ENGR-3000:

Renewable Energy, Technology, and Resource Economics

Geothermal Power

S. David Dvorak. Ph.D, P.E.

World Learning SIT Study Abroad

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Ísafjörður, Iceland

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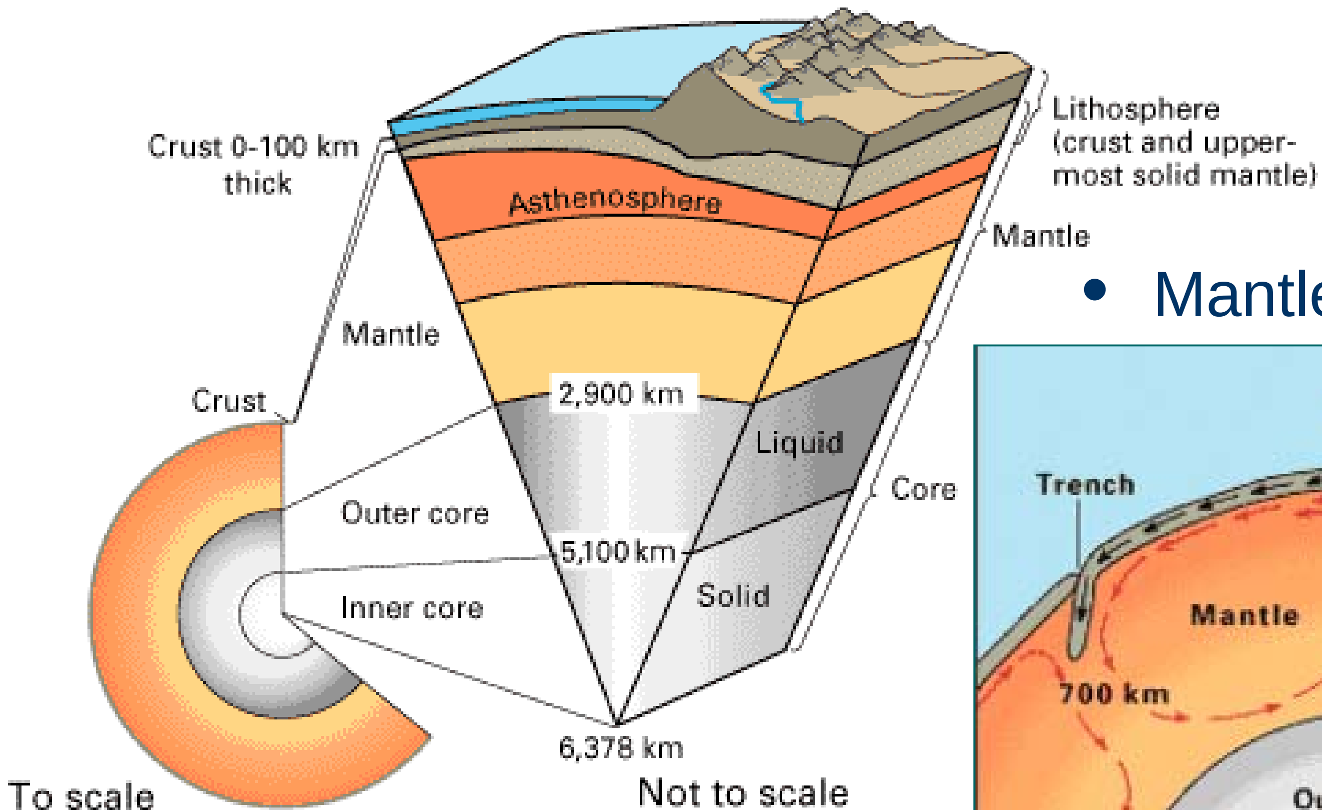
Geothermal Power: Outline

- Origins of Geothermal Energy
  - Structure of the Earth
  - Plate Tectonics
- Geothermal Fields
  - High Temperature
  - Low Temperature
  - Hot Dry Rock
- Iceland Deep Drilling Project
- Types of Geothermal Power Plants
  - Single and Double Flash
  - Binary
  - Enhanced Recovery
- Environmental Implications

Origins of Geothermal Energy

- Structure of earth



- Mantle convection

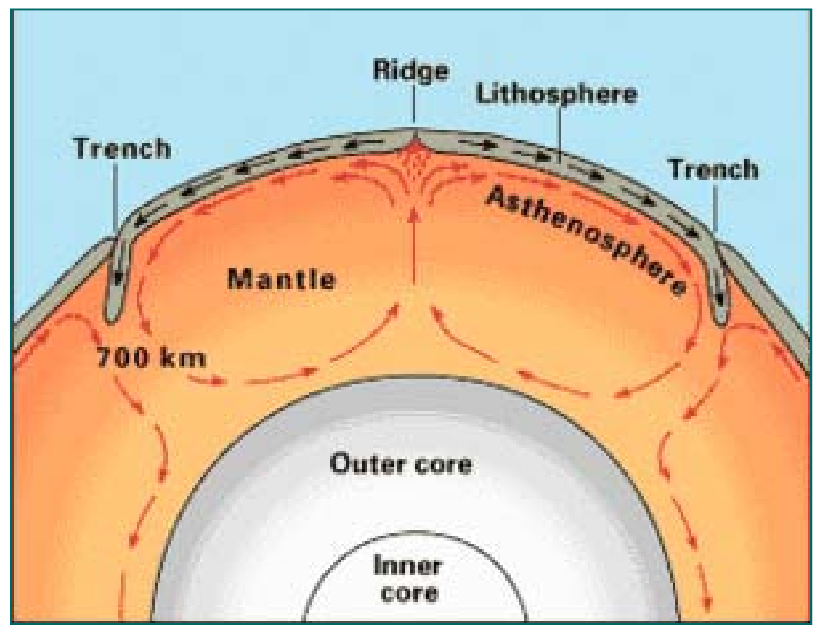
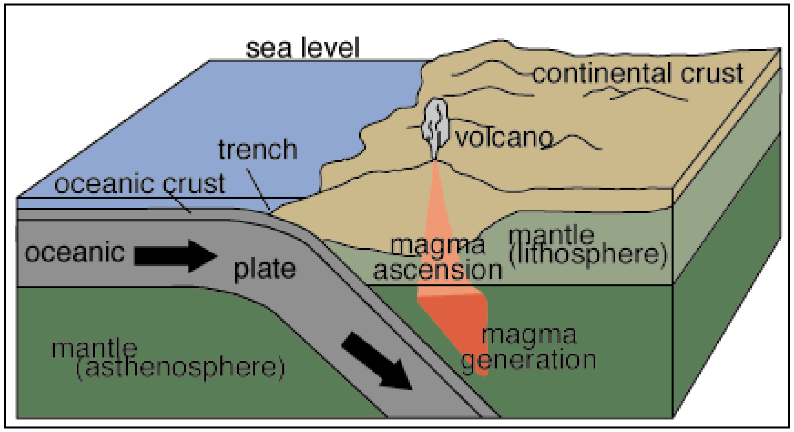
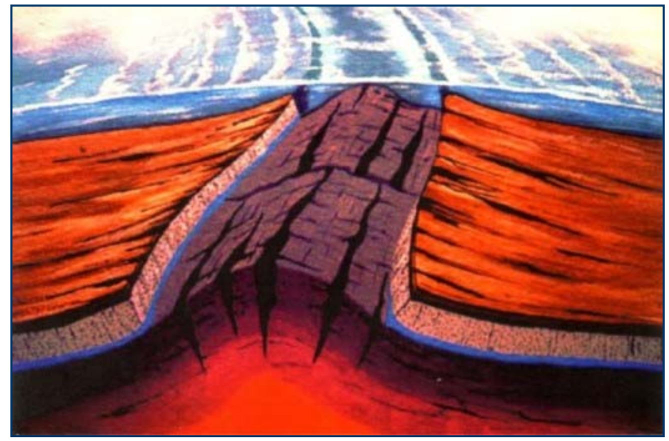


