Geothermal Energy:
Geophysical Concepts, Applications and Limitations

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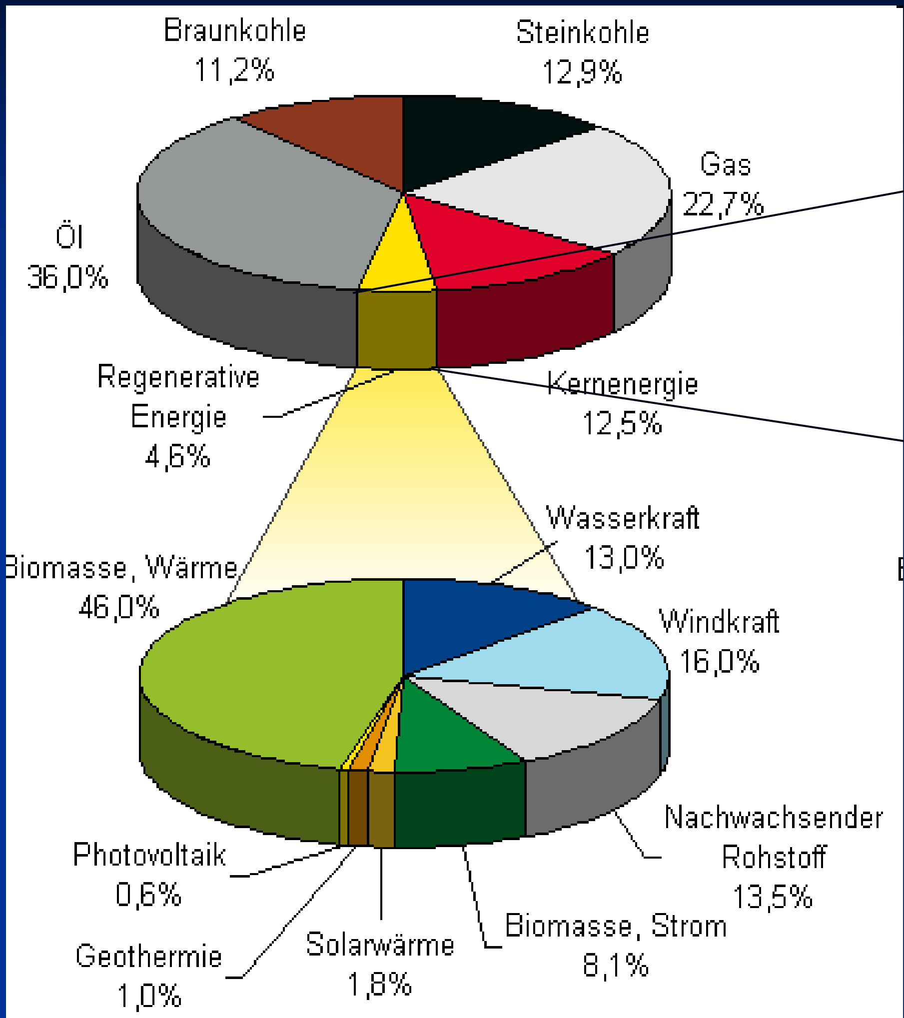
Kassel Winter University, January 11, 2013

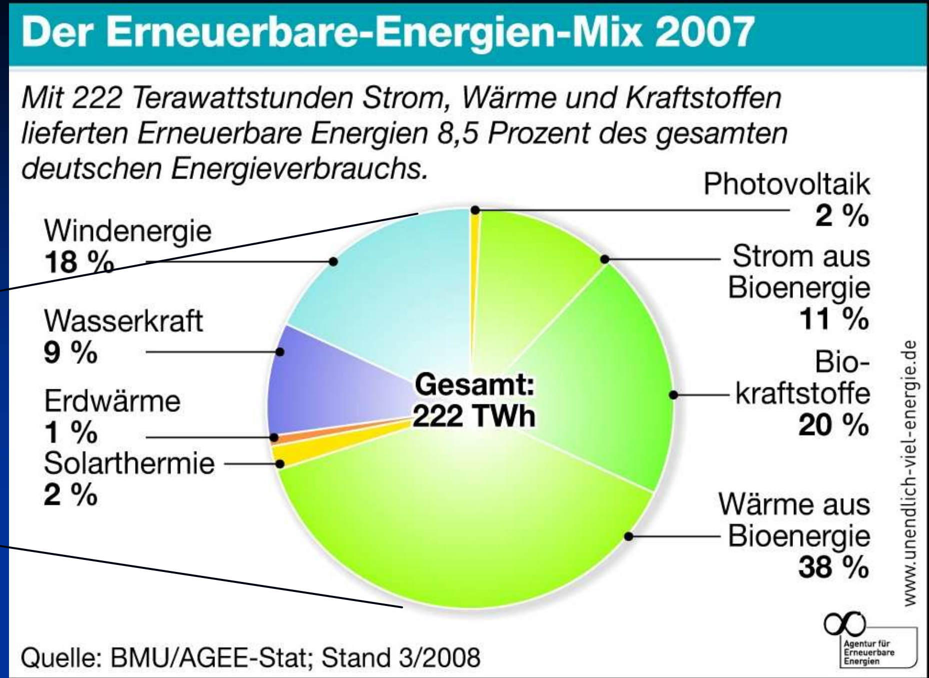
Overview

Overview

0 Energy statistics/Germany



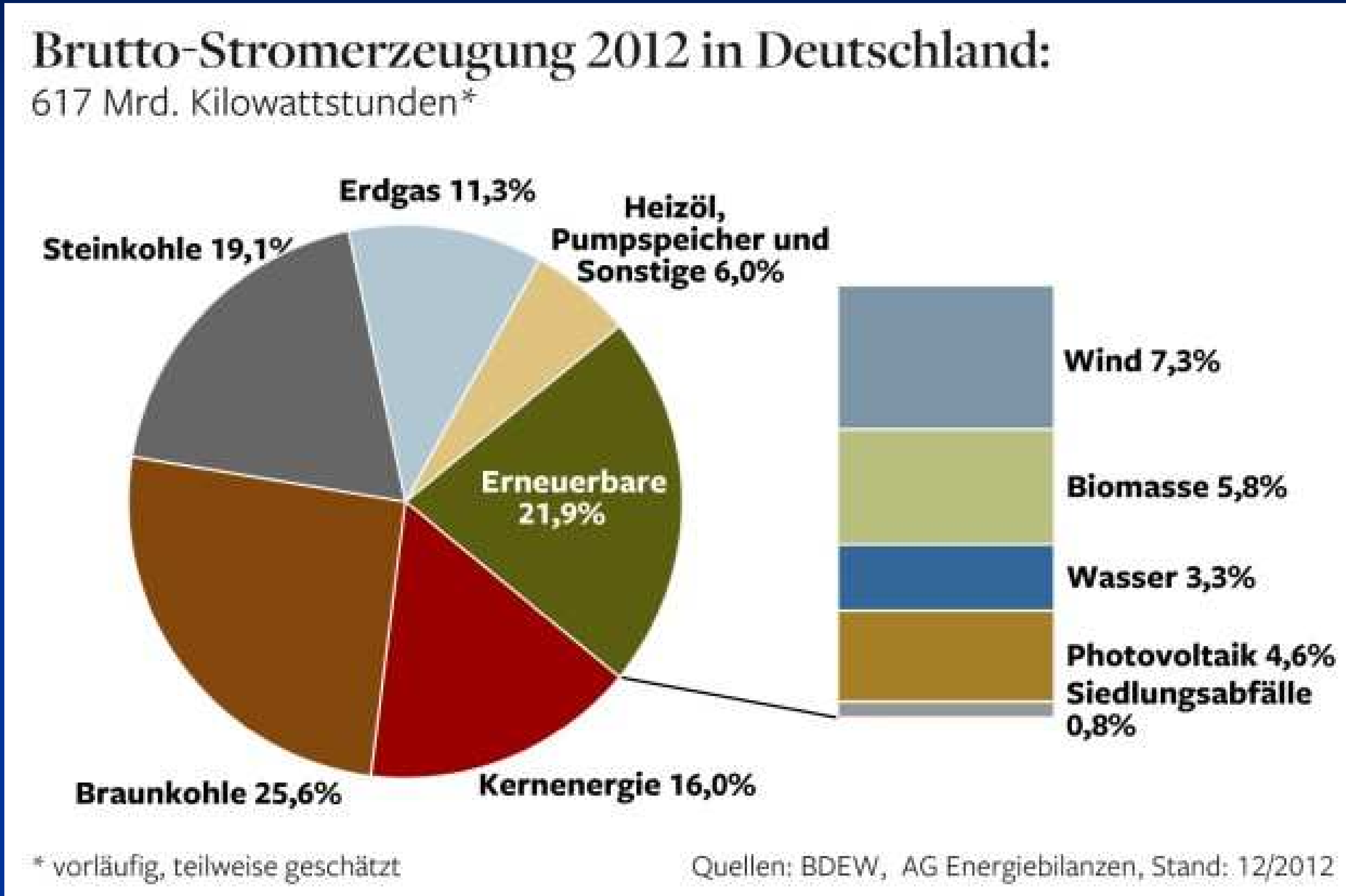
Primary energy mix for Germany



Renewable energy production in Germany

Users of energy in Germany

0 Energy statistics/ Germany/ electric power generation



Electricity production mix for Germany in 2012

0 Energy statistics/geothermal power capacity in the world

Renewable energy – geothermal

Cumulative installed geothermal power capacity*

Megawatts	1985	1990	1995	2000	2003	2004	2005	2006	2007	2008	**2009**	Change 2009 over 2008	2009 share of total
Argentina		0.7	0.7	0.7	–	–	–	–	–	–	**–**	–	♦
Austria		–	–	–	1.3	1.2	1.2	1.2	1.2	1.2	**1.4**	16.7%	♦
Australia		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	**1.1**	450.0%	♦
China		30.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	24.0	**24.0**	–	0.2%
Costa Rica		–	55.0	142.5	162.5	162.5	162.5	162.5	162.5	162.5	**166.0**	2.2%	1.5%
El Salvador		95.0	105.0	161.0	161.0	151.0	151.0	195.0	195.0	204.4	**204.4**	–	1.9%
Ethiopia		–	–	7.3	7.3	7.3	7.3	7.3	7.3	7.3	**7.3**	–	0.1%
France (Guadeloupe)		4.2	4.2	4.2	4.2	14.7	14.7	14.7	14.7	16.0	**16.0**	–	0.1%
Germany		–	–	–	0.2	0.2	0.2	0.2	3.2	6.6	**6.6**	–	0.1%
Guatemala		–	–	28.0	33.0	33.0	33.0	33.0	52.0	52.0	**52.0**	–	0.5%
Iceland		44.6	50.0	172.1	202.1	202.1	202.1	312.1	485.1	575.1	**575.1**	–	5.4%
Indonesia		144.8	309.8	589.5	807.0	807.0	855.5	921.0	992.0	1060.0	**1197.0**	12.9%	11.2%
Italy		545.0	631.7	785.0	790.5	790.5	790.5	810.5	810.5	810.5	**843.0**	4.0%	7.9%
Japan		214.6	413.7	534.0	534.0	534.0	534.0	536.0	536.0	536.0	**536.0**	–	5.0%
Kenya		45.0	45.0	45.0	121.0	127.0	129.0	129.0	131.0	167.0	**167.0**	–	1.6%
Mexico		803.0	843.0	943.0	953.0	953.0	953.0	953.0	958.0	958.0	**958.0**	–	8.9%
New Zealand		283.2	282.0	431.0	399.0	397.0	435.0	488.0	505.0	628.3	**628.3**	–	5.9%
Nicaragua		35.0	70.0	70.0	77.5	77.5	77.5	77.5	87.5	87.5	**87.5**	–	0.8%
Papua New Guinea		–	–	–	5.5	5.5	5.5	36.0	56.0	56.0	**56.0**	–	0.5%
Philippines		888.0	1154.0	1931.0	1931.0	1931.0	1931.0	1969.7	1908.7	1904.0	**1904.0**	–	17.8%
Portugal (The Azores)		3.0	5.0	16.0	16.0	16.0	16.0	16.0	29.0	29.0	**29.0**	–	0.3%
Russia (Kamchatka)		11.0	11.0	23.0	73.0	79.0	79.0	79.0	82.0	82.0	**82.0**	–	0.8%
Thailand		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	**0.3**	–	♦
Turkey		20.6	20.4	20.4	20.4	20.4	20.4	27.8	27.8	34.6	**81.6**	135.8%	0.8%
US		2774.6	2816.7	2228.0	2020.0	2534.0	2653.0	2687.0	2849.6	2910.6	**3086.6**	6.0%	28.8%
Total World	**4764**	**5943.6**	**6845.5**	**8160.0**	**8347.8**	**8872.2**	**9079.7**	**9484.8**	**9922.4**	**10313.1**	**10710.2**	**3.9%**	**100.0%**

*End of year.
♦Less than 0.05%.

Sources: International Geothermal Association, conference papers presented at various IGA workshops and congresses.

http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2010_downloads/renewables_section_2010.pdf

Geothermal Energy and Geothermics

- Geothermal energy is that part of the total heat energy stored within the Earth's interior that is available for human use. That means practically that it is related to the heat energy stored in the upper layers (crust) of the earth.

- Although the earth's stored heat is theoretically finite, its large amount (12.6×10^{24} MJ) makes geothermal energy practically a renewable energy that can theoretically sustain the energy needs of mankind many times.

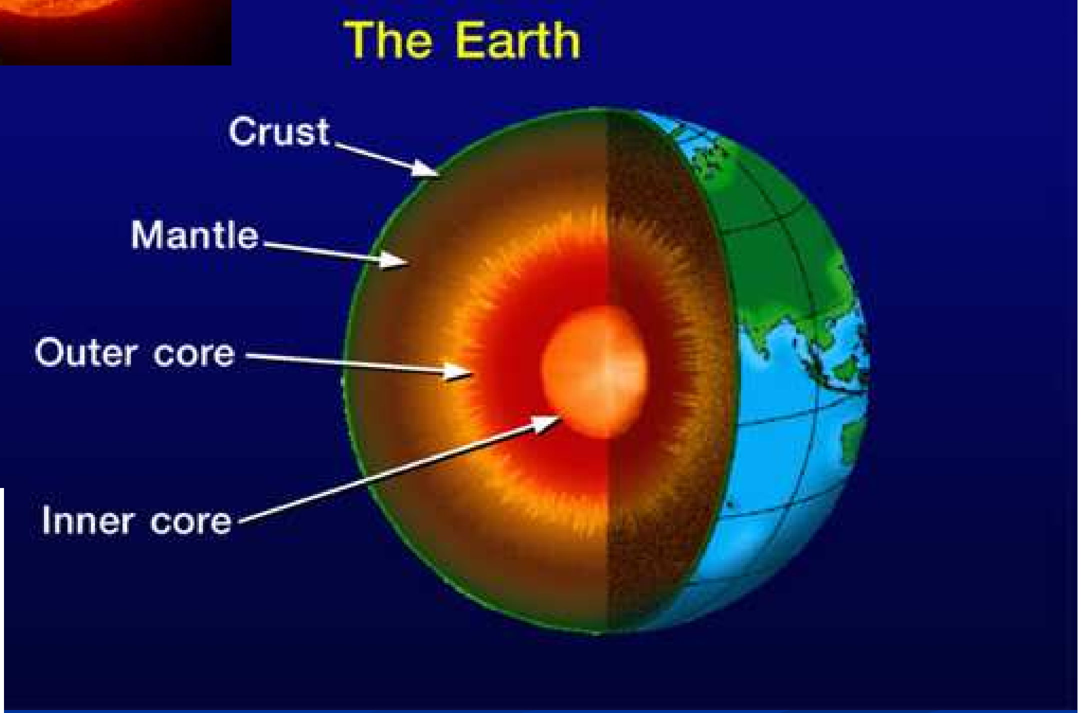
- Geothermics is the science that deals with the theoretical study of the thermal regime of the earth as well as the engineering aspects to use the earth's heat for heating / cooling and electric power generations.

1 Origins of geothermal energy

- 1. Left-over heat from the time of the accretion of the earth (4.6 By BC) (30%)

- 2. heat generated by the decay of the long-lived radioactive isotopes of uranium (U238, U235), thorium (Th232) and potassium (K40) (70%).

