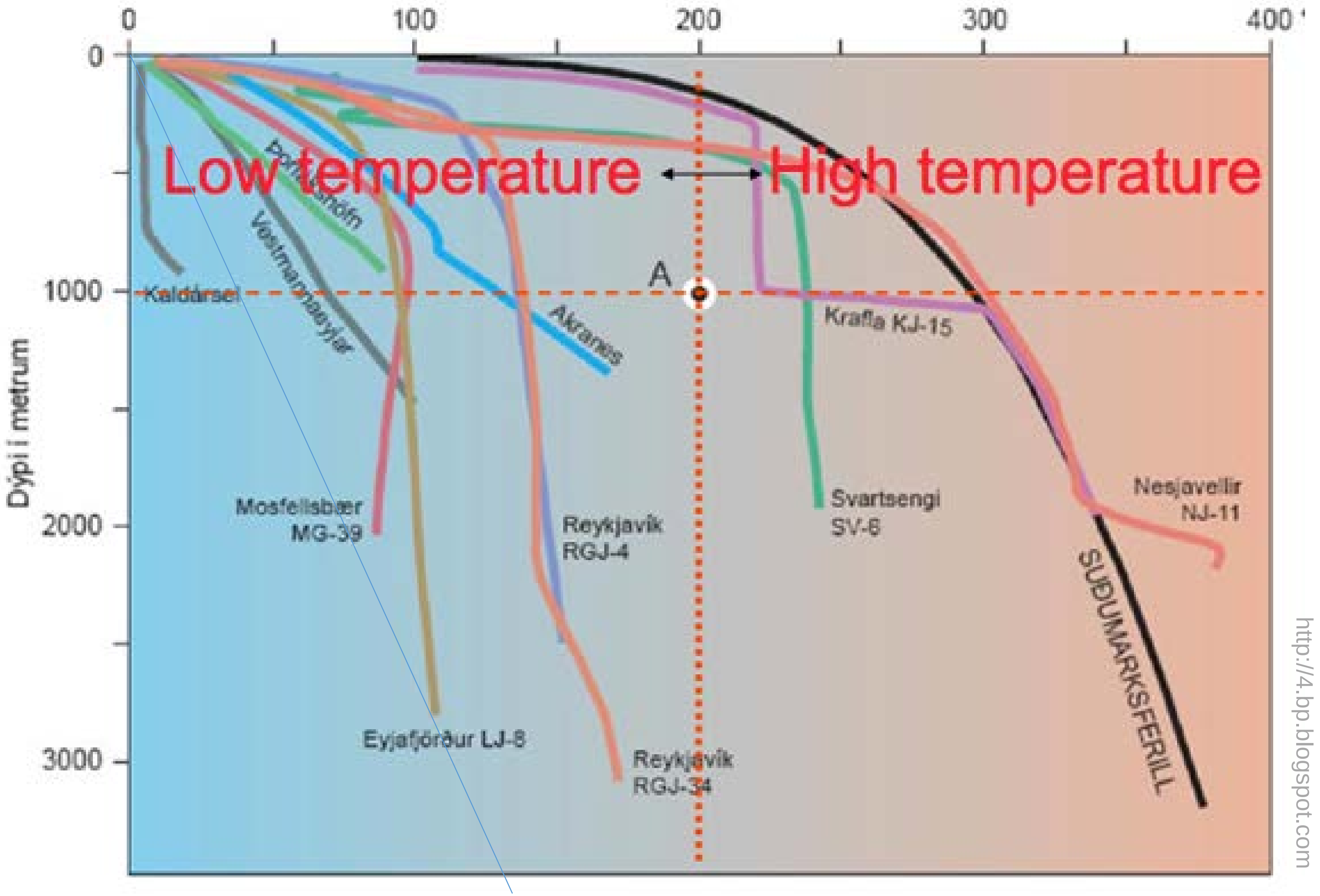
→100 °C/km in rift regions

→200 °C/km: in young continents, plate boundaries, with volcanic activity

<1 °C/km in mantle

High–enthalpy geothermal energy

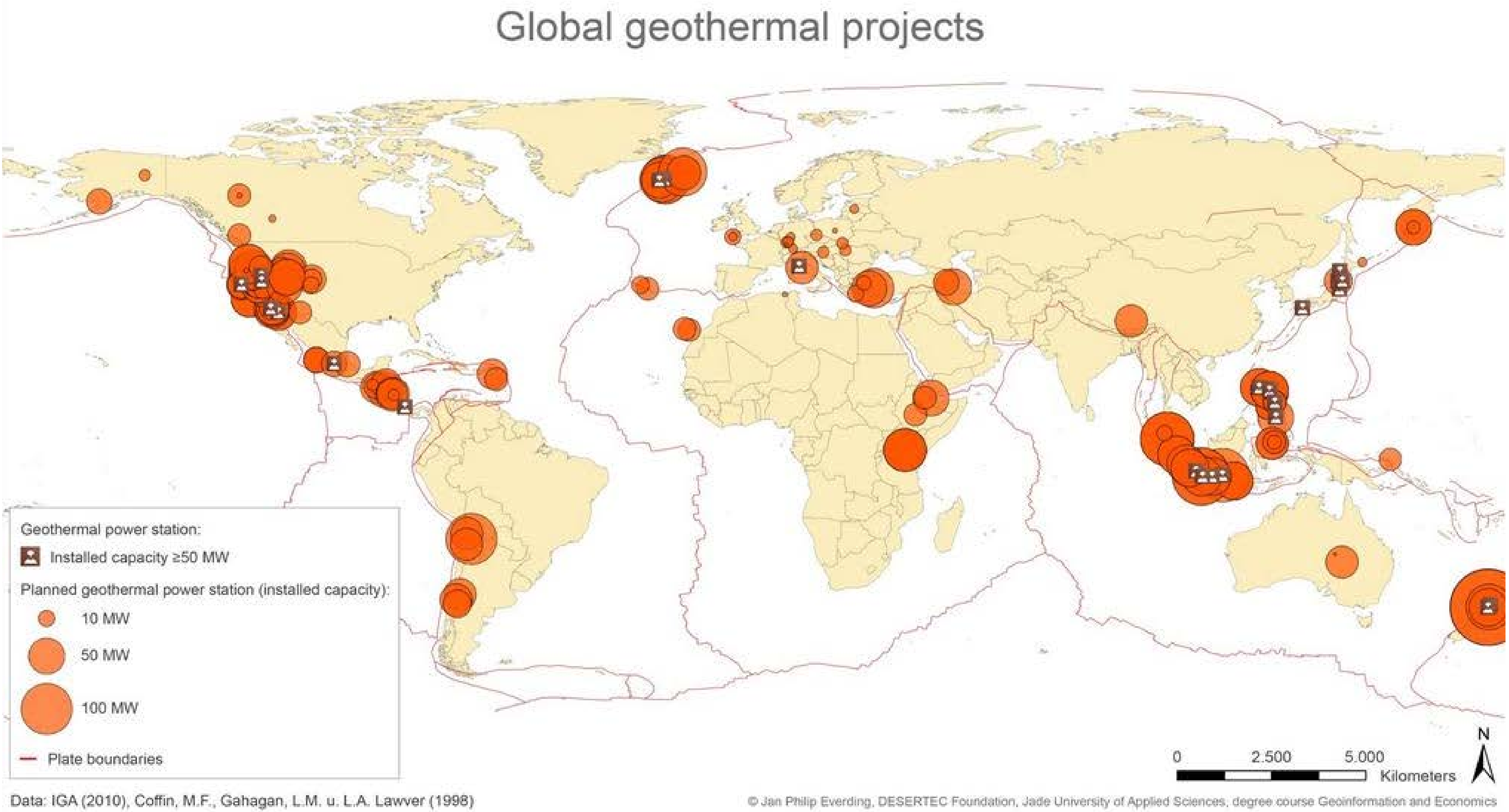
Geothermal gradient



… “low temperature” in Iceland .

High–enthalpy geothermal energy

Plate tectonics and geothermal power generation



> 10,000 years ago: history says that American Paleo-Indians were the first to use of geothermal energy – they used water from **hot springs** for cooking, bathing and cleaning.

http://geothermaleducation.org

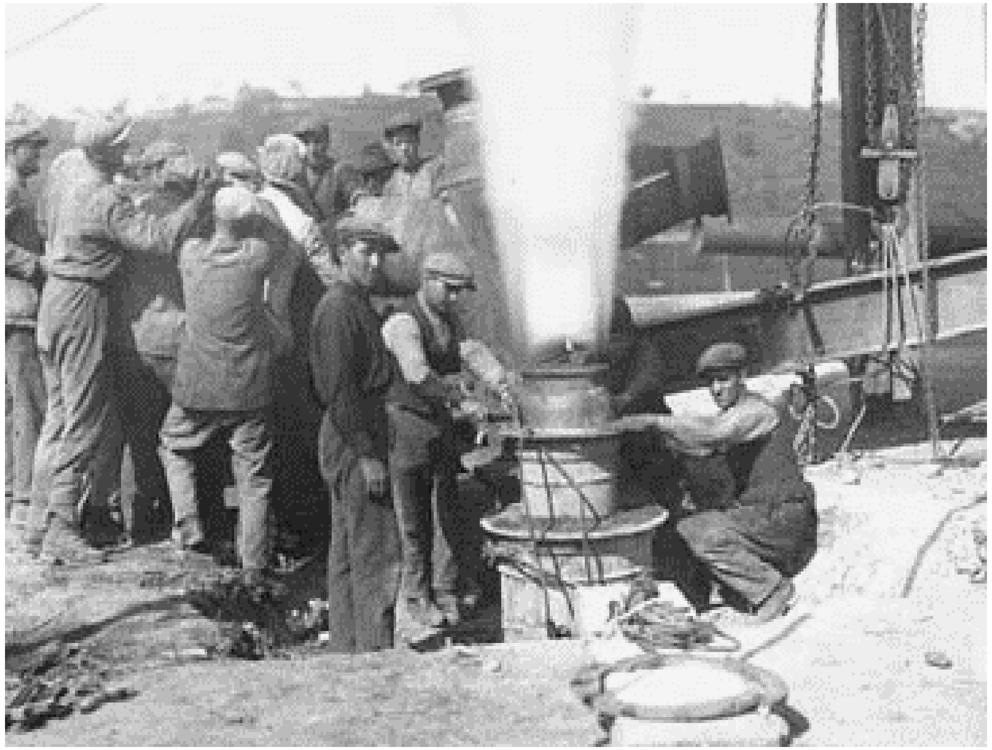
High–enthalpy geothermal energy

History

1827: The first industrial use began near Pisa, Italy. Steam coming from natural vents (and from drilled holes) was used to extract **boric acid** from the hot pools that are now known as the *Larderello* fields.

1904: The birth of **geothermal power generation** ("indirect use")
1911: The first commercial power plant at Larderello

alchetron.com



www.reuk.co.uk

Prince Piero Ginori Conti tested the first geothermal power generator on 4 July 1904. The Larderello power plant was the world's only industrial producer of geothermal electricity until New Zealand built a plant in 1958.

…until today: current generation of ~600 MWe at Larderello, “dry steam”.

.

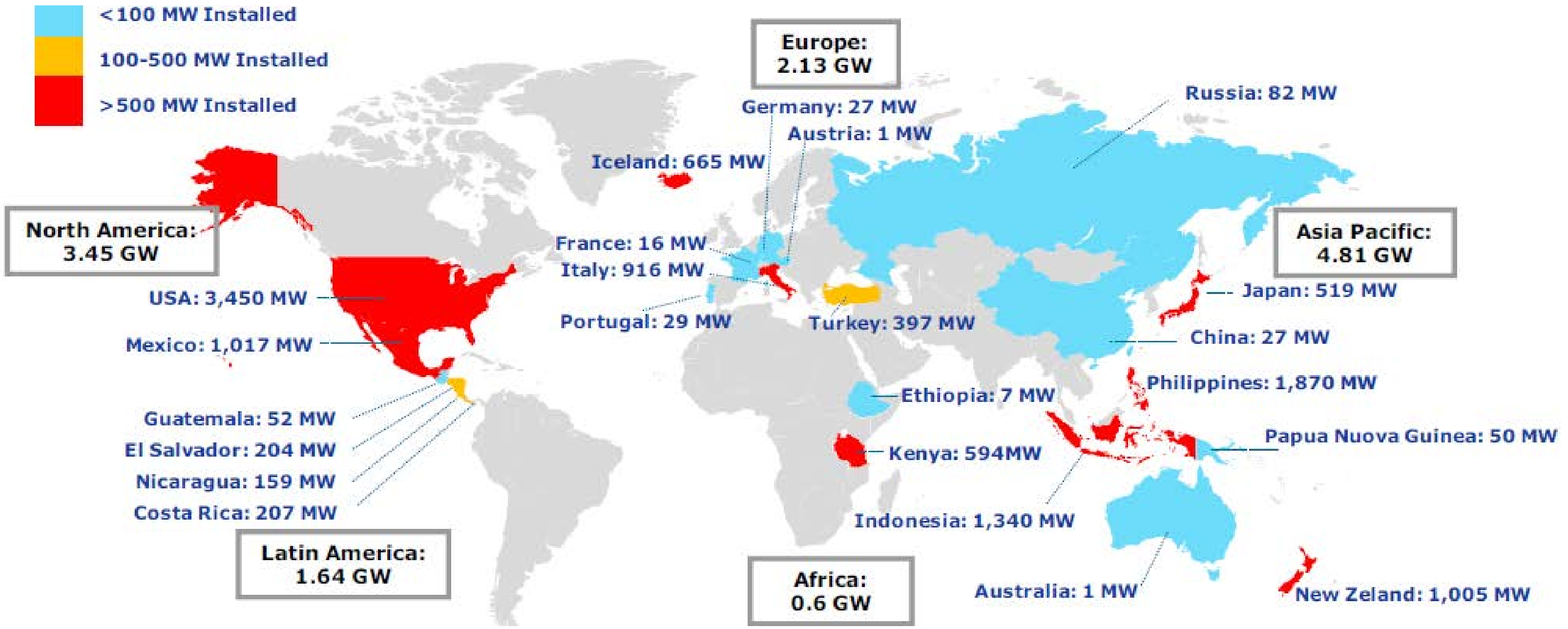
Currently around 1 Mio. homes are powered by geothermal electricity from Larderello ~10% of the world’s total geothermal electricity production.

www.reuk.co.uk

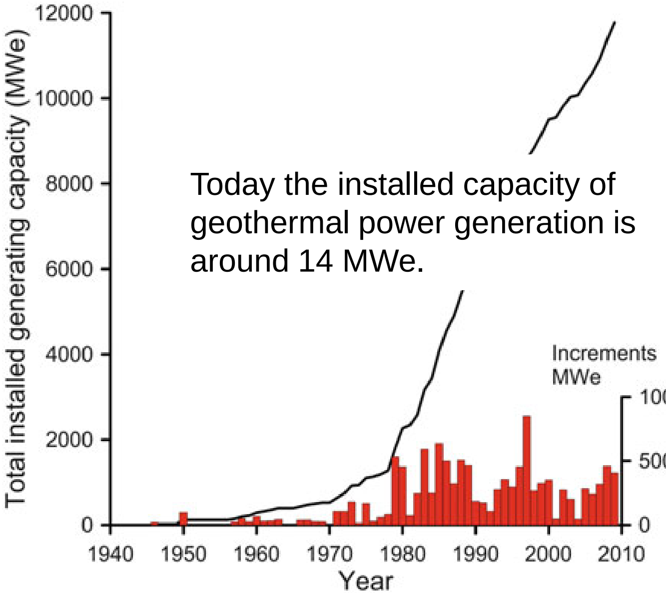
Todays view at Larderello power station.

High–enthalpy geothermal energy

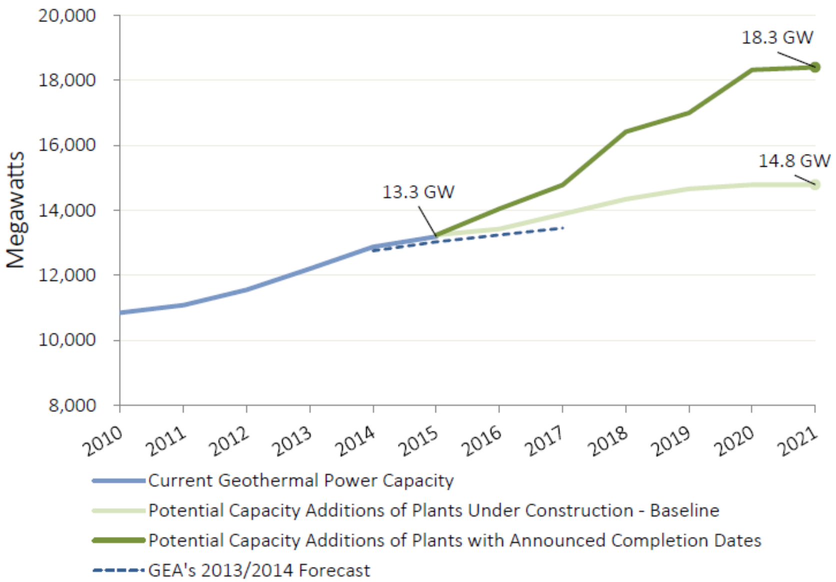
History



Bertani, WGC, 2015



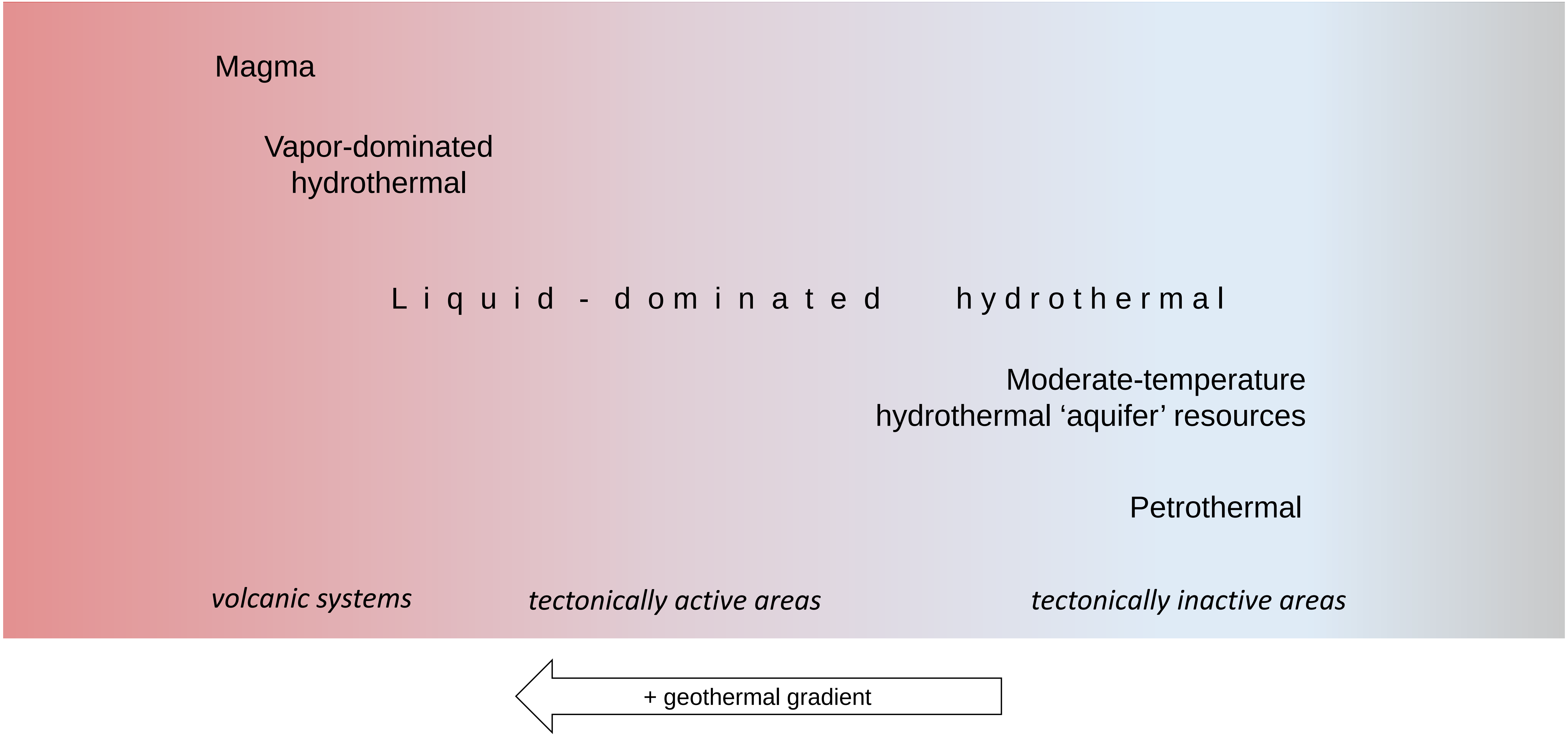
Today the installed capacity of geothermal power generation is around 14 MWe.