Plate Tectonics

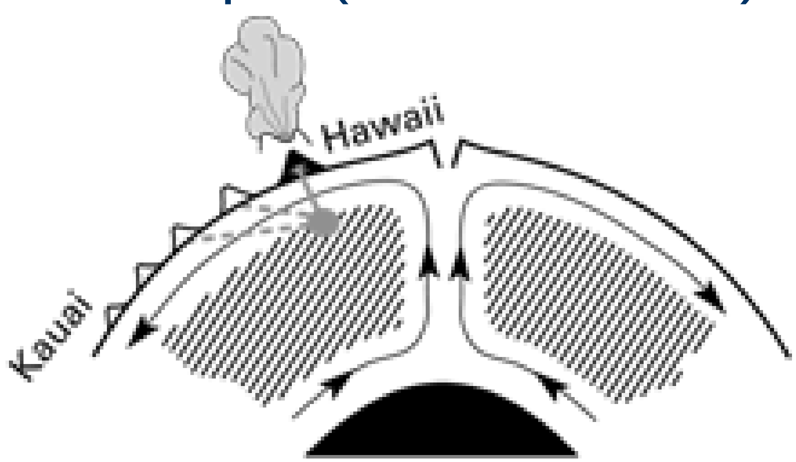
- Subduction Zone

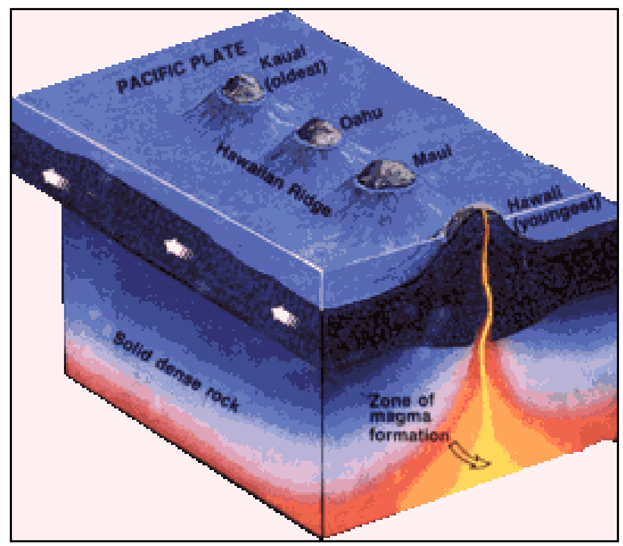


- Spreading Rift Zone



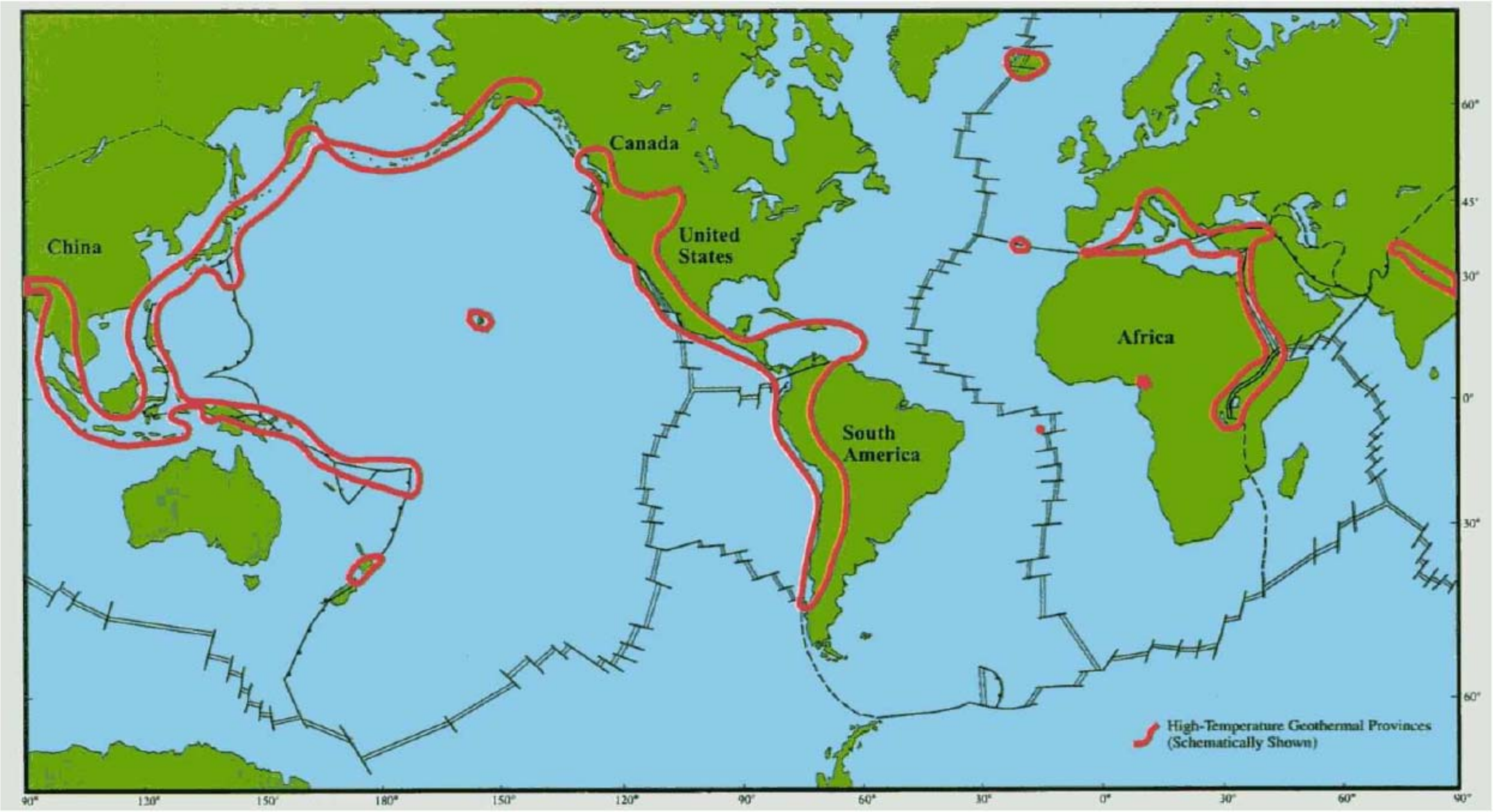
- Hot Spot (Mantle Plume)





High Temperature Areas

- Tectonic Plate Boundaries and “Hot Spots.”



Applications of Geothermal Energy

- Direct Use (Heating)
  - Spas, Resorts, DHW
  - Greenhouses
  - District Heating
- Power Generation
- Heat Pump Systems

Geothermal Energy: Direct Use

	Installed (MWt)	Used (TJ/yr)
• China	3687	45373
• Sweden	3840	36000
• USA	7817	31239
• Iceland	1791	23813
• Hungary	694	7939
• Germany	504	2909
• Poland	171	838

Geothermal Energy: Direct Use

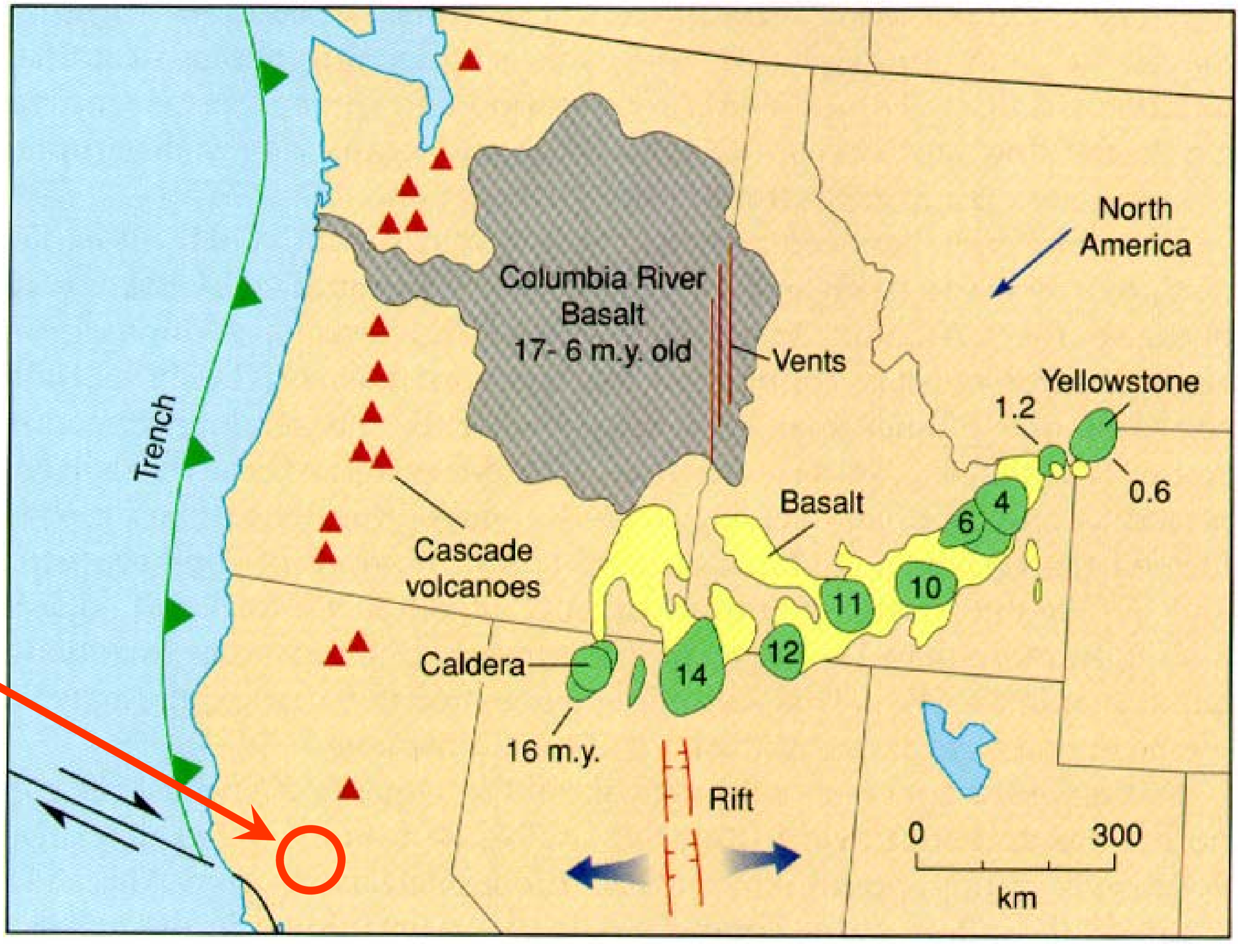
- Le Centre Thermal d'Yverdon-les-Bains

- Greenhouse in Iceland

Geology of the Pacific Northwest

- Subduction off coast, plus volcanoes (Cascade Mts.)
- Yellowstone Hotspot, Snake river formation

