Geothermal potential of sedimentary basins

DAMIEN BONTÉ

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Introduction to geothermal energy

- What is geothermal energy?

Geothermal Energy in the Renewable Energy mix, status, and evolution

Classification

Different use of geothermal energy; Resource <-> Usage

Electricity generation & Direct use

- Thermal processes in the earth system

Geodynamic and surface heat flow

Lithospheric thickness and composition

Punctual thermal perturbation:

Kinematic, magmatism, radiogenic heat production, hydrology

- Geothermal energy in sedimentary basins

General principles on sedimentary basins

Modelling geothermal energy

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GEOTHERMAL ENERGY

Renewable energies

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WHAT IS GEOTHERMAL ENERGY?

Renewable energies

Geothermal Energy is the **exploitation** of the **thermal** energy naturally produced from the **earth**

Comes from the greek
geo (γεω): earth
thermós (θερμός): warm

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GEOTHERMAL ENERGY

- Geothermal power a stable production output, unaffected by climatic variations,
  - -> high capacity factors (60% to 90%)
  - -> suitable for baseload production

- The resource is not equally distributed
  - (e.g. at 1000m up to 200°C in Iceland and about 40°C in the Netherlands)

- Two main elements are to be looked for to securely developed a geothermal project: **temperature** & **flow**

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Renewable energies

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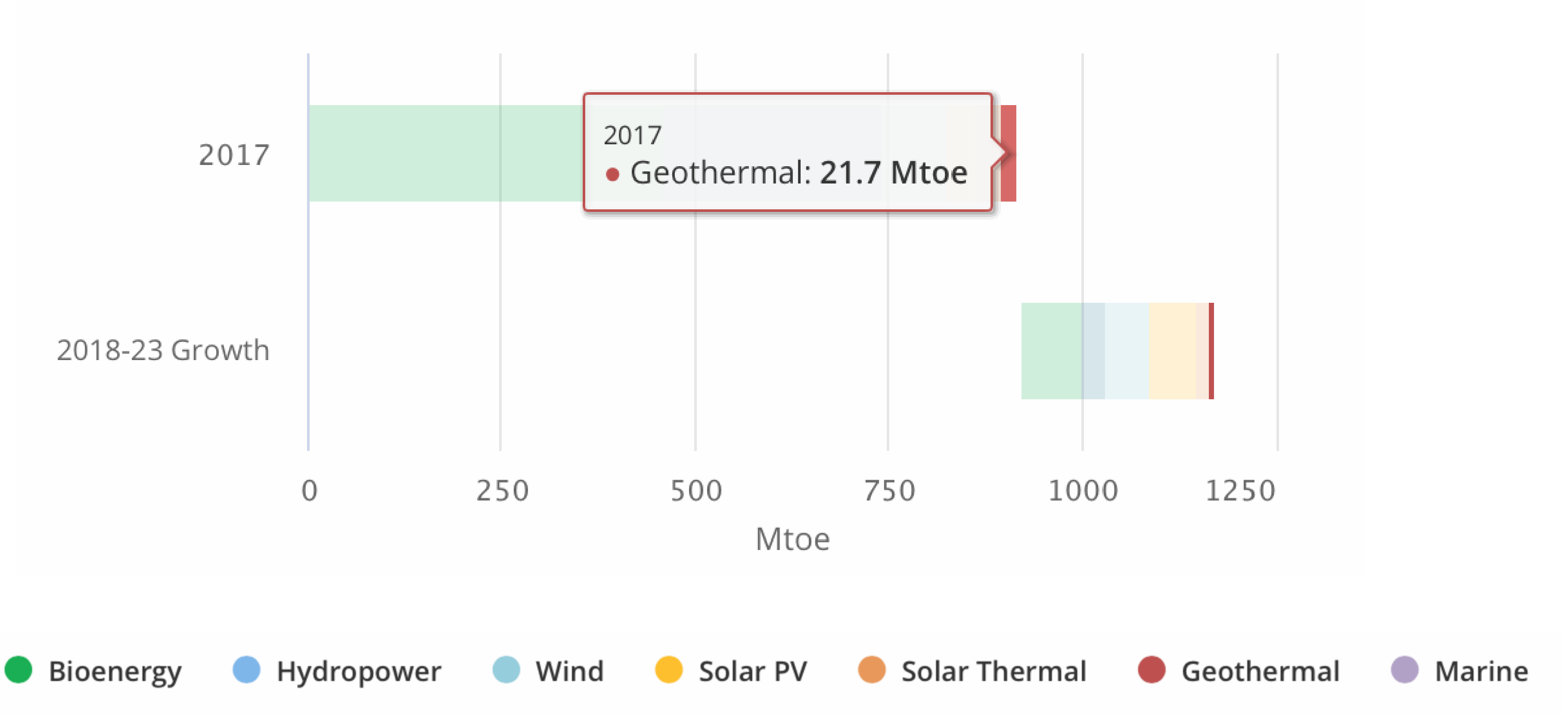
RENEWABLE ENERGY: THE PLACE OF GEOTHERMAL ENERGY

Renewable energies

Renewable energy consumption by technology, 2017-23



Source: IEA (https://www.iea.org/renewables2018/)

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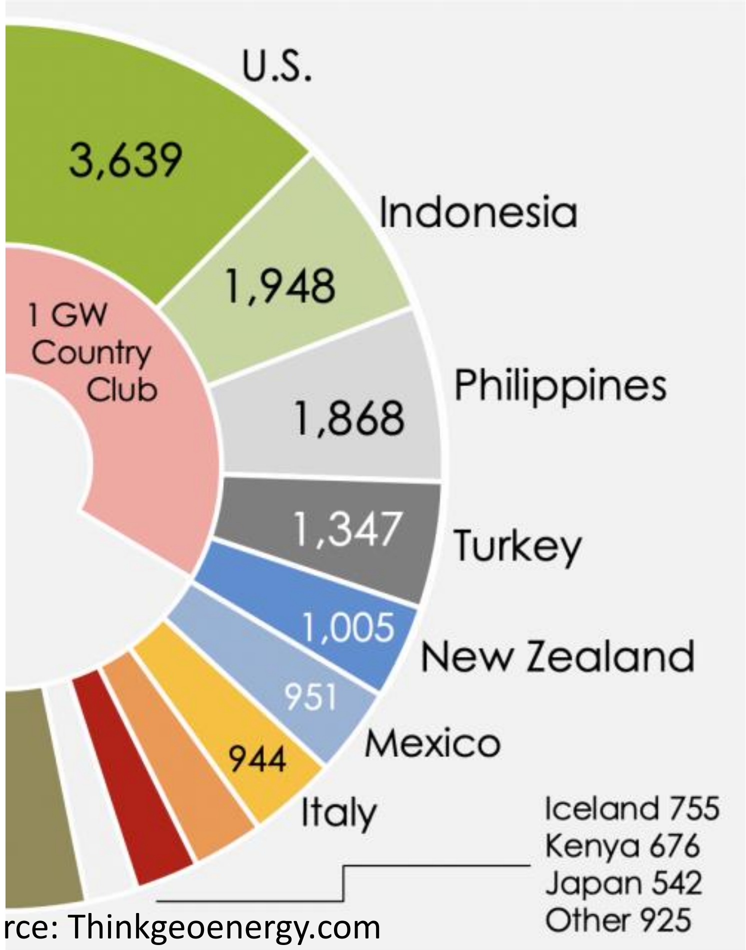
STATUS AND EVOLUTION OF GEOTHERMAL ENERGY: ELECTRICITY GENERATION

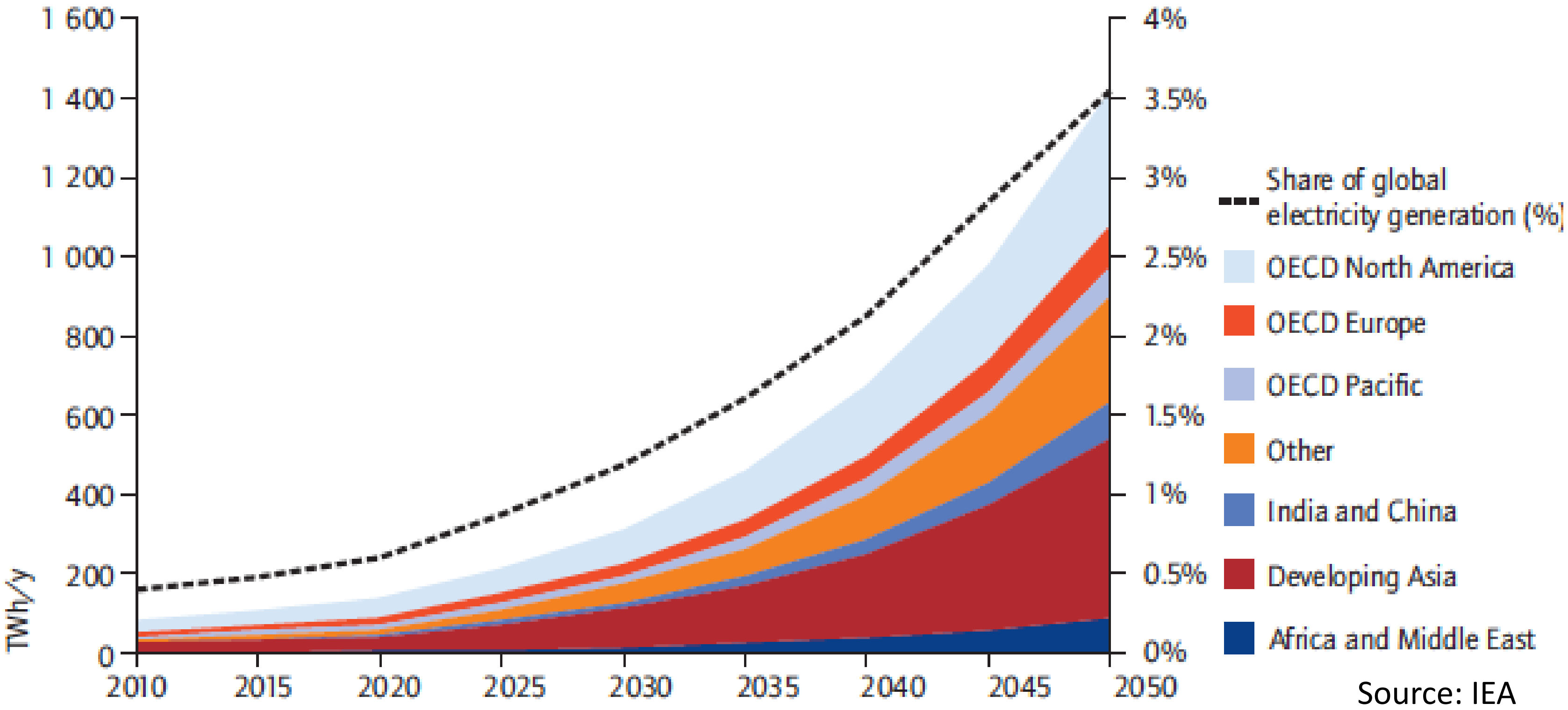
Renewable energies

Total installed capacity (end 2018)
for electricity generation: 14 600 MW



Source: Thinkgeoenergy.com

Roadmap vision of geothermal power production by region (TWh/y) (IEA roadmap, 2011)



Source: IEA

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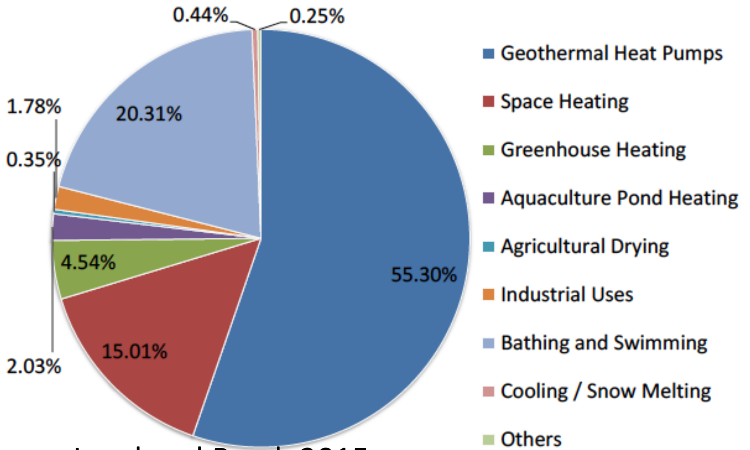
STATUS AND EVOLUTION OF GEOTHERMAL ENERGY: DIRECT USE

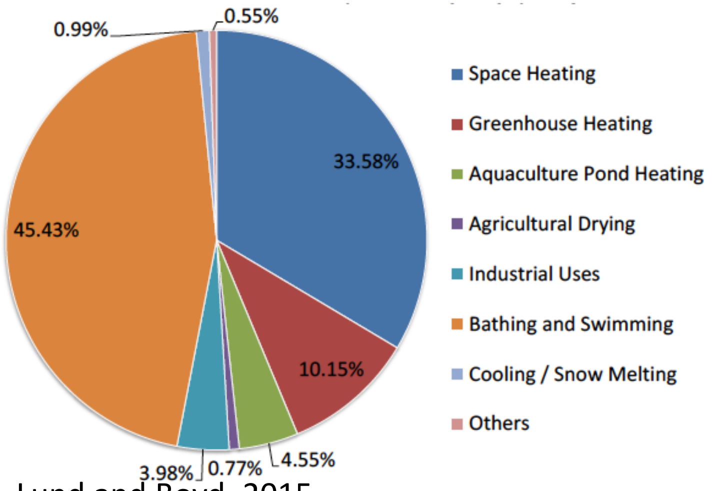
Renewable energies

World-Wide Utilization (with heat pumps), TJ/yr



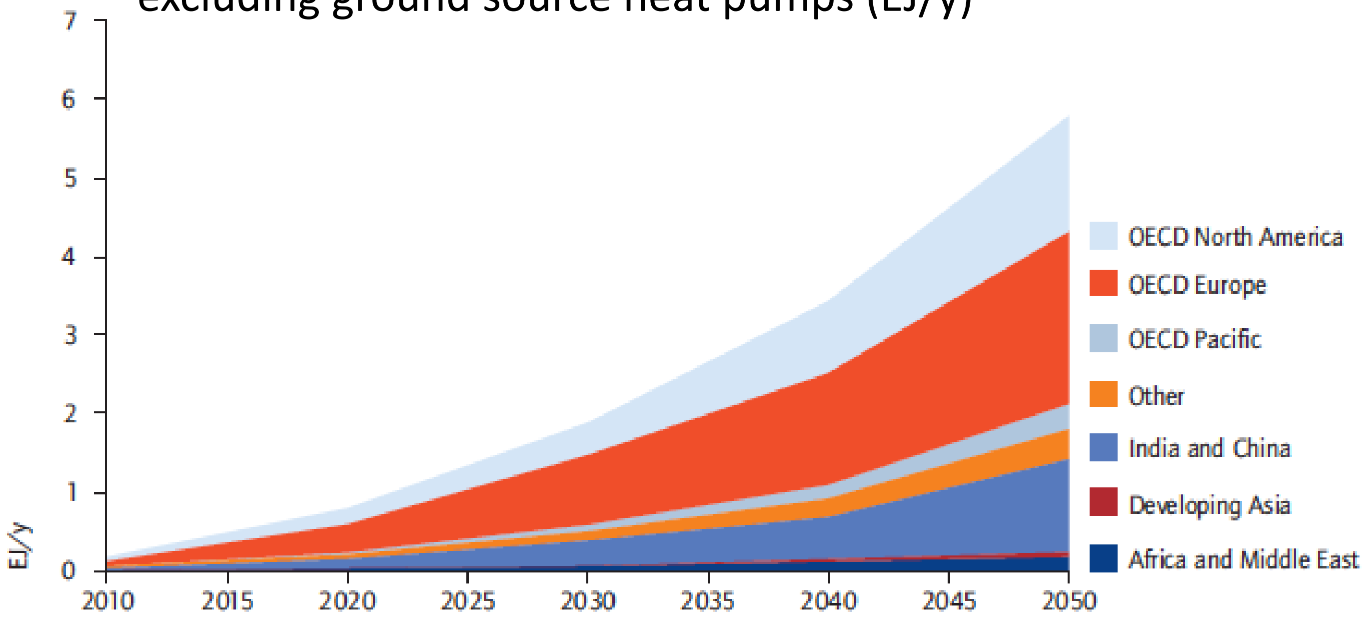
Lund and Boyd, 2015

World-Wide Utilization (without heat pumps), TJ/yr



Lund and Boyd, 2015

EIA roadmap vision of direct use of geothermal heat by region, excluding ground source heat pumps (EJ/y)



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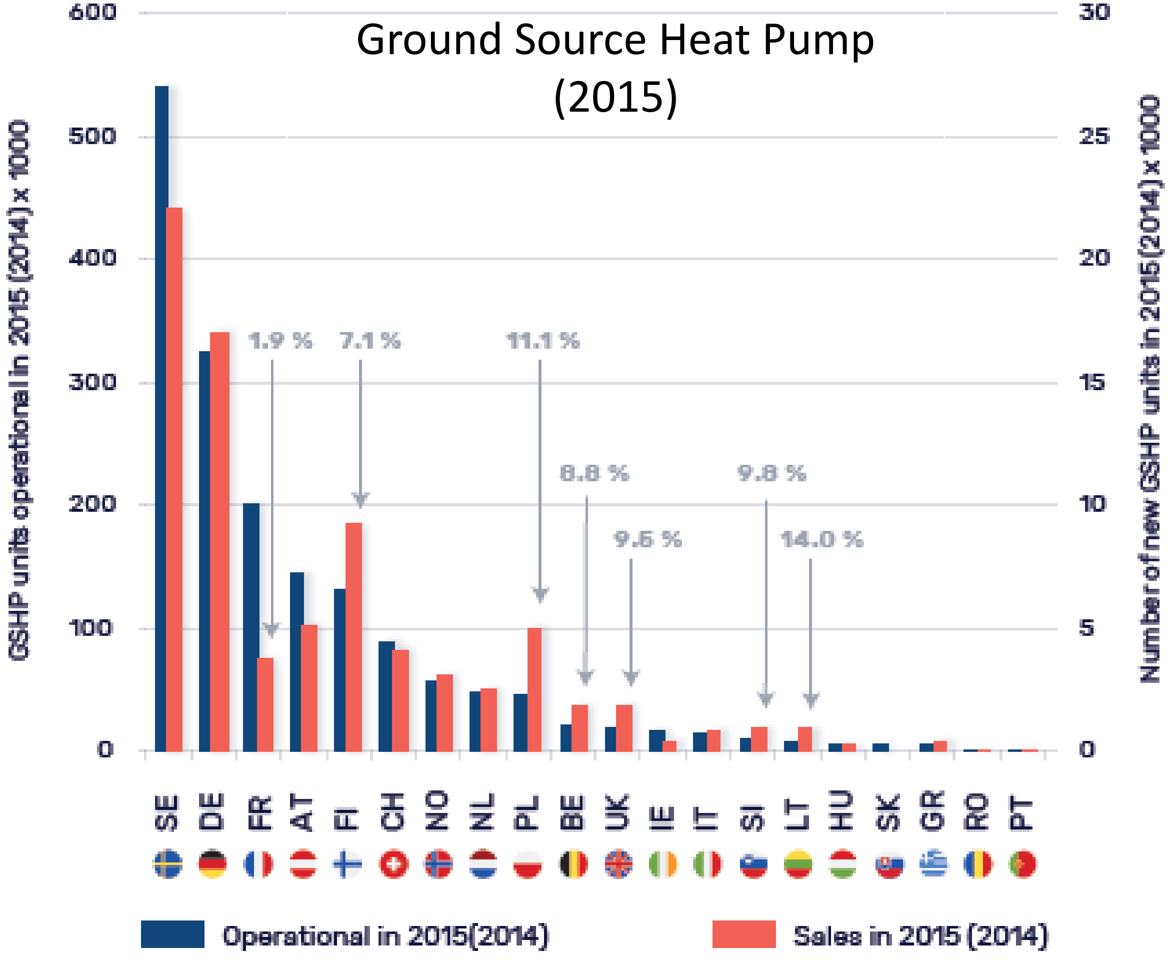
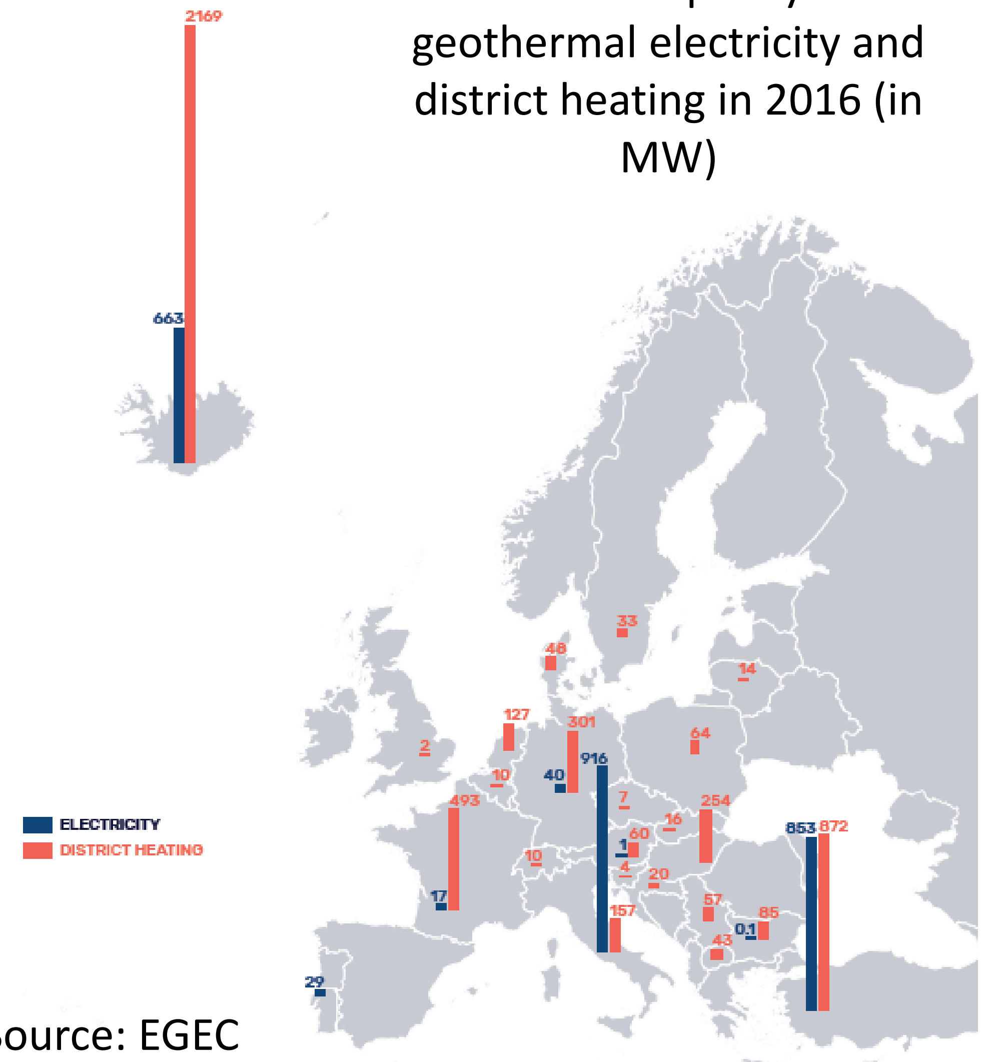
STATUS AND EVOLUTION OF GEOTHERMAL ENERGY: EUROPE

Renewable energies

Ground Source Heat Pump (2015)



Installed capacity for geothermal electricity and district heating in 2016 (in MW)



Source: EGEC

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GEOTHERMAL ENERGY CLASSIFICATION

Renewable energies

Moeck, 2014

	1978	1988	1990	1988		
	Muffler [8] (°C)	Hochstein [9] (°C)	Benderitter and Cormy [12] (°C)	Haenel et al. [10] (°C)		
Low enthalpy	< 90	< 125	< 100	< 150		
Moderate enthalpy	90–150	125–225	100–200	–		
High enthalpy	> 150	> 225	> 200	> 150		
2005 Sanyal [13]	Non-electrical (°C)	Very low (°C)	Low (°C)	Moderate (°C)	High (°C)	Ultra high (°C)
	< 50–100	100–150	150–180	180–230	230–300	> 300

Geothermal classification was relying on two aspects:

- temperature of the system (enthalpy)
- the usage of the system (electrical generation vs direct heat use)

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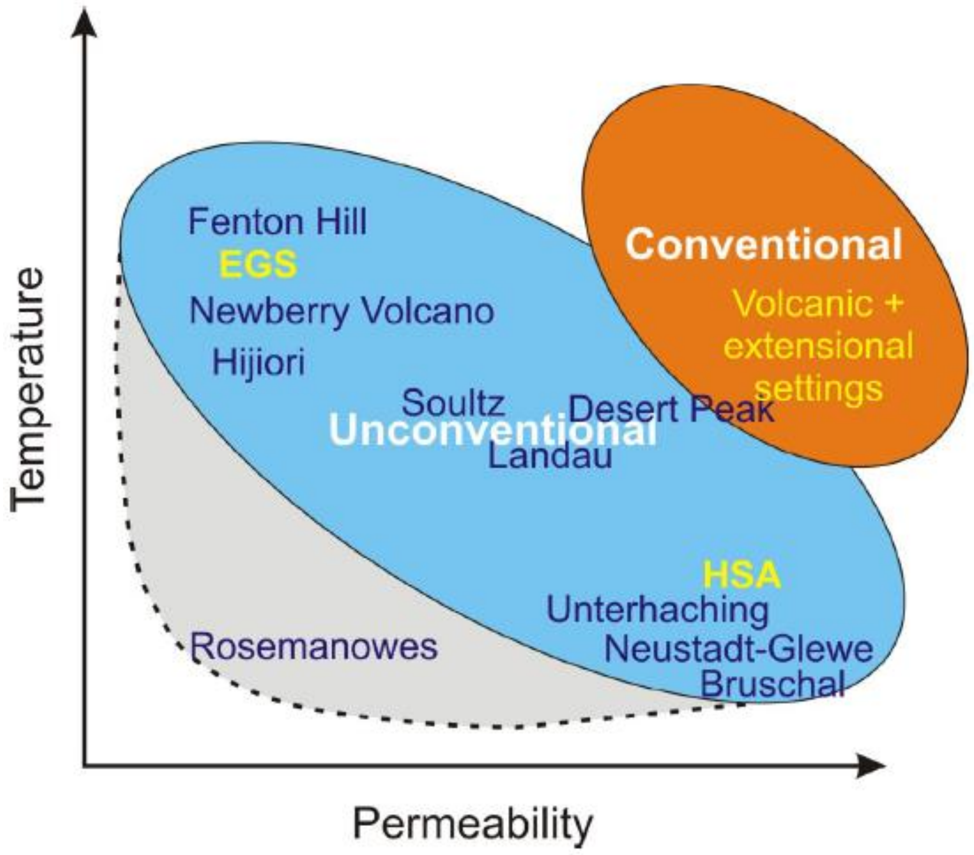
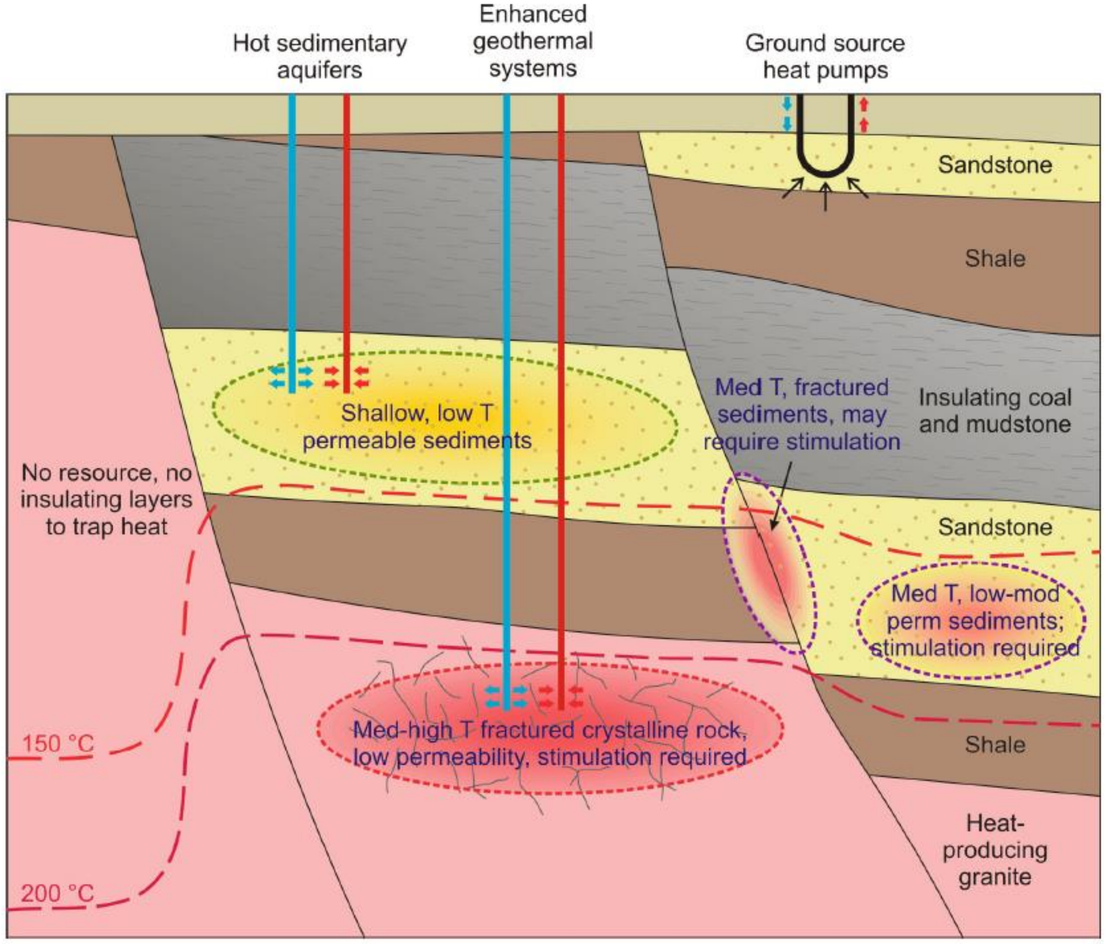
GEOTHERMAL ENERGY CLASSIFICATION

Renewable energies

Conventional vs Unconventional





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GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF “*PLAY*”

Renewable energies

“**Plays**” is a concept developed in the **petroleum industry**

A play is “**groups of accumulations and prospects that resemble each other closely geologically, sharing similar source, reservoir, seal and trap conditions**”

a very human concept, popular and useful just because it is not a precise, scientific concept, but...

This concept is needed because:

- To identify where and to what **objective future exploration activity** should be directed. i.e. which areas or trends are likely to become core future productive areas,
- **Management of the risks** associated with drilling mapped prospects by grouping them into families and comparing them with successful analogue fields,
- Prediction of **future possible volumes** using successful analogue fields or statistical techniques,
- Helping estimate the potential value of exploring in areas or for particular prospect types
- Identification of the **technologies needed** to explore for particular types of prospect as well as those needed to maximize the commerciality of discoveries through field development,
- Deciding when a type of prospect is no longer worth pursuing or when an exploration venture should **be terminated**.
- …in short, plays rather than individual prospects **should form the basis of exploration strategy** definition

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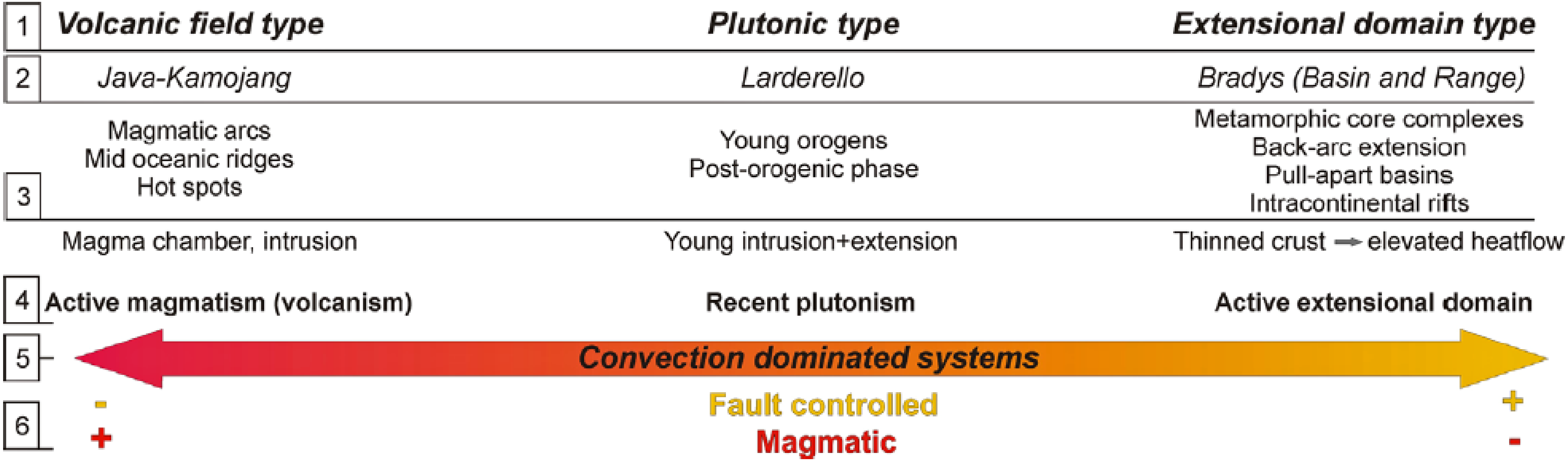
GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF "*PLAY*"

Renewable energies

Convection-dominated geothermal plays

Moeck, 2014



1 – Play type
2 – Typus locality
3 – Plate tectonic setting
4 – Geologic habitate of potential geothermal reservoirs
5 – Heat transfer type
6 – Geologic controls.

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GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF “*PLAY*”

Renewable energies

1 ***Volcanic field type***

2 *Java-Kamojang*

Magmatic arcs
Mid oceanic ridges
Hot spots

3

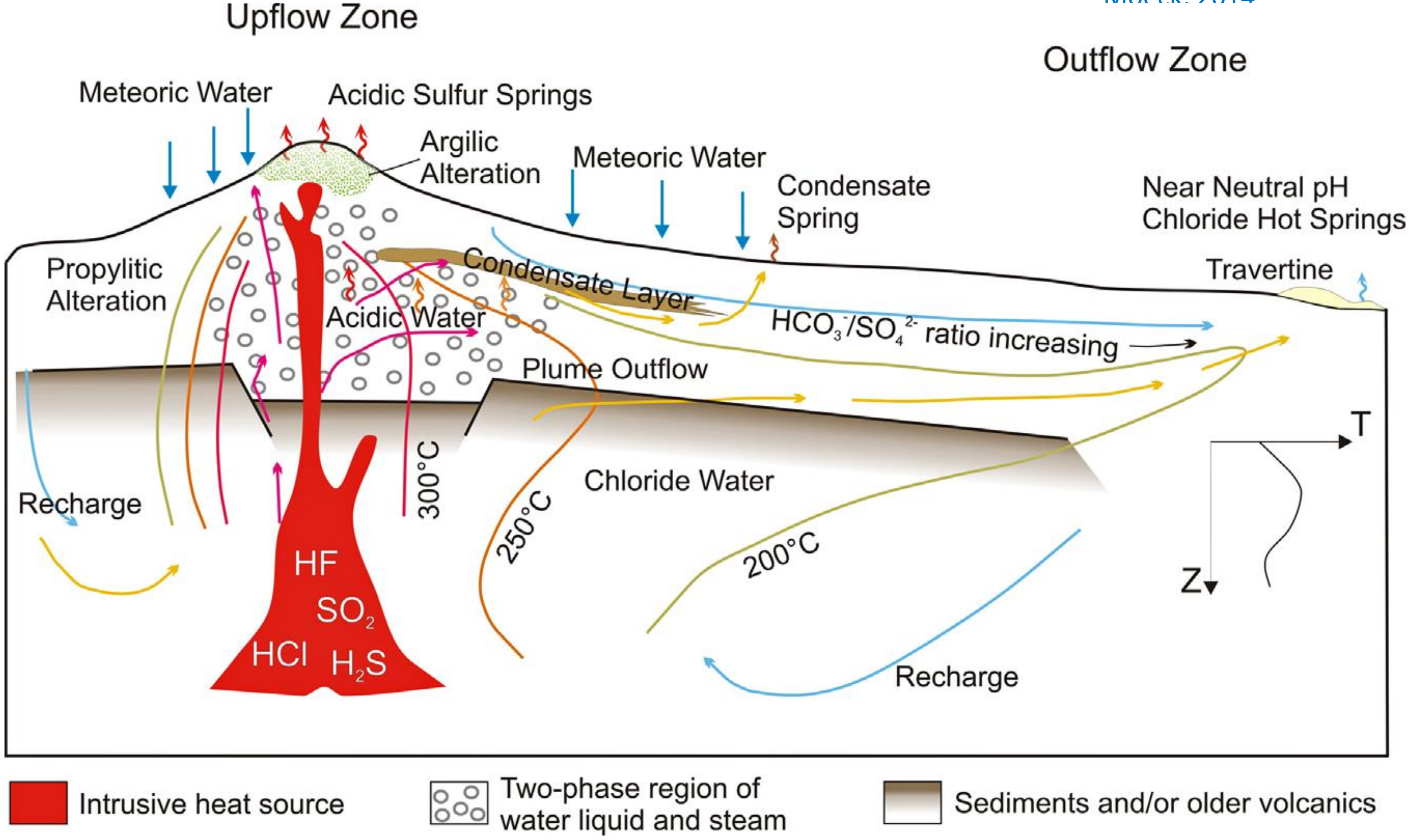
Magma chamber, intrusion

4 **Active magmatism (volcanism)**

5

6 -
+

Moeck, 2014



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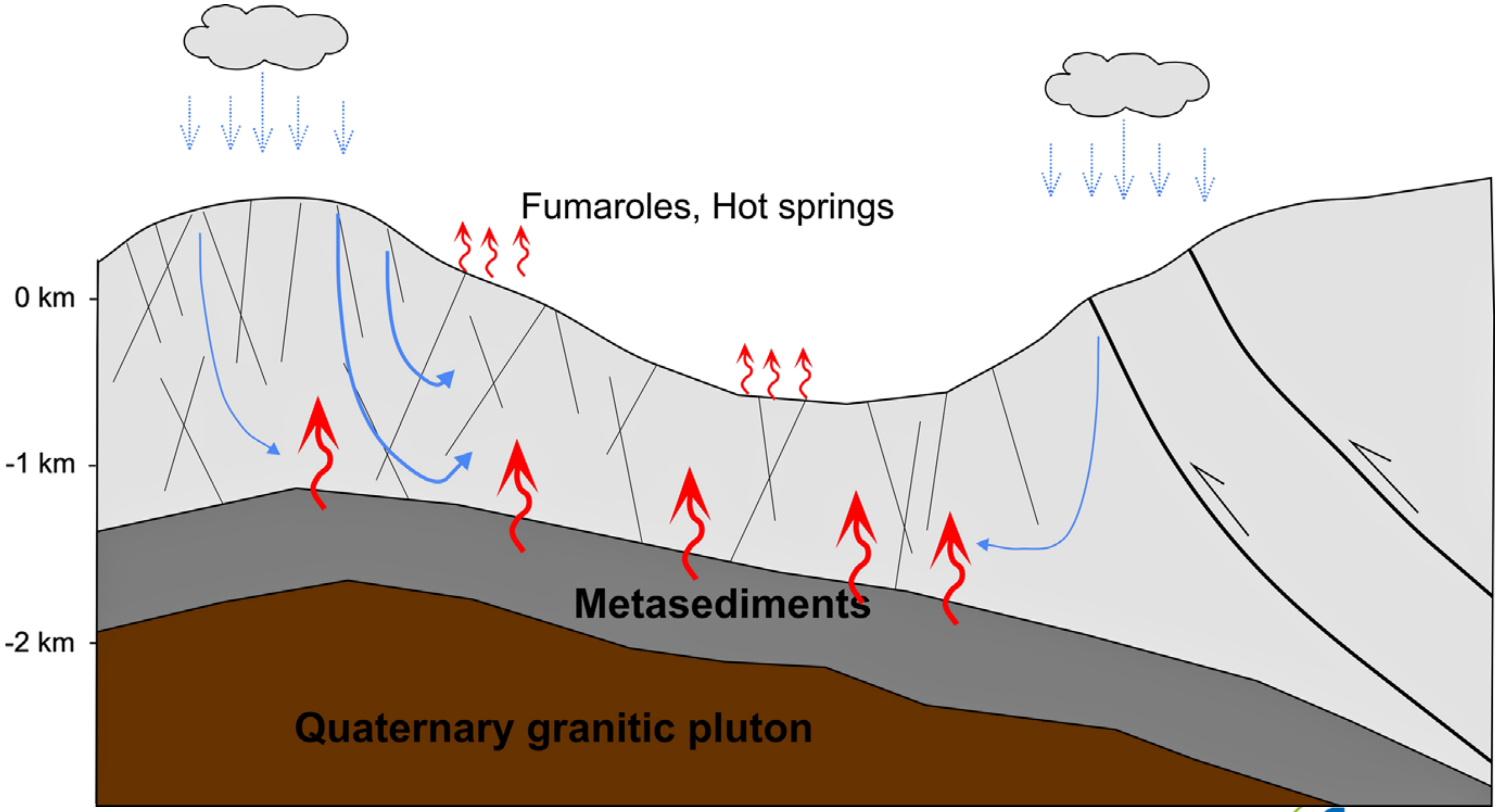
GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF “*PLAY*”

Renewable energies

Plutonic type
Larderello
Young orogens Post-orogenic phase
Young intrusion+extension **Recent plutonism**
Convection dominated systems
Fault controlled **Magmatic**

Moeck, 2014



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GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF “*PLAY*”

Renewable energies

Extensional domain type

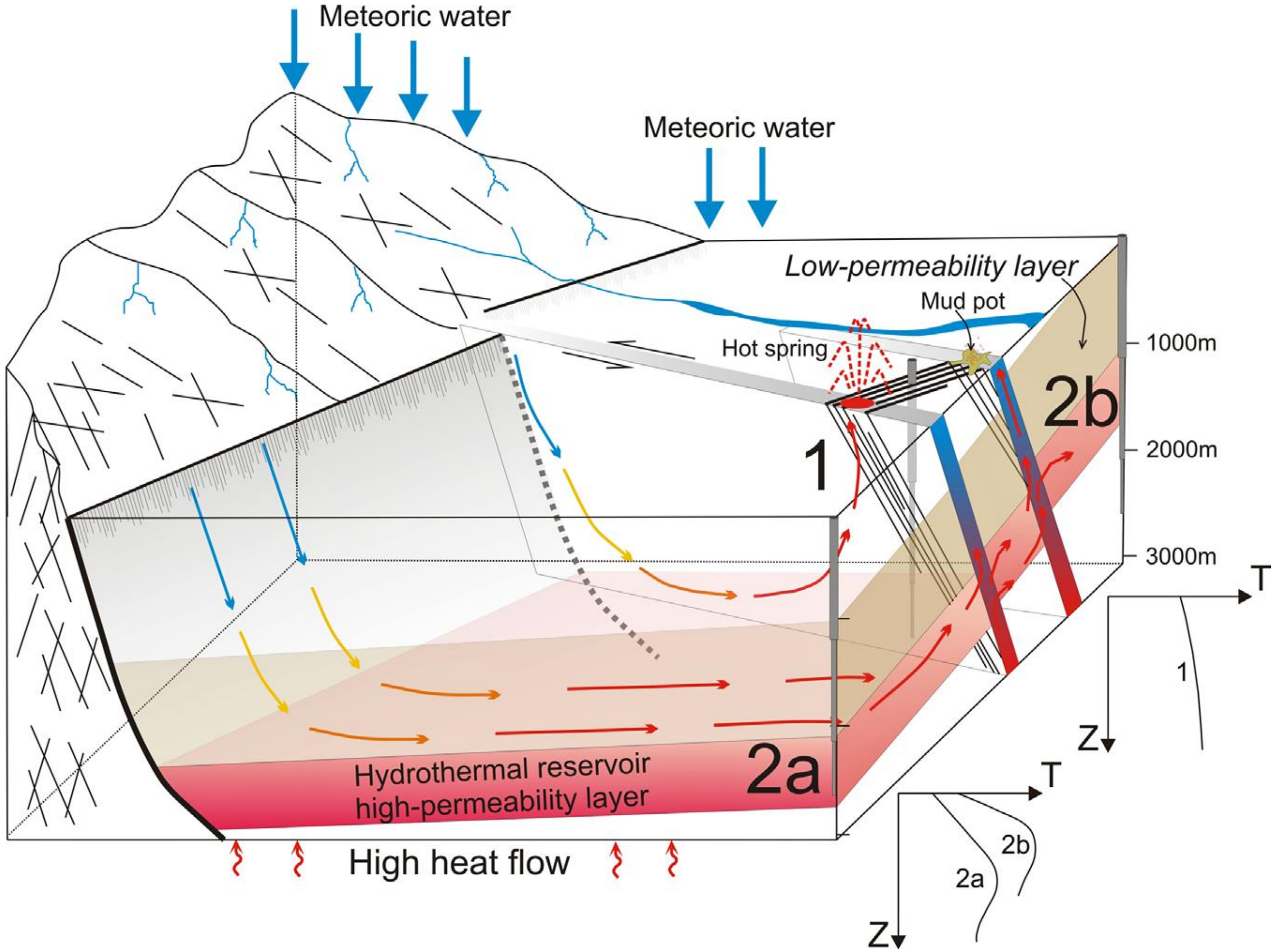
Bradys (Basin and Range)

Metamorphic core complexes
Back-arc extension
Pull-apart basins
Intracontinental rifts

Thinned crust → elevated heatflow

Active extensional domain

\+
\-



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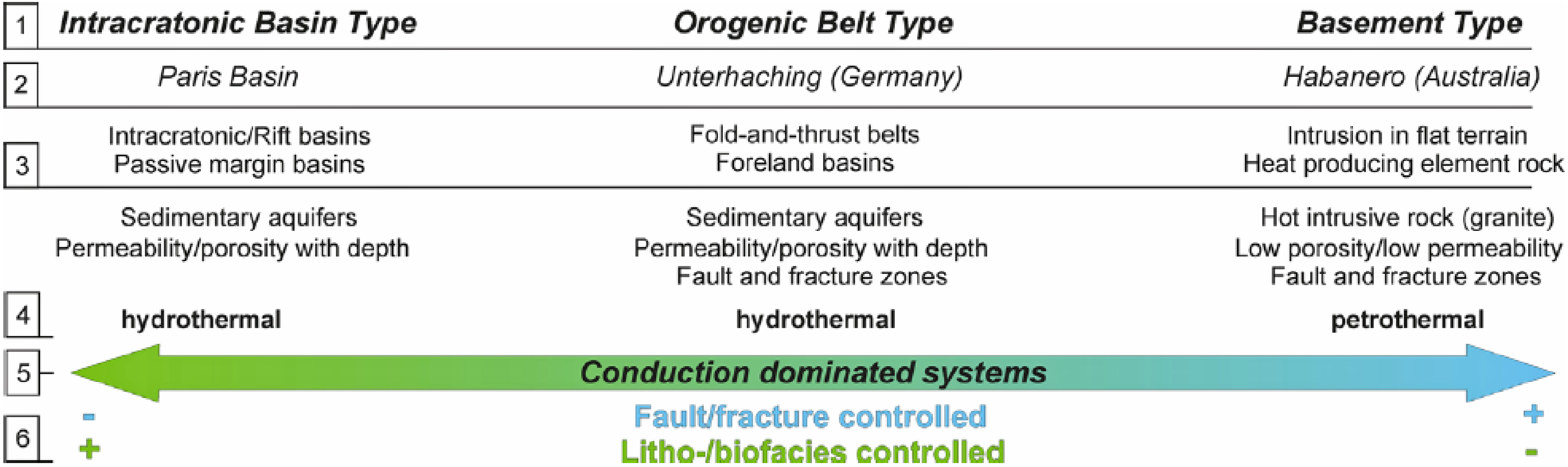
GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF "*PLAY*"

Renewable energies

Conduction-dominated geothermal plays

Moeck, 2014



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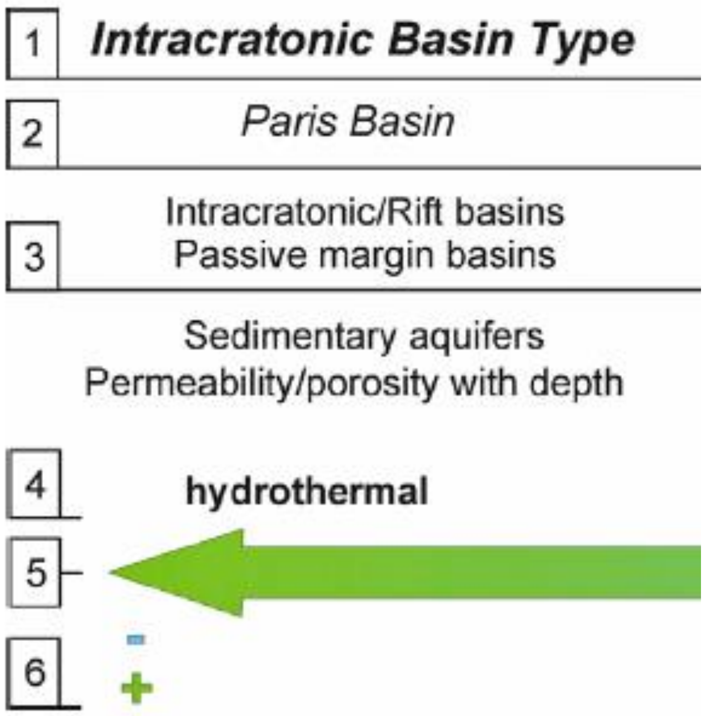

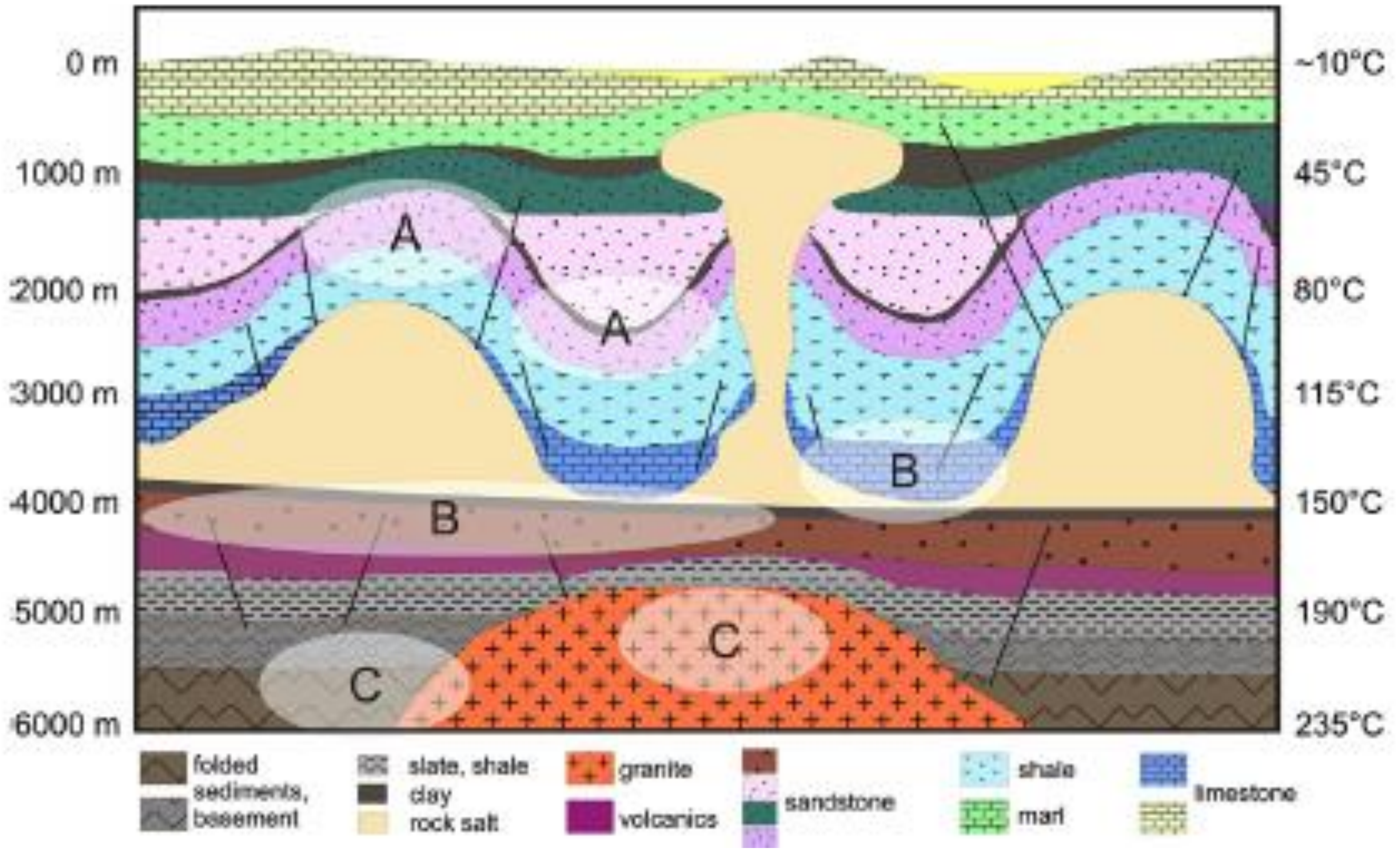

A – Geothermal plays above 3km depth with temperature suitable for district heating,
B – Deep geothermal plays below 3km depth suitable for heating and electricity
C – Very deep geothermal plays below 4km depth as potential HDR systems

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GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF “*PLAY*”

Renewable energies

Orogenic Belt Type

Unterhaching (Germany)

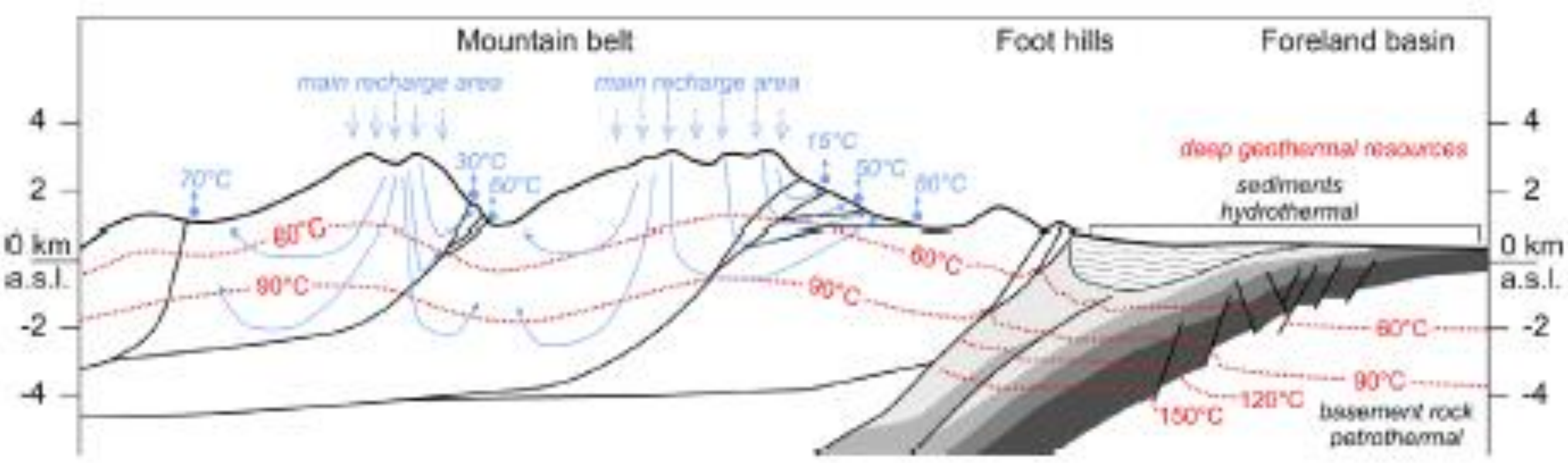
Fold-and-thrust belts
Foreland basins

Sedimentary aquifers
Permeability/porosity with depth
Fault and fracture zones

hydrothermal

Conduction dominated systems

Fault/fracture controlled
Litho-/biofacies controlled



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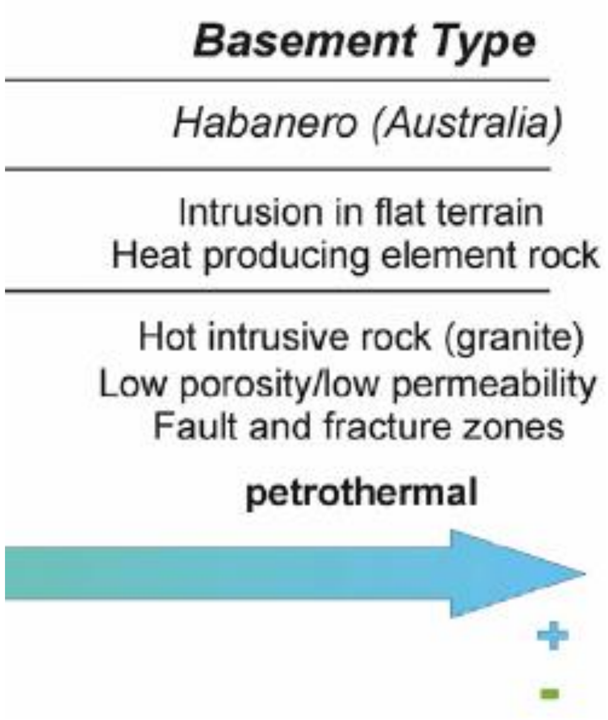
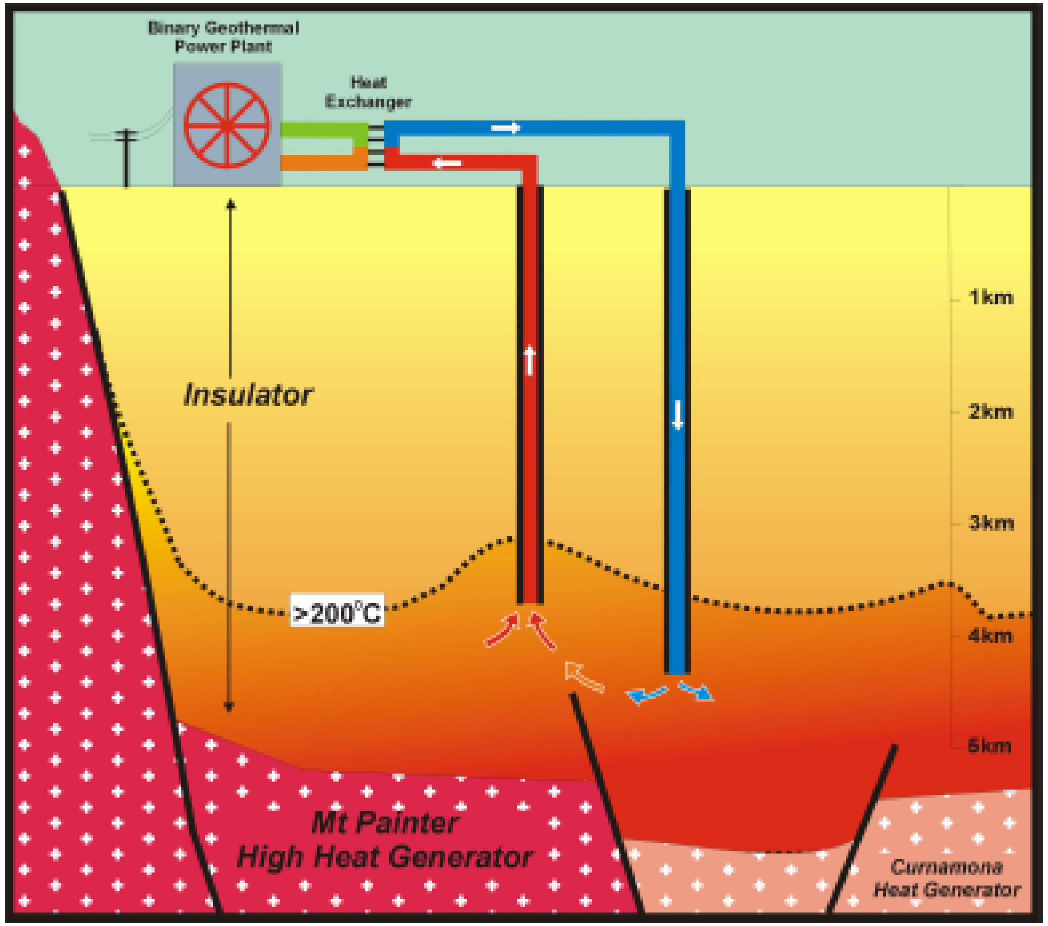
GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF "*PLAY*"



Moeck, 2014



Reid et al, 2010

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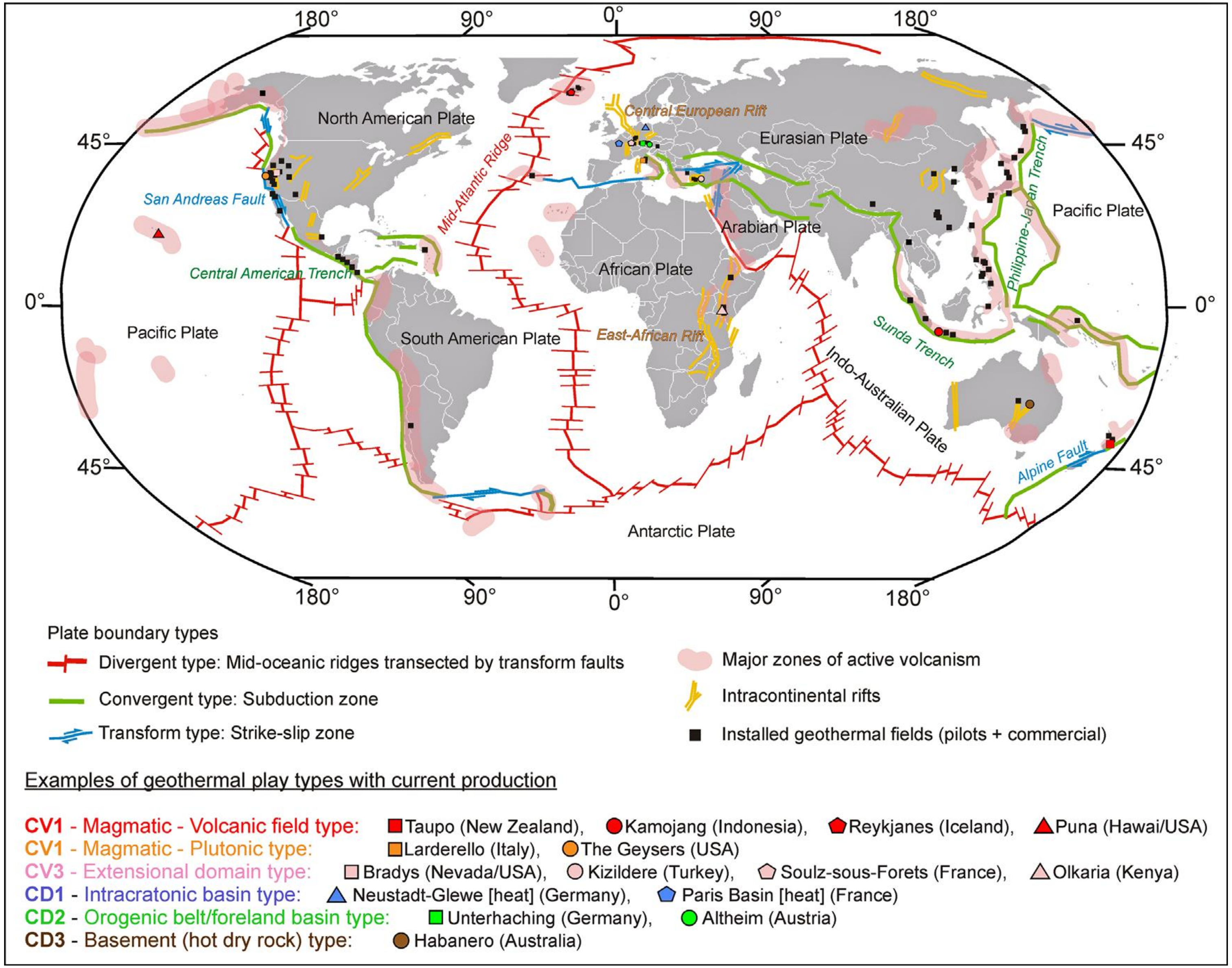
GEOTHERMAL ENERGY CLASSIFICATION: APPLICATION OF THE CONCEPT OF "*PLAY*"

Renewable energies



Moeck, 2014.

