GEB

Co-funded by the
Erasmus+ Programme
of the European Union

Faculty of Engineering
Cairo University

Geothermal Resources and Reservoir Engineering

Lecture 1: Introduction to Geothermal resources

Introduction to the course

Class attendance	YES		**Research**		NO	**Oral exam**		NO
Experimental work	YES		**Report**	YES				
Essay	YES		**Seminar paper**		NO			
Preliminary exam	YES		**Practical work**		NO			
Project		NO	**Written exam**	YES		**ECTS credits (total)**	**3**	

Course overview

At the end of the course, you should be learned the following:

- Understand theories and fundamentals of geothermal systems and geothermal wells in terms of:
  - the governing heat transfer and
  - fluid flow equations.
- Able to identify, analyse and prioritize complex engineering problems in Geothermal engineering and Reservoir engineering in terms of:
  - reservoir rock Properties and
  - reservoir fluids properties.

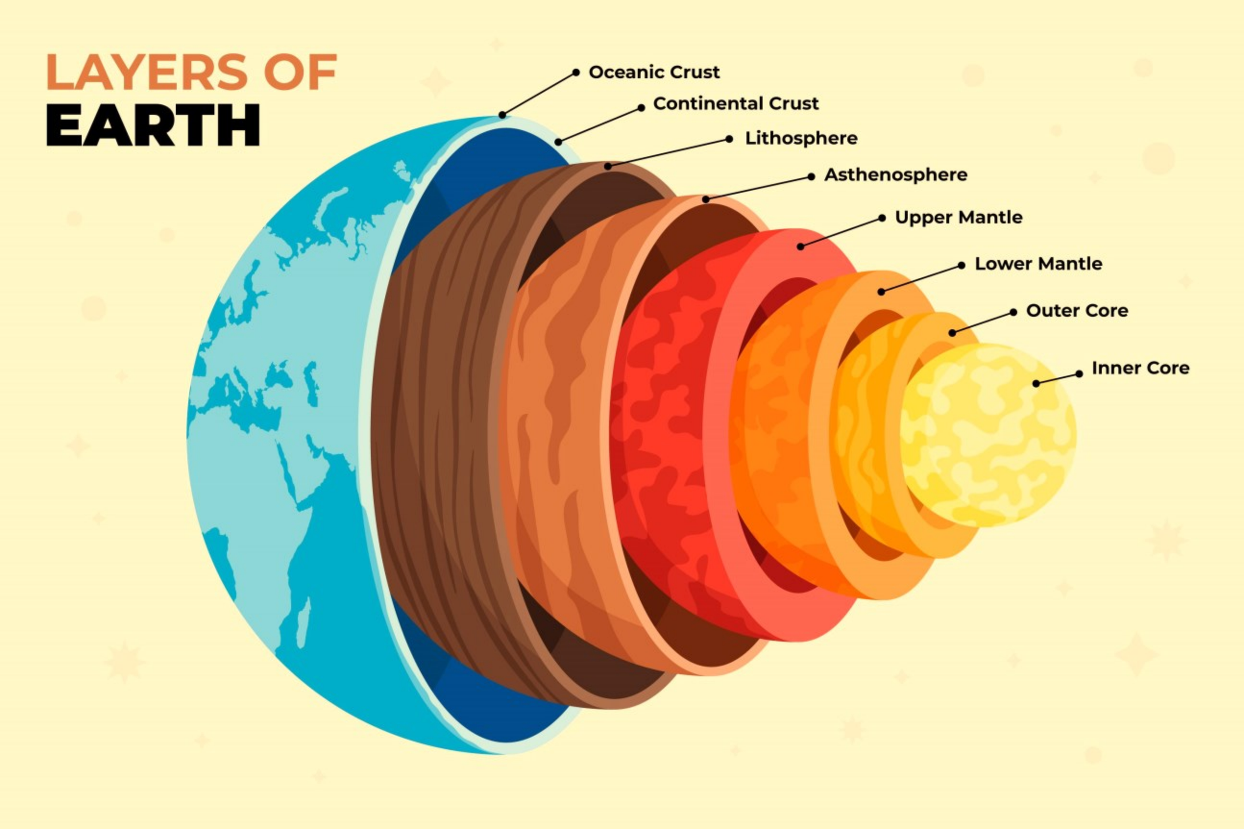
Course overview

At the end of the course, you should be learned the following:

- Capability of predicting reservoir behaviour and behaviour of geothermal water production system.
- the estimation of the energy potential and efficiency of geothermal facilities as well as assessing their environmental impact.
- Employment of available software tools for the estimation of geothermal facilities’ energy potential, efficiency and the assessment of their environmental impact

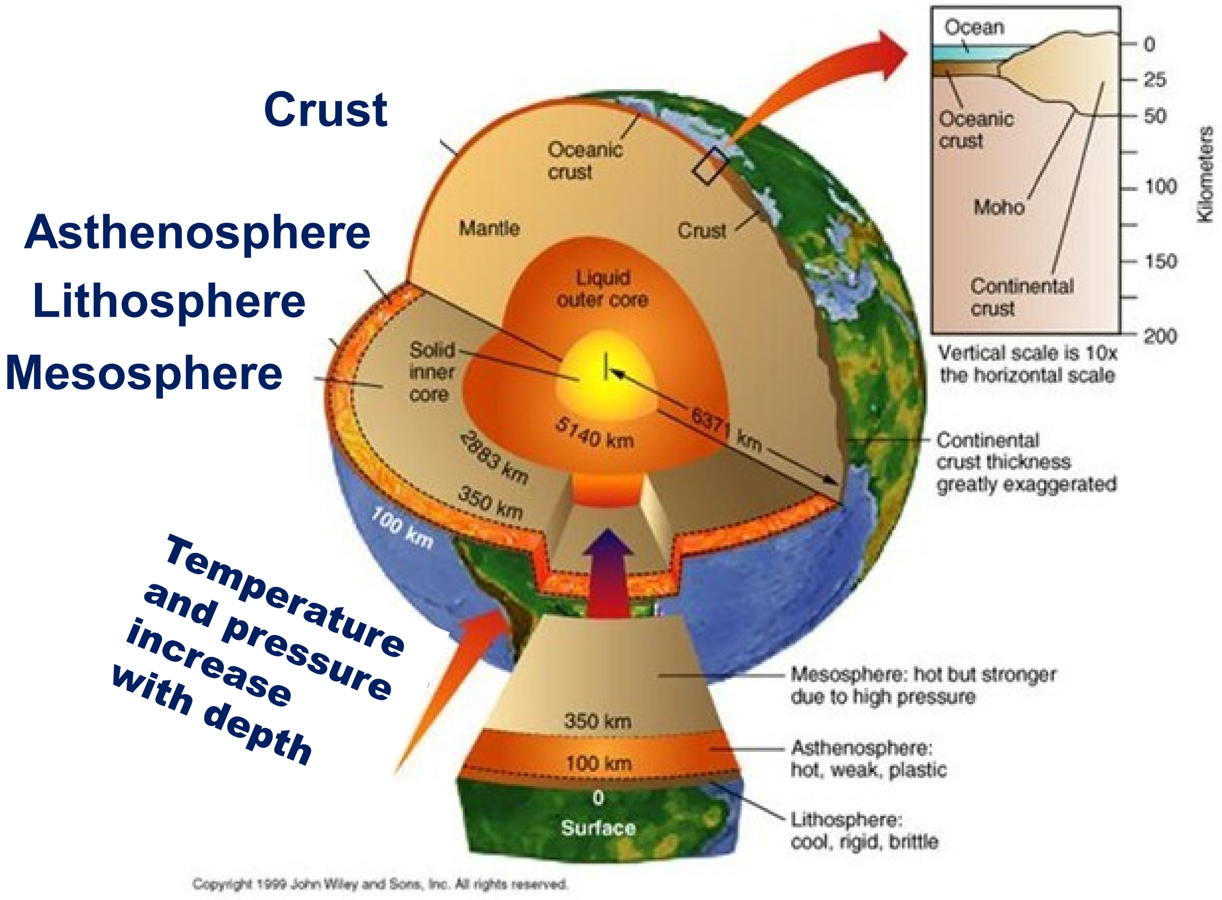
1. Introduction to Geothermal resource and reservoir engineering

- The word "geothermal" comes from ancient Greek "ge-thermos", meaning the Earth heat.
- Generally, such heat results of (still active) radioactive decay in lithosphere and, specially, in the core.
- Both are long-lasting sources, that will be active many milliard years -> renewable source.



1. Introduction to Geothermal resource and reservoir engineering

- The subsurface heat can be transferred to surface in numerous ways, but for practical application it is transferred by water and steam.
- Temperature in subsurface is not increased linearly, but the largest increment is in the lithosphere, due to geothermal gradient.



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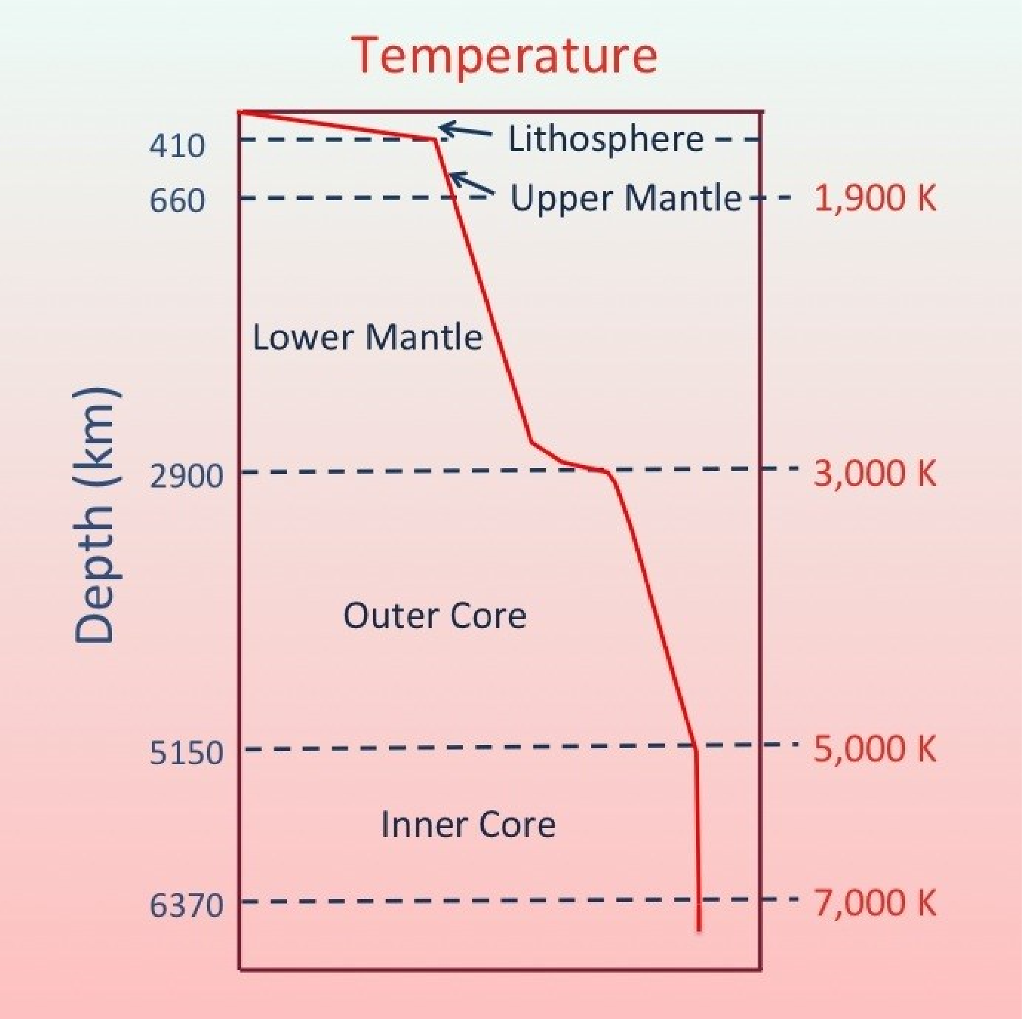
- Generally, the Thermal gradient is between 17-30 °C/km in lithosphere (where saturation water is heated).
- Deeper in the mantle temperatures vary 650-1250 °C, eventually reach 6000 °C in the core.
- Some very rough estimation stated that total geothermal potential in 50,000 higher than energy in remained recoverable hydrocarbons.



Geothermal gradient adapted from Boehler (1996). Melting temperature of the earth's mantle and core: Earth's thermal structure.

2. Advantages and Disadvantages of Geothermal Energy

Advantages	Disadvantages
• Can be extracted without burning; • Geothermal plants produce 6 to 20 times lower of the carbon dioxide compared with fossil fuelled power plants and 4 times less than solar PV; • Geothermal binary plants release no emissions; • Geothermal energy is always available; • Relatively inexpensive and can be directly used; • Through proper reservoir management, the rate of energy extraction can be balanced with a reservoir's natural heat recharge rate.	• The main concern is the release of hydrogen sulphide (migrated in reservoirs through deep faults); • Disposal of some geothermal fluids, which may contain low levels of toxic materials; • Geothermal sites can, heating for many decades, eventually cool down.

3. Applications and employment of Geothermal energy

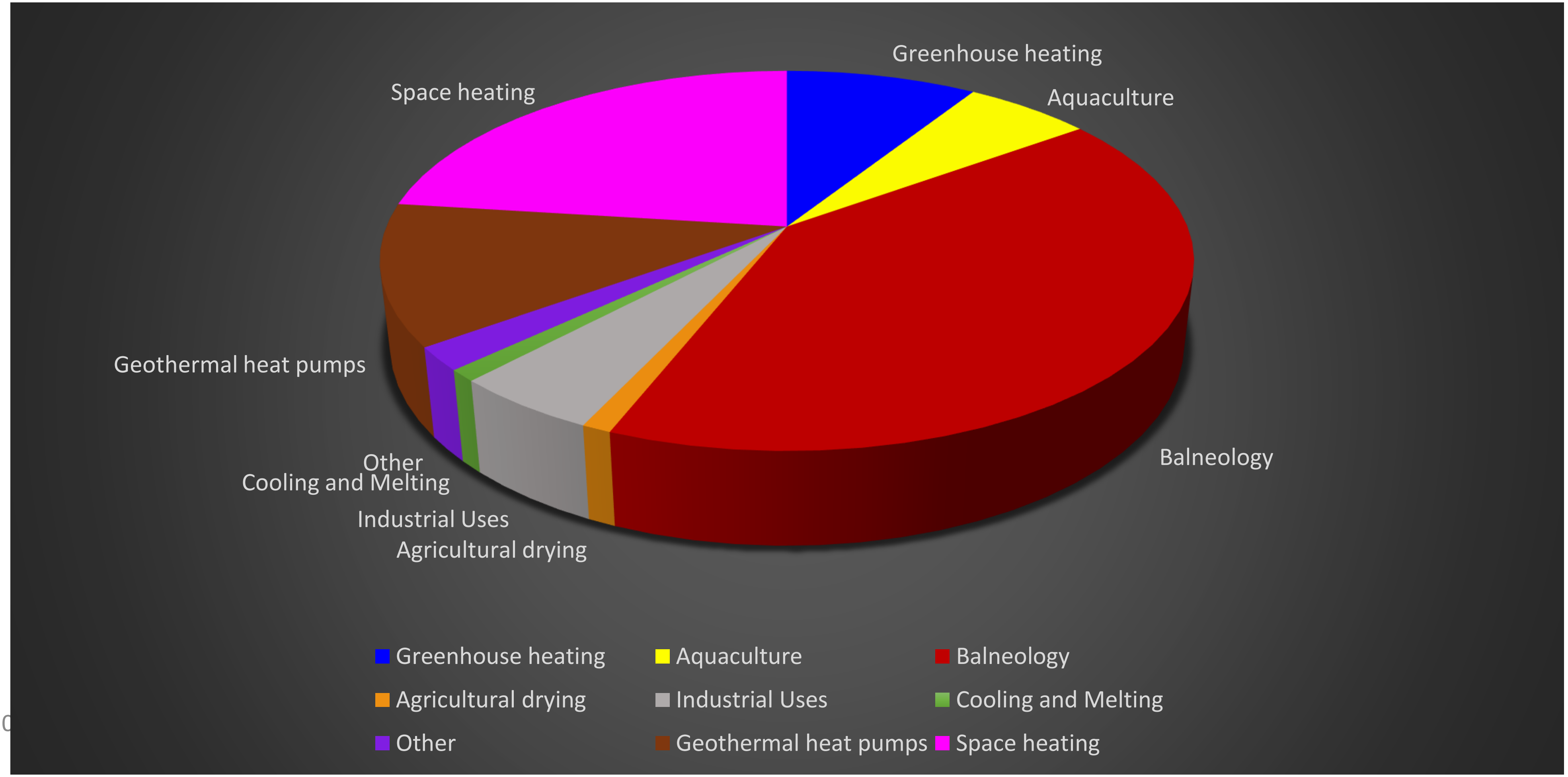
- Geothermal energy utilization in power generation is generated in over 20 countries.
- The **United States is the world's largest producer**, and the largest geothermal development in the world is The Geysers north of San Francisco in California.
- In Iceland, many of the buildings and even swimming pools are heated with geothermal hot water.
- Such reserves are valid for deep geothermal systems, where heated fluid is available in subsurface reservoirs and can be more-less directly used.

Geysers north San Francisco, California

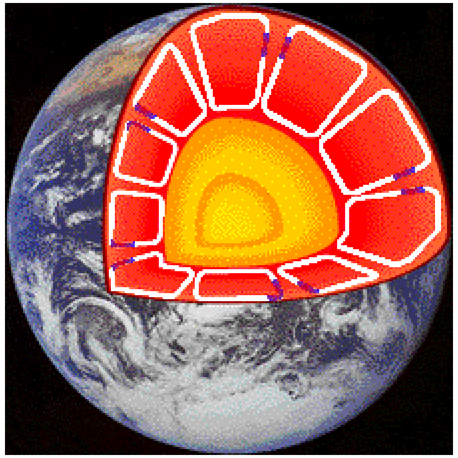
3. Applications and employment of Geothermal energy

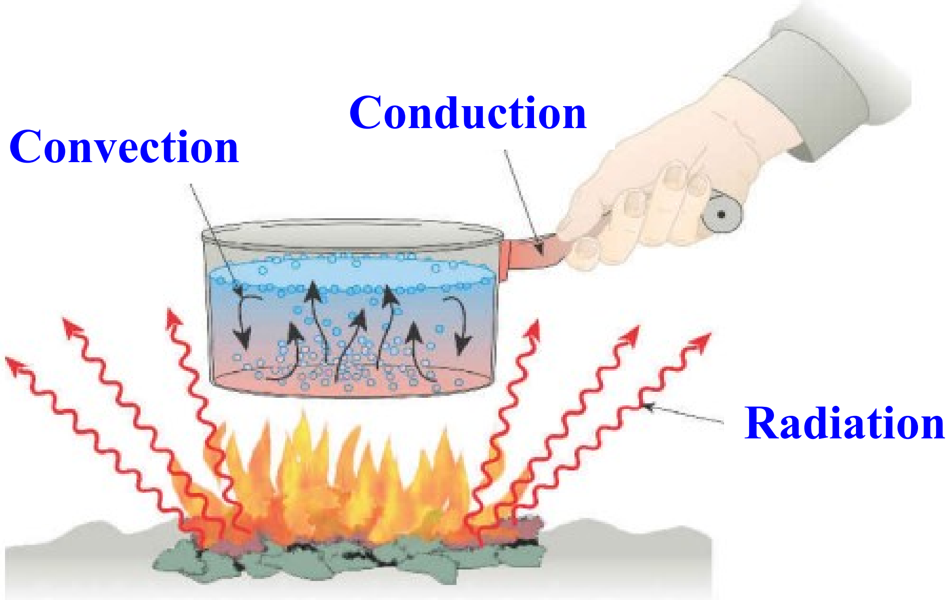
- Apart from Deep Geothermal Energy utilization, the shallow geothermal energy (i.e., the direct use), is based on application of geothermal heat pump systems.
- It takes advantage of the constant temperature somewhere in first few (e.g., 3) meters close to the surface.
- Due to the temperature differences compared with surface/home/building/greenhouse temperature, such system can extract heat from the building and transfer it back to cooler ground (summer) or heating from subsurface (winter).
- Such geothermal heat pumps are able to heat, cool, and even supply the house with hot water.

4. World use of Geothermal Energy for Direct use



5. Hear Transfer





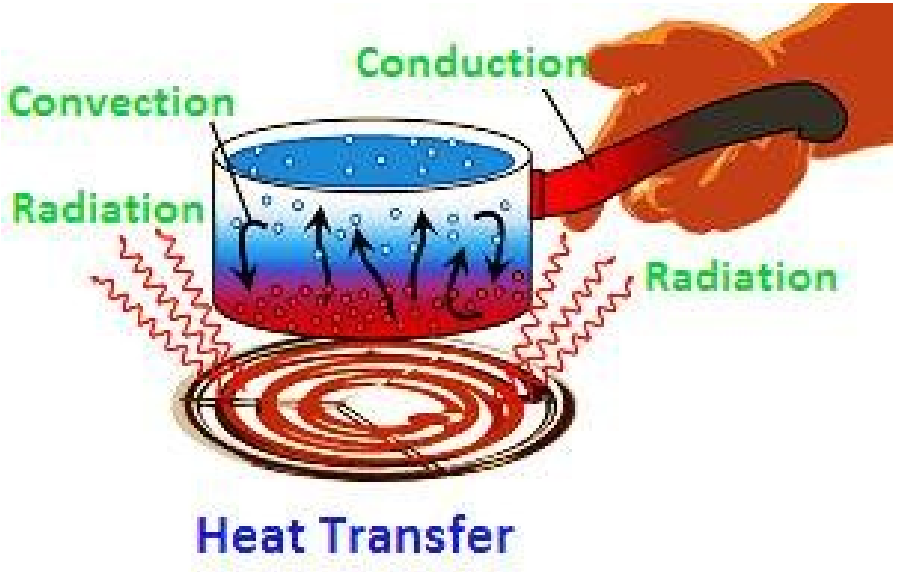
BASIC MODES OF HEAT TRANSFER

- Conduction
- Convection
- Radiation

All modes require the existence of a temperature difference

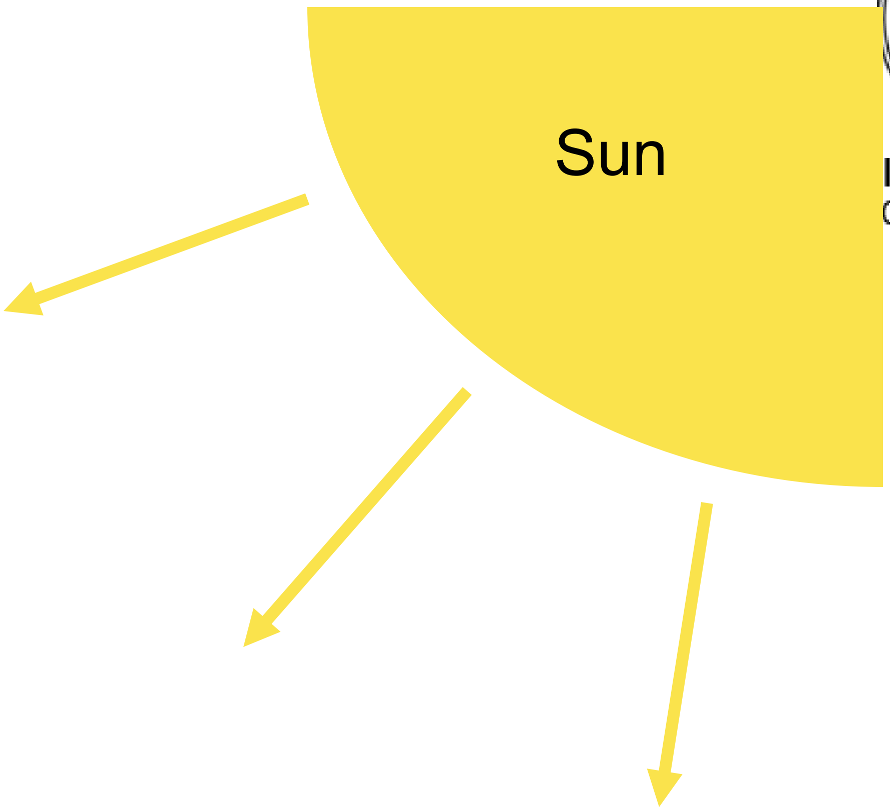
5. Heating transfer concept

- Heat transfer occurs between states of matter whenever a temperature difference exists.
- The heat transfer occurs only in the direction of decreasing temperature, meaning from a hot object to a cold object.
- Although the mechanisms and laws governing the three modes of heat transfer are quite different, all three modes can occur at the same time.



https://mechanicalnotes.com/heat-transfer-definition-methods-formula/

Heat transfer: the sources



From the Earth interior:
- **4×10^{13} W**
- **8×10^{-2} Wm^{-2}**

<u>Derives deep Processes:</u>
- **Mantle convection**
- **Geodynamics**
- **Plate tectonics**
- **Metamorphism**
- **Volcanism**

From the sun:
- **2×10^{17} W**
- **4×10^{2} Wm^{-2}**

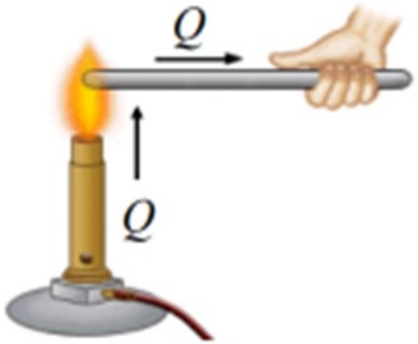
<u>Derives surface processes:</u>
- **Water cycle**
- **Biosphere**
- **Rain**
- **Erosion**

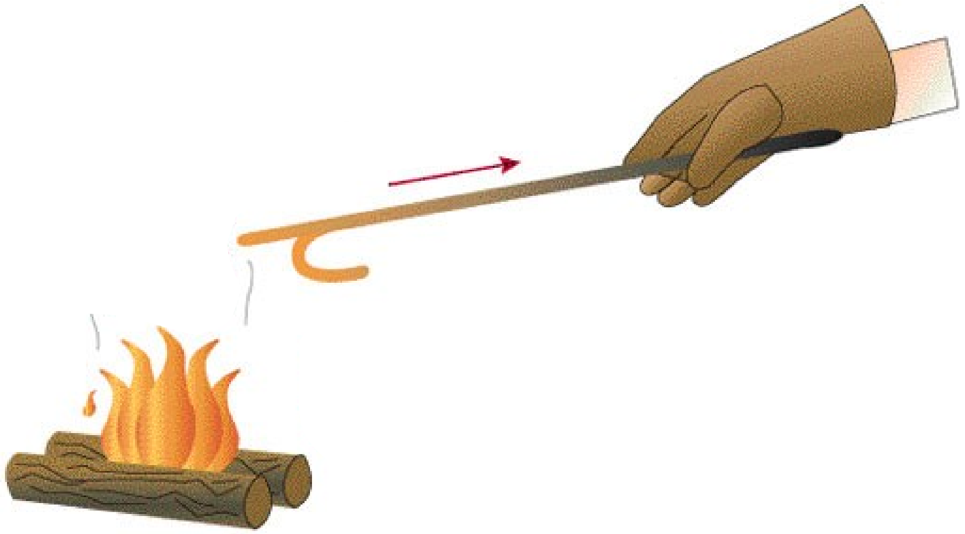
Power or Heat Flux [W]
Heat Flux Density [W.m^{-2}]

5. Heating transfer concept

5.1 Conduction

- The Conduction occurs via transfer of energy between atoms (and electrons) of a material (solids or liquids).
- The rate at which thermal equilibrium is achieved will depend, primarily, on the thermal conductivity and diffusivity of the material.
- Can be happened in solids, liquids or gases due to a temperature difference which is a driving force.
- The rate of heat conduction through a medium depends on: (Geometry of the medium - Thickness -The material of the medium - Temperature difference across the medium).

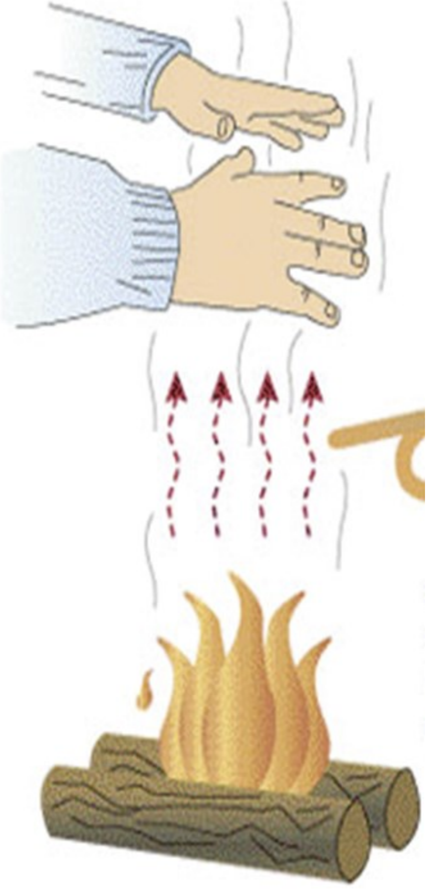


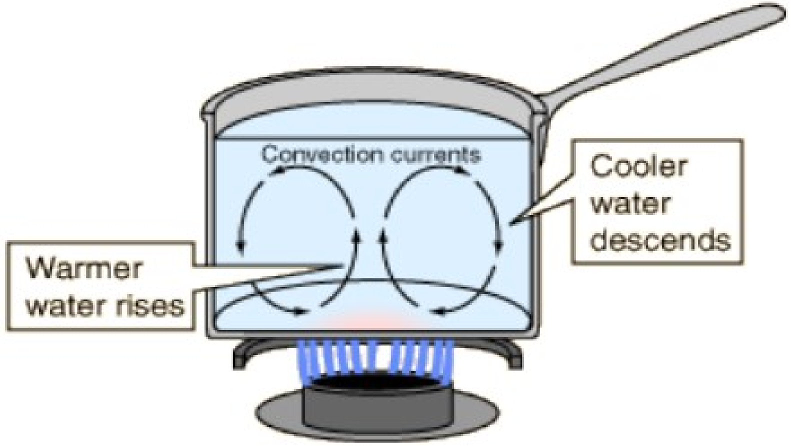


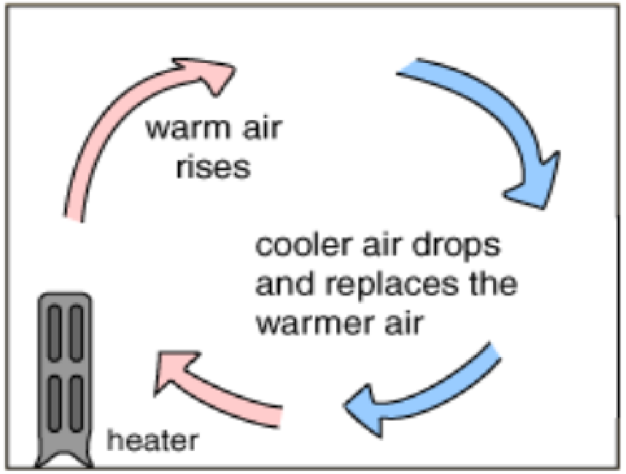
5. Heating transfer concept

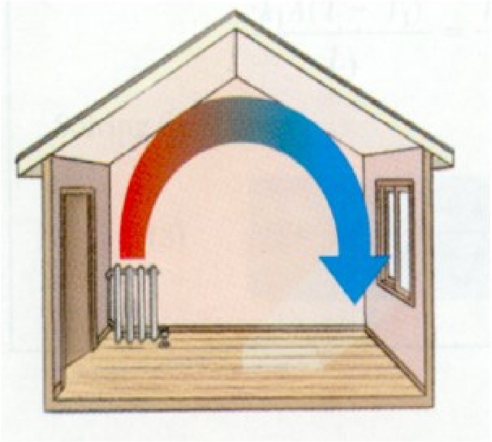
5.2 Convection

Convection is the heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.



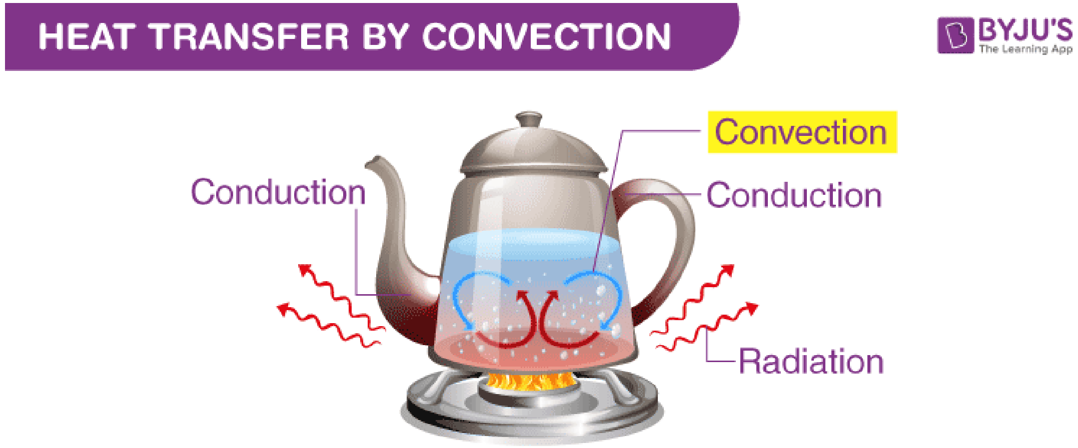






5. Heating transfer concept Convection vs. Conduction

- The Conductive heat transfer occurs without movement of mass.
- A warm mass of any material flowing into a cooler medium is also a means for accomplishing heat transfer (i.e., Convective heat).
- The flow of the heated mass into the cooler medium is not accompanied by any heat conduction, the process is called advection. Like air moves horizontal only.
- Under most circumstances in the Earth, the movement of the mass will occur as heat is simultaneously being conducted away.
- This combined process of heat being transferred by both mass movement and heat conduction is called convection.



https://byjus.com/physics/heat-transfer-convection/

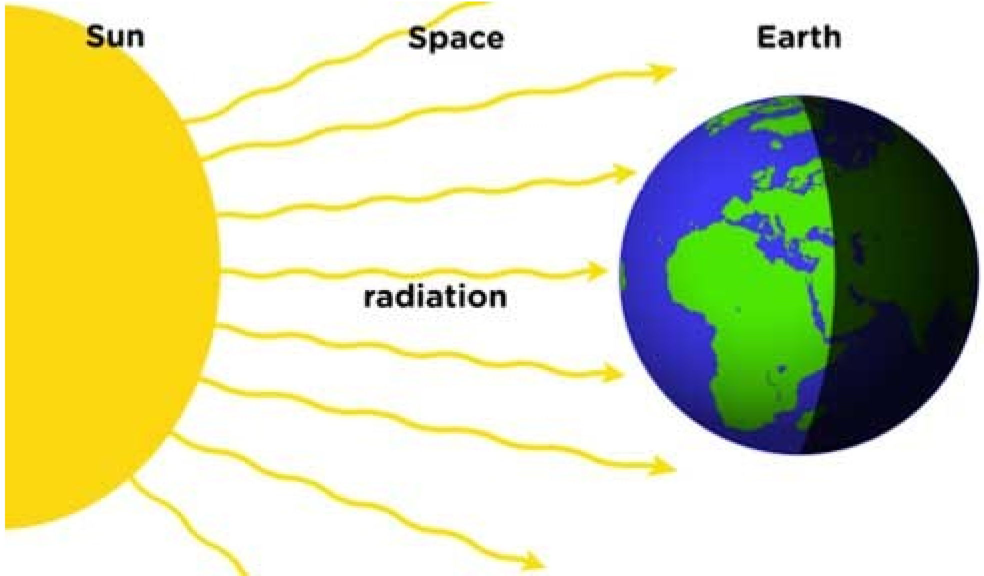
5. Heating transfer concept

5.3 Radiation

- RADIATION –The transfer of thermal energy by waves moving through space. ALL OBJECTS radiate energy!

5. Heating transfer concept 5.3 Radiation

Heat can be transferred radiatively by the emission and absorption of electromagnetic thermal photons.

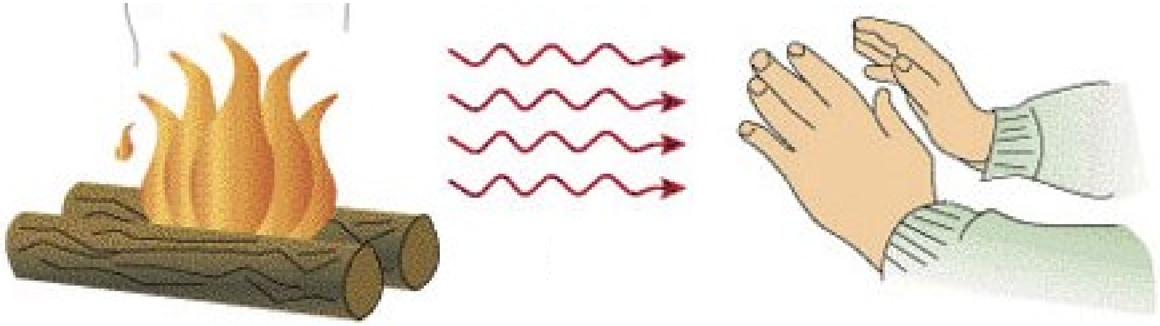


https://science4fun.info/heat-transfer/.

Heat transfer: the mechanisms

Radiation:

The transfer of heat via electromagnetic radiation. Example - the Sun.



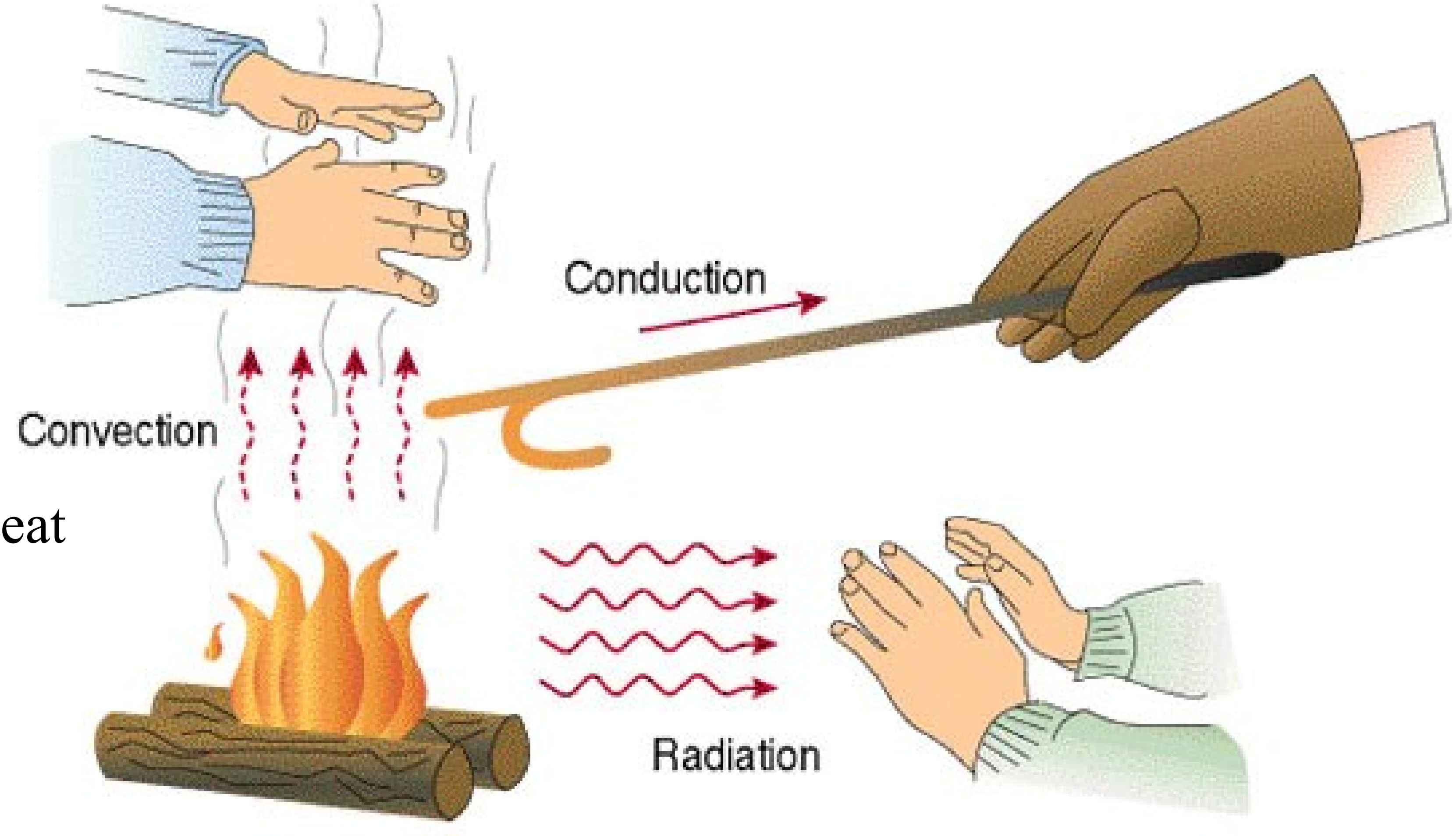
5. Heating transfer: the mechanisms

Heat transfer

If we say, the Heat Q is transferred between bodies due to temperature difference ΔT. There are three mechanisms of heat transfer:

1. conduction: within a body or between two bodies in contact
2. convection: heat carried by motion of mass
3. radiation: heat transfer by electromagnetic radiation

5. Heating transfer: the mechanisms



Three mechanisms for heat transfer:

- conduction,
- convection and
- radiation.

5. Heating transfer: the mechanisms

- In the Earth, both conduction and convection are important.
- In the lithosphere, the temperature gradient is controlled mainly by conduction (Limited fluid flow), the lithosphere is mainly solid.
- Convection in the lithosphere does play a role in:
  - ➢ Mid-ocean ridges in the form of hydrothermal ocean circulation.
  - ➢ Volcanism and emplacement of magmatic bodies.

Convection in the lithosphere plays a role in:

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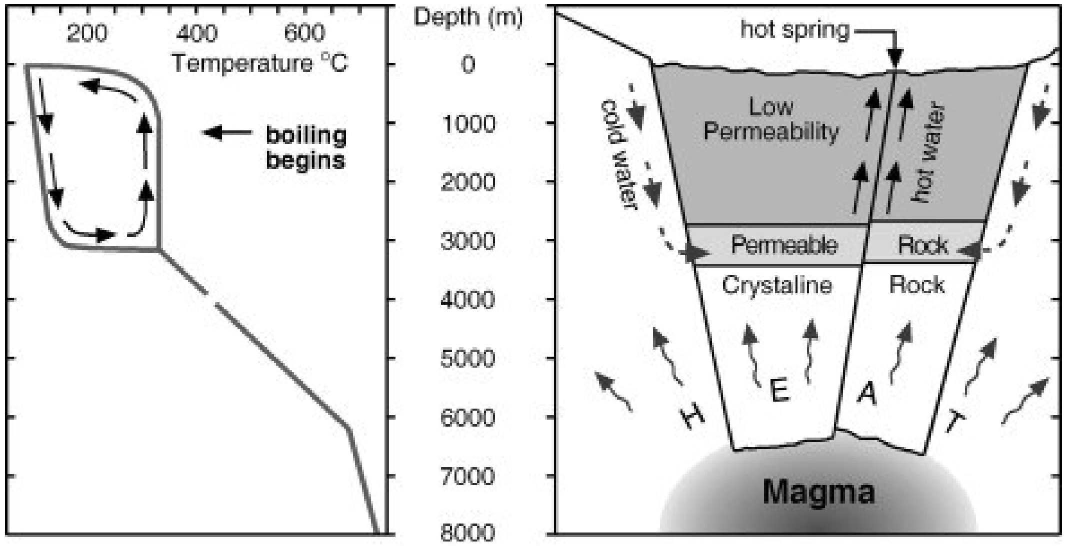
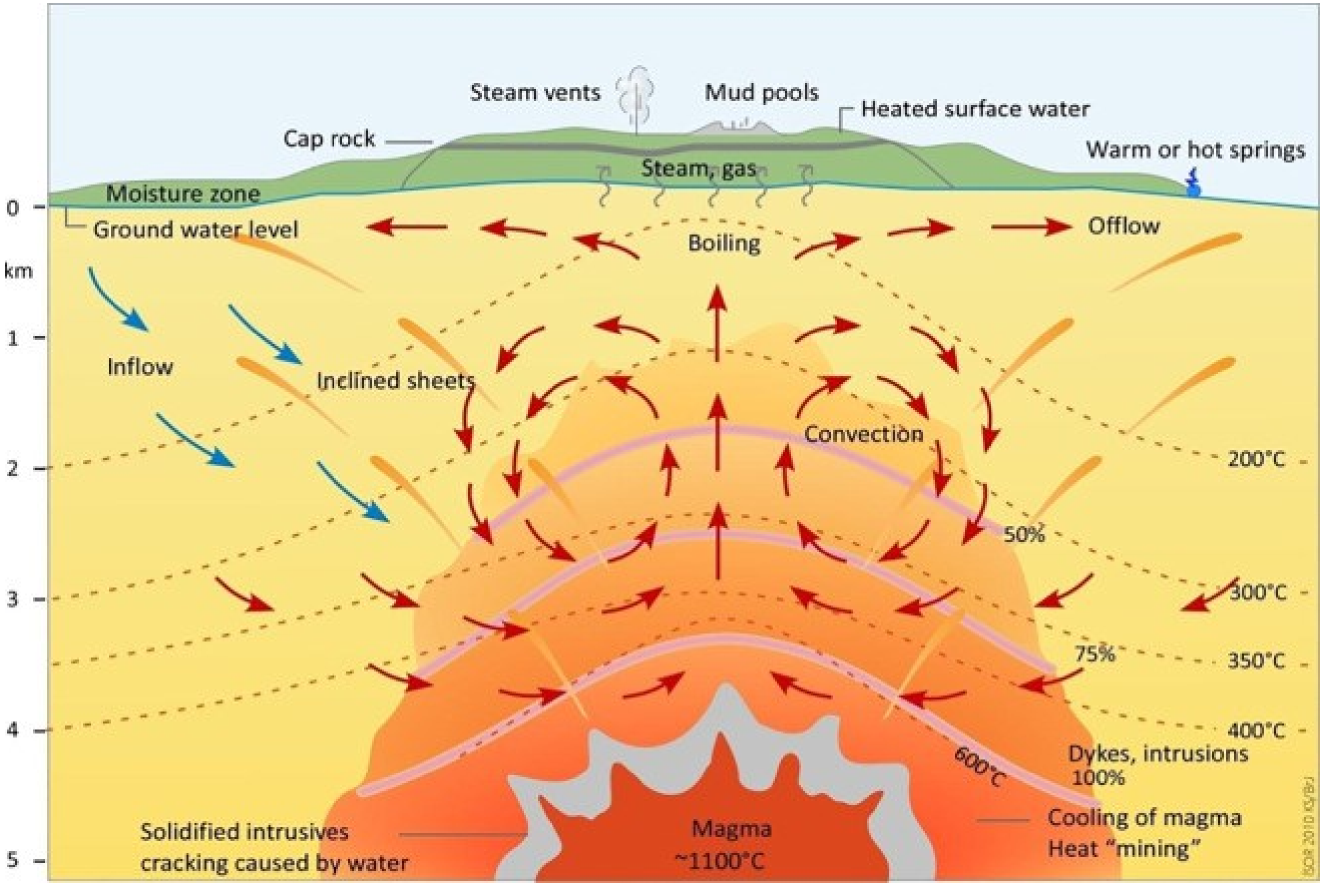
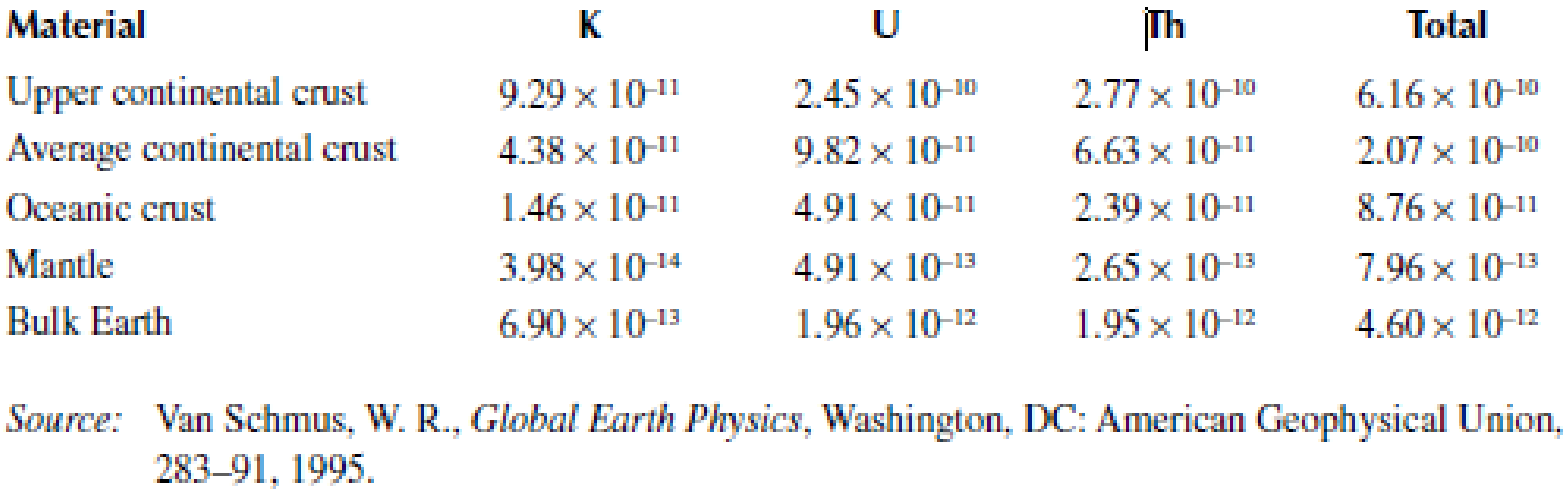




Simplified model of a high temperature system within a rifting volcanic system.

Heat Production from Radioactivity, in J/kg-s

- Part of the heat that generated inside the earth is released resulting from the disintegration of long-lived radioactive atoms present in the Earth.
- The main radioactive elements are Potassium (K), Uranium (U), and Thorium (Th).
- 1 J/kg/s = 1 Watt/kg



Material	K	U	Th	Total
Upper continental crust	9.29×10^{-11}	2.45×10^{-10}	2.77×10^{-10}	6.16×10^{-10}
Average continental crust	4.38×10^{-11}	9.82×10^{-11}	6.63×10^{-11}	2.07×10^{-10}
Oceanic crust	1.46×10^{-11}	4.91×10^{-11}	2.39×10^{-11}	8.76×10^{-11}
Mantle	3.98×10^{-14}	4.91×10^{-13}	2.65×10^{-13}	7.96×10^{-13}
Bulk Earth	6.90×10^{-13}	1.96×10^{-12}	1.95×10^{-12}	4.60×10^{-12}

Source: Van Schmus, W. R., *Global Earth Physics*, Washington, DC: American Geophysical Union, 283–91, 1995.

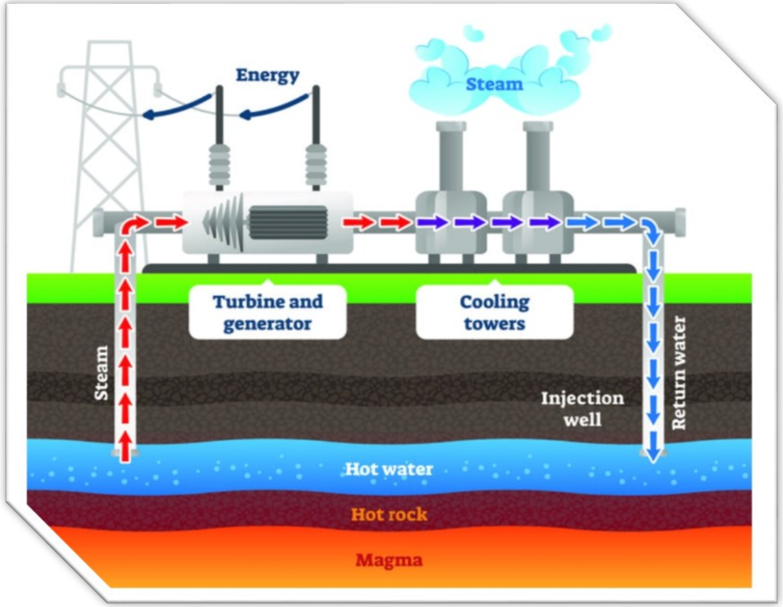
6. Geothermal resource: Thermodynamics

- **First law of thermodynamics (The Law of Conservation of Energy)**
- The energy can neither be created nor destroyed, but it can be changed from one form to another.
- Law of energy conservation applied to a thermal system (The total amount of energy remains constant.)

Note: Thermal energy can be increased within a system by adding thermal energy or by performing work on a system, but the total amount of energy in existence doesn't increase.

- **Second law of thermodynamics (The Entropy Law)**
- The entropy in an isolated system always increases.
- Any isolated system spontaneously evolves towards thermal equilibrium.
- Thermal energy flows from hot to cold.
- The transfer or conversion of the heat energy is irreversible and always move towards the disorder.

6. Geothermal resource: Sub-surface fluid flow



- It is governed by the Darcy's law.
- The law is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance.

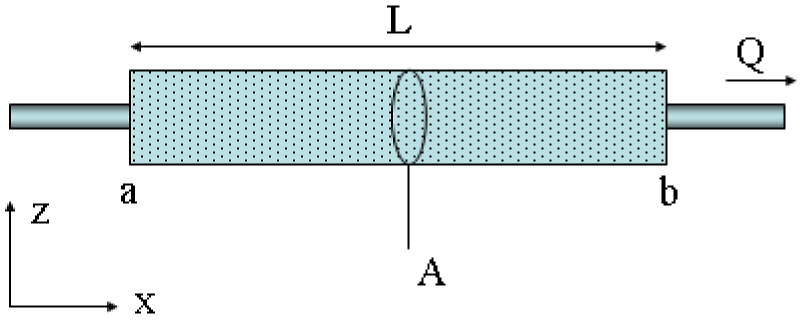
$$Q = \frac{-\kappa A}{\mu}\frac{(P_b - P_a)}{L}$$

Q (units of volume per time, e.g., ft³/s or m³/s)

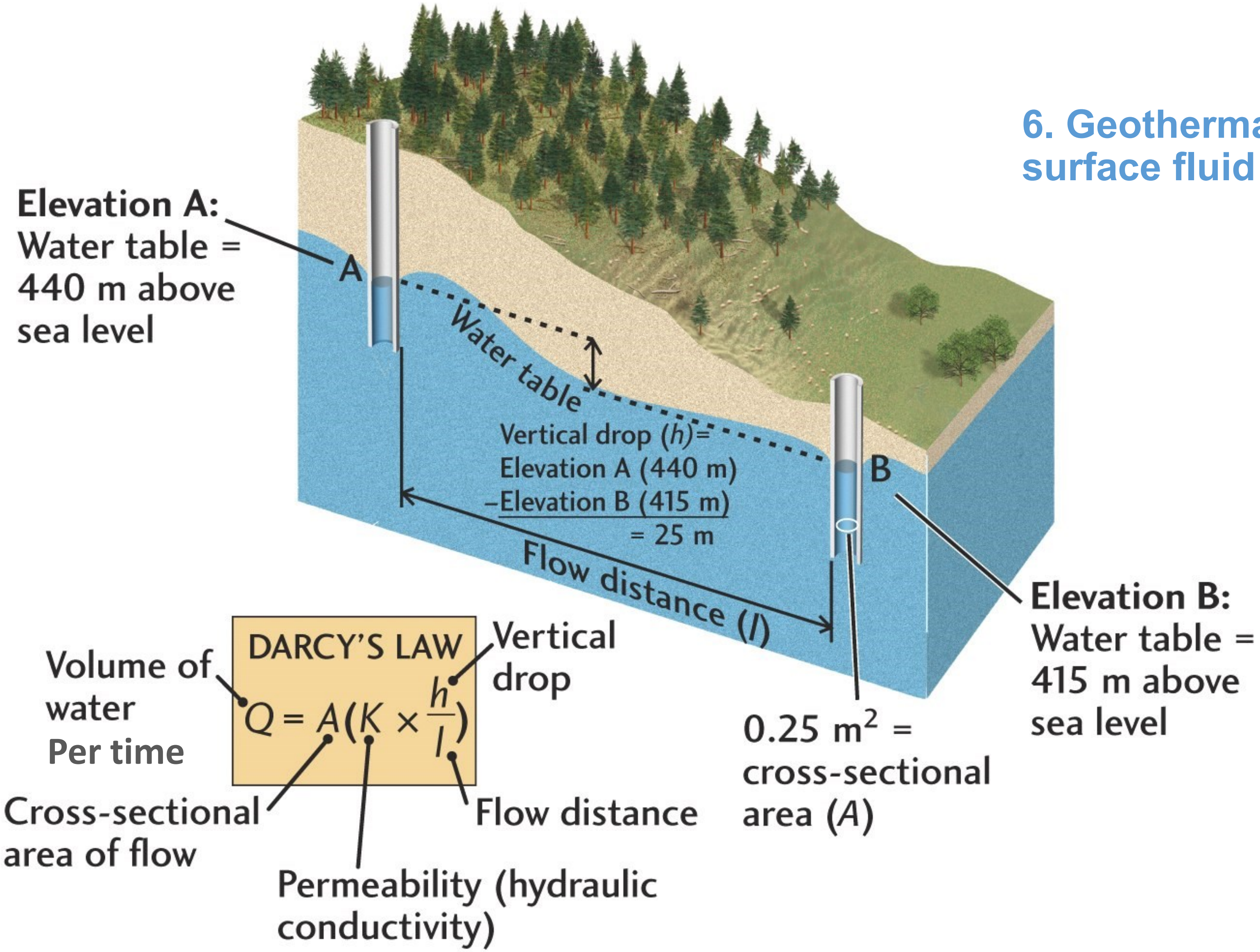
κ is the permeability, A is (units of area, e.g. m²)

$(P_b - P_a)$ is the pressure drop (due to the work),

L (Length)



6. Geothermal resource: Sub-surface fluid flow - Example



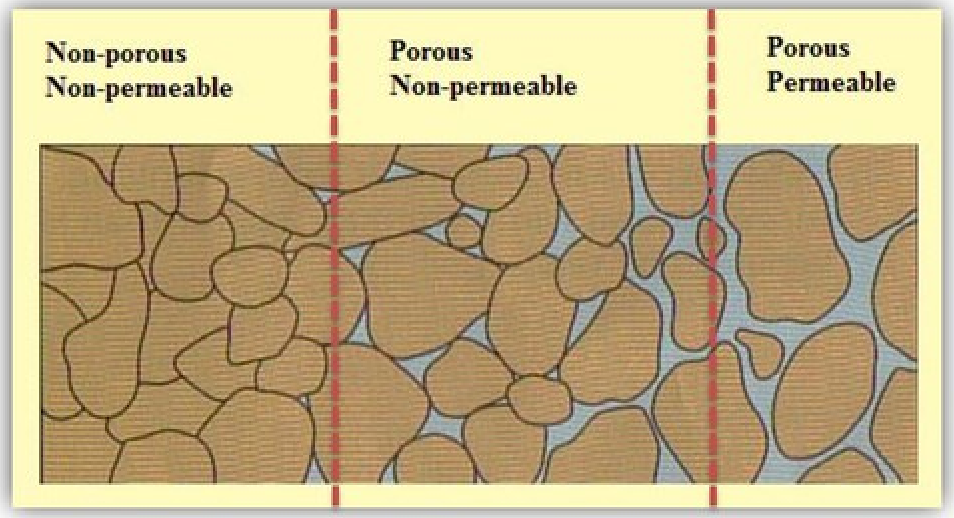
$$Q = A\left(K \times \frac{h}{l}\right)$$

$$v = \frac{q}{\phi}$$

6. Geothermal resource: Sub-surface fluid flow

The pore velocity (*v*) is related to the Darcy flux (*q*) by the porosity (ϕ)

- *Darcy flux (q) is the volume of water flows through a unit cross sectional área of porous media per unit time.*
- *Porosity: the volume of void space (available to contain fluid or air) in a sediment or sedimentary rock.*
- *Permeability: related to how easily a fluid will pass through any granular material.*



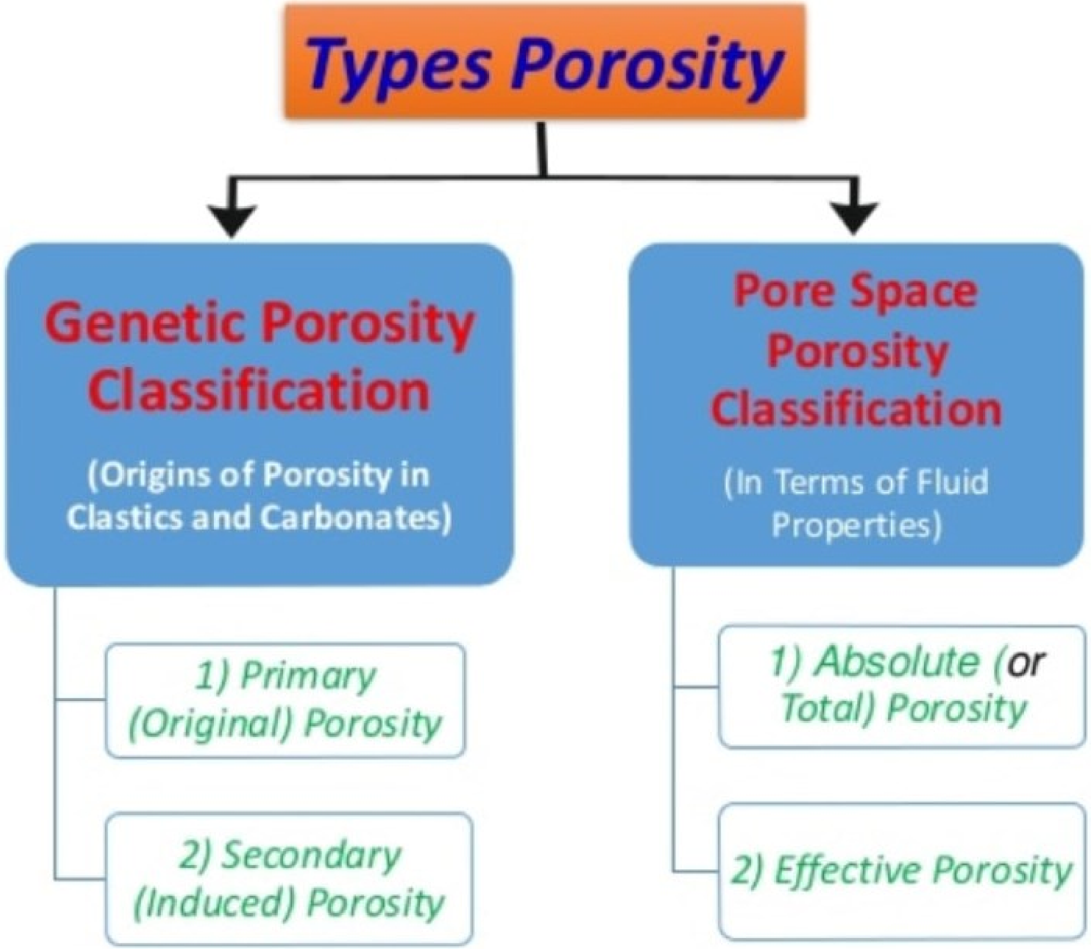
$$\phi = \frac{V_P}{V_T} \times 100$$

V_P: The total volume of pore space
V_T: The total volume of rock or sediment.

Effective porosity is the ratio of the total volume of interconnected pores to the bulk volume (Always lower than Total or Absolute Porosity)

6. Geothermal resource: Sub-surface fluid flow - Porosity

- The Primary porosity is represented by the spaces between grains in a sediment or sedimentary rock.
- The Secondary porosity is porosity that has developed after the rock has formed; such as: fracture porosity — space within fractures in any kind of rock.
- Some volcanic rock has a special type of porosity related to vesicles, and some limestone has extra porosity related to cavities within fossils.



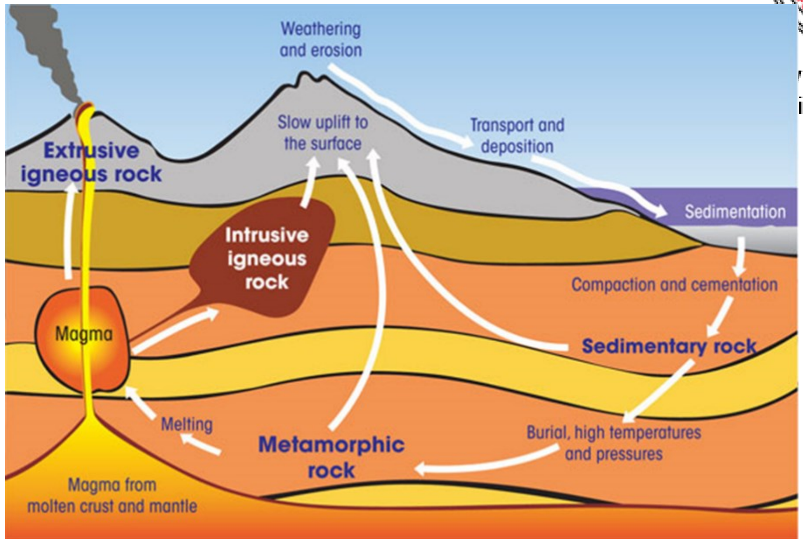
Types Porosity

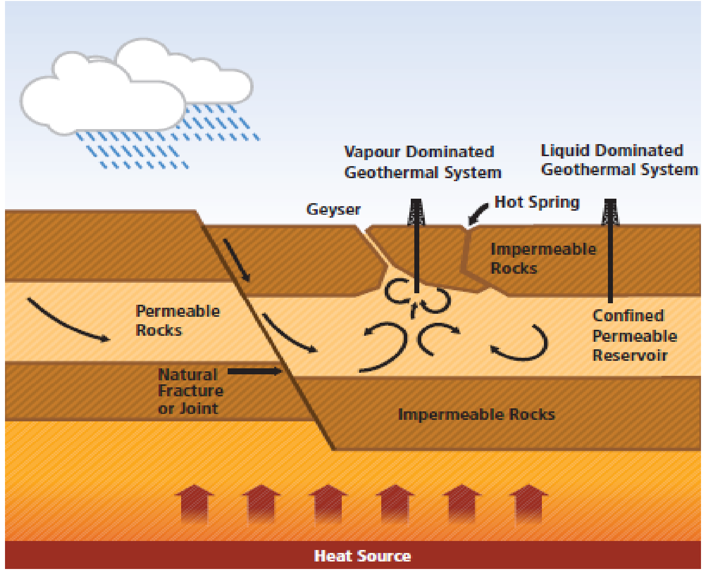
Genetic Porosity Classification
(Origins of Porosity in Clastics and Carbonates)
- *1) Primary (Original) Porosity*
- *2) Secondary (Induced) Porosity*

Pore Space Porosity Classification
(In Terms of Fluid Properties)
- *1) Absolute (or Total) Porosity*
- *2) Effective Porosity*

6. Geothermal resource: Sources of Heat

- Magma chambers: Hot water can be released through geysers, hot springs, steam vents, underwater hydrothermal vents, and mud pots.
- Plate Boundaries where the most active geothermal resources are usually found.
- Most of the geothermal activity in the world occurs in an area known as the "Ring of Fire." The Ring of Fire rims the Pacific Ocean and is bounded by Japan, the Philippines, the Aleutian Islands, North America, Central America, and South America.

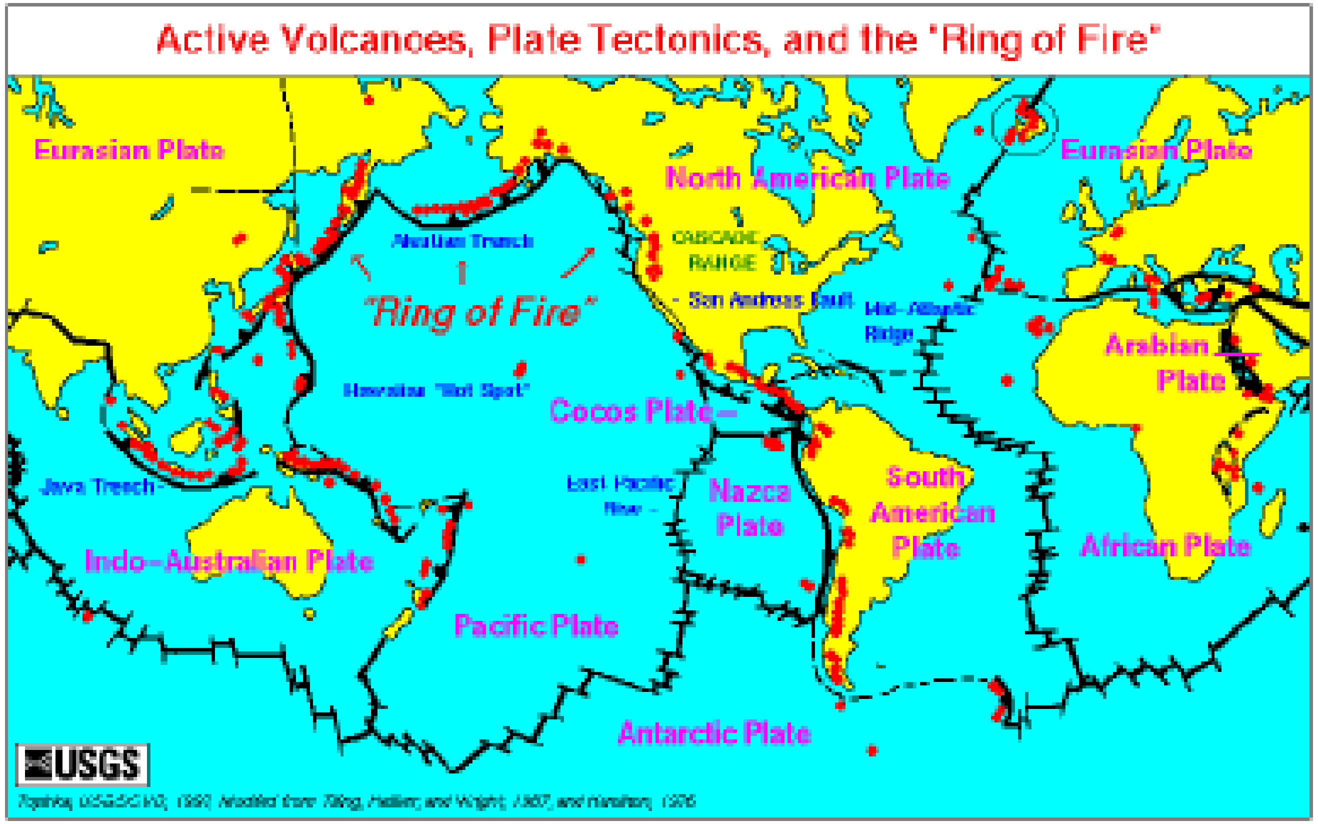




https://commons.wikimedia.org/wiki/File:Geothermal_energy_methods.png

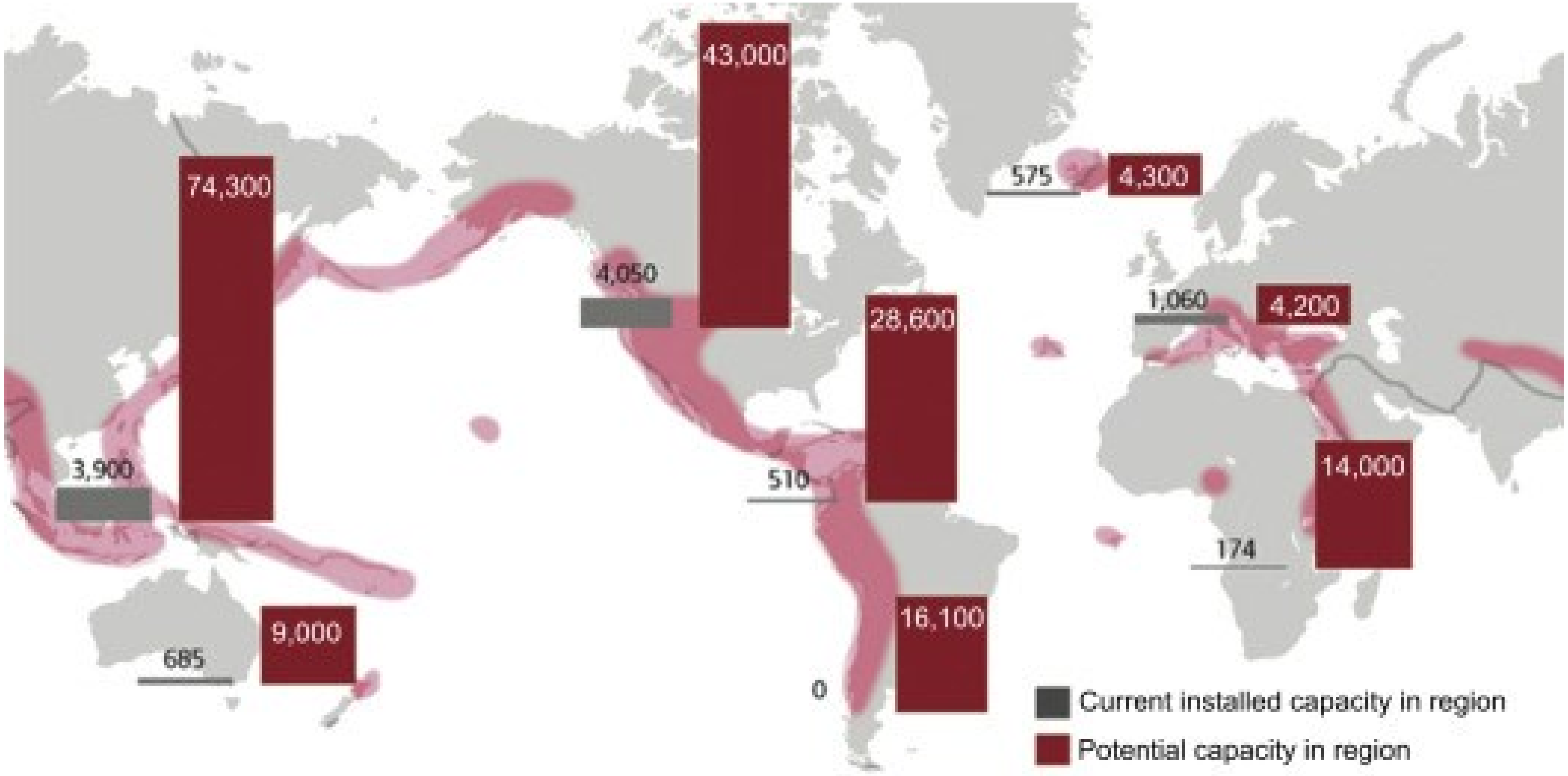
6. Geothermal resource: Sources of Heat - Plates

- Globally, area of the large volcanic (tectonic) activity are zones with far largest heat flow.
- Consequently, they are regions with large numbers of surface geothermal phenomenon.



"Earth fire ring" (USGS public material)

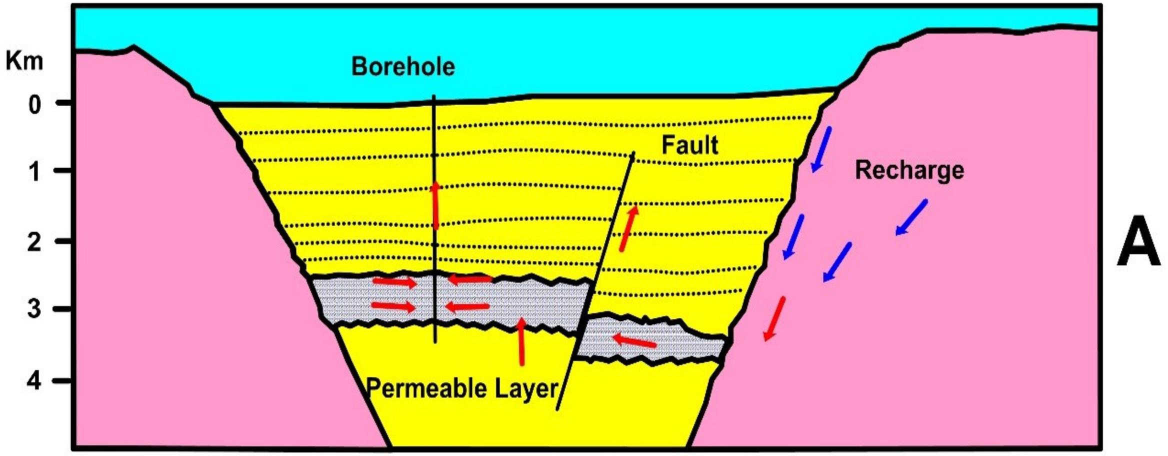
6. Geothermal resource: Potential resources



Distribution of geothermal potential along with the ring of fire (Islandsbanki, 2011).

7. Geothermal Reservoirs

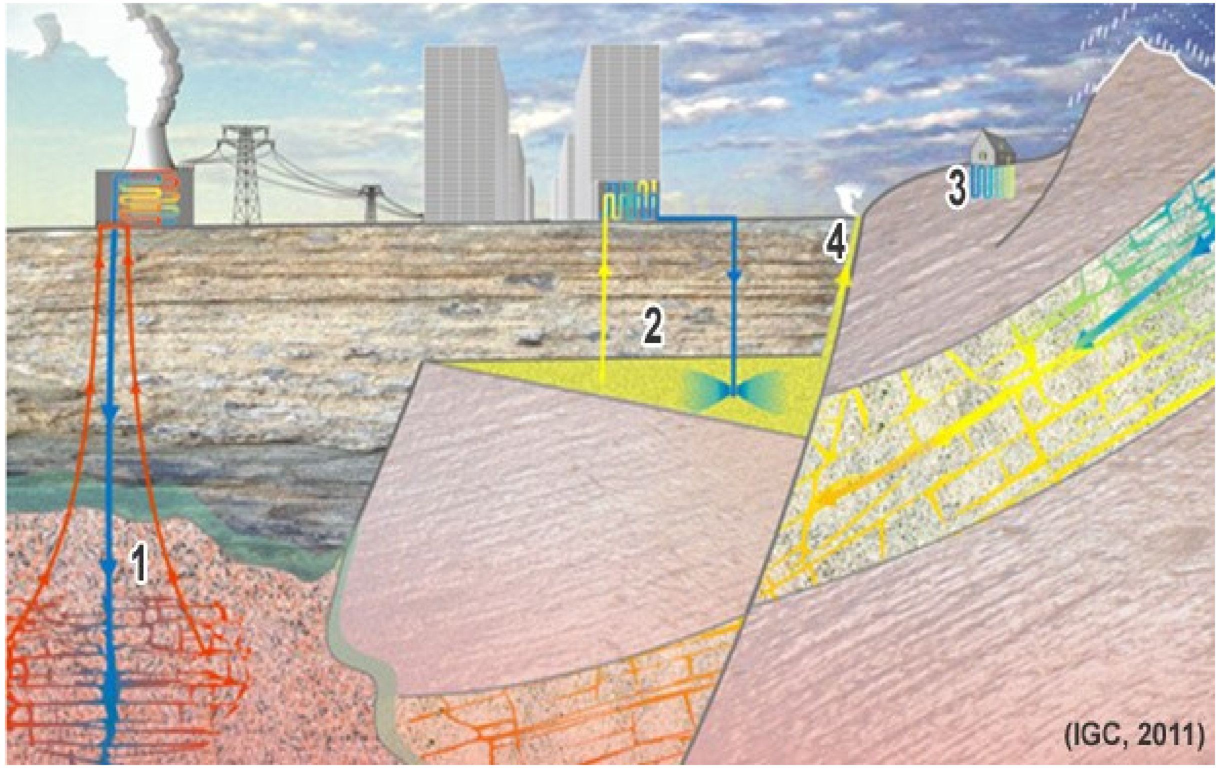
- Geothermal resources are reservoirs of hot water that exist at varying temperatures and depths below the Earth's surface.
- Deep wells can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for use in a variety of applications.