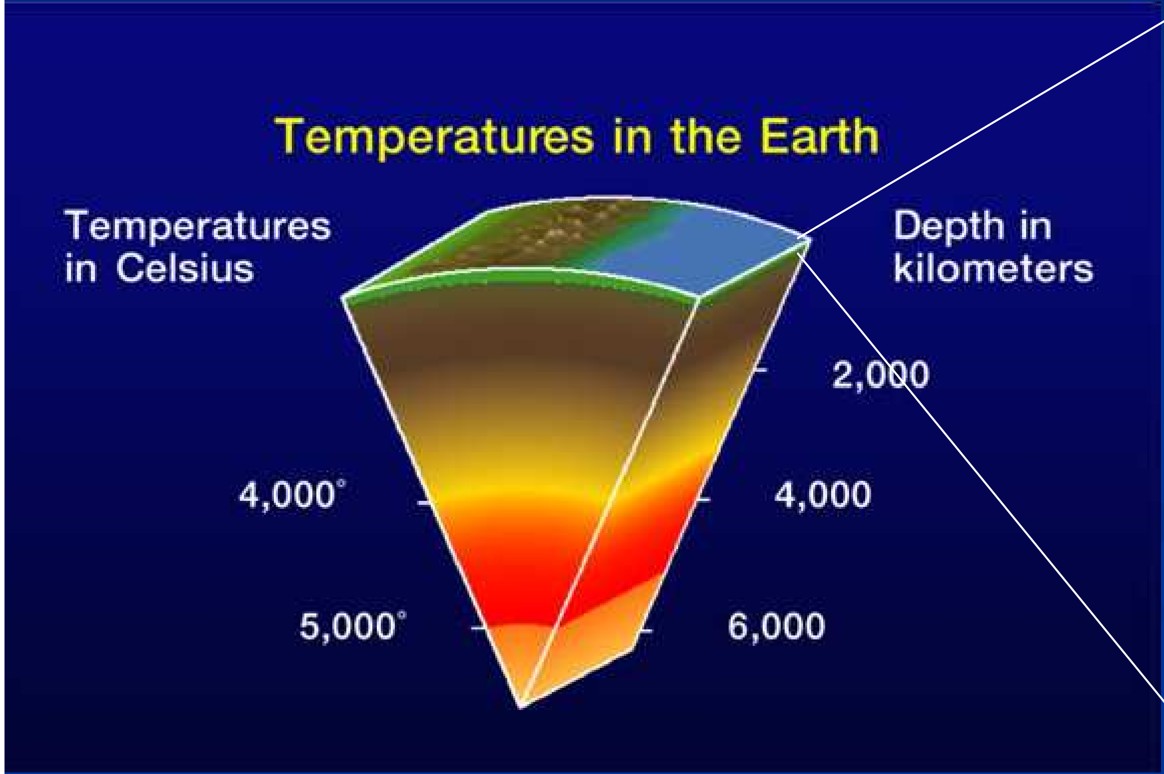
Isotope	Half-life (x 10^9 y)	Heat generation ($mWkg^{-1}$)
K^{40}	1.3	2.8×10^{-2}
Th^{232}	13.9	2.6×10^{-2}
U^{235}	0.7	56.0×10^{-2}
U^{238}	4.5	9.6×10^{-1}

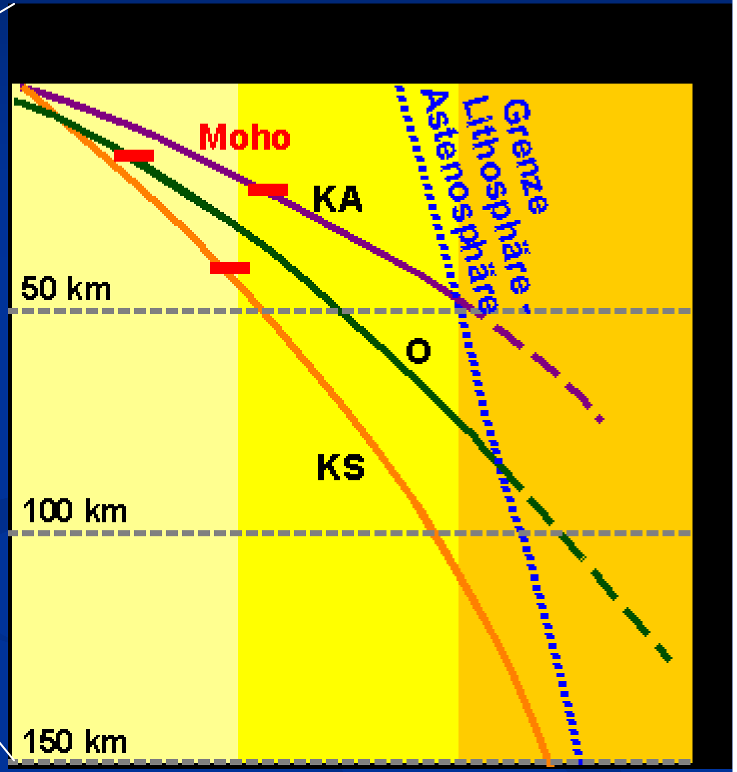


Basic structure of the earth's interior

1 Origins of geothermal energy

Temperature distribution in the earth





Temperatures in the earth

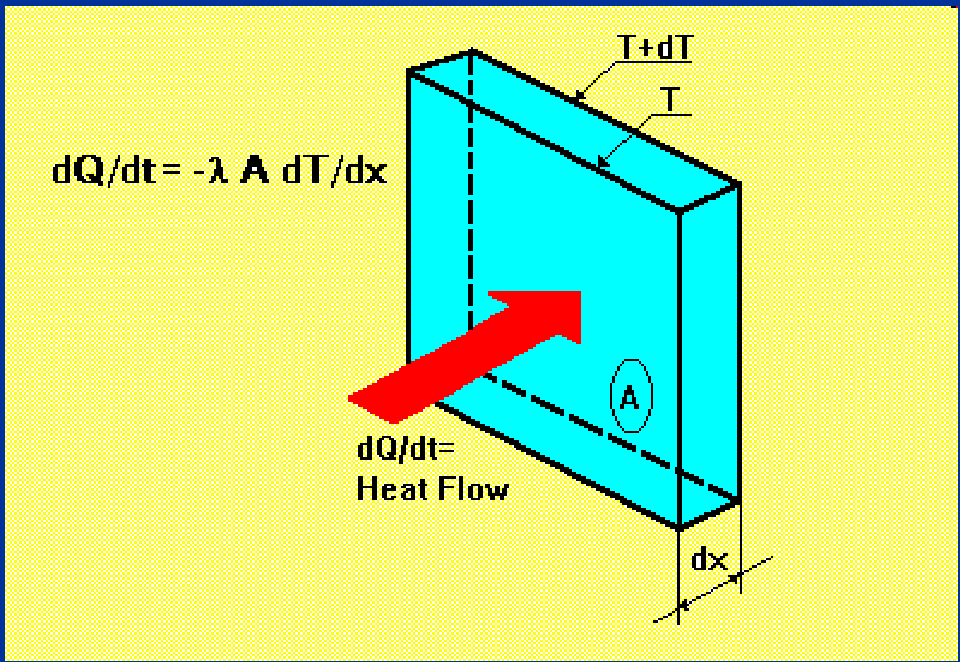
Geothermal gradient in the upper 150km
dT/dz ~ 30 °C/km

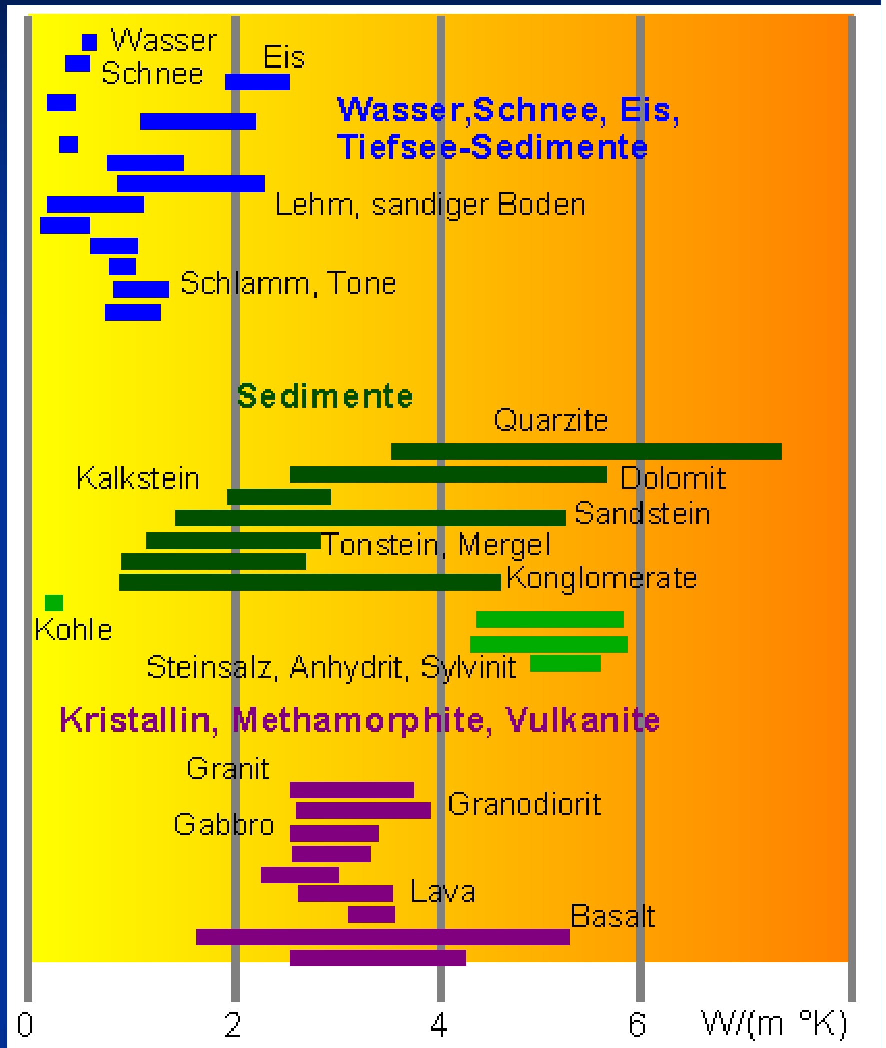
1 Origins of geothermal energy

Mechanisms of heat transport in the earth

1) Heat transport by conduction

Fourier's law





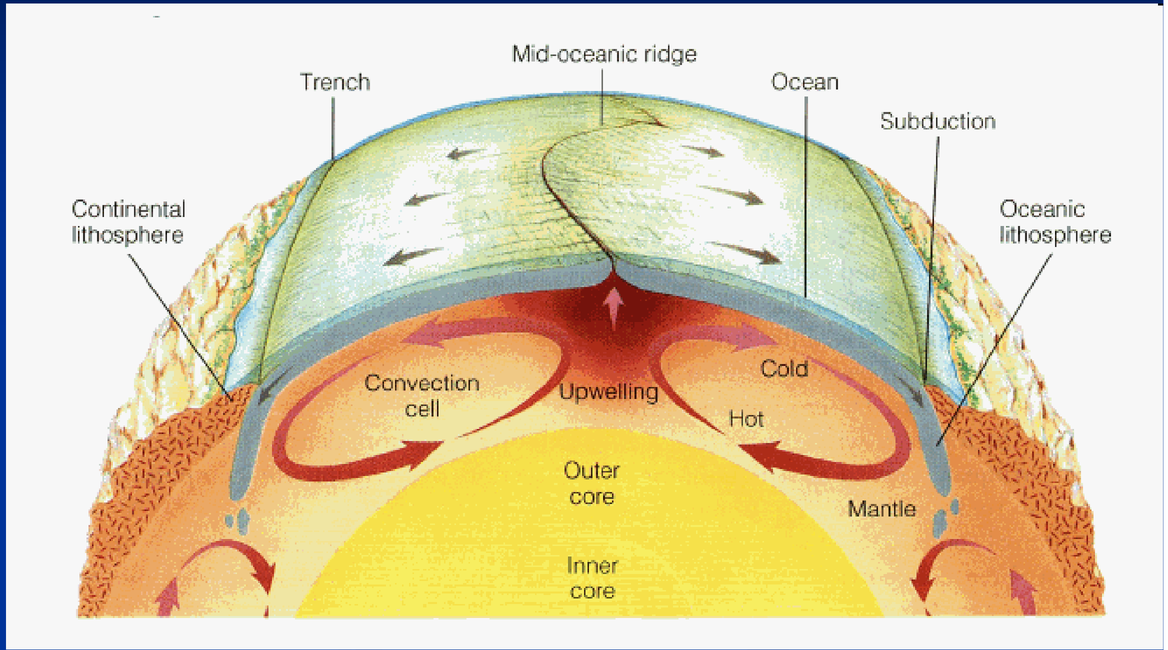
Thermal conductivity of rocks

1 Origins of geothermal energy

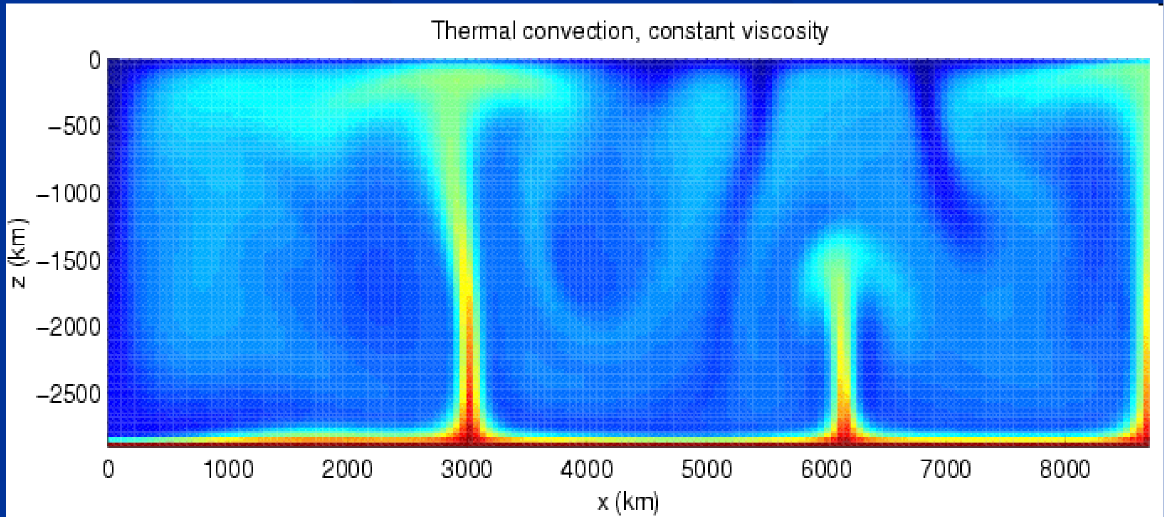
Mechanisms of heat transport in the earth

(2) Heat transport by convection

Mantle convection driving the plates



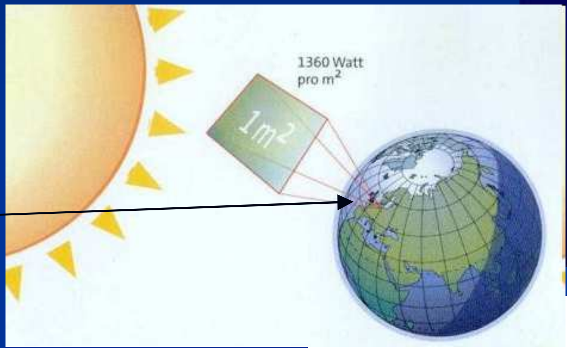
Numerical simulation of Mantle convection