Geothermal fields installed worldwide in a plate tectonic setting. Geothermal play types with example fields:

CV – Convection dominated heat transfer,

CD – conduction dominated heat transfer. (List of geothermal fields from http://geothermal-powerplant.blogspot.com; www.thinkgeoenergy.com; Zheng and Dong (2008); plate tectonic map based on Frisch and Löschke (2003).

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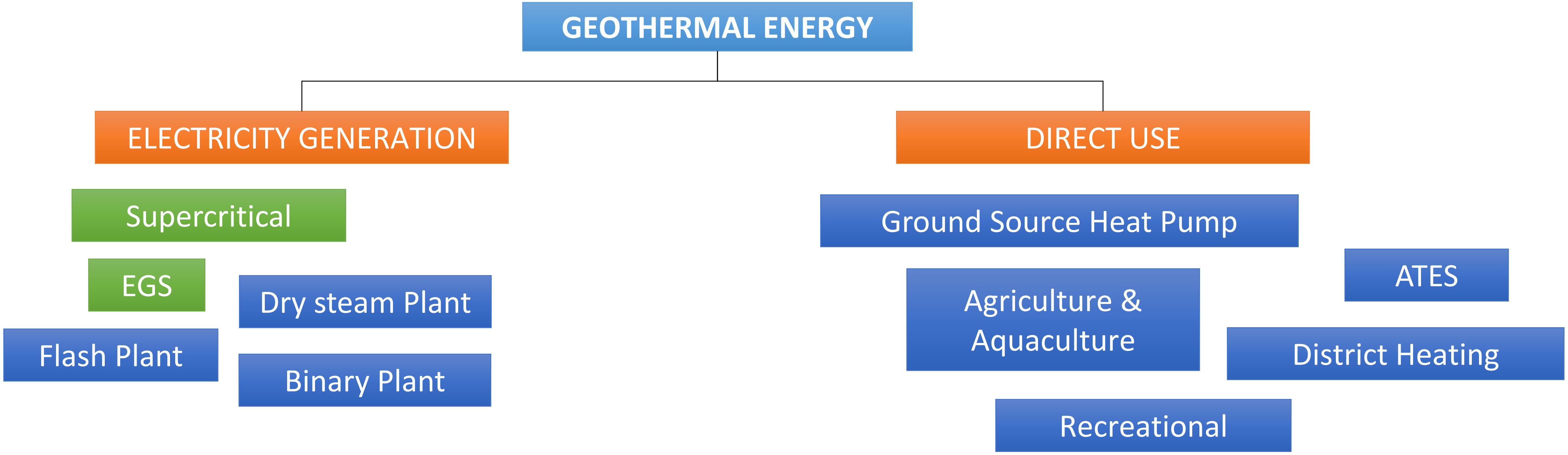
DIFFERENT USE OF GEOTHERMAL ENERGY



	Muffler [8] (°C)	Hochstein [9] (°C)	Benderitter and Cormy [12] (°C)	Haenel et al. [10] (°C)		
Low enthalpy	< 90	< 125	< 100	< 150		
Moderate enthalpy	90–150	125–225	100–200	–		
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Sanyal [13]	Non-electrical (°C)	Very low (°C)	Low (°C)	Moderate (°C)	High (°C)	Ultra high (°C)
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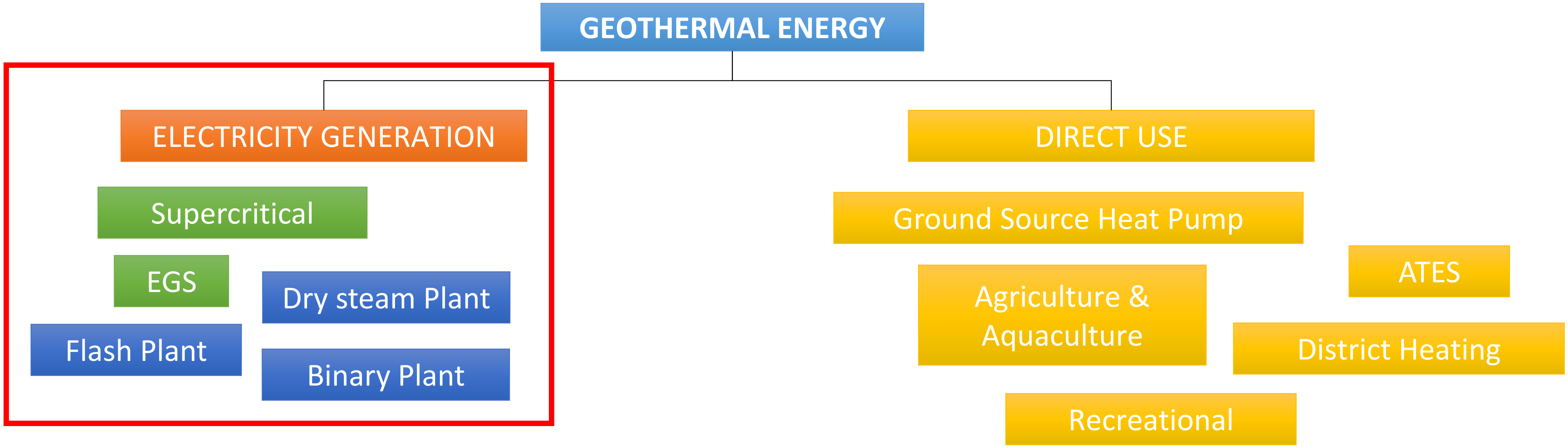
DIFFERENT USE OF GEOTHERMAL ENERGY

Renewable energies



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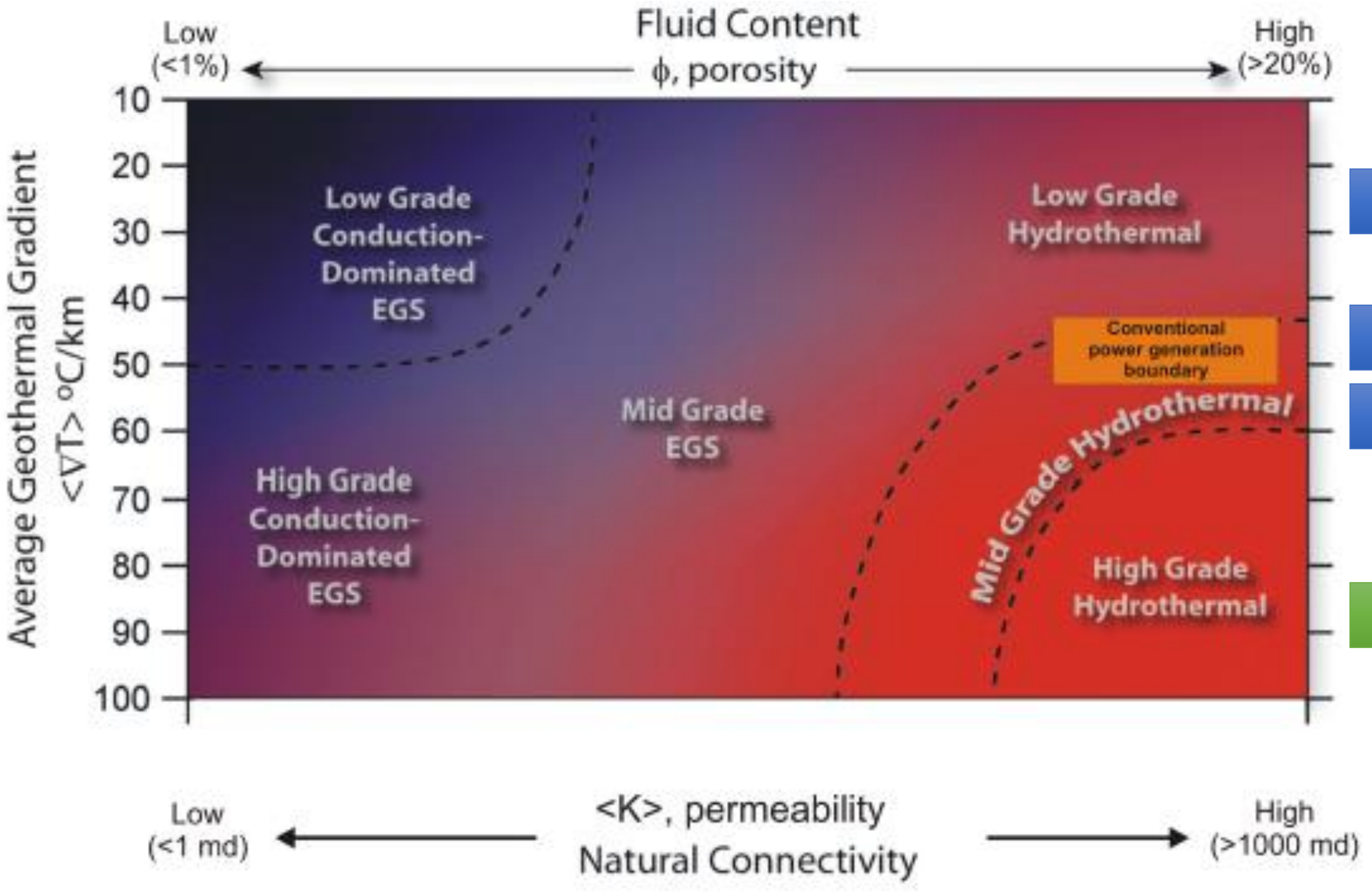
DIFFERENT USE OF GEOTHERMAL ENERGY – ELECTRICITY GENERATION

Renewable energies

EGS



(Adapted from J. Tester)

Binary Plant

Flash Plant

Dry steam Plant

Supercritical

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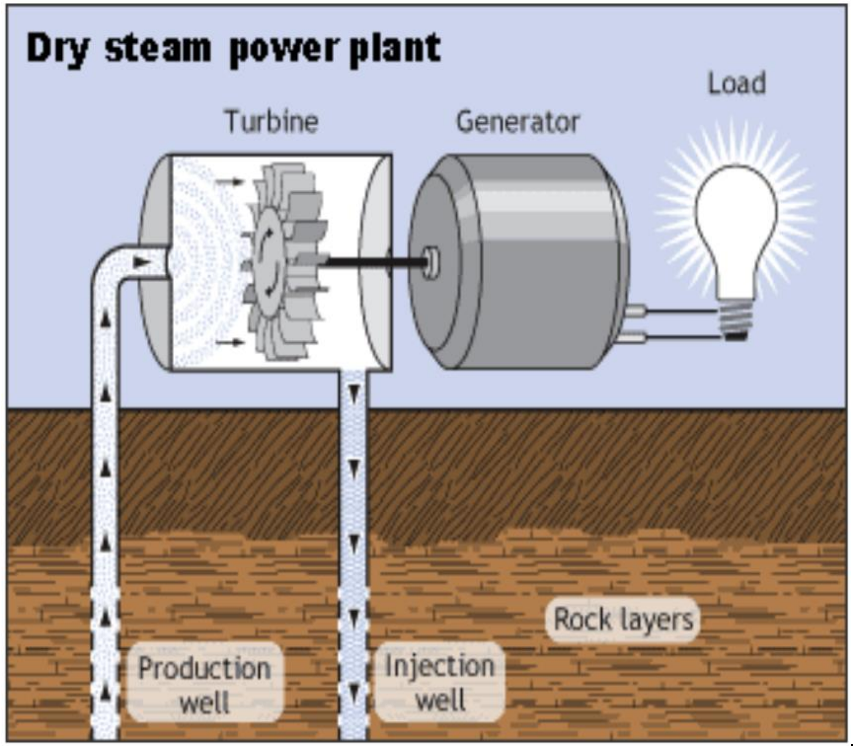
DIFFERENT USE OF GEOTHERMAL ENERGY – ELECTRICITY GENERATION

Renewable energies

Electricity generation: Dry steam plant

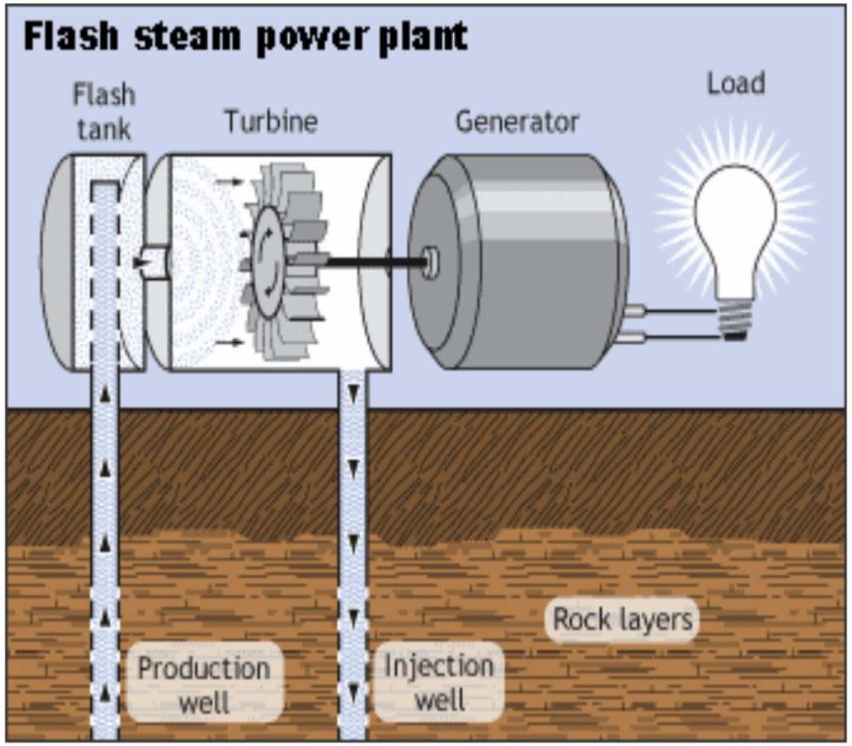


First system to be developed (1904 in Tuscany) with the steam being delivered directly to the turbine to generate electricity.

DIFFERENT USE OF GEOTHERMAL ENERGY – ELECTRICITY GENERATION

Renewable energies

Electricity generation: Flash plant



Source: US Departement of energy

Most commonly used system. A flash chamber allow a drop of pressure that creates steam that is then used by the turbine to generate electricity.

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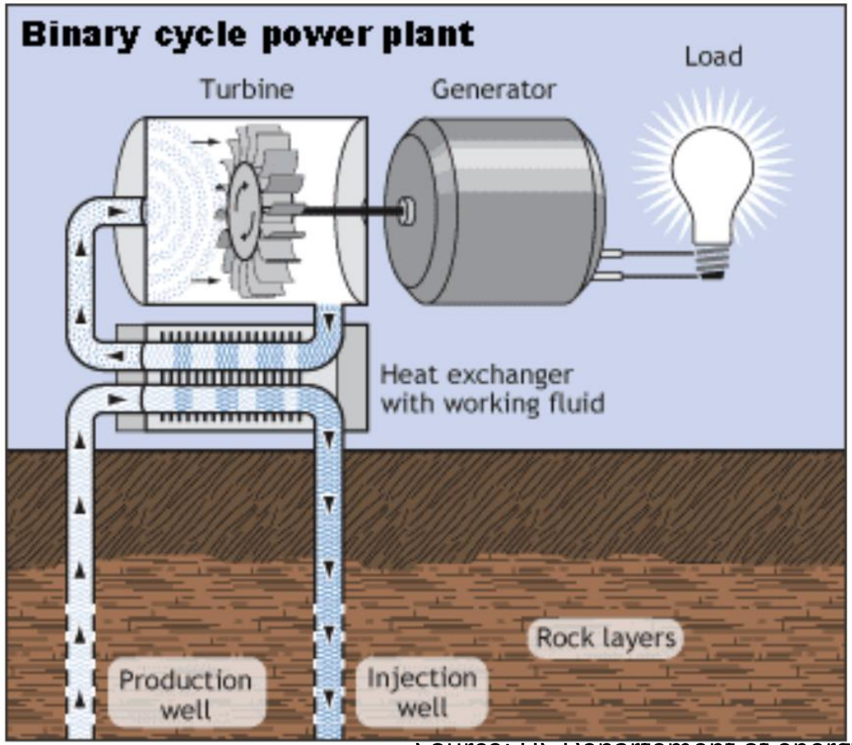
DIFFERENT USE OF GEOTHERMAL ENERGY – ELECTRICITY GENERATION

Electricity generation: Binary plant



Source: US Departement of energy

The heat from geothermal hot water is transferred to a working fluid that is vaporised to run the turbine, generating electricity.

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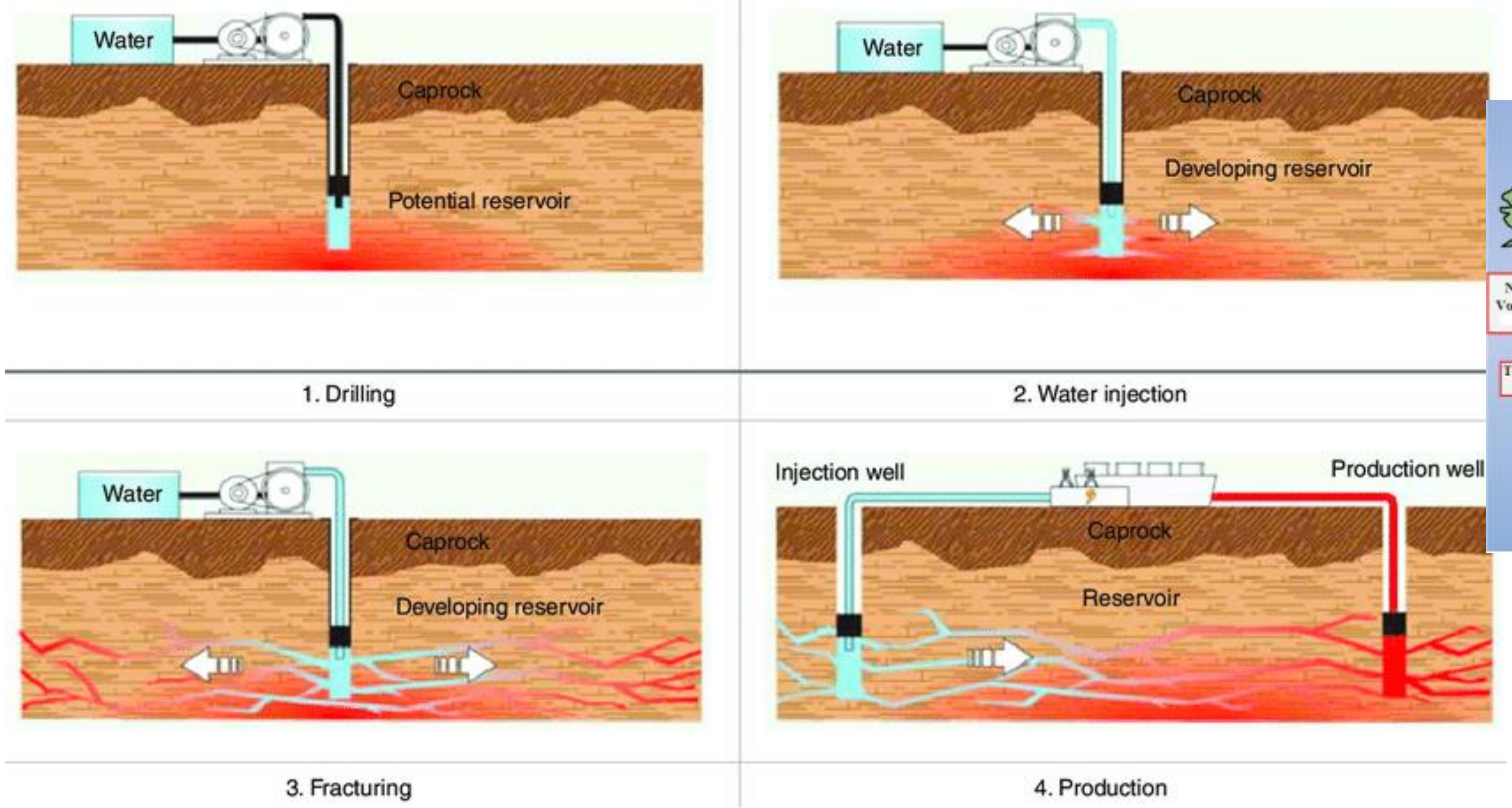
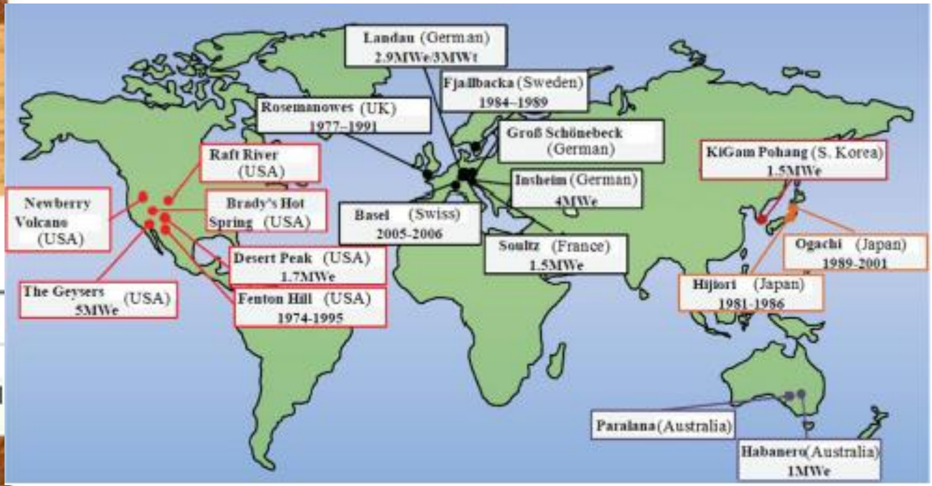
DIFFERENT USE OF GEOTHERMAL ENERGY – EGS (ENHANCED GEOTHERMAL SYSTEMS)

Renewable energies

In EGS:
- the reservoir is created or enhanced using mechanical or chemical methods.
- the temperature is already available and only the heat transport is created



Following the creating of the reservoir the resulting plant depends on the resource (heat + reservoir)



In January 2018, 18 EGS system were in production/development

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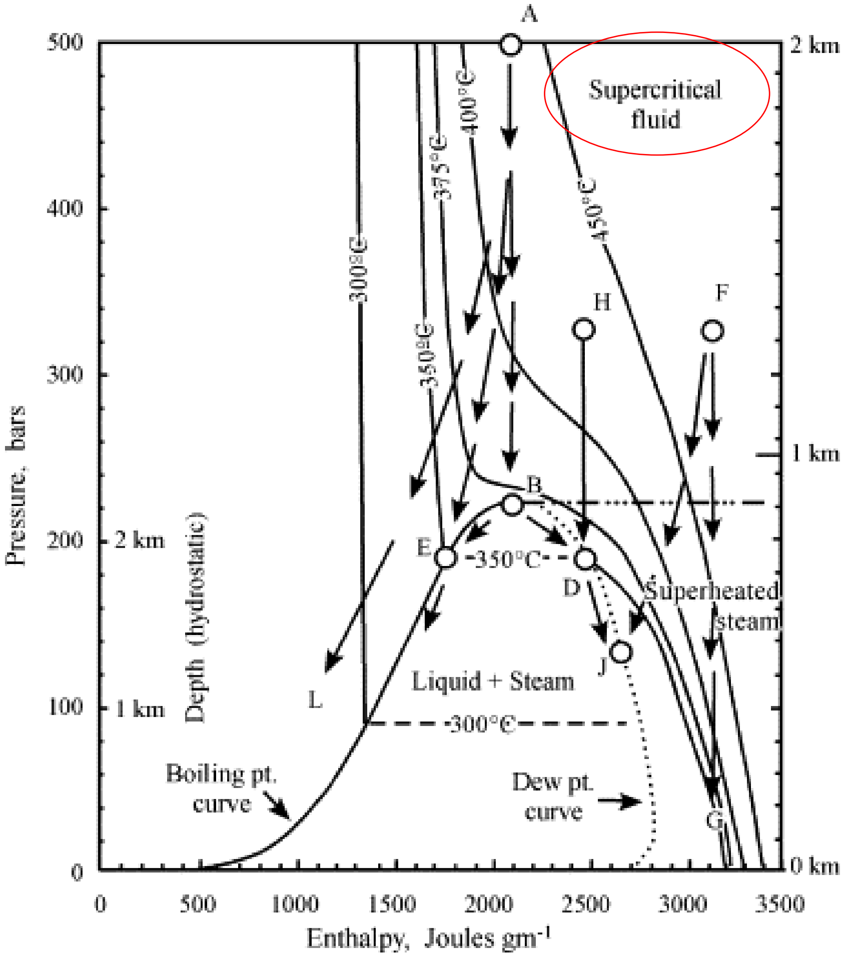
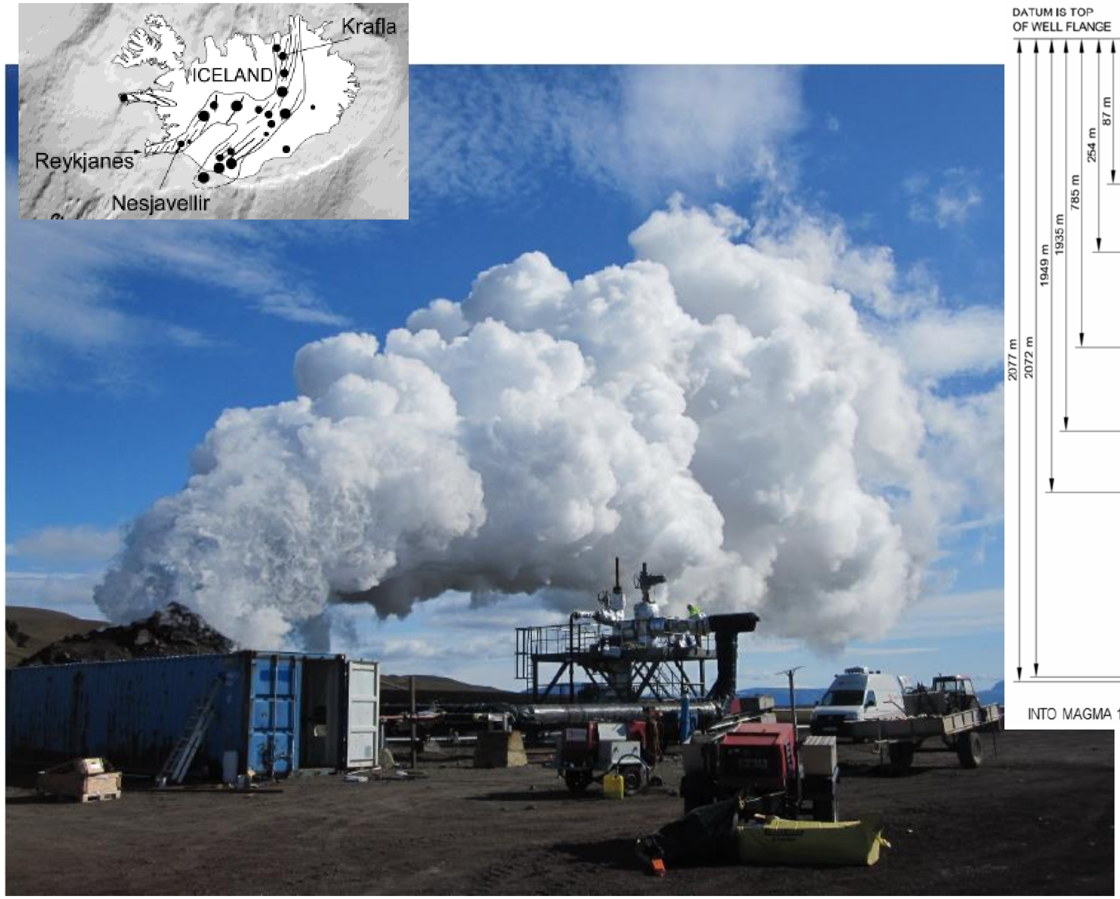
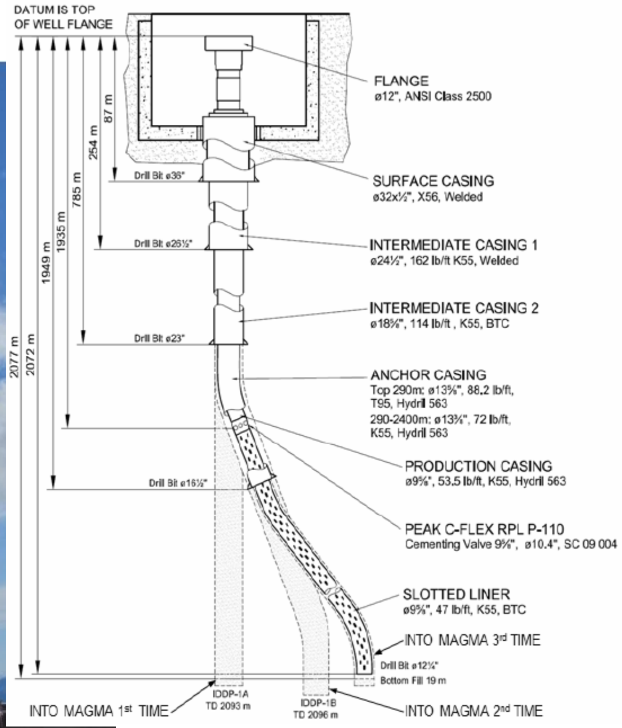
DIFFERENT USE OF GEOTHERMAL ENERGY – SUPERCRITICAL (IDDP PROJECT)

Renewable energies







Critical point for fresh water is 374◦C and 22.1 Mpa (Krafla)

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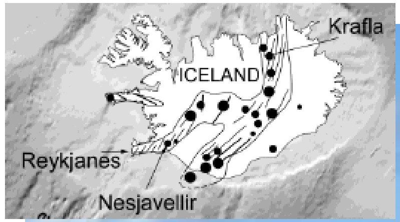
DIFFERENT USE OF GEOTHERMAL ENERGY – SUPERCRITICAL (IDDP PROJECT)

Renewable energies

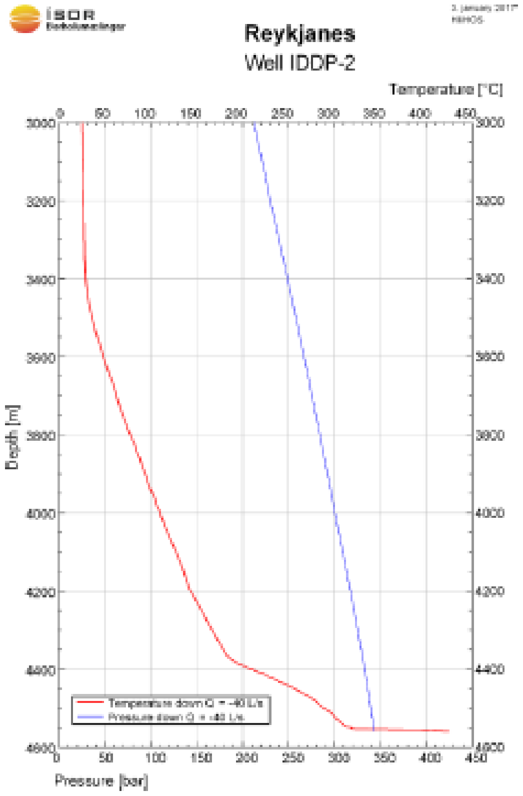


5MW
Typical power output of a geothermal well

VS

50MW
Predicted output of a "supercritical" well

SOURCE: DOI.ORG/FMPP3D



Reykjanes field have a salinity of seawater so the critical point is reached at 406°C and 298 bars

Final depth: 4659m - Max. temperature: 427°C – Max pressure: 340 bars.

Supercritical for geothermal is still at the research stage and many question still need answering!!

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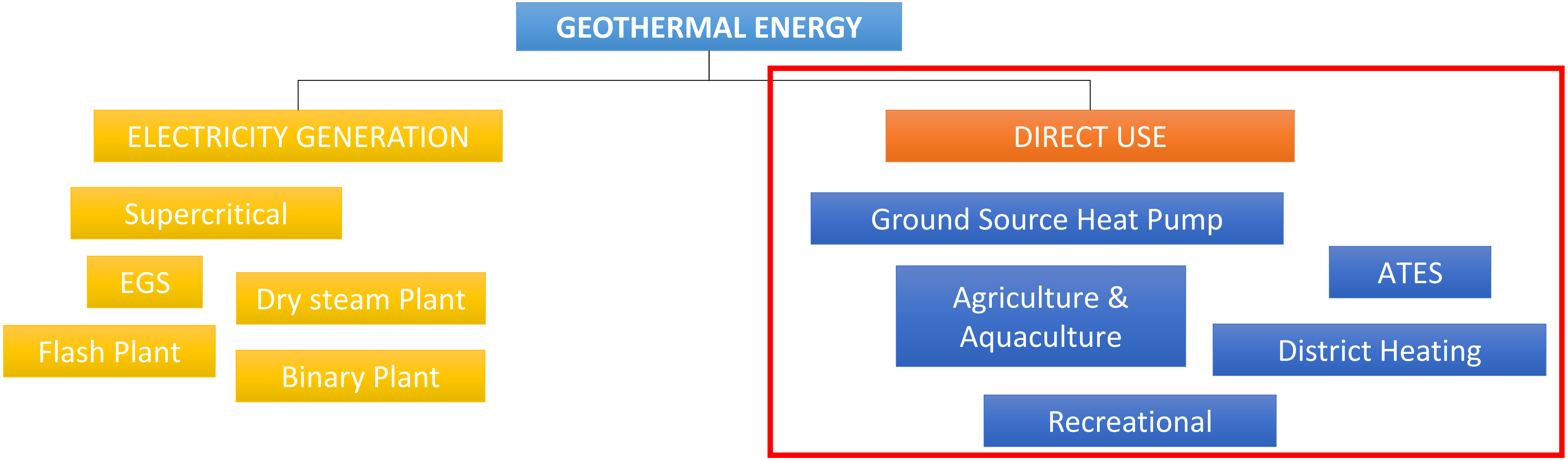
DIFFERENT USE OF GEOTHERMAL ENERGY

Renewable energies



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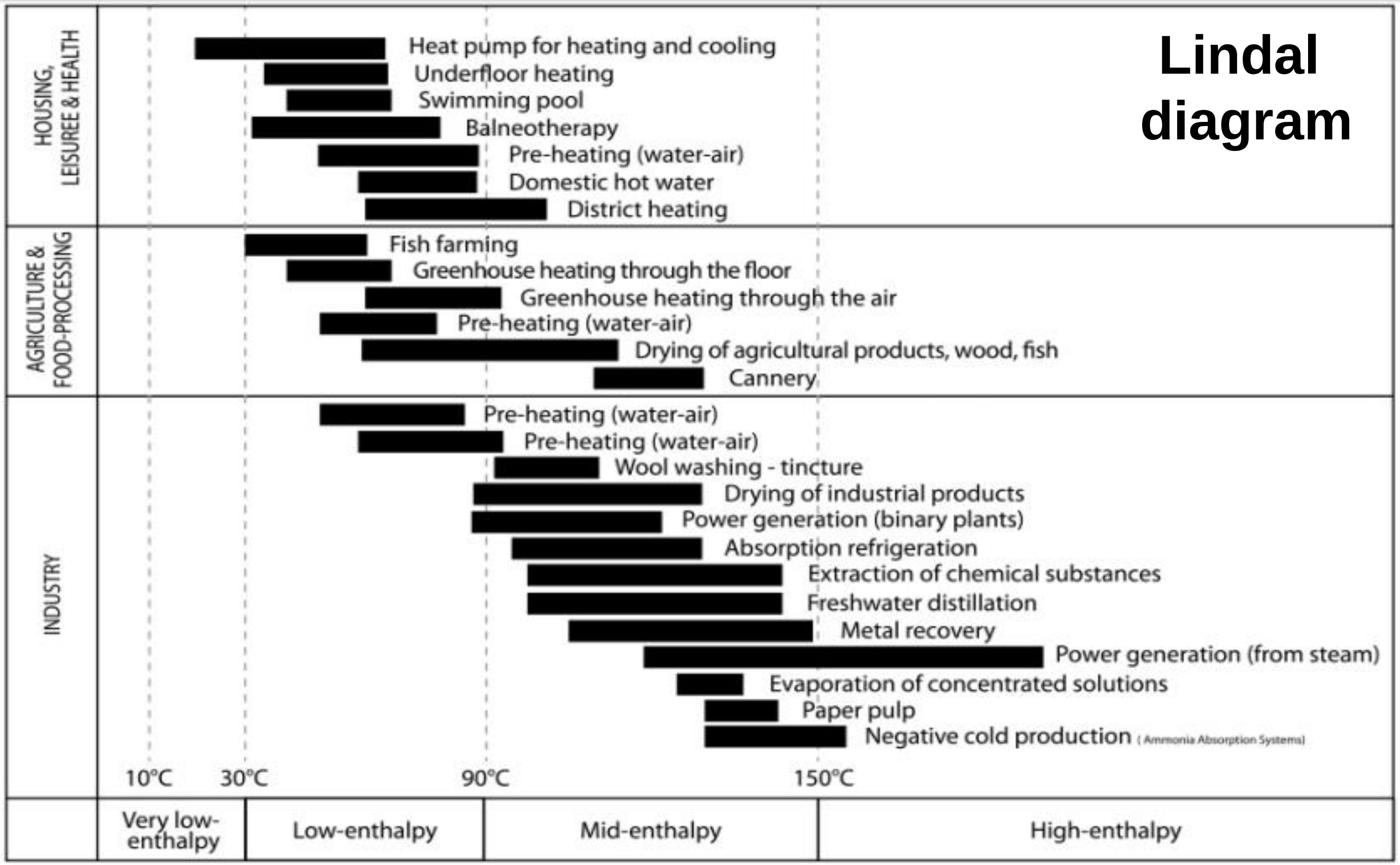
DIFFERENT USE OF GEOTHERMAL ENERGY – DIRECT USE

Renewable energies



Lindal diagram

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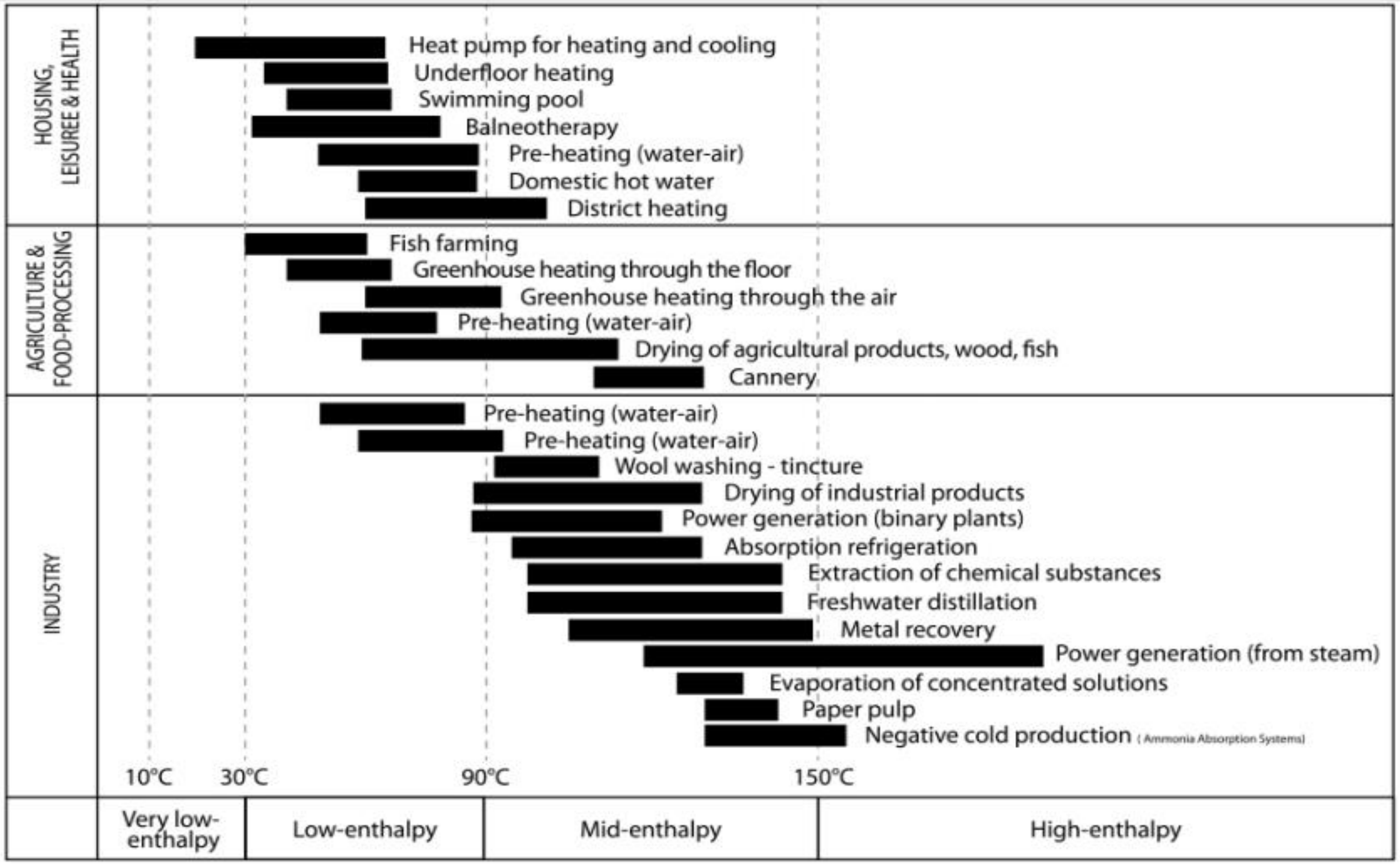
IFP Energies nouvelles

DIFFERENT USE OF GEOTHERMAL ENERGY – DIRECT USE

Renewable energies



Lindal diagram

Ground Source Heat Pump

ATES

Agriculture & Aquaculture

District Heating

Recreational

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DIFFERENT USE OF GEOTHERMAL ENERGY – RECREATIONAL: SPA & BATHING


Seljavallalaug, Iceland


Japan


Huaqing Palace, China


Pamukkale, Turkey


Manikaran, Himachal Pradesh, India

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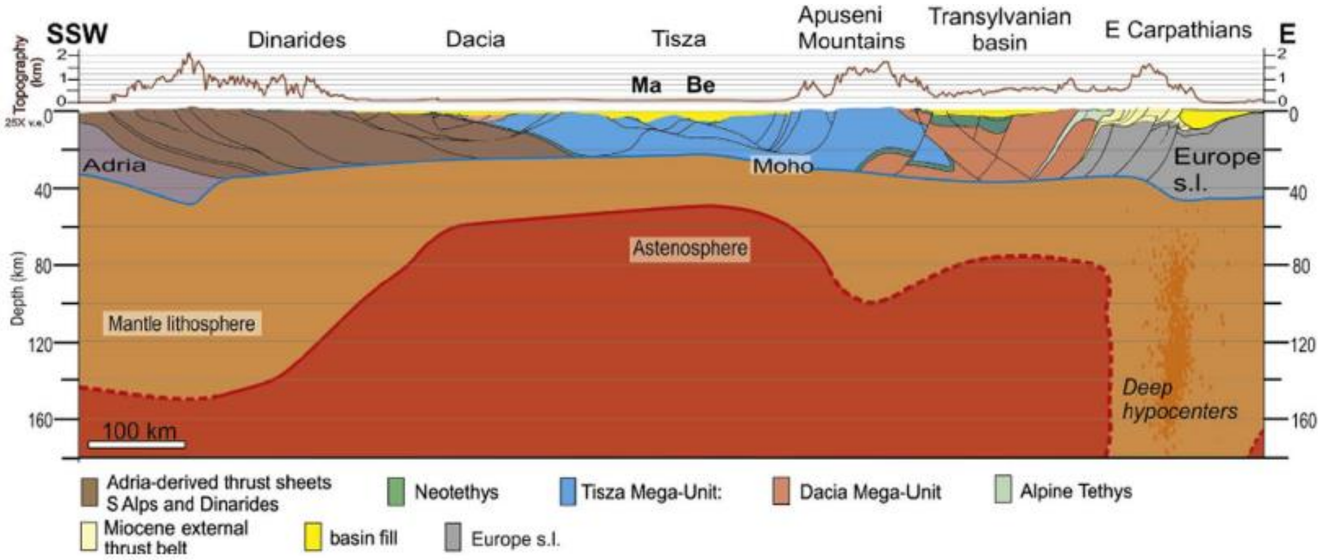
DIFFERENT USE OF GEOTHERMAL ENERGY – RECREATIONAL: SPA & BATHING

Renewable energies

Spa have developed in tectonic and geodynamic settings naturally favourable



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DIFFERENT USE OF GEOTHERMAL ENERGY – RECREATIONAL: SPA & BATHING

Renewable energies

Iceland – Blue Lagoon

The Blue Lagoon is the "by-product" of the Svartsengi Power Station at 40ºC
Svartsengi Power Station is in operation since 1977 and have now a capacity of 76.5 Mwe.