7. Geothermal Reservoirs

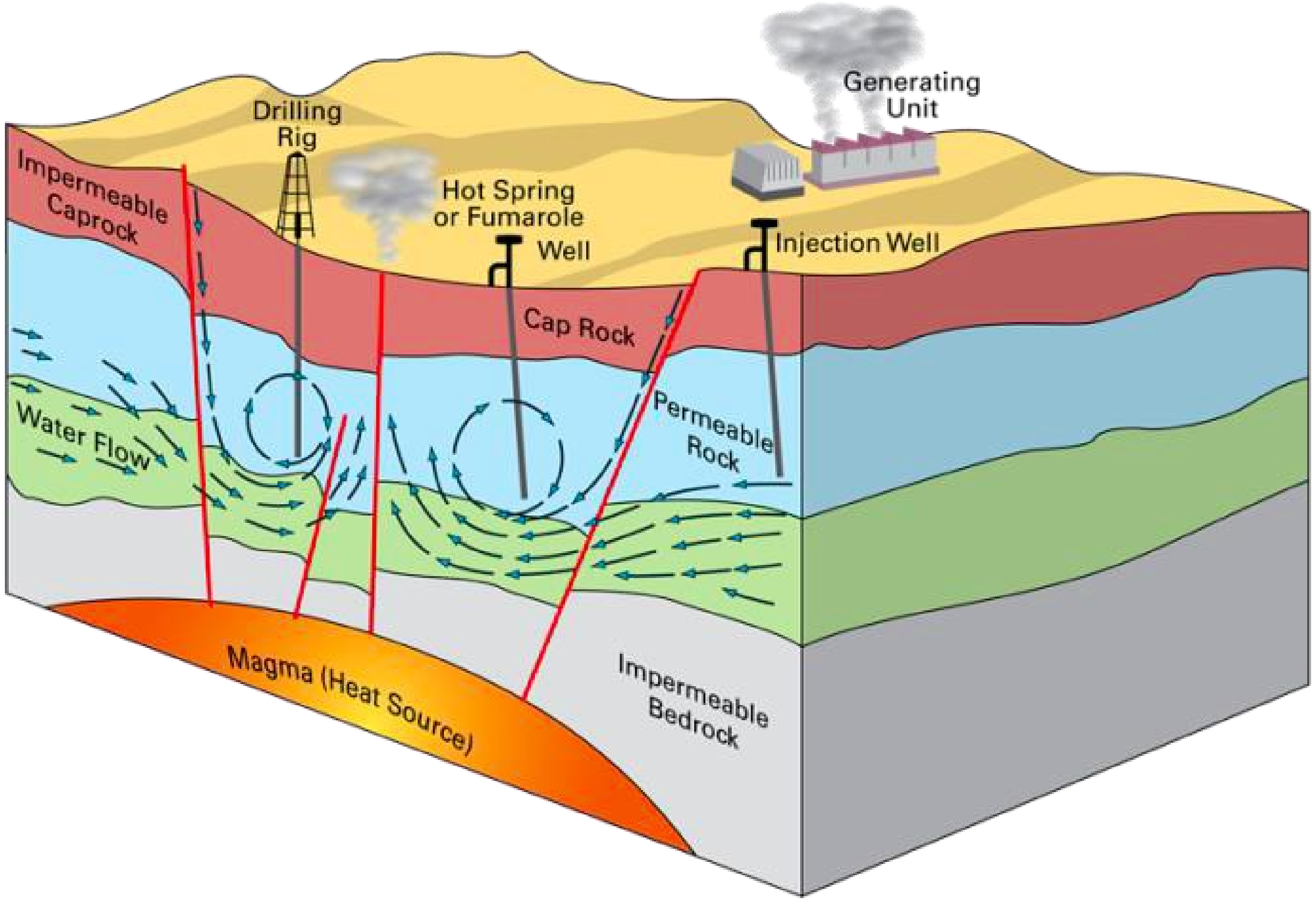
- Geothermal reservoir is a volume of rocks in the subsurface whose exploitation in terms of heat can be economically profitable.
- For producing the heat from the subsurface, it is necessary the presence of a transport fluid (usually water).
- There are four types of geothermal reservoirs can be defined:

1. **High temperature**
2. **Middle temperature**
3. **Low temperature**
4. **Very Low temperature**



(IGC, 2011)

7. Geothermal Reservoirs



Two crucial elements of geology are visible on schematic view:

(1) <u>Depth of reservoir</u>, deeper reservoirs are exposed to larger temperature and closer to possible heat sources;

(2) <u>Reservoir volume</u> and <u>re-filling</u> are important for geothermal source lastings.

A simple model of Geothermal system (ČULJAK, 2018)

7. Geothermal Reservoirs: Porous vs. Fractured

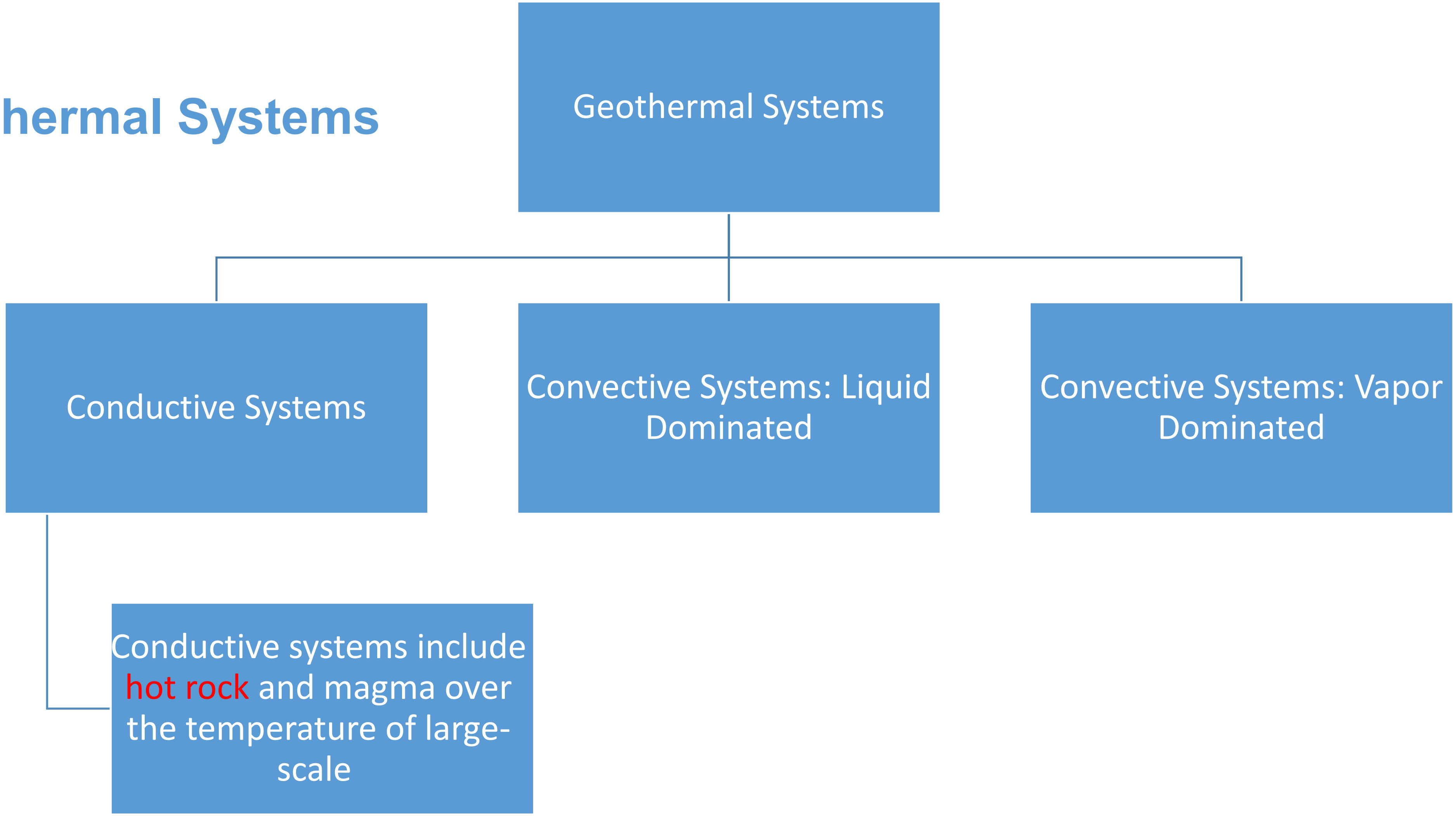
Porous reservoirs

- They are the reservoirs that composed mainly from rocks with high percentage of primary porosity, and
- The fluid lays on their porosity like sandstone reservoirs

Fractured reservoirs

- They are the reservoirs that composed mainly from rocks that have high percentage of secondary porosity, and
- The fluid lays on their porosity like limestone reservoirs.

8. Geothermal Systems



Geothermal Systems

Conductive Systems

Convective Systems: Liquid Dominated

Convective Systems: Vapor Dominated

Conductive systems include hot rock and magma over the temperature of large-scale

8. Geothermal Systems: Heat transfer in geothermal systems

Category		Heat Transfer Mechanisms
Warm water (low temperature)		Conduction
Hot water (intermediate temperature)		Convection
Two-phase (high temperature)	low-enthalpy (very hot water)	Strong convection Some counter-flow
	high enthalpy (boiling water and steam)	Moderate convection Counter-flow
	vapor – dominated (dry steam)	Negligible convection Counter-flow, conduction

8. Geothermal Systems: Heat transfer in geothermal systems

- **Conductive Systems**
  - Warm Groundwater Basins
  - Deep Sedimentary Aquifers
  - Warm Springs and Fracture and Fault Systems
  - Geopressured Systems
  - Hot, Dry Rock or Engineered Geothermal Systems

8. Geothermal Systems (Conductive): Warm Groundwater Basins

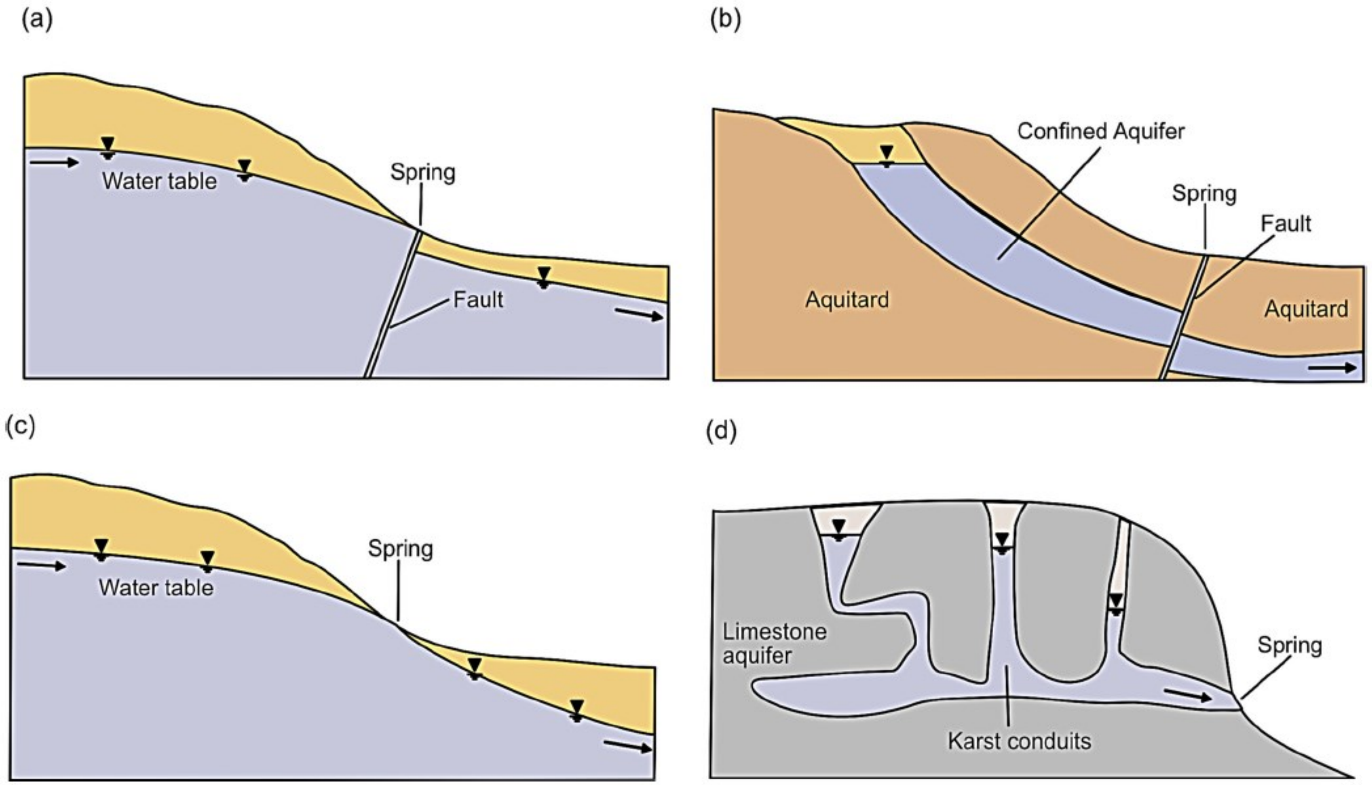
- Shallow Low-temperature geothermal energy is associated with the warm ground water in several sedimentary basins around the world.
- The flux of heat to the surface of some sedimentary formations of the world are sufficiently high to be utilized for house heating using shallow boreholes and ground source heat pumps.
- The heat of the earth's interior come out to the near surface due to plate movement and store in the fractures zone or some porous layers of sedimentary rocks in the basin which can be utilized as geothermal energy, especially in direct uses, example Yangtze River Basin about 50-150 m depth.

8. Geothermal Systems (Conductive): Deep Sedimentary aquifers

- Deep sedimentary aquifers heated by the normal thermal gradient are found in many continental environments.
- These aquifers are usually not part of a currently active circulation system. This simple two-well system in an aquifer is very common in groundwater or petroleum engineering. The only difference is that the fluid is warm.
- A typical example of this type of system is a carbonate/sandstone aquifer that was developed using production-injection well pairs for district heating in the Paris Basin and located between 1,500 and 2,000 meters deep.
- Since the first drilling was carried out in the basin at Melun in 1969, geothermal projects have followed one another in Ile-de-France (so the French name for the greater Paris area). Today, around fifty heating networks supply the equivalent of 250,000 homes.

8. Geothermal Systems (Conductive): Warm Springs

- Many warm springs are found along major fault and fracture lineation.
- The difference between this system and Warm Groundwater Basins is that in this system the water not trapped underground



8. Geothermal Systems (Conductive): Warm Springs

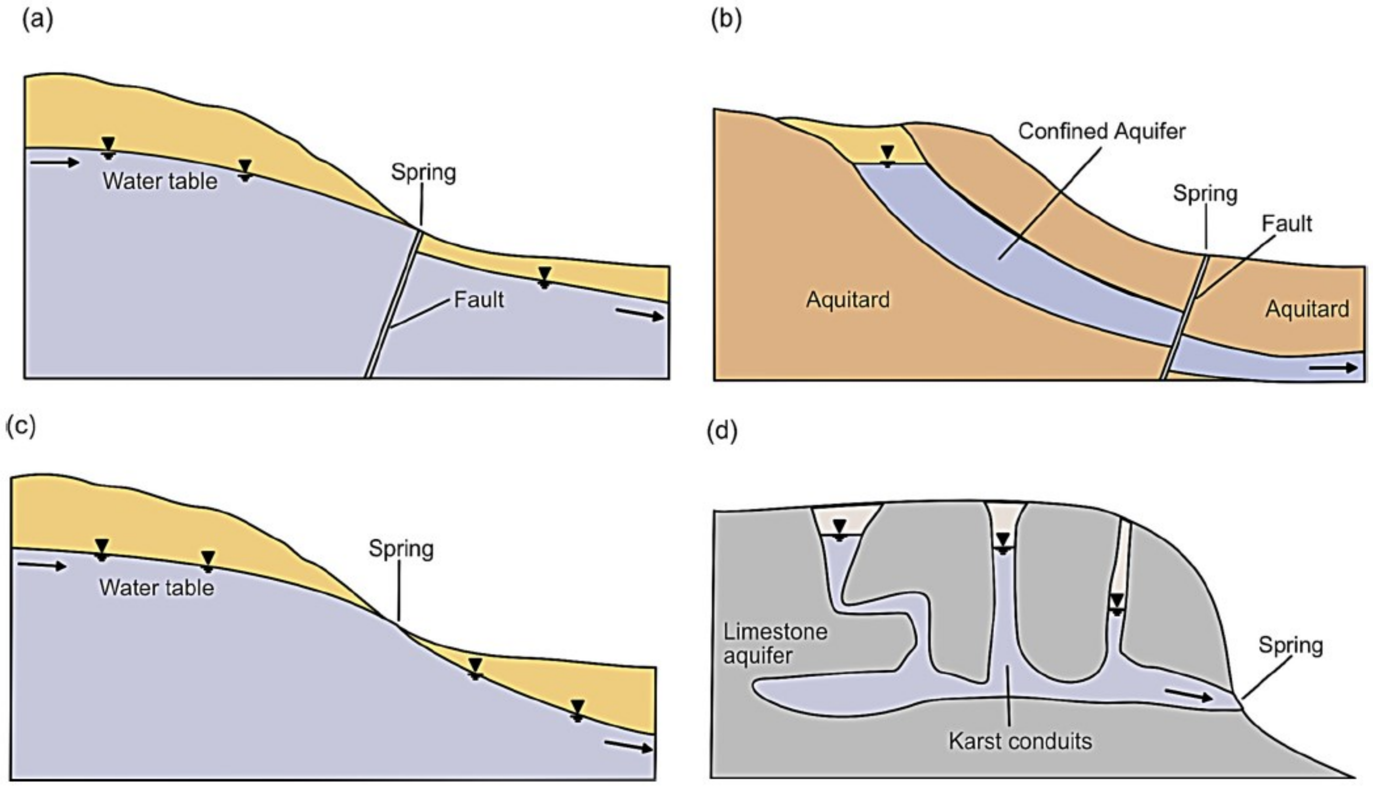
- Spring conceptual models for the spring types described by Meinzer (1923) showing:

a) A contact spring where the water table outcrops along a fault,

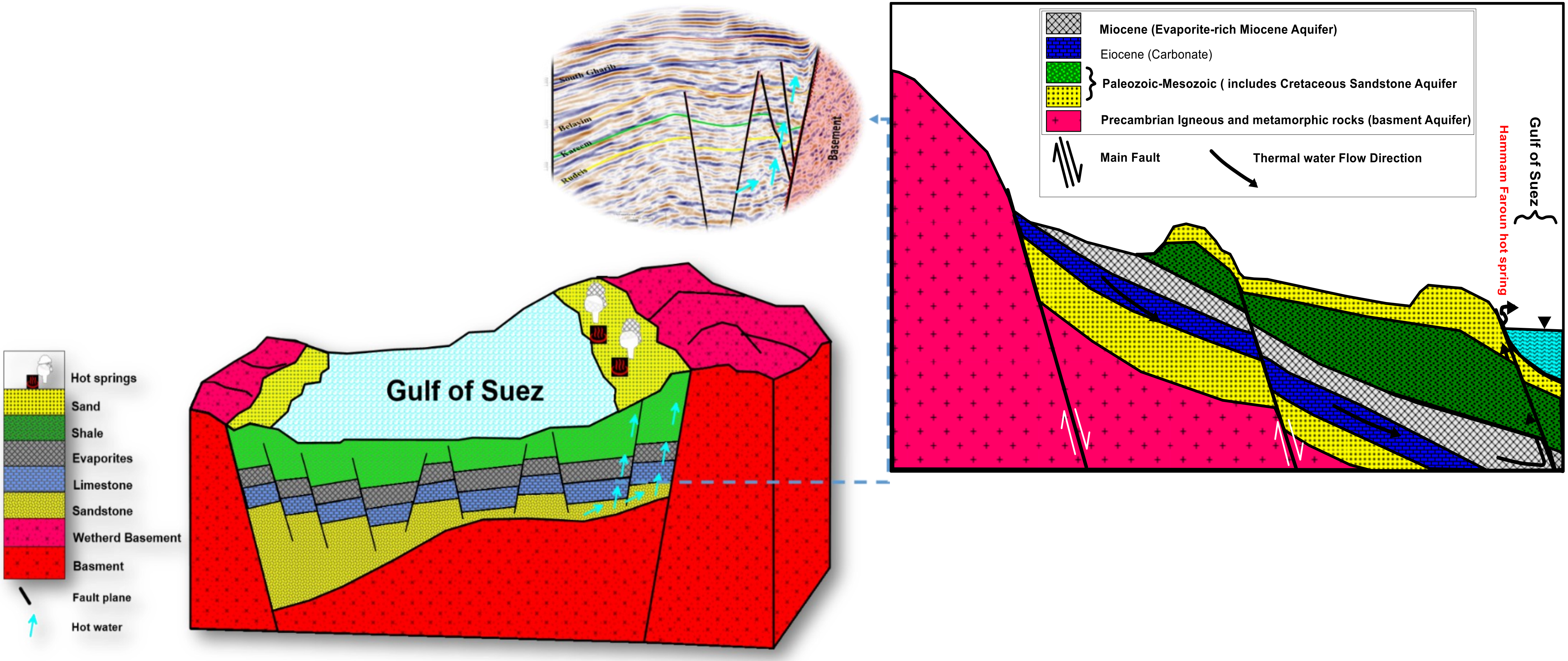
b) A fissure/fault spring where a fault provides a conduit for flow from a confined aquifer,

c) A depression spring where the water table intersects the surface and

d) A tubular or fracture spring where water flows through karst conduits and discharges through an orifice (opening) at lower elevation.

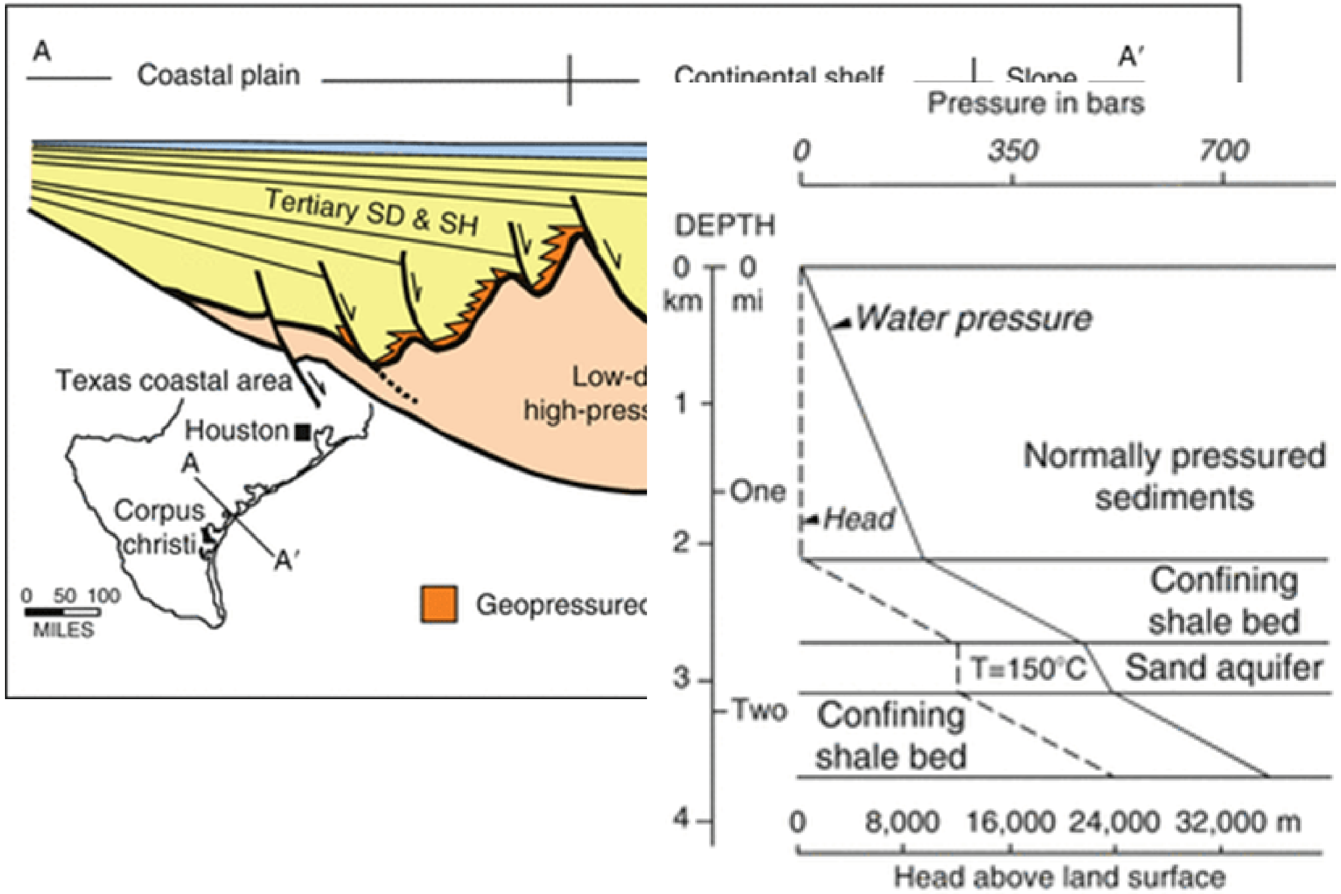


8. Geothermal Systems (Conductive): Warm Springs



8. Geothermal Systems (Conductive): Geopressured Systems

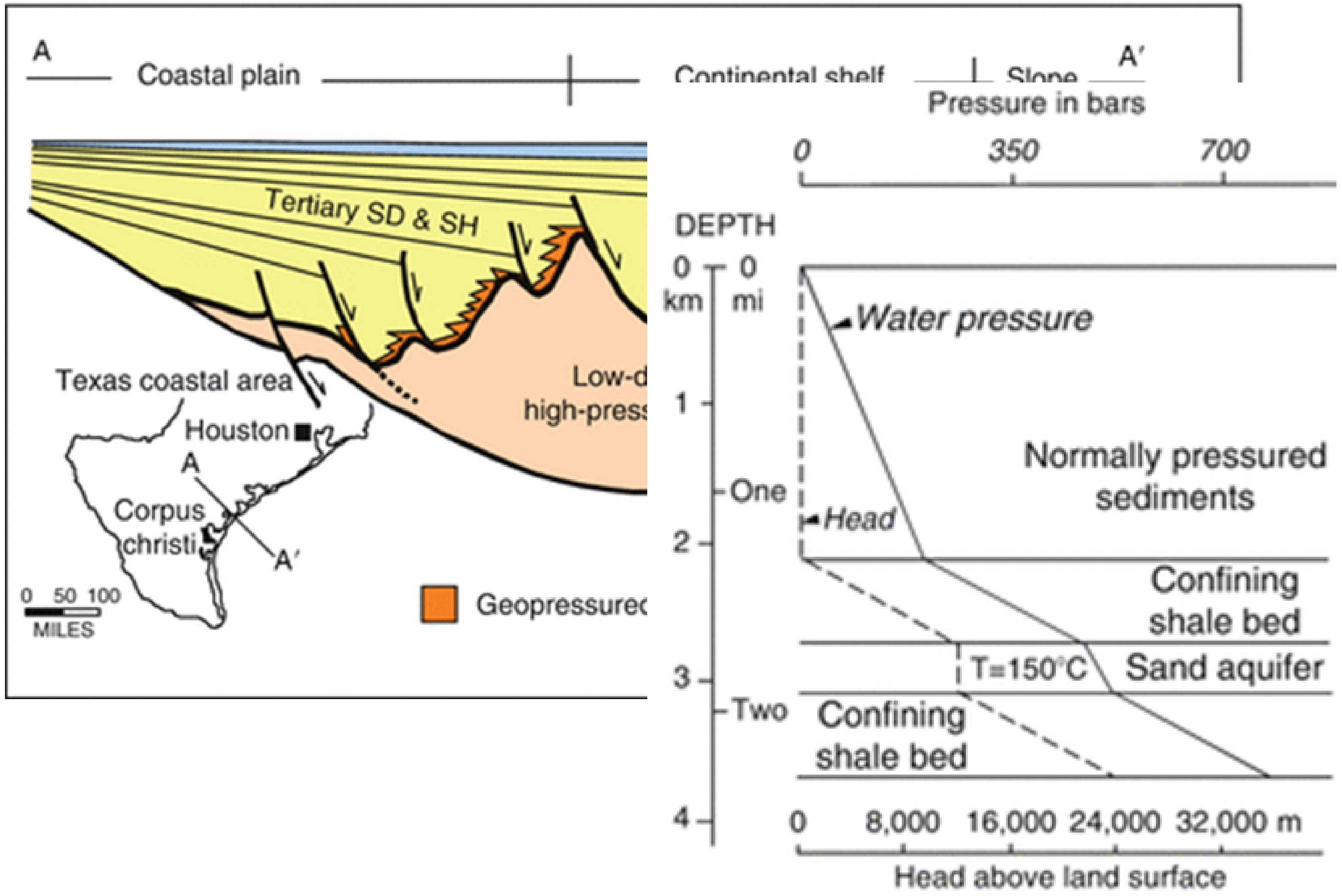
- The basin environments where deeply buried fluids are contained in permeable sedimentary rocks and warmed in a normal or enhanced geothermal gradient by their great burial depth.
- The fluids are tightly confined by surrounding impermeable rock and bear pressure much greater than hydrostatic.
- Thermal waters under high pressure in sand aquifers are the target for drilling, mainly as they contain dissolved methane.



Geopressured geothermal system. (Bebout, et al., 1978)

8. Geothermal Systems (Conductive): Geopressured Systems

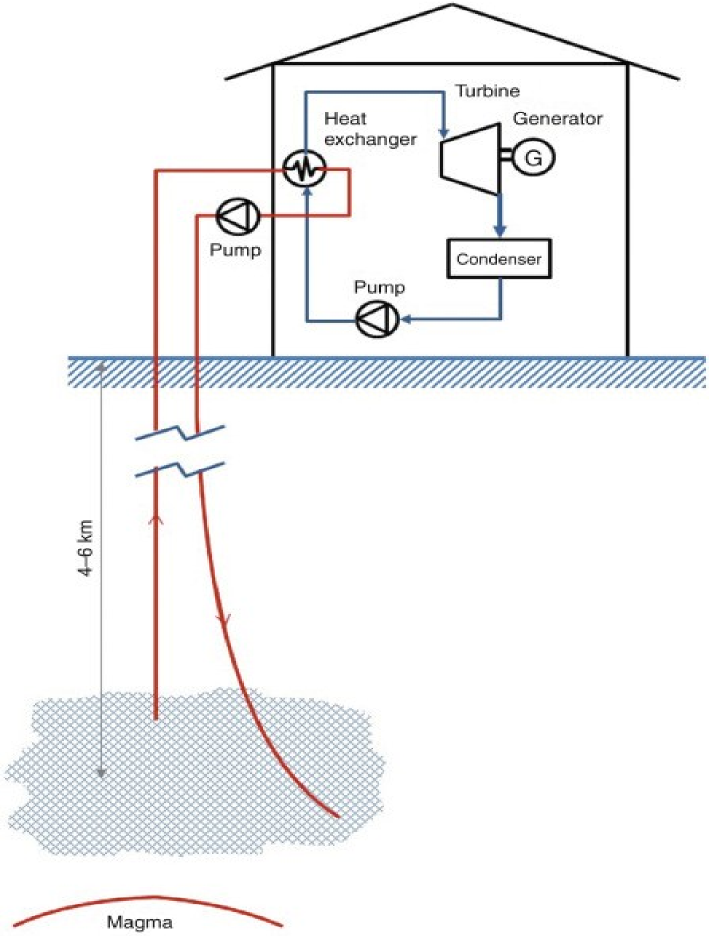
- The source of energy available from this type of resource consists of:
  1. heat;
  2. Mechanical energy; and,
  3. Methane.
- Such reservoirs are generally relatively deep, at least 2 km, with reservoir temperatures range from 90 to 200˚C.
- It can be found on the Gulf of Mexico coast, along the Pacific west coast, in Appalachia.



Geopressured geothermal system. (Bebout, et al., 1978)

8. Geothermal Systems (Conductive): Hot Dry Rock

- It is a condition where water is not naturally present at the site, and the magma only heats dry rock on top of it.
- To tap heat from the dry rock, two wells can be drilled into the rock: One well is used to carry water from the surface down into the HDR.
- Once the water is heated, the steam is created and then channelled up through the second well into a turbine above the surface.
- Example, at Fenton Hill, New Mexico, federal Los Alamos Laboratory the depth of about 2.6 km, with rock temperatures of 185 °C



Simple diagram of a Hot Dry Rock geothermal power plant.

1. Boehler, R. (1996): Melting temperature of the earth's mantle and core: earth's thermal structure. Annual review of earth and planetary sciences, 24, 1, 15–40.
2. Glassley, W. E. (2014). Geothermal energy: renewable energy and the environment. CRC press.
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Co-funded by the
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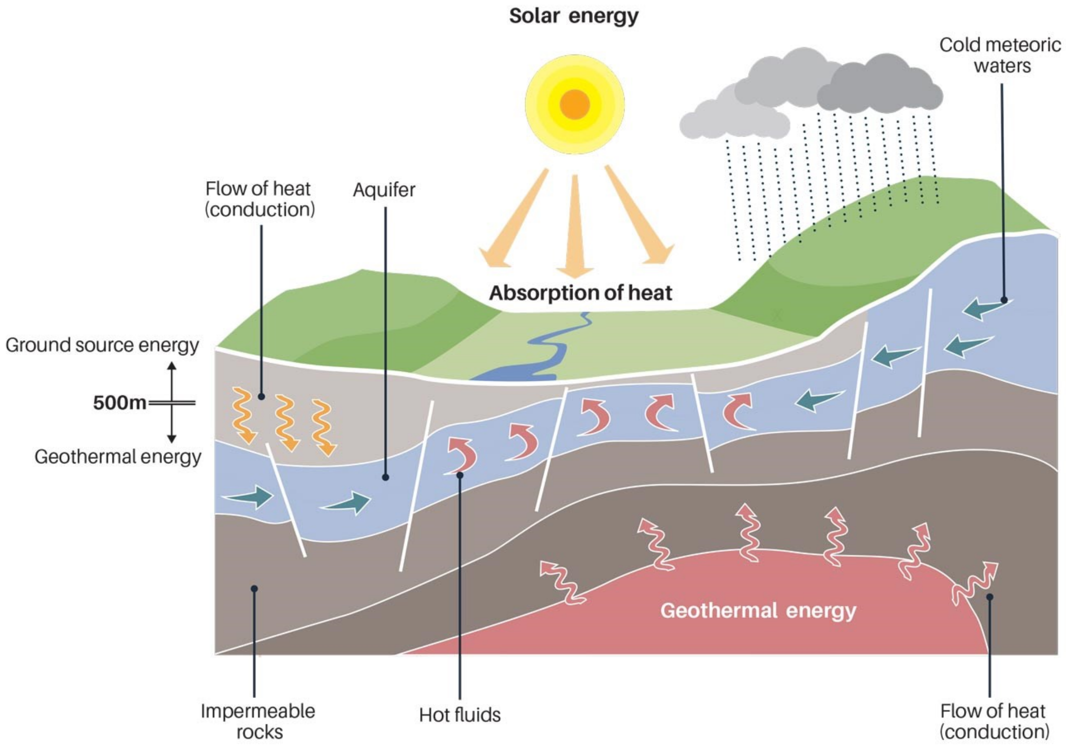
Faculty of Engineering
Cairo University

Geothermal Resources and Reservoir Engineering

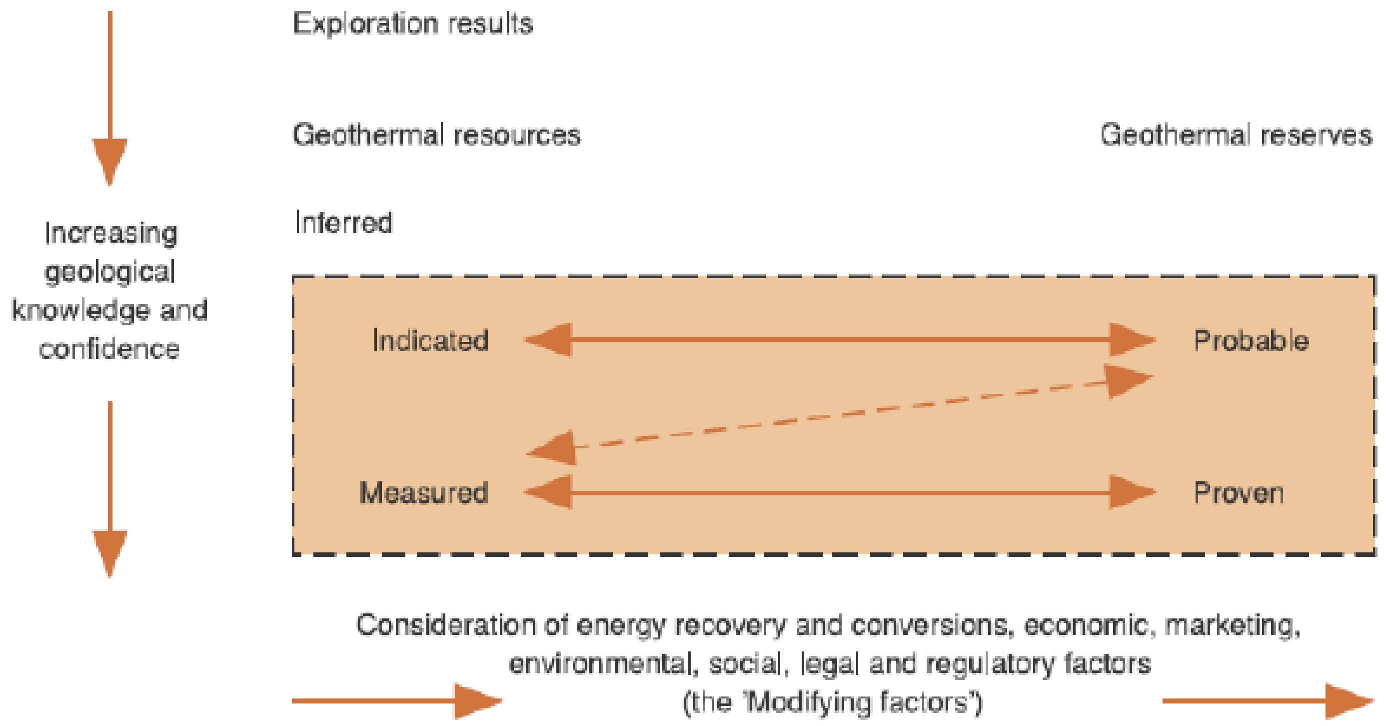
Lecture 2: Geothermal Resource Estimation and Characterization

1. Introduction

- Geothermal resource estimation (resource assessment) is a process of evaluating surface discharge and downhole data and integrating it with other geoscientific information obtained from geological, geophysical and geochemical measurements.
- The focus of the resource assessment is to confirm the existence of a geothermal resource that could be exploited at a certain capacity for a certain period with well defined fluid characteristics.
- The resource management strategies are also plotted to ensure production sustainability over a long-term period.



1. Introduction

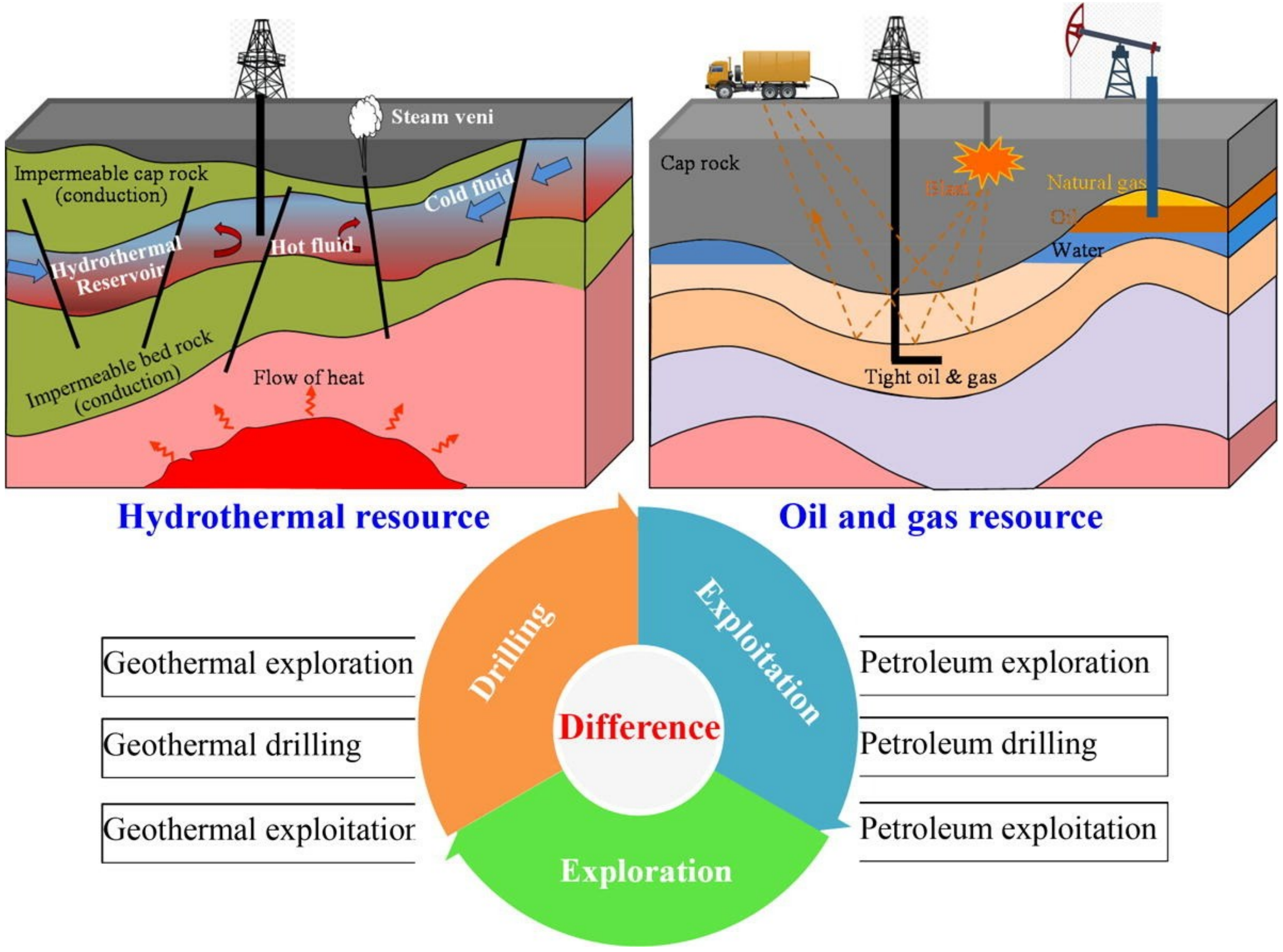


Falcone & Beardsmore 2015

- An assessment of geothermal resources can be also made during the reconnaissance and exploratory stage prior to well drilling.
- Dealing with the extent and characteristics of the thermal surface discharges and manifestations, geophysical boundary anomaly, and the geological setting and subsurface temperatures inferred from geothermometers.

1. Introduction

- The exploration, drilling, and development of high-temperature hydrothermal geothermal resources usually borrow ideas from the oil and gas industry.
- However, some techniques in the oil and gas industry are not entirely applicable for geothermal resources due to the difference in geological conditions and exploitation objectives.

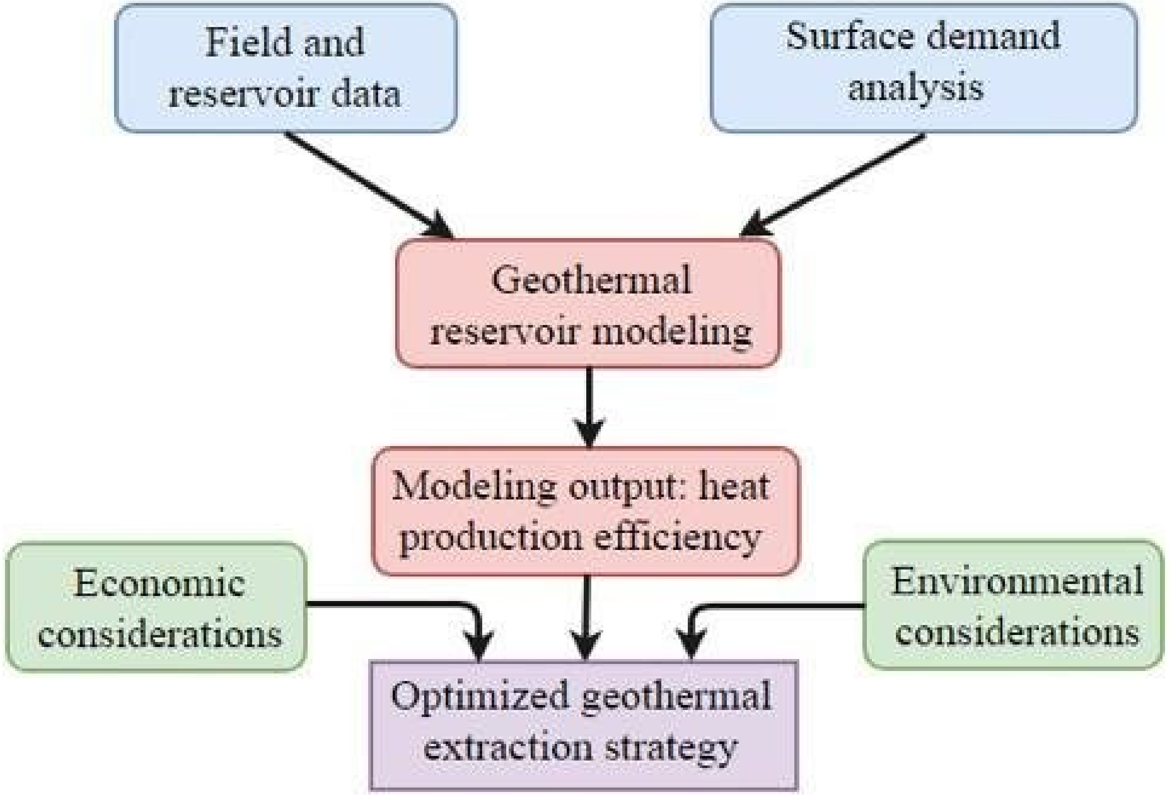


Cui et al. 2023

1. Introduction

The resource assessment methods which are used for geothermal reservoirs may depend on:

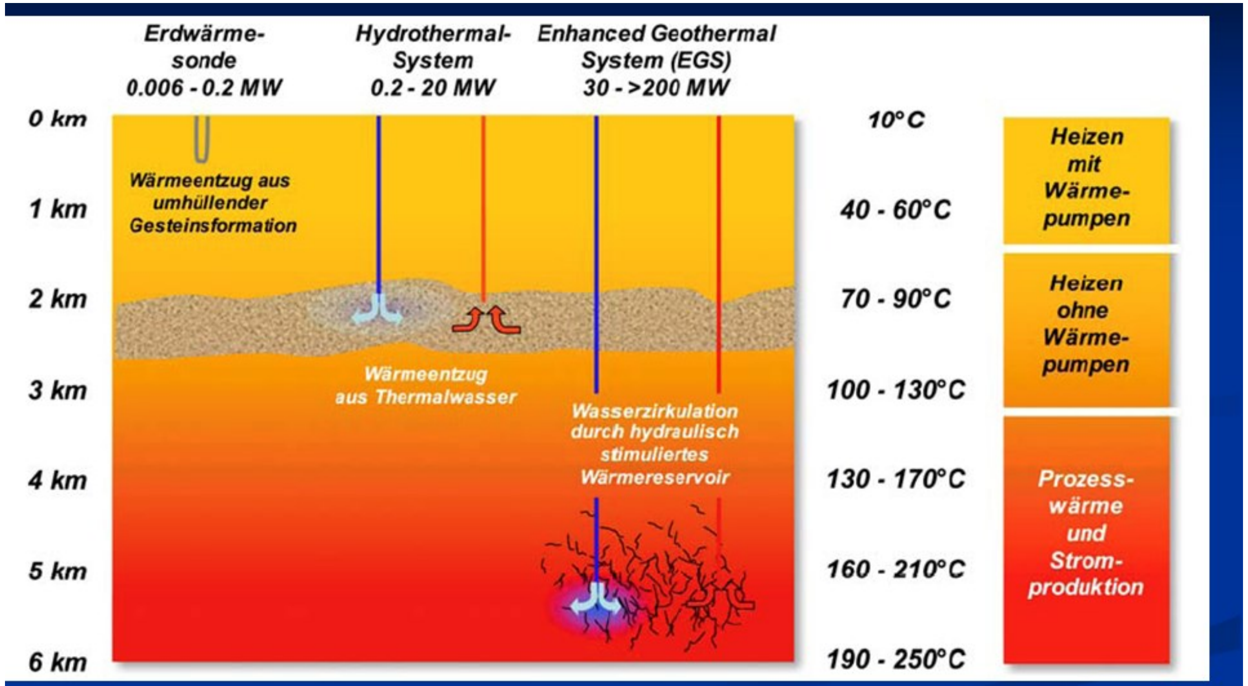
1) The amount and quality of available field data: the stage of field exploration, development or exploitation.
2) The characteristics of the reservoir: if it is liquid-dominated (low or high enthalpy), liquid dominated with a steam cap, or two-phase vapor dominated.



Guo et al. 2019

1. Introduction

- Characterization of the mechanism of how a geothermal system was formed is one of the primary aims of a geothermal resource assessment.
- The main classification of geothermal systems:
  - ❑ Conductive Systems.
  - ❑ Convective Systems: Liquid Dominated.
  - ❑ Convective Systems: Vapor Dominated.



Use of geothermal energy from surficial, hydrothermal and deep petrothermal reservoirs

www.sliderbase.com

2. Methods for Resource Estimation (Static vs Dynamic)

There are several simple and complex resource assessment methods available for quantifying the potential of a geothermal system. These methods can be grouped into two broad categories based on the nature of data of their input parameters:

1) A single point or static – methods that do not need production history data.
2) Historical or dynamic – methods that require production history data.

2. Methods for Resource Estimation (Static)

Example of static methods requiring a single point data for the input parameters are as follows:

1) Method of surface heat flux
2) Planar fracture
3) Magmatic heat budget
4) Total well flow
5) **Stored heat (volumetric)**
6) Mass-in-Place
7) Power density

2. Methods for Resource Estimation (Dynamic)

Example of Dynamic methods that utilize a series of data or historical information for the input parameters are as follows:

1) Decline analysis
2) Lumped-parameter
3) Numerical reservoir simulation

3. Static Methods for Resource Estimation (Surface Heat Flux)

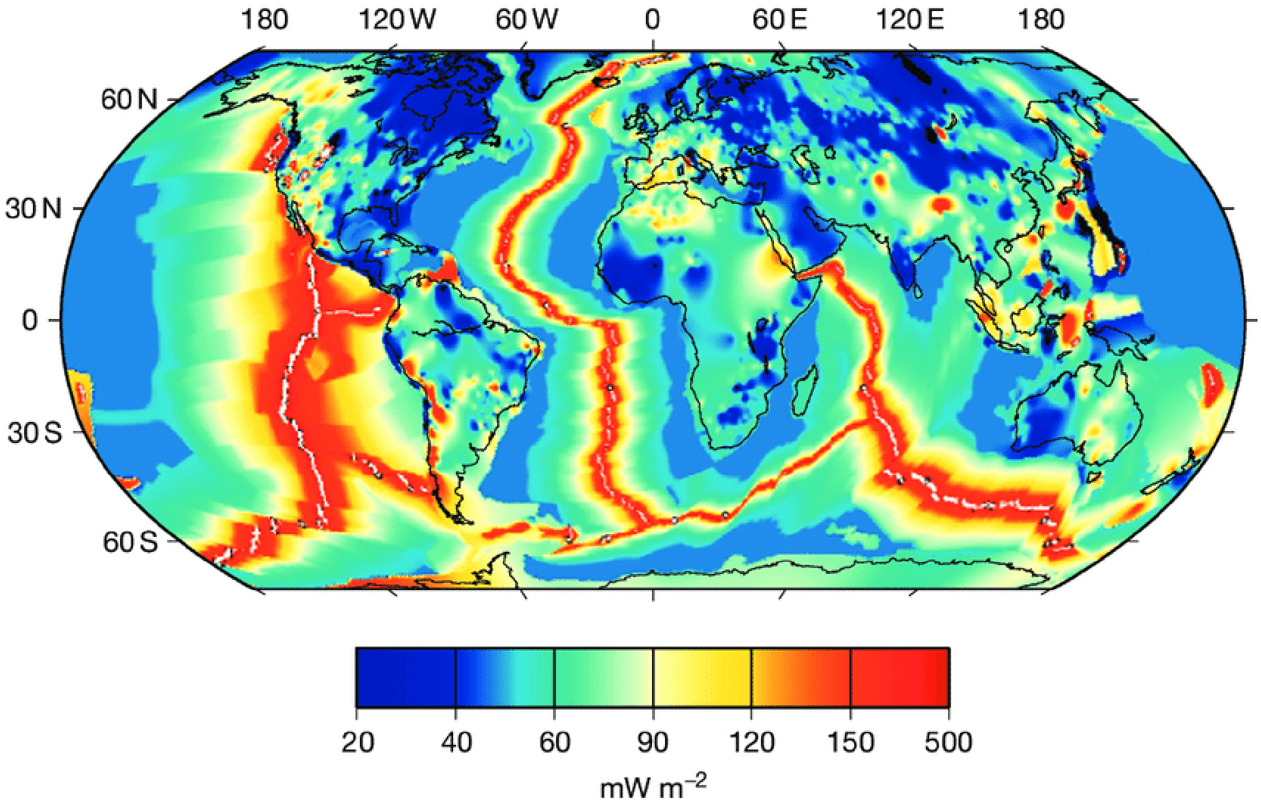
Estimate the reservoir enthalpy and reservoir temperature by deducting the thermal output, through the combination of conductive and convective heat transfer calculation. Preliminary assessment, very early exploration phase.

Advantages

The simplest method that only require surface thermal discharges and conductive heat from soil to atmosphere/surface water data.

Disadvantages:

This method results can only be assumed as the minimum natural heat flux from the system; thus, it does not represent the whole reservoir system.



Mareschal & Jaupart 2011

3. Static Methods for Resource Estimation (Surface Heat Flux)

- The total amount of natural heat q_{tot} (W), expressed as the heat above 0°C, in the natural heat discharge is the sum of the convective q_{si} (W) and conductive q_c (W) components.

$$q_c = Ak\frac{dT}{dz} \qquad \textbf{(1)}$$

$$q_{tot} = \sum_{i}^{n} q_{si} + q_c \qquad \textbf{(2)}$$

where:

A Surface area of a hot ground (m^2)
k Thermal conductivity of rock (W/m °C)
T Temperature (°C)
z Depth (m)

3. Static Methods for Resource Estimation (Planar Fracture)

- Extraction of heat through flow of water along extensive, planar fractures, with heat being transferred to the fractures only by conduction.
- Mainly in early exploration phase.

Advantages

- ✓ Enable calculation of recoverable thermal energy from a minimum number of physical parameters **without** going through the intermediate step of calculating the accessible resource base.

Disadvantages:

- ❖ It is not reliable to the most common geologic situation characterized by folding and faulting.

3. Static Methods for Resource Estimation (Planar Fracture)

- A fluid with an initial temperature ***T_r*** is being heated to a certain final temperature ***T_o*** as it passes through the hotter fracture.
- The final temperature of the fluid as it exits the fracture is dictated by the initial temperature of the rock ***T_o*** which is being heated through conduction. This final fluid temperature is considered as the initial production temperature of the fluid.
- The planar fracture model can be applied to multiple fractures on the condition that the minimum distance ***d*** between them is equivalent to Nathenson & Muffler (1975).

$$r = \frac{T_m - T_{rech}}{T_0 - T_{rech}} \qquad \textbf{(1)}$$

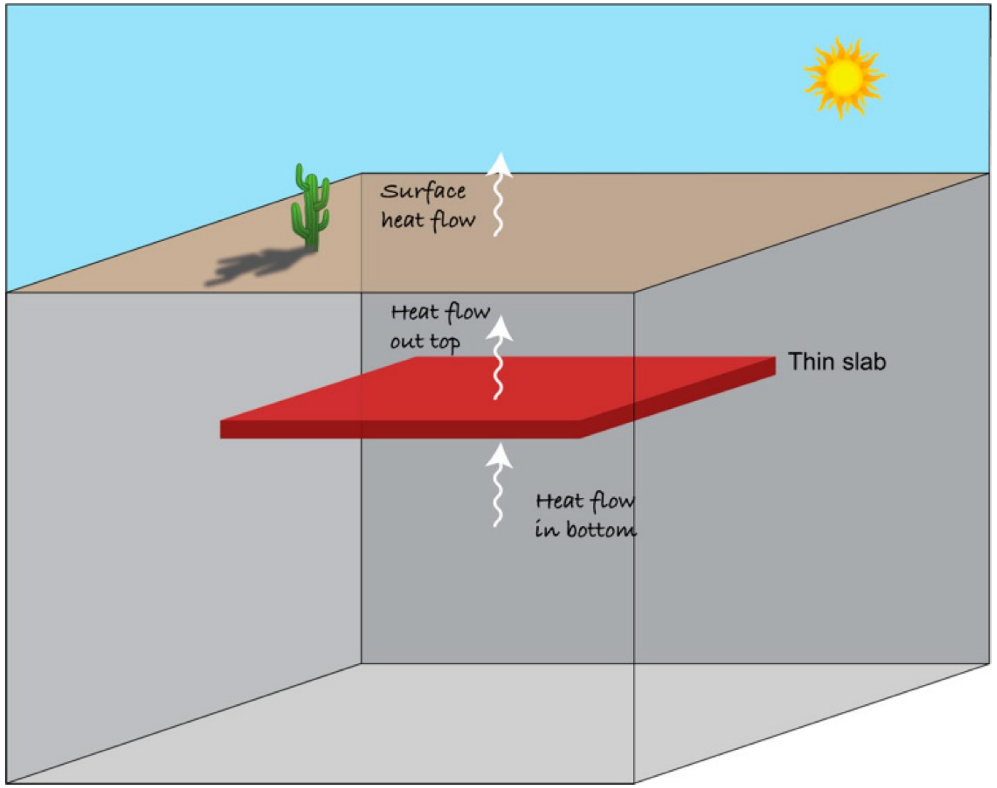
where: T_m Minimum rock temperature (°C)
T_o Initial rock temperature (°C)
T_{rech} Recharge water temperature (°C)

$$d/2 = 3\sqrt{\alpha \times t_0} \qquad \textbf{(2)}$$

where: α is the thermal diffusivity
t_0 is the production period.

3. Static Methods for Resource Estimation (Magmatic Heat Budget)

- Estimate the volume of the magma chambers to appraise their age of emplacement.
- To calculate the amount of geothermal energy remaining in the intrusion and adjacent country rock using conventional calculations of conductive heat loss.



Advantages

✓ Preliminary assessment, can be used in the very early phase.

Disadvantages:

❖ Gives a broad overview of the accessible resource base with little quantitative insight.

3. Static Methods for Resource Estimation (Magmatic Heat Budget)

- The energy reserves could be calculated if the temperature distribution around the magma body is known and by using the *equation below*. Case study can be found in Noguchi, T. (1970): *An evaluation of geothermal energy in Japan* [**REPORT**].

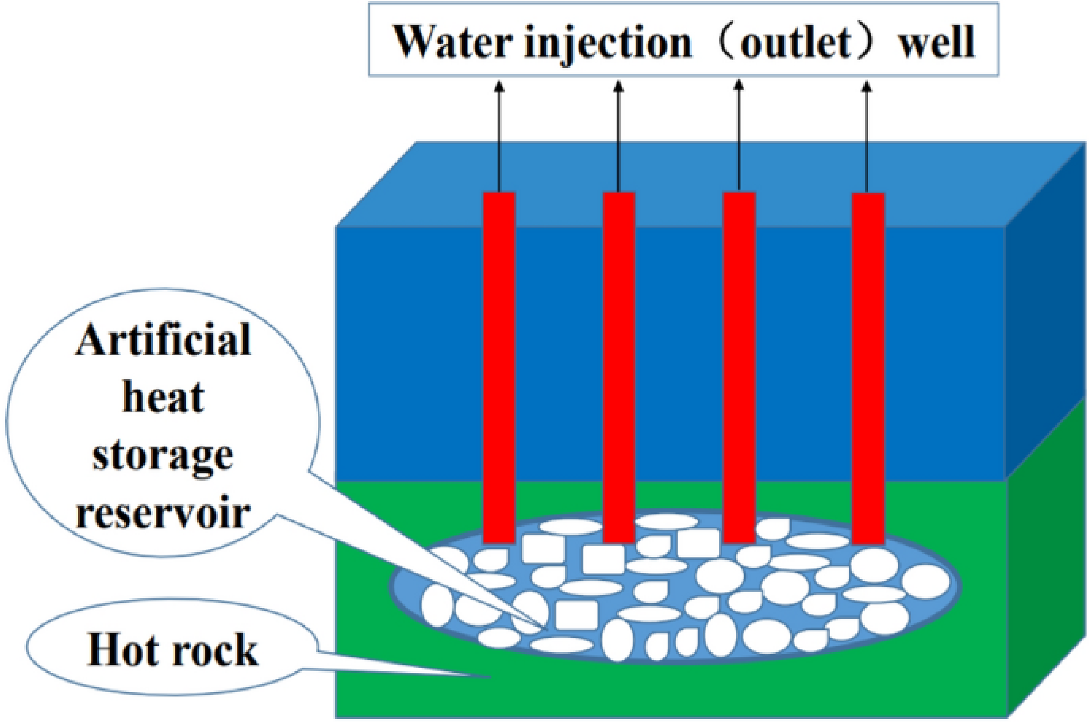
$$E = \frac{d \times c_v \times (T - T_f) \times R_f \times \eta_{conv}}{L\,F}$$

where:

E MW$_e$ reserves per km^2 at a given distance from the center of the caldera
d The depth down to which the energy reserves are to be estimated
c_v Volumetric specific heat of the reservoir
T Calculated average temperature (in absolute unit) between the ground surface and depth at a given distance from the center of the caldera
T_f Average annual ambient temperature
F Power plant capacity factor
R_f Recover factor (defined as the fraction of thermal energy in-place)
η_{conv} Conversion efficiency
L Power plant life.

3. Static Methods for Resource Estimation (Total Well Flow)

- In the absence of knowledge, the total flow of the drilled wells has been taken as an indication of the field capacity. (sometimes incorrect)
- The reservoir reserves are the amount of fluid or steam in the resource.
- As **disadvantage**: the discharged flow from wells depends on the drilling technique and well design and neglecting the reservoir complexity and properties.



Gao & Shi 2021

3. Static Methods for Resource Estimation (Stored heat [Volumetric])

- This is the oldest method, and its theoretical basis is simple:
  - ➢ Use the isotherms to estimate the total amount of heat contained within the reservoir,
  - ➢ Then the fraction that can be recovered is estimated.
- This method has significant weaknesses:
  - ➢ There is little experimental evidence to validate the recovery factor used.
  - ➢ It is also very easy to include within the rock volume, regions of low permeability that in practice will not contribute to the producible reserves.
  - ➢ For these reasons stored heat often leads to overestimates of field capacity, sometimes by large multiples.

3. Static Methods for Resource Estimation (Stored heat [Volumetric])

- The thermal energy ***q*** stored in the reservoir (***J***) can be calculated by dividing the reservoir into ***n*** different regions of volume V_i and temperature T_i, $i = 1, 2, .., n$; using the equation:

$$q = \sum_{i=1}^{n} \rho_i c_i V_i \left(T_i - T_f\right)$$

where:

$\rho_i c_i$ Volumetric heat capacity of a saturated rock, J/°C m^3
V_i Volume of i^{th} region of n numbers of lithology. The product of area A and thickness h of the reservoir ($V = A \times h$), m^3
T_i Initial temperature of i^{th} lithology, °C and
T_f Cut-off or final abandoned reservoir temperature, °C

3. Static Methods for Resource Estimation (Stored heat [Volumetric])

- For a given volume of the reservoir, the total **mass** of the fluid (kg), denoted by $\boldsymbol{m_r}$; can be calculated using:

$$m_r = \varphi(\rho_l S_l + \rho_v S_v)$$

where:

φ Rock porosity
ρ_l, ρ_v Density of water and steam
S_l, S_v Saturation of liquid and vapour, $S_l + S_V = 1.$

3. Static Methods for Resource Estimation (Stored heat [Volumetric])

The evaluation of heat stored in a given volumes, following Sarmiento and Steingrimsson (2007):

$$q = Ah \times \left\{\left[\rho_r c_r (1-\varphi)\left(T_i - T_f\right)\right] + \left[\rho_{wi}\varphi S_w\left(u_{wi} - u_{wf}\right)\right] + \left[\rho_{si}\varphi(1-S_w)(u_{si} - u_{wi})\right]\right\}$$

q stored heat (thermal energy), J	***c_r rock grain specific heat, J/kg °C***
A reservoir area, m^2	***ρ_r rock density, kg/m^3***
h reservoir thickness, m	***φ rock porosity, dimensionless***
T_i initial reservoir temperature, °C	***S_w aqueous phase saturation, dimensionless***
T_f base temperature, °C	***u_{wi} internal energy of liquid water, J/kg***
u_{si} internal energy of steam, J/kg	***u_{wf} internal energy of liquid water at base temperature, J/kg***
ρ_{si} density of steam, kg/m^3	***ρ_{wi} density of liquid water, kg/m^3***

3. Static Methods for Resource Estimation (Mass-in-Place)

- The total mass is another volumetric method that uses the total Mass-in-Place (MIP) instead of stored-heat in-place (Parini and Riedel, 2000), and described as:

  $$MIP = V\varphi\rho(T_i)$$

  where: ***V***: Volume of the reservoir, m^3, $\boldsymbol{\varphi}$: Average total porosity, $\boldsymbol{\rho(T_i)}$: Fluid density (kg/m^3) at the average reservoir temperature T_i(°C).

- The MIP method calculates the total available and recoverable mass of a geothermal resource by implementing volumetric method calculation.

- This method is prone to underestimating the true potential of the resource.

- Numerical example can be found in Ciriaco, A. E., Zarrouk, S. J., & Zakeri, G. (2020).

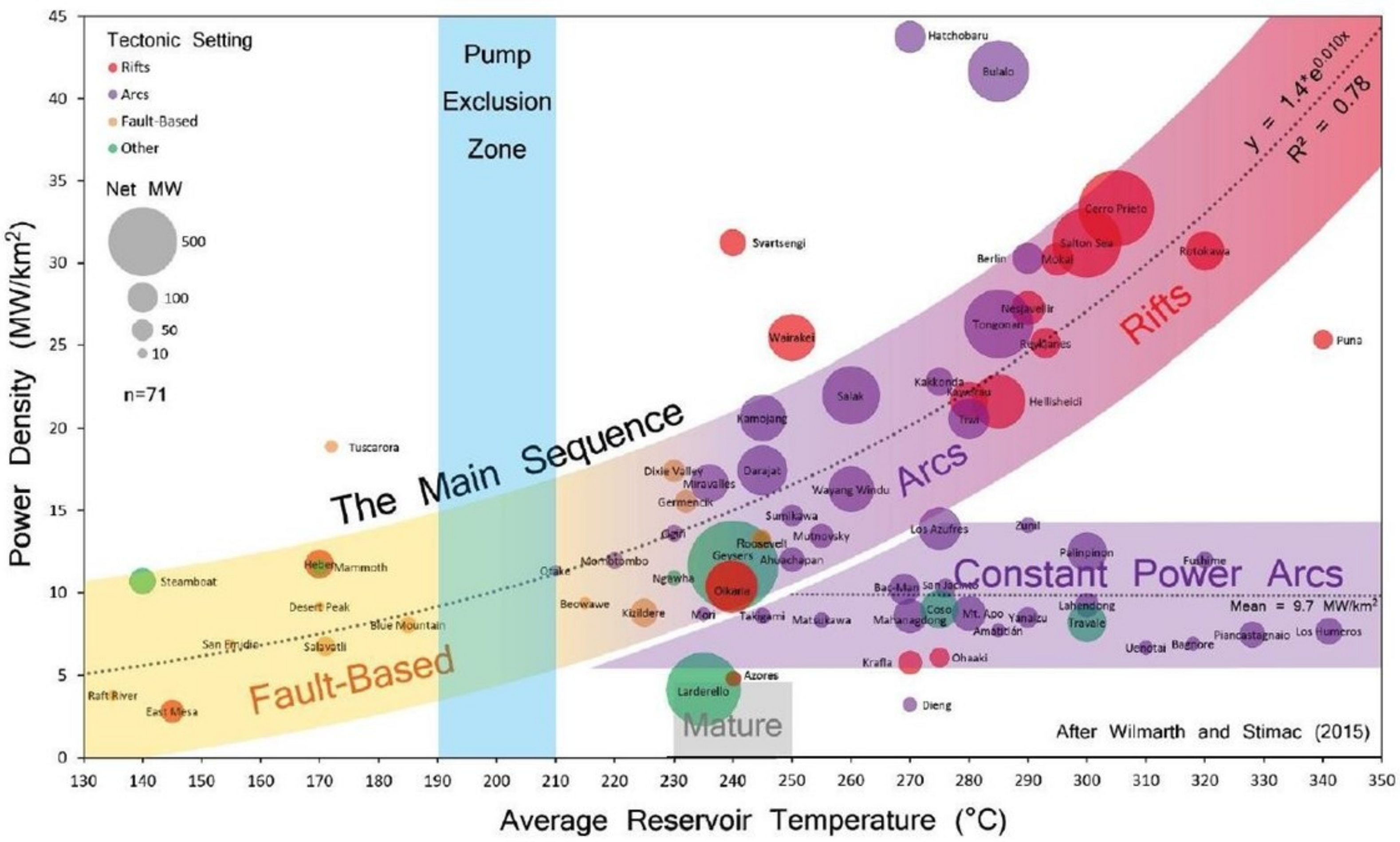
3. Static Methods for Resource Estimation (Power Density)

- It is based on the evaluation of reservoir areal extension and average temperature and the use of average power potential per unit reservoir area as function of temperature derived from statistics of geothermal reservoirs presently exploited all over the World.
- It is a highly empirical method based on data obtained from fields having quite different geological and geodynamic settings, different characteristics and subject to different exploitation and reinjection strategies.
- The power density method **assumes** that power capacity per unit area MW_e/km^2 of the productive resource is a function of reservoir temperature T_i:

$$\frac{MW_e}{km^2} = \left(\frac{T}{86.9}\right)^2$$

- Case study can be found in Beate, B., & Urquizo, M. (2015, April).

3. Static Methods for Resource Estimation (Power Density)

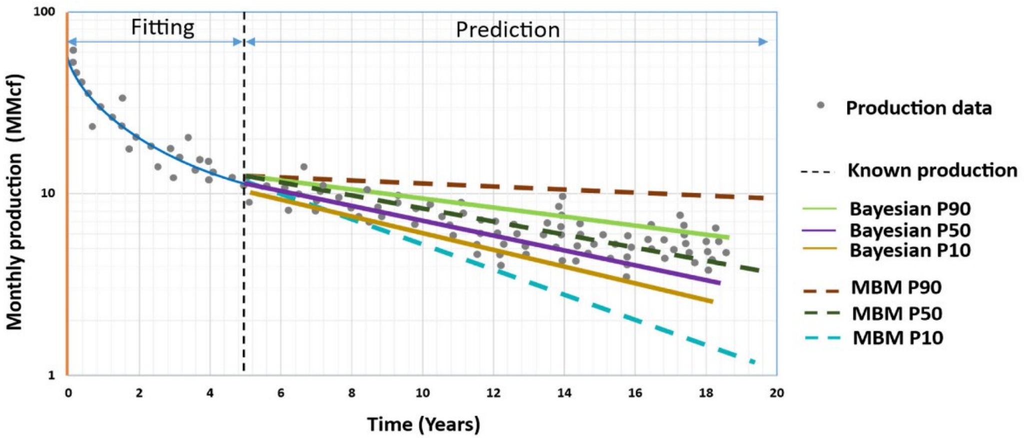


After Wilmarth and Stimac (2015)

- Power density vs. reservoir temperature categorized by geological setting.
- The pump exclusion zone refers to resources where temperature is too low for economic flash production for direct steam utilization, but it is too hot for pumped production.
- Some wells within fields have flash production supporting binary generation in this gap.

4. Dynamic Methods for Resource Estimation (Decline Analysis)

- This method fits the history of flow from a well or group of wells to one of a family of standard curves.
- Ideally the flow is a constant wellhead pressure, but usually pressure varies, and flow is adjusted to compensate.
- The standard curve is then used to predict future flow and hence total cumulative production.
- It is adjusted from petroleum practice and is applicable to a group of wells that are not subject to any change in management or change in number.
- The method was previously used at The Geysers as means of resource assessment, and apparently is still used.



4. Dynamic Methods for Resource Estimation (Decline Analysis)

- A limitation of the method is that it applies to a constant number of wells. If more wells are added *the decline rate increases*.
- It is also the case that the reserves proven by this method are the reserves of the entire drainage area of the wells.
- It is also used more frequently and used today like the Lumped-parameter dynamic method, as a means of projecting well flow for a few years, in order to monitor rundown and predict makeup drilling requirements. ***[In other words: to monitor the efficiency of the well]***

4. Dynamic Methods for Resource Estimation (Decline Analysis)

- The main concept of the method is that the production data declines with time.
- This decline in production is normally assumed to follow harmonic or exponential decline trends.
- the equations used for analyzing decline flowrate are generally based on the empirical assumption that the decline rate *dW/dt* is proportional to the production rate *W* raised to some empirically derived exponent *b*:

$$\left(\frac{1}{W}\right)\frac{dW}{dt} = -D \times W^{b}$$

  where $b = 0$ (exponential) or $b = 1$ (harmonic) and D is the decline rate.

- Case study can be found in Orizonte, R. G., Amistoso, A. E., & Malate, R. C. (2005).

4. Dynamic Methods for Resource Estimation (Numerical Simulation)

- The purpose of geothermal modelling is:
  - ➢ Firstly, to obtain information on the conditions in a geothermal system as well as on the nature and properties of the system. This leads to proper understanding of its nature and successful development of the resource.
  - ➢ Secondly, the purpose of modelling is to predict the response of the reservoir to future production and estimate the production potential of the system and to estimate the outcome of different management actions.
- Diverse information needs to be continuously gathered throughout the exploration and exploitation history of a geothermal reservoir.
- Information on reservoir properties is obtained by disturbing the state of the reservoir (fluid-flow, pressure) and by observing the resulting response, and is done through well and reservoir testing and data collection.

5. Assessing the uncertainty in Geothermal Resources

- Due to the location of natural resources in the subsurface, there is an appreciable amount of risk and uncertainty associated with exploration for such resources whether they are petroleum, mineral, groundwater, or geothermal.
- Assessment and quantification of exploration risk and uncertainty can inform important aspects of a resource exploration program such as: selection of drilling targets, estimation of resource volume, decision-making for allocation of limited exploration capital, as well as communication with potential investors and insurers.
- There is a strong need in the geothermal sector to reduce risk and uncertainty, especially in the exploration stage. Improving our ability to quantify and characterize geothermal resource risk and uncertainty would, ideally, lead to more successful projects. Risk and uncertainty analysis is a large field of study.

5. Assessing the uncertainty in Geothermal Resources

- The biggest risk in developing geothermal energy is resources overestimation, especially in an exploration phase when a deep well is not constructed yet.
- The greatest effort at the beginning of a geothermal project is always focused to understand the resource in conjunction with adequate capital allocation. The result of resource assessment can determine the sustainability of a geothermal project. Therefore, resource assessment must be conducted using a reliable method and must be carried out whenever more data enters.
- One of the challenges of the geosciences is the inherent problem of incomplete knowledge of the geologic and engineering properties (geologic geometries, temperature distribution, mechanical moduli, permeability, etc.) of the subsurface.

5. Assessing the uncertainty in Geothermal Resources

- The accuracy of the methods used in geothermal reserves estimation depends on the type, amount, and quality of geoscientific and engineering data, which are also dependent on the stage of development and maturity of a given field.
- Generally, the accuracy increases as the field is drilled with more wells and more production data become available.
- Uncertainties have commonly been ascribed to one of two categories: epistemic uncertainty and aleatory variability (Paté-Cornell, 1996). This distinction was introduced into the geoscience parlance with probabilistic seismic hazard analysis (Budnitz et al., 1997).
- Epistemic uncertainty is a result of lack of knowledge. With additional observations epistemic uncertainties can be reduced and a more accurate value ascertained. For example, the epistemic uncertainty of the geometry of a fault system can be reduced by drilling a well that intersects the fault in the subsurface.

Assessing the uncertainty in geothermal projects:

- Aleatory variability, conversely, is unpredictability due to inherent randomness. Aleatory variability is also a function of scale, with variability ranging from the size of an individual grain to field-scale, influencing unpredictability in the geologic aspects of a geothermal site. For example, the primary permeability of a stratigraphic unit may be approximated as a single value at the basin-scale, but at the well-bore scale it may be highly variable due to local stratification, grain-size, cementation, or fracture characteristics.
- Understanding these different types of geoscience uncertainty is important to guide where and how to expend effort to reduce uncertainty associated with an exploration project. Importantly, for the case of aleatory variability, the collection of more data may not always further reduce uncertainty.
- Case study can be found in Miranda, M. M., Raymond, J., & Dezayes, C. (2020).

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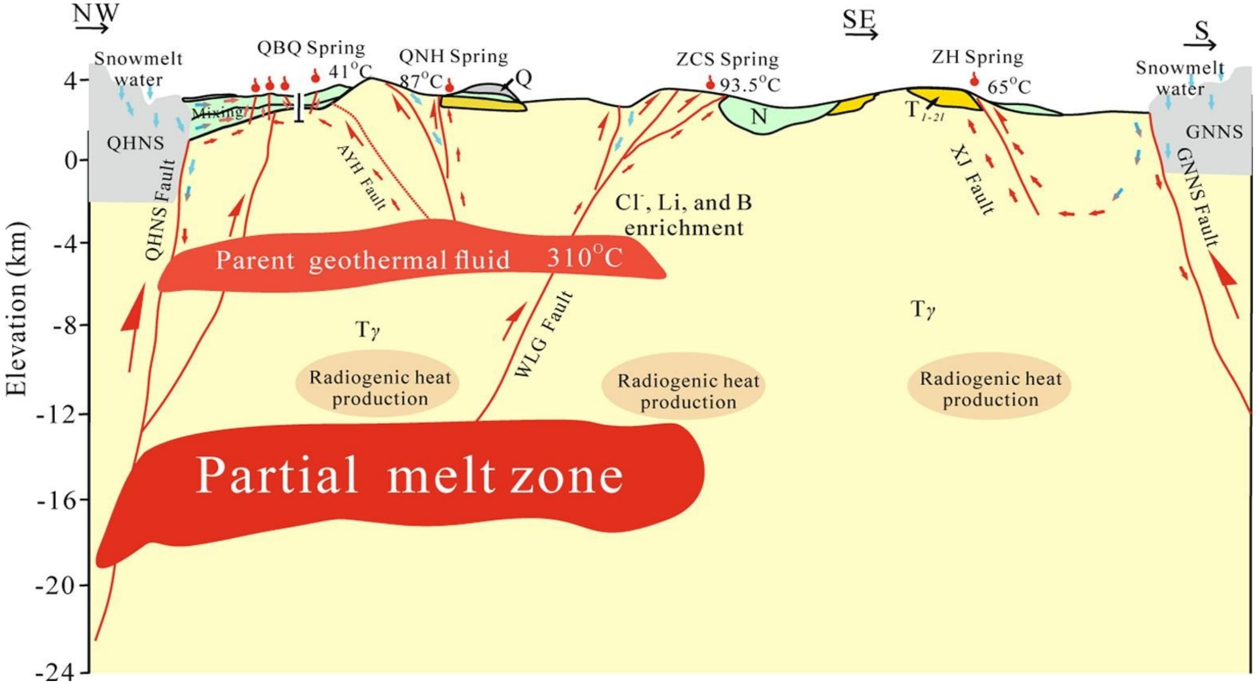
Faculty of Engineering
Cairo University

Geothermal Resources and Reservoir Engineering

Lecture 3 : Geothermal Fluid Production

1. Geochemistry of Geothermal Fluids

- Geothermal geochemistry is used to:
    - identify the origin of geothermal fluids and,
    - quantify the processes that govern their compositions and the associated chemical and mineralogical transformations of the rocks with which the fluids interact.
- Geothermal chemistry constitutes an important tool for the exploration of geothermal resources and in assessing the production characteristics of drilled geothermal reservoirs and their response to production.