2016 Annual U.S. & Global Geothermal Power Production Report

High–enthalpy geothermal energy

Sorted categories



Hydrothermal systems: where the reservoir contains significant quantities of water that can be mobilized.

Almost all operational geothermal systems are of this type.
- They come in many different forms.
- Generally speaking, these systems are **built by nature**, and so the resource is **limited**.
- The principal challenge is to **find** them.

There are three geothermal power plant technologies being used to convert hydrothermal fluids to electricity. The conversion technologies are dry steam, flash, and binary cycle. The type of conversion used depends on the state of the fluid (whether steam or water) and its temperature.

State of the fluid		Power plant conversion technology
Dry steam (Vapor dominated)	→	Dry steam plant
Liquid dominated	→	Flash steam systems (> 180 °C), Binary cycle (>120 °C)
Moderate-temperature ‘aquifer’ resources	→	Binary cycle (>120 °C)

High–enthalpy geothermal energy

Exergy of steam

*Note: The exergy (the energy available for work) of steam is much higher than of water. This is largely due to the huge amount of energy needed to transform 1 kg of water to steam (**latent heat of evaporation of water**), which is 2.27x10^{6} J/kg!*

For example:
- *50 kg/s of water at 200°C cooled to 30°C will produce ~6 MW$_{el}$.*
- *However, 50 kg/s of steam at 200°C cooled to 30°C will yield ~34 MW$_{el}$.*

Turbines for geothermal electricity production only work with steam or gas (water would destroy them). High-temperature wells do not need production pumps. You open the wellhead and the steam emerges – usually rather violently.

Vapor-dominated or dry steam reservoirs are full of steam.

Many reservoirs may contain vapor-dominated zones (“steam cap”), particularly at shallow depth.

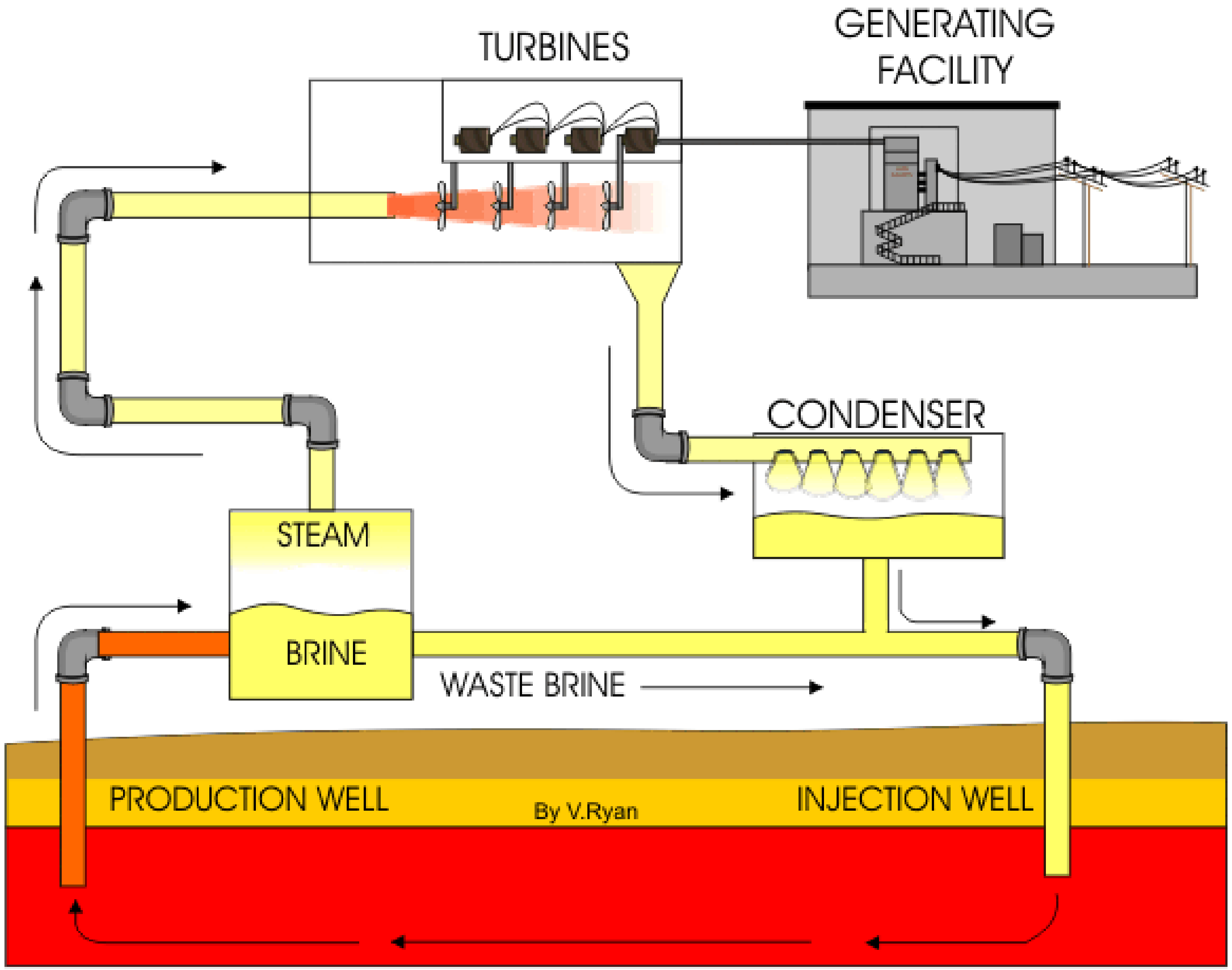
Examples are
The Geysers (California, USA),
Larderello (Italy)
Kamojang, Darajat (both in Java, Indonesia)

Darajat Unit I
total capacity: 240 MW_{el}

http://www.thinkgeoenergy.com

High-enthalpy geothermal energy

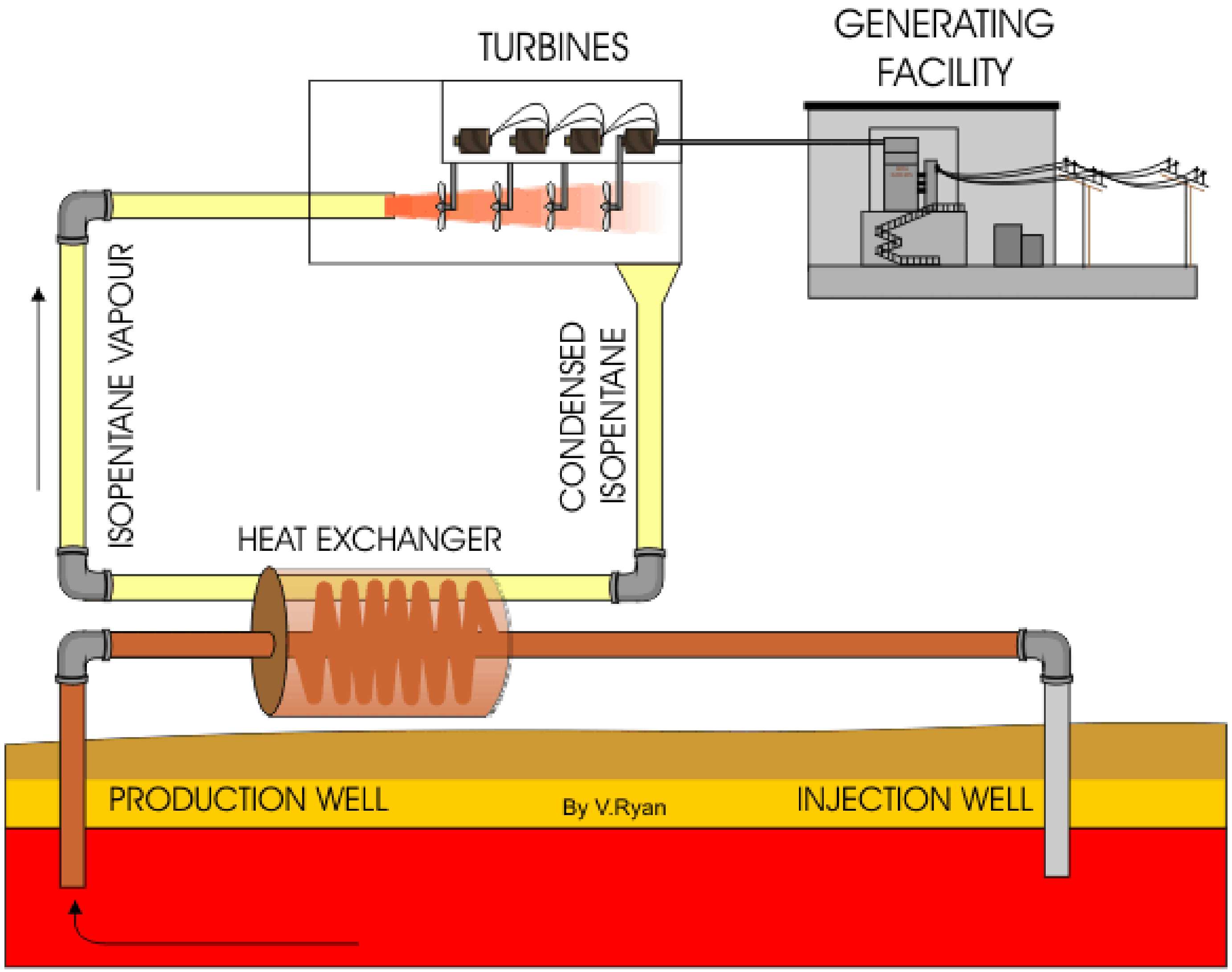
Energy conversion: Flash steam



www. technologystudent.com

High-enthalpy geothermal energy

Energy conversion



www. technologystudent.com

If the water that reaches the surface is not hot enough to produce steam, it can still be used to produce electricity by feeding it into a Binary Power Plant.

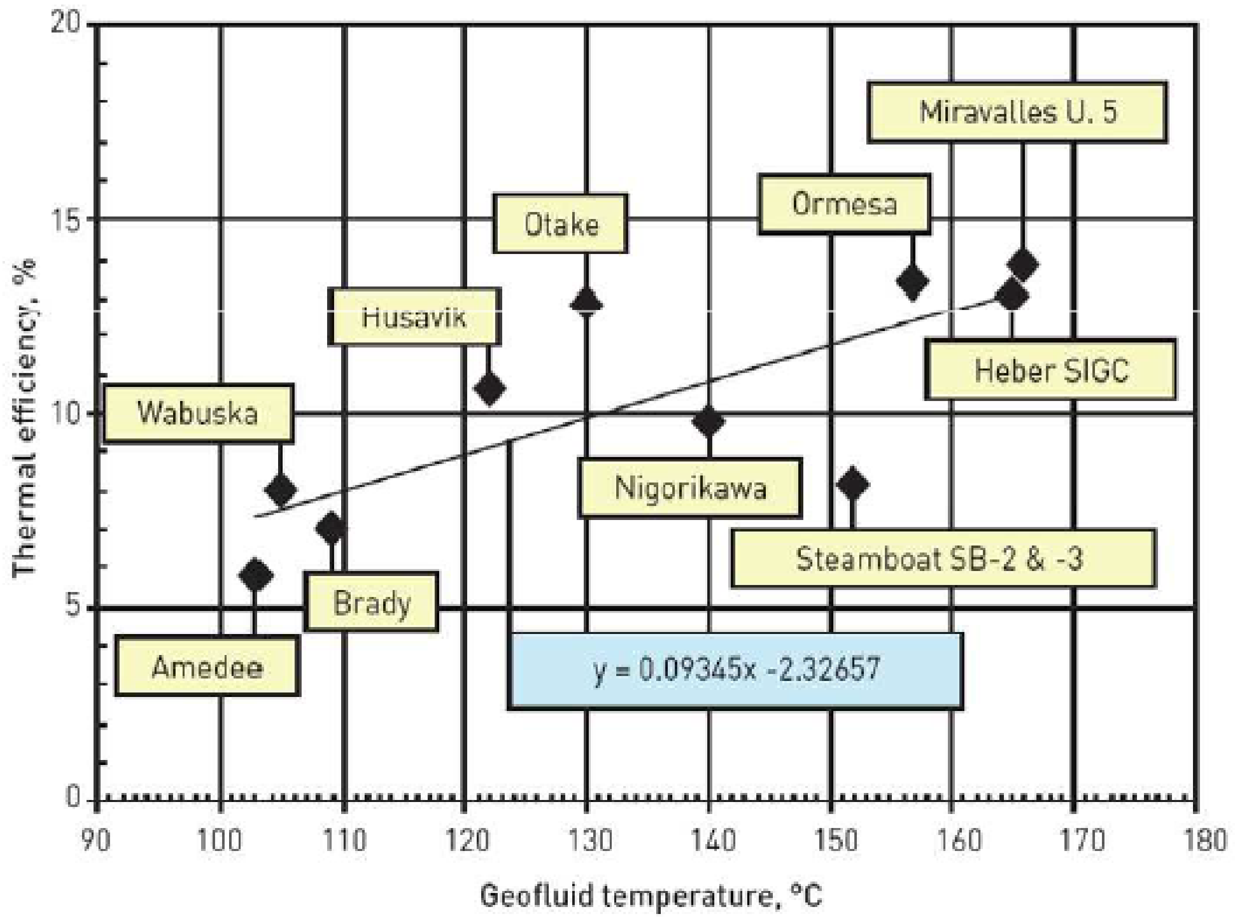
The hot water is fed into a heat exchanger. The heat from the water is “absorbed” by a liquid which boils at a lower temperature.

The fluid used for this are ‘organic’. Thus, the systems are commonly referred to as ‘Organic Rankin Cycle (ORCs)’. Ammonium-water also used as a working fluid (Kalina-cycle)

Binary power plants are closed systems.

High–enthalpy geothermal energy

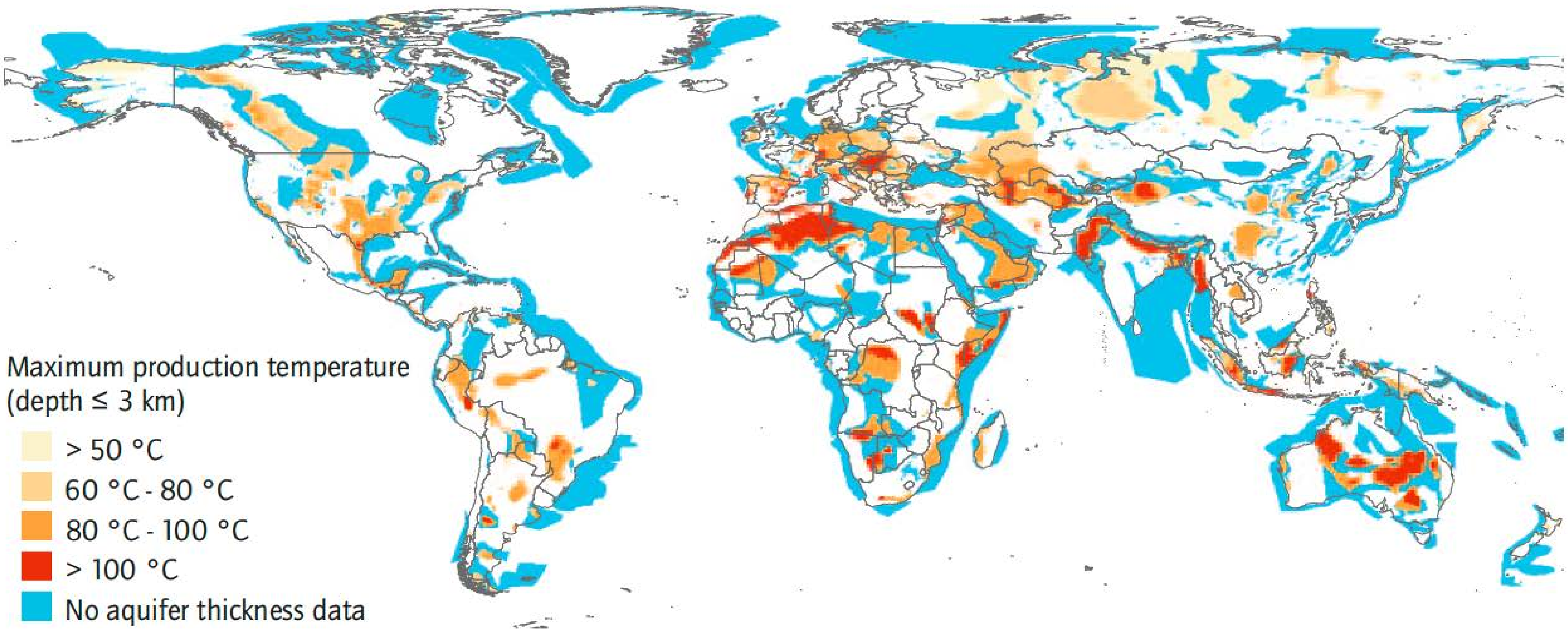
Energy conversion



Typical efficiencies for electricity generation for 50°C cooling and production fluid temps. of 100°C and 170°C are <**10% and 18%** resp.
Binary plants are usually constructed in small modular units of a few MW_{el} capacity. These units can then be linked up to create power-plants of a few tens of megawatts.

