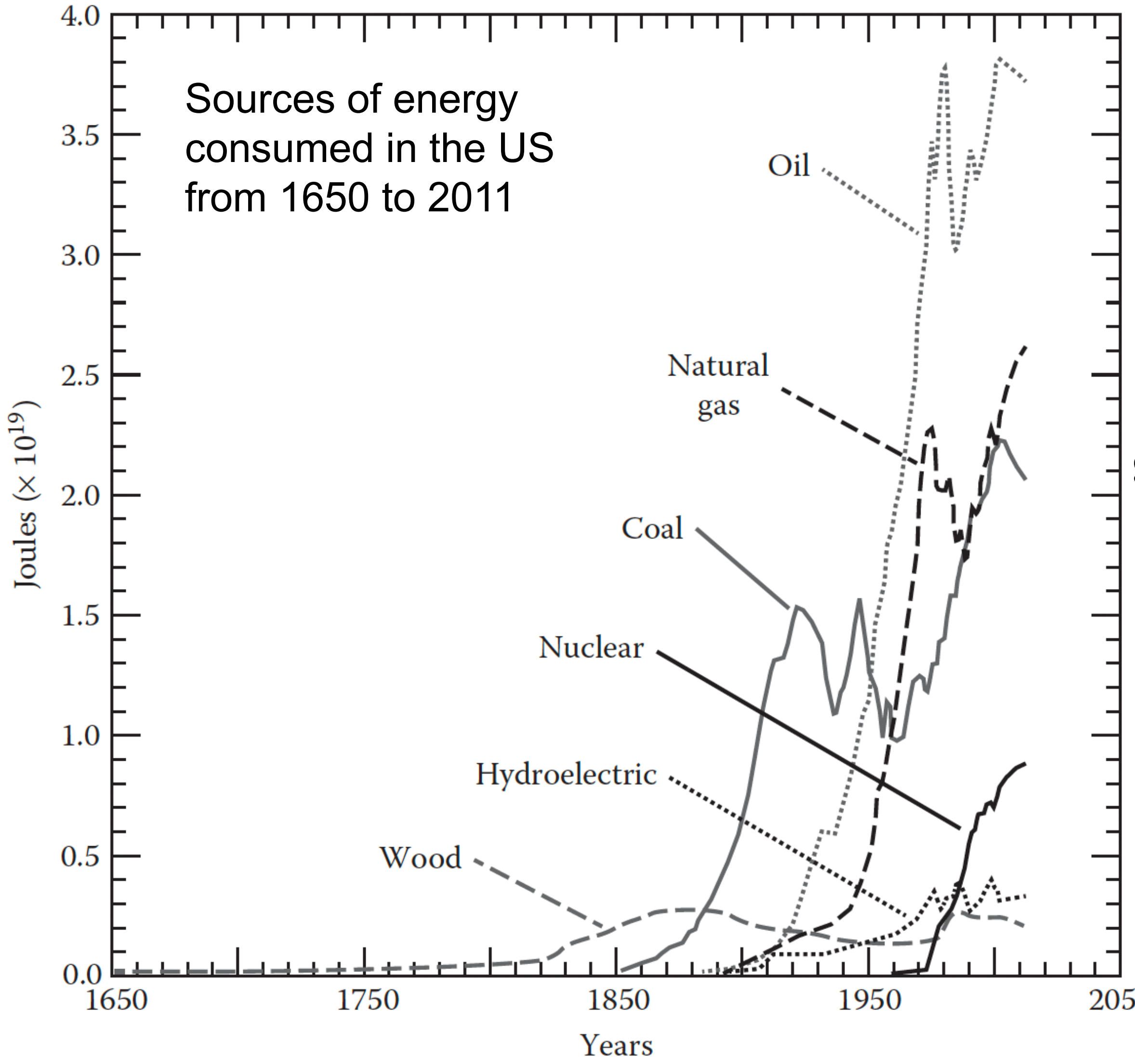
EPFL

(Deep) Geothermal Energy

Marie Violay
Slide from A. Kushnir

Fuel use through history

- Industrial activity and economic growth require access, control, and maintainence of fuel sources
- Example: 85% of the energy used in the US comes from wood, coal oil and natural gas, which are not renewable resources
- Coal, oil, natural gas reserves take millions of years to form
- The rate of extraction far exceeds the rate of formation



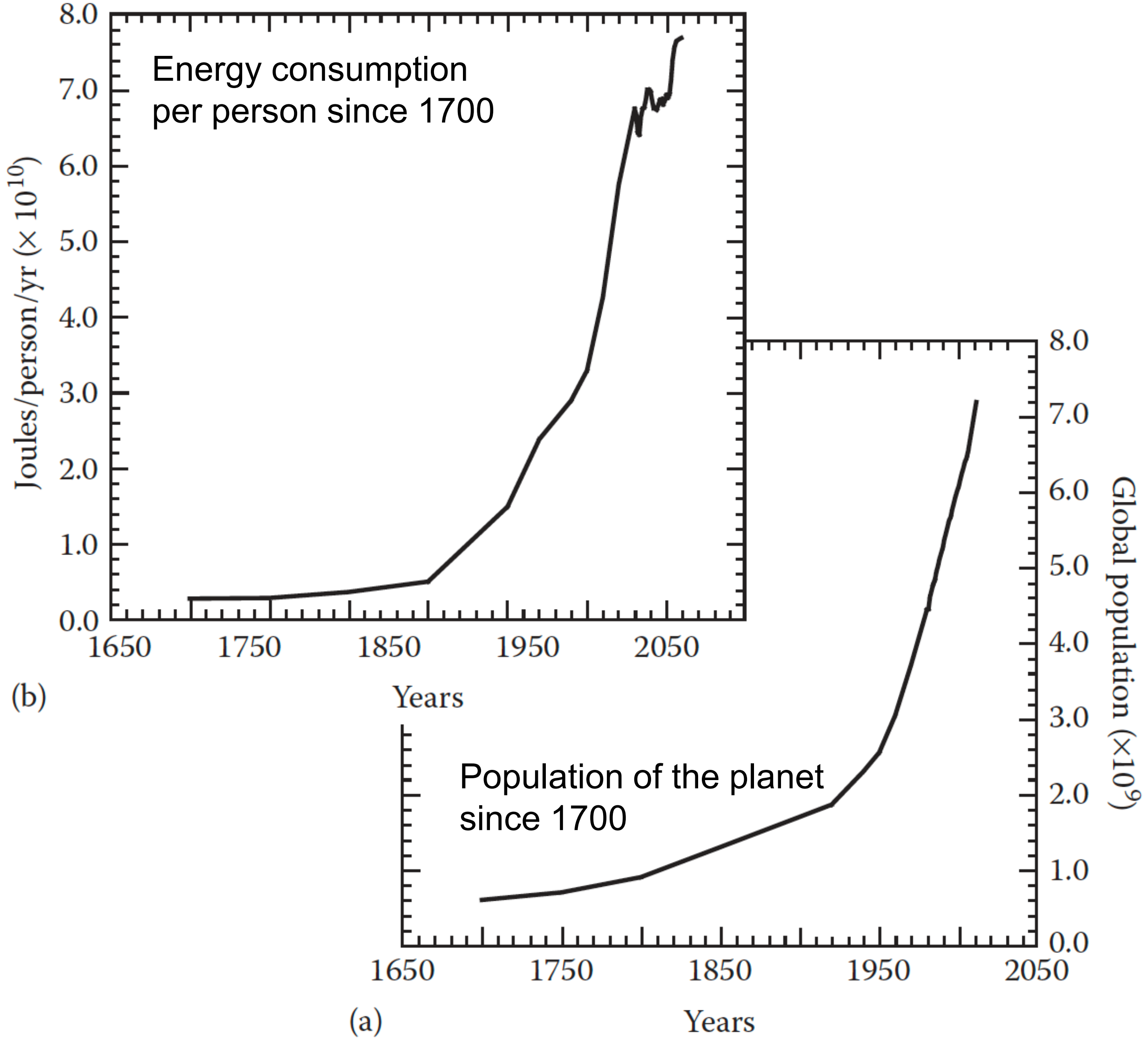
Source: United States Energy Information Administration

Population growth and per capita energy use

- Global population has increased by 5x between 1850 (1.3 billion) and 2010 (6.9 billion)
- Global population is projected to increase by 57% between 2000 and 2050
- Energy use per capita has increased by more than 15x between 1850 and 2010

Take home points:

- Global population is increasing
- EACH person uses more energy now than in 1850



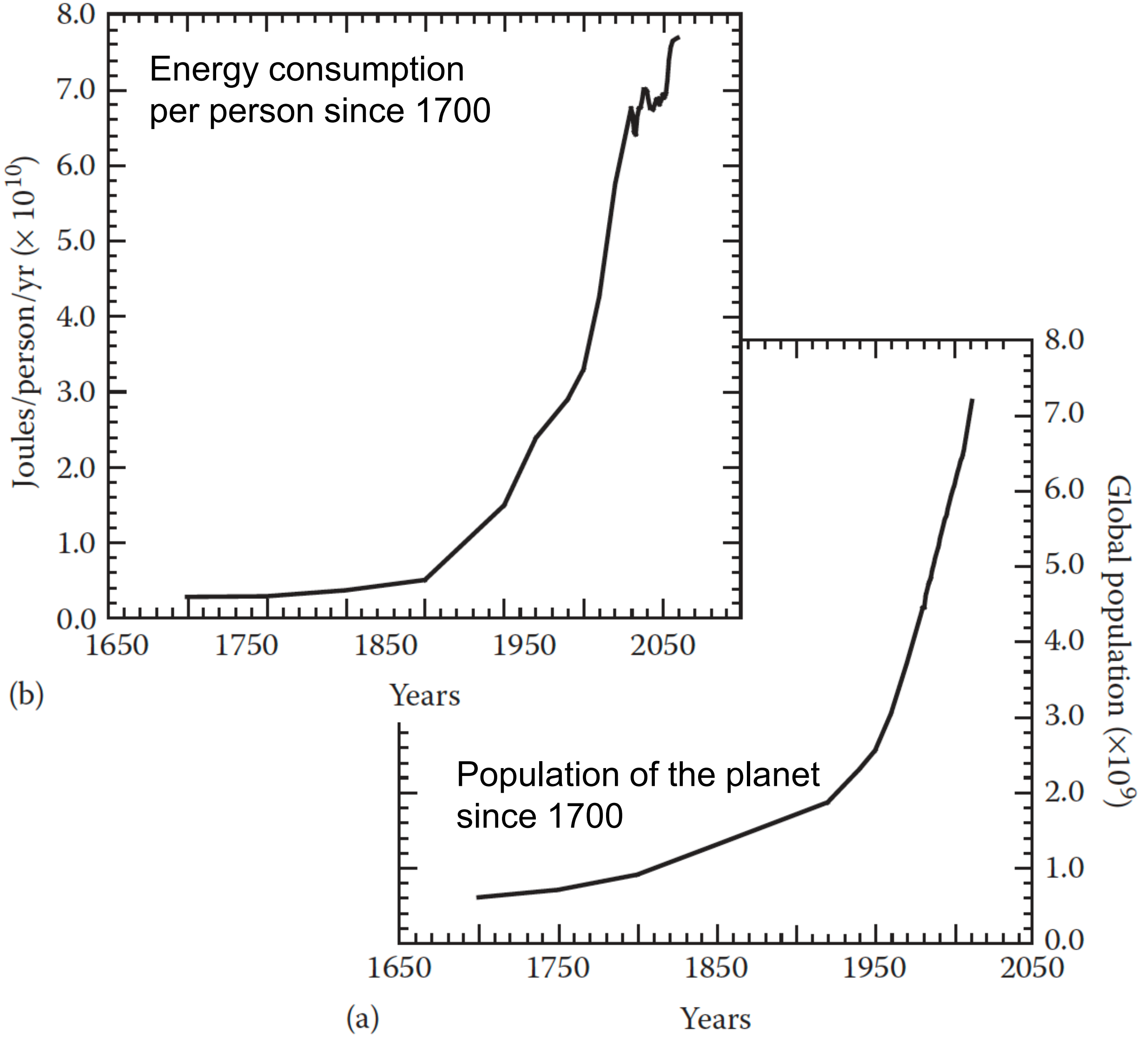
Source: Glassley, W. E., *Geothermal Energy*

Population growth and per capita energy use

Loss of access to energy has societal, economic, industrial political implications.

Examples:

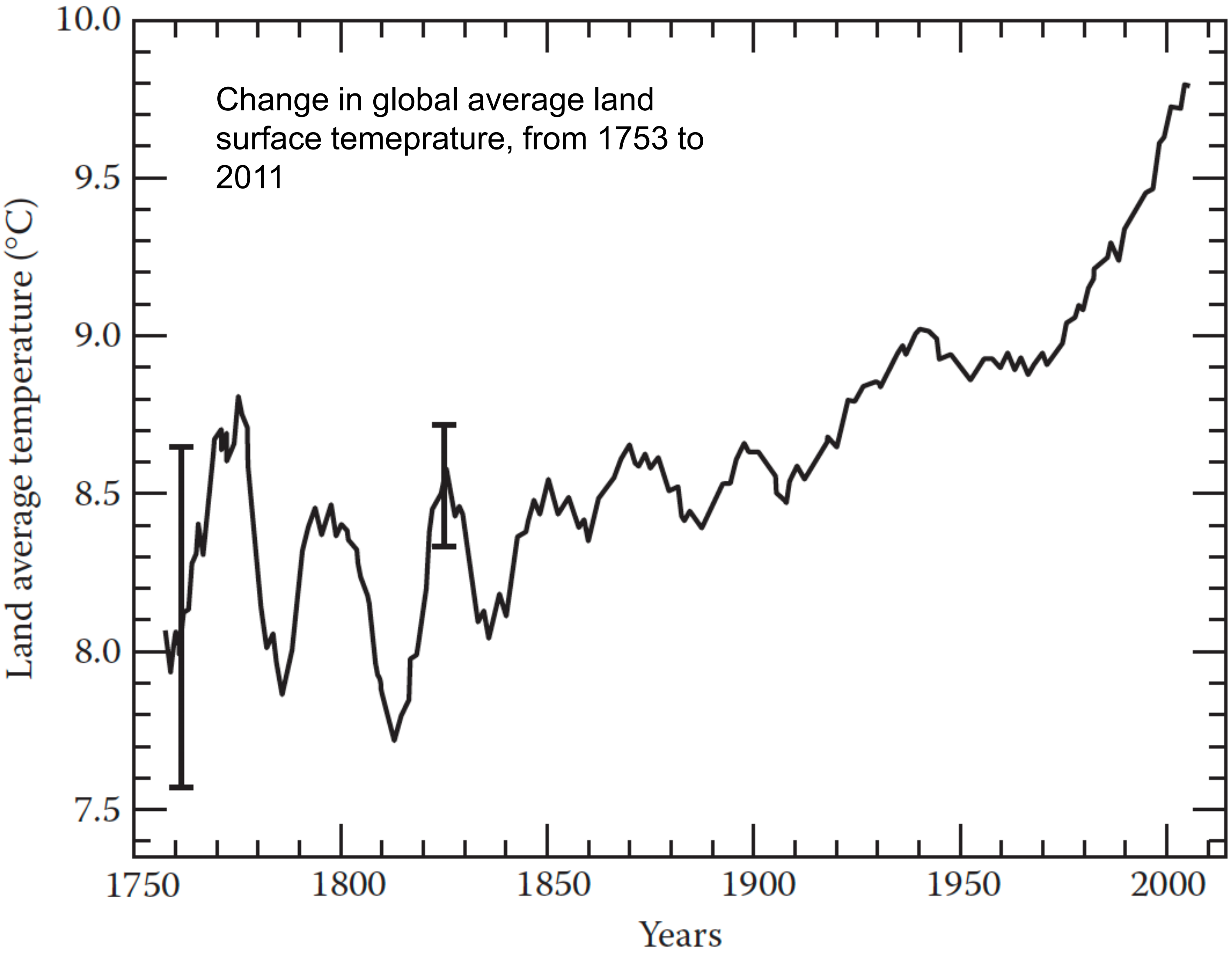
- 1973 oil crisis
- 1979 oil crisis
- 2007/2008 oil shock
- 2022 energy crisis