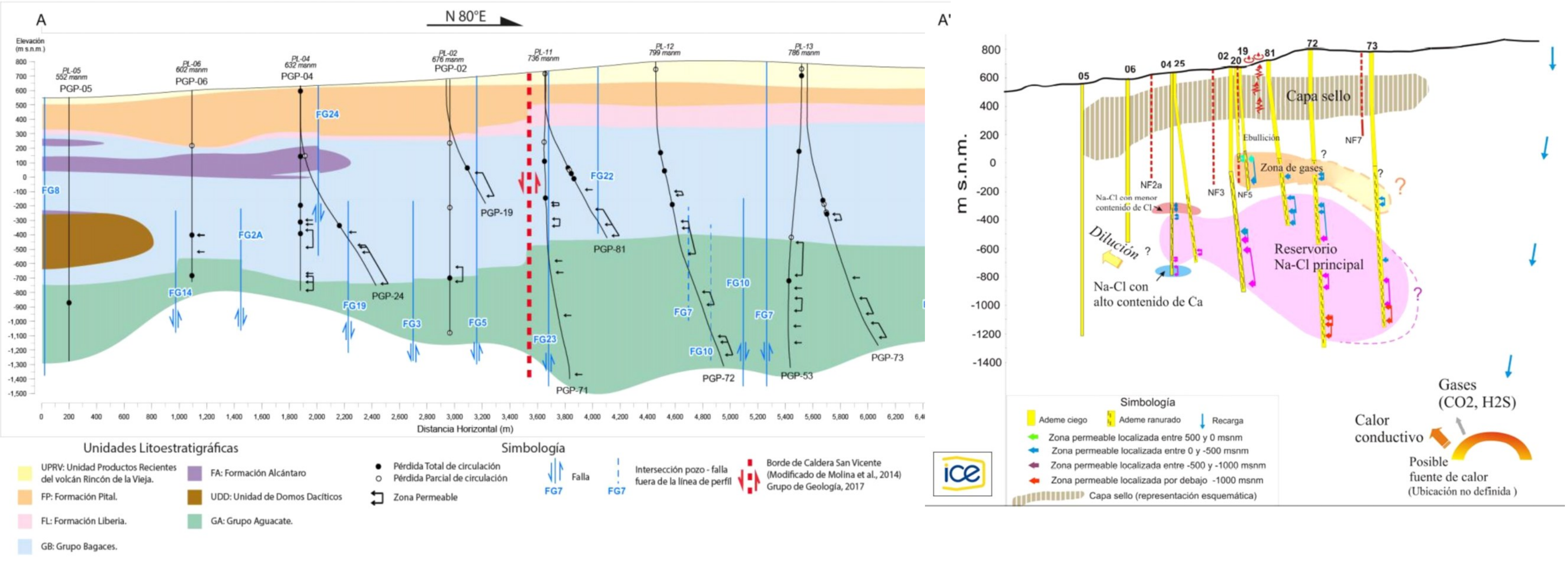


Pan et al. 2021: Magmatic origin of geothermal fluids, Tibetan Plateau

1. Geochemistry of Geothermal Fluids

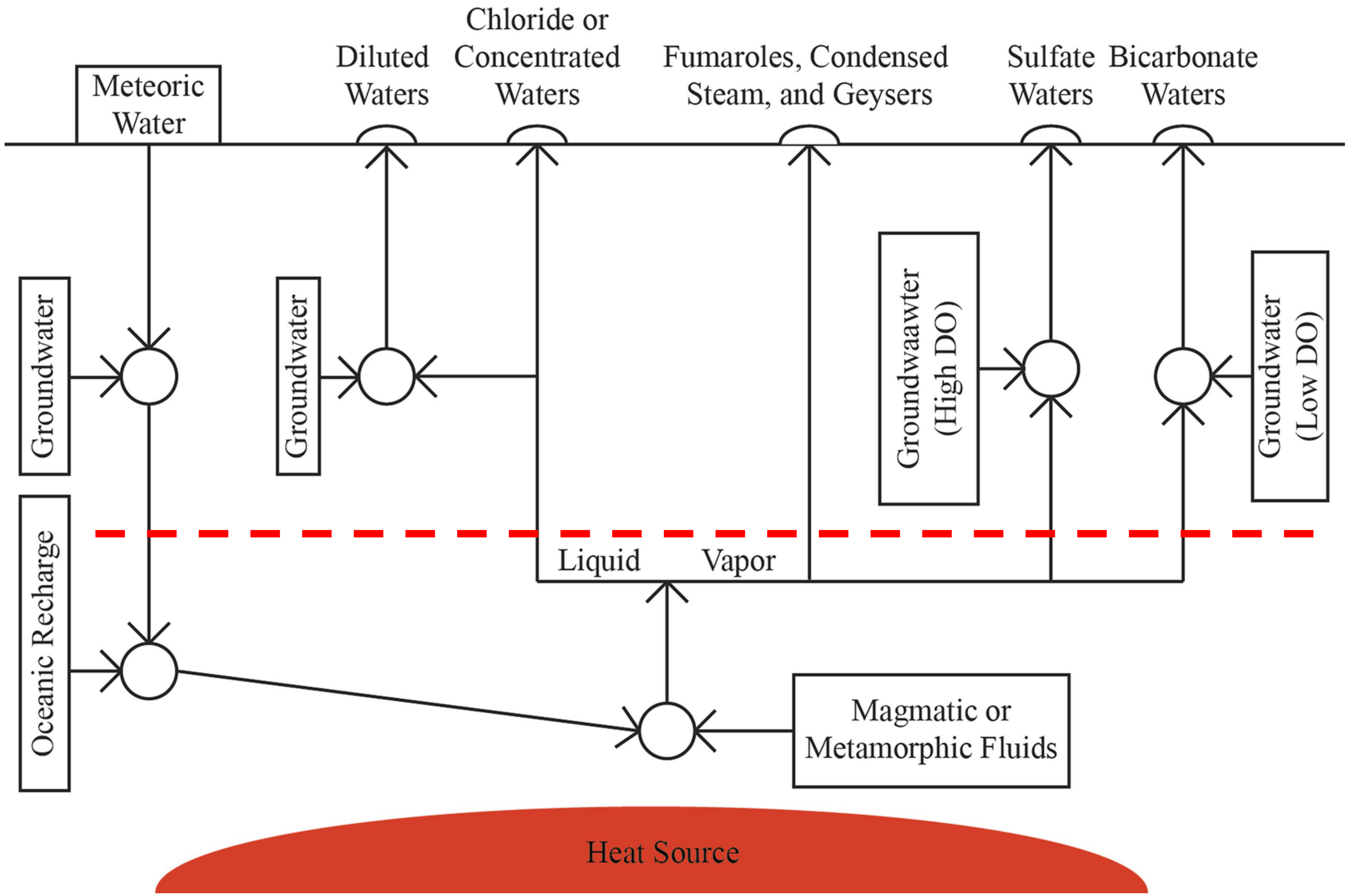
- Understanding chemical processes within active geothermal systems is a composition of several aspects: **thermodynamic**, **Structure Geology**, and **numerical modeling of fluid flow**.
- The geochemist responsibilities are identifying whether the resource is vapor- or liquid dominated, estimating the minimum temperature of the geofluid, determine the chemical properties of the fluid both in reservoir and in the produced state, and characterize the recharge water, including its nature and resources.
- Geothermal fluids are broken down into **primary** and **secondary** fluids.

1. Geochemistry of Geothermal Fluids



Solis & Kastl 2019: Verification of ....geothermal exploration in Central America

2. Primary Vs. Secondary



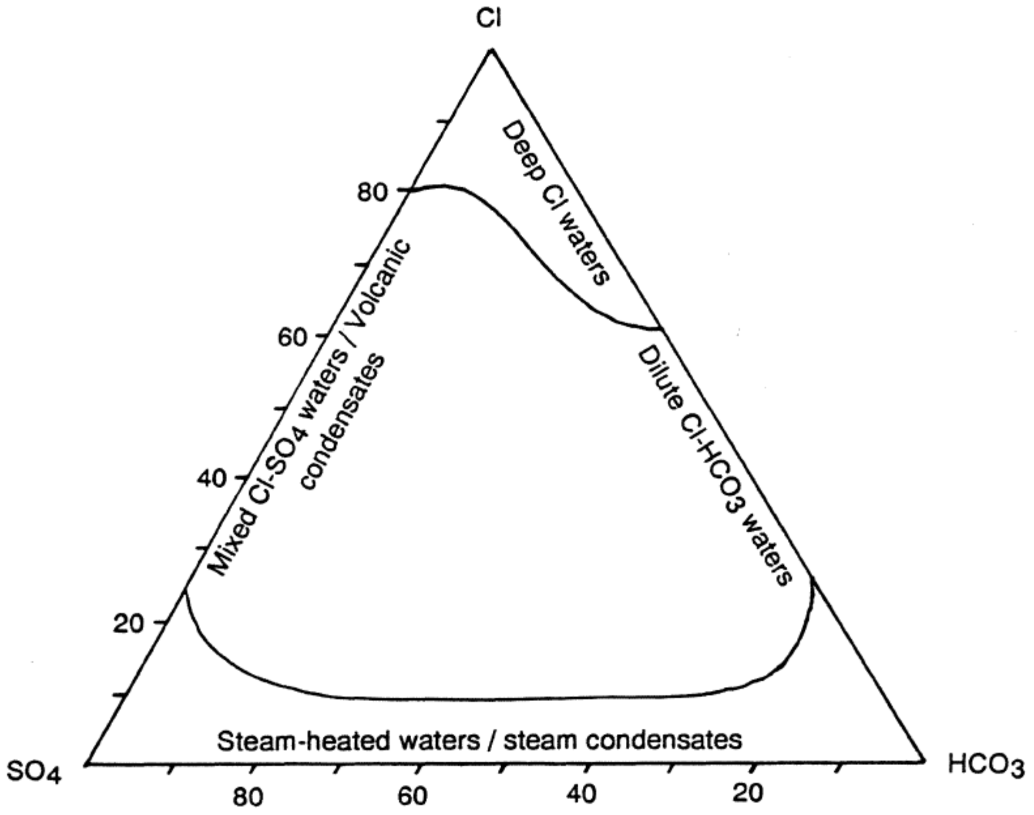
Hawkins & Tester 2018: Geothermal Systems

Schematic of fluid circulation through a geothermal system. Several potential sources, including <u>meteoric</u>, <u>groundwater</u>, <u>oceanic</u>, and <u>magmatic/metamorphic form primary fluids</u> near a heat source.

As ***primary fluids*** *rise buoyantly towards Earth's surface, they form* ***secondary fluids*** *as they interact with rock minerals, undergo phase changes, and <u>mix with near-surface waters</u>*

2. Geochemistry of Geothermal Fluids: Primary

- Geothermal fluids are considered "**primary**" fluids when they are **at**, or **near**, their heat source.
- They may be a mixture of two or more fluid components such as **meteoric** and **seawater** and magmatic **volatiles**.
- The main types of primary fluids are **Na-Cl waters**, **acid-sulfate** waters and **high salinity brines**.
- When primary fluids rise towards the surface, they can undergo fluid phase separation and fluid mixing to form secondary geothermal fluids.



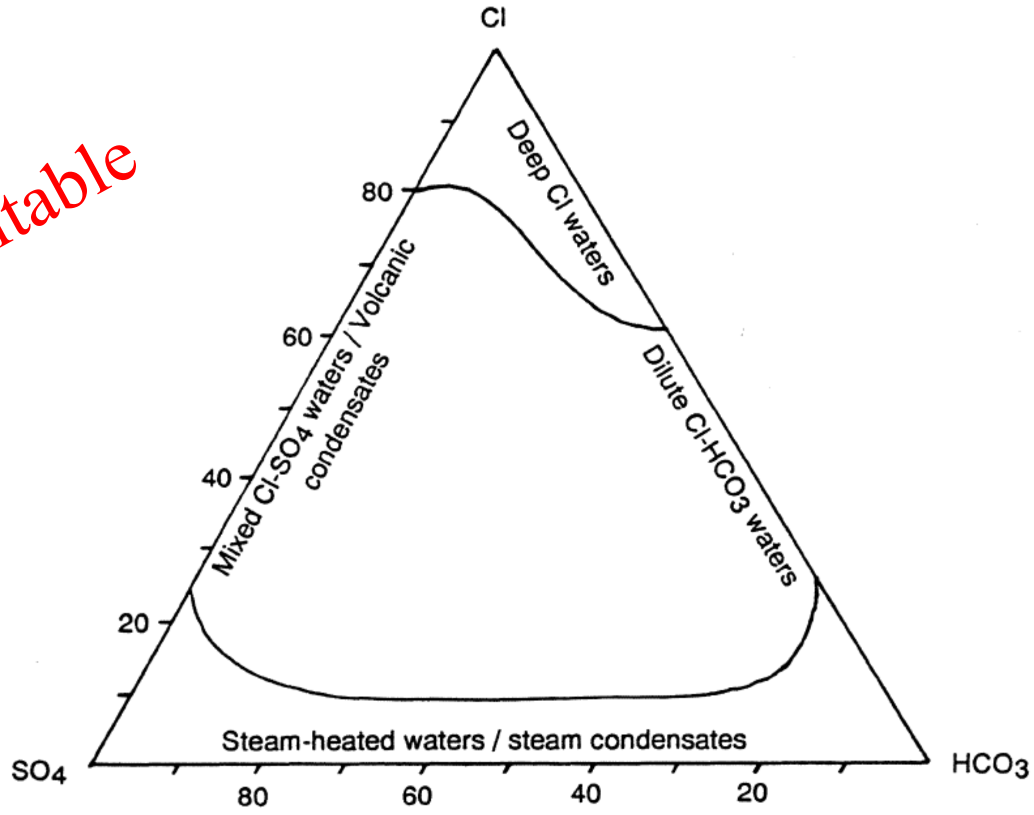
Ternary plot used to classify the geothermal fluids

Nicholson 1993: Geothermal fluids

2. Geochemistry of Geothermal Fluids: Primary

- Geothermal fluids are considered "**primary**" fluids when they are **at**, or **near**, their heat source.
- They may be a mixture of two or more fluid com such as **meteoric** and **seawater** and mag **tles**.
- The main types of primary f **Na-Cl waters**, **acid-sulfate** waters and **ity brines**.
- When primar se towards the surface, they can undergo fluid hase separation and fluid mixing to form secondary geothermal fluids.

Mixing with secondary fluids is inevitable



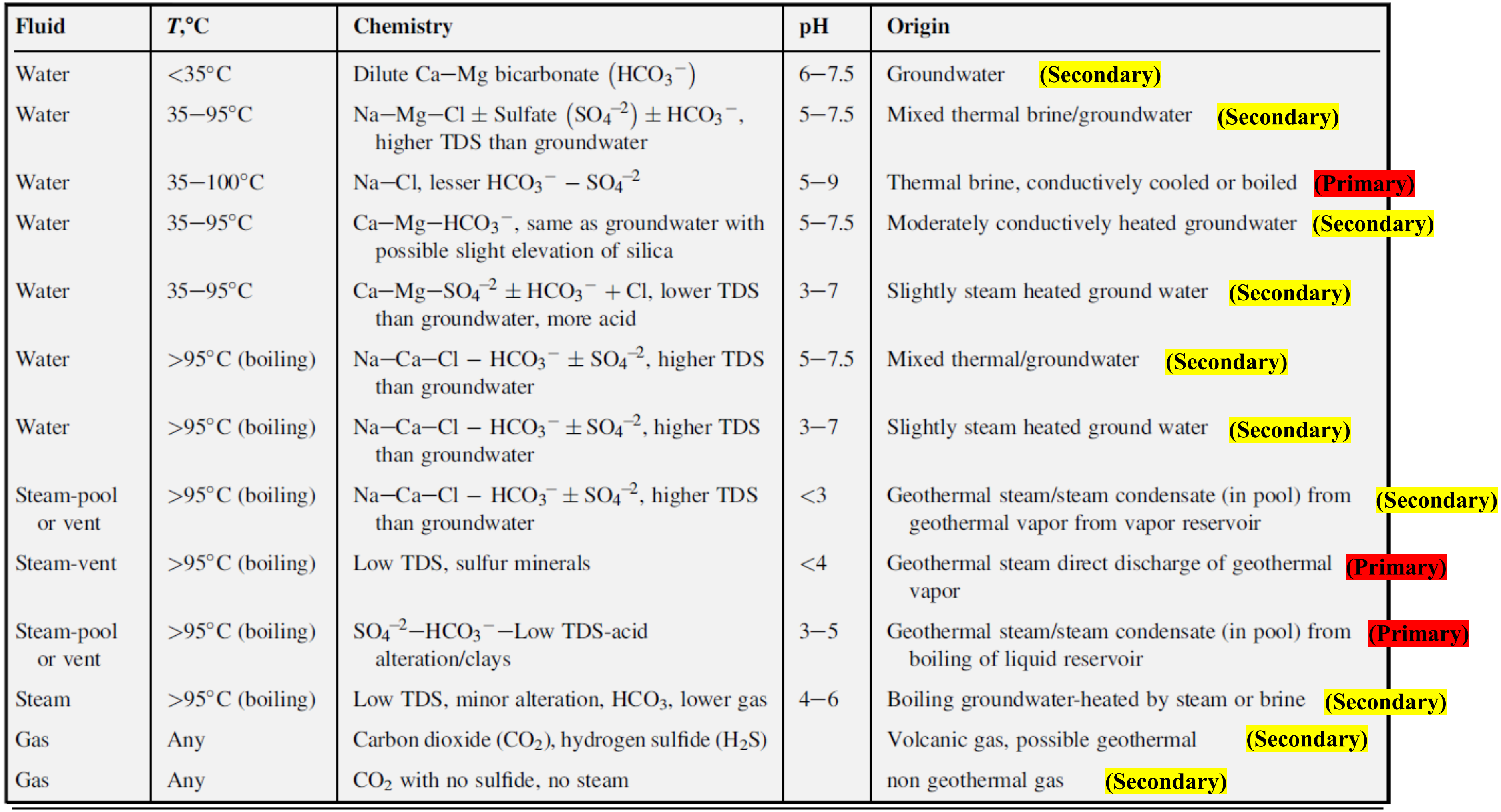
Ternary plot used to classify the geothermal fluids

Nicholson 1993: Geothermal fluids

2. Geochemistry of Geothermal Fluids: Secondary

- The most important processes that lead to the formation of secondary geothermal fluids are:
  1) Depressurization boiling to yield boiled water and a steam phase with gas.
  2) Phase separation of saline fluids into a hypersaline brine and a more dilute vapor.
  3) Vapor condensation in shallow ground water or surface water to produce acid-sulfate, carbon-dioxide or sodium bicarbonate waters.
  4) Mixing of CO_2 gas from a deep source with thermal ground water.
  5) Mixing of geothermal fluids with shallower and cooler ground water.
- The main types of secondary fluids are Steam-heated acid sulfate waters, Carbon-dioxide waters, and Mixed waters.

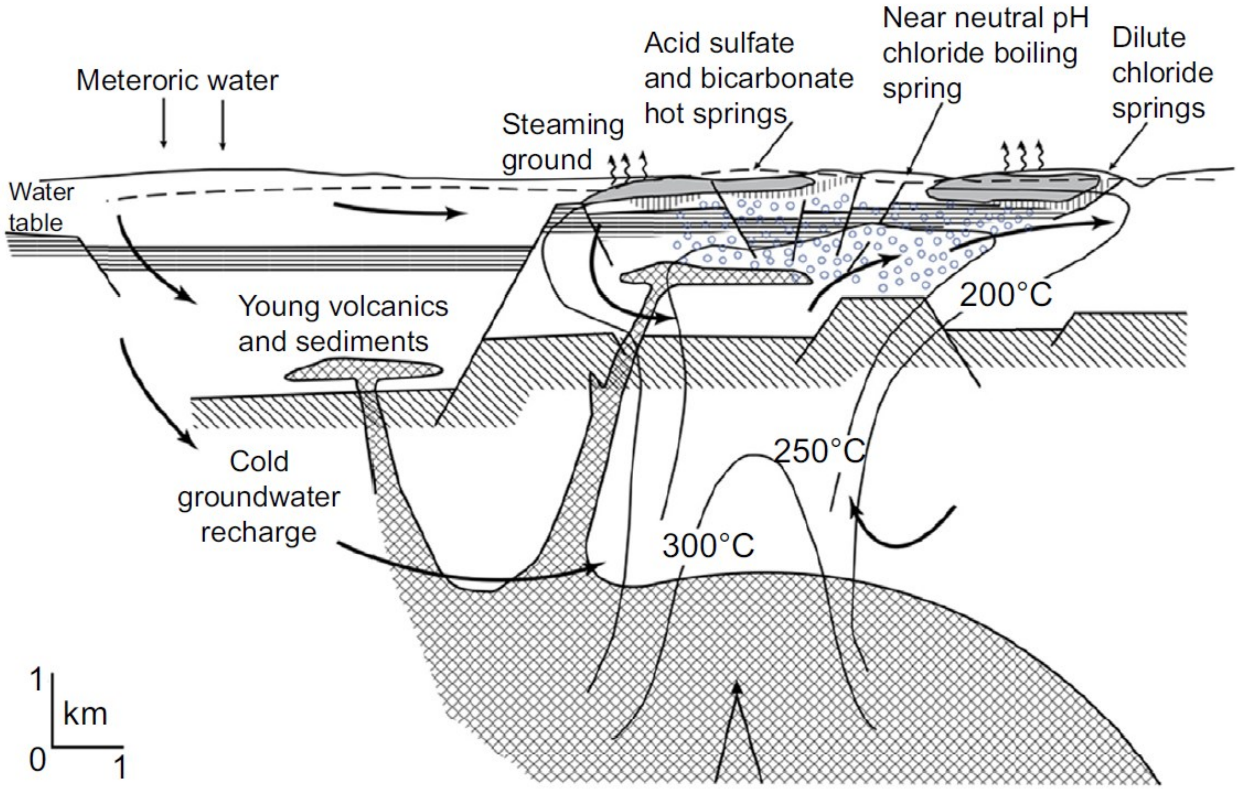
2. Primary vs. Secondary



Fluid	T,°C	Chemistry	pH	Origin
Water	<35°C	Dilute Ca–Mg bicarbonate (HCO_3^-)	6–7.5	Groundwater **(Secondary)**
Water	35–95°C	Na–Mg–Cl ± Sulfate (SO_4^{-2}) ± HCO_3^-, higher TDS than groundwater	5–7.5	Mixed thermal brine/groundwater **(Secondary)**
Water	35–100°C	Na–Cl, lesser HCO_3^- – SO_4^{-2}	5–9	Thermal brine, conductively cooled or boiled **(Primary)**
Water	35–95°C	Ca–Mg–HCO_3^-, same as groundwater with possible slight elevation of silica	5–7.5	Moderately conductively heated groundwater **(Secondary)**
Water	35–95°C	Ca–Mg–SO_4^{-2} ± HCO_3^- + Cl, lower TDS than groundwater, more acid	3–7	Slightly steam heated ground water **(Secondary)**
Water	>95°C (boiling)	Na–Ca–Cl – HCO_3^- ± SO_4^{-2}, higher TDS than groundwater	5–7.5	Mixed thermal/groundwater **(Secondary)**
Water	>95°C (boiling)	Na–Ca–Cl – HCO_3^- ± SO_4^{-2}, higher TDS than groundwater	3–7	Slightly steam heated ground water **(Secondary)**
Steam-pool or vent	>95°C (boiling)	Na–Ca–Cl – HCO_3^- ± SO_4^{-2}, higher TDS than groundwater	<3	Geothermal steam/steam condensate (in pool) from geothermal vapor from vapor reservoir **(Secondary)**
Steam-vent	>95°C (boiling)	Low TDS, sulfur minerals	<4	Geothermal steam direct discharge of geothermal vapor **(Primary)**
Steam-pool or vent	>95°C (boiling)	SO_4^{-2}–HCO_3^-–Low TDS-acid alteration/clays	3–5	Geothermal steam/steam condensate (in pool) from boiling of liquid reservoir **(Primary)**
Steam	>95°C (boiling)	Low TDS, minor alteration, HCO_3, lower gas	4–6	Boiling groundwater-heated by steam or brine **(Secondary)**
Gas	Any	Carbon dioxide (CO_2), hydrogen sulfide (H_2S)		Volcanic gas, possible geothermal **(Secondary)**
Gas	Any	CO_2 with no sulfide, no steam		non geothermal gas **(Secondary)**

3. Upflow and Downflow

- Upflow zones represent the highest temperatures at the shallowest depth and typically zones of high permeability, often defined by faults.
- Therefore, such zones can provide good drilling targets, especially for the first well.
- The geochemistry of these zones is sometimes distinguished by boiling and formation of gas-rich steam.
- If the gaseous upflow reaches the surface, acidic fluids are produced when the gas-rich steam interacts with shallow groundwater creating acidic, low- (or no) chloride surface manifestations.

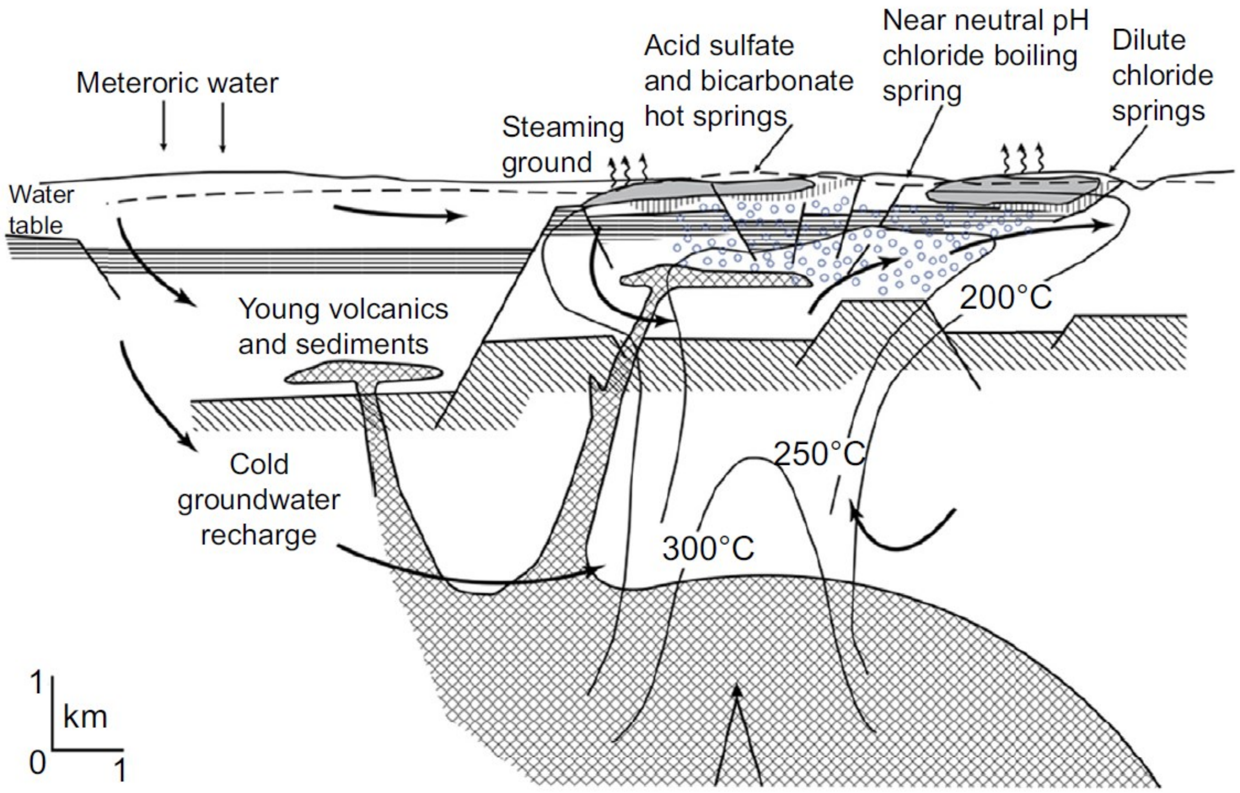


Surface manifestations of a moderate to high temperature liquid-dominated geothermal system

3. Upflow and Downflow

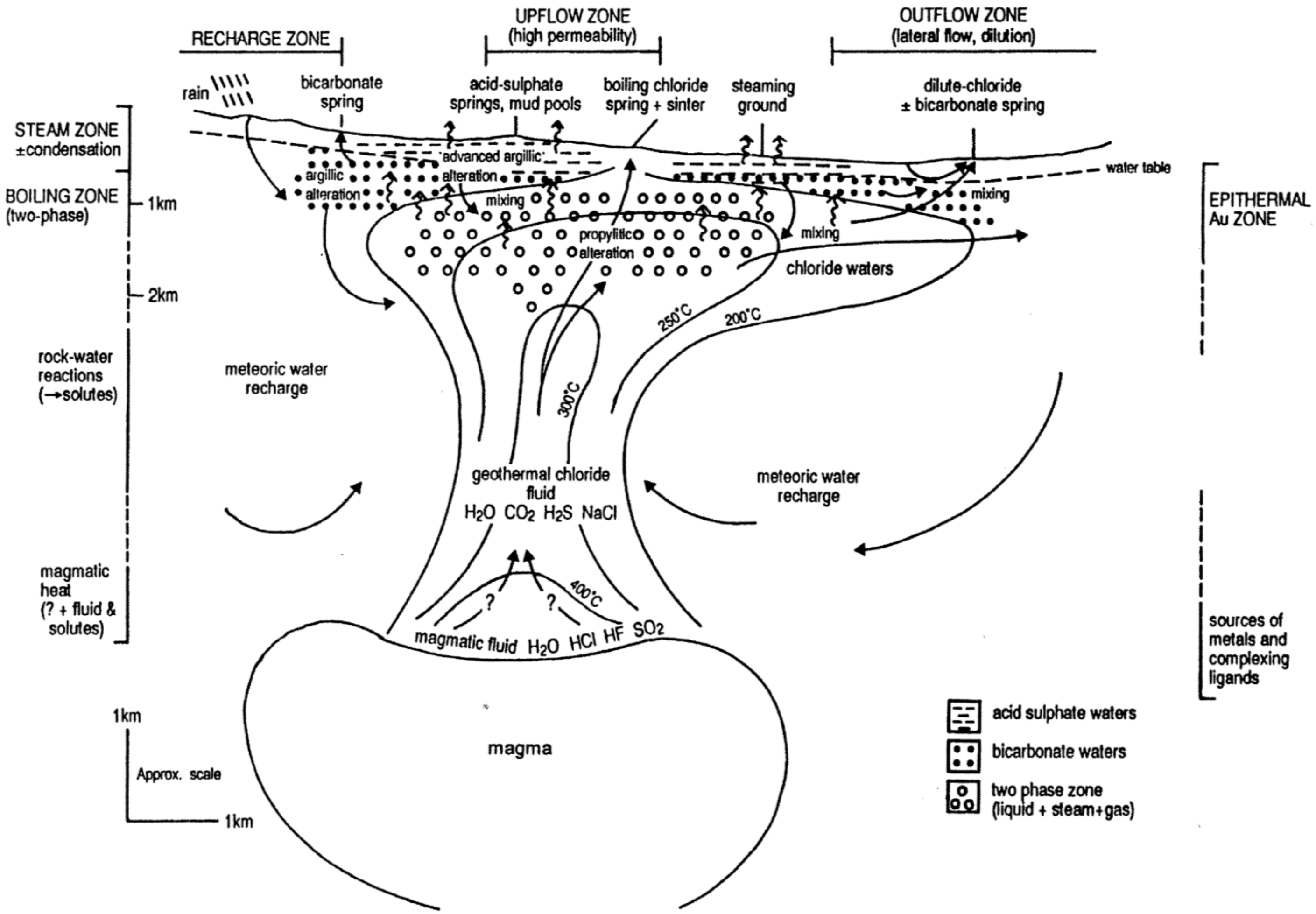
- Hot and warm springs of Downflow zones are distinguished geochemically by either increasing dilution (mixing with low Cl groundwater) or, if cooled conductively, decreasing silica geothermometers.

- Well fluids in outflow zones can also be distinguished by dilution, lower geothermometer temperatures, “immature” water, and lower gas concentrations.

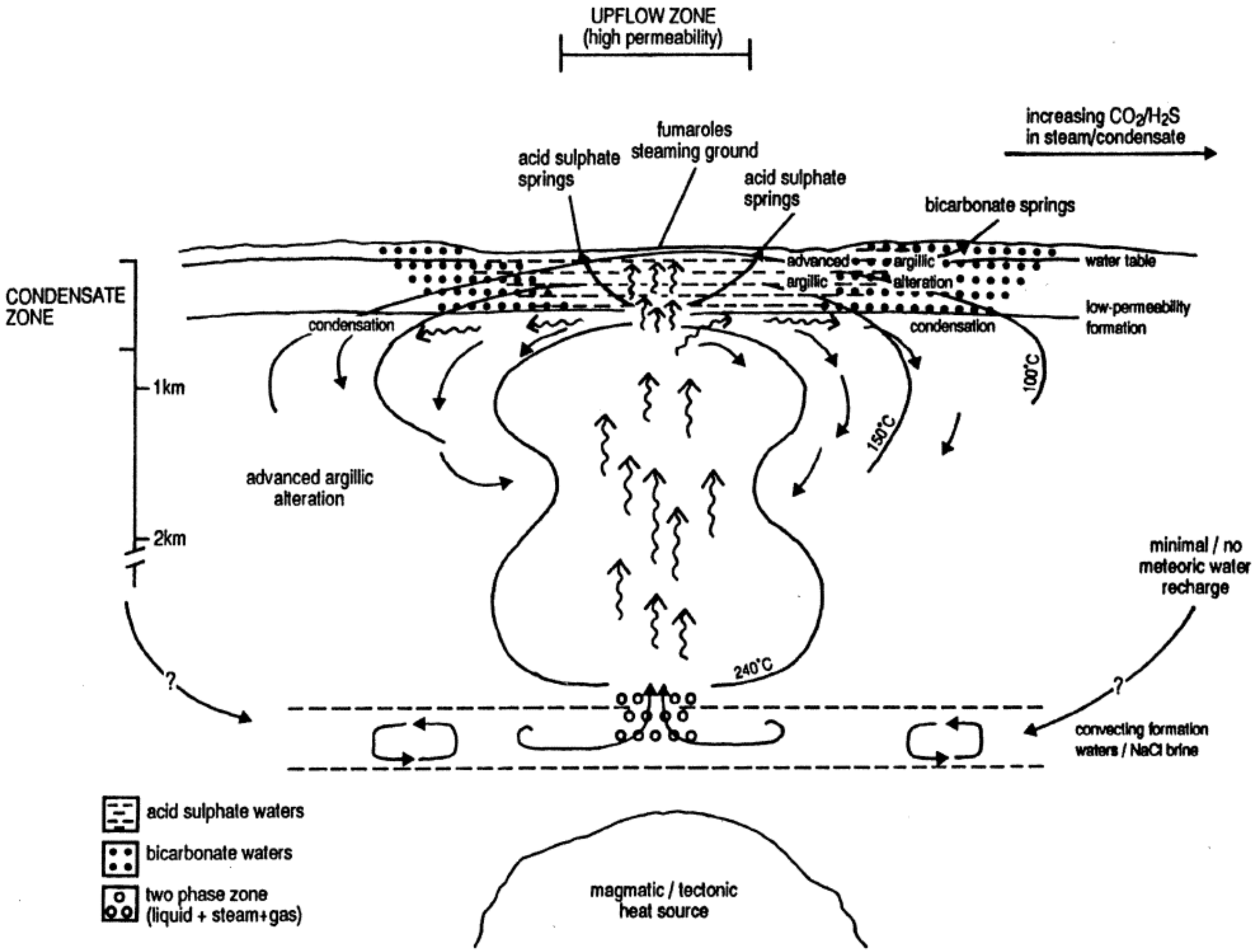


Surface manifestations of a moderate to high temperature liquid-dominated geothermal system

4. Liquid-Dominated geothermal systems



5. Vapor-Dominated geothermal systems

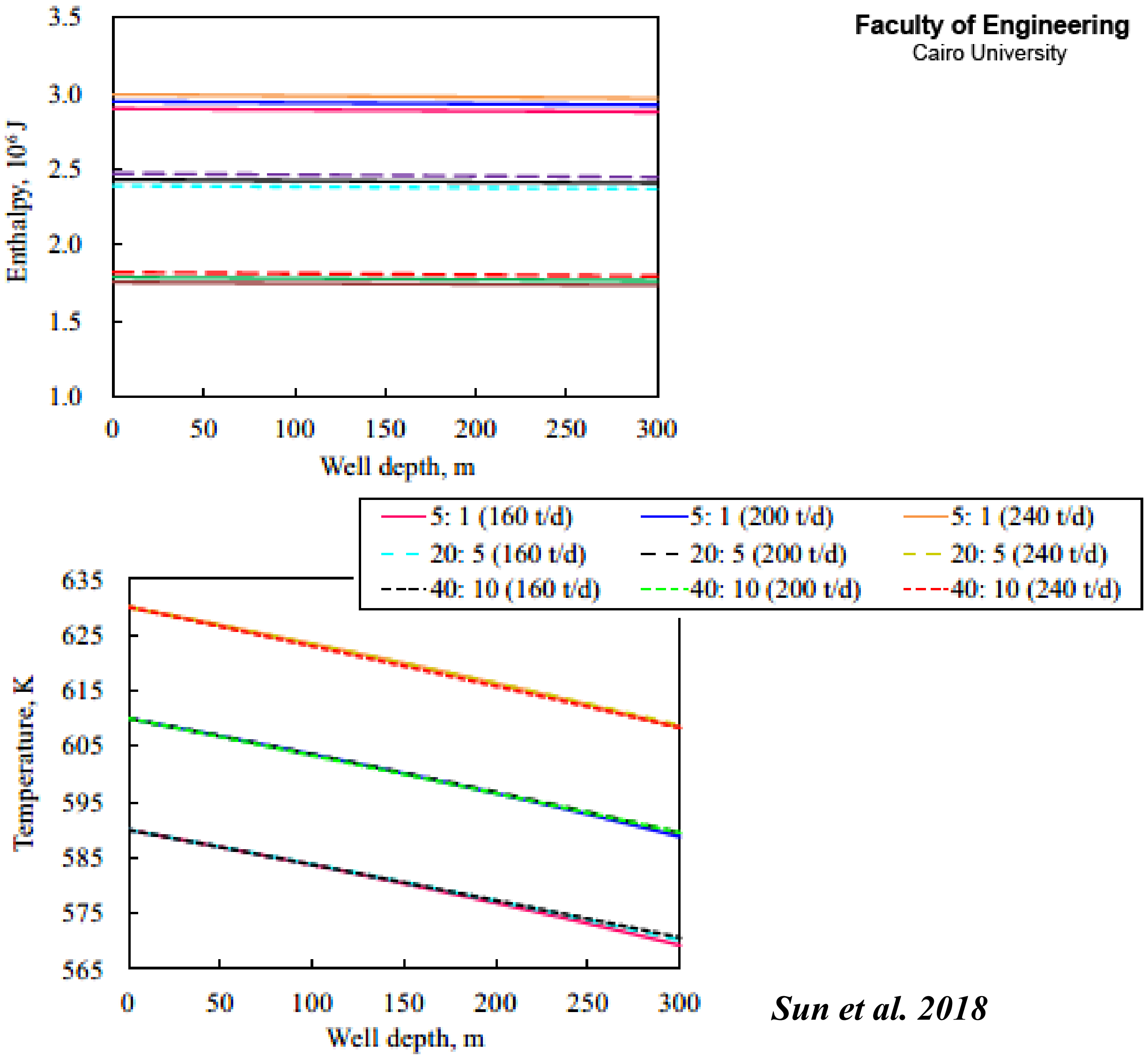


6. Non-Condensable Gases (NCG)

- Non-condensable gases (**NCG**), such as: sulfur oxide, carbon dioxide, methane, ammonia, hydrogen sulfide, hydrogen, are the gaseous emissions that are found dissolved in the geothermal secondary fluids.
- The presence of NCG concentrations in geothermal fluids can strongly affect power plant and gathering system design and operation.
- Thus, a good estimate of resource NCG is **critical** to project design, because NCG partitions strongly into steam when fluid boils (flashes).
- The smaller the steam fraction, the higher is the gas concentration in the steam at a given concentration of NCG in the total fluid. (**They have boiling degrees below the water**)
- In multiple-stage flash plants, the NCG that partitions into the liquid during the initial flash is carried over to partition into vapor phase at the next flash level, affecting the gas loading and sizing of gas extraction for each stage.

6. Non-Condensable Gases (NCG)

- High levels of NCG can affect the temperature and enthalpy of the **steam** and **brine** discharge from the separation station, and the pressure in the turbine after the steam is condensed (flash plant). (*Ratio of CO_2*).
- In addition, high NCG in liquid-dominated reservoirs produces high initial reservoir pressures 2-3 times the water pressure producing high initial flow rates, which can *decrease dramatically if NCG decreases with production*.
- NCG concentrations also affect the pressure distribution and depth of boiling (bubble point) in flowing wells.



Sun et al. 2018

Co-funded by the
Erasmus+ Programme
of the European Union

Faculty of Engineering
Cairo University

Introduction to environmental aspects of geothermal systems

Environmental impact assesment of the geothermal project

- No significant environmental impact from workover activities
- Environmental impacts during construction

BIODIVERSITY

- No significant negative impact on endangered and rare habitat types

GEODIVERSITY

- No impact on on the geodiversity

WATERS

- should not have a negative impact on drinking water sources protected by sanitary protection zones

SOIL

- spatially limited and short-term impact

AIR

- negligible and short-term

MINERALOGICAL / PETROGRAPHIC DIVERSITY

-bedrock geology

-superficial geology

-fossil evidence

PALAEONTOLOGICAL DIVERSITY

-earth history

-evolution

GEODIVERSITY

STRUCTURAL AND TECTONIC DIVERSITY

-continental evolution

-structural history

-regional and local structure

GEOMORPHOLOGICAL AND PEDOLOGICAL DIVERSITY

-geological inheritance

-landform history

-landform and soil patterns

-landscape sensitivity to change

GEODIVERSITY

- No impact on on the geodiversity

GEB
Co-funded by the Erasmus+ Programme of the European Union

Geothermal resources and reservoir engineering

Faculty of Engineering
Cairo University

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Environmental impact assesment of the geothermal project

- No significant environmental impact from workover activities
- Environmental impacts during construction

LANDSCAPE

- there is no visually dominant content

CULTURAL AND HISTORICAL HERITAGE

- no impact on cultural and historical heritage is expected

Zvuk	nivo jačine zvuka (dB)
prag čujnosti	0
šapat	20
govor	50
stan u prometnoj ulic	60
prometna ulica	70
automobil	70
kamion	90
avion	120
prag bola	130

NOISE

- the impact will be short-term and spatially limited (propulsion engines)

WASTE

- The generation of larger amounts of waste is possible in the event of an accident during workover and/or mining

TRANSPORT AND INFRASTRUCTURE

- no negative impacts on infrastructure elements are expected

Environmental impact assesment of the geothermal project

- No significant environmental impact from workover activities
- Environmental impacts during construction

AGRICULTURE

- No significant impact on agricultural and other economic activities

FORESTRY & HUNTING

- negative impacts on forest habitats as well as on wildlife

INDUSTRY

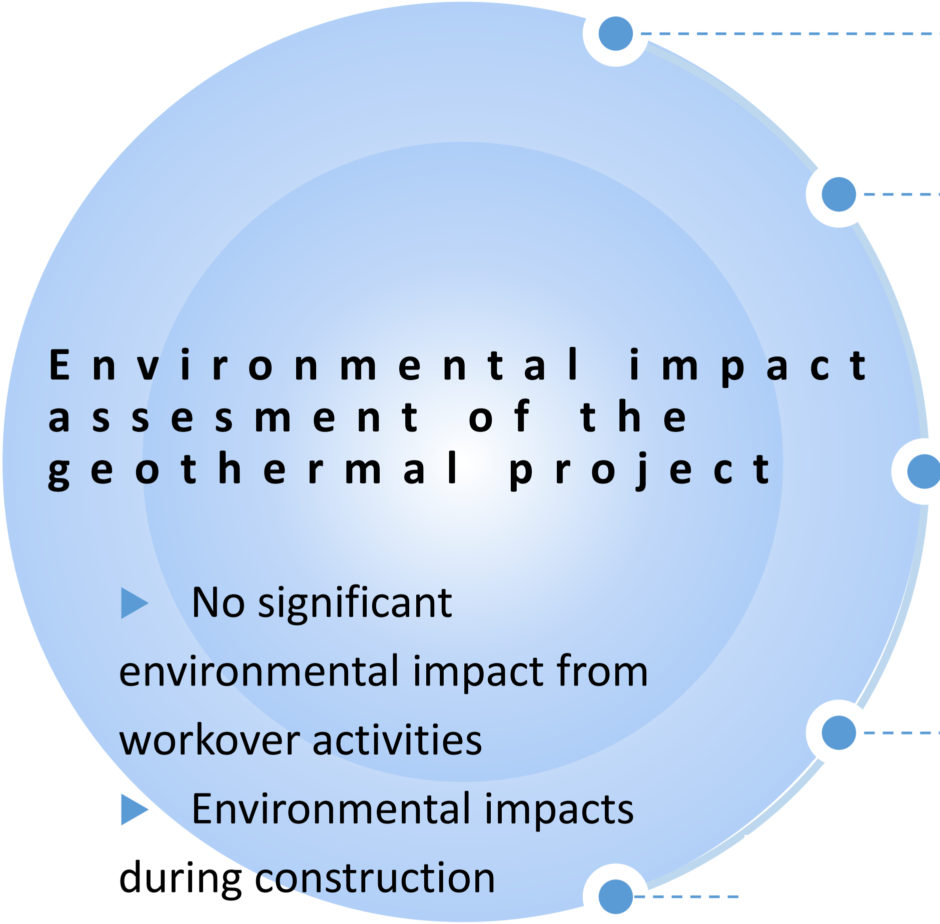
- positive effects on the economic activities of the area at the sites

POPULATION

- possible to expect temporary and short-term impact on the population due to noise or dust during the works, but no significant impact

ECOLOGICAL ACCIDENT AND RISK OF ITS OCCURRENCE

- It is not expected that activities could significantly disrupt the state of the environment in the observed area



Environmental impact assesment of the geothermal project

- No significant environmental impact from workover activities
- Environmental impacts during construction

ENVIRONMENTAL IMPACTS AFTER ACTIVITIES

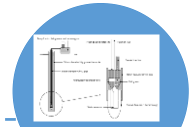
- no danger of harmful effects on the environment after the project

CROSS-BORDER IMPACTS

- no transboundary or global impact on the environment

ENVIRONMENTAL PROTECTION MEASURES

- closed system of exploitation and transport of geothermal water; supervision



MONITORING

- shallow monitoring wells - piezometers for monitoring the quality of drinking water aquifers should be instoled

ENVIRONMENTAL BENEFITS OF GEOTHERMAL RESOURCES

- **Environmental advantages of developing geothermal resources include limited gaseous emissions, small footprint, low amounts of emitted particulate matter, reduced water consumption, low noise impacts, and the ability of geothermal operations to blend in with their natural surroundings.**
- **These environmental assets are in addition to the general 24-hour availability of geothermal energy, be it for electrical power or direct use (such as space heating)**

INTRODUCTION

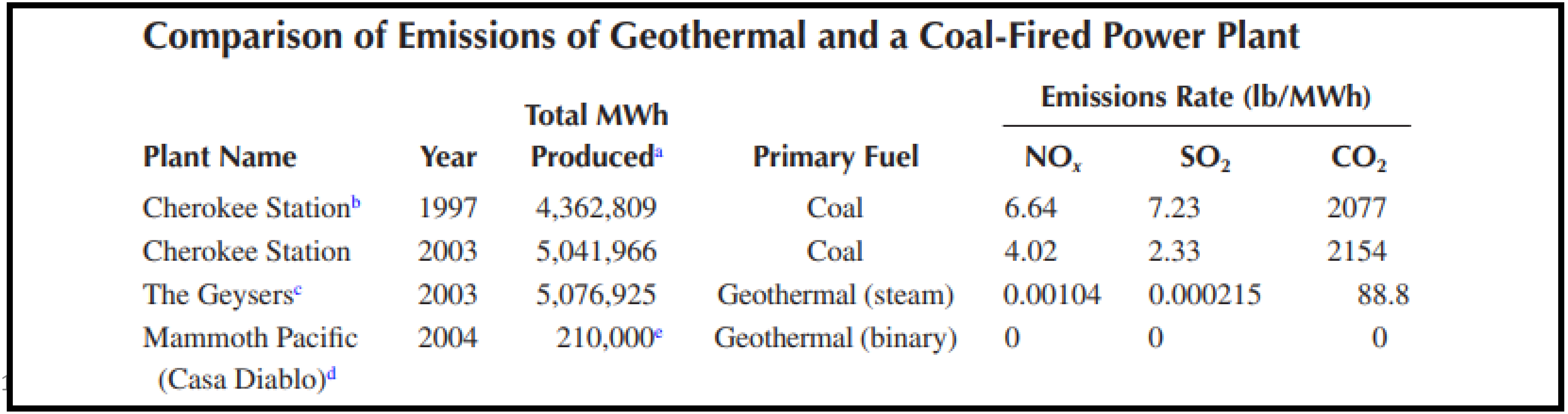
- **As with any construction project, development of geothermal resources has environmental impacts; however, these impacts, compared to those produced from fossil fueled power sources and even other renewable energy sources, are small and rather benign. The potential impacts explored include the following:**

1. **Gaseous emissions to the atmosphere**
2. **Land usage**
3. **Solids emissions to the surface and atmosphere**
4. **Water usage**
5. **Noise pollution**
6. **Land subsidence (sinking)**
7. **Induced seismicity**

Gaseous Emissions (Air Pollution)

- The main gases produced from dry- and flash-steam geothermal plants are CO_2, hydrogen sulfide (H_2S), and minor amounts of nitrous oxides (NO_x), ammonia, and possibly mercury (Hg).
- Air-cooled binary geothermal plants emit essentially no gases because only the heat of the geothermal fluid is transferred to the working fluid via a heat exchanger.

- Compared to fossil-fuel-fired power plants, the emissions of flash or dry-steam geothermal power plants represent a small amount .
- lb/MWh means the pounds of emissions emitted per the megawatts of electricity produced per hour.

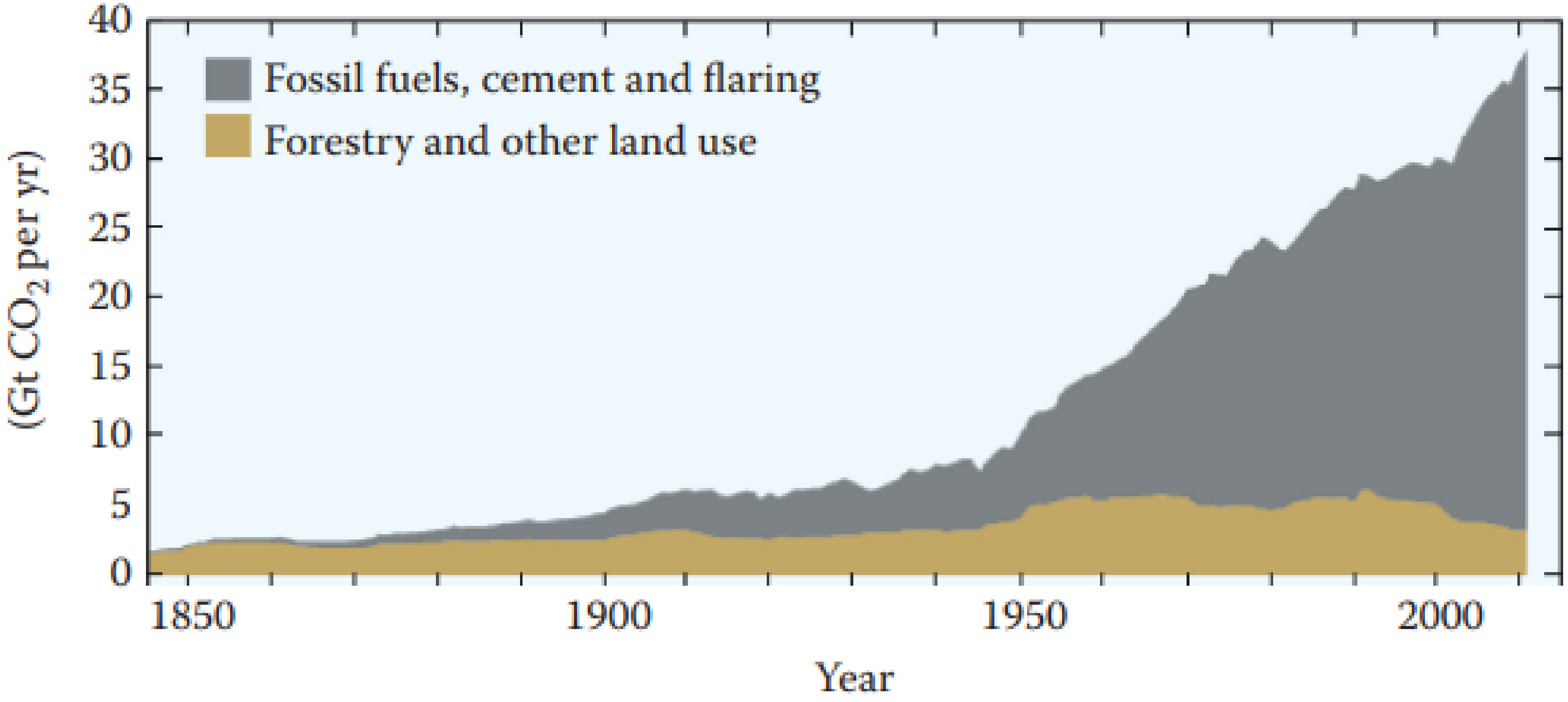


Comparison of Emissions of Geothermal and a Coal-Fired Power Plant

Plant Name	Year	Total MWh Produced[a]	Primary Fuel	Emissions Rate (lb/MWh)		
				NO_x	SO_2	CO_2
Cherokee Station[b]	1997	4,362,809	Coal	6.64	7.23	2077
Cherokee Station	2003	5,041,966	Coal	4.02	2.33	2154
The Geysers[c]	2003	5,076,925	Geothermal (steam)	0.00104	0.000215	88.8
Mammoth Pacific (Casa Diablo)[d]	2004	210,000[e]	Geothermal (binary)	0	0	0

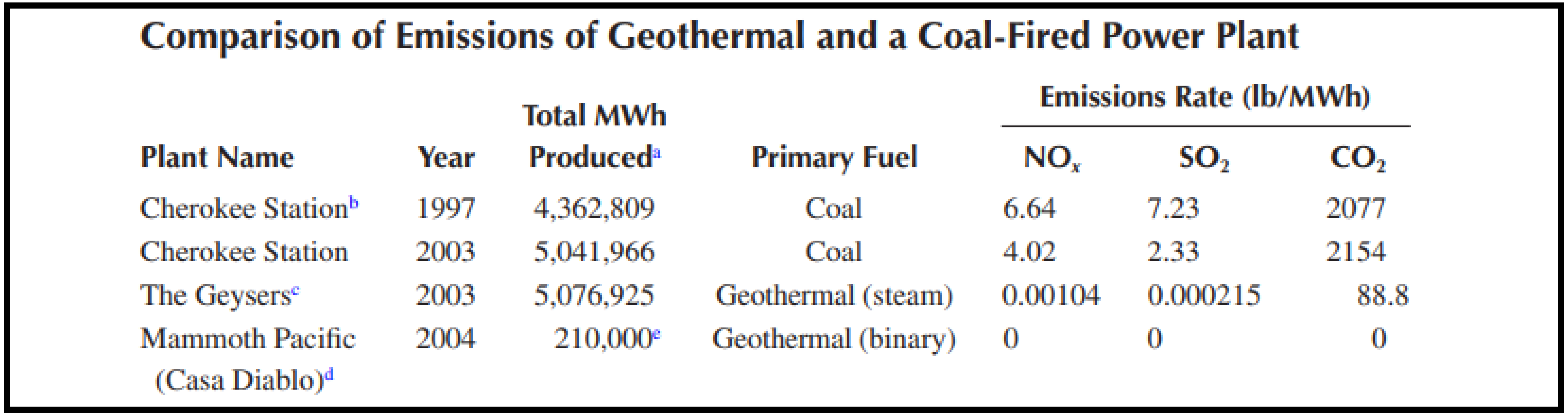
Gaseous Emissions (Air Pollution)

- **Global anthropogenic CO_2 emissions measured in gigatons per year (GT/yr).**
- **Note the abrupt increase of CO_2 emissions since about 1950.**



Gaseous Emissions (Air Pollution)

- **According to a report by the Geothermal Energy Association (Kagel et al., 2007), a coal-fired power plant emits “24 times more carbon dioxide, 10,837 times more sulfur dioxide, and 3,865 times more nitrous oxides per megawatt hour than a geothermal steam plant.”**
- **These observations are based on a comparison of emissions from the dry-steam power production facilities at The Geysers with a comparable coal-fired power plant .**



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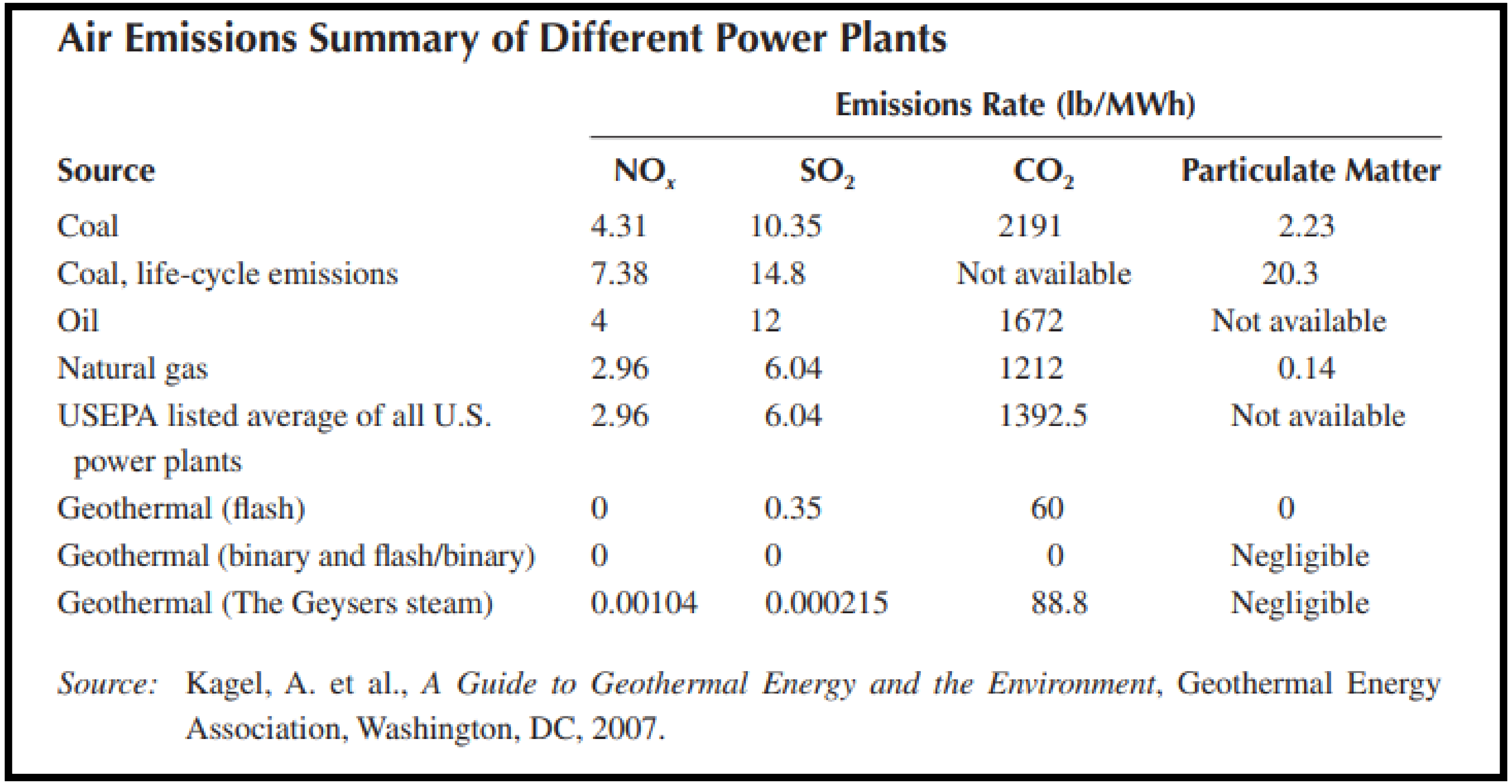
Gaseous Emissions
(Air Pollution)



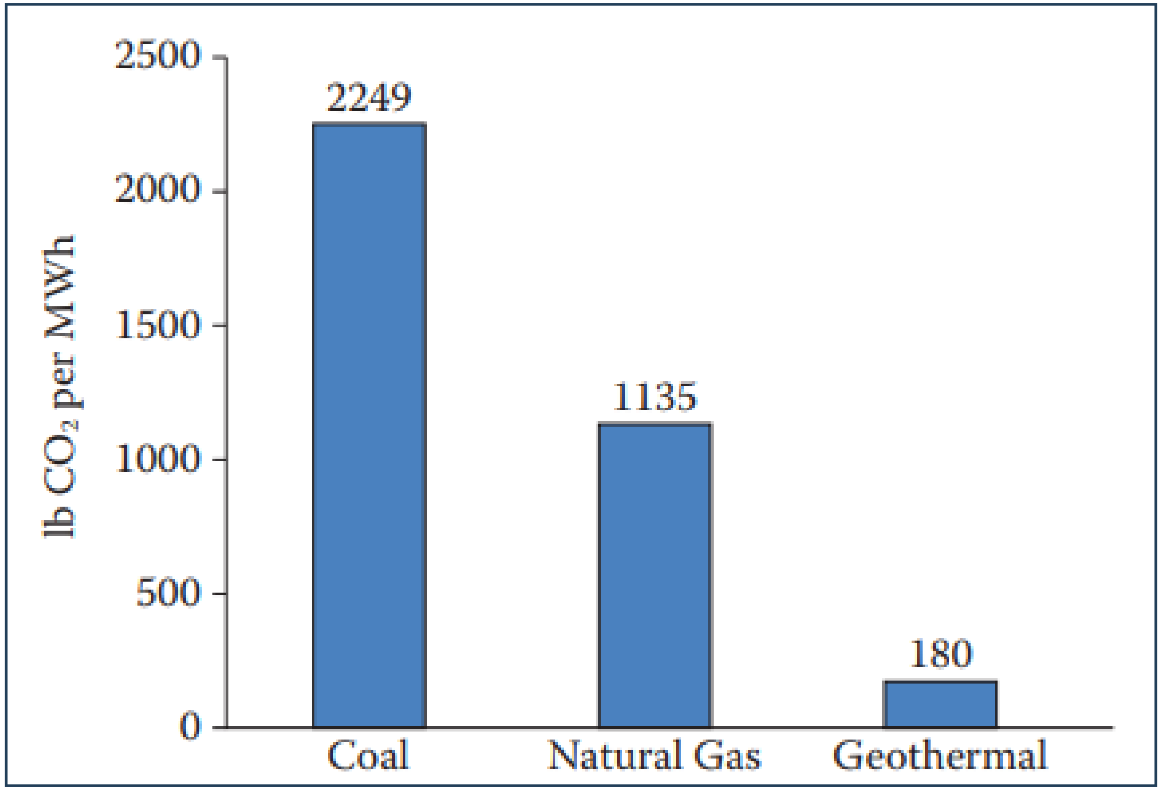
Air Emissions Summary of Different Power Plants

	Emissions Rate (lb/MWh)			
Source	**NO_x**	**SO_2**	**CO_2**	**Particulate Matter**
Coal	4.31	10.35	2191	2.23
Coal, life-cycle emissions	7.38	14.8	Not available	20.3
Oil	4	12	1672	Not available
Natural gas	2.96	6.04	1212	0.14
USEPA listed average of all U.S. power plants	2.96	6.04	1392.5	Not available
Geothermal (flash)	0	0.35	60	0
Geothermal (binary and flash/binary)	0	0	0	Negligible
Geothermal (The Geysers steam)	0.00104	0.000215	88.8	Negligible

Source: Kagel, A. et al., *A Guide to Geothermal Energy and the Environment*, Geothermal Energy Association, Washington, DC, 2007.

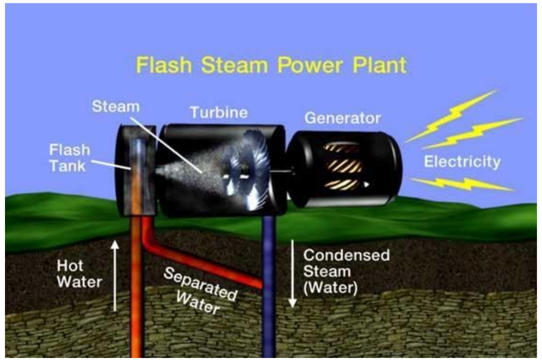
Gaseous Emissions
(Air Pollution)

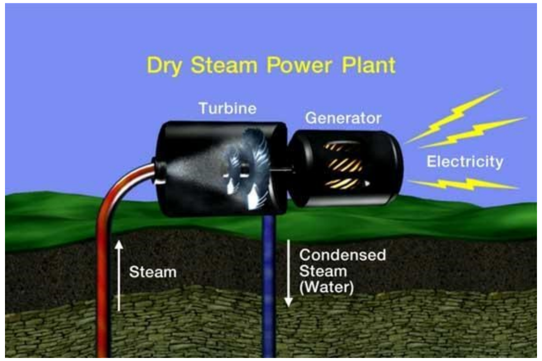
- **Comparison of CO_2 emissions from coal-fired, natural gas-fired, and geothermal power plants (flash and steam only) for California facilities.**
- **Data are from the California Air Resources Board, U.S. Environmental Protection Agency, California Energy Commission, and Geothermal Energy Association.**

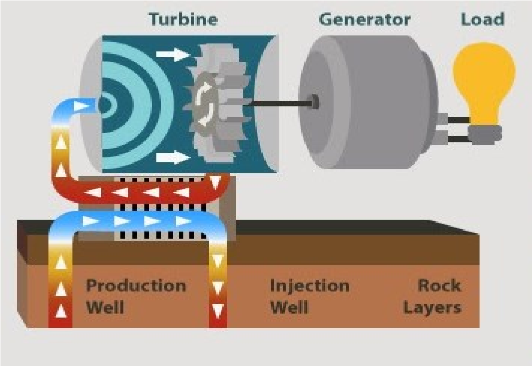


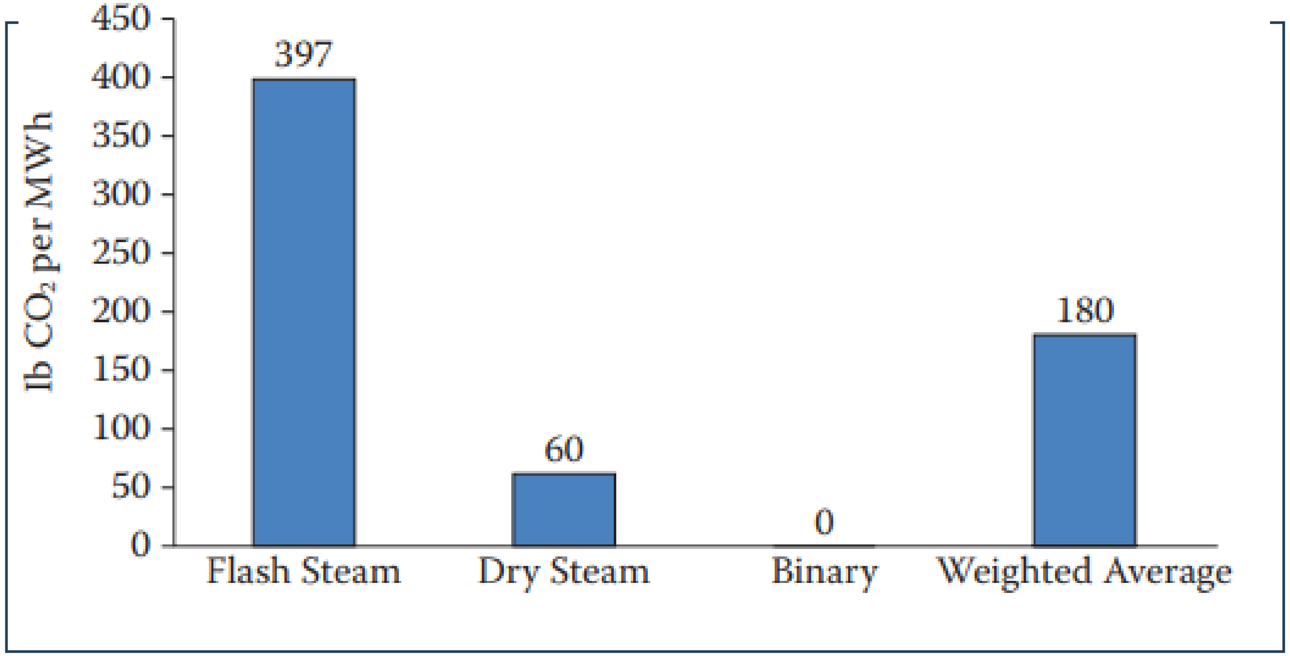
Gaseous Emissions
(Air Pollution)

- **Average geothermal CO_2 emissions from different generating technologies as compiled from California facilities in 2010.**



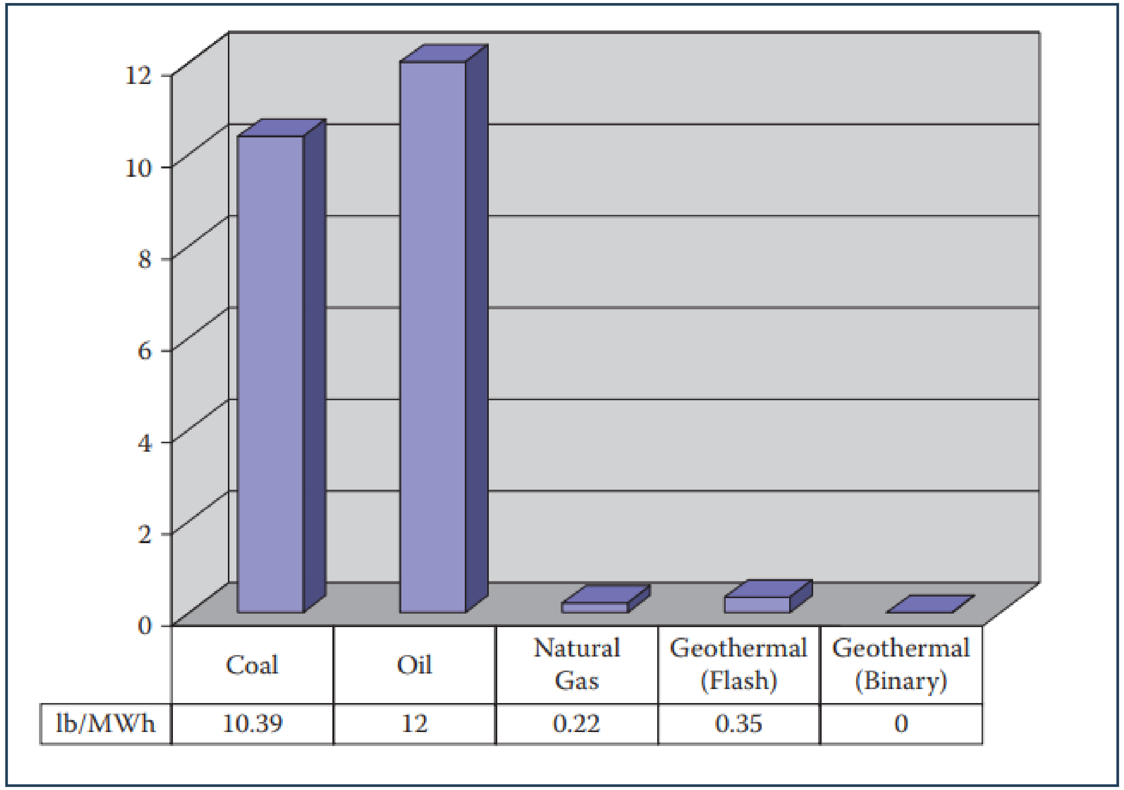






Gaseous Emissions (Air Pollution)

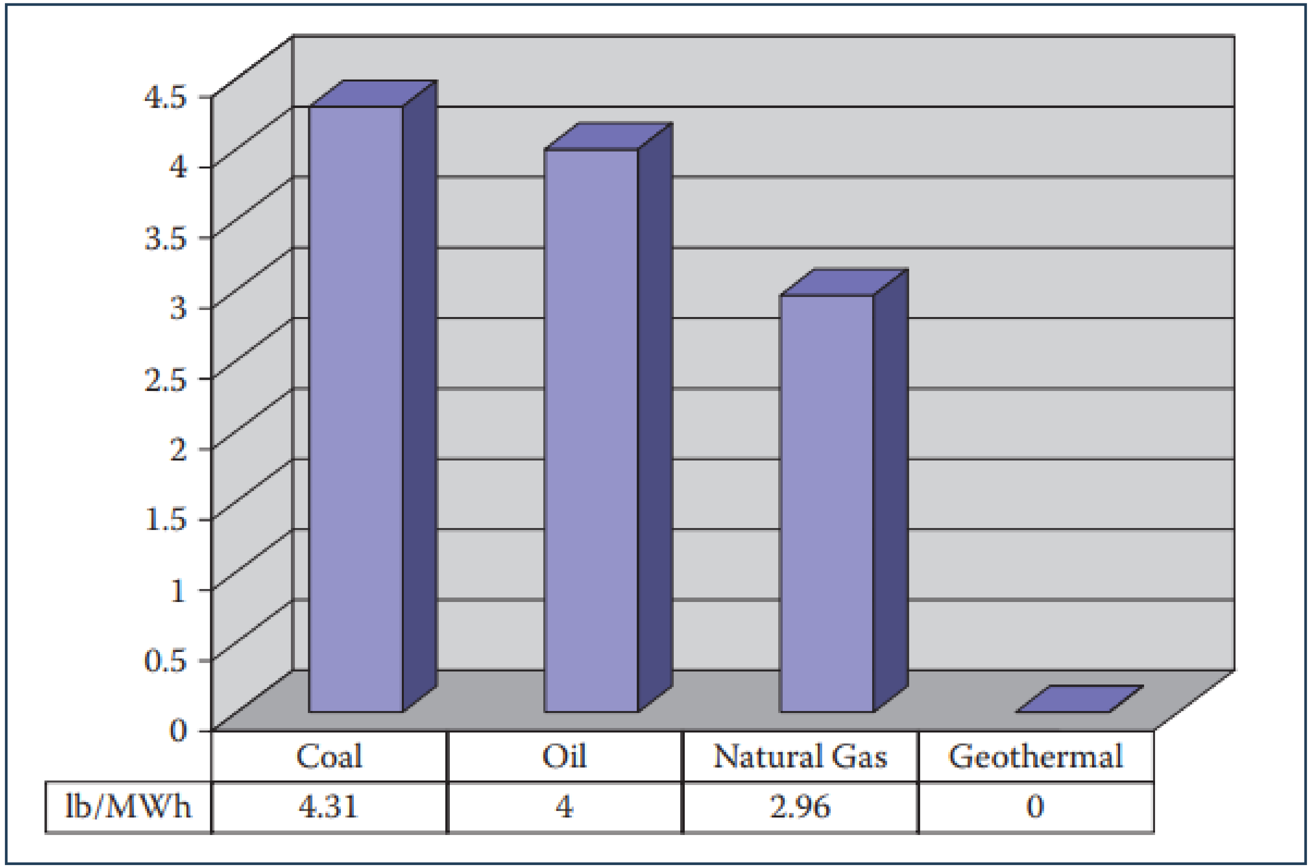
- **Comparison of SO_2 emissions of various power plants. For geothermal, the SO_2 amount reflects the conversion of H_2S as it enters the atmosphere, as little SO_2 is directly emitted from geothermal systems.**



	Coal	Oil	Natural Gas	Geothermal (Flash)	Geothermal (Binary)
lb/MWh	10.39	12	0.22	0.35	0

Gaseous Emissions
(Air Pollution)

Comparison of NO$_x$ emissions from various power plants.



	Coal	Oil	Natural Gas	Geothermal
lb/MWh	4.31	4	2.96	0

Gaseous Emissions (Air Pollution)

- Carbon dioxide (CO_2) and hydrogen sulfide (H_2S) are the most common Non Condensable Gases (NCGs) produced from geothermal steam, followed by minor amounts of ammonia (NH_3), methane (CH_4), nitrous oxides (NO_x), and mercury depending on the geologic characteristics of the developed geothermal system.

- Typically, non condense able gases make up only a few weight percent of the steam, and carbon dioxide usually represents in excess of 90% of the NCGs.

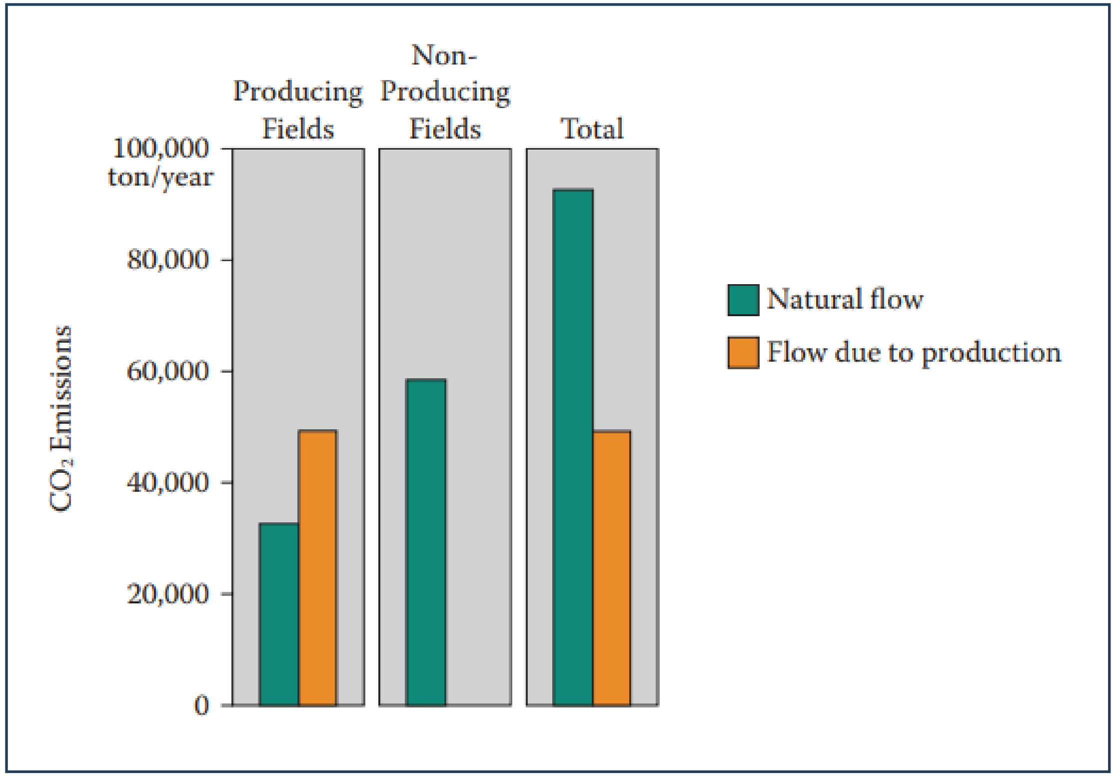
- At present, it is not required to capture or remove CO_2, but H_2S is rigorously regulated because of its unpleasant odor at low concentrations (30 parts per billion) and toxicity at higher levels (>500 ppb).

- It is a relatively straightforward to remove the H_2S through oxidation ($2H_2S + O_2 \rightarrow 2S0 + 2H_2O$) and produce elemental sulfur that can be sold in the manufacture of fertilizers.