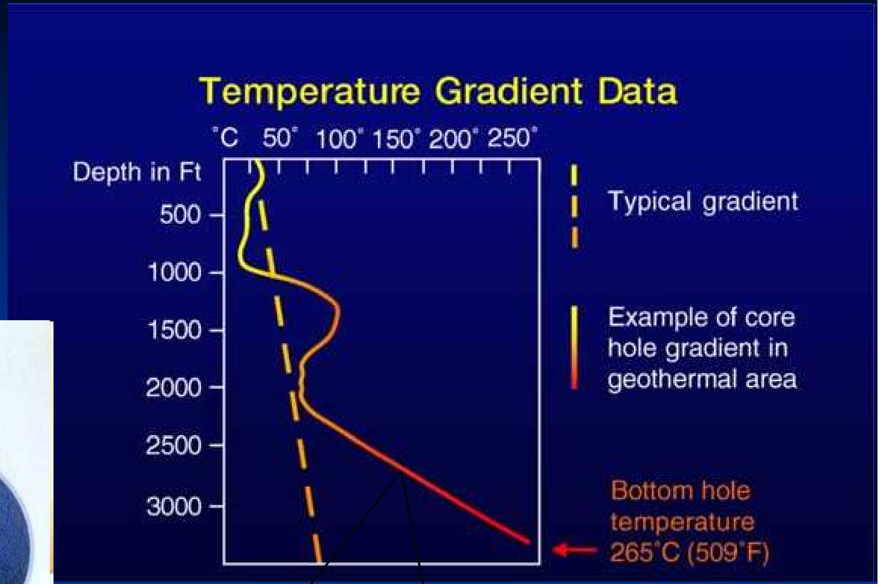


1 Origins of geothermal energy

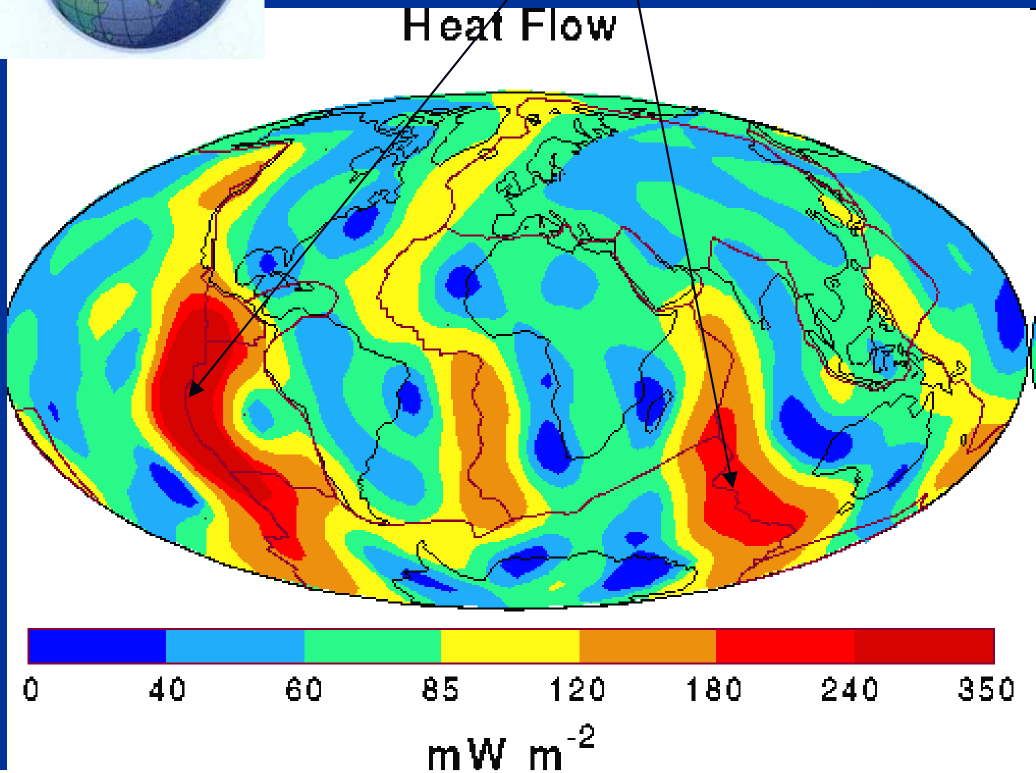
Heat flow at the earth's surface

- Average heat flow
  $= 60 mW/m^2$
- Compare with
  Solar Constant
  $S = 1360\ W/m^2$





- Note the large lateral variations across the surface of the earth

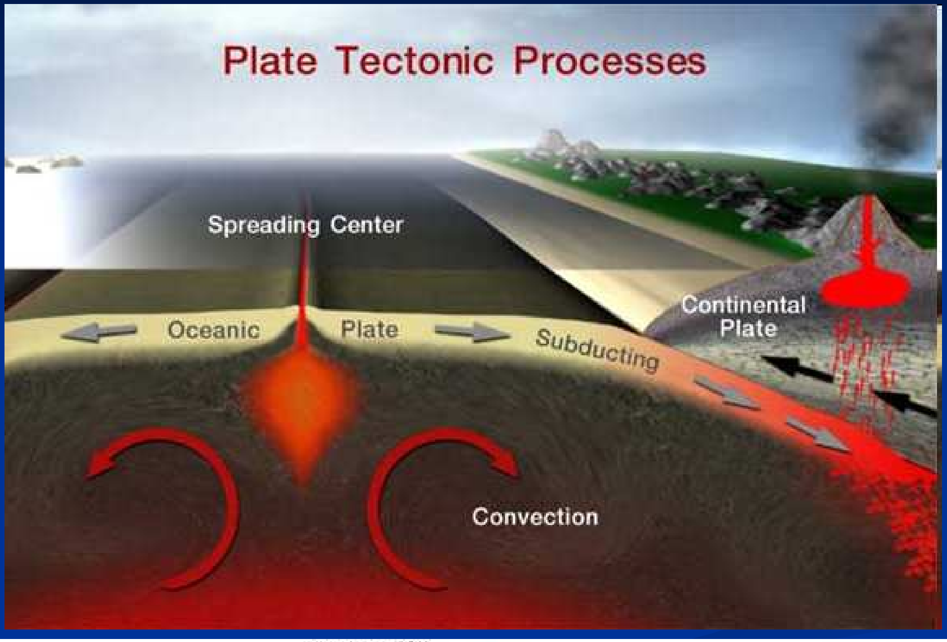


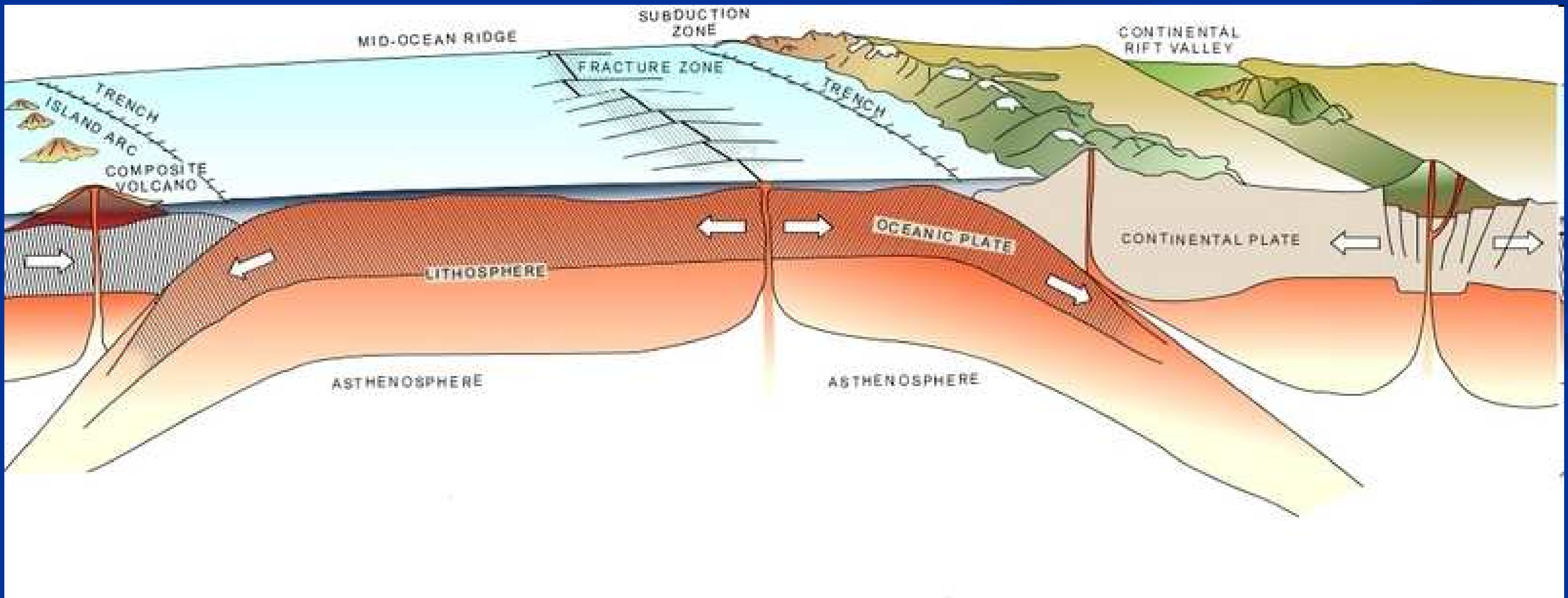
Explanation by

Theory of Plate Tectonics

1 Origins of geothermal energy

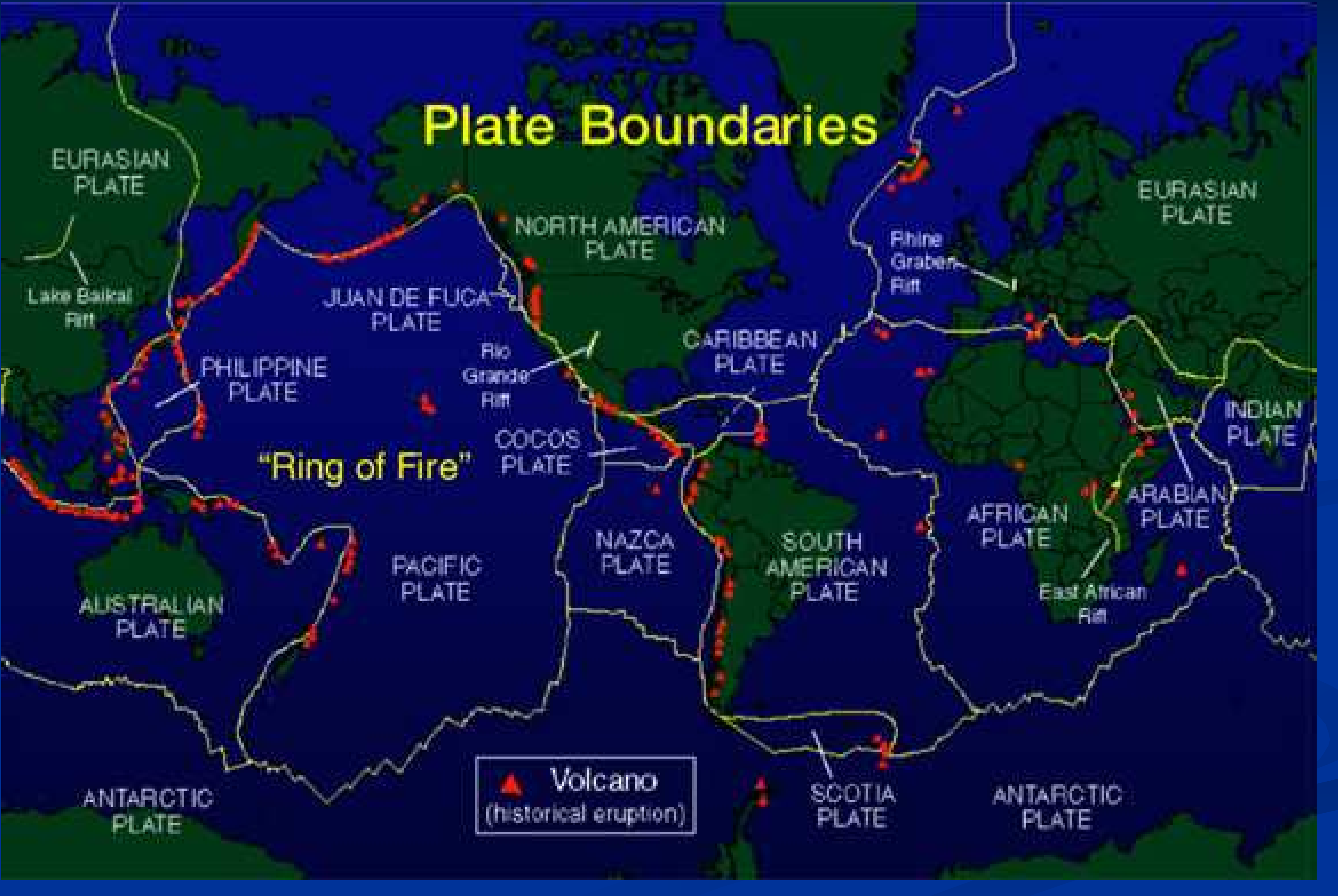
The earth's thermal regime and relation with plate tectonics





1 Origins of geothermal energy

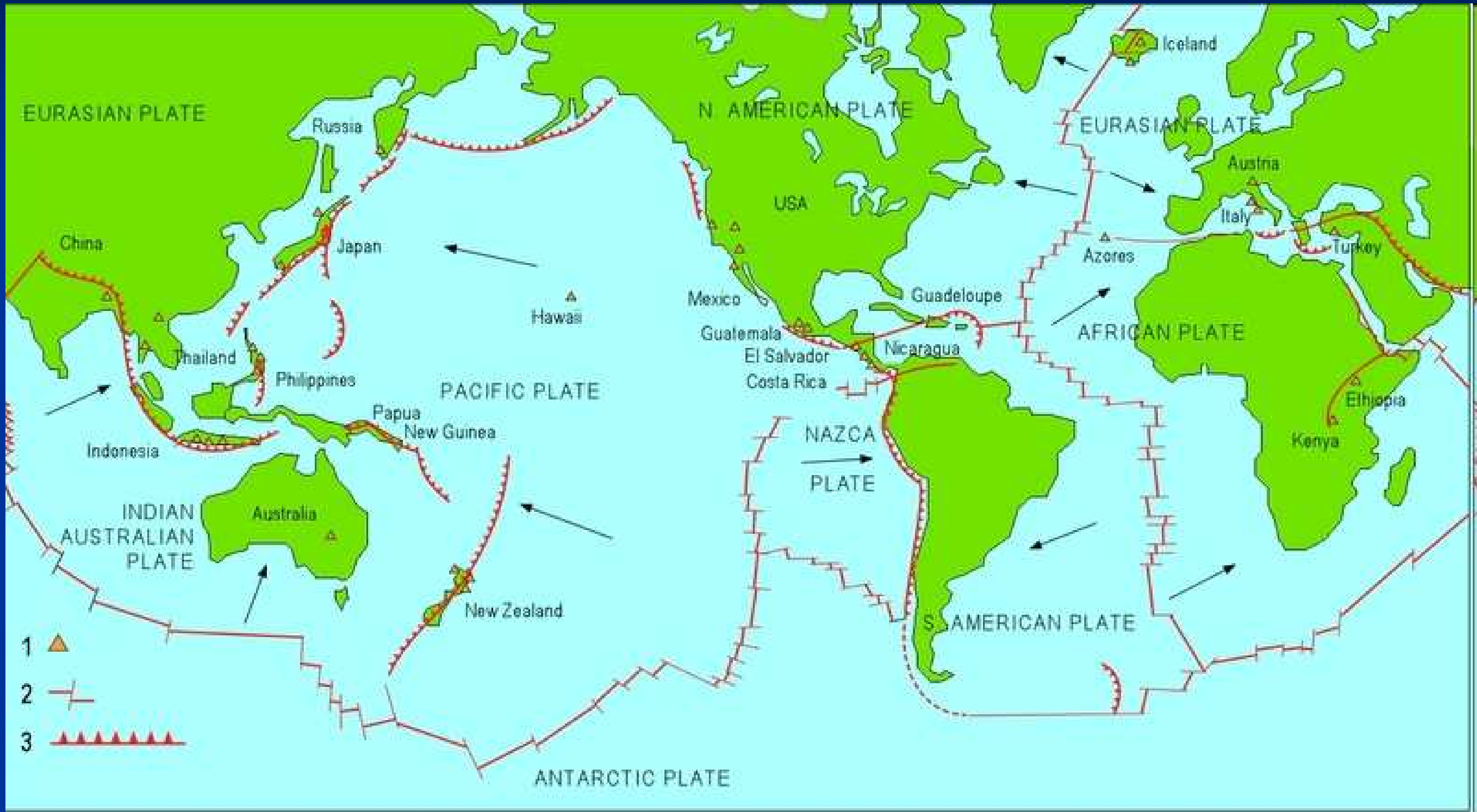
The earth's thermal regime and relation with plate tectonics