High–enthalpy geothermal energy

Hydrothermal, moderate–temperature ‘aquifer’ resources



From IEA ‘Technology Roadmap-Geothermal’ 2011

Many areas of the world are underlain by **aquifers** at depths of 2-5 km that contain water at temperatures of 70-160°C, depending upon the local heat flow.

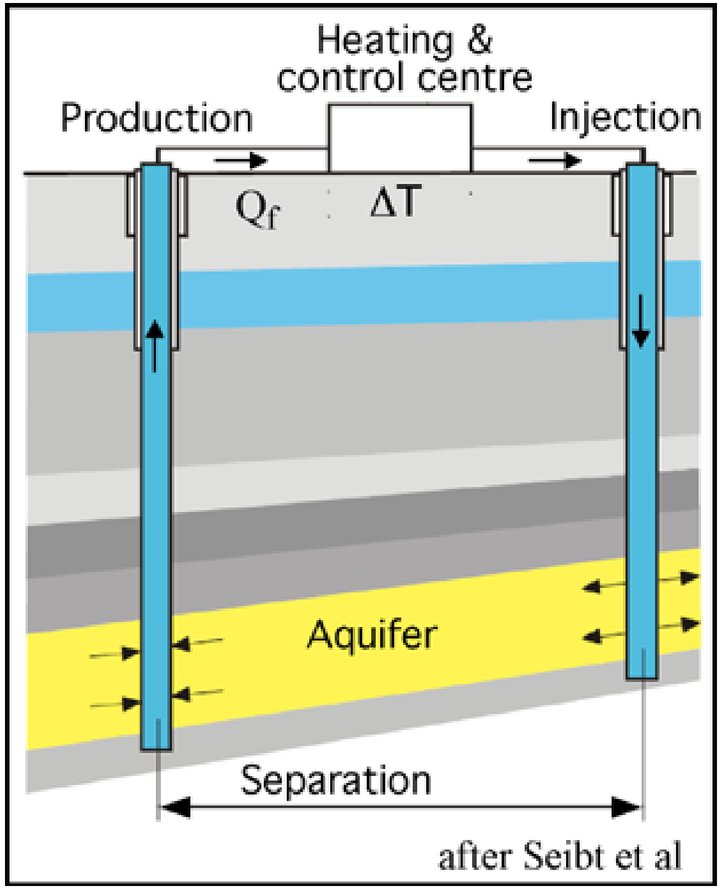
In many places there is sufficient **permeability** from primary (matrix) porosity or from faults or fractures to allow geothermal system development.

High–enthalpy geothermal energy

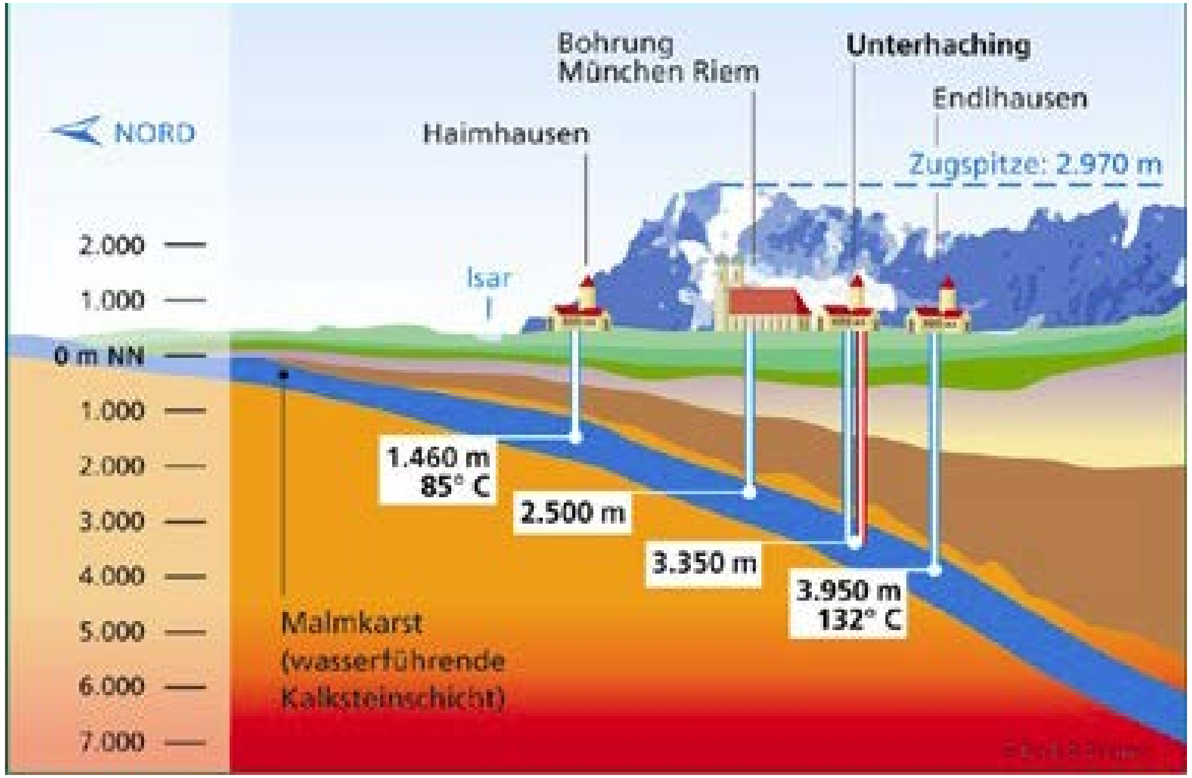
Hydrothermal, moderate–temperature ‘aquifer’ resources

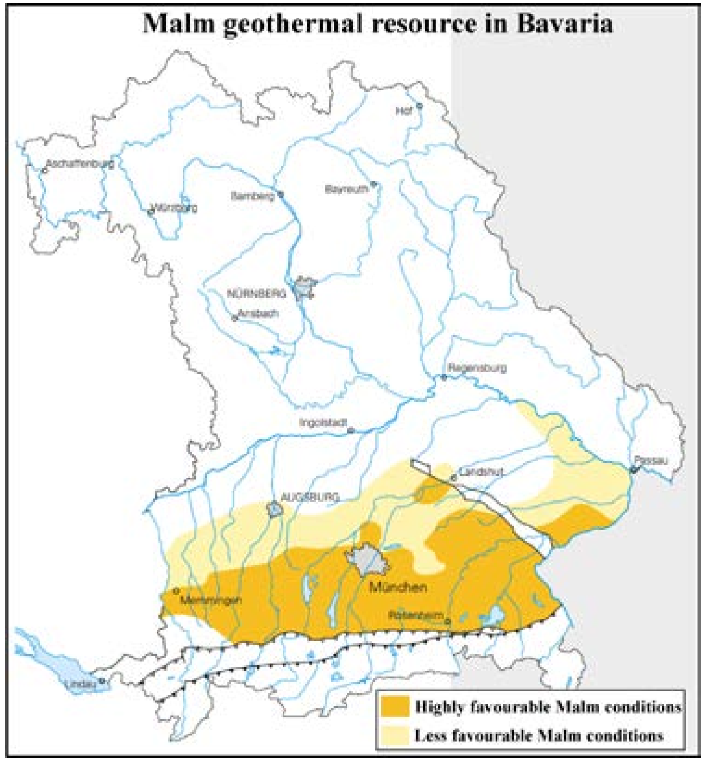
Most geothermal development in Europe outside the ‘volcanic’ areas exploit moderate temperature ‘aquifers’. The systems are predominantly used to supply district heating systems, although many now produce electricity in the summer months.

Usually there are one or two production wells and one injection well (doublet and triplet resp.).



The *Malm* is an extensive late Jurassic carbonate bed found extensively over Europe.
In the South German/Austrian Molasse basin from west of Munich eastward into Austria, the Malm has proven to be a particularly productive source of geothermal water, thanks to faulting and karstification. The first drilling to supply water for district heating was in Austria in the mid-1970’s. In the last 10 years there has been a surge in activity, with numerous communities using the water for district heating. The Malm unit is typically several hundred meters thick and lies on or just above crystalline basement. It deepens towards the south. The shallowest systems in the north are ~750 m (37°C) and the deepest in the south of Munich are 6,036 m (165°C, *Geretsried*, <10 l/s → sidetracks planned).

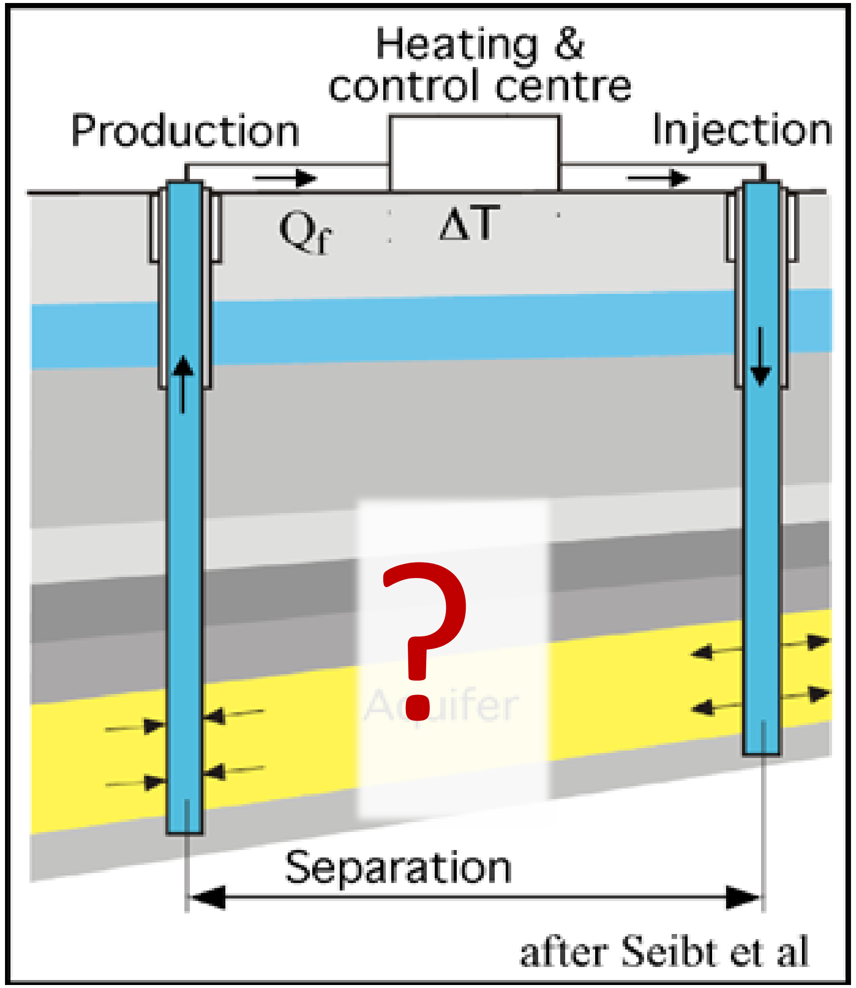




The pattern of flow within deep geothermal reservoirs is rarely understood, especially if it is fracture, fault or karst controlled.

It is not essential (or possible) that the geometry of the flow field is known. Geothermal project developers are primarily concerned with ensuring the wells can produce commercial quantities of hot fluid for modest driving pressures.

The problem of longevity is solved by placing the injection and production wells sufficiently far apart so that thermal breakthrough does not occur for many years.

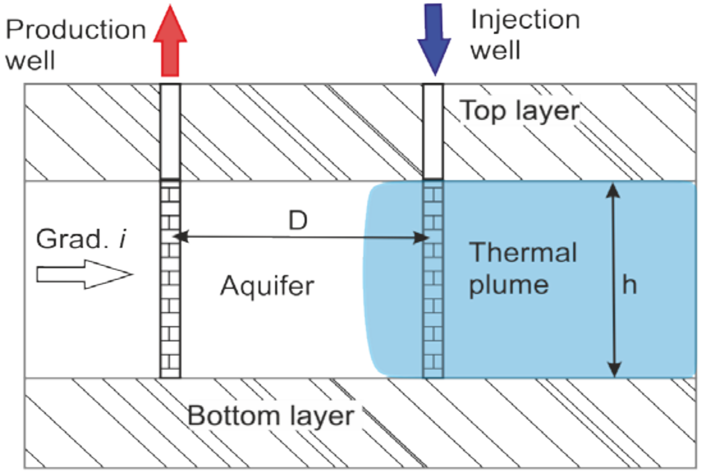


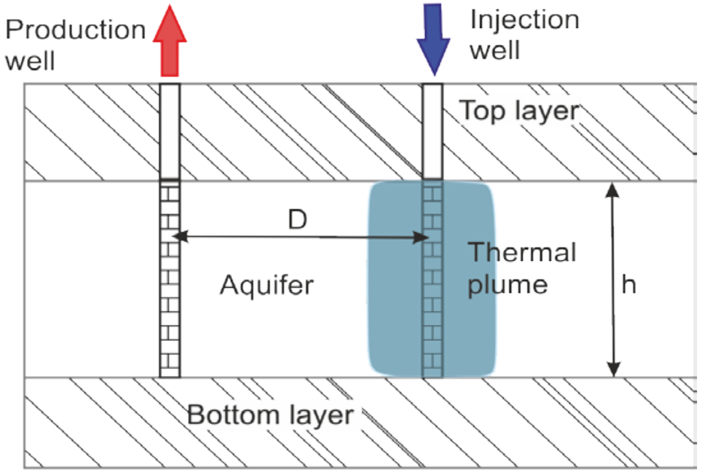
High-enthalpy geothermal energy

Hydrothermal, moderate-temperature 'aquifer' resources

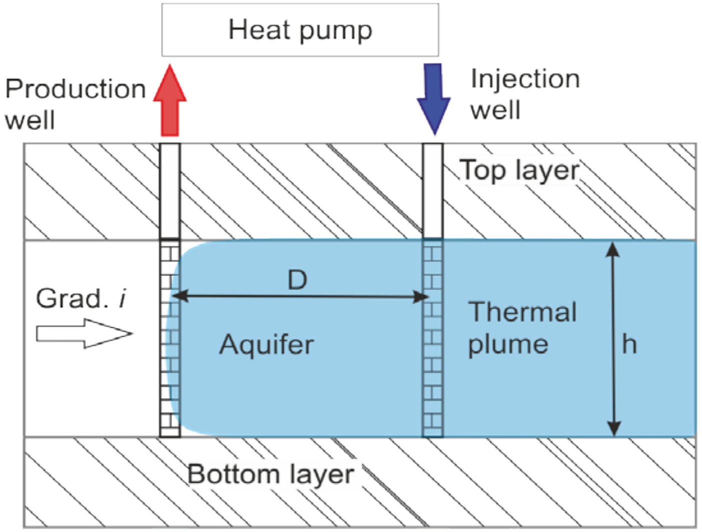
groundwater flow

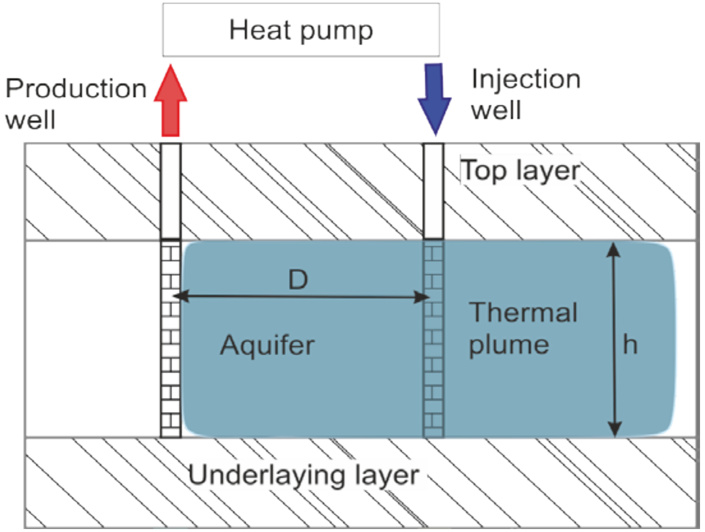
no groundwater flow





no thermal breakthrough





thermal breakthrough

CASE A - background flow:

Assuming homogeneous hydraulic and thermal properties of the ground, neglecting heat diffusion and loss to the (impermeable) formations below and above the aquifer layer, the minimum well distance for avoiding thermal breakthrough is calculated as:

$$D > \frac{2Q}{\pi\, h\, K\, i}$$

where *K* is the hydraulic conductivity [m/s], and *h* [m] is the vertical width (or thickness) of the aquifer.

In practice, the value of *D* required to ensure that there is zero risk of thermal feedback is usually unrealistically large, especially in densely populated urban areas.
For instance, for values of $h \cdot K$ = 250 m^2/day (e.g. sandy aquifer of 20 m thickness), i = 0.01, Q = 850 m^3/day, a well separation of D = 680 m is required.

A more practical approach is defining a certain time, where no thermal breakthrough is allowed, and accepting potential breakthrough at later stages..

CASE B - no background flow: Especially in deep hydrothermal applications natural groundwater flow is negligible. Assuming no background flow can be considered as extreme case A, and this means thus the lower limit for well distance *D* would be infinite. In other words, there will be always thermal breakthrough, and thus it is only possible to set a time limit.