- This is routinely done at power stations at The Geysers

Gaseous Emissions (Air Pollution)

- **Natural CO_2 emissions from non-producing geothermal fields having surface manifestation such as hot springs, fumaroles, and geysers are higher than producing fields.**
- **Combining the two sets of data indicates that the natural flow of CO_2 is about twice that resulting from flash geothermal plants.**



Gaseous Emissions (Air Pollution)

- **Geothermal energy can also cause air pollution and local air quality issues. Extracting geothermal fluids releases gases that are harmful to both the environment and our health. Some of these gases include:**

- **Hydrogen Sulfide (H_2S) – The most abundant gas a geothermal power plant can release.**
- **Carbon Dioxide (CO_2) – One of the key greenhouse gases contributing to climate change.**
- **Ammonia (NH_3) – A compound of nitrogen and hydrogen that can cause serious health issues and/or death in high concentrations.**
- **Methane (CH_4) – Another powerful greenhouse gas contributing to climate change.**

- **This is more prevalent in open-loop systems where gases are not contained. Closed-loop systems tend to be less affected. Air pollution is one of the main disadvantages of geothermal energy.**

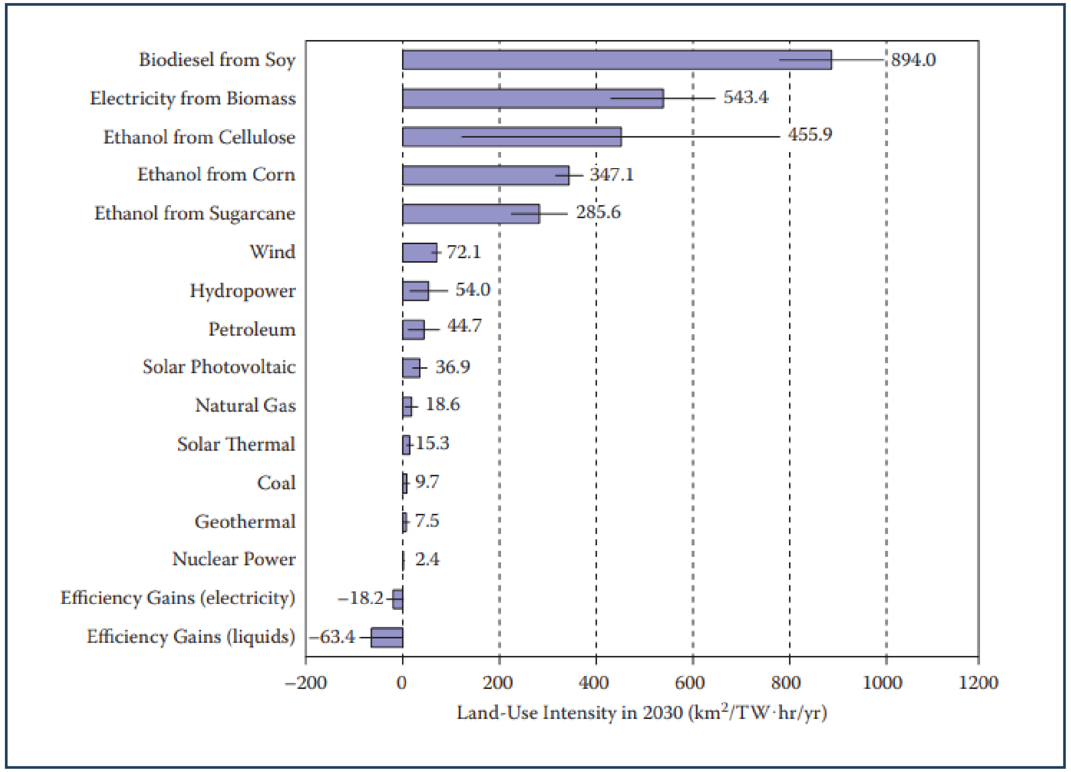
Land usage

- **Land use is another environmental impact of geothermal energy. Although geothermal power stations are often much smaller than fossil fuel alternatives, they still take up space. This does depend on the type and size of the plant but will often leave a mark on the environment.**

Geothermal power plants can leave a blot on the landscape.

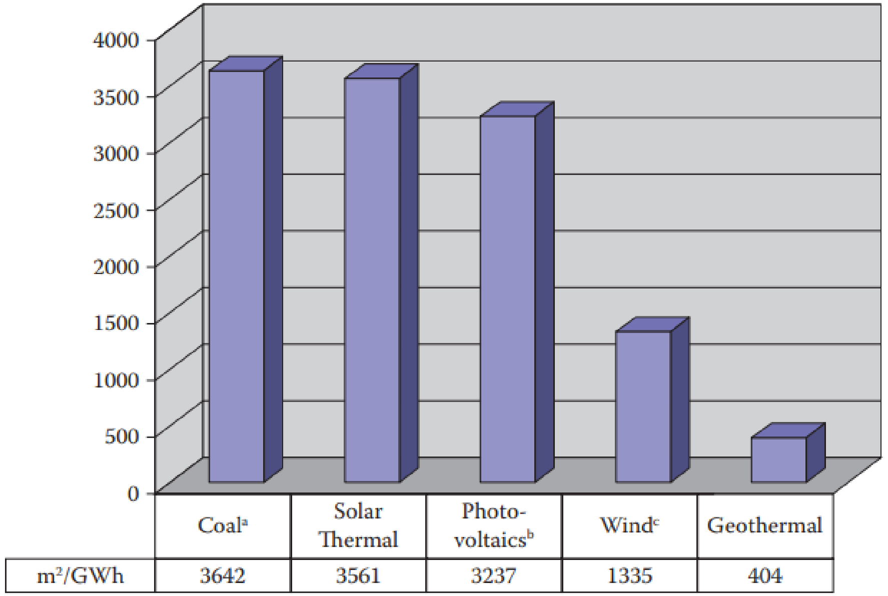
Land usage

- **Compared to other fossil-fuel-based power sources and even other renewable sources of energy (wind, solar, hydropower, and biomass), geothermal has the second lowest footprint behind nuclear**
- **A nuclear power plant has the smallest footprint for power produced; however, if you consider the area of the uranium mines supplying fuel for the nuclear plants, then geothermal would actually have the smallest footprint for all energy conversion technologies**



Land usage

- The actual area required for a geothermal power plant depends on the size of the power plant, size of the supporting well field (both production and injection), access roads, pipelines, substation, and auxiliary buildings. The well field typically represents the largest amount of area, on the order of 5 to 10 km2 for a 20- to 50-MWe plant. However, the well pads themselves typically consume only about 2% of that 5 to 10 km2, an amount that can be reduced further if directional drilling is employed, allowing two or more wells to be drilled on a given pad



	Coal[a]	Solar Thermal	Photo-voltaics[b]	Wind[c]	Geothermal
m^2/GWh	3642	3561	3237	1335	404

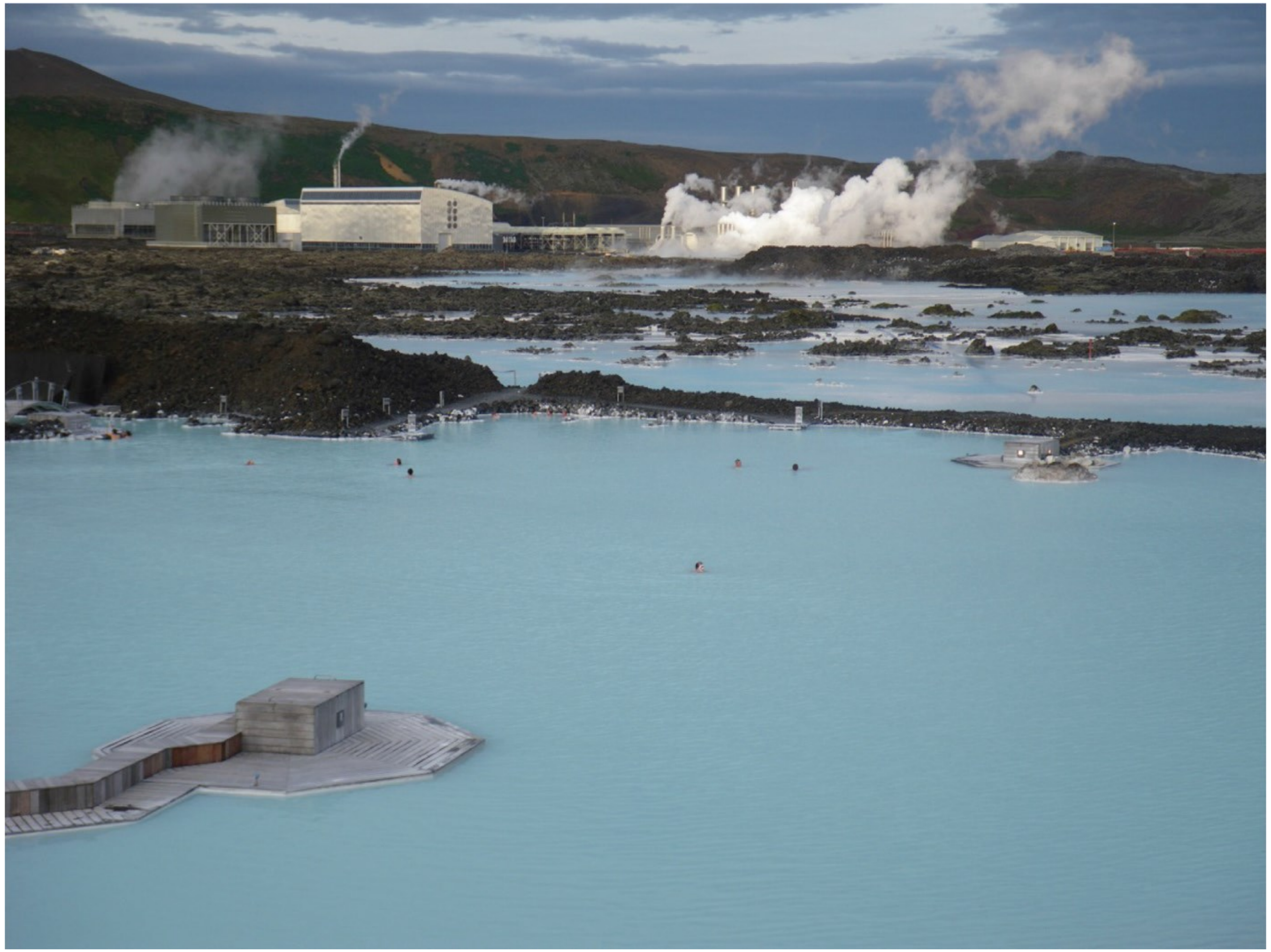
[a] Includes mining.
[b] Assumes central station photovoltaic project, not rooftop PV systems.
[c] Land actually occupied by turbines and service roads.

Area of land used per gigawatt-hour (GWh) for coal, solar thermal, solar photovoltaic, wind, and geothermal. (From Kagel, A. et al., A Guide to Geothermal Energy and the Environment, Geothermal Energy Association, Washington, DC, 2007.)

Land usage

Land usage

Land usage



Land usage

Solids discharge to air and ground

- Solar, wind, and nuclear also have no particulate emissions to the atmosphere.
- Discharge of solids at the surface is generally not a problem in most geothermal systems; the solids remain dissolved in solution and then are reinjected into the ground after use to recharge the geothermal reservoir and prevent possible surface contamination.

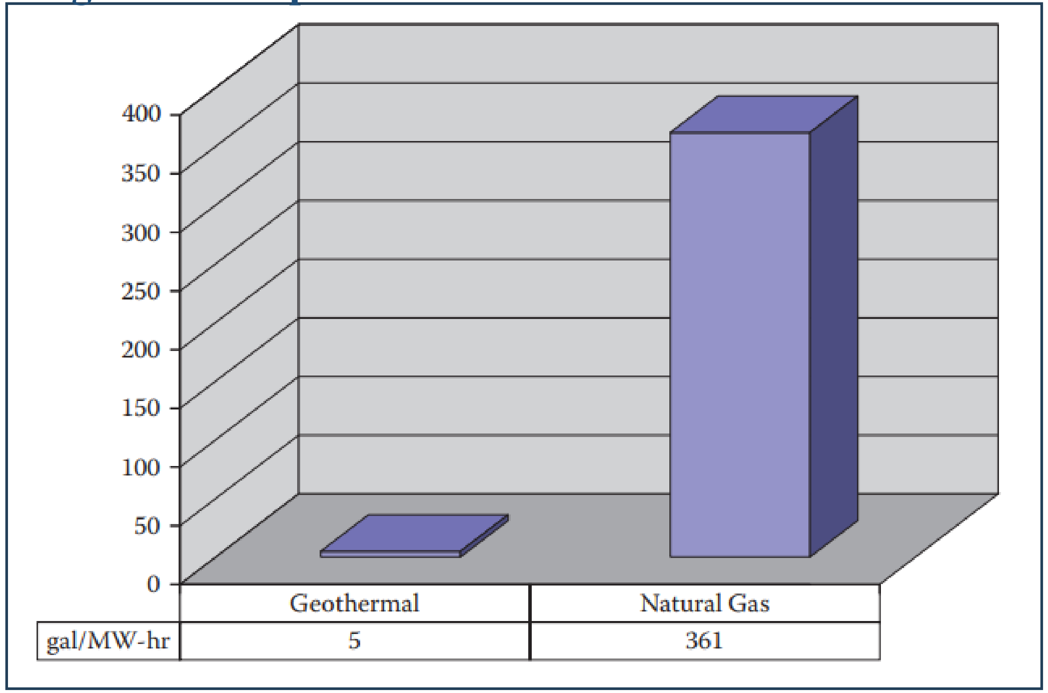
- The main exception to this is the hypersaline brines of the Salton Sea geothermal field of southern California, which contain over 200,000 ppm dissolved solids (for comparison, average sea water contains about 33,000 ppm dissolved salts).

- Because of the corrosive and potentially clogging nature of these fluids, it took many years of research to successfully manage the hypersaline brines for power production and avoid surface contamination

Water usage
(Water Consumption)

- **Water is used in the development and operation of geothermal facilities.**
- **The two main activities that use water are drilling wells during development and rejection of waste heat if water cooling is used to condense turbine steam exhaust.**
- **Water in drilling is used to cool the drill bit,**
- **For example, a 500-MWe combined-cycle gas power plant would require 4 million gallons of water per day, whereas a 48-MWe water-cooled geothermal flash plant requires about 6000 gallons per day (Kagel et al., 2007). So, MWe for MWe, the gas plant would consume about 70 times more water than the geothermal plant**

Water-use comparison of a water-cooled geothermal flash plant and a combined cycle natural gas power plant. (From Kagel, A. et al., A Guide to Geothermal Energy and the Environment, Geothermal Energy Association, Washington, DC, 2007.)

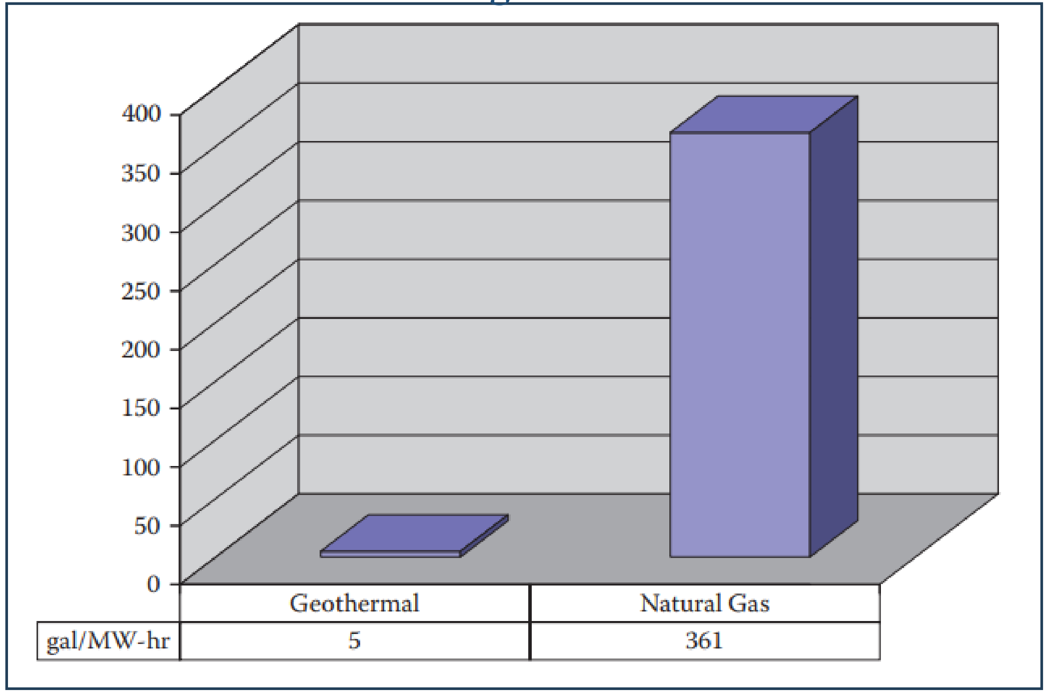


Water usage (Water Consumption)

- Water consumption is another example of how geothermal energy can affect the environment. Geothermal power plants consume water in two distinct ways:

- For Cooling Purposes – This process mostly uses spent geothermal fluids but sometimes uses local supplies of freshwater.
- For Replenishing Geothermal Reservoirs – Open-loop systems need to replenish the water inside their underground reservoirs to ensure an ongoing supply. Closed-loop systems also need to do this as some of the geothermal fluids are lost as steam.

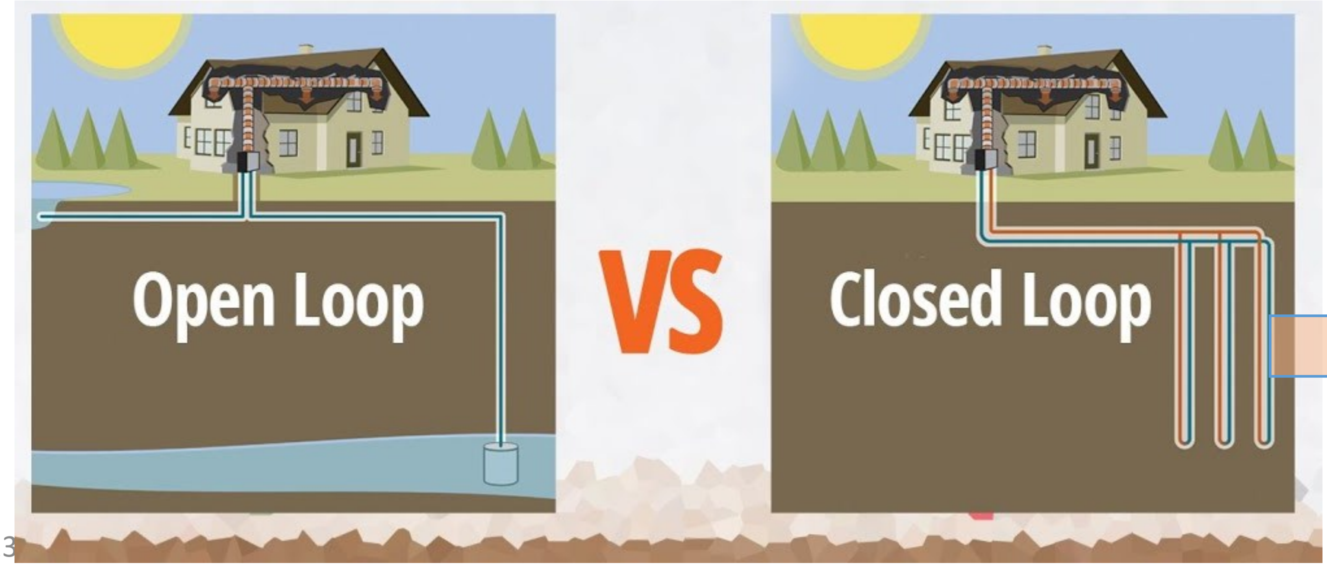
Tower cooled geothermal plants can consume up to 5,147 gallons of water per megawatt-hour (MWh). This is according to a report by the National Renewable Energy Laboratory. The same report shows how geothermal has the second highest water consumption of all renewable and non-renewable power plants. It is only beaten by hydropower (for obvious reasons).

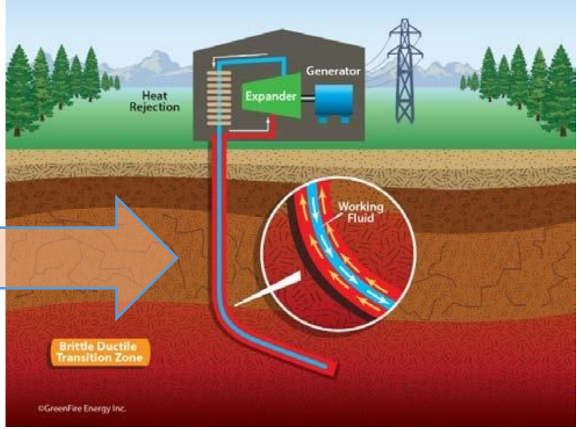


Water-use comparison of a water-cooled geothermal flash plant and a combined cycle natural gas power plant. (From Kagel, A. et al., A Guide to Geothermal Energy and the Environment, Geothermal Energy Association, Washington, DC, 2007.)

Water Contamination

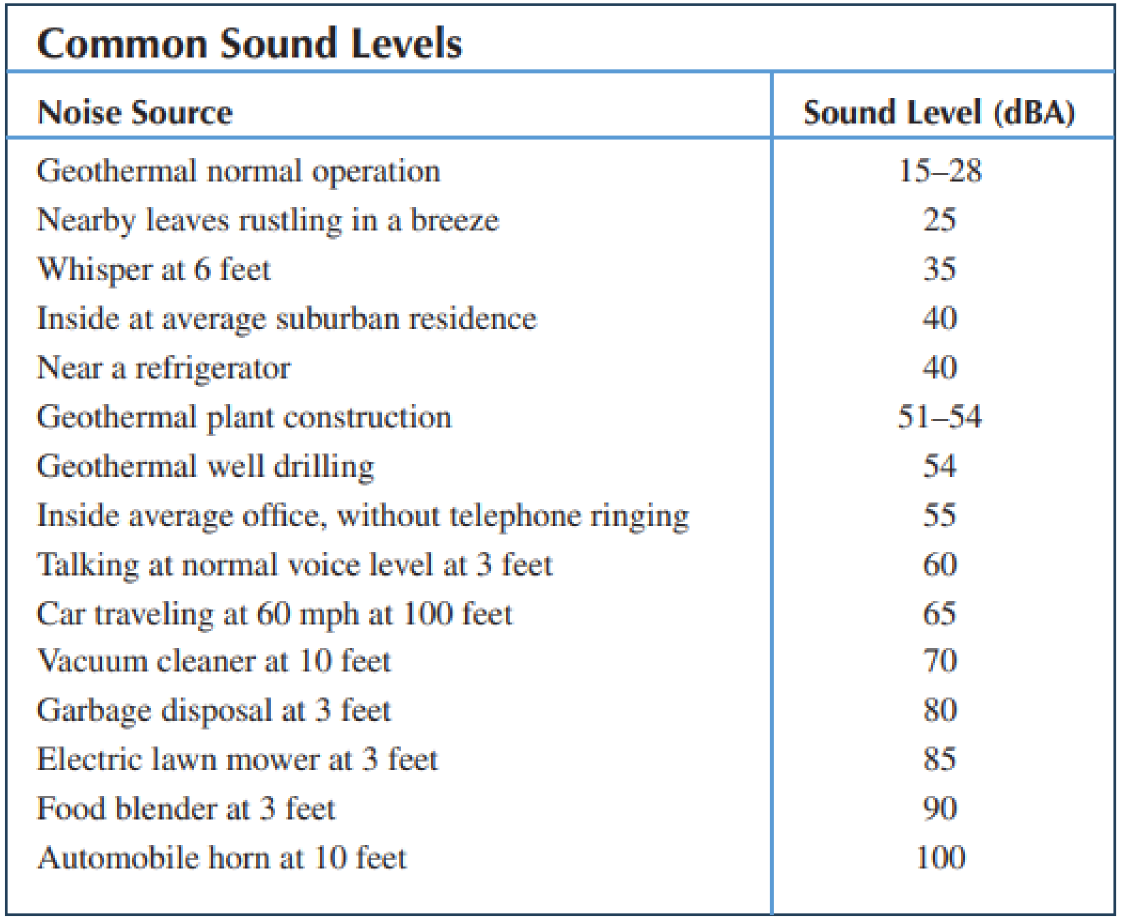
- **Geothermal power plants can cause water quality and contamination problems. Underground geothermal reservoirs often contain high concentrations of harmful substances. These can include sulfur, salts and other compounds and minerals.**
- **In open-loop geothermal power plants, these substances can seep out into the local environment. This then has the potential to affect the quality of the local water table.**
- **Water quality is less of a concern in closed-loop systems. Here, as the term suggests, the water is closed off and contained within the system. Such power plants will then often reinject the fluids back where they came from**





Noise

- Numerous federal and local regulations apply to geothermal operations.
- At the federal level, the Bureau of Land Management, on which many of the geothermal facilities are developed, require that the noise level at 0.5 mile from a geothermal plant or lease boundary, whichever is closer, cannot exceed 65 units of A-weighted decibels (dBA).
- A-weighting is an electronic technique to mimic the human auditory response to sound at all frequencies. A comparison of various common levels and the sound of normal geothermal operation is provided.



Common Sound Levels

Noise Source	Sound Level (dBA)
Geothermal normal operation	15–28
Nearby leaves rustling in a breeze	25
Whisper at 6 feet	35
Inside at average suburban residence	40
Near a refrigerator	40
Geothermal plant construction	51–54
Geothermal well drilling	54
Inside average office, without telephone ringing	55
Talking at normal voice level at 3 feet	60
Car traveling at 60 mph at 100 feet	65
Vacuum cleaner at 10 feet	70
Garbage disposal at 3 feet	80
Electric lawn mower at 3 feet	85
Food blender at 3 feet	90
Automobile horn at 10 feet	100

Noise

- Note that the sound of normal geothermal operation is about half of that which occurs during drilling and construction and is comparable to the nearby rustle of leaves in a breeze.
- The only time the sound would exceed normal operation would be if the turbine should trip, possibly due to a problem in the transmission system, and the steam flow would have to be directed away from the turbine.
- Doing so allows the wells to remain open without sudden closure, which could damage well casings or wellhead valves. The steam is instead directed to rock mufflers or silencers where the velocity of the steam is drastically reduced. Because the noise associated with a moving gas stream is proportional to the velocity raised to the eighth power (Doppio, 2012), if the steam velocity is reduced by half then the sound emitted is lowered by 256 times.
- Also, the intensity of sound drops rapidly with distance so that a geofluid issuing vertically from a wide-open well would register about 65 dBA at a distance of 1 km. Thus, the noise issuing from an operating geothermal plant will probably not disturb anyone living nearby,

Noise

- The noise pollution geothermal energy can create. Although geothermal power plants are fairly quiet, they still emit noise from cooling systems and other components. For those living close to such facilities, this can become an issue.

- Fortunately, most geothermal power plants are far enough away from populated areas for this to cause problems. Wind turbines tend to be a greater concern for residents where noise pollution is concerned.

Land Subsidence

- Because fluid is withdrawn from a reservoir at depth, a potential exists for the overlying ground to subside
- As pressure declined in the underlying reservoir from fluid withdrawal, pore fluid in the cap rock may have drained downward, effectively reducing support and causing the cap rock to compress and overlying ground to subside. If so, compression and subsidence would be greatest where the cap rock is thickest.
- Four main conditions favor subsidence:

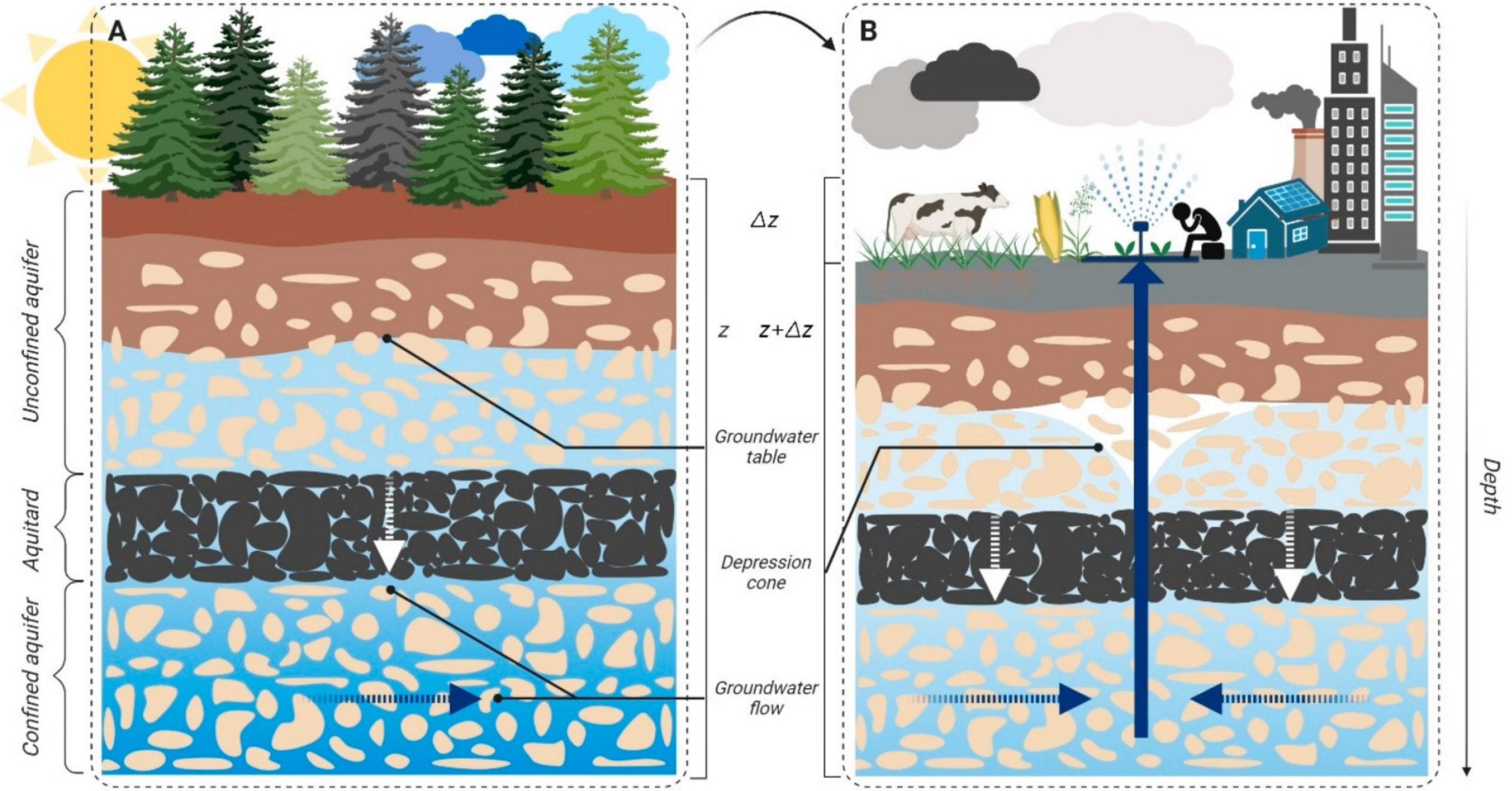
1. Withdrawal of geofluids that exceeds recharge either naturally or through piped reinjection
2. Mechanically weak and compressible rocks within the geothermal reservoir and capping the reservoir
3. Thermal contraction of rocks in the vicinity of injection wells, as may be the case in the Mukai geothermal field in New Zealand (Bromley, 2006)
4. Geothermal reservoirs where fluid pressure is under lithostatic pressure (fluid bears the weight of the overlying rock column) rather than hydrostatic pressure (weight of water only)

Land Subsidence

- Most designs of geothermal power plants extract superheated fluids from deep beneath the earth's surface. If these are not replenished, then an empty pocket is left. Over time, the land above this pocket may subside to fill the space. This can cause subsidence at ground level, affecting both man-made structures and the environment.

- The extraction of geothermal fluids has also been linked to seismic instability. This is, however, more of a safety issue than an environmental concern.

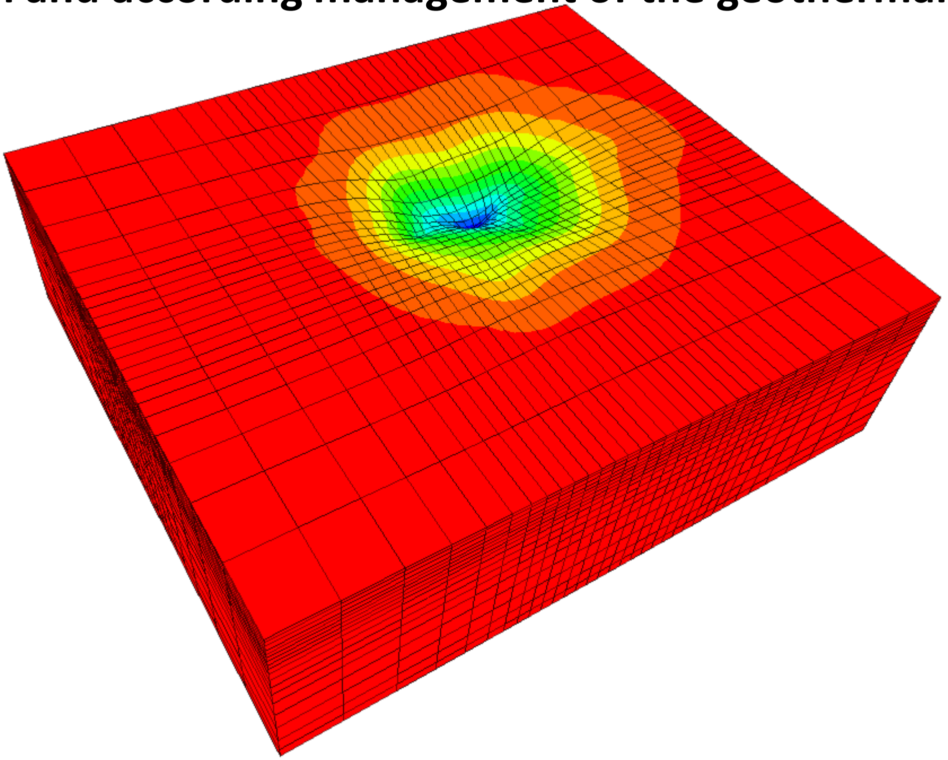
Land Subsidence

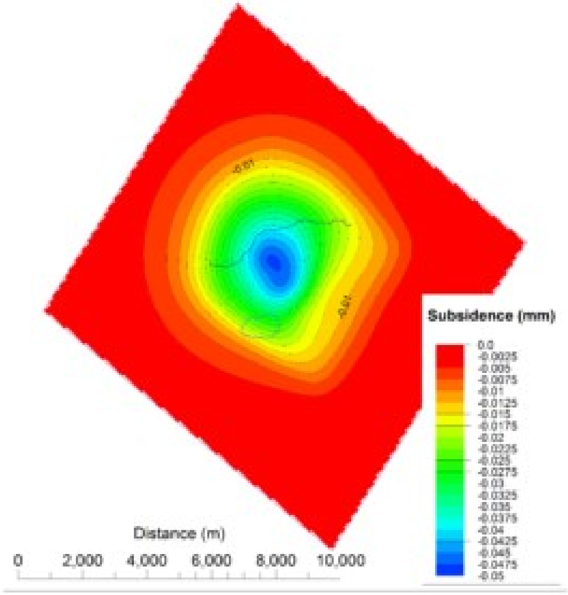


Schematic vertical cross-section of the groundwater system containing relatively coarse- (aquifers) and fine-grained (aquitard) deposits; (A) original hydrodynamic equilibrium; (B) disruption of the initial hydrodynamic balance as a consequence of groundwater pumping; lowering of the groundwater table and compaction of the compressible aquifer resulting in land subsidence.

Land Subsidence

Surface subsidence from conventional geothermal operations has been observed and studied for many decades. Surface subsidence can induce a devastating effect in the structure and safety of facilities, such as buildings, pipelines, and other infrastructure. It can also interrupt the balance ecosystems nearby. Frequent monitoring of the surface level and according management of the geothermal operations can reduce the risk of subsidence.





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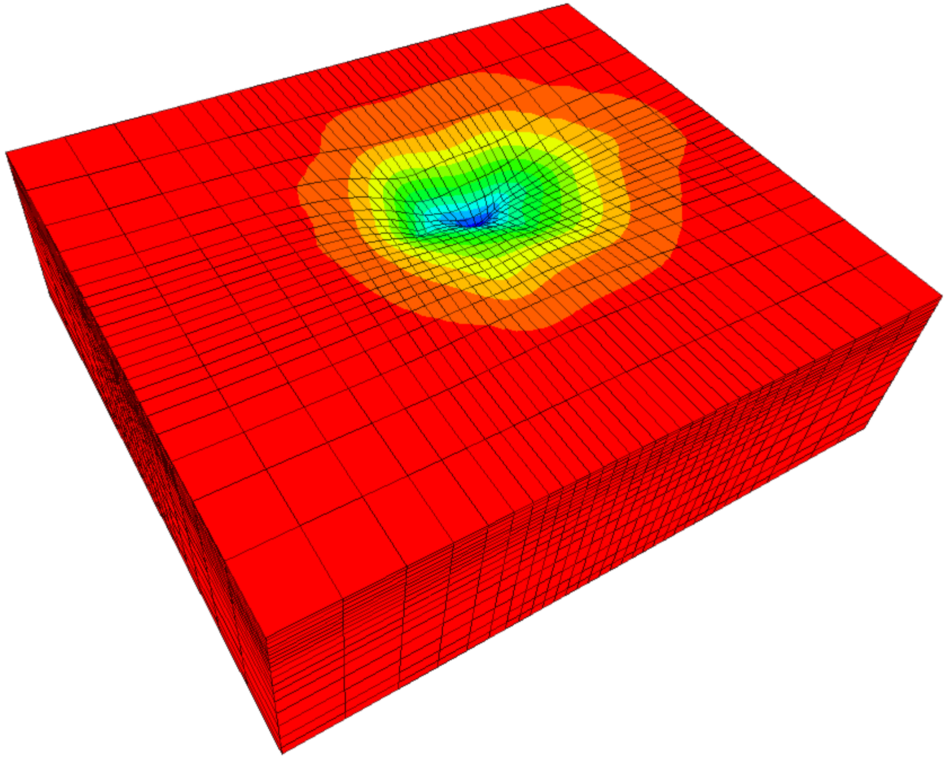
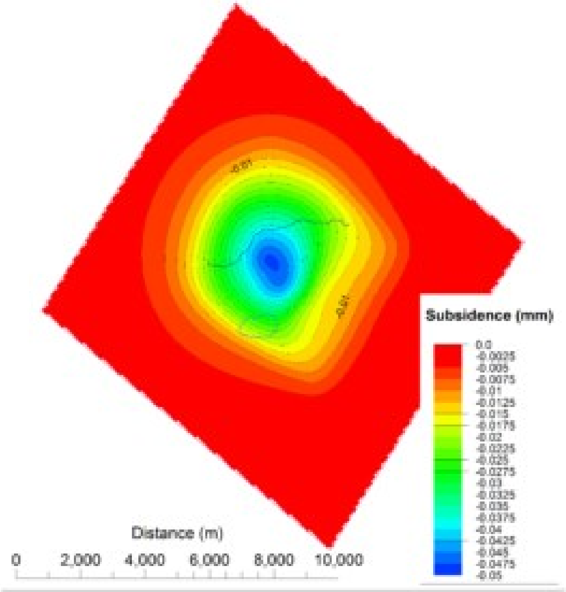
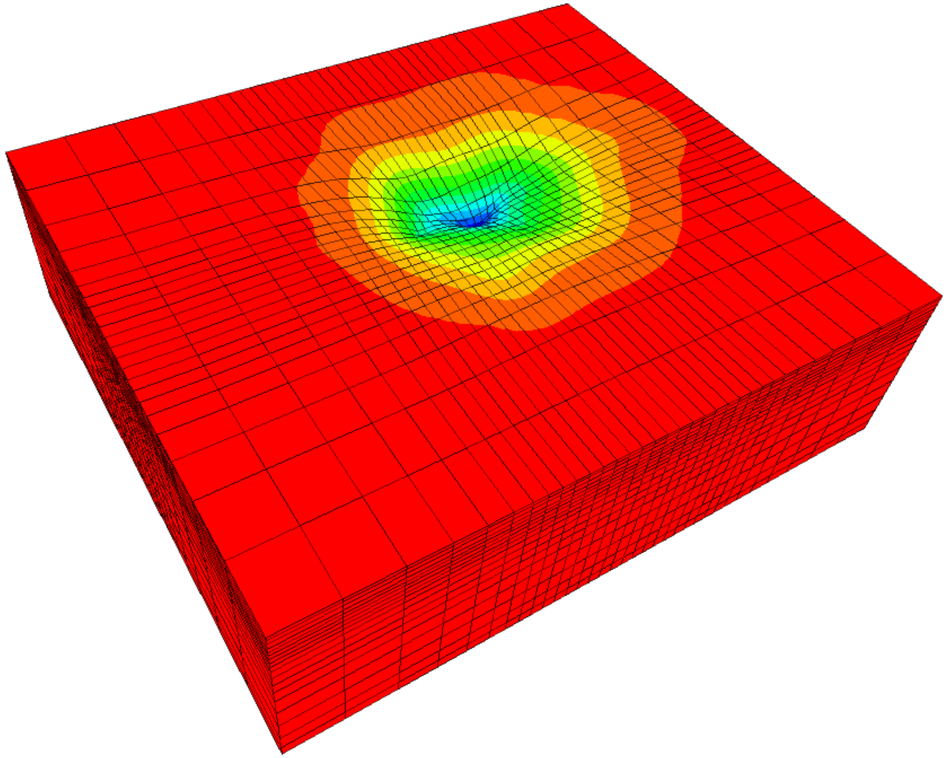
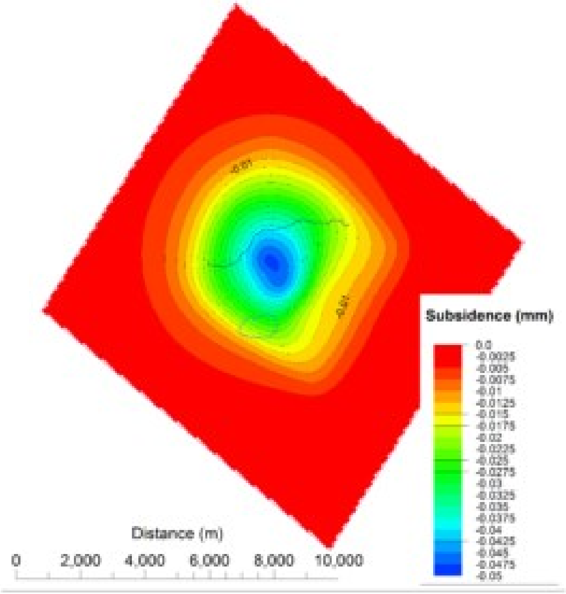




Land Subsidence

An integrated 3D geomechanical model was developed based on the geological, fluid, and heat flow models available. These properties are usually estimated from available log data, well test data, and lab test data. The geomechanical model was calibrated with the observed historical survey data and then applied to simulate future scenarios to predict surface subsidence and provide a guideline to optimize field development.





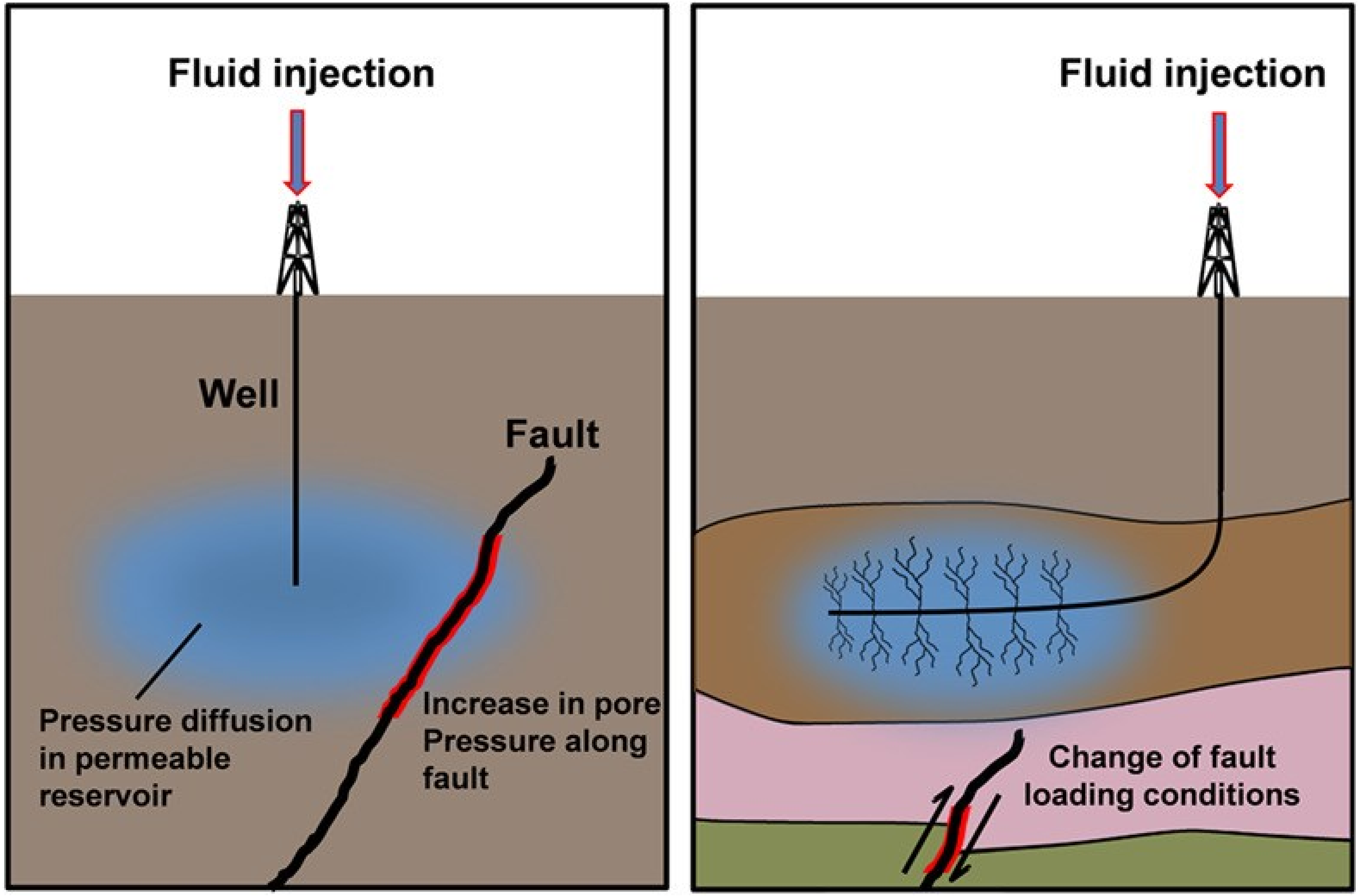
Induced Seismicity

- Seismicity related to geothermal operations can develop from several factors:

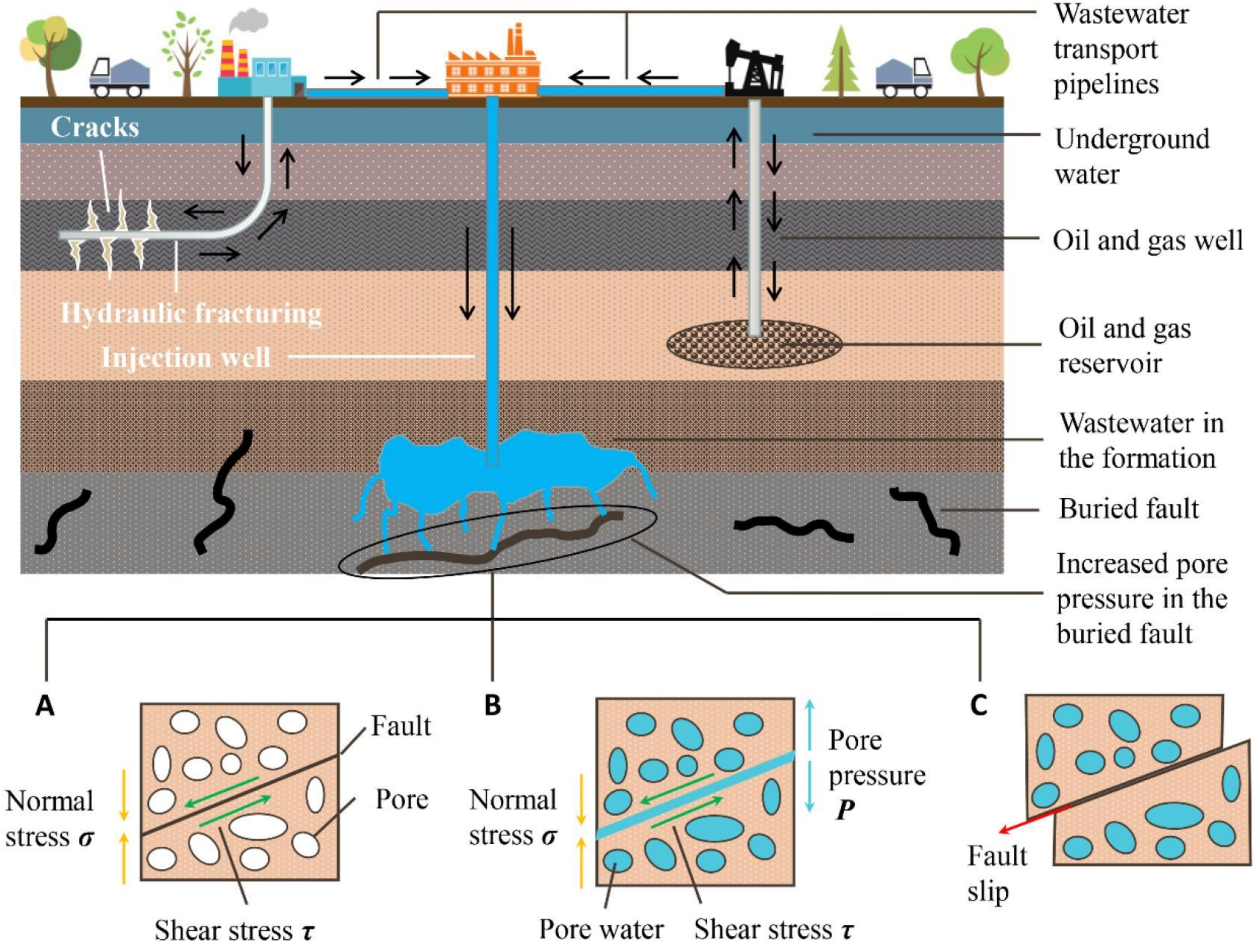
- Injection of cool waters into hot rock causing thermal contraction and fracturing
- Fluid extraction from reservoirs causing a change in fluid pressure resulting in movement of fractured rocks (this happens in oil and natural gas fields at times during extraction)
- Injection of fluids under high pressure causing rocks to fracture and increase reservoir permeability (analogous to filling hydroelectric reservoir for the first time)

- Nearly every geothermal field under exploitation has experienced induced seismicity to some extent. In most cases, such induced seismicity cannot be felt by people, and the resulting tremors, called microearthquakes (magnitudes generally <2), are detected only by sensitive seismic-measuring instruments.

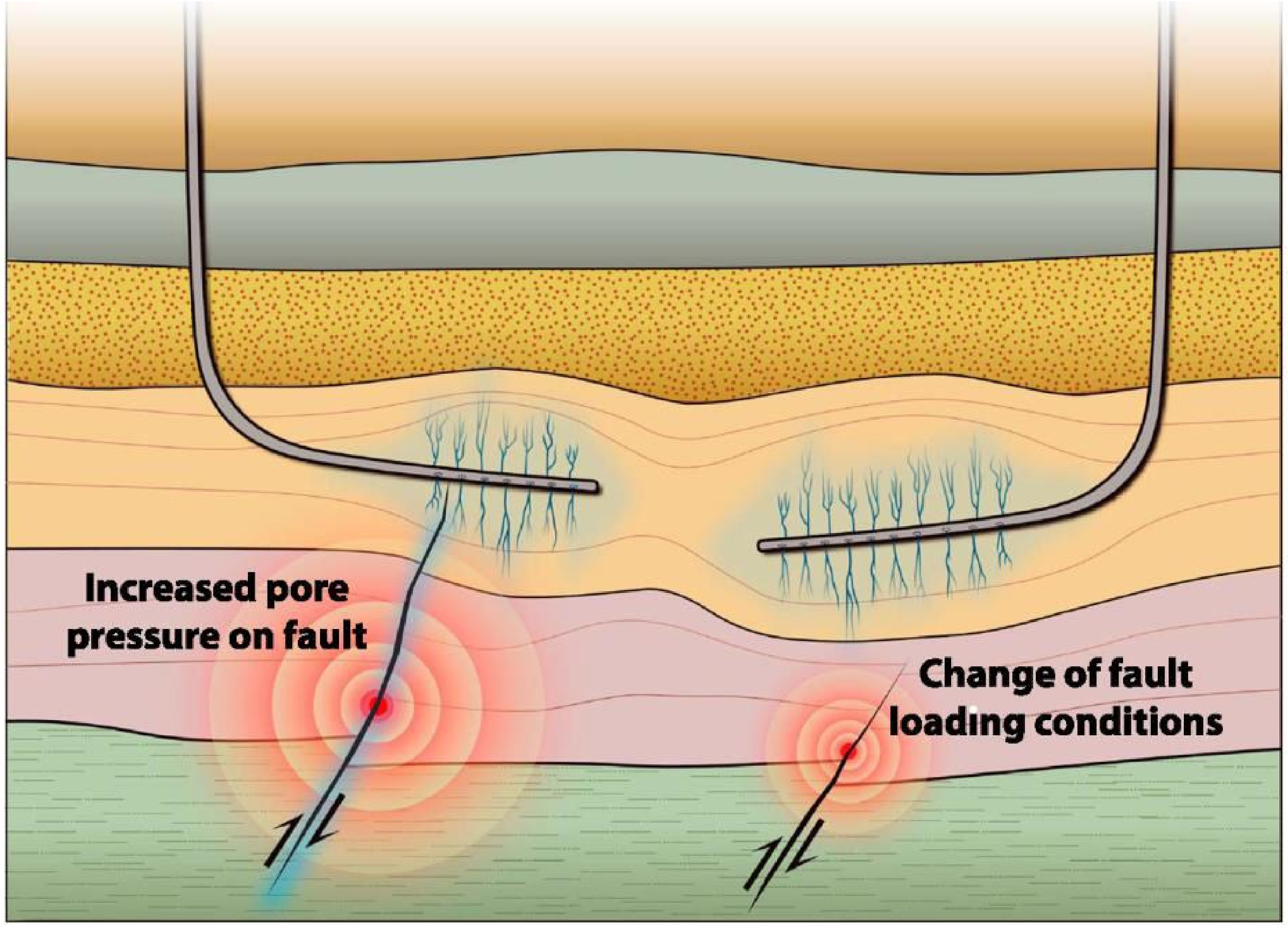
Induced Seismicity



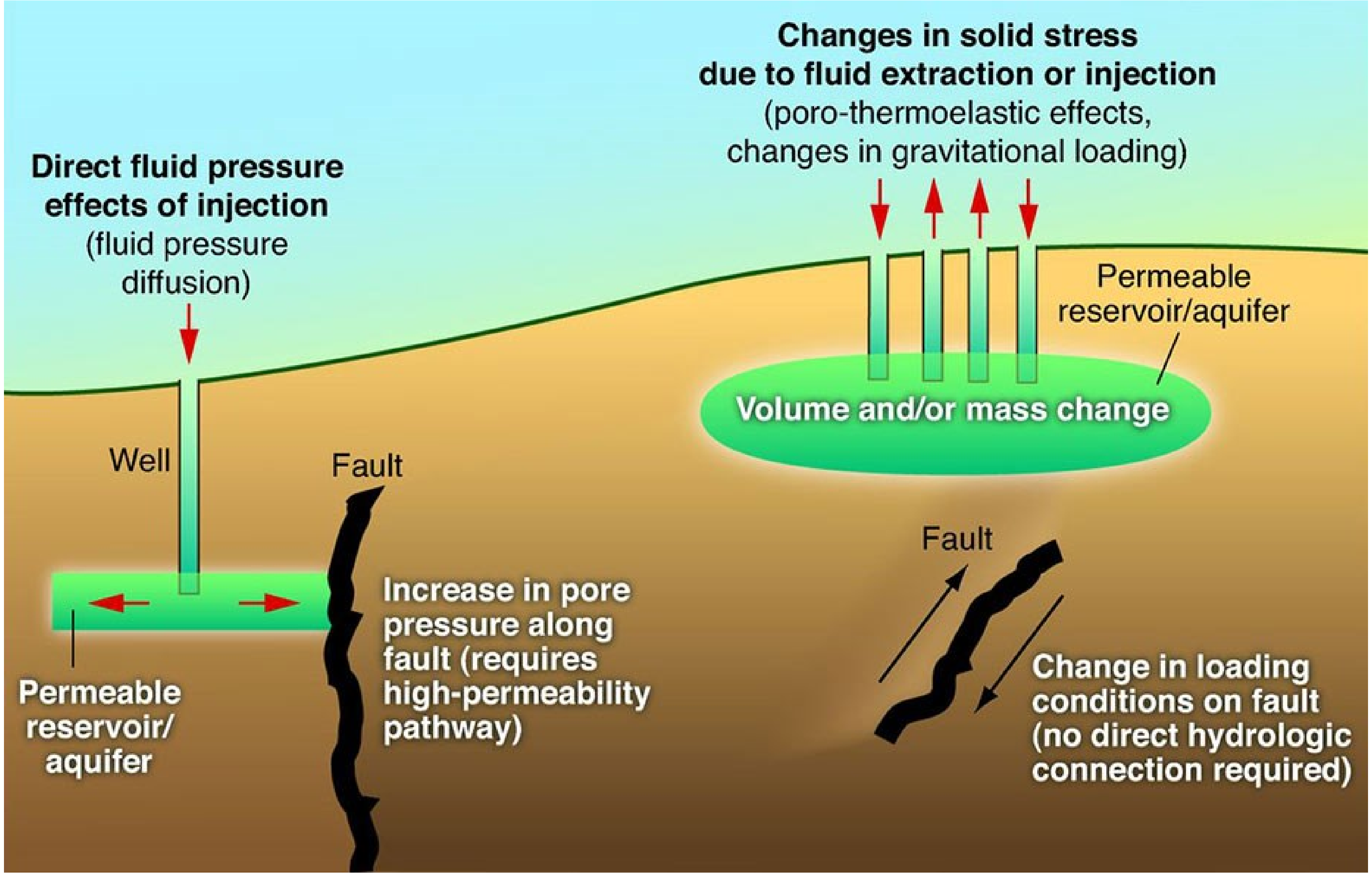
Induced Seismicity



Induced Seismicity



Induced Seismicity



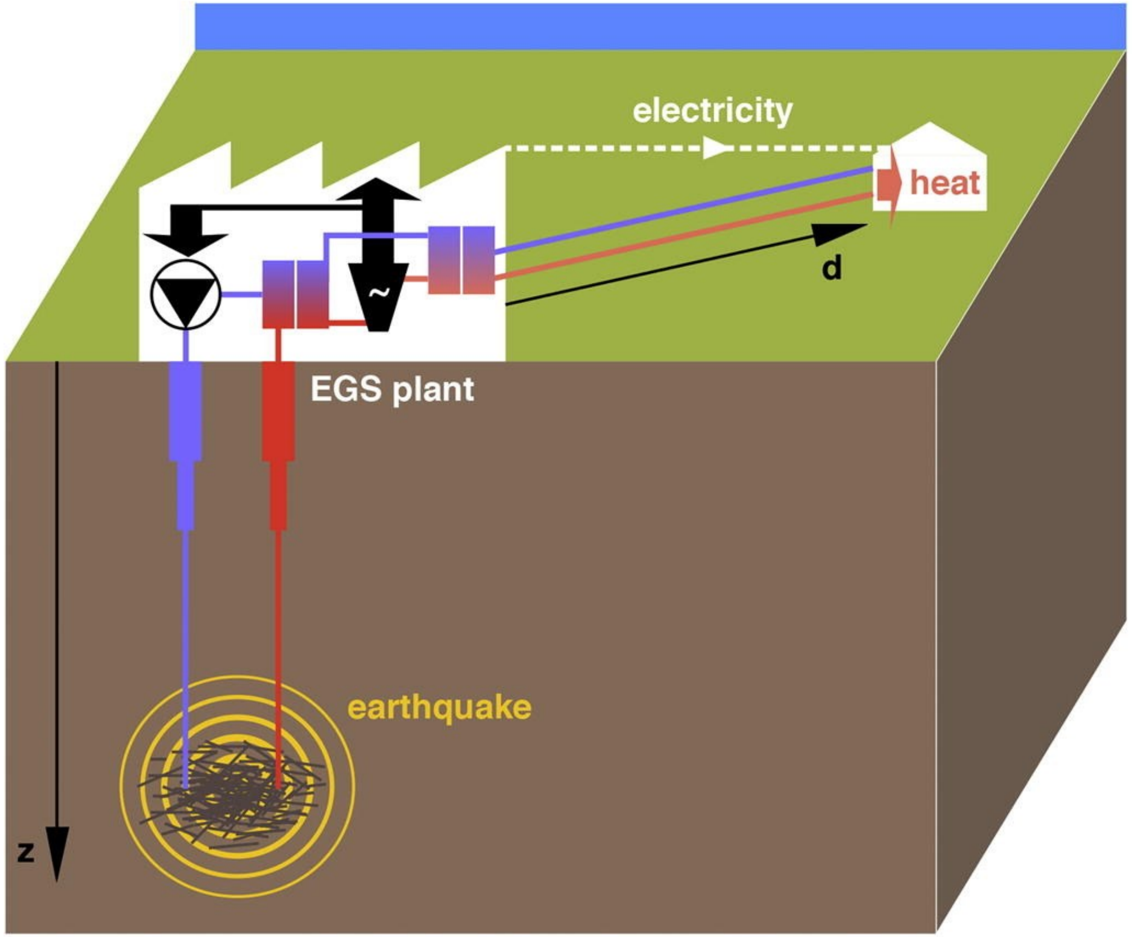
Changes in solid stress due to fluid extraction or injection
(poro-thermoelastic effects, changes in gravitational loading)

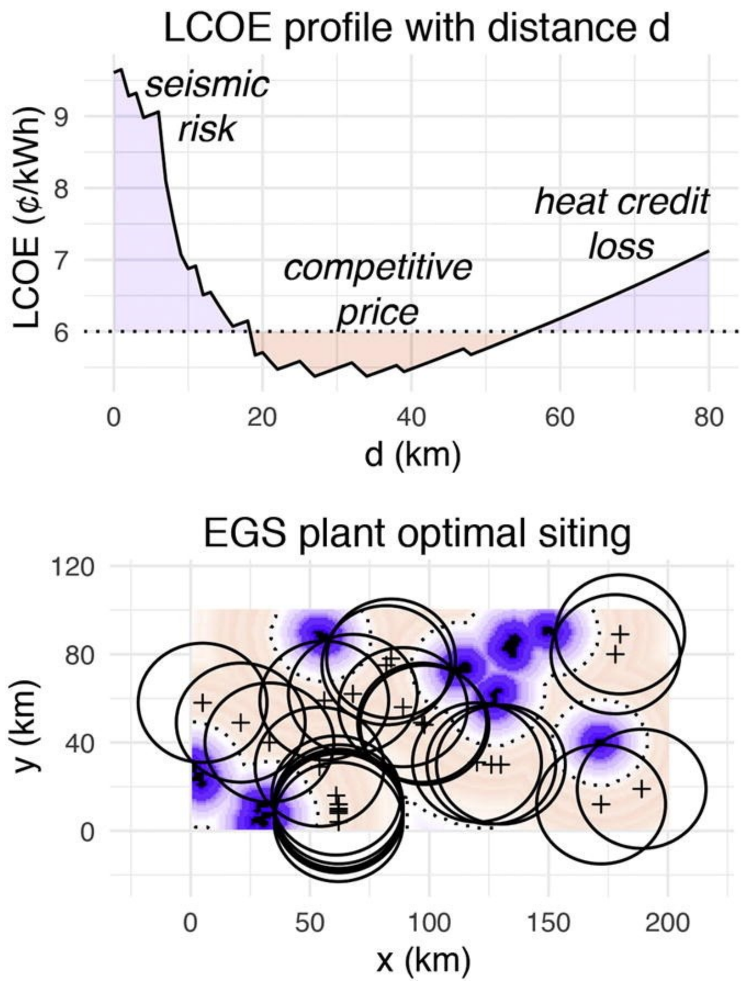
Direct fluid pressure effects of injection
(fluid pressure diffusion)

Increase in pore pressure along fault (requires high-permeability pathway)

Change in loading conditions on fault (no direct hydrologic connection required)

Induced Seismicity





What is the most important question here

So, Is Geothermal Energy Bad For The Environment?

- **There are significant concerns surrounding the environmental impact of geothermal energy. Having said this, there are other aspects you should take into account.**

- **Geothermal energy has lots of positive effects on the environment. For instance, by using it to generate power, we reduce the level of fossil fuels we burn. This has wide-ranging benefits, not just on the environment but also on our health.**

- **Reducing the level of fossil fuels we burn also reduces overall emissions of greenhouse gases. Whilst geothermal power plants can release such gases, they emit far less per kWh than fossil fuels. As an example, geothermal power has lifecycle emissions of around 95% less than coal. This factor alone outweighs the environmental impacts of geothermal energy.**

- **We can conclude that geothermal energy is good for the environment. It may not be the cleanest renewable energy source but it's still far better than fossil fuel alternatives.**

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Faculty of Engineering
Cairo University

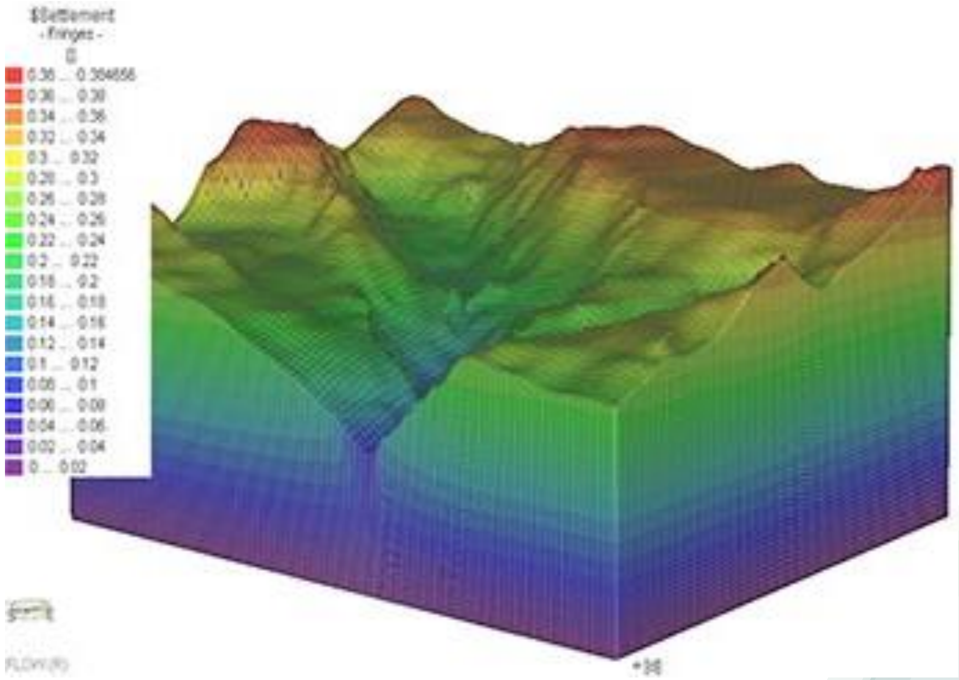
Geothermal Resources and Reservoir Engineering

Lecture 6: Numerical modelling for geothermal applications
Numerical Simulation using FEFLOW- Part-1

Numerical simulation with FEFLOW

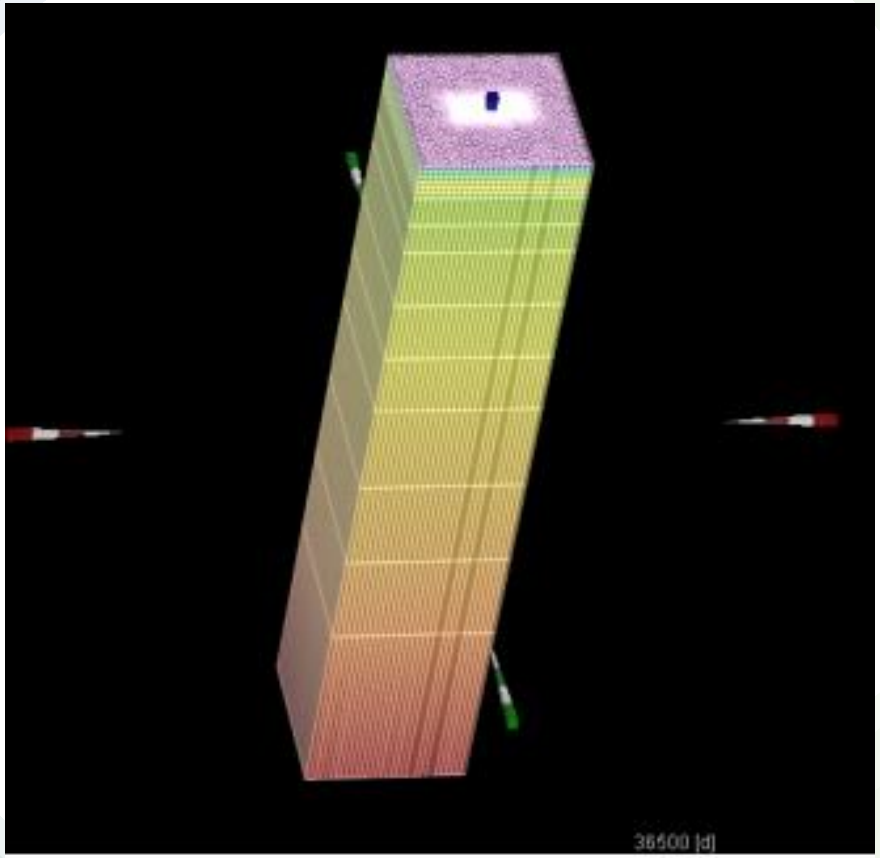
- Finite Element subsurface FLOW system (FEFLOW) is a software to simulate of groundwater flow and heat transfer in porous media.

- FEFLOW can calculate the groundwater age, expect the lifetime, and the exit probability.



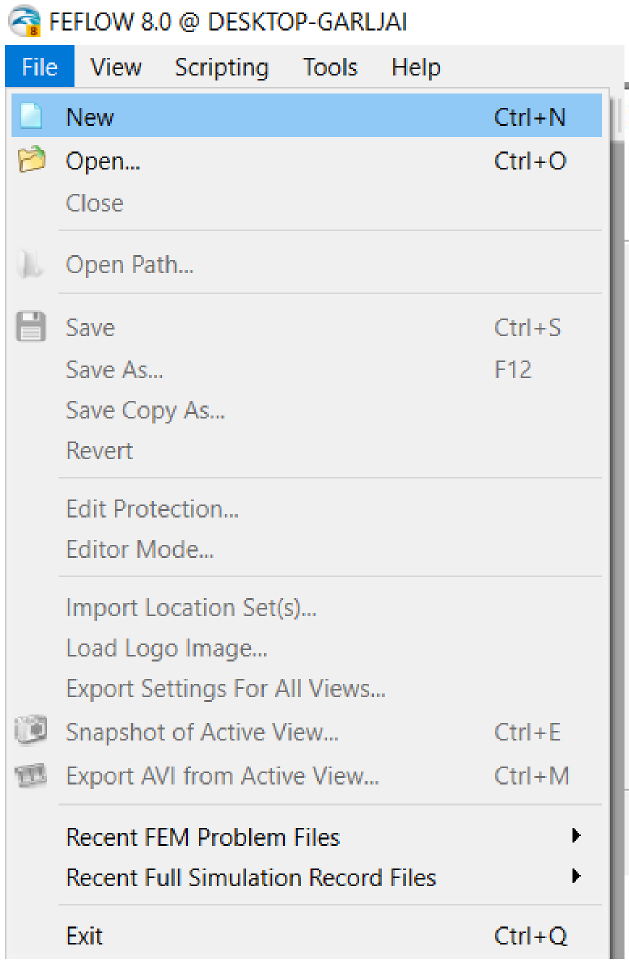
Numerical simulation with FEFLOW

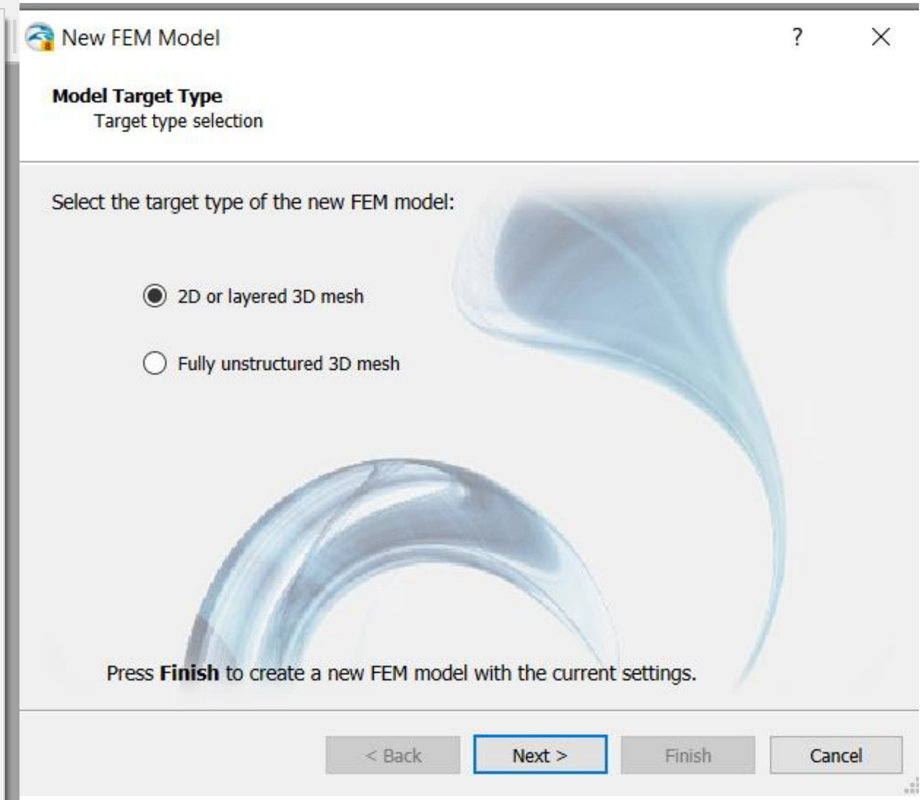
- Numerical methods vs Analytical solution:
  - The analytical solution only gives an initial approximation of the measured property or behavior.
  - Numerical simulation takes into consideration the spatial variation of properties.
  - Also, simulation along the lifetime with variable conditions.



STEPS of modelling Using FEFLOW

1- Constructing new model





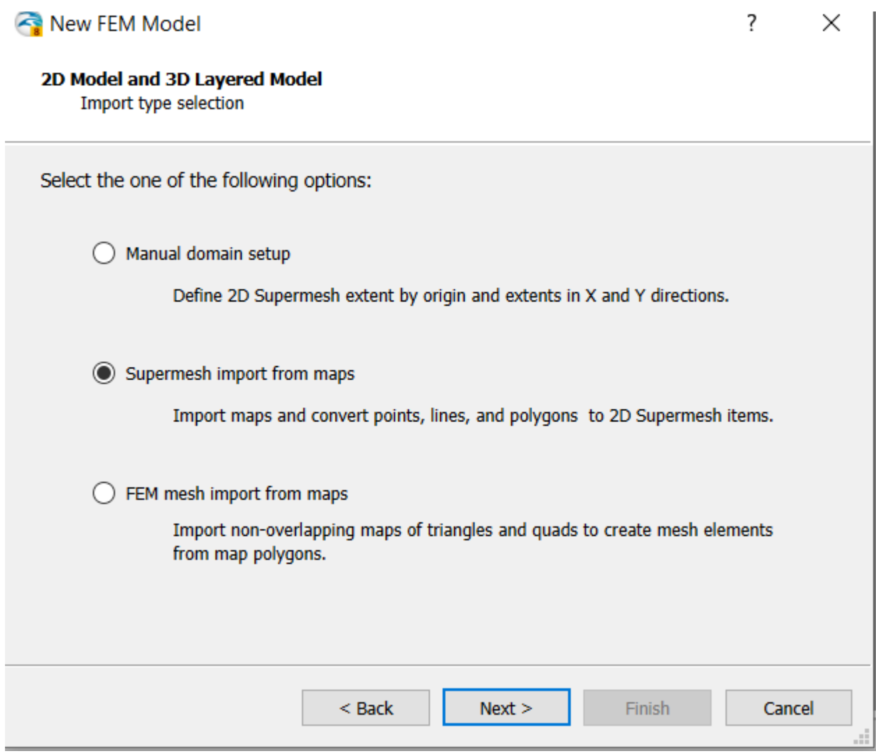
Model Target Type
Target type selection

Select the target type of the new FEM model:

● 2D or layered 3D mesh

○ Fully unstructured 3D mesh

Press **Finish** to create a new FEM model with the current settings.



2D Model and 3D Layered Model
Import type selection

Select the one of the following options:

○ Manual domain setup

Define 2D Supermesh extent by origin and extents in X and Y directions.

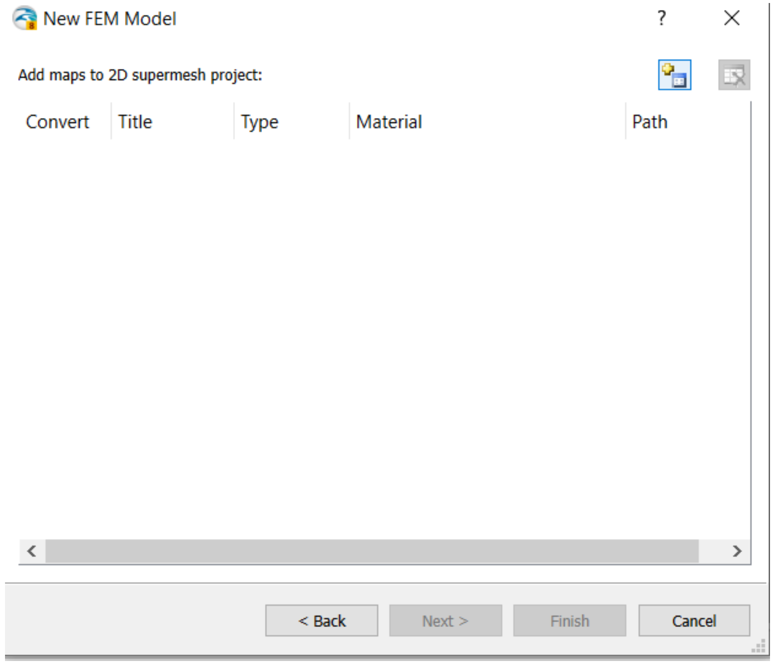
● Supermesh import from maps

Import maps and convert points, lines, and polygons to 2D Supermesh items.

○ FEM mesh import from maps

Import non-overlapping maps of triangles and quads to create mesh elements from map polygons.