Source: Glassley, W. E., *Geothermal Energy*

Greenhouse gas emissions

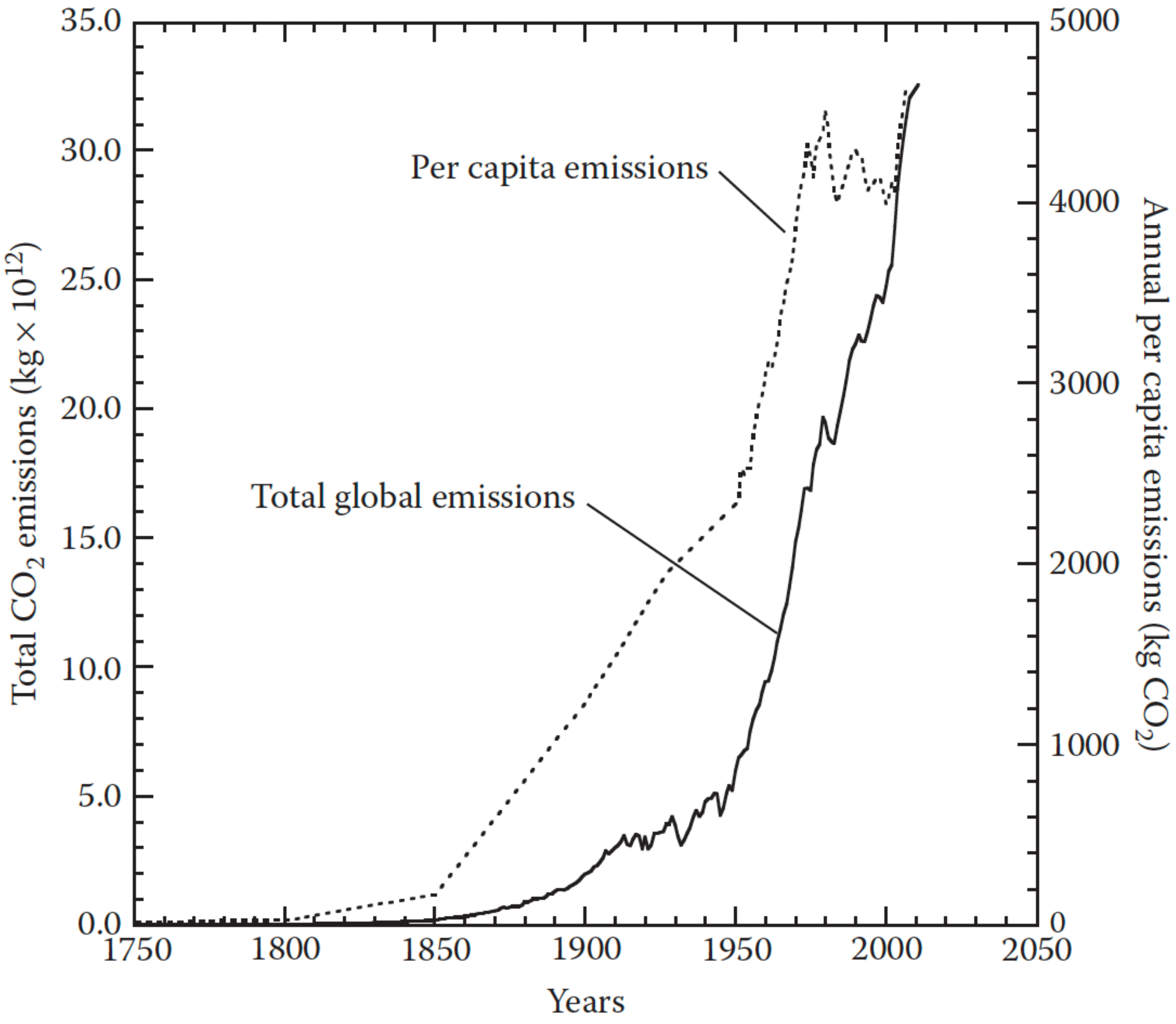
- Carbon-based fuels increases greenhouse gas (CO_2, CH_4) concentration in the atmosphere
- Greenhouse gases reduce the transmissivity of the atmosphere to thermal energy: the atmosphere traps heat
- Surface temperature increases



Source: Rohde et al. (2013) *Geoinformatics & Geostatistics: An Overview*

Greenhouse gas emissions

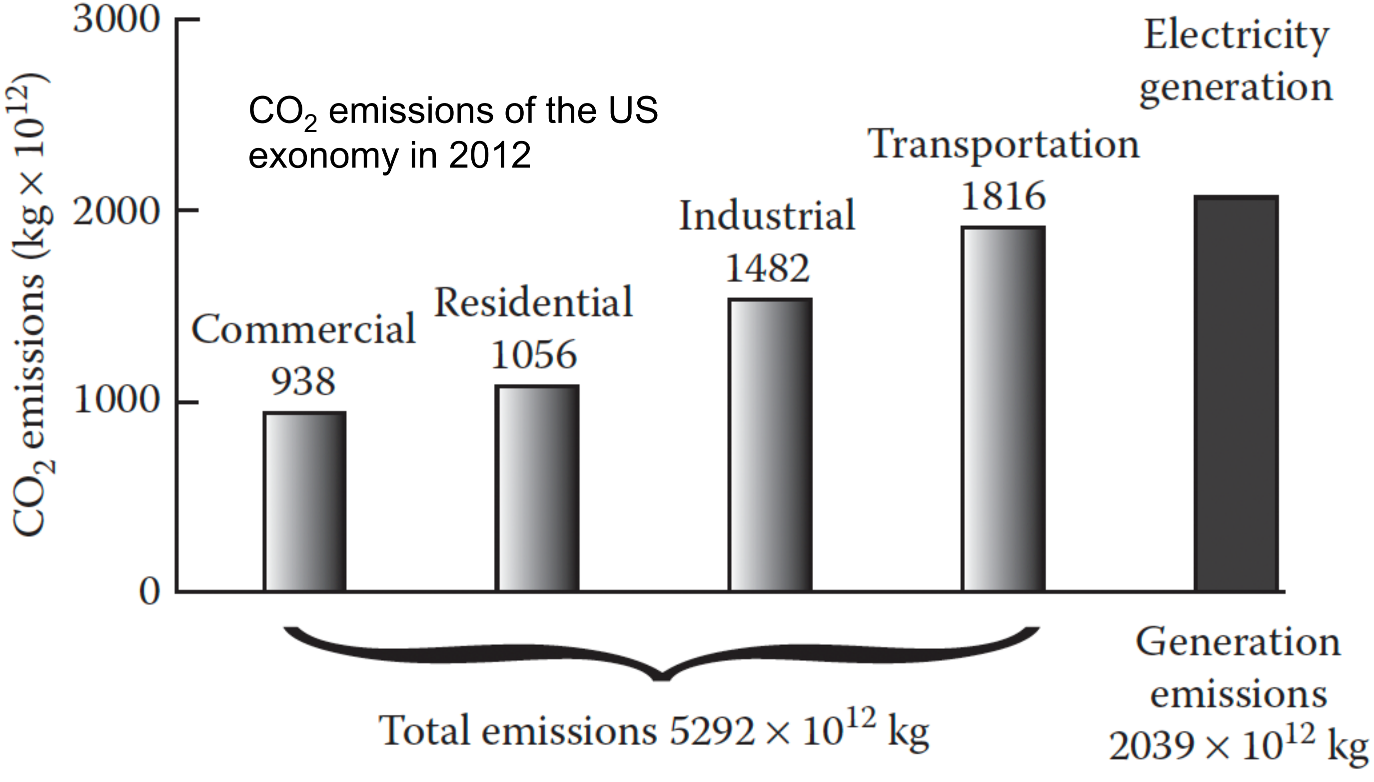
- Total global CO_2 emissions from burning fossil fuels increased by 16x between 1750 and 2011
- Per capita CO_2 emissions increased almost 30x between 1750 and 2011



Source: Glassley, W. E., *Geothermal Energy*

What do we use energy for?

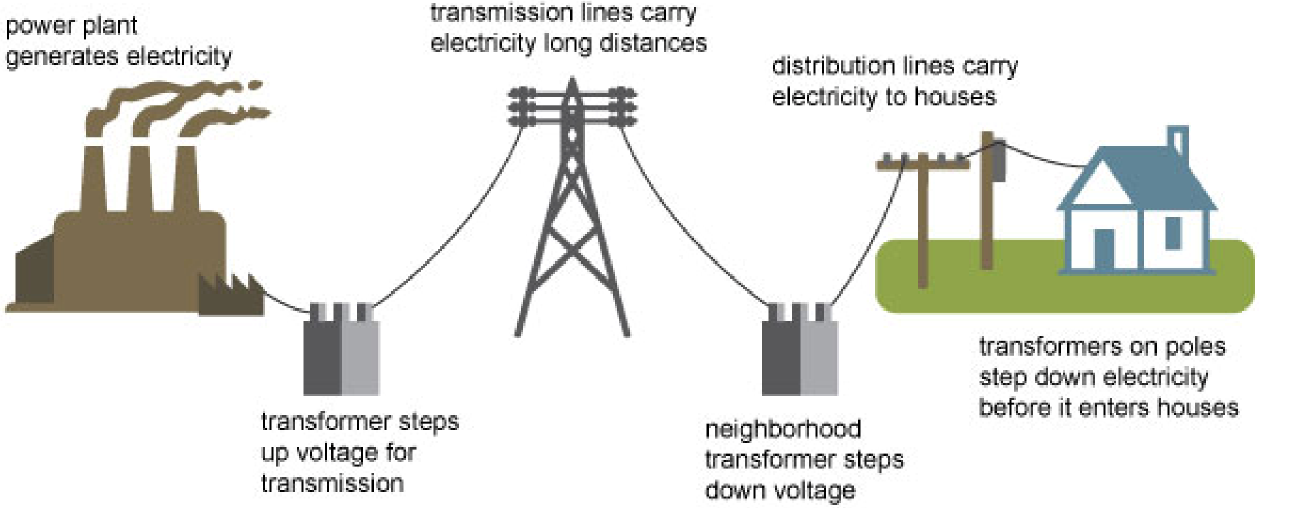
- Total CO_2 emissions in the US in 2012: 5292×10^{12} kg
- >50% of CO_2 emissions result from generation of electricity for:
    - Commercial
    - Residential
    - Industrial
    - Transportation sectors
- Electricity generation accounts for >50% of all greenhouse gas production



Source: Glassley, W. E., *Geothermal Energy*

Supplying electricity to the power grid

Electricity generation, transmission, and distribution

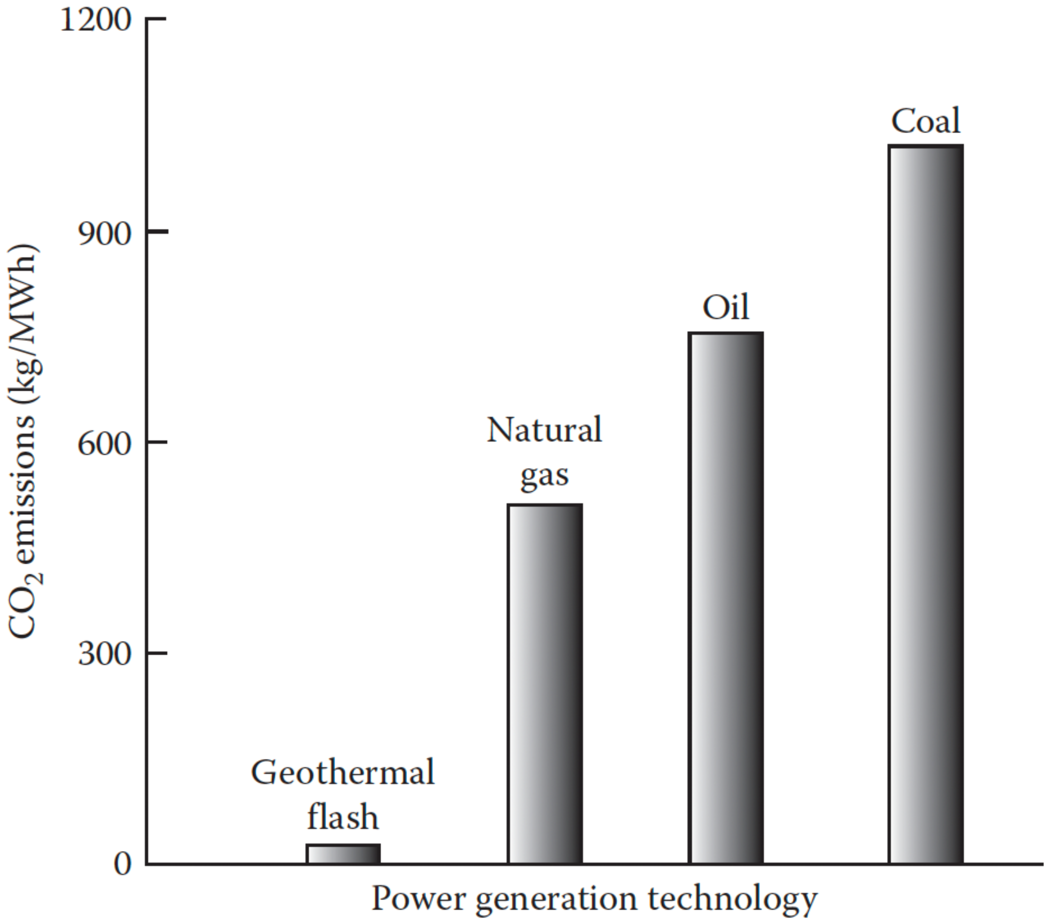


Source: Adapted from National Energy Education Development Project (public domain)

- Electrical grid links power generators and power users
  - A system of distribution and transmission lines
- Commonly segmented into regions supplied and administered by operators and regulators

How do we reduce our reliance on fossil fuels

- Reduce demand for electricity
- Replace fossil fuel-based electricity generation with renewable energy sources
- Replace liquid fossil-fuels with other forms of portable energy sources



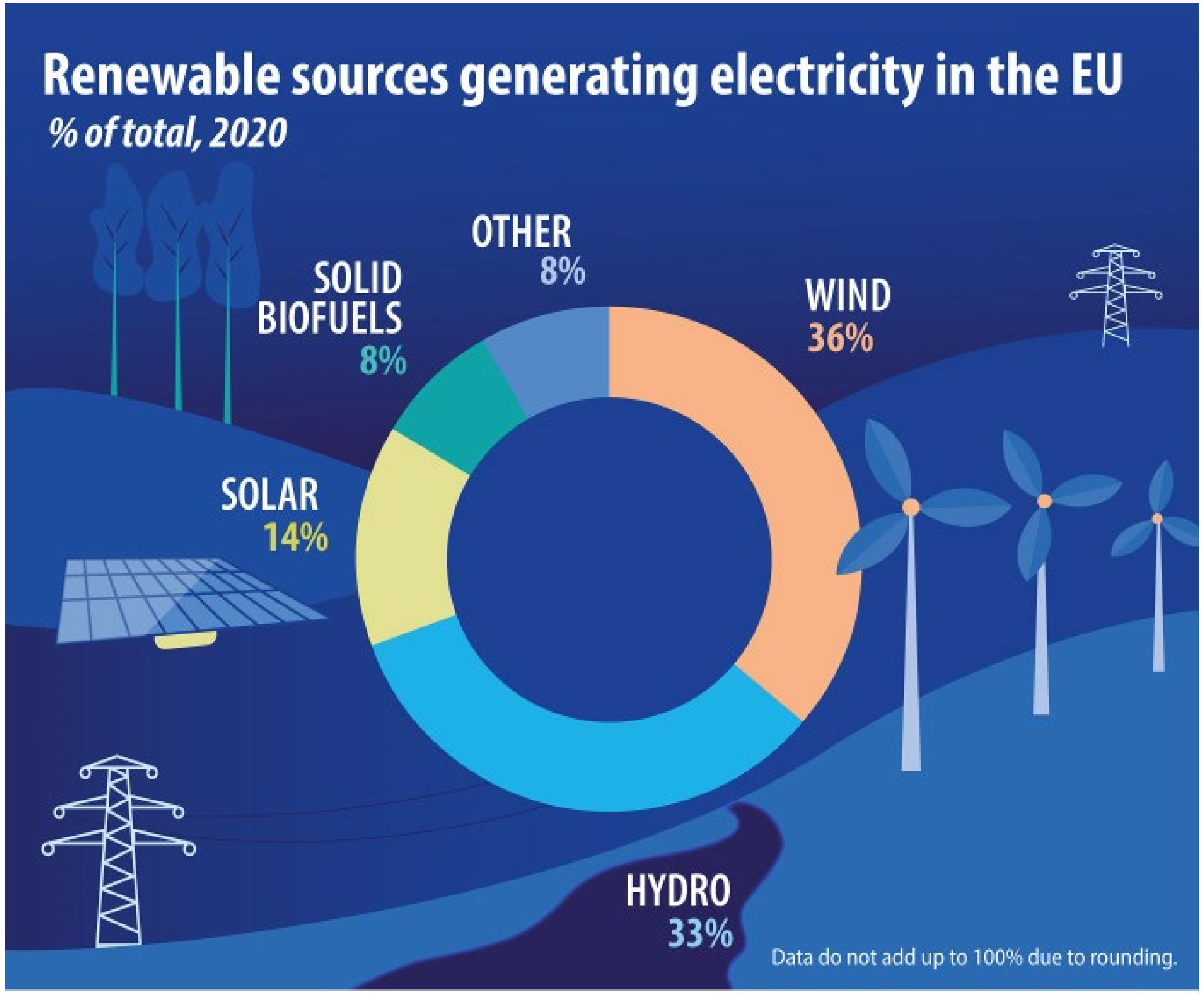
Source: Glassley, W. E., *Geothermal Energy*

Replacing fossil fuels

To replace fossil fuels, new fuel sources need to meet certain criteria:

- Sufficiently abundant to meet a significant percentage of the market demand
- Obtained at a cost competitive with existing energy sources
- Reduce or eliminate greenhouse gas emissions
- Renewable: is it self-replenishing?