Geysers
Power Plant



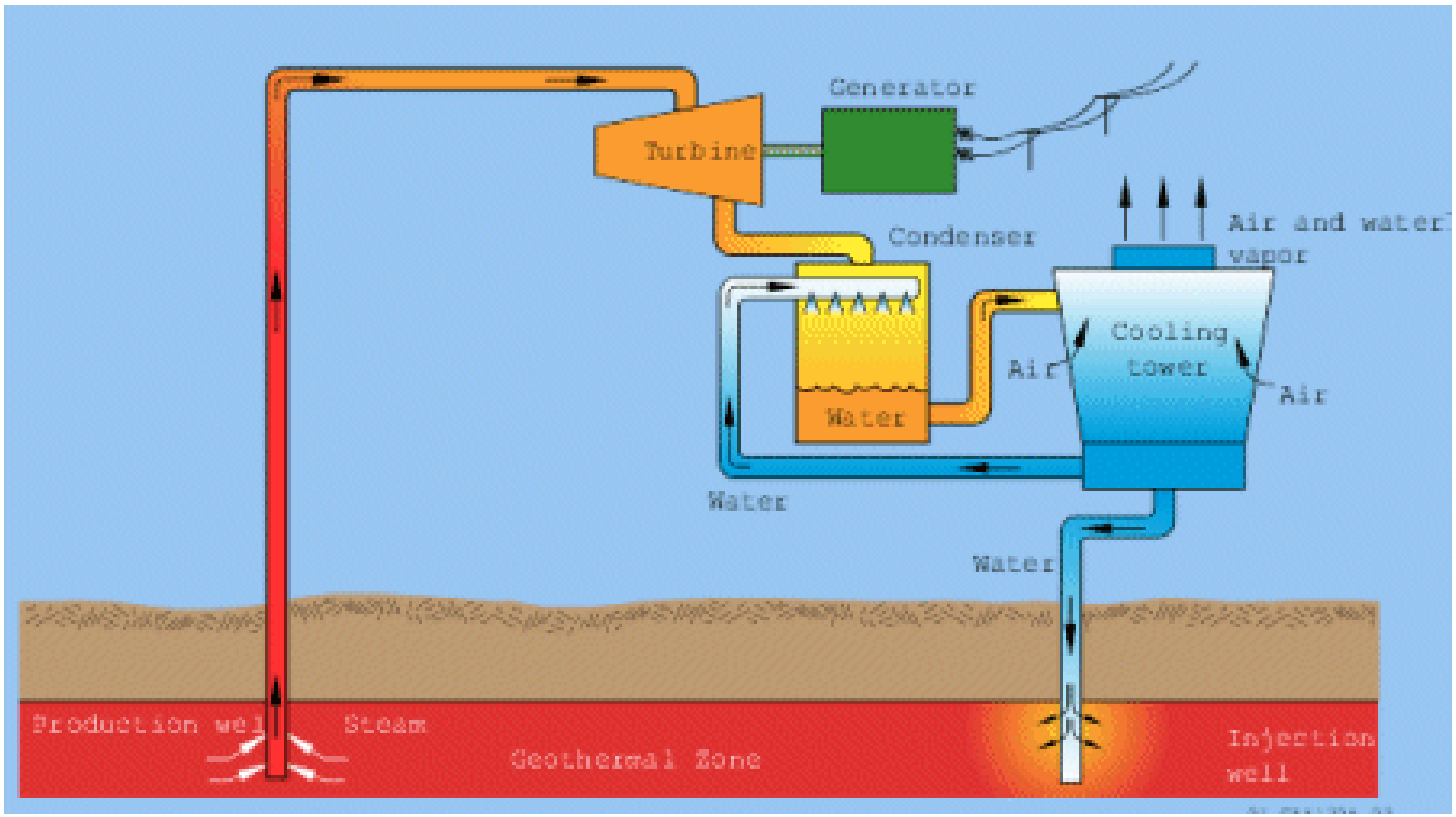
"The Geysers" Geothermal Power Plant

- Dry steam resource (uncommon)
- 30 mi^2 area, 70 mi north of San Francisco
- Total of 15 power plants
- 725 MWe net generating capacity

http://www.blm.gov/ca/st/en/prog/energy/geothermal.html

Dry Steam Power Cycle

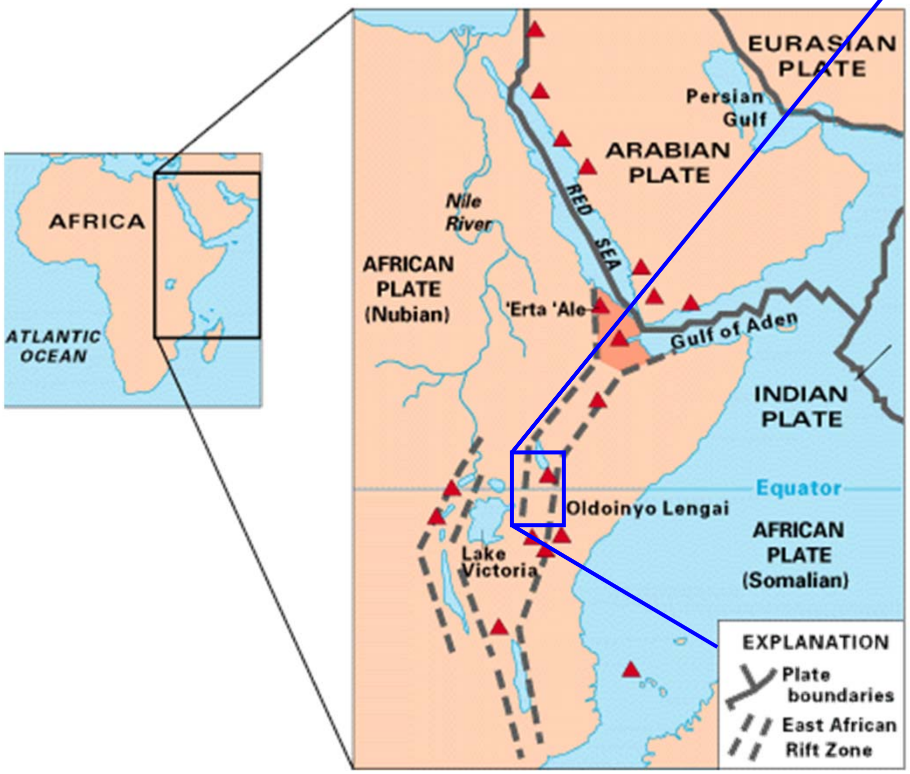
- Steam from geothermal well is used directly in a rankine cycle.
- The geothermal steam contains few impurities

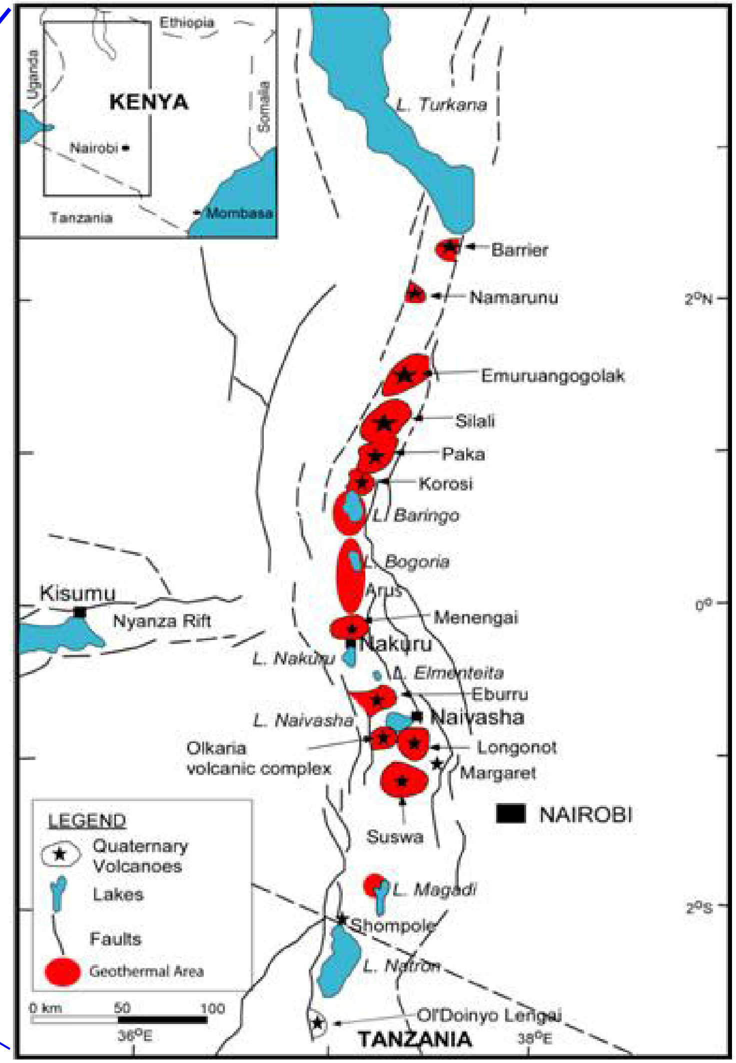


https://inlportal.inl.gov

Geothermal Areas in Africa

- Olkaria Power Plant, Kenya





Great Rift Valley, Kenya

- Mt. Longinot and Lake Naivasha

- Olkaria Power Plant

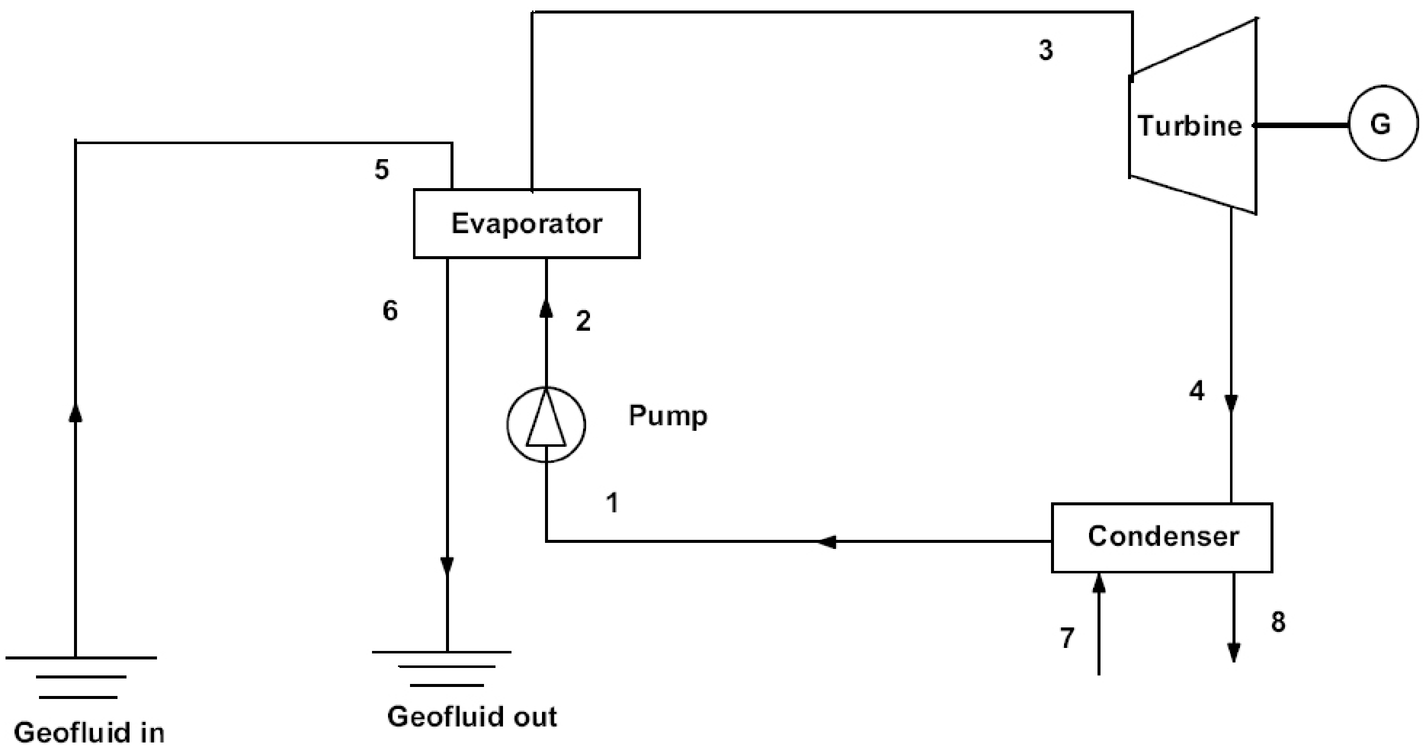
Olkaria Power Plant, Kenya

- Three Units, Olkaria I comissioned in 1981 (45 MWe)
- Currently expanding from 70MWe to 105 MWe

- Uses “Organic Rankine Cycle.”