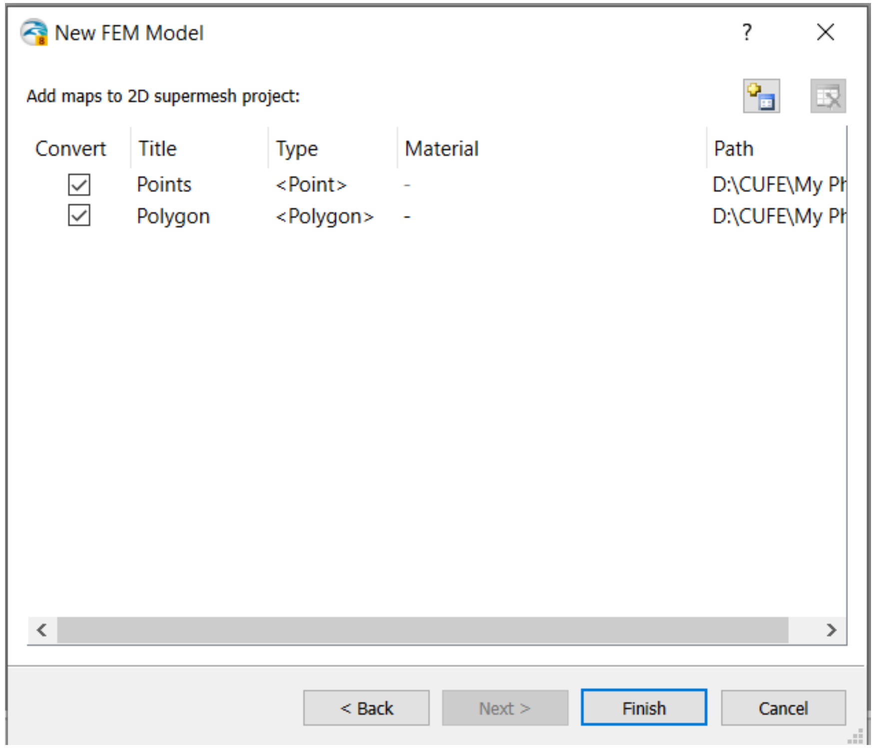
2- Constructing 2-D model



New FEM Model

Add maps to 2D supermesh project:

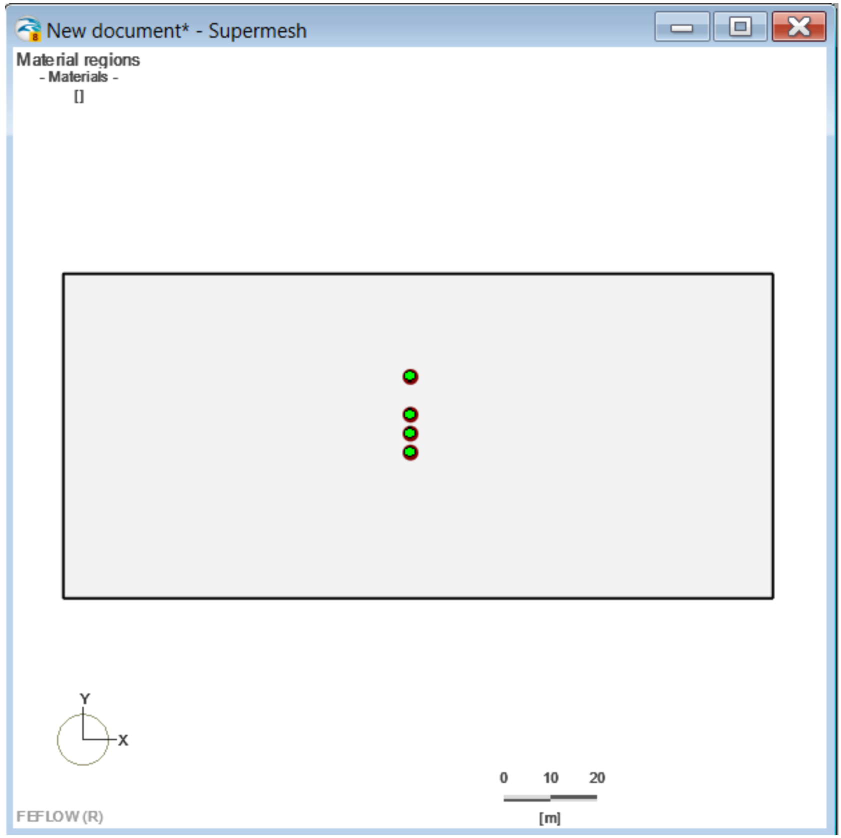
Convert	Title	Type	Material	Path



New FEM Model

Add maps to 2D supermesh project:

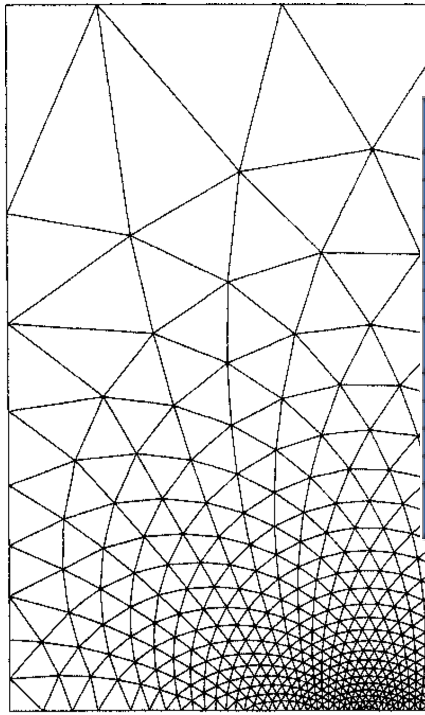
Convert	Title	Type	Material	Path
☑	Points	<Point>	-	D:\CUFE\My Pl
☑	Polygon	<Polygon>	-	D:\CUFE\My Pl



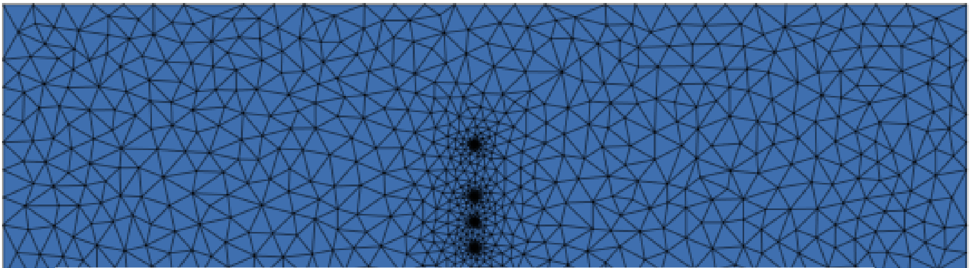
New document* - Supermesh

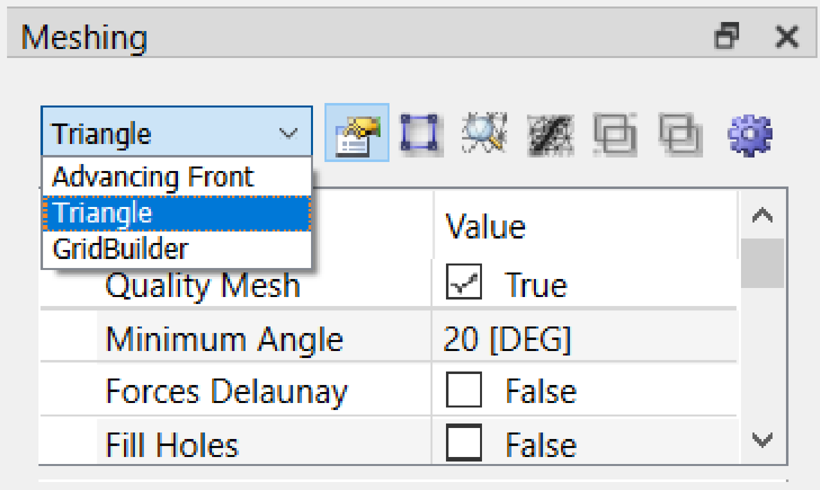
Material regions
- Materials -
[]

3- Constructing the supermesh



Triangle meshing



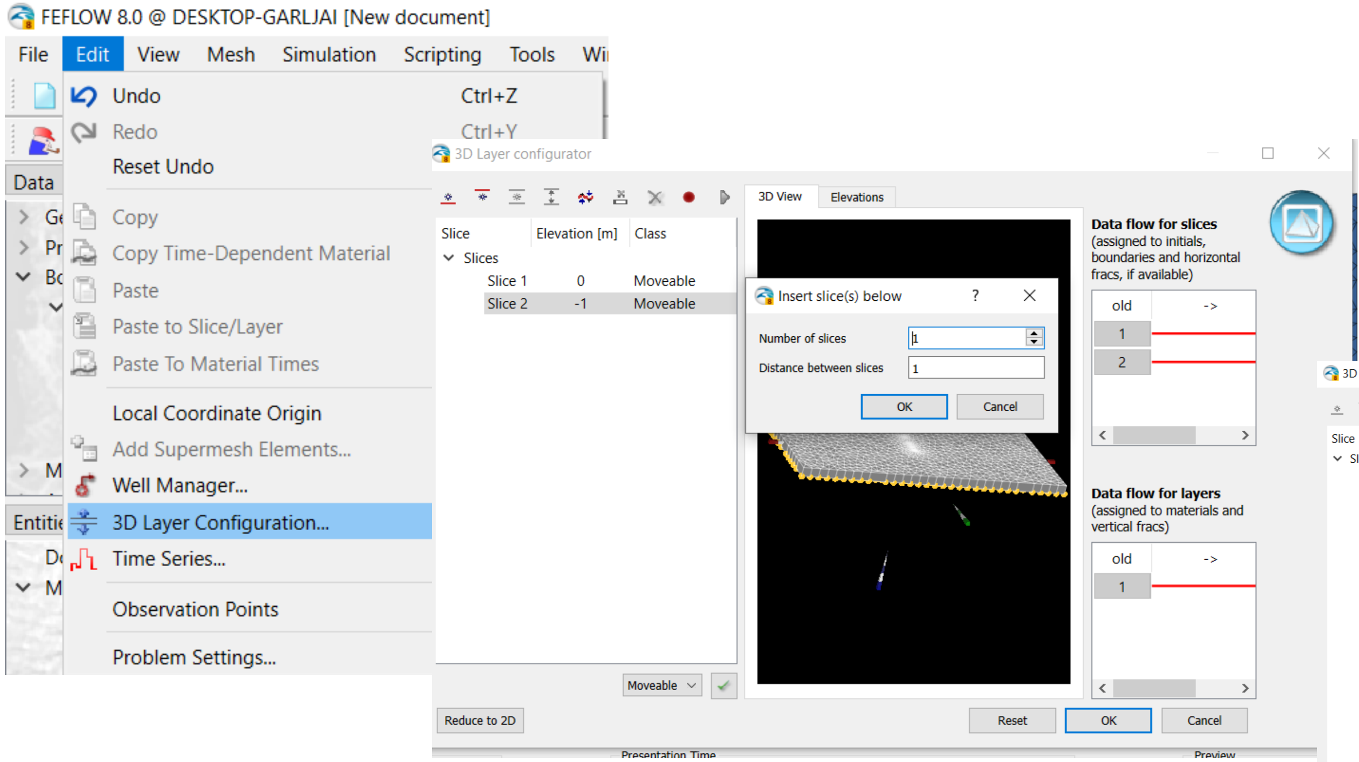


	Value
Quality Mesh	☑ True
Minimum Angle	20 [DEG]
Forces Delaunay	☐ False
Fill Holes	☐ False

- The ground is modeled as a 2-D supermesh by the following procedures:
  - Get the AutoCad map for the area.
  - Transform the map into shape file (Shp) through GIS.
  - Insert separate shp files for the polygons (Area), Lines (Buildings), and Points (Wells or Borehole heat exchangers).
  - Generate meshes (i.e. Triangulation).

3- Constructing the 3-D supermesh

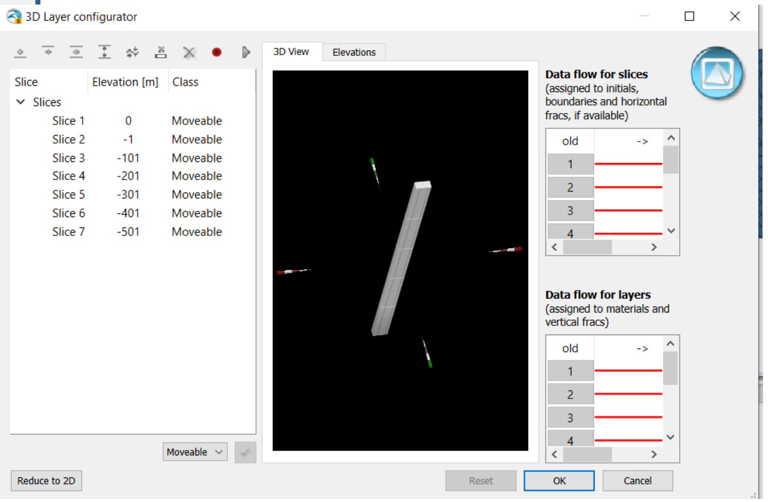
- Then, a 3-D model is built. According to the real thickness and layers.



Slice	Elevation [m]	Class
Slices		
Slice 1	0	Moveable
Slice 2	-1	Moveable

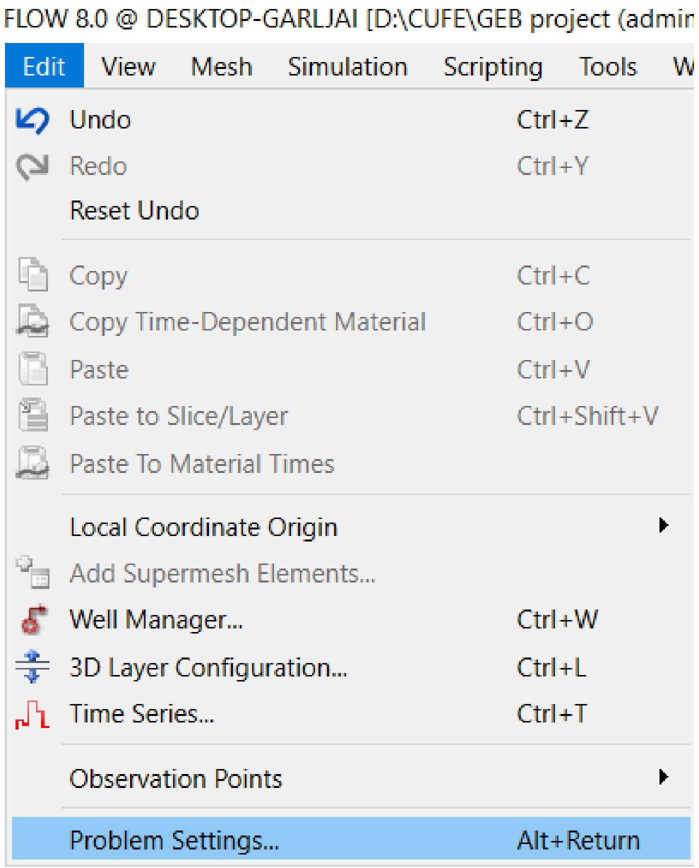
Number of slices 1
Distance between slices 1

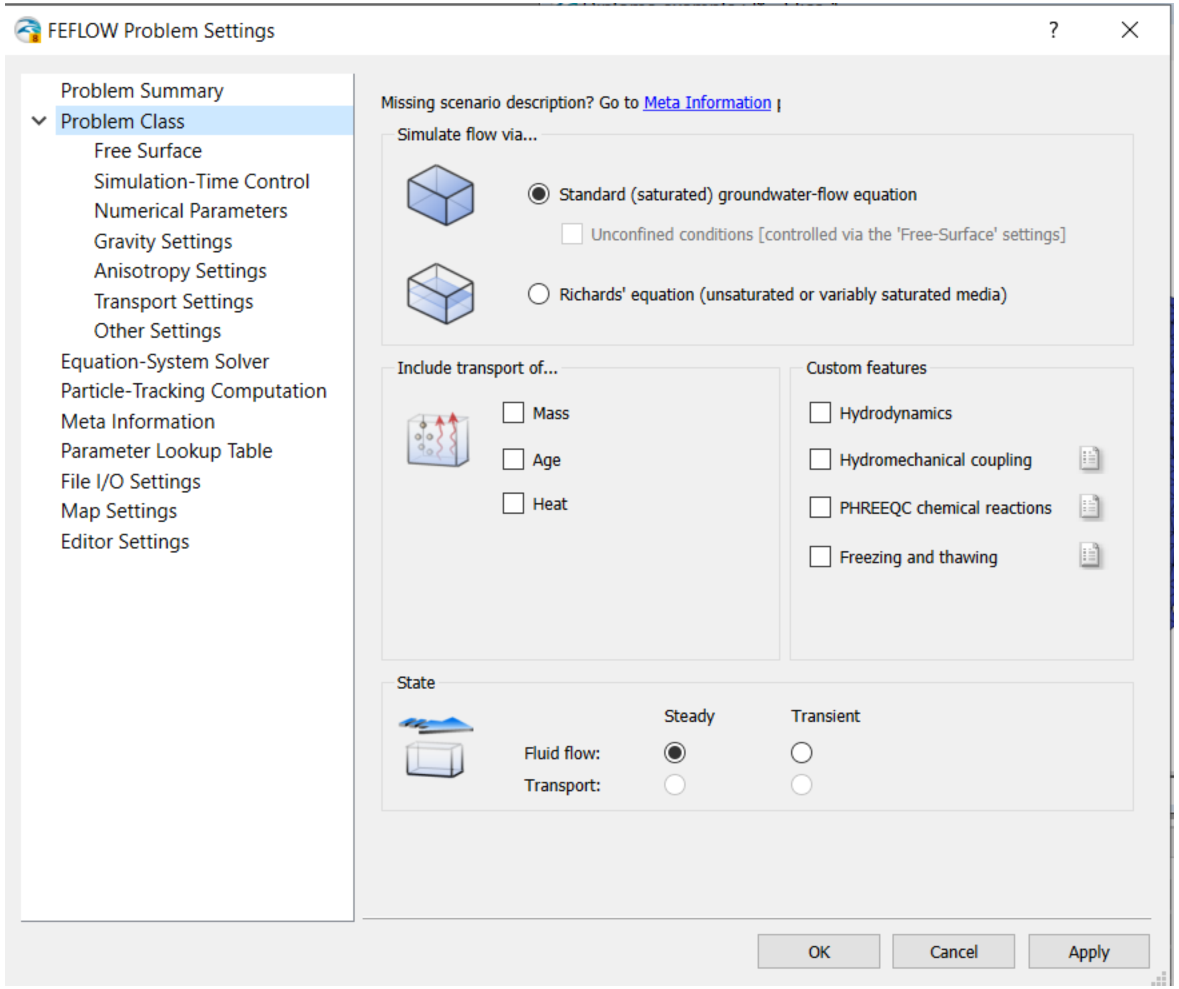
3-D model transformation



Slice	Elevation [m]	Class
Slices		
Slice 1	0	Moveable
Slice 2	-1	Moveable
Slice 3	-101	Moveable
Slice 4	-201	Moveable
Slice 5	-301	Moveable
Slice 6	-401	Moveable
Slice 7	-501	Moveable

4- Selecting the flow type





Missing scenario description? Go to Meta Information

Simulate flow via...

● Standard (saturated) groundwater-flow equation

☐ Unconfined conditions [controlled via the 'Free-Surface' settings]

○ Richards' equation (unsaturated or variably saturated media)

Include transport of...

☐ Mass

☐ Age

☐ Heat

Custom features

☐ Hydrodynamics

☐ Hydromechanical coupling

☐ PHREEQC chemical reactions

☐ Freezing and thawing

State

	Steady	Transient
Fluid flow:	●	○
Transport:	○	○

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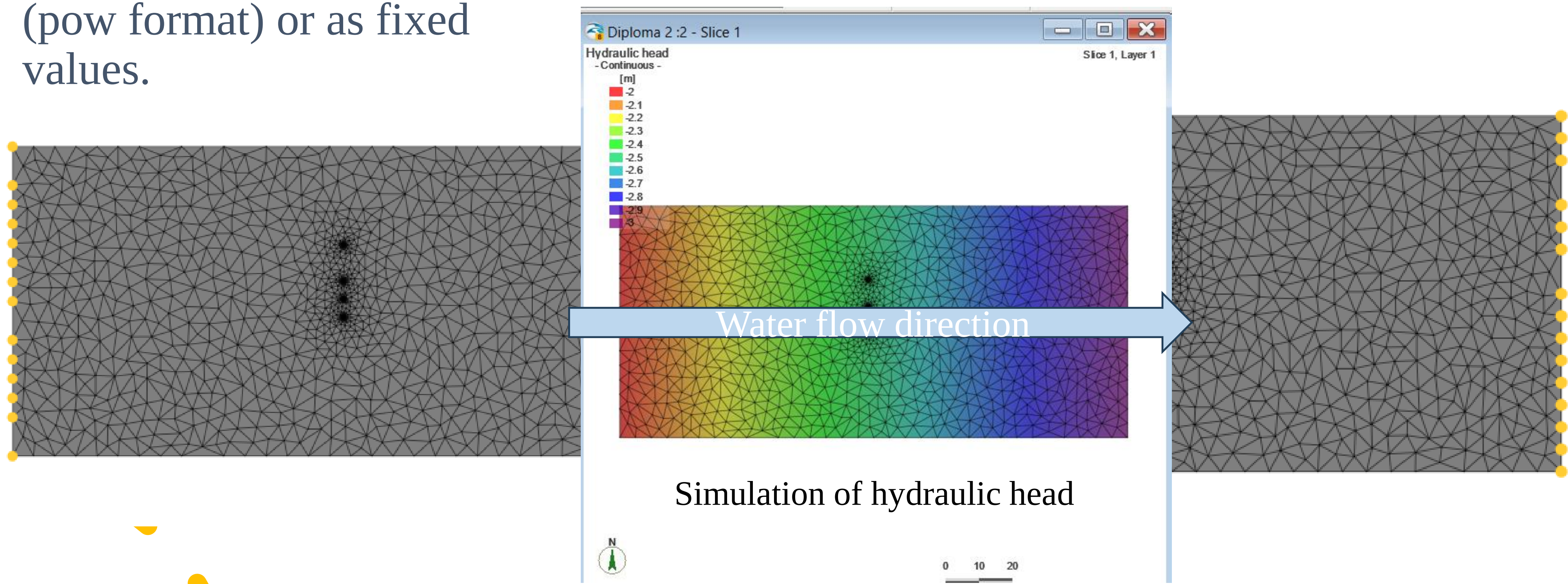
5- Boundary conditions for Hydraulic head and material properties

- The boundary conditions for hydraulic head are inserted as time series in (pow format) or as fixed values.



Simulation of hydraulic head

5- Boundary conditions (BC) for Hydraulic head and material properties

- The material properties are inserted into the model to represent the real case.
- These properties may be thermal, hydrological, and geological.

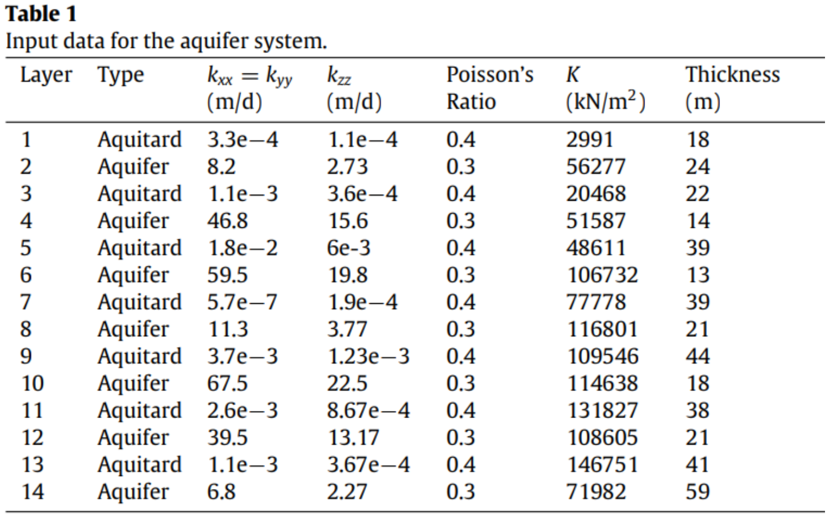
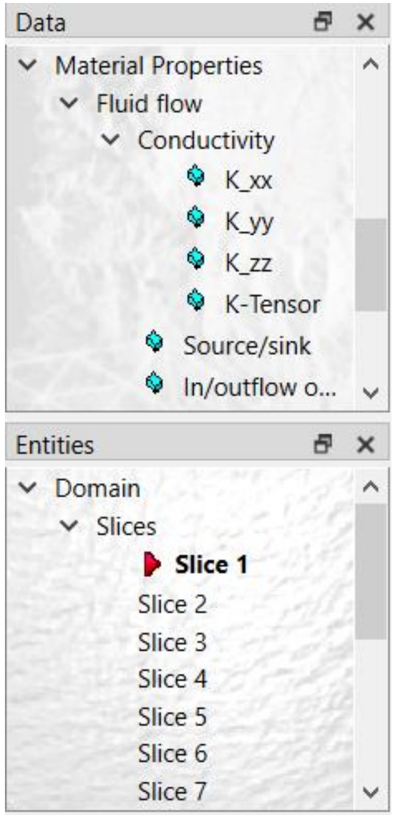
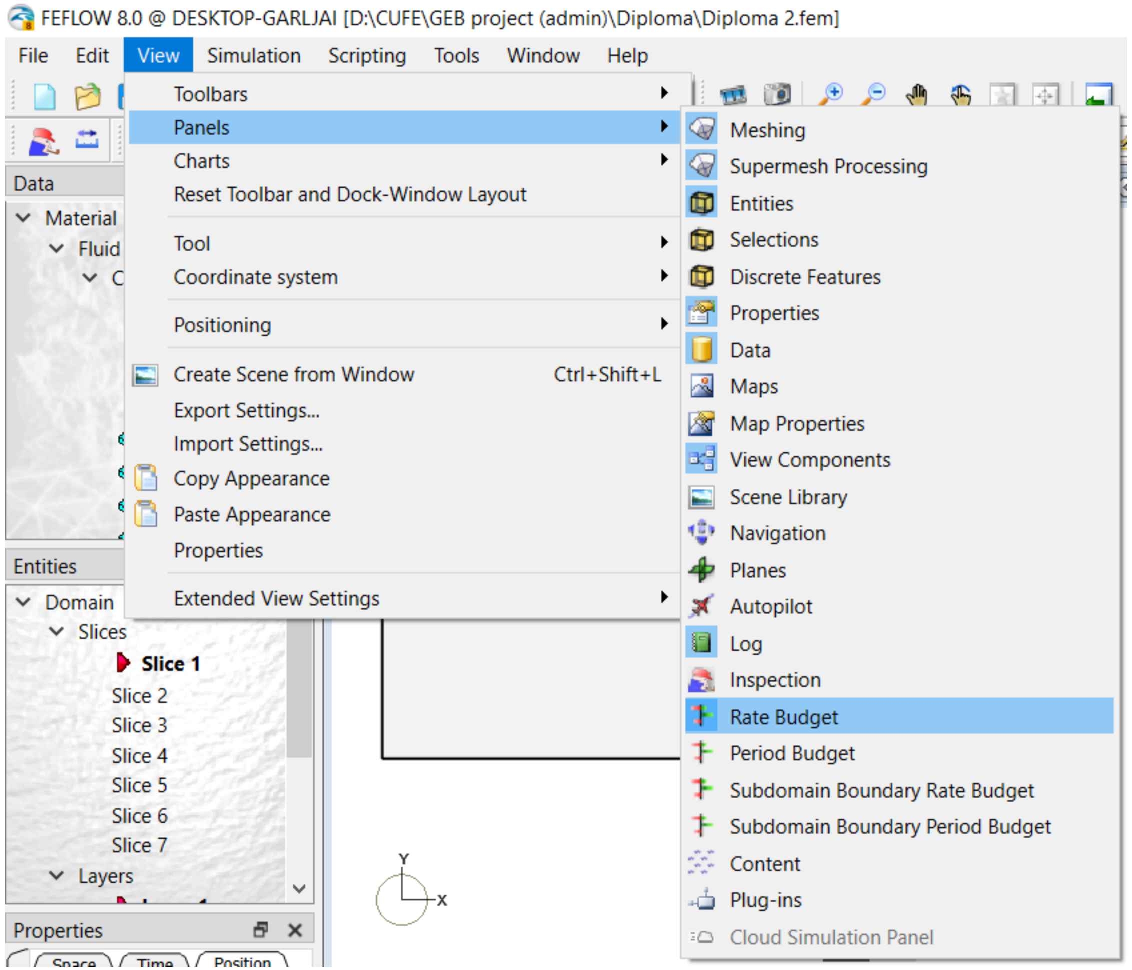


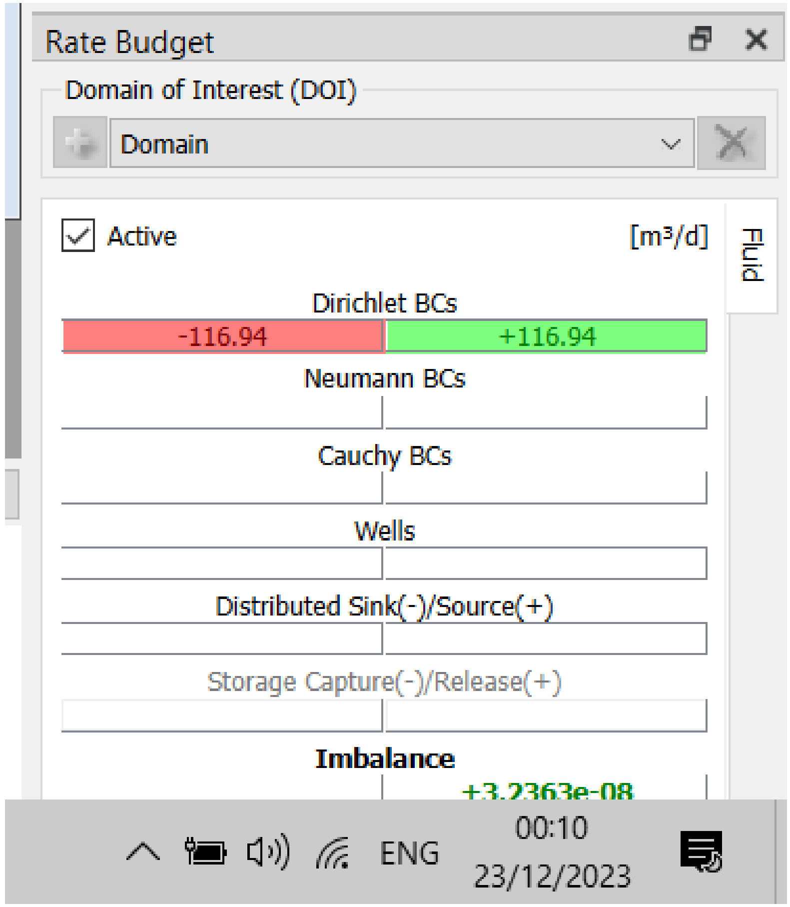
Table 1
Input data for the aquifer system.

Layer	Type	$k_{xx} = k_{yy}$ (m/d)	k_{zz} (m/d)	Poisson's Ratio	K (kN/m^2)	Thickness (m)
1	Aquitard	3.3e−4	1.1e−4	0.4	2991	18
2	Aquifer	8.2	2.73	0.3	56277	24
3	Aquitard	1.1e−3	3.6e−4	0.4	20468	22
4	Aquifer	46.8	15.6	0.3	51587	14
5	Aquitard	1.8e−2	6e-3	0.4	48611	39
6	Aquifer	59.5	19.8	0.3	106732	13
7	Aquitard	5.7e−7	1.9e−4	0.4	77778	39
8	Aquifer	11.3	3.77	0.3	116801	21
9	Aquitard	3.7e−3	1.23e−3	0.4	109546	44
10	Aquifer	67.5	22.5	0.3	114638	18
11	Aquitard	2.6e−3	8.67e−4	0.4	131827	38
12	Aquifer	39.5	13.17	0.3	108605	21
13	Aquitard	1.1e−3	3.67e−4	0.4	146751	41
14	Aquifer	6.8	2.27	0.3	71982	59



6- Check the water balance into the model





☑ Active [m³/d]

Dirichlet BCs: -116.94 | +116.94

Neumann BCs

Cauchy BCs

Wells

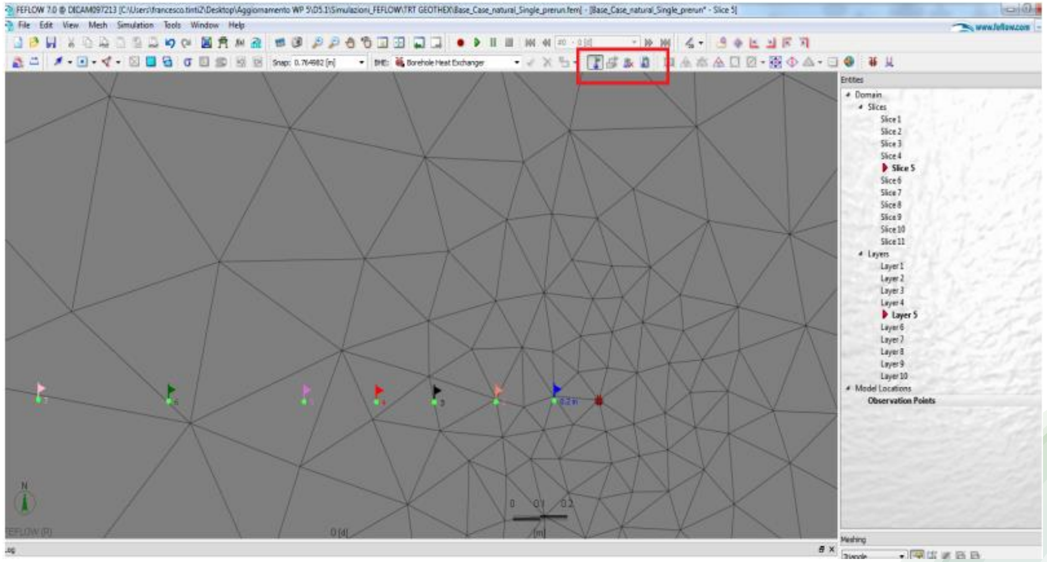
Distributed Sink(-)/Source(+)

Storage Capture(-)/Release(+)

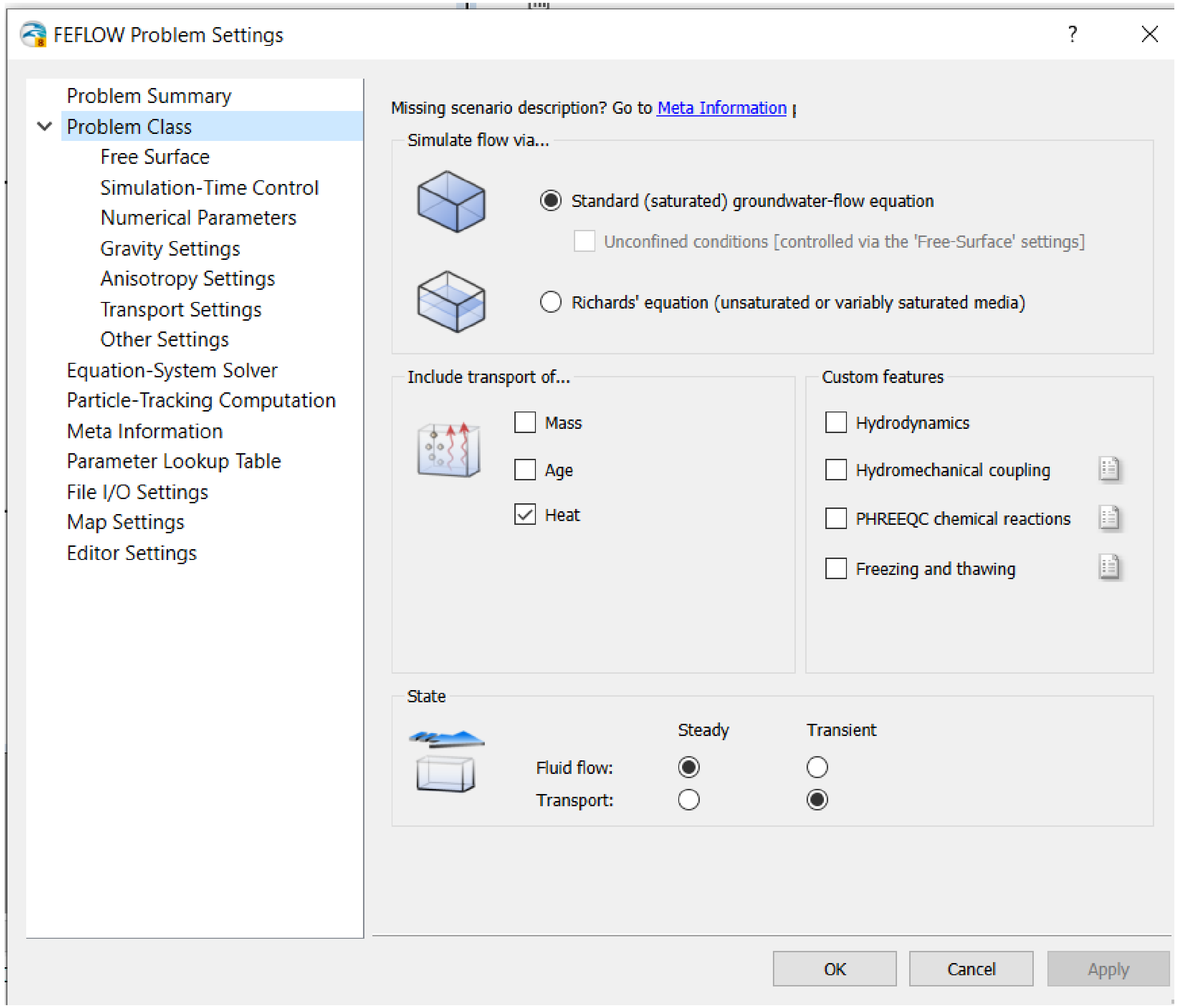
Imbalance: +3.2363e-08

7- Initial state validation

- In order to validate the initial state of a model, observation points are set in the numerical model.
- Data obtained from the observation points is compared to the recorded data through sensors in site (such as downhole temperature, water table in a pre-drilled well or piezometer).



8- Heat transfer Problem



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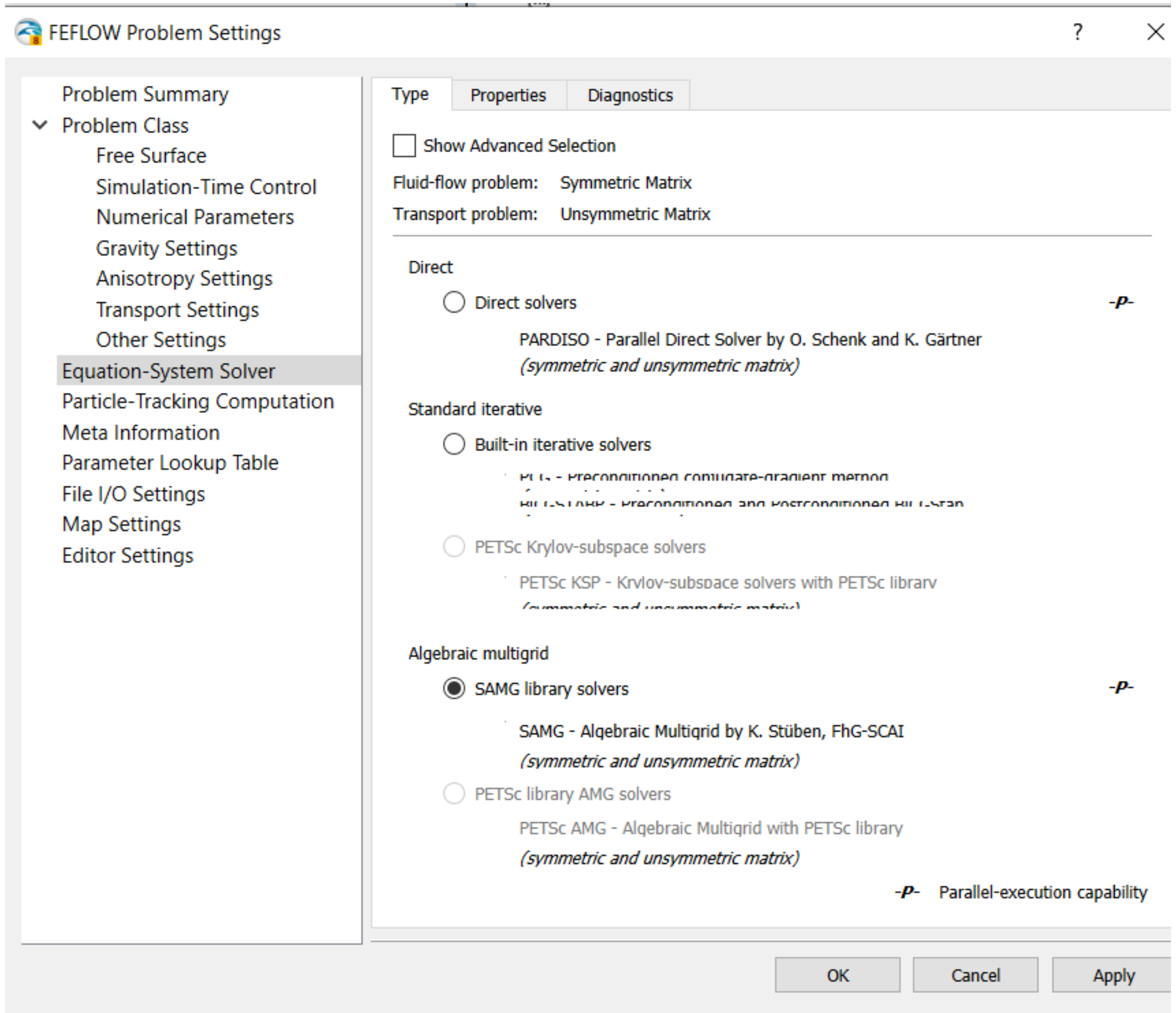
State

	Steady	Transient
Fluid flow:	●	○
Transport:	○	●



☐ Show Advanced Selection

Fluid-flow problem: Symmetric Matrix

Transport problem: Unsymmetric Matrix

Direct

○ Direct solvers -P-

PARDISO - Parallel Direct Solver by O. Schenk and K. Gärtner
(symmetric and unsymmetric matrix)

Standard iterative

○ Built-in iterative solvers

PCG - Preconditioned conjugate-gradient method

BiCGSTABP - Preconditioned and Postconditioned BiCGStab

○ PETSc Krylov-subspace solvers

PETSc KSP - Krylov-subspace solvers with PETSc library
(symmetric and unsymmetric matrix)

Algebraic multigrid

● SAMG library solvers -P-

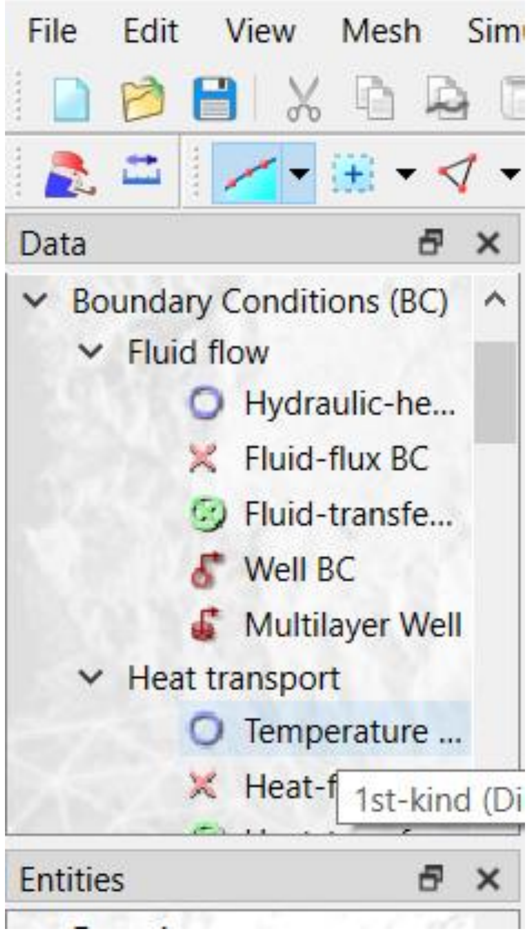
SAMG - Algebraic Multigrid by K. Stüben, FhG-SCAI
(symmetric and unsymmetric matrix)

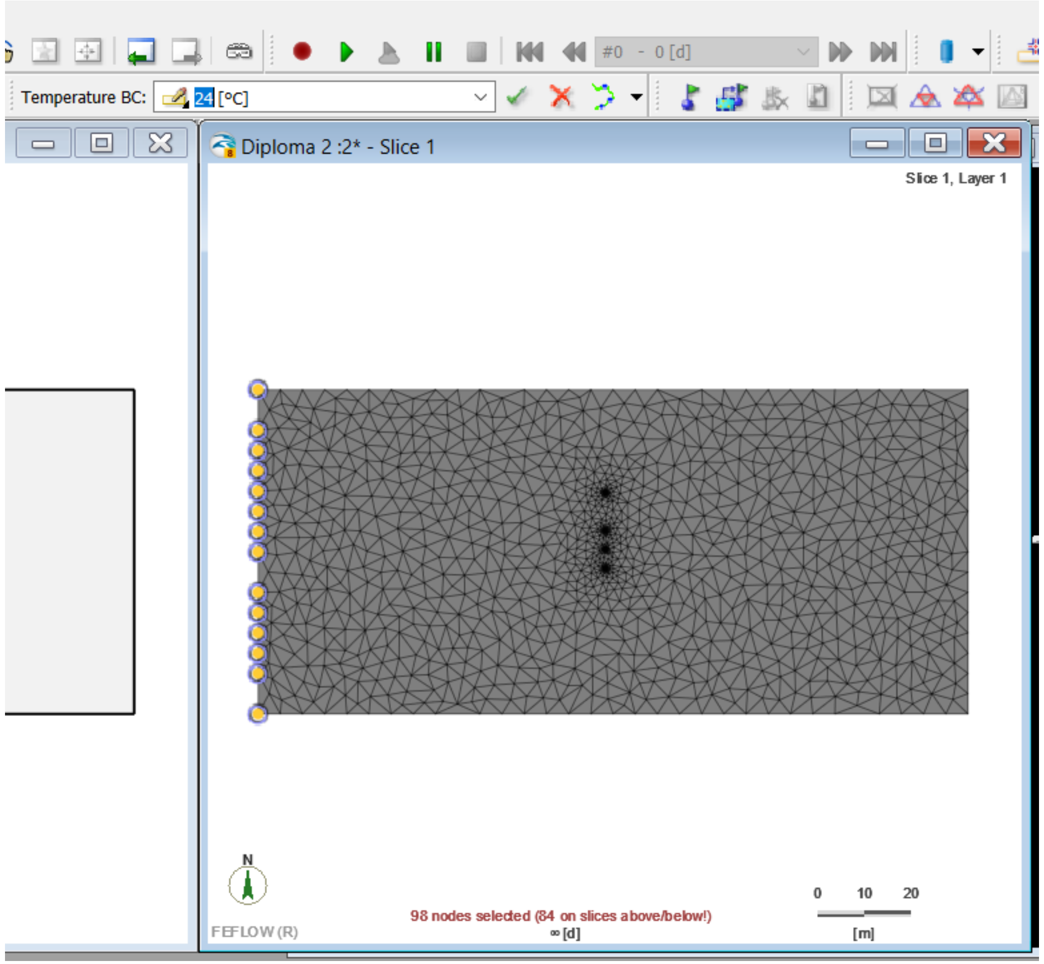
○ PETSc library AMG solvers

PETSc AMG - Algebraic Multigrid with PETSc library
(symmetric and unsymmetric matrix)

-P- Parallel-execution capability

8- BC for Heat transfer



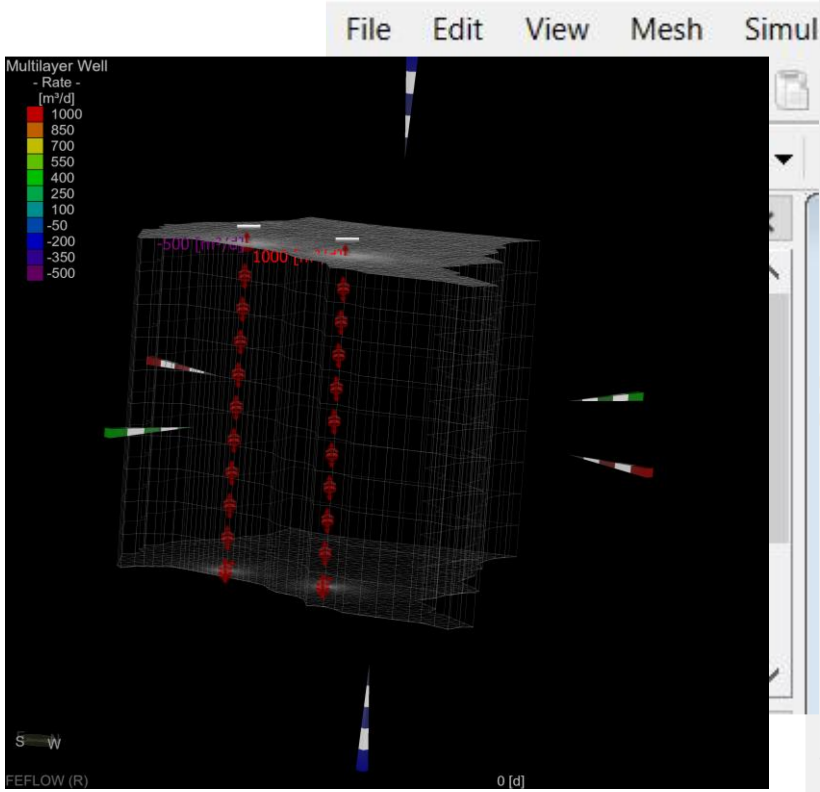

Temperature BC: 24 [°C]

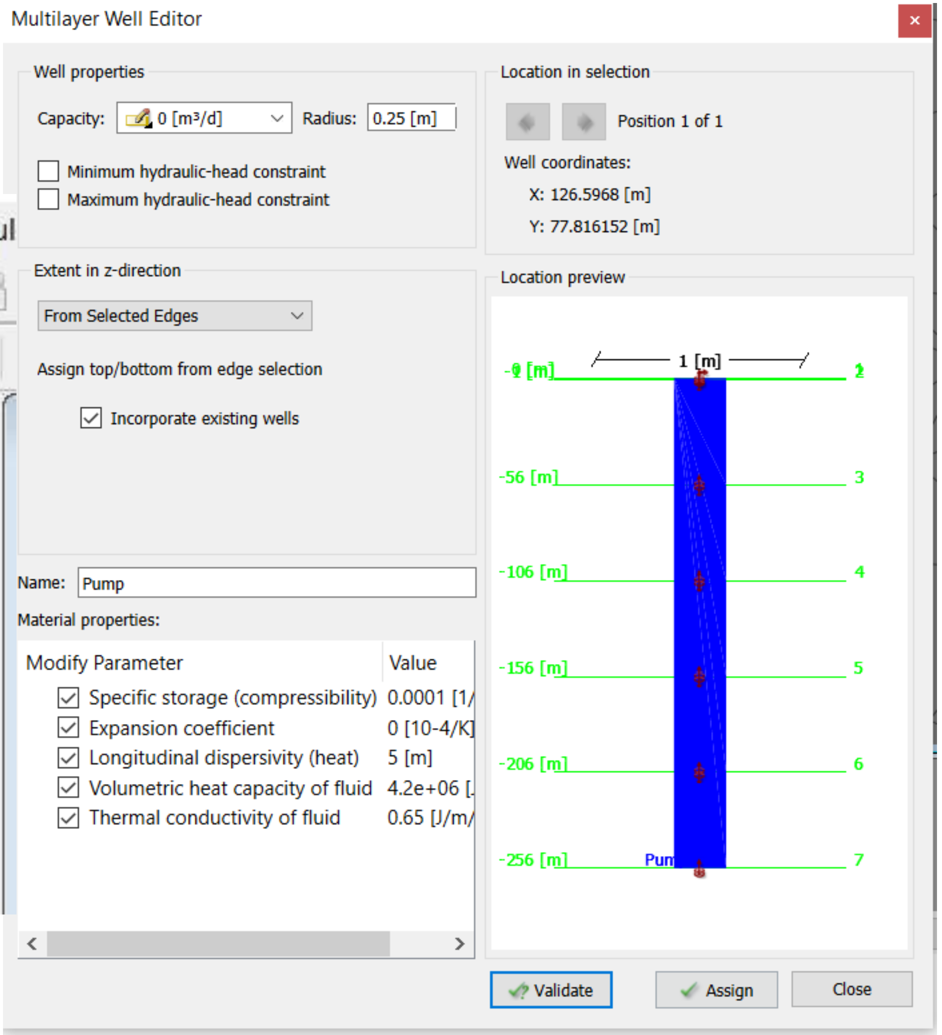
98 nodes selected (84 on slices above/below!)

- Set the Temperature BC for the inflow water at the border.

9- Multilayer well

- Set production or injection wells at the points by selecting Multilayer Well from the Boundary conditions list at the nodes.




Multilayer Well Editor

Well properties

Capacity: 0 [m³/d] Radius: 0.25 [m]

☐ Minimum hydraulic-head constraint
☐ Maximum hydraulic-head constraint

Location in selection

Position 1 of 1

Well coordinates:
X: 126.5968 [m]
Y: 77.816152 [m]

Extent in z-direction

From Selected Edges

Assign top/bottom from edge selection

☑ Incorporate existing wells

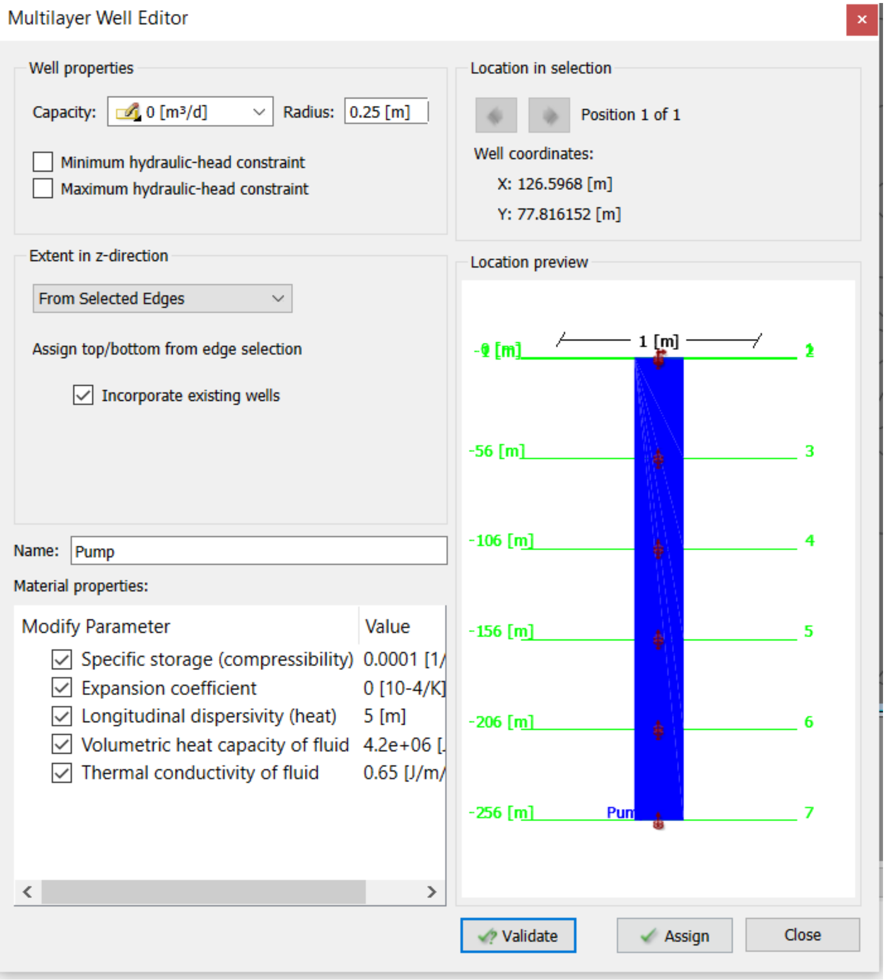
Name: Pump

Material properties:

Modify Parameter	Value
☑ Specific storage (compressibility)	0.0001 [1/
☑ Expansion coefficient	0 [10-4/K]
☑ Longitudinal dispersivity (heat)	5 [m]
☑ Volumetric heat capacity of fluid	4.2e+06 [
☑ Thermal conductivity of fluid	0.65 [J/m/

10- BC for Multilayer well

- The pumping rate should be assigned to each well (m³/day) as fixed value or variable with time (Time series).
  - Extraction +ve
  - Injection –ve


Multilayer Well Editor

Well properties

Capacity: 0 [m³/d] Radius: 0.25 [m]

☐ Minimum hydraulic-head constraint
☐ Maximum hydraulic-head constraint

Location in selection

Position 1 of 1

Well coordinates:
X: 126.5968 [m]
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From Selected Edges

Assign top/bottom from edge selection

☑ Incorporate existing wells

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Material properties:

Modify Parameter	Value
☑ Specific storage (compressibility)	0.0001 [1/
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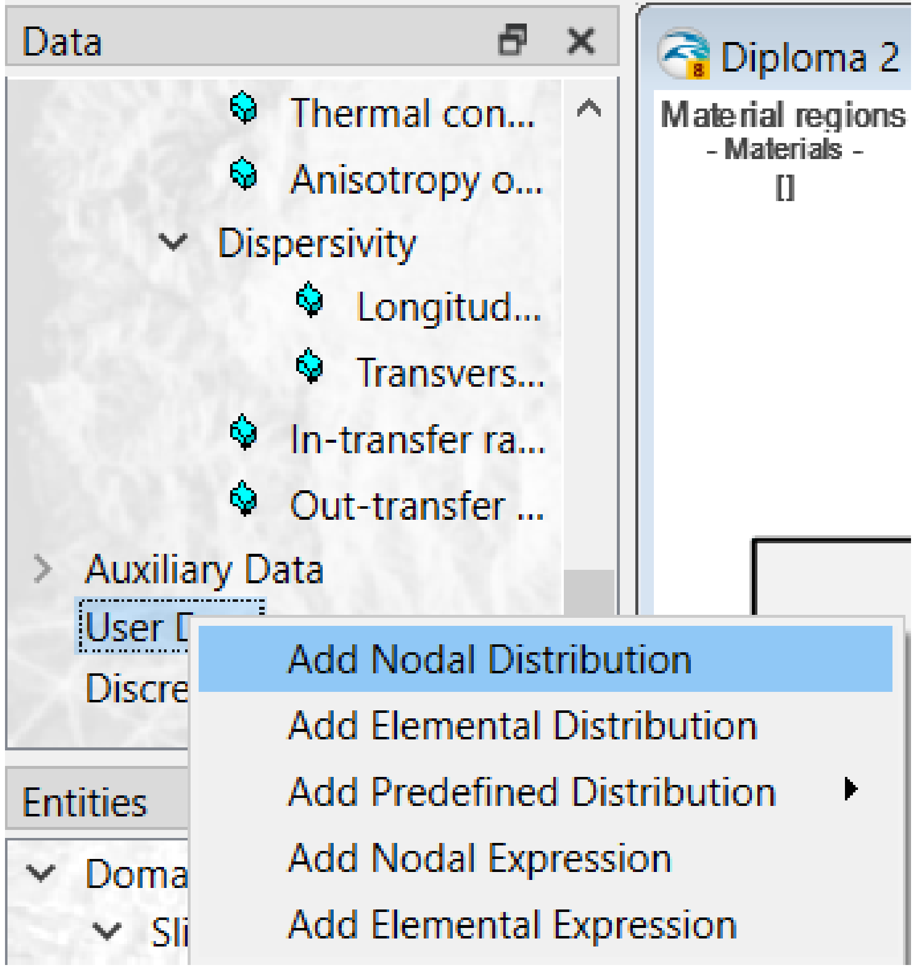
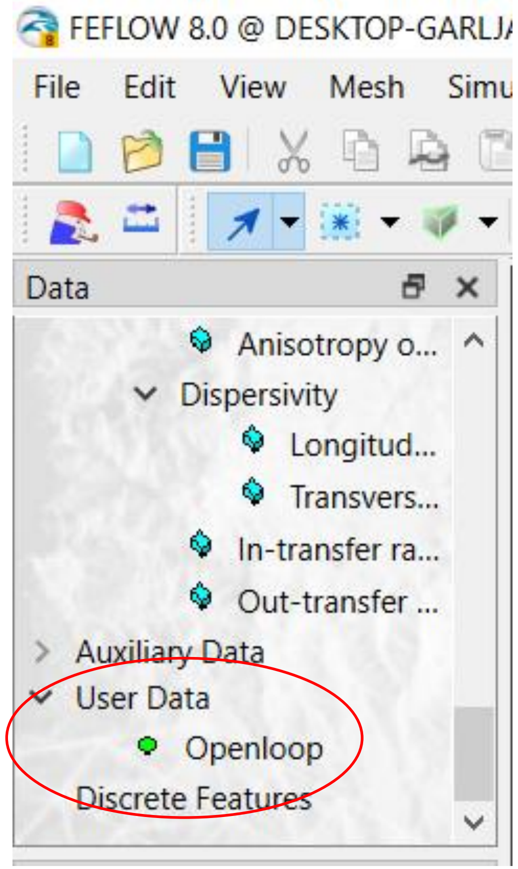
☑ Longitudinal dispersivity (heat)	5 [m]
☑ Volumetric heat capacity of fluid	4.2e+06 [
☑ Thermal conductivity of fluid	0.65 [J/m/

Location preview

11- Connect the Multilayer wells

- The production and injection wells are connected into an open loop plugin.
- The two wells are connected considering the temperature difference between the inlet and outlet water.

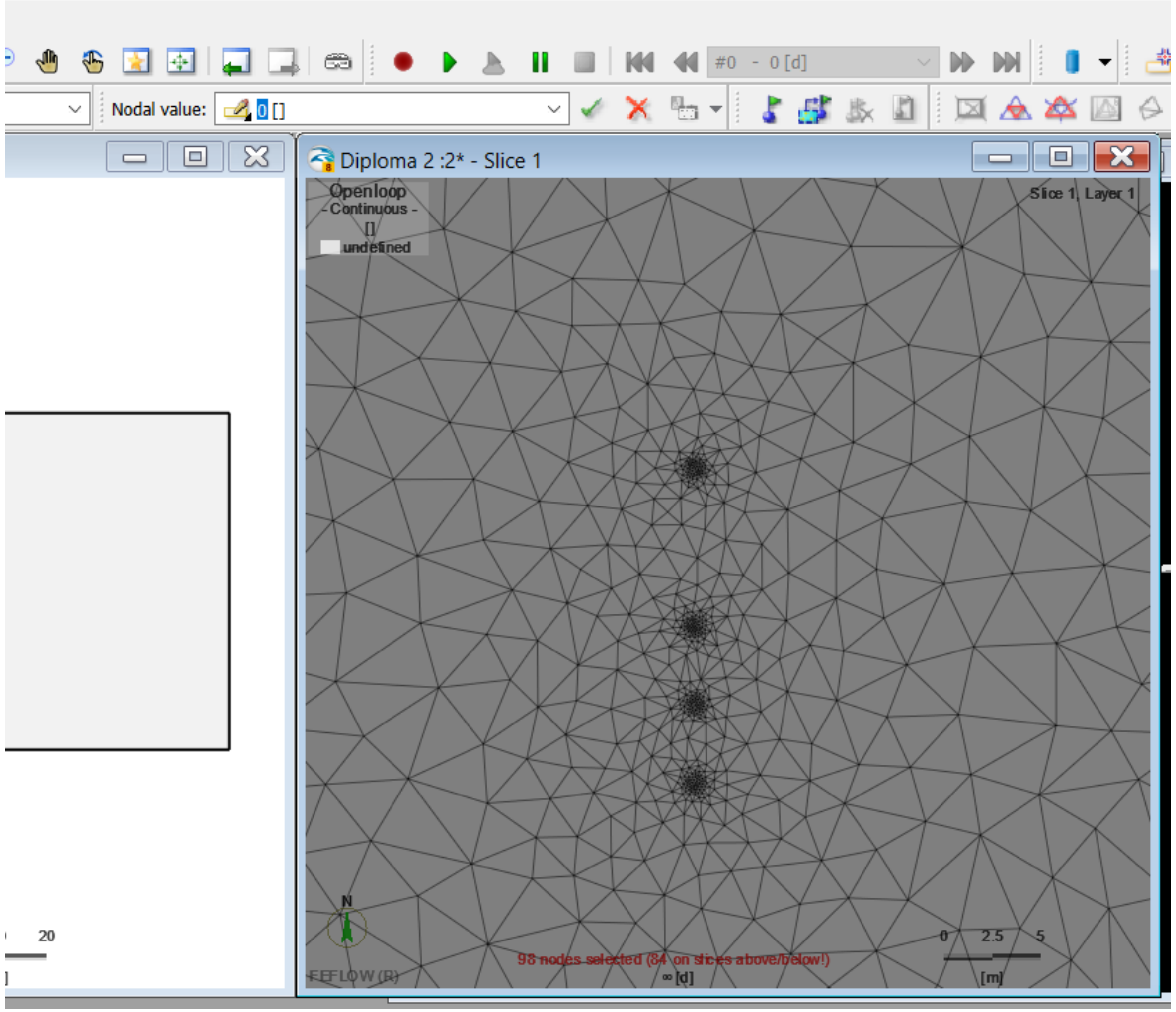




11- Connect the Multilayer wells

- In the above nodal value, insert the ID number of the Time series of the temperature difference.

- Then add the plugin to be valid.

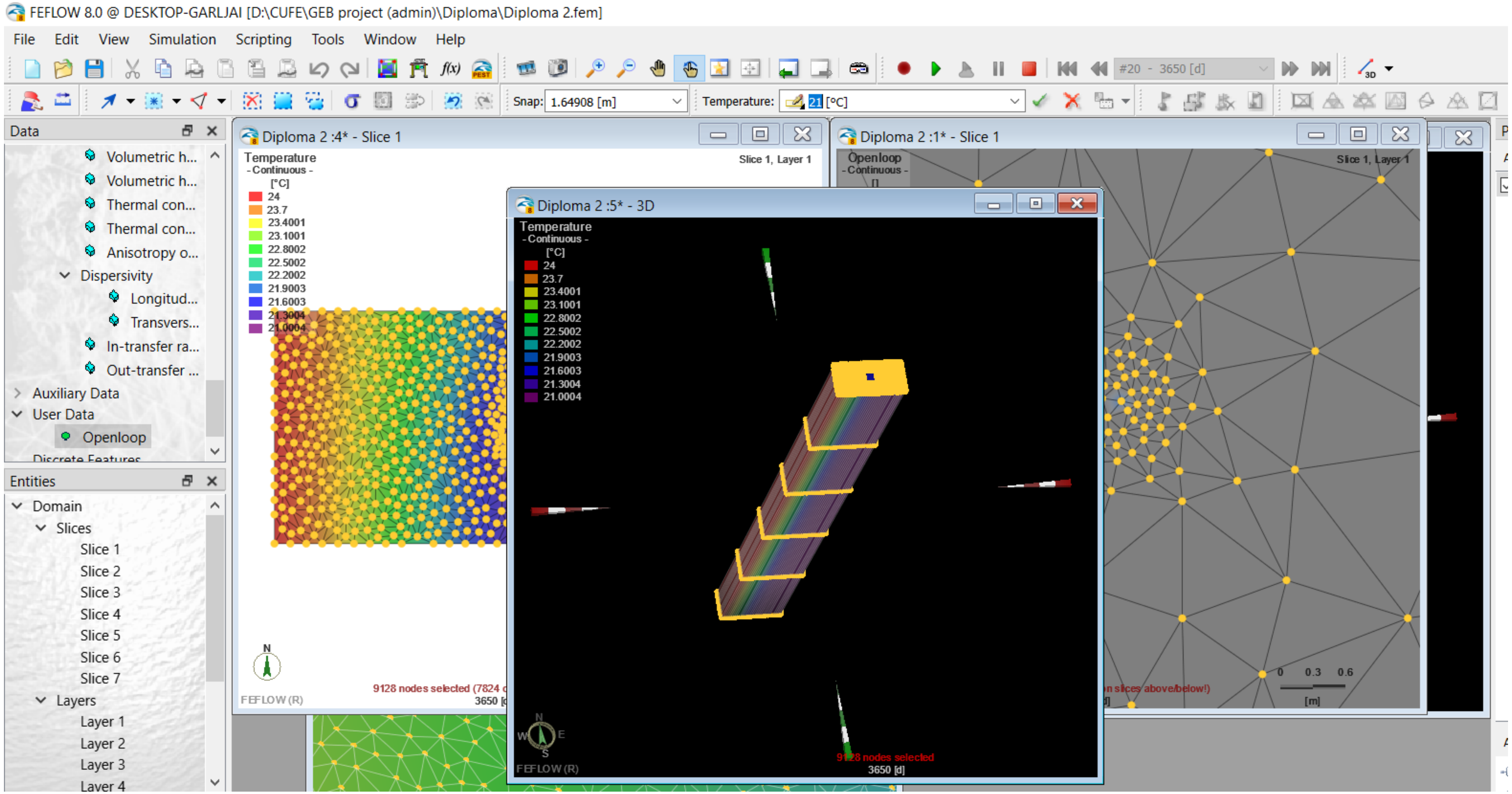


Nodal value: 0 []

98 nodes selected (84 on slices above/below!)

12- Assuming initial model temperature

- Start assuming an initial value of the model temperature. i.e 23 C and



FEFLOW 8.0 @ DESKTOP-GARLJAI [D:\CUFE\GEB project (admin)\Diploma\Diploma 2.fem]

Snap: 1.64908 [m]

Temperature: 21 [°C]

9128 nodes selected

3650 [d]

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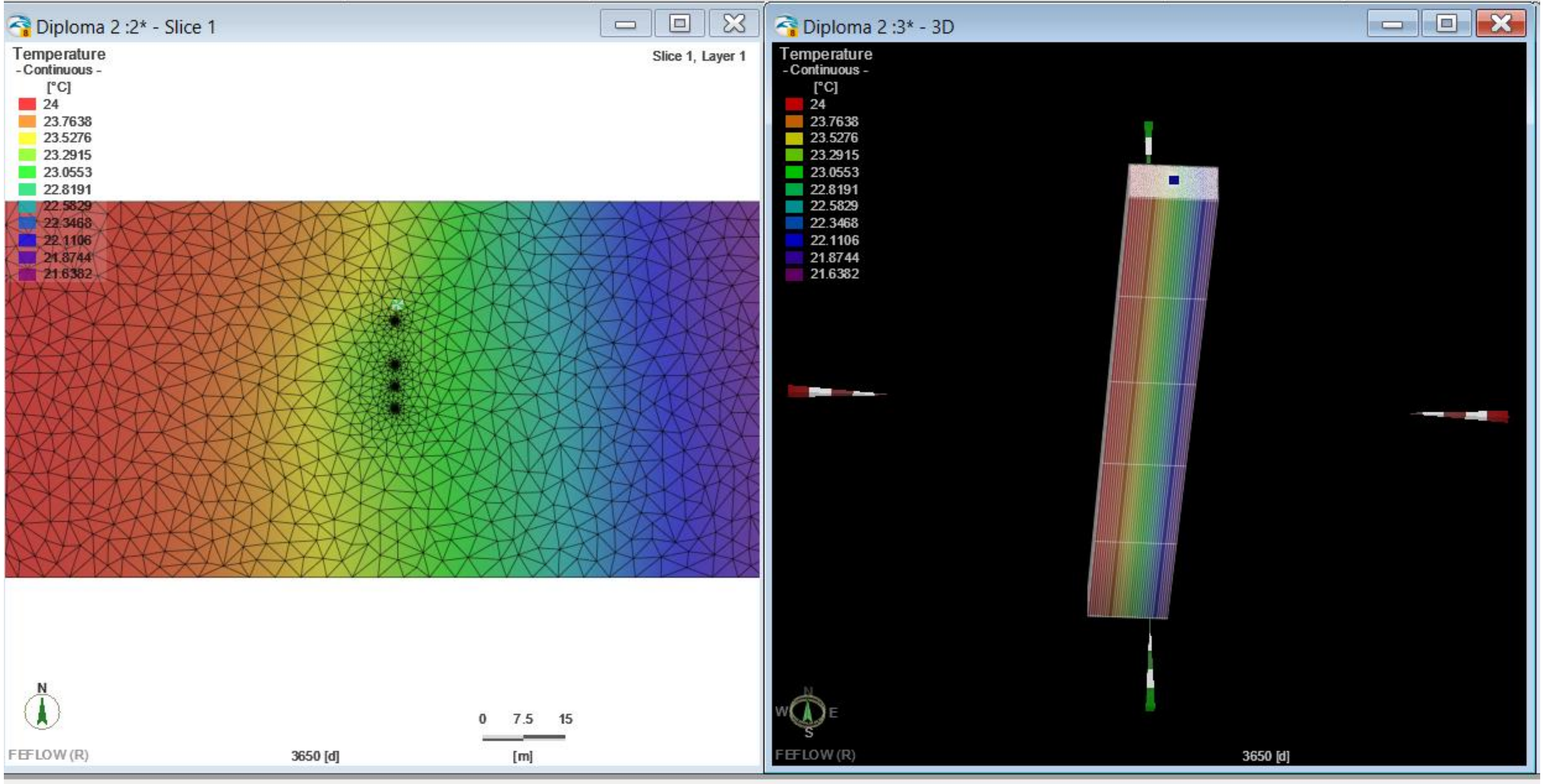
of the European Union

Faculty of Engineering
Cairo University

13- Running the simulation



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Cairo University

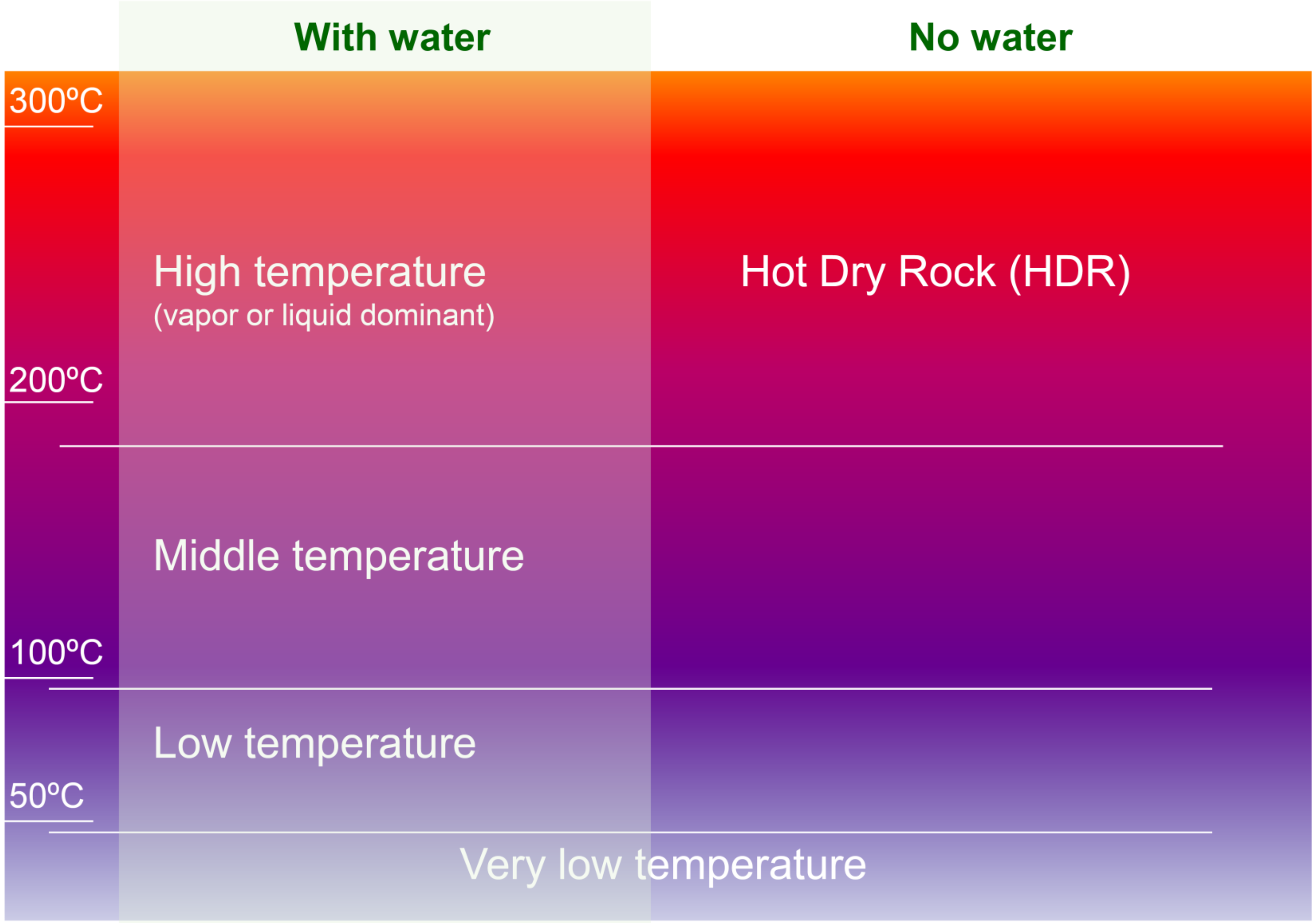
Geothermal Resources and Reservoir Engineering

Lecture 7: Geothermal Power Production

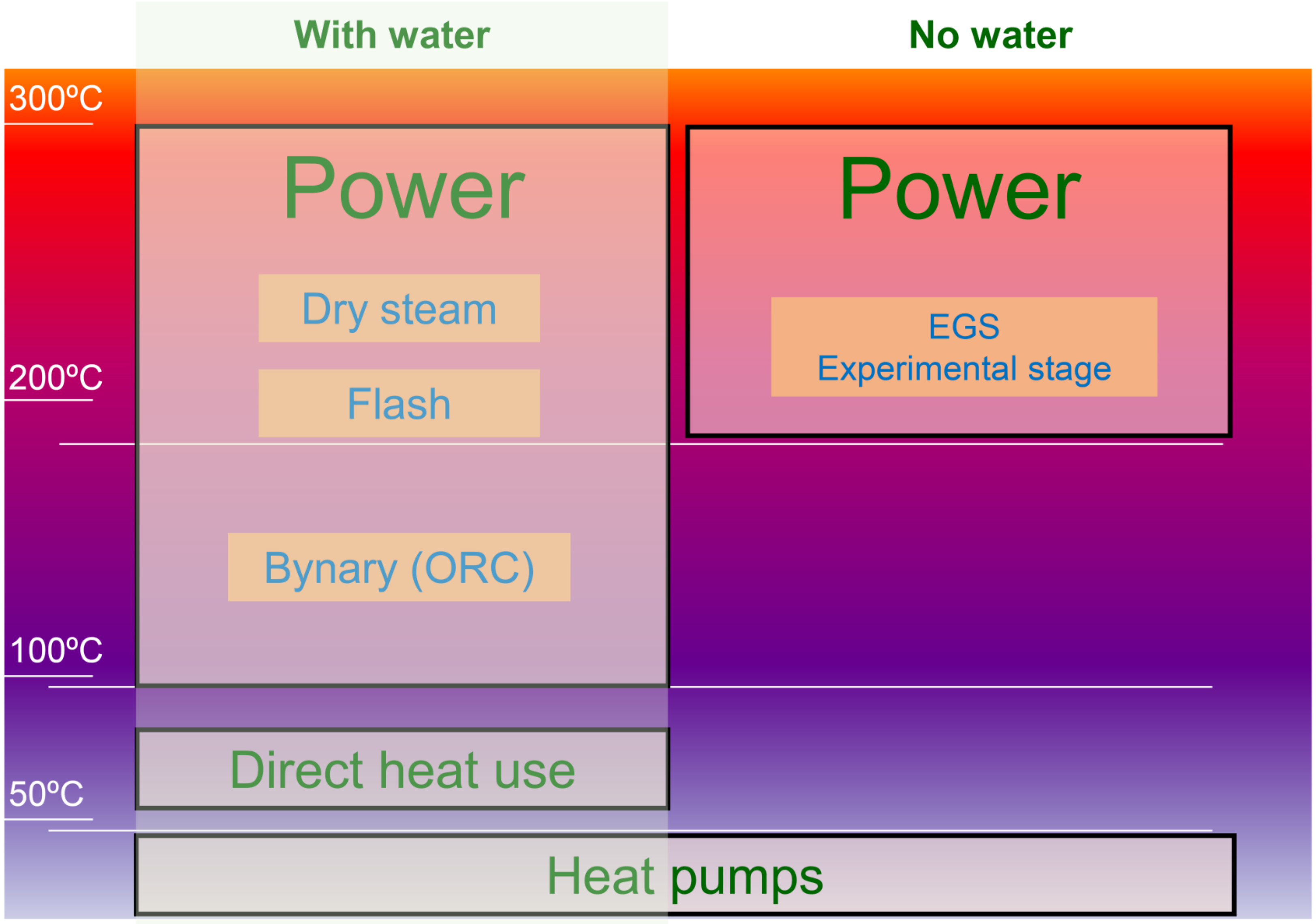
1. Initial Question

- Is it technically possible to obtain electricity from geothermal energy?
- Is it economically viable?
- How many countries have geothermal power plants?
- What is the total installed capacity?
- How many countries could have geothermal power plants?