In 2020, renewable energy generated about 37% of all electricty in the EU



ec.europa.eu/eurostat

Replacing fossil fuels

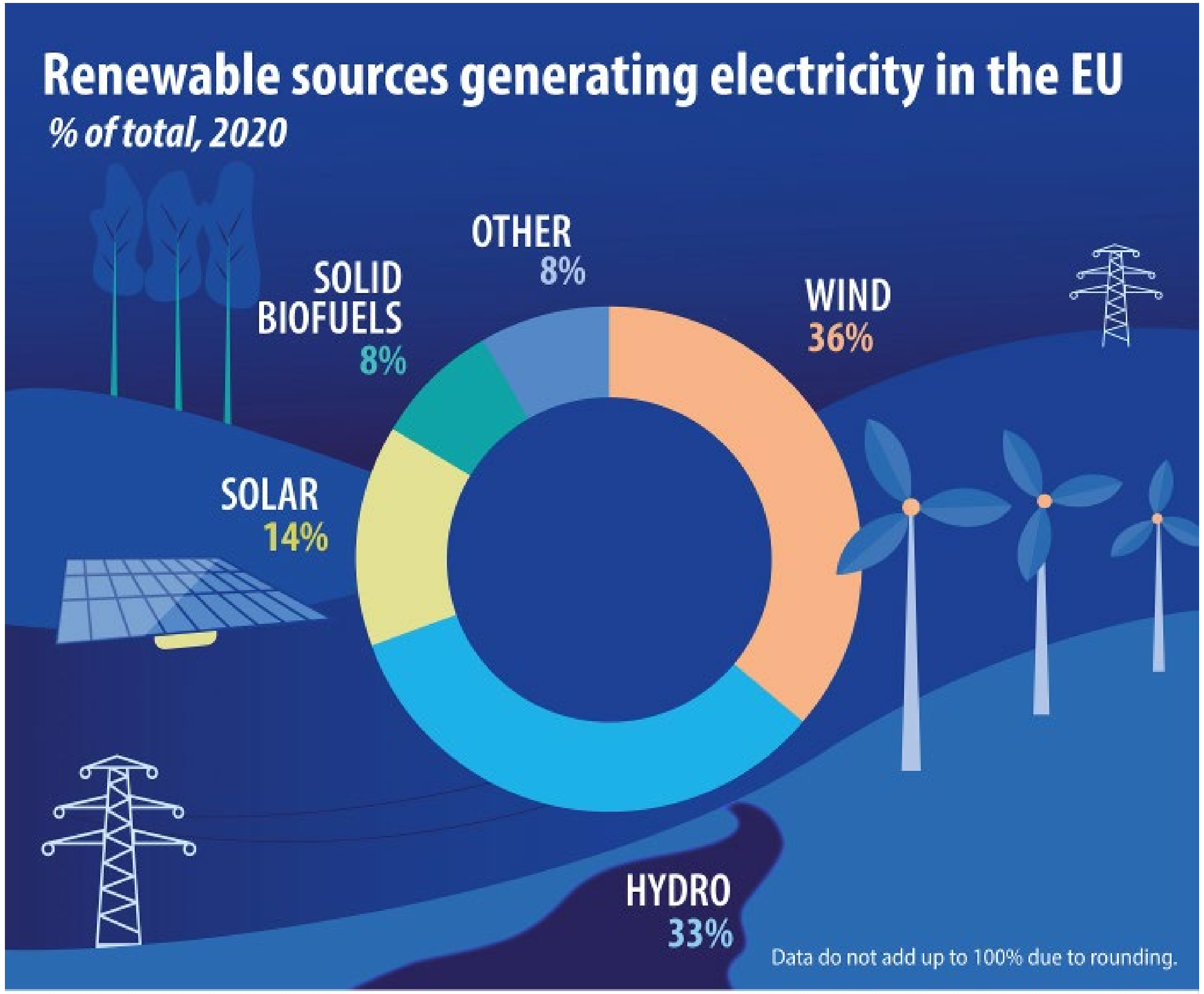
Solar and wind energy are intermittent:

- Their output does not remain constant due to diurnal and seasonal variations

Geothermal energy is not intermittent:

- Can be used as a baseload power source and, with management, can be dispatchable

In 2020, renewable energy generated about 37% of all electricty in the EU



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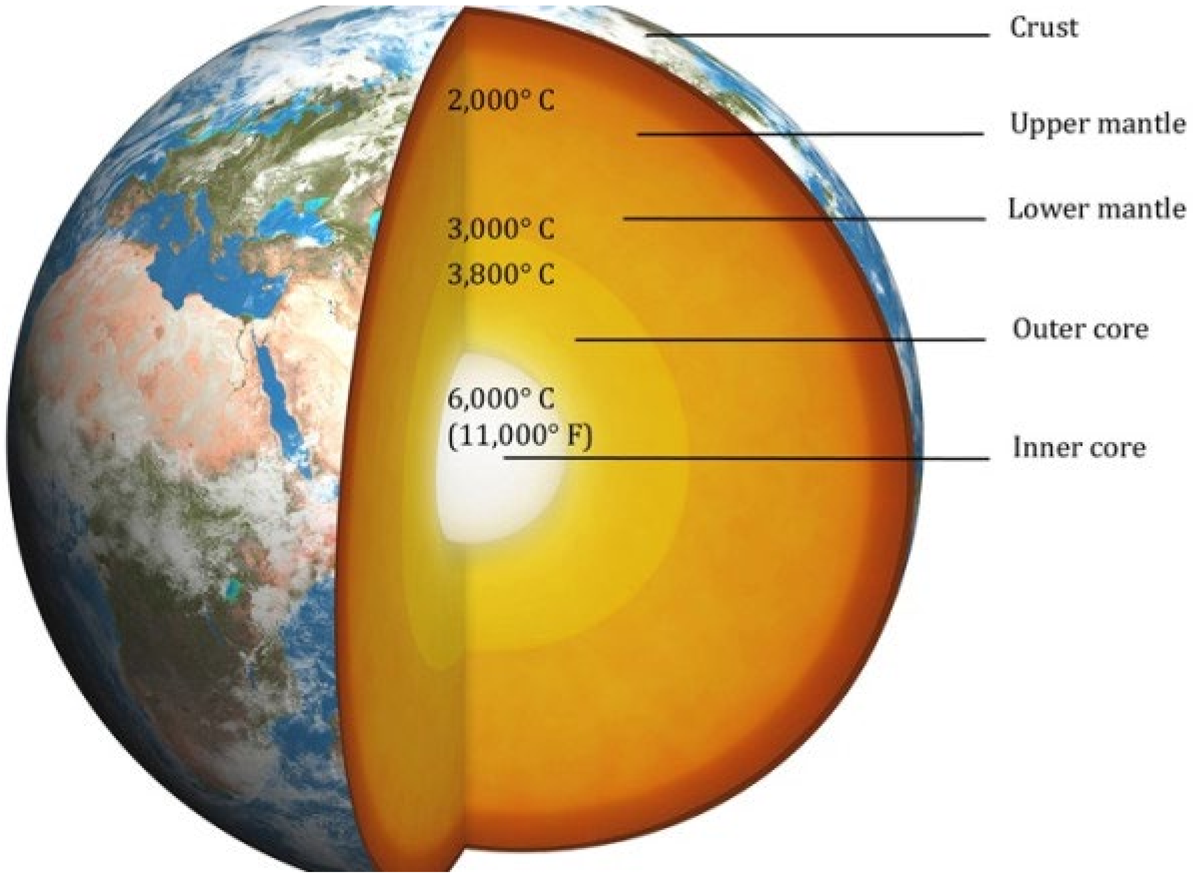
What is Geothermal Energy?



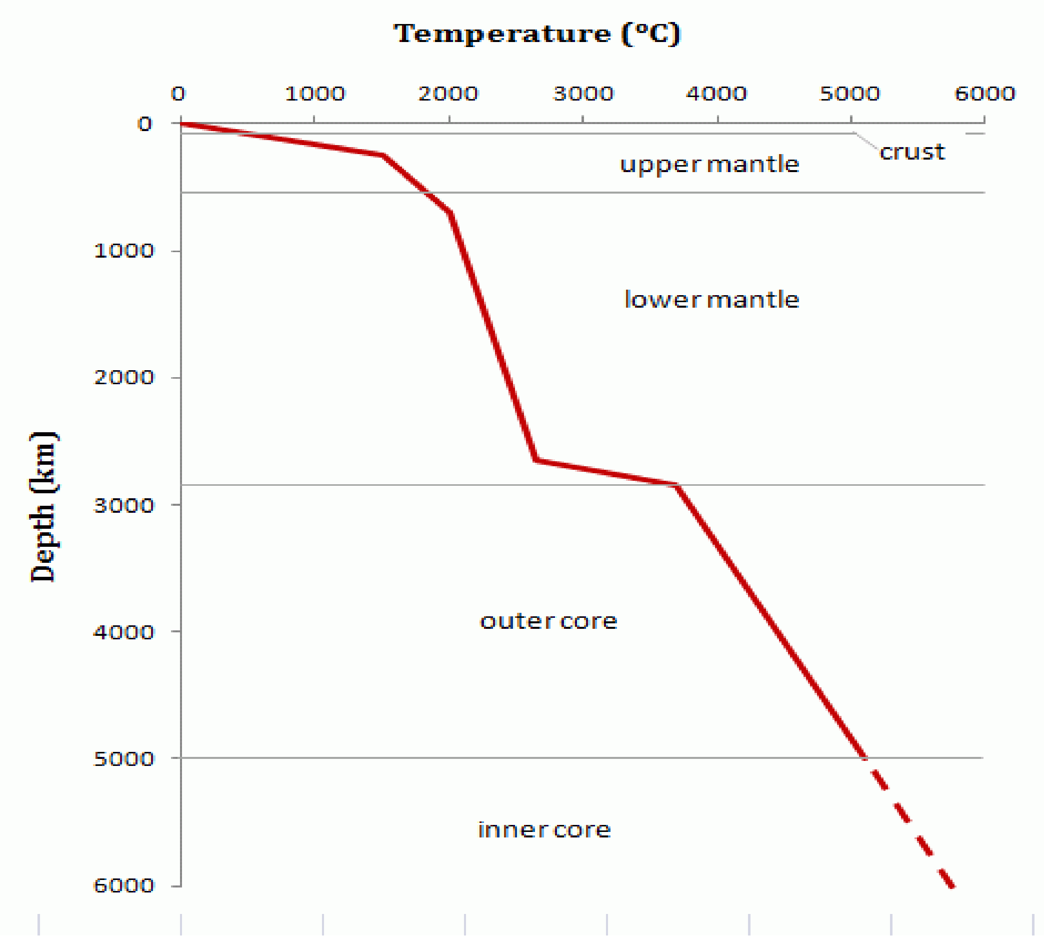
It is simply the heat energy of the earth, generated by various natural process, such as

- heat from when the planet formed and accreted (20 TW)
- Decay of radioactive element (24 TW)
- Friction (minor contributions)

- Energy flux: 44.2 TW

The deeper you go, the hotter it is

What is Geothermal Energy?



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The deeper you go, the hotter it is

Where does the heat come from?

Radioactive decay: U, K, Th decay is responsible for up to 85% of continental heat production

Rock type	Average heat production ($\mu W/m^3$)
Granite	1.0 – 7.0
Gneiss	1.0 – 4.0
Sedimentary	0.7 – 1.5
Peridotite	0.03 – 0.1
Soutlz-sous-Forêts granite	3.0 – 6.0
High Heat-Producing (HHP) granite	10 – 30

Crust / Mantle	Average heat production ($\mu W/m^3$)
Continental crust	~ 1.0
Oceanic crust	~ 0.5
Mantle	~ 0.02

Where does the heat come from?

Radioactive decay: U, K, Th

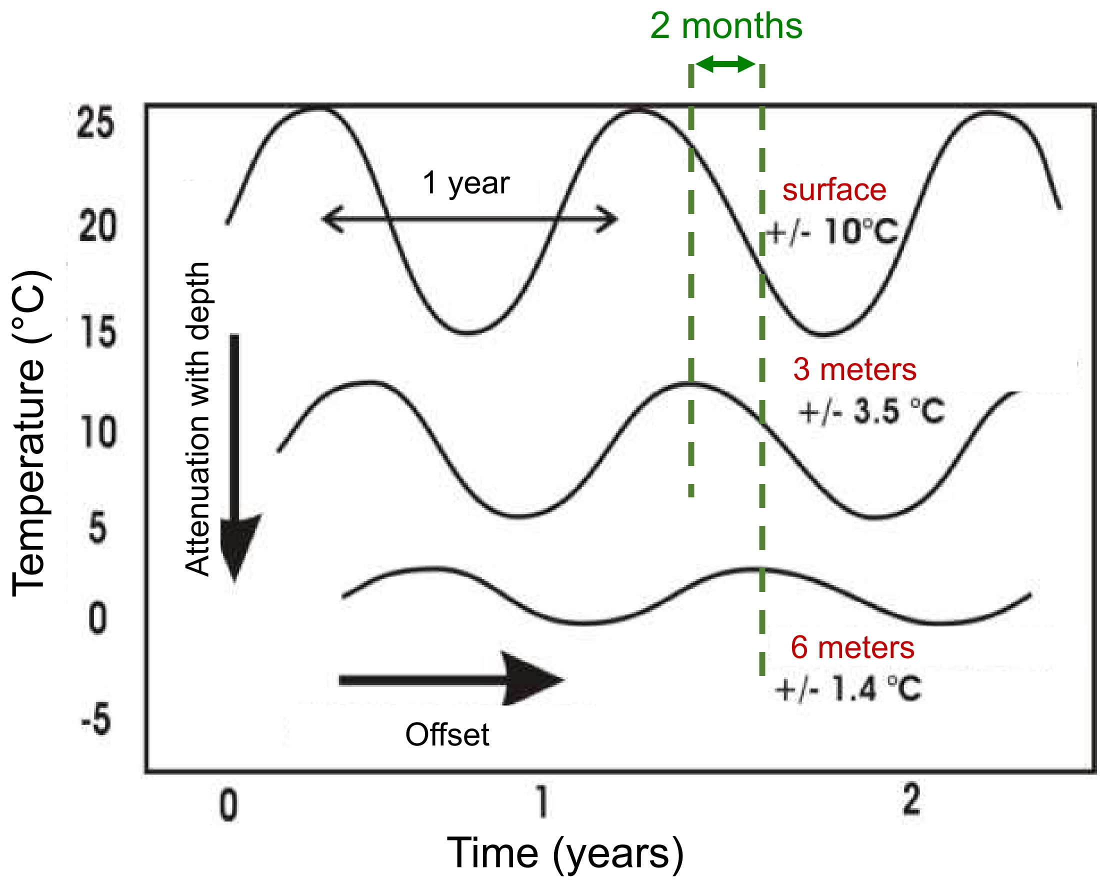
- Up to 85% of continental heat production

Residual heat from the Earth's interior

- Mantle + Core
- Mantle makes up 1/2 of the Earth's radius and 85% of the Earth's volume

Solar radiation

- Down to 5 - 25 m
- Seasonal variations up to 10 m



Below 10 m, seasonal variation does not change geothermal temperatures. Geothermal temperatures are constant 24 hours a day, 365 days a year!!

How is heat transferred in the Earth?

Heat moves from hot to cold.

Heat transfer mechanisms:

- radiation
- conduction
- convection

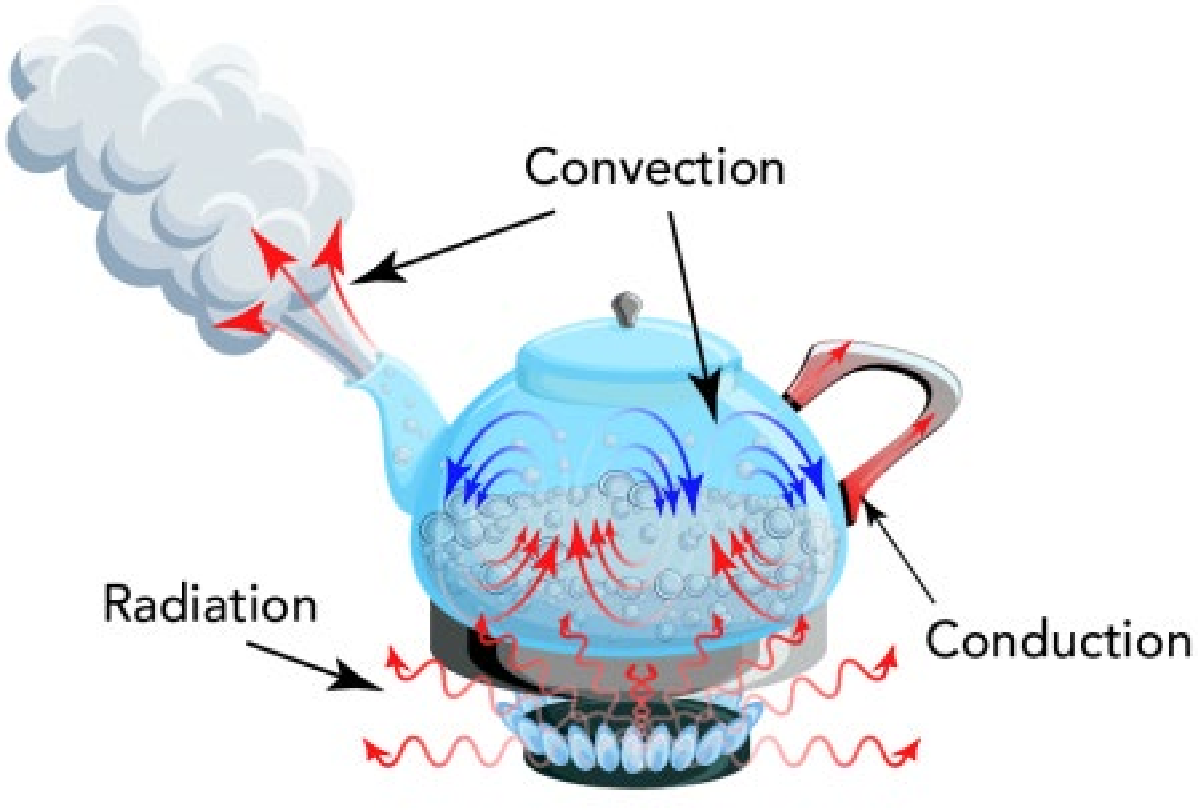
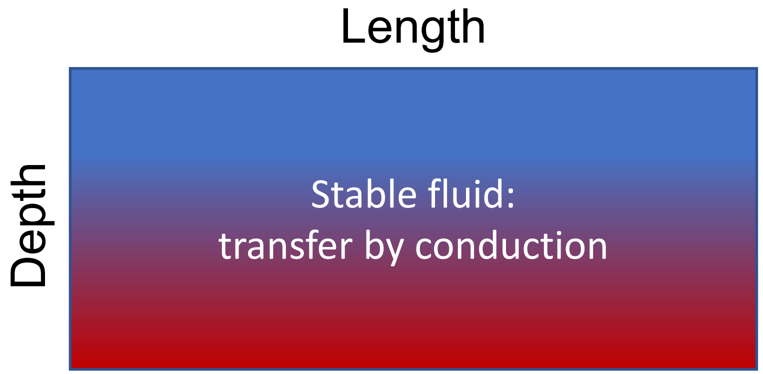
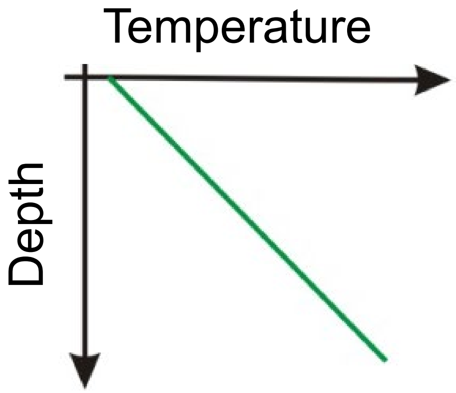


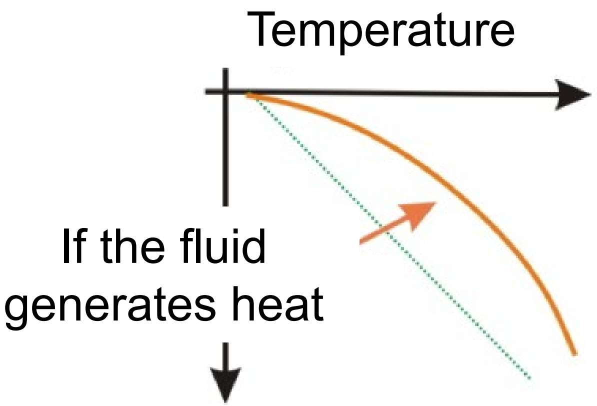
Image source: https://letstalkscience.ca/educational-resources/backgrounders/introduction-heat-transfer

How is heat transferred in the Earth?