Organic Rankine Cycle

- Useful for lower temperature resources.
- Geothermal heat is transferred to a separate working fluid:
  - Example: Isopentane (boiling pt. 26°C at P_{atm}.)



Yari, Renewable Energy, 35 (2010) p112-121

Pico Vermelho, São Miguel, Azores

Pico Vermelho

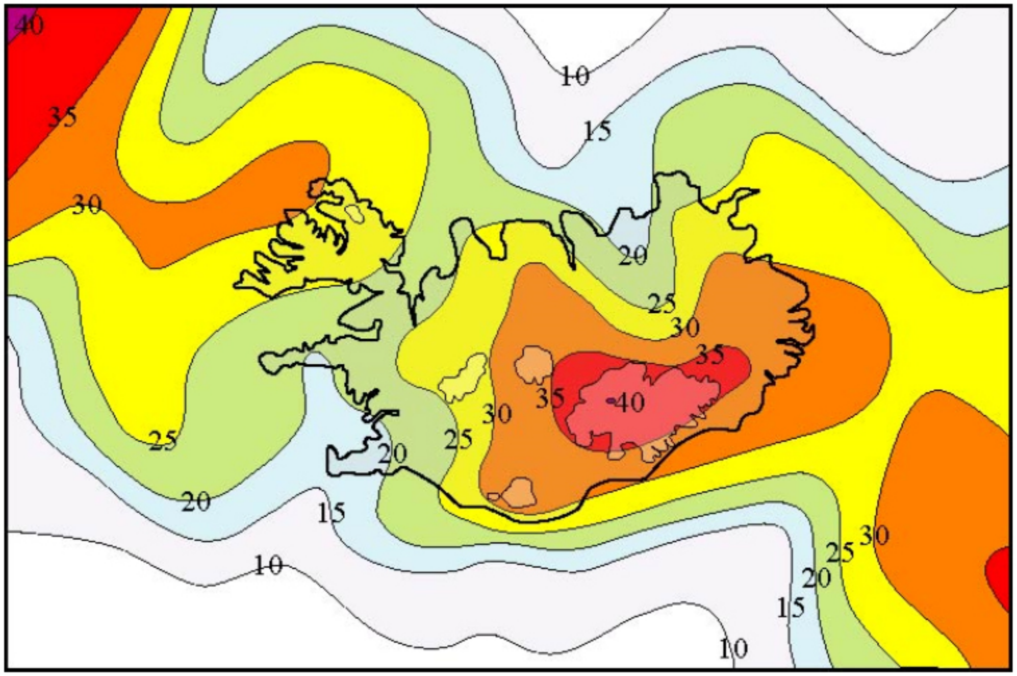
- Binary Cycle 13 MW

- Mean Reservoir Temperature = 238ºC

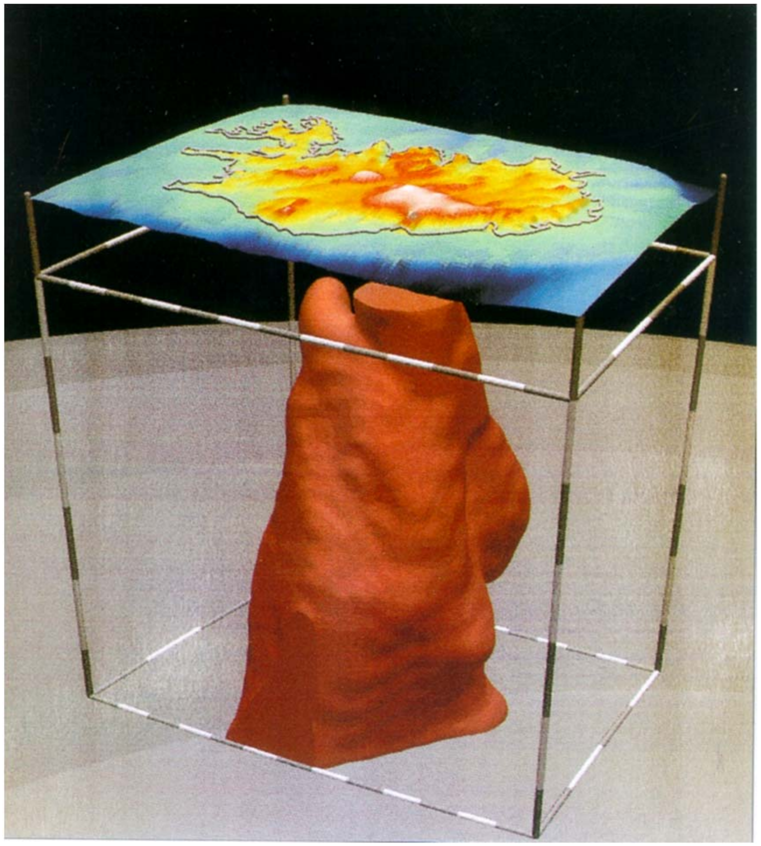
Iceland and the Mid-Atlantic Ridge

The Geology of Iceland: Volcanic Origins
Deep Mantle Plume ("Hot Spot")

- The mantle plume creates a thicker crust, raising the surrounding area:



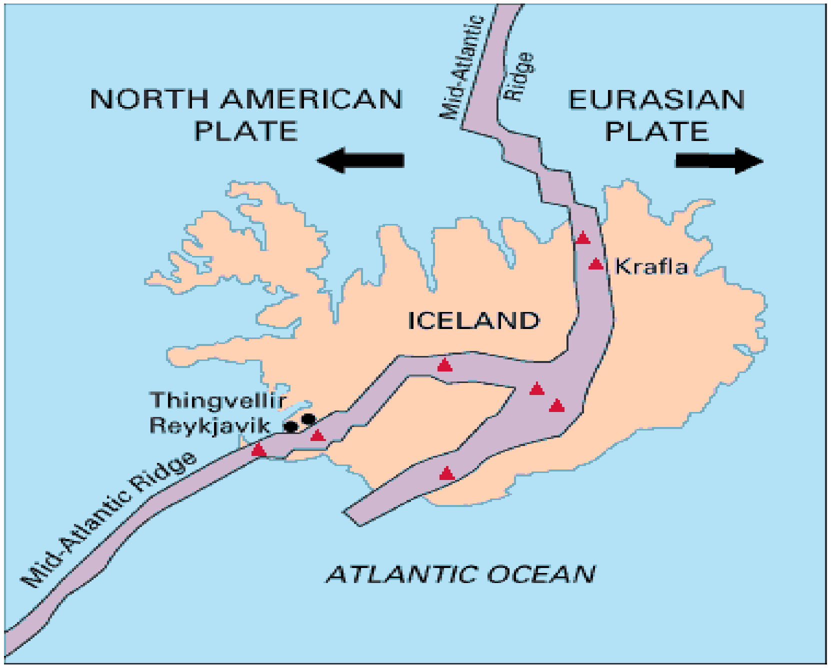
Numbers indicate crustal thickness (km)

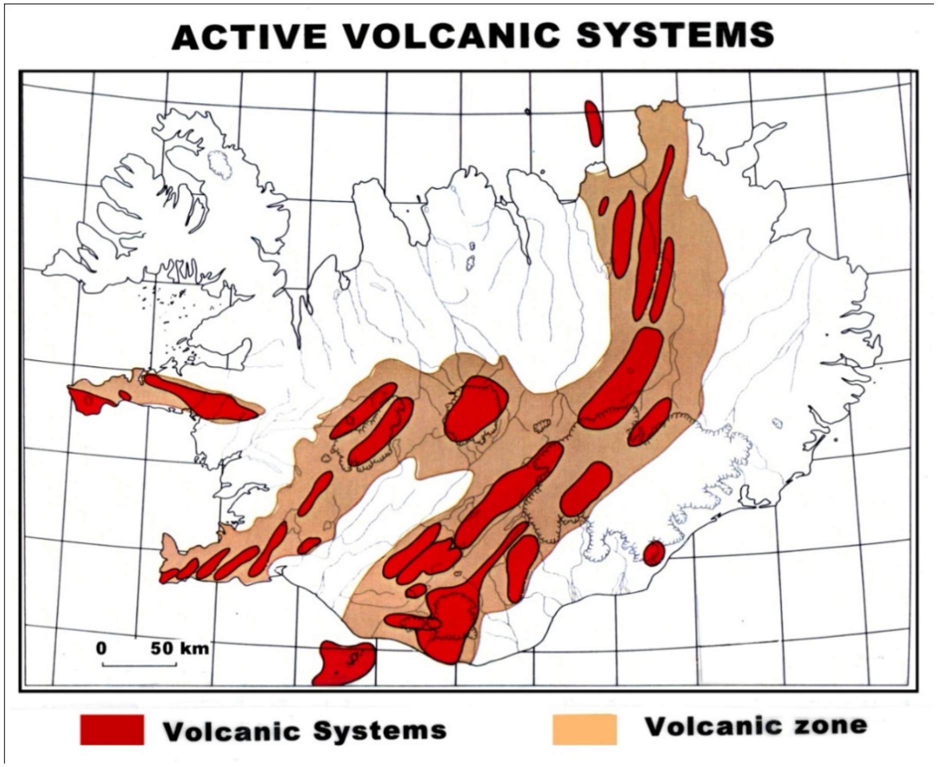


R. Tronnes, "Geology and Geodynamics of Iceland," Nordic volcanological Institute, University of Iceland

The combination of the mid-atlantic ridge and the deep mantle plume create the geologically active rift zones above sea level