Plates, plate boundaries and distribution of volcanoes across the earth

1 Origins of geothermal energy

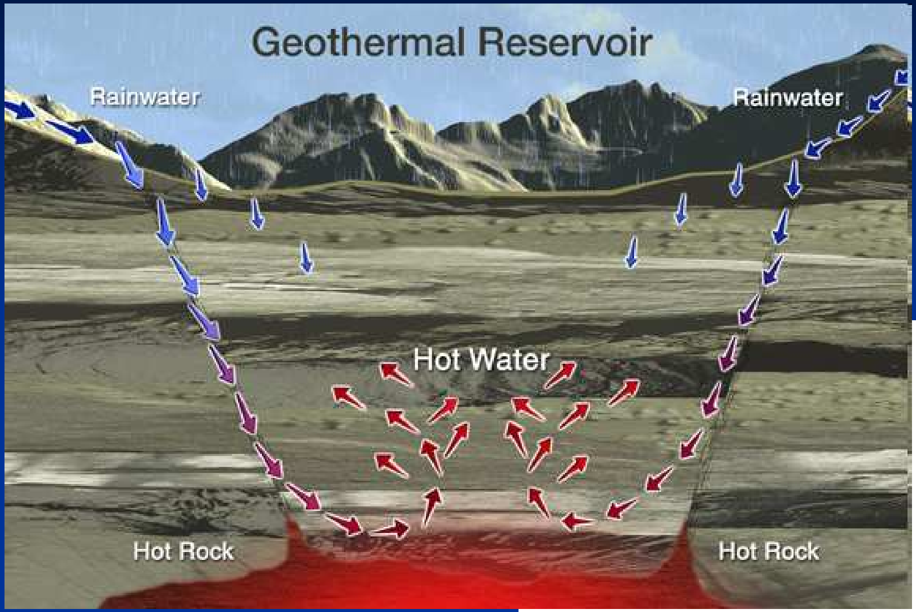
Plate tectonics and geothermal fields



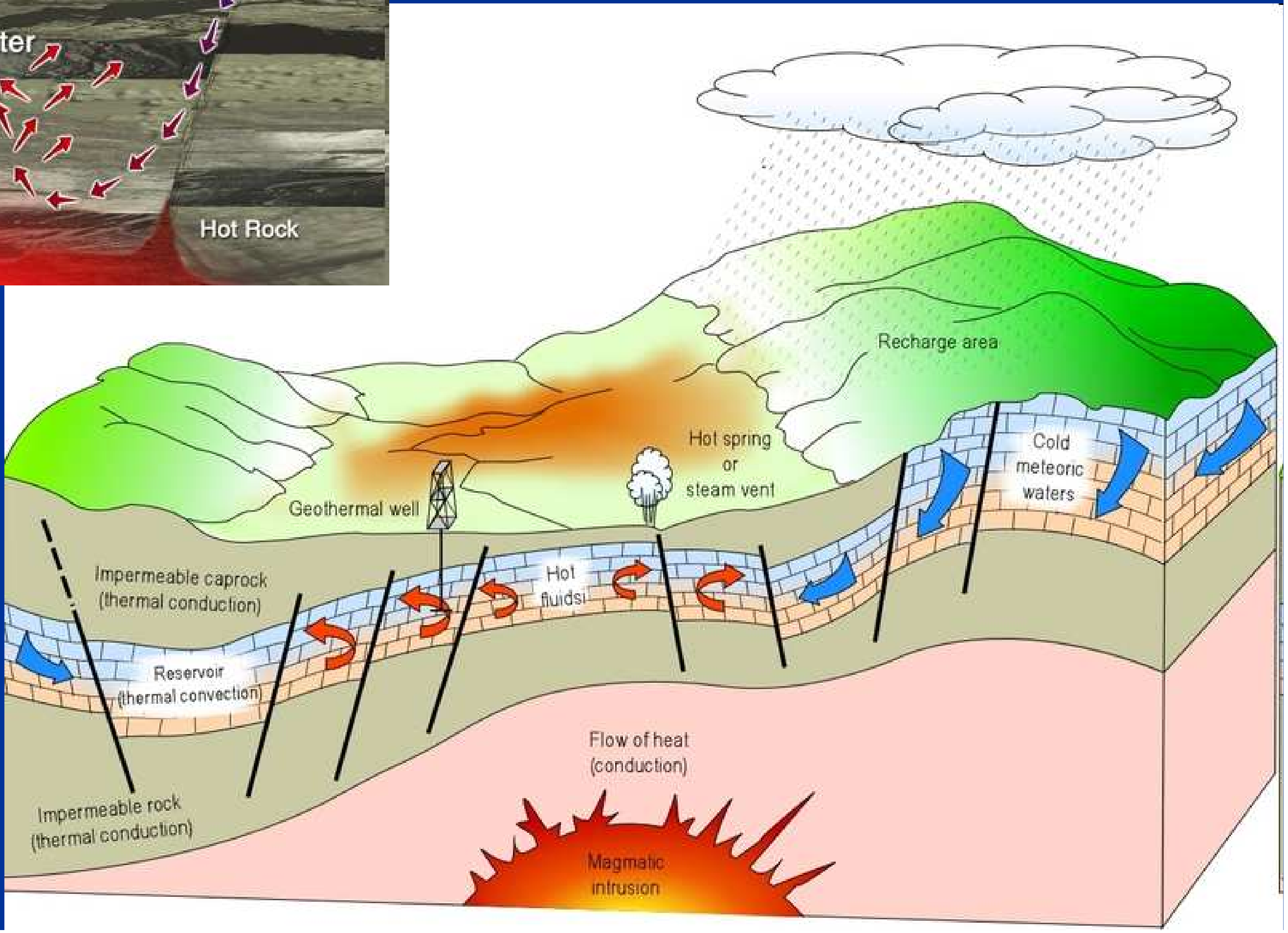
World pattern of plates, oceanic ridges, oceanic trenches, subduction zones, and geothermal fields.

http://www.geothermal-energy.org/105,interactive_map.html

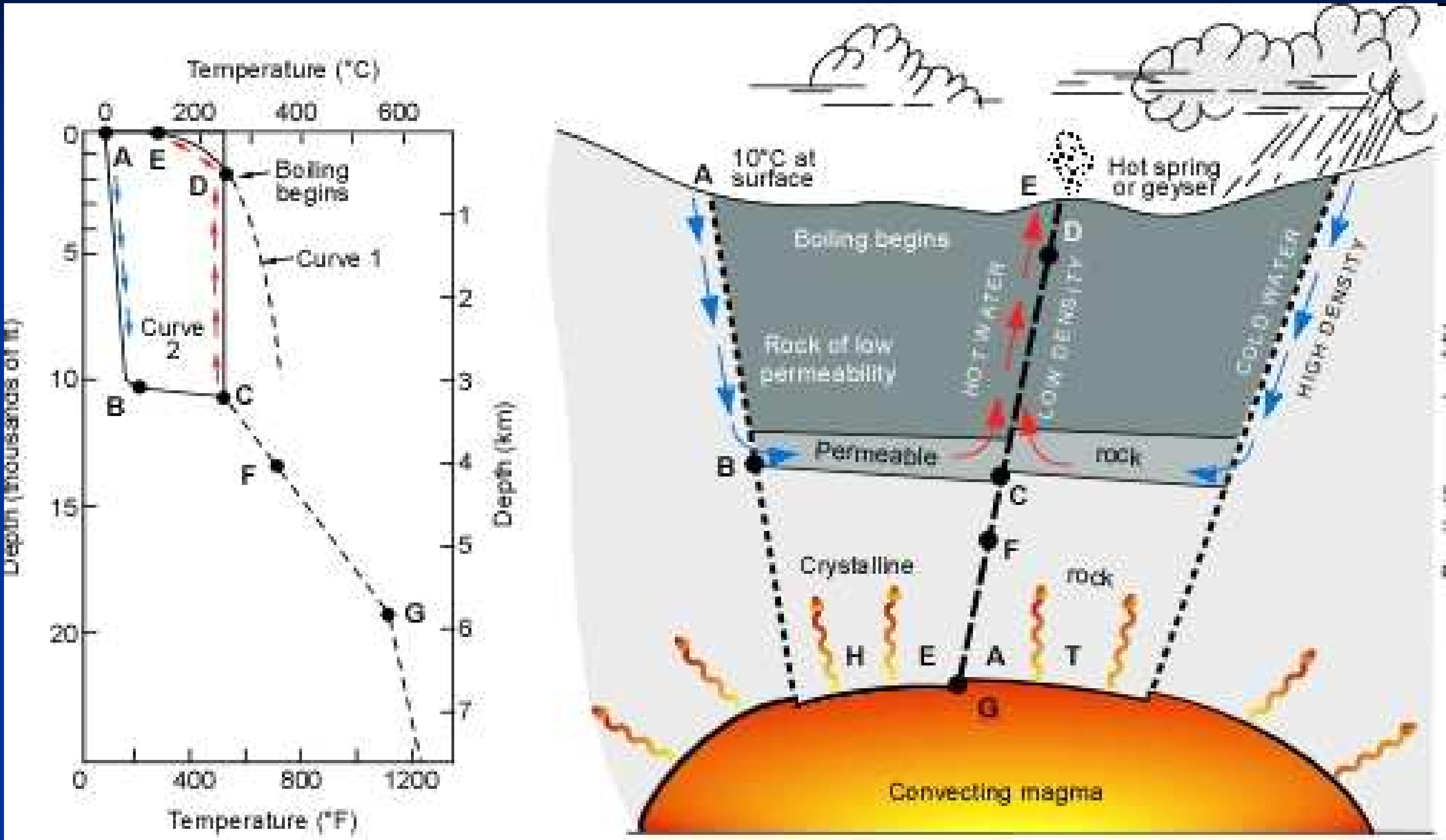
2. Classification of geothermal systems/reservoirs



The "ideal geothermal reservoir"
= high temperatures + water
= steam!!!

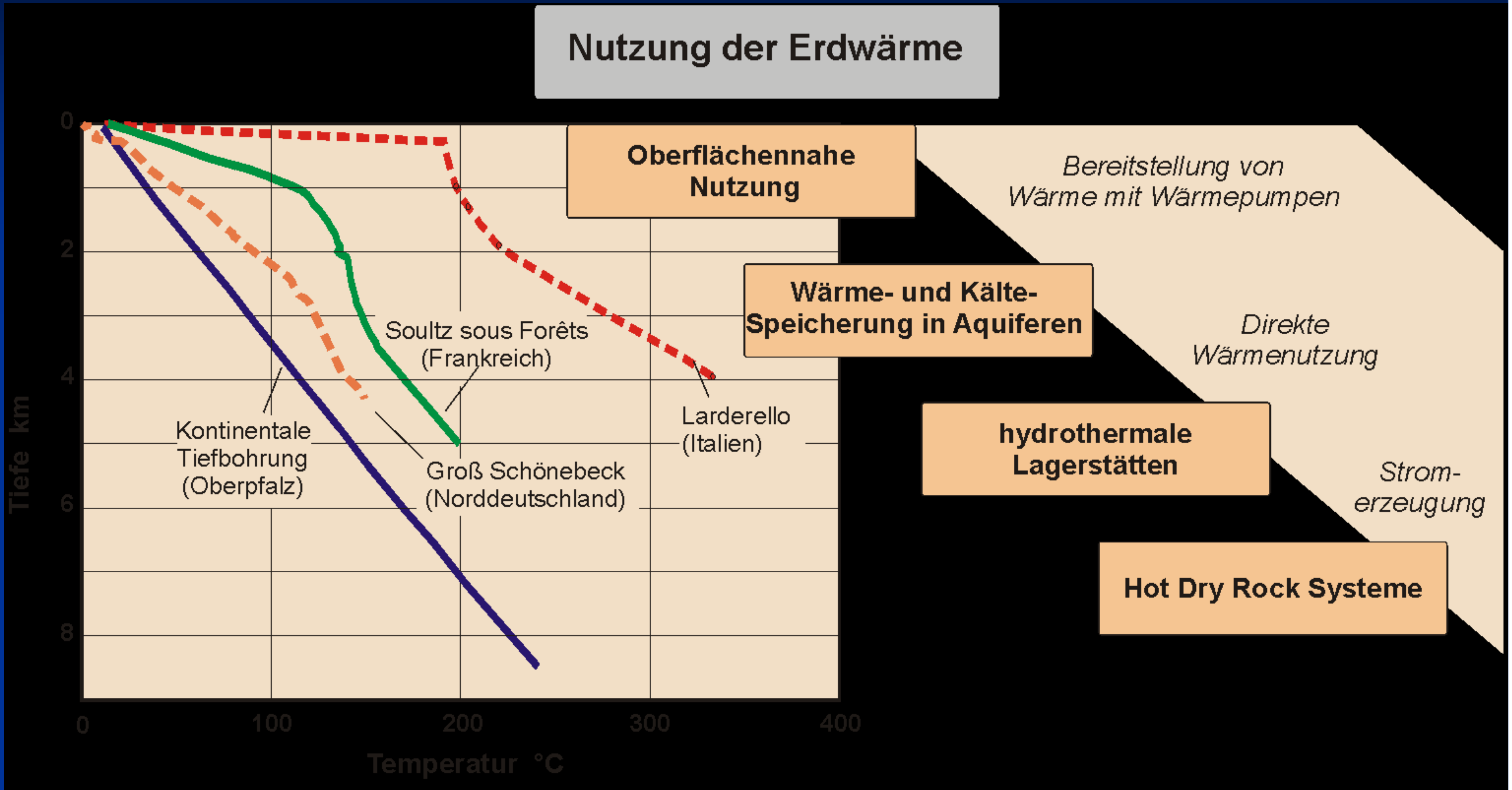


2. Classification of geothermal systems/reservoirs



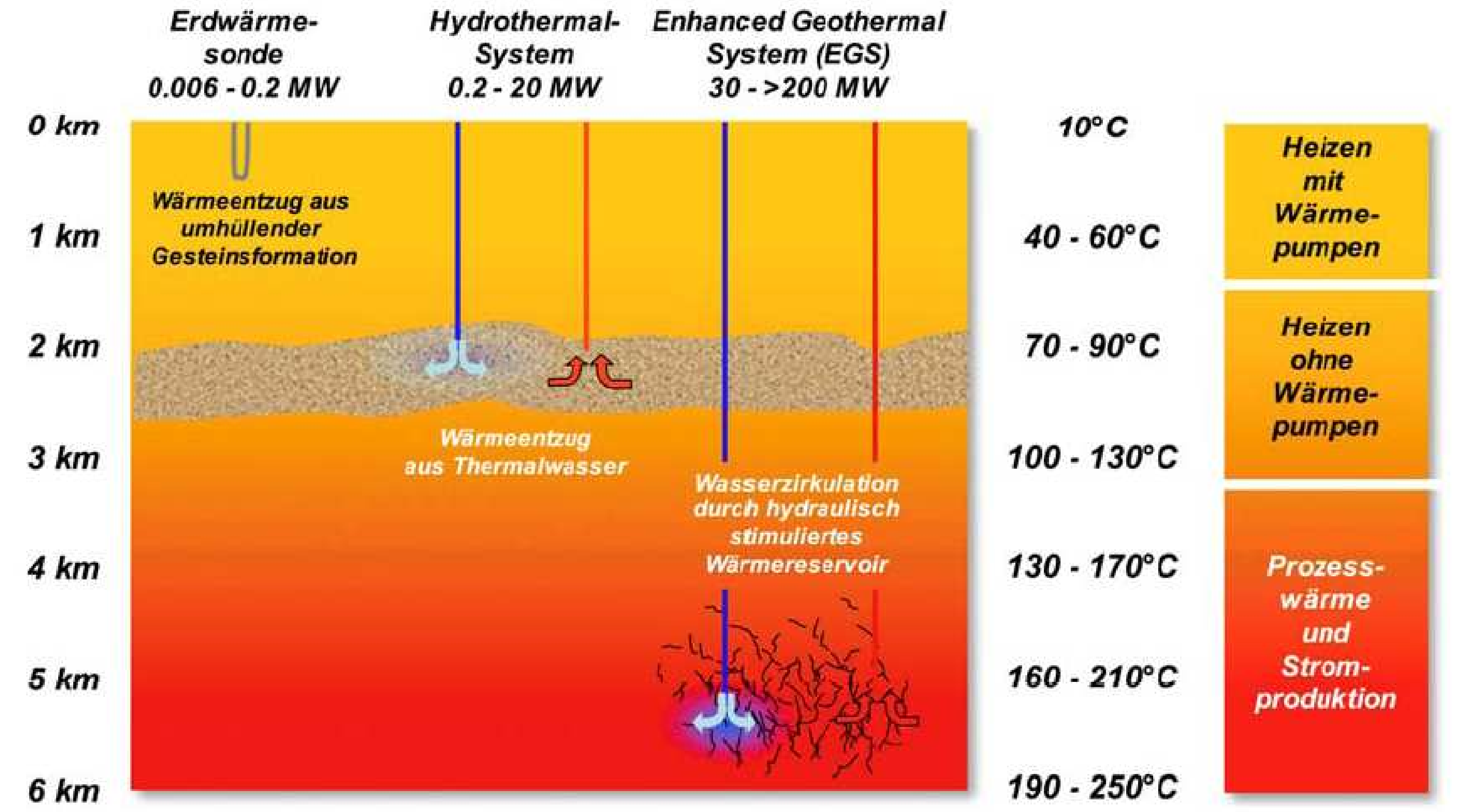
Thermal processes in an "ideal geothermal reservoir" resulting in the formation of hot steam

2 Classification of geothermal systems



Temperature distribution with depth at different locations and classification of geothermal systems in relation of their depths

2. Classification of geothermal systems



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

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

Low enthalpy resources	< 90	<125	<100	≤150	≤190
Intermediate enthalpy resources	90-150	125-225	100-200	-	-
High enthalpy resources	>150	>225	>200	>150	>190

Different classifications of deep geothermal reservoirs in relation to the temperature °C.