Conduction : no movement of material

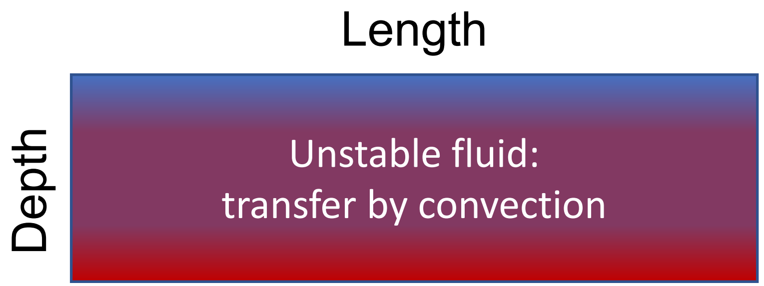




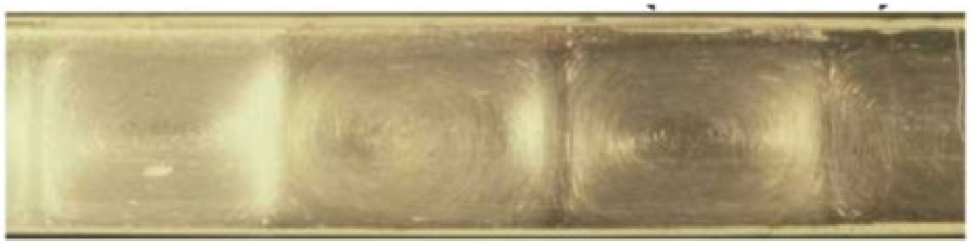


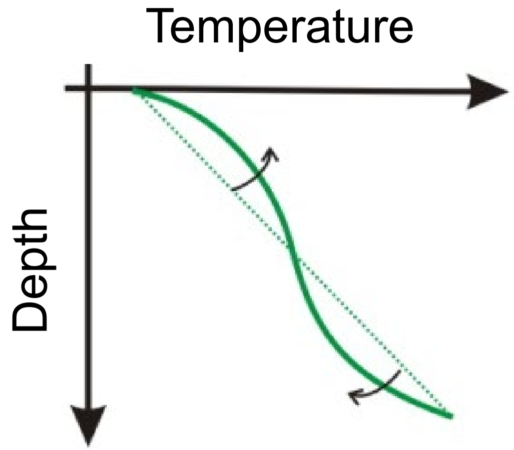
How is heat transferred in the Earth?

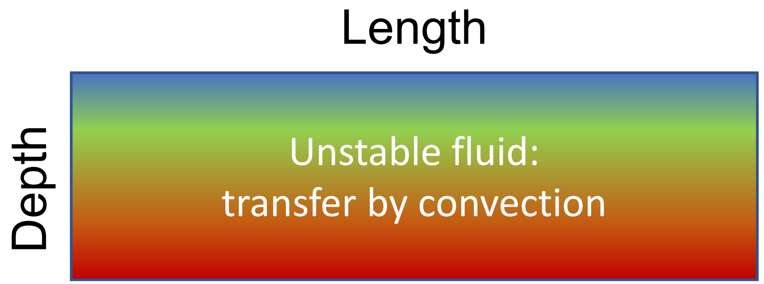
Convection : movement of material



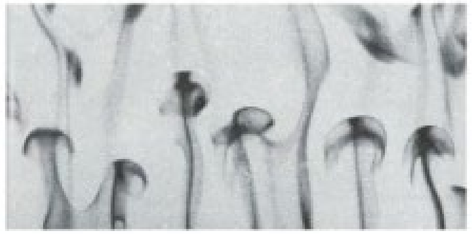
Convection cells

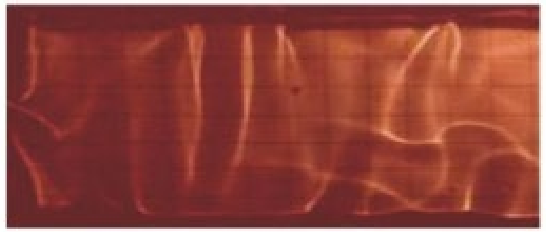


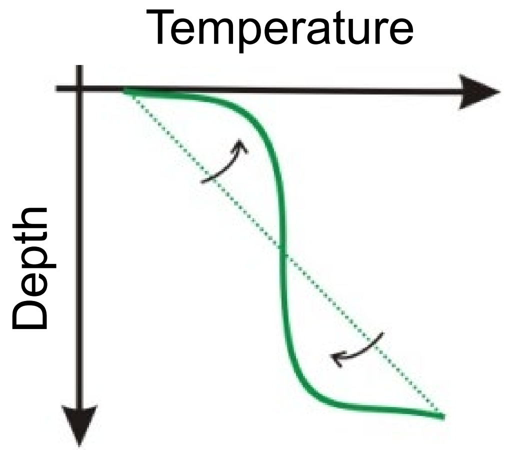




Plumes

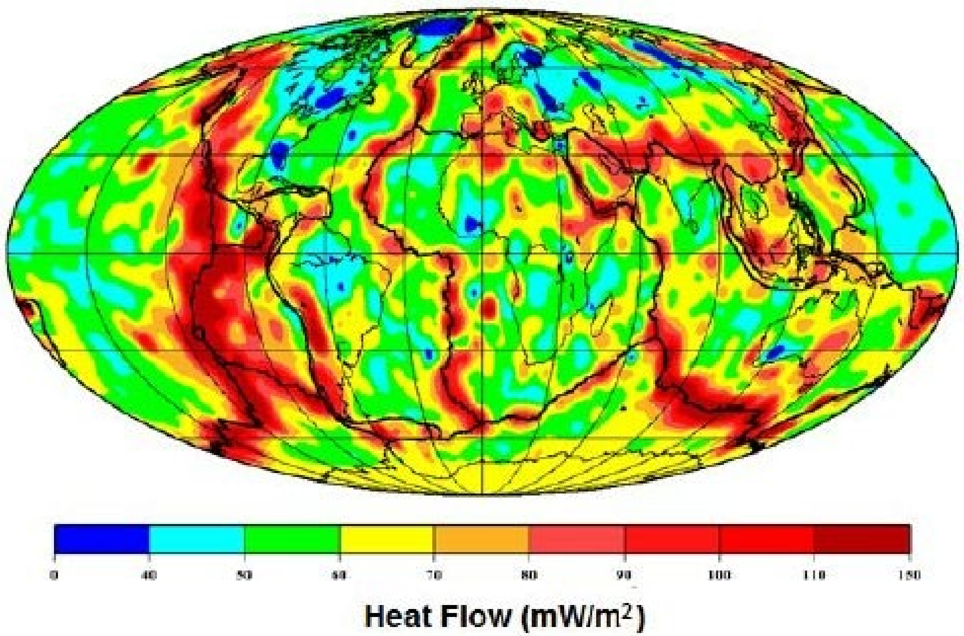






Where do we find heat at the Earth's surface?

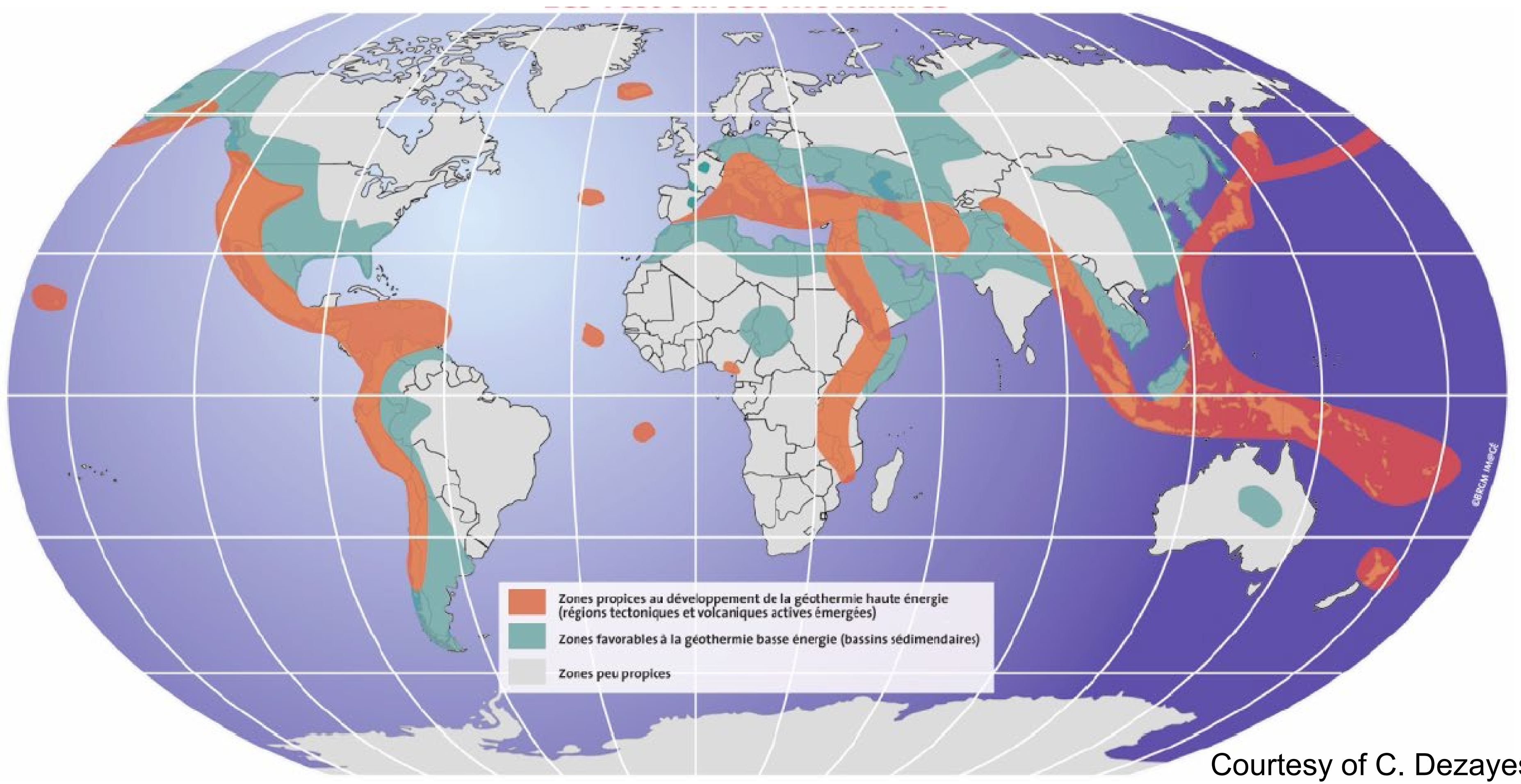
- Most active geothermal resources are found on major plate boundaries



Hamza and Vieira, 2021

World map showing variation in surface heat flow in mW m−2 in relation to continental and oceanic crust, and major plate boundaries.

Where do we find heat at the Earth's surface?



Courtesy of C. Dezayes, 2021

Low temperature resources
Heat production

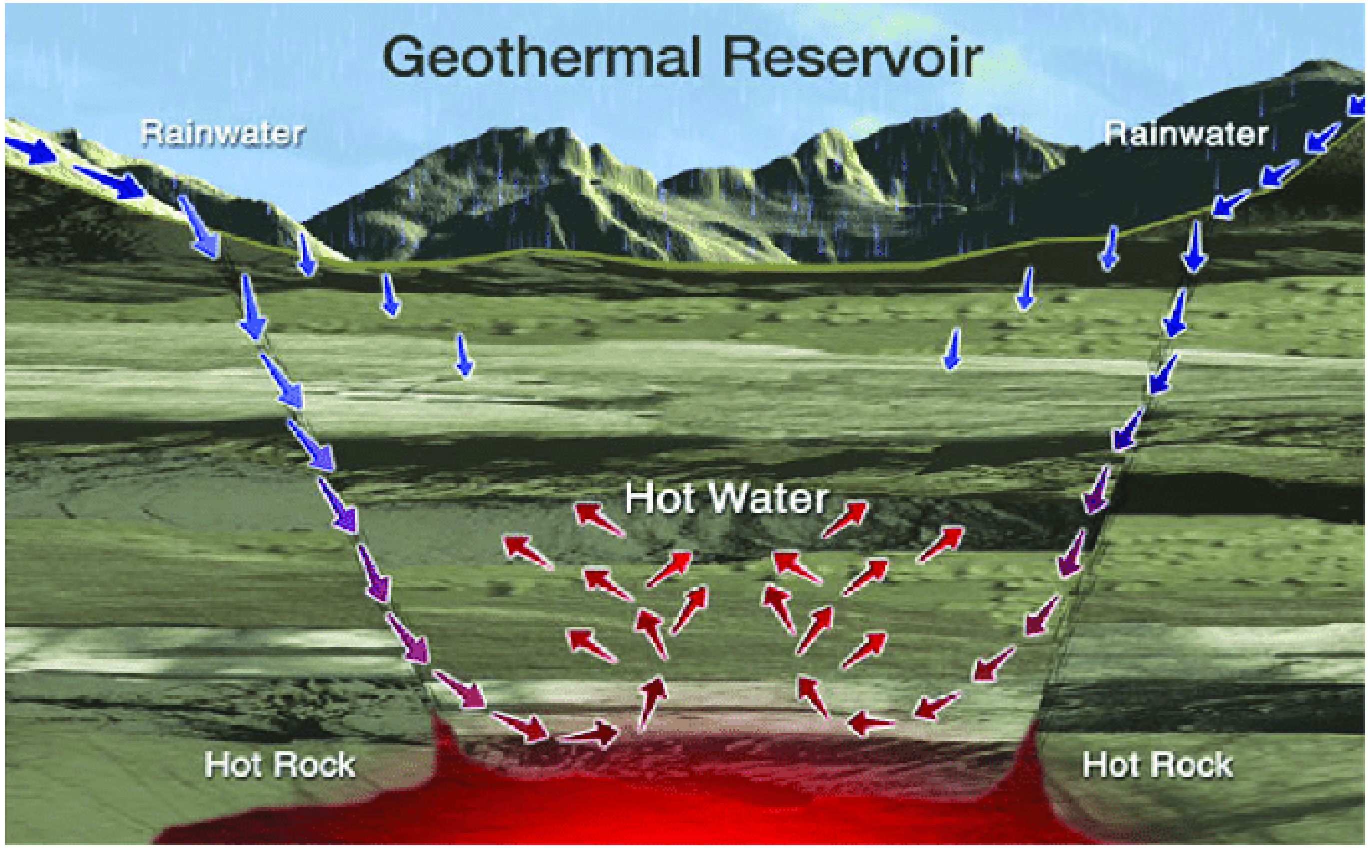
High temperature resources
Electricity production

Geothermal reservoirs

Reservoirs can be suspected in the areas where we find :

- Geysers
- Boiling mud pot
- Volcanoes
- Hot springs

Geothermal reservoirs



- The rising hot water and steam is trapped in permeable and porous rocks to form a geothermal reservoir

History

- Geothermal energy dates back to paleolithic times. Used for bathing, cooking, and heating
- First commercial use was in the first century in England
- Oldest geothermal heating system Chaudes-aigues, France (XIV century)
- One of the first geothermal power plant (to produce electricity) Larderello, Italy (XX century)

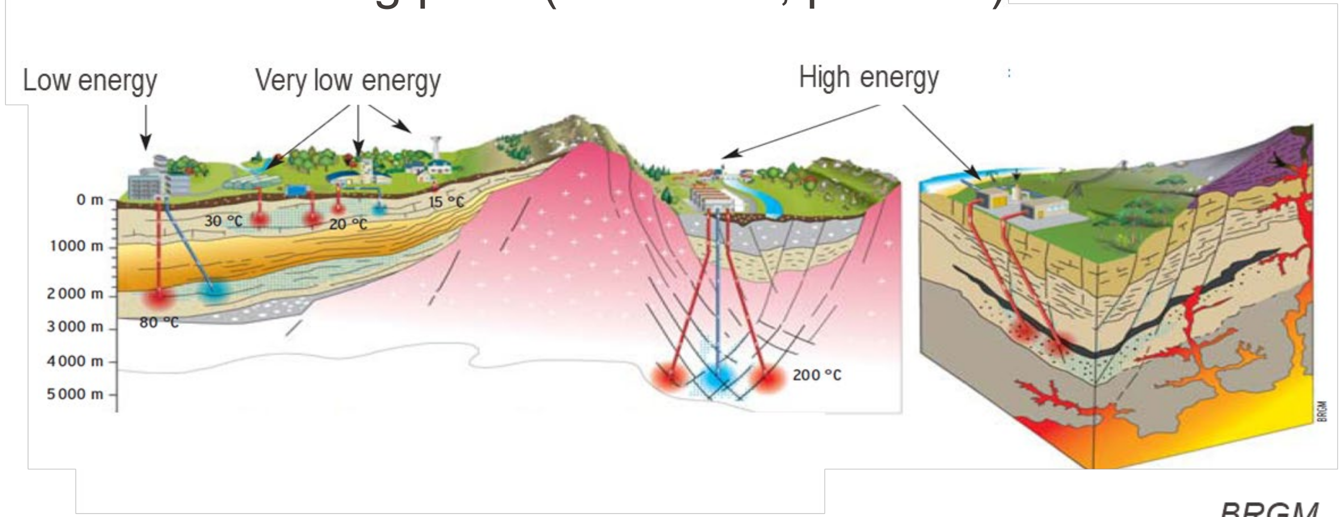

Heating system, Chaudes-aigues, France


geothermal power plant,
Larderello, Italy, 1904

How is Geothermal Energy Used?