The breakthrough time t_B is then obtained as follows:

$$t_B = \frac{\pi}{3} \frac{C_A}{C_w} \frac{hD^2}{Q}$$

where C_A is the volumetric heat capacity of the (water filled) aquifer. The equation states that t_B increases with the volume $h \cdot D^2$ and decreases with the rate Q.
Finally, for times $t > t_B$ the temperature of the produced water T_p (t) can be approximated by (Lippmann and Zhang 1980):

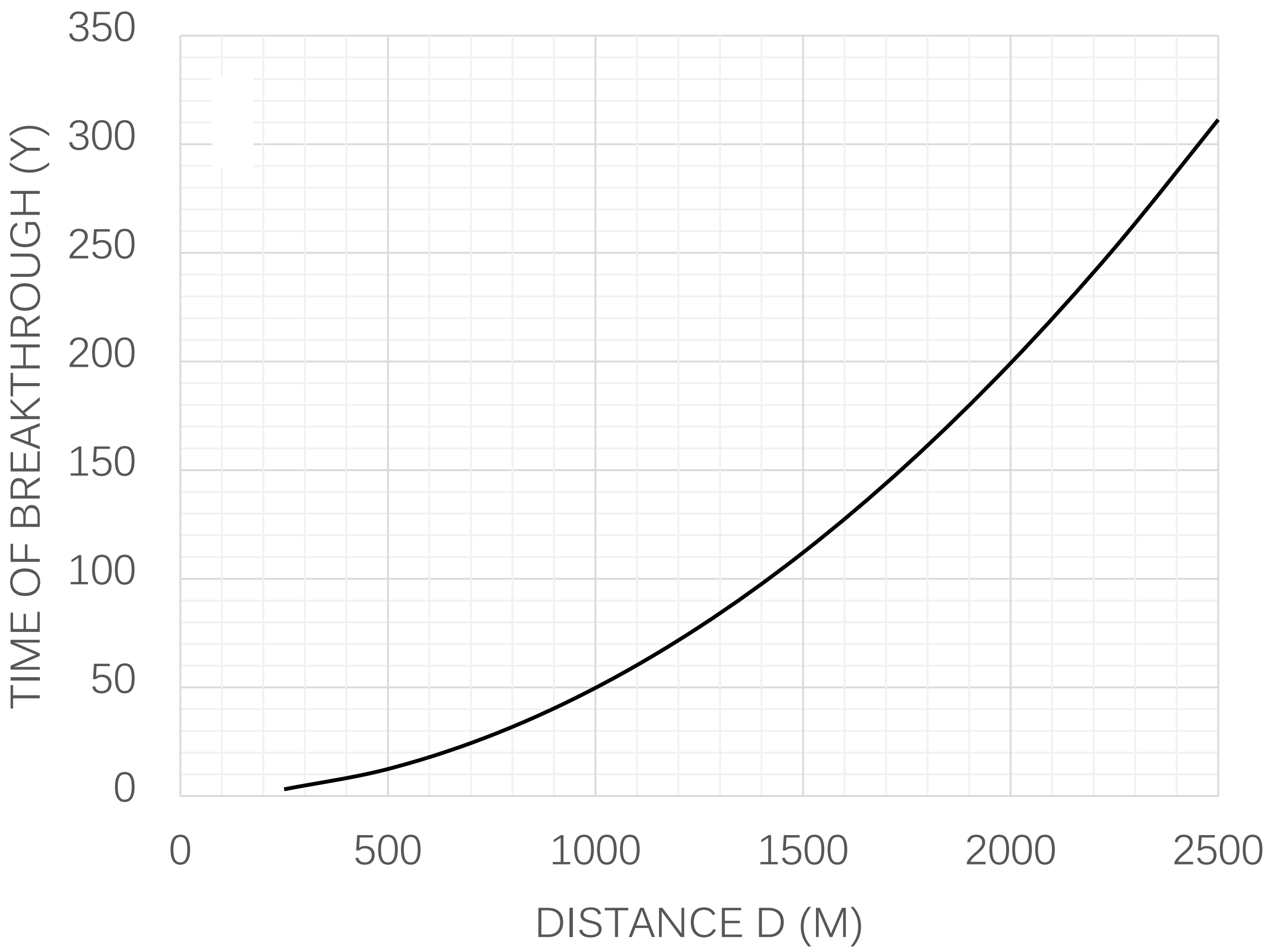
$$\frac{T_p(t) - T_i}{T_0 - T_i} = 0.338\, exp\left(-0.0023 \frac{t}{t_B}\right) + 0.337\, exp\left(-0.1093 \frac{t}{t_B}\right) + 1.368\, exp\left(-1.3343 \frac{t}{t_B}\right)$$

where T_0 is the initial or unaltered temperature of the aquifer, and T_i is the injection temperature.

Example 1 Assume a doublet operating in the Molasse basin in the South of Munich. Specify realistic values (h = 300 m, Q = 100 l/s) and plot the time of thermal breakthrough vs. distance between the wells.

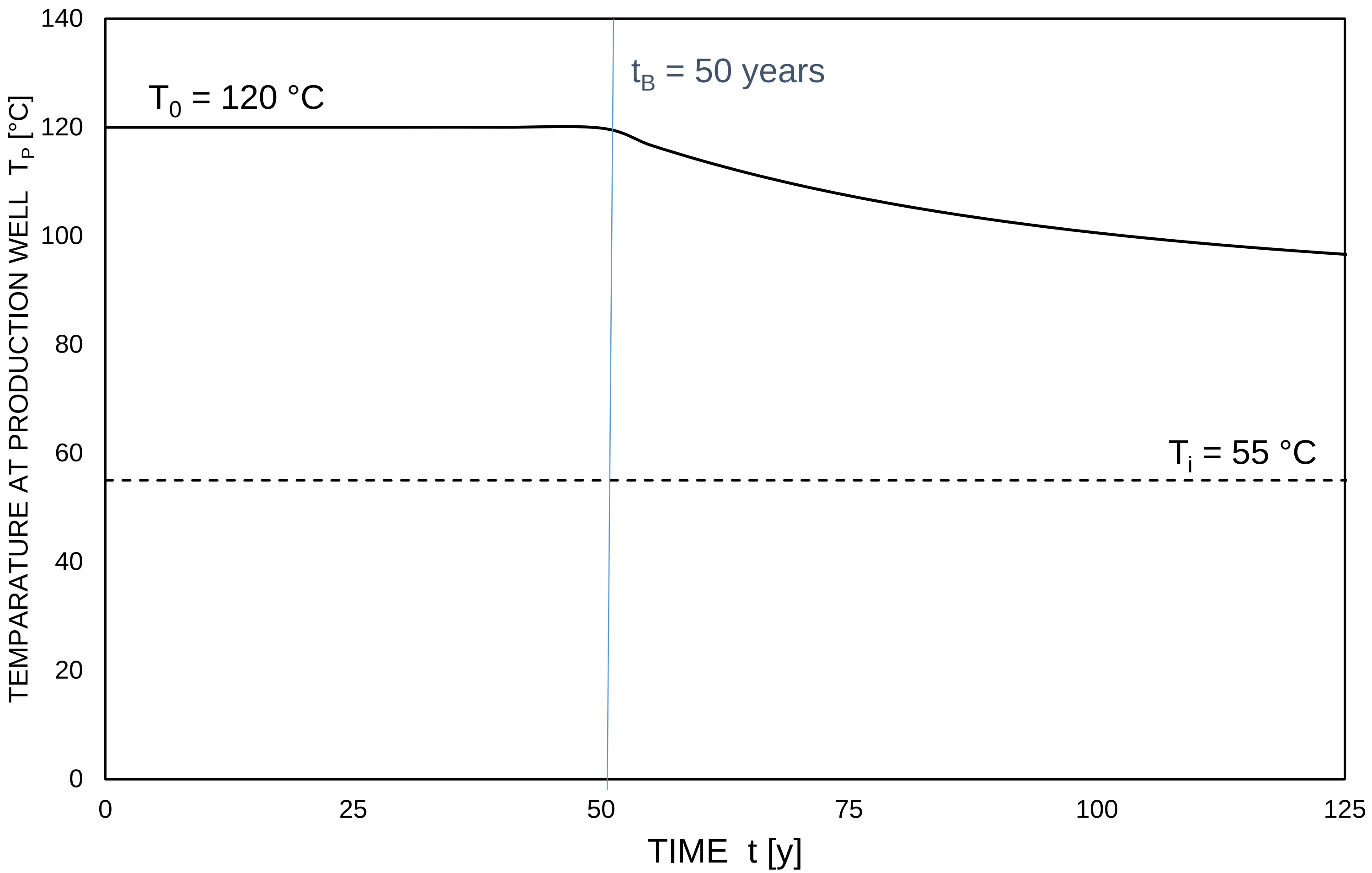
Example 2 Take your assumptions for Example 1 and choose a case for t_B = 50 years. Calculate the temperature in the produced water vs. time. How much has the temperature declined after 100 years?

Example 1: Result (example)



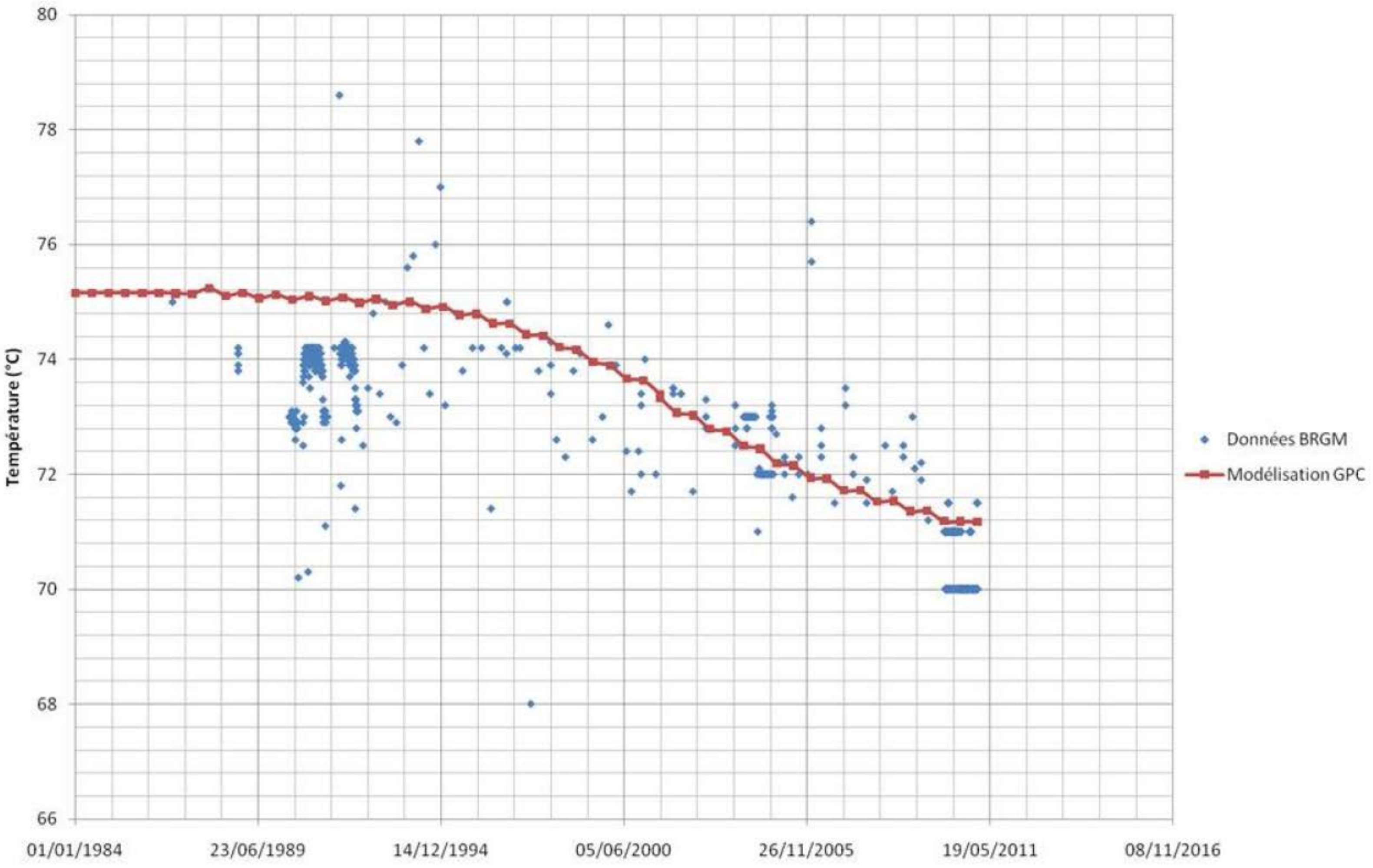
Q = 100 l/s
h = 300 m
$C_A/C_W = 0.5$

Example 2: Result (example)



Q = 100 l/s
h = 300 m
C_A/C_W = 0.5
D =1000 m
t_B = 50 y

Paris Basin – measured data



Ungemach, P., Antics, M. 2015. Assessment of Deep Seated Geothermal Reservoirs in Selected European Sedimentary Environments. – *World Geothermal Congress*, 15 pp.

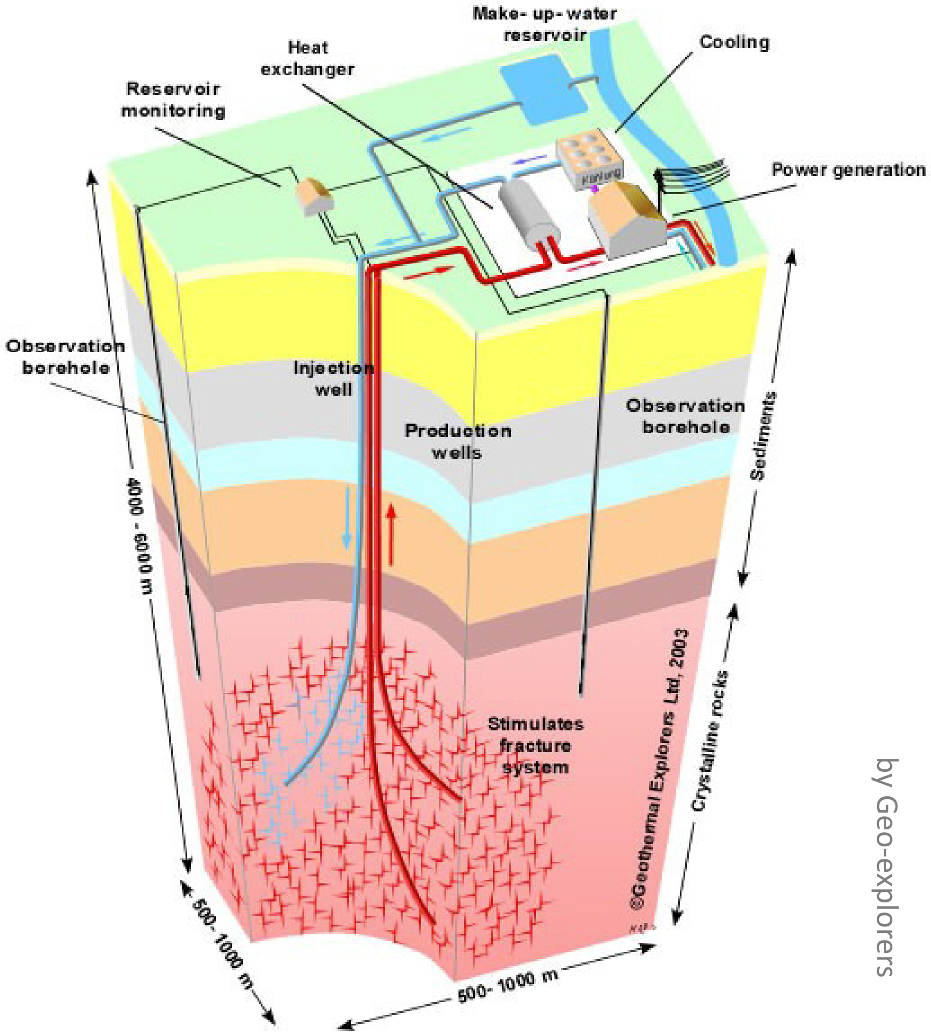
High-enthalpy geothermal energy

Petrothermal

Petrothermal systems are reservoirs that are developed in rocks that have low porosity and little water in-place.

These systems require that a reservoir is engineered by creating or enhancing the permeability of the rock mass between holes so that fluid can be circulated in a loop. This is why these are also Engineered or Enhanced Geothermal Systems (EGS).