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

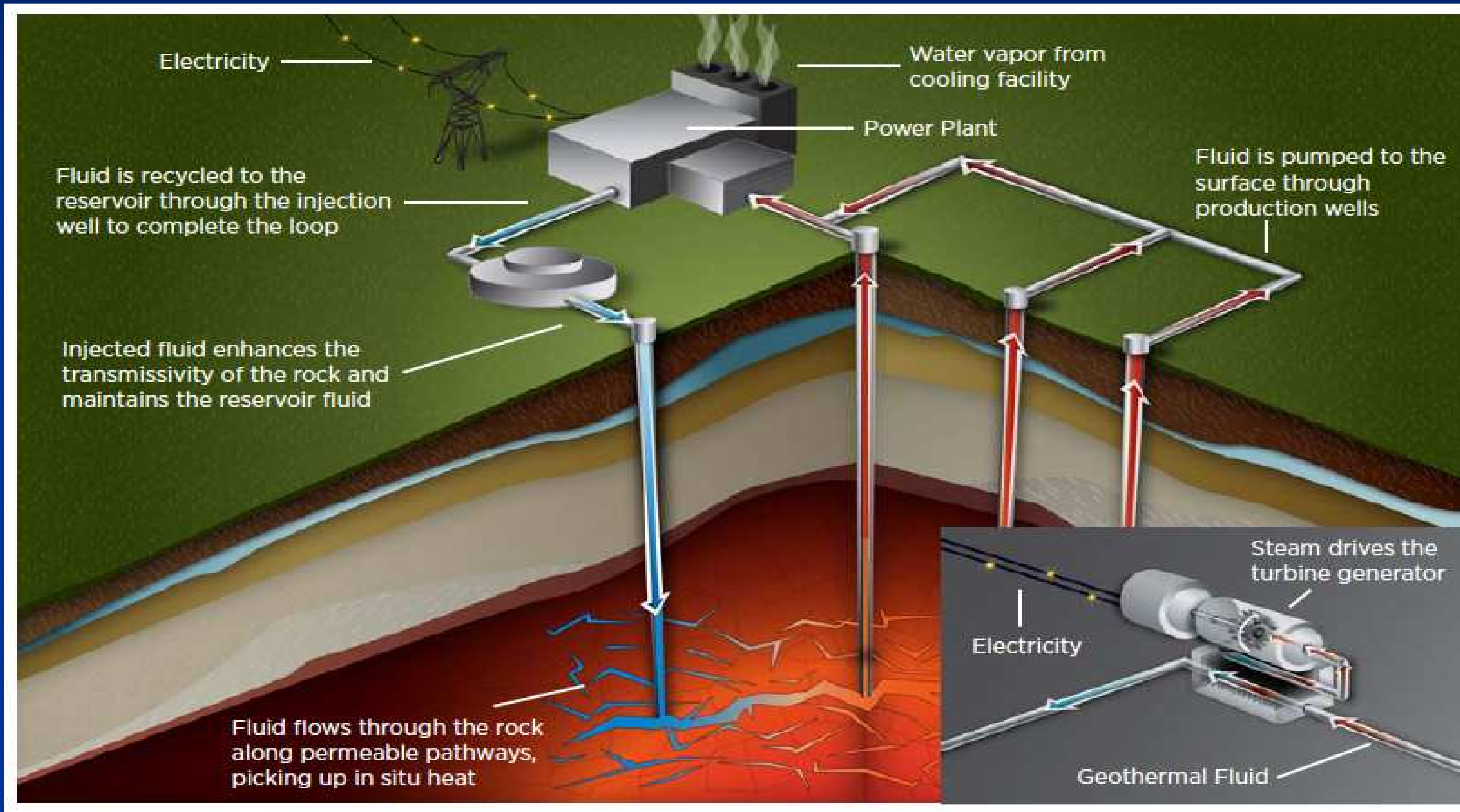
2.1.1 High enthalpy reservoirs

- **Characterization of high enthalpy-systems**
  - Mostly in regions with vulkanic activity
  - Use for generation of electricity (flash-method) and of process heat
  - Temperature range: 90 – 300°C
  - Depending on pressure reservoirs have more steam or water
  - Steam is reinjected
    → no negativ environmental impact
    → higher productivity

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.1 High enthalpy reservoirs



2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.1 High enthalpy reservoirs / World map

http://www.geothermal-energy.org/105,interactive_map.html

http://www.geothermie.de/aktuelles/geothermie-in-zahlen/weltweit.html

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.1 High enthalpy reservoirs/ Examples


First Geothermal Power Plant, 1904, Larderello, Italy

Laradello geothermal power plant

The Geysers geothermal field, California

http://geothermal.marin.org/GEOpresentation/sld036.htm

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.2 Low enthalpy reservoirs

2.1.2.1 Hydrothermal systems

Thermal power extraction

$$P_{therm} = \rho\, c_p\, Q_{flow}\, \Delta T$$

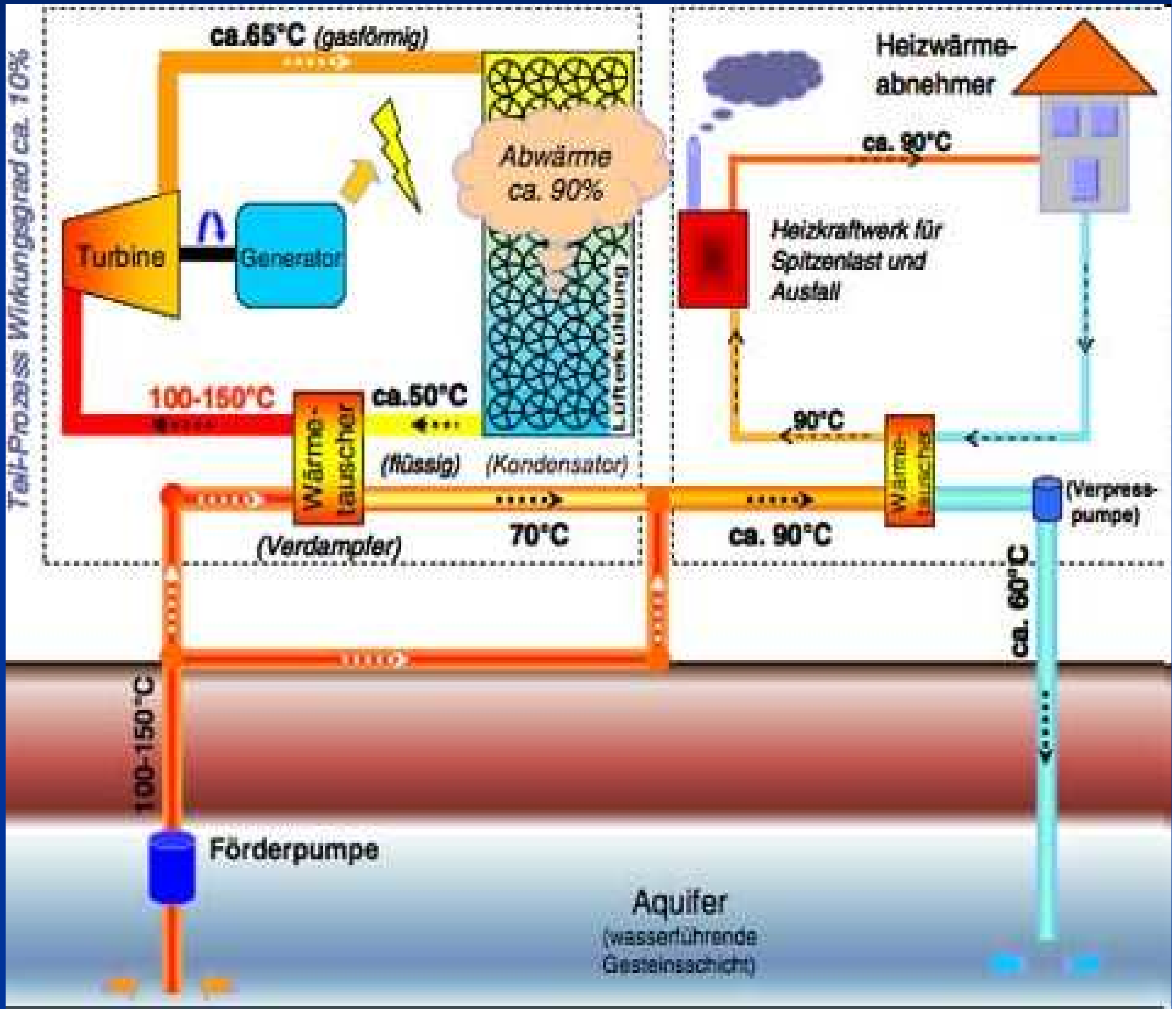
ρ = density of water

c_p = specific heat

Q_{flow} = flow rate

ΔT = T_{hot}-T_{cold}

http://www.unendlich-viel-energie.de/uploads/media/Hydrothermale_Geothermie.pdf

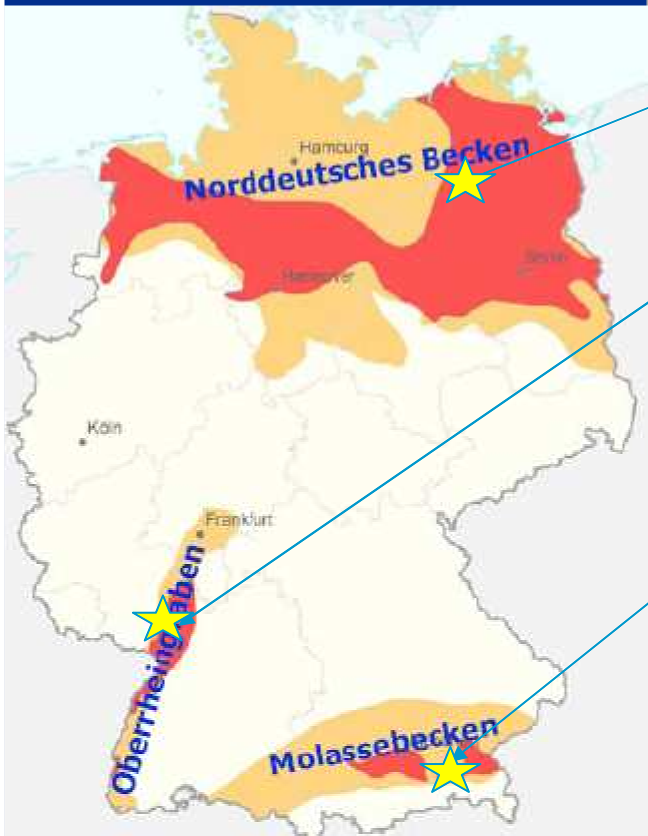


2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.2 Low enthalpy reservoirs

2.1.2.1 Hydrothermal systems/Germany



Geplante und realisierte Geothermieanlagen (Stromerzeugung) in Mitteleuropa

	Geoth. Leistung in MW	Elektr. Leistung in MW	Temperatur in °C	Förderrate in m³/h	Bohrtiefe in m	Geplante Inbetriebnahme Jahr
Deutschland						
Groß Schönebeck	10	1,0	150	< 50	4.294	2008
Neustadt-Glewe	10	0,21	98	119	2.250	Im Kraftwerksbetrieb seit 2003
Bad Urach (HDR-Pilotprojekt)	6–10	ca. 1,0	170	48	4.500	Bohrarbeiten beendet wg. Auslauf der Finanzierung
Bruchsal	4,0	ca. 0,5	118	86	2.500	Im Kraftwerksbetrieb seit 2009
Karlsruhe	28,0		> 150	270	3.100	unbekannt
Landau	22	3	159	70	3.000	Im Probebetrieb seit 2007. Zeitweise eingestellt wegen leichter Beben. Wiederaufnahme mit reduziertem Pumpendruck.[1]
Insheim		4,0–5,0[29]	>155		3.600	voraussichtlich 2011
Schaidt			>155		>3.500	(Bohrbeginn 2011)
Offenbach an der Queich	30–45	4,8–6,0	160	360	3.500	gestoppt wg. Bohrlochinstabilität
Riedstadt	21,5	ca. 3,0		250	3.100	unbekannt
Speyer[30]	24–50	4,8–6,0	150	450	2.900	2005 aufgegeben,[31] weil Erdöl statt Wasser gefunden wurde (drei Bohrungen im Probebetrieb)
Unterhaching	40	3,4	122	> 540	3.577	seit 2008 im Betrieb
Sauerlach	ca. 80	ca. 5[32]	140	> 600	> 5.000	Ende 2011 (Bohrarbeiten erfolgreich beendet)
Dürrnhaar	ca. 50	ca. 5,0	135	> 400	> 4.000	2011 (Bohrarbeiten erfolgreich beendet)
Mauerstetten	40	4,0–5,0	120–130	ca. 300	4.100	unbekannt (zu geringe Schüttung)[33]
Kirchstockach	50	5	130	450	> 4.000	2011 (Bohrarbeiten erfolgreich beendet)
Laufzorn (Oberhaching)	50	5	130	470	> 4.000	2011 (Bohrarbeiten erfolgreich beendet)
Kirchweidach			120	470	> 3.000	2012 (Bohrbeginn 2010)
Bernried			150		> 4.500	2013 (Bohrbeginn 2011)
Taufkirchen			120	470	> 3.000	2012 (Bohrbeginn 2011)
Geretsried					> 4.000	2013 (Bohrbeginn 2011)

2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

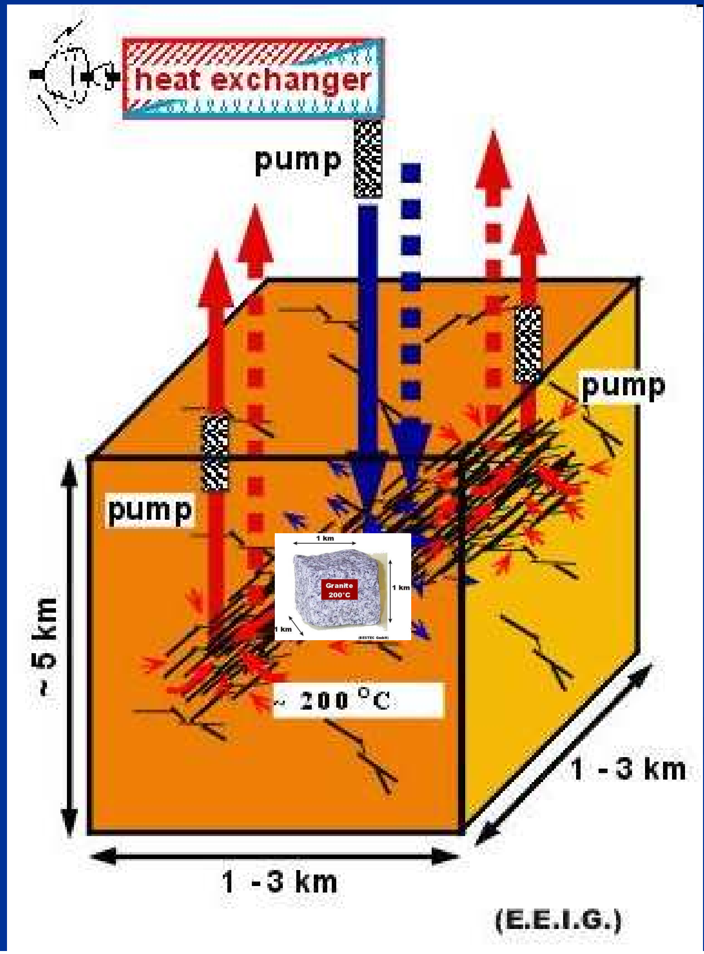
2.1.2 Low enthalpy reservoirs

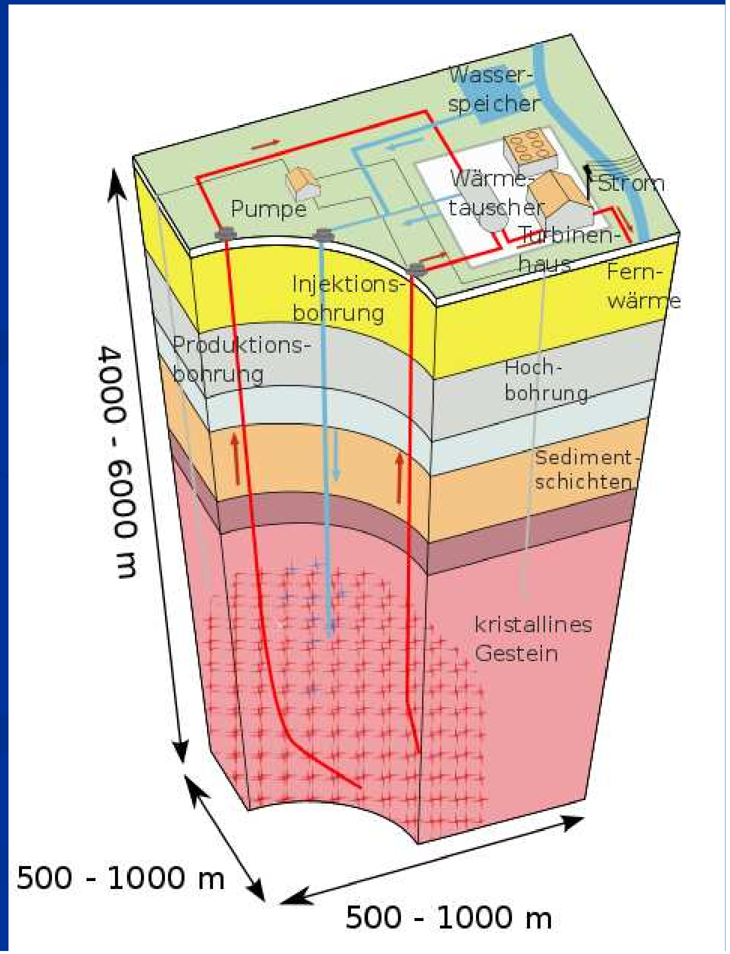
2.1.2.2 Petrothermal systems /HDR/EGS

HDR= Hot Dry Rock Technology
EGS = Enhanced Geothermal System

http://www.soultz.net/version-en.htm

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2008/Kobs_Halim_Hot_Dry_Rock.ppt