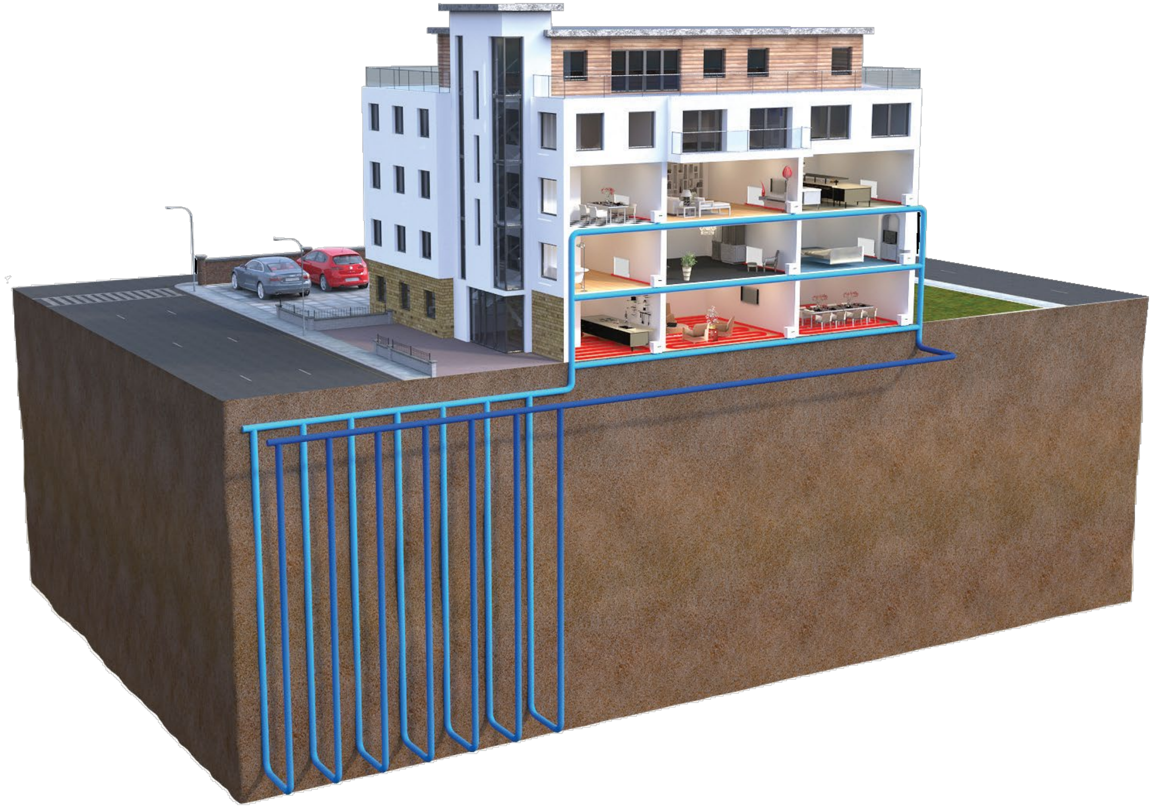
- **Low temperature: Direct Use➔Heating**
  - can start with a hydrothermal resource as low as 10 Celsius.

- **High-temperature:Indirect use➔ electricity production**
  - **Dry steam**: vapor-dominated reservoirs,
  - **Hot water:** (temperature >180 C): most common reservoirs
  - **Flash steam power plant**
  - **Binary cycle:** (100< temperature<180C): Instead of using the steam directly, the hot water heats another fluid with a lower boiling point (isobutane, pentane)



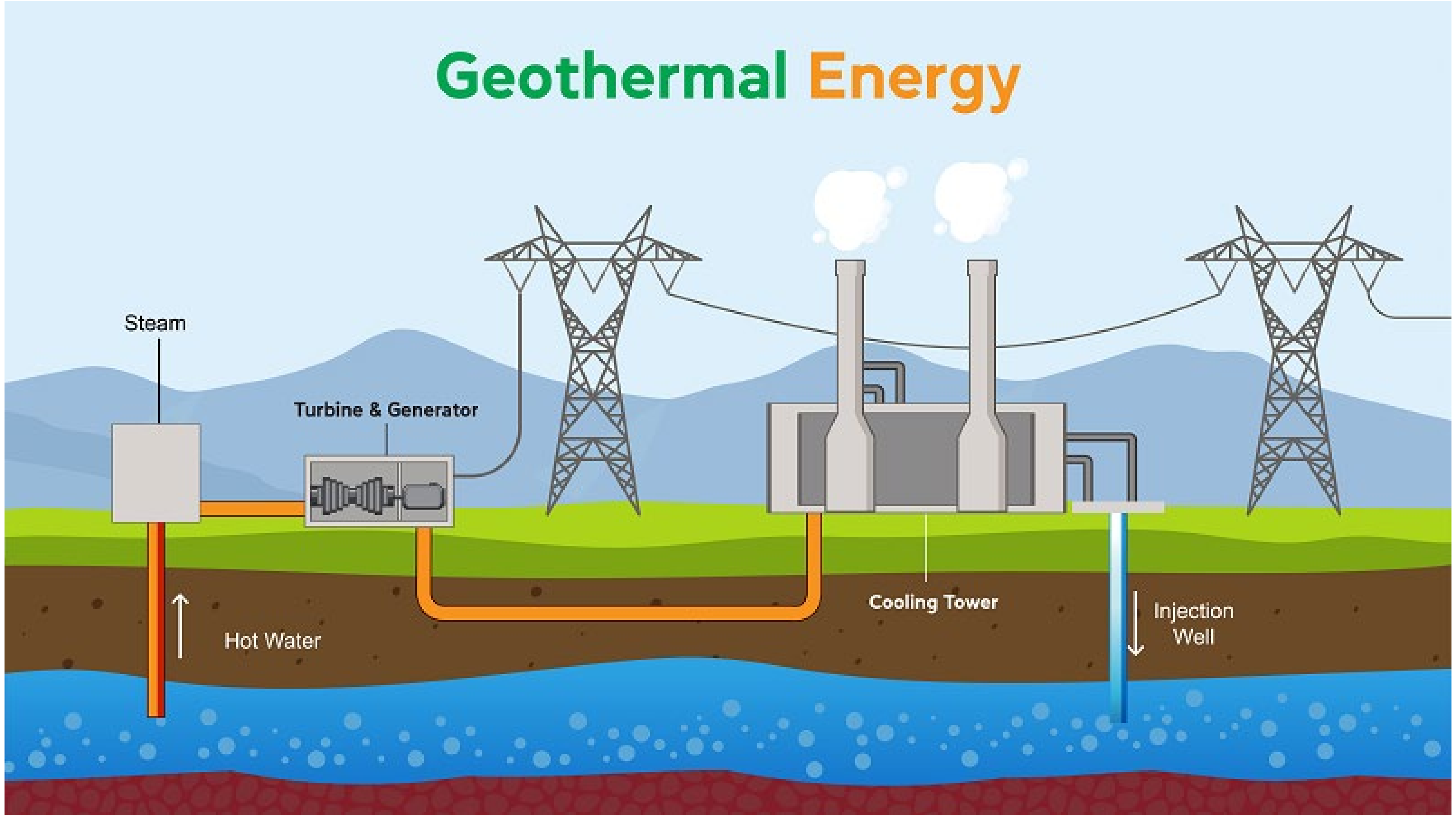
BRGM, (2010)

Direct use of Geothermal Energy



- Hot springs, used as spas
- Heating water at fish farms
- Provided heat for buildings
- Raising plants in greenhouses
- Provides heat to industrial process

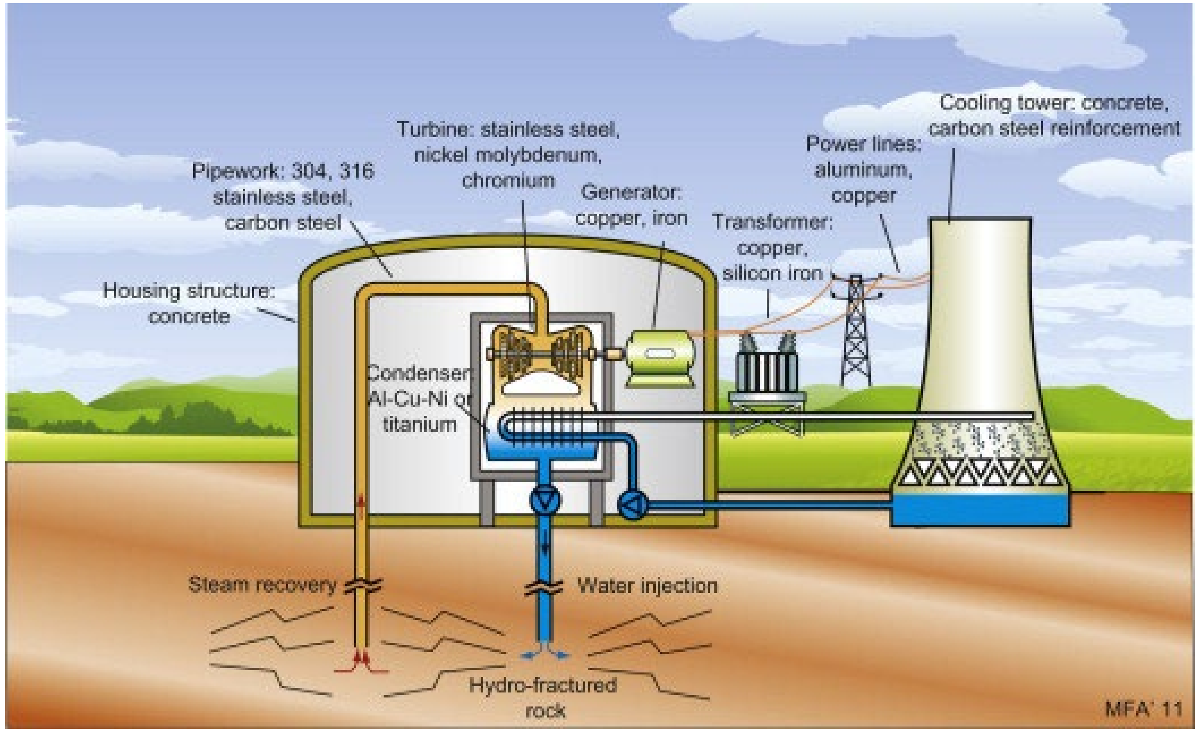
Indirect use of Geothermal Energy



- Electricity generation

Conversion of heat energy

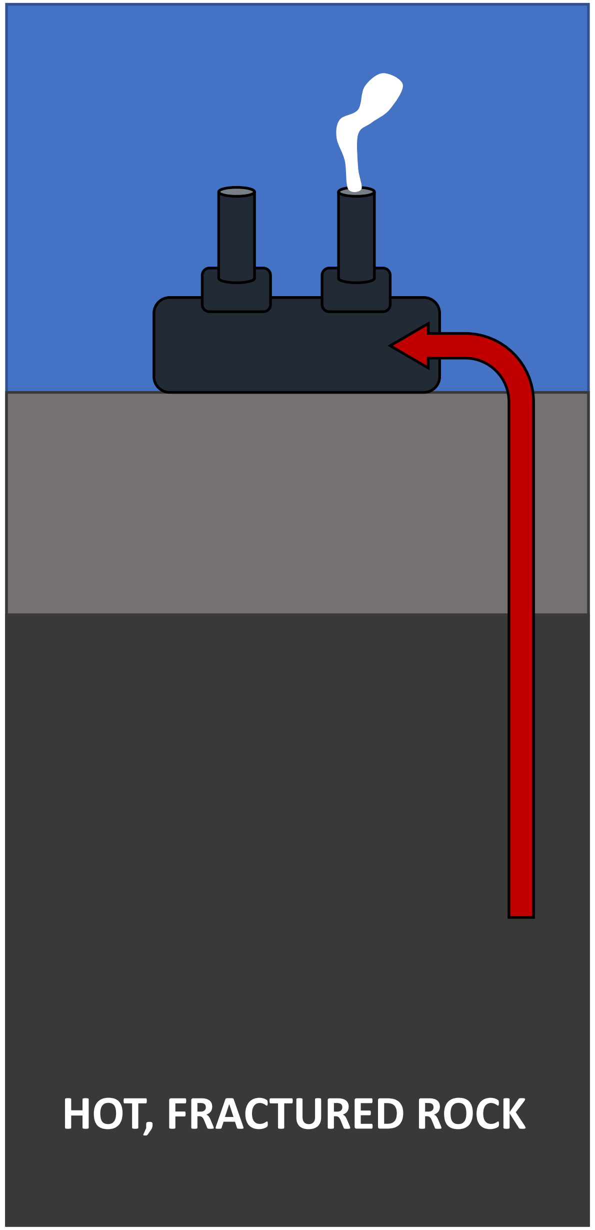
- Heat is drawn from the depths either actively or passively through the movement of hot water
- The heat is then used to boil water
- The steam produced then is fed to a turbine
- The turbine converts the geothermal heat energy into mechanical energy
- The turbine spins a generator which converts mechanical energy into electrical energy



Ashby, 2013

Basics of deep geothermal exploitation

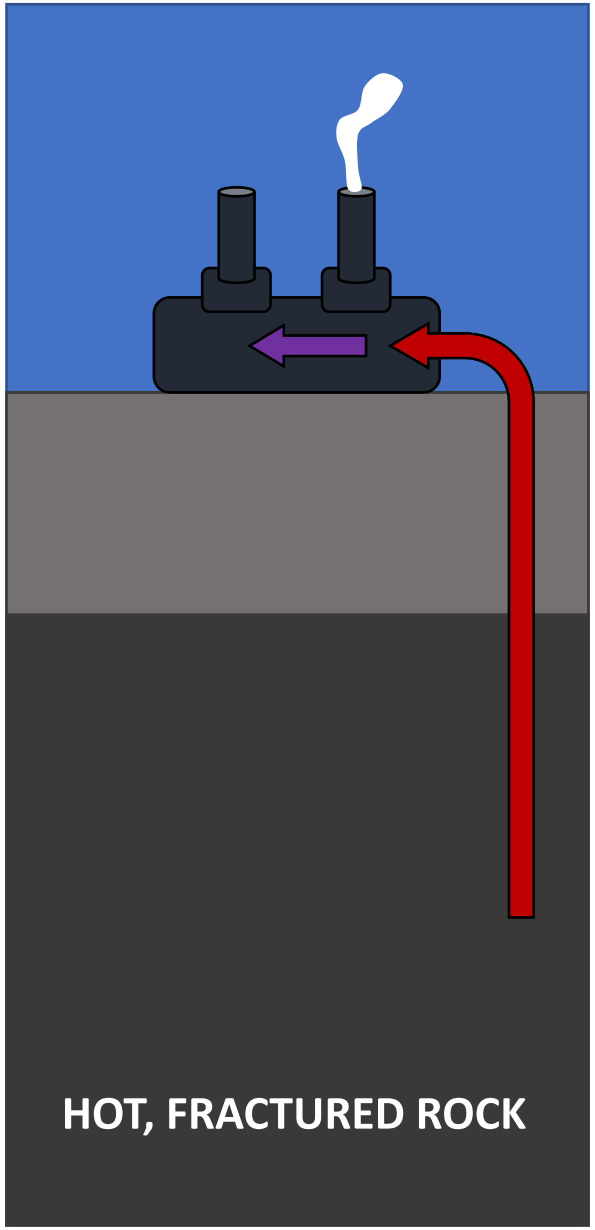
1. Hot water is brought to the surface **(via production well)**