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DIFFERENT USE OF GEOTHERMAL ENERGY – RECREATIONAL: TOURISM

Renewable energies

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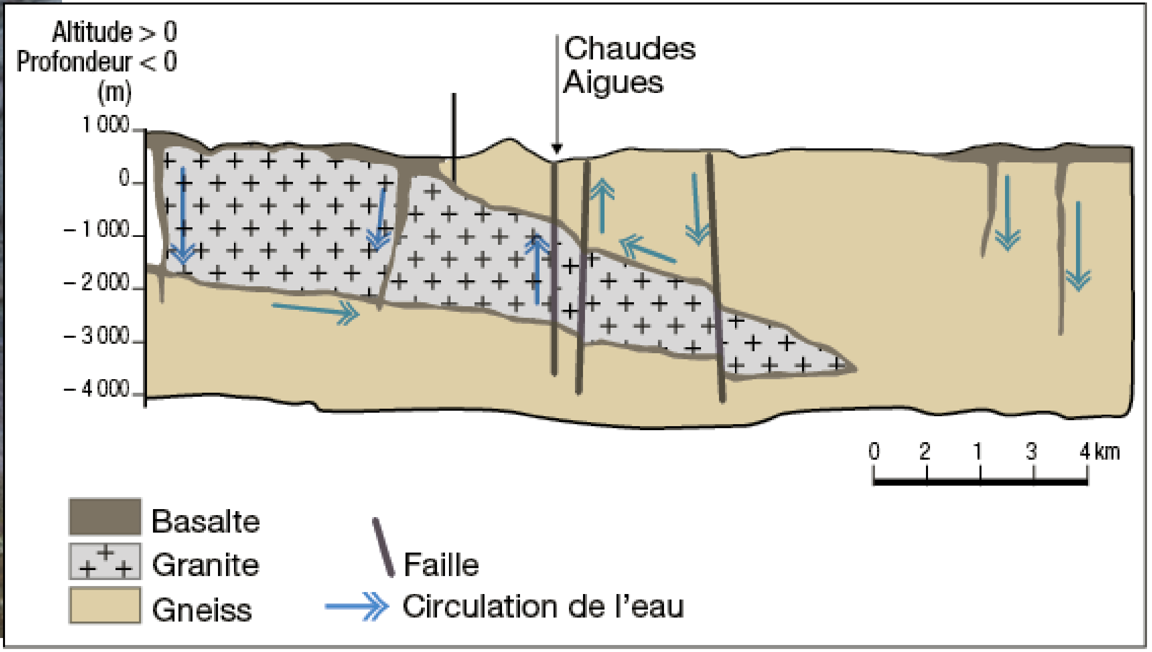
DIFFERENT USE OF GEOTHERMAL ENERGY – DISTRICT HEATING

Renewable energies

1st district heating network (14th century) in Chaude Aigues - France

The Chaudes Aigues fault bring the water at the surface at 82ºC



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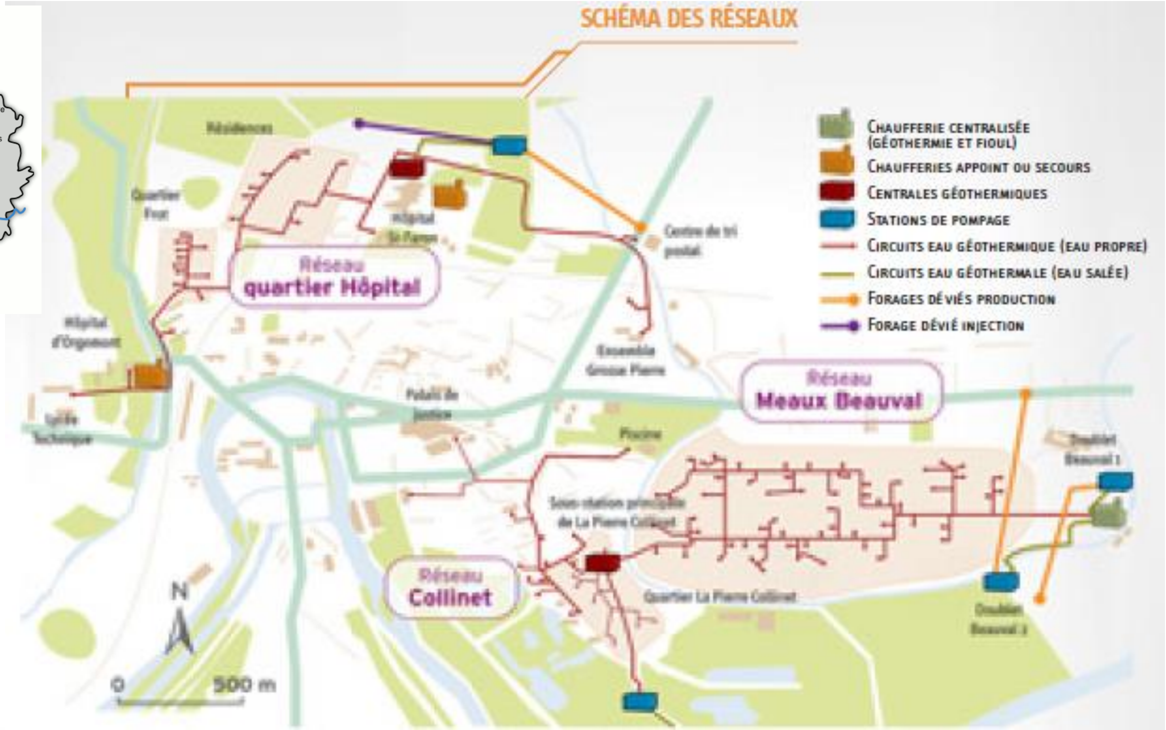
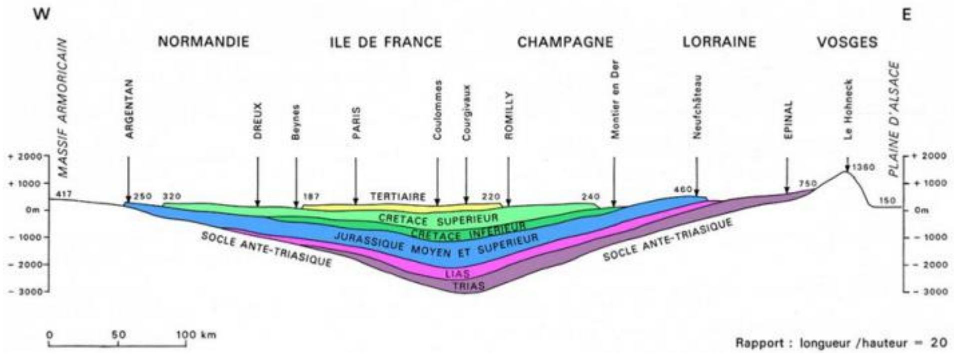
IFP Energies nouvelles

DIFFERENT USE OF GEOTHERMAL ENERGY – DISTRICT HEATING





Meaux District Heating:

Installed since 1982

Reservoir (Dogger) depth 1760 m
Number of Doublets: 4
Temperature: ~75ºC

Network length: 43 km
Annual production by geothermal energy
80 000 MWh

The district heating can be fed by geothermal as well as other source in coordination

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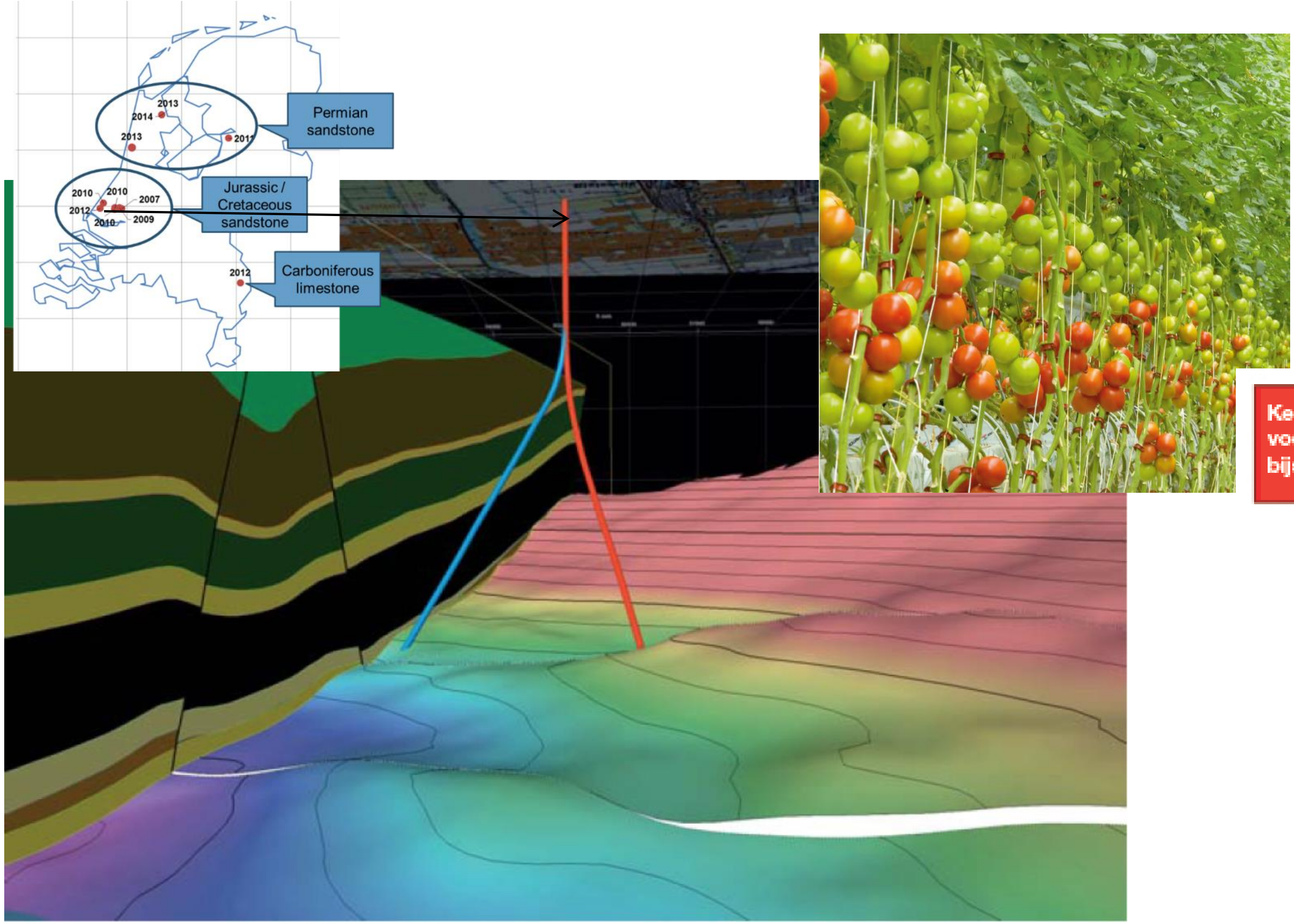
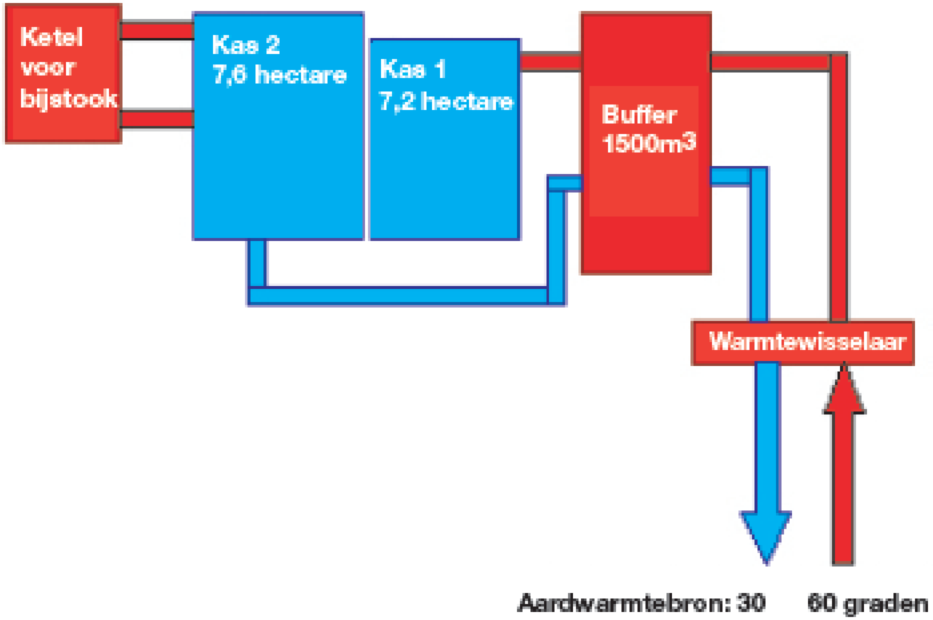
DIFFERENT USE OF GEOTHERMAL ENERGY – GREEN HOUSES

Renewable energies



Lower Cretaceous reservoir
Temperature 60°C
Flow rate 160 m3/h
Capacity 4-5 MWth
Heating 2x7 ha of tomato green house
Avoiding 3 million m3 of gas per yr



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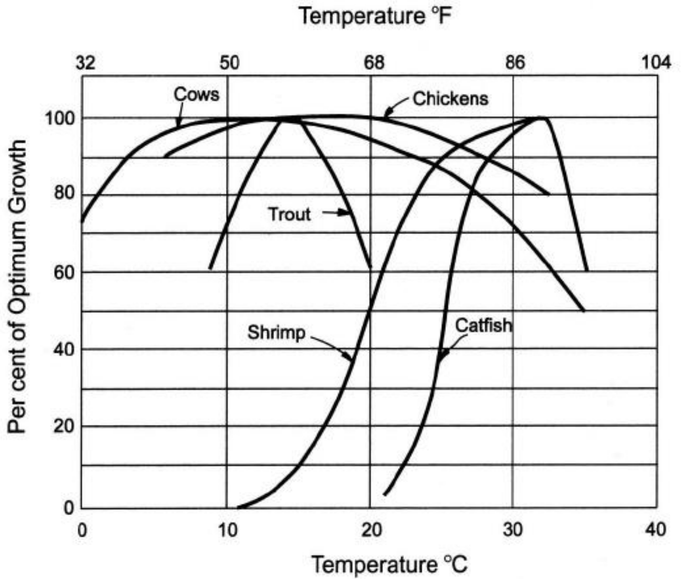
DIFFERENT USE OF GEOTHERMAL ENERGY – AQUACULTURE



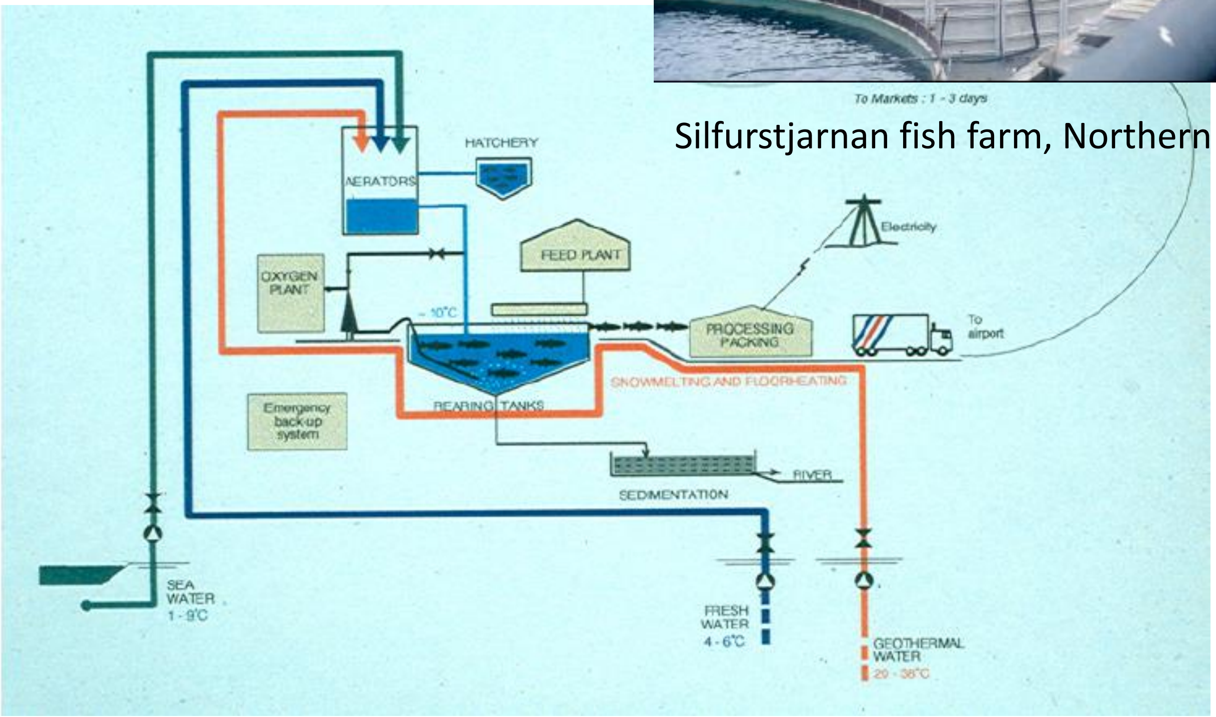
Optimum growing temperature (Dickson and Fanelli, 2005)

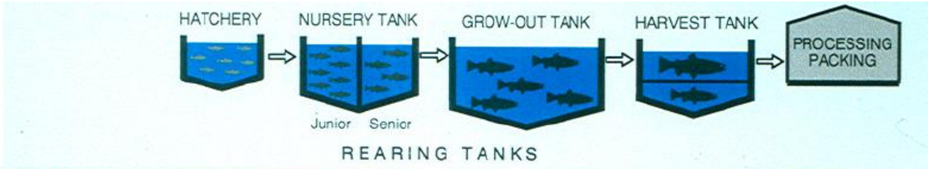
Several well used to balance the temperature and salinity

Rearing temperature is about 9-11°C

Total production is about 1,000 tons per year of salmon

Silfurstjarnan fish farm, Northern Iceland





SALMON				2 - 4 kg
Temperature °C	8	10	10	9.5
Salinity ‰	0	10	10	10
Year	0.5	1	1	0.02

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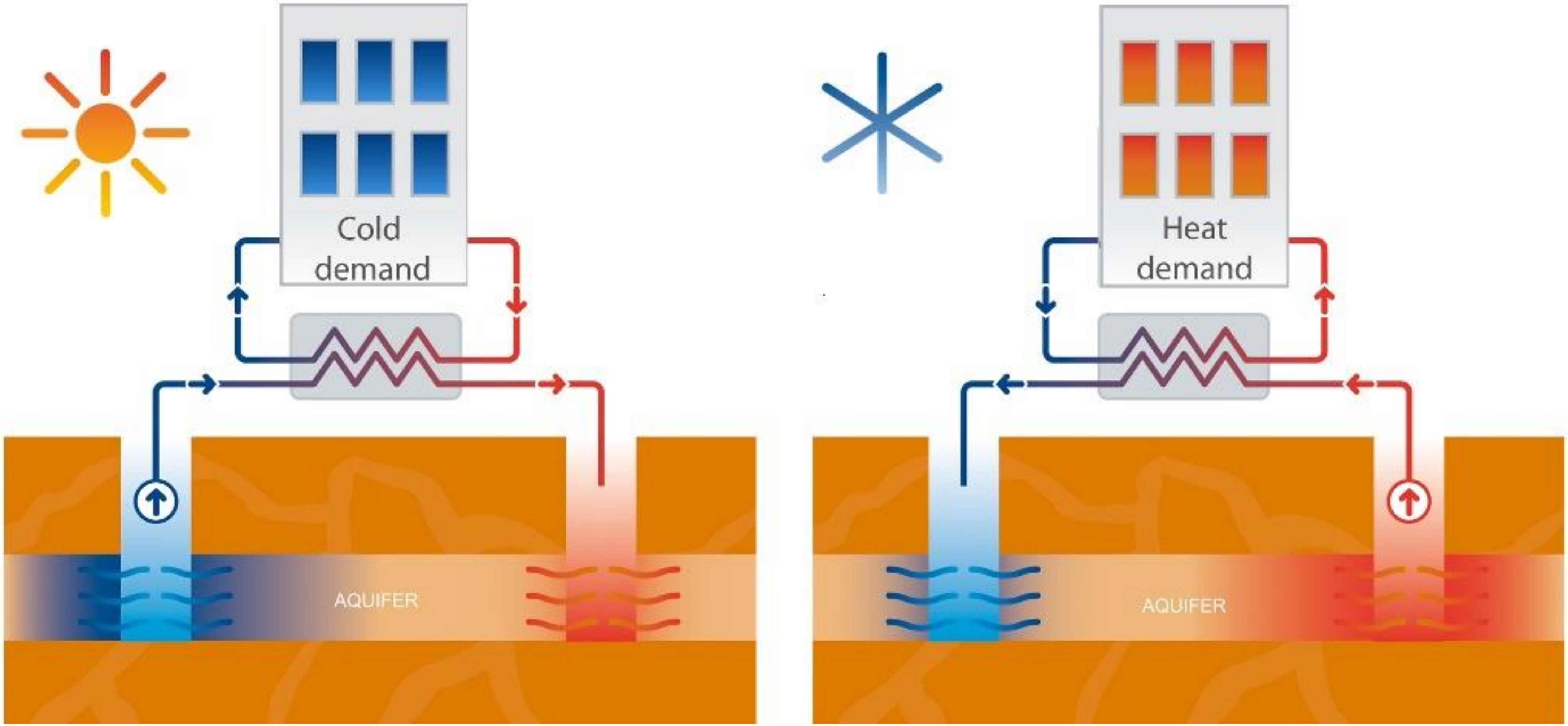
DIFFERENT USE OF GEOTHERMAL ENERGY – ATES (AQUIFER THERMAL ENERGY STORAGE)

Renewable energies



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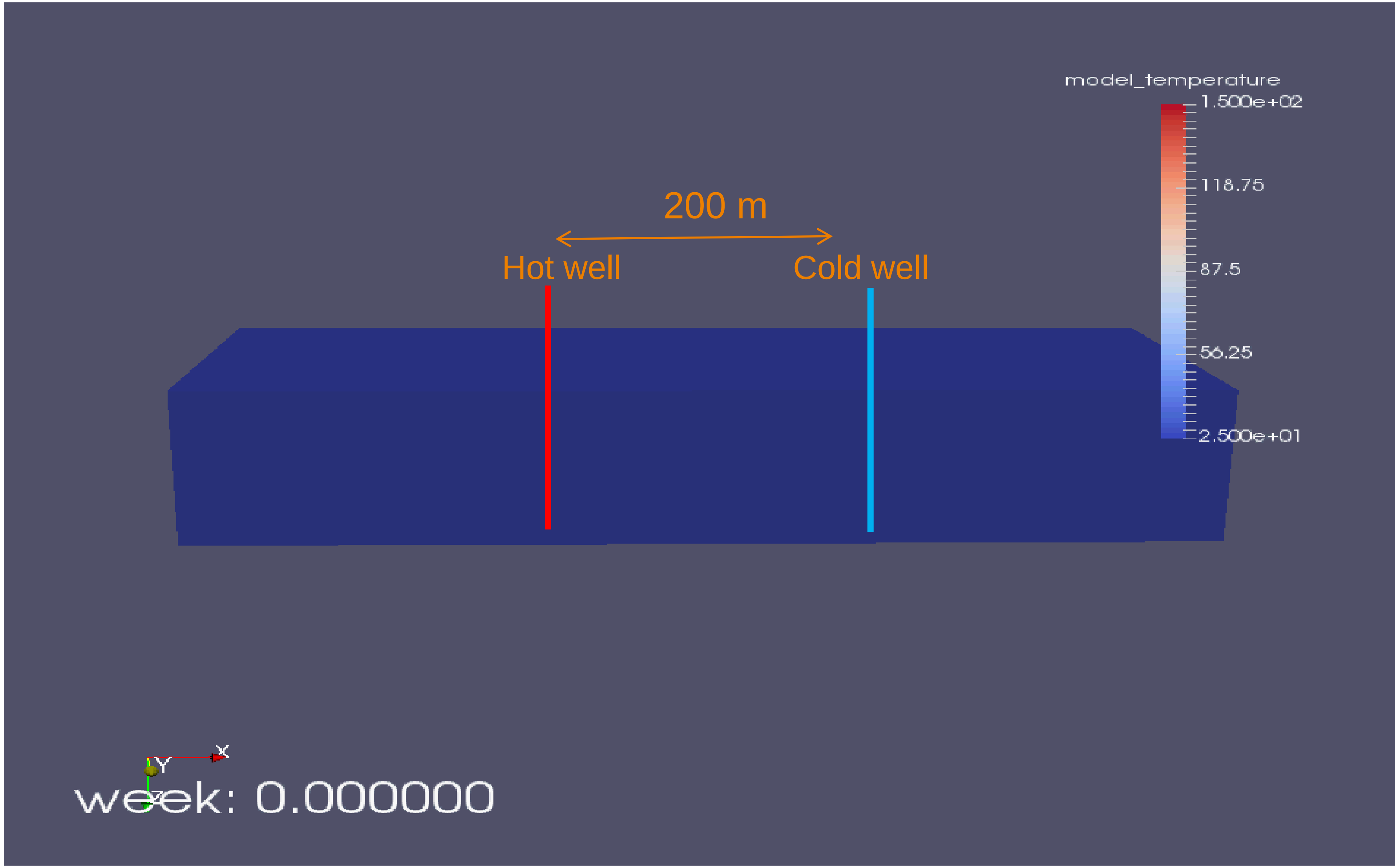
DIFFERENT USE OF GEOTHERMAL ENERGY – ATES (AQUIFER THERMAL ENERGY STORAGE)

Renewable energies



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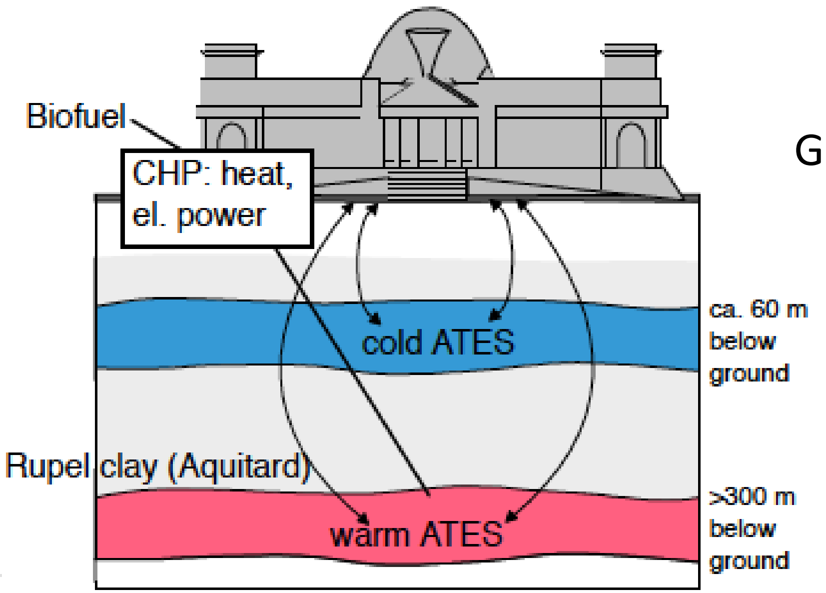
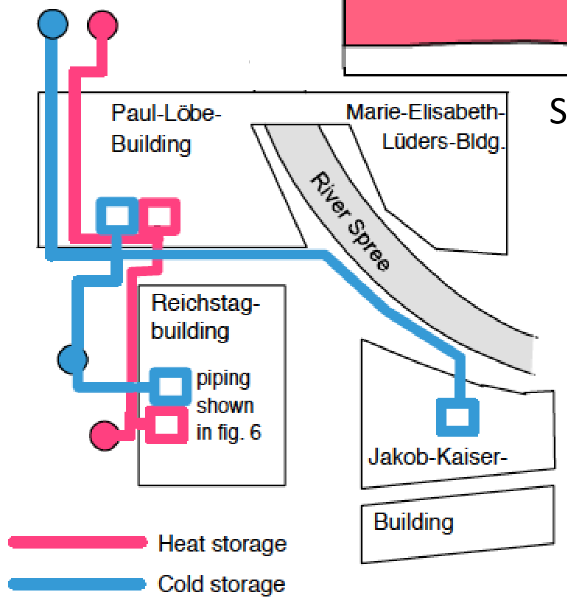
DIFFERENT USE OF GEOTHERMAL ENERGY – ATES (AQUIFER THERMAL ENERGY STORAGE)

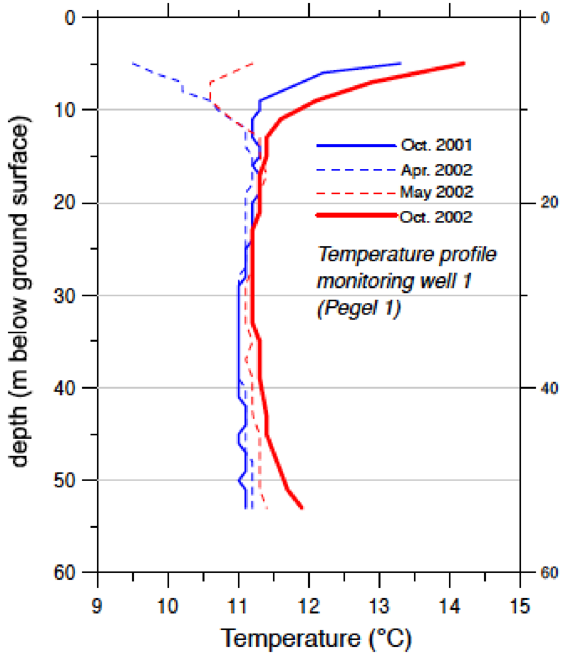
Renewable energies

ATES of the German Parliament in Berlin





Sanner et al., 2005



Energy balance for heat ATES (simulated)

Summer	mean production temp.	20°C
(loading)	injection temperature	70°C
	stored heat	2.650 MWh/a
Winter	production temperature	65 ... 30 °C
(retrieving)	heat retrieved	2.050 MWh/a
Balance	energy for pumping	280 MWh
	ratio of heat retrieved to heat stored	77 %

Energy balance for cold ATES (simulated)

Summer	production temperature	6 ... 10°C
(retrieving)	injection temperature	15 ... 28°C
	cold retrieved	3.950 MWh/a
Winter	mean production temp.	22°C
(loading)	injection temperature	5°C
	cold stored	4.250 MWh/a
Balance	energy for pumping	220 MWh
	ratio of cold retrieved to cold stored	93 %

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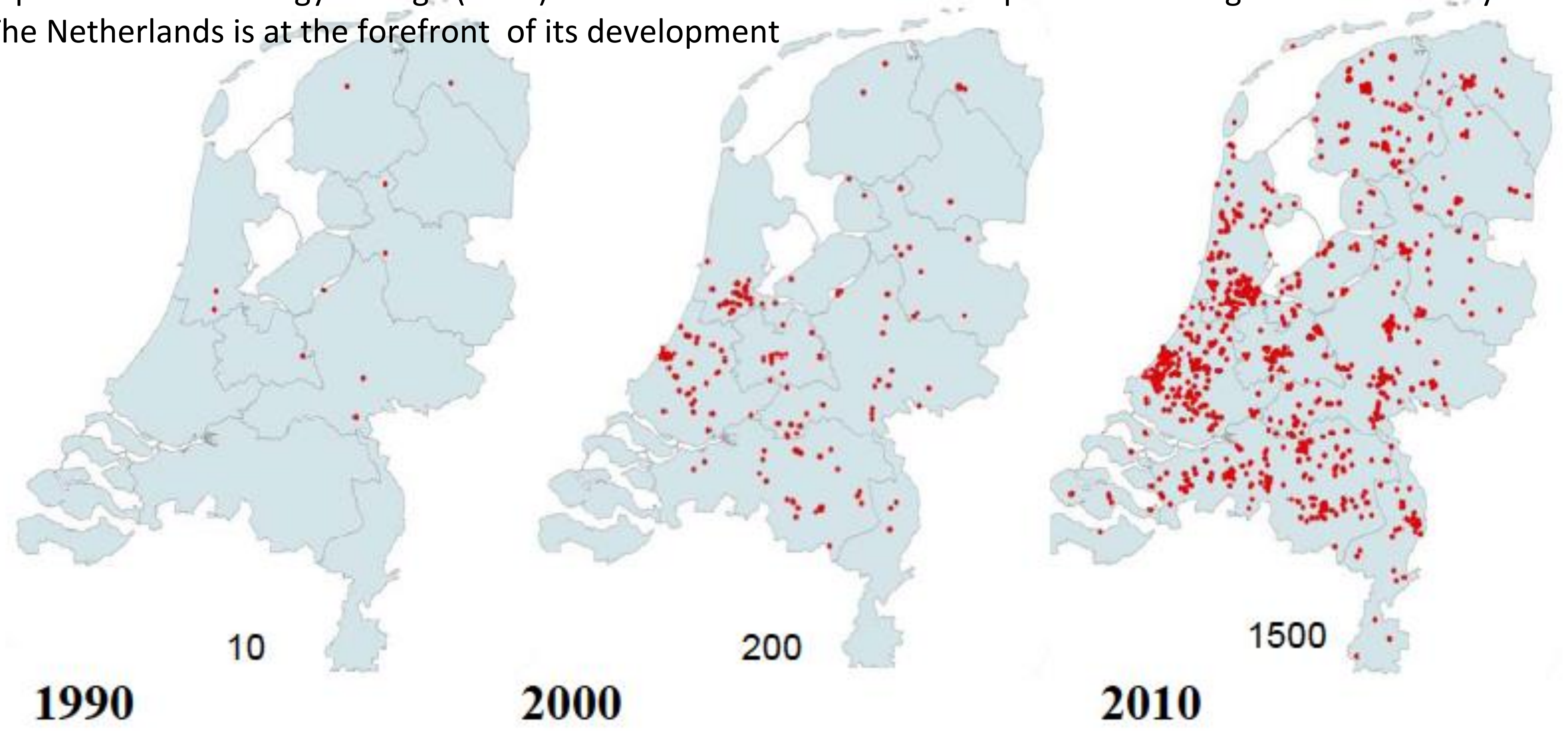
DIFFERENT USE OF GEOTHERMAL ENERGY – ATES (AQUIFER THERMAL ENERGY STORAGE)

Renewable energies

Aquifer Thermal Energy Storage (ATES) are an excellent outcome for optimised multi-generation heat system
The Netherlands is at the forefront of its development



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DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)

Renewable energies

Thermal Response Test (TRT):

A Thermal Response Test (TRT) measures the thermal conductivity of the ground at a specific location.

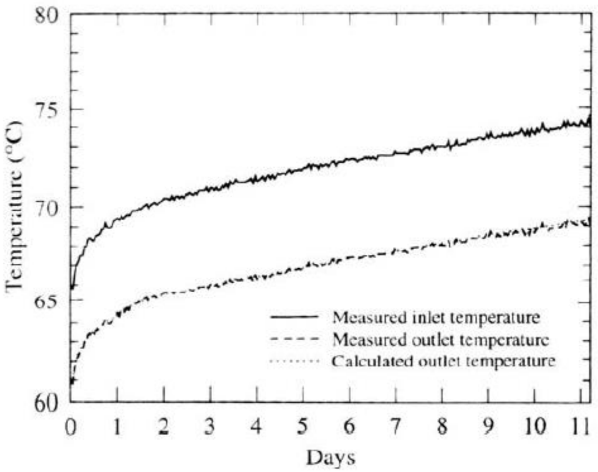
To evaluate thermal response test data we can make use of the line source theory. An approximation is possible with the following formula, given in Eklöf & Gehlin (1996):

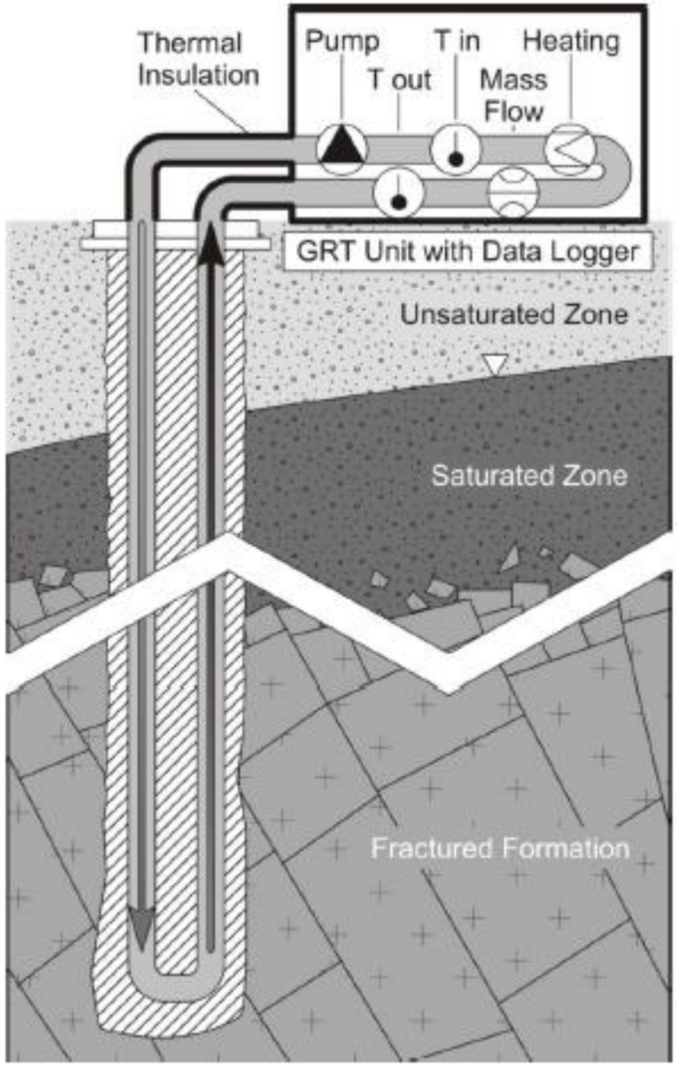
$$k = \frac{Q}{4\pi H \lambda_{eff}}$$

- k Inclination of the curve of temperature versus logarithmic time
- Q heat injection/extraction
- H length of borehole heat exchanger
- λ_{eff} effective thermal conductivity (incl. influence of groundwater flow, borehole grouting, etc.)

To calculate thermal conductivity, the formula has to be transformed:

$$\lambda_{eff} = \frac{Q}{4\pi H k}$$





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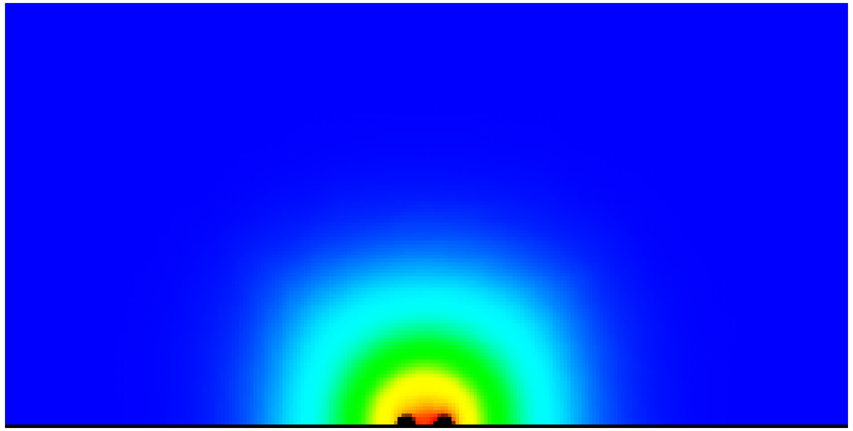
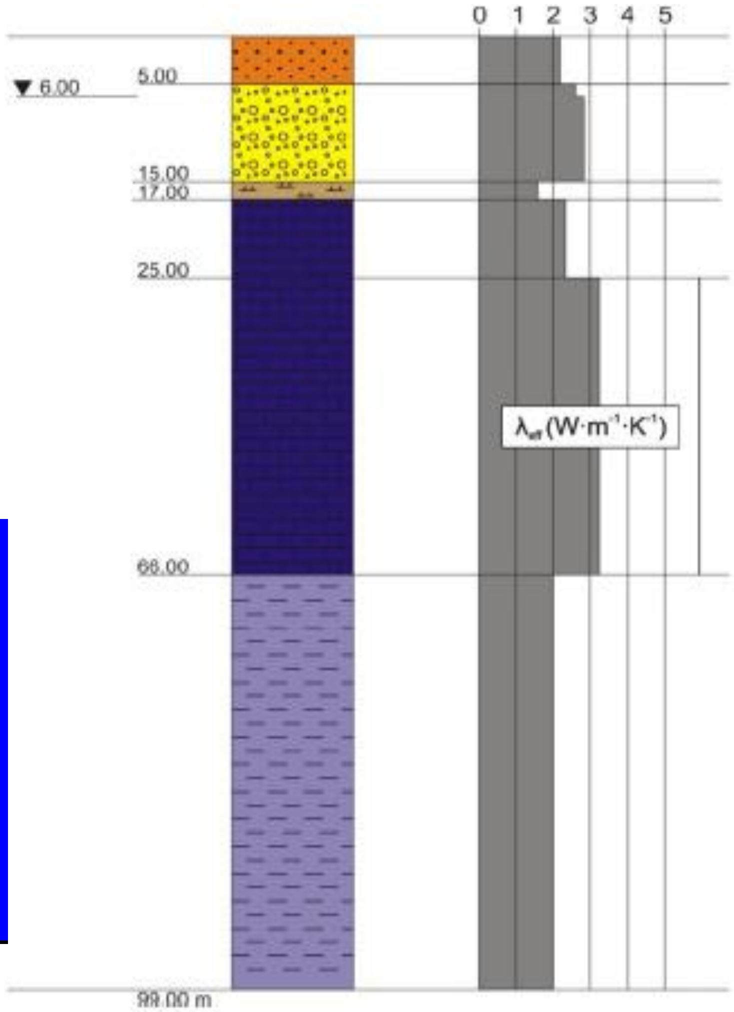
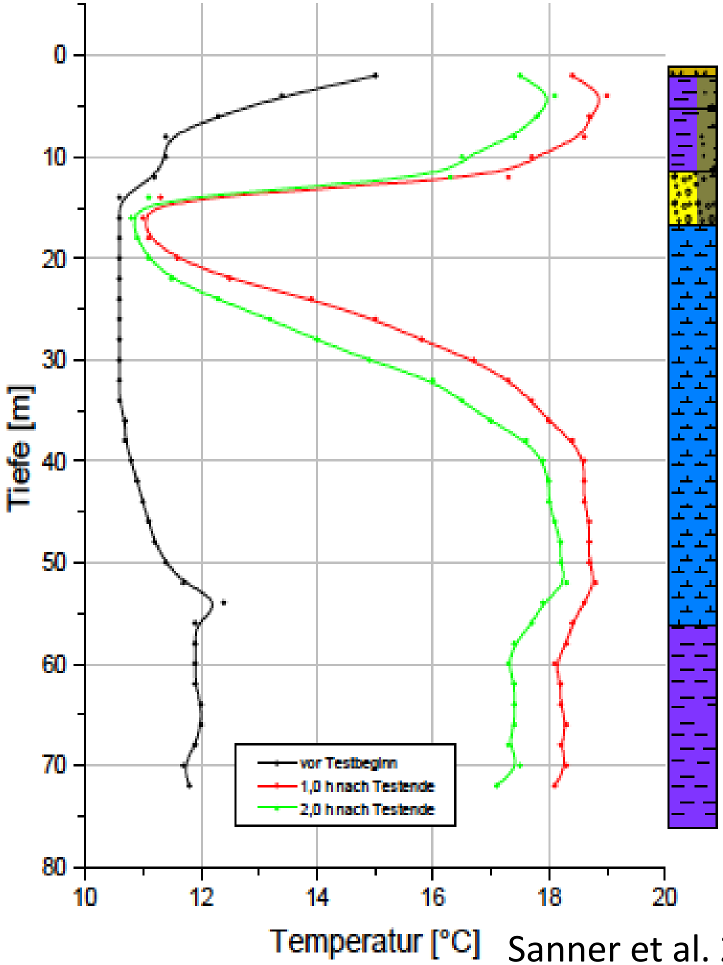
DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)

Renewable energies

Further investigation:
- the thermal conductivity of each individual layers
- Temperature logging (e.g. for aquifer)
- Modelling







Sanner et al. 2008

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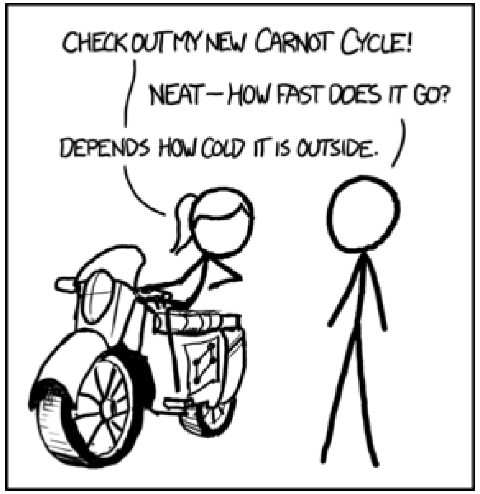
IFP Energies nouvelles

DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)

Principle of heat pump?

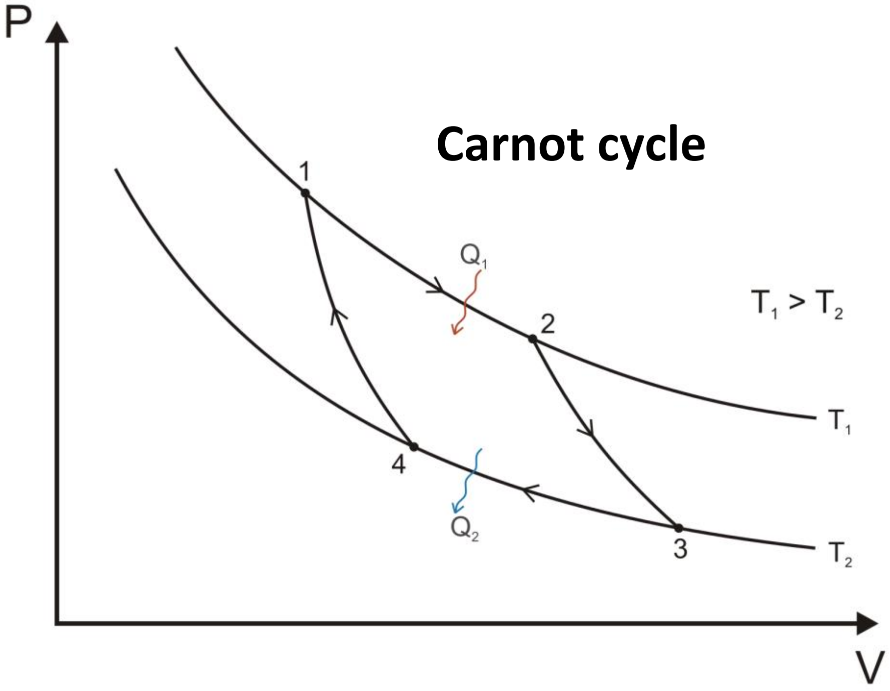
According to the second law of thermodynamics heat cannot spontaneously flow from a colder location to a hotter area; work is required to achieve this.

The operating principle of the second law of thermodynamic is the Carnot Cycle



1. *Reversible isothermal expansion of the gas at the "hot" temperature, TH (isothermal heat addition or absorption).*
2. *Isentropic (reversible adiabatic) expansion of the gas (isentropic work output).*
3. *Reversible isothermal compression of the gas at the "cold" temperature, TC. (isothermal heat rejection).*
4. *Isentropic compression of the gas (isentropic work input).*

Carnot cycle



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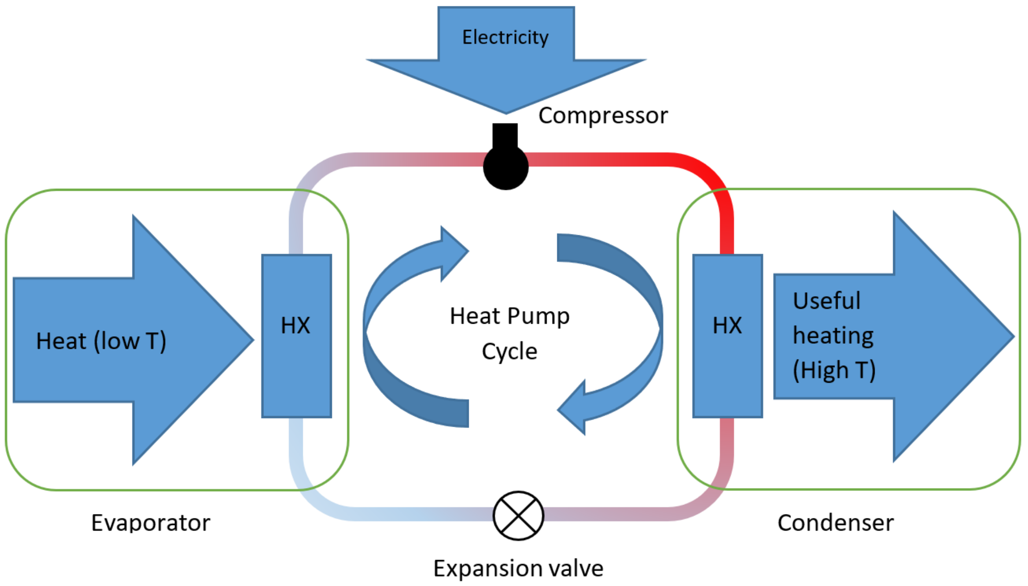
DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)

Renewable energies

What is a heat pump?

A **heat pump** is a device that transfers **heat** energy from a source of **heat** to what is called a **heat** sink. **Heat pumps** move thermal energy in the opposite direction of spontaneous **heat** transfer, by absorbing **heat** from a cold space and releasing it to a warmer one.



Coefficient Of Performance (COP)

The COP of a heat pump is given by the following equation:

COP = Desired Output/Required Input = Heating Effect/Work Input = QH/Wnet,in

The higher the COP the better

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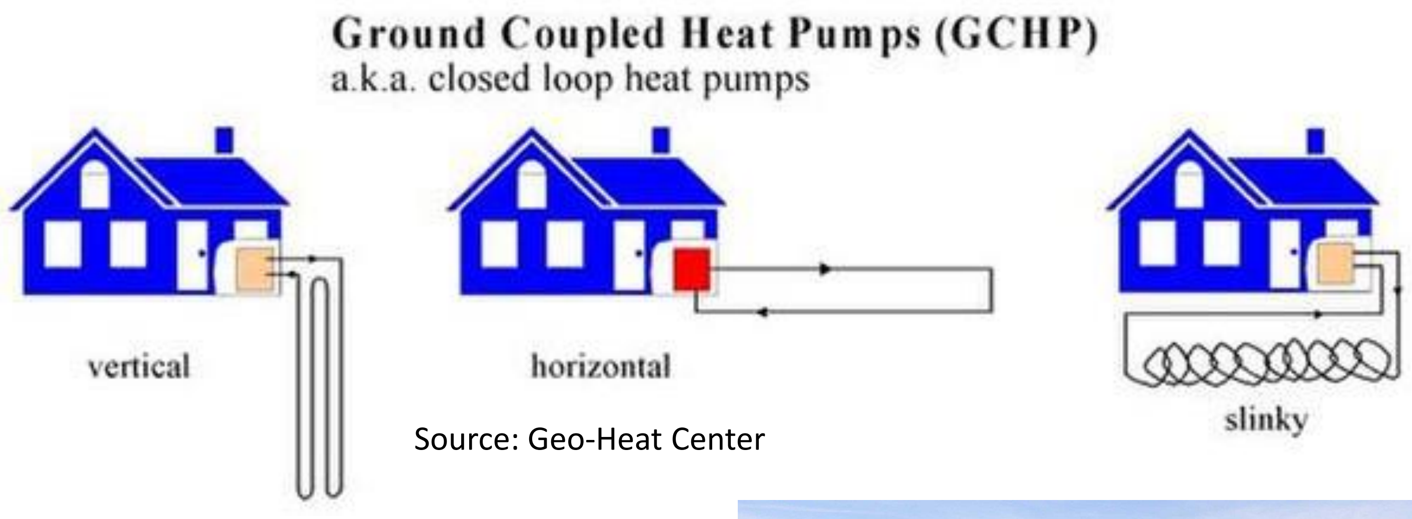
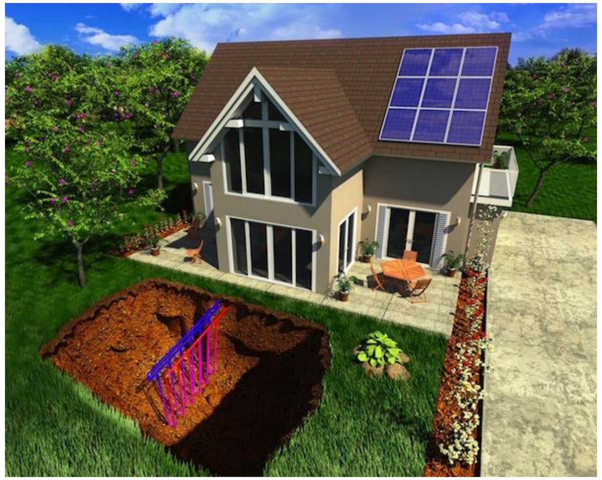
DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)

Renewable energies



Source: Geo-Heat Center



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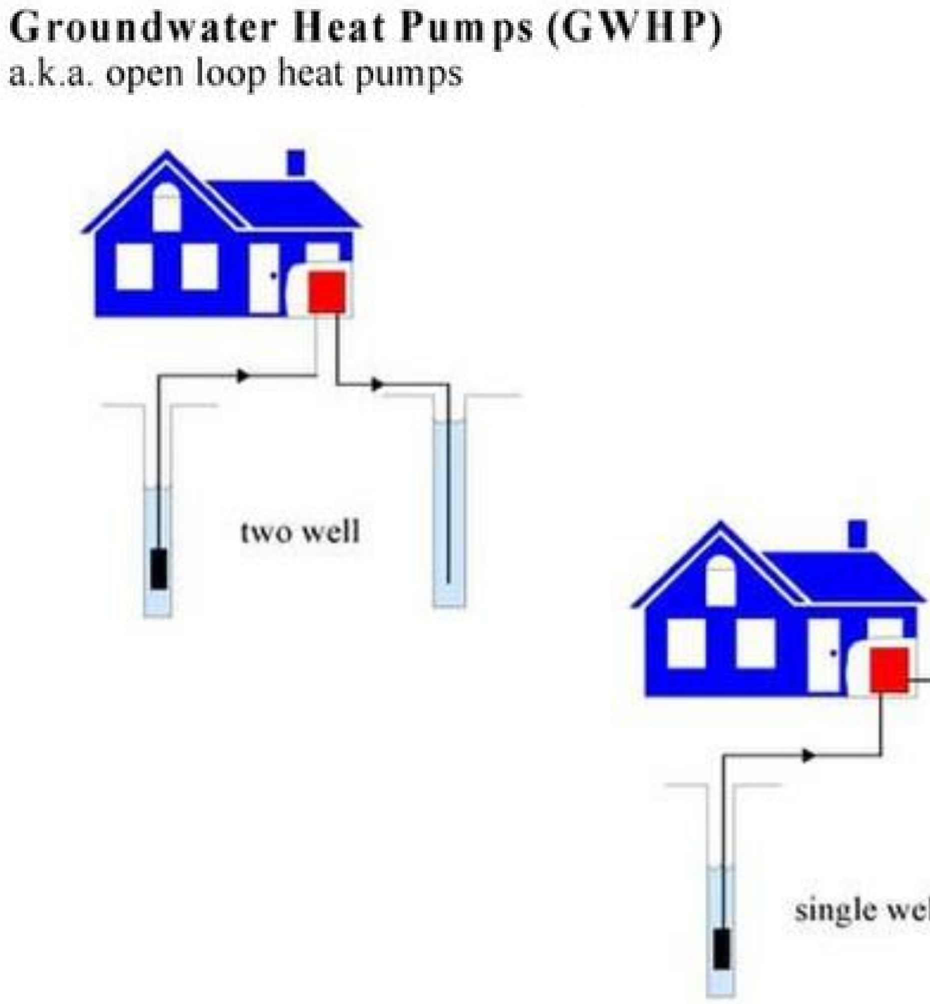
DIFFERENT USE OF GEOTHERMAL ENERGY – GROUND SOURCE HEAT PUMP (GSHP)



Source: Geo-Heat Center

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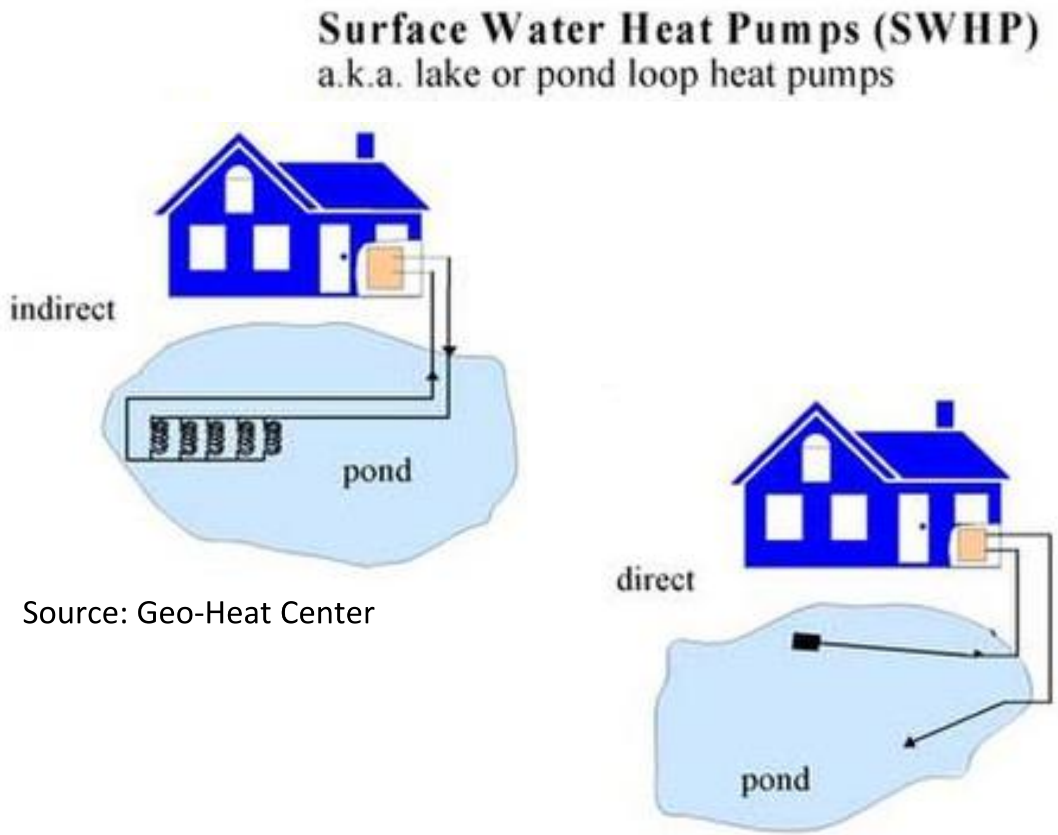
Renewable energies



Source: Geo-Heat Center

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GEOTHERMAL ENERGY

Renewable energies

Introduction to geothermal energy

- **What is geothermal energy?**
  - Geothermal Energy in the Renewable Energy mix, status, and evolution
  - Classification
  - Different use of geothermal energy; Resource <-> Usage
    - Electricity generation & Direct use
- **Thermal processes in the earth system**
  - Geodynamic and surface heat flow
  - Lithospheric thickness and composition
  - Punctual thermal perturbation:
    - Kinematic, magmatism, radiogenic heat production, hydrology
- **Geothermal energy in sedimentary basins**
  - General principles on sedimentary basins
  - Modelling geothermal energy

Geothermal energy potential in India

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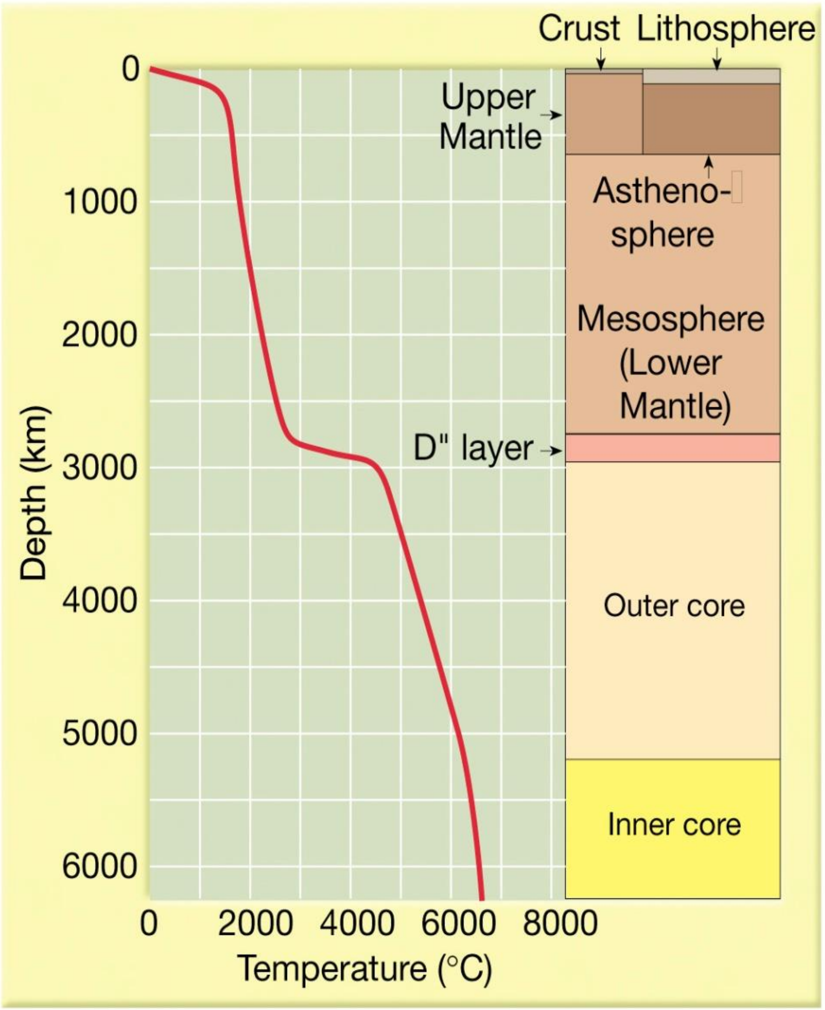
THERMAL PROCESSES IN THE EARTH SYSTEM

Renewable energies



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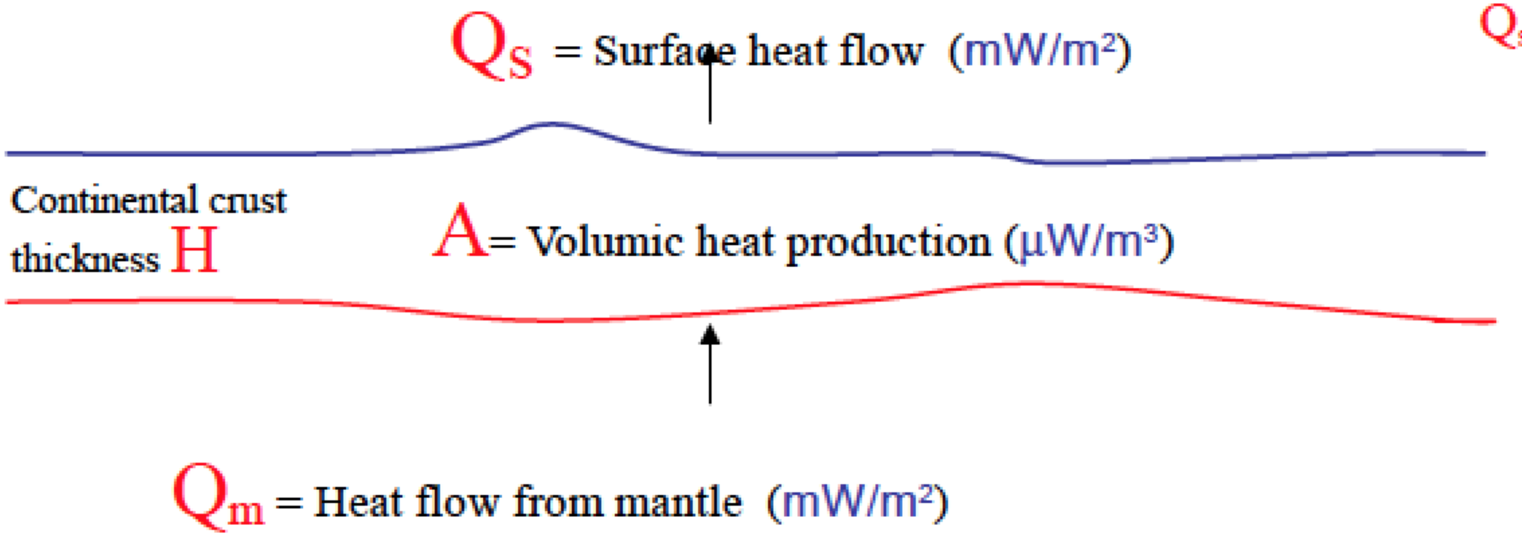
- Surface gradient is average 20-30 ^{o}C/km
- Surface gradient is much higher than in mantle and core
- Gradient varies depending on location

THERMAL PROCESSES IN THE EARTH SYSTEM

$$Q_s = Q_m + A \cdot H$$



Heat production : 20 TW
Measured heat flow Q_S = 44 TW

Average heat production by radioactive disintegration:

in continental crust	~ 1.0 µW/m³
in oceanic crust	~ 0.5 µW/m³
in mantle	~ 0.02 µW/m³

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GEOTHERMAL ENERGY

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Geothermal energy potential in India

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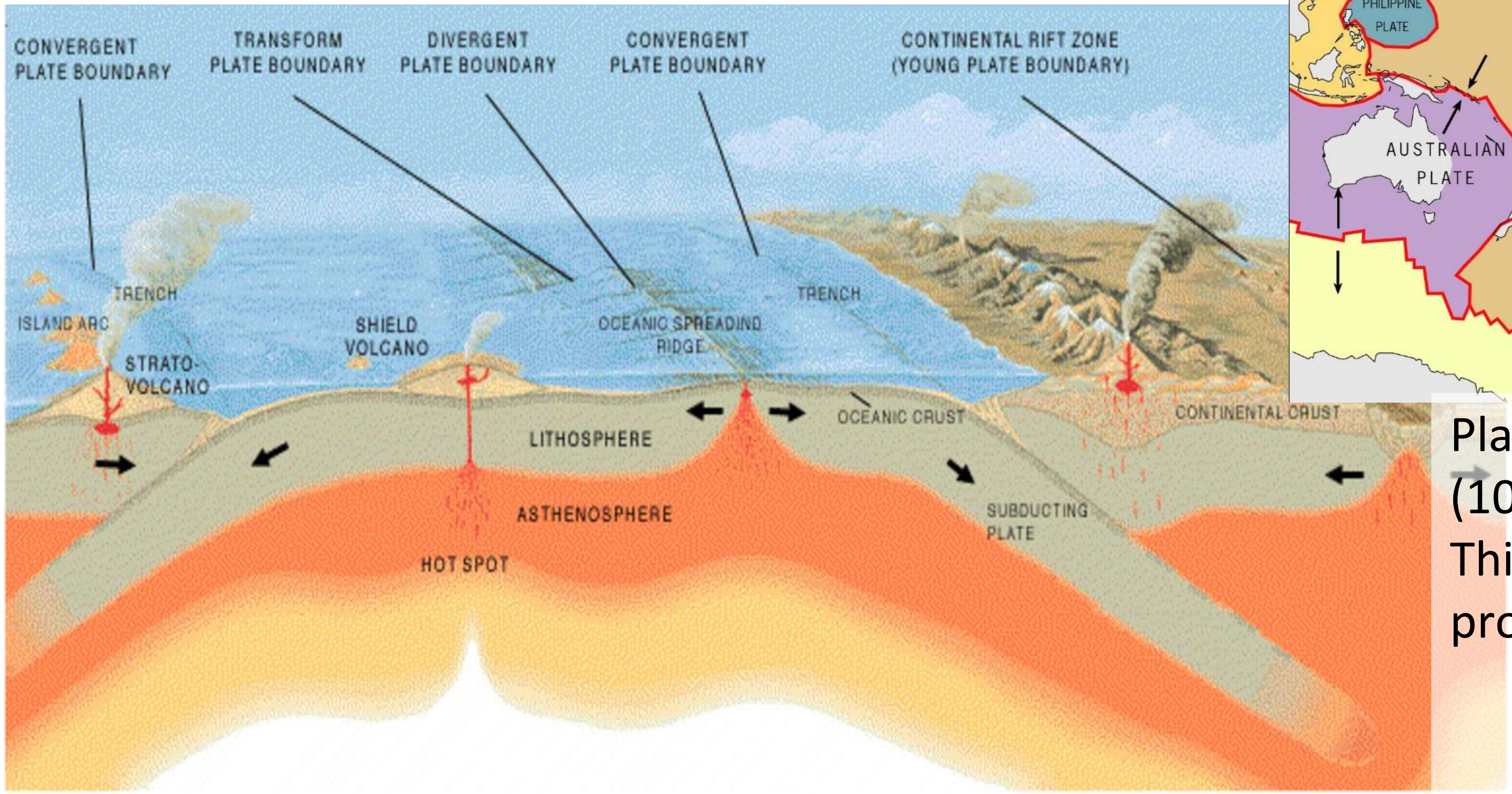
GEODYNAMIC AND SURFACE HEAT FLOW: PLATE TECTONIC