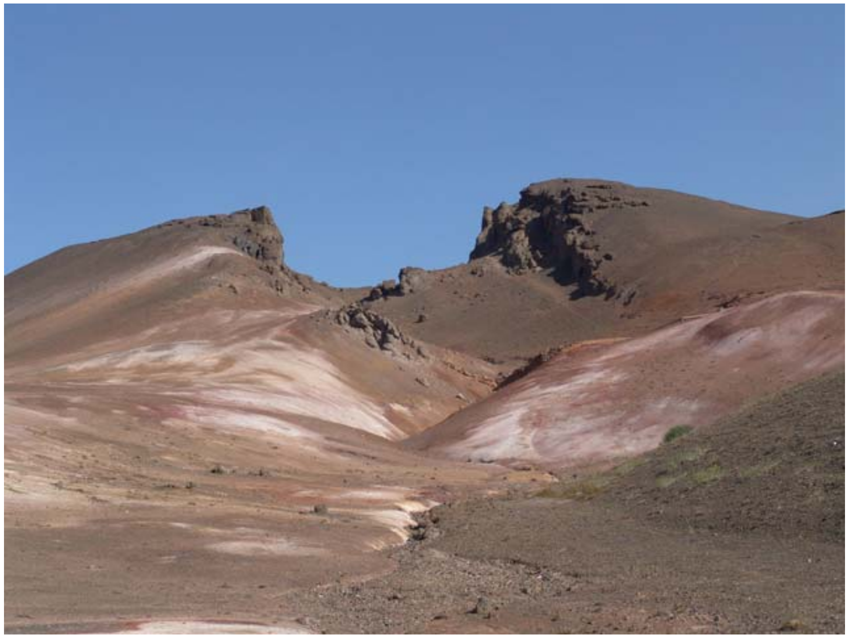
Iceland and the Mid-Atlantic Ridge





Iceland Rift Zone Features

- Mountain in the Northern Rift Zone



- Thingvellir, Central Rift Zone

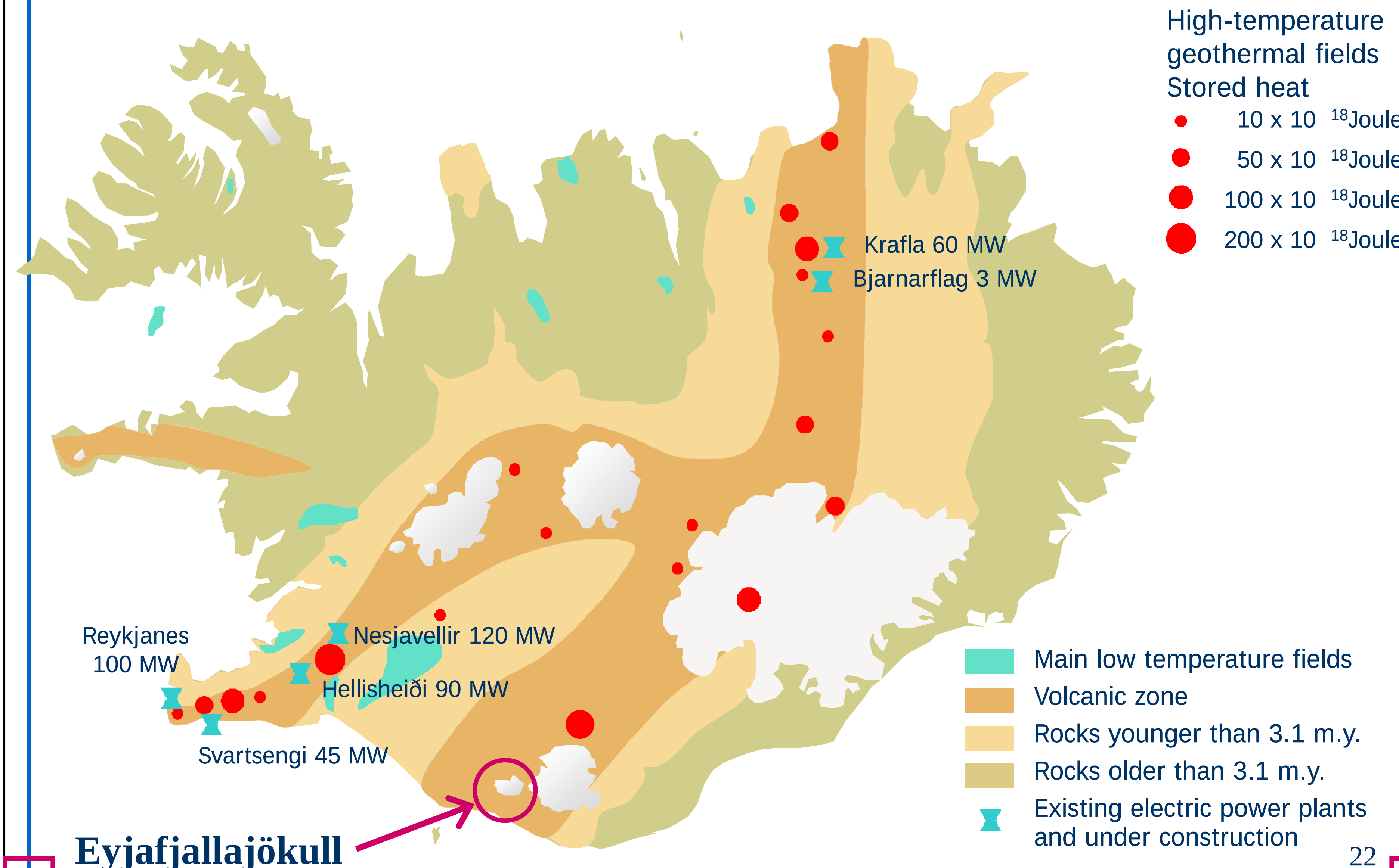
District Heating in Iceland

- Reykjavik around 1930 . . .

- Reykjavik today:

Geothermal Resources in Iceland

Existing electric power plants



Source: Orkustofnun 2005

Geothermal Resources

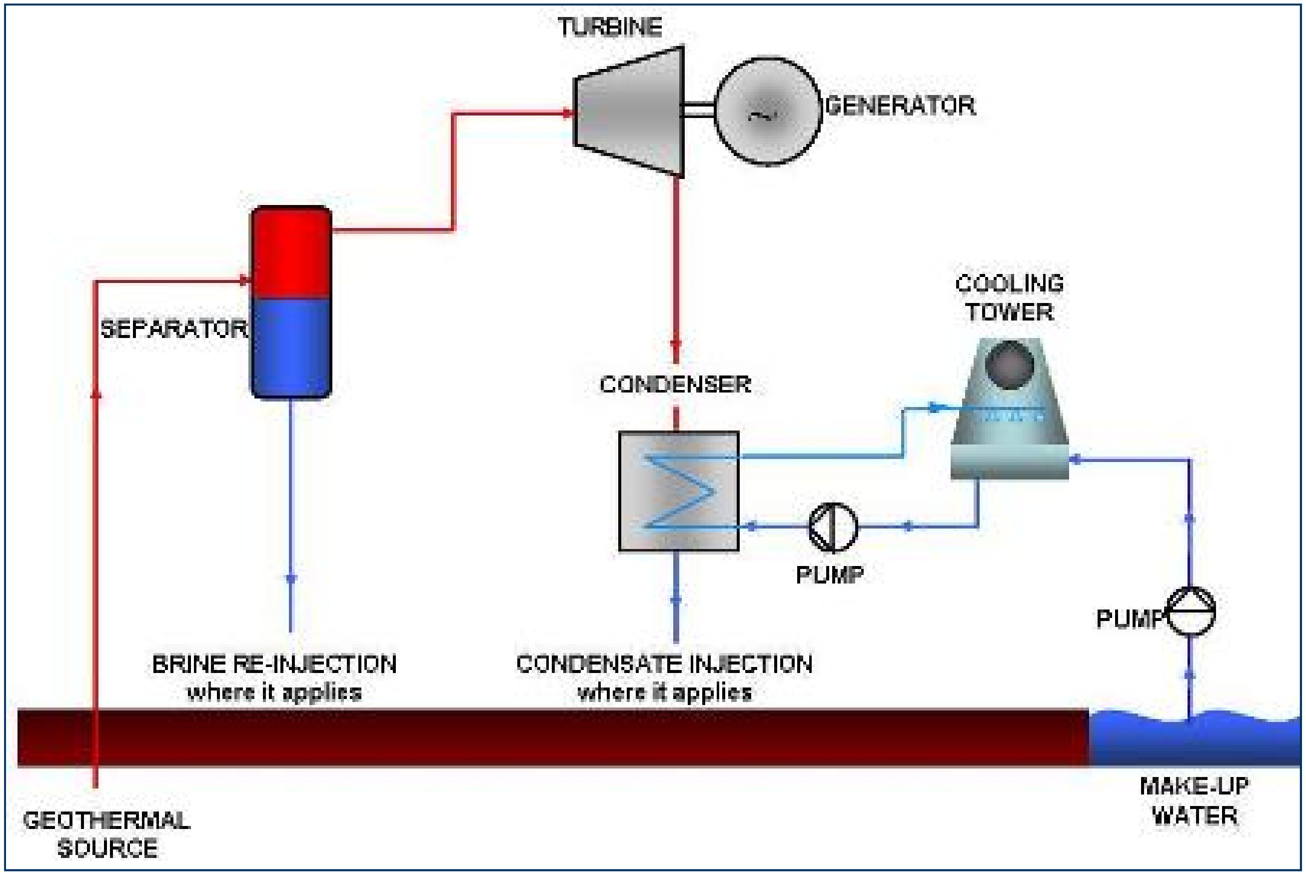
- High Temperature Fields (T > 150°C)
  - Suitable for electricity generation
  - Vapor dominated fields
    - Wells produce steam directly
  - Water dominated fields
    - Wells produce hot water at pressure, which can be “flashed” to steam
    - Water contains more impurities than steam.
  - Hot Dry Rock
- Low Temperature Fields (T < 150°C)
  - Suitable for direct use heating
- Most Locations on Earth: Near Surface Geothermal Energy
  - Suitable for ground loop heat pumps

Bjarnarflag Geothermal Electric Power Plant

- Icelands’ First Geothermal Electric Power Plant, Commissioned 1969
- Steam Turbine Delivers 3.2 MW of Electric Power
- Expansion underway to 40MWe