Basics of deep geothermal exploitation

1. Hot water is brought to the surface **(via production well)**

2. **Heat is extracted** in the geothermal plant

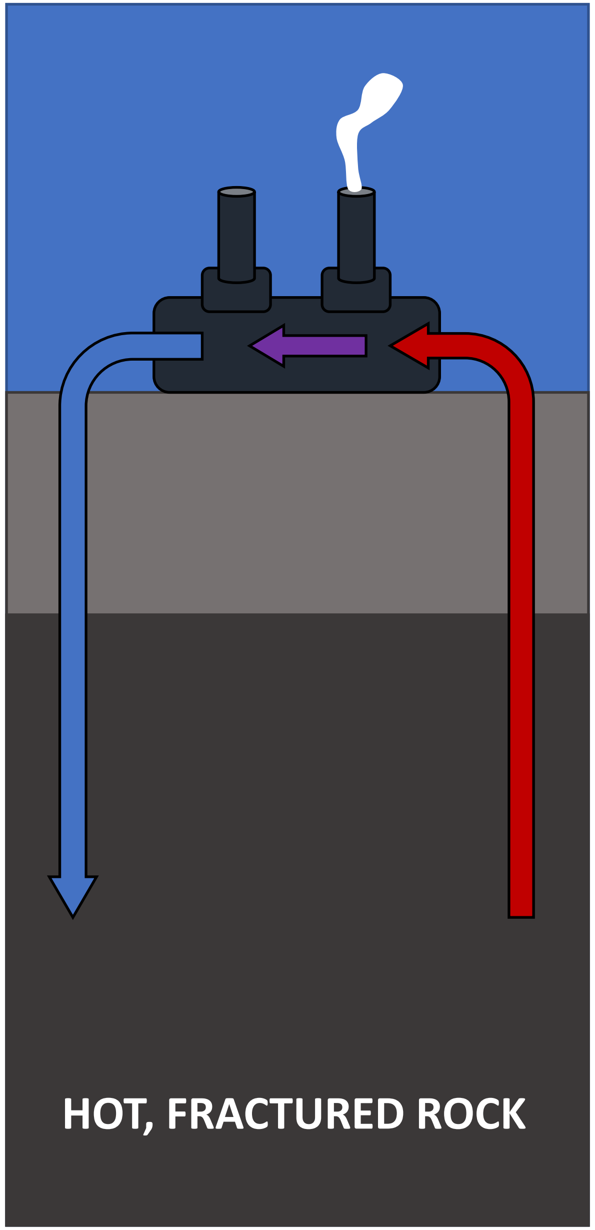


Basics of deep geothermal exploitation

1. Hot water is brought to the surface **(via production well)**

2. **Heat is extracted** in the geothermal plant

3. Cold water is pumped back down into the reservoir **(via injection well)**,



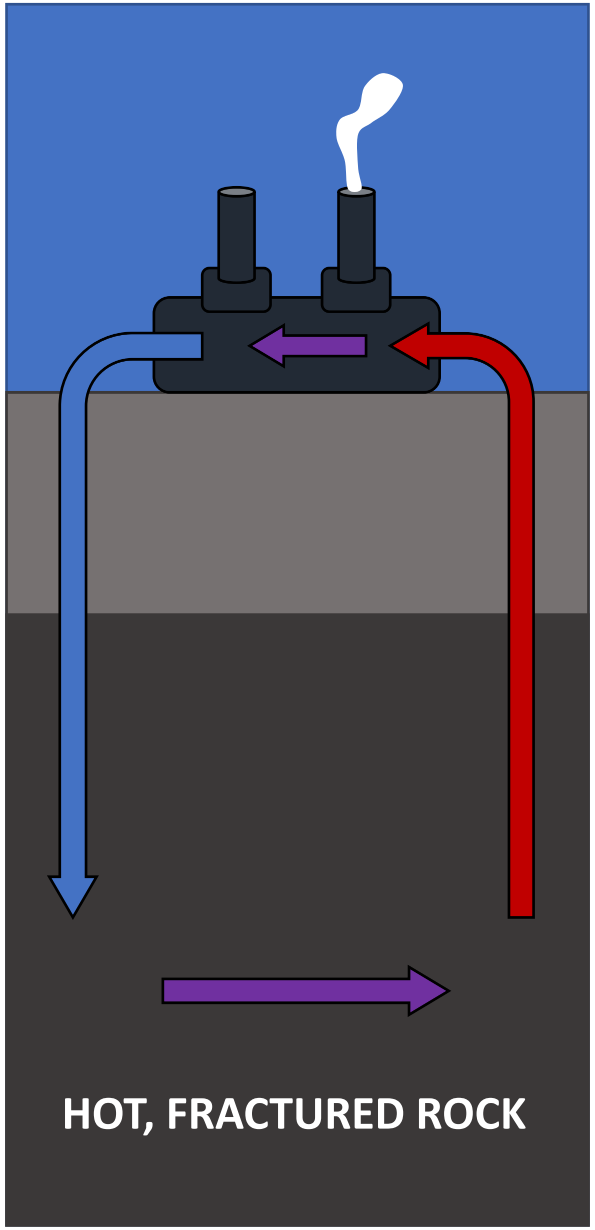
Basics of deep geothermal exploitation

1. Hot water is brought to the surface **(via production well)**

2. **Heat is extracted** in the geothermal plant

3. Cold water is pumped back down into the reservoir **(via injection well)**,

4. Water is **heated again** on the way back to the production well.



Basics of deep geothermal exploitation

Hot Dry Rock (HDR):

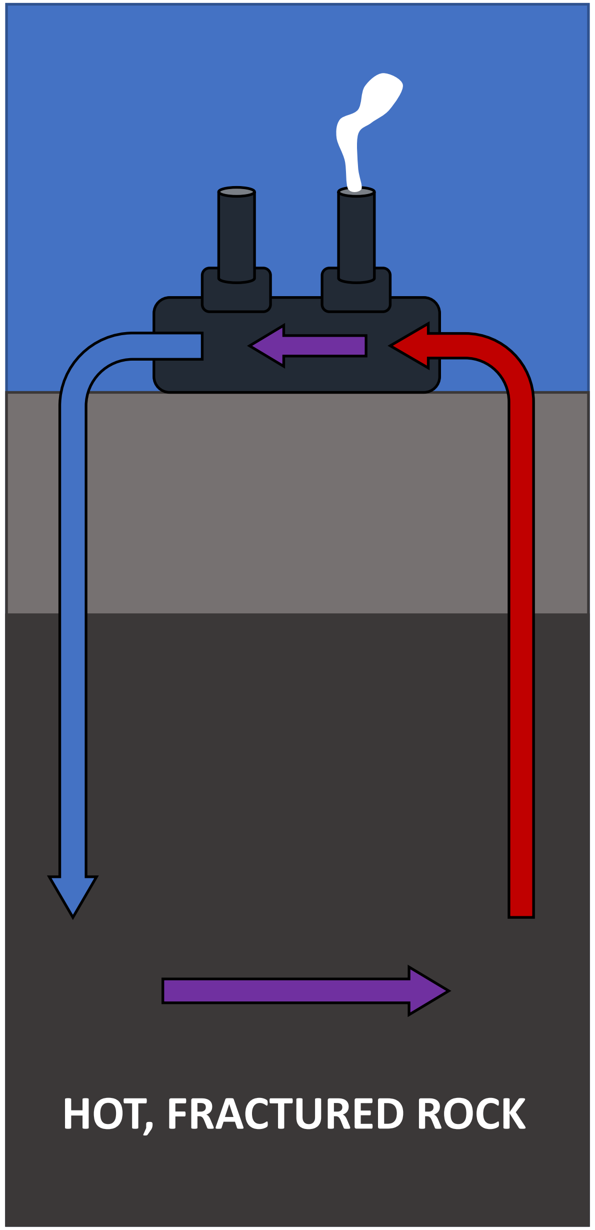
Hot, deep rock that is not naturally permeable and not naturally fluid-rich.

Requires creation of an artificial reservoir through hydraulic fracturing.

Enhanced Geothermal Systems (EGS):

Naturally fractured reservoir, possibly containing water.

Maintain / increase permeability by re-activating these fractures, via chemical, thermal, and/or hydraulic stimulation.



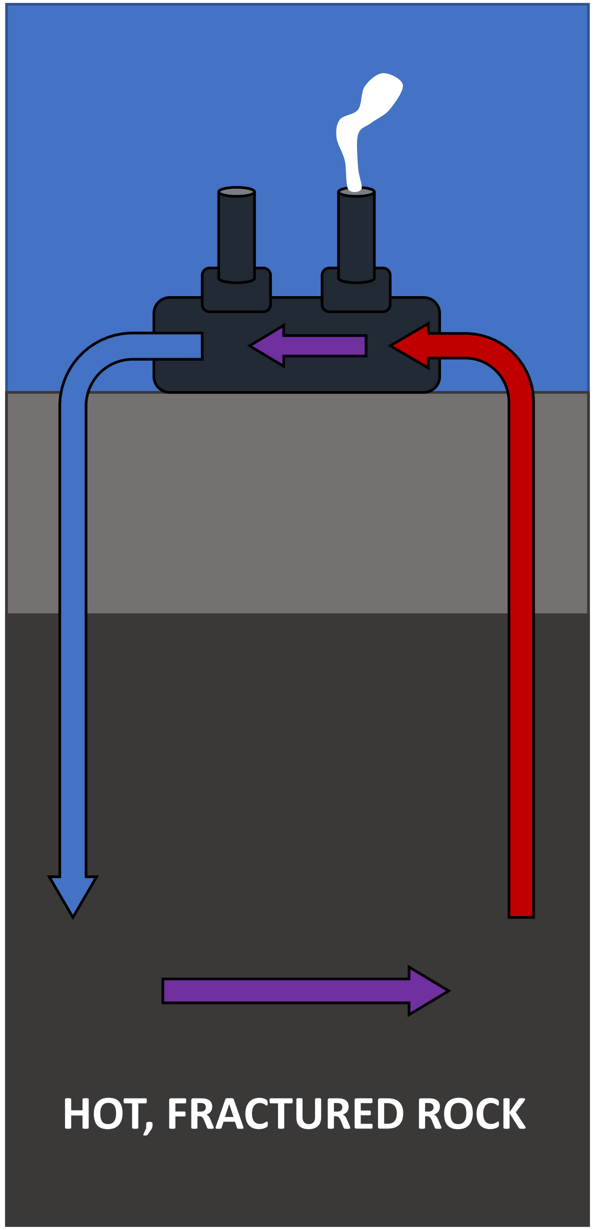
Basics of deep geothermal exploitation

To ensure production efficiency:

- Sufficient volumes of reservoir fluid
- Permeability sufficiently high to allow for groundwater recharge and transport

During production:

- Reinject water to maintain reservoir pressure, maintain water volume.
- Reinjection of a cool fluid encourages precipitation in the reservoir, which can plug cracks and pores, reducing permeability and, therefore, productivity.



Geothermal “plays”

Generalised, conceptual geological models describing the geological factors that might generate a recoverable geothermal resource.

Take into consideration:

Heat source

Heat migration pathway

Heat/fluid storage capacity (reservoir)

Potential for economic recovery

Geothermal "plays"

Characteristics of individual geothermal systems are site-specific:

- Nature and depth of the heat source
- Dominant heat transfer mechanism
- Permeability and porosity distribution
- Rock mechanical properties
- Fluid-rock chemistry
- Fluid recharge rates/sources

Geothermal “plays”

There are 6 broad deep geothermal play types.

They depend on:

- The nature of the heat source (magmatic or non-magmatic)
- Dominant heat-transfer mechanism (convection or conduction)

Convection-dominated plays

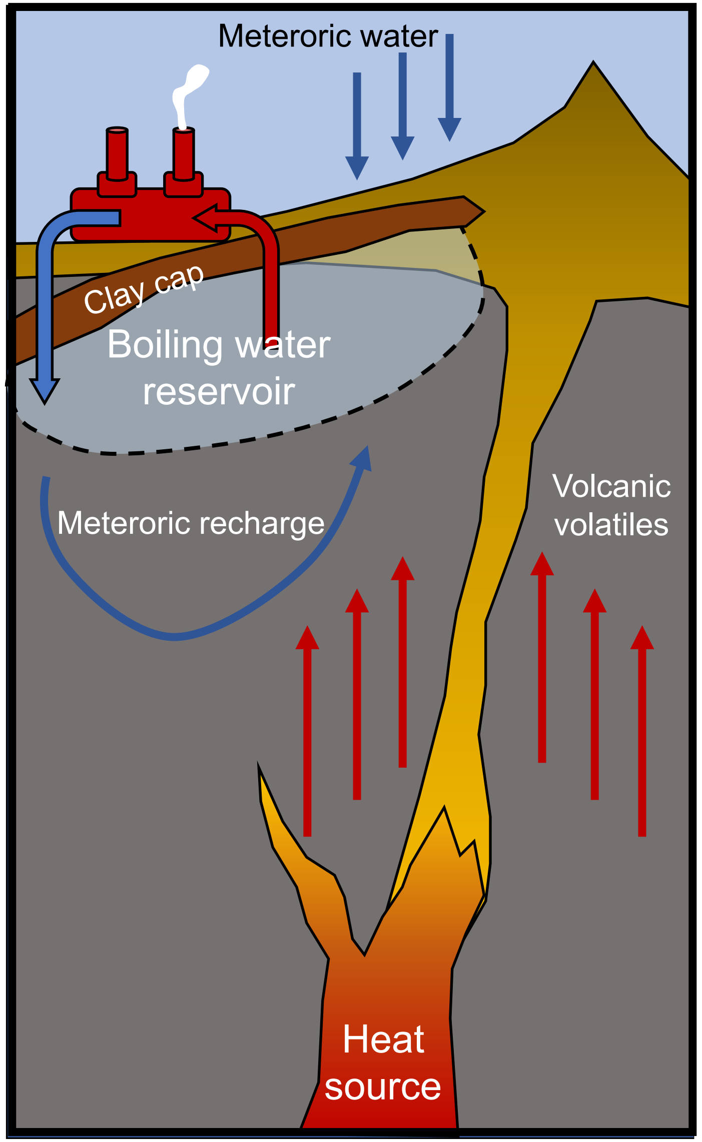
Volcanic field type	*Plutonic type*	*Extensional domain type*
Java-Kamojang	*Larderello*	*Bradys (Basin and Range)*
Magmatic arcs Mid oceanic ridges Hot spots	Young orogens Post-orogenic phase	Metamorphic core complexes Back-arc extension Pull-apart basins Intracontinental rifts
Magma chamber, intrusion	Young intrusion+extension	Thinned crust → elevated heatflow

Moeck, 2014

Temperatures > 200°C; Depths < 3 km

Naturally permeable reservoir, containing convecting fluid.

Convection-dominated plays: Volcanic field type



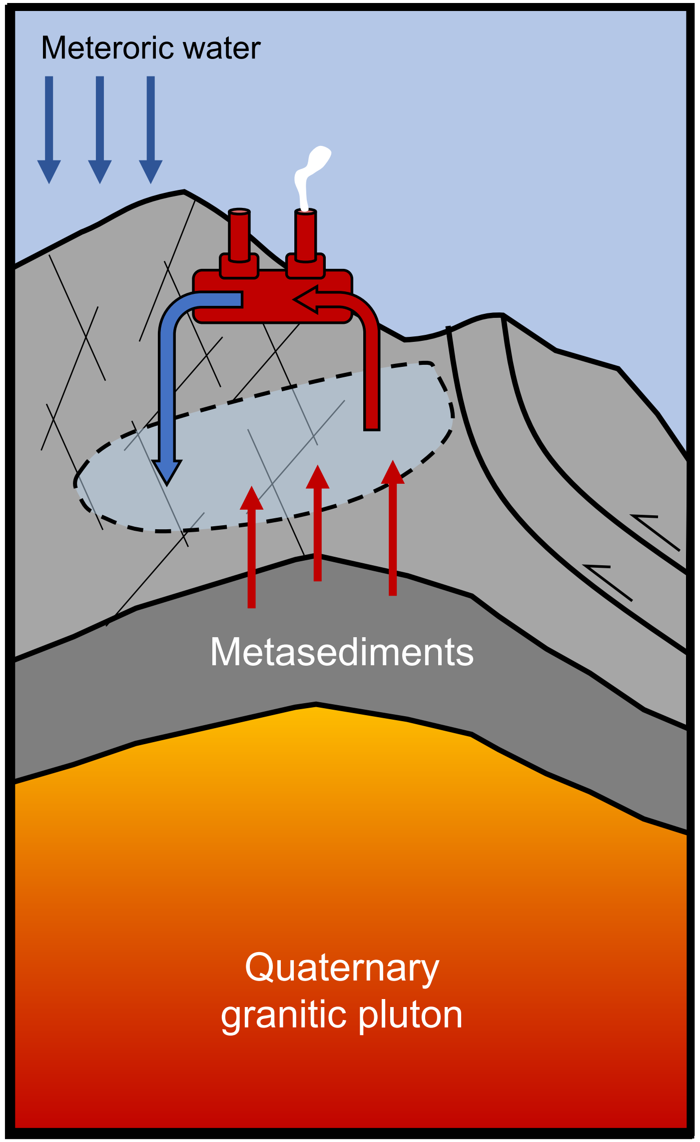
Extrusive

- Shallow, intense heat source: young magma chamber
- Upflow zone + outflow zone, controlled by volcanic topography
- E.g. Iceland, Indonesia

Intrusive

- Active magma chamber, but no volcanism
- Active faulting allows upward movement of fluids
- Hot springs, fumaroles, boiling mud pools
- E.g. Taupo Volcanic Zone (New Zealand)