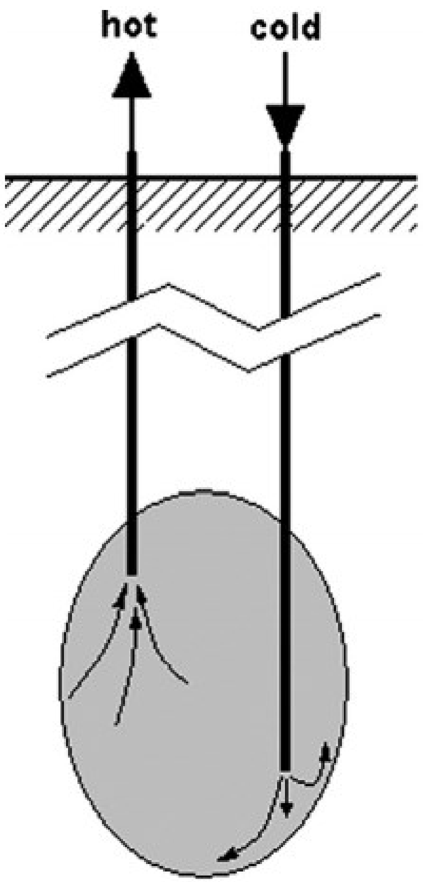
1. Reservoir classification

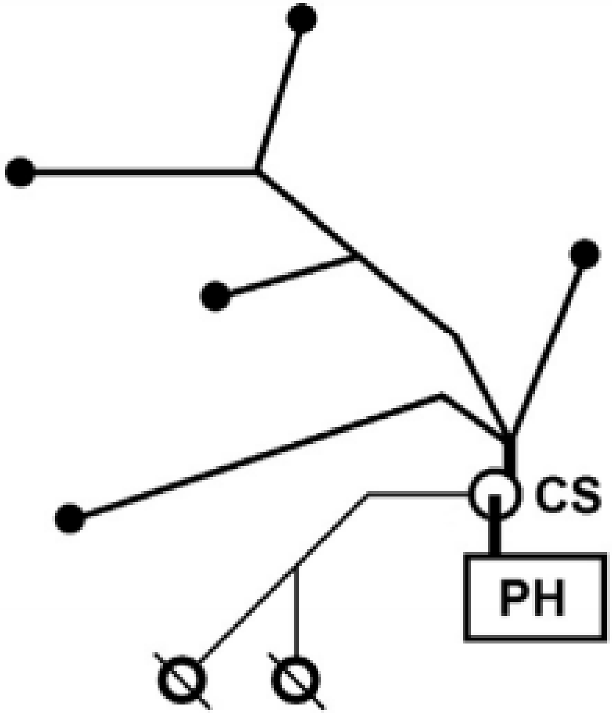


2. Reservoir exploitation

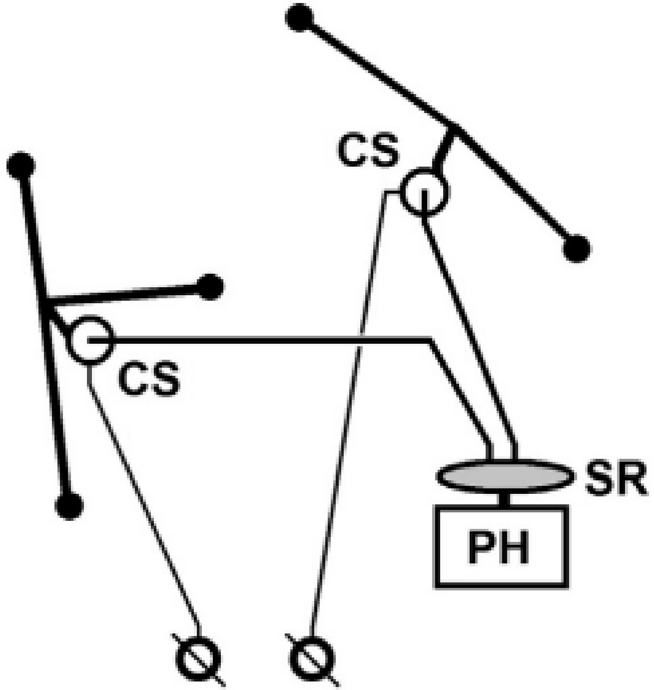


3. Geothermal Production





Two-phase gathering system: CS (Cyclone Separator) at the Power House (PH). Closed circles – Production wells, Open circles – Injection wells



Gathering system with satellite separator stations: Steam pipelines to a Steam Receiver (SR) at the Power House (PH). Closed circles – Production wells, Open circles – Injection wells

Geothermal Power Production

Geothermal Power:

Types of geothermal power plants:

- Dry-steam geothermal power plant,
- Single flash geothermal power plant,
- Double flash power plants geothermal power plant,
- Binary cycle geothermal power plant, and
- Organic Rankine Cycle geothermal power plant.

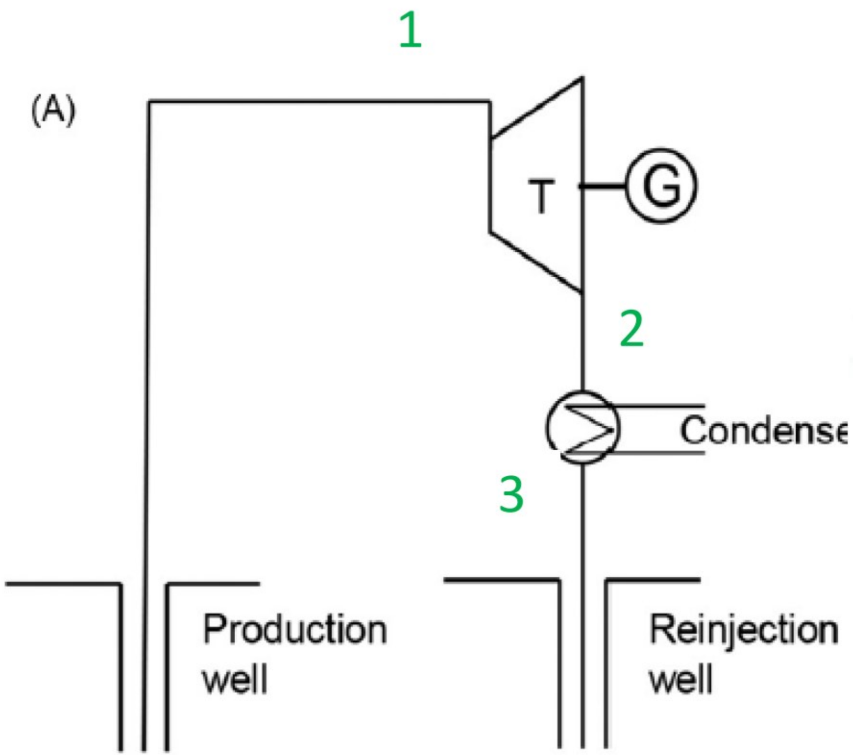
4. Dry Steam

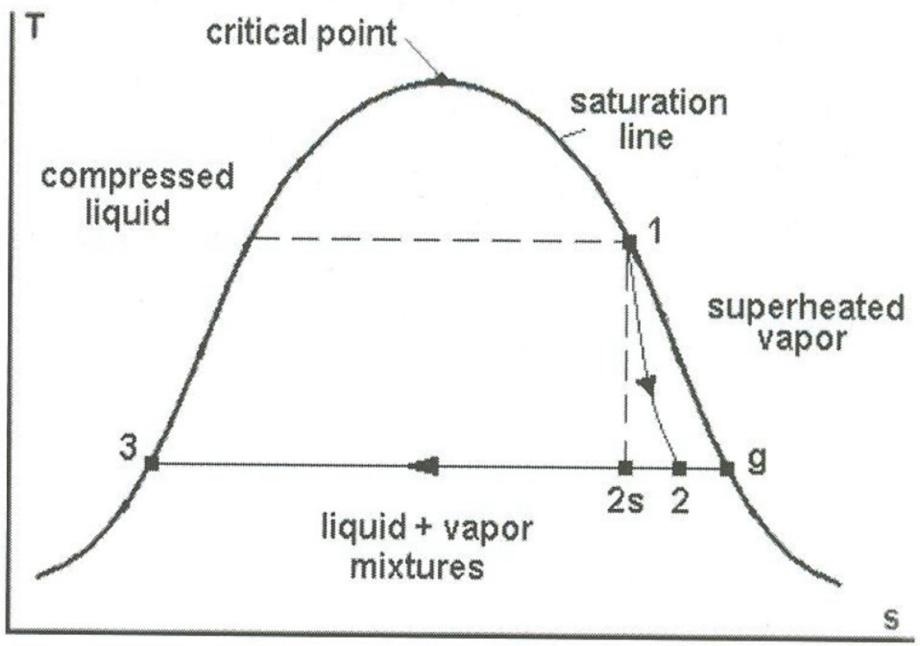
Larderello (Italy). Dry steam. 250 ºC.
Current power capacity installed: 500 MW.

4. Dry Steam

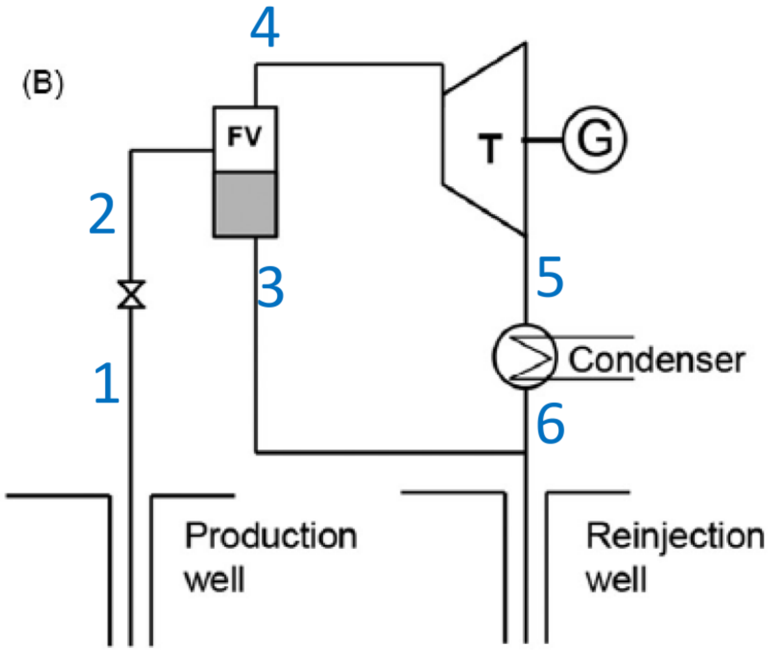
The Geysers (California). Dry steam. 250ºC
20 units. Installed capacity 1400 MW
Recharge of the reservoir with treated municipal waste water.

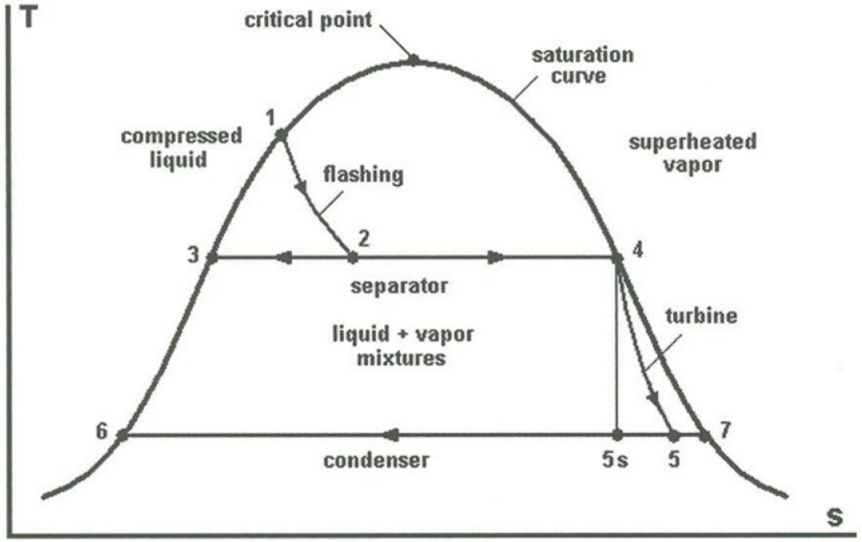
4. Dry Steam


1
(A)
T
G
2
Condense
3
Production well
Reinjection well


T
critical point
saturation line
compressed liquid
1
superheated vapor
3
g
2s
2
liquid + vapor mixtures
s

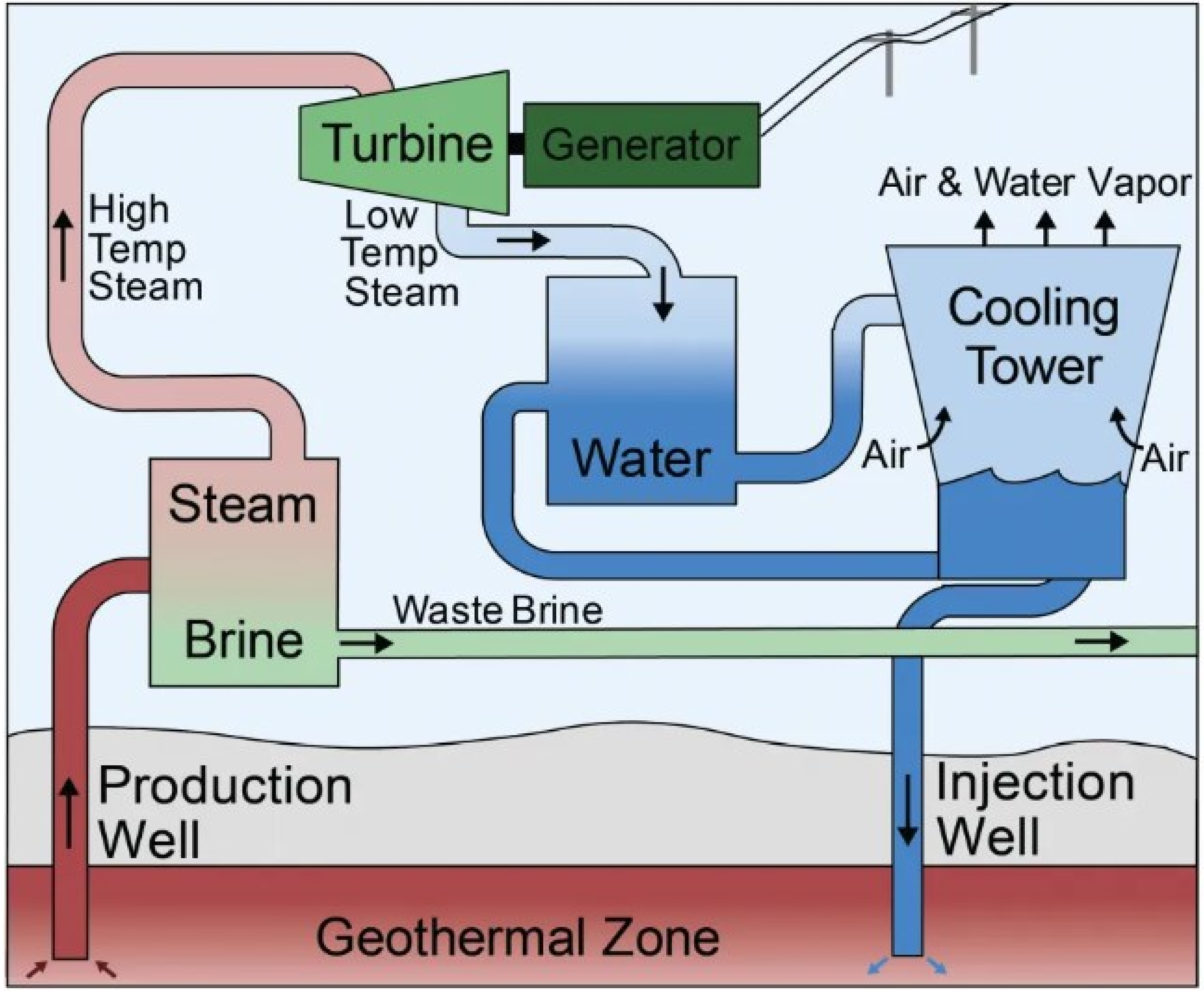
4. Dry Steam (Single Flash)





- Presure at Condenser is a function of the temperature of the cooling medium
- Pressure at the Separator (FV) is a **design parameter**

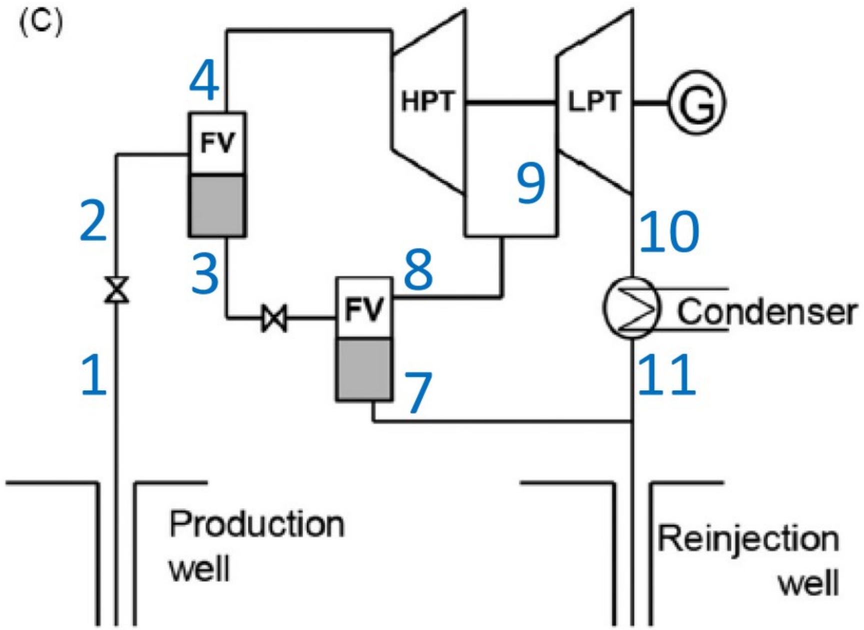
4. Dry Steam (Single Flash)

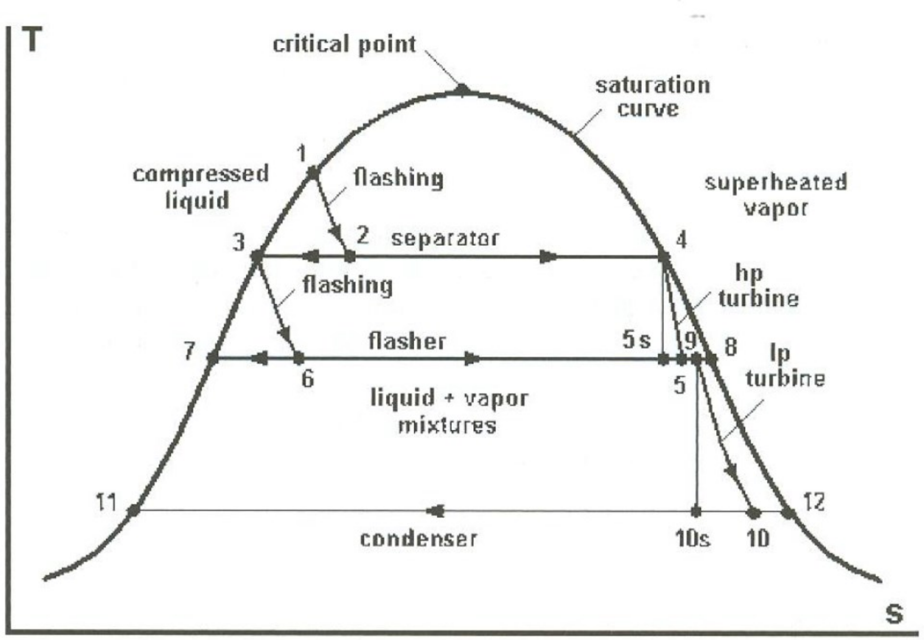


5. Double Flash

Krafla I y II (Iceland)
Double - Flash. 30 MW each.

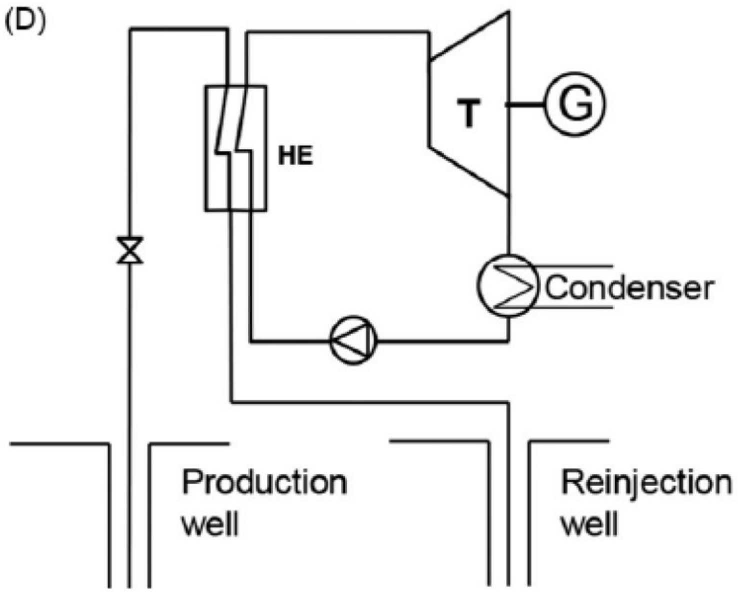
5. Double Flash





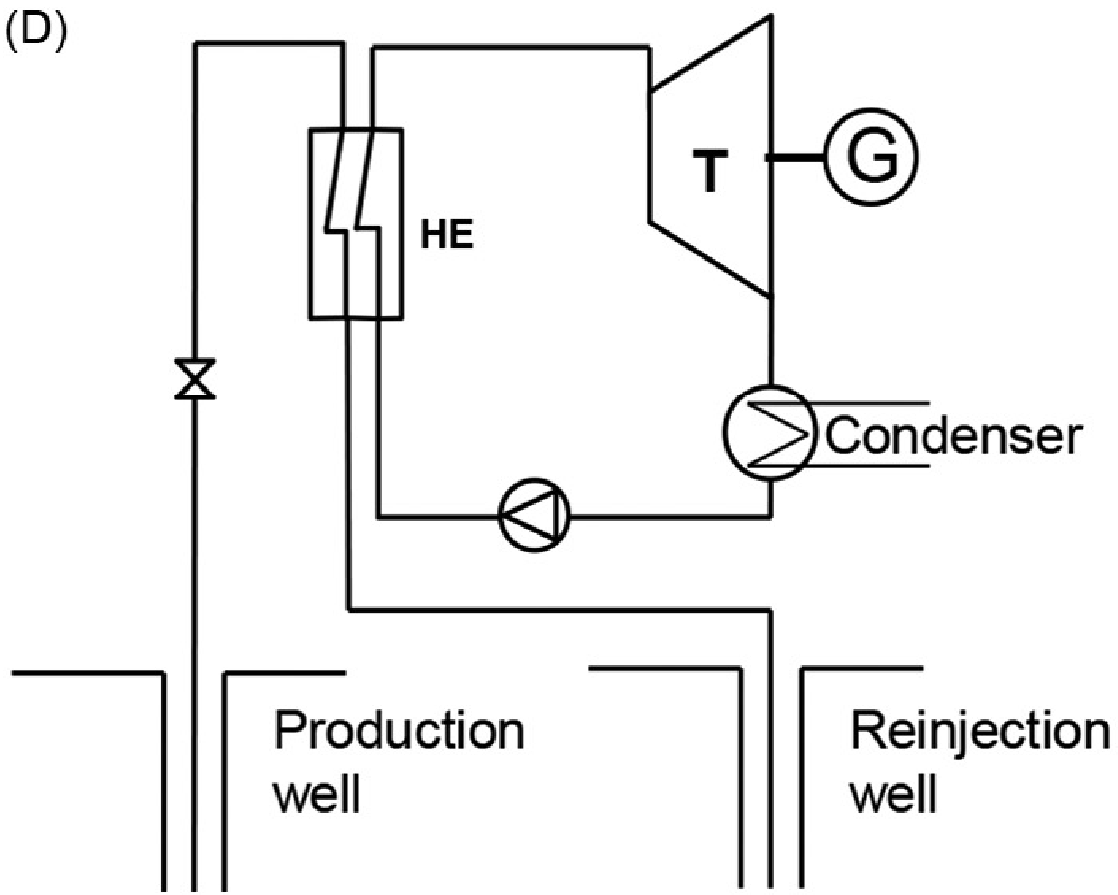
- Presure at Condenser is a function of the temperature of the cooling medium
- Pressure at the Separators (FV) is a **design parameter**

6. Binary Cycle



Operator	Plant	Plant Type	Year	No. of Units[1]	Net Rating MW[2]	Gross Rating MW
Mammoth-Pacific	MP-1	Binary	1984	2	7	10
Mammoth-Pacific	MP-2	Binary	1990	3	10	15
Mammoth-Pacific	PLES-1	Binary	1990	3	10	15

6. Binary Cycle

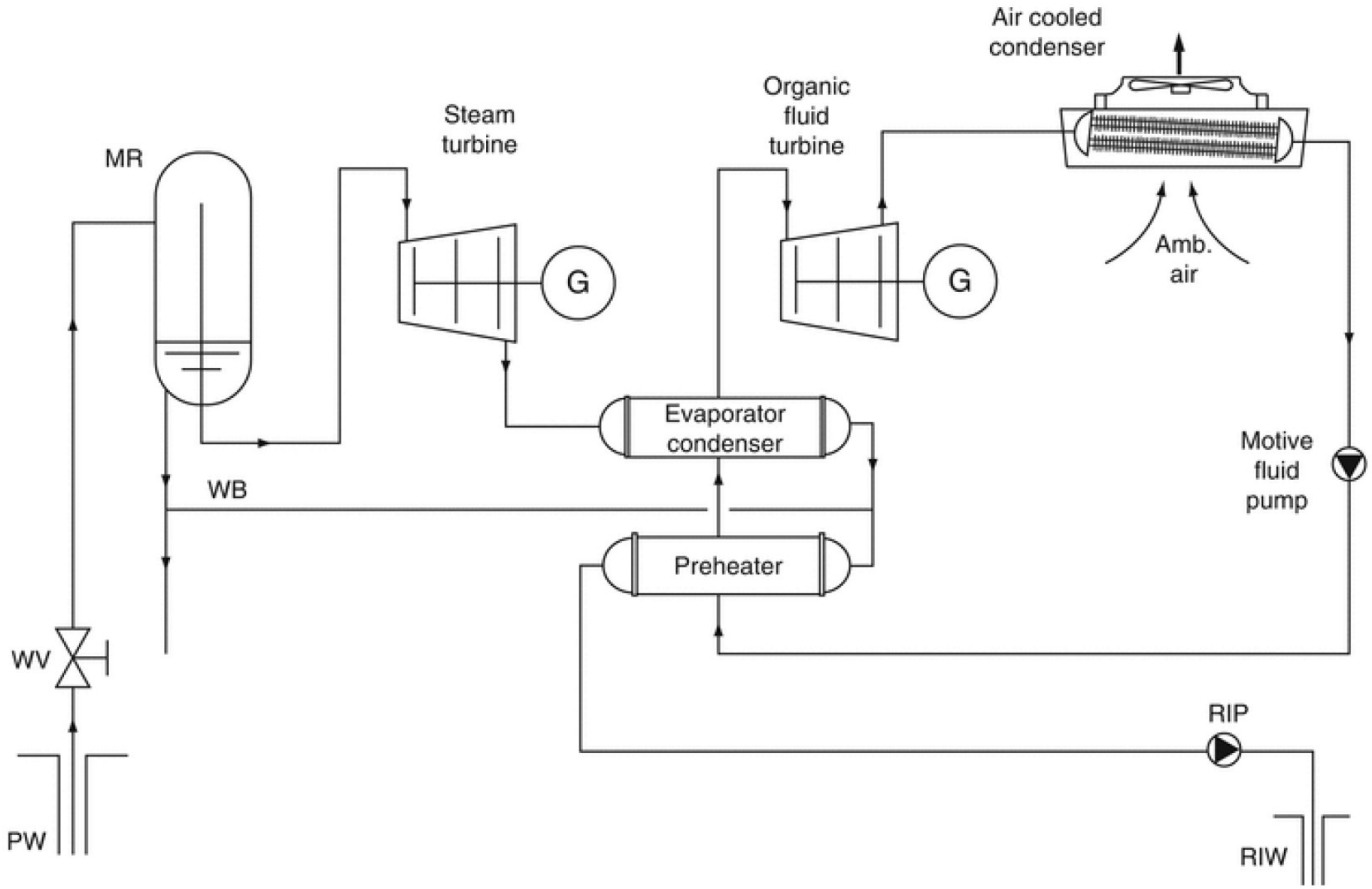


7. Hybrid Flash/Binary system

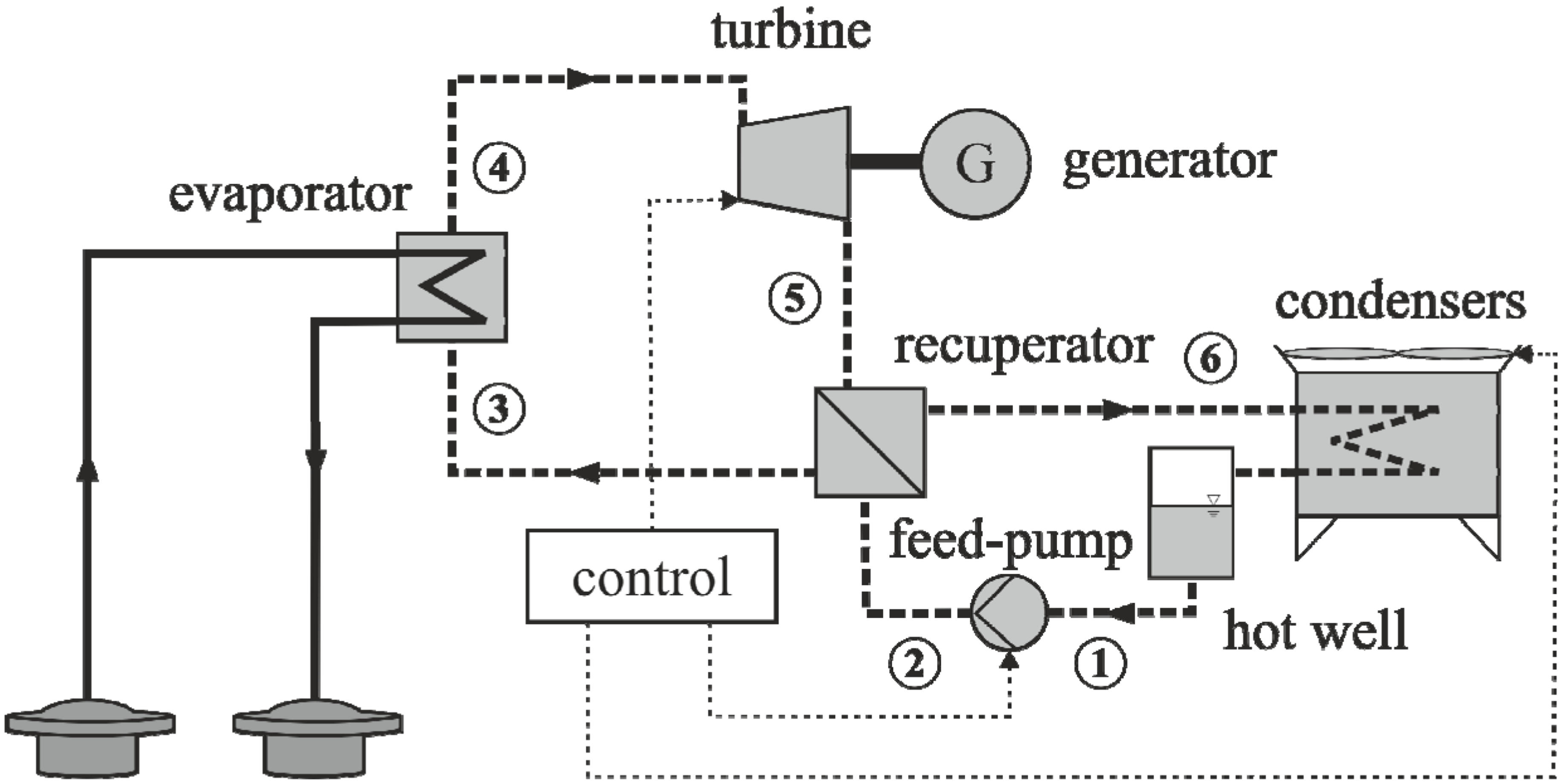
Rotokawa (New Zealand)

- 4 extraction wells
- 5 reinjection wells
- 1 backpressure turbine (16 MW)
- 4 binary cycles (6.5 MW each)

7. Hybrid Flash/Binary system



7. Hybrid Flash/Binary system



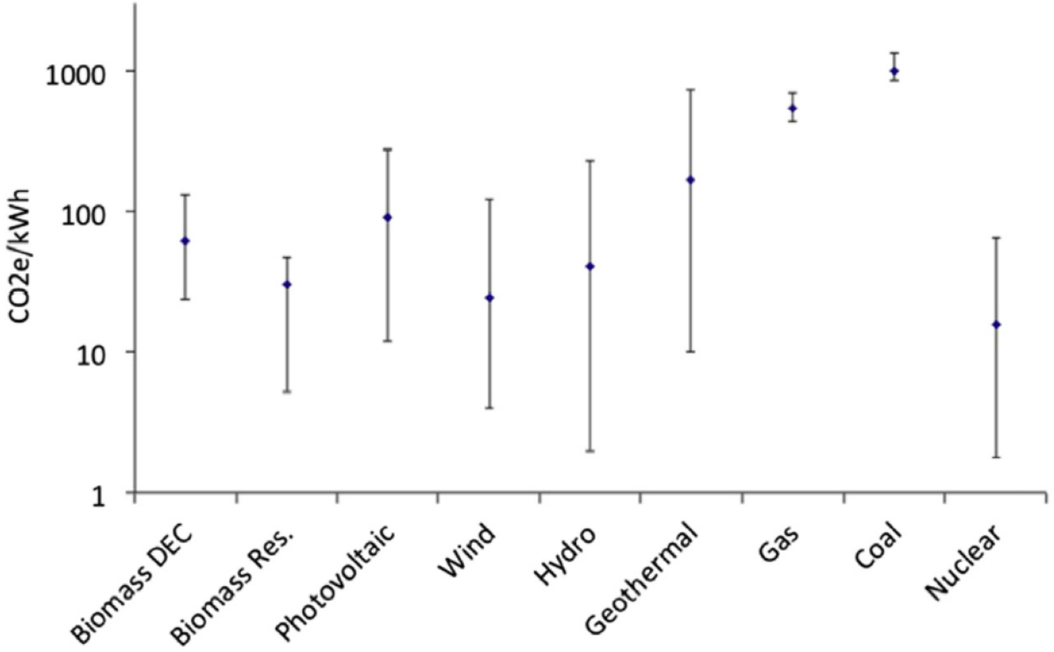
8. Efficiency of Electric Generation

Technology	*Efficiency*
Biomass	16–43%
Photovoltaic	4–22%
Wind	23–45%
Hydro	>90%
Geothermal	10–20%
Gas	45–53%
Coal	32–45%
Nuclear	30–36%

8. Efficiency of Electric Generation

CO_2 emissions (gCO_2e/kWh) for different technologies considering the LCA. (logarithmic scale!)

	gCO_2e/kWh
Nuclear	16
Wind	25
Biomass residues	30
Hydraulic	41
Biomass Dedicated Energy Crops	70
Photovoltaic	90
Geothermal	110
Gas (CC)	550
Coal	1000



8. Efficiency of Electric Generation

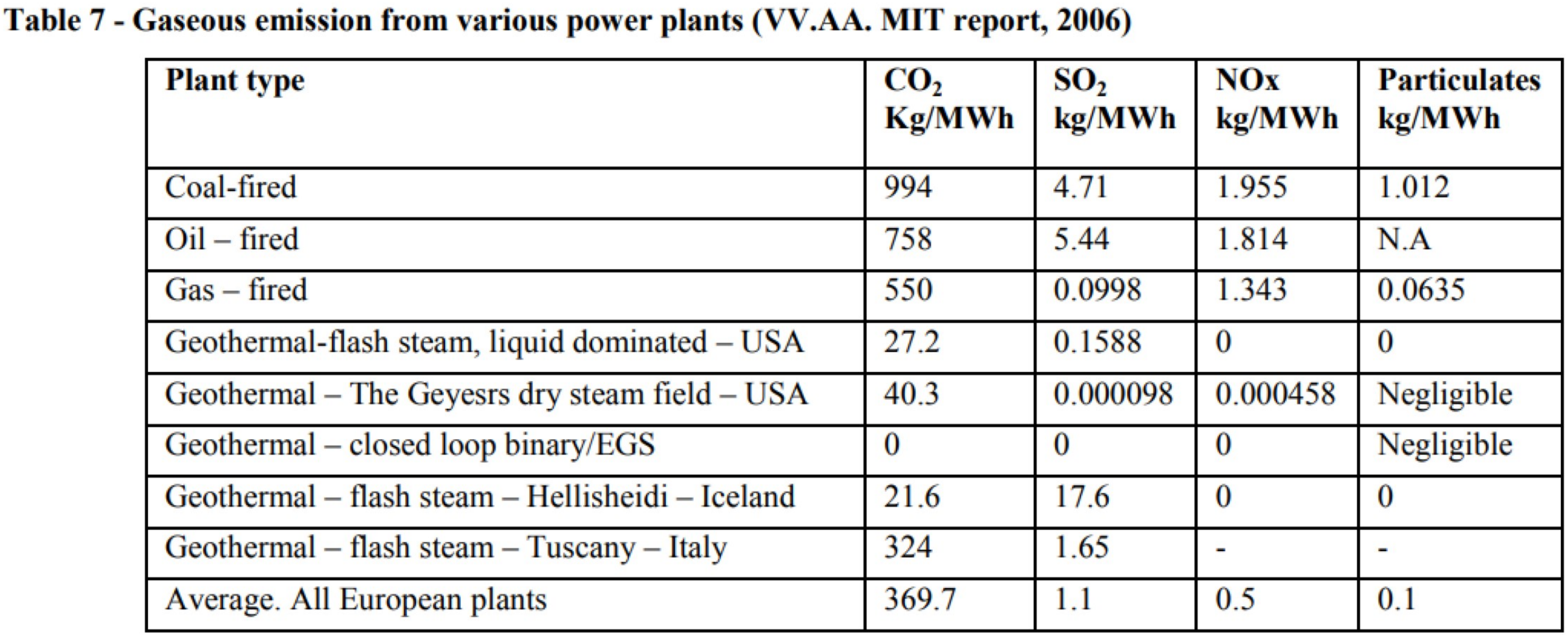
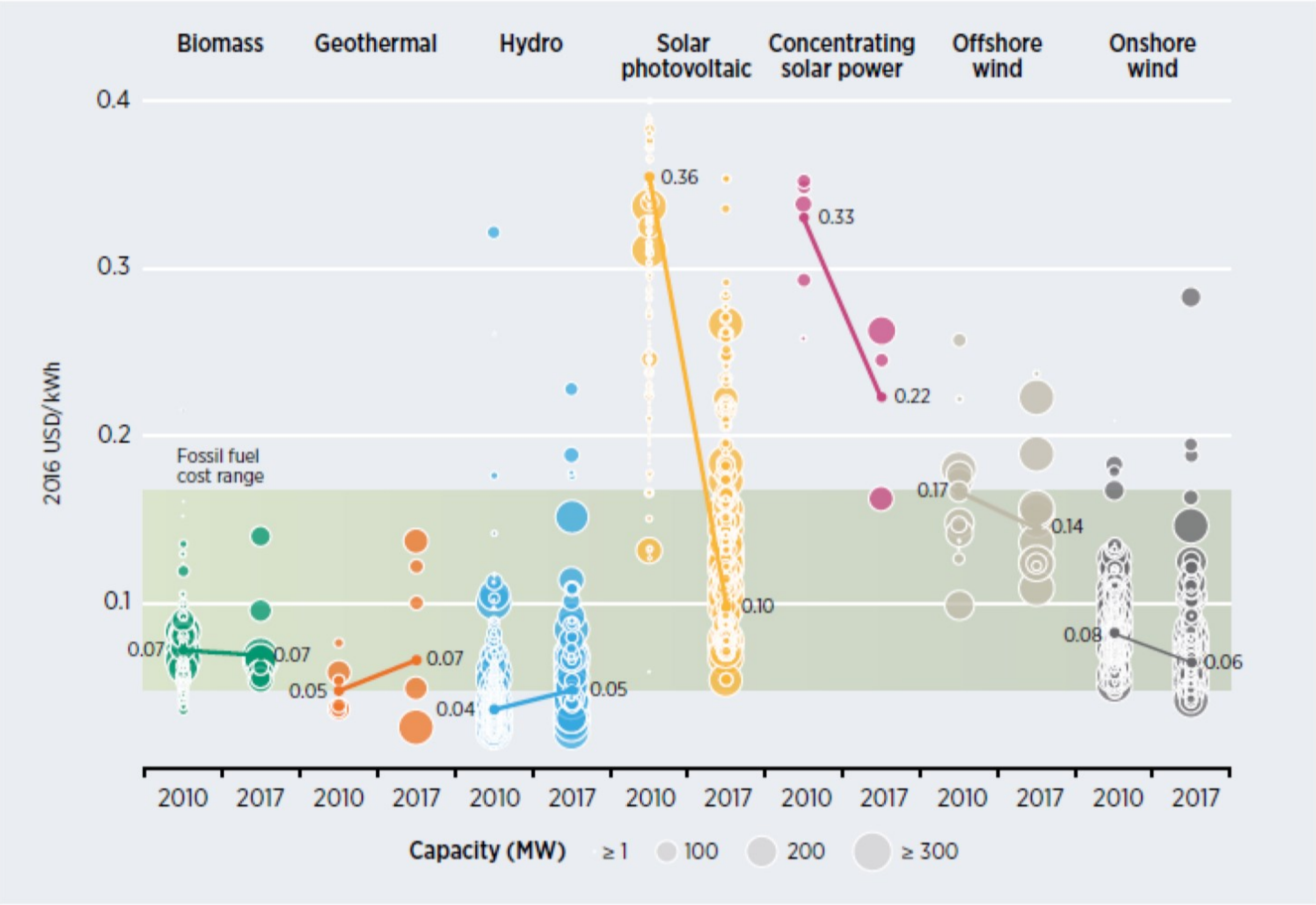


Table 7 - Gaseous emission from various power plants (VV.AA. MIT report, 2006)

Plant type	CO_2 Kg/MWh	SO_2 kg/MWh	NOx kg/MWh	Particulates kg/MWh
Coal-fired	994	4.71	1.955	1.012
Oil – fired	758	5.44	1.814	N.A
Gas – fired	550	0.0998	1.343	0.0635
Geothermal-flash steam, liquid dominated – USA	27.2	0.1588	0	0
Geothermal – The Geyesrs dry steam field – USA	40.3	0.000098	0.000458	Negligible
Geothermal – closed loop binary/EGS	0	0	0	Negligible
Geothermal – flash steam – Hellisheidi – Iceland	21.6	17.6	0	0
Geothermal – flash steam – Tuscany – Italy	324	1.65	-	-
Average. All European plants	369.7	1.1	0.5	0.1

8. Efficiency of Electric Generation – economic aspects



Global levelised cost of electricity from utility-scale renewable power generation technologies, 2010-2017

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8. Efficiency of Electric Generation

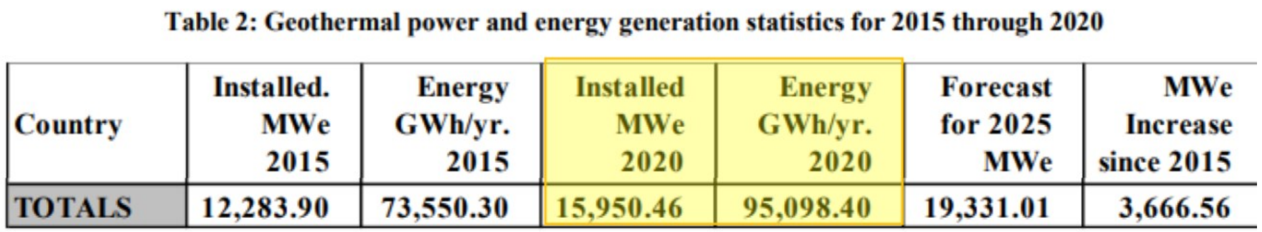


Table 2: Geothermal power and energy generation statistics for 2015 through 2020

Country	Installed. MWe 2015	Energy GWh/yr. 2015	Installed MWe 2020	Energy GWh/yr. 2020	Forecast for 2025 MWe	MWe Increase since 2015
TOTALS	12,283.90	73,550.30	15,950.46	95,098.40	19,331.01	3,666.56

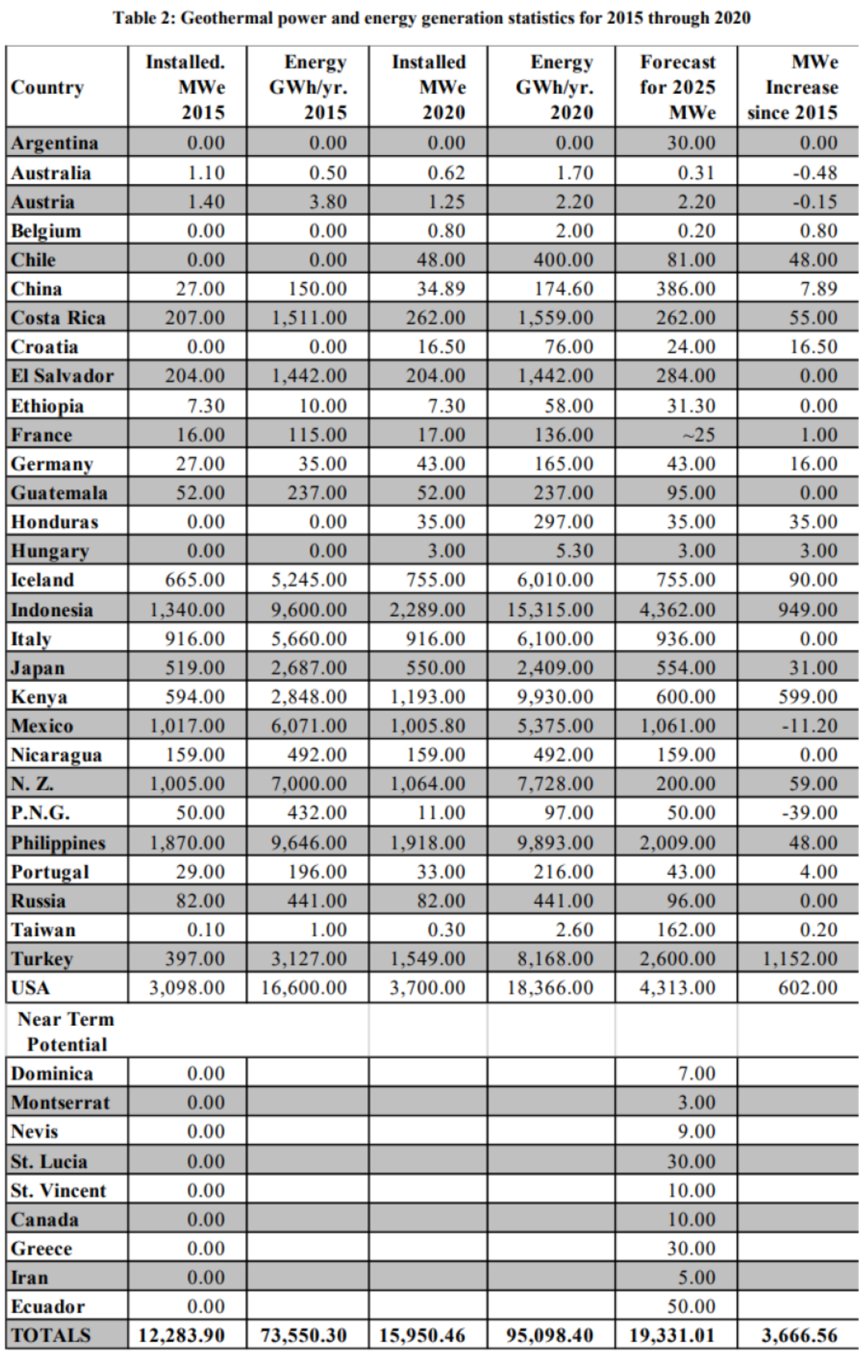


Table 2: Geothermal power and energy generation statistics for 2015 through 2020

Country	Installed. MWe 2015	Energy GWh/yr. 2015	Installed MWe 2020	Energy GWh/yr. 2020	Forecast for 2025 MWe	MWe Increase since 2015
Argentina	0.00	0.00	0.00	0.00	30.00	0.00
Australia	1.10	0.50	0.62	1.70	0.31	-0.48
Austria	1.40	3.80	1.25	2.20	2.20	-0.15
Belgium	0.00	0.00	0.80	2.00	0.20	0.80
Chile	0.00	0.00	48.00	400.00	81.00	48.00
China	27.00	150.00	34.89	174.60	386.00	7.89
Costa Rica	207.00	1,511.00	262.00	1,559.00	262.00	55.00
Croatia	0.00	0.00	16.50	76.00	24.00	16.50
El Salvador	204.00	1,442.00	204.00	1,442.00	284.00	0.00
Ethiopia	7.30	10.00	7.30	58.00	31.30	0.00
France	16.00	115.00	17.00	136.00	~25	1.00
Germany	27.00	35.00	43.00	165.00	43.00	16.00
Guatemala	52.00	237.00	52.00	237.00	95.00	0.00
Honduras	0.00	0.00	35.00	297.00	35.00	35.00
Hungary	0.00	0.00	3.00	5.30	3.00	3.00
Iceland	665.00	5,245.00	755.00	6,010.00	755.00	90.00
Indonesia	1,340.00	9,600.00	2,289.00	15,315.00	4,362.00	949.00
Italy	916.00	5,660.00	916.00	6,100.00	936.00	0.00
Japan	519.00	2,687.00	550.00	2,409.00	554.00	31.00
Kenya	594.00	2,848.00	1,193.00	9,930.00	600.00	599.00
Mexico	1,017.00	6,071.00	1,005.80	5,375.00	1,061.00	-11.20
Nicaragua	159.00	492.00	159.00	492.00	159.00	0.00
N. Z.	1,005.00	7,000.00	1,064.00	7,728.00	200.00	59.00
P.N.G.	50.00	432.00	11.00	97.00	50.00	-39.00
Philippines	1,870.00	9,646.00	1,918.00	9,893.00	2,009.00	48.00
Portugal	29.00	196.00	33.00	216.00	43.00	4.00
Russia	82.00	441.00	82.00	441.00	96.00	0.00
Taiwan	0.10	1.00	0.30	2.60	162.00	0.20
Turkey	397.00	3,127.00	1,549.00	8,168.00	2,600.00	1,152.00
USA	3,098.00	16,600.00	3,700.00	18,366.00	4,313.00	602.00
Near Term Potential						
Dominica	0.00				7.00	
Montserrat	0.00				3.00	
Nevis	0.00				9.00	
St. Lucia	0.00				30.00	
St. Vincent	0.00				10.00	
Canada	0.00				10.00	
Greece	0.00				30.00	
Iran	0.00				5.00	
Ecuador	0.00				50.00	
TOTALS	**12,283.90**	**73,550.30**	**15,950.46**	**95,098.40**	**19,331.01**	**3,666.56**

8. Efficiency of Electric Generation

El Dabaa Nuclear Power Plant (Egypt)

4 units x 1200 MW/unit = 4800 MW

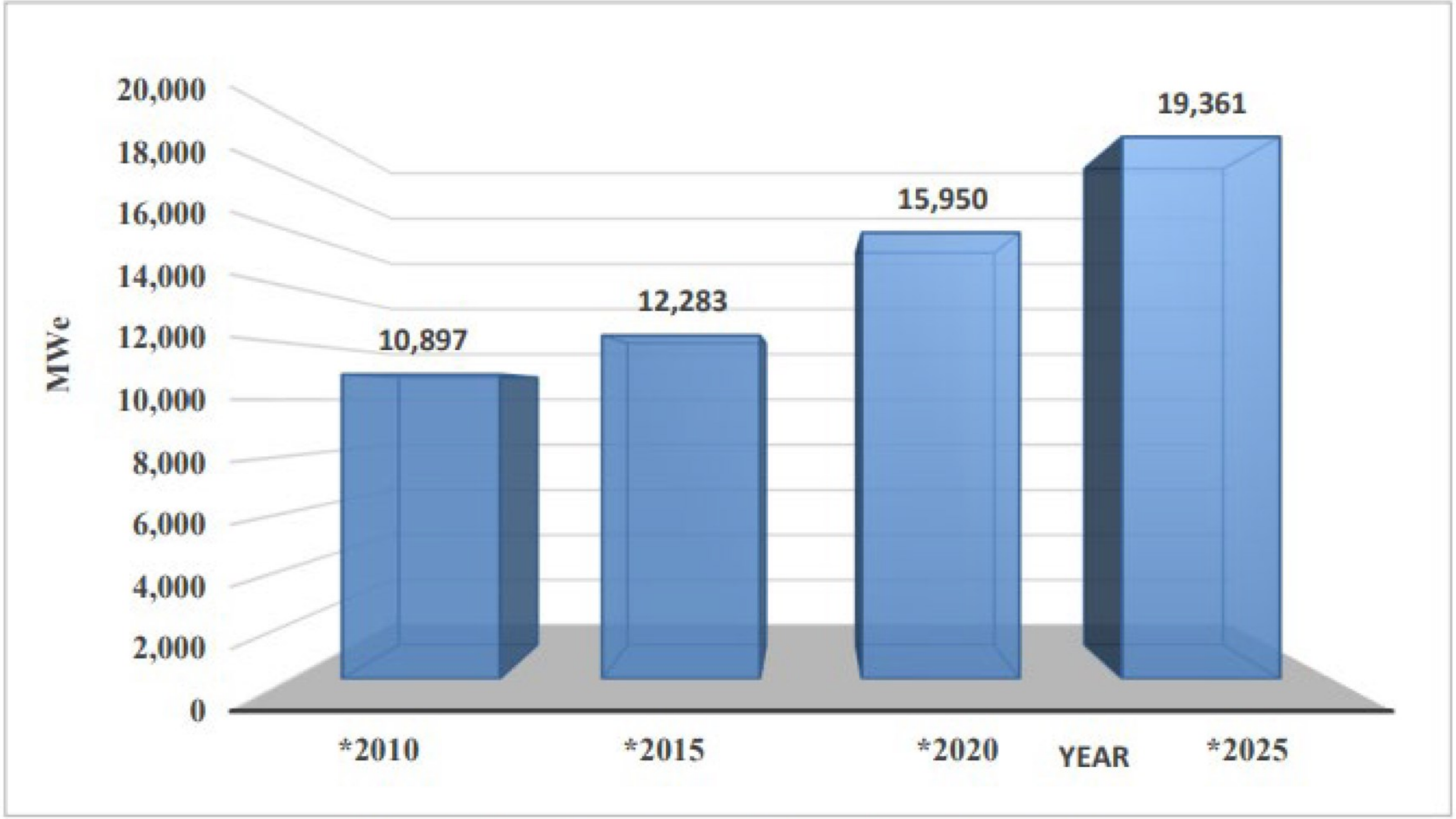
Geothermal (world)

16 000 MW

Three Gorges Dam (China)

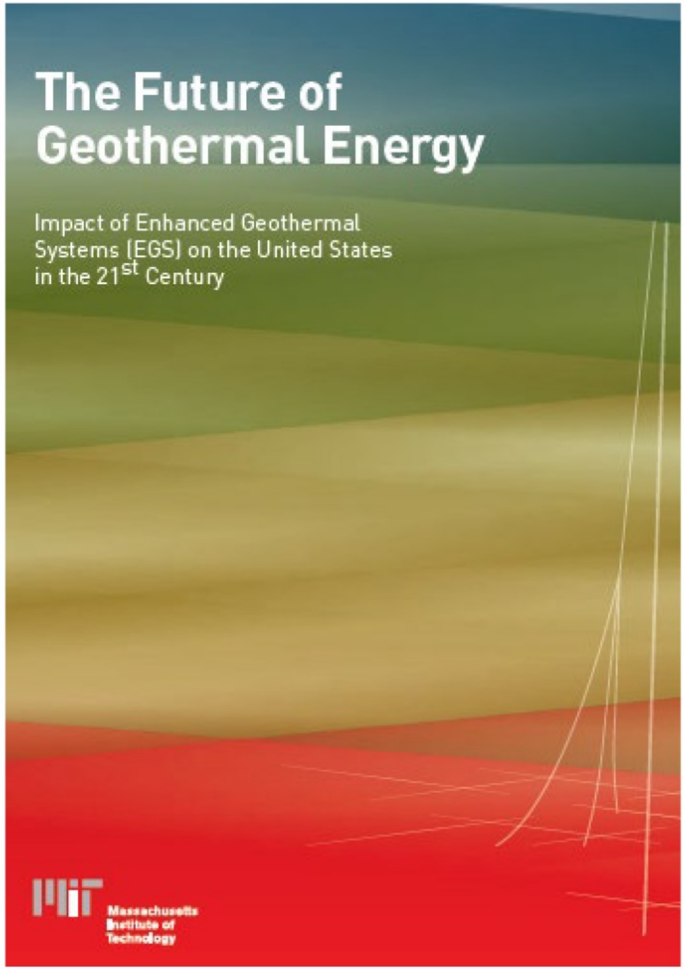
22 500 MW

8. Efficiency of Electric Generation



World Total Installed Capacity 2010 to 2025

8. Efficiency of Electric Generation



The Future of Geothermal Energy

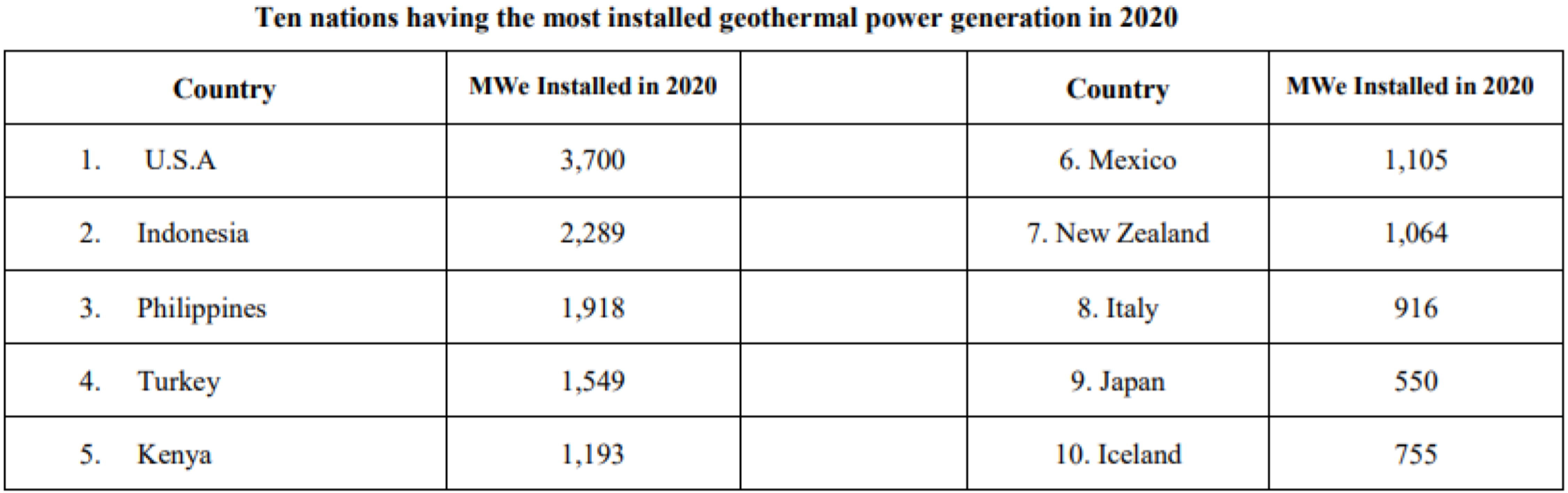
Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century

Massachusetts Institute of Technology

Year 2050: 100.000 MWe

Massachusetts Institute of Technology

8. Efficiency of Electric Generation



Ten nations having the most installed geothermal power generation in 2020

Country	MWe Installed in 2020		Country	MWe Installed in 2020
1. U.S.A	3,700		6. Mexico	1,105
2. Indonesia	2,289		7. New Zealand	1,064
3. Philippines	1,918		8. Italy	916
4. Turkey	1,549		9. Japan	550
5. Kenya	1,193		10. Iceland	755

8. Efficiency of Electric Generation

Estimated reserves. (In 10^9 barrels of oil equivalent)

Hydrothermal reservoirs (< 4 km):	130
Earth crust (3 - 10 km):	79 000 000

(Oil reserves: 5 300)

9. Conclusion

- Is it technically possible to obtain electricity from geothermal energy? **YES**
- Is it economically viable? **YES**
- How many countries have geothermal power plants? **More than 30!**
- What is the total installed capacity? **16 000 MW**
- How many countries could have geothermal power plants? **Many ….**

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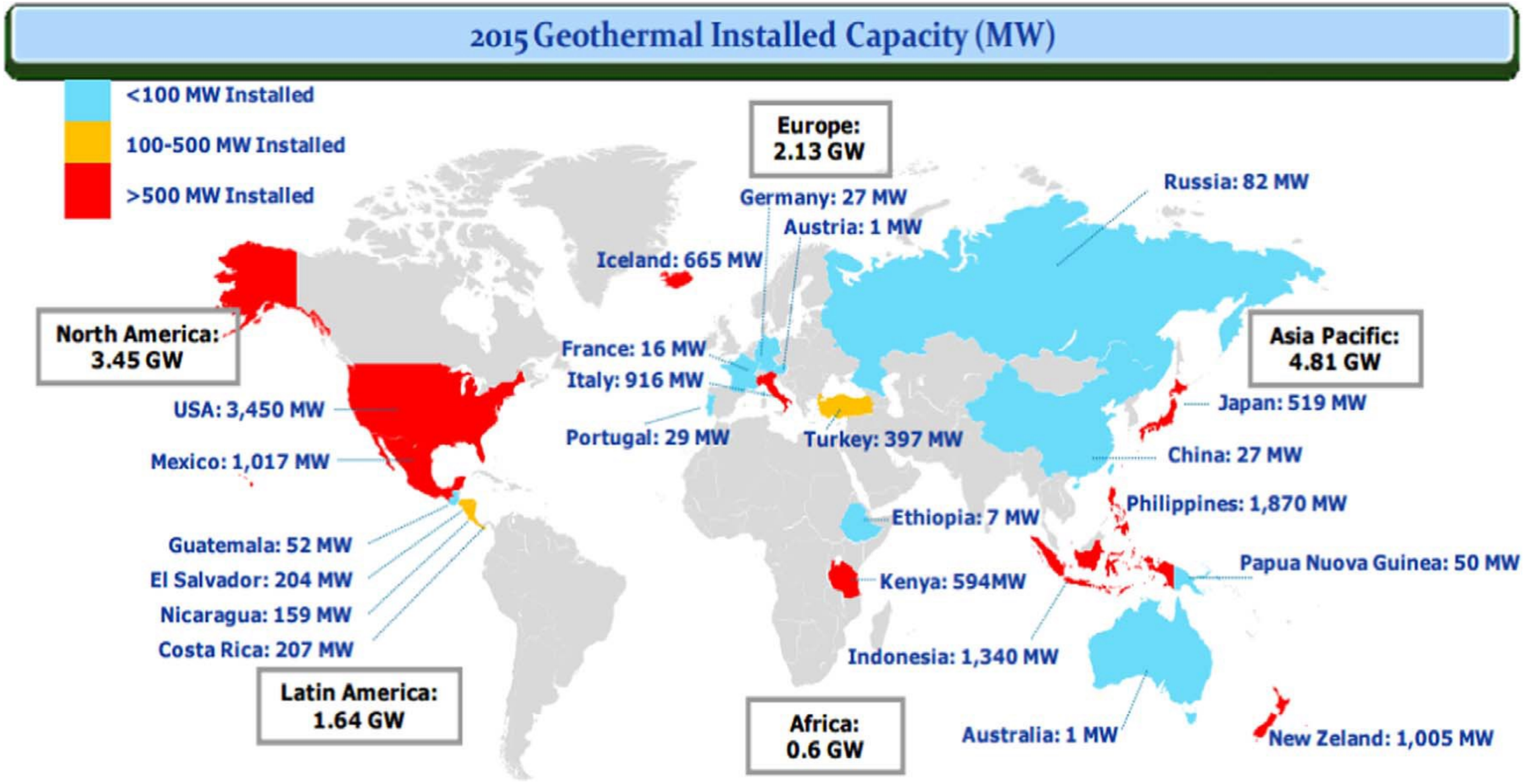
Faculty of Engineering
Cairo University

Geothermal Resources and Reservoir Engineering



Installed capacity at the end of 2014 worldwide (Bertani, 2015).

Geothermal energy in Italy

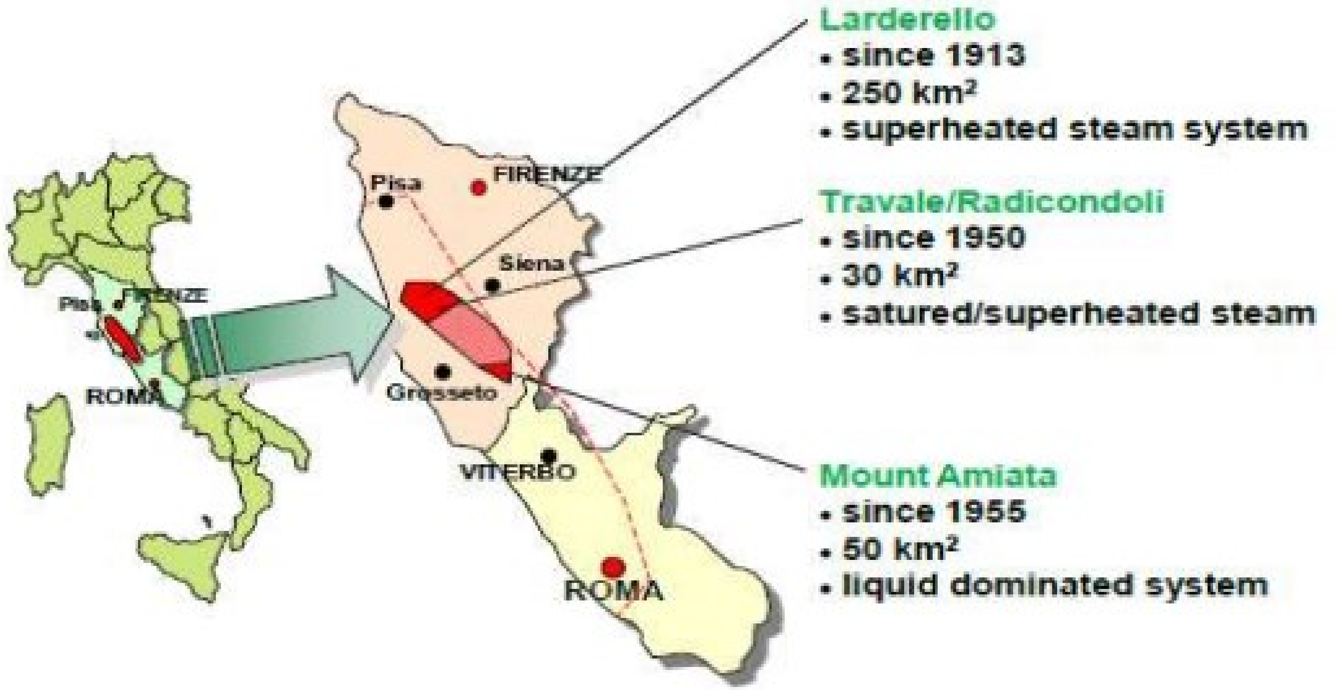
- The advent of Geothermal energy in Italy dates back to the beginning of the 1900s. In reality, however, in the area of present-day Tuscany, historical sources have revealed that people have been exploiting the heat from its natural springs since antiquity: Etruscan populations did so for at least the entire first millennium BC.
- Italy has potential resources of extractable and exploitable Geothermal energy estimated between 5,800 and 116,000 terawatt hours of energy

- Mainly used for electric power production.
- Italy is located above a relatively thin crust, with four large areas of underground heat:

1. Tuscany, with the Larderello fields.
2. Campania, the Phlegraean Fields
3. Very large and not fully explored, in the south of the Tyrrhenian Sea
4. The Strait of Sicily, around the undersea Empedocles volcano and Lampedusa Island

All of the Italian geothermal fields in exploitation for electricity generation are located in Tuscany :

- Larderello.
- Travale-Radicondoli.
- Bagnore and Piancastagnaio (in the Mount Amiata area).



Larderello
- since 1913
- 250 km²
- superheated steam system

Travale/Radicondoli
- since 1950
- 30 km²
- satured/superheated steam

Mount Amiata
- since 1955
- 50 km²
- liquid dominated system

Location of the geothermal fields in Italy

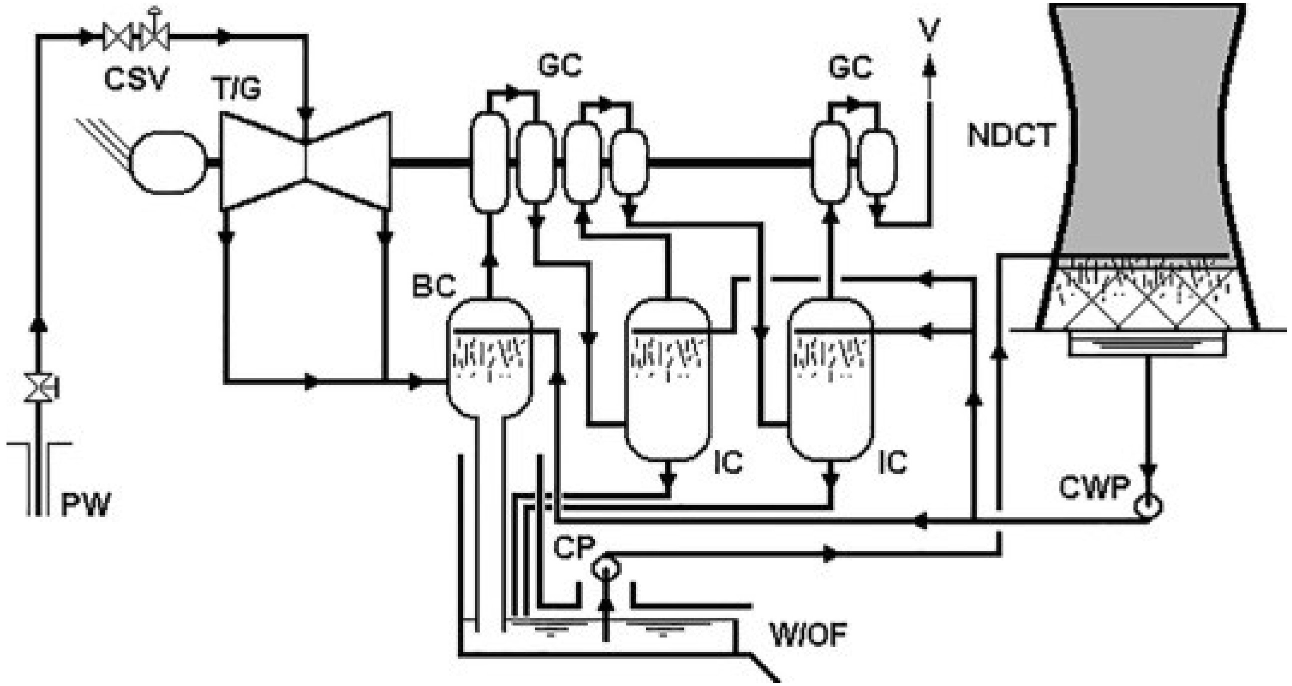
Larderello

- The region of Larderello has experienced occasional phreatic eruptions, caused by explosive outbursts of steam trapped below the surface. The water is contained in metamorphic rocks where it is turned to steam which is then trapped beneath a dome of impermeable shales and clay. The steam escapes through faults in the dome and forces its way out in the hot springs. It possesses a dozen explosion craters 30–250 m in diameter. The largest is the Lago Vecchienna crater which last erupted around 1282, now filled by the Boracifero Lake.

- Larderello geothermal power plant
- Initially, the steam released naturally from the ground was used as an alternative to coal-fired steam engines; later this activity became increasingly oriented to transforming heat into transportable electric energy.
- 250 km^2 in area
- 200 wells produce superheated steam at pressure between 2 and 15 bars and temperature ranging from 150°C to 270°C.
- The installed capacity is 594.5 MWe as of December 2018, with 22 units in operation
- resource sustainability is ensured through two main strategies for the management of the reservoir: reinjection and deep drilling.

- Larderello now produces 10% of the world's entire supply of geothermal electricity, amounting to 4,800 GWh per year and powering about a million Italian households.

The oldest geothermal plant in the world



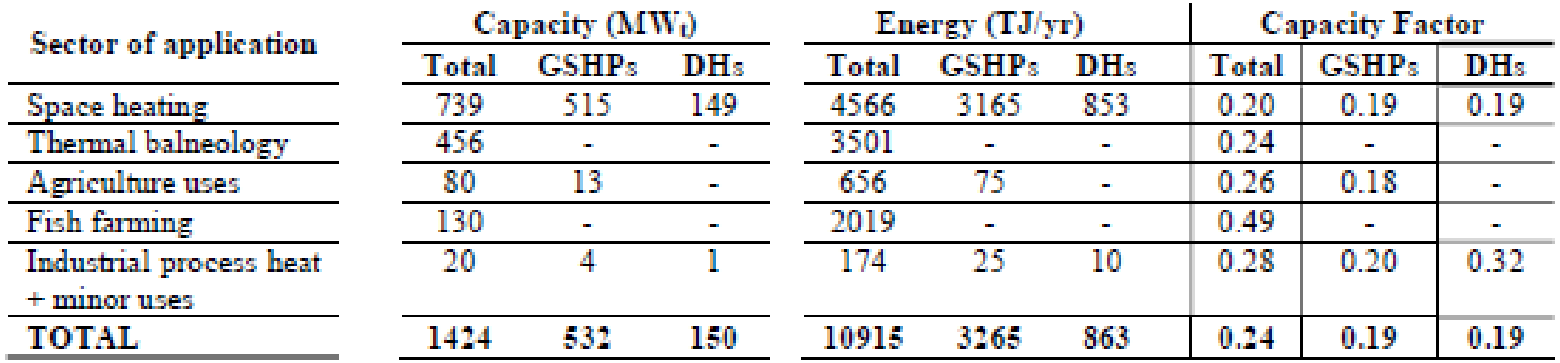
Larderello plant, Italy

Travale-Radicondoli

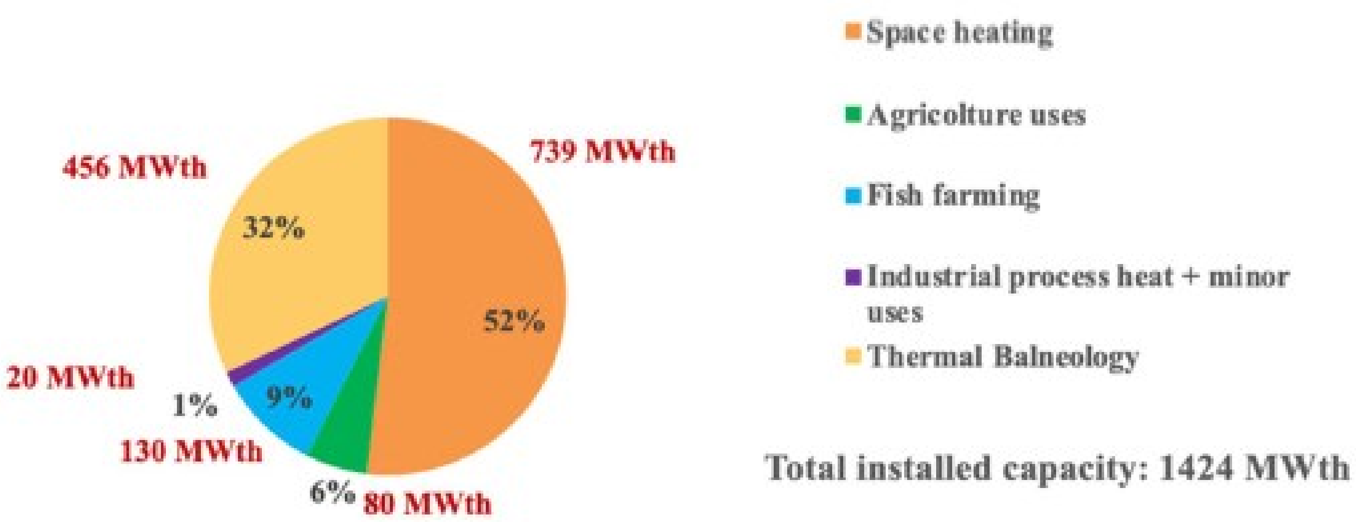
- Exploration of Travale/Radicondoli area began in 1930, development effectively started in the 50s.
- 50 km2 area
- 38 wells produce superheated steam at pressure ranging from 8 to 20 bars and temperature of 190-250°C.
- The installed capacity is 200 MWe with 8 units in operation

Mount Amiata

- Two geothermal fields are located in this area: Bagnore and Piancastagnaio.
- discovered between the late 1950s and the early 1960s.
- producing steam from the shallow carbonate reservoir
- Deep reservoirs (with a pressure of around 200 bars and a temperature of 300-350°C at 3000 m depth) (Bertini et al., 1995)



Sector of application	Capacity (MW_t)			Energy (TJ/yr)			Capacity Factor		
	Total	GSHPs	DHs	Total	GSHPs	DHs	Total	GSHPs	DHs
Space heating	739	515	149	4566	3165	853	0.20	0.19	0.19
Thermal balneology	456	-	-	3501	-	-	0.24	-	-
Agriculture uses	80	13	-	656	75	-	0.26	0.18	-
Fish farming	130	-	-	2019	-	-	0.49	-	-
Industrial process heat + minor uses	20	4	1	174	25	10	0.28	0.20	0.32
TOTAL	1424	532	150	10915	3265	863	0.24	0.19	0.19



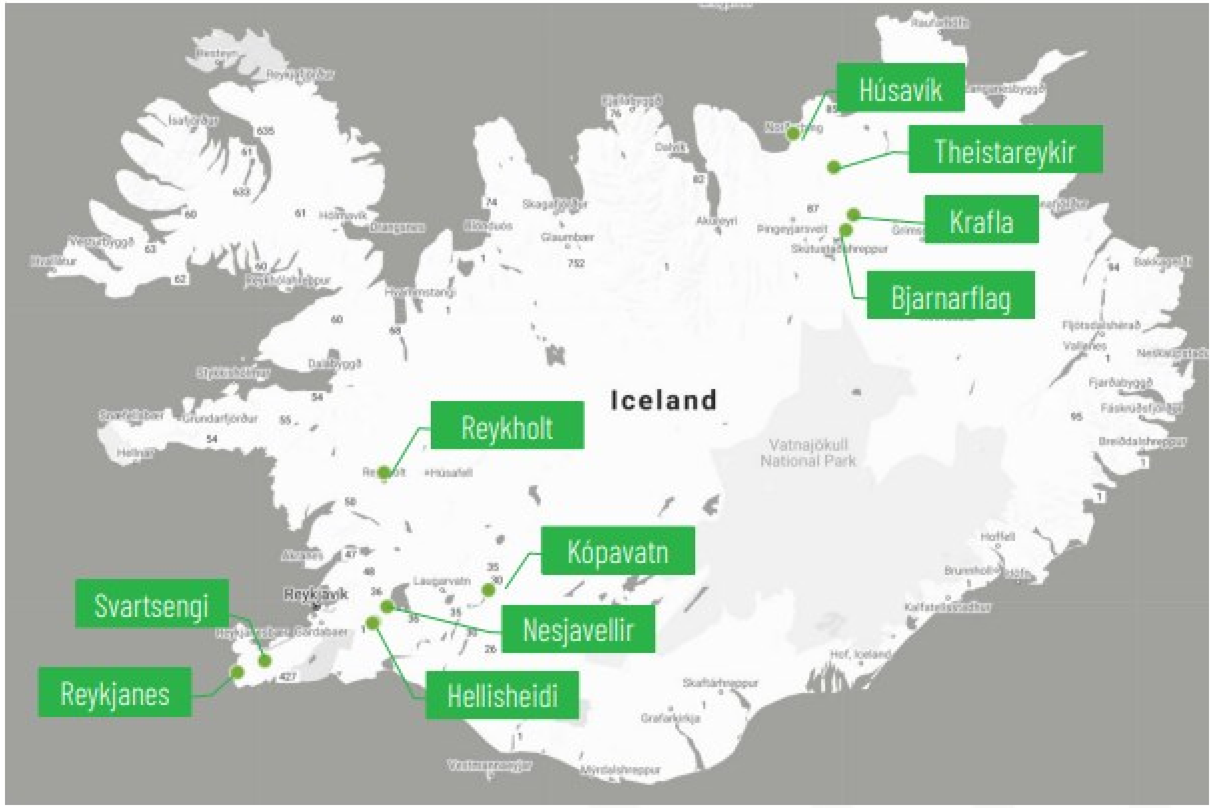
Summary of geothermal direct heat uses as of 31 December 2017 in Italy

Geothermal energy in Iceland

- Iceland’s first geothermal power plant started operation in 1969, followed by two larger plants in 1978 and 1979.
- Geothermal power facilities currently generate 25% of the country's total electricity production.
- Geothermal power generation capacity of 755 MW.
- Iceland is among the top 10 countries in the electricity generation from geothermal

- The geological location of Iceland (over a rift in continental plates), the high concentration of volcanoes in the area is often an advantage in the generation of geothermal energy.
- Geothermal heating approximately 87% of all buildings in Iceland.
- Five major geothermal power plants produce approximately 26.2% (2010) of the nation's electricity.