Renewable energies



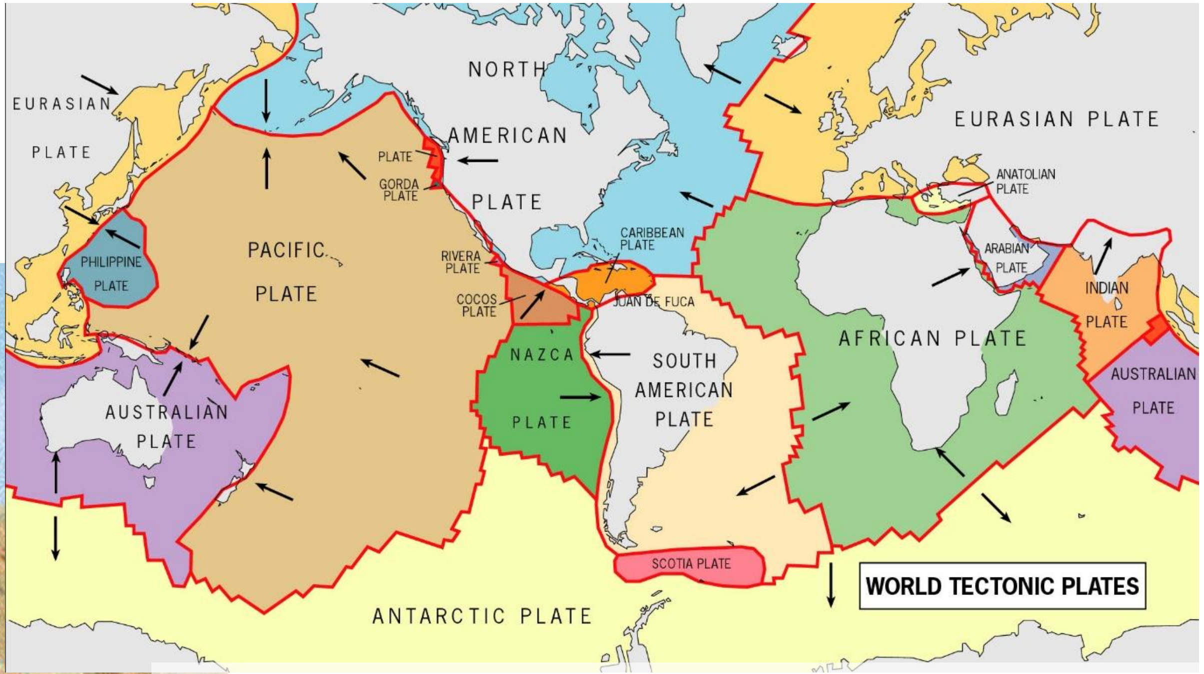


Plate interaction generates enormous forces (1012-1013 N/m)

This will result in several deformation processes at tectonic plate boundaries:

- Earthquakes
- Volcanism
- Orogenesis

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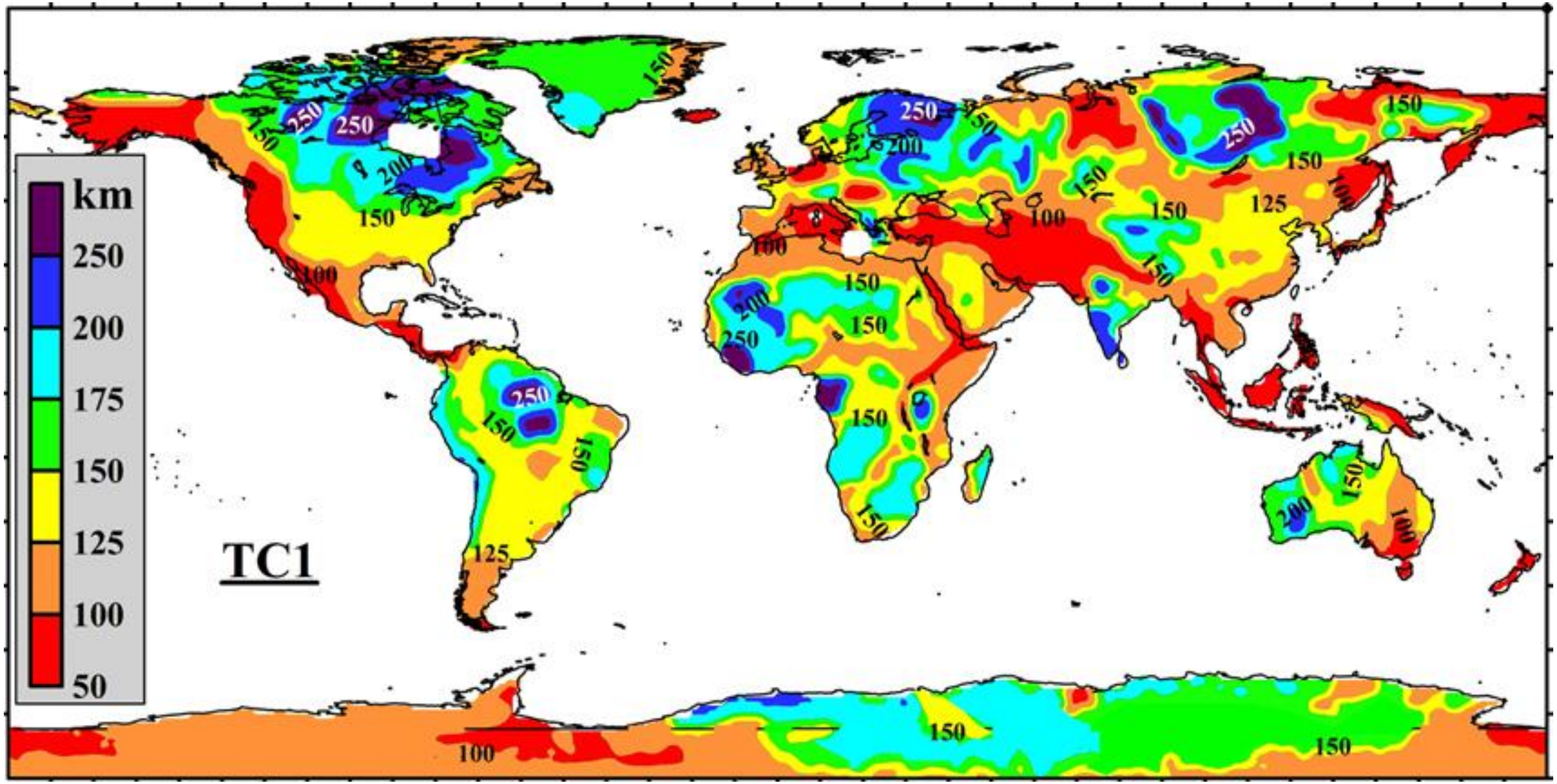
IFP Energies nouvelles

GEODYNAMIC AND SURFACE HEAT FLOW: LITHOSPHERE THICKNESS

Renewable energies



Artemieva, 2008

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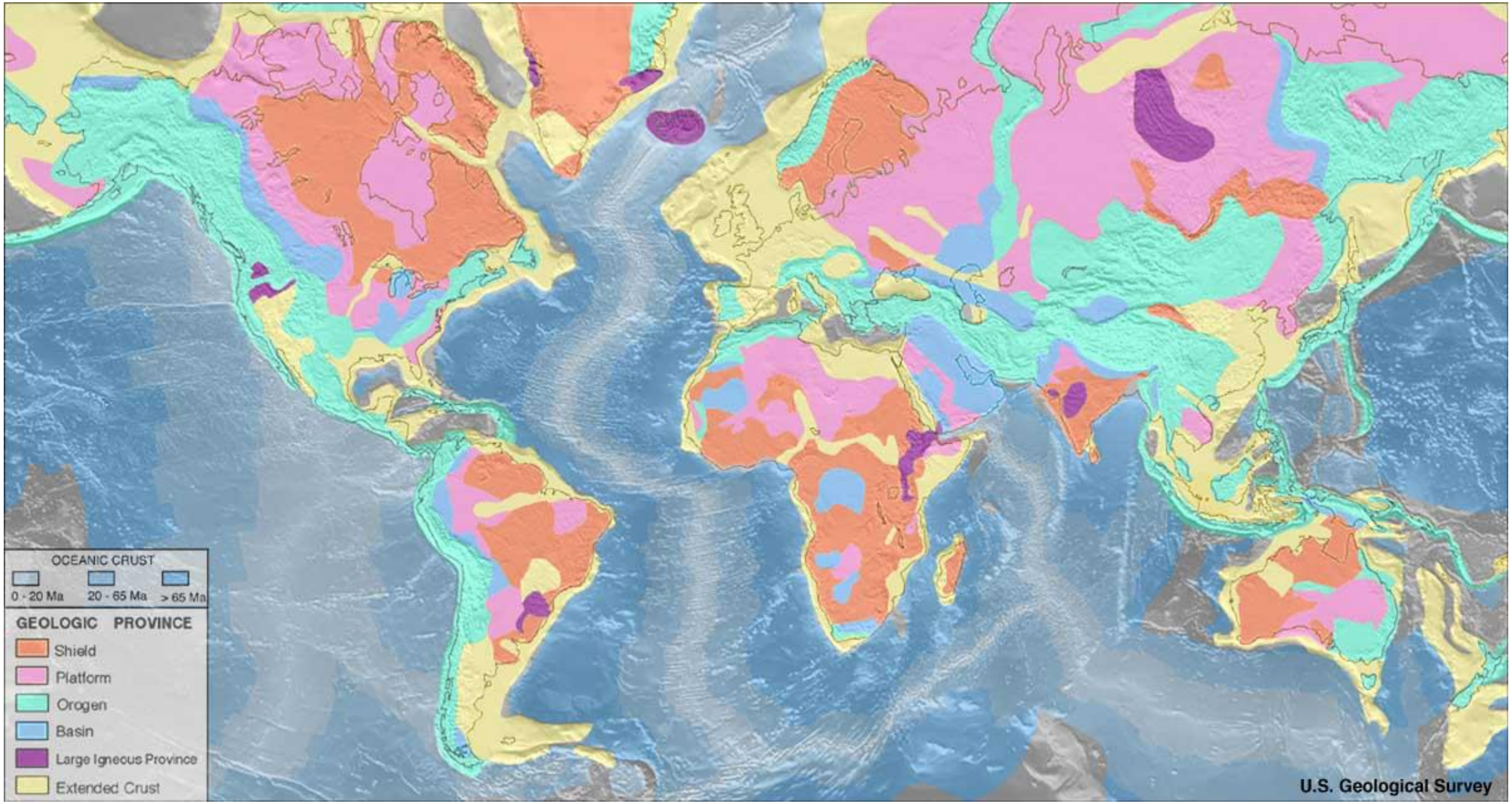
GEODYNAMIC AND SURFACE HEAT FLOW: LITHOSPHERE COMPOSITION

Renewable energies



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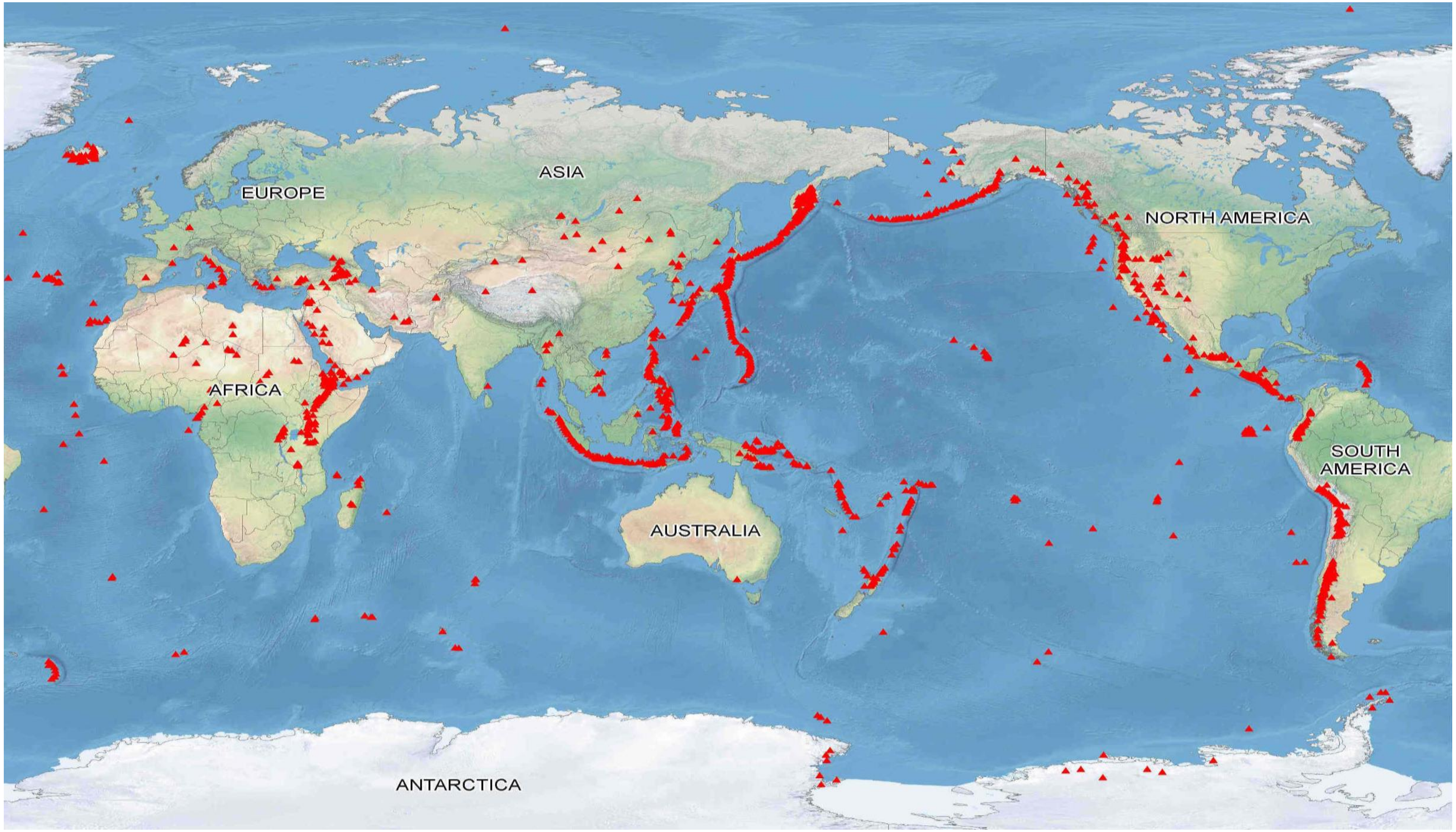
GEODYNAMIC AND SURFACE HEAT FLOW: VOLCANOES

Renewable energies



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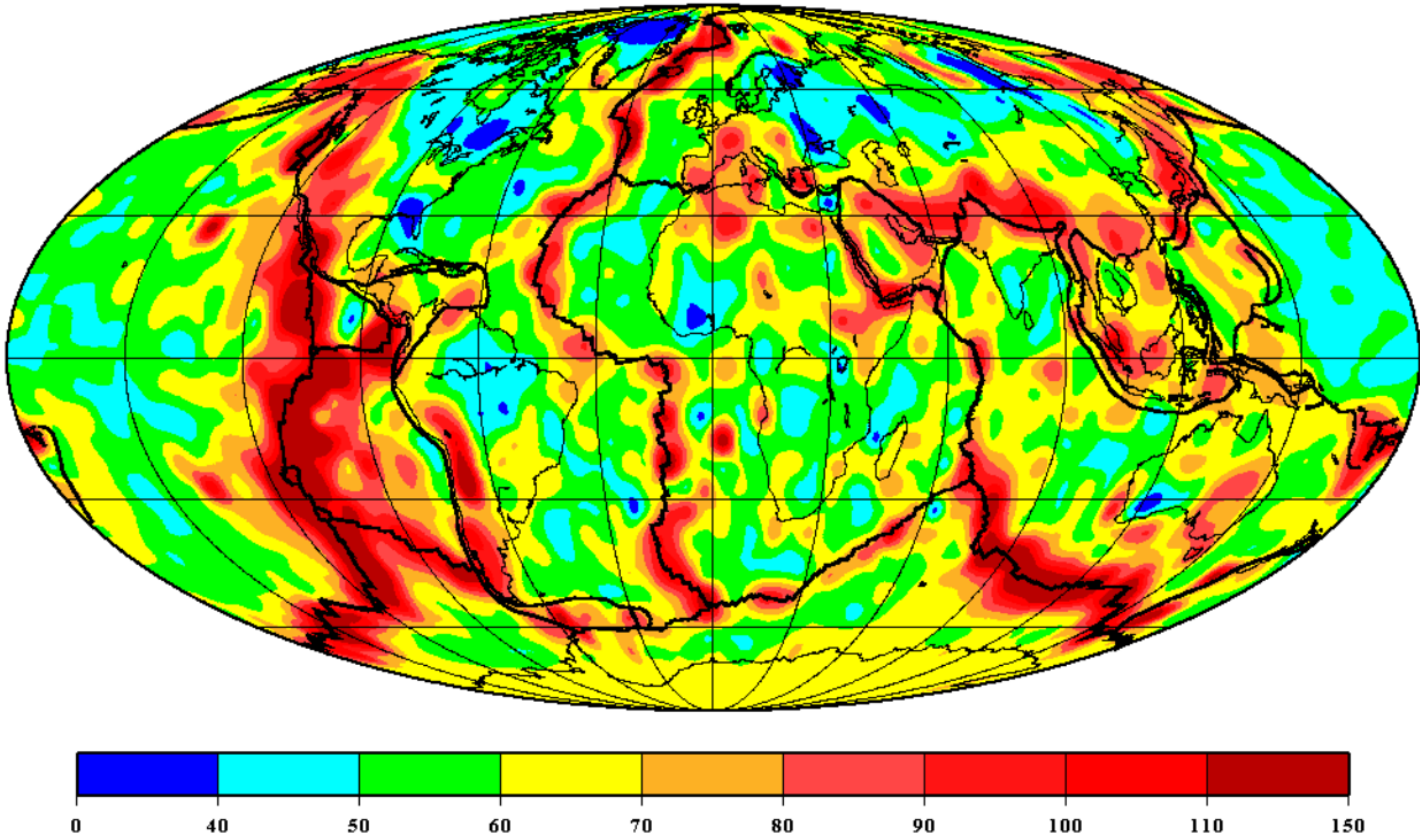
GEODYNAMIC AND SURFACE HEAT FLOW

- The average heat flow
  - for the earth 87 mW/m2,
  - for continents 65 mW/m2,
  - for oceanic crust 101 mW/m2.
- Considering a total global surface area of 5.2 × 1011 m2, the total heat flow or power output is about 4.7 × 1013 W or 47 TW (thermal).
- For comparison, the total installed world power capacity in 2012 was 5.55 TWe (EIA, 2016).



Global representation of heat flow based on observational data, supplemented with estimates derived from digital maps and empirical correlation with age (from Vieira and Hamza, 2018).

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Punctual thermal perturbation:

Kinematic, magmatism, radiogenic heat production, hydrology

tomorrow: Geothermal energy in volcanic settings

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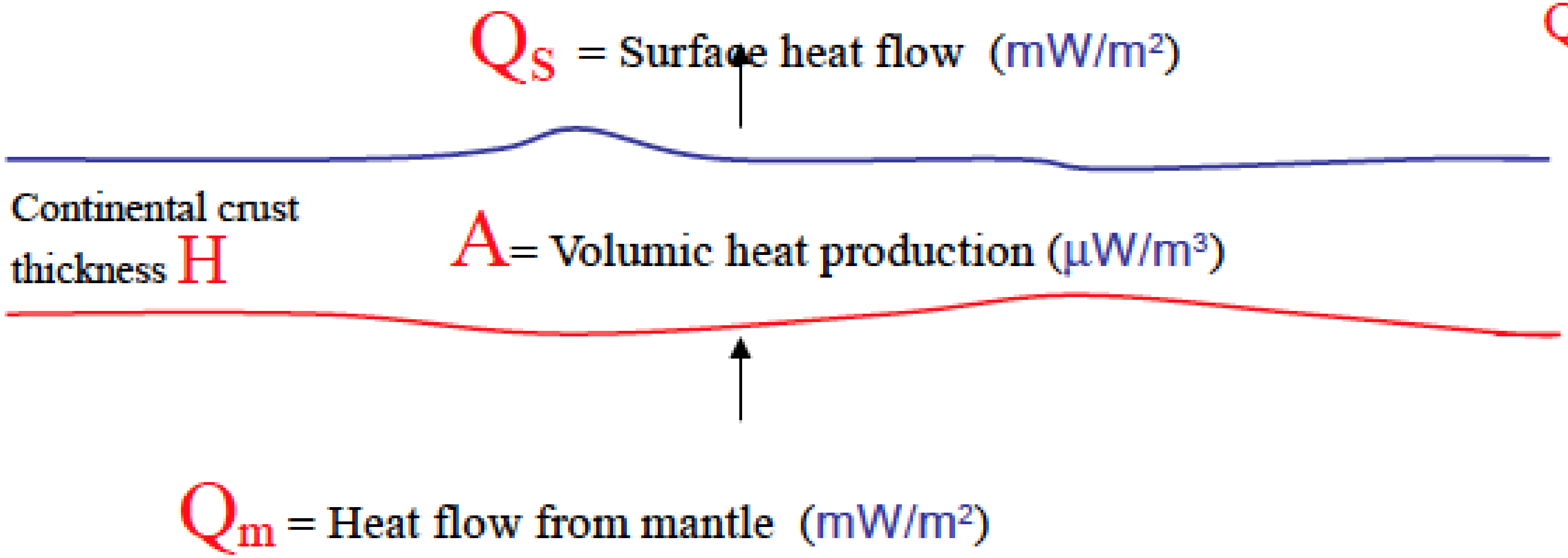
LITHOSPHERIC THICKNESS AND COMPOSITION: HEAT FLOW CHARACTERISATION

$Q_s = Q_m + A \cdot H$



Heat production : 20 TW

Measured heat flow Q_S = 44 TW

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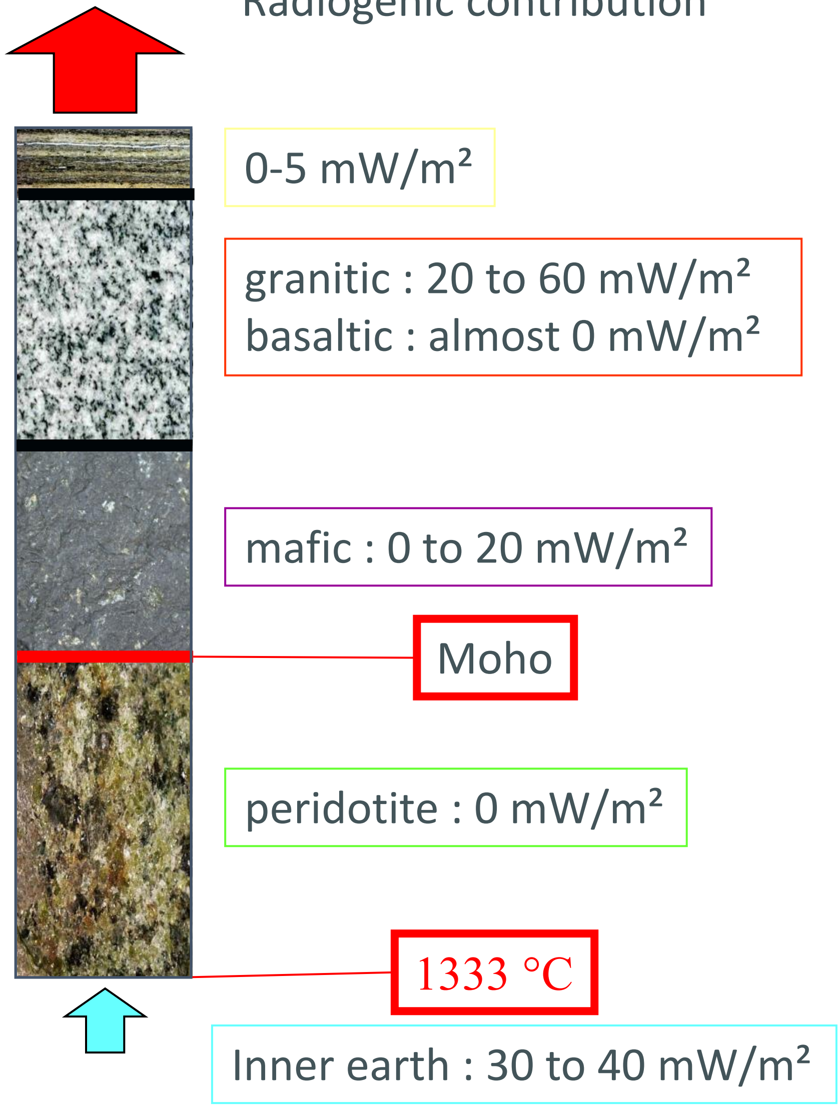
LITHOSPHERIC THICKNESS AND COMPOSITION: HEAT FLOW CONTRIBUTOR

- Sediments
  - radioactive shale or sand
- Crust
  - strong variations with crust nature/age
  - concerned upper crust
- Lithospheric Mantle
  - varies with age and composition of the lithosphere
- Asthenospheric
  - convective mantle
  - main radiogenic source



*In « simple » and steady conditions, the **heat flow** increases toward the surface.*

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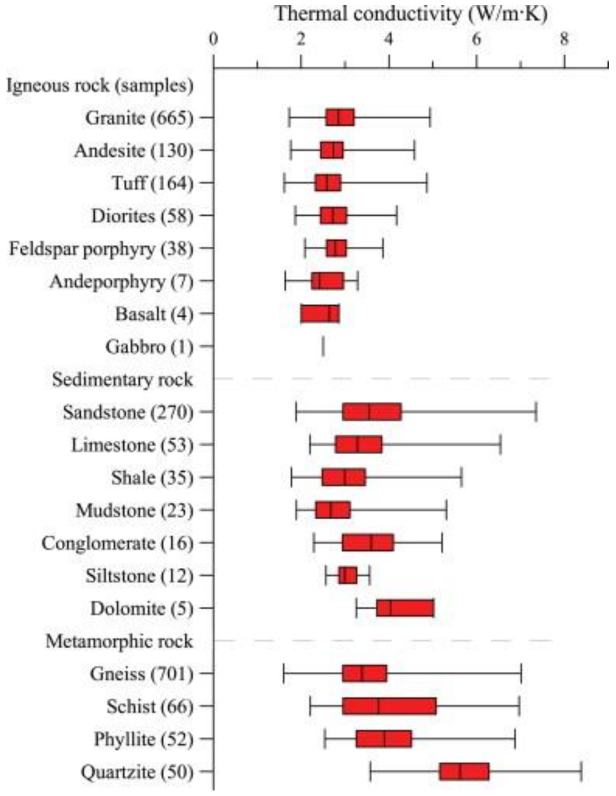
LITHOSPHERIC THICKNESS AND COMPOSITION: HEAT FLOW MEASUREMENT

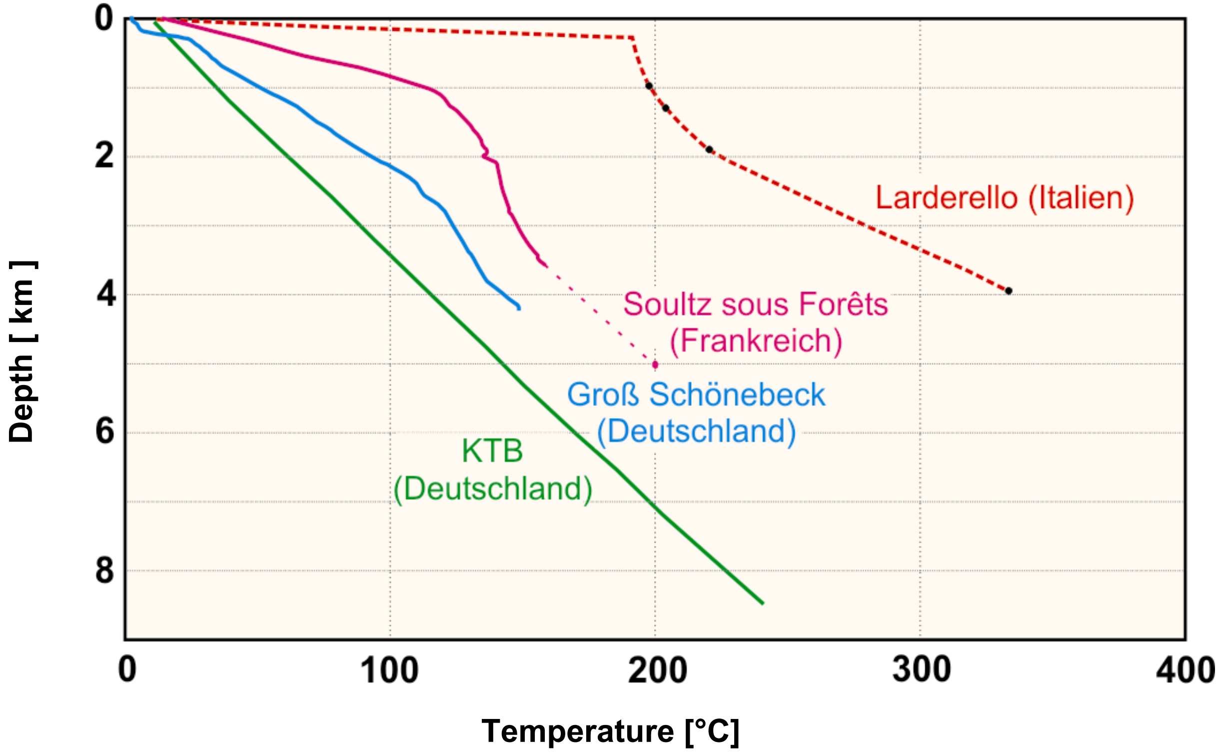
Renewable energies

Heat flow (mW/m²) =
thermal conductivity (W/m/K) × geothermal gradient (° C/km).

Lab measurement



Well measurement



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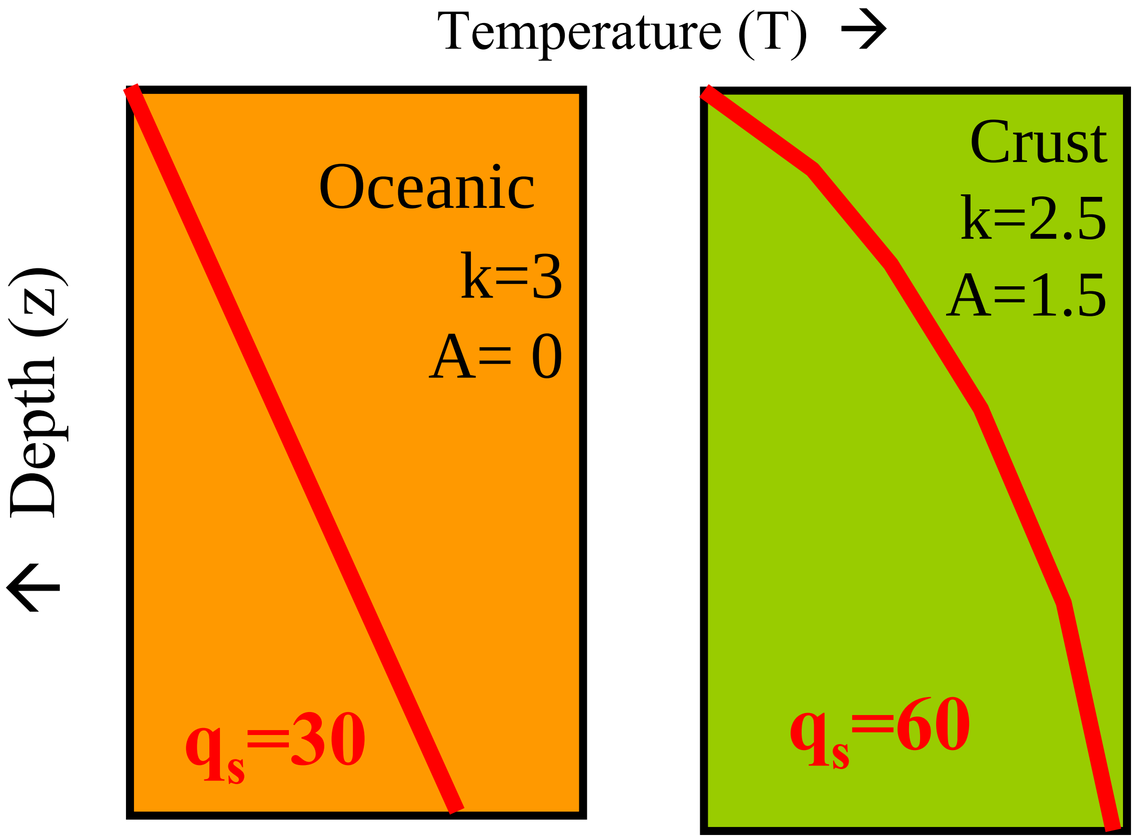
LITHOSPHERIC THICKNESS AND COMPOSITION: RADIOGENIC HEAT PRODUCTION

Radiogenic heat generation A $[\mu W.m^3]$ is a function of relative abundance of radiogenic minerals in rock. It influences the steady state geotherm

$$\frac{dT}{dz}(z) = q_s / k - Az / k$$



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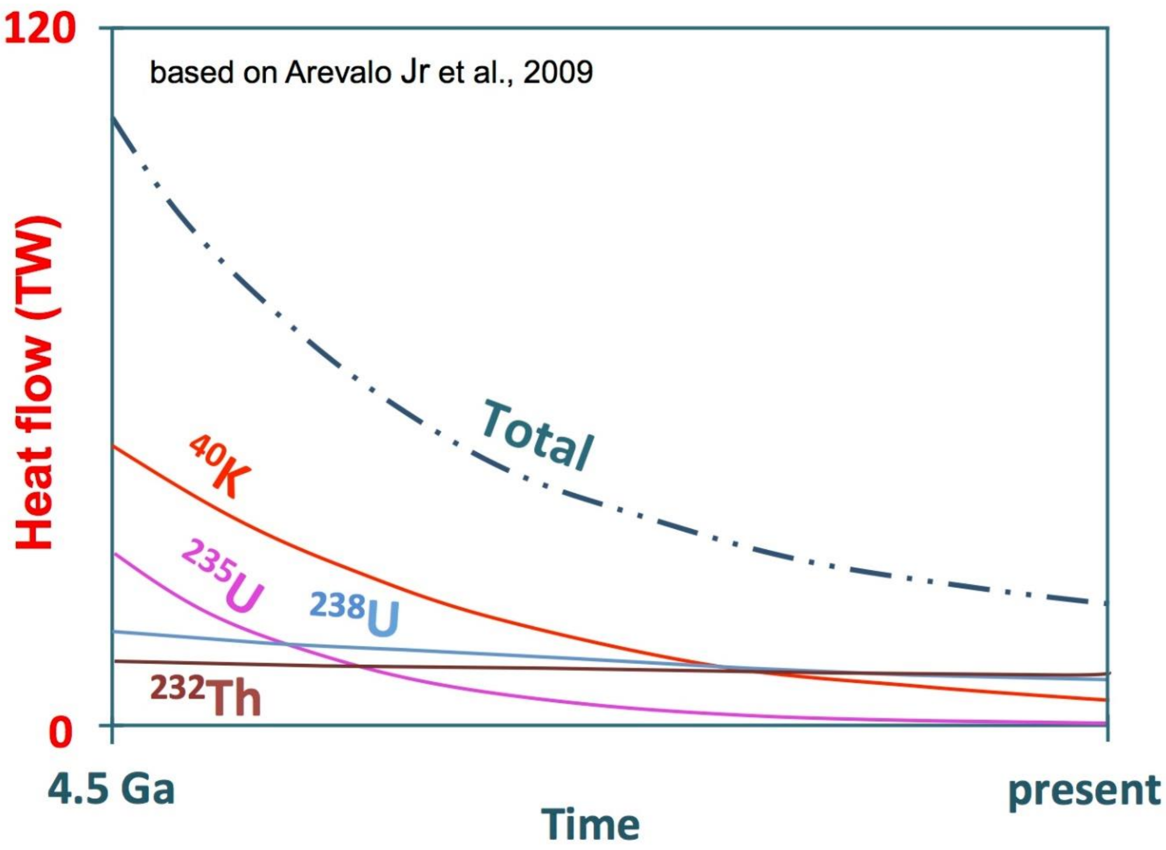
LITHOSPHERIC THICKNESS AND COMPOSITION: RADIOGENIC HEAT PRODUCTION

Renewable energies



$$H = 10^{-5} \rho \,(9.52 \times C_{\mathrm{U}} + 2.56 \times C_{\mathrm{Th}} + 3.48 \times C_{\mathrm{K}}),$$

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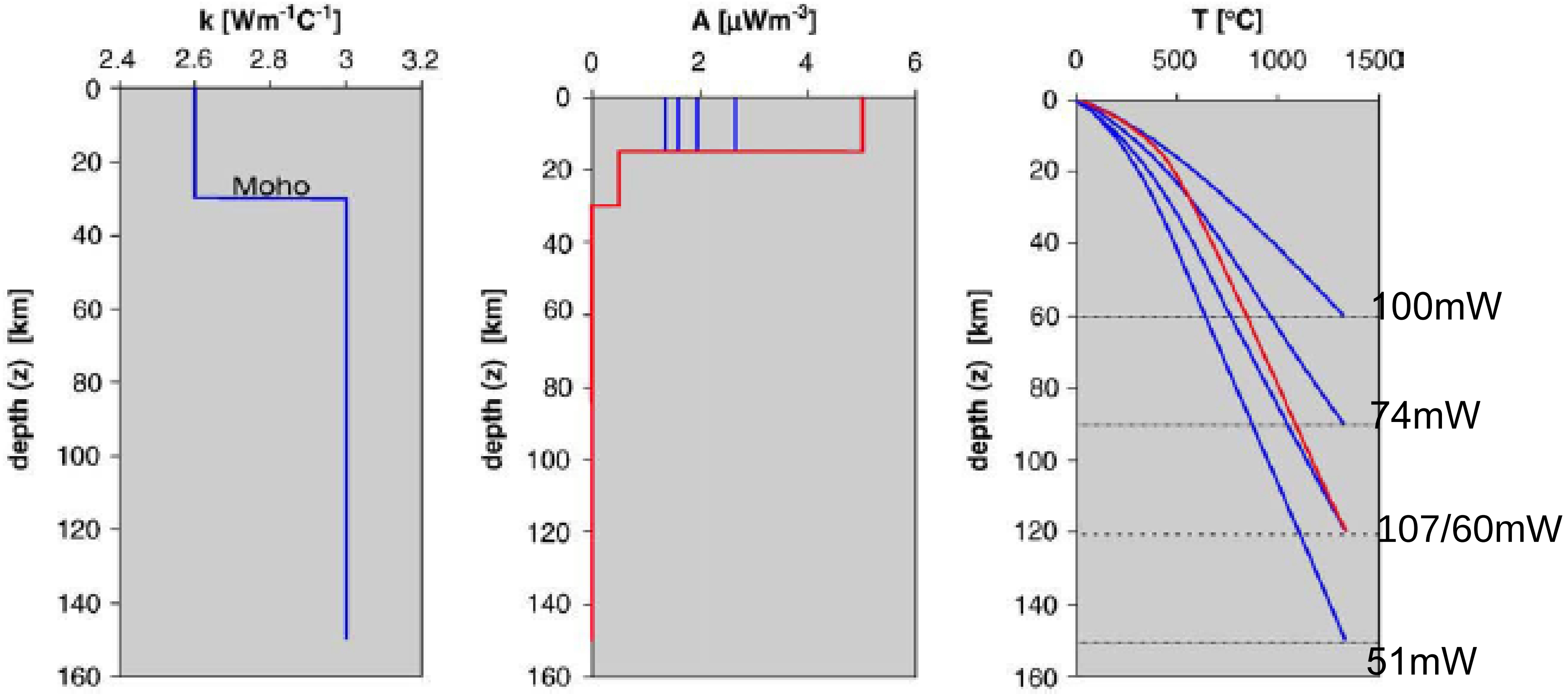
GEODYNAMIC AND SURFACE HEAT FLOW: RADIOGENIC HEAT PRODUCTION IN THE CRUST



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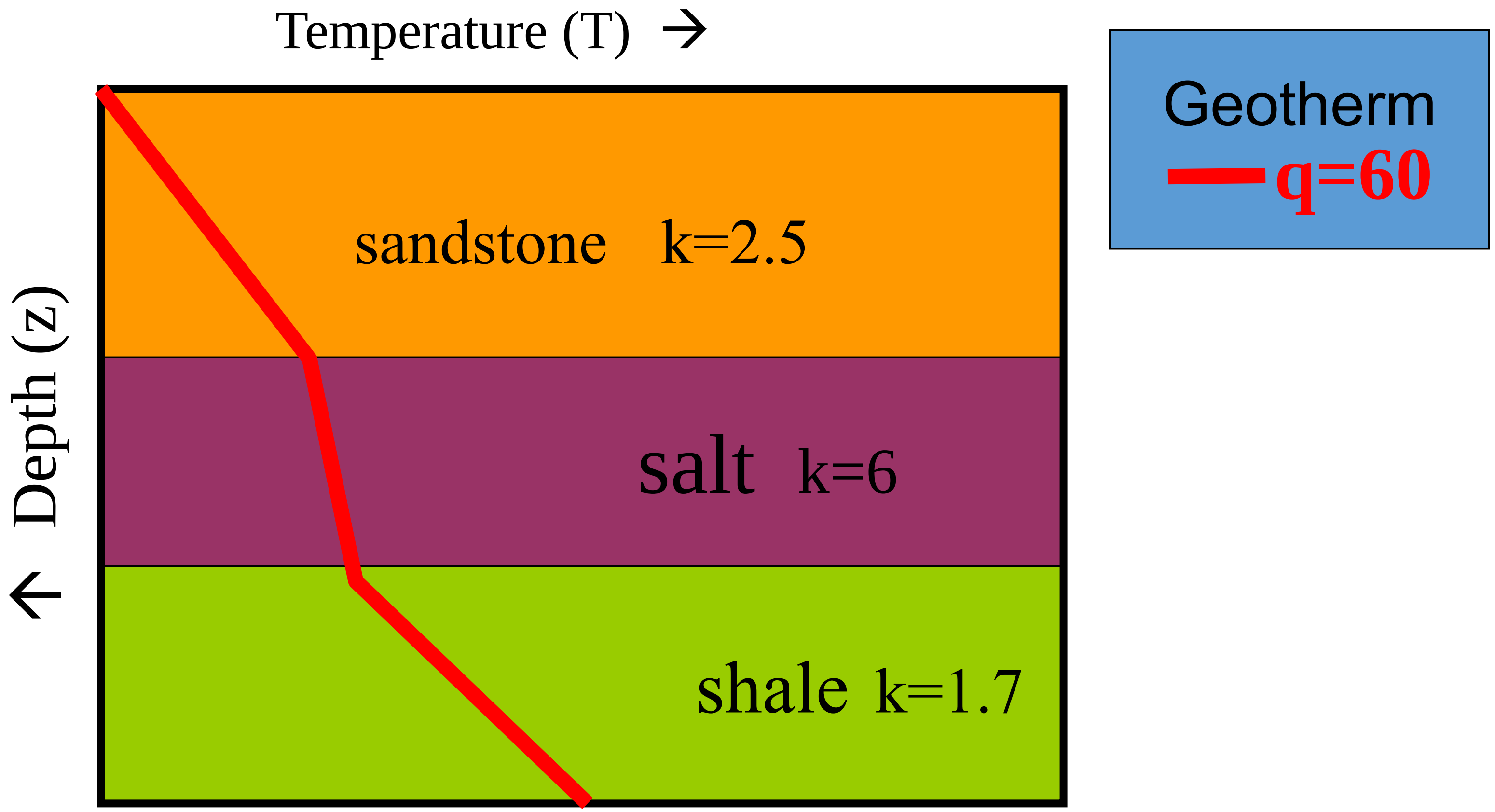
GEODYNAMIC AND SURFACE HEAT FLOW: THERMAL CONDUCTIVITY

Renewable energies

Temperature is reconstructed using a steady state geotherm (conductive approach)

Heat flow q [mW/m^{-2}] is an important boundary condition in basin modeling. It determines the temperature gradient in sediments in conjunction with **rock conductivity k** [W m^{-1} C^{-1}]

$$\frac{dT}{dz} = q / k$$



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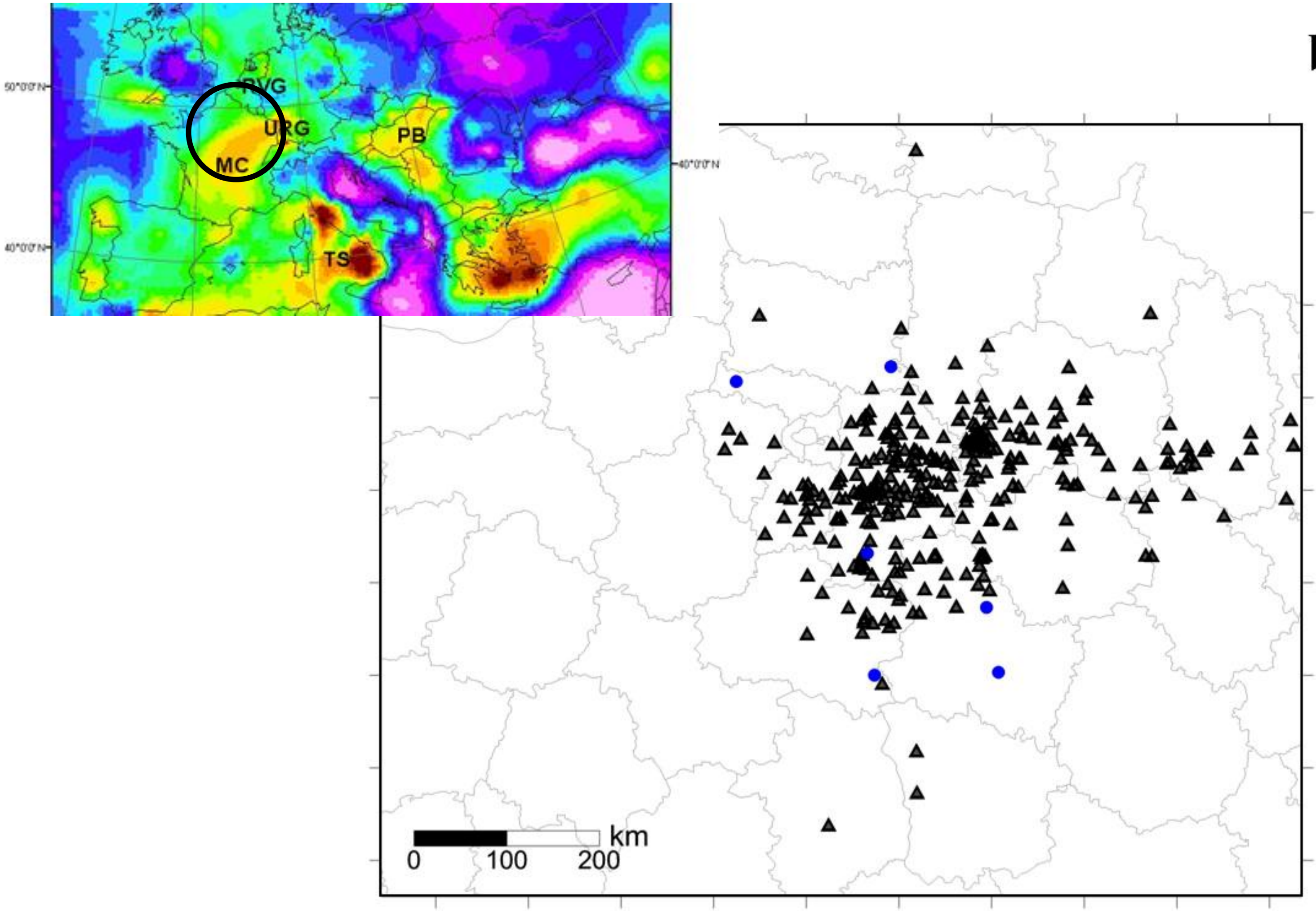
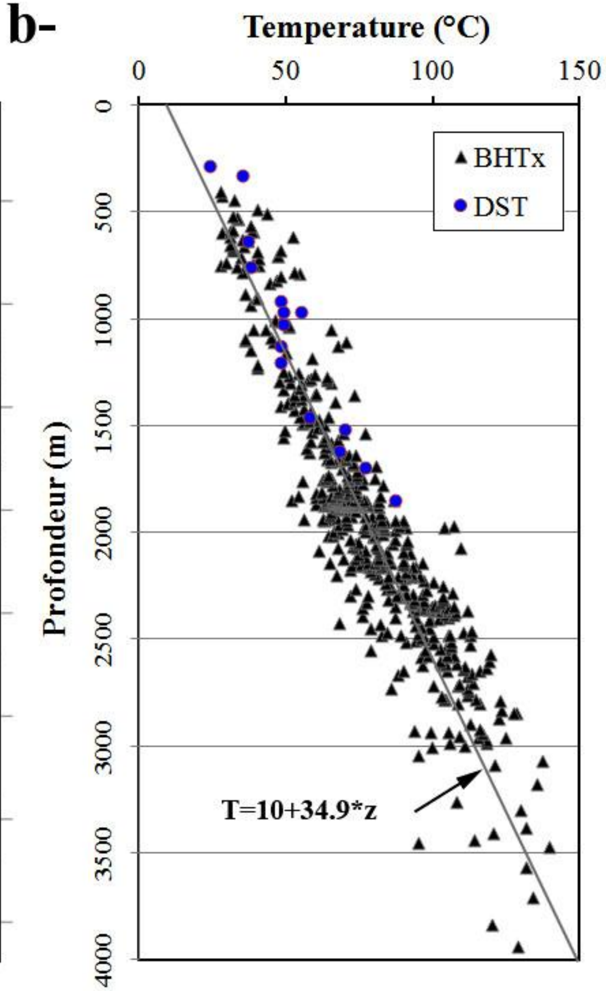
Energies nouvelles

GEODYNAMIC AND SURFACE HEAT FLOW: THERMAL CONDUCTIVITY (E.G. PARIS BASIN)

Renewable energies





Bonté et al., 2013

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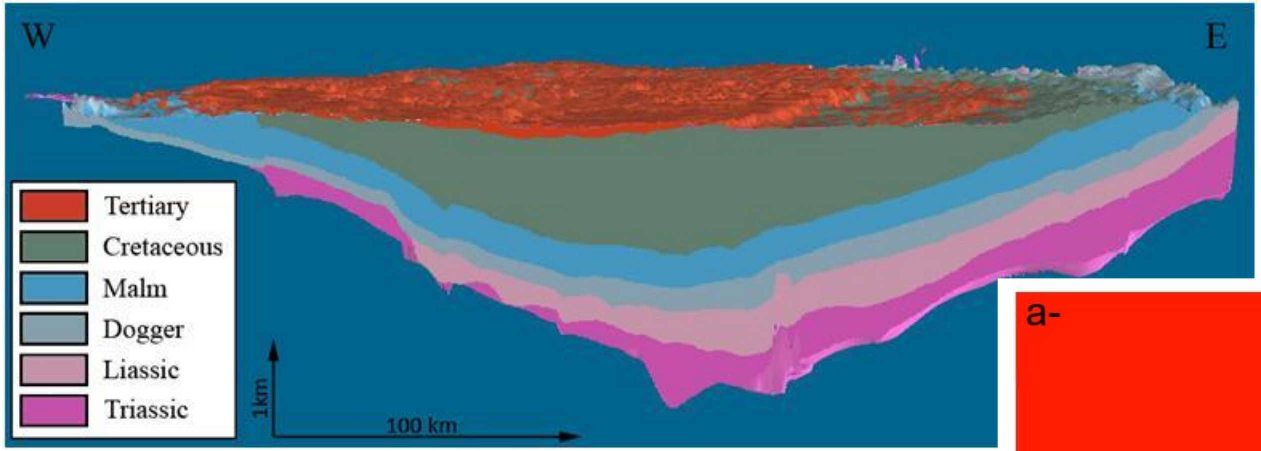
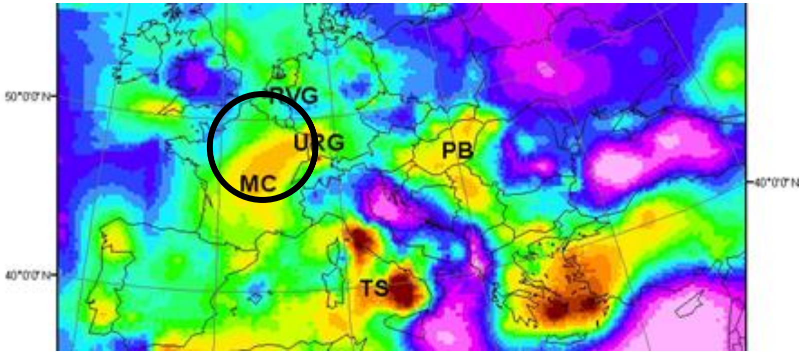
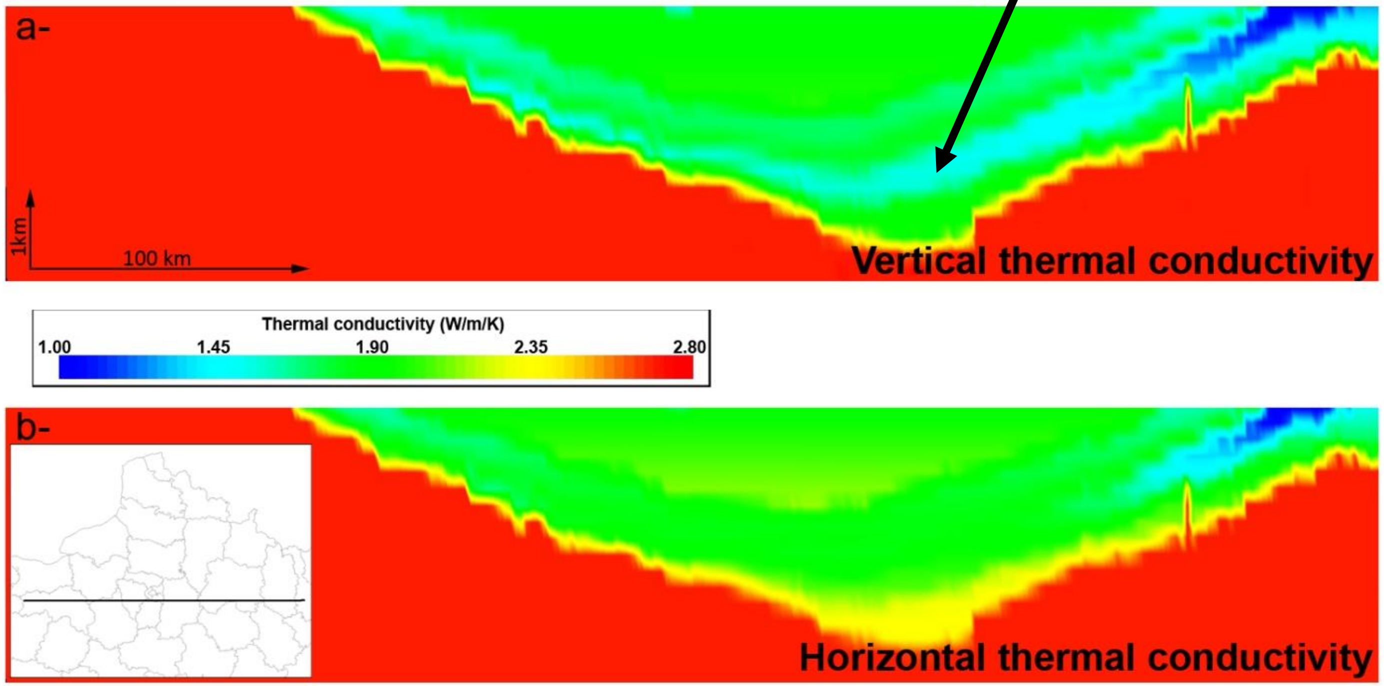
Renewable energies





Low conductivity of the Lias “Schiste Carton”