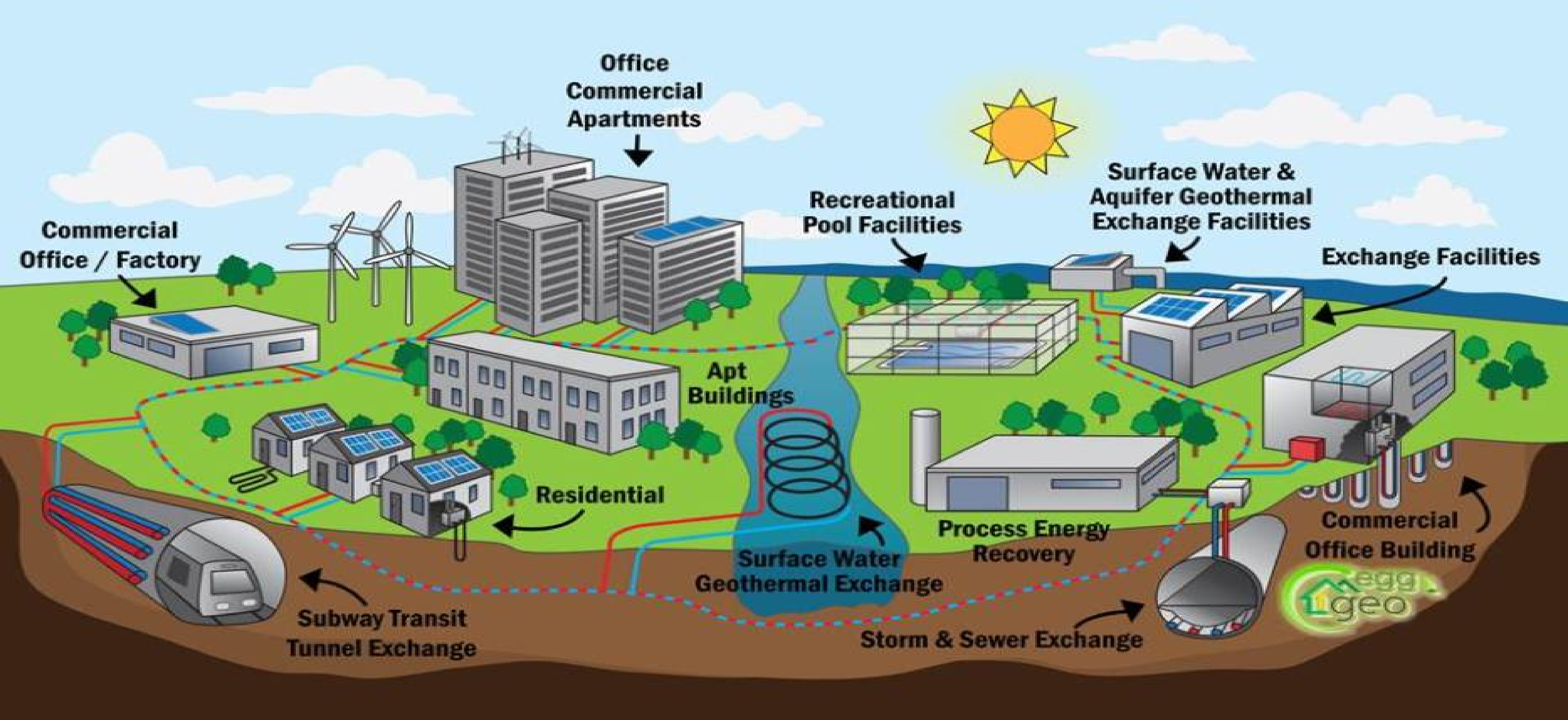
- The attraction of these systems lies in the fact that low porosity rocks at temperatures of 150-200°C underlie large areas of Europe at depths of 5 km, mostly in crystalline rock.
- Thus, they could be built in large numbers, and produce electricity.



by Geo-explorers

Low-enthalpy geothermal energy

... be creative!



http://energyblog.nationalgeographic.com

Low–enthalpy geothermal energy

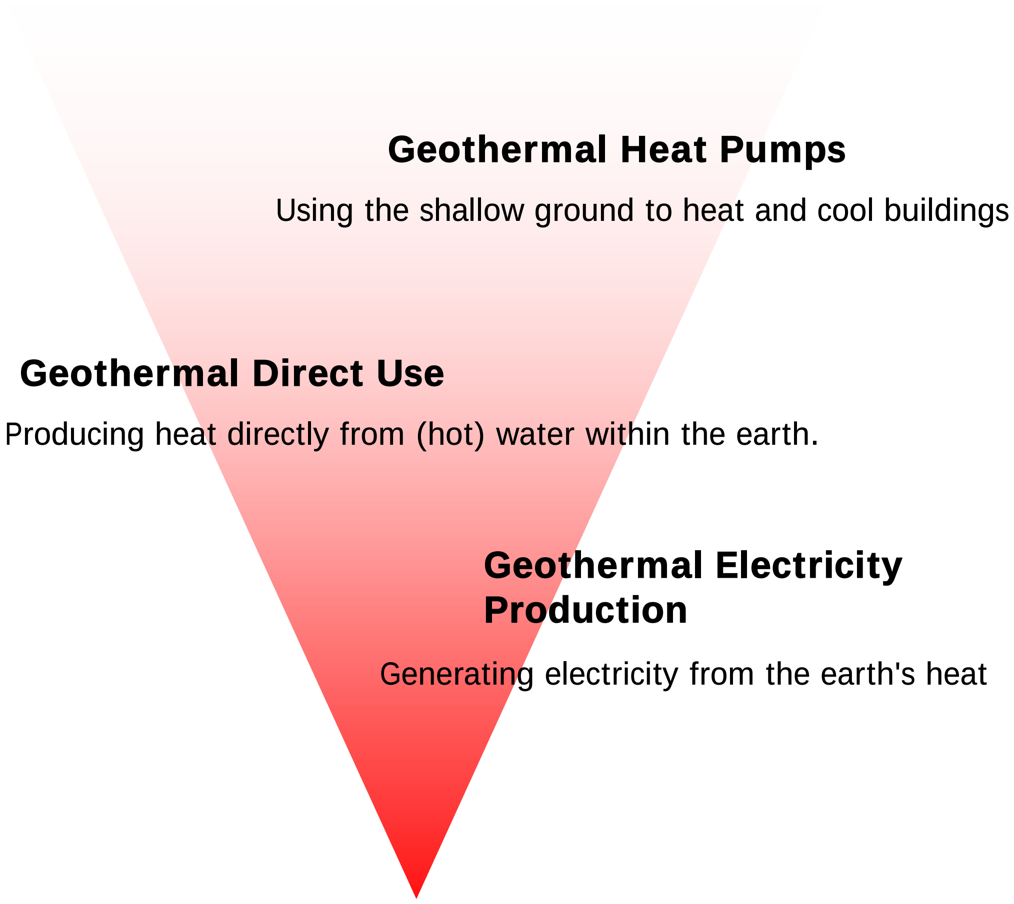
Classification cont‘d

<u>*Remember:*</u>

→ Classification *based on depth* does not automatically correlate with classification *based on use*

→ Classification based on *depth* reflects local geothermal gradient, but also role of accessibility, field construction (drilling, boreholes, etc.), depth-based regulation

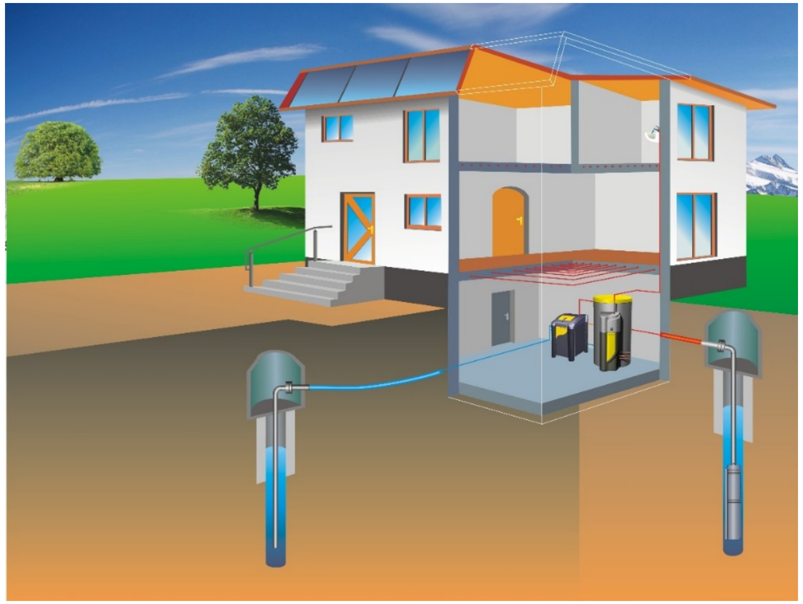
→Classification based on *use* reflects technologies that are efficient based on the local geothermal gradient

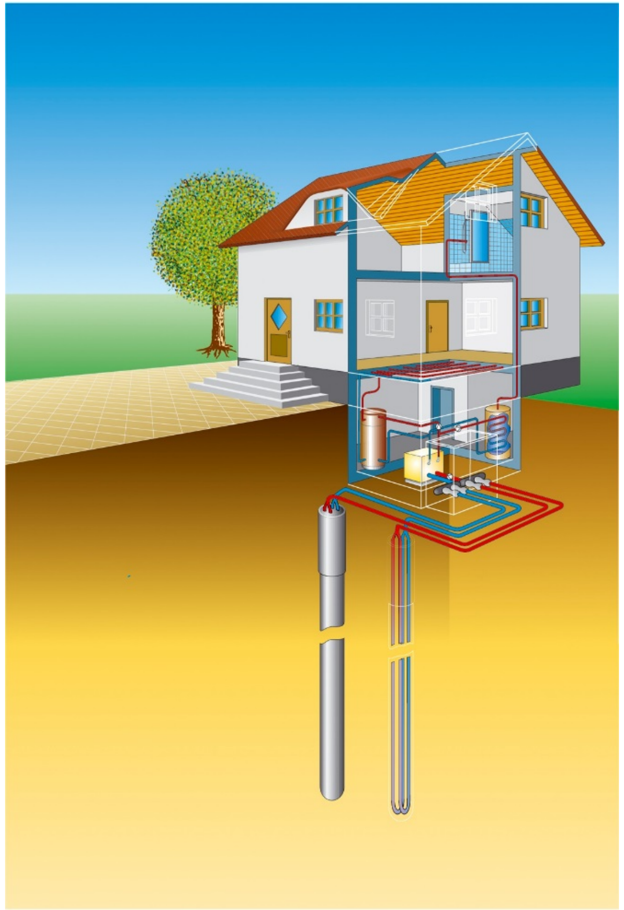


Low–enthalpy geothermal energy

Classification cont'd

Open (loop) systems, groundwater is directly used (we could say these are *shallow hydrothermal systems*).





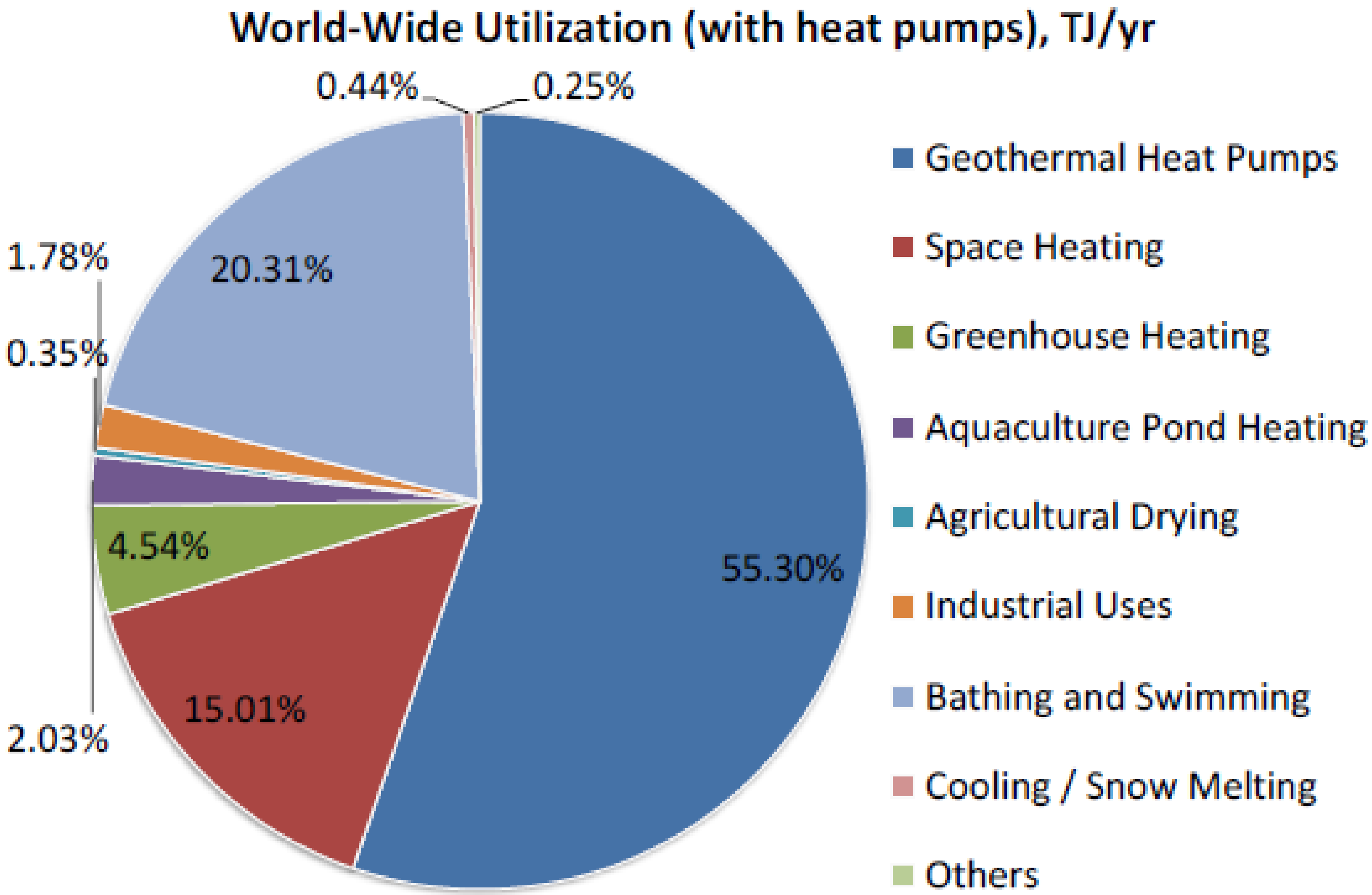
Bundesverband Wärmepump e.V.

Closed (loop) systems: In tubes installed in the subsurface, an extra heat carrier fluid is circulated.

As this fluid circulates around the loop, it absorbs heat from, or releases heat to, the ground in heating or cooling mode, respectively. There exist many variants depending on depth, form of tubes and heat carrier fluid.

Low–enthalpy geothermal energy

Current worldwide direct use

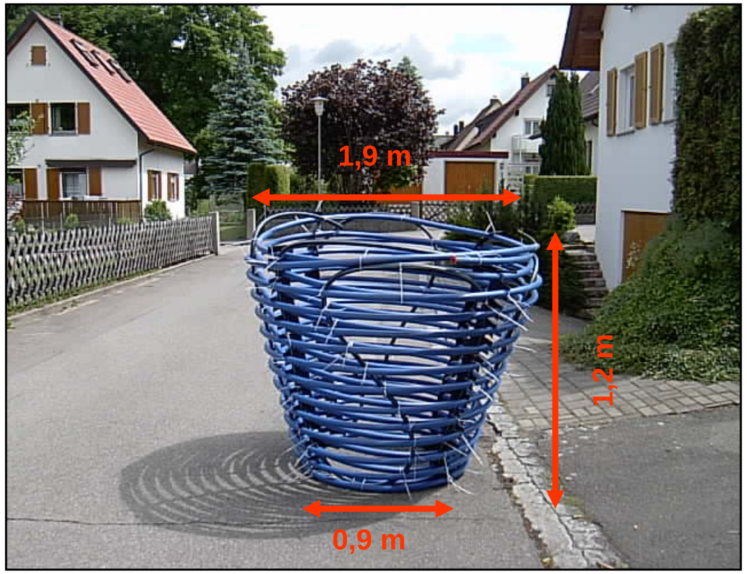


Lund & Boyd, WGC 2015

Horizontal ground heat exchangers

Low-enthalpy geothermal energy

Coils



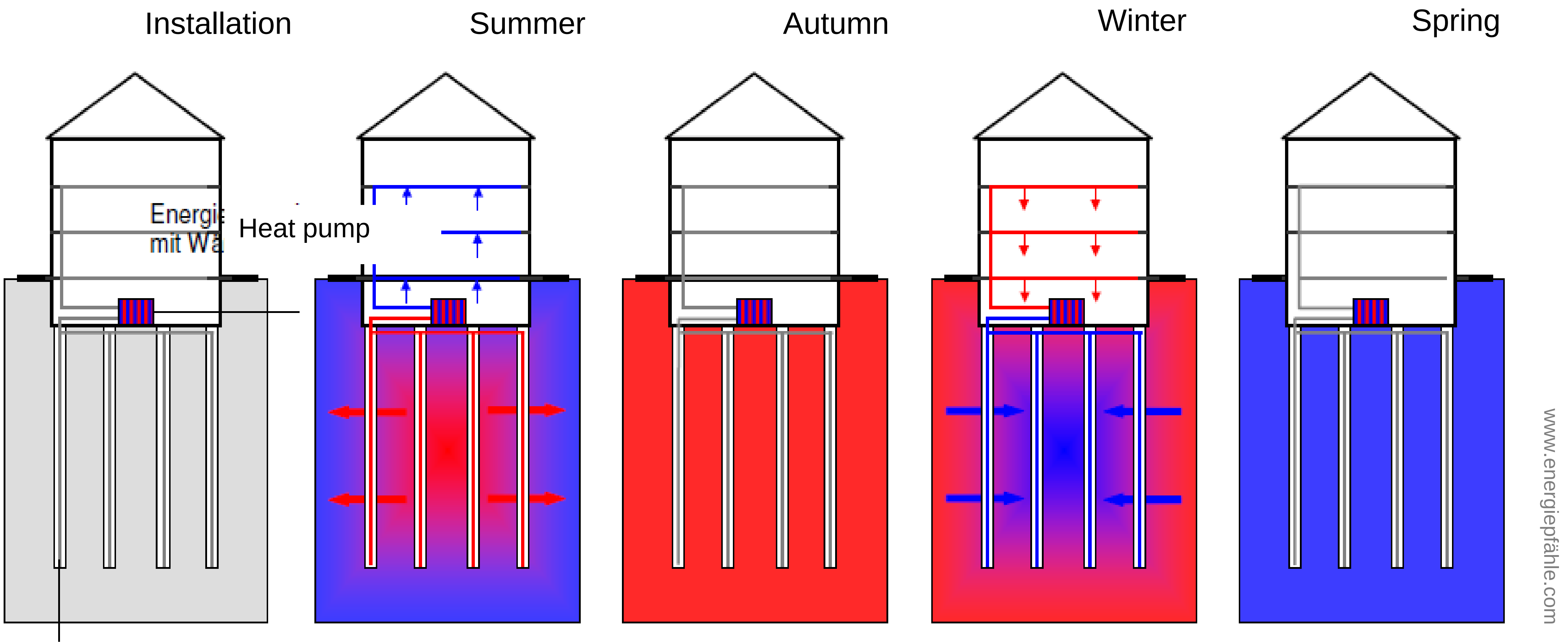
Low-enthalpy geothermal energy

Energy piles

Low–enthalpy geothermal energy

Energy piles

Annual operation with alternating heating and cooling periods:



Example: Terminal E, Zurich airport

200‘000 m^3 construction space

58‘000 m^2 energy supply area

2120 MWh/a heating, 1240 MWh/a cooling load

300 energy piles of 30 m

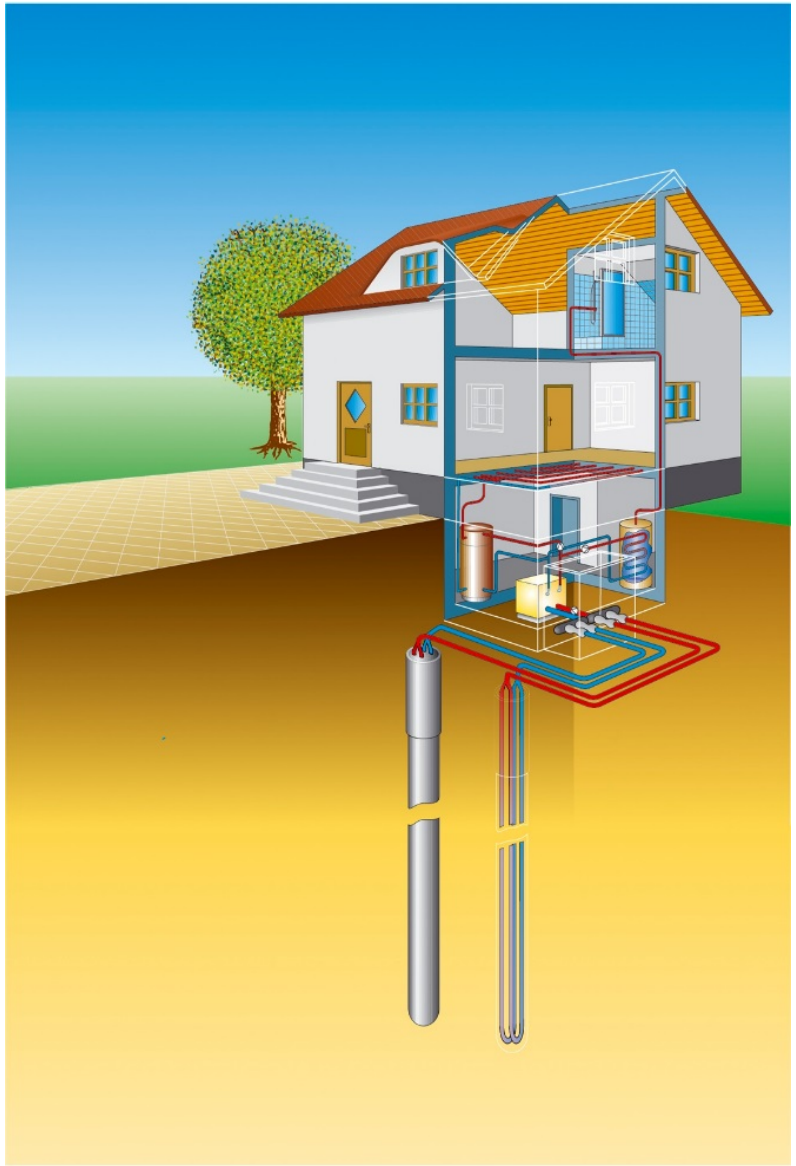
Low–enthalpy geothermal energy

Definition and size

The (vertical) borehole heat exchanger (BHEs) is the **most common** variant in shallow geothermal energy use. As the name says, it represents a heat exchanger installed in a borehole.