Convection-dominated plays: Plutonic type



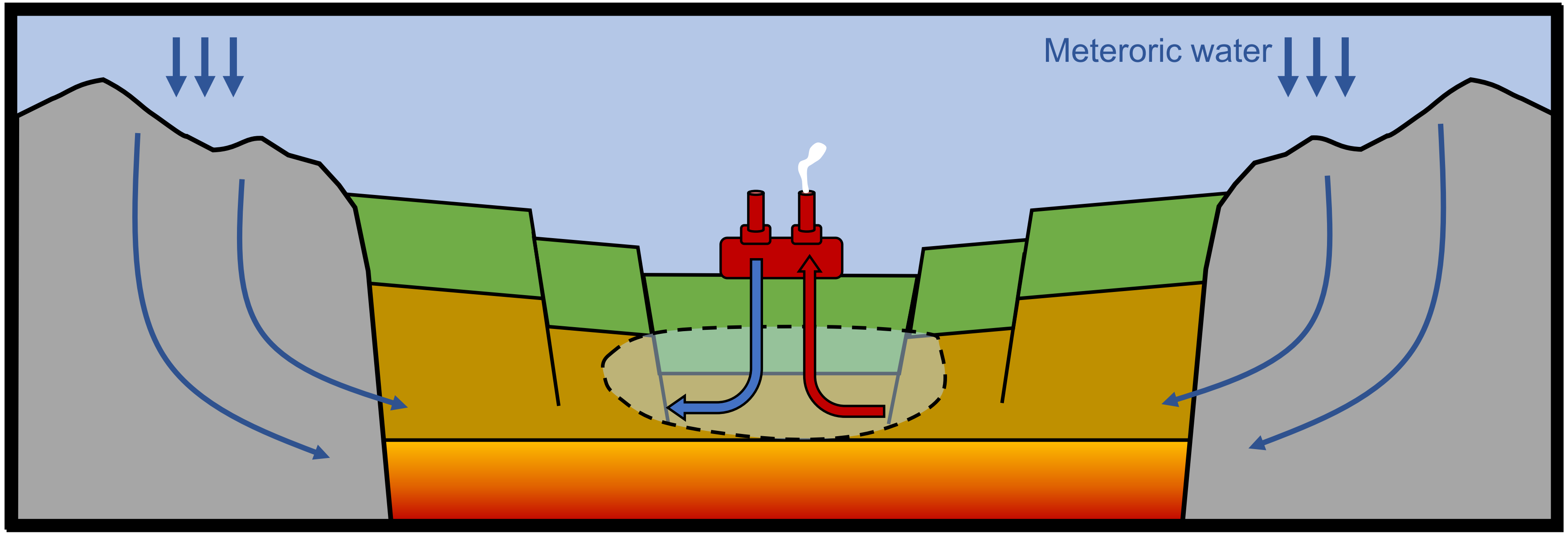
Recent or active volcanism

- Cooling igneous body associated with active volcanism
- Rapid recharge of meteoric water drives hydrothermal circulation
- E.g. Lardarello (Italy)

Inactive volcanism

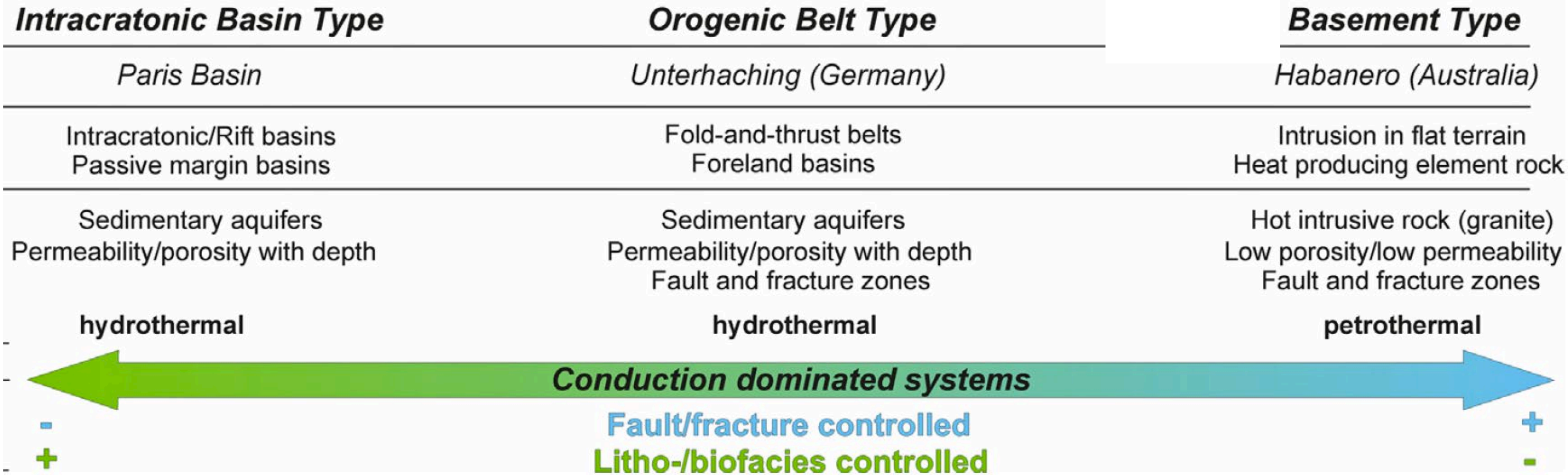
- Mature subduction zones; ageing continental volcanism
- Fore- or back-arc regions of fold-thrust belts
- E.g. Geyers geothermal field in California (USA)

Convection-dominated plays: Extensional domain type



- Elevated mantle resulting from crustal extension and thinning
- Main heat source: mantle **(not volcanism!!)**
- High thermal gradients heat meteoric water
- Fluid flow facilitated through deep faults and permeable formations
- E.g. Great Basin (USA), Western Turkey, Upper Rhine Graben (Europe), African Rift

Conduction-dominated plays



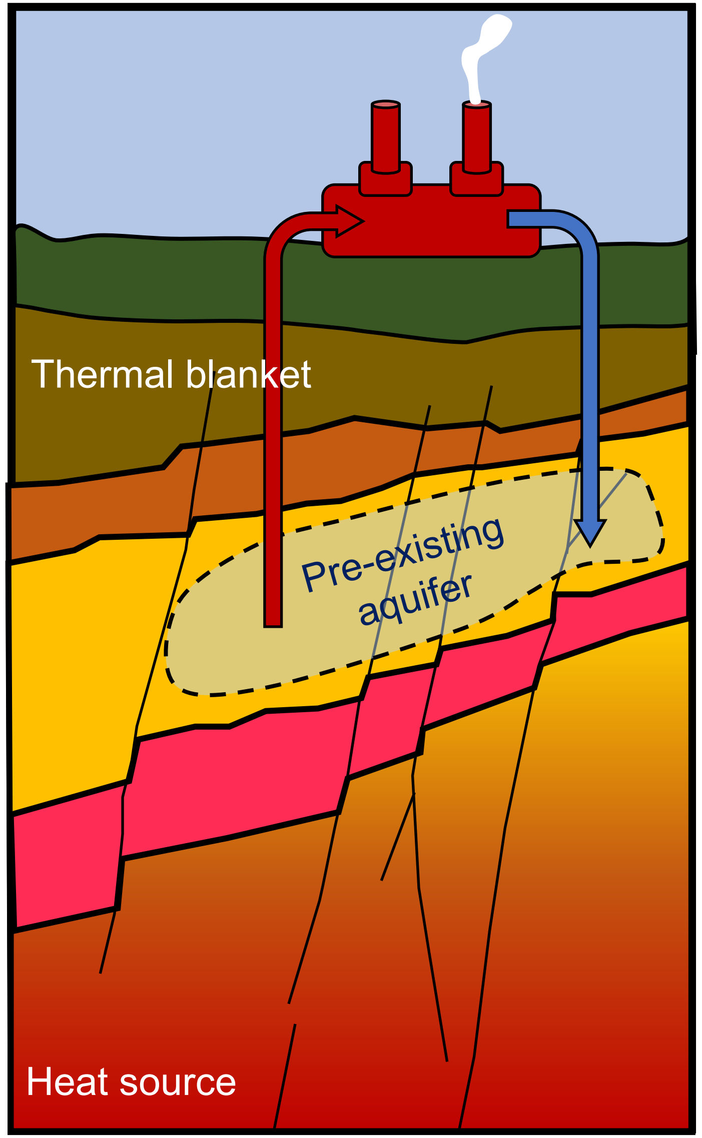
Moeck, 2014

Temperatures < 200°C; Depths up to 5 km

Passive tectonic setting: temperature increases steadily with depth.

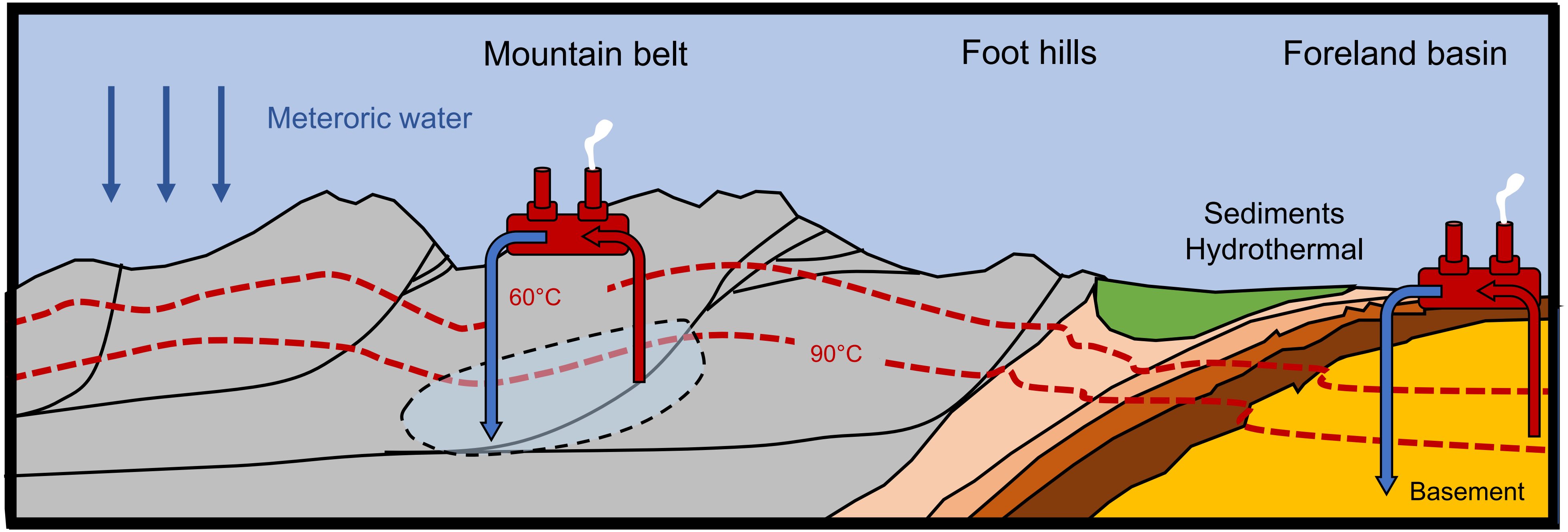
Absence of rapidly convecting fluids. Low permeability may necessitate reservoir engineering.

Conduction-dominated plays: Intracratonic basin type



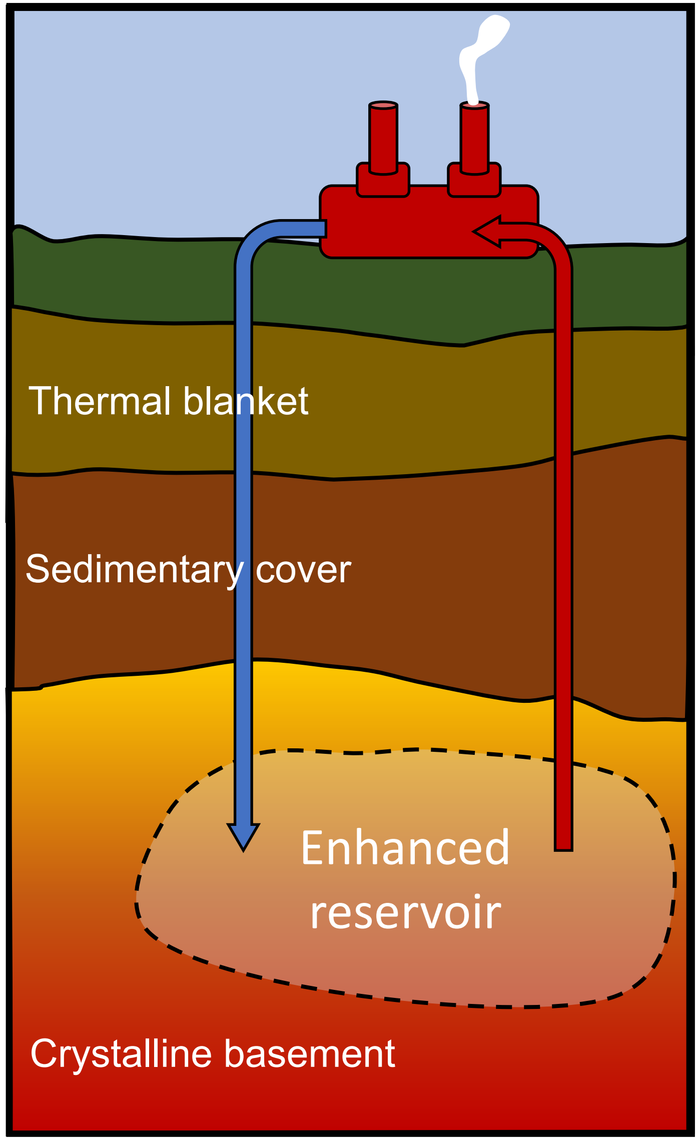
- Reservoir: thick sedimentary sequence in thermal sag basins, fossil rift grabens
- Lithology and local structural features control permeability
- Low to high heat flow
- E.g. Paris basin (France)

Conduction-dominated plays: Orogenic belt type



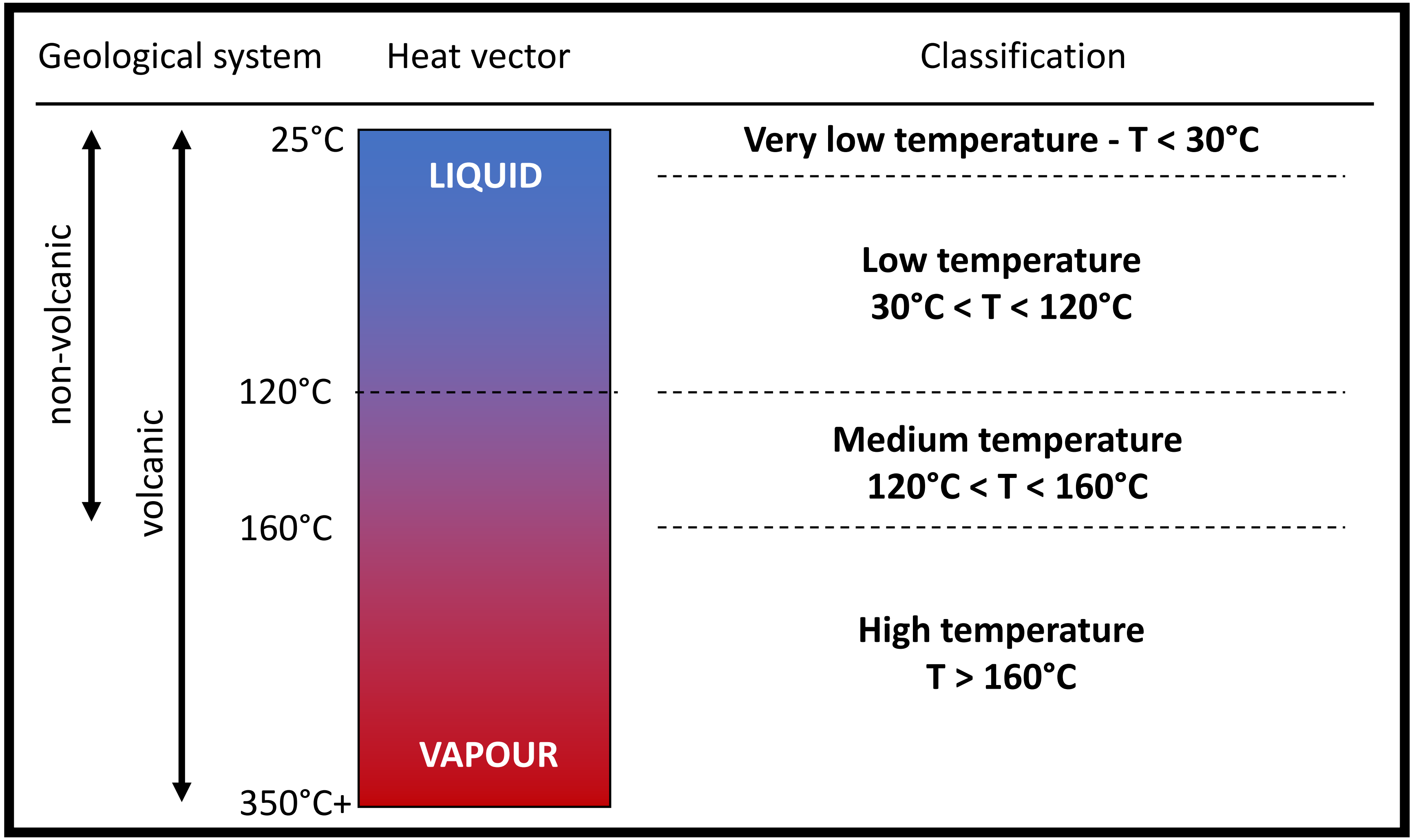
- Sedimentary reservoir within foreland basin or orogenic mountain belt
- Significant crustal subsidence (km) resulting from the weight of the thickened crust and erosional products: aquifers get deeper with proximity to the orogen
- E.g. Unterhaching (Germany)