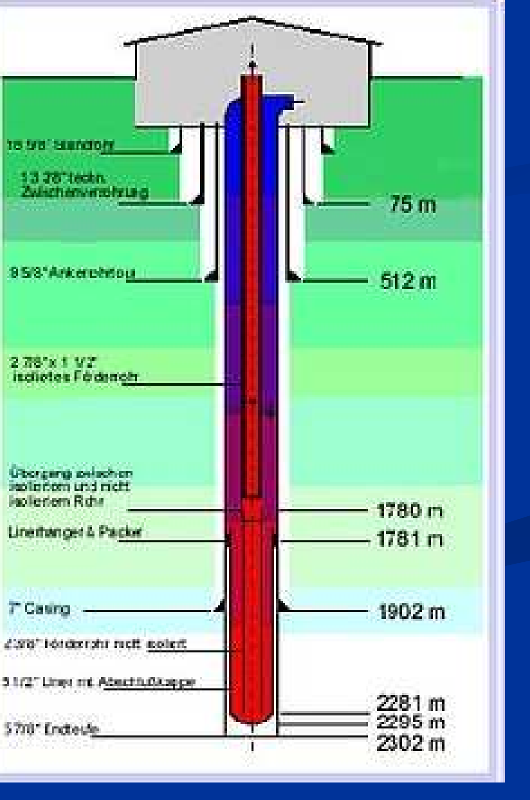
2. Classification of geothermal systems

2.1 Deep geothermal energy reservoirs

2.1.2 Low enthalpy reservoirs

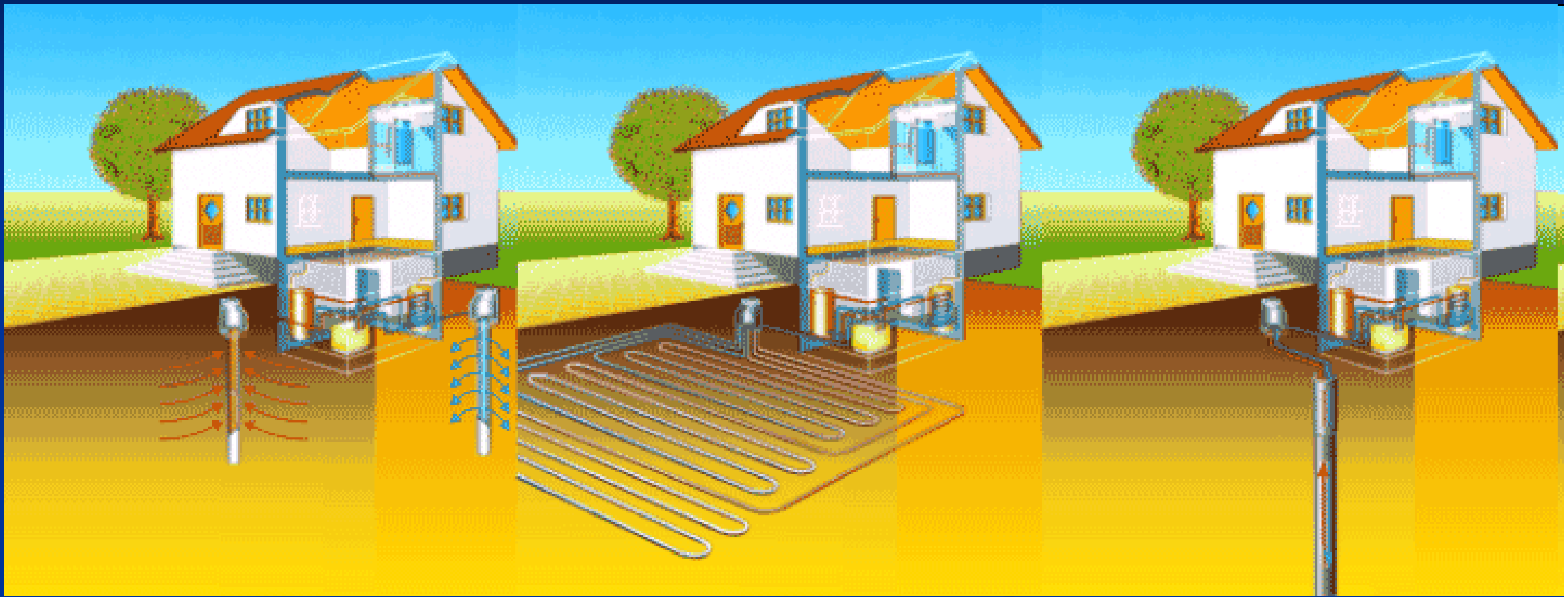
2.1.2.3 Deep earth tubes/Super C Aachen

Drilling for the Super C Aachen project. Stopped for economic reasons after a depth of 2500 m was reached.



2. Classification of geothermal systems

2.2 Surficial geothermal energy use with heat pumps



Open dublett system | horizontal ground loops | vertical U-tube loop (most common)

In 2009 in Germany 330.000 **ground source heat pumps** (GSHP) installed with 51.000 new installations in 2010

2. Classification of geothermal systems

2.2 Surficial geothermal energy use with heat pumps/Principle

Heat Pump:

Coefficient of Performance

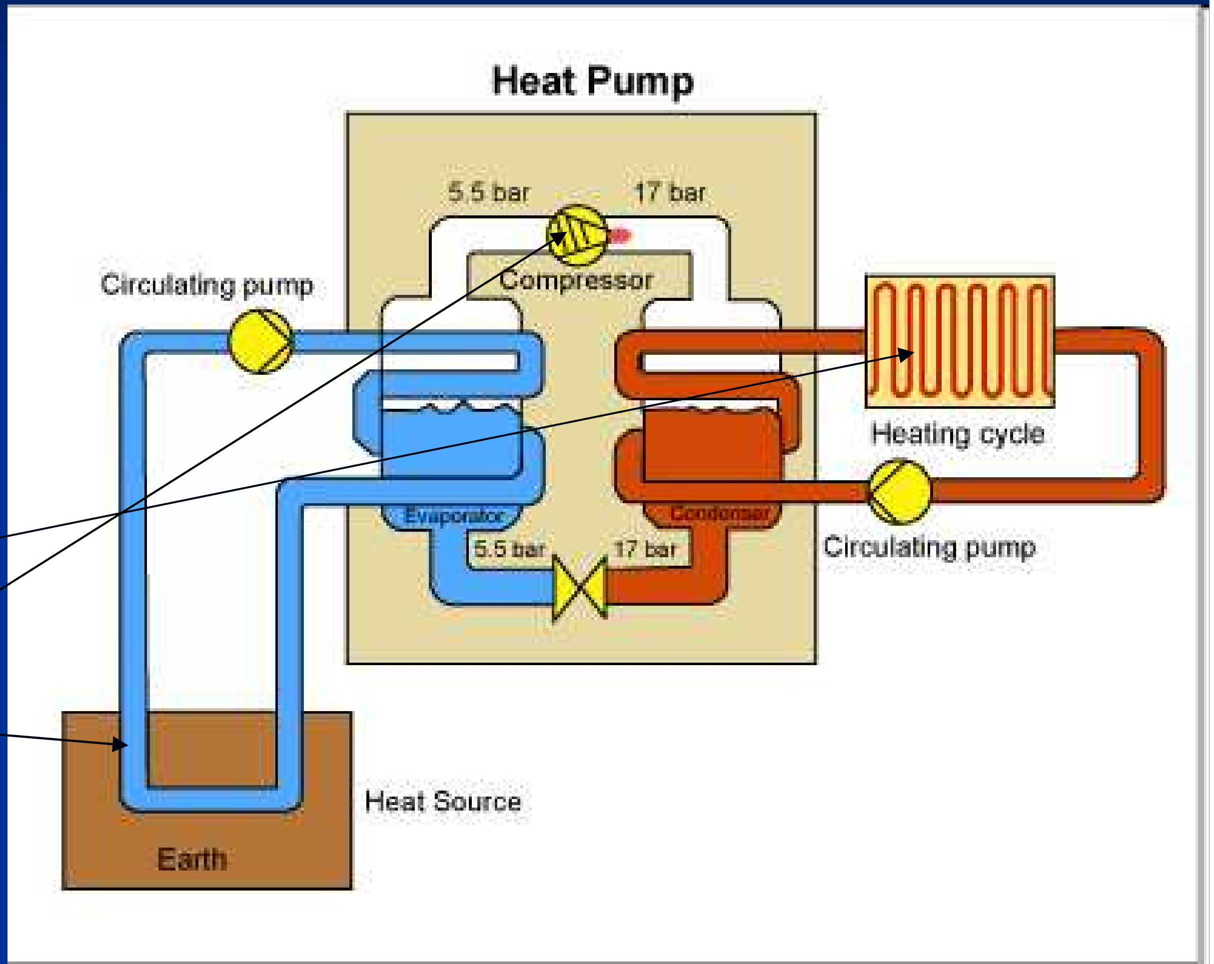
COP= Q_{th} / W_{el} ~ 4-5

with

Q_{th} = output heat rate

$= Q_{in} + W_{el}$

W_{el} = electric power input



2. Classification of geothermal systems

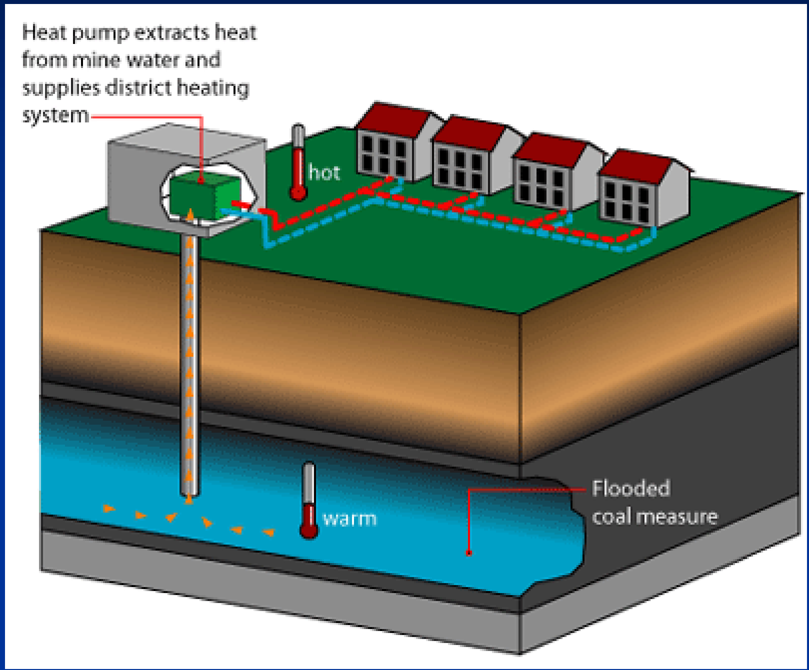
2.3 Geothermal energy use from tunnels/Switzerland

http://www.geothermie.ch/index.php?p=examp_tunnels

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2010/Pfaffel.ppt

2. Classification of geothermal systems

2.4 Geothermal energy use from old mining shafts



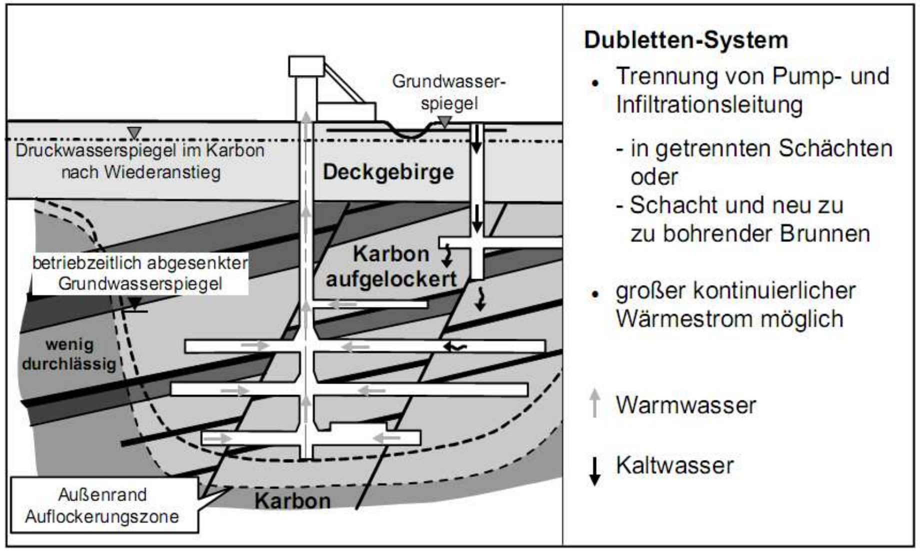


Abb. 1: Schematisches Bergwerk mit Förderschacht- und Infiltrationsbrunnen, Wärme-/Wasserkreislauf im Dubletten-System