Bonté et al., 2013

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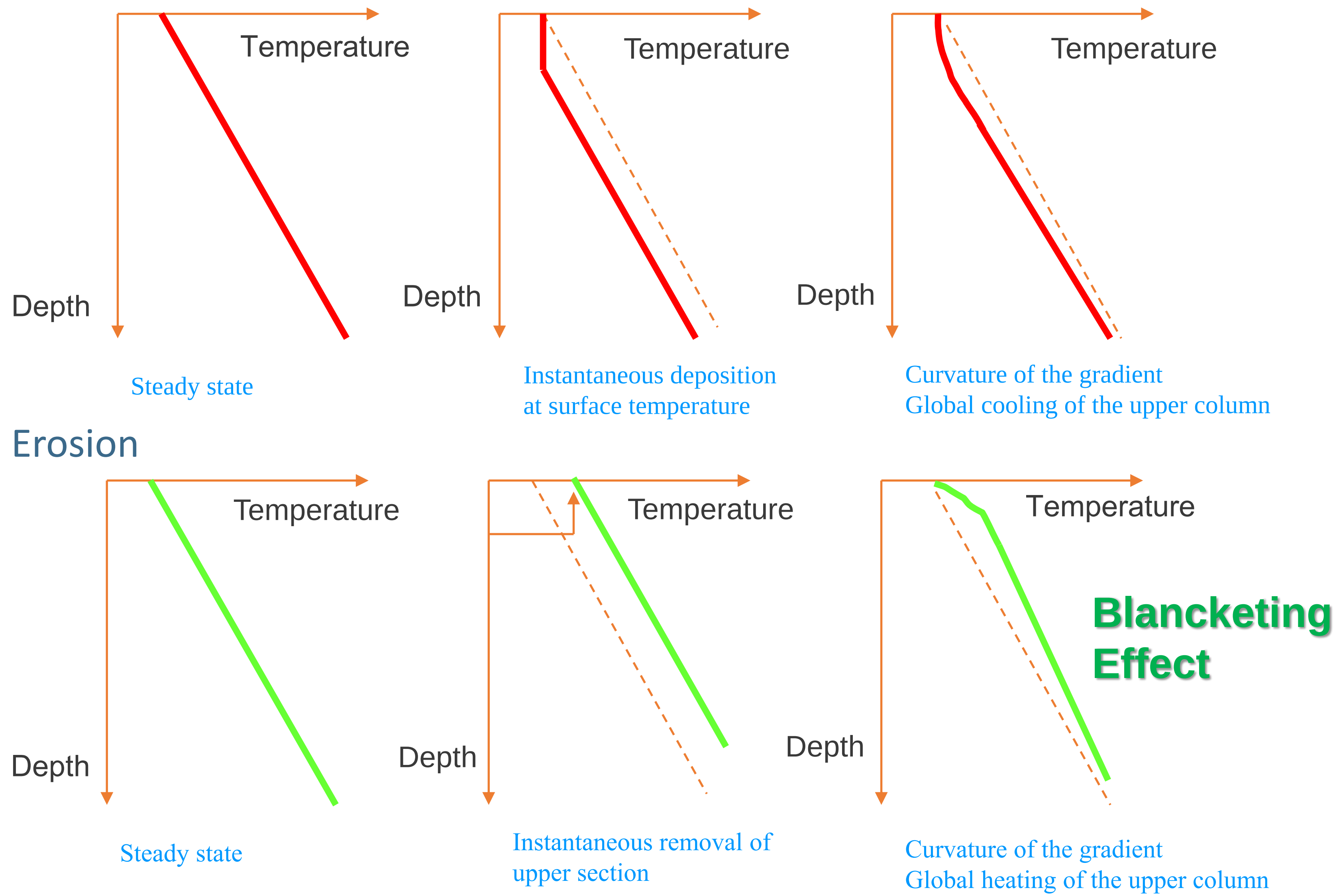
THERMAL STRUCTURE OF THE LITHOSPHERE: TRANSIENT THERMAL REGIME

Fast sedimentation in short time (blanketing effect)



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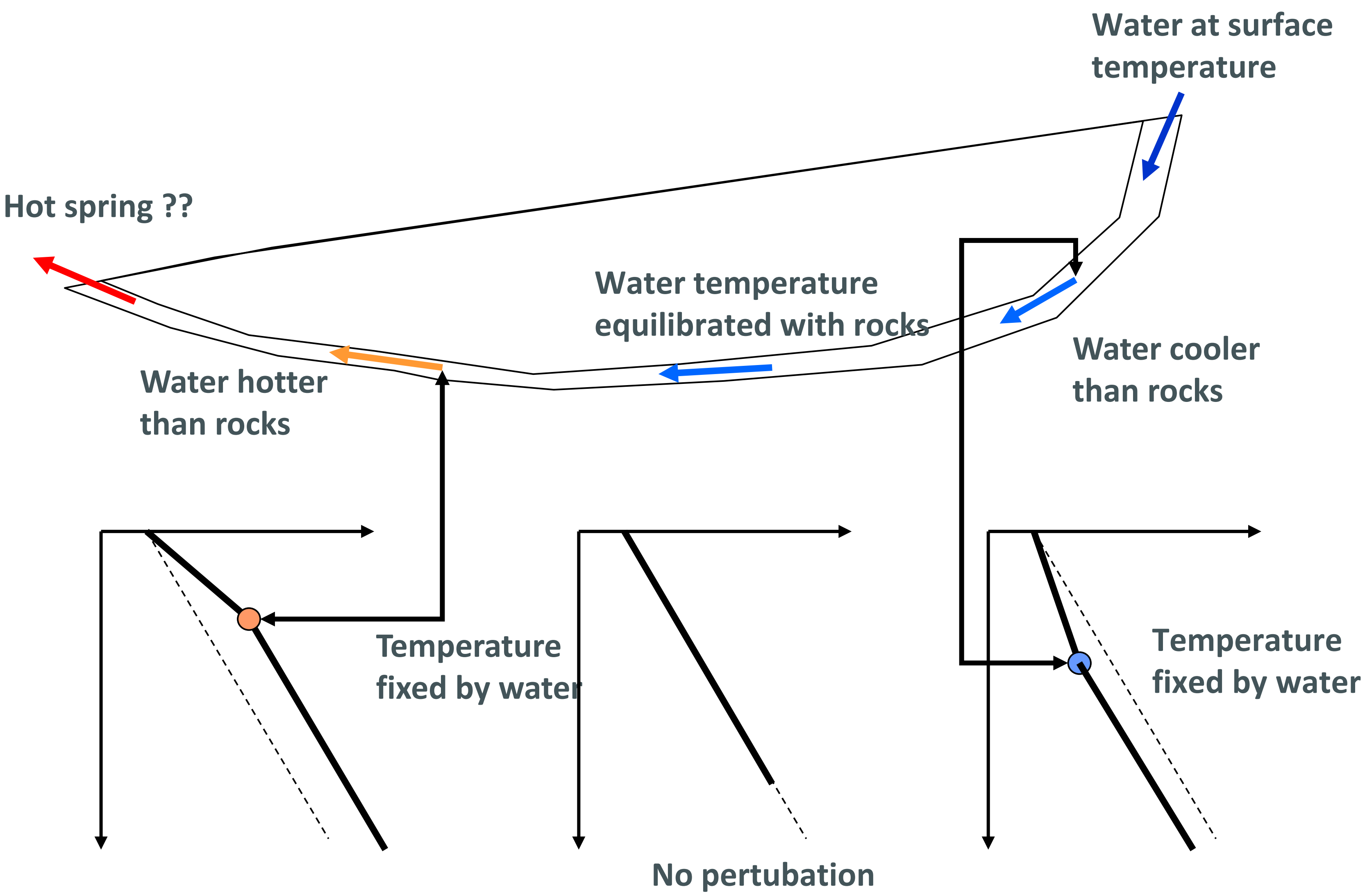
THERMAL STRUCTURE OF THE LITHOSPHERE: EFFECTS OF FLUID CIRCULATION

Renewable energies



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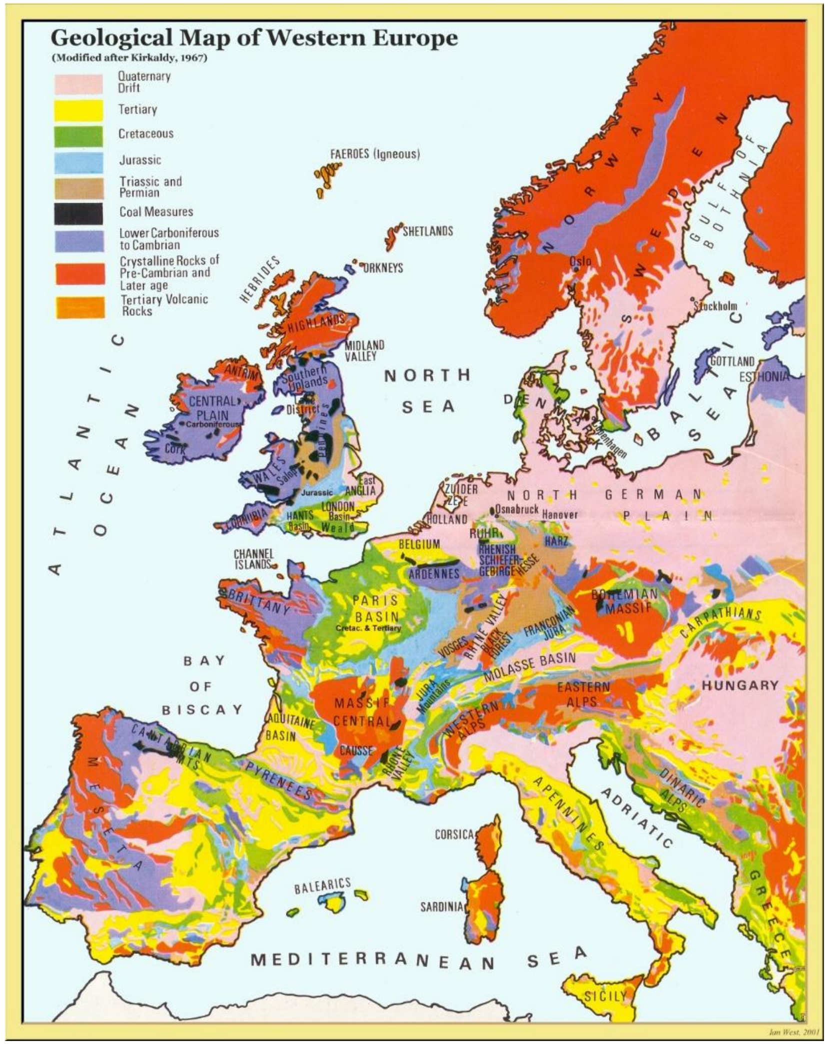
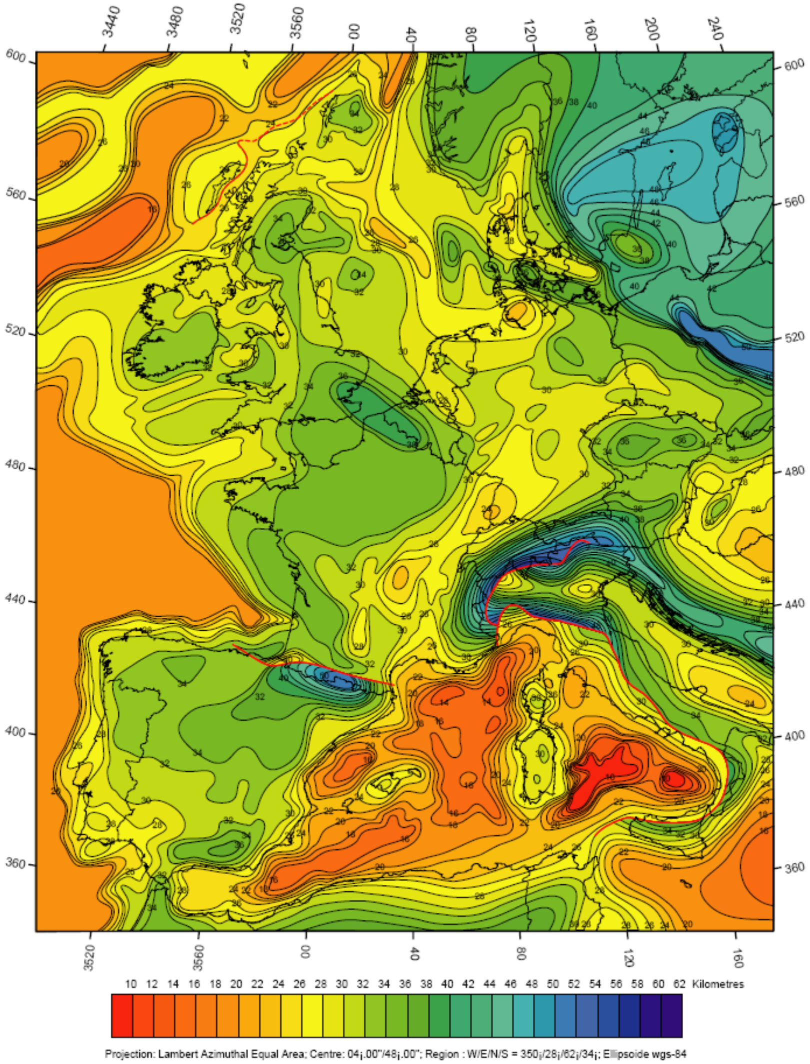
LITHOSPHERIC THICKNESS AND COMPOSITION: CASE OF EUROPE

Renewable energies





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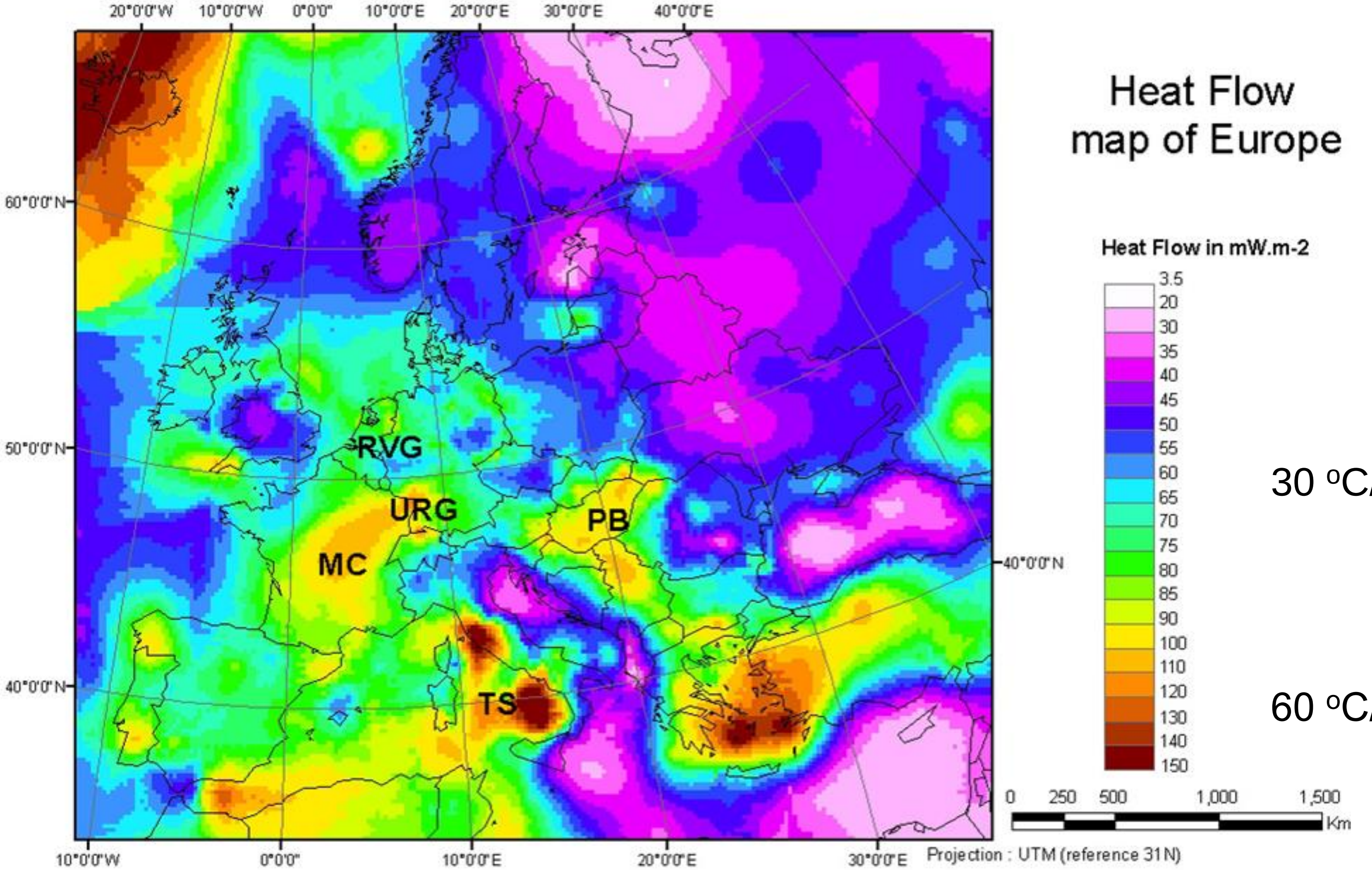
LITHOSPHERIC THICKNESS AND COMPOSITION: CASE OF EUROPE

Renewable energies



30 °C/km

60 °C/km

Cloetingh et al. (2010)

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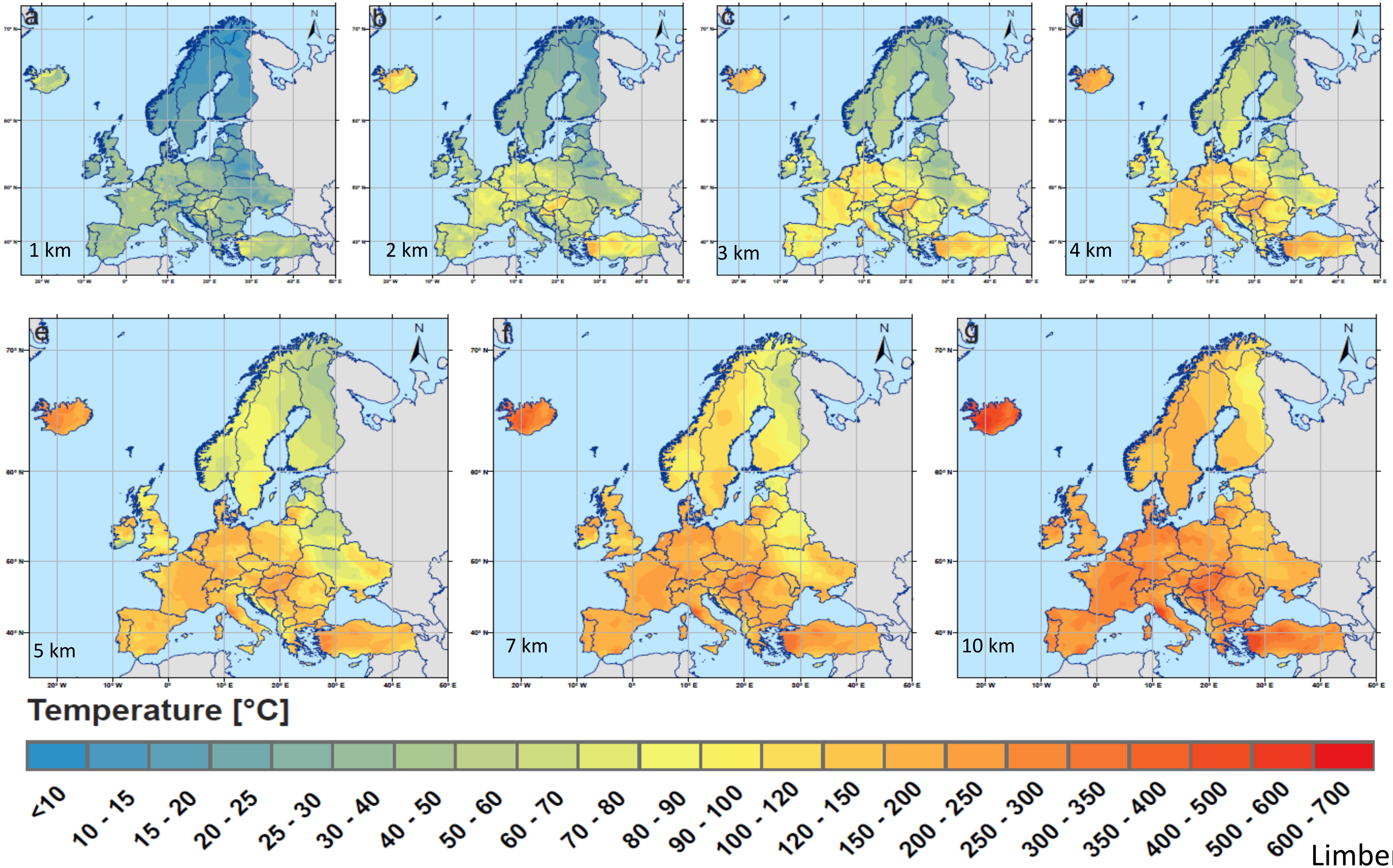
LITHOSPHERIC THICKNESS AND COMPOSITION: CASE OF EUROPE

Renewable energies



Limberger et al., 2014

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GEOTHERMAL ENERGY

Renewable energies

Introduction to geothermal energy

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  - Different use of geothermal energy; Resource <-> Usage
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    - Kinematic, magmatism, radiogenic heat production, hydrology

tomorrow: Geothermal energy in volcanic settings

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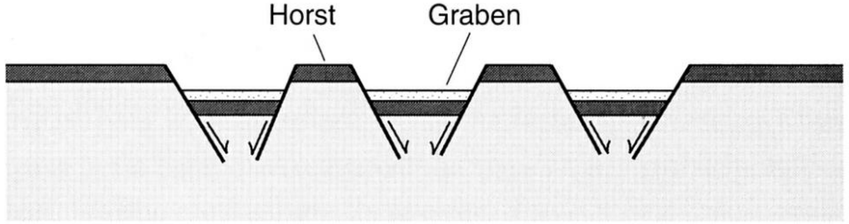
PUNCTUAL THERMAL PERTURBATION: KINEMATIC

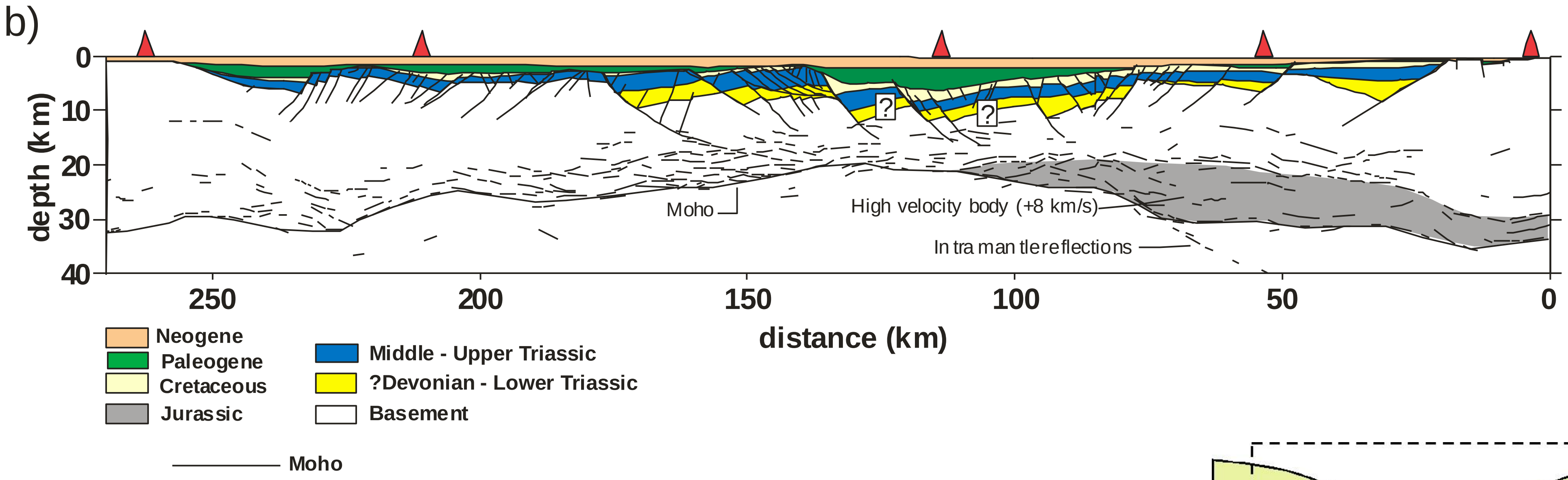
Renewable energies

FAULT SYSTEMS

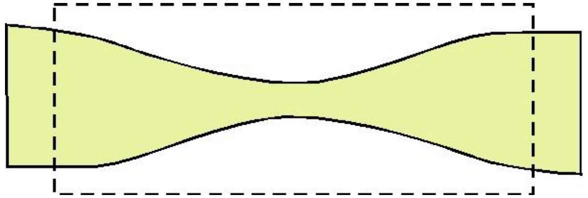
Assemblage of planar faults

Assemblage of listric faults





Note: these faults accommodate a pure shear deformation (also called non rotational



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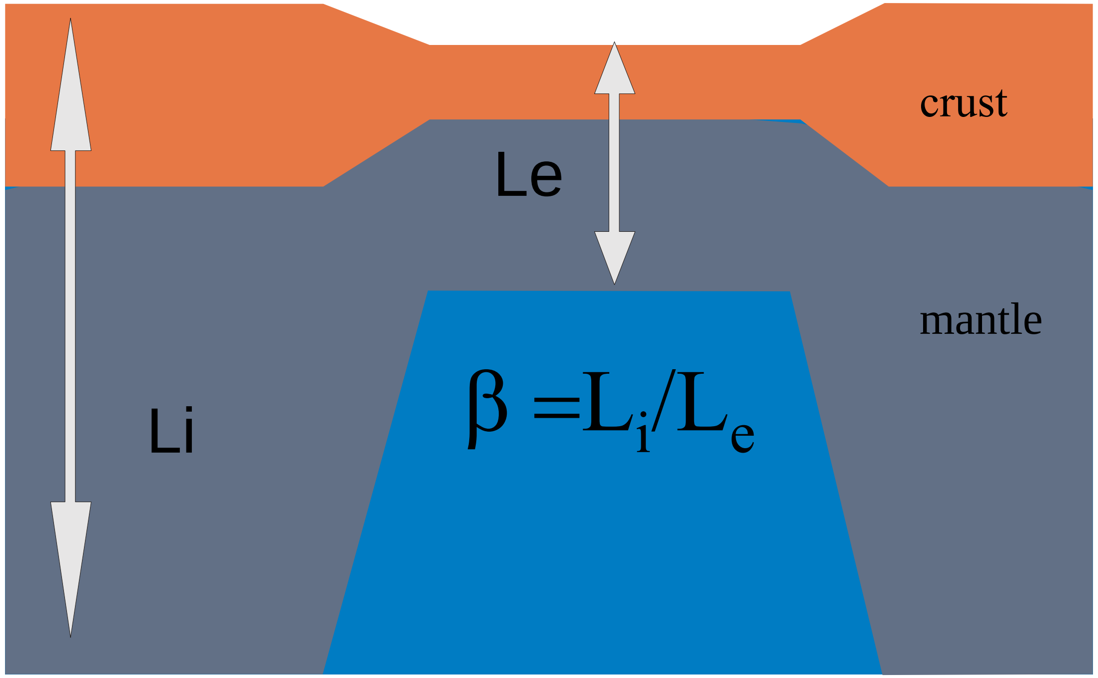
PUNCTUAL THERMAL PERTURBATION: KINEMATIC

Renewable energies

Tectonic Numerical kinematic models predict temperature effects of lithosphere deformation.
The 1D McKenzie Model (1978) is a classic for continental lithosphere extension (rifting)



McKenzie model: lithosphere is instantaneously thinned by factor β

McKenzie heat flow No Good:

- No crustal heat production
- No sediment infill

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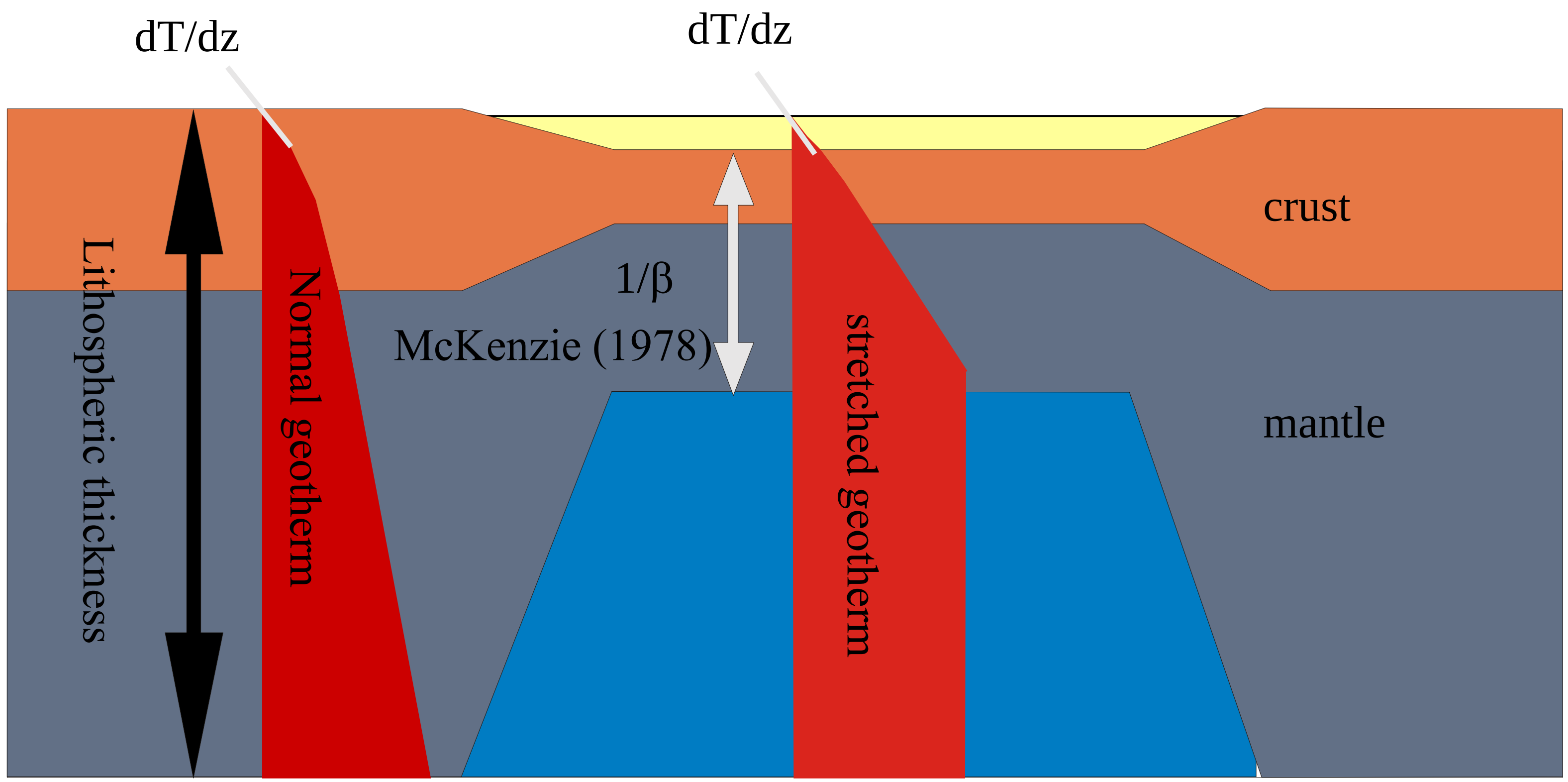
PUNCTUAL THERMAL PERTURBATION: KINEMATIC

Renewable energies

Tectonic-heat flow should include sediments and heat production in the crust
(The single stretching factor is valid in certain cases but not all)



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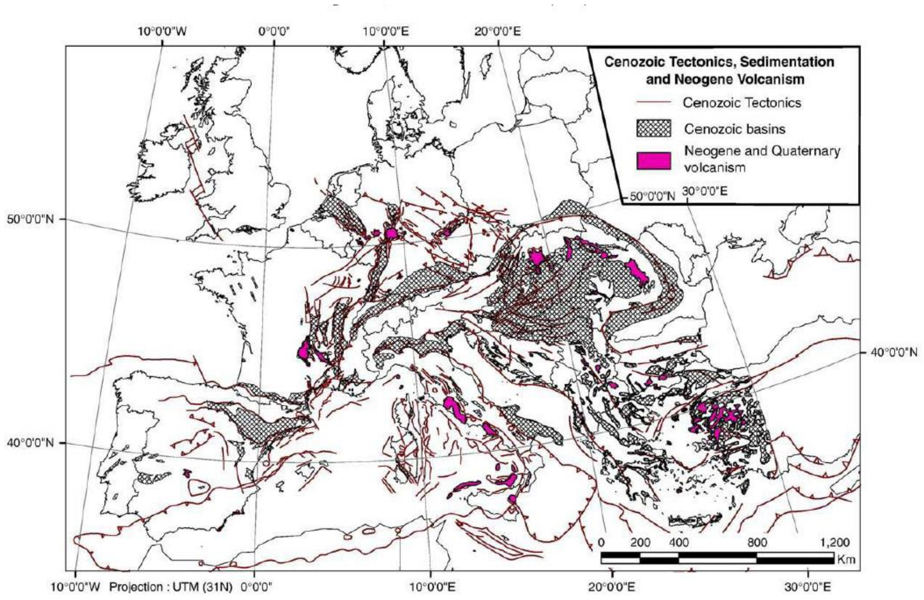
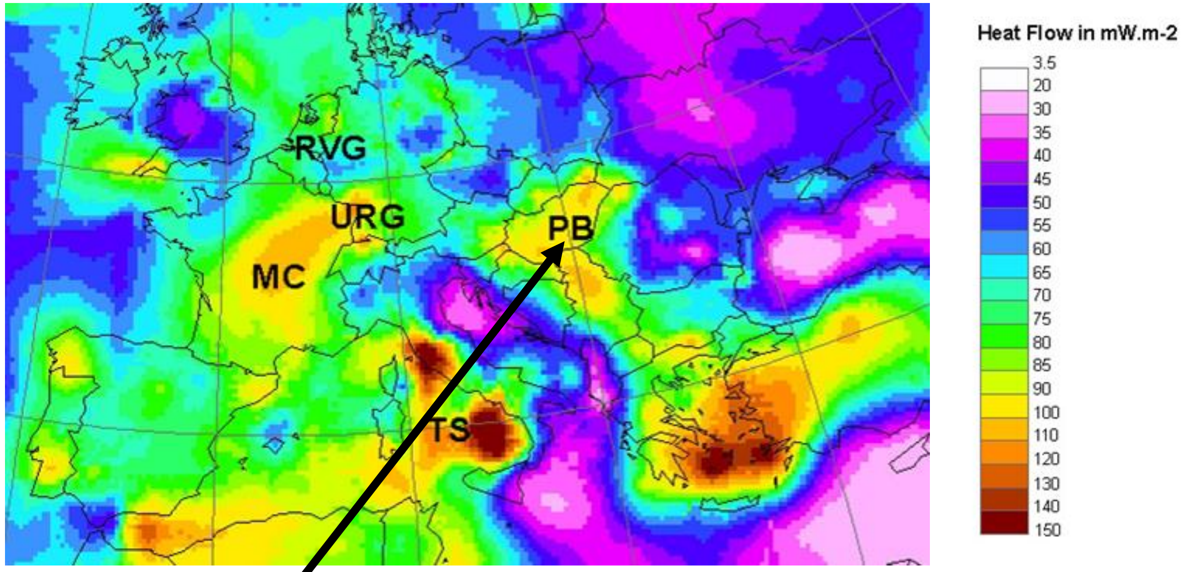
IFP Energies nouvelles

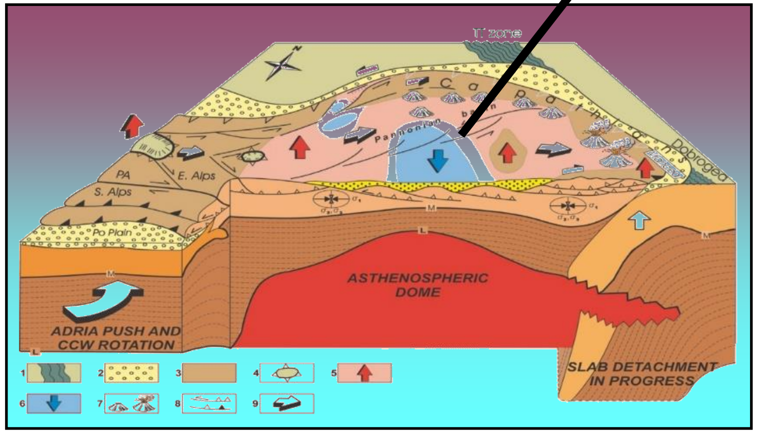
PUNCTUAL THERMAL PERTURBATION: KINEMATIC

Renewable energies





Cloetingh et al. (2010)



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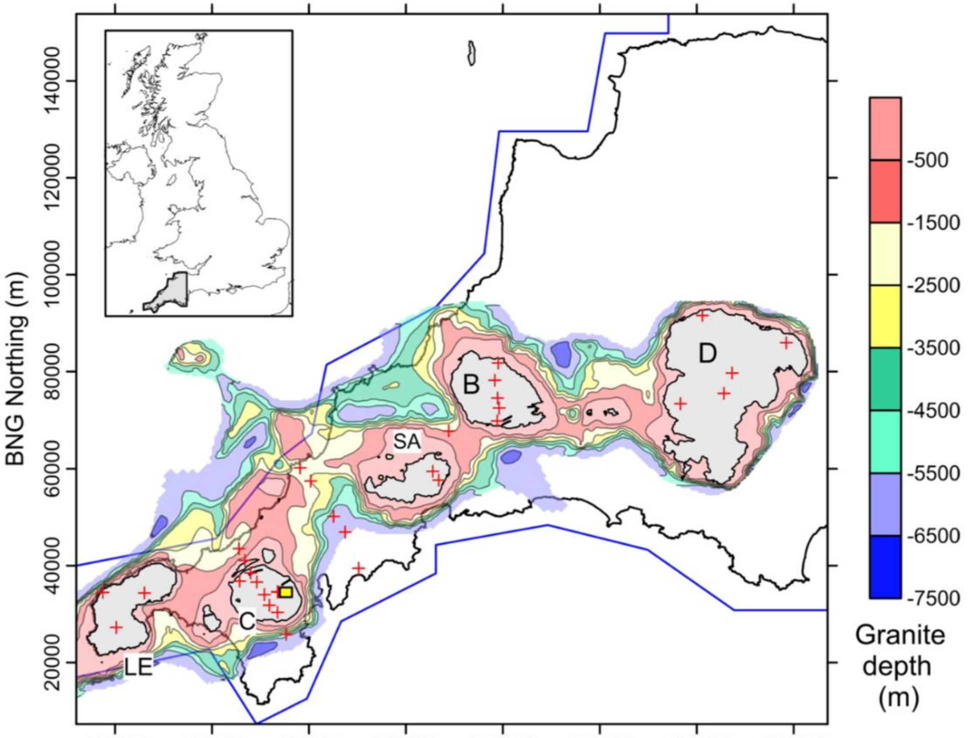
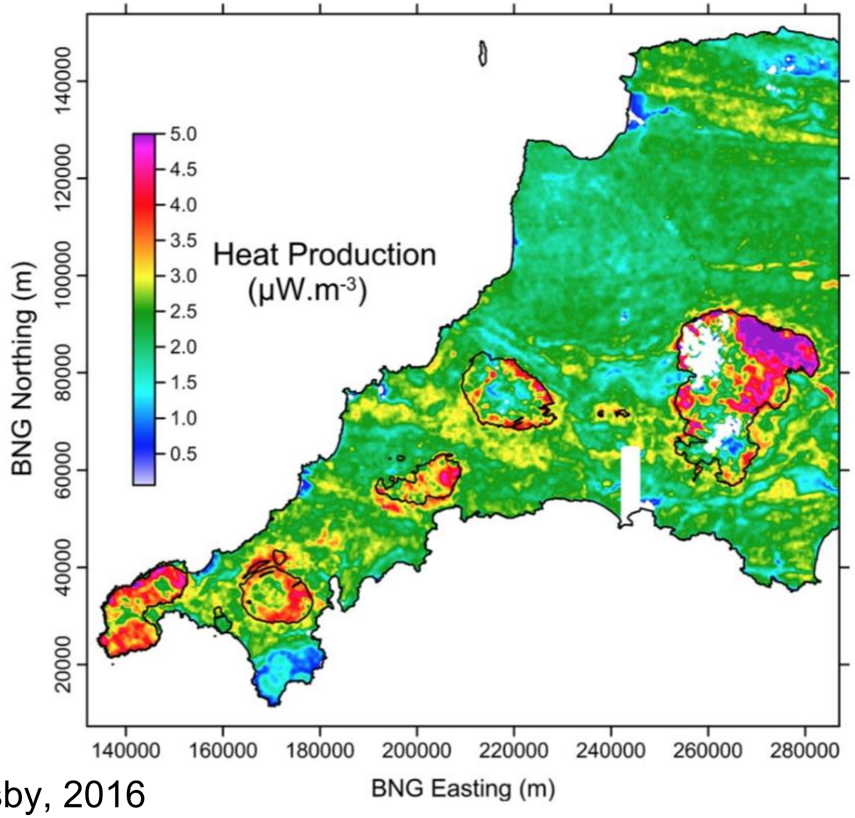
PUNCTUAL THERMAL PERTURBATION: RADIOGENIC BODIES (CORNWALL)

Renewable energies





Beamish and Busby, 2016

The Cornwall Batholith high heat flow values

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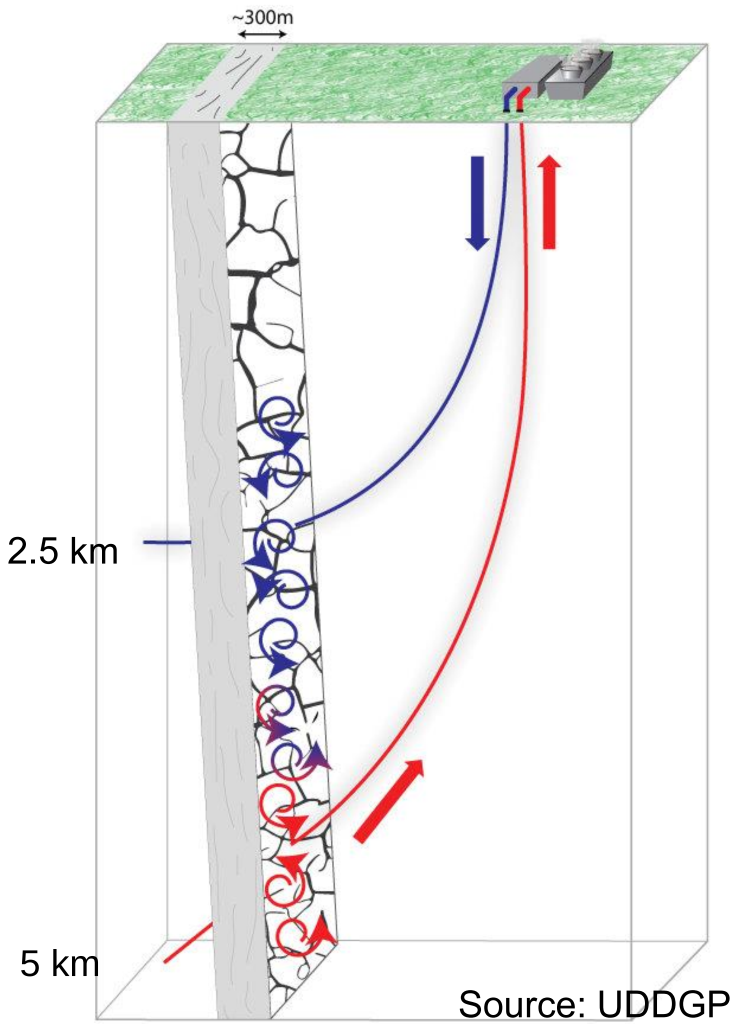
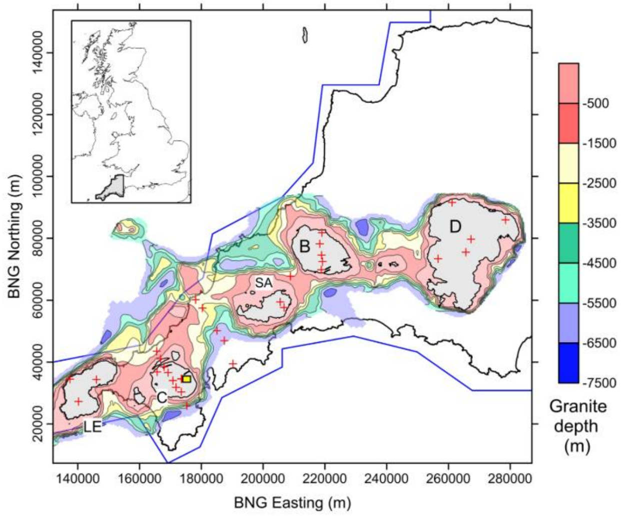
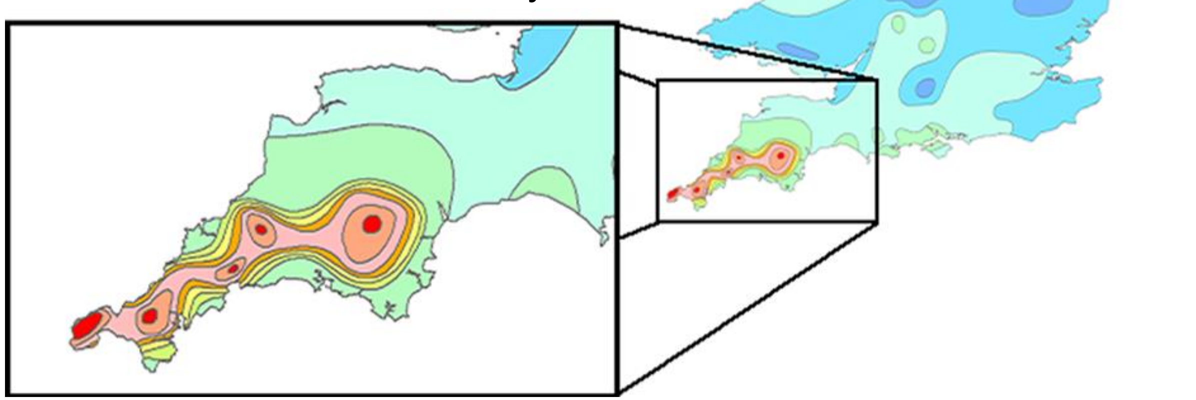
PUNCTUAL THERMAL PERTURBATION: RADIOGENIC BODIES (CORNWALL: UDDGP PROJECT)

Renewable energies



Source: UDDGP project





Beamish and Busby, 2016

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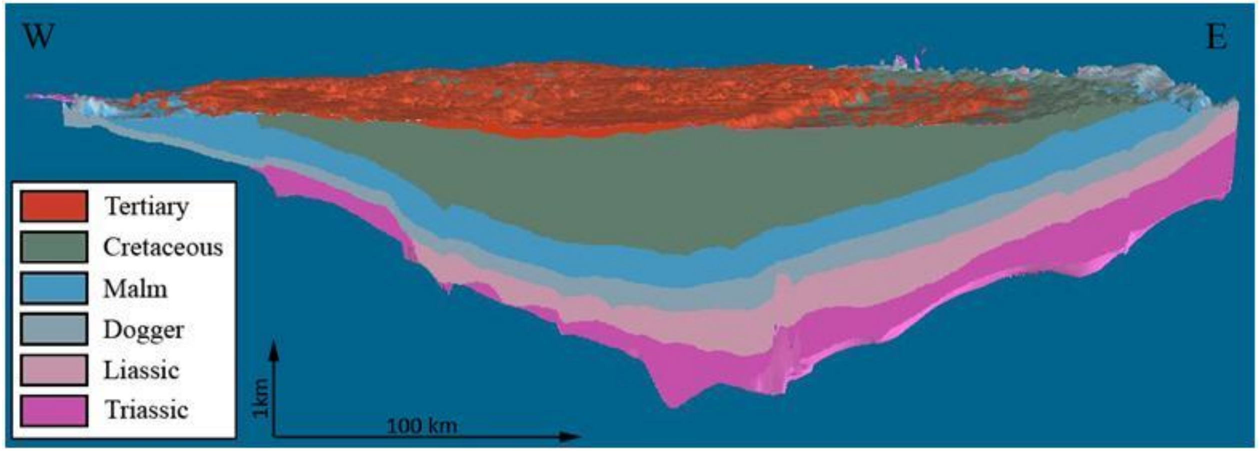
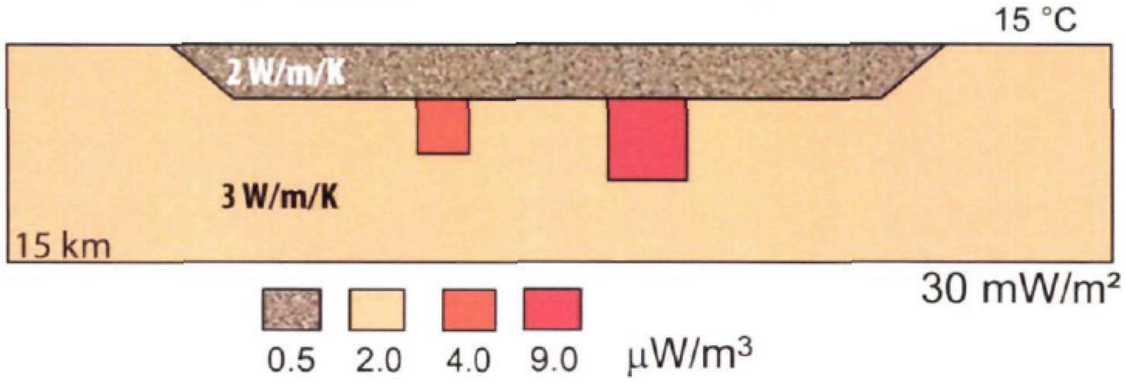
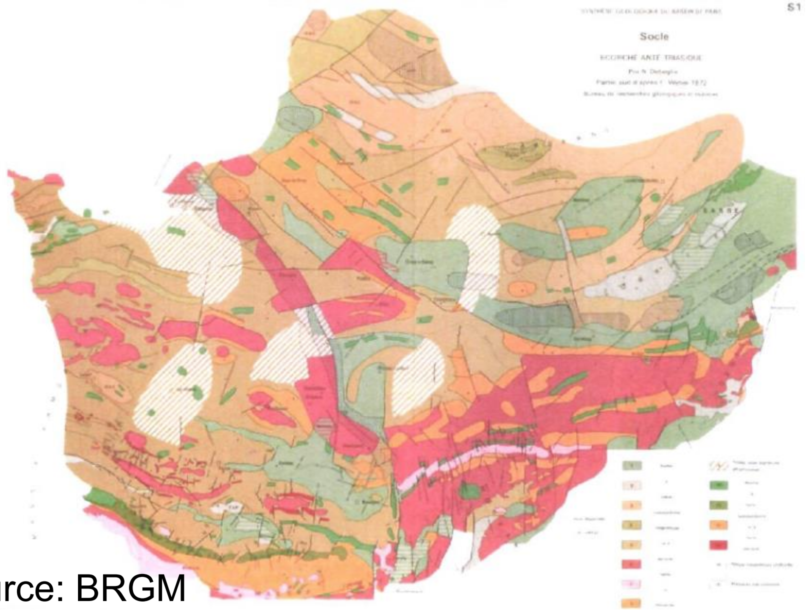
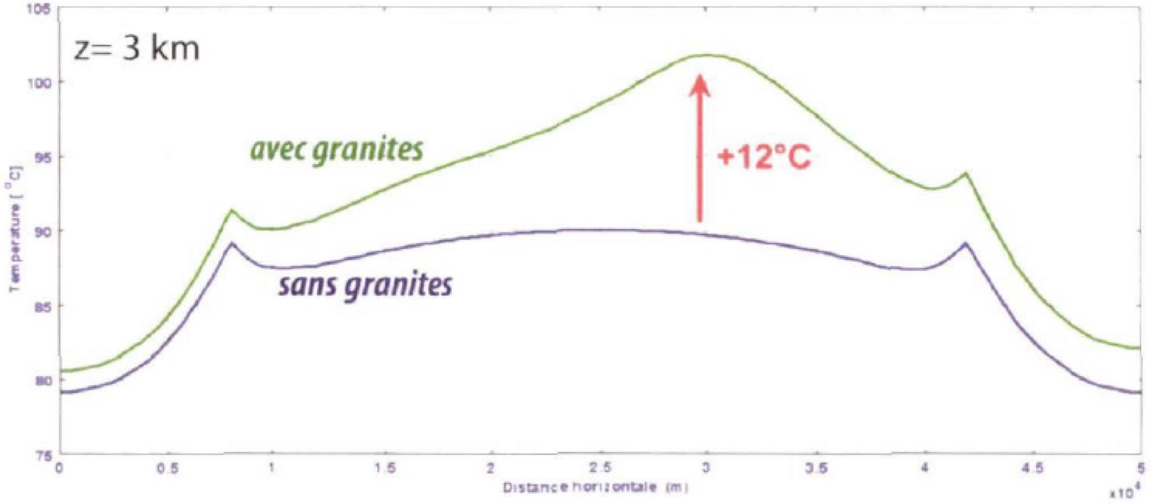
PUNCTUAL THERMAL PERTURBATION: RADIOGENIC BODIES (PARIS BASIN)







Source: BRGM



Guillou-Frottier et al, 2011

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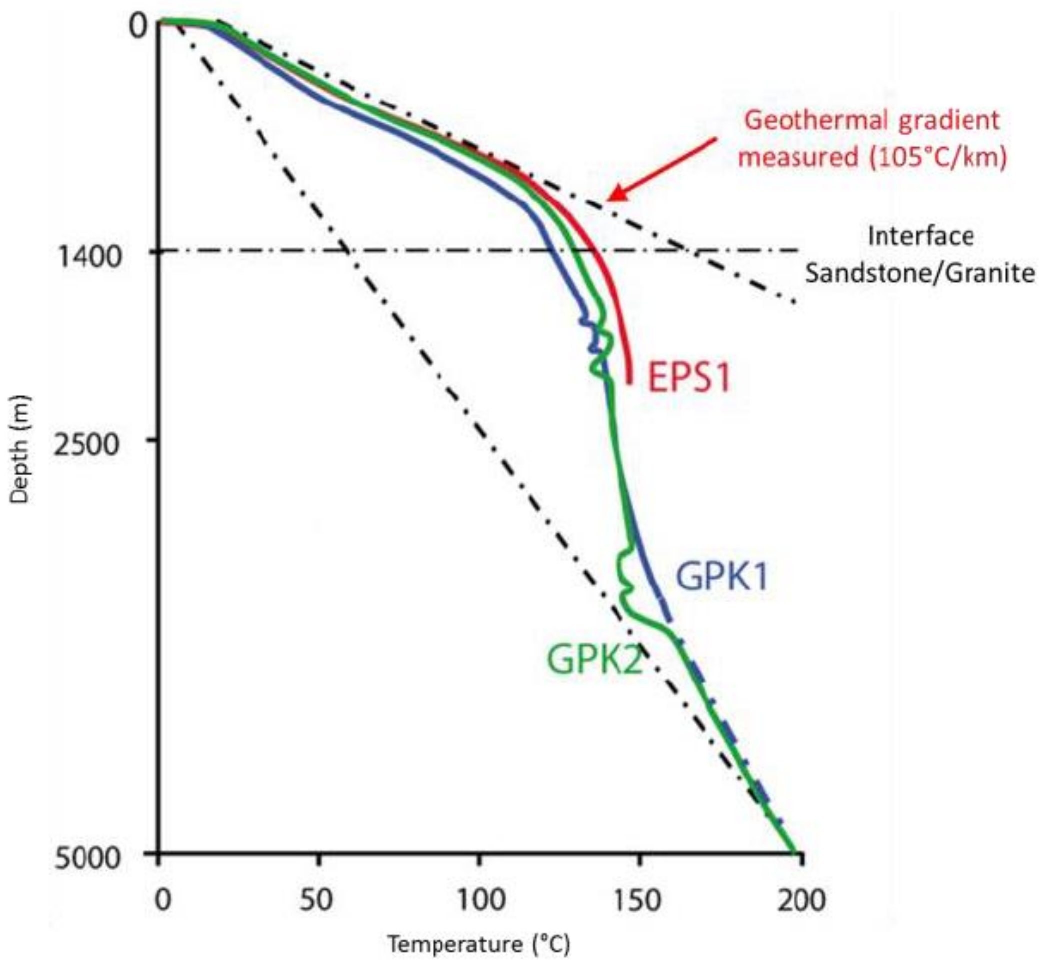
PUNCTUAL THERMAL PERTURBATION: HYDROGEOLOGY (SOULTZ-SOUS-FORÊT)

Renewable energies



Pribnow et al. (1999)

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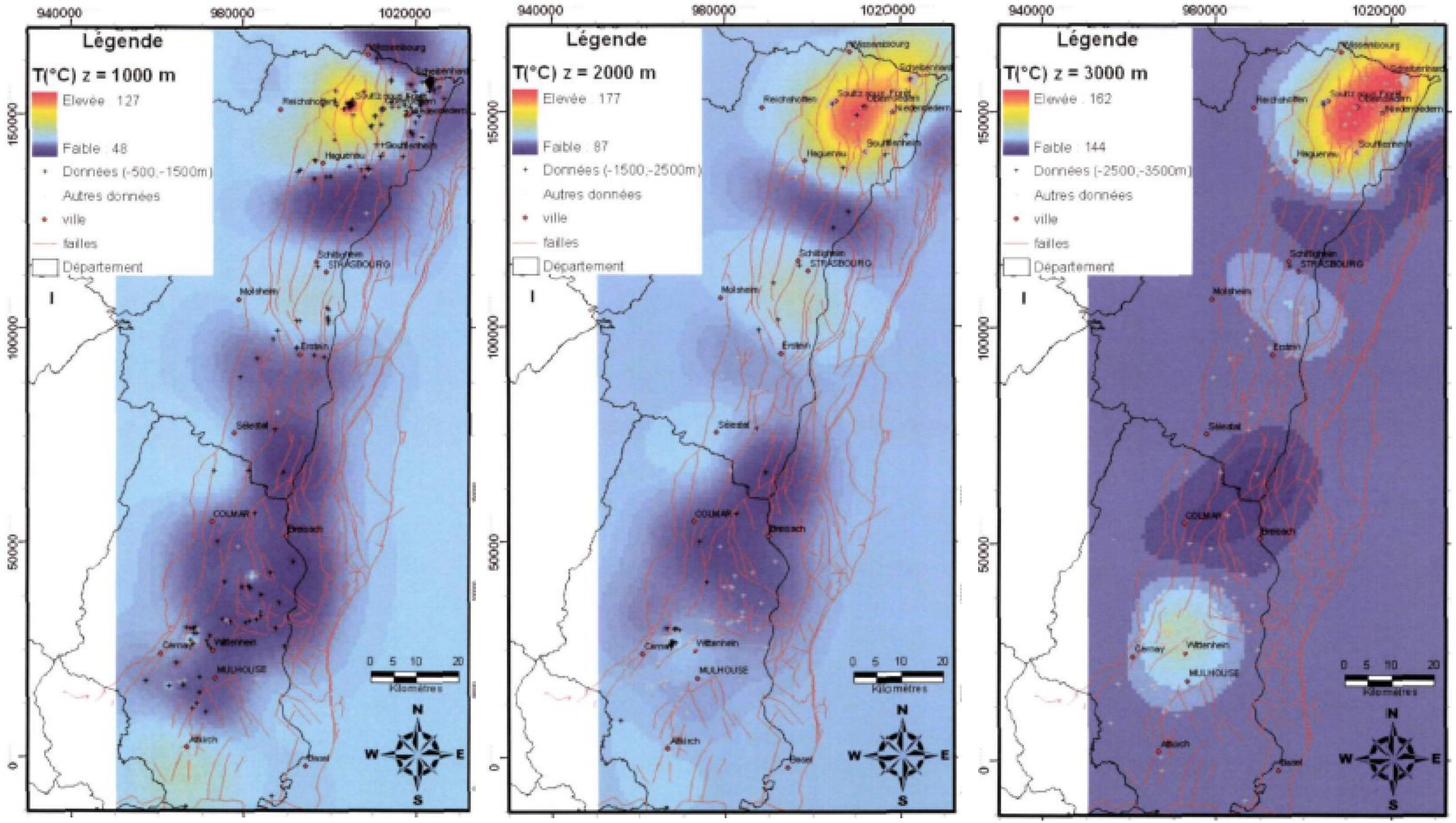
PUNCTUAL THERMAL PERTURBATION: HYDROGEOLOGY (SOULTZ-SOUS-FORÊT)