- Hellisheidi Power Station Nesjavellir Geothermal Power Station
- Reykjanes Power Station
- Svartsengi Power Station
- Krafla Power Station (60 MW)



Hellisheidi Power Station

- The third-largest geothermal power station in the world.
- 71 wells (57 production wells, 14 re-injection), produces approximately 303 MW.of electrical power
- The power plant offers educational tours and presentations about sustainable energy as part of its Geothermal Energy Exhibition.

Nesjavellir Geothermal Power Station

- The second-largest geothermal power station in Iceland.
- The facility is located 177 m (581 ft) above sea level.
- Geothermal power and water heating began in 1947, 26 wells, with a heating capacity of 150 MWt, and produces approximately 120 MW of electrical power

Reykjanes Power Station

- The Plant is the only seawater cooled geothermal power plant in the world and has one of the highest intake pressure to a geothermal turbine.
- The power plant generates 100MWe from two 50MWe turbines, using steam and brine from a reservoir at 290 °C to 320 °C from 12 wells.
- The power plant is open to the public and houses the *Power Plant Earth* interpretative exhibition.

Svartsengi Power Station

- Built in 1976 it was the world´s first geothermal power plant for electric power generation and hot water production for district heating.
- 13 production boreholes connected to the six plants
- The generation capacity increased to 150 MW for the district heating and the nameplate capacity to 75 MW for electricity power.

Krafla geothermal power plant

- It is Iceland's largest power station.
- Launched in the early 1977.
- 17 high-pressure production wells with 110 kg/second of 7.7 bar and, due to new technologies, 5 low-pressure production wells with 36 kg/s of 2.2 bar.

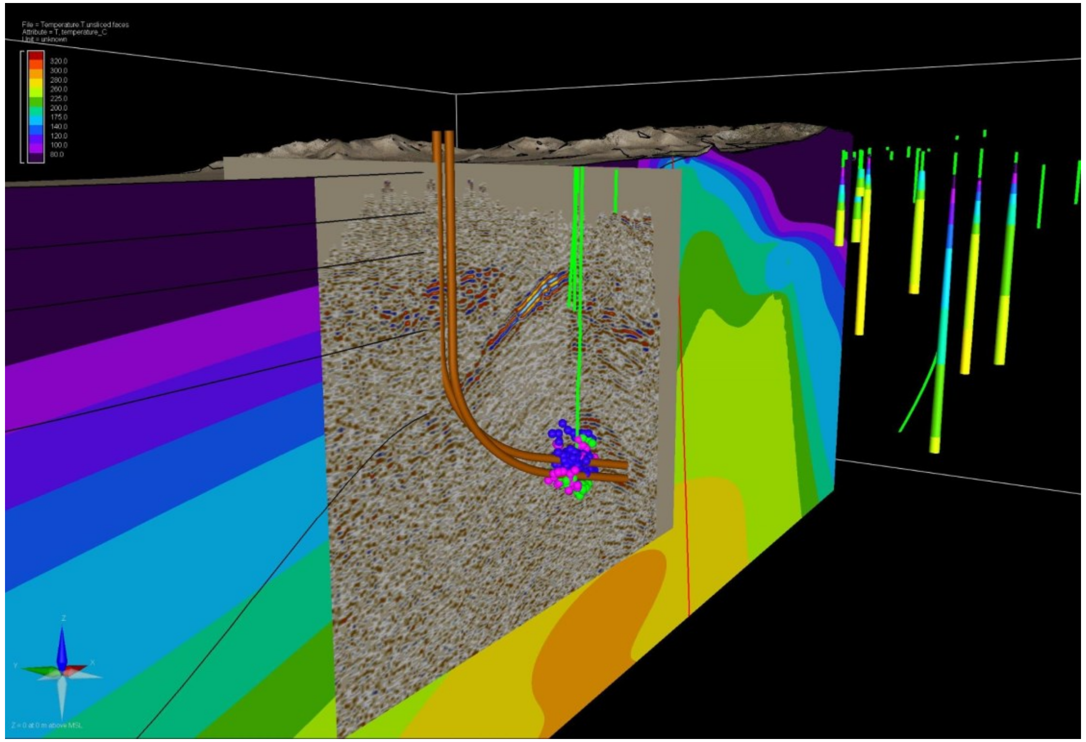
Enhanced geothermal systems

Enhanced geothermal systems

- Enhanced Geothermal System (EGS) concept consists simply of drilling at least two boreholes into deep fractured rock to implying artificial enhancements of rock permeabilities.

Modelling of enhanced geothermal systems

- Like any development of subsurface resources, enhanced geothermal systems involve risk. However, with the aid of software that enables geologists, geophysicists, and reservoir engineers to analyze geothermal resources, development teams can reduce the risk and fully realize the potential of enhanced geothermal systems.
- Geoscientists are looking for subsurface regions with significant volumes of hot, dry rock that can be fractured. Seismic surveys and core samples provide insight into the geology, depth of the active formation, and its petrophysical properties. From this data, exploration teams can create 3D structural models that depict the extent of the active area, reveal regional faults, and show stress distributions. Rock data can provide guidance regarding natural fractures that have sealed up since originally formed. Ideally, exploration teams are looking for crystalline basement rock that doesn’t require proppants for fracturing and doesn’t present any overpressure issues.
- In addition to the geological 3D model, fluid modelling can be done using the thermal model of the geothermal reservoir in preparation for determining the optimum locations of the injector well and the producing well. Geologic models also guide wellbore design with the intent to avoid subsurface conditions that increase drilling risk or cost or jeopardize long term wellbore stability.



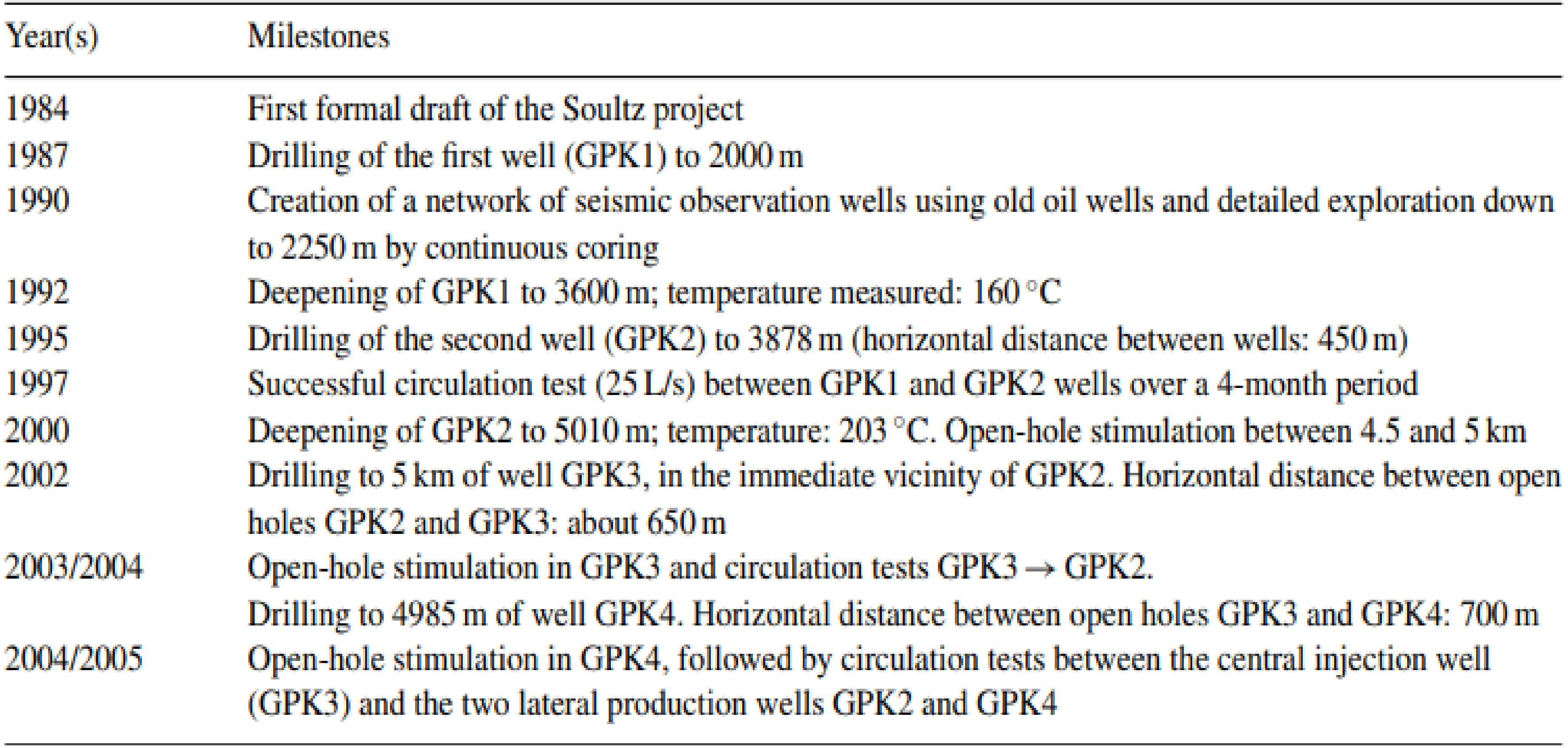
integrating temperature models with seismic, microseismic, and well log data allow for better-informed decisions on EGS well placement. Data source: Utah FORGE, Geothermal Data Repository (GDR), U.S. Department of Energy Geothermal Technologies Office (DOE GTO).

Organic Rankine Cycle (ORC)

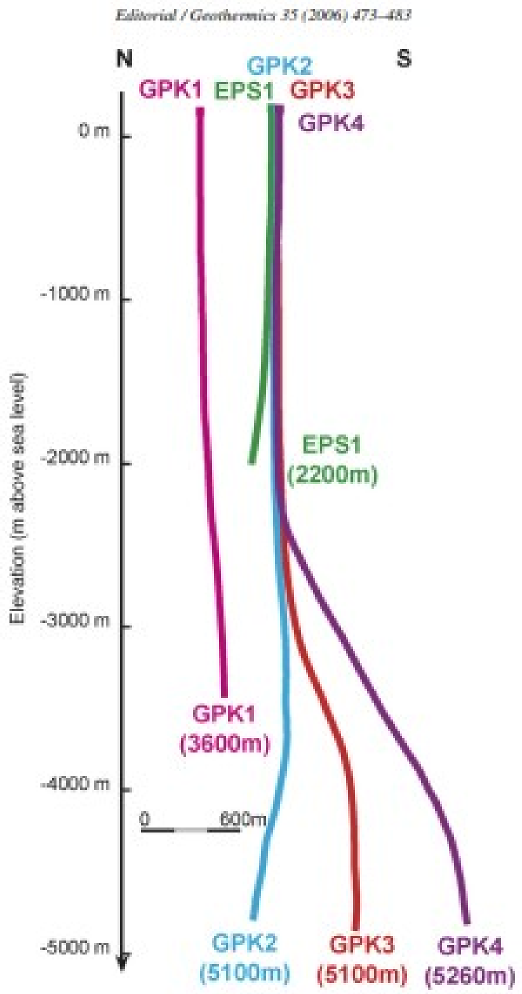
- The Organic Rankine Cycle (ORC) is one of the most promising heat-driven technologies converting heat into mechanical power or electricity.ORC system can recover various heat sources such as biomass combustion heat, solar energy, geothermal heat, and industry wasted heat and heat from Internal Combustion Engine (ICE). Adopting ORC technology for engine waste heat recovery can effectively improve the overall system efficiency and reduce the emissions. A well-designed ORC system can potentially achieve around 2–5 years payback period through fuel saving. However, Velez et al 2012. pointed out the market available ORC system with the power ranges of 0.2–2 MWe under the cost around 1and 4 × 103 € /kWe, and lower powers are in pre-commercial status because of the relatively long payback period using small-scale ORC system.

The deep EGS (Enhanced Geothermal System) project at Soultz-sous-Forets (Alsace, France)

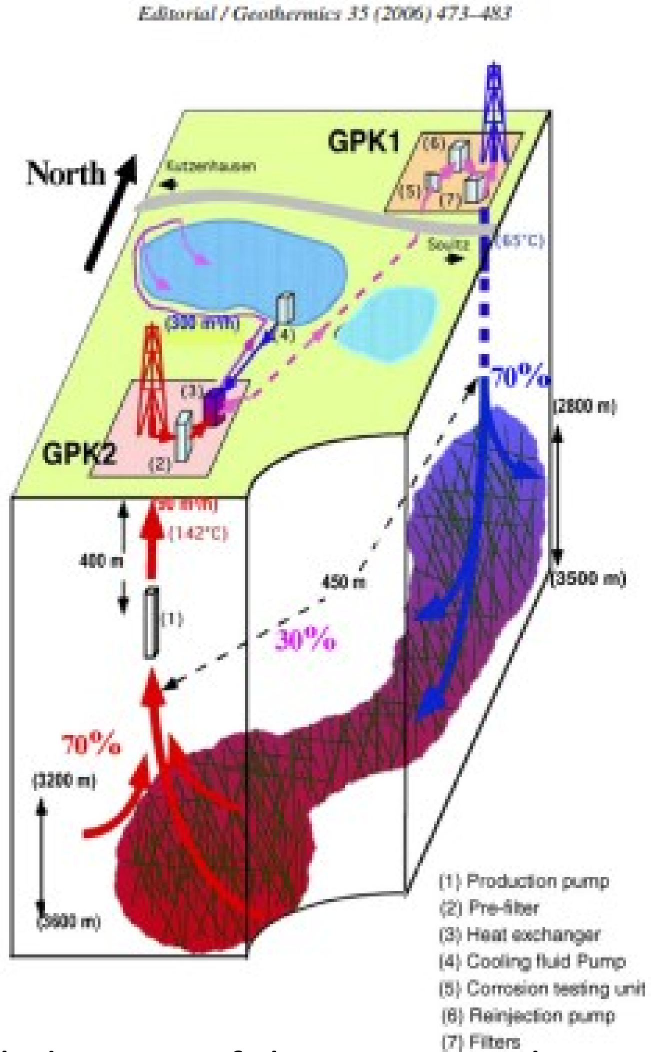
History of the Soultz project



Year(s)	Milestones
1984	First formal draft of the Soultz project
1987	Drilling of the first well (GPK1) to 2000 m
1990	Creation of a network of seismic observation wells using old oil wells and detailed exploration down to 2250 m by continuous coring
1992	Deepening of GPK1 to 3600 m; temperature measured: 160 °C
1995	Drilling of the second well (GPK2) to 3878 m (horizontal distance between wells: 450 m)
1997	Successful circulation test (25 L/s) between GPK1 and GPK2 wells over a 4-month period
2000	Deepening of GPK2 to 5010 m; temperature: 203 °C. Open-hole stimulation between 4.5 and 5 km
2002	Drilling to 5 km of well GPK3, in the immediate vicinity of GPK2. Horizontal distance between open holes GPK2 and GPK3: about 650 m
2003/2004	Open-hole stimulation in GPK3 and circulation tests GPK3 → GPK2. Drilling to 4985 m of well GPK4. Horizontal distance between open holes GPK3 and GPK4: 700 m
2004/2005	Open-hole stimulation in GPK4, followed by circulation tests between the central injection well (GPK3) and the two lateral production wells GPK2 and GPK4


Editorial / Geothermics 35 (2006) 473–483

Vertical N–S cross-section through Soultz boreholes EPS1, GPK1, GPK2, GPK3 and GPK4.


Editorial / Geothermics 35 (2006) 473–483

Block diagram of the 1997 circulation test performed at Soultz

The Soultz geothermal system

- The granitic basement, covered by a 1.5 km layer of sedimentary formations, is characterized by fractures ranging from micro-cracks to large normal faults. The abnormally high geothermal gradient of about 100 ◦C/km
- The present targets for heat exploitation are the fractures at 4.5–5 km depth, where temperatures can reach 200 ◦C

- Early stimulation experiments demonstrated that permeability enhancement is mostly limited to weak natural fractures in the hydrothermally altered, cataclastic shear zones intersected by the boreholes (Genter et al., 2000; Dezayes et al., 2004; Evans et al., 2005).
- Permeability enhancement during stimulation is the result of shear dislocation on these fractures (Evans et al., 2005; Gentier et al., 2005).
- The interaction between local permeable fractures and the natural fluid circulation system is crucial to the success of stimulation techniques in EGS projects.
- By hydraulic and chemical stimulation, the natural permeability of the fracture network has been significantly increased around the boreholes through induced shear and chemical leaching.

Case Study on Groß Schönebeck EGS Project Research in Germany

- Enhanced geothermal system(EGS) demonstration project conducted in Groß Schönebeck, Northerm Germany, focusing on hydraulic stimulation.
- The project was conducted with doublet system in sandstone and volcanic formations at 4 - 4.4 km depth.
- Under normal faulting to strike-slip faulting stress regime, hydraulic stimulations were conducted at injection and production wells by massive waterfrac and gel-proppant fracturing.

- Injectivity index increased from 0.97 m3 /(hr*MPa) to 7.5 m3 /(hr*MPa) and productivity index increased from 2.4 m3 /(hr*MPa) to 10.1 m3 /(hr*MPa) by a series of hydraulic stimulations at both wells.

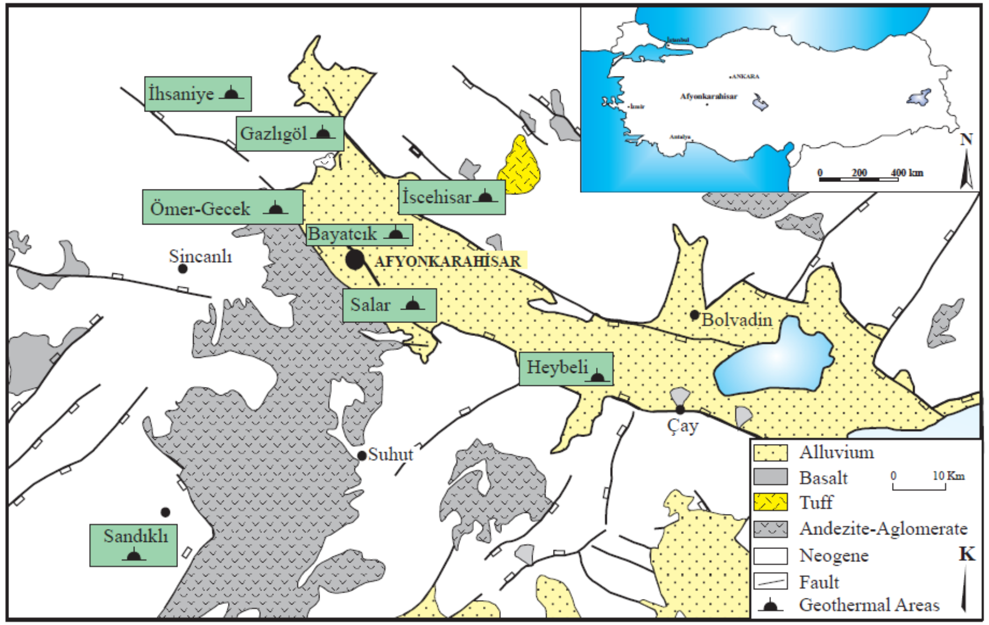
Lithium

- Lithium (Li) is the lightest metal and lithium and its products are widely used in glass, catalysts, aluminium production, rubber synthesis, pharmaceuticals, and Liion batteries due to its unique physicochemical properties (Zante et al., 2019; Swain, 2017; Wang et al., 2020)
- Brine reservoirs contain 66% of global lithium reserves and lithium is contained in salt waters, lakes, salars, oilfield and geothermal brines (Bauer, 2000; Mohr et al., 2012)
- The lithium concentration of geothermal fluids varies between 0.10 and 58.66 mg/L.

Case study Lithium extraction from geothermal waters of Ömer-Gecek (Afyonkarahisar) geothermal area

(Article in TURKISH JOURNAL OF EARTH SCIENCES · December 2021)

- There are approximately 1000 geothermal and mineral water sources in Turkey. The temperature of 170 geothermal resources is higher than 40 °C.
- Afyonkarahisar is one of the most important geothermal fields in Western Anatolia. Geothermal resources in Afyonkarahisar are distributed in Ömer-Gecek, Gazlıgöl, Sandıklı, Heybeli, Bayatçık, İscehisar, Salar and İhsaniye provinces (Başaran et al., 2020; Yıldız et al., 2020; Karaoğlu, 2021).
- Geothermal samples for lithium enrichment were obtained from Ömer-Gecek (Afyonkarahisar), where hosts geothermal resources with low-medium enthalpy containing 3.5 mg/L Li.



The distribution of geothermal areas in the Afyon-Akşehir graben system (modified from Gürsoy et al., 2003).

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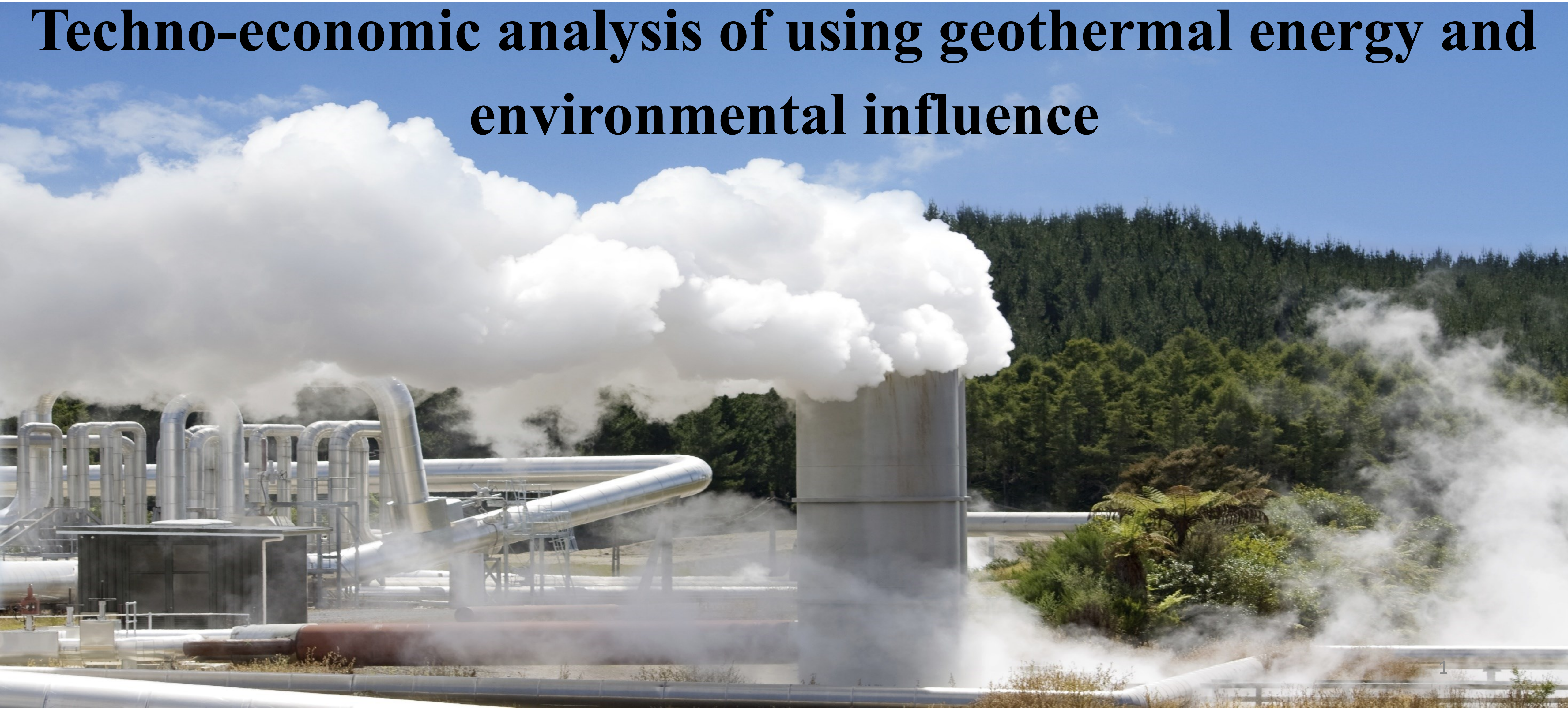
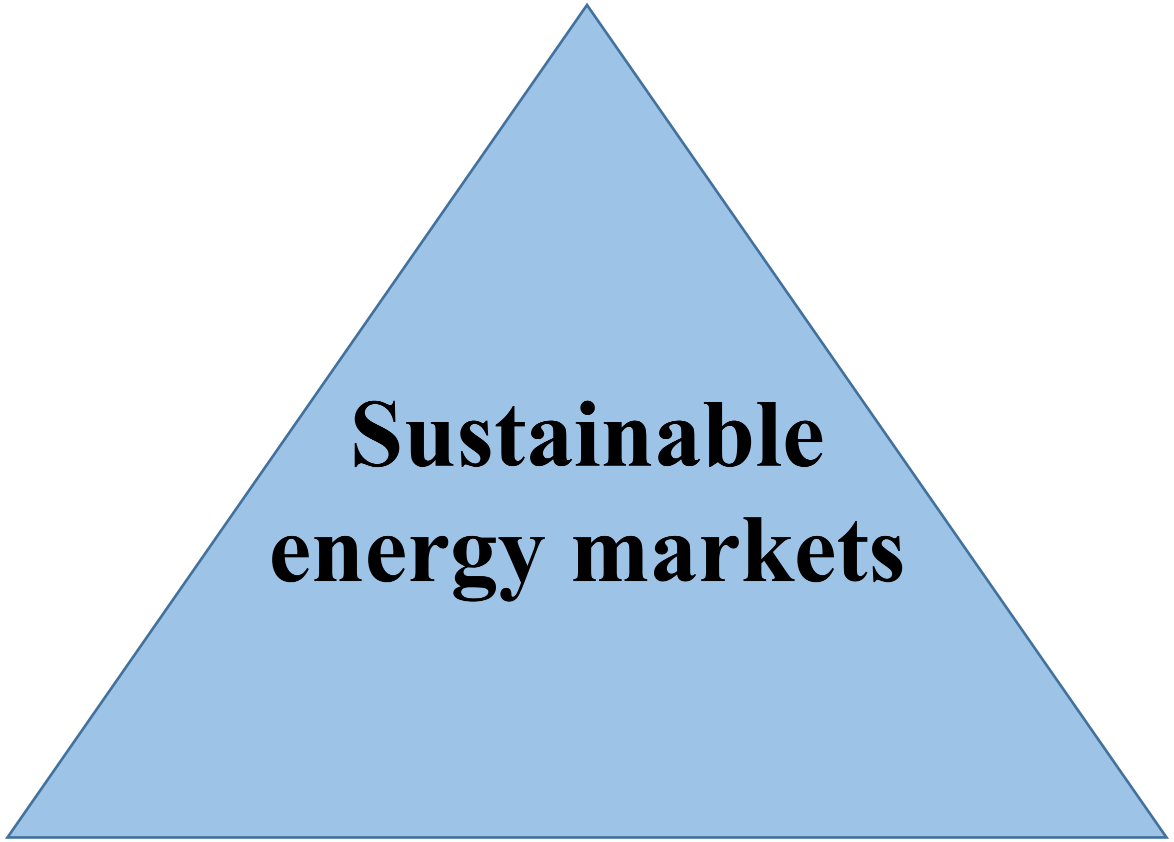
Techno-economic analysis of using geothermal energy and environmental influence





Economic affordability

Sustainable energy markets

Security of energy supplies

Environmental compatibility

Energy markets are not driven only by demand and supply. The provision of energy addresses also social and political issues for the present and future generations. On one side, today's living standard is directly linked to the use of energy. And to maintain and improve this living standard energy must be securely available and affordable. On the other side, today's energy provision depletes finite fossil resources and emits substances, which are damaging the local environment as well as the global climate

Sustainable energy markets, avoiding unwanted effects resulting from the provision and the use of energy, therefore need to manage the three dimensions: security of supply, economic affordability, and environmental compatibility

Economic affordability

Finding and developing geothermal resources, particularly for power production, are expensive and entail risk. Currently, the total cost for putting a geothermal power plant in production, including initial exploration and development drilling, ranges from $3000/kw to more than $7000/kW.

The cost

is sensitive to

1- Temperature of the resource

2-Geologic conditions

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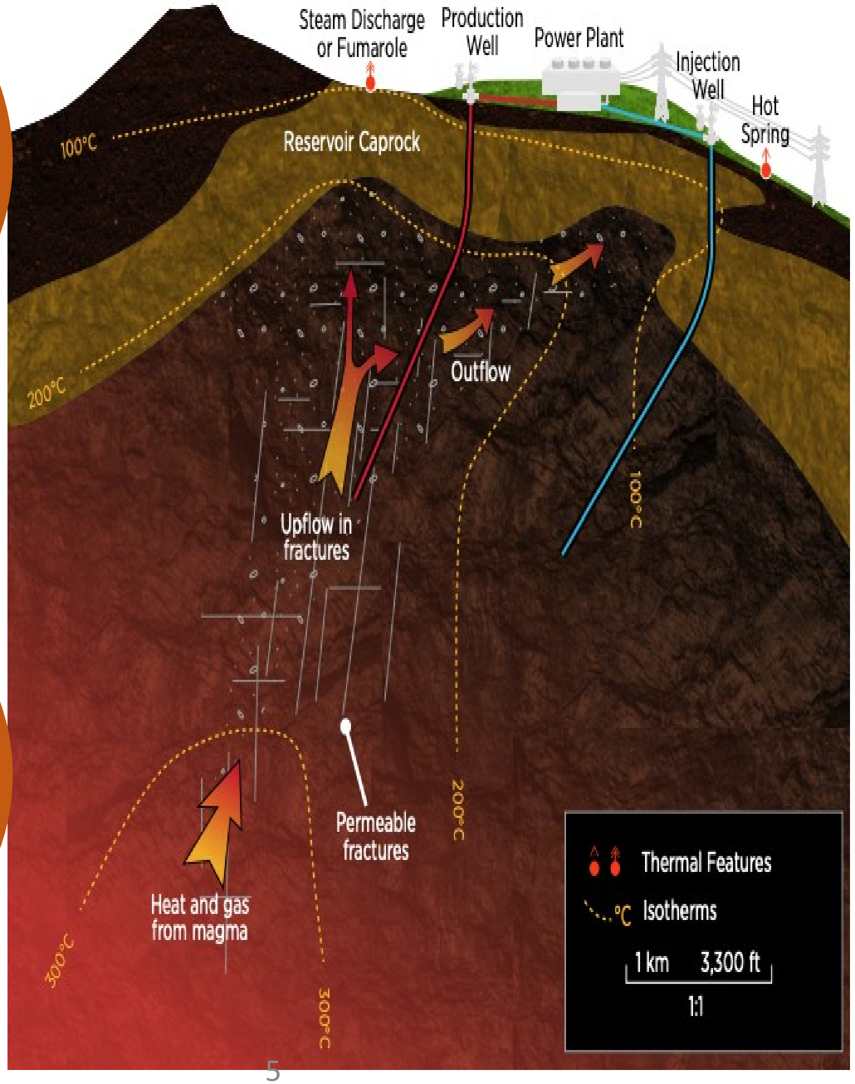
Geologic conditions

- **The depth of the resource**
- **Flow rates of geothermal fluids**
- **Success or difficulty of drilling**
- **Existing infrastructure**



For example

a 30-MWe binary plant utilizing a moderate temperature resource of **165° to 175°C** would cost about **$120M** and can take **5 to 7** years to realize from initial exploration to beginning of production.

In general, economic affordability can be measured by the costs for a product in relation to the amount that the purchaser is able or willing to pay. For the provision of heat and/or electricity based on EGS, this means that the average energy provision cost, typically referred to as levelized cost of energy (LCOE),

levelized cost of energy (LCOE)

The LCOE is calculated based on the total costs throughout the overall economic lifetime of a plant related to the provided energy. The calculation of the LCOE is therefore an important and commonly applied approach in economic evaluation because it allows the comparison of different energy provision technologies or options with each other and with the prices that are paid on the energy markets.

The methodology to calculate the LCOE

It accounts all payments of an EGS project in the monetary value of the reference year, which include the following:

01 **costs of capital related to the investments**

02 **operation costs such as for service and personnel**

03 **cost for consumables such as for supplies and auxiliary power**

04 **revenues for by-products such as heat in case of power and heat supply.**

05 **other costs such as for insurance and taxes**

The annuity method

Using the annuity method, these costs are converted in a series of constant annual payments. The following equation distinguishes between annual costs for consumables, operation and other expenses, annual revenues, and annualized capital user costs.

$$\mathrm{LCOE} = \frac{A_{total}}{E_a} = \frac{O_a + R_a - I_a}{E_a}$$

where,

LCOE = levelized cost of energy
$\mathbf{A_{total}}$ = annualized overall payments
$\mathbf{E_a}$ = annually provided energy
$\mathbf{O_a}$ = annual costs for consumables, operation and miscellaneous
$\mathbf{I_a}$ = annualized capital user costs
$\mathbf{R_a}$ = annual revenues for by-products

The following equation derives the annualized capital user costs from the investments for installing and maintaining the plant, to which an annuity factor is applied.

$$I_a = a \times \mathbf{I}_{\mathbf{total}} = \frac{\mathbf{i}(1+\mathbf{i})^{\mathbf{L}}}{\mathbf{i}(1+\mathbf{i})^{\mathbf{L}} - 1} \mathbf{I}_{\mathbf{total}}$$

where,

a = annuity factor

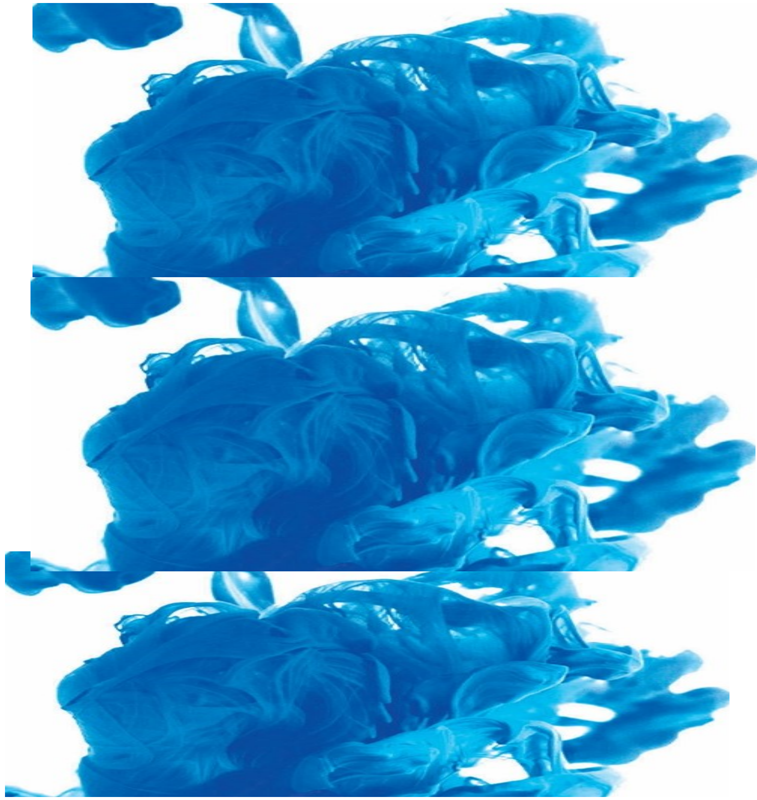
$\mathbf{I}_{\mathbf{total}}$ = total capital investments

$\mathbf{i}$ = imputed interest rate

$\mathbf{L}$ = number of annual periods within economic lifetime

Cost Analysis

The total costs of an EGS project are dominated by the investments at the beginning of the project. These investments mainly consist of costs for



01 reservoir exploration

02 well drilling and completion

03 reservoir engineering measures

04 installation of the geothermal fluid loop

05 construction of the plant on the surface for power and/or heat provision.

Well costs

1 Rig rent

2 Material costs

3 Energy costs

4 Service costs

1- Rig rent

❑ The rig rent is usually paid on an hourly or daily rate for the time the drilling rig is used.

❑ The rate for drilling rig depends on its specifications such as:

01 **hook load**

02 **depth capacity**

❑ From an economic viewpoint, the choice of the drill rig is therefore a compromise between rig capacity and drilling progress.

2- Material costing

The material costs basically include

- **01 The expenditures for casings**
- **02 drilling mud**
- **03 drilling bits**

These costs depend on the borehole design, such as diameter, depth, and well course, as well as on the site-specific stratigraphy, which for example, determines the casing material and its insulation thickness.

3- Energy costs

The energy costs refer to the power to drive the

- **01 The drilling rig**
- **02 The drilling mud pumps**

and depend on the means of energy provision

(e.g., energy provision from electricity grid or diesel electric rig drive).

4- Service costs

The service costs include quantity-dependent service costs, which are borehole-related services such as:

01 **Installation of the casings**

02 **Cementation**

03 **Logging**

and drilling site–related activities such as:

01 **Installation and dismantling of the drilling rig**

02 **Drilling site preparation**

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Impacts on the Environment

Like all other options of energy provision, EGS has impacts on the global and local environment. Therefore, it is important to identify and evaluate any impact which results from the implementation of an EGS plant at the beginning of a project.

The goal must be to avoid or minimize negative impacts on the environment during all stages of an EGS project (e.g., construction, operation, and deconstruction) and to meet the objectives and requirements of climate and environment protection, nature conservation, and preservation of finite resources.

Regarding the development of conventional geothermal resources, several local environmental changes have been reported in the last 40 years. Some of them have been significant and even severe. In part of Wairakei field (New Zealand), for example, the withdrawal of fluid from the reservoir led to a subsidence of about **15** m.

The degradation of geothermal reservoirs was observed at several sites like Larderello (Italy), The Geysers (USA), and Wairakei (New Zealand). Today, it is known that these problems mainly occurred due to much larger production than injection rates and so adapted reservoir management systems and strategies were developed in order to avoid further impacts.

Drilling operations have a large impact on the environment and are related to different risks. Since EGS well drilling uses mainly the same processes as for gas and oil exploration, the different environmental impacts and risks are known and technical measures and safety precautions do exist in order to avoid or minimize them.

Drilling Operations impact on the environment

- Airborne emissions
- Waste disposal
- Visual impact
- site preparation
- Noise emissions
- Subsurface emissions

Drillings site preparation

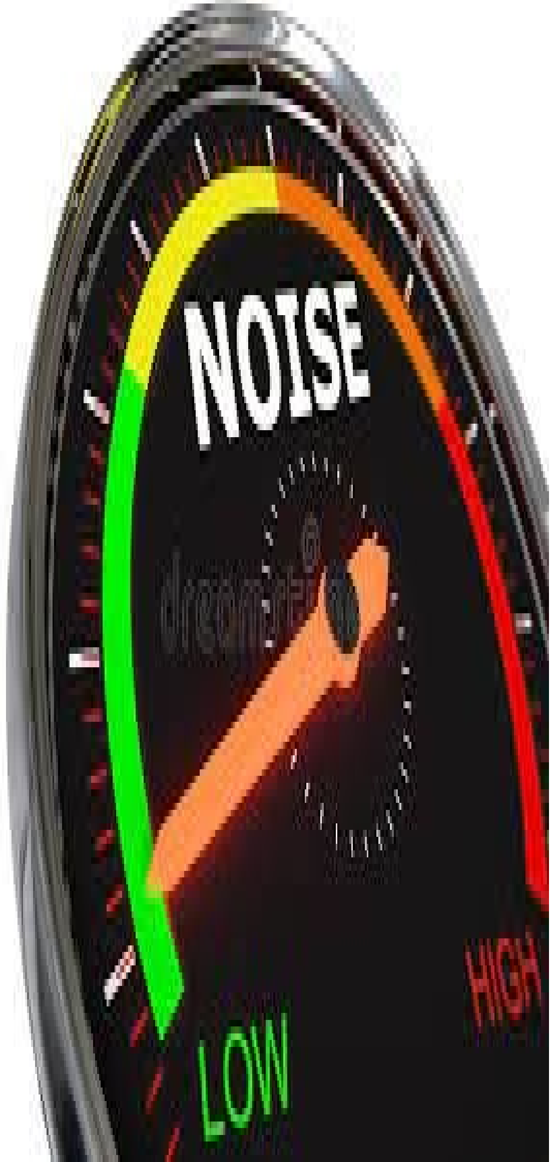
The drilling site needs to be prepared in such a way that drilling operations can be carried out safely, both for persons working at the drilling site and the environment.

An important aspect is the covering of the soil in order to prevent its pollution with material which is mounted and handled at the site (such as drilling mud or fuel). In order to do this, the preparation of the drilling site usually includes destruction of local vegetation

Noise emissions

Drilling operations are related to the emission of noise. Operating the drilling rig, handling of casings, or simply communication of the drilling crew causes a noise level between **70 and 125 dB(A)**

Depending on the proximity to housing areas and animal habitat and also topographical and meteorological site conditions, this can be an environmental impairment. By using mufflers or implementing proper noise insulation measures (such as sound insulating walls), these emissions can generally be reduced to a tolerable minimum. In many countries, allowed noise thresholds for specific areas are defined and need to be considered in order to get a drilling permission.



Subsurface emissions

The normal drilling process involves local emissions of drilling mud in the subsurface surrounding of a drilled well. Intersecting geologic anomalies such as fault zones also more extensive emissions are possible.

For environmental but also safety reasons (e.g., open hole stabilization), the drilling mud composition is adapted to the geological conditions. The emission of drilling mud into already drilled areas or causing a hydraulic short circuit between different aquifers (which can both lead to the pollution of groundwater bearing formations) is a known environmental risk. It is prevented by immediate casing (and cementing) after finishing a drill section.

In many countries, the composition of the drilling mud and the closing-off of different drill sections is a matter of legal regulations.

Airborne emissions

Besides the possible creation of fumes and dust during drilling operations, gaseous emission can occur when gas components (such as **CH_4, Co_2, H_2S)** dissolved in the drilling mud are released at the surface.

Hazardous concentrations for the environment, however, are normally not expected and with the use of gas separators, such emissions can be avoided. Furthermore, small amounts of gaseous emissions related to well testing can also occur.

Waste disposal

Related to drilling, large amounts of waste such as disused drilling mud and cuttings must be handled and disposed properly. Whereas the disposal of disused drilling mud (and cuttings) on the basis of freshwater is not very critical, drilling mud on the basis of saltwater or oil has to be handled with care.

With proper drilling operation management, the disposable amounts can be reduced, for example, by reusing drilling mud for other wells or using cuttings as filling material for civil engineering.

Visual impact

The installed drilling rig and nocturnal lighting can be an inconvenience for the surrounding environment. However, this visual impact is temporary.

Other incidents which can possibly lead to adverse impacts on the local environment are severe geomechanical changes triggered by the drilling process and uncontrolled well blow outs. However, such geomechanical changes are only possible in tectonically active regions. Regarding well blow outs, the use of blow-out-preventers at the wellhead is state-of-the-art.

Visual
Impact

Analysis of environmental influence

Life Cycle Assessment LCA

The methodology of life cycle assessment (LCA) is introduced and applied for representative EGS plants. Based on this approach, the emission of pollutants, which add to the anthropogenic greenhouse effect and the acidification and eutrophication of natural eco systems, as well as the consumption of finite energy resources are quantified.

LCA involves two main stages:

01 **The collection of data, related to the product or duty and relevant for the environment**

02 **The interpretation of the collected information. For transparency and traceability of LCA results, standards, such as ISO 14040, ISO 140441) have been developed.**

Therefore, within an LCA the overall life cycle of a product is investigated from “cradle to grave.” For EGS plants, this is true for all environmental impacts directly and indirectly related to the construction, operation, and deconstruction of the plant.

Methodological Approach

The LCA methodology is based on the fact that the environmental impacts of a product (such as the power generation from geothermal energy) are not limited to the production process itself (i.e., the power conversion process).

Substantial environmental impacts may also occur within the prechains such as the production and transportation of material needed for the production of the analyzed product (i.e., diesel fuel for running the drilling rig, steel for the completion of the wells).

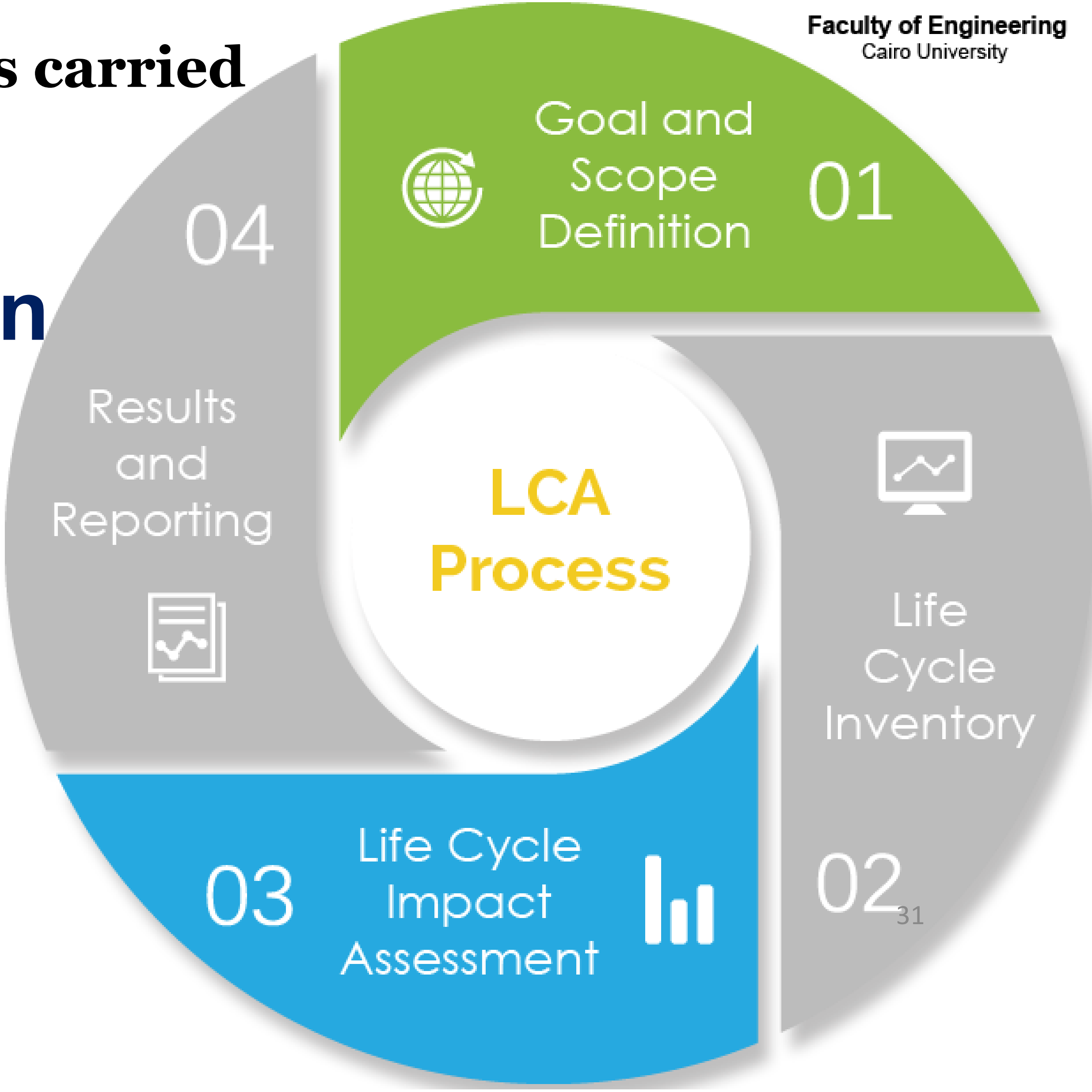
According to given standards, the LCA is carried out in four steps:

01 **Goal and scope definition**

02 **Inventory analysis**

03 **Impact assessment**

04 **Results and Reporting**



1-Goal and scope definition

Goal and scope definition: The goal of LCA is to assess selected environmental effects in the different life cycle stages as well as throughout the whole life cycle of EGS plants.

The environmental effects which will be analyzed in LCA are the cumulated demand of finite energy resources, the contribution to the anthropogenic greenhouse effect, as well as the acidification and the eutrophication effects on natural eco systems.

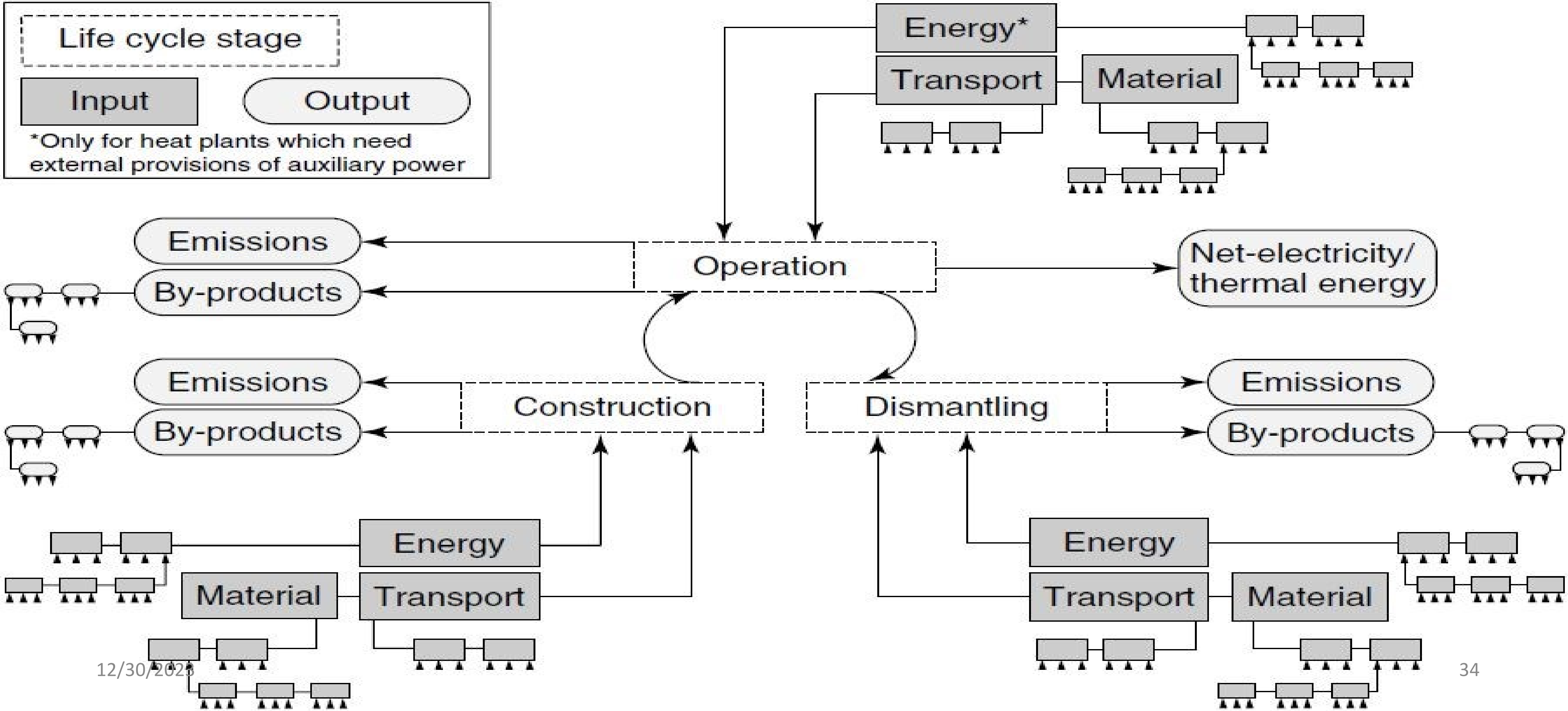
2- Inventory analysis

In this step, the material and energy flows for all products and processes required to provide 1 kWh net-electricity from an EGS reservoir are quantified and assigned to different process chains. Energy flows include

for example, the electricity needed to operate the drilling rig which is provided by diesel generators. The diesel fuel is produced from different types of crude oil. Its use at the drill site as well as the provision of the fuel to the site results
in airborne emissions.

Life
Cycle
Inventory

02

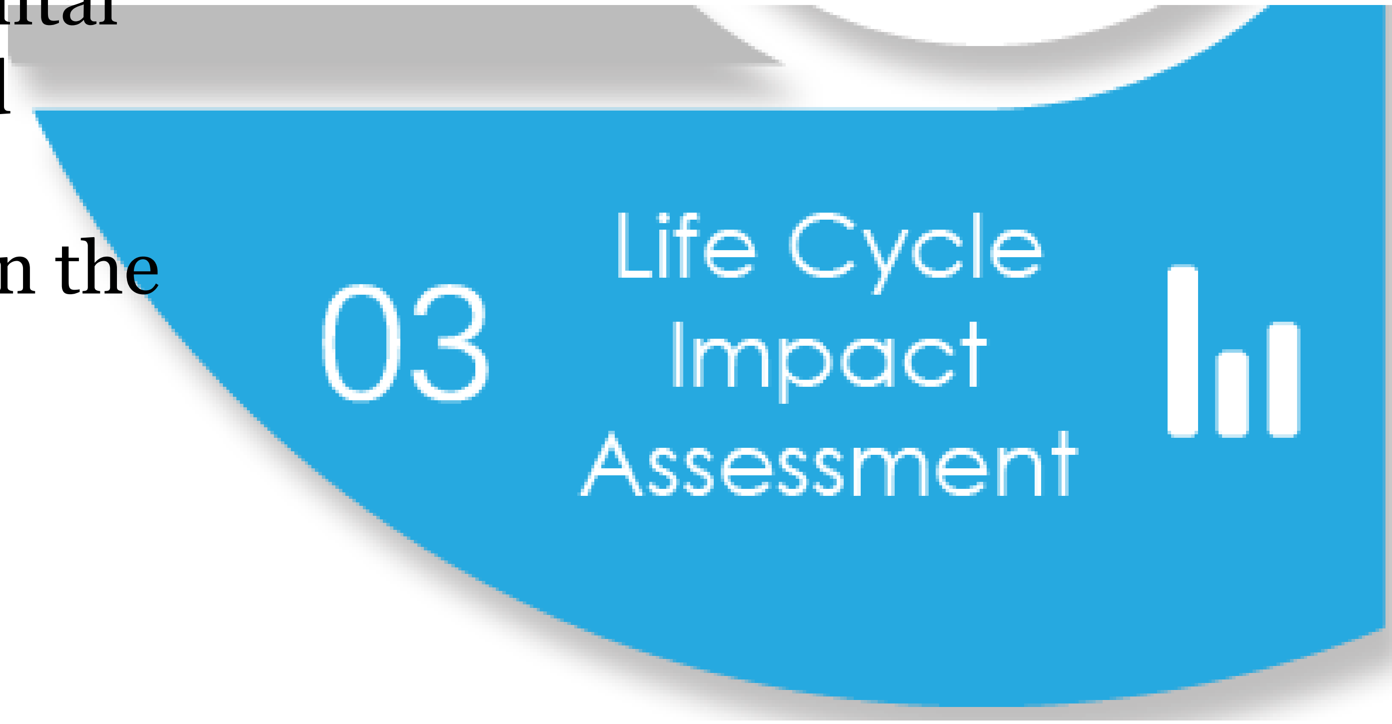


Life cycle stage
Input
Output
*Only for heat plants which need external provisions of auxiliary power

Energy*
Transport
Material
Operation
Emissions
By-products
Net-electricity/ thermal energy
Construction
Emissions
By-products
Energy
Material
Transport
Dismantling
Emissions
By-products
Energy
Transport
Material

3- Impact assessment

In order to quantify the environmental effects, all inventoried material and energy flows are transformed to different impact indicators based on the conversion factors



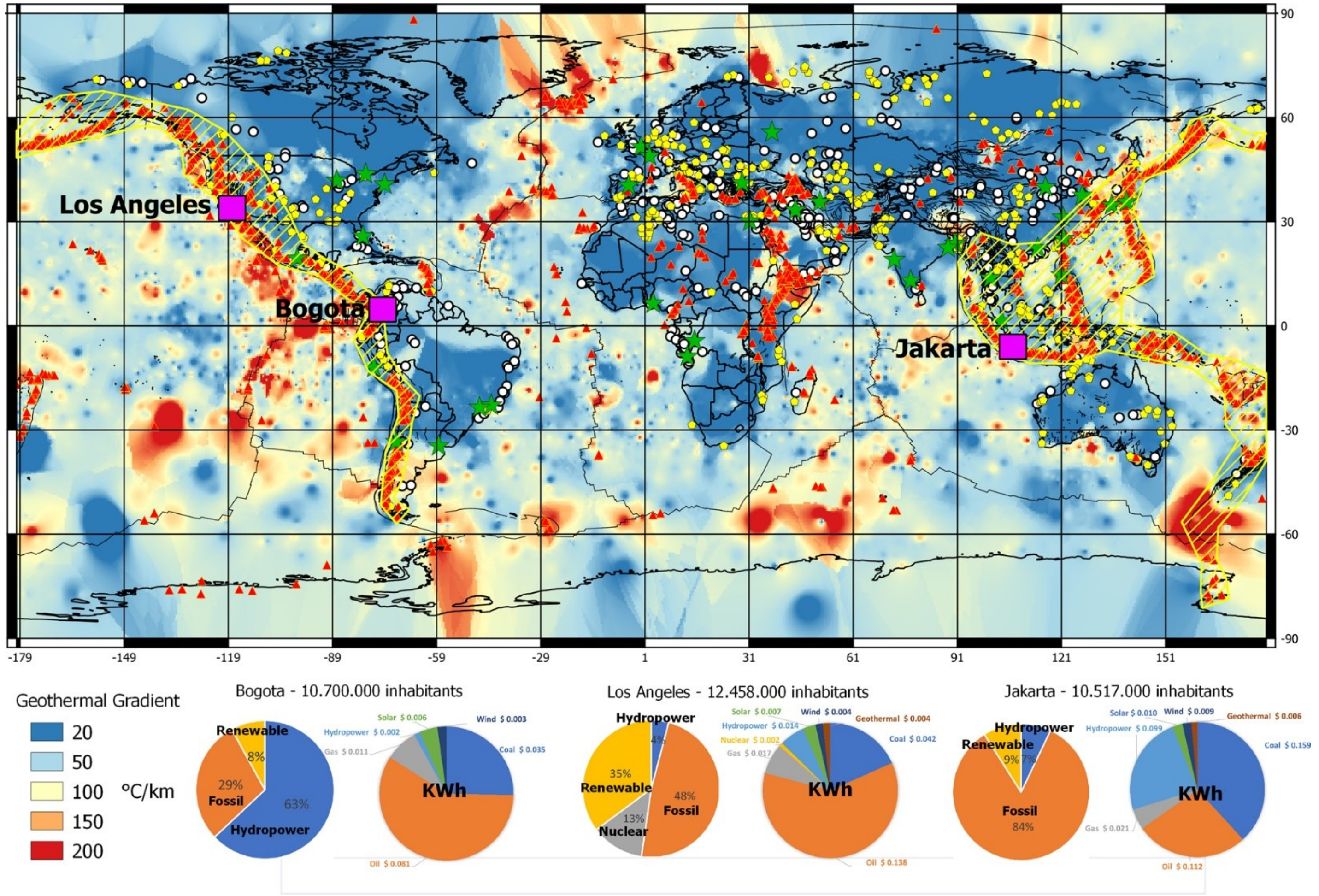
4- Results and Reporting

The interpretation of the results from the impact analysis is realized qualitatively by separately discussing the single impact categories

The geological conditions can significantly vary. Based on the presented results it can, however, be derived that sites which need larger amounts of material and energy for the construction of the subsurface part and thereof especially drilling and completing the deep wells, can also be environmentally promising; the precondition is that the provided energy compensates the larger mass- and energy flows

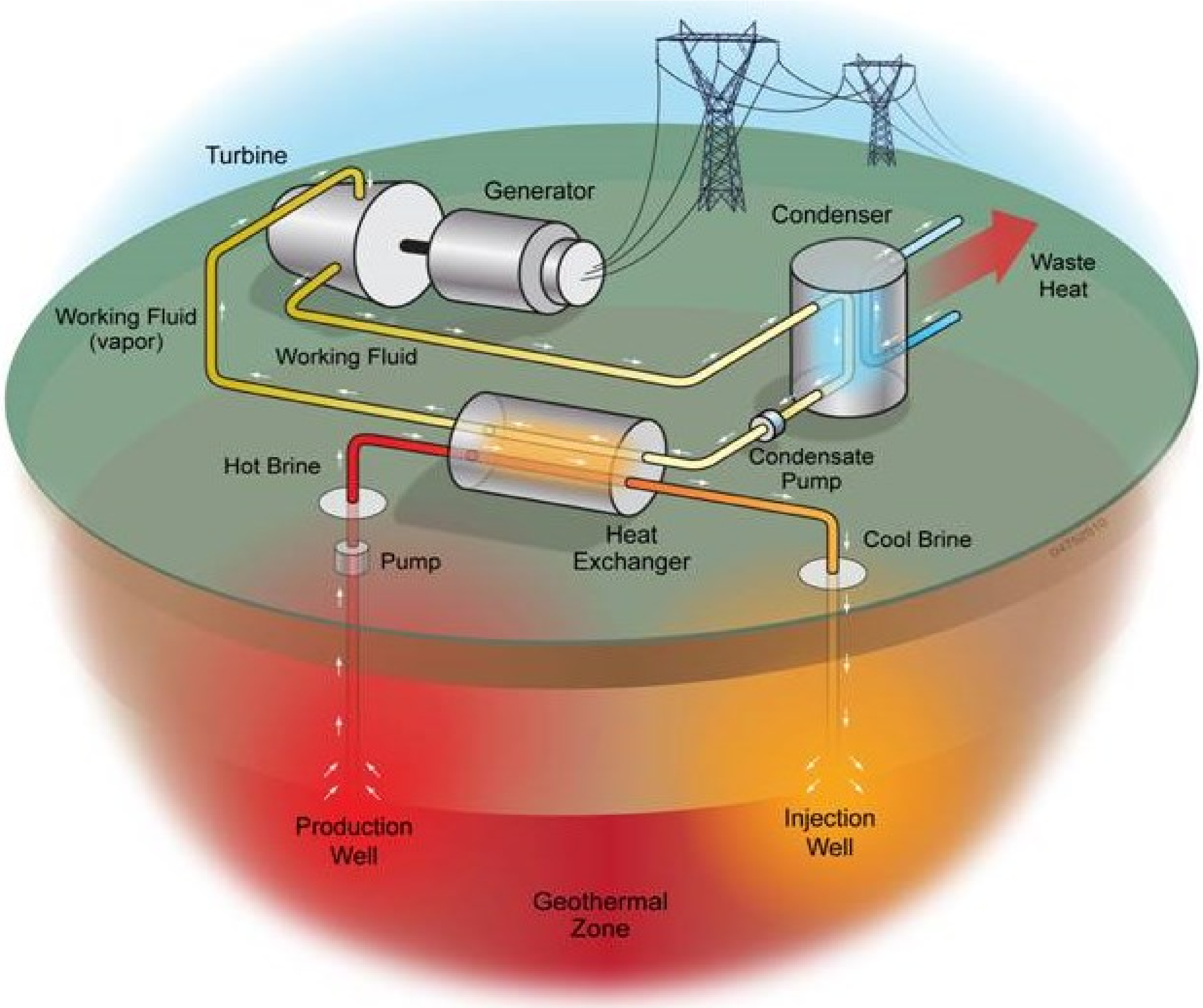
04

Results
and
Reporting



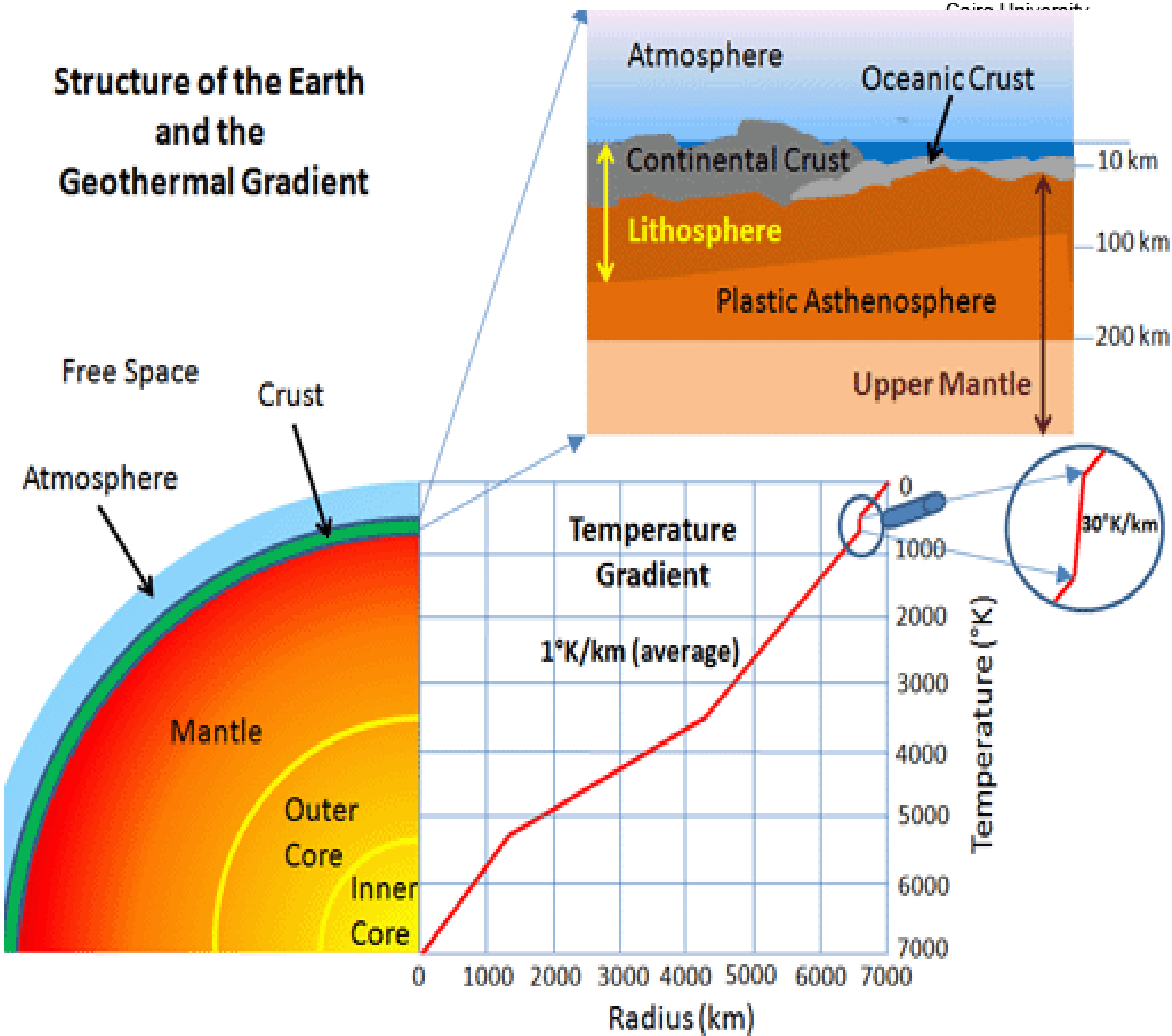
Worldwide distribution of geothermal gradient anomalies.

Determining available thermal energy from geothermal reservoir



The geothermal energy available from the Earth is potentially enormous. A United States Government energy agency estimates that the total energy available from global geothermal resources is approximately 15,000 times the energy contained in all the known oil and gas reserves in the world.

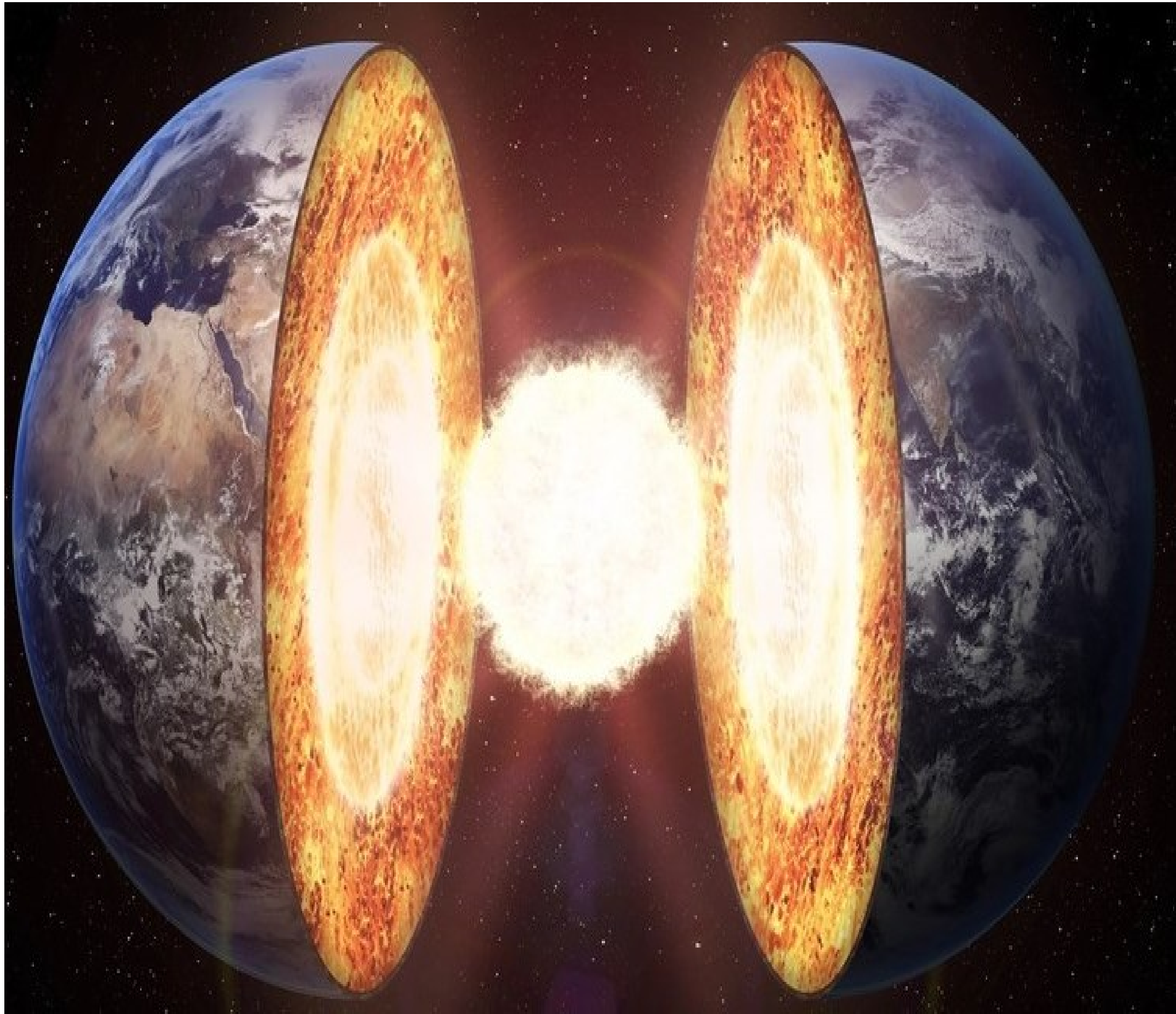
Unlike solar and wind energy, the supply of geothermal energy is constant and doesn't vary with the time of day or change with the weather.



Structure of the Earth and the Geothermal Gradient

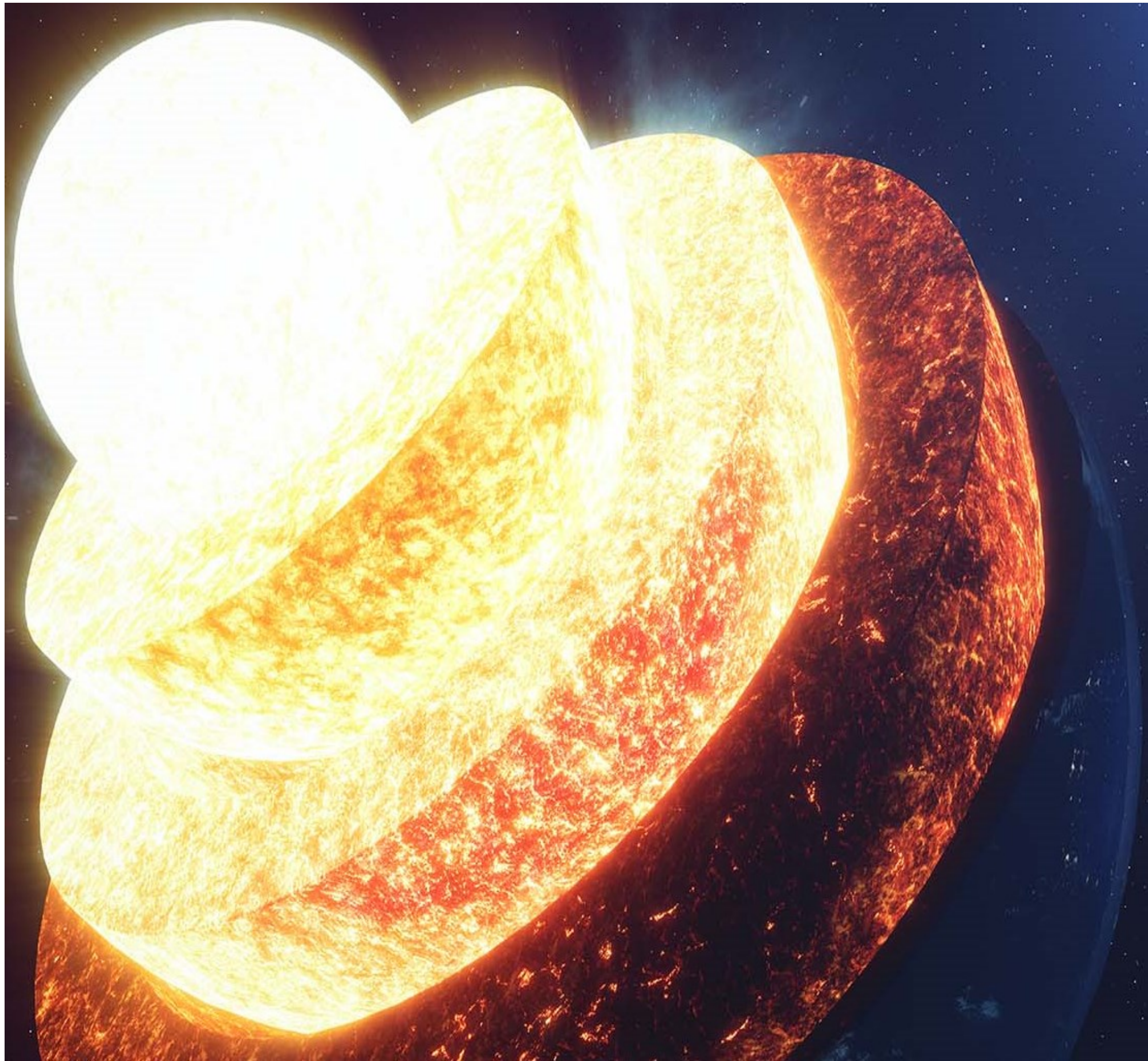
The Earth's core maintains temperatures in excess of 6000°K due to the heat generated by the gradual radioactive decay of the elements it contains. Modern estimates (Sclater 1981)

for the total present rate of radioactive heat generation within the Earth are about **2×10^{3} W**. This heat energy continuously flows outwards from the hot core due to conductive and convective flows of the molten mantle beneath the crust.



The thermal power that is generated in Earth's mantle travels to the ground surface through the rock formations of the crust by thermal conduction. This generates an average conductive temperature gradient between 20 and 30C/km (Armstead, 1978), which results in a heat flux of about 4060 mW/m2.

This geothermal heat flow is trivial compared with the 1000 W/m^2 of solar energy impinging on the surface of the Earth in the other direction from the Sun (1367 W/m^2 at the outer surface of the atmosphere).



This energy manifests itself at the surface from time to time through seismic and volcanic activities mainly along tectonic plate boundaries. Earth also has a massive stored thermal energy (inertia) estimated around 12.631024 MJ. Of these, 5.431021 MJ (1.531012 TW h) of energy is in the Earth's crust (Armstead, 1978). Knowing that the total world energy consumption in 2012 was 154,795 TW h (USEIA, 2017),

geothermal energy can effectively provide all of humanity's energy needs for many generations to come. Theoretically, the ge'othermal energy stored and generated underground is more than all other (fossil and renewable) energy sources combined.

Geothermal Gradient

The geothermal or temperature gradient is the rate of increase in temperature per unit depth in the Earth due to the outflow of heat from the center.

The thermal gradient is often thought of as linear, though in reality a higher thermal gradient is expected through less conductive rock, and a lower gradient expected through rock that is more conductive. For example the deep EGS well of the Habanero project in Australia has a local thermal gradient that ranges between 32.3 and 63.3C/km depending on the rock type.

Coal, and rocks bearing hydrocarbons are less conductive than other rock types and can act as thermal insulators, trapping heat underneath. In addition, some deep volcanic rocks (e.g. granite) generate heat by radioactive decay which can also result in an above average thermal gradient through these rock types.

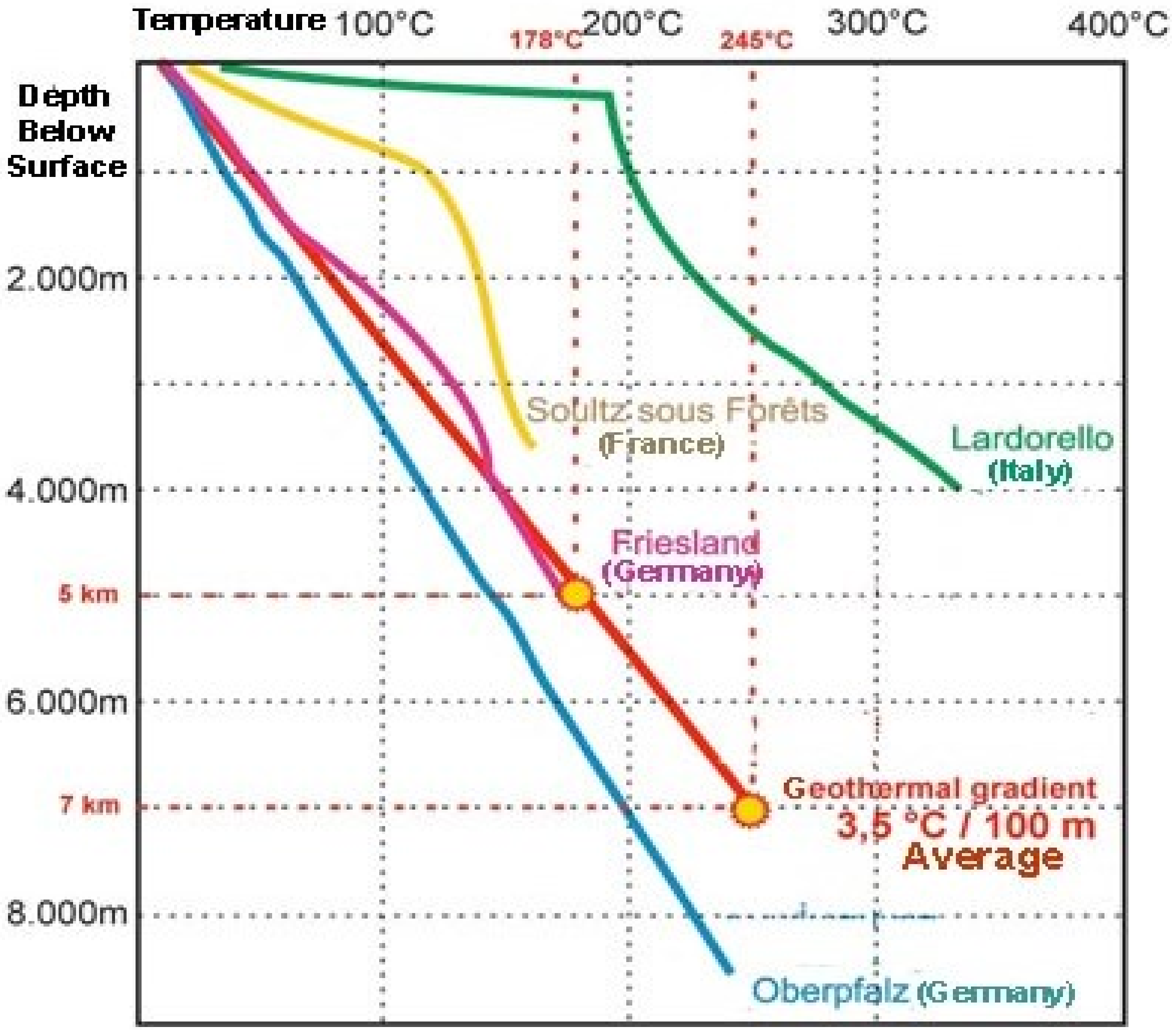
The temperature gradient between the center of the Earth and the outer limits of the atmosphere averages about 1°C per kilometer. The temperature gradient in the Earth's fluid layers, the magma, tend to be lower because the mobility of the molten rock tends to even out the temperature. This mobility however does not exist in the solid crust where temperature gradient is consequently much higher, typically between 25 °C and 30 °C per kilometer depending on the location and higher still in volcanic regions and along tectonic plate boundaries where seismic activity transports hot material to near the surface.