The depth (or length) of the BHE is commonly around 100 m (range: 50 - >400m), depending on drilling costs, regulations, geology, energy and space requirements.

Often, multiple BHEs are combined in BHE fields to provide an energy demand that could not be supplied by a single BHE.



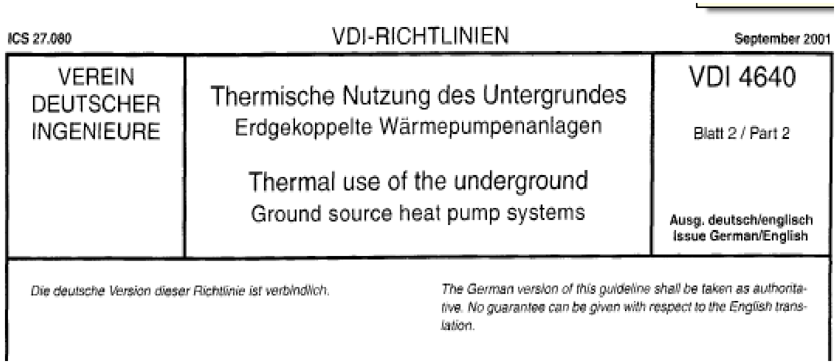
Bundesverband Wärmepump e.V.

Low–enthalpy geothermal energy

BHE installation

Double U-Tube

Planners have many degrees of freedom, and there exist crucial guidelines for shallow geothermal systems (e.g. VDI 4640).



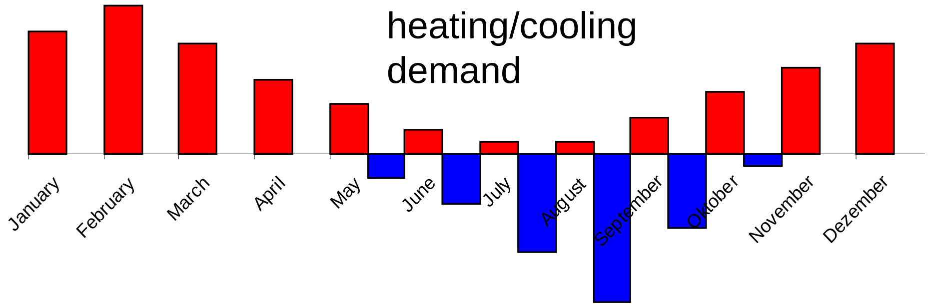
ICS 27.080 — VDI-RICHTLINIEN — September 2001

VEREIN DEUTSCHER INGENIEURE	Thermische Nutzung des Untergrundes Erdgekoppelte Wärmepumpenanlagen Thermal use of the underground Ground source heat pump systems	VDI 4640 Blatt 2 / Part 2 Ausg. deutsch/englisch Issue German/English

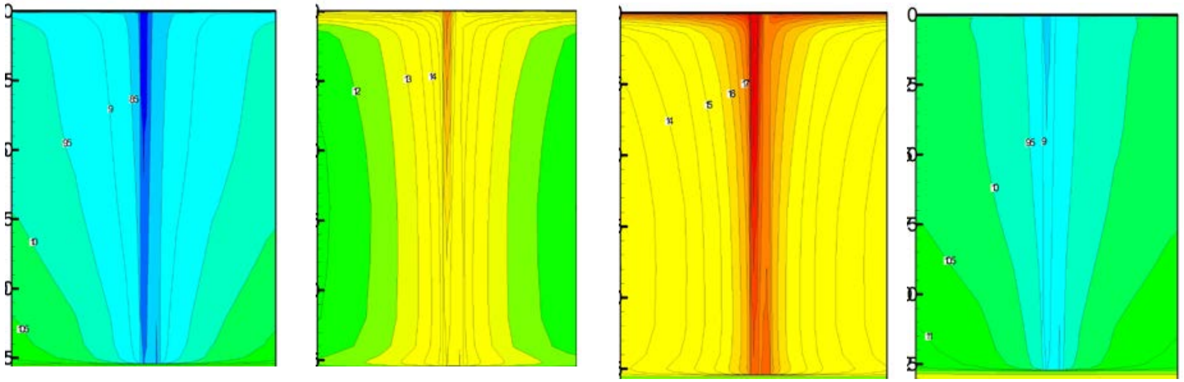
Die deutsche Version dieser Richtlinie ist verbindlich.

The German version of this guideline shall be taken as authoritative. No guarantee can be given with respect to the English translation.

Annual heating/cooling demand



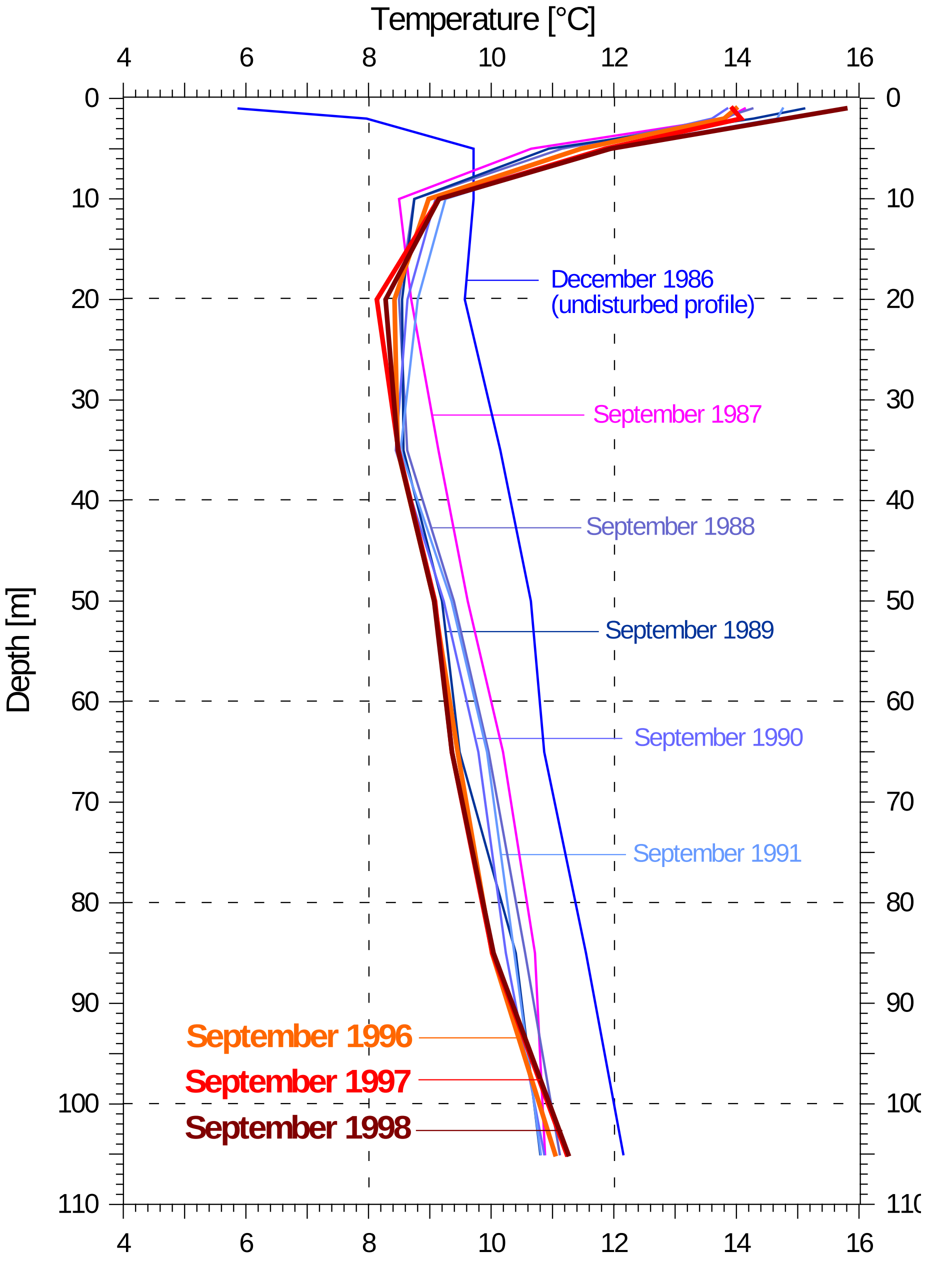
The different variants have different pros and cons, and based on the heating/cooling requirements, the regulatory/ physical/geological boundary conditions, available heat pump types, planner´s experience and costs, a preferred variant is designed.



Simulated evolution of ground temperature profile around BHE

Low–enthalpy geothermal energy

Elgg field site / CH

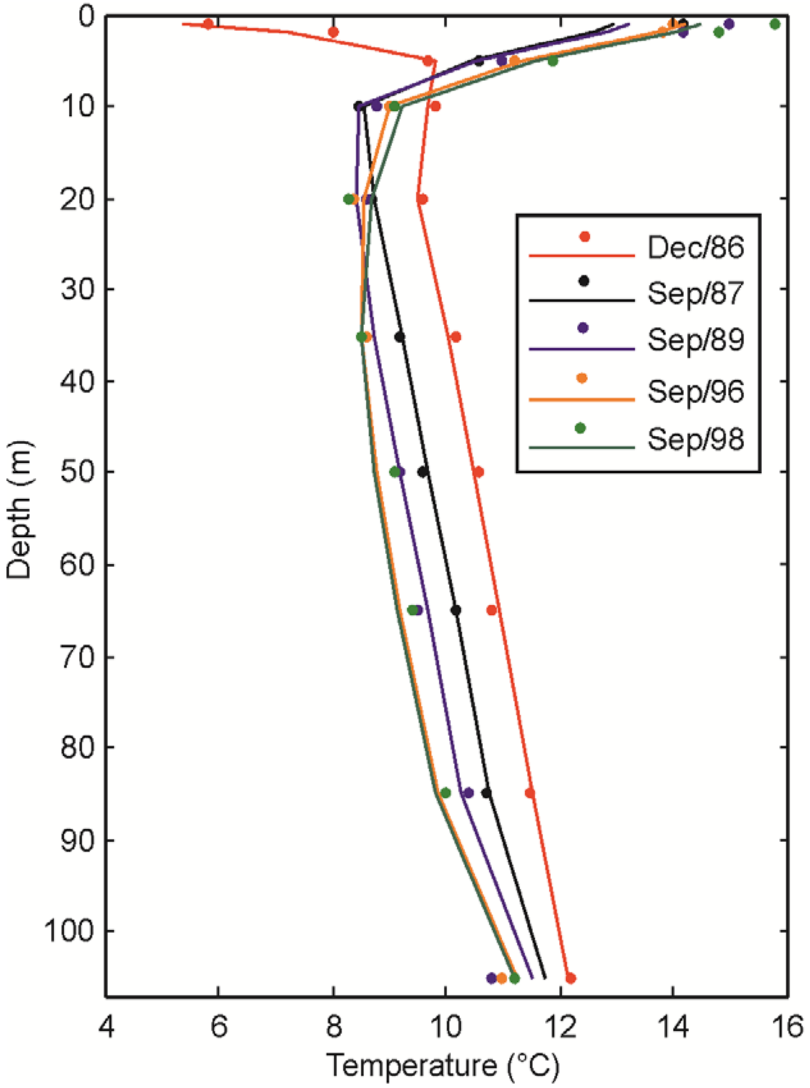


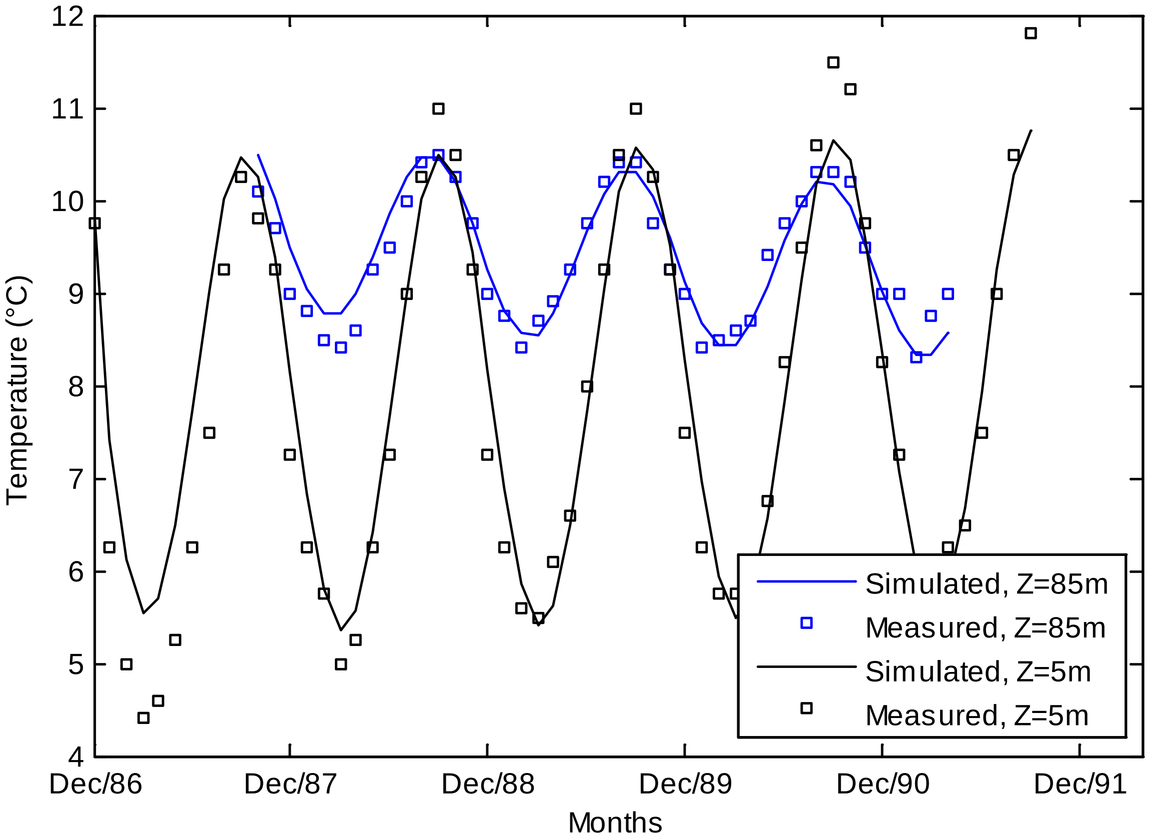
Ground temperature profiles at 1 m distance from the BHE

(Rybach & Eugster 2002)

Low-enthalpy geothermal energy

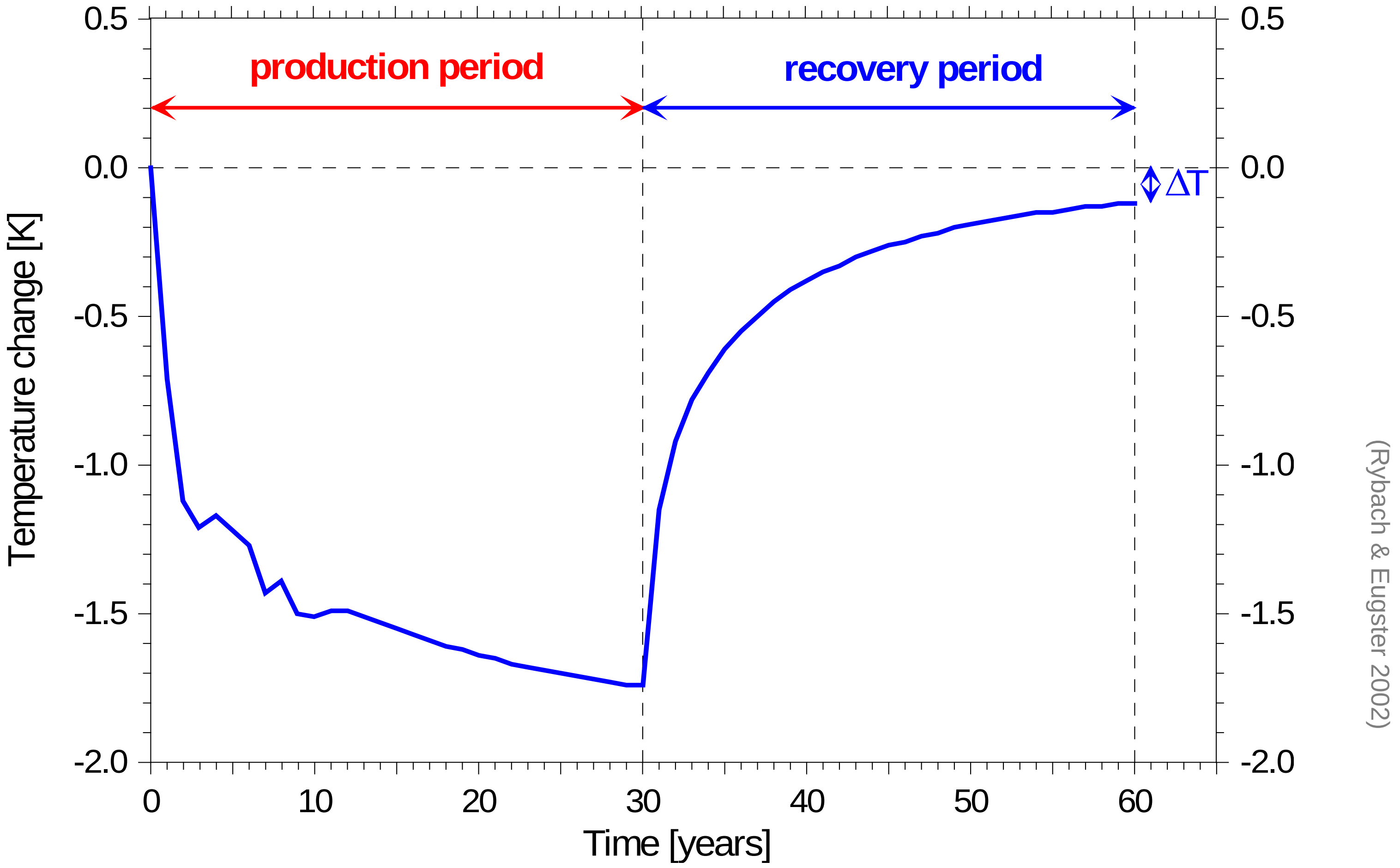
Elgg field site / CH: Calibration





Source: Rivera et al. 2015

Regeneration (simulated)