Renewable energies



Guillou-Frottier et al, 2011

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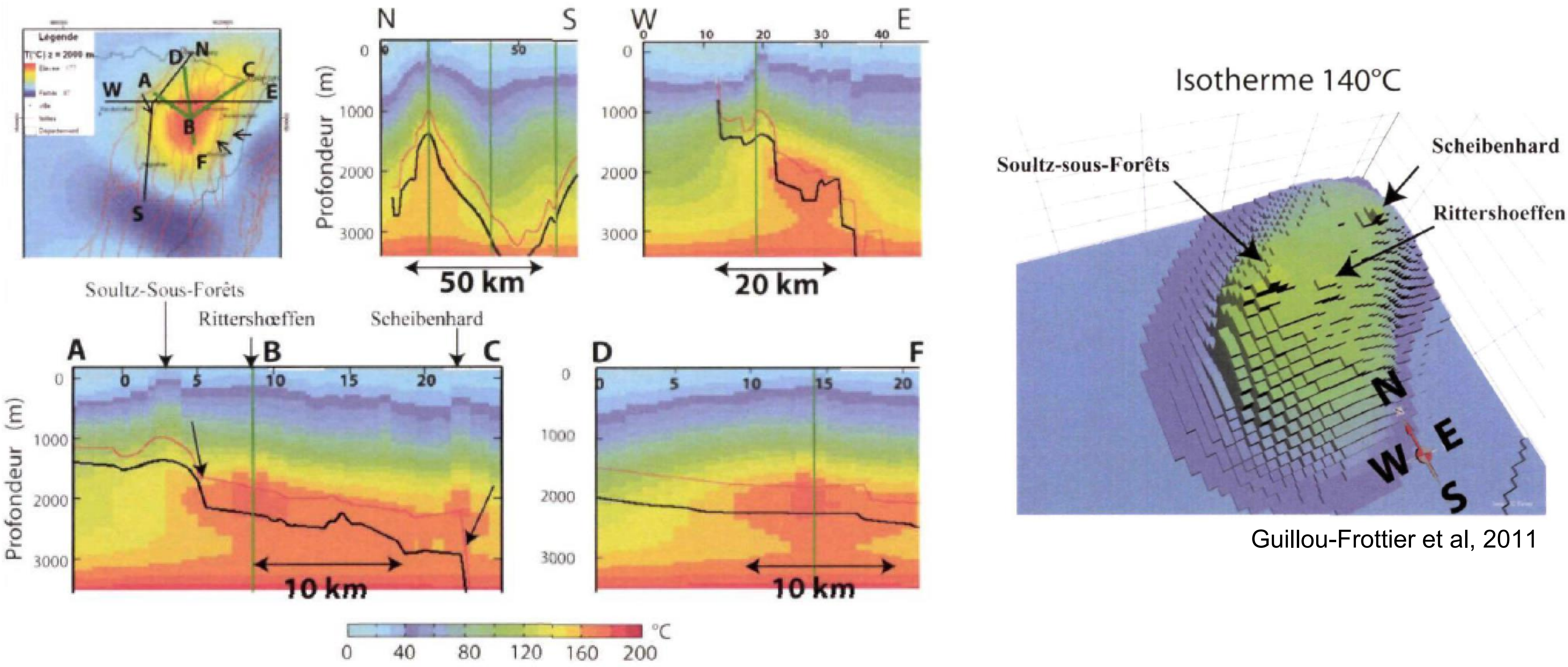

Guillou-Frottier et al, 2011

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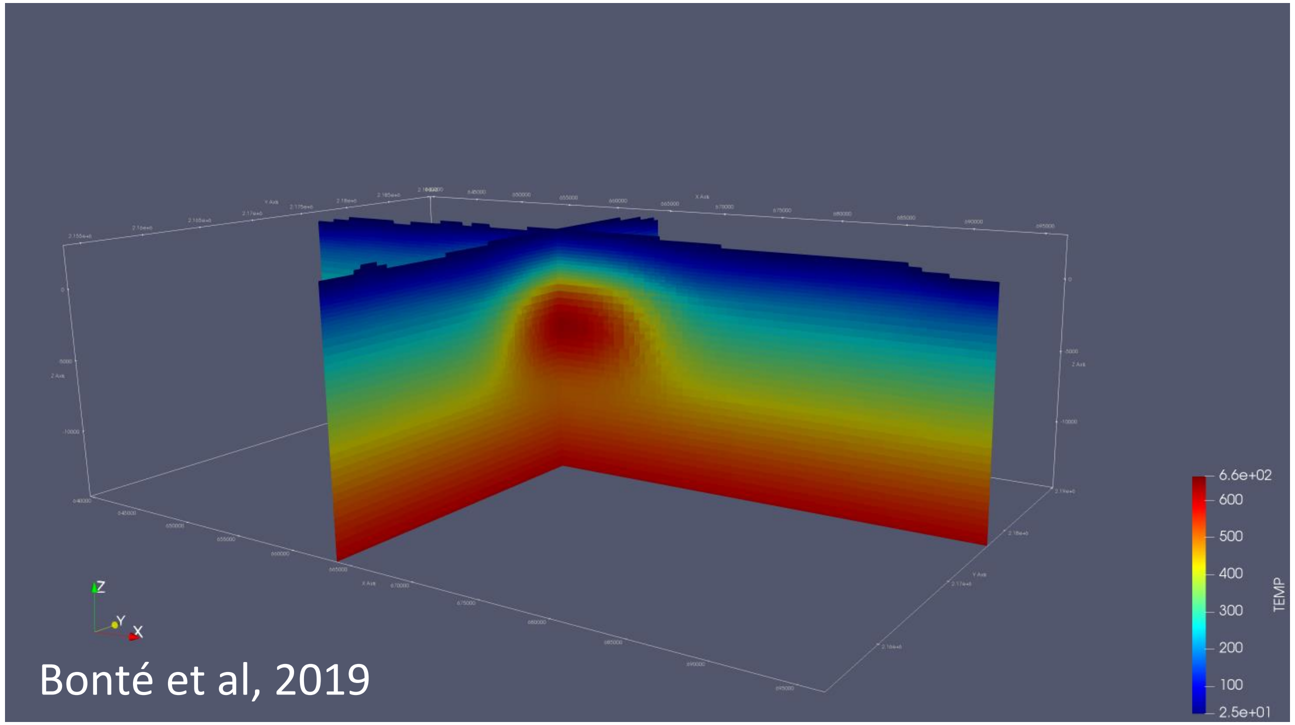
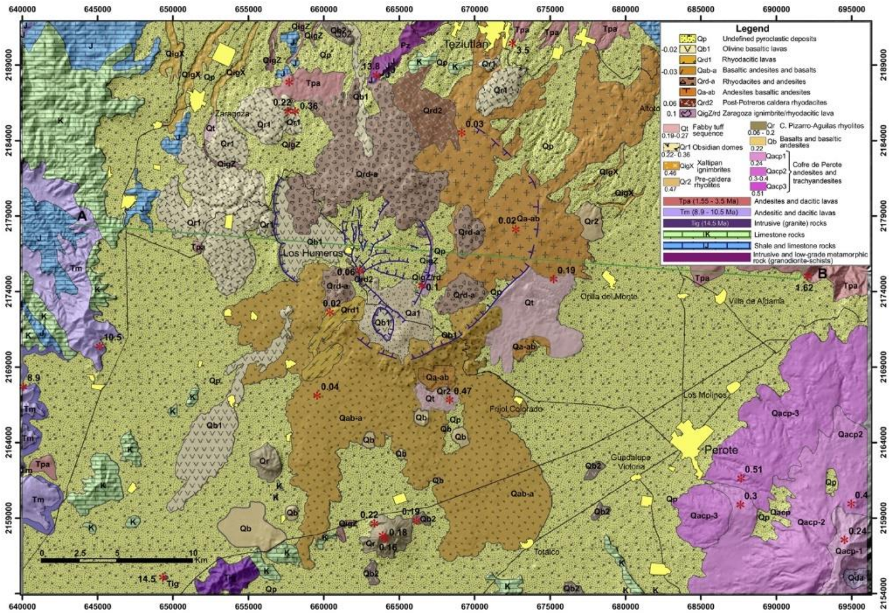
PUNCTUAL THERMAL PERTURBATION: MAGMATIC INTRUSION

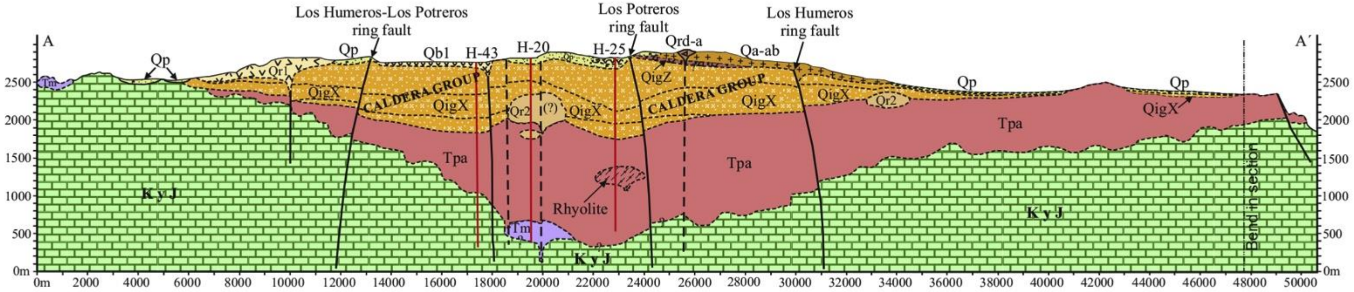
Renewable energies



Bonté et al, 2019



Carrasco et al., 2017



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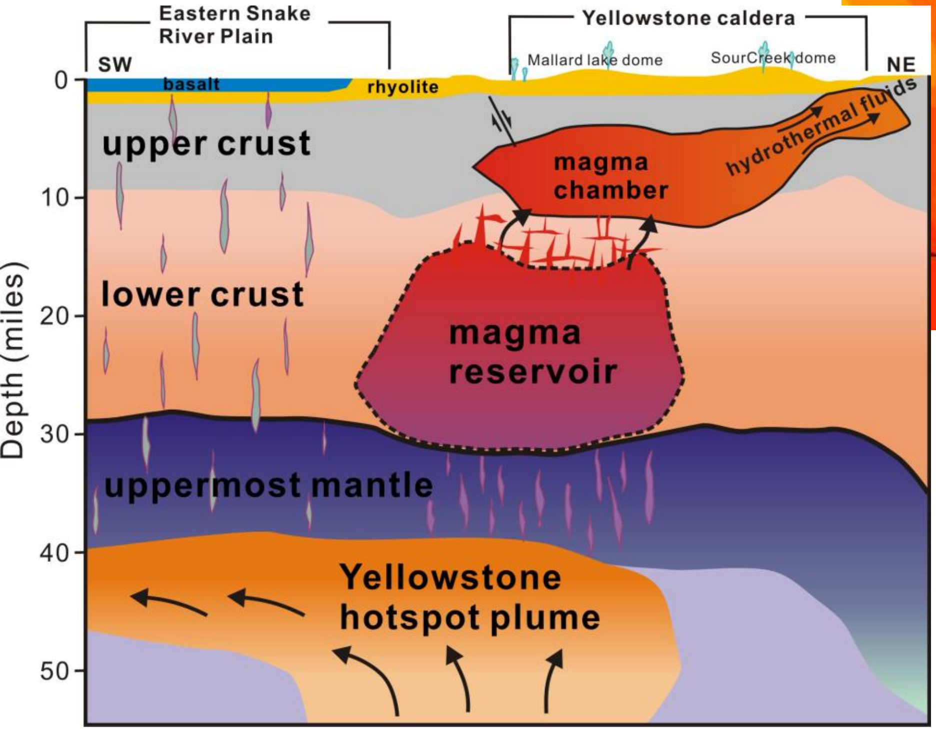
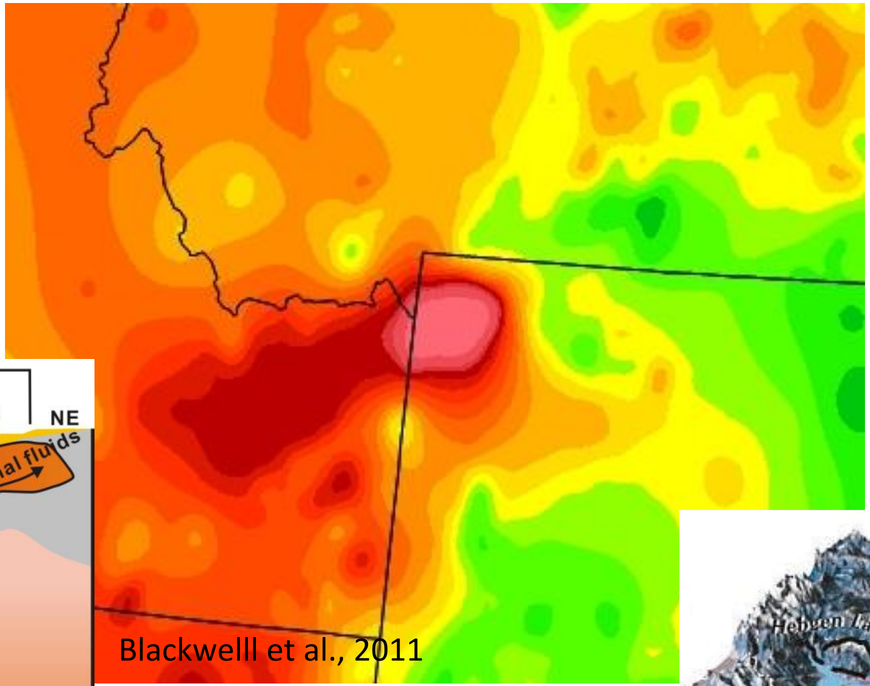
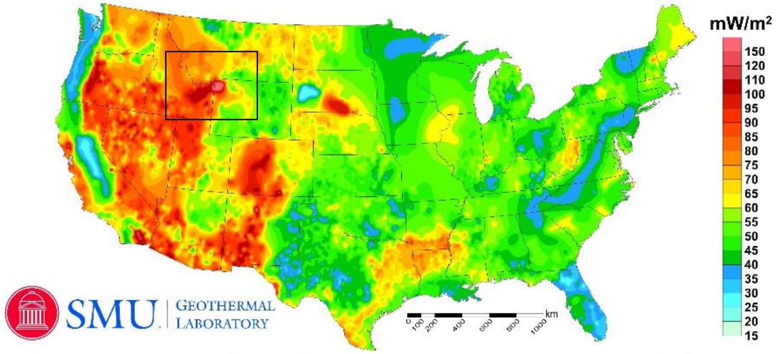
PUNCTUAL THERMAL PERTURBATION: MAGMATIC INTRUSION

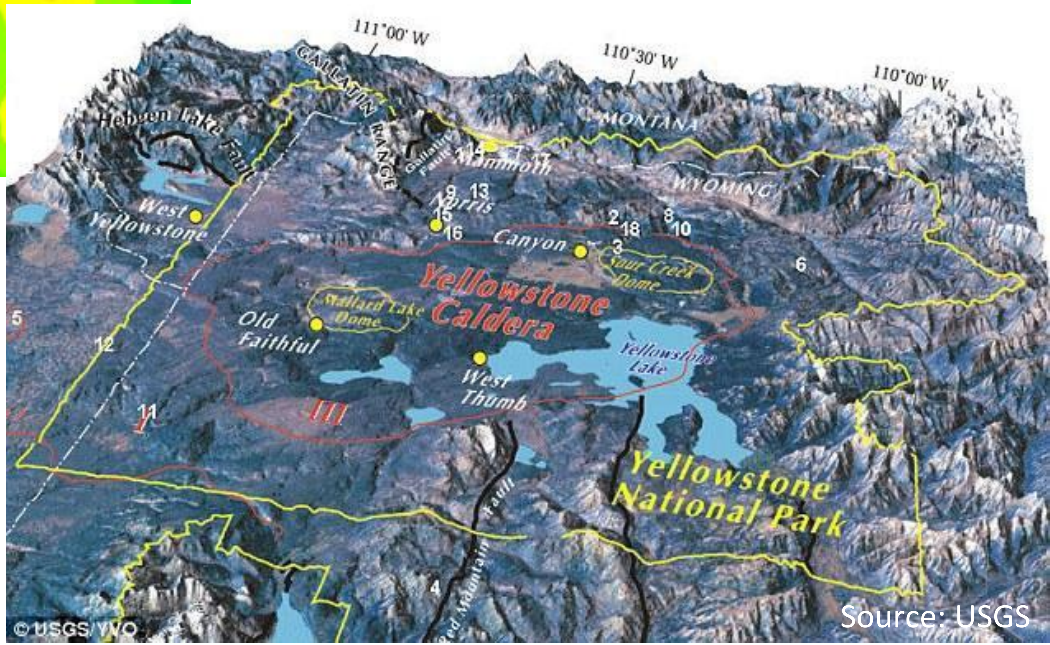
Renewable energies





Blackwelll et al., 2011





Source: USGS

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GEOTHERMAL ENERGY

Renewable energies

Introduction to geothermal energy

- What is geothermal energy?

Geothermal Energy in the Renewable Energy mix, status, and evolution

Classification

Different use of geothermal energy; Resource <-> Usage

Electricity generation & Direct use

- Thermal processes in the earth system

Geodynamic and surface heat flow

Lithospheric thickness and composition

Punctual thermal perturbation:

Kinematic, magmatism, radiogenic heat production, hydrology

- Geothermal energy in sedimentary basins

General principles on sedimentary basins

Modelling geothermal energy

Geothermal energy potential in India

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WHAT IS A BASIN?

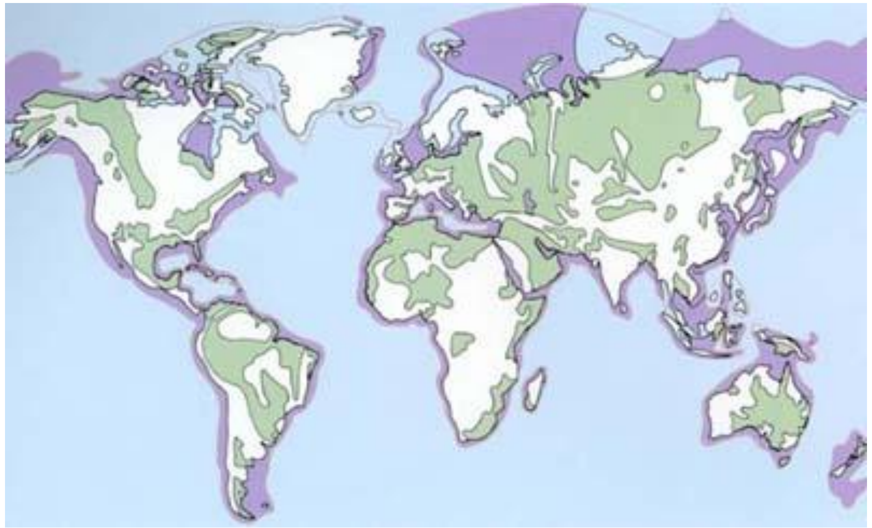
Renewable energies

Sedimentary Basin:

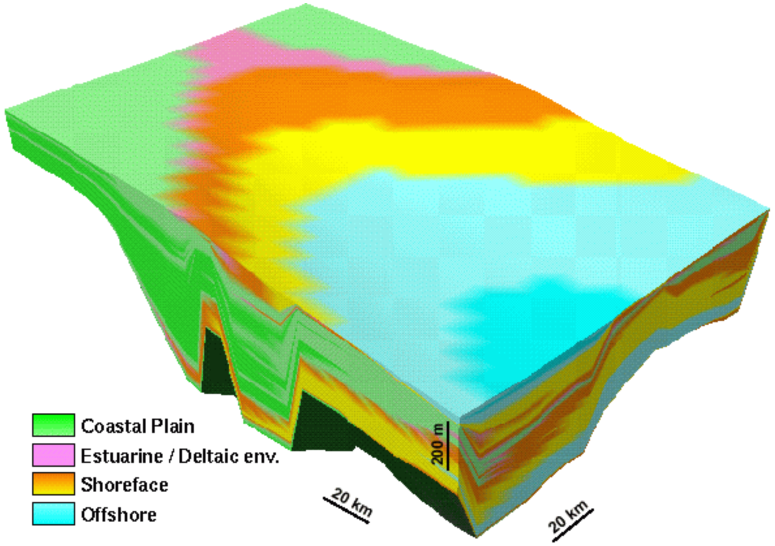
- A geologically depressed area with thick sediments in the interior and thinner sediments at the edges (Mitchell, A.H.C. and Reading, H.G 1986)
- Any geographical feature exhibiting subsidence and consequent infilling by sedimentation and potentially uplift.

It is common to categorize sedimentary basins according to the mechanism of formation: tectonic compression (e.g., foreland basins, caused by lithospheric flexure), tectonic extension (e.g., back-arc basins, caused by lithospheric stretching), and tectonic strike-slip (such as pull-apart basins).

The study of sedimentary basins helps understanding the processes of basin formation and evolution.



Middle East Well Evaluation Review Number 10, p. 8



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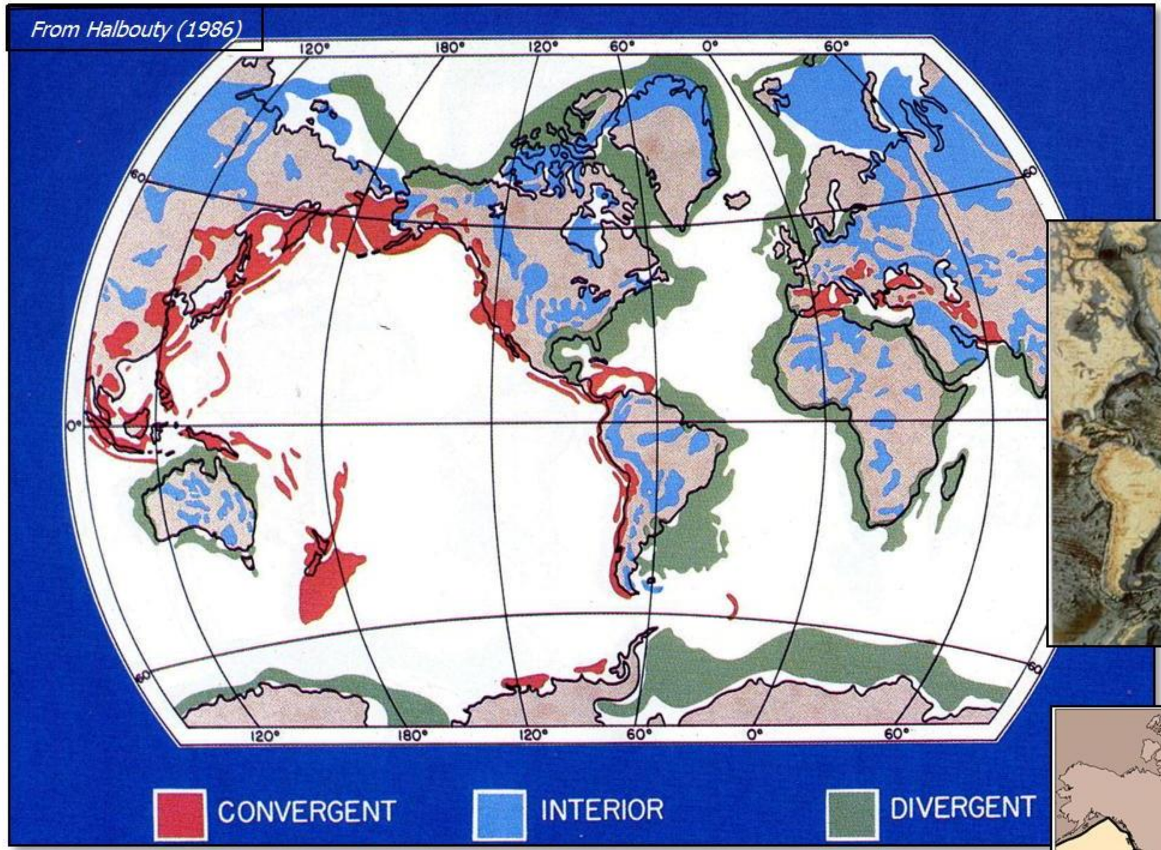
DISTRIBUTION OF SEDIMENTARY BASINS

Renewable energies



Sedimentary Bassins in different tectonic context

1- Extension - Rifting
- Passive margin

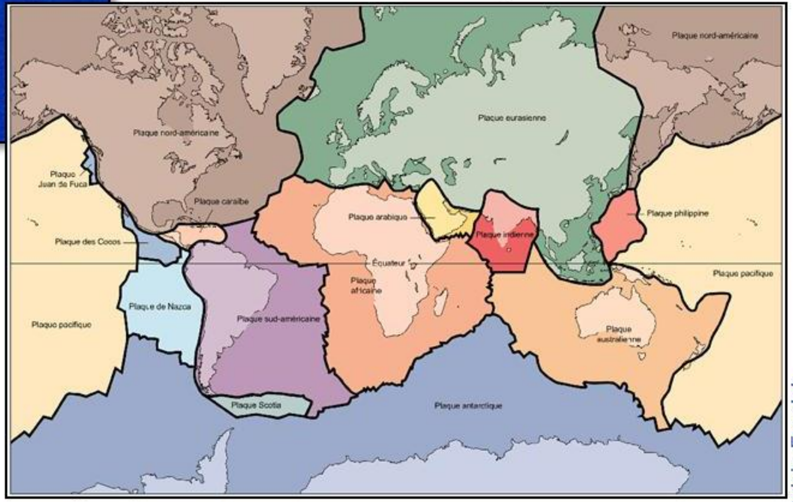
2- Subduction
- Fore-arc basin
- **Back-arc basin**

3- Convergent plate
- Foreland basin

4- Transcurrentes
- Pull-aparts

5- Intracratonic

Plate margins



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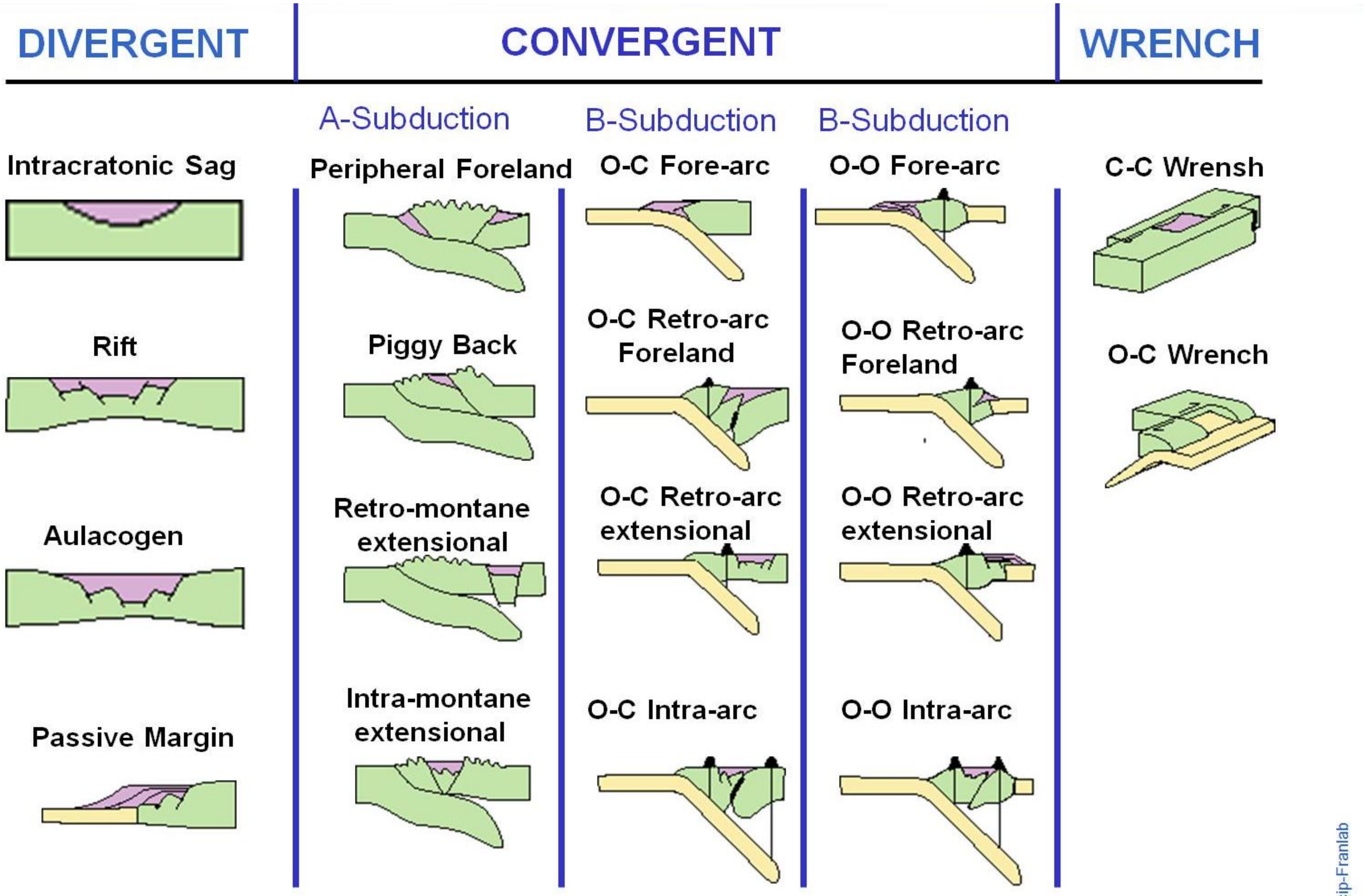
SEDIMENTARY BASINS IN DIFFERENT TECTONIC CONTEXT

Renewable energies



Different tectonic regimes and main types of sedimentary basins.

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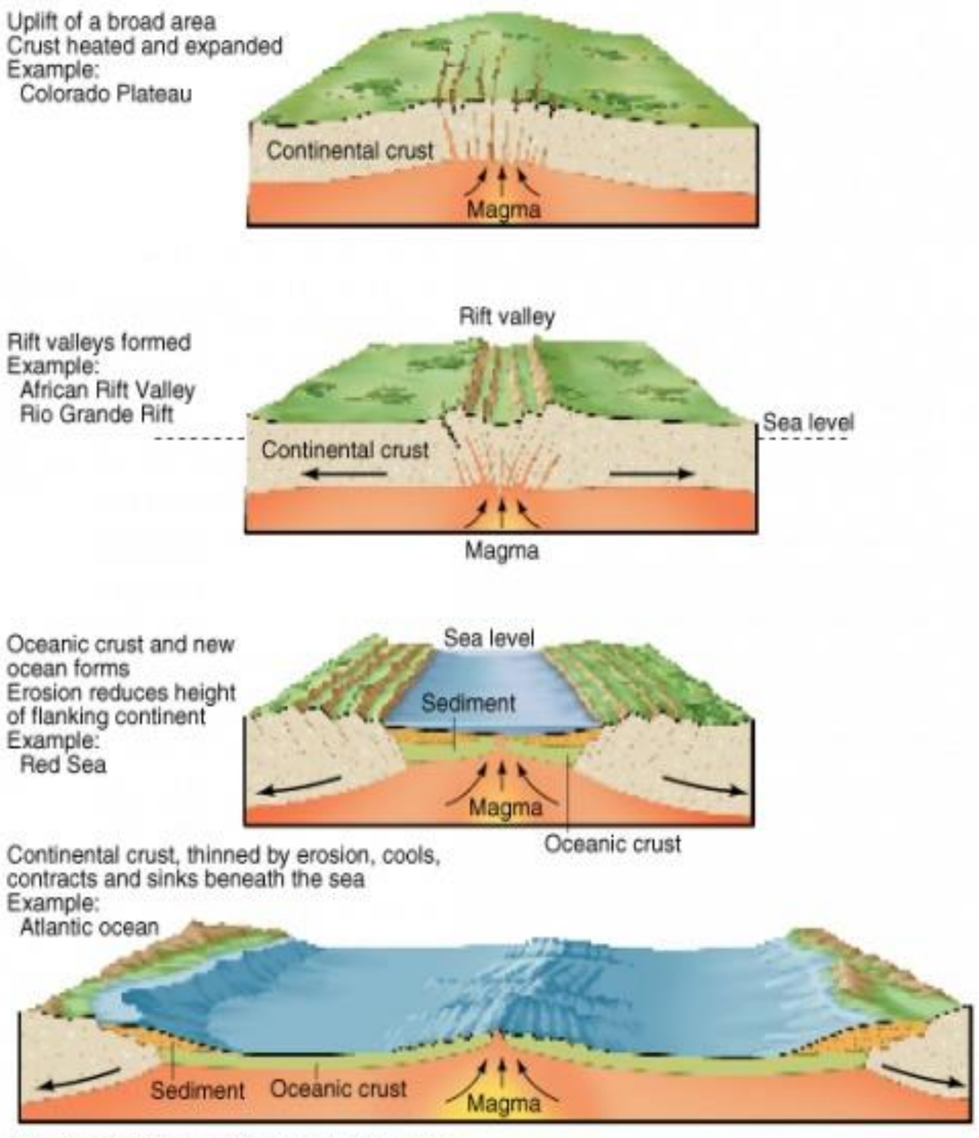
RIFTING



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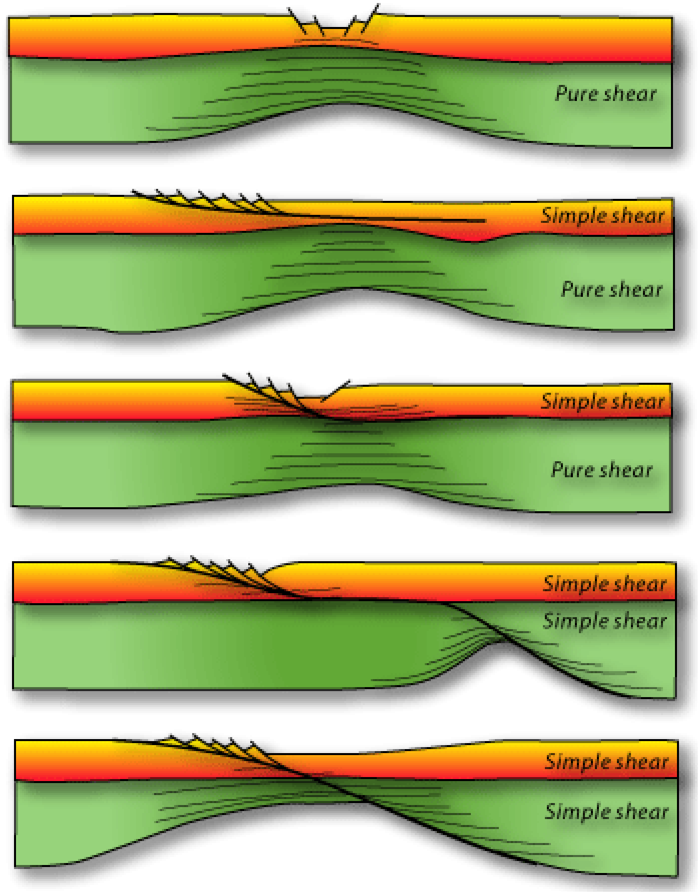
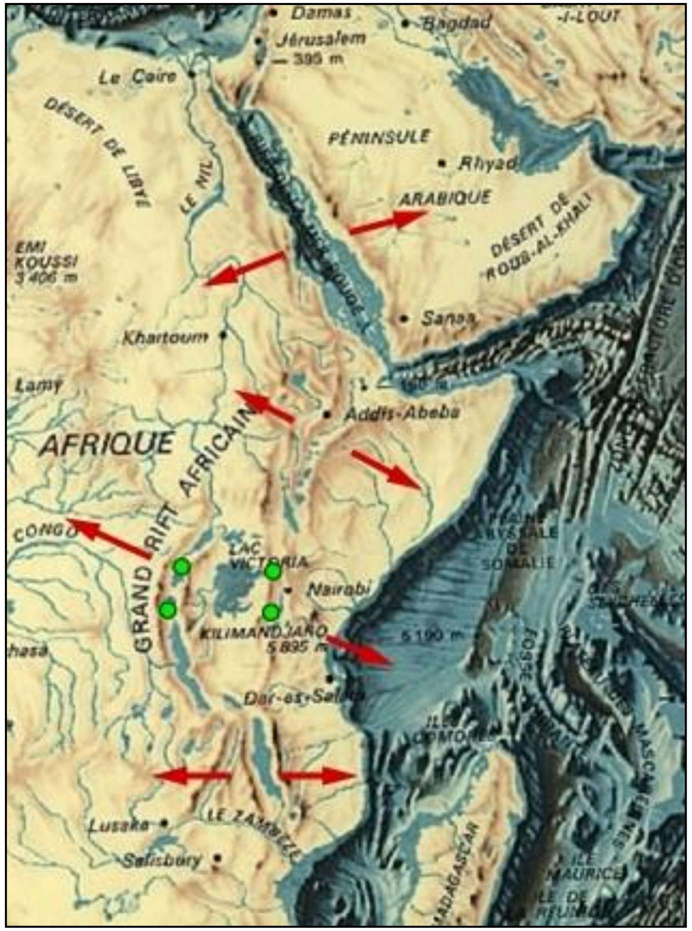
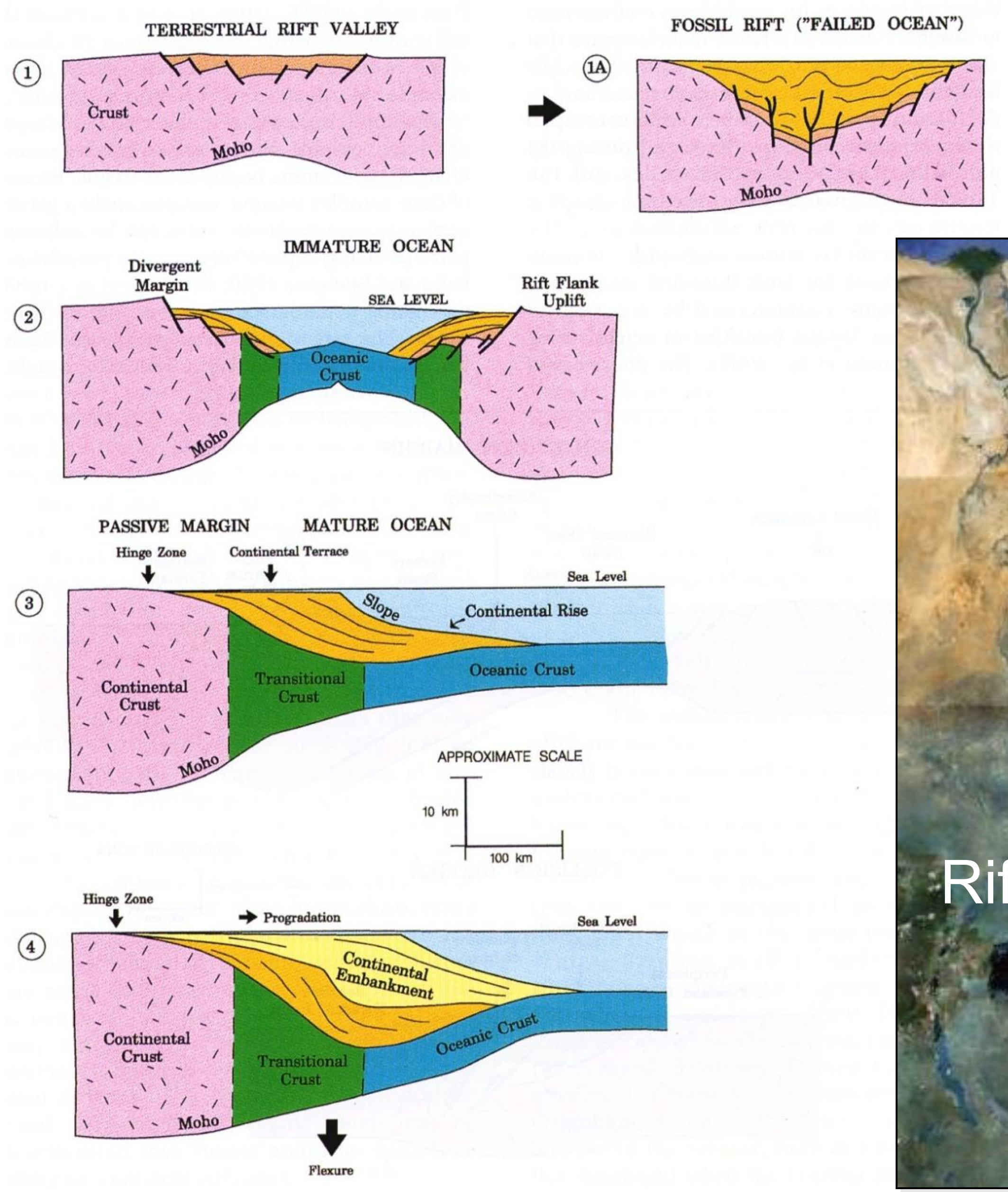


RIFTING


Damas
Jérusalem
— 395 m
Bagdad
Le Caire
DÉSERT DE LIBYE
LE NIL
PÉNINSULE
Rhyad
ARABIQUE
DÉSERT DE ROUB-AL-KHALI
EMI KOUSSI
3 406 m
Sanaa
Khartoum
Lamy
Addis-Abeba
AFRIQUE
GRAND RIFT AFRICAIN
CONGO
LAC VICTORIA
Nairobi
KILIMANDJARO
5 895 m
5 190 m
Lusaka
Salisbury
MADAGASCAR

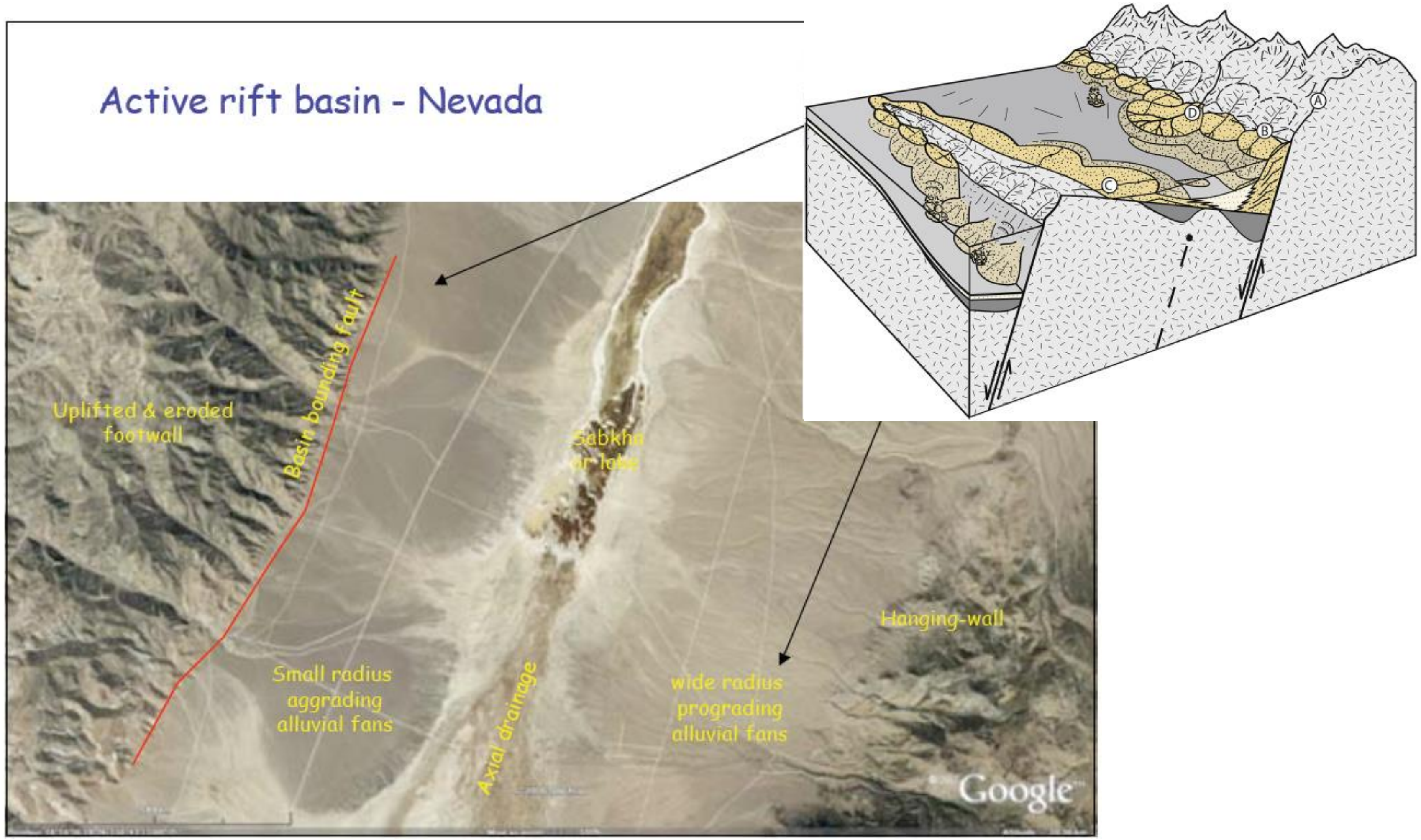
RIFTING


TERRESTRIAL RIFT VALLEY
1
Crust
Moho
FOSSIL RIFT ("FAILED OCEAN")
1A
Moho
IMMATURE OCEAN
Divergent Margin
SEA LEVEL
Rift Flank Uplift
2
Oceanic Crust
Moho
PASSIVE MARGIN
MATURE OCEAN
Hinge Zone
Continental Terrace
Sea Level
3
Slope
Continental Rise
Continental Crust
Transitional Crust
Oceanic Crust
Moho
APPROXIMATE SCALE
10 km
100 km
Hinge Zone
Progradation
Sea Level
4
Continental Embankment
Continental Crust
Transitional Crust
Oceanic Crust
Moho
Flexure


Red Sea
Rift Valley
Indian Ocean

RIFTING

Renewable energies



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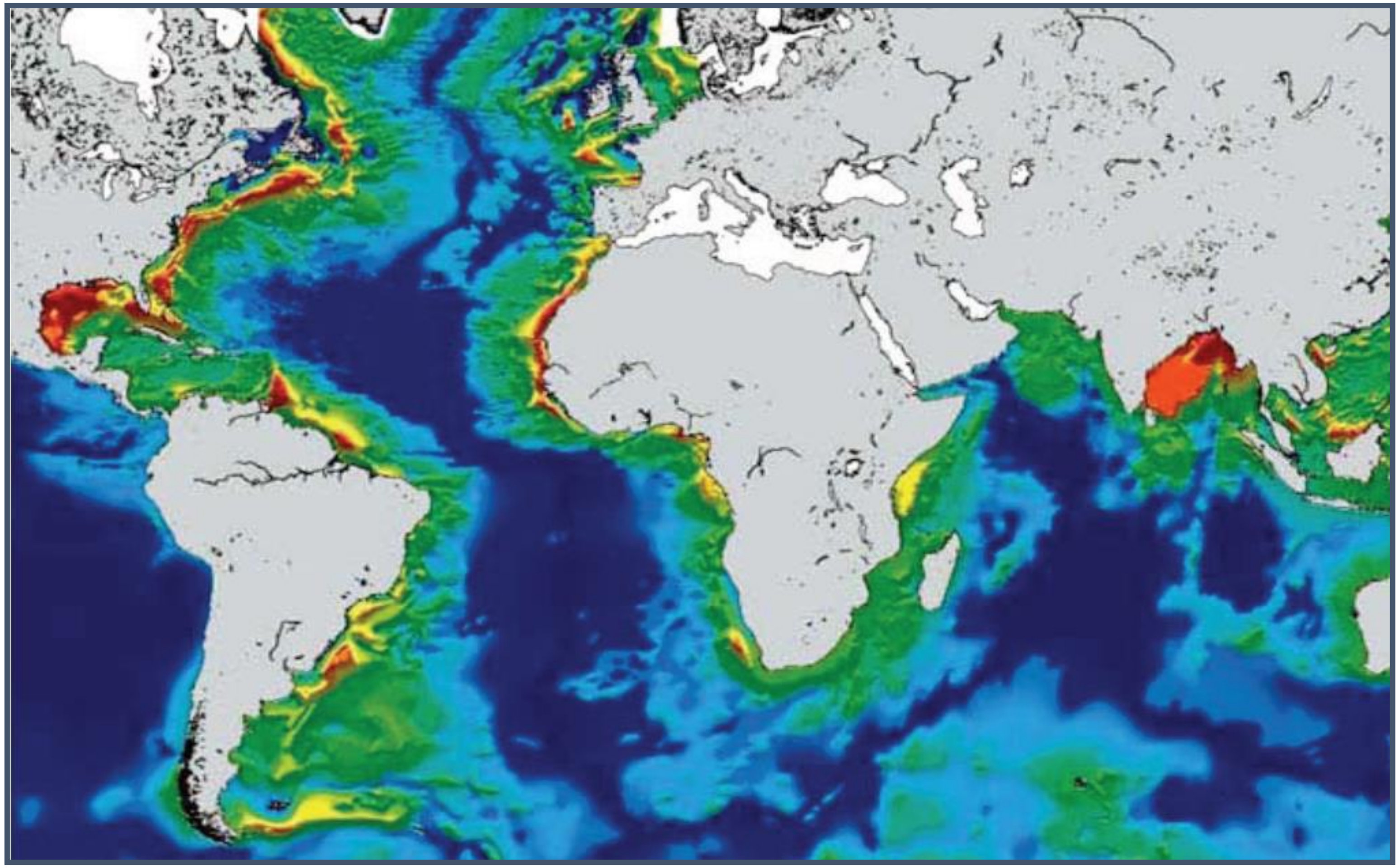
PASSIVE MARGIN



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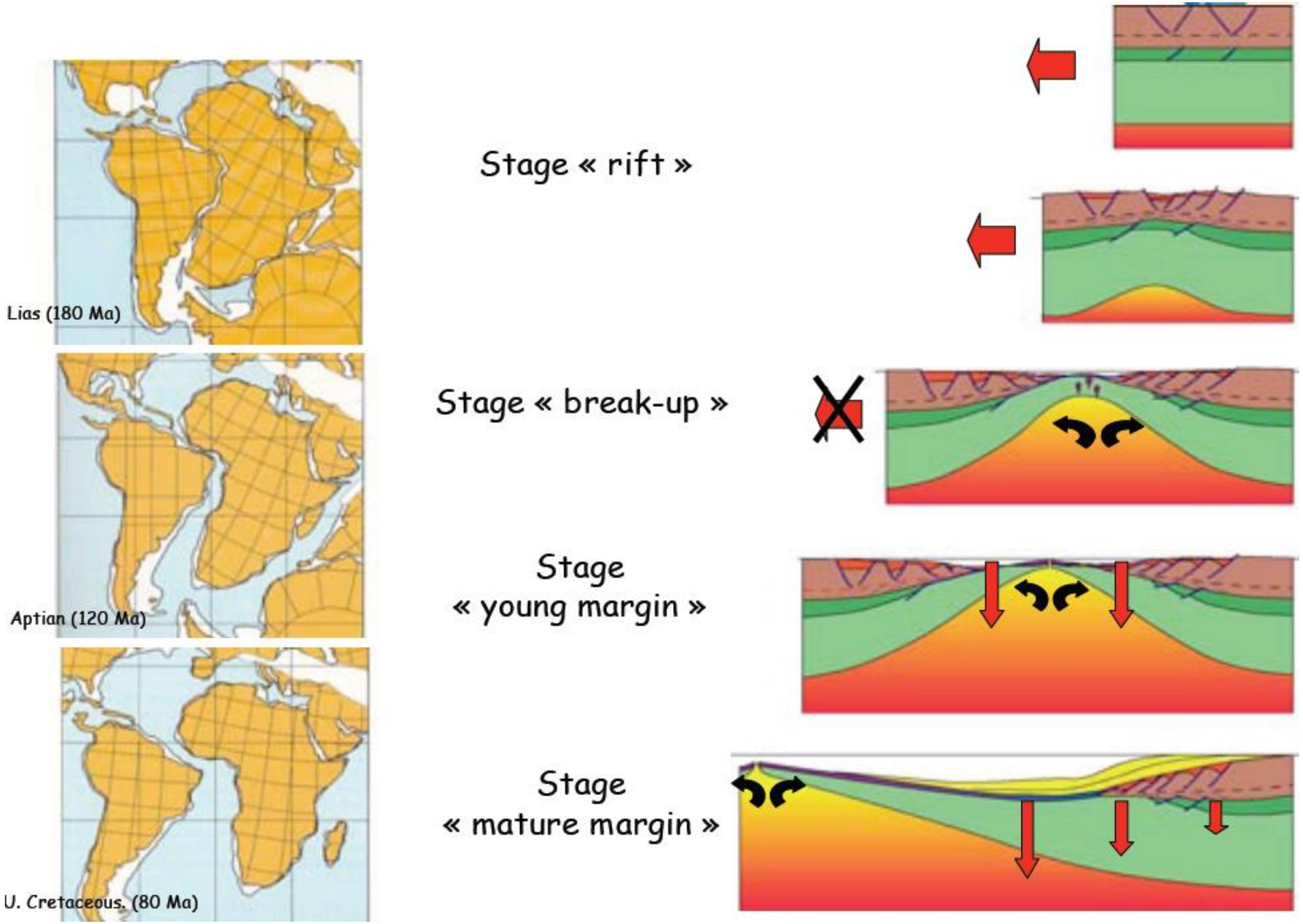
PASSIVE MARGIN



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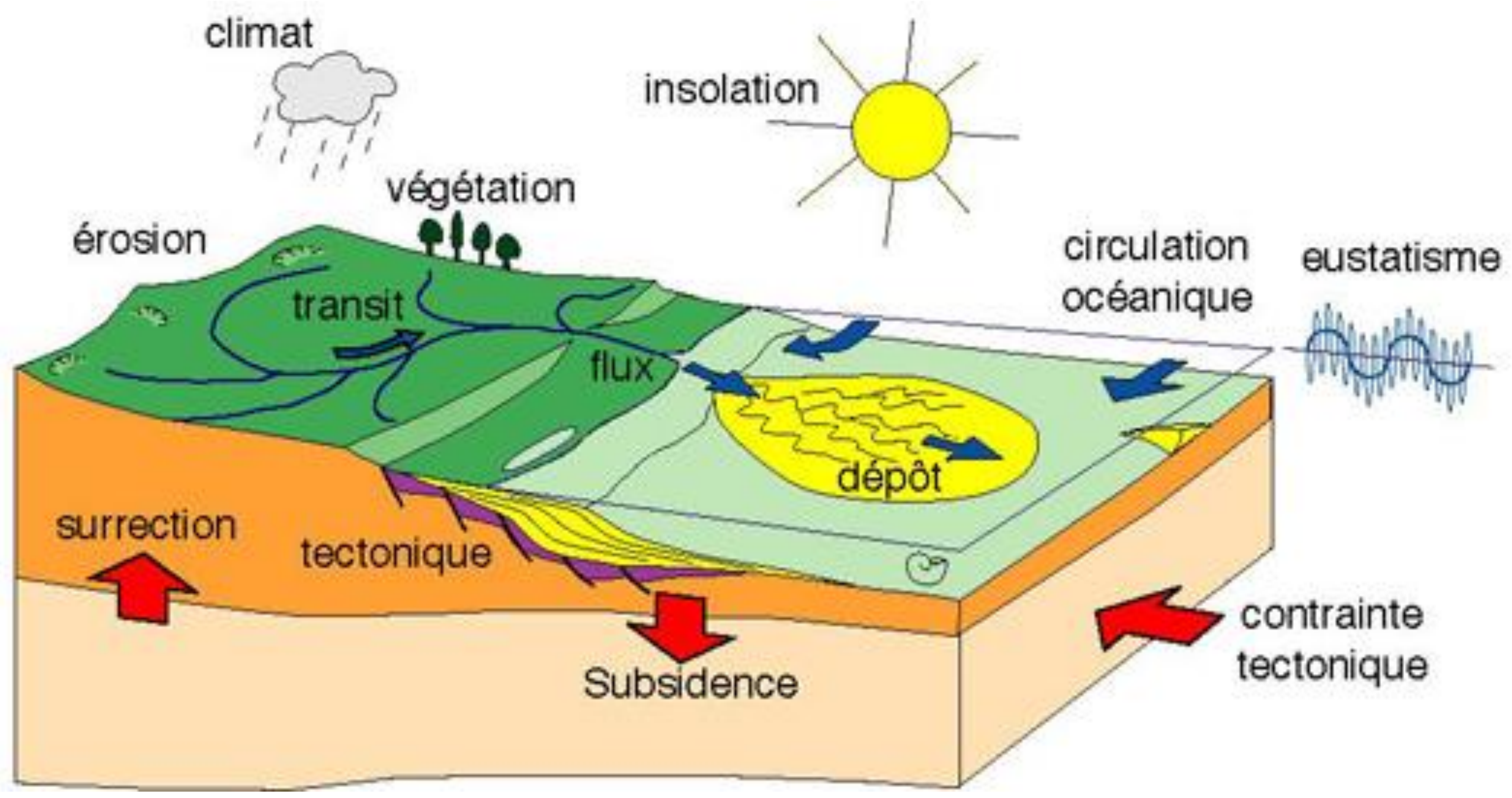
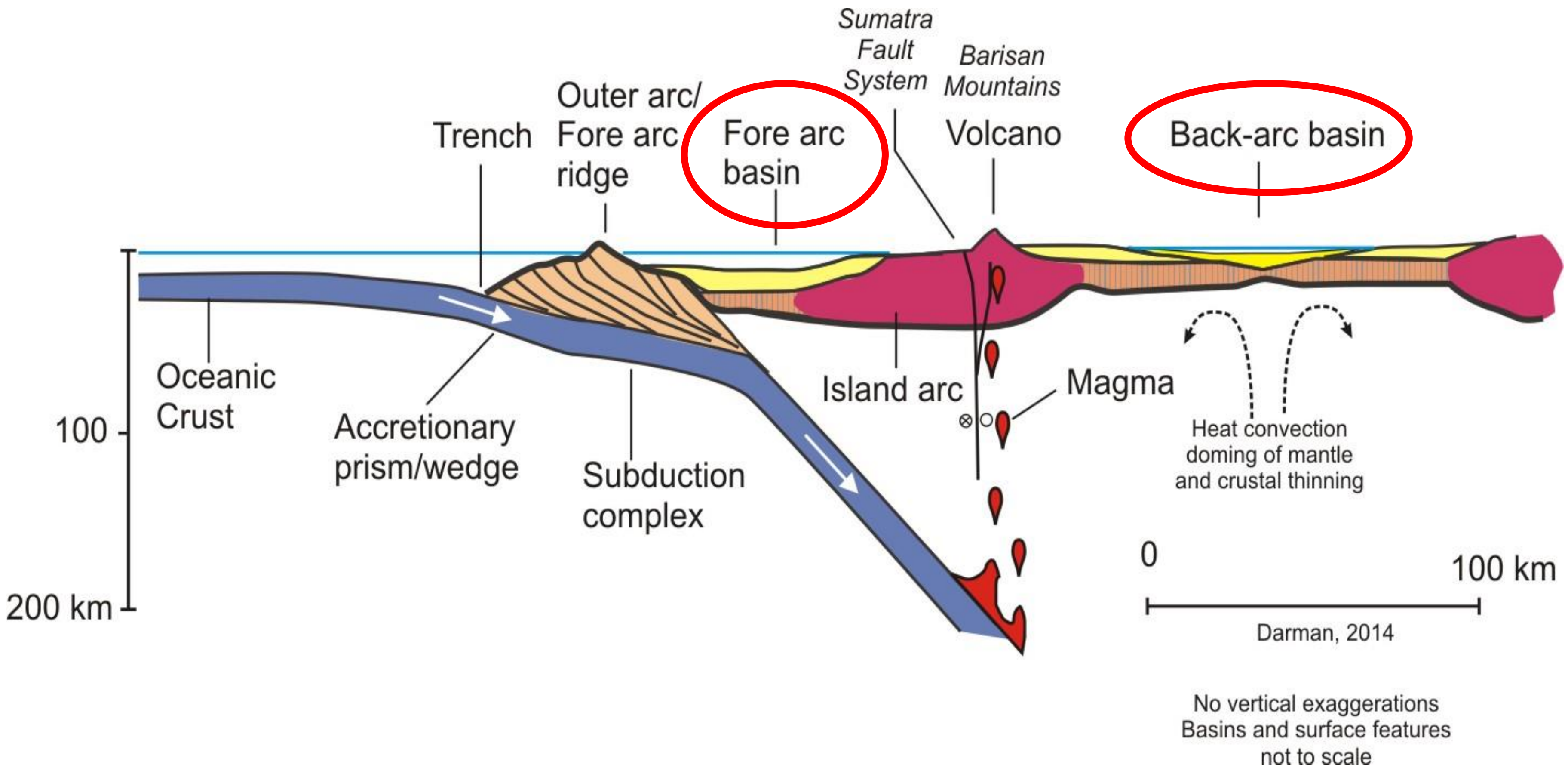
PASSIVE MARGIN