Conduction-dominated plays: Basement type

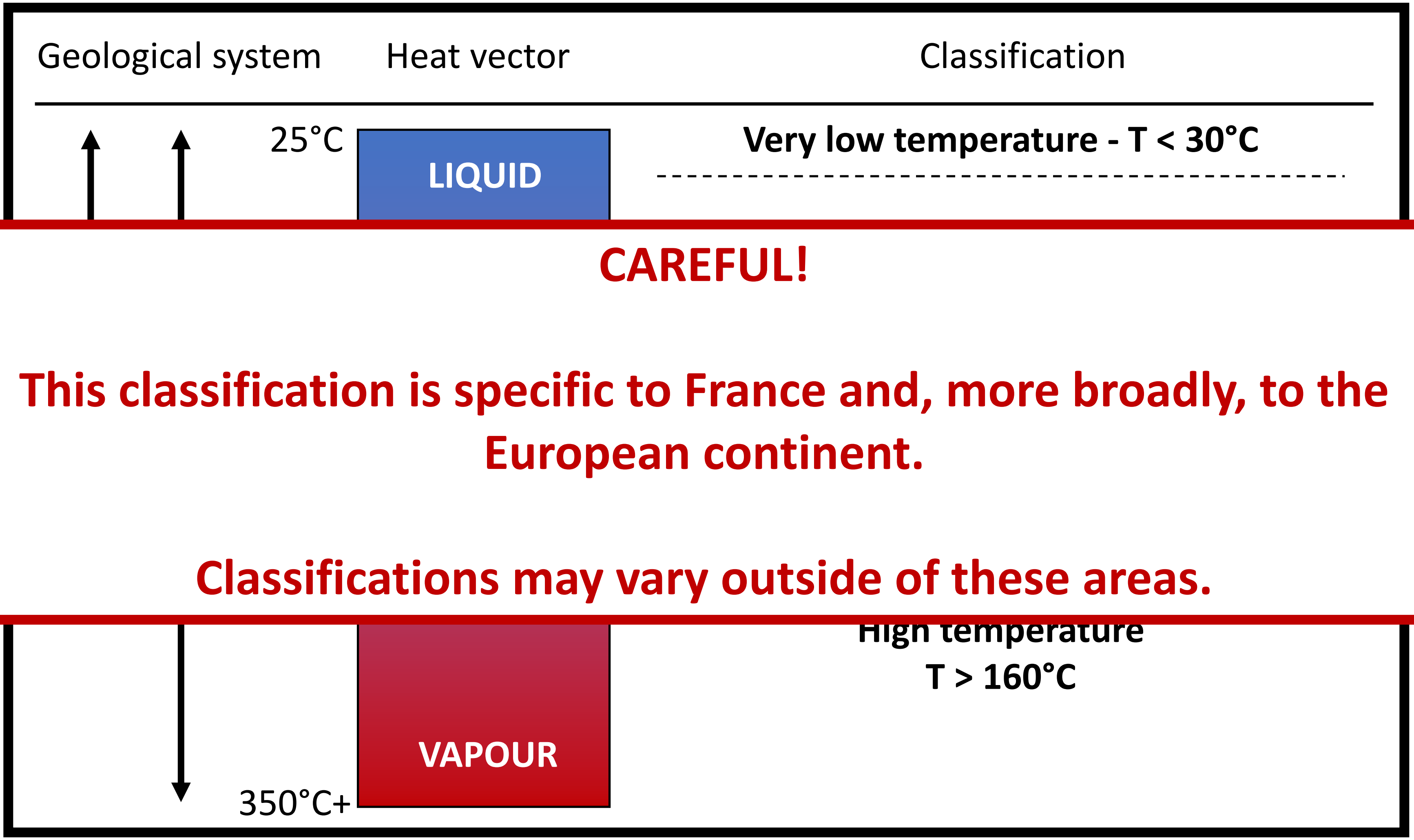


- Faulted / fractured crystalline rock
- Low natural permeabillity, but hot
- Requires reservoir engineering to create a heat-exchanger at depth
- E.g. High Heat-Production (HHP) granites (Australia), Soultz-sous-Forêts (France)

What can we do with geothermal heat?



What can we do with geothermal heat?

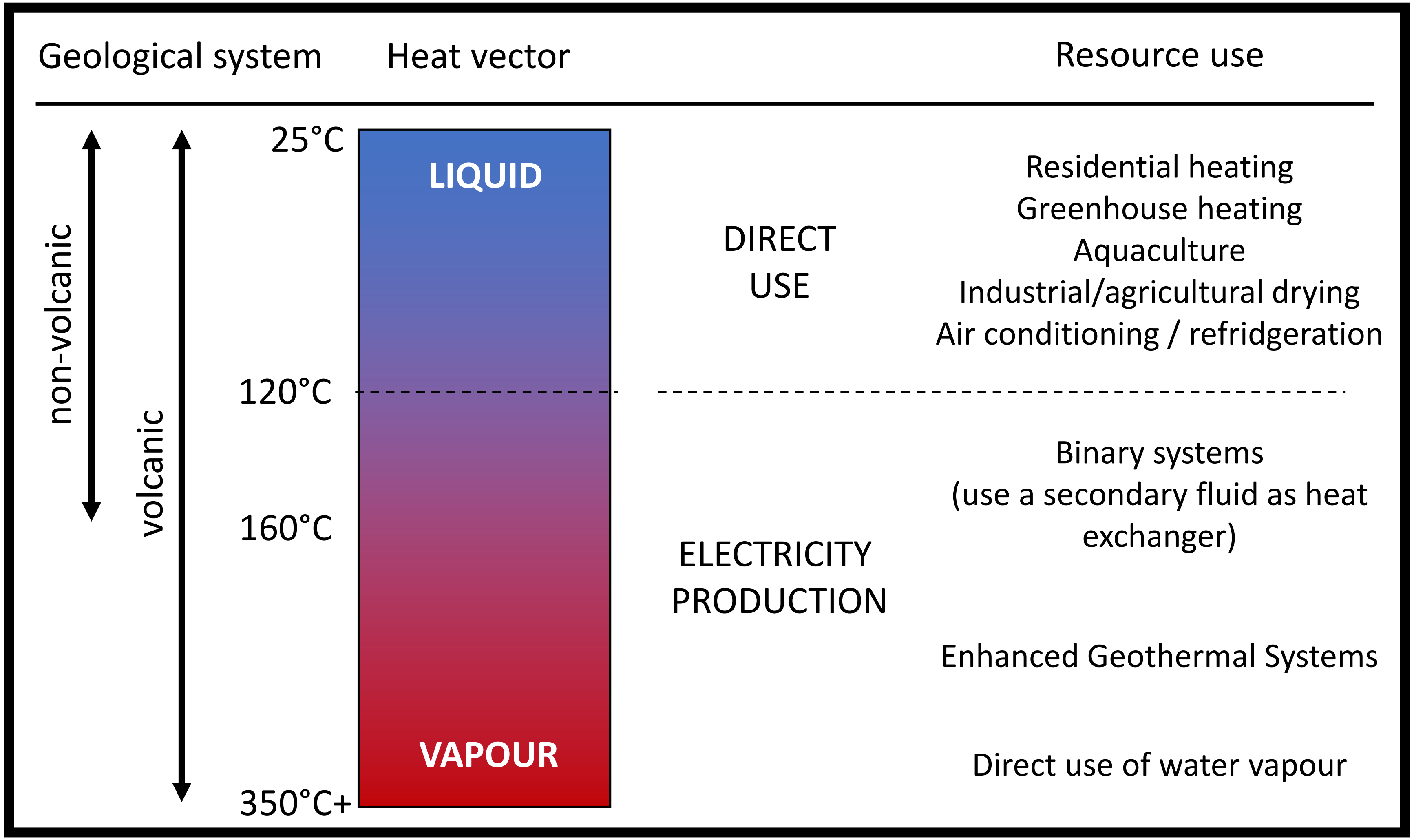


CAREFUL!

This classification is specific to France and, more broadly, to the European continent.

Classifications may vary outside of these areas.

What can we do with geothermal heat?



Global heat production in 2010: Electricity

In 2010:

24 countries

10.7 GWe

Predicted 2015:

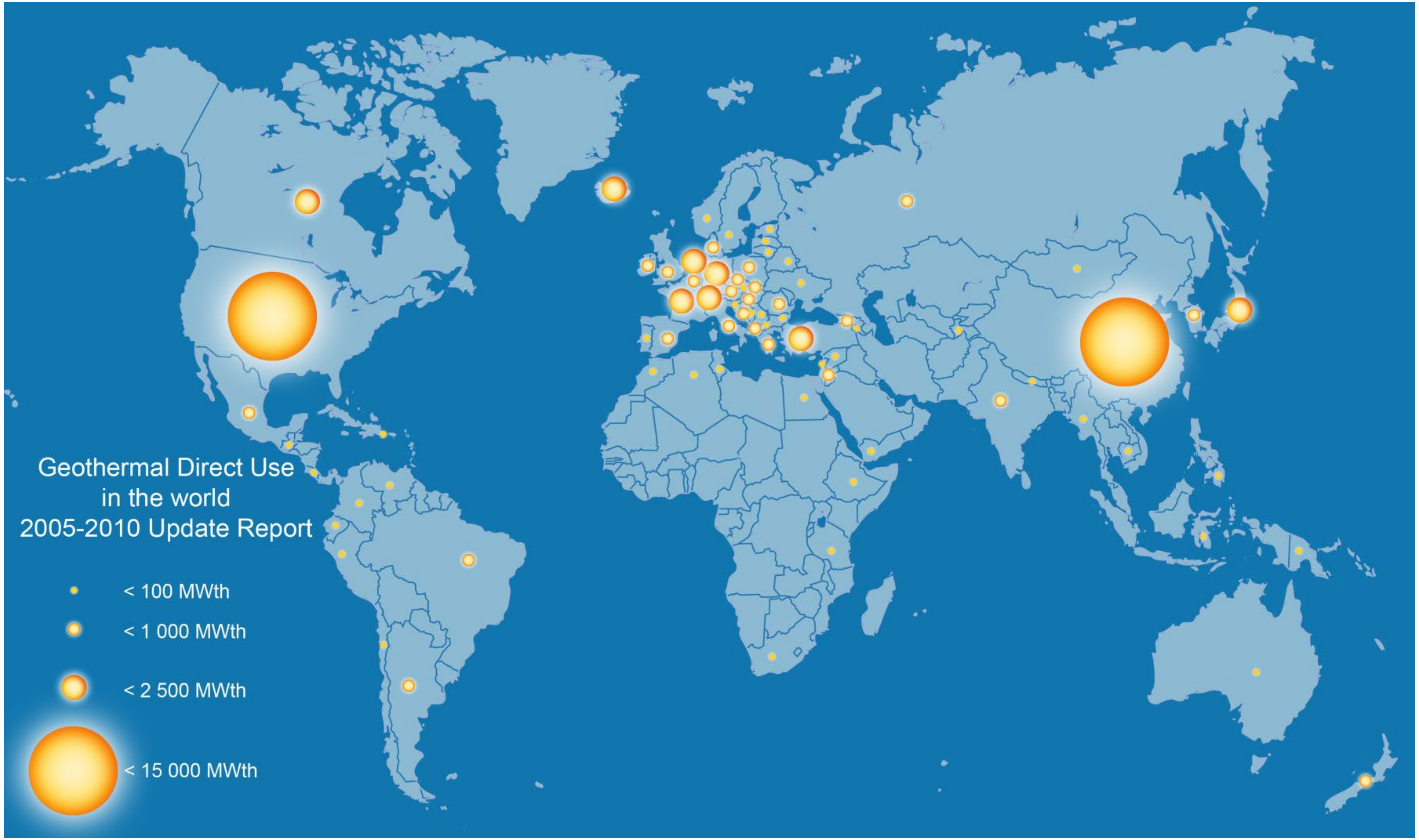
18.5 GWe

Predicted 2050:

70 GWe

(Bertani, 2010)

Global heat production in 2010: Heat



In 2010:

79 countries

43 GWth

Uses:

Greenhouses

Aquaculture

Residential heating

District heating

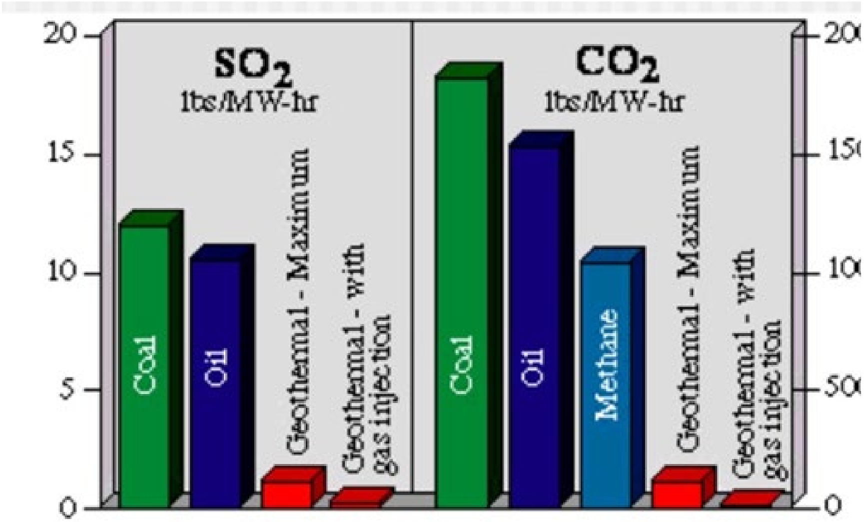
Pros and cons of geothermal energy

Pros

- Renewable resource
- “Local” resource that does not need transporting
- High production potential compared to other renewable energy sources (10s – 100s of MWe)
- Does not vary over the year (constant production 24 hours, 365 days a year)

Why geothermal? does Little damage to the environnment

- Release less than 1% to 4% of Carbon dioxide compared to coal plants
- Emit only about 3% sulfur compounds compared to coal and oil plants
- Small physical foot print : They can be used at an time, day or night, or with no wind.
- Low cost



HOWEVER:

- Strongly site dependent
- GEO-mechanical issues

Pros and cons of geothermal energy

Pros

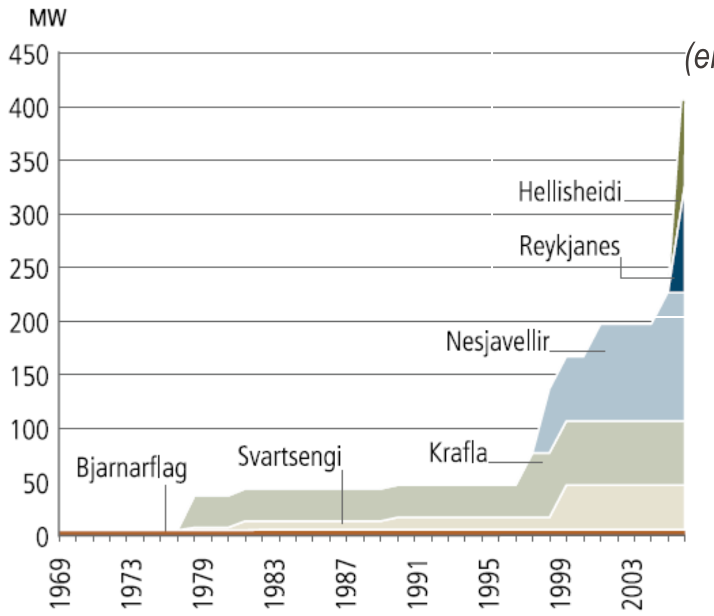
- Renewable resource
- “Local” resource that does not need transporting
- High production potential compared to other renewable energy sources (10s – 100s of MWe)
- Does not vary over the year (constant production 24 hours, 365 days a year)

Cons

- Exploitation requires deep drilling: are we drilling in the right place?
- Upfront investment (exploration and drilling) cost is high
- Long timeframe from project inception to production

Supercritical fluid interest

Conventional geothermal exploitation (200°C - 350°C)



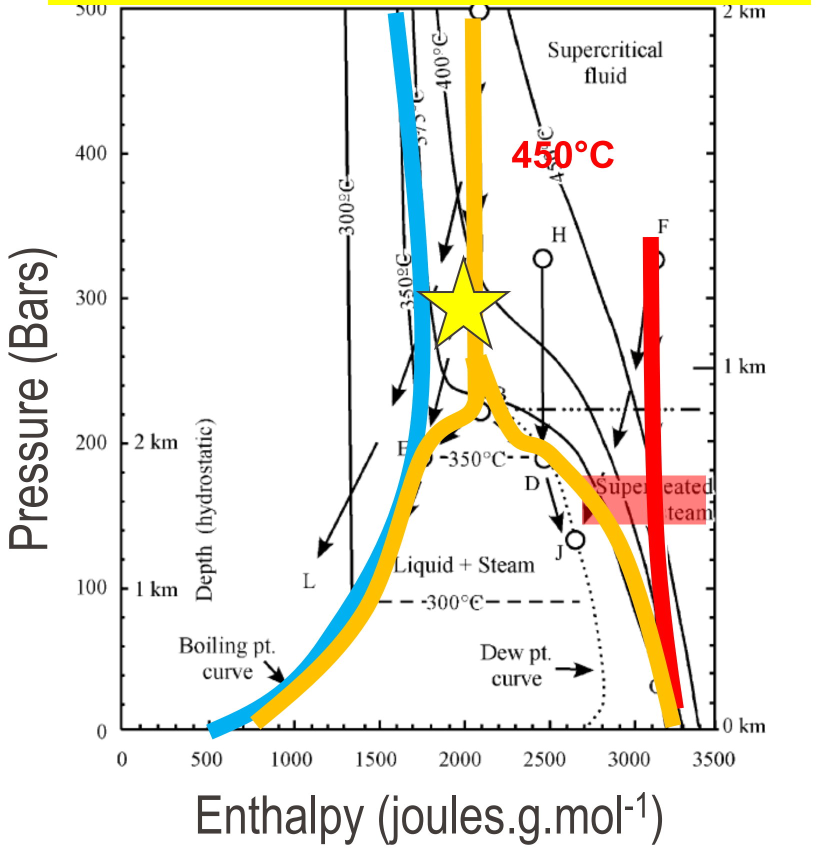
x 10

(energy production)

Installed capacity of geothermal power plants in Iceland (1969–2006)

After ORKUSTOFNUN, (National energy Autority) (2006)

Supercritical pt pure water : 374°C 22 MPa



Fournier, (1999)