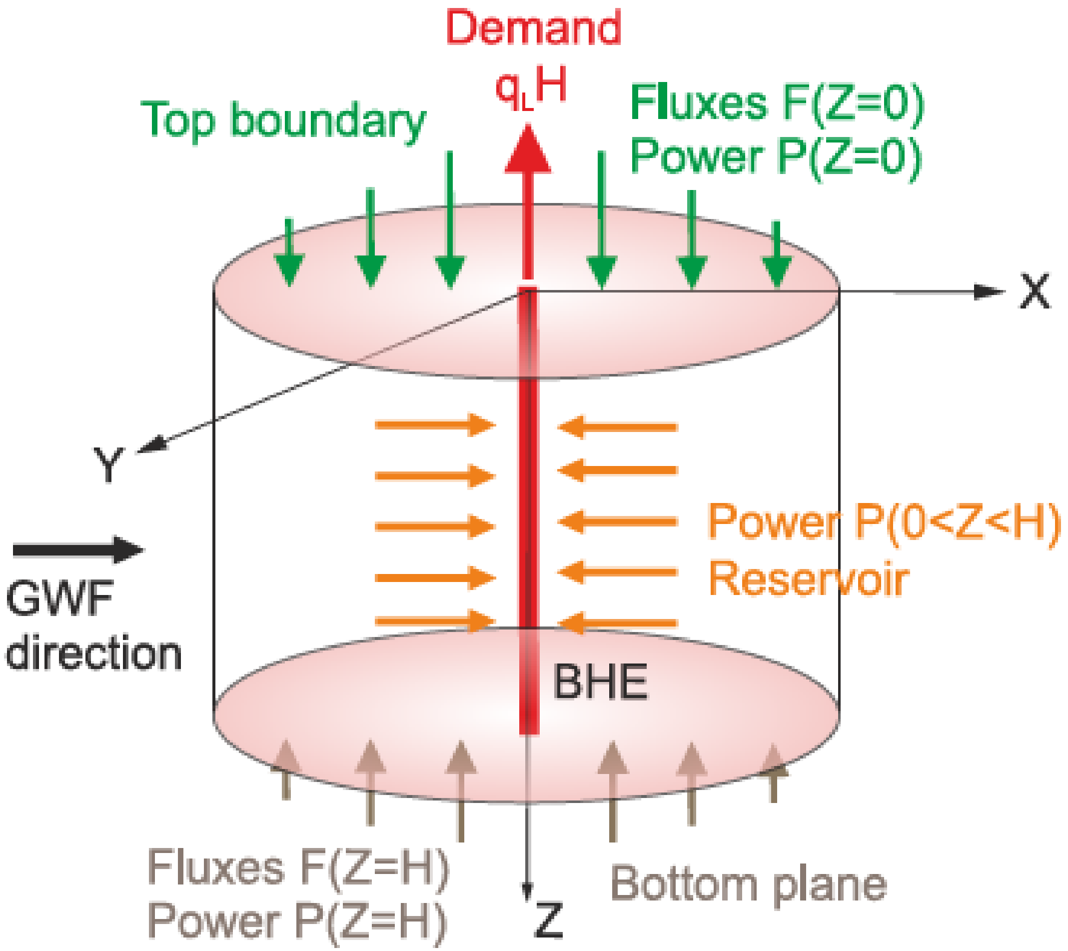


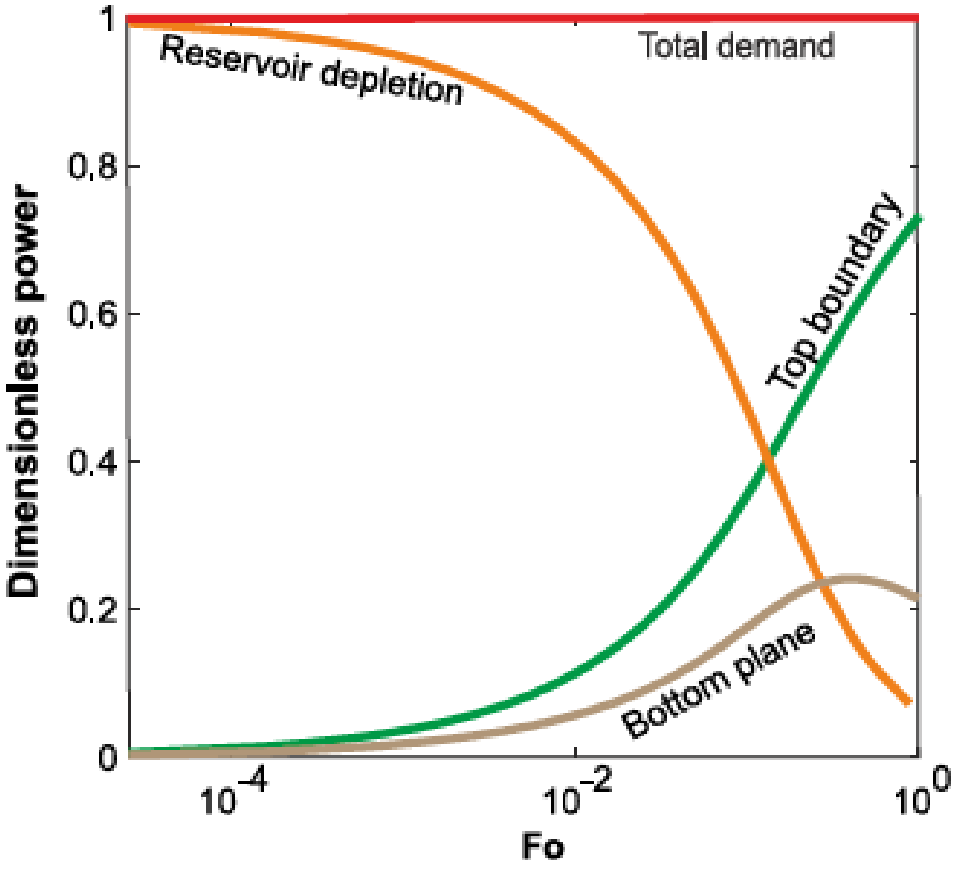
Asymptotic temperature decline and recovery at

- 50 m depth and
- 1 m distance from the BHE

Low–enthalpy geothermal energy

Heat balance





(Rivera et al. 2015)

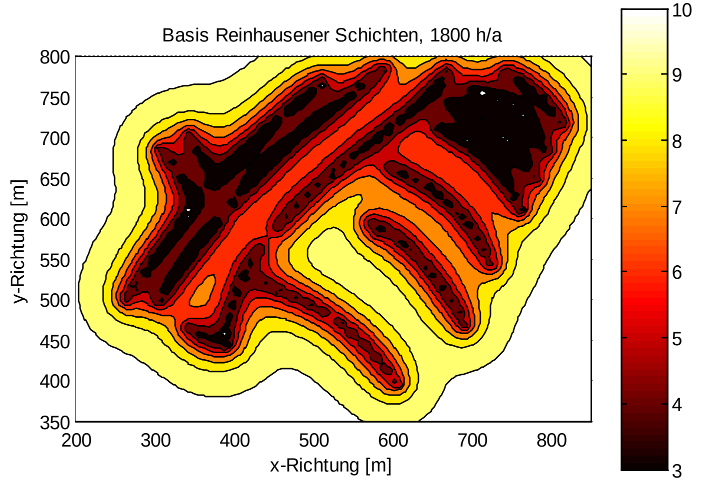
Low–enthalpy geothermal energy

Examples: Residential district in Regensburg (planned)

- 140 single-family homes
- ca. 1.4 MW total heating output
- free cooling

→ BHE-field with ~500 boreholes in depths of 60 and 90 m

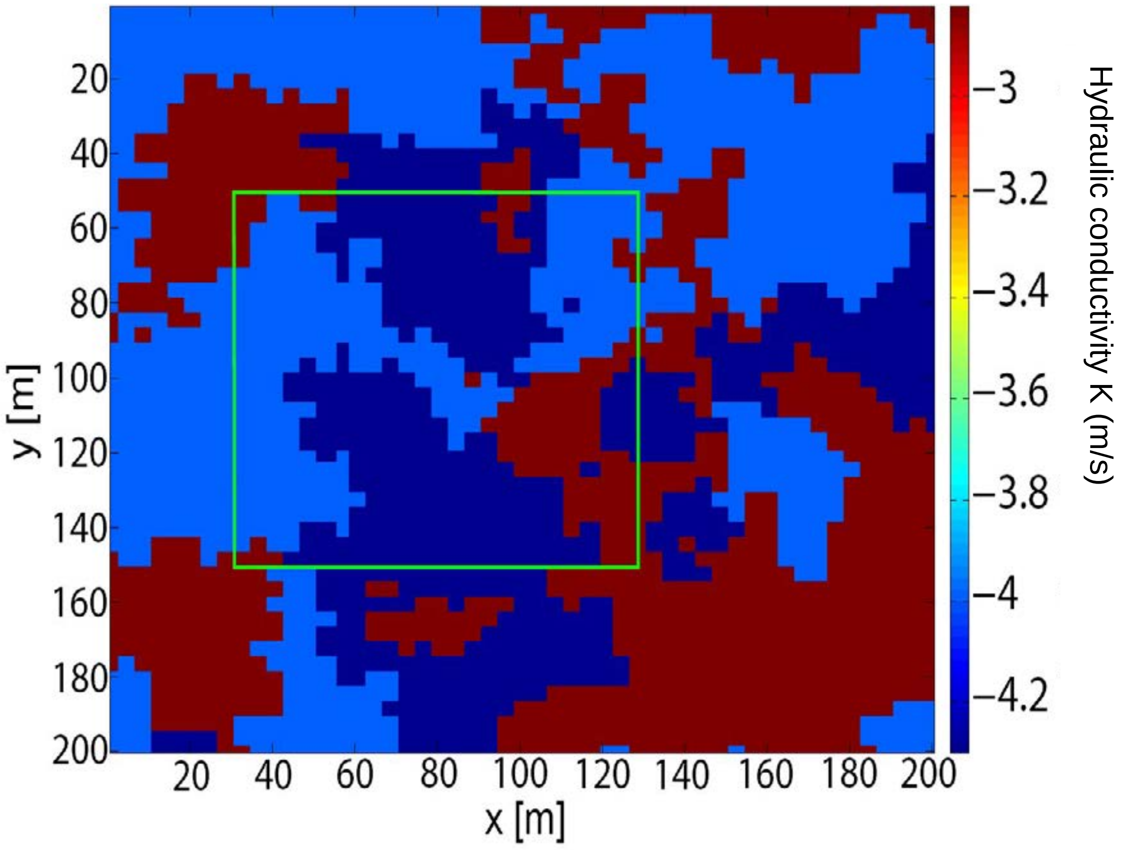
Simulated ground temperature distribution after 25 years:

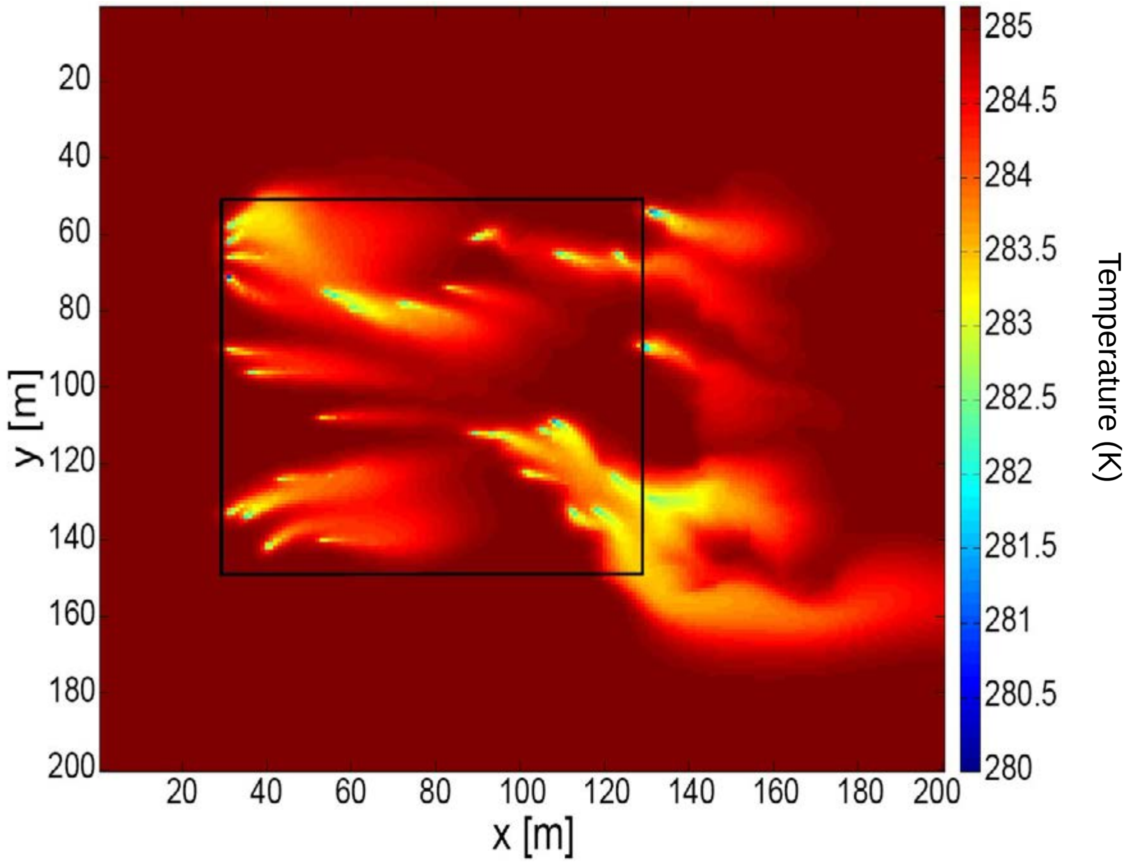


Ganghofersiedlung Regensburg (planned)

source: tewag GmbH

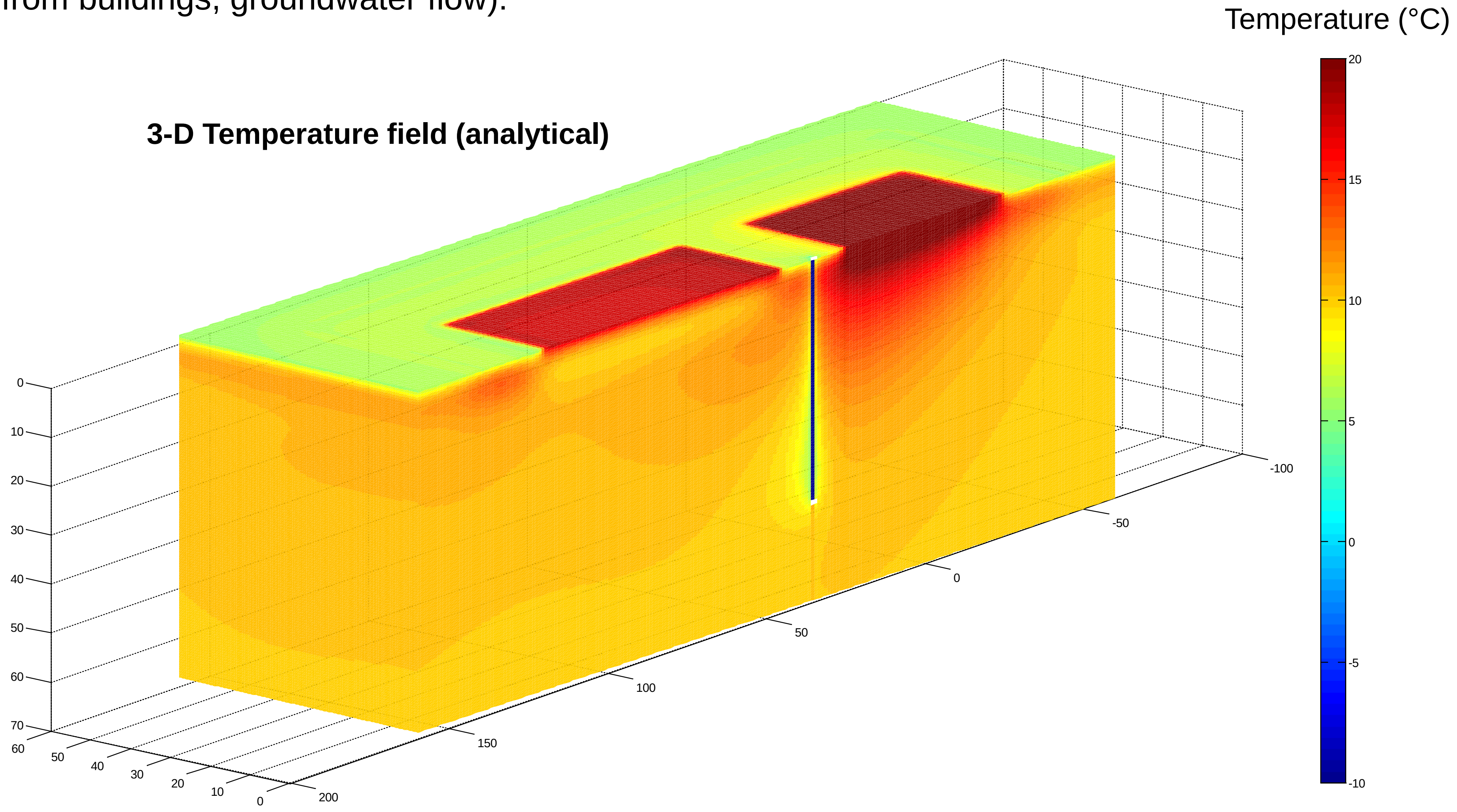
Numerical (finite differences) example with top view at BHE field, simulated in arbitrary heterogeneous ground (spatially variable hydraulic conductivity, left figure). There is groundwater flow from left to right. The cold plumes from local heat extraction generate an impressive nonuniform picture of plumes on the right.