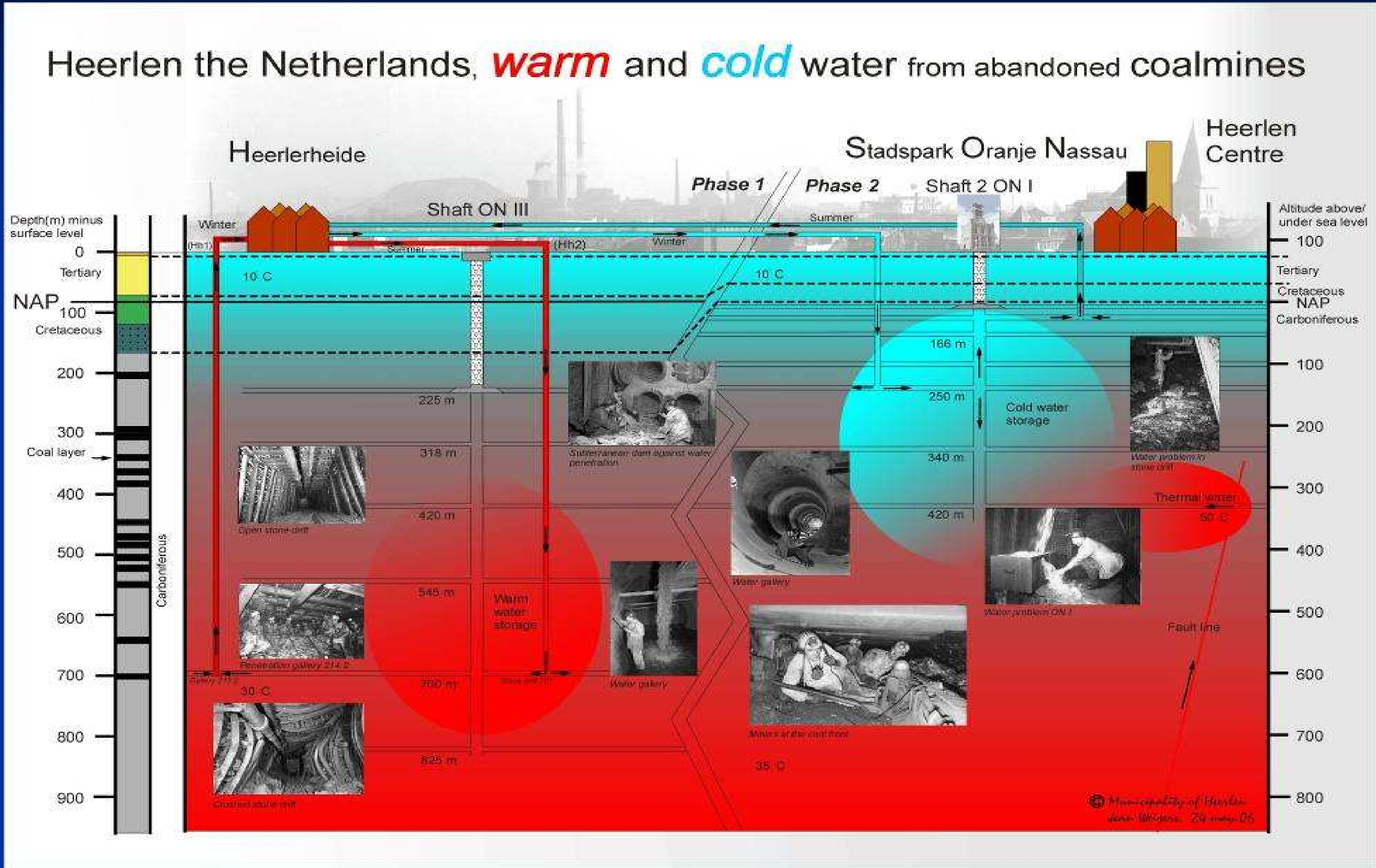
Extraction of warm water from mining shaft

Doublett-system of pumping and injection wells for water from a mining shaft

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2010/Gemmeke.ppt

2. Classification of geothermal systems

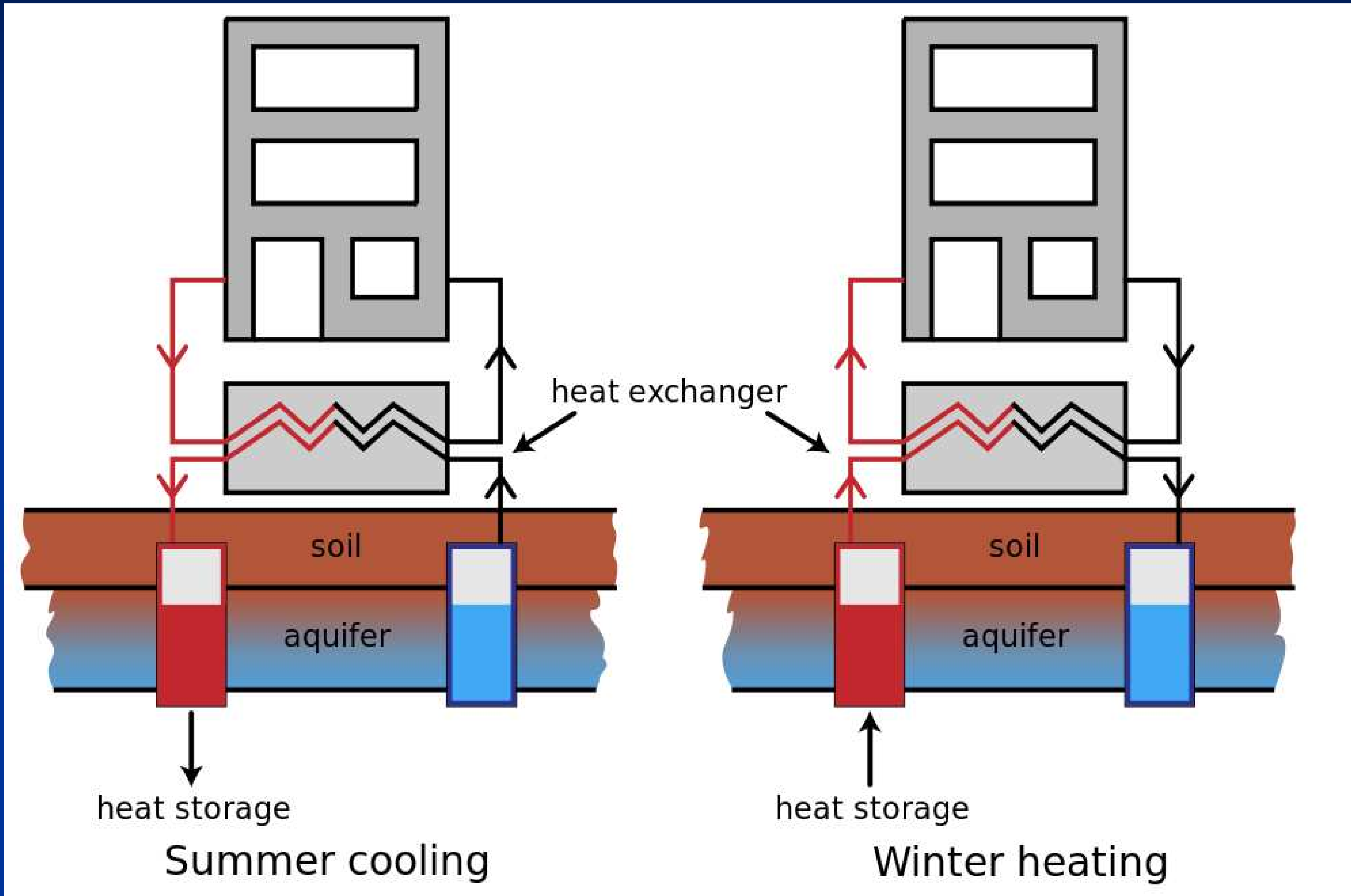
2.4 Geothermal energy use from old mining shafts/Project Heerlen



http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2008/Kallert_Remining_Low_Ex.ppt

2. Classification of geothermal systems

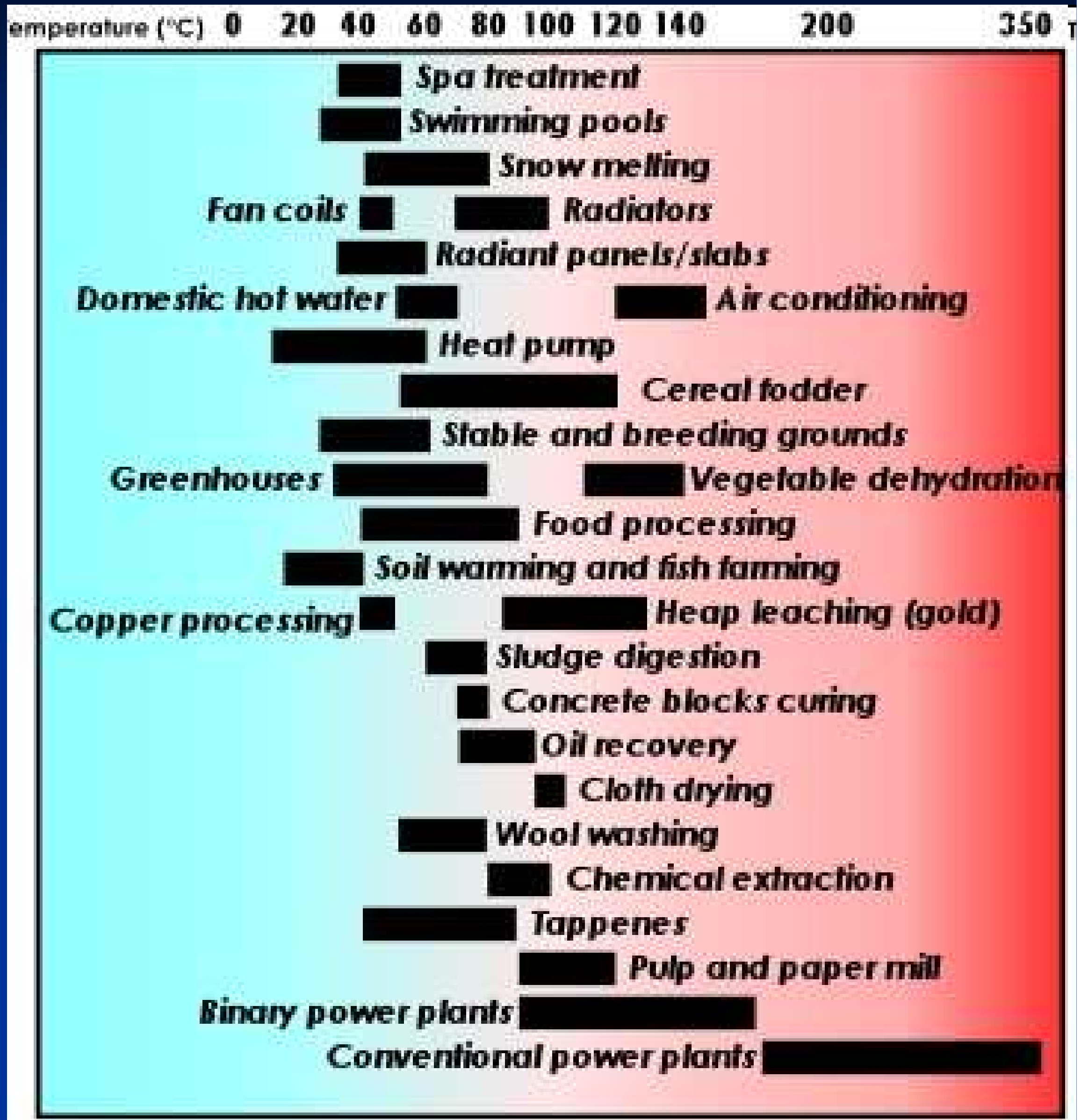
2.5 Geothermal energy use for seasonal storage



3. Use of geothermal energy

Lindal-Diagram

Geothermal use depend on the temperature of the geothermal reservoir



3. Use of geothermal energy

3.1 Direct use

Direct Uses

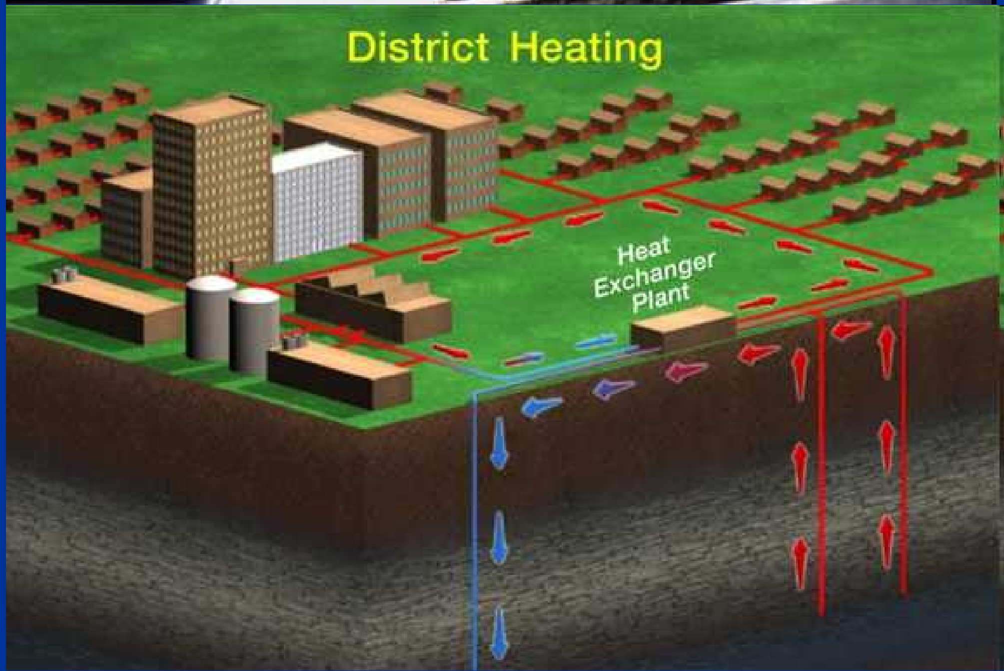
- Balneology (hot spring and spa bathing)
- Agriculture (greenhouse and soil warming)
- Aquaculture (fish, prawn, and alligator farming)
- Industrial Uses (product drying and warming)
- Residential and District Heating

http://geothermal.marin.org/GEOpresentation/sld072.htm

3. Use of geothermal energy

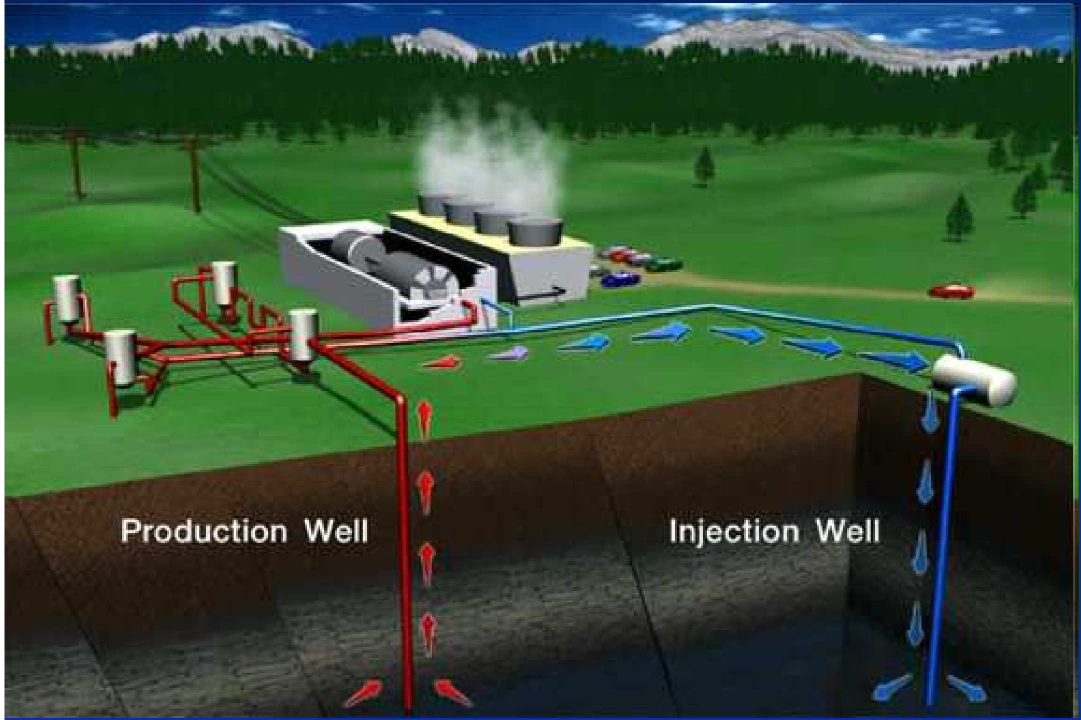
3.2 Heating and cooling

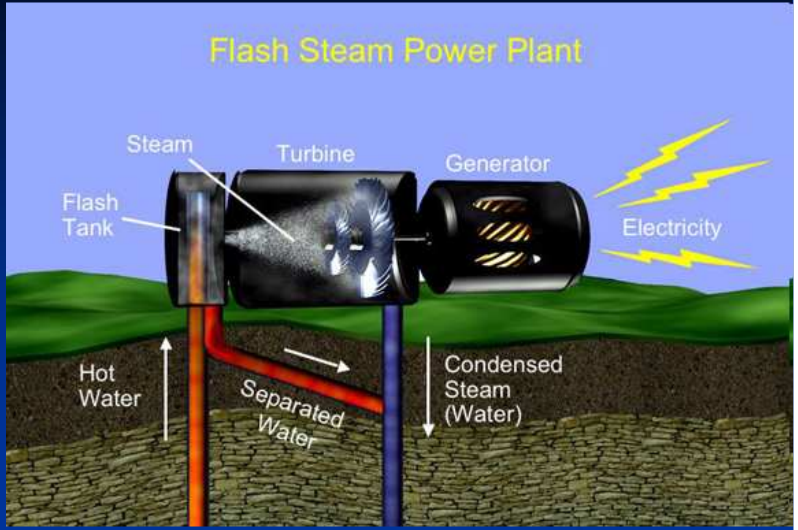
http://geothermal.marin.org/GEOpresentation/sld089.htm