In some parts of the world the local thermal gradient is higher than 30C/km, for example the measured thermal gradient of Huntly, New Zealand, ranges between 52 and 55C/km (Zarrouk and Moore, 2007). The geothermal gradient is also affected by the thermal conductivity of the different rock formations that it passes through, following Fourier’s law of thermal conduction.

The temperature profile varies, depending on factors such as the porosity of the rock, the degree of liquid saturation of the rock and sediments, their thermal conductivity, their heat storage capacity and the vicinity of magma chambers or heated underground reservoirs of liquid.

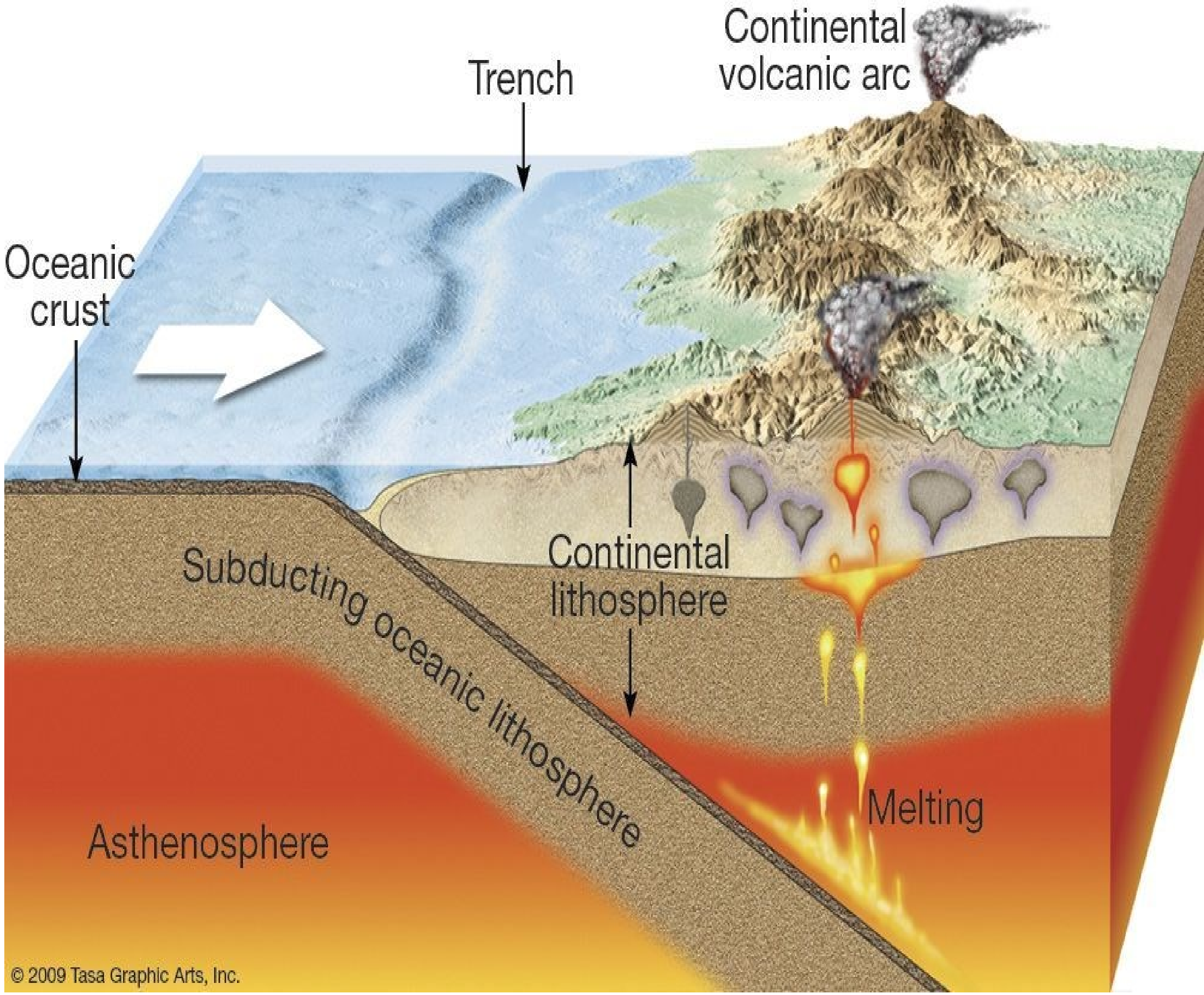
Low temperature gradients mean that boreholes must be very deep to reach high temperature rock but because of the difficulties involved in deep drilling and extraction, high temperature gradients are needed to get heat from reasonable depths. Suitable conditions are only available in a few locations

Earth's Crust Temperature Profile at Different Locations



In areas along Earth's plate tectonic boundaries the natural thermal gradient can be as high as 100C/km.

When there is reasonable permeability in the surrounding rocks and good natural supply of water (meteoric or seawater), the thermal gradient will become unstable giving way to convective heat transfer through water movement, which carries much more thermal energy than thermal conduction.



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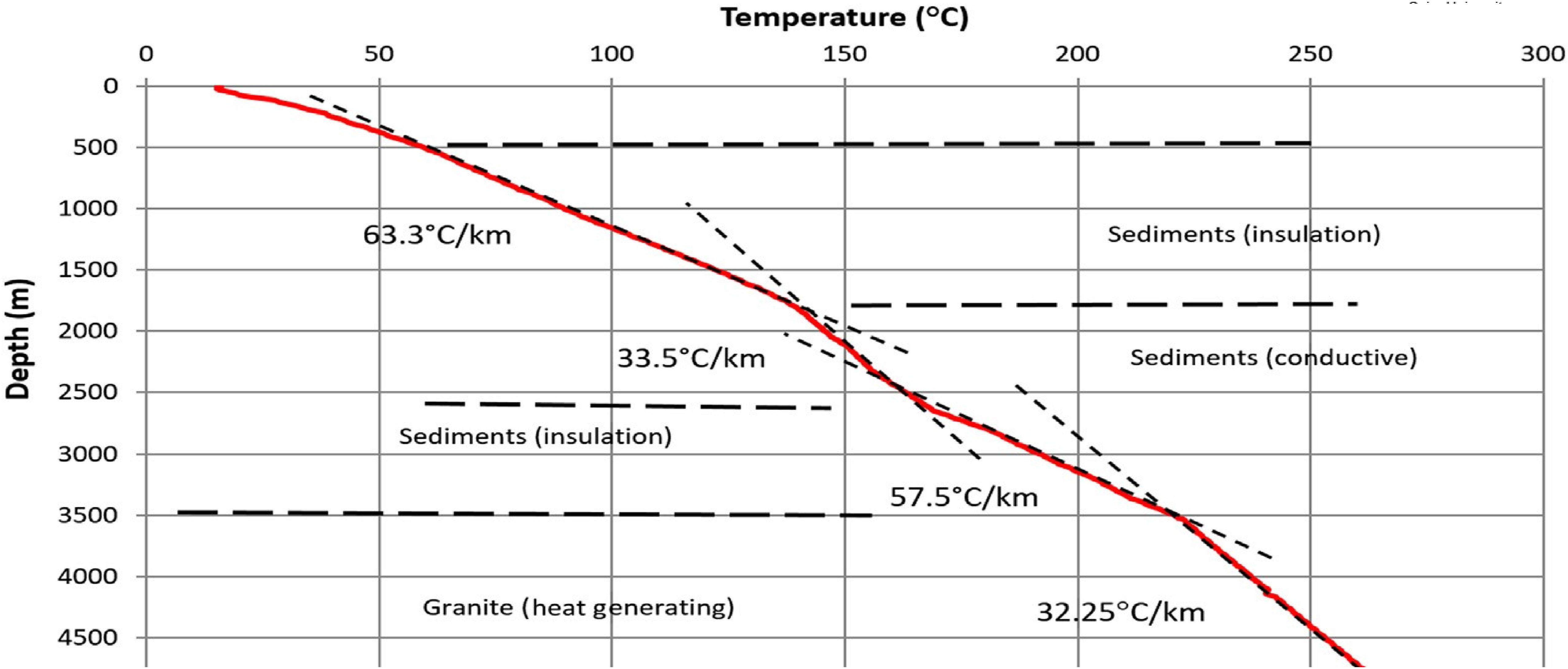
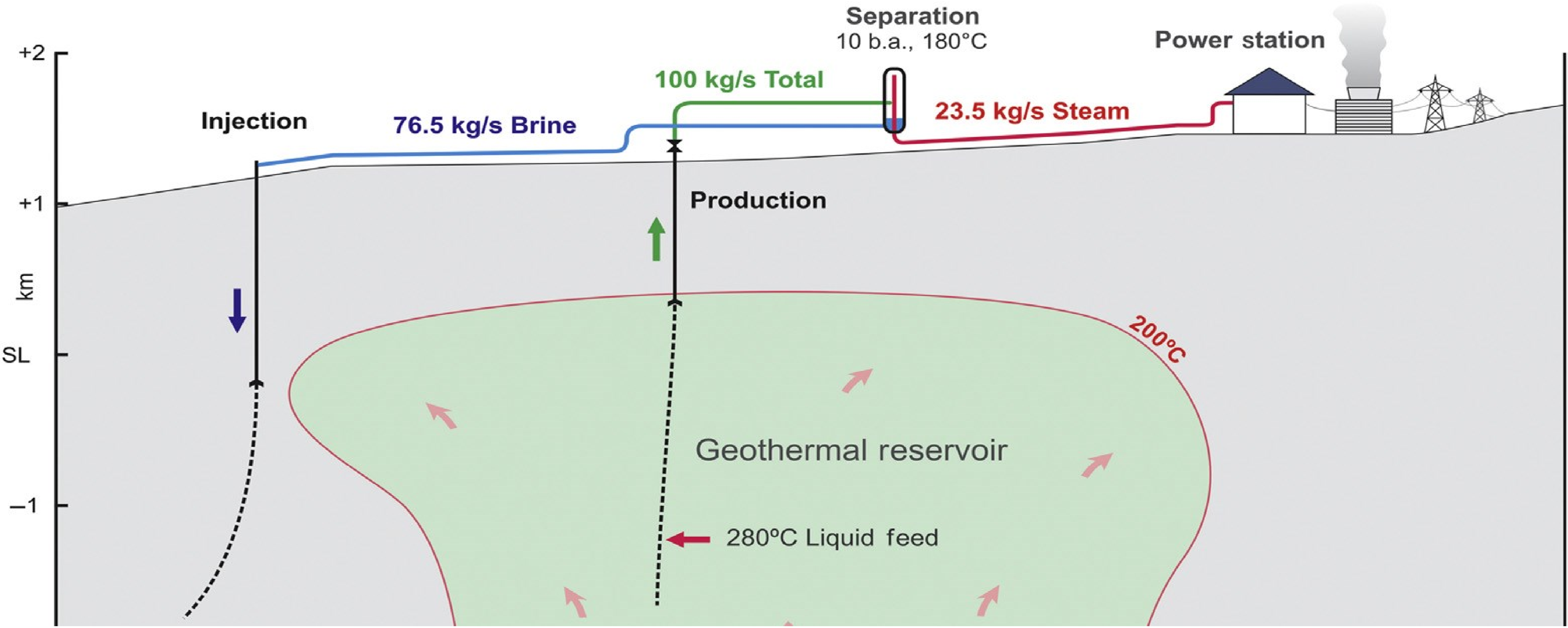


Example of the geothermal gradient of the H01 Habanero well



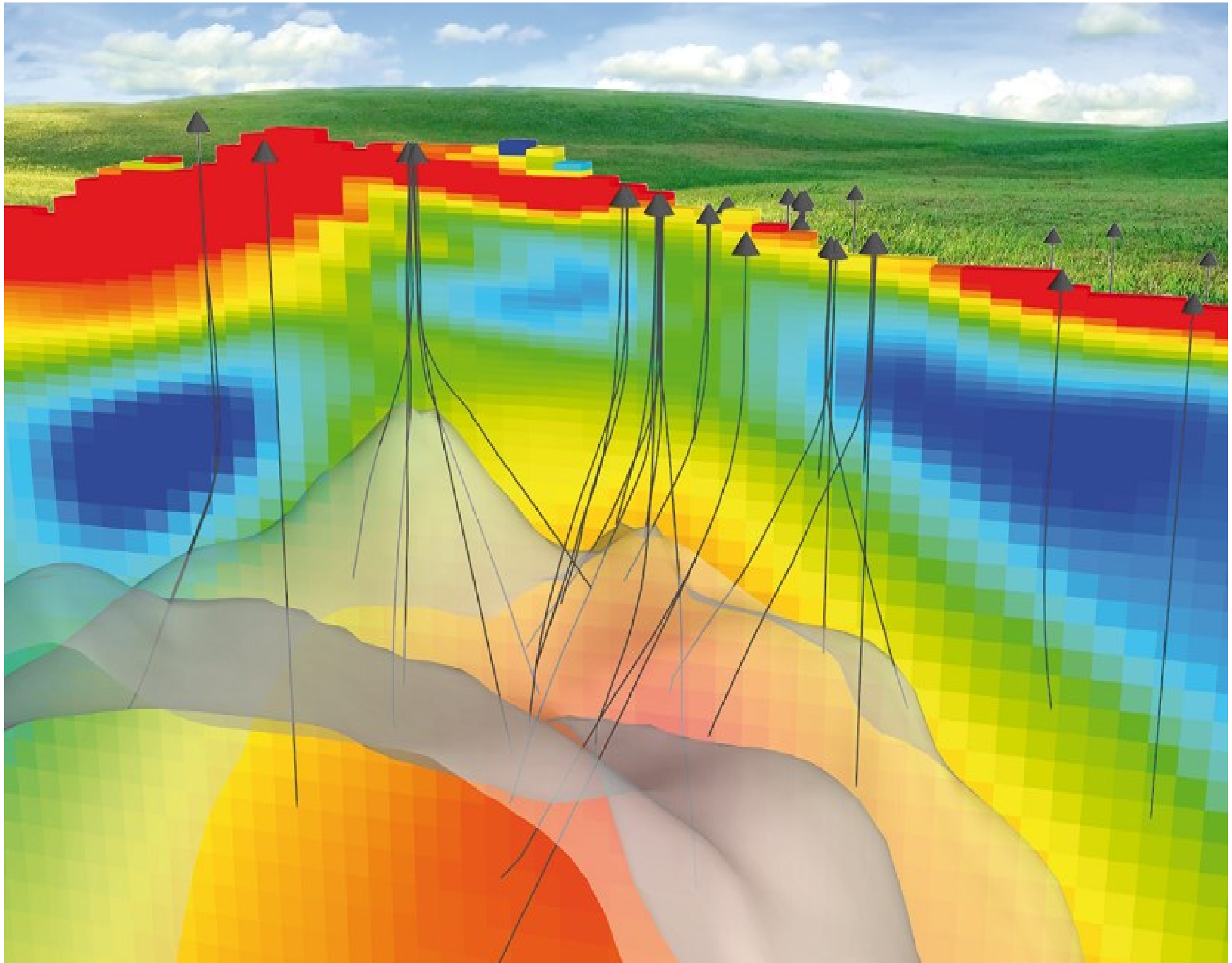
Cross section through a convective geothermal system utilized for power production. From Brian Lovelock,

Available Energy

The key factors influencing the amount of heat which can be extracted from a hot rock system are:

- **01** **The temperature of the hot rock**
- **02** **The flow rate of water through the hot rocks**
- **03** **The volume and surface area of the hot rock exposed to the circulating water**
- **04** **The permeability in the hot rock (Sufficient to allow free flow of injected water through a large volume of rock).**
- **05** **The energy needed to drive the water pumping system.**

Thermal efficiency



The thermal efficiency of ideal heat engines depends on temperature difference between input and output temperatures of the system.

Carnot's Law gives the maximum efficiency as (**1 - Tc / Th**) where T is the temperature in degrees Kelvin

Hot Rock systems have a low efficiency because of low temperature difference between the water pumped out of the Earth and the water pumped back in. For a system with a water supply temperature of 85°C and a return temperature of 35°C, the maximum possible thermal efficiency will be

$$1 - (35+273)/(85+273) = 1 - 308/358 = 14\%$$

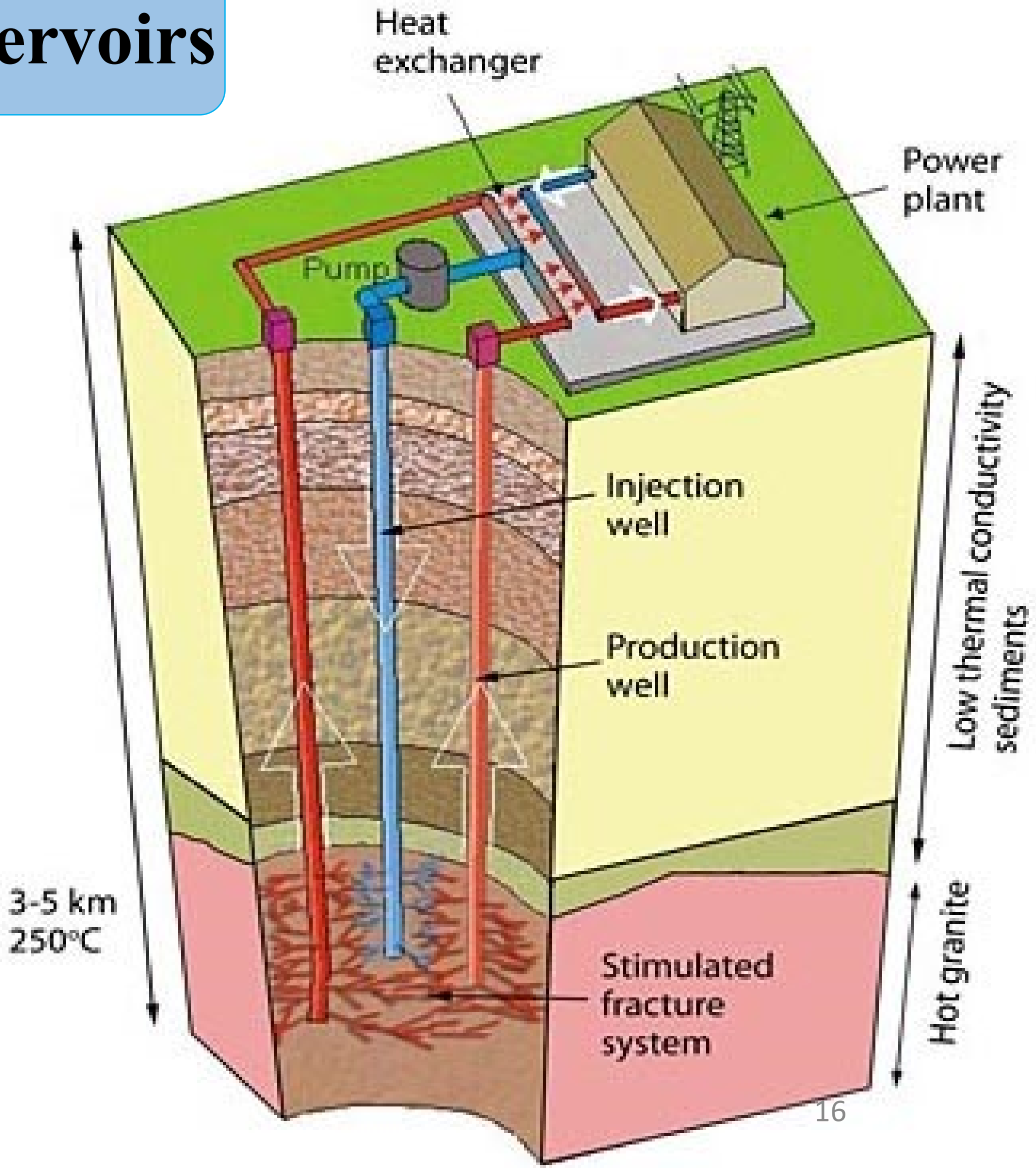
Because of the energy lost in heat transfer from the rock and in the pumping energy required for the water circulation circuit, the system conversion efficiency will be much lower, possibly reducing the thermal efficiency by more than half in low temperature systems.

Thermal energy Resources

Thermal energy from hot rocks geothermal reservoirs

In operation, cold water is pumped at high pressure down into the very high temperature fractured hot rock where it becomes superheated as it passes through the rock on its way to the extraction borehole(s).

The working fluid, a low boiling point liquid, circulating through the secondary circuit of the heat exchanger is vaporized by the heat extracted from the well water and used to drive the turbine.



EGSs are resources that contain a large amount of thermal energy but lack sufficient in situ water, permeability, or both, so that the reservoir must be engineered to extract the thermal energy. EGS resources are divided into (1) near-hydrothermal-field EGS resources, which are located near conventional hydrothermal fields, and (2) deep EGS resources, which, in theory, can be developed anywhere by drilling deeply enough to access high-temperature reservoirs.

Low temperature co-produced geothermal resources can be accessed as a part of oil and gas production activities. During oil and gas production, large quantities of water can be co-produced with the oil and gas. Some of this co-produced water is at a high enough temperature that it can be used to generate electricity. It is estimated that active oil and gas wells in the United States are capable of producing 300 MW of geothermal power with the majority of this power potential located in Texas outside of the Eastern Interconnection.

The available heat flow is given by :

$$q = K_t \frac{\Delta T}{z}$$

Where

q is the heat flow per square meter in W/m^2

$\mathbf{K_t}$ is the thermal conductivity of the rock in W/m/°C

ΔT is the temperature difference in degrees Centigrade

z is the thickness of the hot rocks layer in meters.

Thus **ΔT/z** is the temperature gradient

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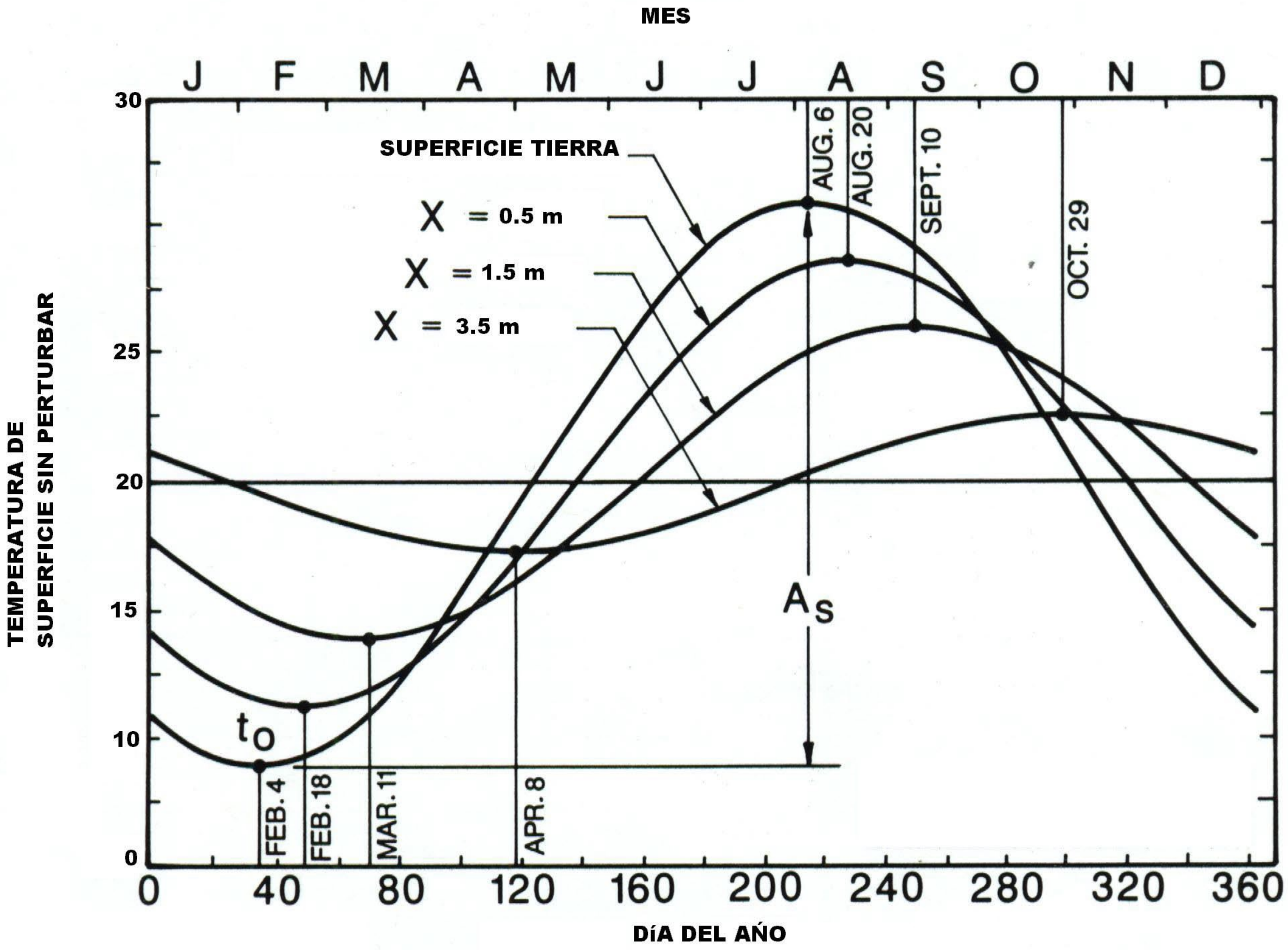
Determining Temperature in Shallow Geothermal Systems



$$T_{(z,t)} = \mathrm{T_s} - \Delta \mathrm{T_s} \ . \, e^{-z\sqrt{\frac{\pi}{\sigma\pi}}} . \cos\left(\frac{2\pi t}{\sigma t} - \theta\right)$$

$T_{(z,t)}$ Is the undisturbed ground temperature as a function of time and depth

T_s Is the average annual soil surface temperature in deg c

ΔT_s Is the amplitude of the soil temperature changes throughout the year in deg

θ Is the phase shift or day of the minimum surface temperature

σ Is the thermal diffusivity of the ground

t Is time constant , 365

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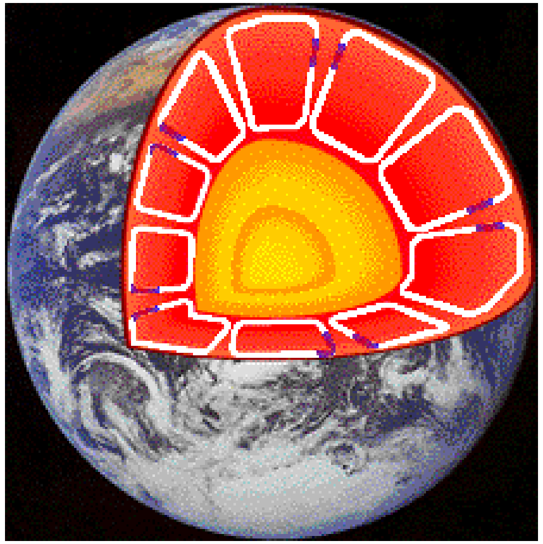
Overview of regulations & directions of managing Geothermal Systems



Special geological conditions can cause a number of problems with installation as well as environmental damage. Being aware of these conditions and using protective measures can reduce problems and risk:

- Artesian aquifers
- Very shallow water table where reinjection can be problematic
- Perched groundwater layers
- Two or multiple aquifer layers
- Mineral water resources
- Thermal water resources
- Gas occurrences - Mining areas - Evaporates - Swellable rocks
- Karst area - Flood and erosion area - Landslide area - Costal zone

Areas of public interests

- Water protections zone
- Nature protected ecosystem area
- Contaminated soil

Operation criteria

The group of operation criteria is divided in criteria valid for all systems, criteria valid for open loop systems or closed loop systems.

Operation criteria valid for all systems

- Drilling below groundwater table allowed
- Minimum distance to neighbouring plots
- Minimum distance to buildings
- Minimum distance to neighbouring wells
- Minimum distance to neighbouring closed loop systems
- Groundwater investigation necessary
- Certification for drilling companies needed
- Numerical simulations required

Operation criteria valid for open loop systems

- Minimum distance between pumping and reinjection site
- Reinjection of groundwater
- Temperature difference between extracted and reinjected water
- Absolute allowed temperature range of reinjected water
- Allowed temperature change to other installations
- Accepted drawdown
- Pumping test obligatory

Operation criteria valid for closed loop systems

- Minimum distance to other heat exchangers of the same installation
- Target value for the average initial and input temperature of the heat carrier fluid
- Regulations for heat-carrier-fluid type
- Regulations for refrigerant type
- Regulations for the backfilling of BHE
- Leakage test of ground loop and refrigerant tubing required
- Borehole drilling report
- Taking core samples required
- Thermal response test required
- Calculation of drilling depth required

Questionnaire

The questionnaire is based on the identified criteria and on questions concerning the legal regulation and licencing. Therefore, batteries of questions to following four main topic areas were asked:

- Topic area A: Legal regulations/Licensing procedures
- Topic area B: Flow charts for licensing procedures in the pilot areas
- Topic area C: Special geological and geographical conditions which can limit the installation of shallow geothermal energy systems
- Topic area D: Regulation elements for the installation, implementation and operation of shallow geothermal energy systems Legal regulation and licencing procedures query national, regional and local conditions of SGES while flow charts and criteria concentrate more on the pilot areas. The questionnaire was sent out in two parts.

Criteria for granting and revoking licenses

- Applicants must submit information relating to their technical and financial capability, as well as a description of the reservoir and an analysis of the development project
- Landowner’s consent is generally required
- Licenses can generally be revoked if (i) fees are not paid; (ii) general conditions of the license are not met; (iii) laws, including environmental regulations, are not followed; and (iv) only in certain cases if works have not commenced within a certain period from the issuing of the license

Surveillance

- Exploitation License holders are generally subject to periodical (annual, semi-annual or quarterly) reporting obligations.

- Governmental authorities have in many instances a unilateral right to perform site visits and inspections.

- In certain cases, peer review is required, which transfers decision making from public authorities to other market participants or scholars.

Environmental aspects

- An environmental impact assessment is generally required for exploitation licenses.
- The framework for environmental assessment is by and large similar between countries, whereas the administrative procedures, timelines etc. may vary somewhat.

How do Regulatory Frameworks have an impact on bankability?

- Regulatory frameworks in respect of geothermal licensing procedures (terms of application, information on the applicant, criteria for granting a license etc.) are in many respects similar between countries, however:
- the structure of public decision making varies considerably
- technical regulatory requirements and lack of legal clarity are making geothermal projects less bankable

Example of public bodies which the developer needs to deal with

- Ministry of Energy
- Ministry of Transport
- Ministry of Natural Resources
- Ministry of Environment
- Ministry of Justice
- Ministry of Land Rights
- Ministry of Labor etc

General regulatory requirements affecting finance:

- General terms of licenses; term, pre-emptive right for production, revocation etc
- Tax issues
- Environmental issues .
- Incentives for investment.
- Terms of PPA’s and Transmission Agreements, if regulated. Consequences of default .
- Capital controls, if applicable.
- The application and amount of liquidated damages in case of default.

- **Legal regulations and licencing procedures.**

The questions give attention to:

- Definitions
- Regulation of SGES in national, regional and local scale and the documents
- Licencing procedures and the responsible authorities Licencing documents
- Monitoring of SGES
- Liquidations procedures
- Flow charts of the licencing procedure in the pilot area

Example 1 of regulatory requirements affecting finance:

- Restriction on (i) transfer of shares or (ii) change in board members, in the license holder
- Financing parties must be able to assume control of the license holder in case of defaults in the financing agreements, either through share transfer or control through board members
- Solution: Two-tier system of license holder, Parent and Subsidiary, where the shares of the Parent are transferable and board members can be changed
- Solution: „Direct Agreement“ between Public Authority and Financing parties

Example 2 of regulatory requirements impacting financing:

- Guarantees to be submitted to the Public Authority in charge, before exploration drilling or exploitation
- If guarantees are required for drilling or exploitation, the amounts in question must be sufficiently clear in the application process
- Financing parties must be able to assess the nature and impact of such guarantees and evaluate the costs involved

Example 3 of regulatory requirements impacting financing:

- "Peer review" of the project prior to exploration drilling or exploitation
- If Public Authorities are transferring the decision process to a Peer Review process, such process needs to be clearly defined in the application process
- Financing parties need to understand the potential impact of such Peer Review and the authority of such review to require changes in the project schedule

Example 4 of regulatory requirements impacting financing:

- Duration and terms of land lease agreements, to the extent regulated
- If the land under the project is leased, Financing parties will be concerned with:
  - a sufficiently long term of the land lease agreement
  - provisions for renewal – whether the License Holder has a unilateral option to extend the term
  - decommissioning - whether the License Holder needs to remove all assets at the end of the term
  - whether the Public Authority can terminate the land lease agreement

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Introduction to environmental aspects of geothermal systems

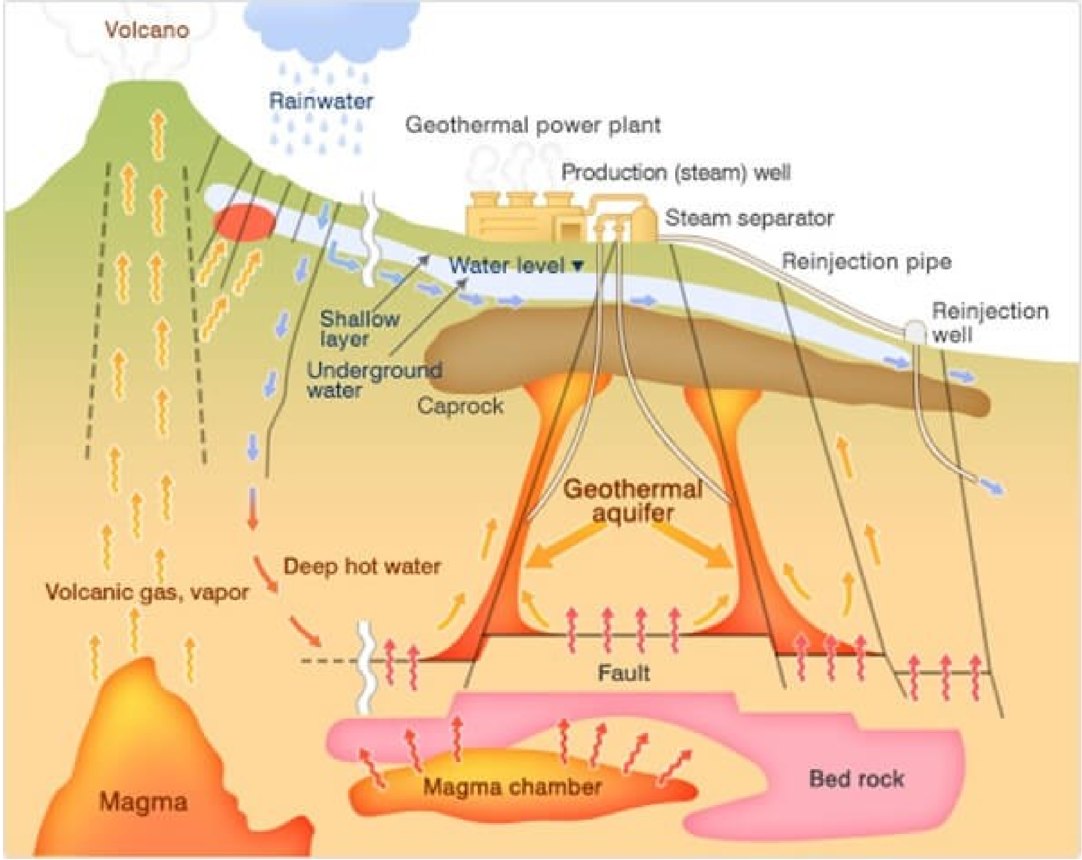


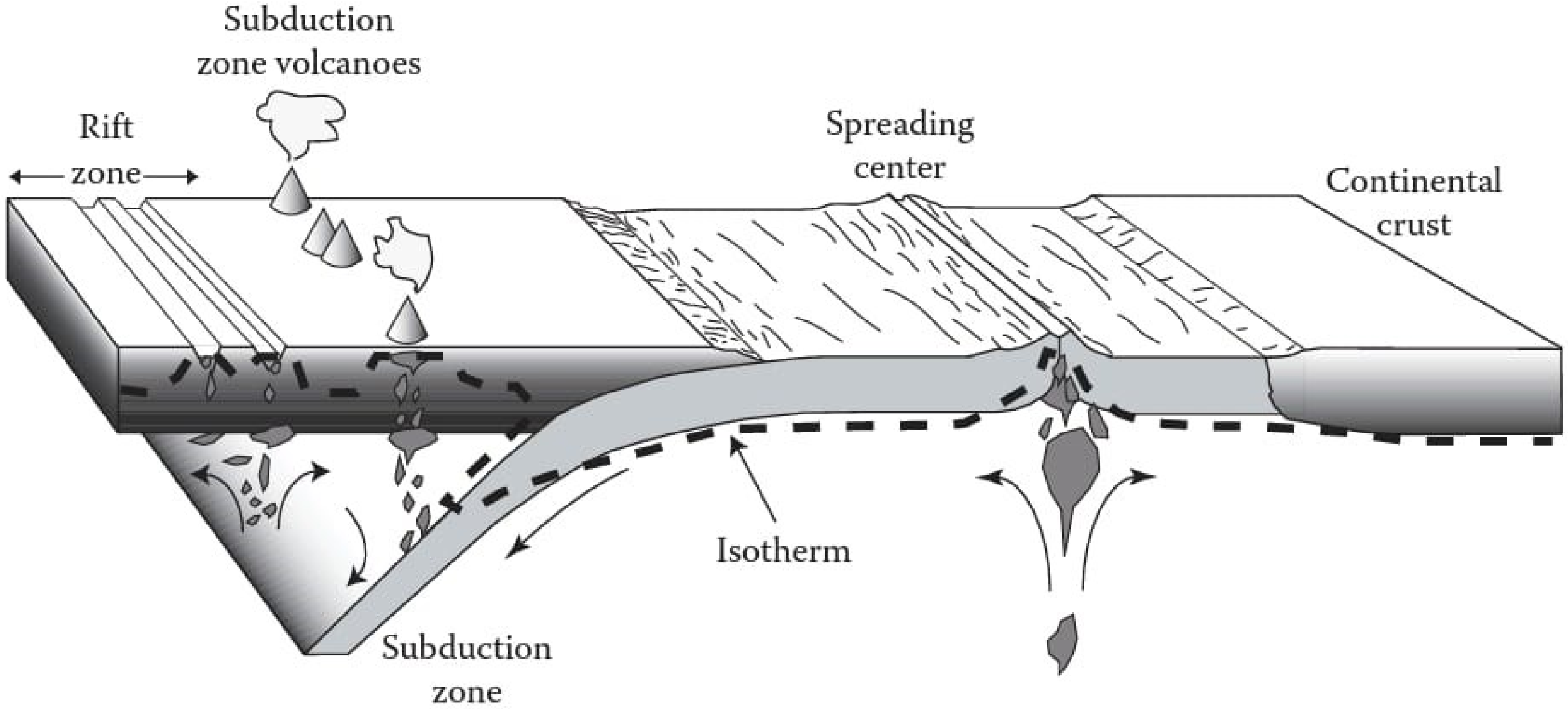
Plate Tectonics and The distribution of geothermal resources

- In 1912, Alfred Wegener published his landmark paper on what became known as continental drift. The hypothesis proved to be extremely controversial. It was not until the 1960s that the geological community overwhelmingly came to accept the view that the continents and ocean basins are, in fact, mobile.
- After the Second World War when oceanographic research vessels were outfitted with magnetometers that were originally intended to be used to detect submarines during the war. Evidence obtained from oceanic surveys documented the presence of a globe-encircling mountain chain that became known as the mid-ocean ridge system.

Plate Tectonics and The distribution of geothermal resources

- As the magnetometer-equipped vessels cruised the world ocean, they discovered unexpected patterns of magnetic anomalies that paralleled the ocean ridge system and that extended for hundreds of miles on either side of them.
- The only explanation for this symmetry was that ocean crust must be forming at the ridges and spreading away from it. For that to be the case, it was postulated that the mantle must be upwelling at the mid-ocean ridge system. That upwelling process was bringing hot, deep mantle rocks to the surface, which resulted in melting of the hot rock as it rose to shallower levels in the earth where pressures were lower. This process of hot, upwelling mantle was a classic example of convection.
- The places where the upwelling convection cells intersect the surface of the earth are called spreading centers because they define those places where crust forms and migrates away to either side of the ridge system.

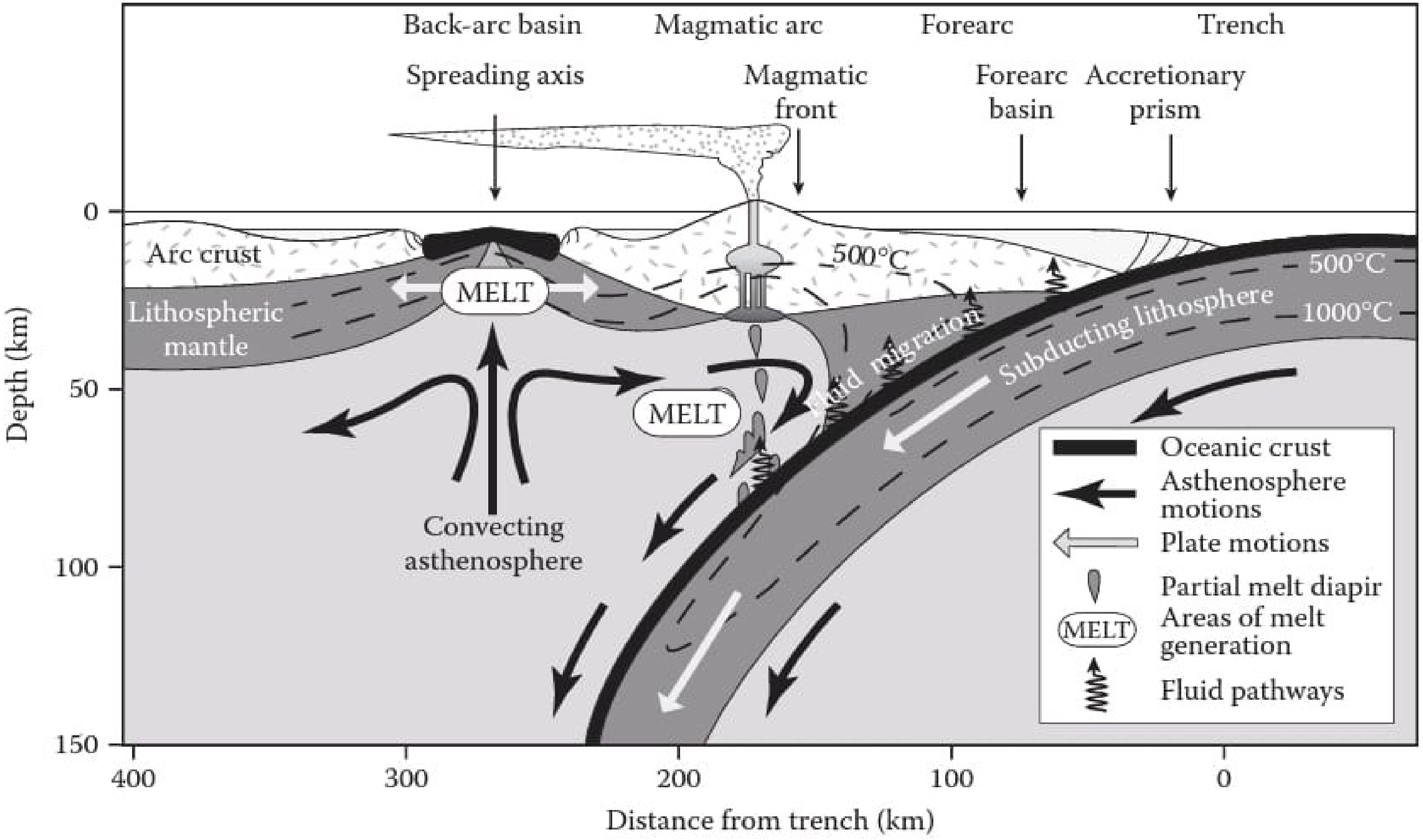
Rift zones



- To balance the upward flow of the hot, convecting mantle required that there exist a downward flow as well. Otherwise, the earth would be expanding, and conservation of mass arguments made it clear such could not be the case. It was quickly realized that most of the volcanoes on the planet were associated with deep ocean trenches and zones of very deep earthquakes, which were the likely locations for the downwelling portion of the convecting mantle system. These locations became known as subduction zones.

Schematic cross section through a subduction zone similar to that in Japan.

- Heat is also brought to the surface in the regions behind the volcanic front that forms at subduction zones. It is believed that the subduction process gives rise to small-scale convection cells above the descending slab. The upwelling part of these convection cells often causes the overlying crust to spread apart, forming rift zones and rift basins that can be in places where shallow-level magma chambers develop.



Classification of Geothermal systems by their geological context

- The relationship between plate tectonics and heat at the earth's surface is fundamental. The locations of geothermal systems correlate with specific geological settings, when considered within a plate tectonics context.
- The principal structural elements of plate tectonics are spreading centers, subduction or convergence zones, and transform faults. Each of these elements, and how they interact, establishes a particular type of environment that has specific geological manifestations. These manifestations are mainly expressions of how the crust responds to stresses generated by the underlying driving forces that cause plate tectonics.

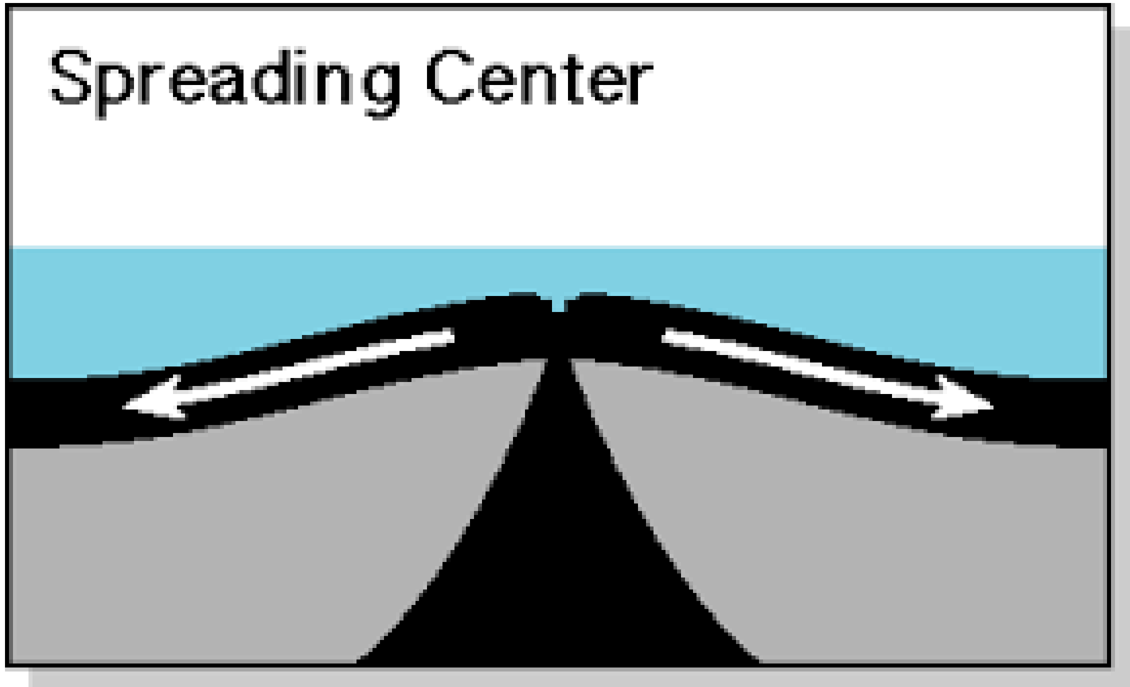
1) Extensional Environments

- There are three distinct types of extensional environments, all of which are related to fundamental plate tectonics processes:

1. Spreading centers
2. back-arc basins
3. Intra-continental rift zones

1. *Spreading centers*

- Spreading centers are one such extensional system. They are sites where diverging limbs of uprising mantle convection systems move in opposite directions, transporting the crust laterally. The uprising mantle carries with it melts that are extruded at these spreading centers, forming hot, young new crust. The vast majority of the globe's spreading center extent is underwater in the world oceans.

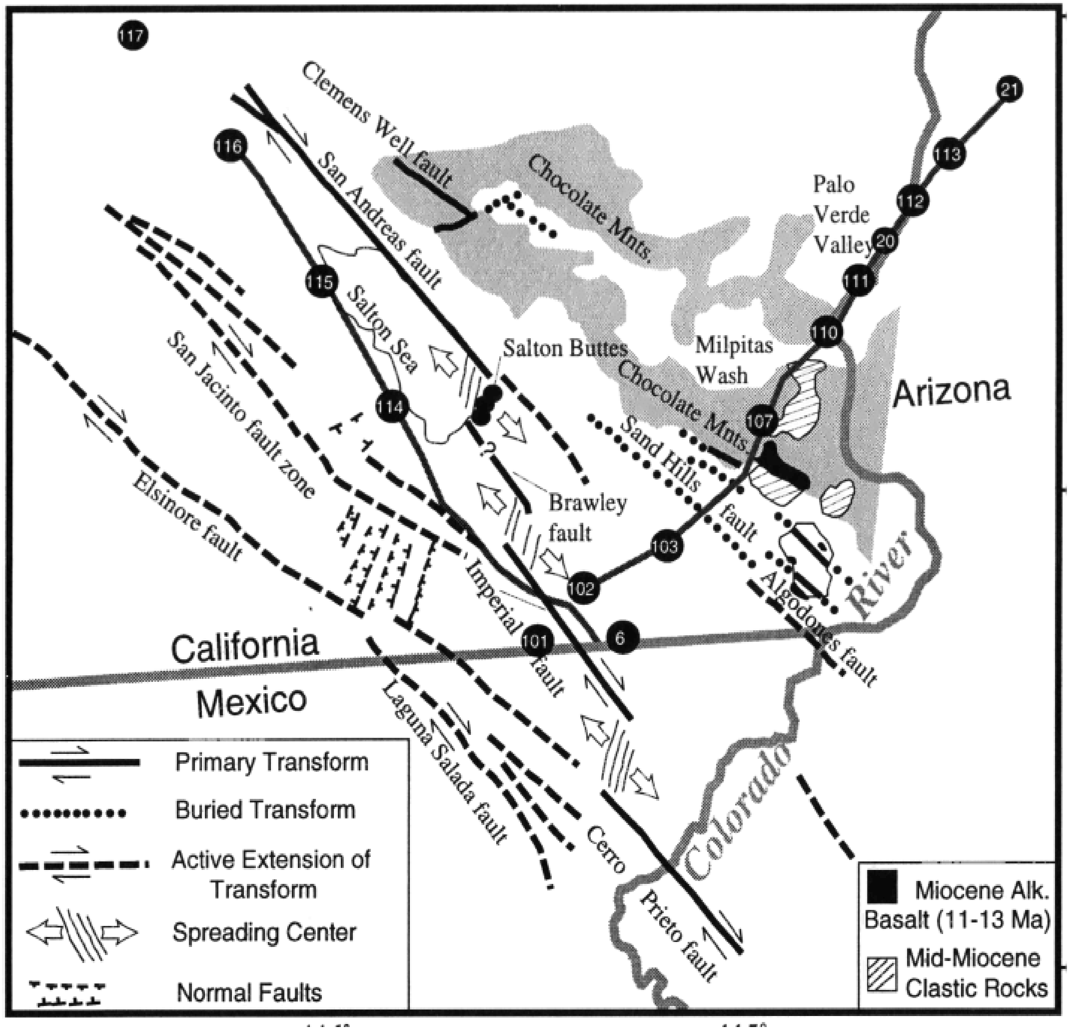


Spreading centers

- Extensive surveys of these systems by oceanographic research vessels have documented the pervasive presence of hydrothermal/geothermal systems at these sites.
- Recent estimates are that these systems have a heat flux of between 2 and 4×10^{12} W and a total hydrothermal flux of about 9×10^{12} W. Oceanic spreading centers are thus a huge, but currently untapped, potential source of geothermal energy.
- However, such systems are not restricted solely to the ocean basins. They extend on land in Africa (the East African Rift system) and the Imperial Valley of California.

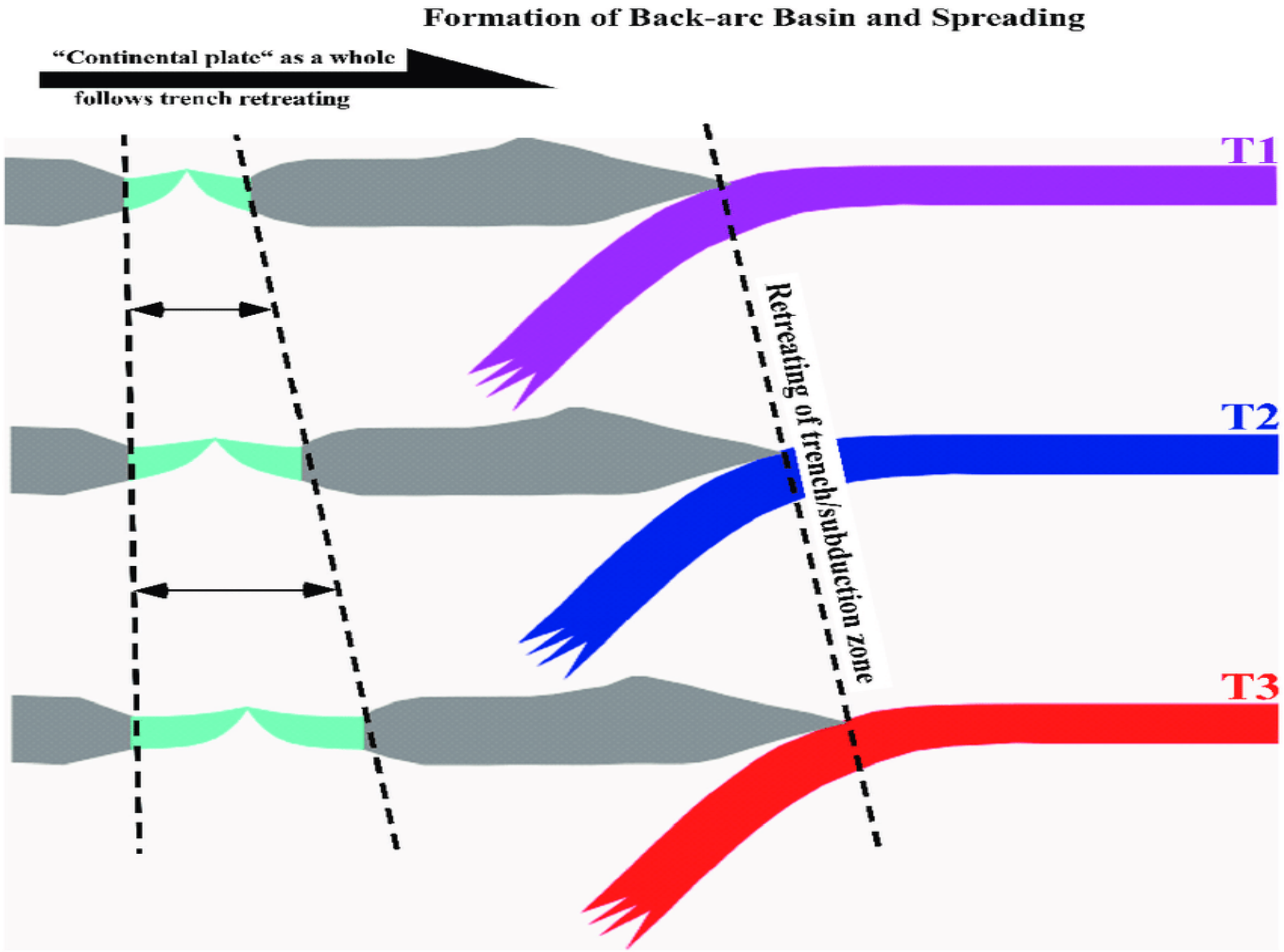
Spreading centers in the Salton Trough region

- The Gulf of California has its northern termination at the junction of Baja California and mainland Mexico. The Gulf of Mexico is a new ocean basin, formed by an extension of the main spreading center in the Pacific Ocean, the East Pacific Rise. Spreading along that extension caused a sliver of Mexico (i.e., Baja California) to split away from the mainland, beginning about 20 million years ago.



2. Back-arc basins

- These regions form behind island arcs in oceanic settings. The underlying motivating forces that control development of these features remain obscure, although they are likely related to mantle flow that occurs in response to subducting crust.



Back-arc basins

- As these basins form, spreading of the crust occurs, much in a manner similar to that of oceanic spreading centers, with the concomitant formation of melts and new, hot young crust.
- As with spreading centers, most back-arc basins are restricted to oceanic settings and are deeply submerged. However, in a few locations such systems extend on to major landmasses.
- The northern portion of the North Island of New Zealand is a location where back-arc spreading appears to extend onto land. It is within this area that one of the world’s best-developed complexes of geothermal systems has been established.

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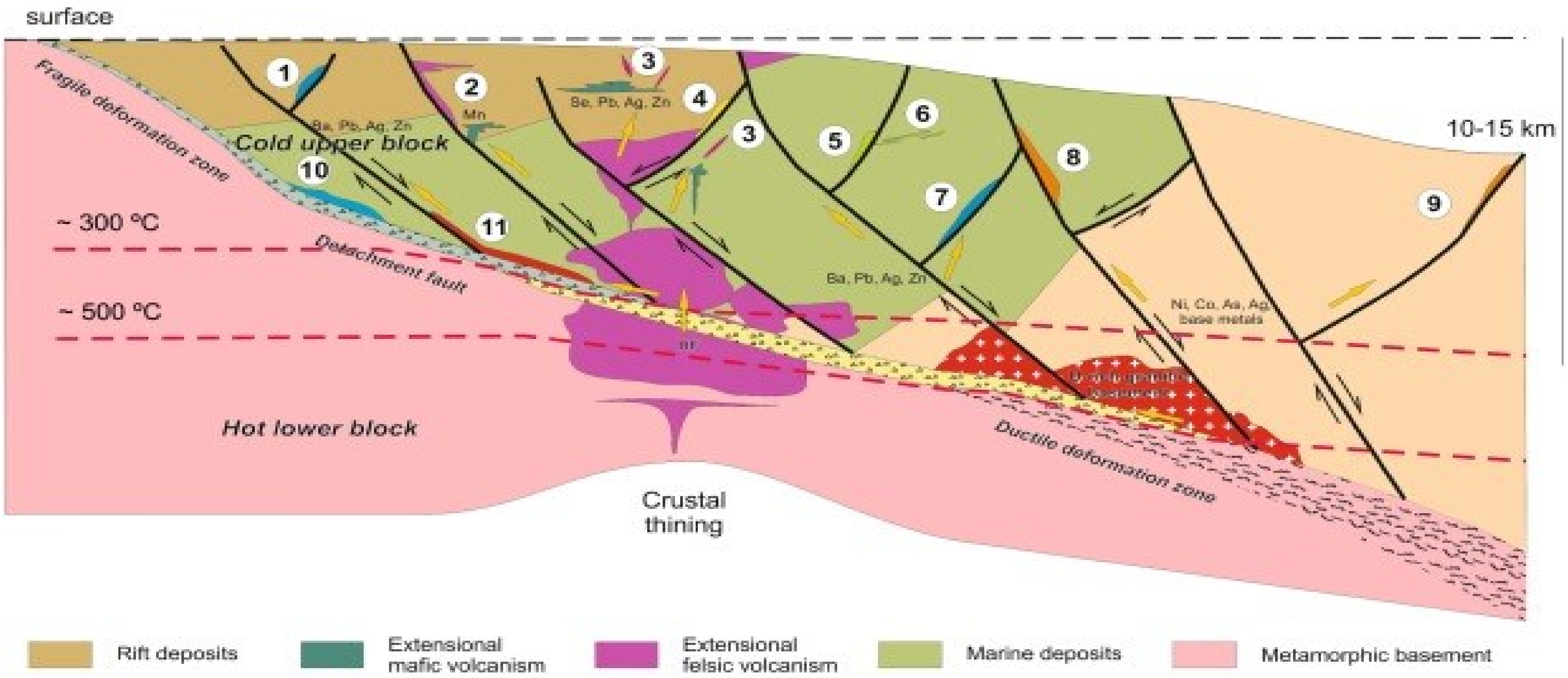
3. Intra-continental rift zones



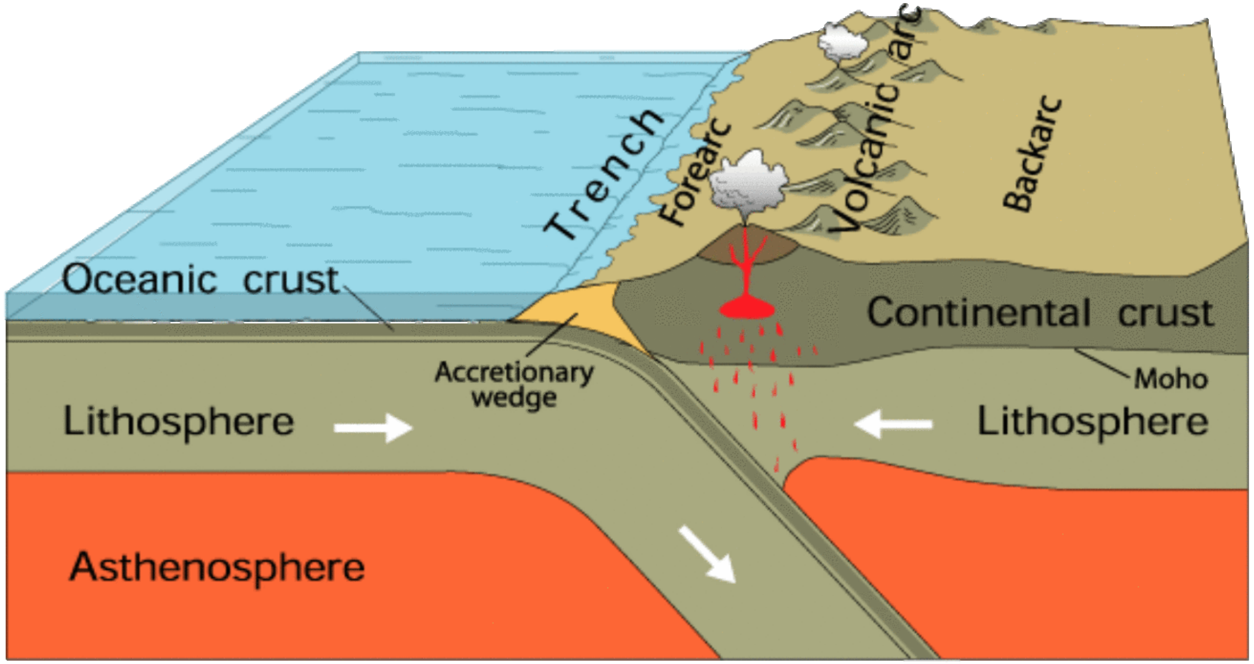
- Extension of the crust results from geological processes in which portions of the crust become thin and separate.

Intra-continental rift zones

- This thinning reduces pressure on the underlying mantle, allowing it to rise. This decompression also allows the formation of melts to occur in the mantle, which rise through buoyancy effects.
- These melts invade the crust, providing extensive heat sources at shallow to deep levels. As with back-arc basins, the underlying global dynamics that cause such systems to form is not well known.
- The Great Basin of the western United States is an example of such a system. Extensive geothermal development is underway in this region, most of which is concentrated in Idaho and Nevada.

2) Compressional Environments

- These settings are regions where converging plates result in the subduction of one plate under another. As the subducting plate descends to depths in excess of 100 km, a variety of processes result in the formation of melts.

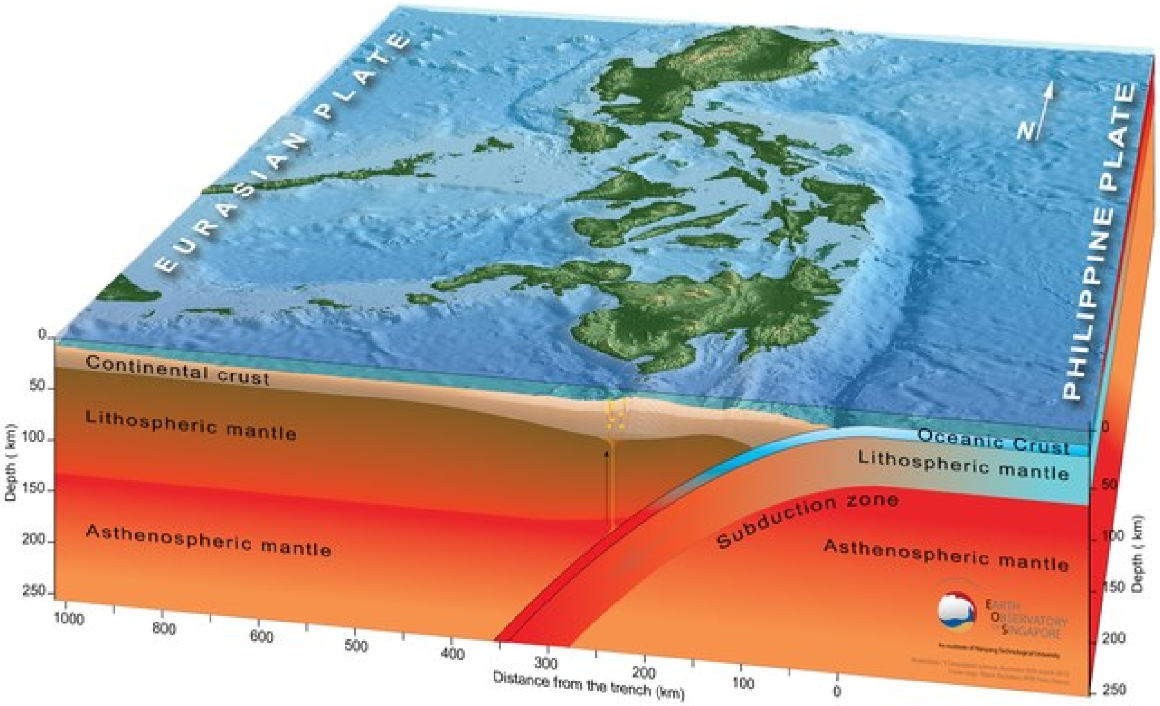


Compressional Environments

- The melts that are generated in this environment rise through the mantle, eventually erupting as volcanoes on the overriding plate. Because subduction generally lasts for tens of millions of years, these very hot volcanic systems are long lived, providing a persistent heat source that drives very extensive geothermal systems.
- Examples of such compressional settings that host geothermal systems are the volcanic chains in Indonesia, New Zealand, the Philippines, Japan, the Aleutians, the Pacific Northwest of the United States, Central America, and South America (the so-called Pacific Ring of Fire).

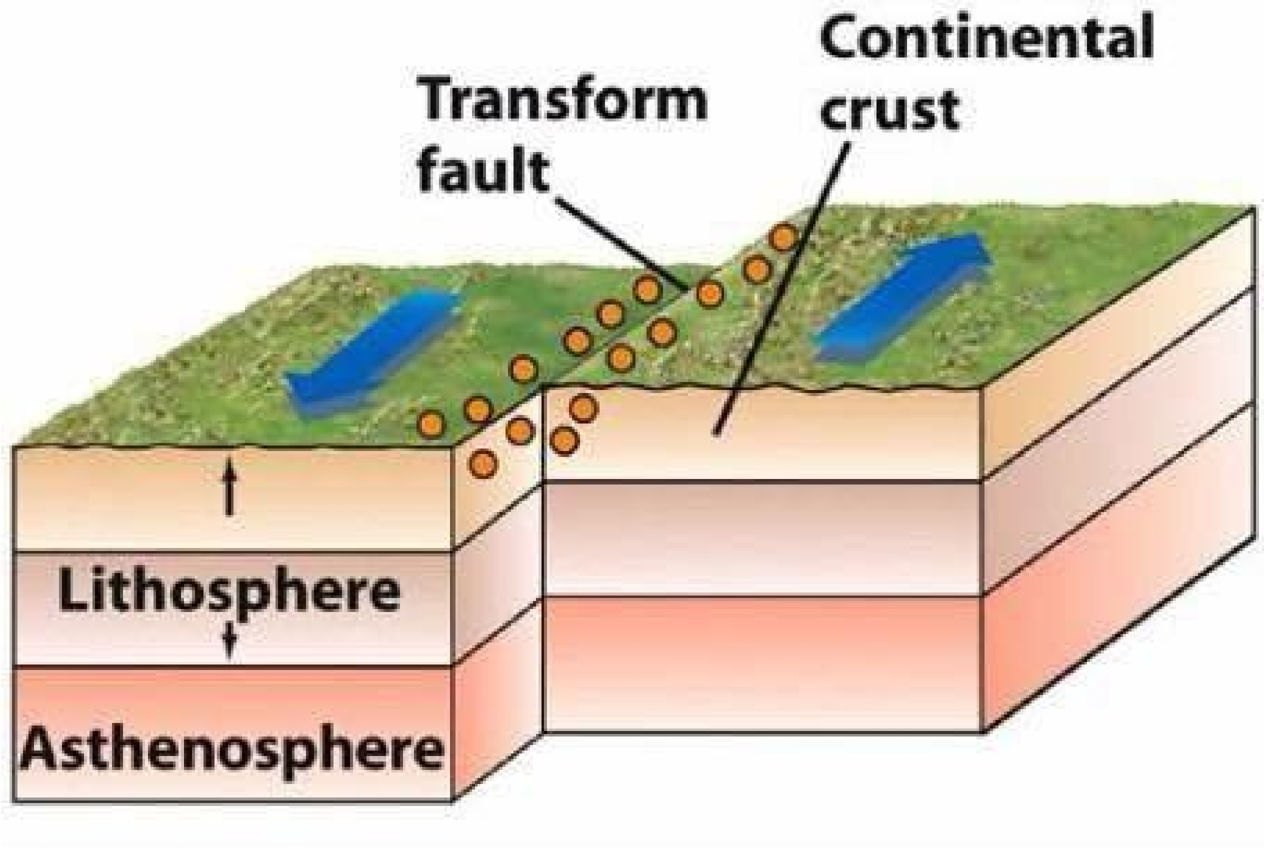
Subduction zone beneath the Philippines

- The Philippine Islands are a complex of over 500 volcanoes formed above the westward subducting Pacific plate.
- Beginning in 1977, geothermal power production was initiated on the island of Leyte.
- As of June, 2008, that initial effort had grown to more than 1900 MW of electric power production distributed among the islands of Luzon, Negros, Mindanao, and Leyte.
- Geothermal power production now accounts for 18% of the country’s electrical needs. The national goal is to achieve 3131 MWe of geothermal power by 2013.
- Worldwide, the Philippines rank second to the United States in producing geothermic energy.



3) Translational Environments

- An important structural element that defines a third type of plate tectonic boundary is a transform fault.



Translational Environments

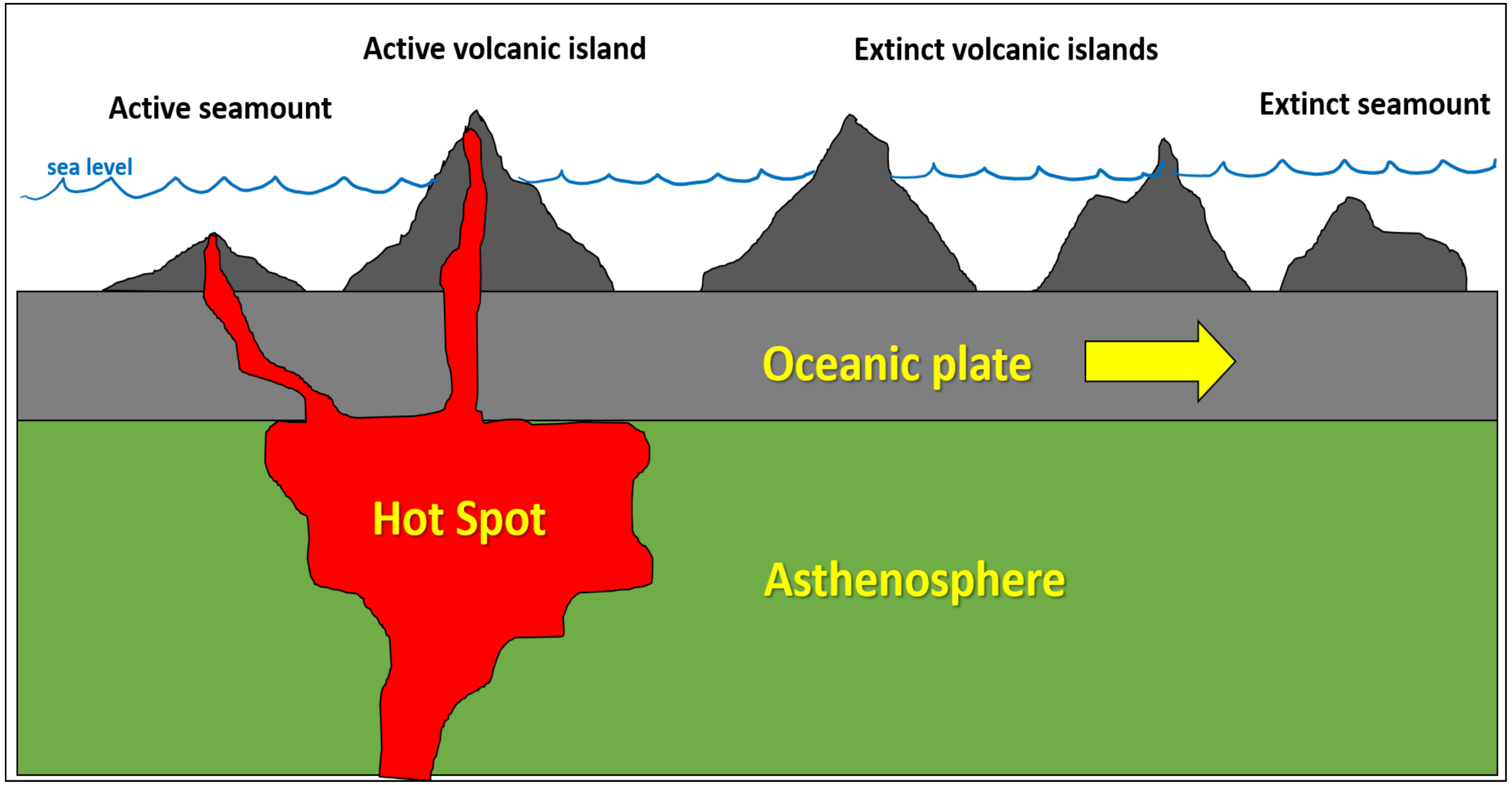
- These settings are places where tectonic plates move horizontally past each other. Perhaps the most famous of these is the San Andreas Fault in California.
- Other examples are the Anatolian Fault in northern Turkey, the Alpine Fault Zone in New Zealand, and the Dead Sea Fault that runs through Israel, Lebanon, Palestine, and Syria. Such zones are major ruptures in the crust that allow the circulation of fluids to great depths, often with the result that hot springs are present along them.
- In addition, evidence exists that such systems also allow the escape of mantle fluids. In addition to the three basic plate tectonic settings in which geothermal resources are located, other settings can host geothermal systems as well. Some of these are, in fact, some of the largest geothermal resources on the planet.

4) Hot Spots

- Among the most prodigious localized heat sources on the planet are hot spots. These are locations where magma persistently erupts in a localized region.

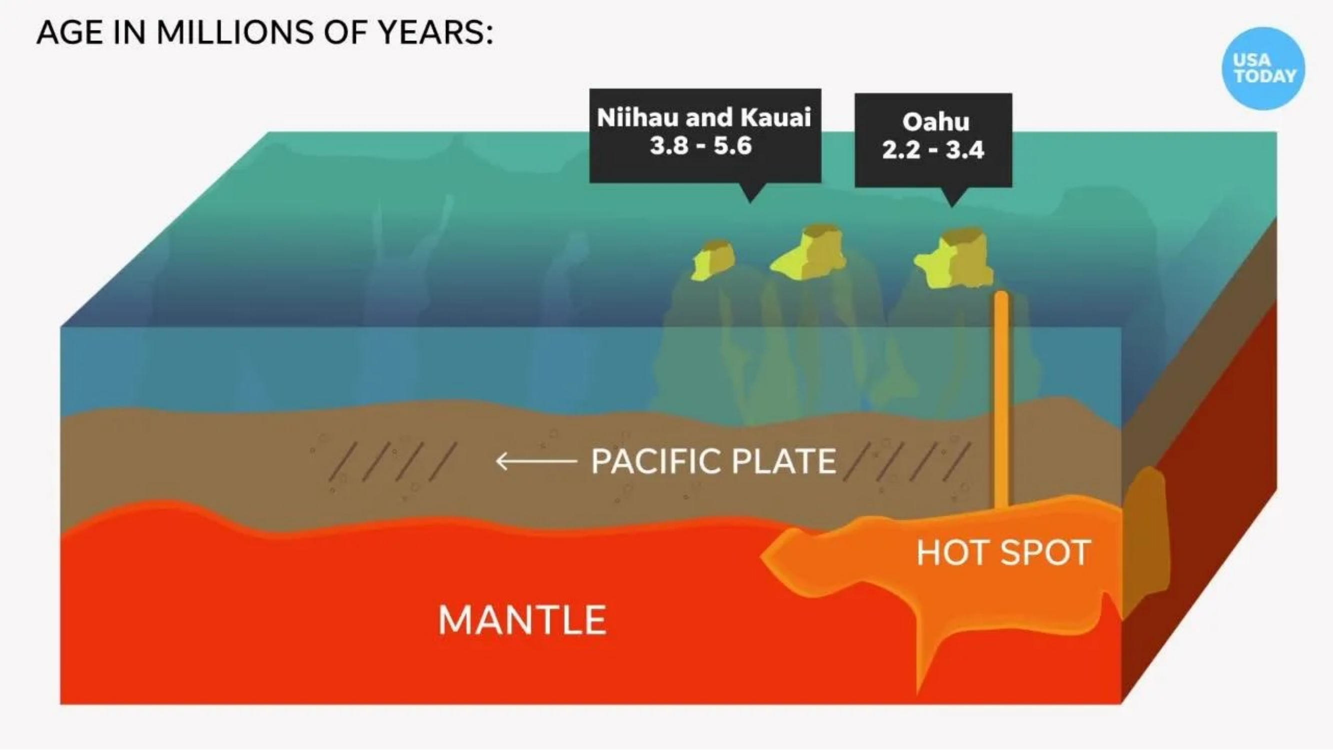
Hot Spots

- The causes of these localized volcanic sources are hotly debated and may, in fact, be diverse. Whatever their underlying cause, they are important hosts for geothermal resources. Iceland and Hawaii are two classic examples of hot spots. Both of these have geothermal resources already being used for power production. Other hot spots include the Canary Islands, the Cape Verde Archipelago, the Galapagos Islands, the Cook Islands, and Yellowstone, Montana.



Hawaii hotspot

- The Hawaiian Island chain tracks the movement of the Pacific plate over a mantle hotspot that has persisted for more than 80 million years. Geothermal exploration was started in this area during the 1960s, eventually leading to development of a small (3 MWe) power generating facility in 1981. Power production continued until 1989 when the plant was shut down. A newer facility was built in 1993, which has continuously produced 25–30 MWe of baseload power. The geothermal resource in the region is capable of providing about 200 MWe of power on a continuous basis.



5) Transitional Settings

- Plate boundaries can often be sites of complex interactions between the crust and mantle. This particularly holds true when a site is evolving from one type of boundary to another or is at the junction between two types of environments.
- One type of transitional setting that is an example of what happens as a plate boundary evolves is in the vicinity of The Geysers in California.

Transitional Settings

- The Geysers provides one of California's most important geothermal resources. The Geysers is located near the triple junction between the San Andreas transform fault, the Humboldt fracture zone (another transform fault), and the subducting Gorda plate (part of the greater Pacific plate system).
- The plate motions in this area, and the interactions with the underlying mantle, are complex and evolving.
- They appear to have resulted in the formation of a "window" that allows hot mantle to interact with the overlying crust, resulting in the generation of magmas that rise to relatively shallow levels. The result is a hybrid system that generates very hot, dry steam. It is this dry steam resource that provides energy for generating power in this region.