Renewable energies



SUBDUCTION



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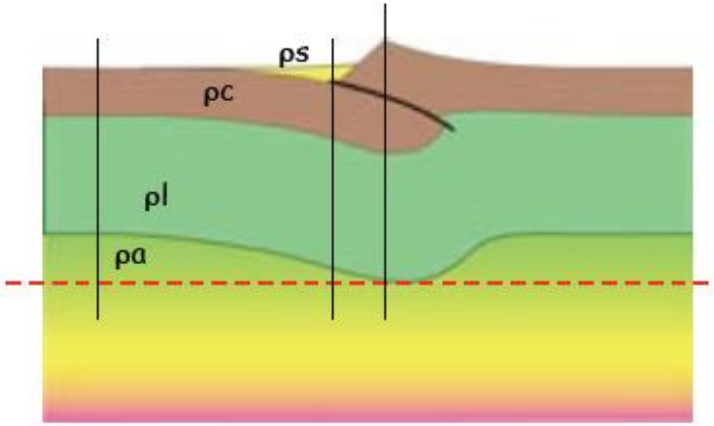
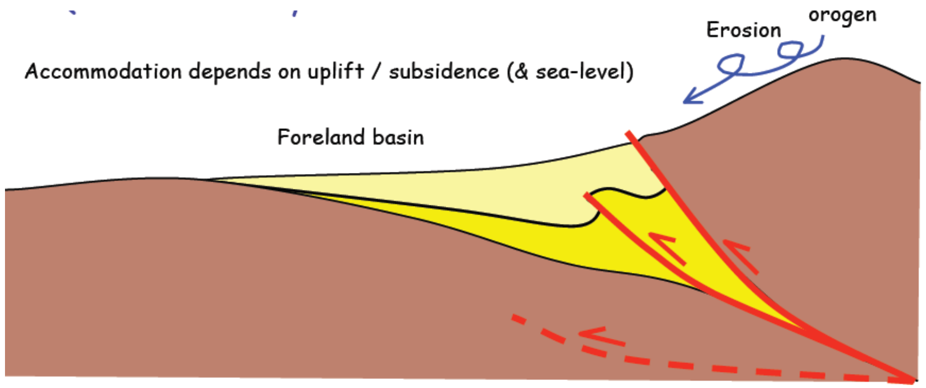
CONVERGENT

Renewable energies



ρs < ρc < ρl < ρa



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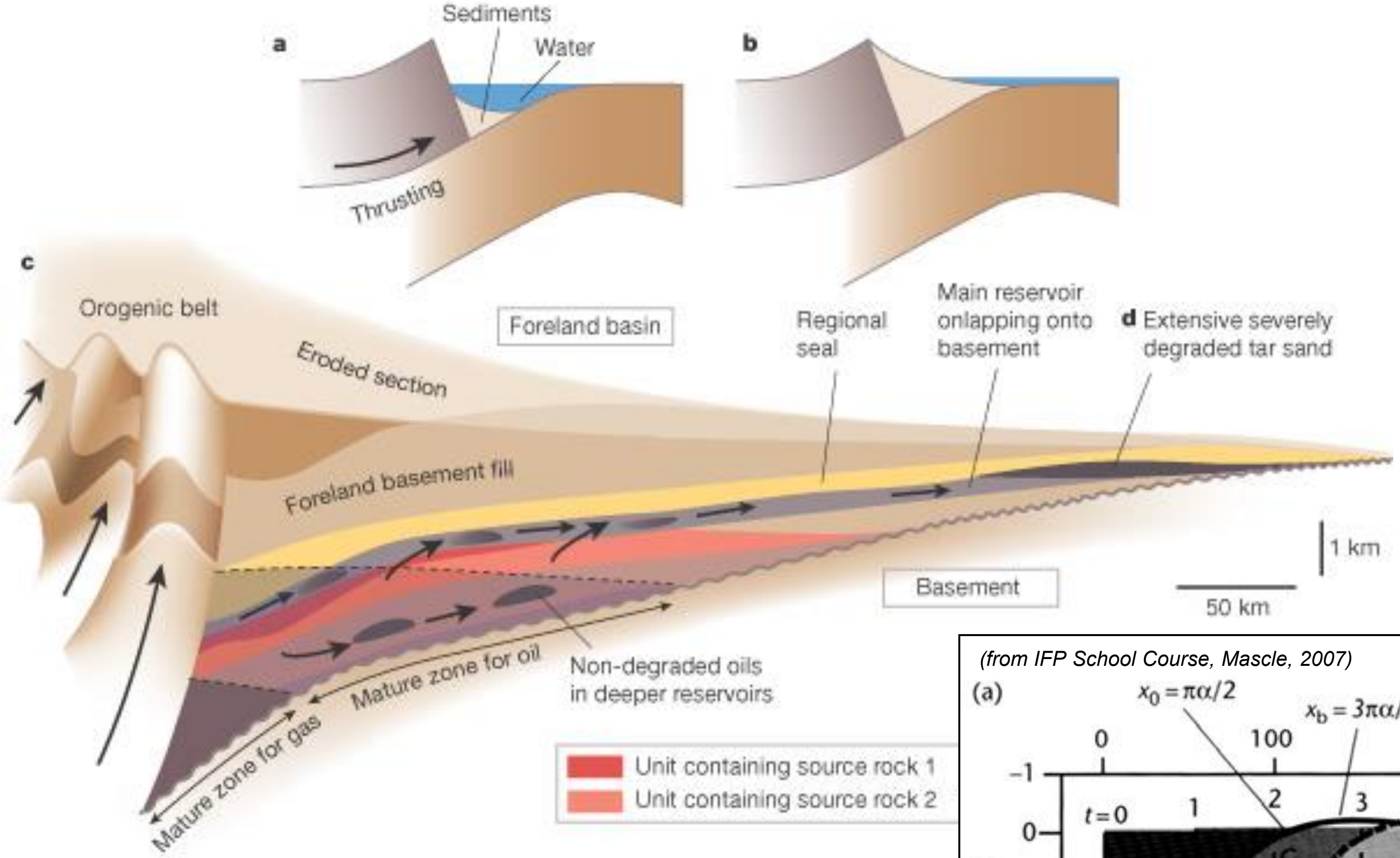
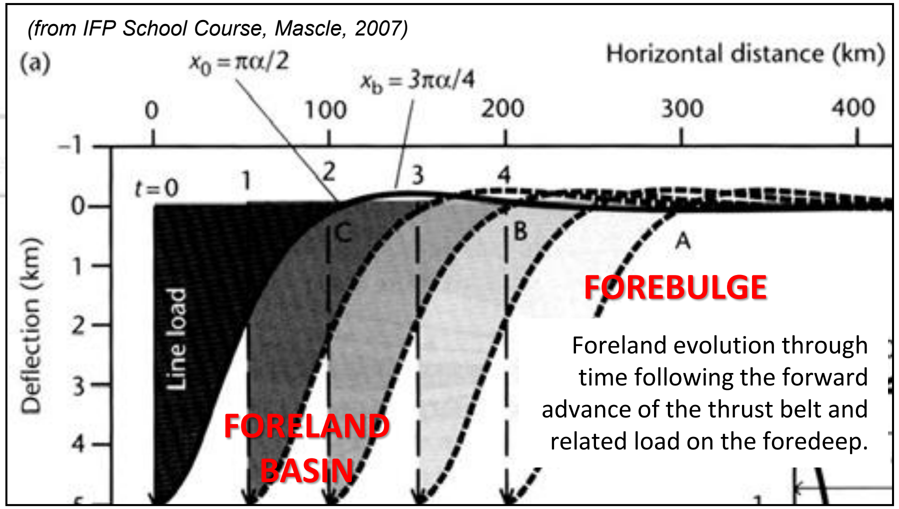
CONVERGENT

Renewable energies

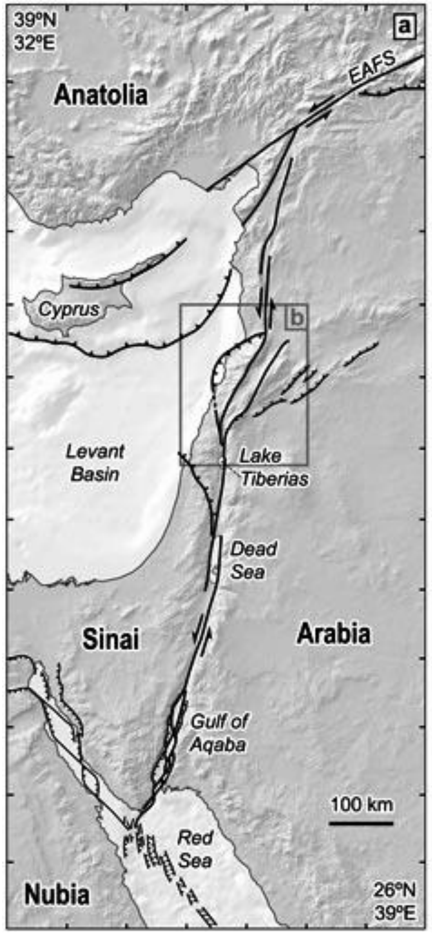


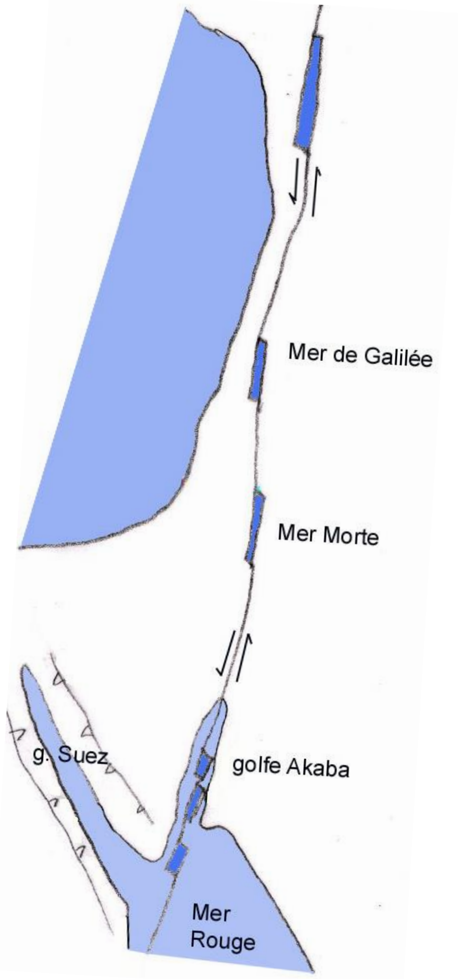


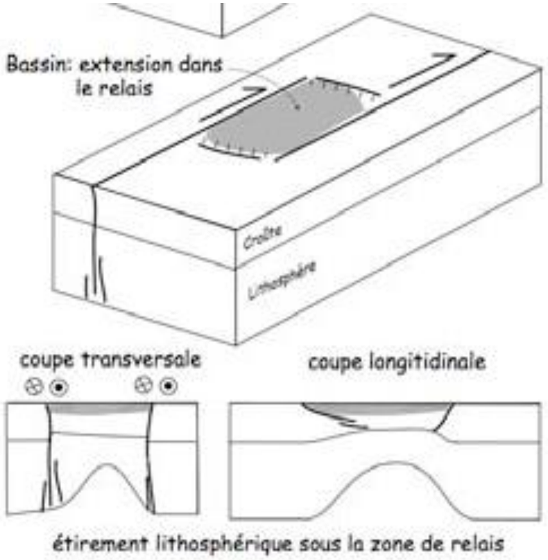
IFP Energies nouvelles

TRANSCURRENT : PULL APART

Renewable energies







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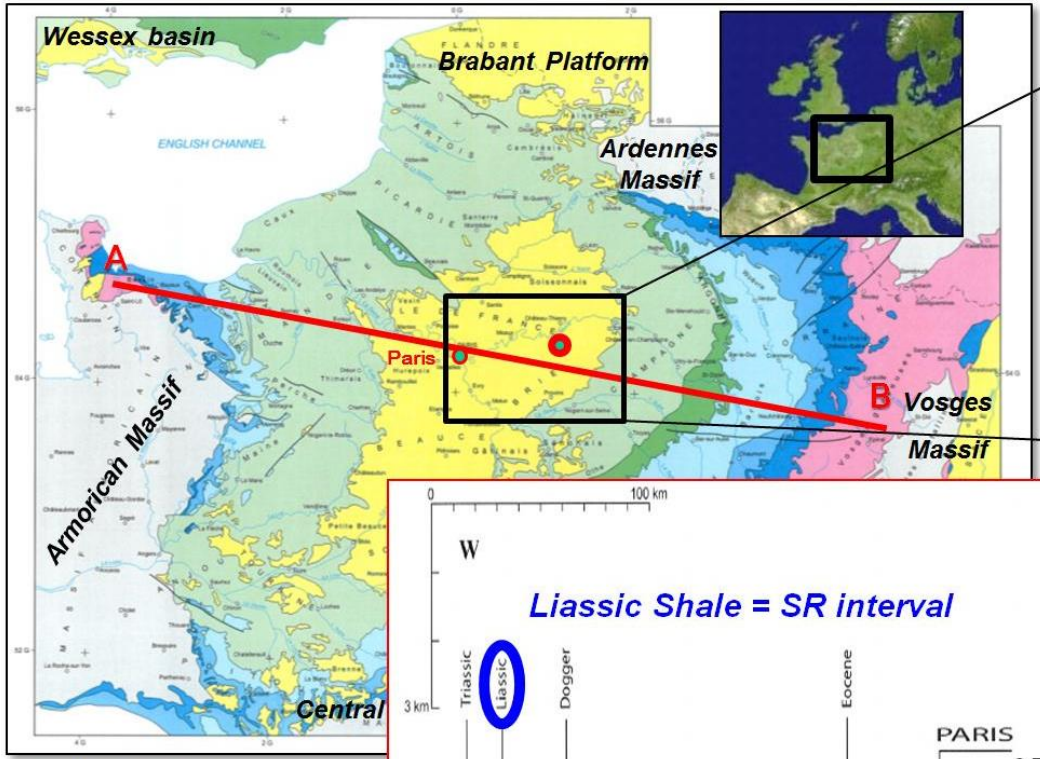
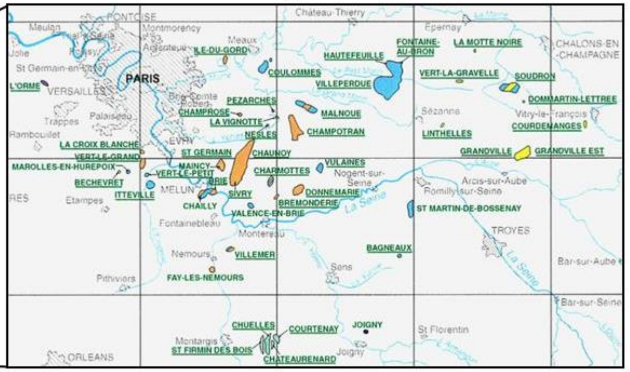
IFP Energies nouvelles

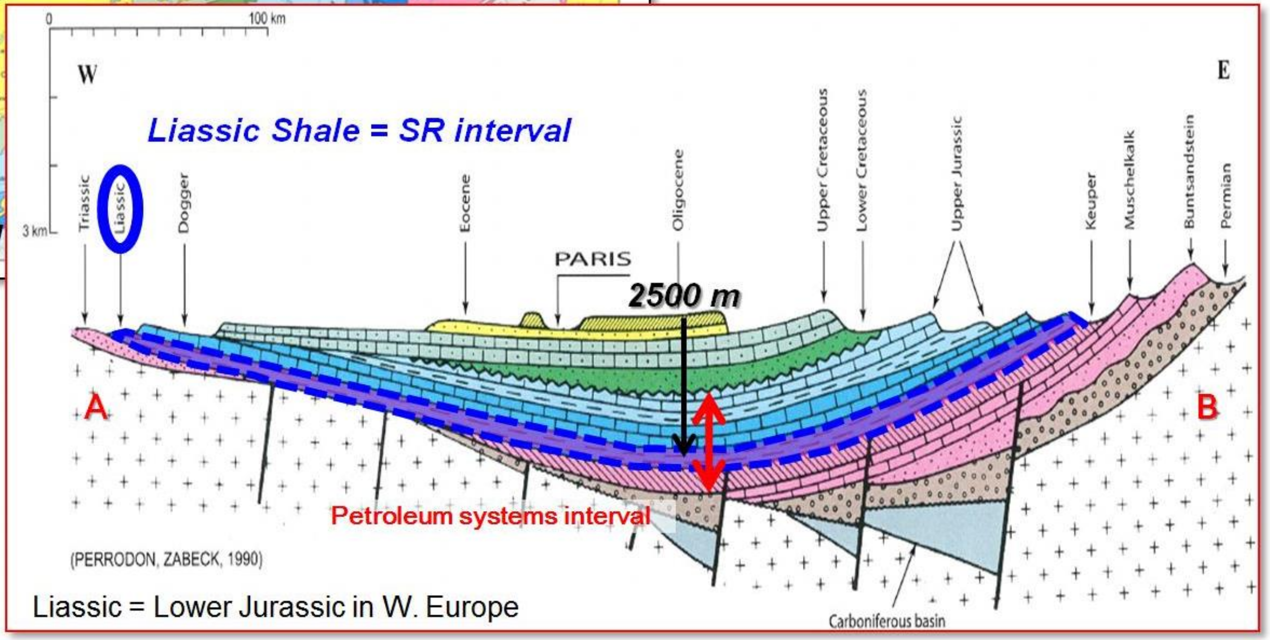
INTRACRATONIC



From IFP Report, 2002

Conventional petroleum fields





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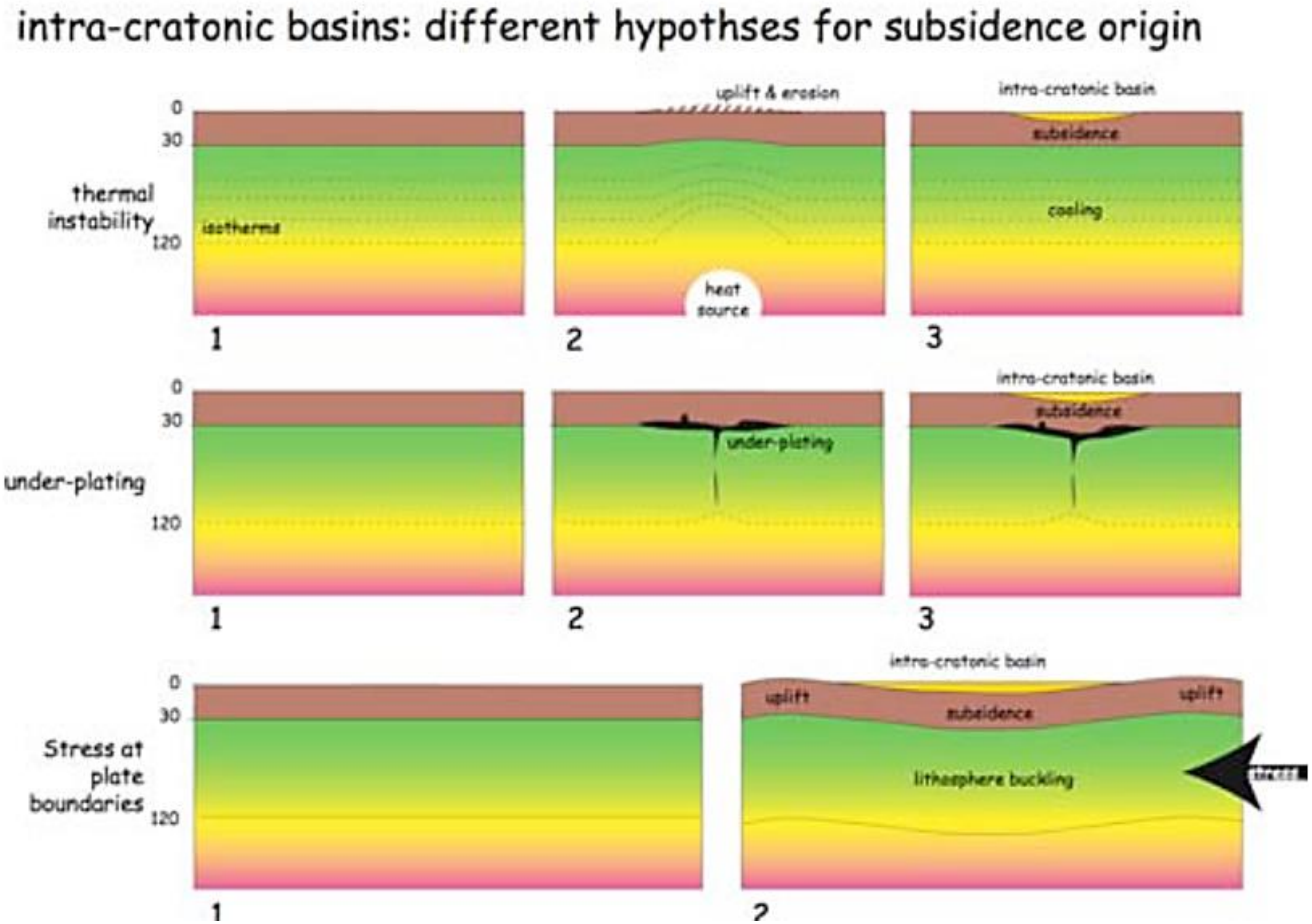

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GEOTHERMAL ENERGY

Introduction to geothermal energy

- What is geothermal energy?

Geothermal Energy in the Renewable Energy mix, status, and evolution

Classification

Different use of geothermal energy; Resource <-> Usage

Electricity generation & Direct use

- Thermal processes in the earth system

Geodynamic and surface heat flow

Lithospheric thickness and composition

Punctual thermal perturbation:

Kinematic, magmatism, radiogenic heat production, hydrology

- Geothermal energy in sedimentary basins

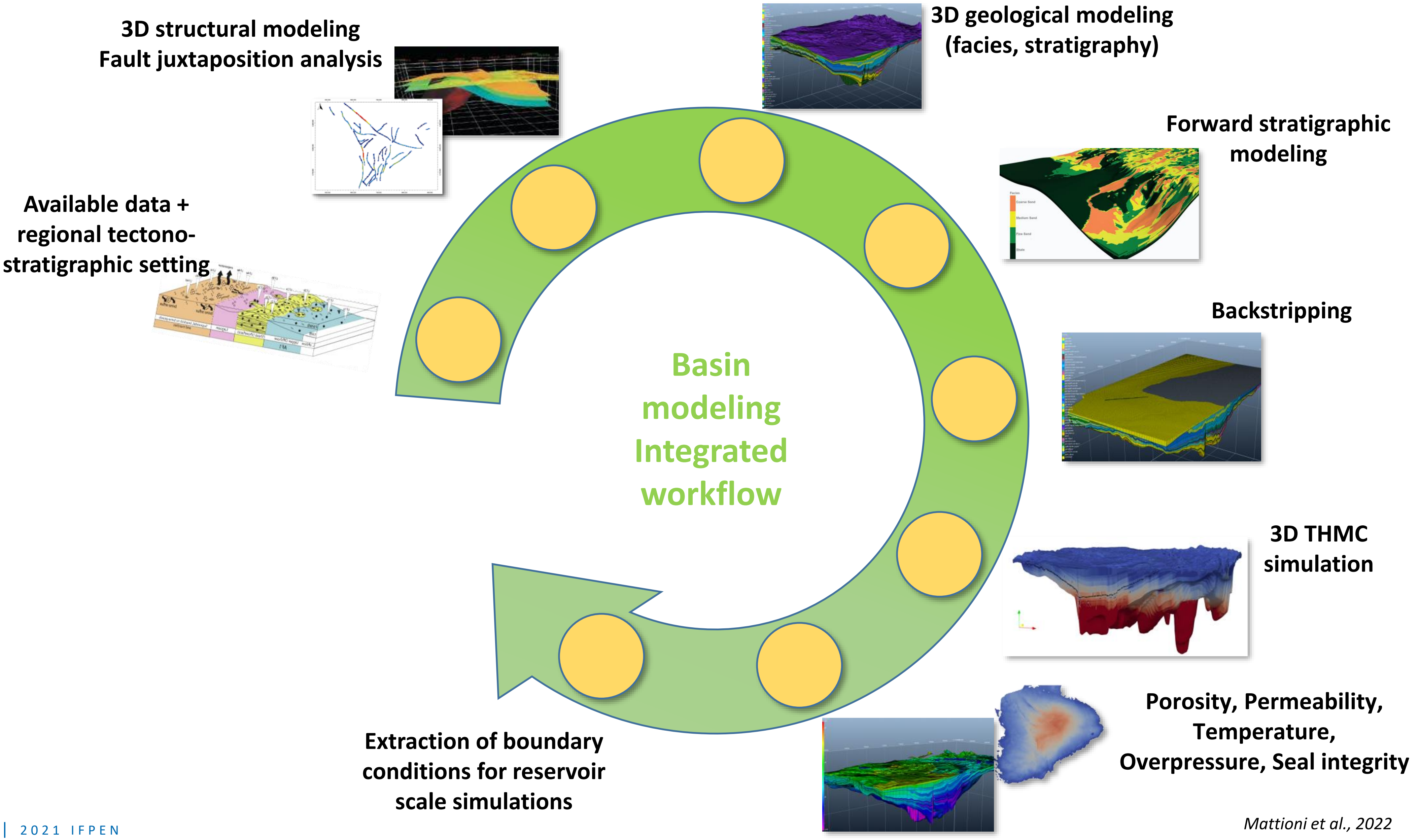
General principles on sedimentary basins

Modelling geothermal energy

Geothermal energy potential in India

EXPLORATION > BASIN SCALE – INTEGRATED APPROACH

Renewable energies



Mattioni et al., 2022

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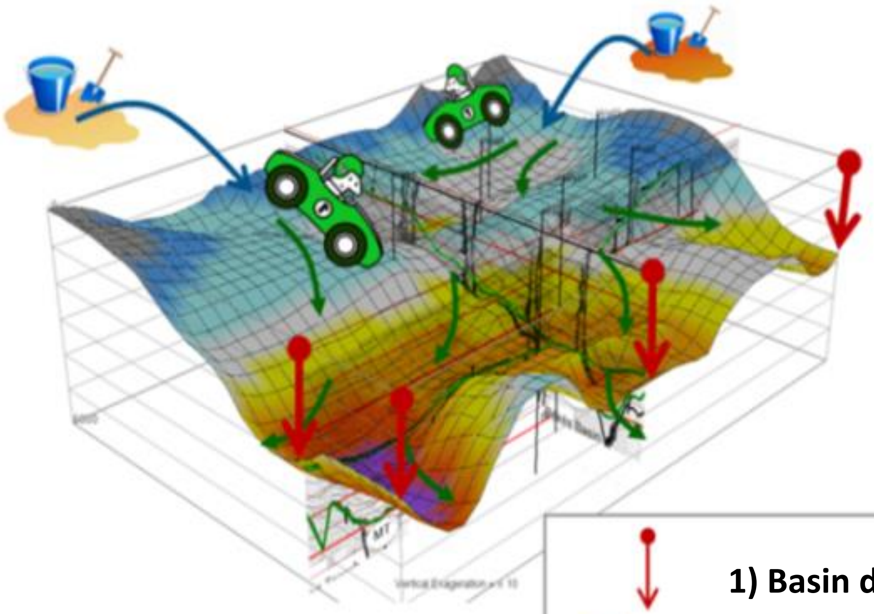
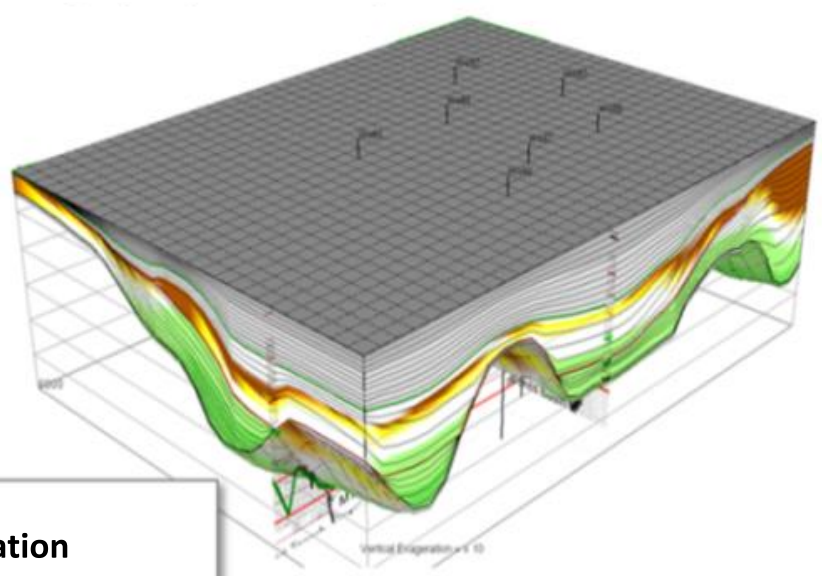
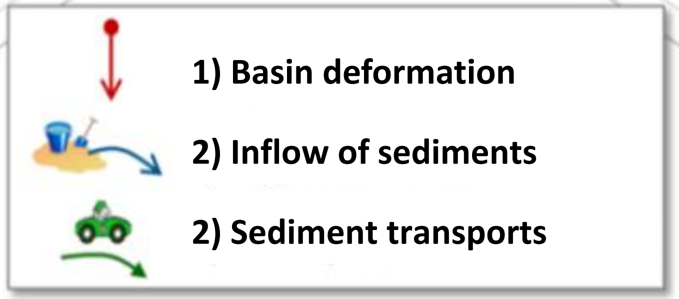
- Principles of the forward stratigraphic modelling
  - Constructing sedimentary basins by modelling basin scale processes (space – 10s to 100s of km / time – 1s to 100s of Ma)
  - The workflow is constraints by data: parameters estimated from seismic data and well logs constraining the simulation over the data
  - The workflow is driven by concepts: forward stratigraphic modelling of the stratigraphic processses.

Simulated processes in a digital stratigraphic model



Example of a result for a digital stratigraphic model





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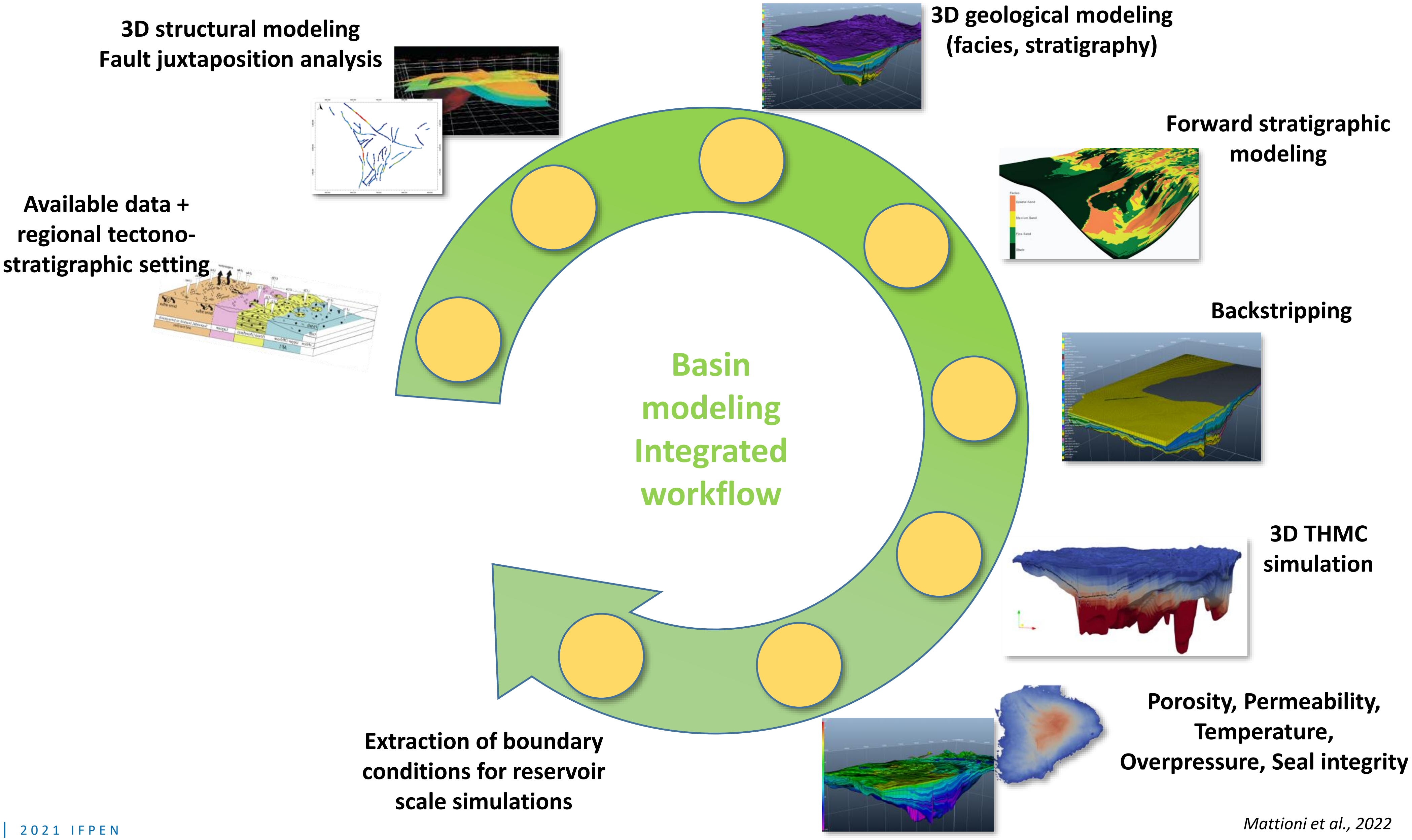
EXPLORATION > BASIN SCALE – INTEGRATED APPROACH

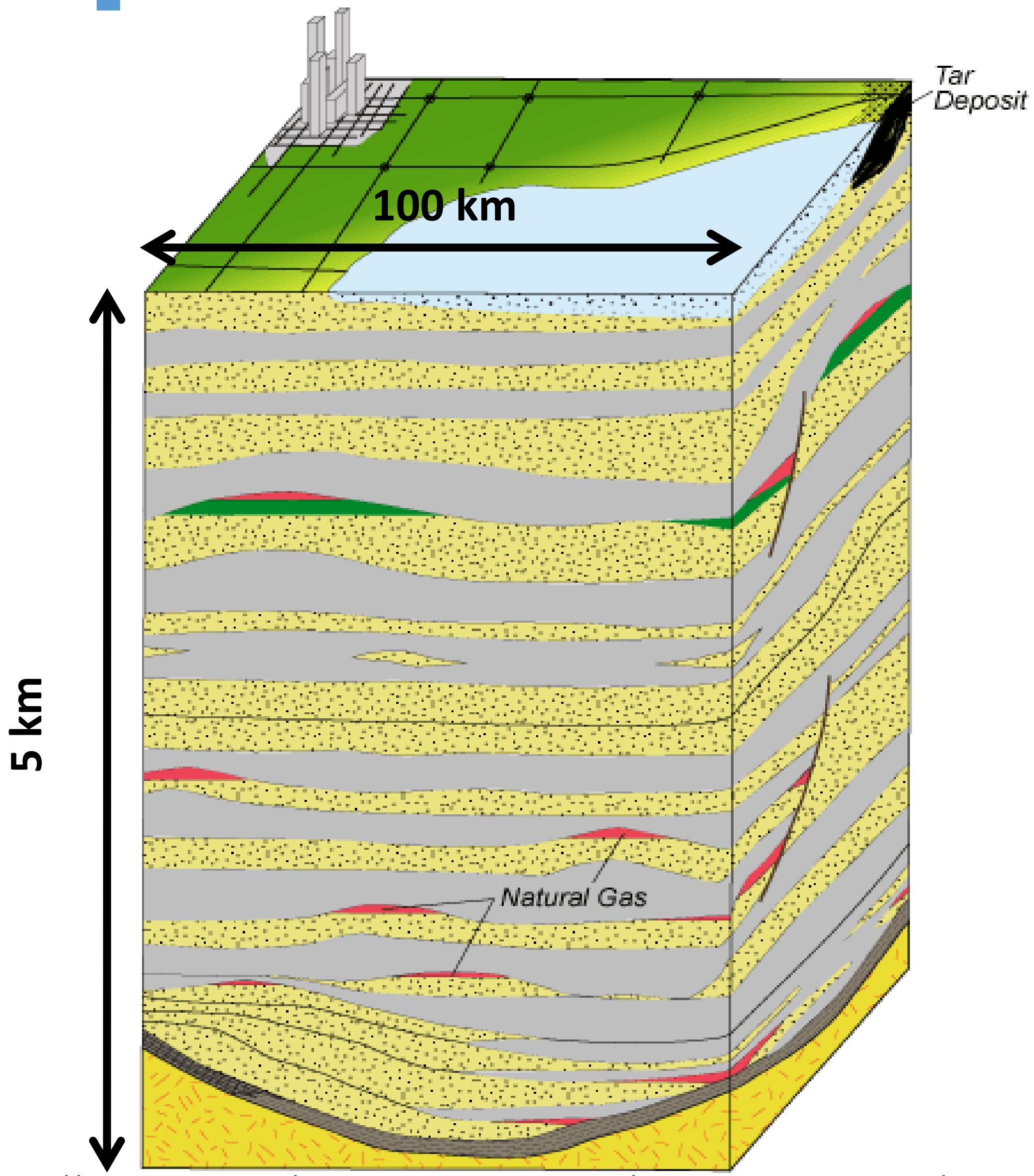
Renewable energies



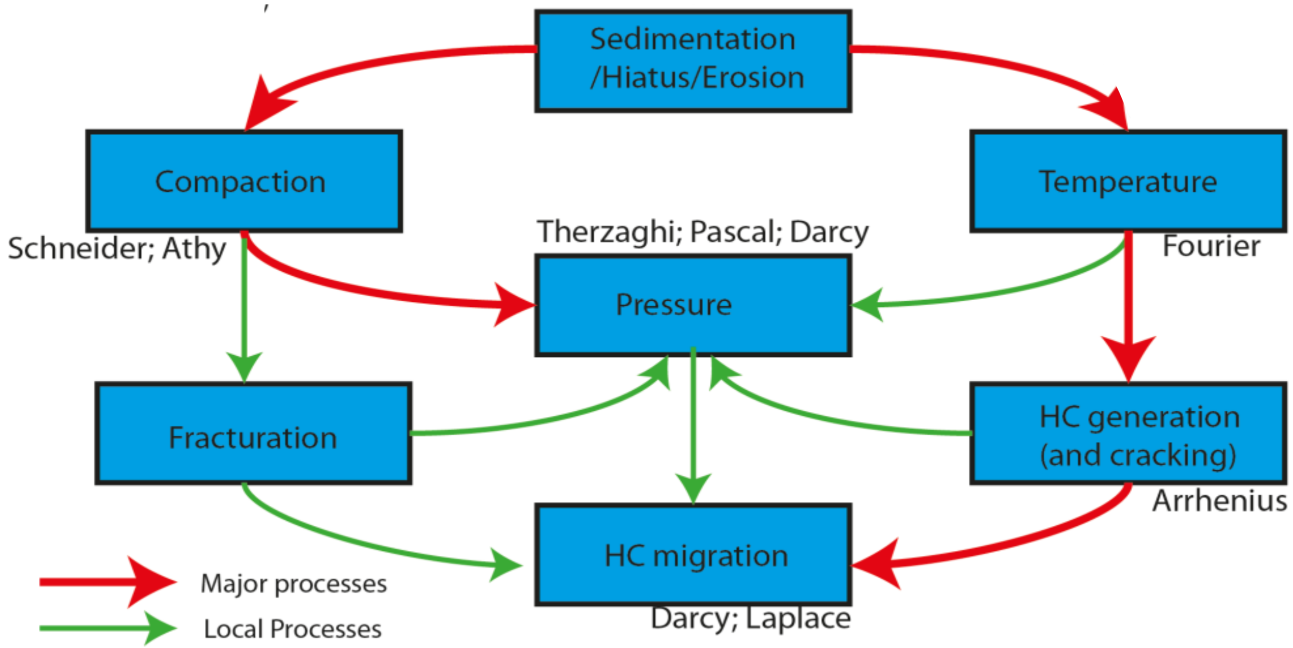
Mattioni et al., 2022

EXPLORATION > BASIN SCALE

Renewable energies



Simulation THMC



http://energy.usgs.gov/GeochemistryGeophysics/GeochemistryResearch/OrganicOriginsofPetroleum.aspx

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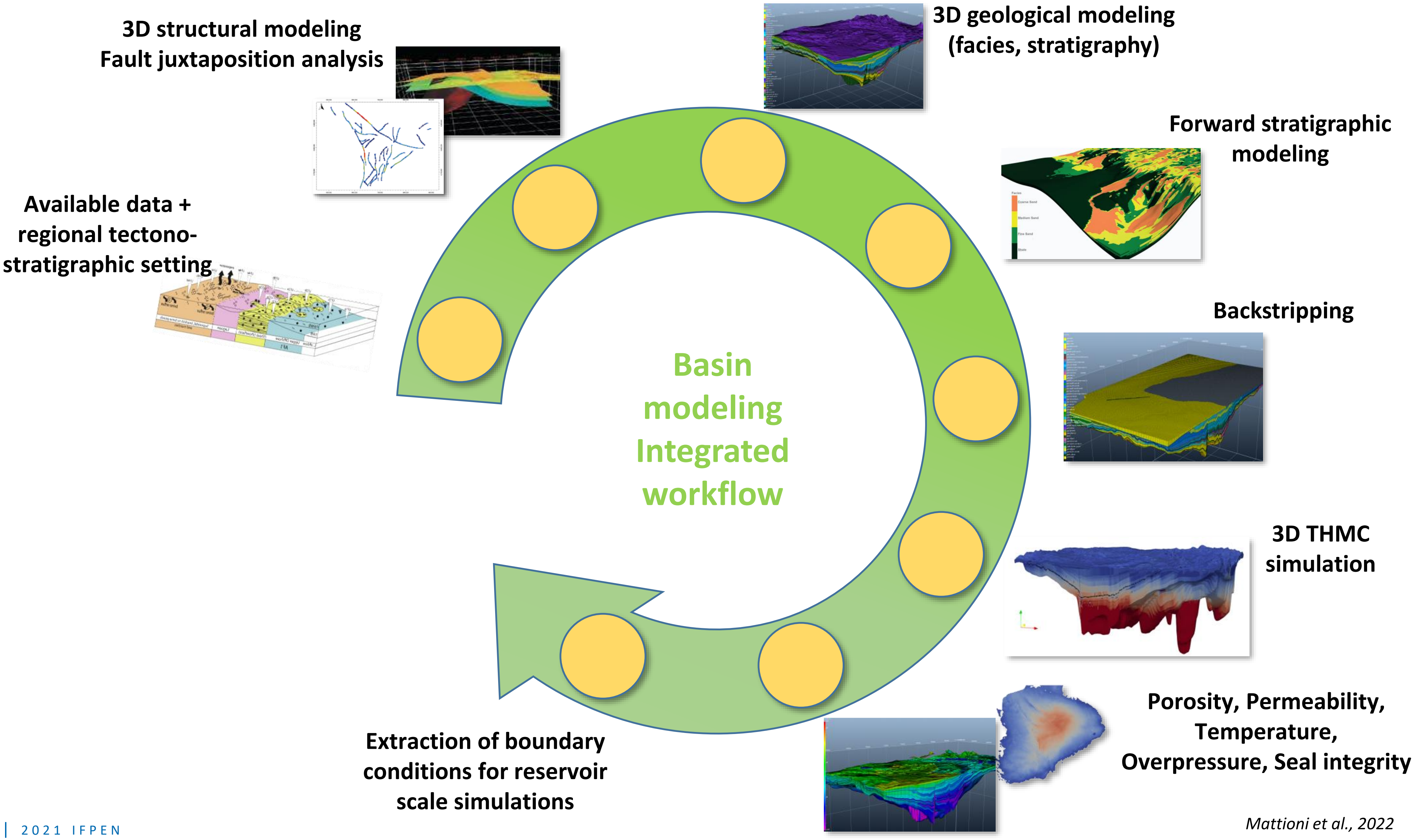
EXPLORATION > BASIN SCALE – INTEGRATED APPROACH



Mattioni et al., 2022

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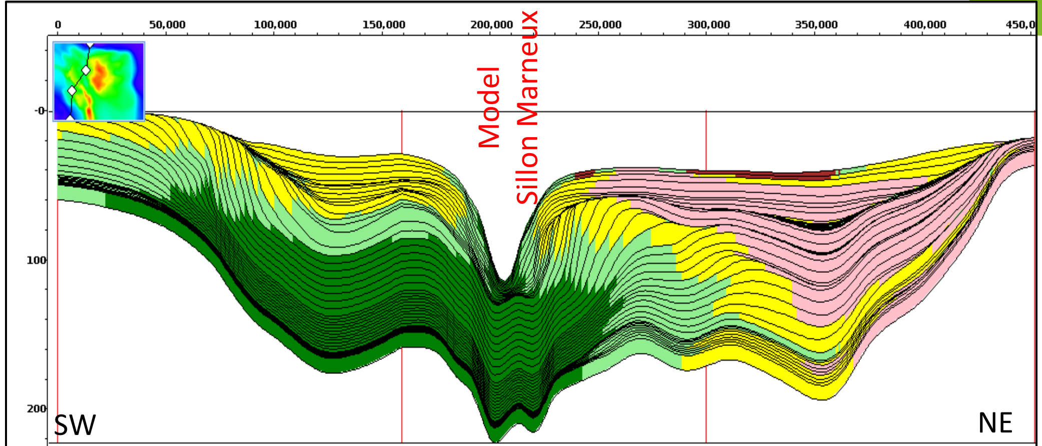
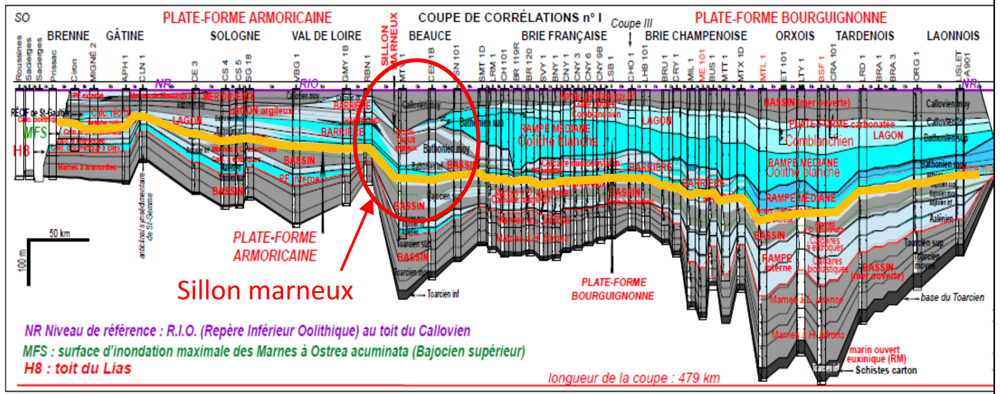
EXPLORATION > BASIN SCALE

- Stratigraphic modelling of the Dogger in the Paris Basin (Mattioni et al. 2022, target CCUS)
- Achieve a simulations that allows a good fit with the data :
  - Total thickness of the deposits (Delmas et al., 2013)
  - Facies distribution (Delmas et al., 2013)
  - Stratigraphic cross section from the literature

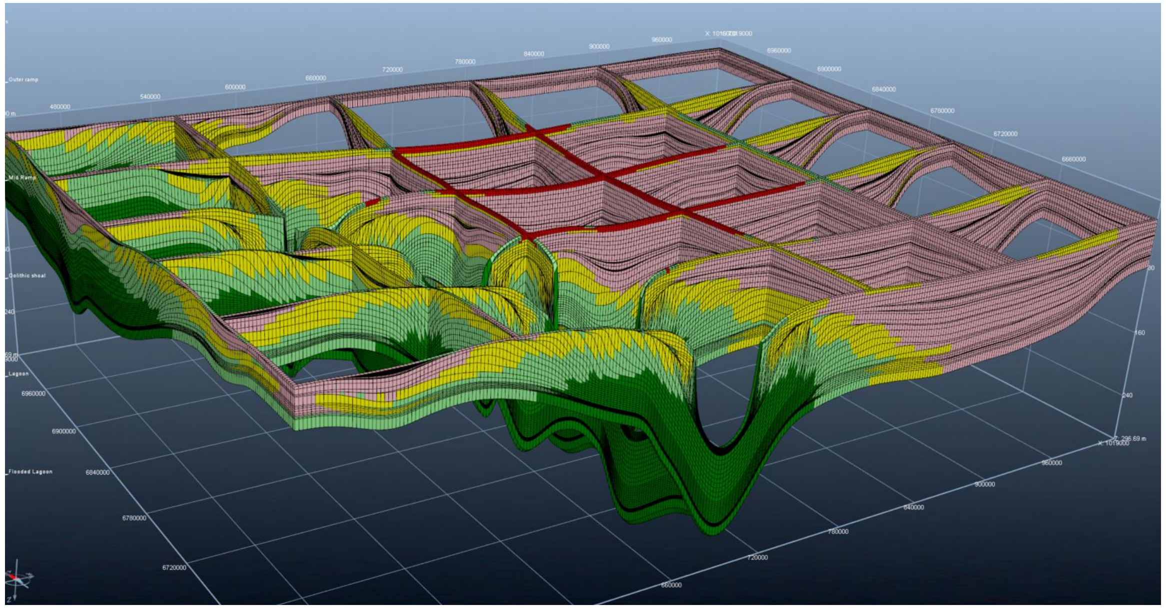


Mattioni et et al., 2022



Delmas et et al., 2013

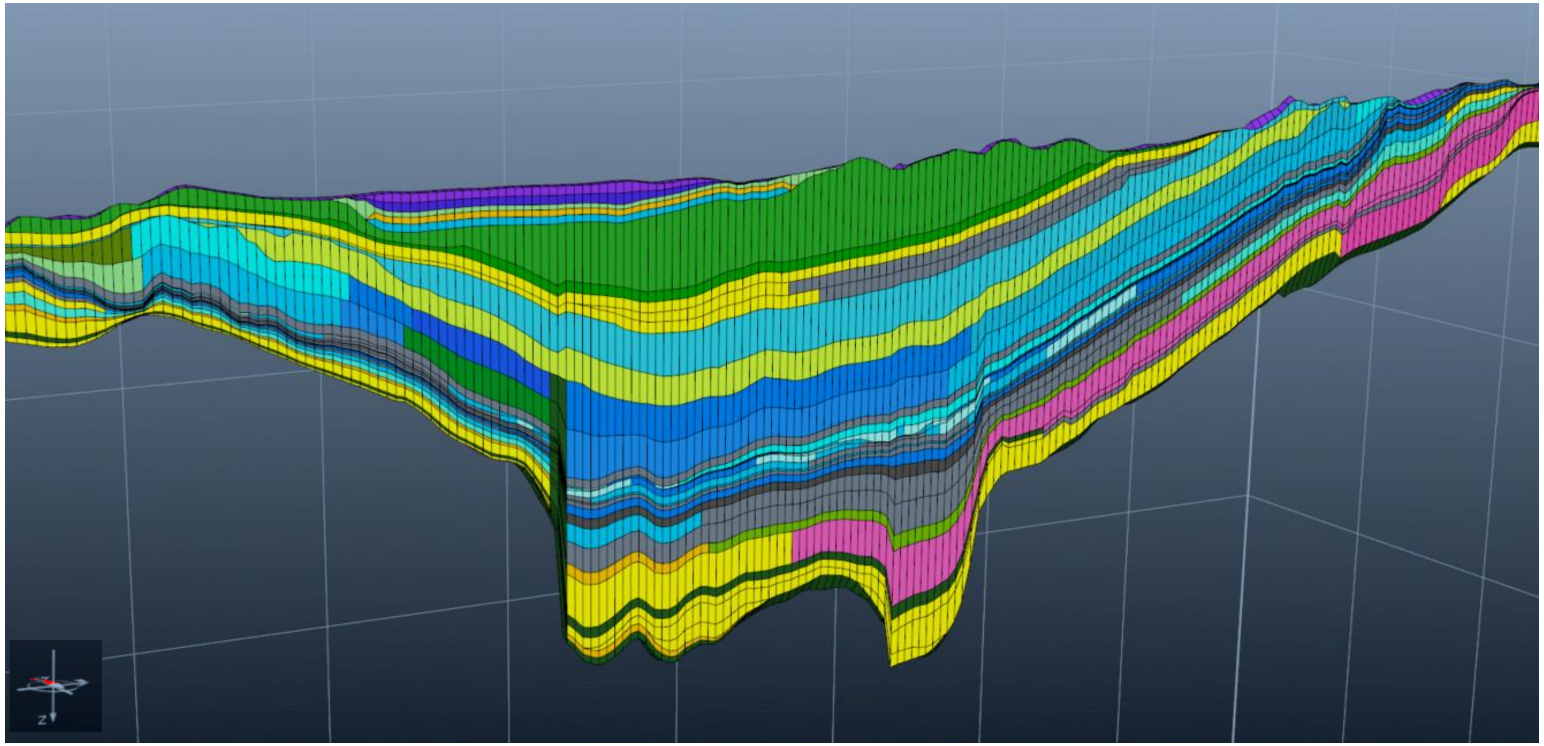
- Flooded lagoon (Dalle Nacrée Fm)
- Lagoon (Comblanchian Fm)
- Oolithic Shoal (Oolithe blanche Fm)
- Outer ramp (sillon marneux)
- Mid ramp

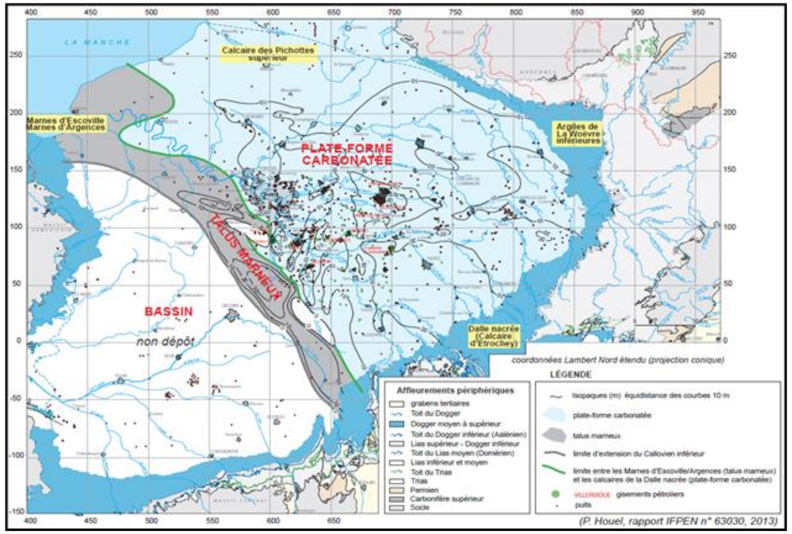


Mattioni et et al., 2022

EXPLORATION > BASIN SCALE

Renewable energies





- The « sillon marneux » provides an efficient seal for HC, preventing its migration towards the western part of the Paris Basin.
- Its presence is one of the major critical parameters (but not the only) that explains the lack of important HC accumulations in the western part of the Paris Basin.