(Beck et al. CEC 2010)

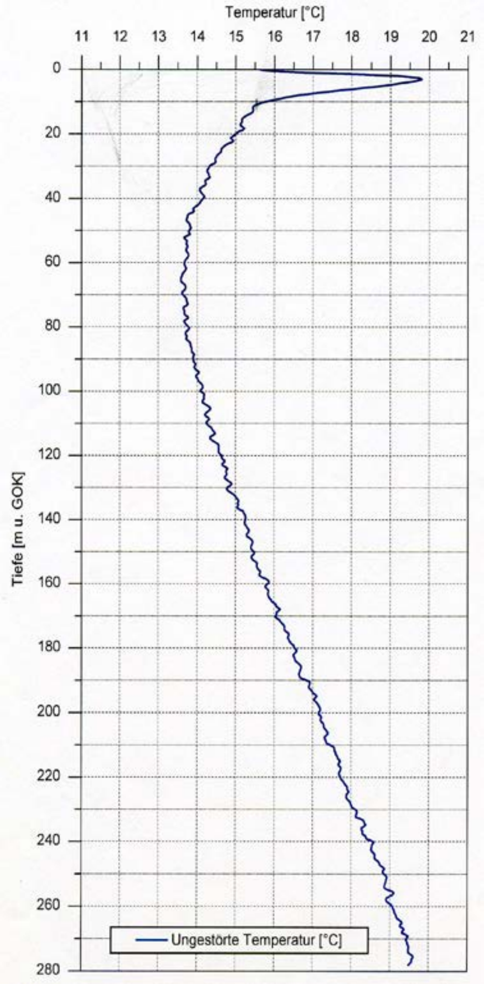
Analytical simulation of single BHE (homogeneous ground, nonuniform surface heat flow from buildings, groundwater flow):



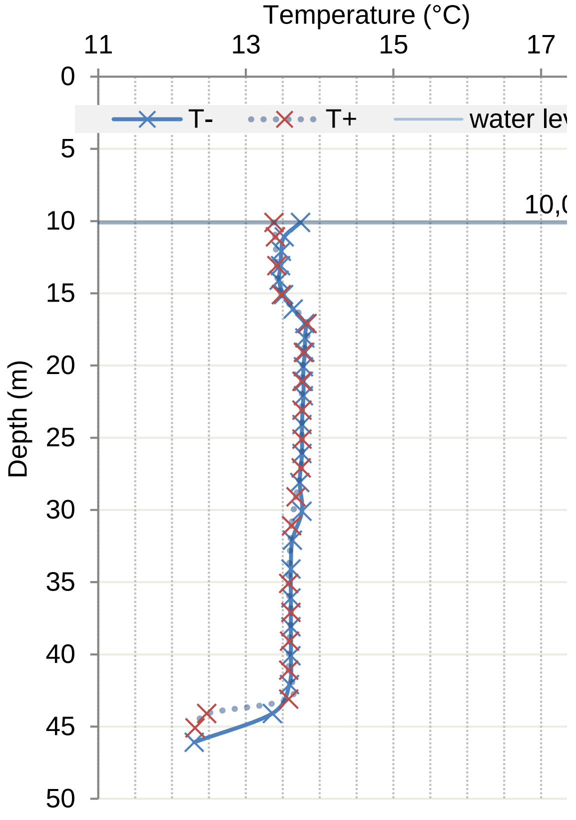
(Rivera et al. 2016)

Low-enthalpy geothermal energy

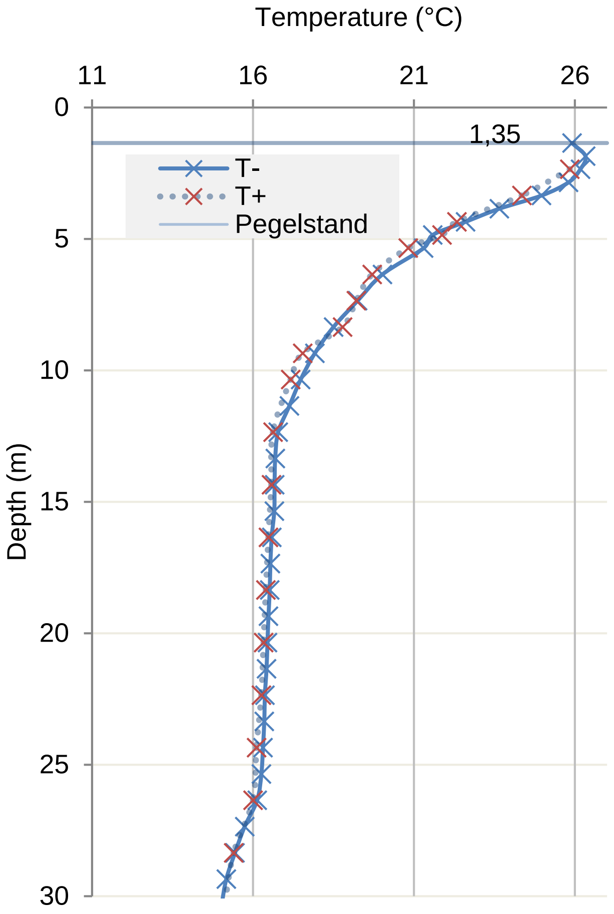
Measurements in Zurich



Temperature profile taken in an area "unperturbed" by groundwater flow



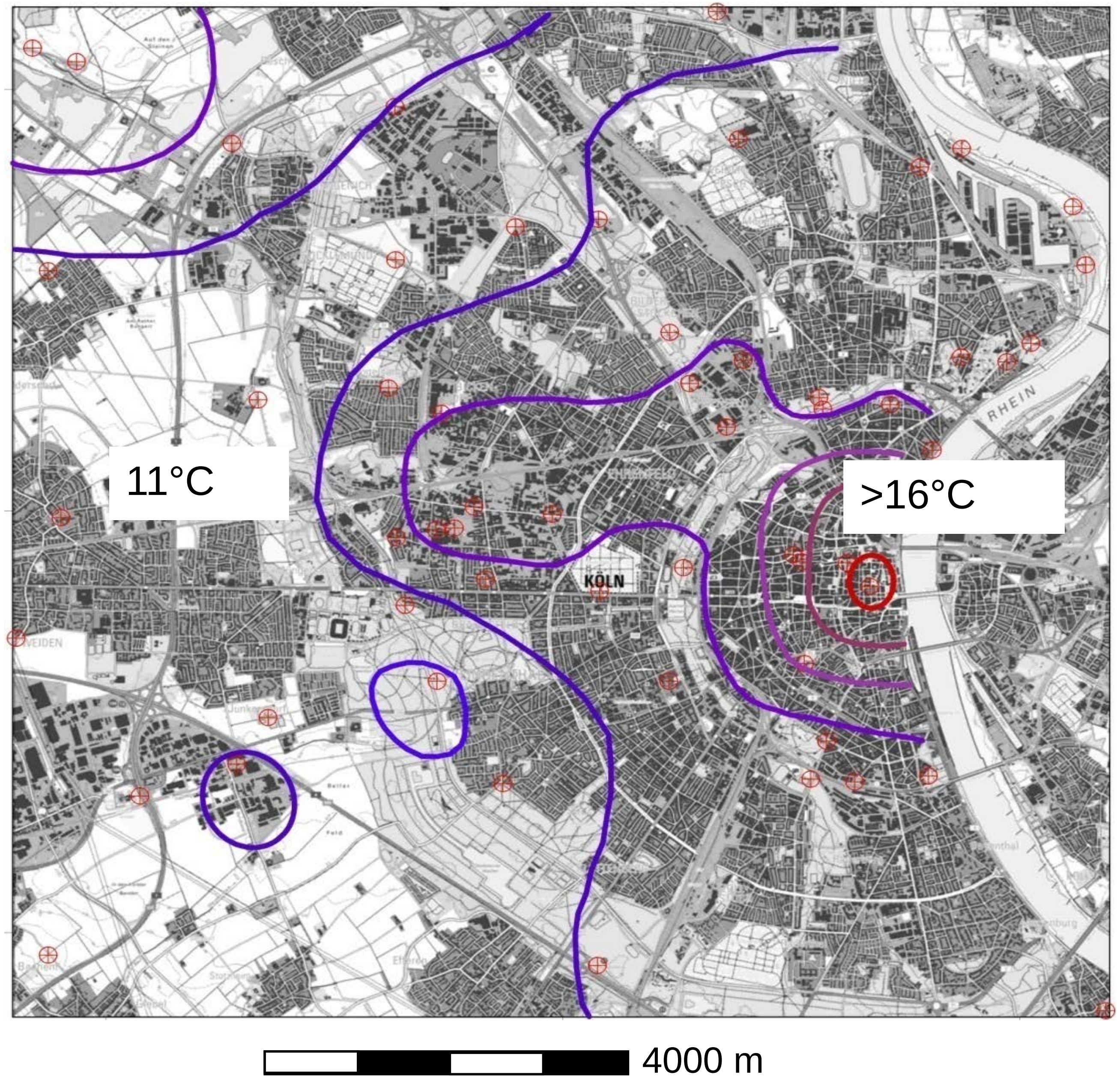
Temperature profile taken in an area influenced by groundwater flow (rather common in the study area)



Temperature profile taken in an area influenced by strong anthropogenic heat fluxes (Parkhaus Urania)

Low-enthalpy geothermal energy

Measurements in Cologne

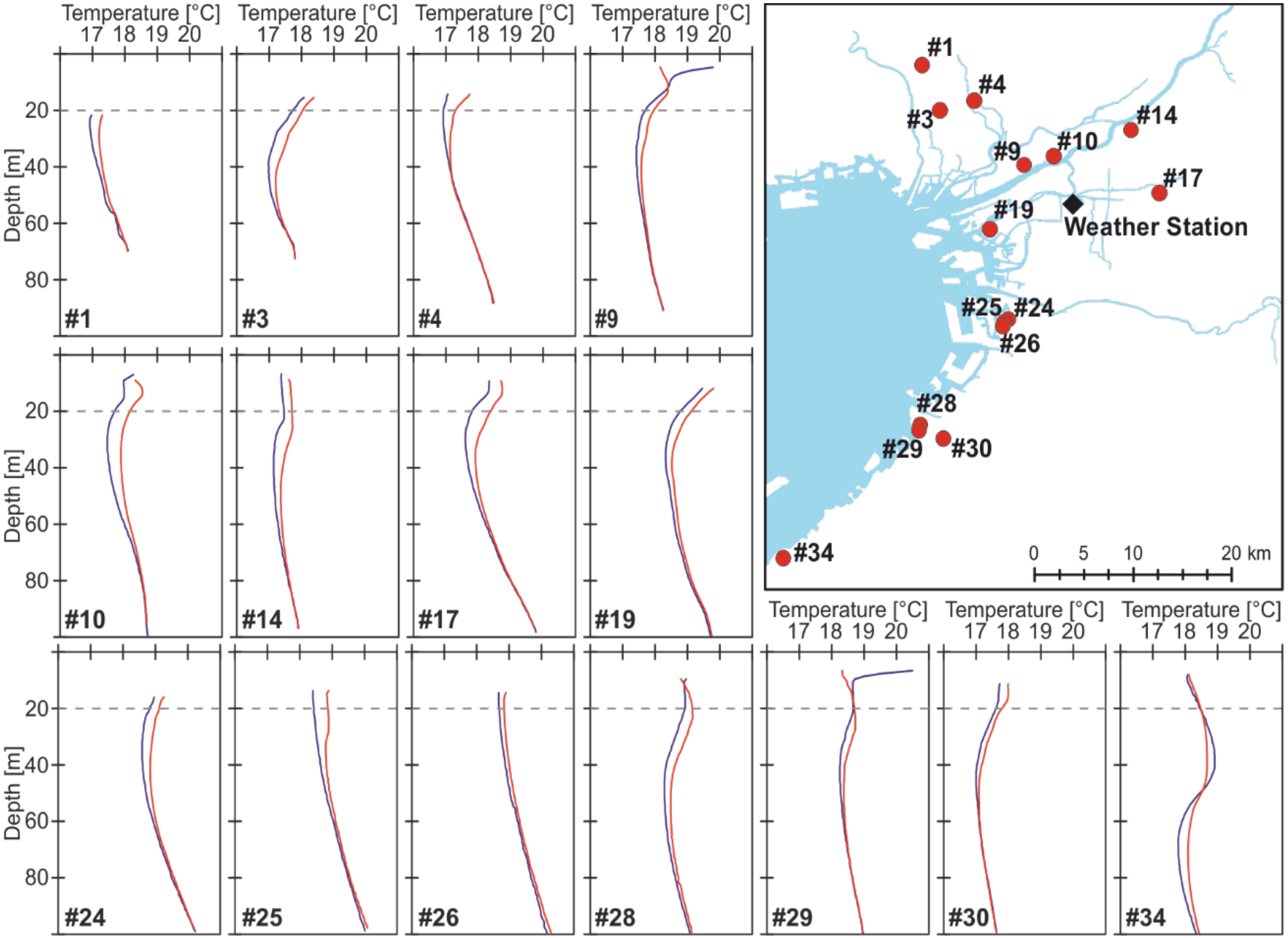


(Zhu et al. 2010, Menberg et al. 2013)

Low–enthalpy geothermal energy

Measurements in Osaka

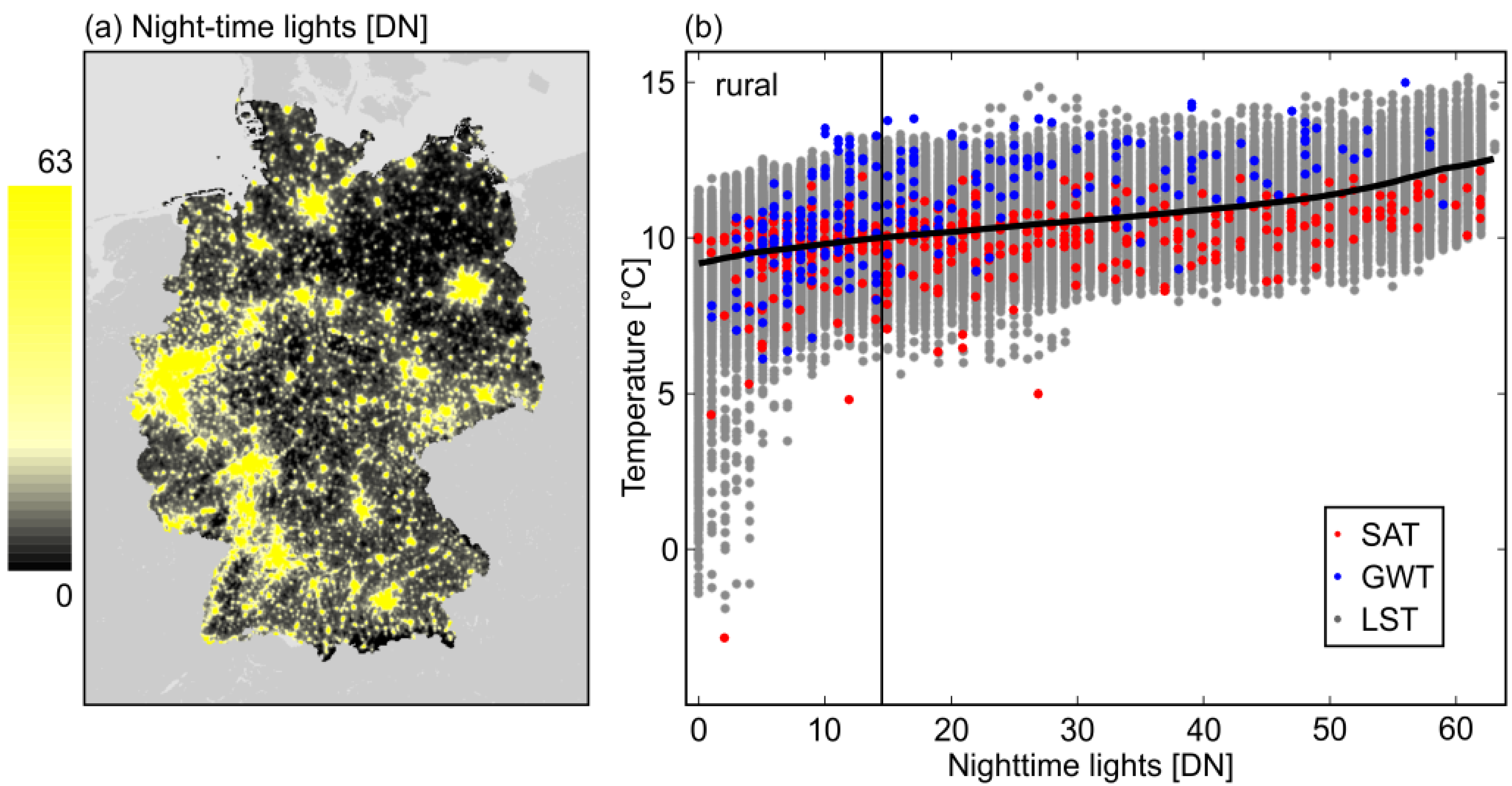
Map of all wells and the weather station in Osaka, and corresponding groundwater temperatures in 2003 (blue) and 2011 (red).



(Benz et al. 2018)

Low–enthalpy geothermal energy

Measurements in Cologne



(Benz et al. 2017)

Peter Bayer

GEOTHERMAL ENERGY

Ingolstadt University of Applied Sciences
Germany
mail@bayerpeter.com