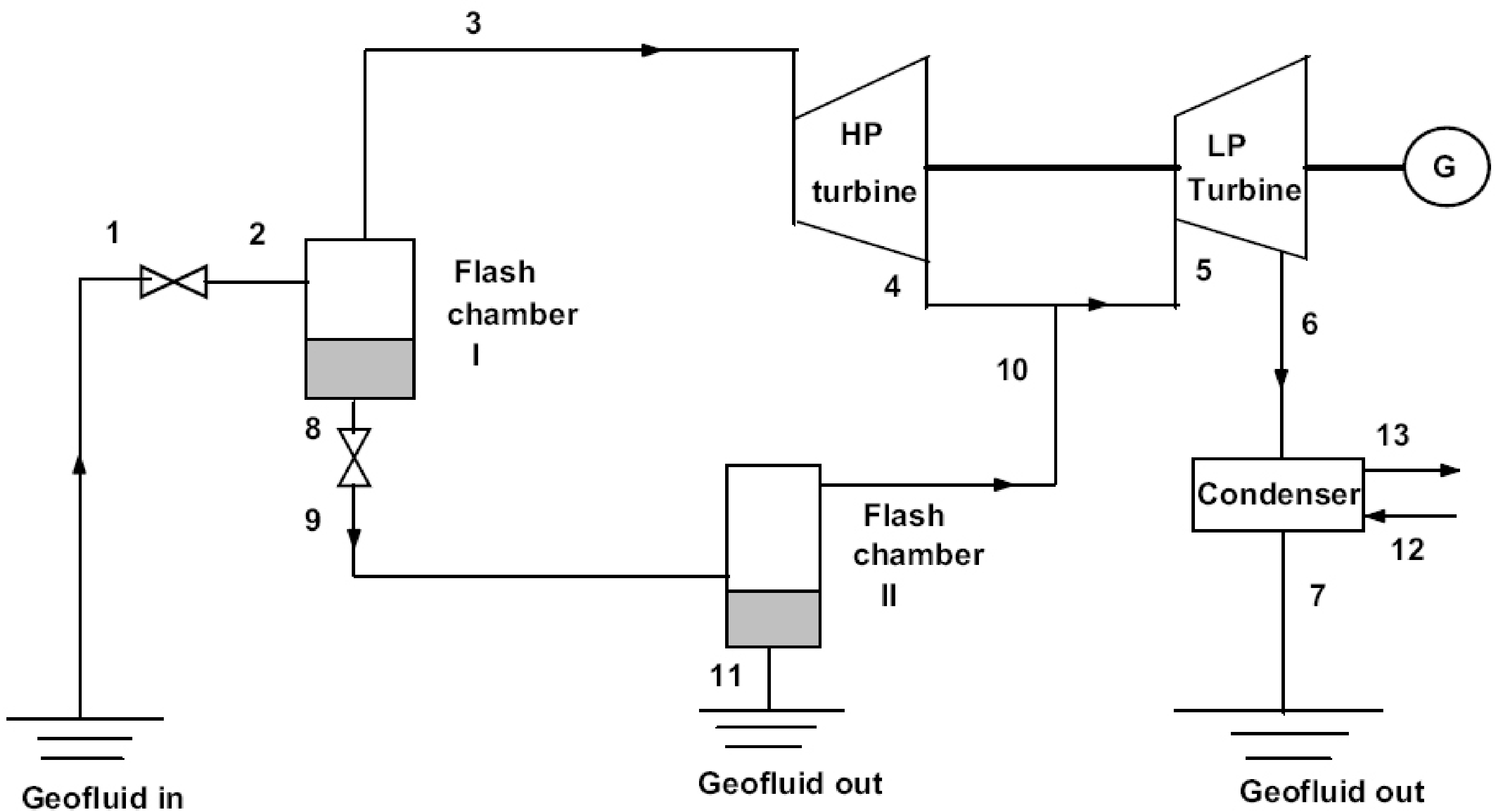
Single Flash Power Plant

Simplified schematic for a ”single-flash” power plant



Note: brine from the geothermal source can be used for heating before (or in place of) re-injection

Double Flash Power Plant

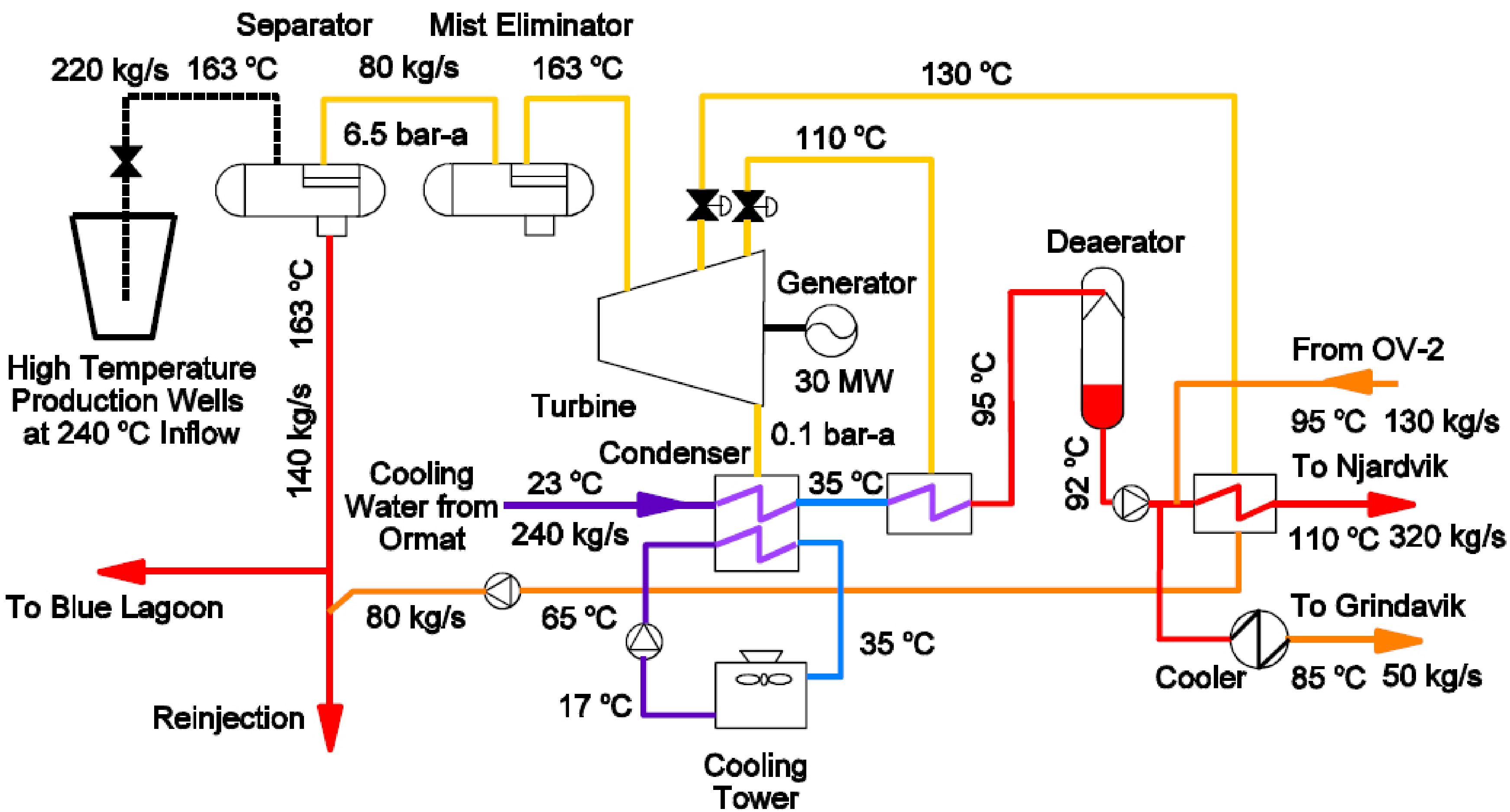


Yari, Renewable Energy, 35 (2010) p112-121

Svartsengi Geothermal Power Plant

- **Plant capacity 46 MWe and 150 MWth**
- **Owned by the local communities in the Suðurnes area**

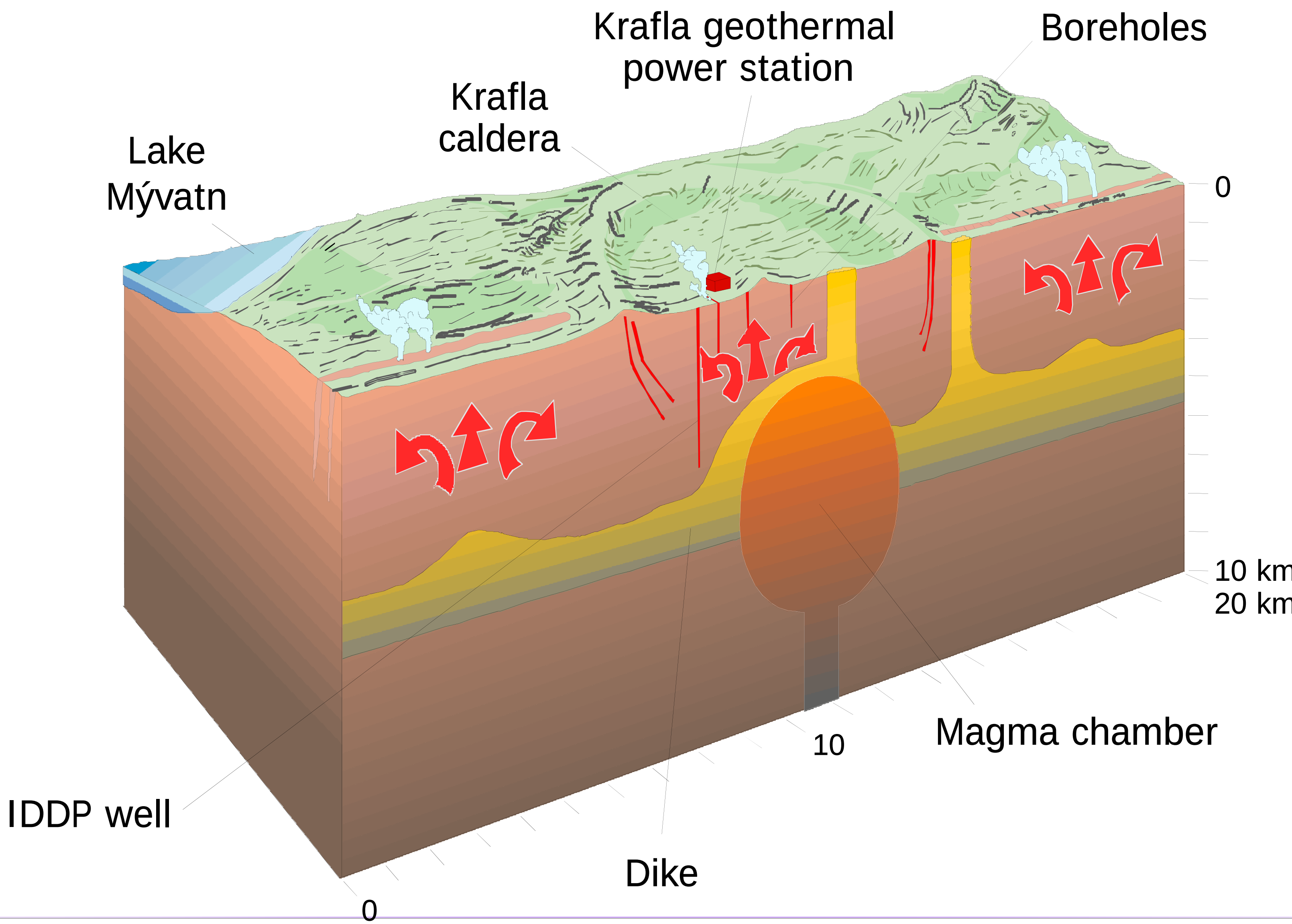
Svartsengi "Power Plant 5"