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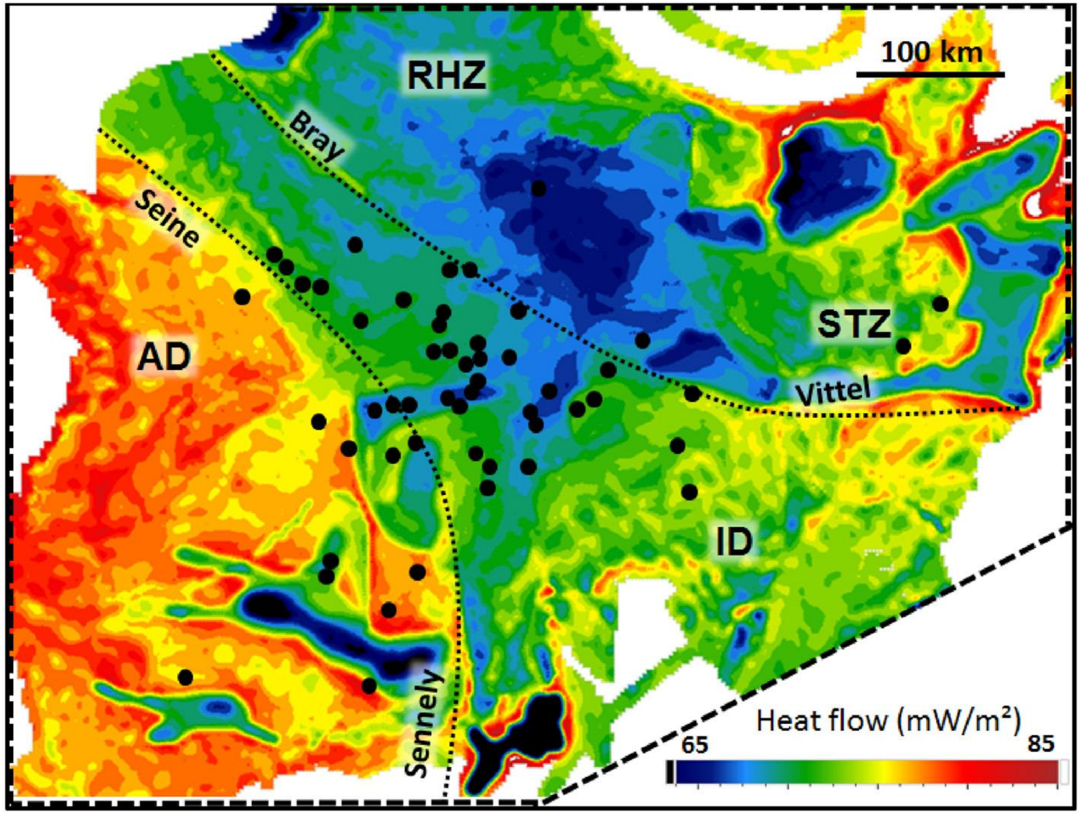
EXPLORATION > BASIN SCALE

Renewable energies



Torelli et al., 2022

- The THC modelling (Torelli et al., 2020) shows that the thermal structure in the basin is dominated by the conduction, no heat advection has been identified.
- The obtained heat flow map at the base of the sediments shows a variability mostly related to the structure and nature of the basement but also in relation with the overlying sedimentary cover (cold area = depocenter and permo-carboniferous basins). The impact of the couple basement-cover on the map justify the couple modelling. The flow varies between 65 and 85 mW/m2.
- A better understanding of the thermal history, a better evaluation of the eroded volumes and therefore a better calibration of the flowing mechanism.

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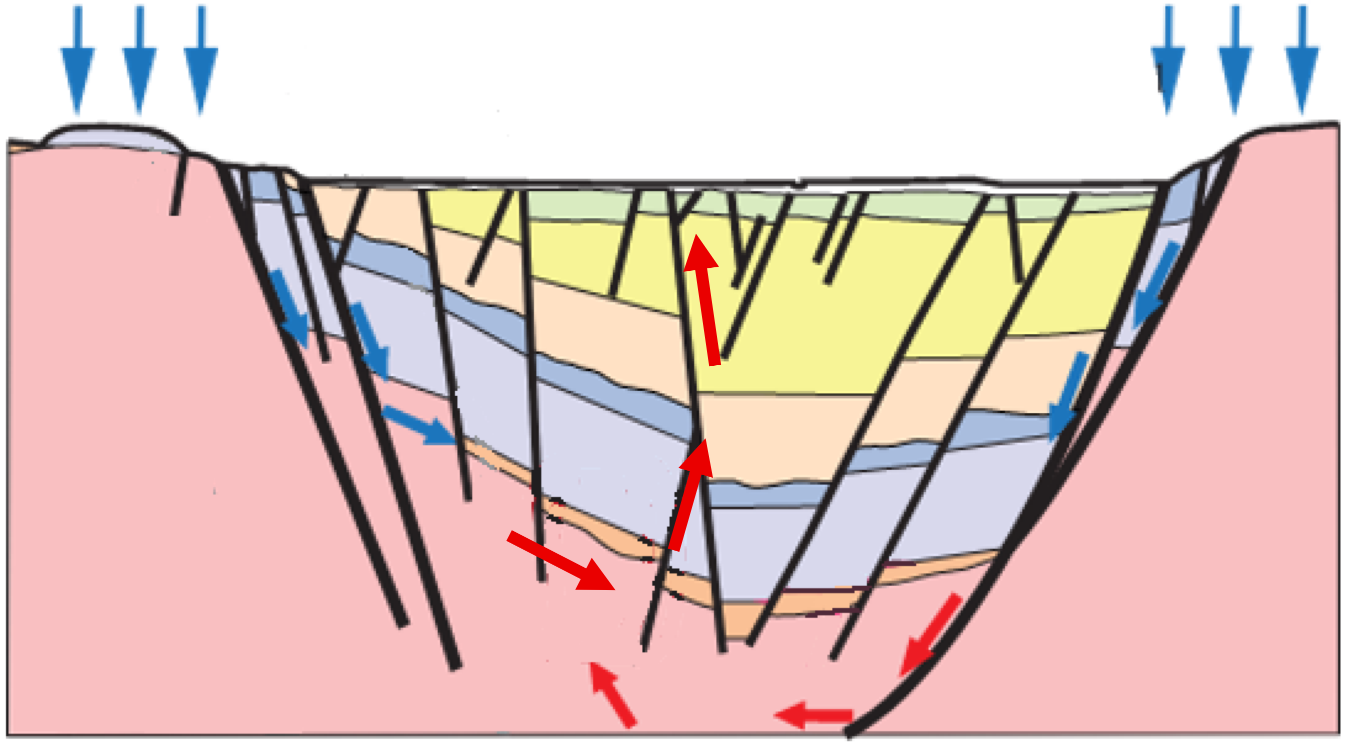
EXPLORATION > BASIN SCALE – FAULTS AND FLUID ADVECTION

Renewable energies

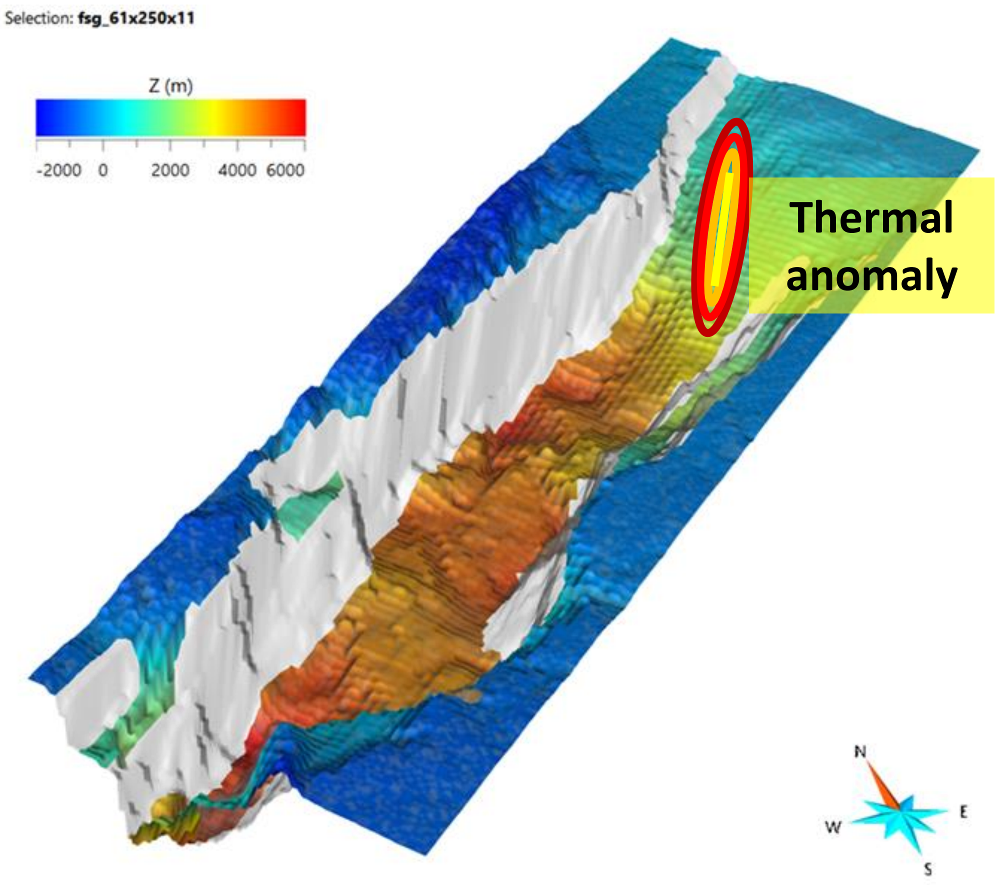
Conceptual scheme:

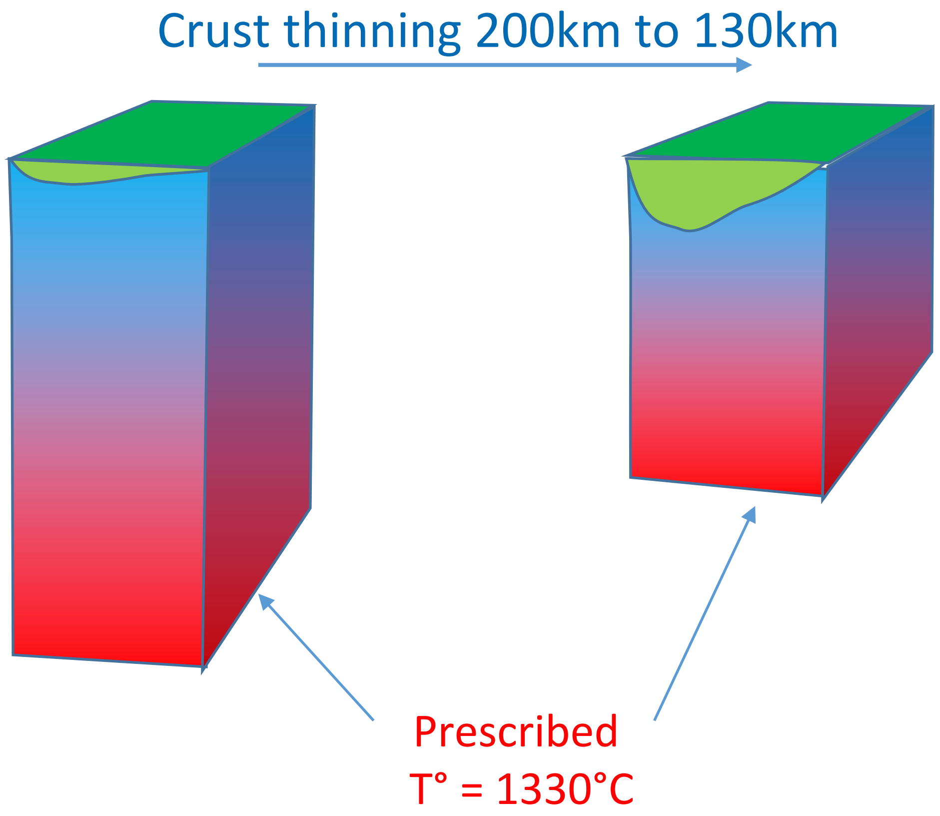


Adapted from Dezayes, 2018

EXPLORATION > BASIN SCALE - HYDROTHERMAL SYSTEM MODELING

Renewable energies

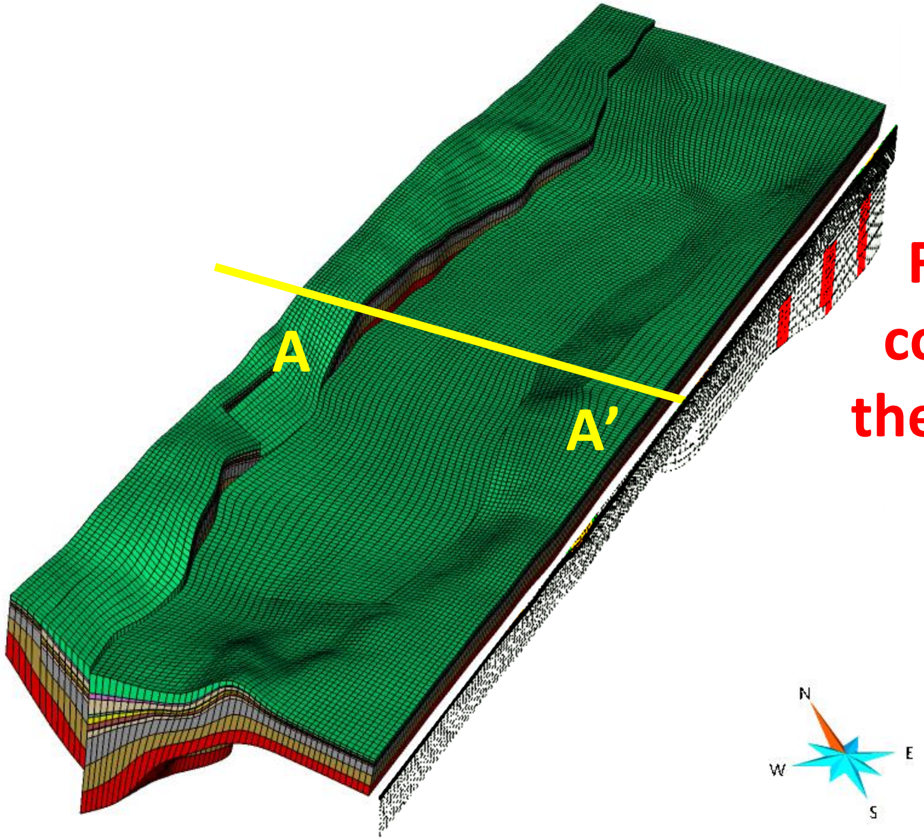




Cacas-Stentz et al., 2021

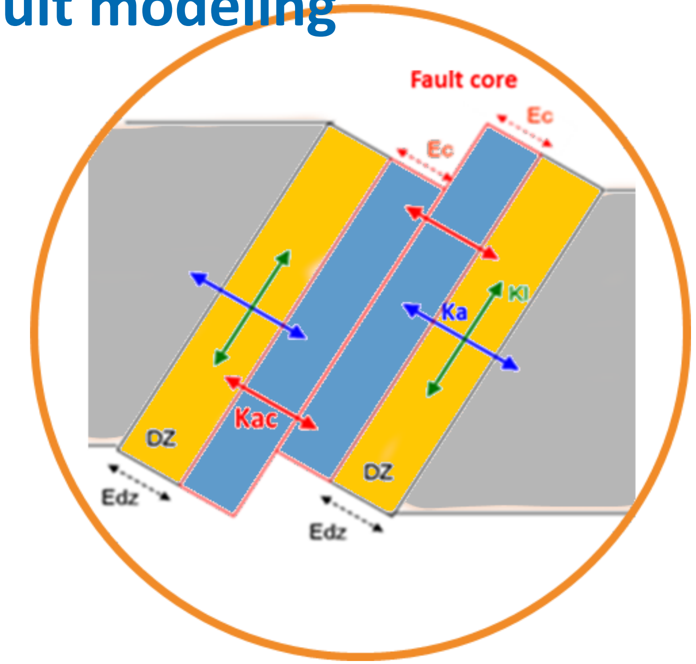
EXPLORATION > BASIN SCALE – HYDROTHERMAL SYSTEM MODELING

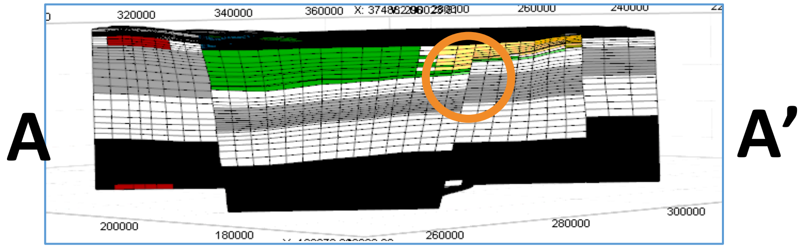
Renewable energies



Fractured corridors in the basement

Fault modeling

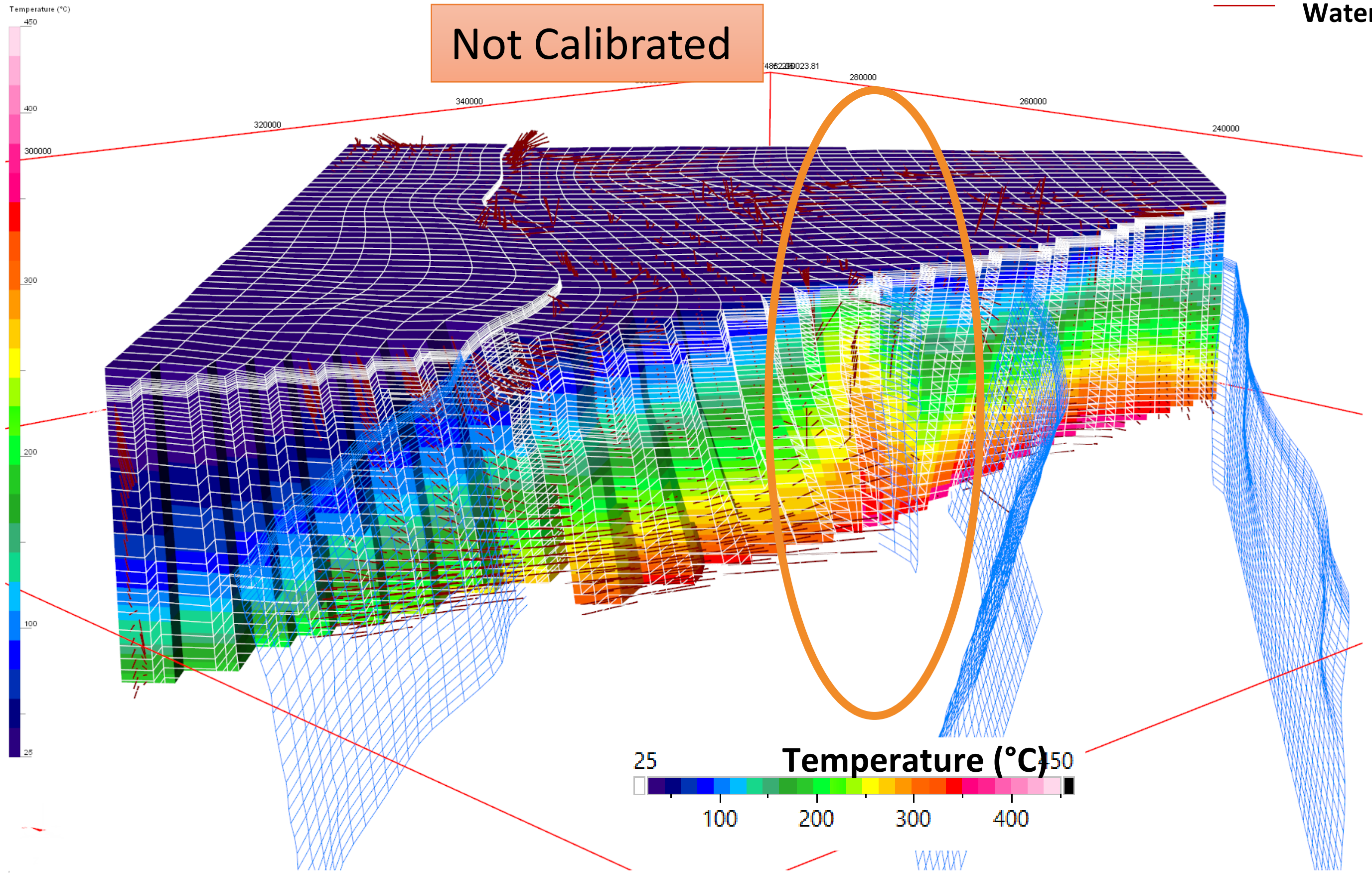


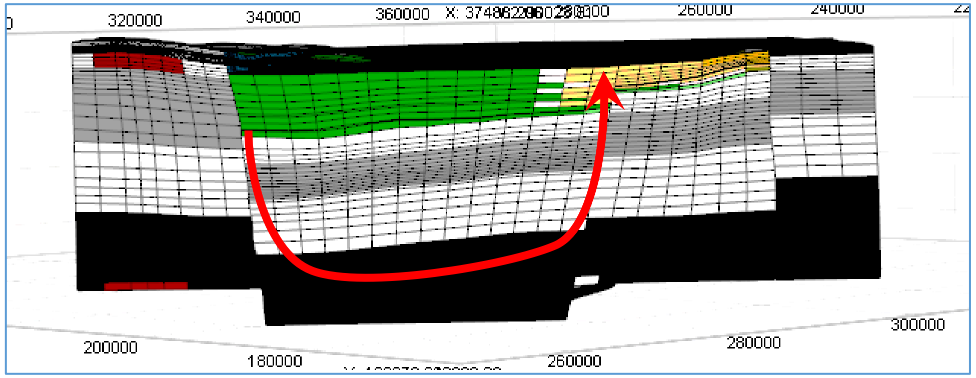


Cacas-Stentz et al., 2021

EXPLORATION > BASIN SCALE – THERMAL RESULTS WITH ADVECTION

Renewable energies



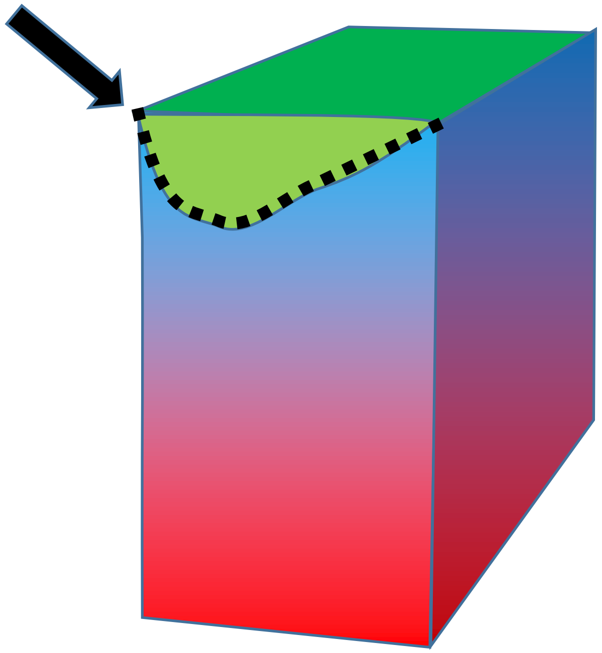


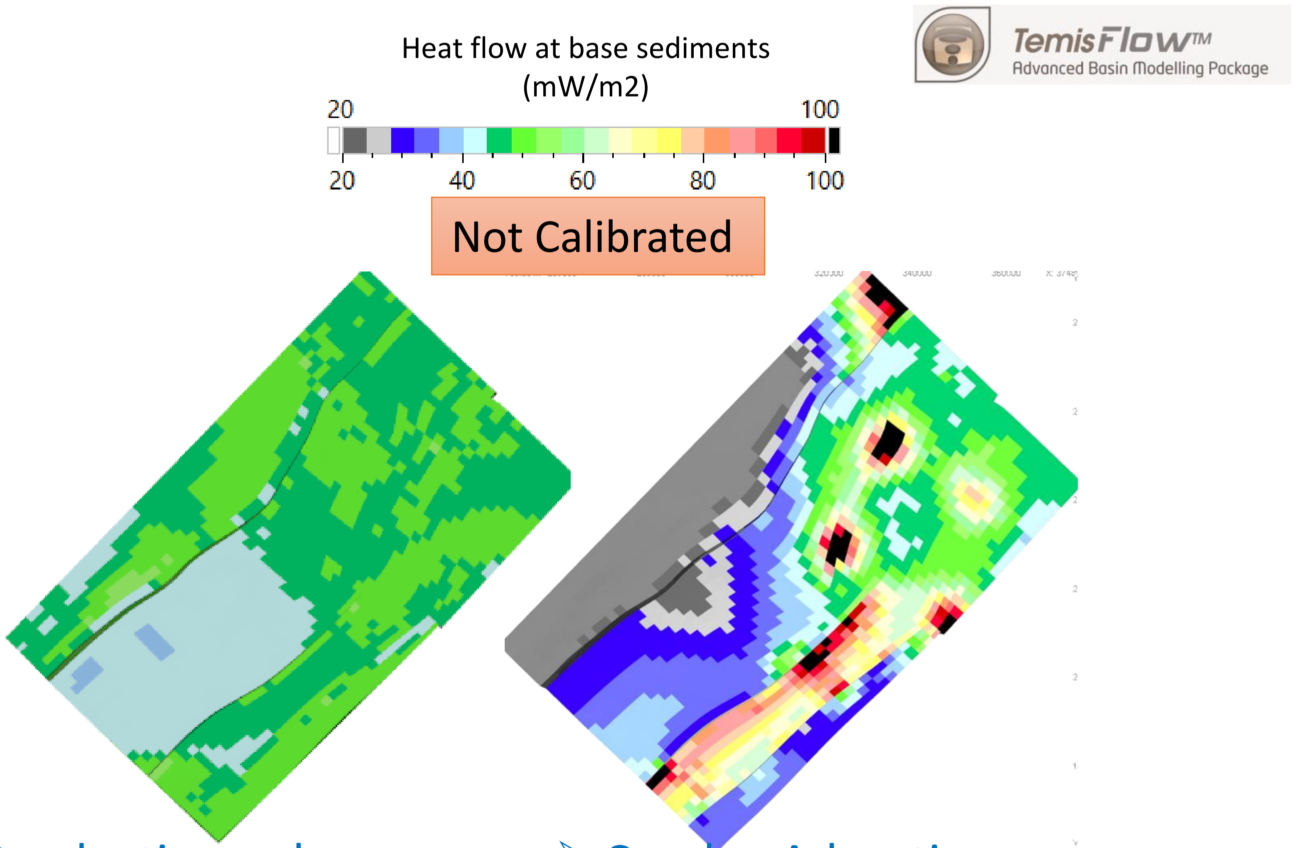
TemisFlow™ Advanced Basin Modelling Package

Cacas-Stentz et al., 2021

EXPLORATION > BASIN SCALE – HYDROTHERMAL SYSTEM MODELING

Heat flux maps at the base of the sediments:





- Conduction only
- Cond. + Advection with fracture zones

Cacas-Stentz et al., 2021

EXPLORATION > BASIN SCALE

- Basin modelling allows:
  - the integration of existing data and testing different geological interpretations (calibration data are required).
  - to test the sensibility of several parameters to identify those who have the most impact on the overall geothermal potential and focus the acquisitions.
  - the creation of potential maps.
- Modelling tools are appropriate for geothermal exploration, but can be completed to go further
- Requirements:
  - Ongoing work on the taking into consideration of the diagenesis in the stratigraphic modelling.
  - Working on the recharge and its evolution through time.
  - Consideration of minerals rich in lithium and lithium mobility towards the geothermal fluid.

GEOTHERMAL ENERGY

Renewable energies

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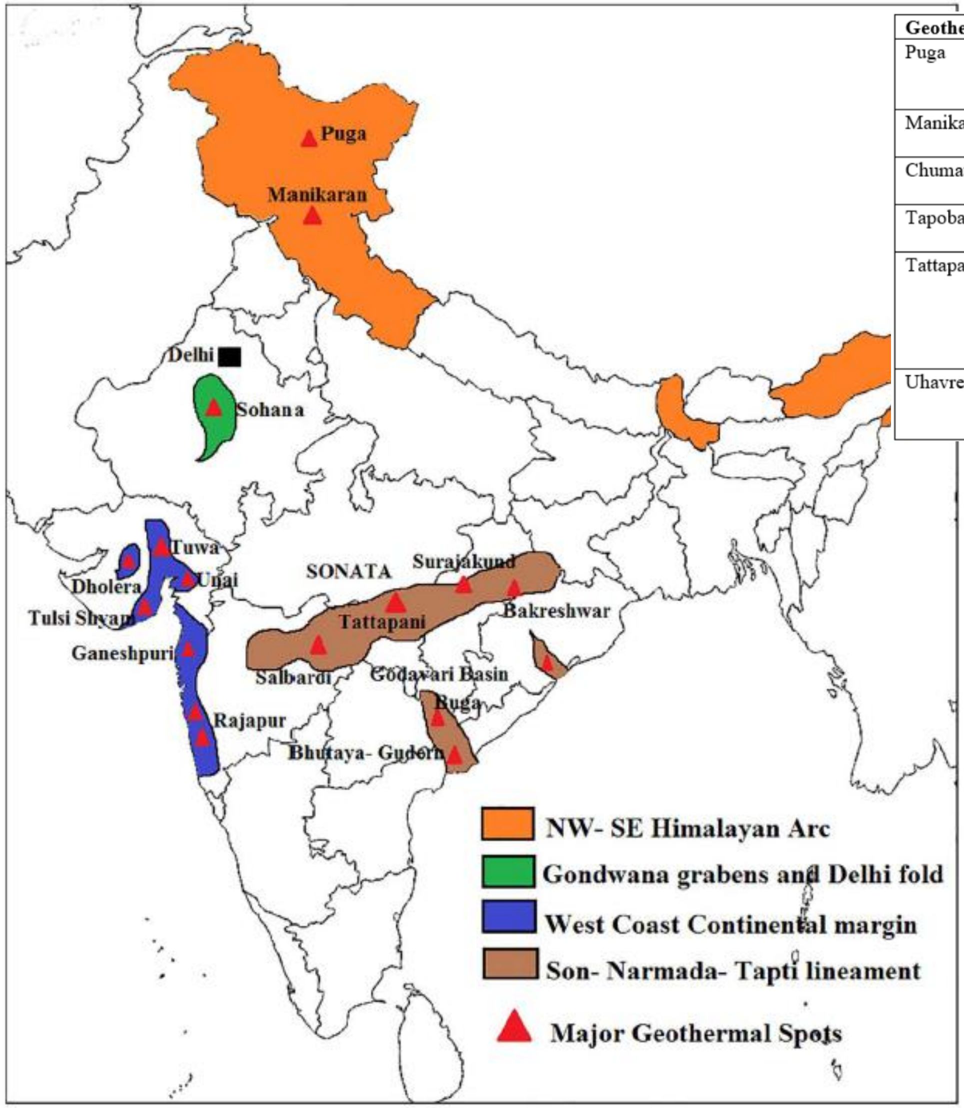
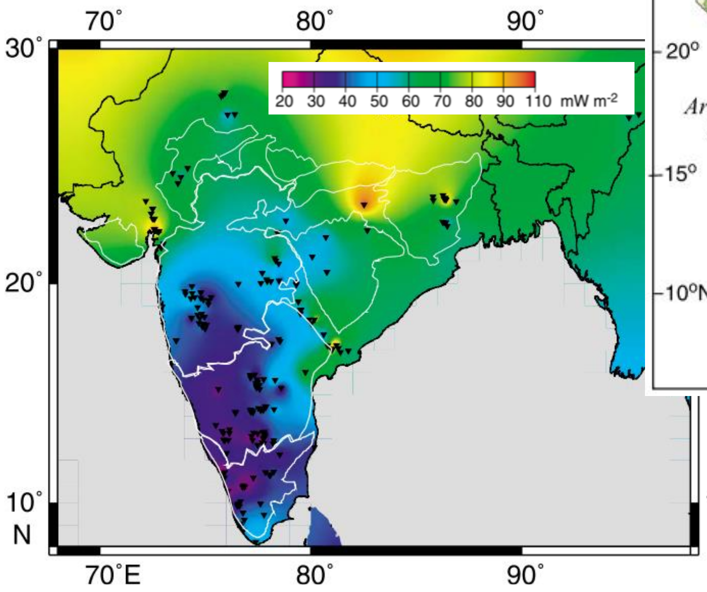
GEOTHERMAL ENERGY – POTENTIAL IN INDIA

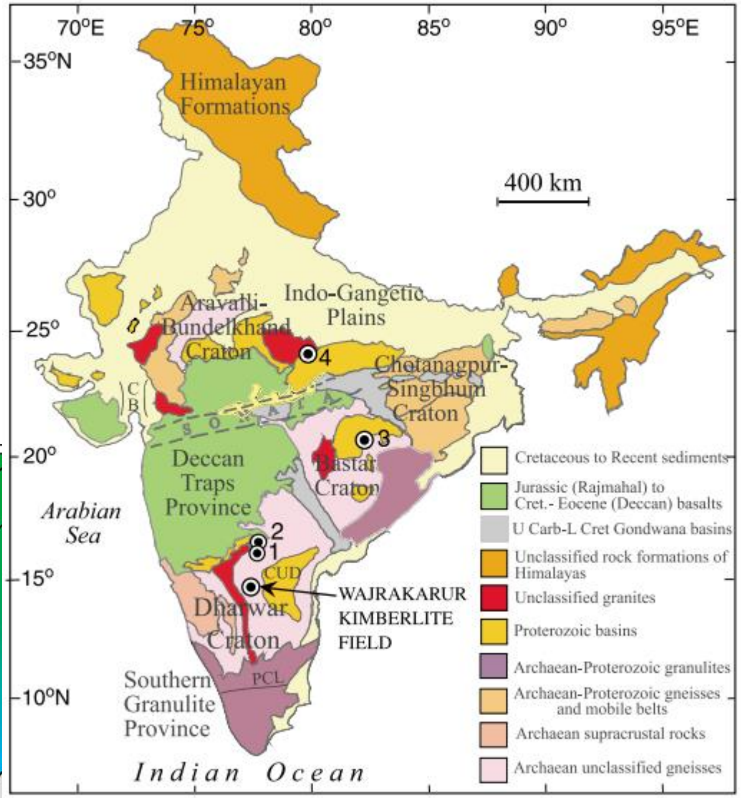


Yadav & Sircar(2021) modified from Chandrasekharam & Chandrasekharam (2015)

Puppala and Jha, 2018

Geothermal Field	Geothermal Province	Direct Uses
Puga	Himalayan	Refinement of Sulphur & borax; Space heating; Poultry farming; Mushroom cultivation
Manikaran	Himalayan	Potato farming, Cold storage, Hot water baths, Spa
Chumathang	Himalayan	Greenhouse cultivation; Growing of vegetables
Tapoban	Himalayan	Green house cultivation; Growing of vegetables
Tattapani	SONATA	Mushroom cultivation; Cold storage; Tourist development (Spa); drying & caning of fish; Cocoon boiling for extraction of silk; Space heating purpose
Uhavre Ked	West Coast	Fish drying; Curing of cement Slabs, Spas, Cold storage; Boiling of mineral water



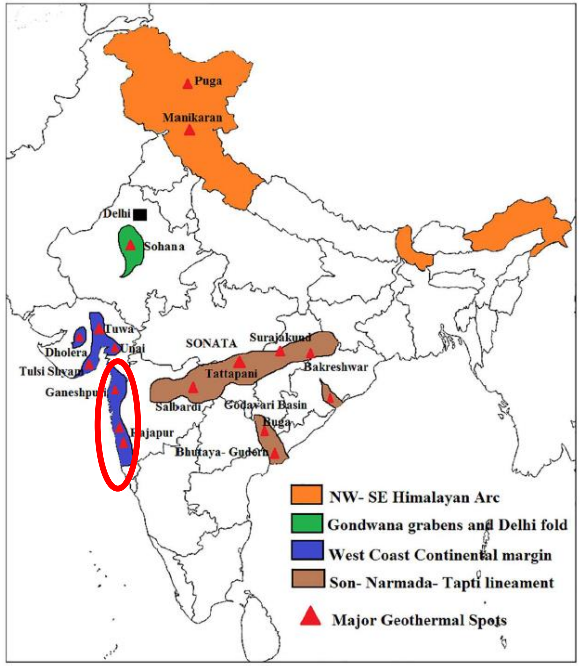


Roy and Mareschall (2011)

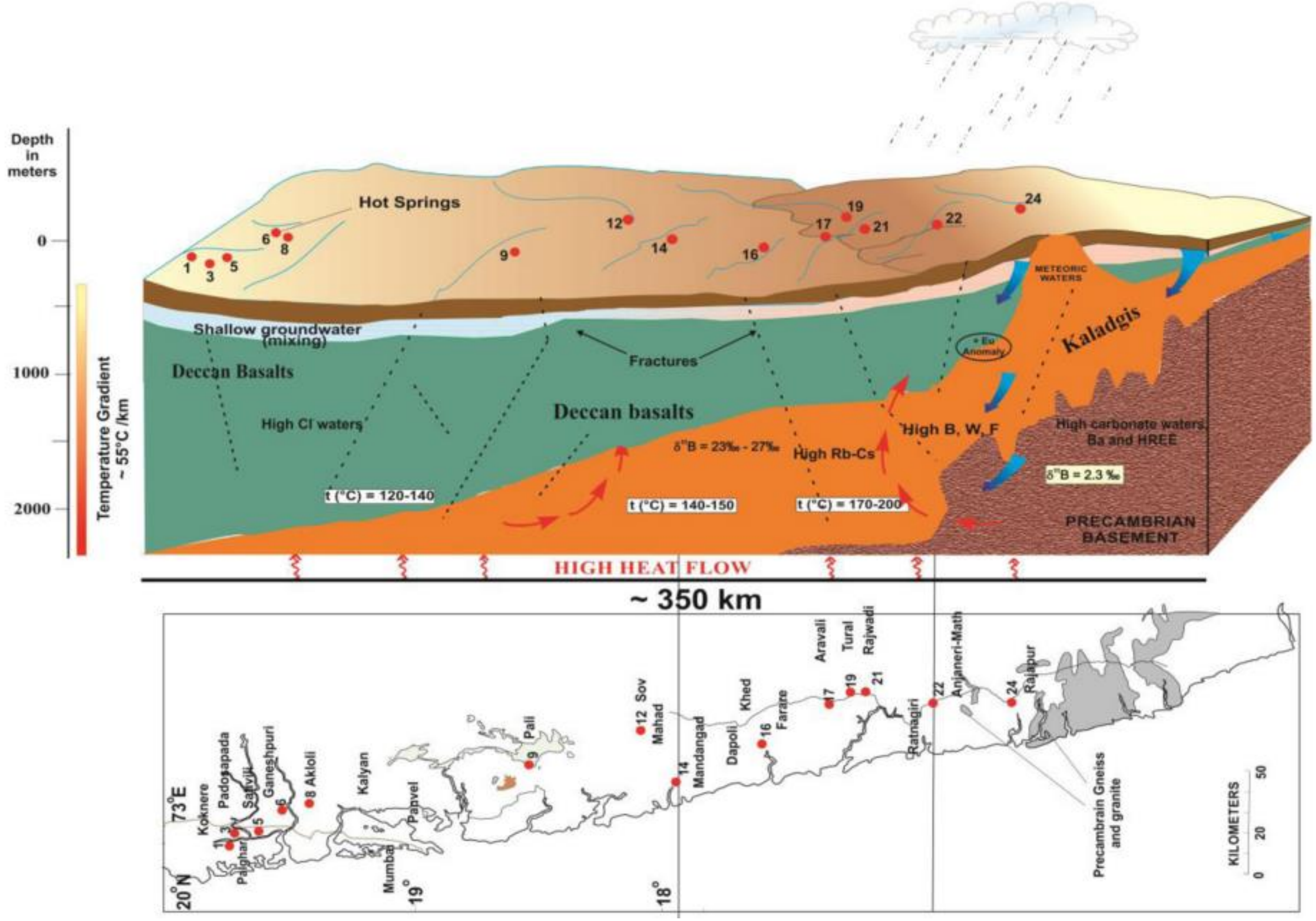
Thermal Province	Temperature at Surface (°C)	Temperature at Reservoir (°C)	Heat Flow (mW/m²)	Thermal Gradient (°C/km)
Himalayan Province	>90	260	468	100
Cambay Province	40–90	150–175	80–93	70
West Coast Province	46–72	102–137	75–129	47–59
Sonata Province	60–95	105–217	120–290	60–90
Godavari Province	50–60	175–215	93–104	60

GEOTHERMAL ENERGY – WEST COAST

Renewable energies



Yadav & Sircar(2021) modified from Chandrasekharam & Chandrasekharam (2015)



Trupti et al (2011)

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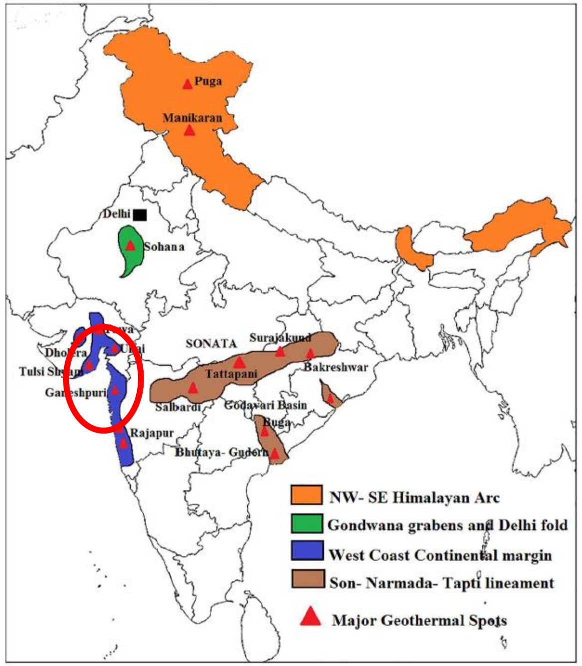
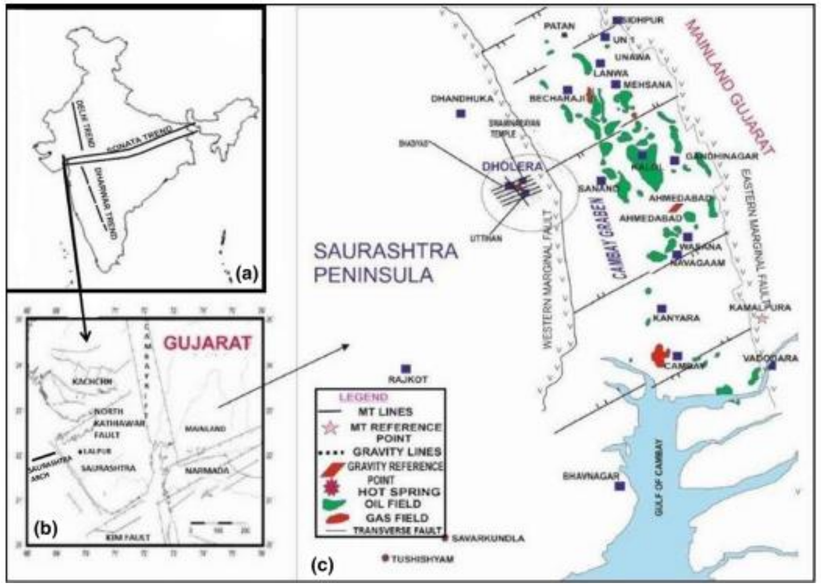
IFP Energies nouvelles

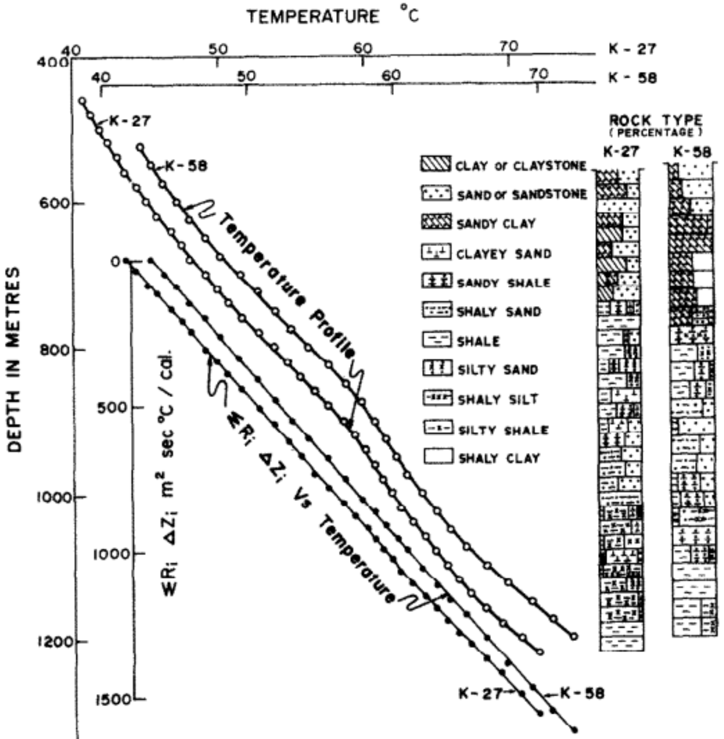
GEOTHERMAL ENERGY – GUJARAT



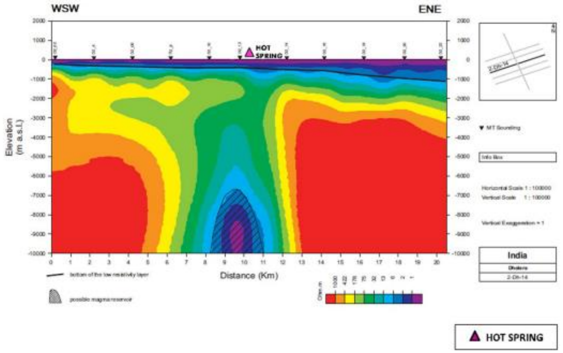
Yadav & Sircar(2021) modified from Chandrasekharam & Chandrasekharam (2015)

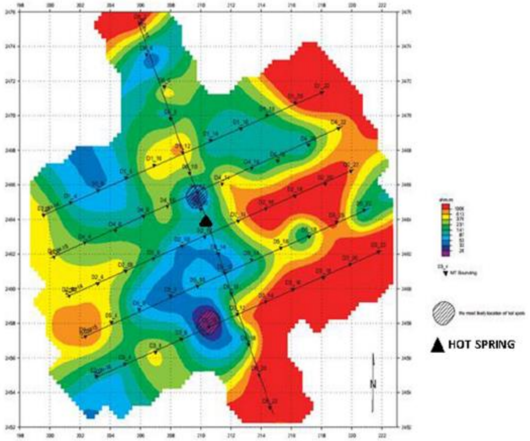


Sircar et al (2015)



Dholera Hot Spring (50°C)





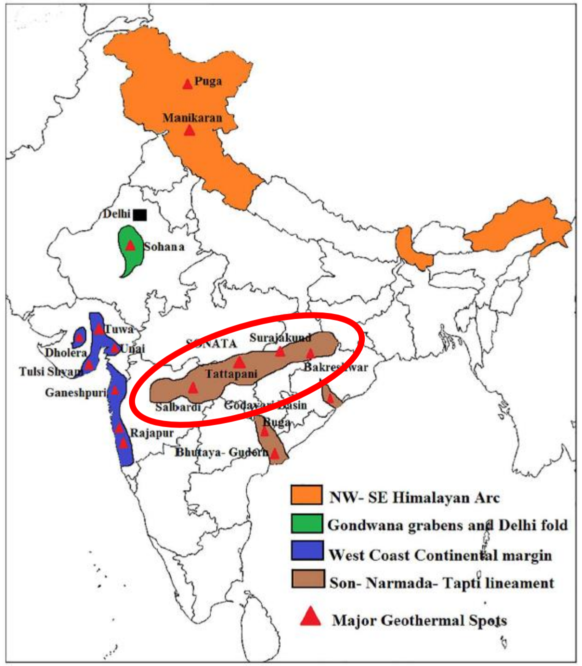
Section at 3 km depth

Locality	Basement depth (m)	Average heat flow µ cal./cm² . sec	
Cambay gasfield	2,200	2.3	96.3 mW/m2
Kathana oilfield	2,400	2.2	92.1 mW/m2
Nawagam oilfield	2,700	1.9	79.5 mW/m2
Kalol oilfield	3,000–3,200	1.85	77.5 mW/m2

Gupta et al (1970)

GEOTHERMAL ENERGY – SON – NARMADA – TAPI RIFT (SONATA)

Renewable energies



Yadav & Sircar(2021) modified from Chandrasekharam & Chandrasekharam (2015)

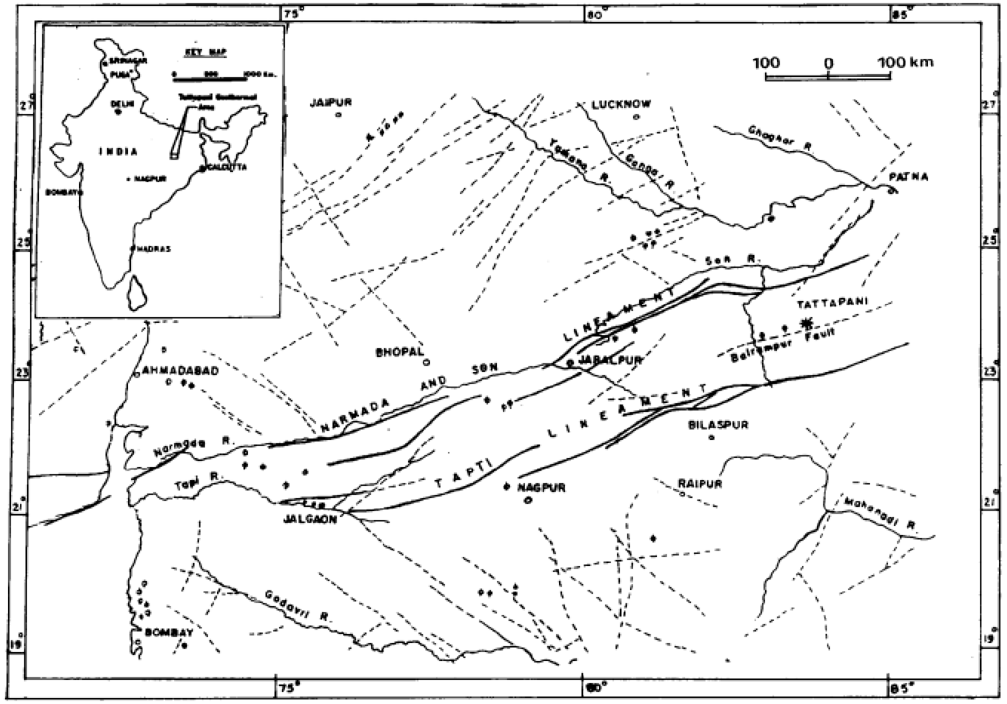


Fig. 1. Lineament map of central India with hot spring locations.

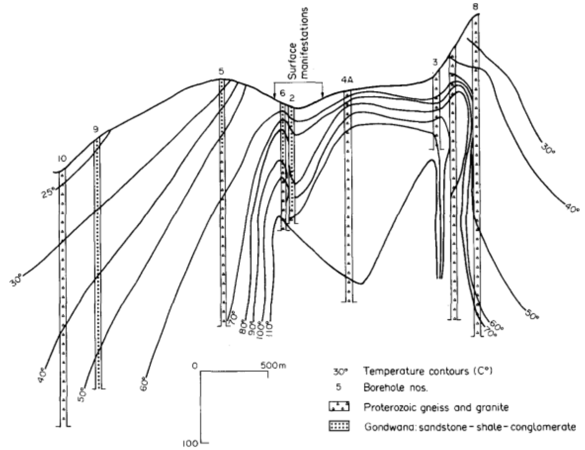
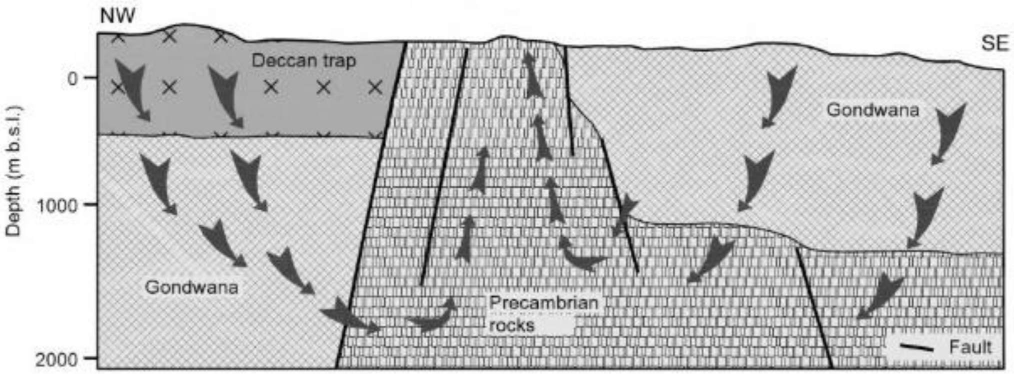
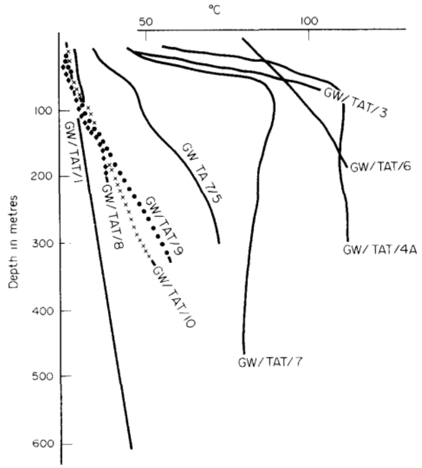


Fig. 9. Distribution of temperature in boreholes in Tattapani hot spring area.

Shanker et al (1987)



Chandrasekharam & Bundschuh (2008)



. 8. Distribution of temperature in boreholes in Tattapani hot spring area.

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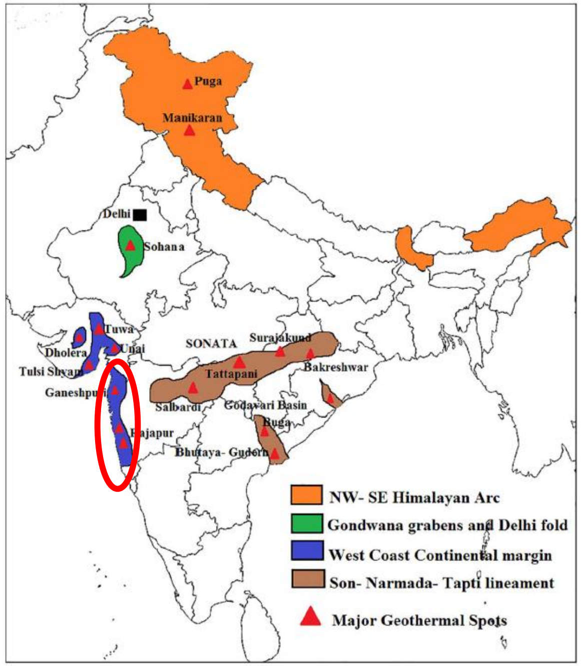
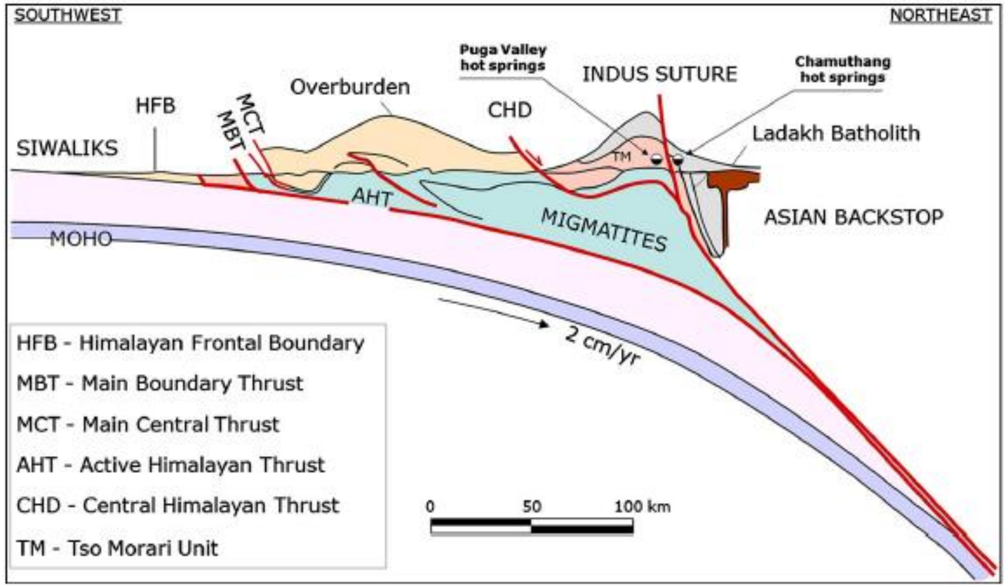
GEOTHERMAL ENERGY – WEST COAST

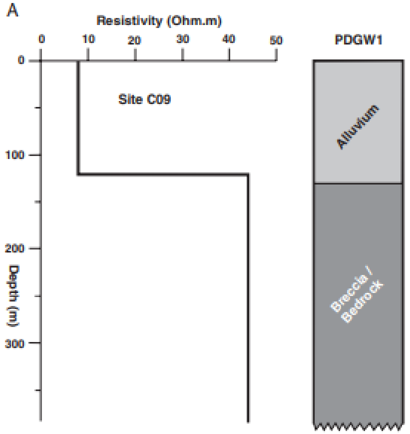
Renewable energies

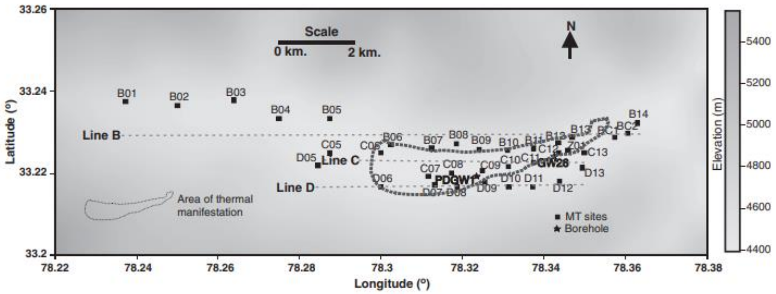


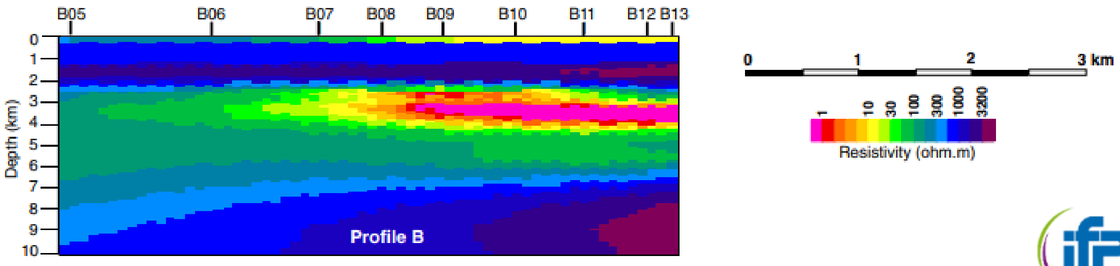
Yadav & Sircar(2021) modified from Chandrasekharam & Chandrasekharam (2015)

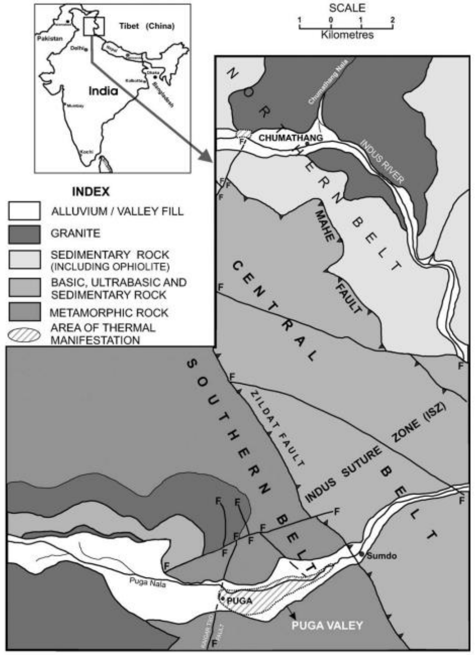
Yadav and Sircar (2020)











Harinarayana et al, 2006

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TAKE HOME MESSAGES:

Renewable energies

- Geothermal has a role to play in the renewable energy mix

- For a better development of geothermal, a precise classification is important

- Geothermal can produce from electricity to single house heat
  ... however, this depends on the geological resource

- Basin scale modelling bring the first order to understand geothermal occurences


Thank you

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