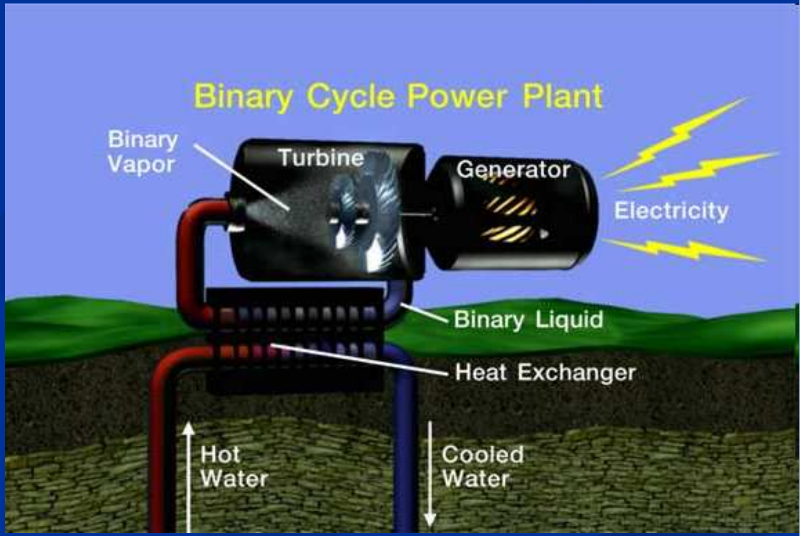


3. Use of geothermal energy

3.3 Electric power generation







Carnot thermodynamic efficiency

$$\eta = W/Q_{therm} = 1 - T_{cold}/T_{hot}$$

http://geothermal.marin.org/GEOpresentation/sld036.htm

4. Economic and regulatory aspects for the use of geothermal energy in Germany

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2007/Angebotspotential_Schmidmeier.ppt

5 Ecological aspects of geothermal energy

5.1 Energy potential of a geothermal reservoir

(meaning it is basically a regenerative energy source)

5.2 Regeneration of a geothermal reservoir (sustainability)

5.2.1 Regeneration in a fissured rock system with convective heat transport

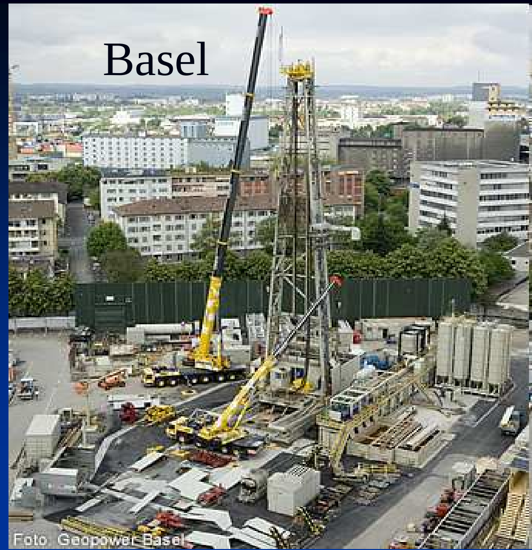
5.2.2 Pure heat conduction in a solid rock system

(requires complicated numerical modeling of the flow and heat transport in a reservoir)

6 Risks of the use of geothermal energy

6.1 Risks of seismic events

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2009/Boos_Basel_Projekt.ppt

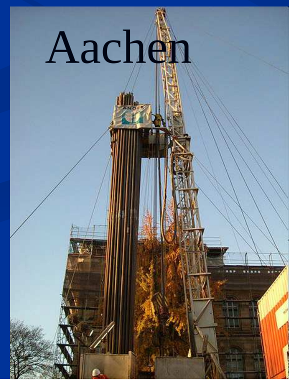


6.2 Risks at buildings due to vertical deformations of the earth's surface or from drilling

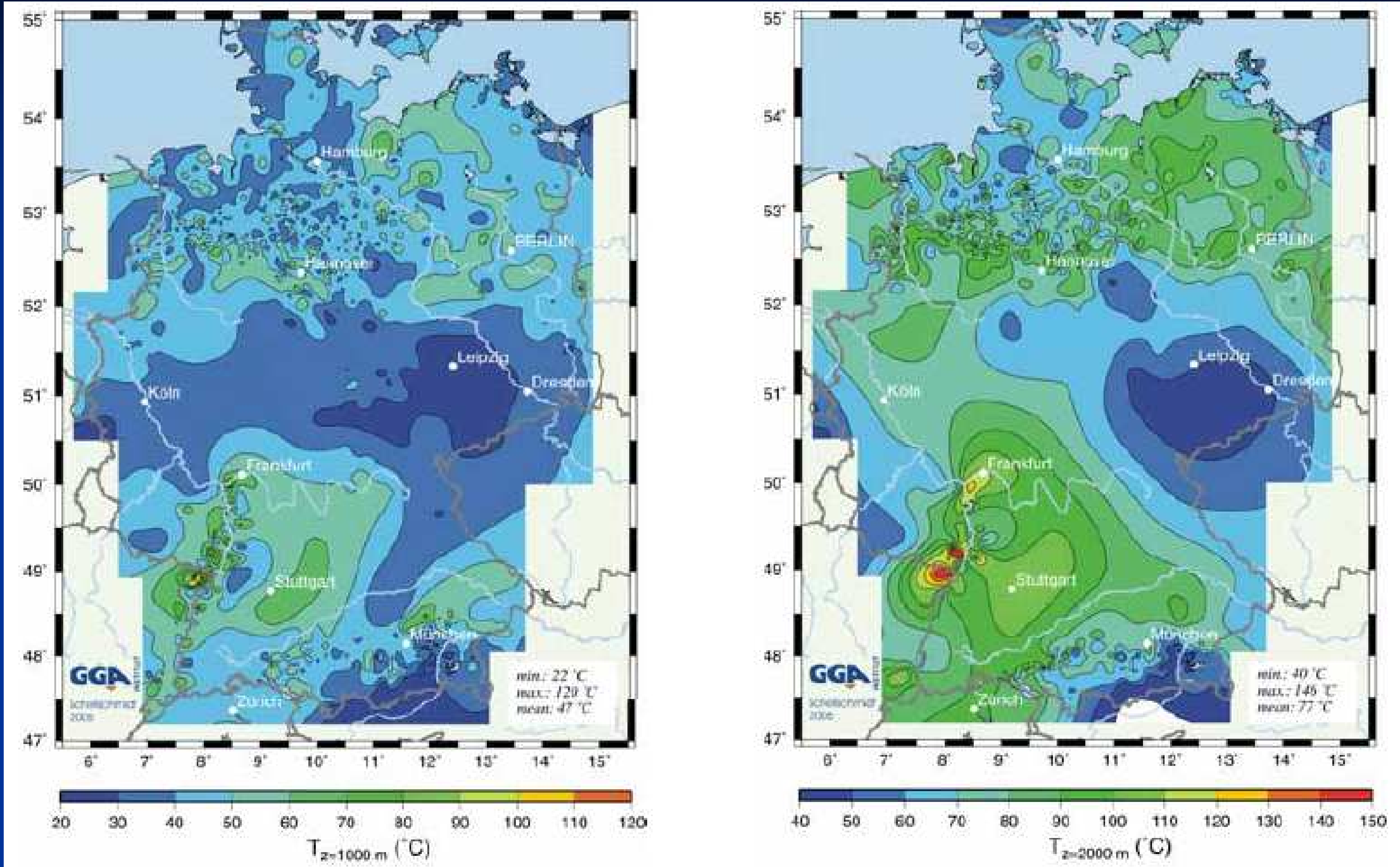
http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2009/Seeliger_Staufen_Projekt.ppt

6.3 Economic risks

http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Vortraege_2007/Angebotspotential_Schmidmeier.ppt

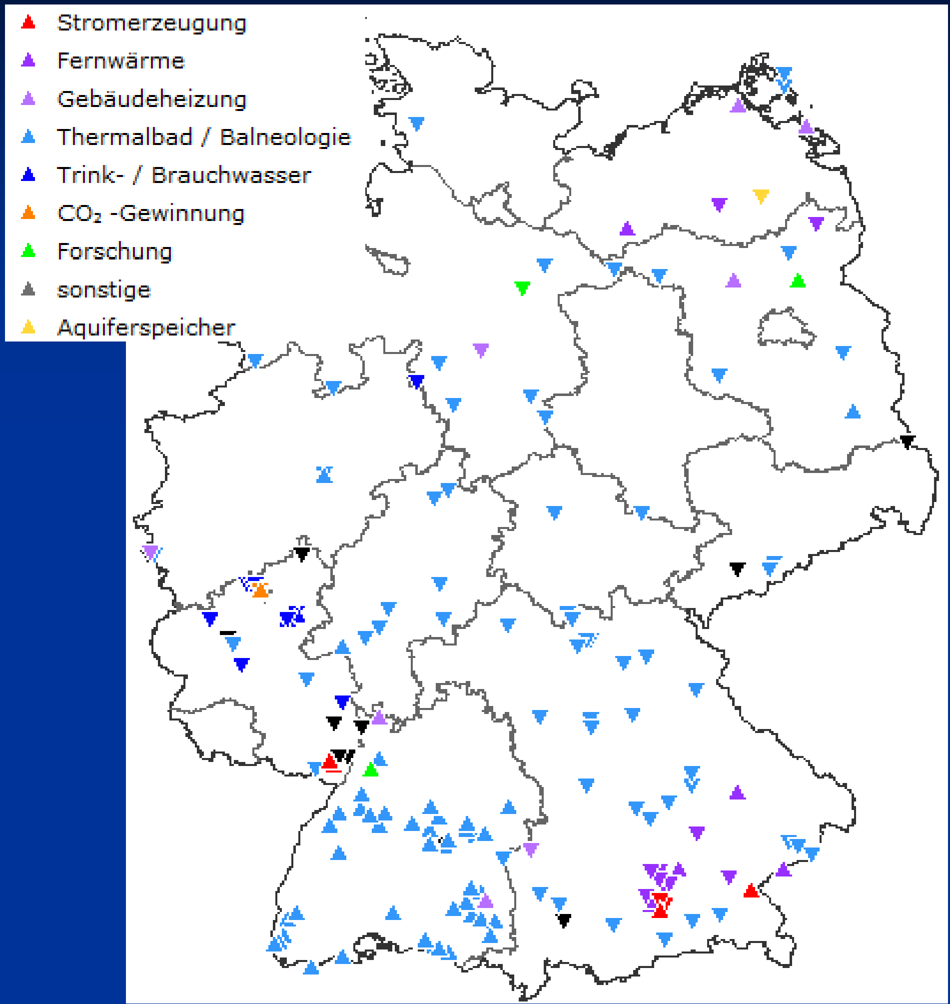


7. Potential of geothermal energy for Germany

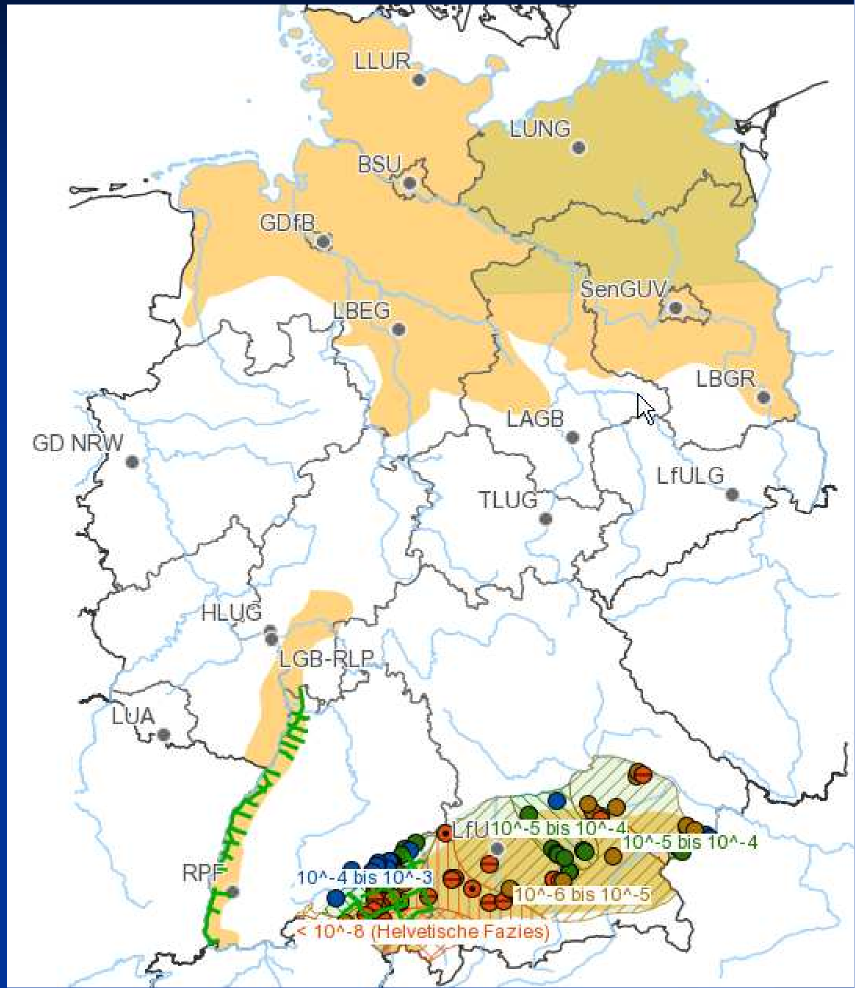


Geothermal temperatures underneath Germany at depths of 1000m and 2000m

7. Potential of geothermal energy for Germany

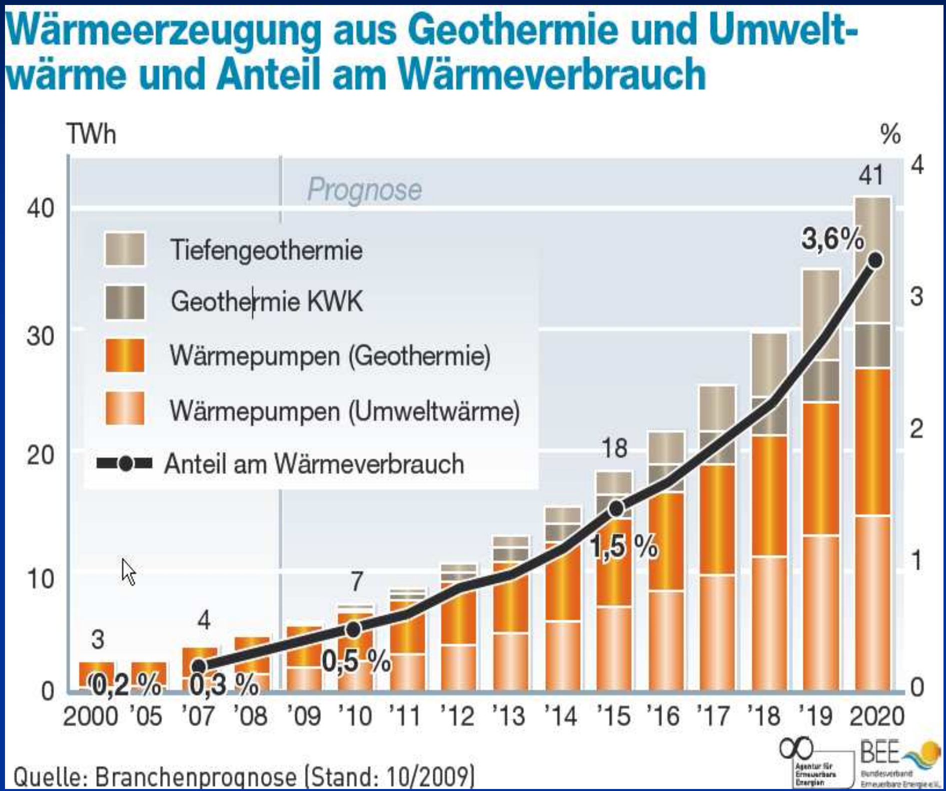


Present-day geothermal locations in Germany with different uses



Regions with highest geothermal potential with values of hydraulic conductivity for the Molasse region in the south

7. Potential of geothermal energy for Germany /Projection



Geothermal heat production

Geothermal electrical power production

8. References

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http://www.uni-kassel.de/fb14/geohydraulik/Lehre/Geophysik_Geothermie/Geophysik.html

http://geo-energy.org/Basics.aspx