Thorolfsson, GHC Bullitin, 2005

The Blue Lagoon

Iceland Deep Drilling Project (IDDP)



Iceland Deep Drilling Project (IDDP)

	Conventional dry-steam well	**IDDP well**
Downhole temperature	235 °C	430 - 550 °C
Downhole pressure	30 bar	230 - 260 bar
Volumetric rate of inflow	0.67 m^3/s	0.67 m^3/s
Electric power output per well	~ **5 MW_e**	~ **50 MW_e**

This comparison is based on the same volumetric flow rate of inflowing steam



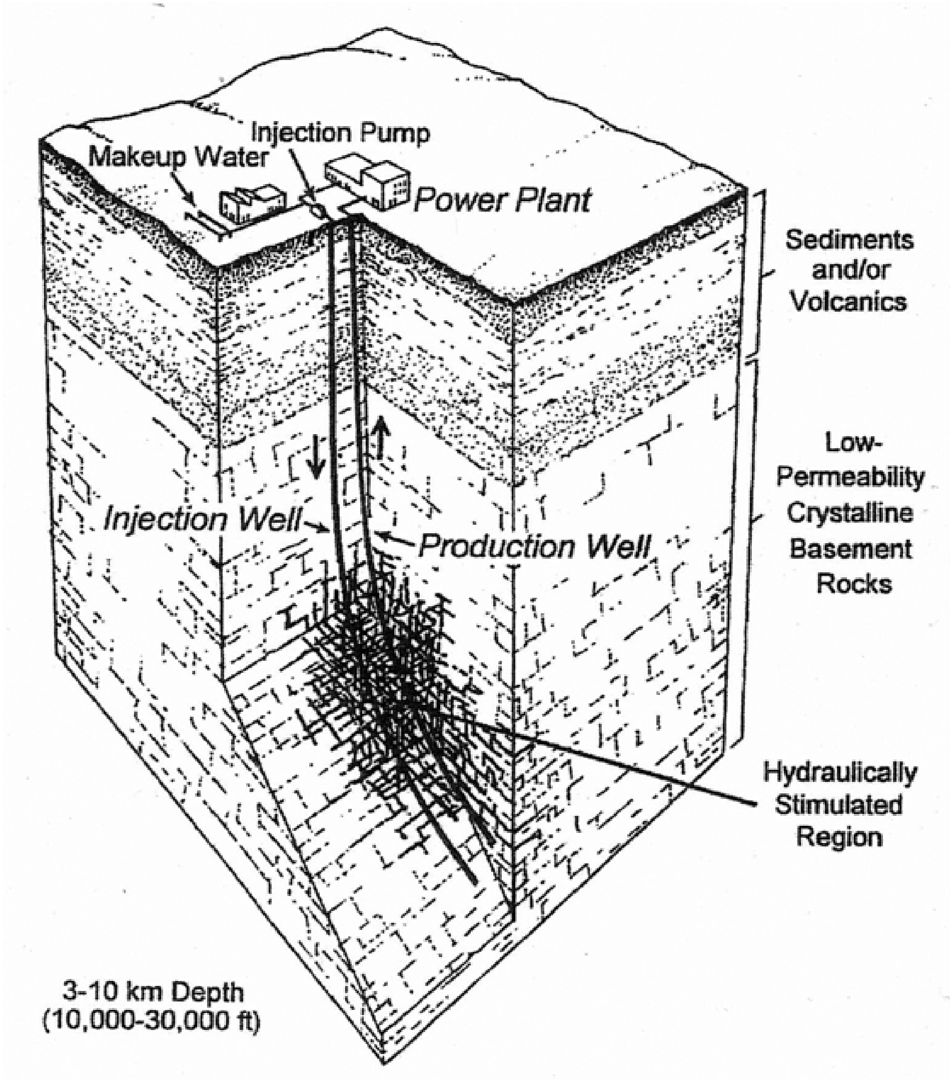

Iceland Deep Drilling Project

- First attempt IDDP-1 near Krafla drilled into magma at 2104 m depth (June 2009)
- Successful IDDP-1 tests from Aug 2011 to 2012 40-50kg/s dry superheated steam at 410°C at 40 Bar, equivalent to a power output potential of 30-40 MWe
- IDDP-2 drilled near Reykjanes geothermal plant, completed Jan 2017 at a depth of 4659 m, supercritical steam conditions 427°C at 340 Bar.

www.iddp.is Geothermics 49 (2014) 1

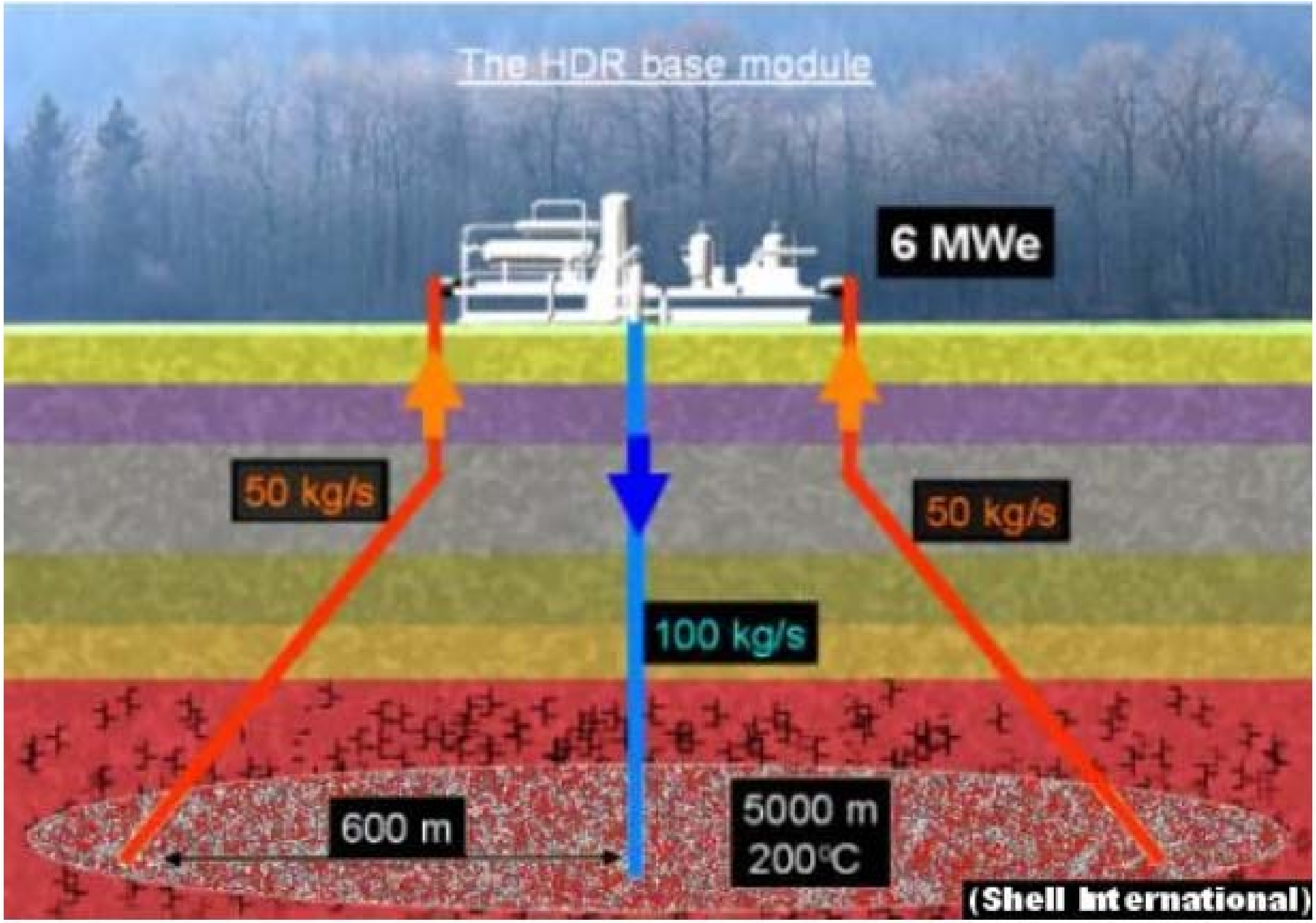
Enhanced Recovery from Hot Dry Rock

- Use “hydraulic shearing” to increase porosity of rock.
- Lower pressure than hydro-fracking; actually the smaller shear fractures improve heat transfer



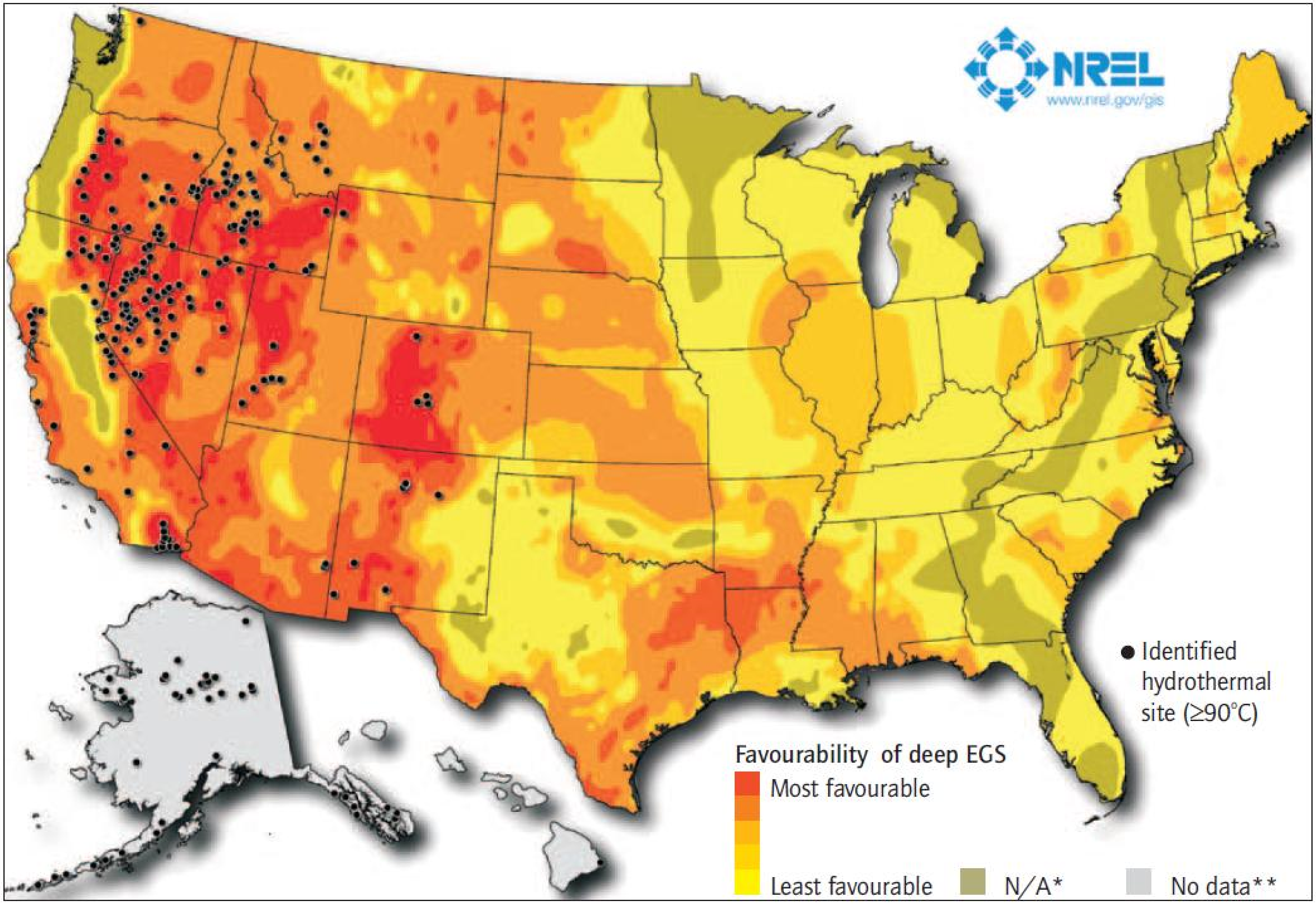
Tester, et. al., Sustainability

HDR Pilot Plant

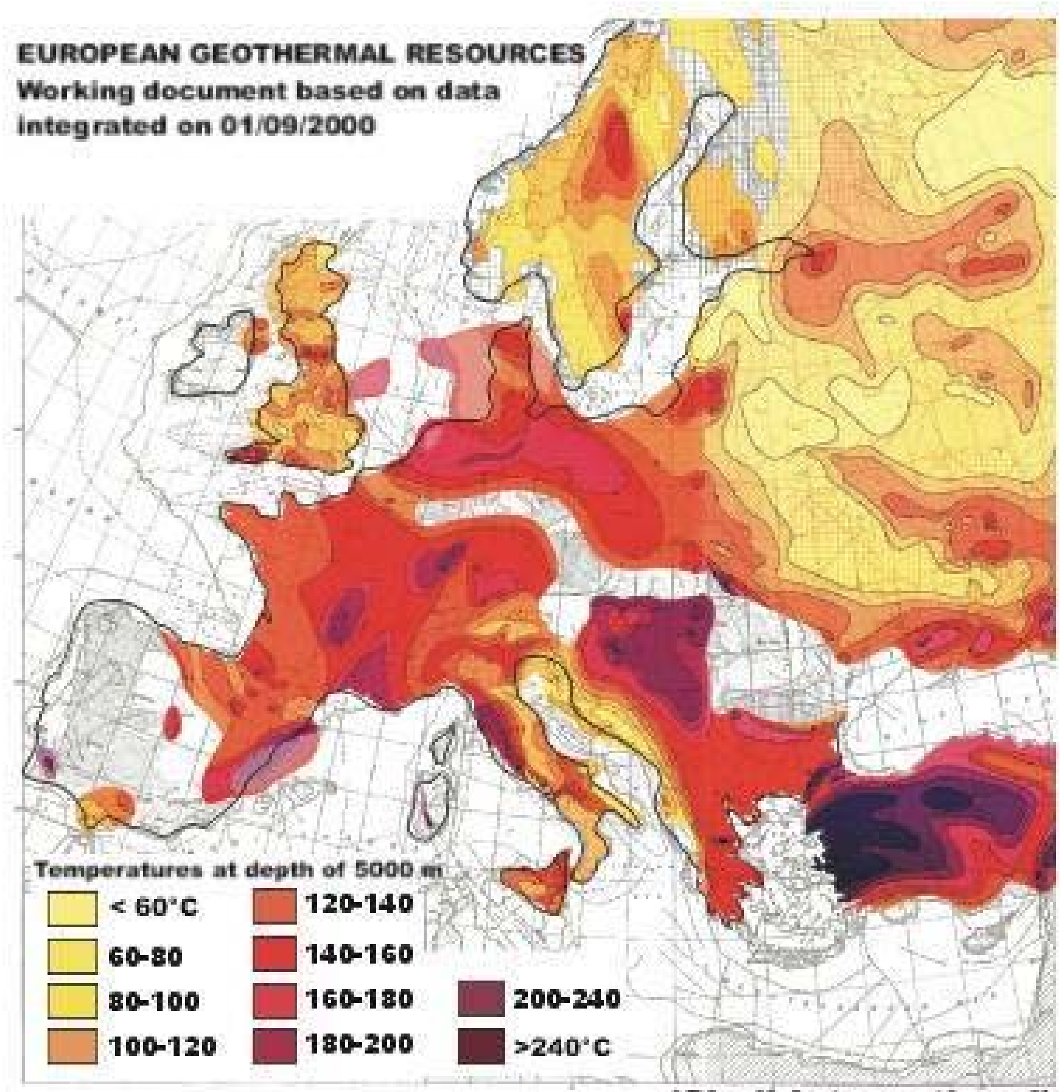


www.soultz.net/version-en.htm

High Temperature Resources: USA



High Temperature Resources: Europe

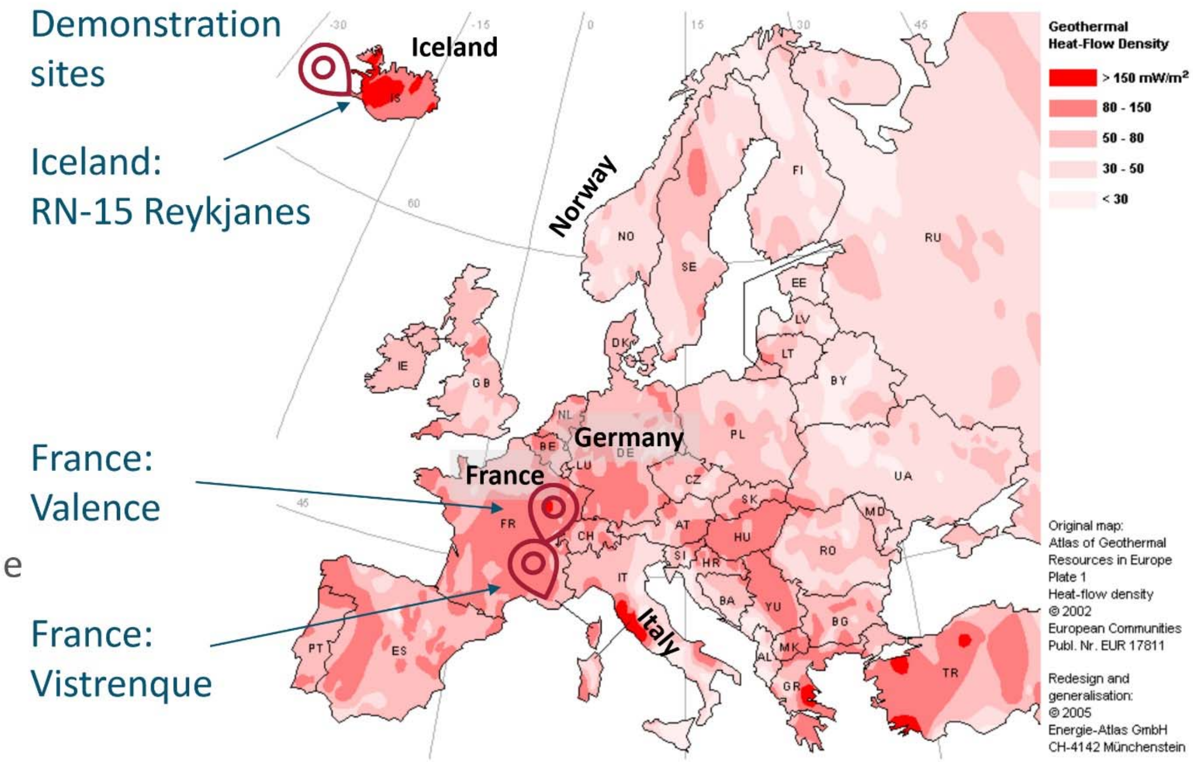


(Shell International)

DEEPEGS Project

Deep Enhanced Geothermal Systems

- Reykjanes (2016)
  - o 5 km
  - o 550°C
- Valence (2017)
  - o 4.5 – 5.5 km
  - o 180 - 200°C
- Vistrenque (2019)
  - o 4 – 6km
  - o 150 - 200°C



www.deepegs.eu/publications

Environmental Implications

- Excessive Noise during site development (however plants are very quiet during operation).
- Subsidence of terrain (caused by inadequate reinjection).
- Induced seismicity (concern for ERS).
- Loss of natural geothermal features (geysers, etc.)
- Pollution from non-condensible gasses: H_2S, CO_2, SO_2, &c.
  - CO_2 emissions:
    - Geothermal power plant (average) ≈ 122g/kWh
    - Natural gas power plant ≈ 460g/kWh
    - Coal power plant ≈ 960g/kWh

Geothermal Sustainability Assessment Protocol

- Patterned after the Hydropower Systainability Assessment Protocol
- developed as apartnership project of Landsvirkjun, Reykjavik Energy, HS Orkaand the Icelandic Environment Agency
- Theistareykir (under construction) is the first plant to be assessed: