A Guide to Geothermal Energy

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Origins of geothermal energy

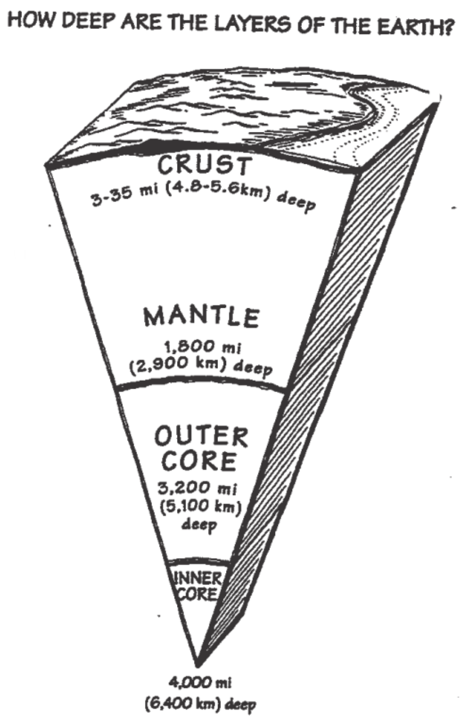
Geothermal = mining of thermal energy

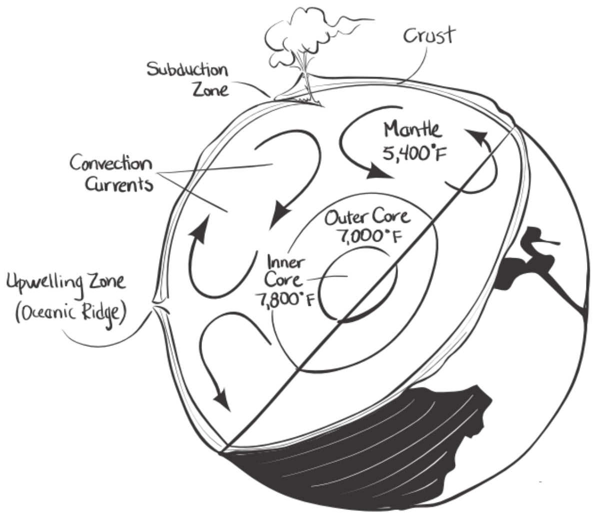
Kilauea Volcano, Hawaii. Volcanoes demonstrate that there is a great deal of thermal energy within the planet. *(Hawaii Volcanoes National Park)*

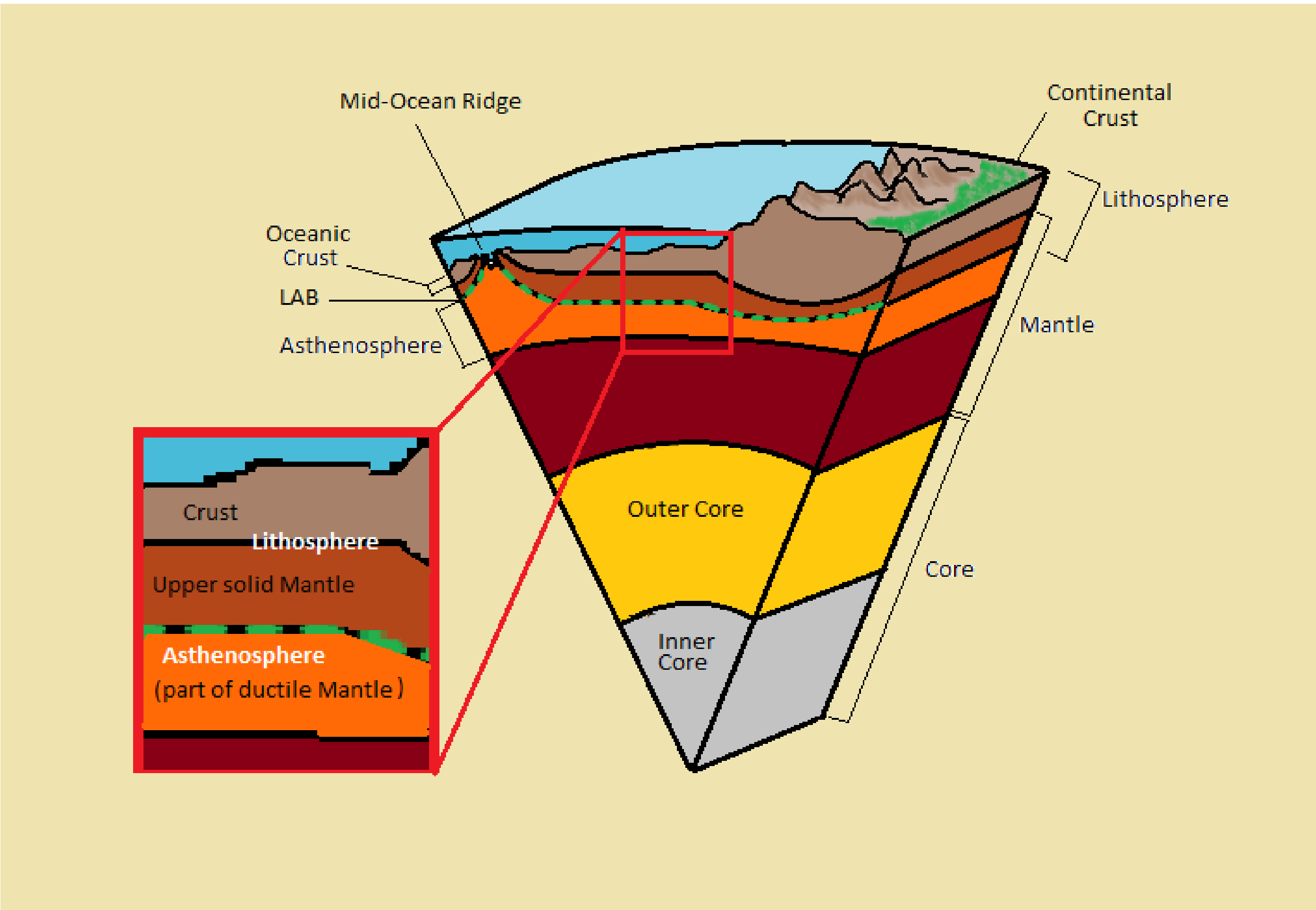
Geothermal heat is maintained by ongoing radioactive decay within the geosphere

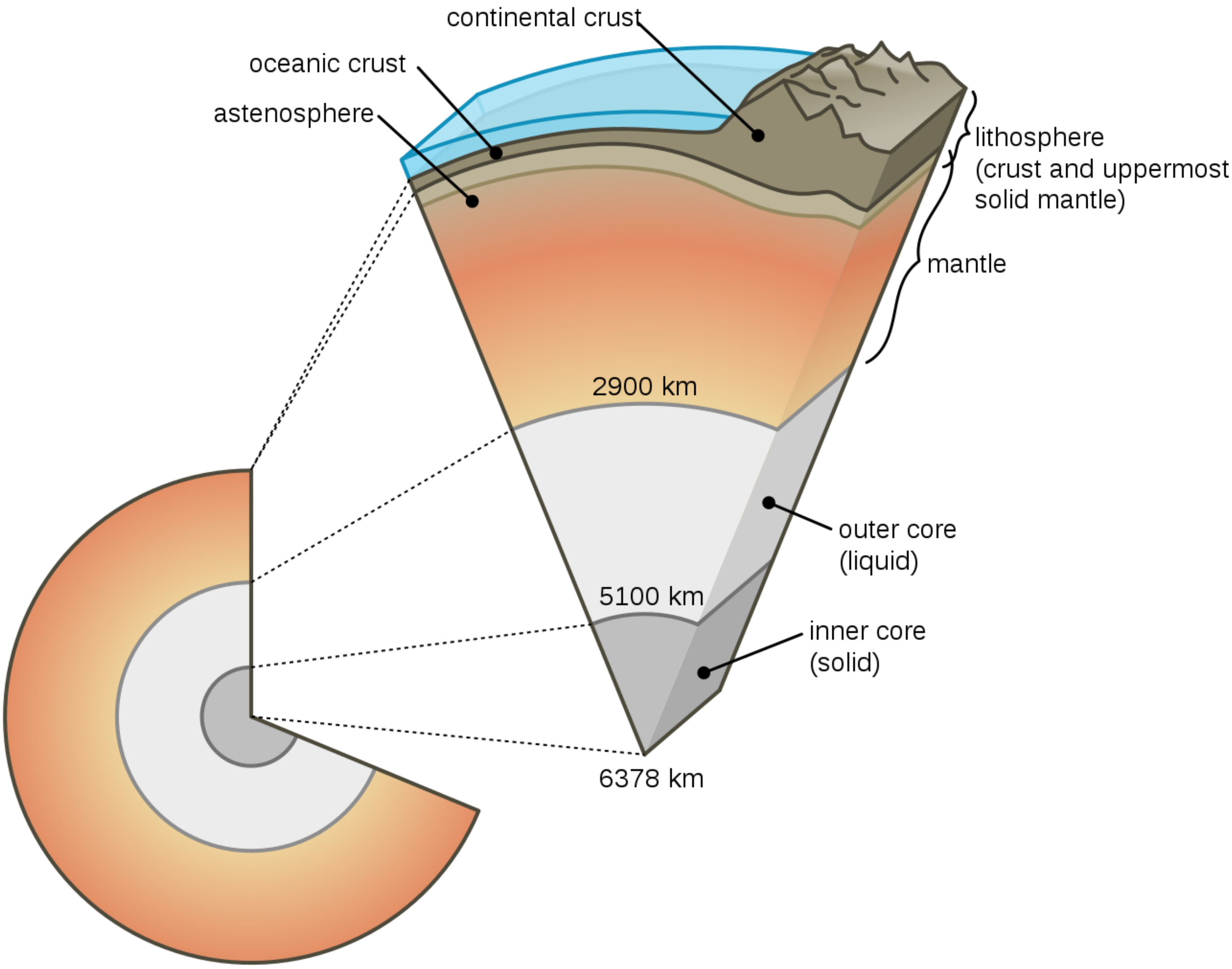
Table 1.2 Radioactive elements in common rocks in the Earth's crust.

Rock	Concentration			Heat generation, 10^{-6} cal/g · yr		
	U, ppm	Th, ppm	K, %	U	Th	K
Granite	4.7	20	3.4	3.4	4.0	0.9
Basalt	0.6	2.7	0.8	0.44	0.54	0.23
Peridotite	0.016	0.004	0.0012	0.012	0.001	0.0003


HOW DEEP ARE THE LAYERS OF THE EARTH?
CRUST
3-35 mi (4.8-5.6km) deep
MANTLE
1,800 mi
(2,900 km) deep
OUTER
CORE
3,200 mi
(5,100 km)
deep
INNER
CORE
4,000 mi
(6,400 km) deep


Crust
Subduction
Zone
Mantle
5,400°F
Convection
Currents
Outer Core
7,000°F
Inner
Core
7,800°F
Upwelling Zone
(Oceanic Ridge)


Mid-Ocean Ridge
Continental
Crust
Lithosphere
Oceanic
Crust
LAB
Asthenosphere
Mantle
Outer Core
Core
Inner
Core
Crust
Lithosphere
Upper solid Mantle
Asthenosphere
(part of ductile Mantle)


continental crust
oceanic crust
astenosphere
lithosphere
(crust and uppermost
solid mantle)
mantle
2900 km
outer core
(liquid)
5100 km
inner core
(solid)
6378 km

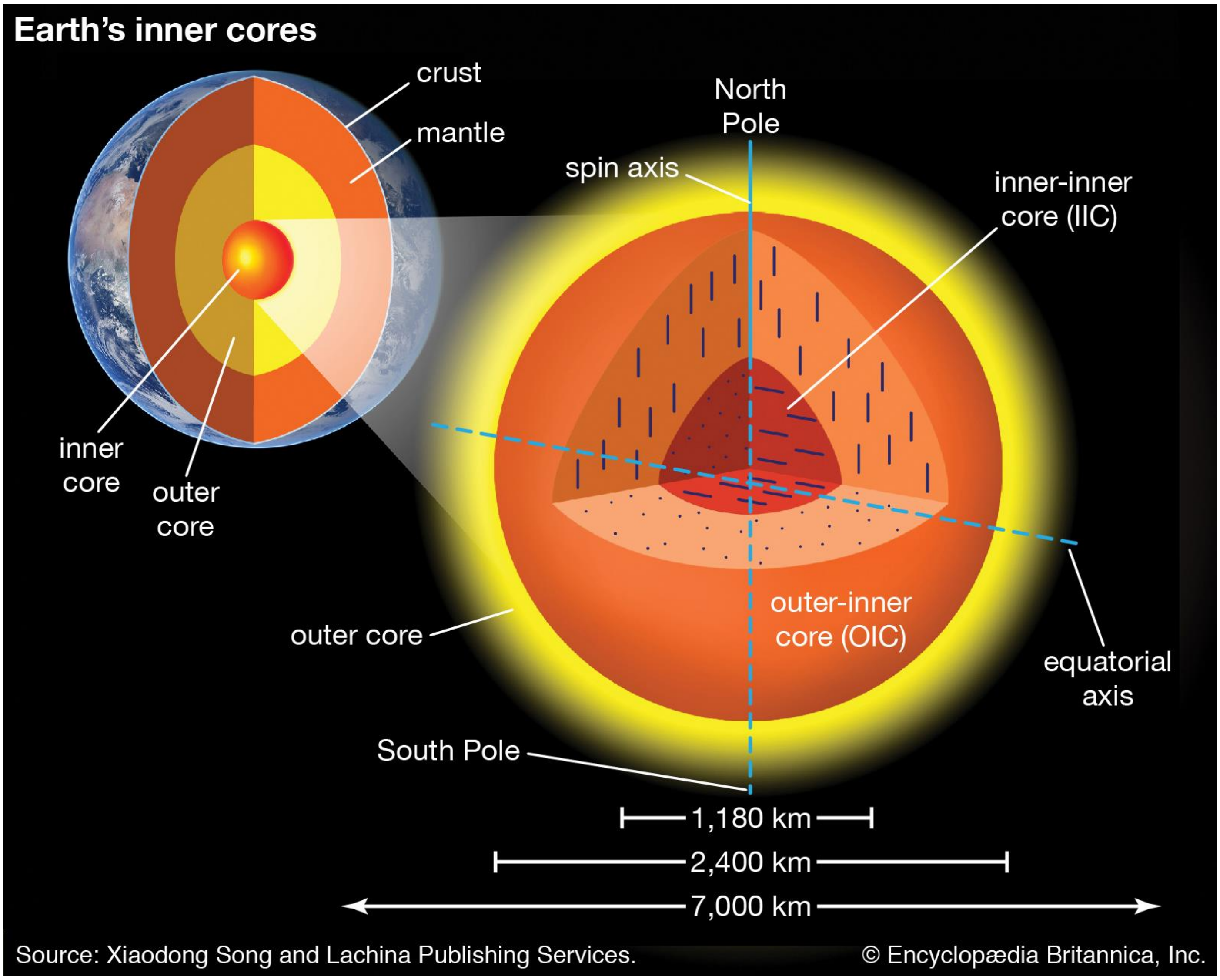

Earth's inner cores
crust
mantle
inner core
outer core
North Pole
spin axis
inner-inner core (IIC)
outer-inner core (OIC)
outer core
equatorial axis
South Pole
1,180 km
2,400 km
7,000 km
Source: Xiaodong Song and Lachina Publishing Services.
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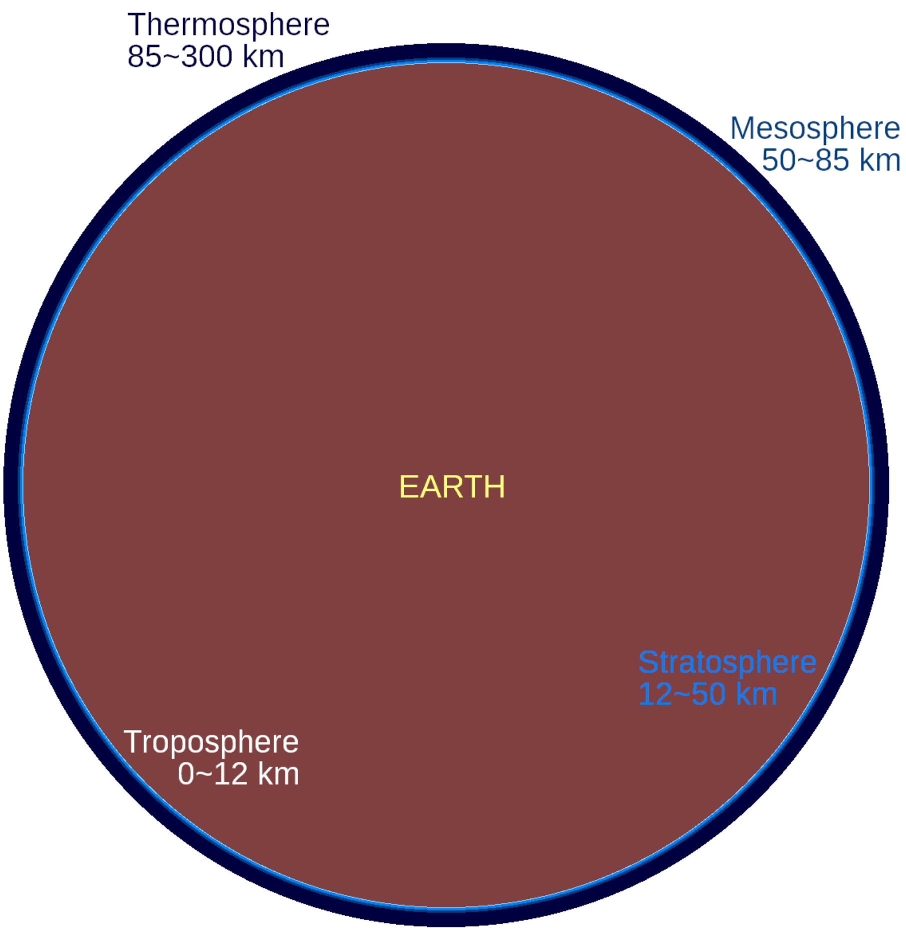
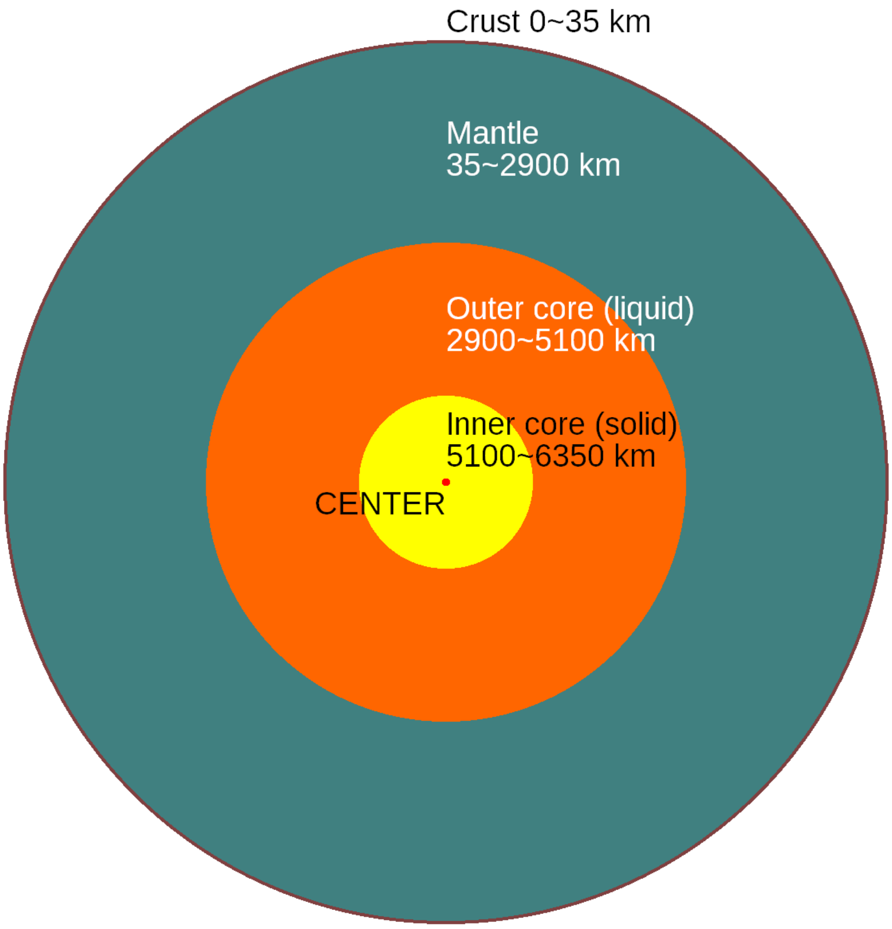
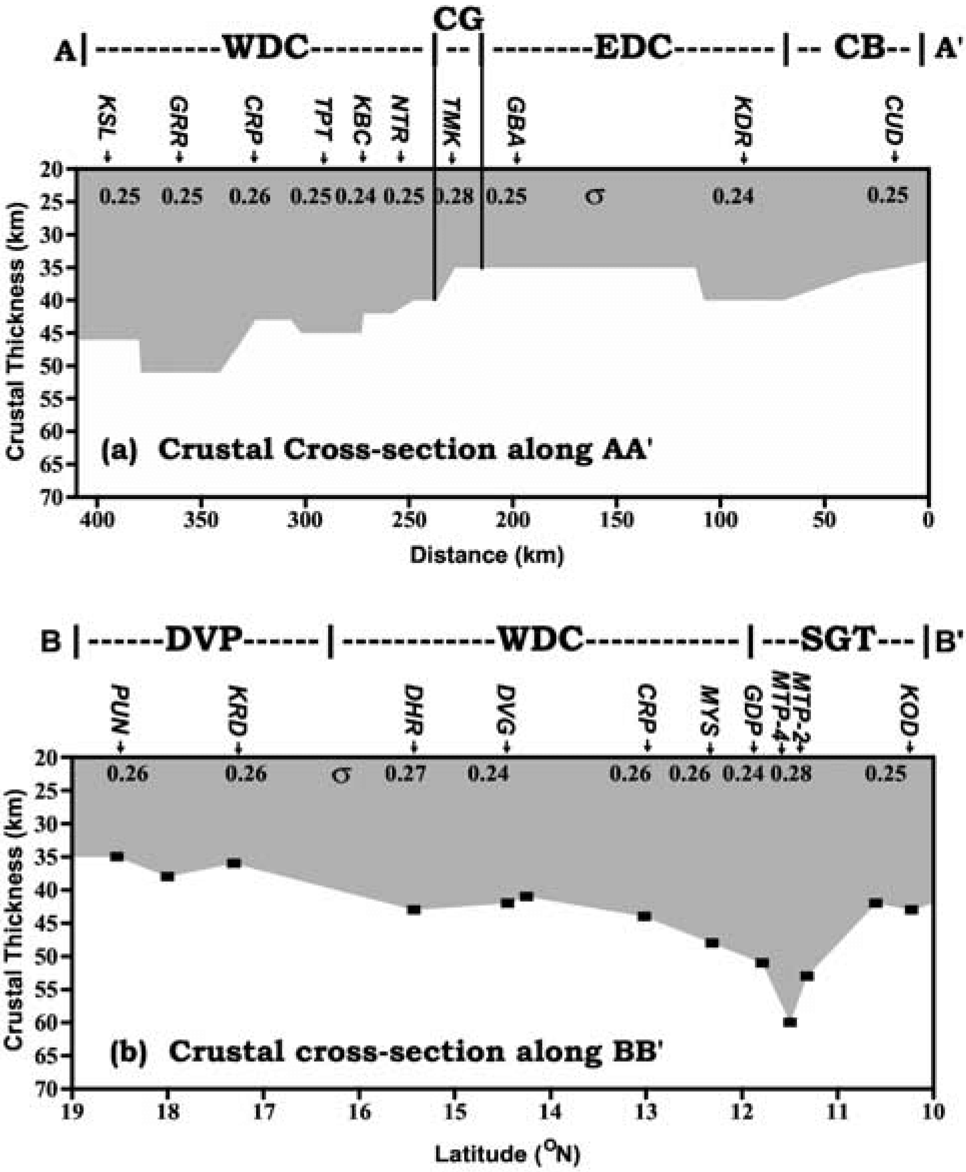
Table 1.1 Data on the Earth and its atmosphere from various sources; distances are not shown to scale.

Region	Distance from surface km	Temperature °C	Density g/cm^3
	300	1125	3.6×10^{-14}
Thermosphere			
	85	−95	2×10^{-8}
Mesosphere			
	50	0	1×10^{-6}
Stratosphere			
	12	−60	3×10^{-4}
Troposphere			
Surface	0	10	2.7 continental 3.0 oceanic
Crust			
	35	1100	3.3
Mantle			
	2900	3700 to 4500	5.7 10.2
Liquid (iron) core			
	5100	4300 to 6000	11.5
Solid inner (iron) core			
(center)	6350	4500 to 6600	11.5

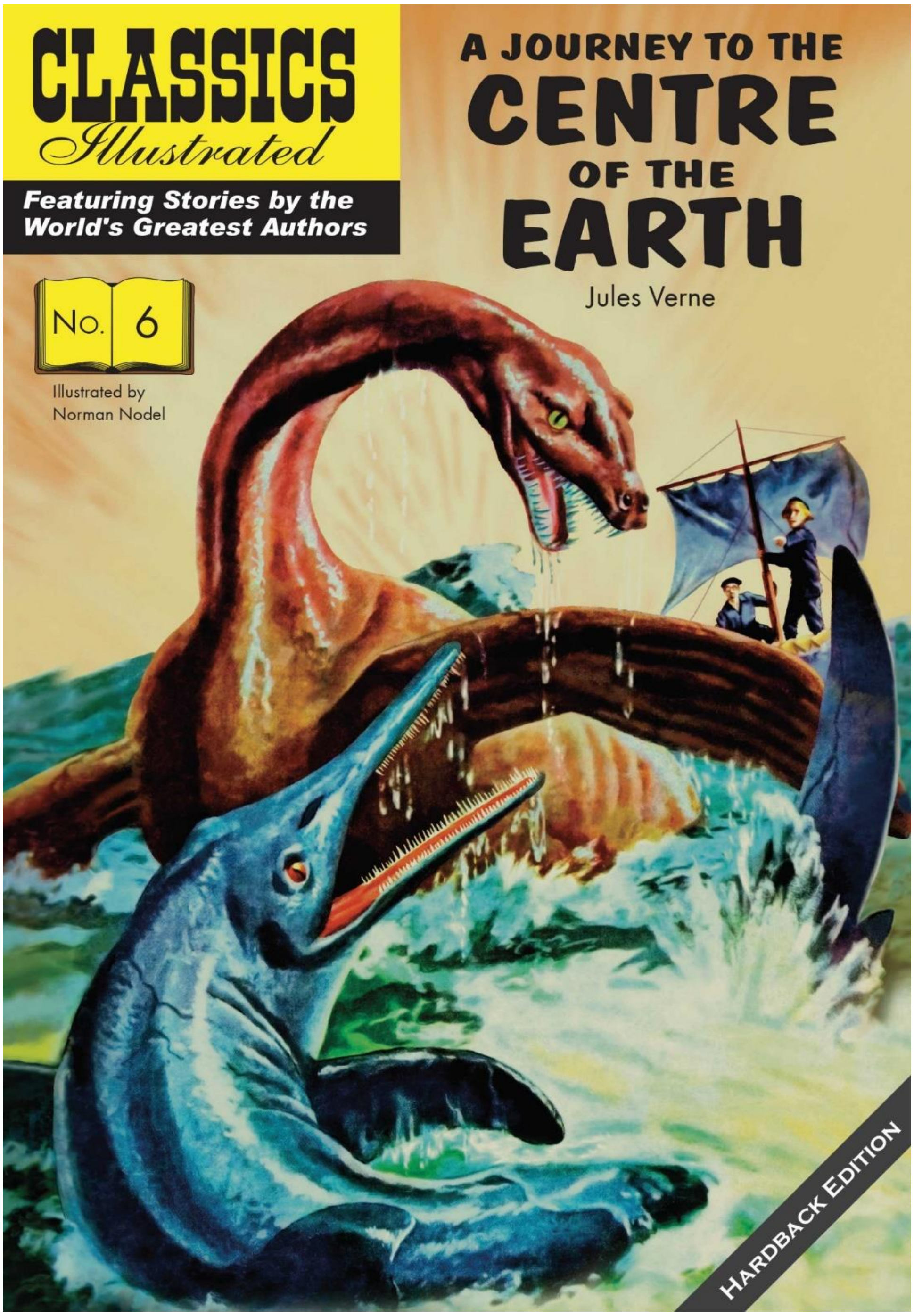




«Global observations show that the crustal thickness varies through the tectonic regions. While the continental crust is 30−70 km thick, the oceanic crustal thickness is 6−12 km. The oceanic crust is also denser (2.8−3.0 g/cm³) than the continental crust (2.6−2.7 g/cm³)»
(https://www.sciencedirect.com/science/article/pii/B9780128136850000091)

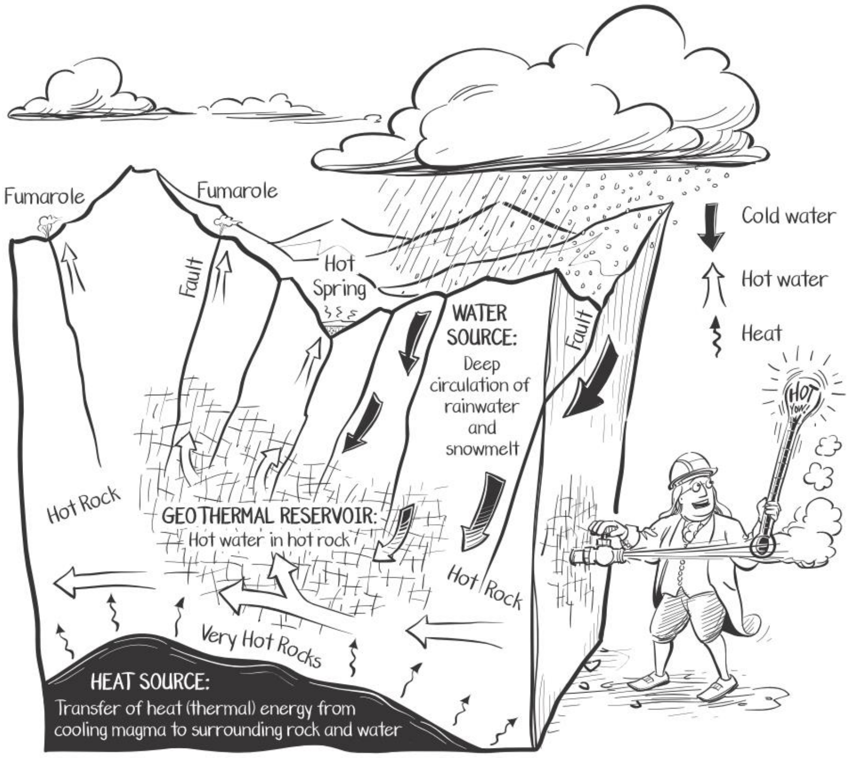


For every 100 m, the temperature of the rock increases by about 3°C



JOURNEY TO THE CENTRE OF THE EARTH: Jules Verne - FULL AudioBook (https://youtu.be/fNGMcJleEpM)

Hot rocks heat water, which is trapped below impenetrable rock formation and forms geothermal reservoirs



A geothermal reservoir is a large underground area of hot permeable rock saturated with hot water and steam.

Temperature of geothermal reservoirs can reach 300°C

When this hot water comes up to the surface of the earth through cracks, it forms geysers or hot springs, which can be put to direct heating use

Pools, buildings, greenhouses

Old Faithful Up Close! (https://youtu.be/tShhZvvIM84)

Unbelievable Footage of the World's Most Famous Geyser (https://youtu.be/dldtGjOMlwI)

Characteristics of geothermal energy

Geothermal energy is a global resource

Geothermal has a surprising historical component

Prehistory, archaeology, anthropology, geology

For over 1,000 years, human populations have utilized geothermal energy directly (i.e. in non-electric applications)

Beginning in the 20th century, near-surface geothermal emerged as an important renewable energy resource for electricity generation

Utilization of geothermal

Technological research and development

Economic and political trends

Geothermal

Naturally occurring hydrothermal

Enhanced Geothermal Systems (EGS)

Issues in energy transformation and power generation

Technical, nontechnical, scientific, political

Residents of communities weighting the alternatives

Relying on nonrenewable power

Development of geothermal energy

Six continents of Earth

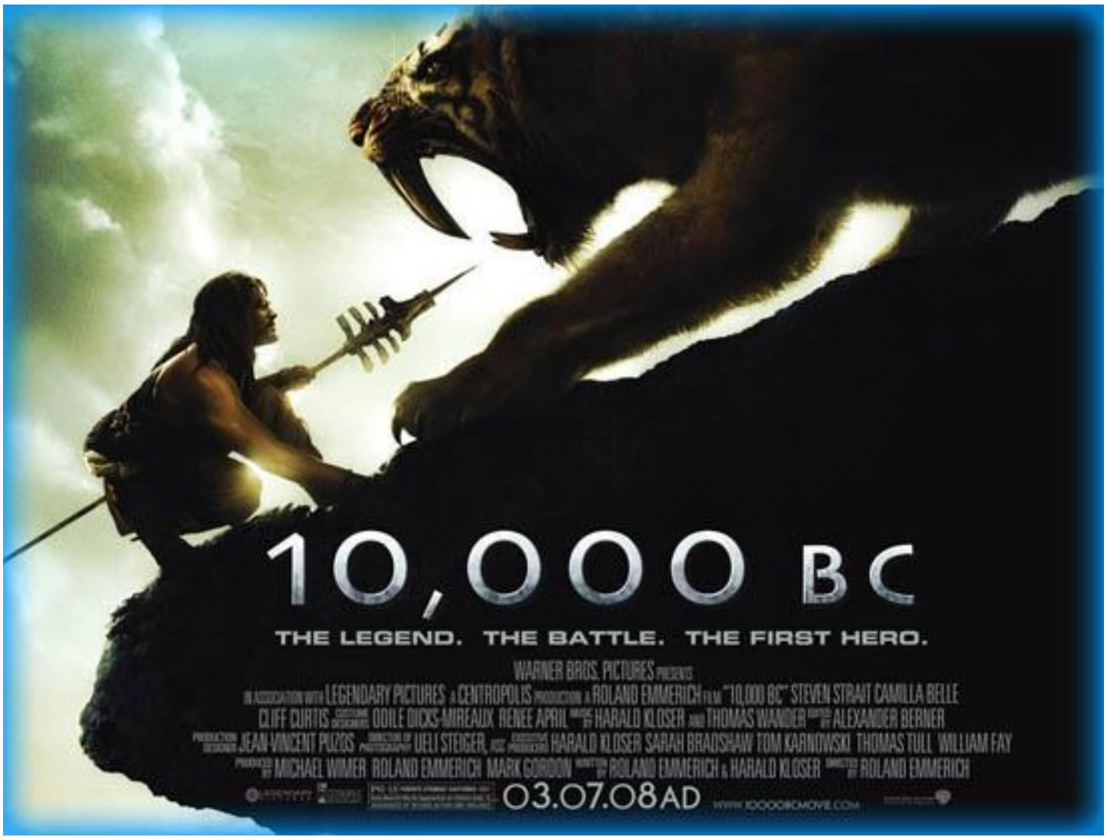
Geologic features

Mountains, geysers, fertile farmland, volcanoes, valleys

Determine if a site is likely to have geothermal energy

Prehistory

From 10,000 BC



Official Trailer: 10,000 BC (2008) (https://youtu.be/J73aDZuAx2I)

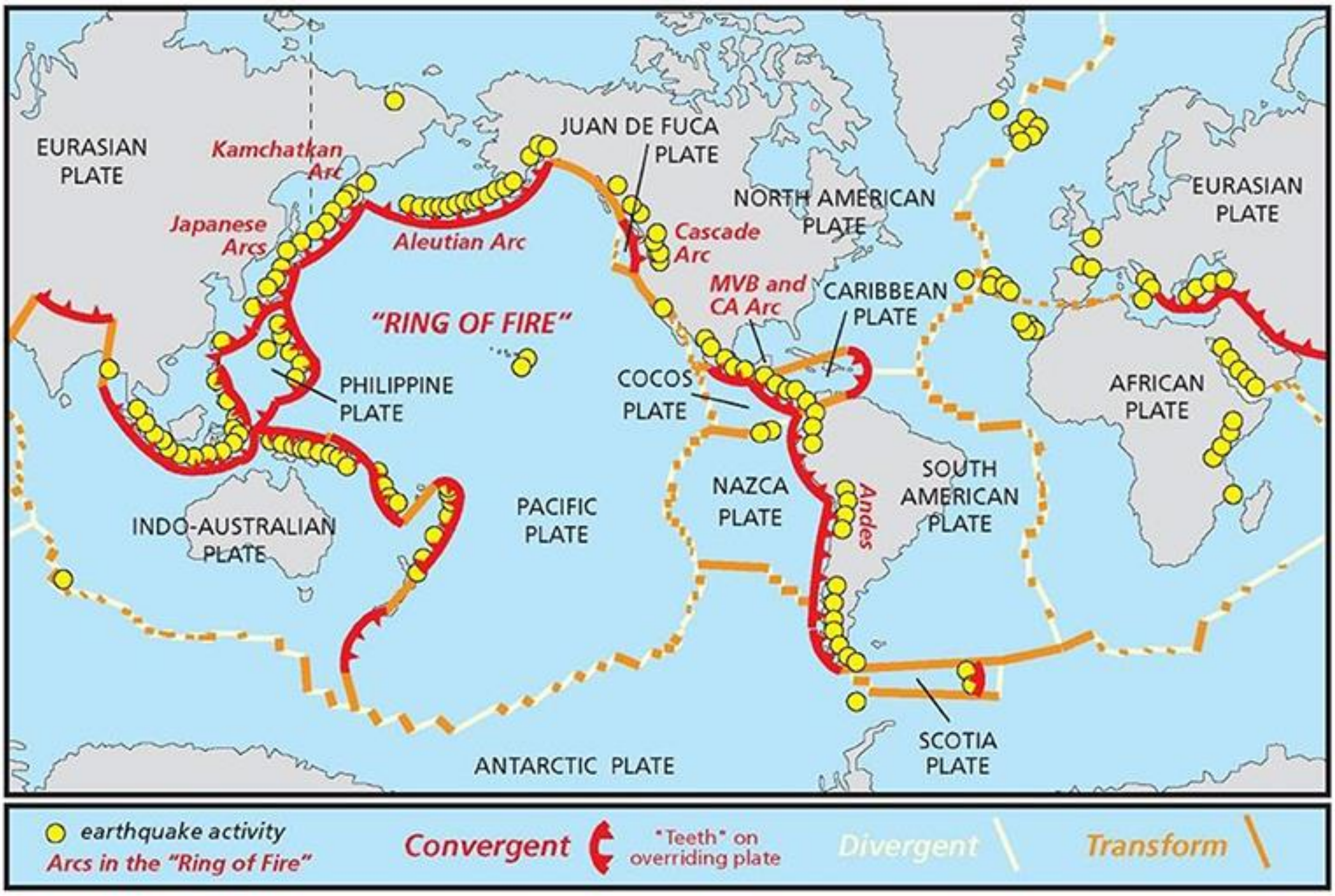
Events related to geothermal

Earthquakes, volcanic eruptions, hot springs

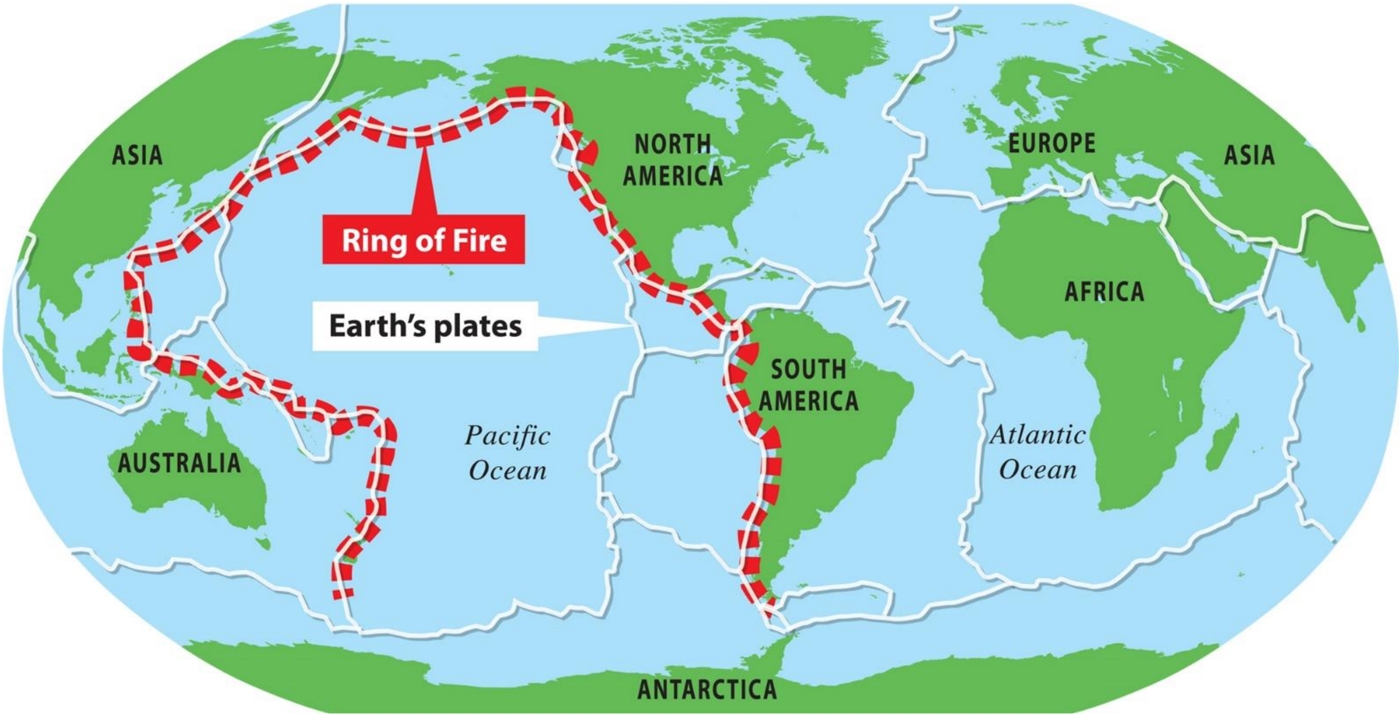
Geothermal reservoirs, plate boundaries, convection currents

Cartography

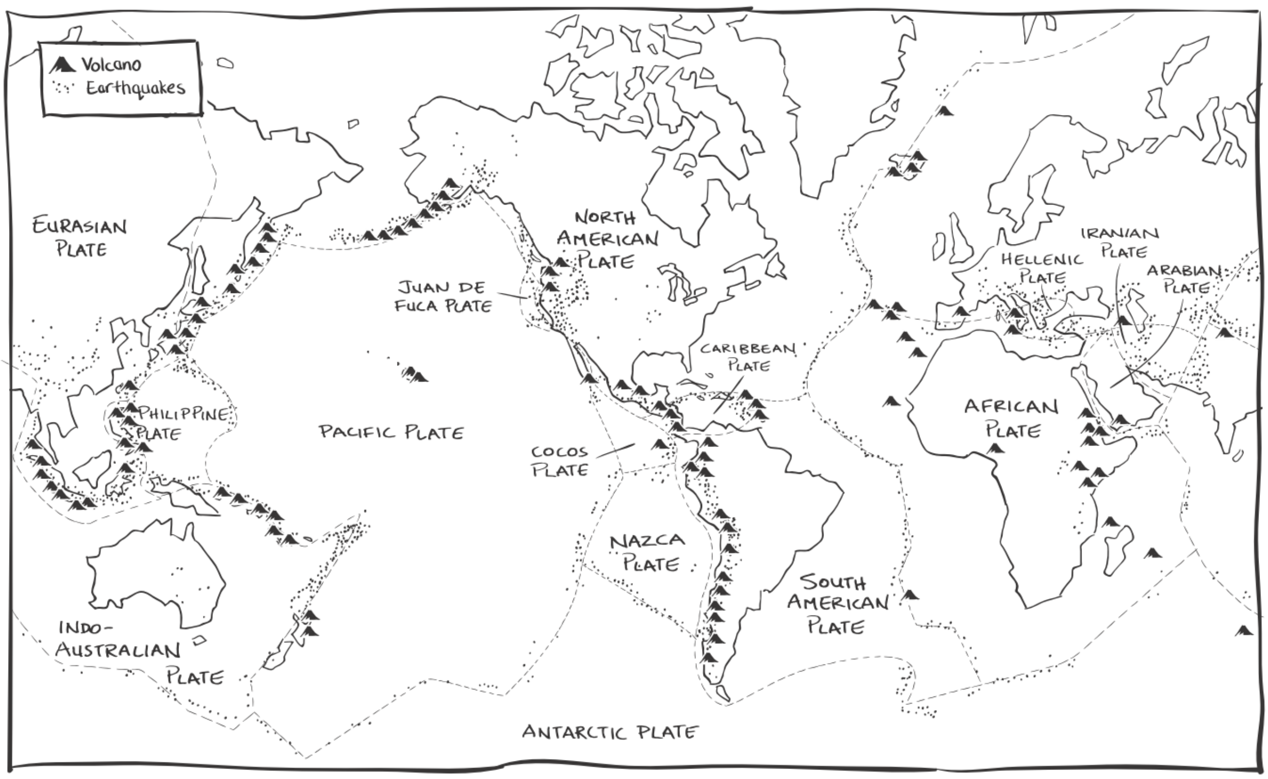
Ring of Fire



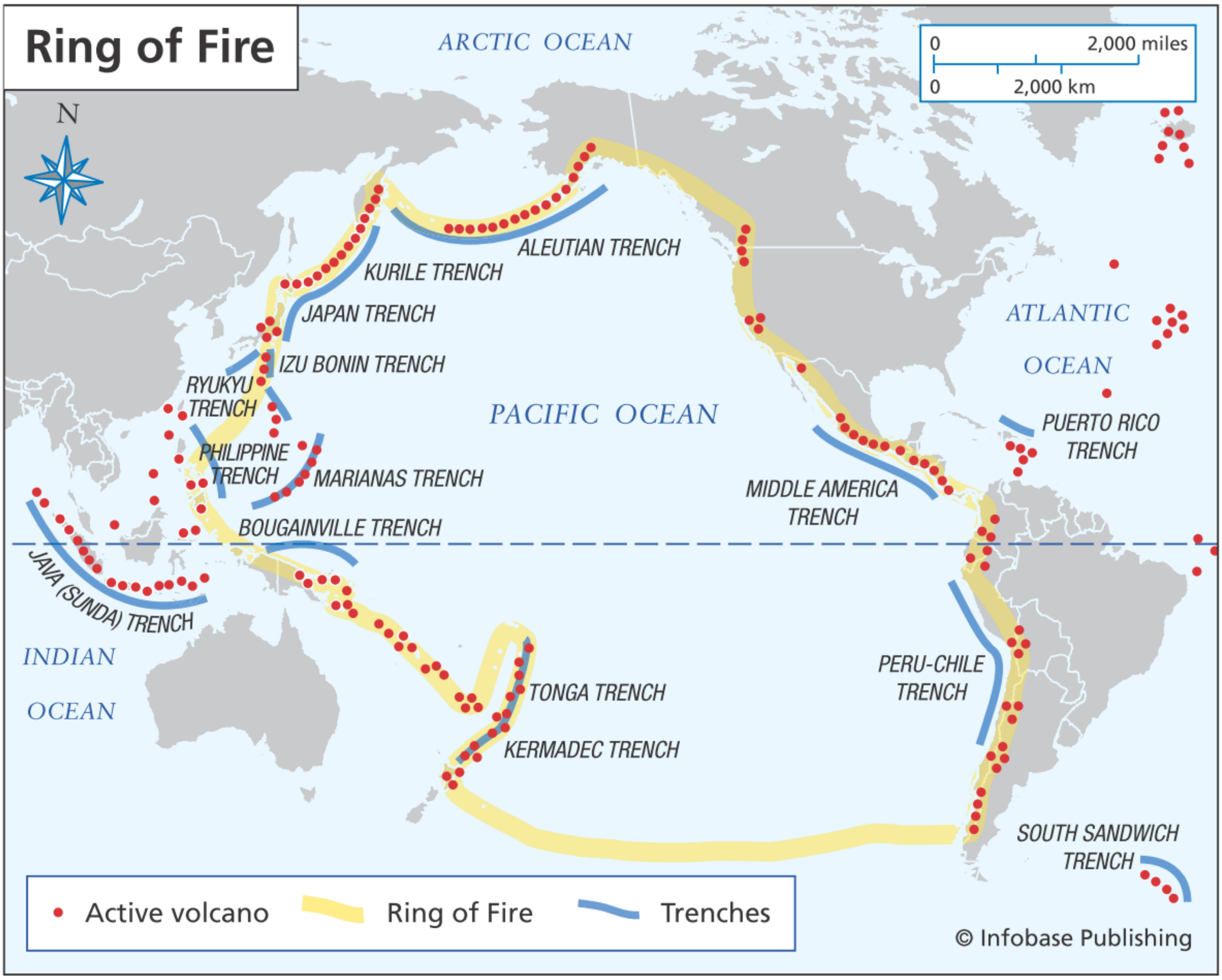
EURASIAN PLATE
Kamchatkan Arc
Japanese Arcs
Aleutian Arc
JUAN DE FUCA PLATE
Cascade Arc
NORTH AMERICAN PLATE
EURASIAN PLATE
MVB and CA Arc
CARIBBEAN PLATE
"RING OF FIRE"
PHILIPPINE PLATE
COCOS PLATE
AFRICAN PLATE
NAZCA PLATE
Andes
SOUTH AMERICAN PLATE
PACIFIC PLATE
INDO-AUSTRALIAN PLATE
SCOTIA PLATE
ANTARCTIC PLATE
earthquake activity
Arcs in the "Ring of Fire"
Convergent
"Teeth" on overriding plate
Divergent
Transform



ASIA
NORTH AMERICA
EUROPE
ASIA
Ring of Fire
AFRICA
Earth's plates
SOUTH AMERICA
Pacific Ocean
Atlantic Ocean
AUSTRALIA
ANTARCTICA



This map shows the edges of the tectonic plates that form the Pacific "Ring of Fire." The edges of the continents that surround the Ring of Fire are prone to earthquakes and volcanoes and have some of the best geothermal resources in the world. This includes the western part of North, Central and South America; New Zealand; Indonesia; the Philippines; Japan; and Kamchatka (eastern Russia). Some of the other prime geothermal locations include Iceland, Italy, the Rift Valley of Africa, and Hawaii.



Ring of Fire. Most of the major producers of geothermal energy are located along the Ring of Fire.

Krafla Geothermal Station in northeast Iceland. Despite having the richest geothermal resources in the world, in Iceland most electricity is generated with hydroelectric power. *(Mike Schiraldi)*

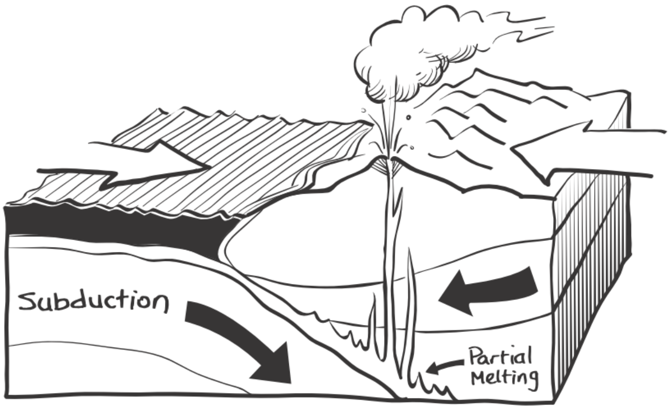
Archaeological digs are very expensive

Africa, Middle East, Asia

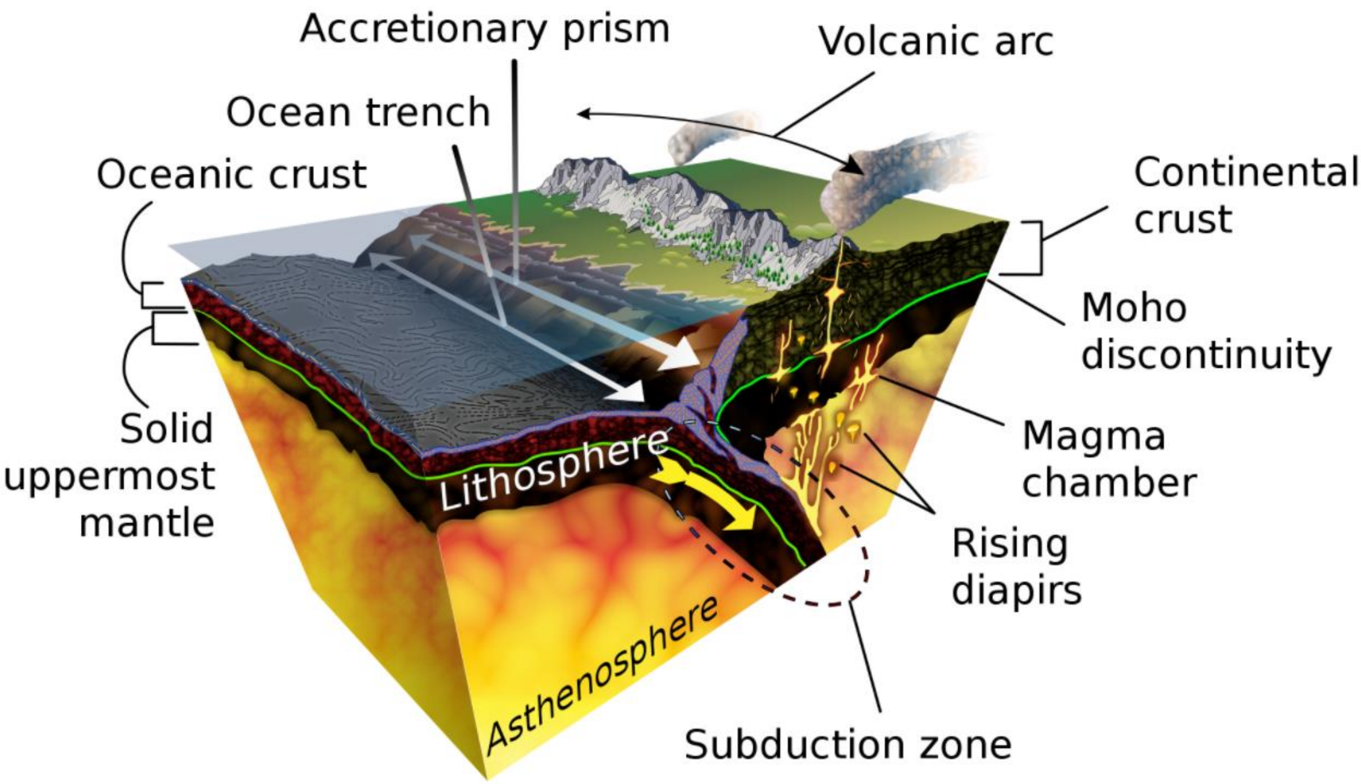
Did prehistoric people use geothermal energy?

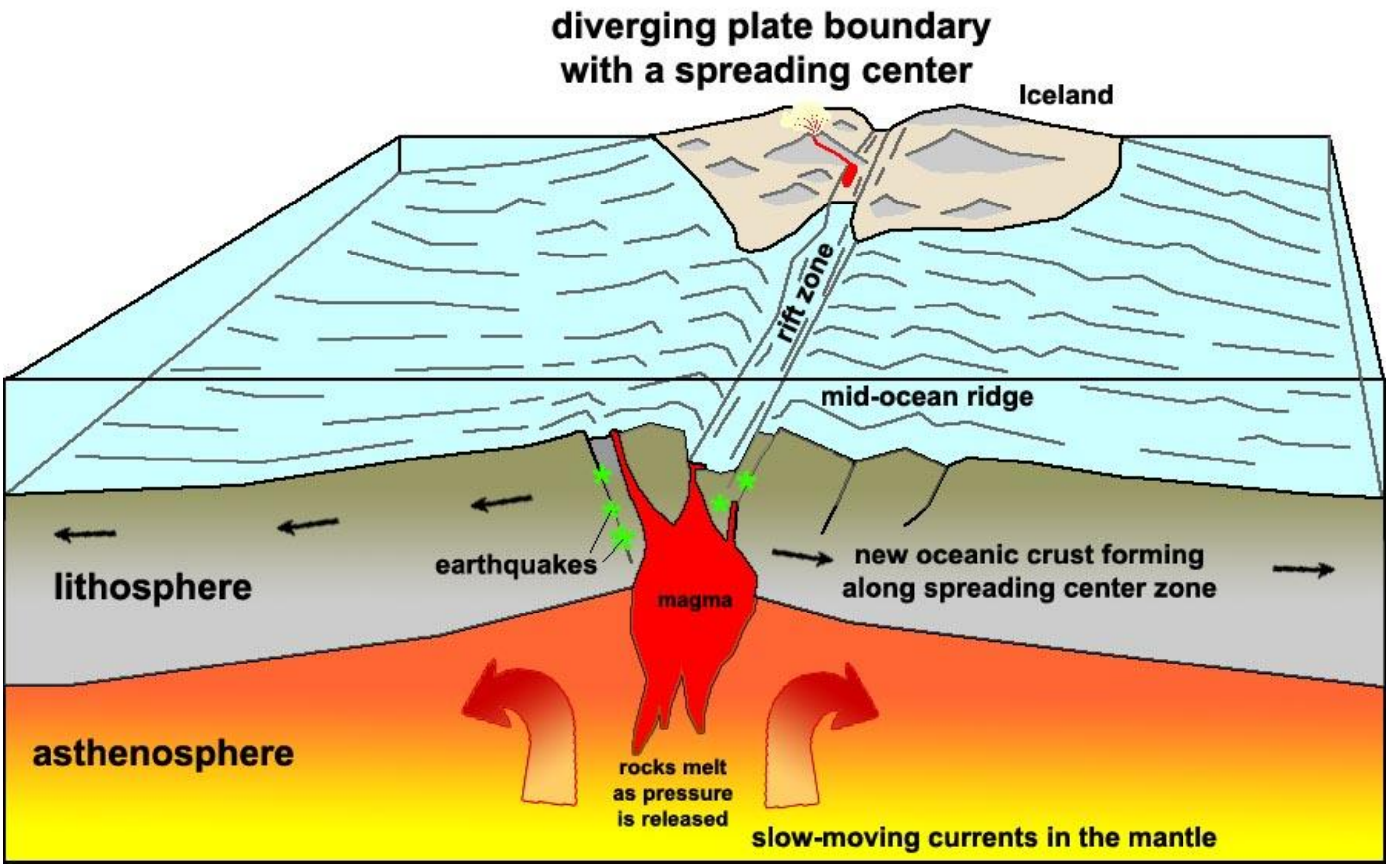
Important terms for geothermal locations on the globe

Ring of Fire, plate tectonics, subduction, spreading centers, hot spots



Magma can reach the earth's surface, or near the surface, where the crust is "fractured" or thinned, such as at plate boundaries.


Accretionary prism
Volcanic arc
Ocean trench
Oceanic crust
Continental crust
Moho discontinuity
Solid uppermost mantle
Lithosphere
Magma chamber
Rising diapirs
Asthenosphere
Subduction zone


diverging plate boundary with a spreading center
Iceland
rift zone
mid-ocean ridge
lithosphere
earthquakes
magma
new oceanic crust forming along spreading center zone
asthenosphere
rocks melt as pressure is released
slow-moving currents in the mantle

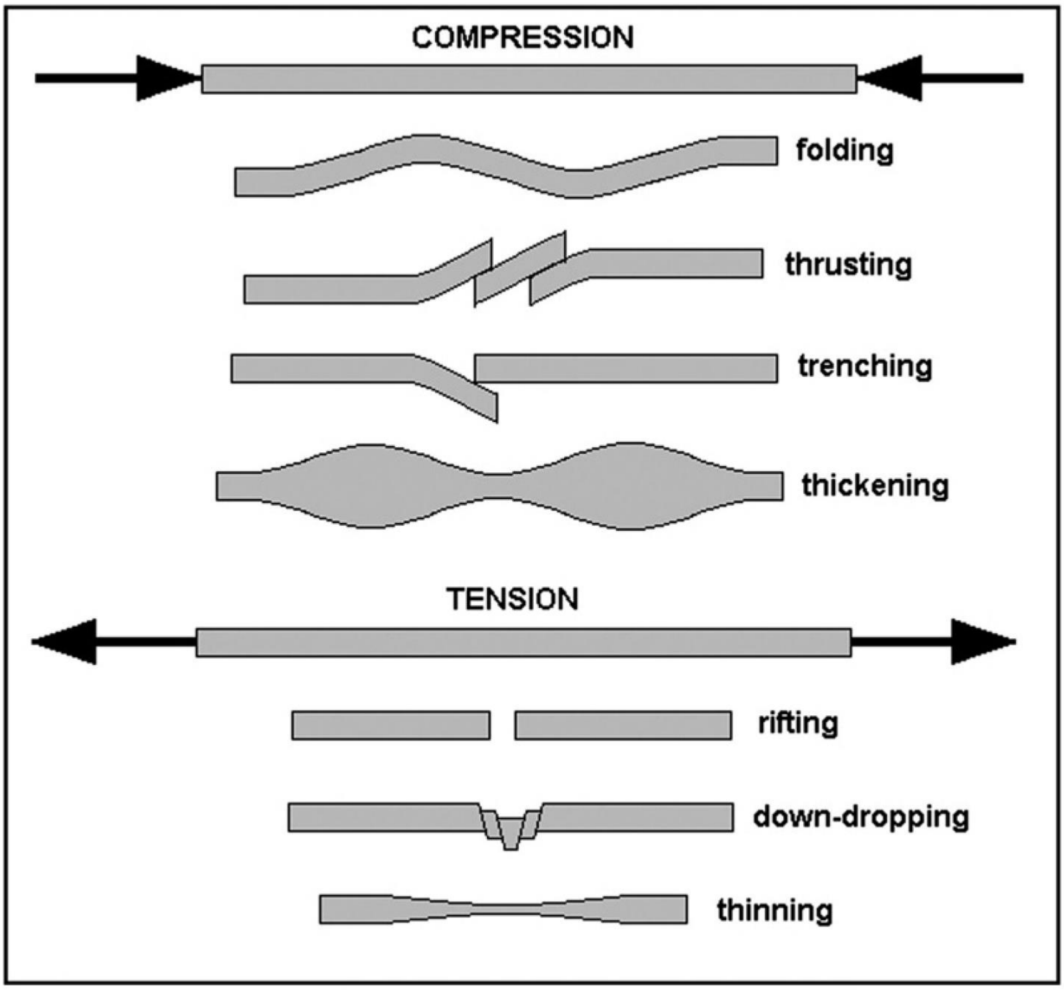


Fig. 1.1 Response of plates to compression and tension.

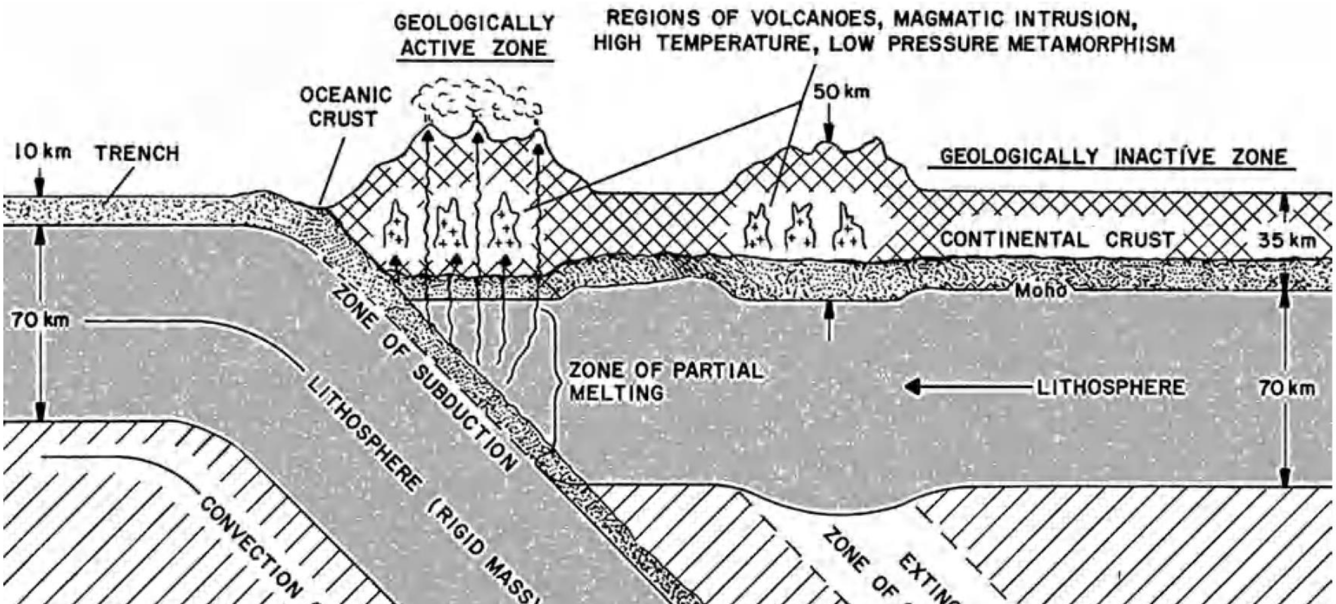


Fig. 1.3 Schematic model of a trench or subduction zone; after [20].

Surface features important in geothermal

Volcanoes, geysers, mineral deposits, hot springs, fumaroles

Prehistoric artifacts or fossils

- Might be related to use of geothermal energy

Big concepts in history

- Time, chronology, causality, change, conflict, complexity

Representations of Earth

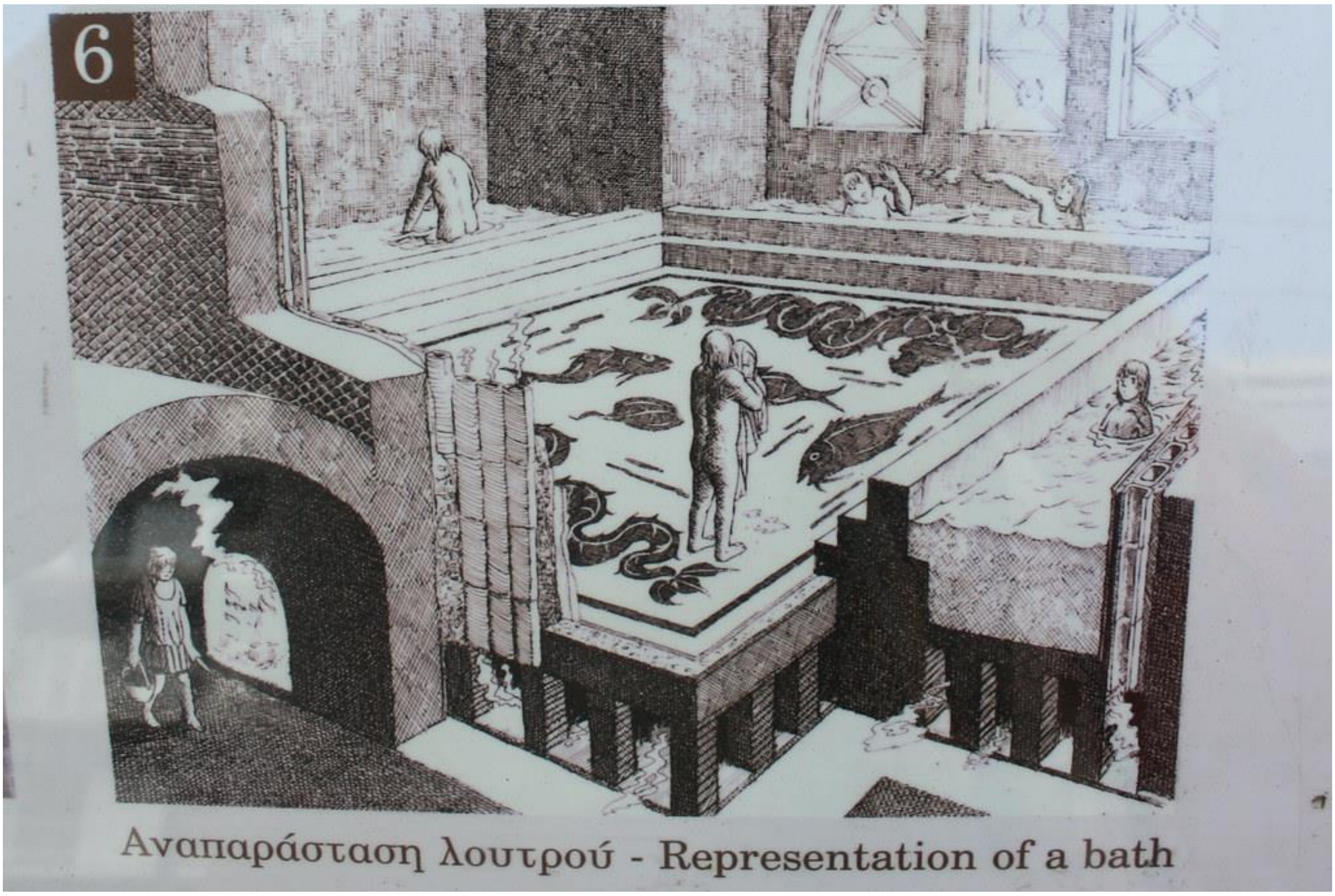
- Maps, globes, photos

Chronological thinking

- Past, present, future

Roman society

- Political and social importance of Roman bathhouses



Using geothermal energy to heat a bathhouse

Designing deluxe heated floors

Ancient civilization's use of geothermal energy before the Romans

Roman use of geothermal energy

Using scientific methods to determine the location of bathhouses

Historically, were all people immediately accepting new technologies?

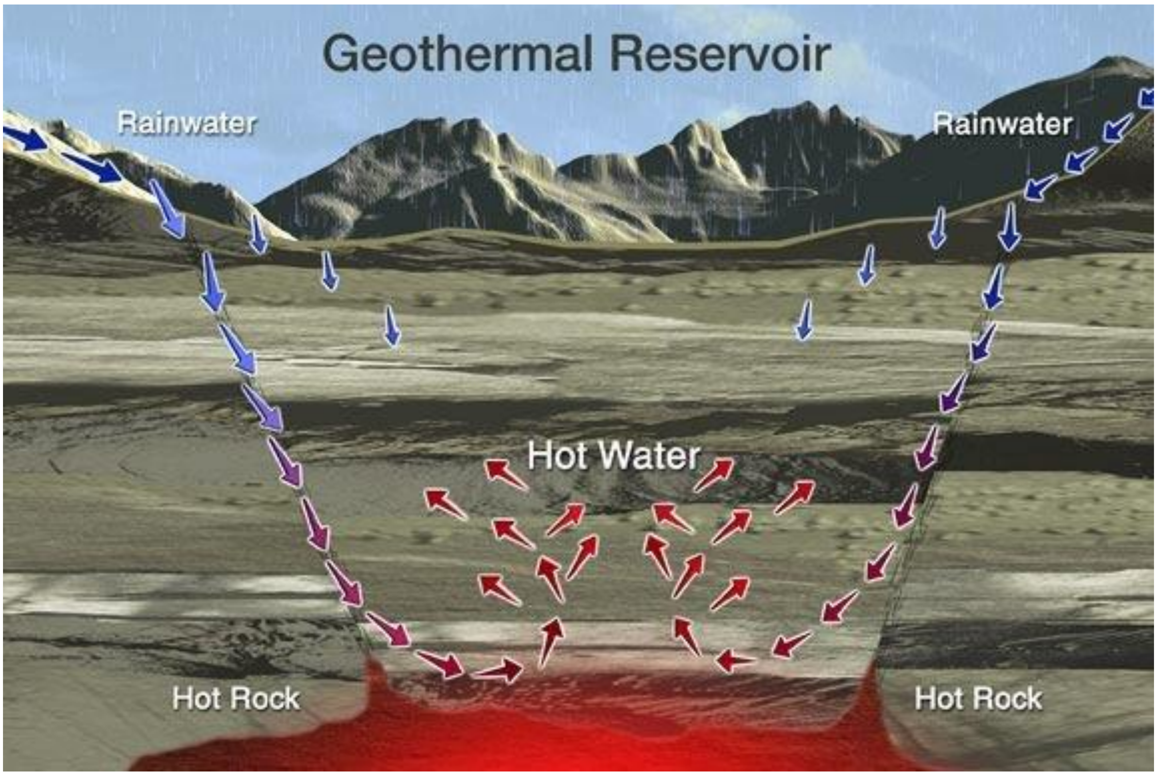
Societal attitudes towards renewable energy, geothermal energy, and biofuels

Historical evolution of how people used geothermal energy

Bringing geothermal energy to widespread use

Industrial revolution (James Watt, Tomas Edison)

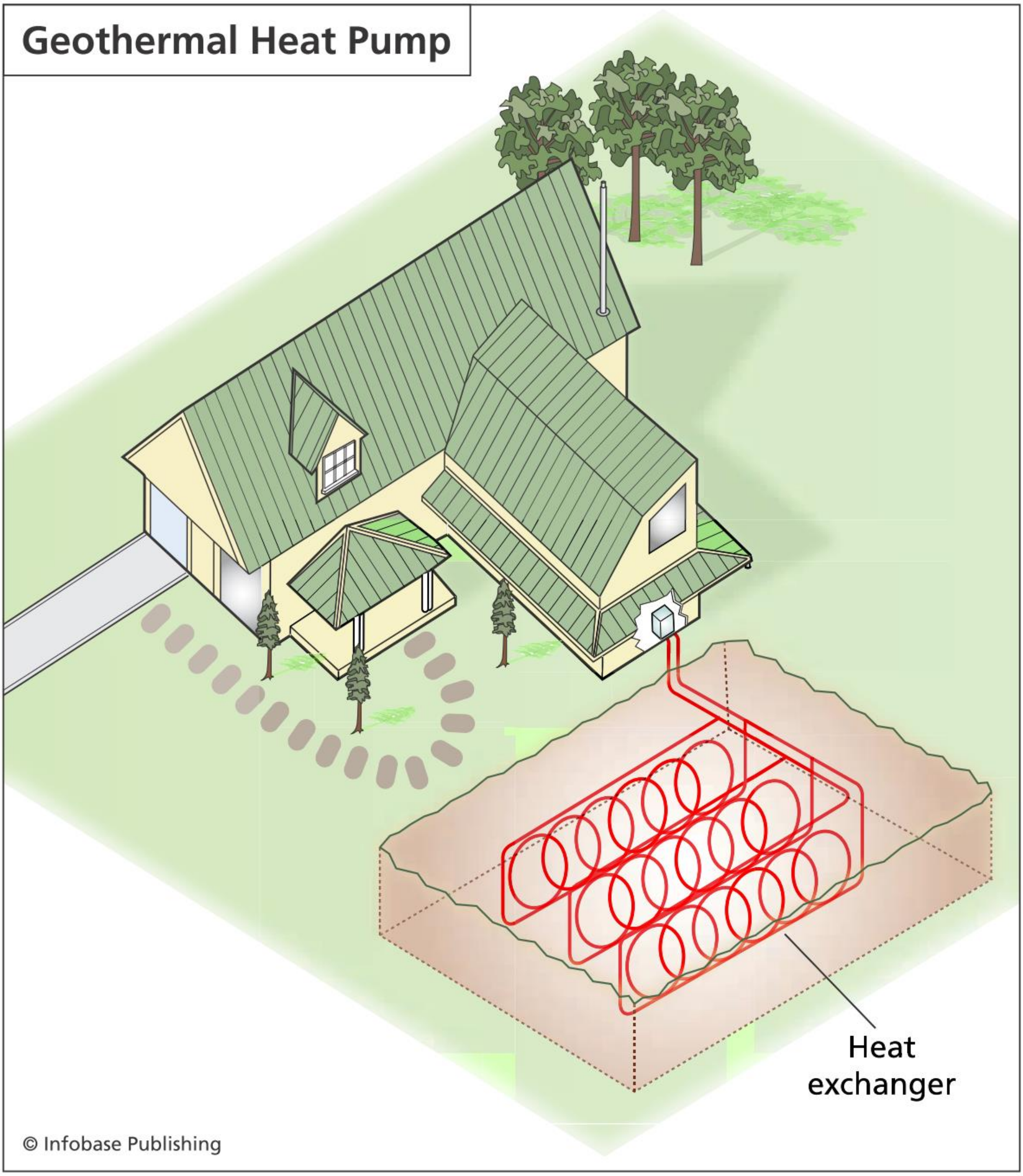
Geothermal reservoirs



Heat is abundant in the earth, but it varies by location

Geothermal heat pump systems

- Geothermal energy may be captured (just a few meters underground or underwater)
- Heat and cool buildings directly (without the need for storage)

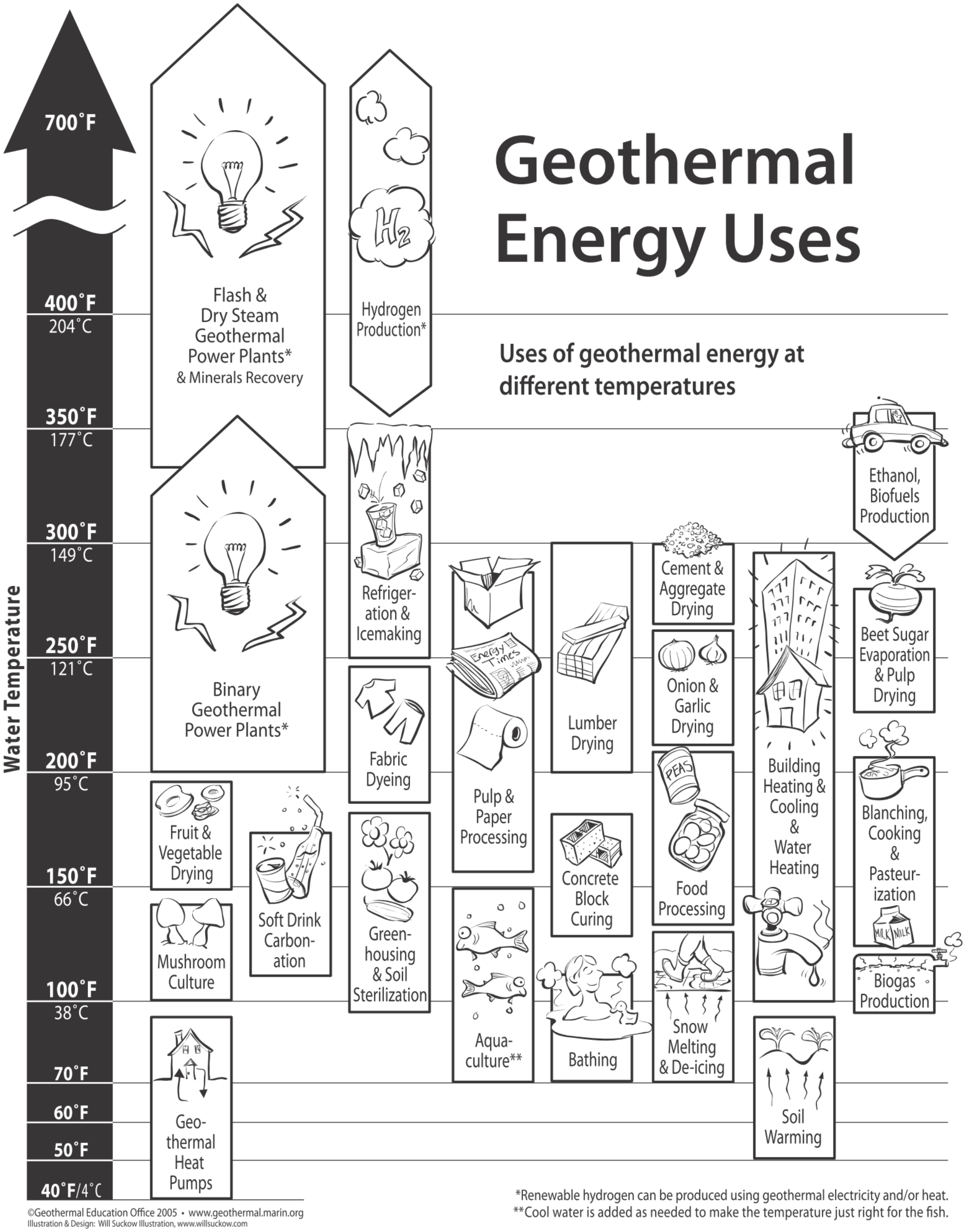


A geothermal heat pump system is a very energy-efficient way to heat and cool. *(Source: EERE)*

Patterns of concentrated features where the temperature of the Earth is higher

- Tectonic plate boundaries of subduction zones and spreading centers
- Hot spots, e.g. Hawaii, Iceland, Yellowstone; crustal expansion in the western US, between the Pacific and North American plates

Uses of geothermal energy



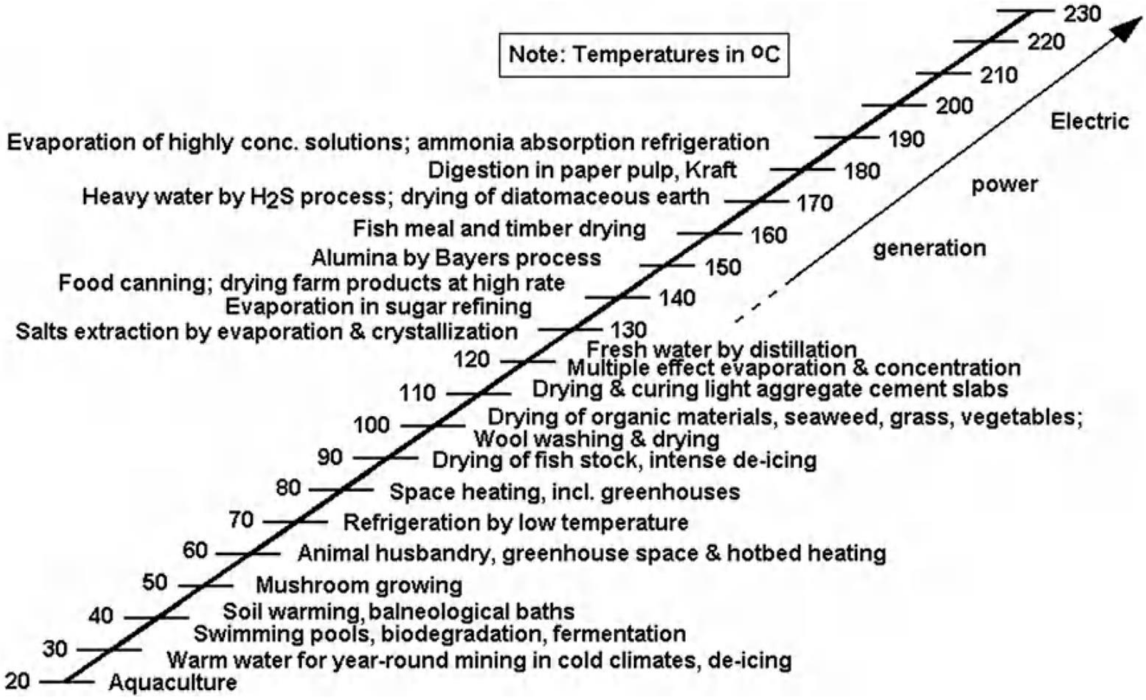


Fig. I.1 Modified Lindal diagram showing applications for geothermal fluids.

Geothermal drilling

Fig. 3.1 Discharge from a well at the Ahuachapán field, El Salvador [1] [WWW].

Fig. 3.2 Initial blowing of an Indonesian well at the Dieng geothermal field [1] [WWW].

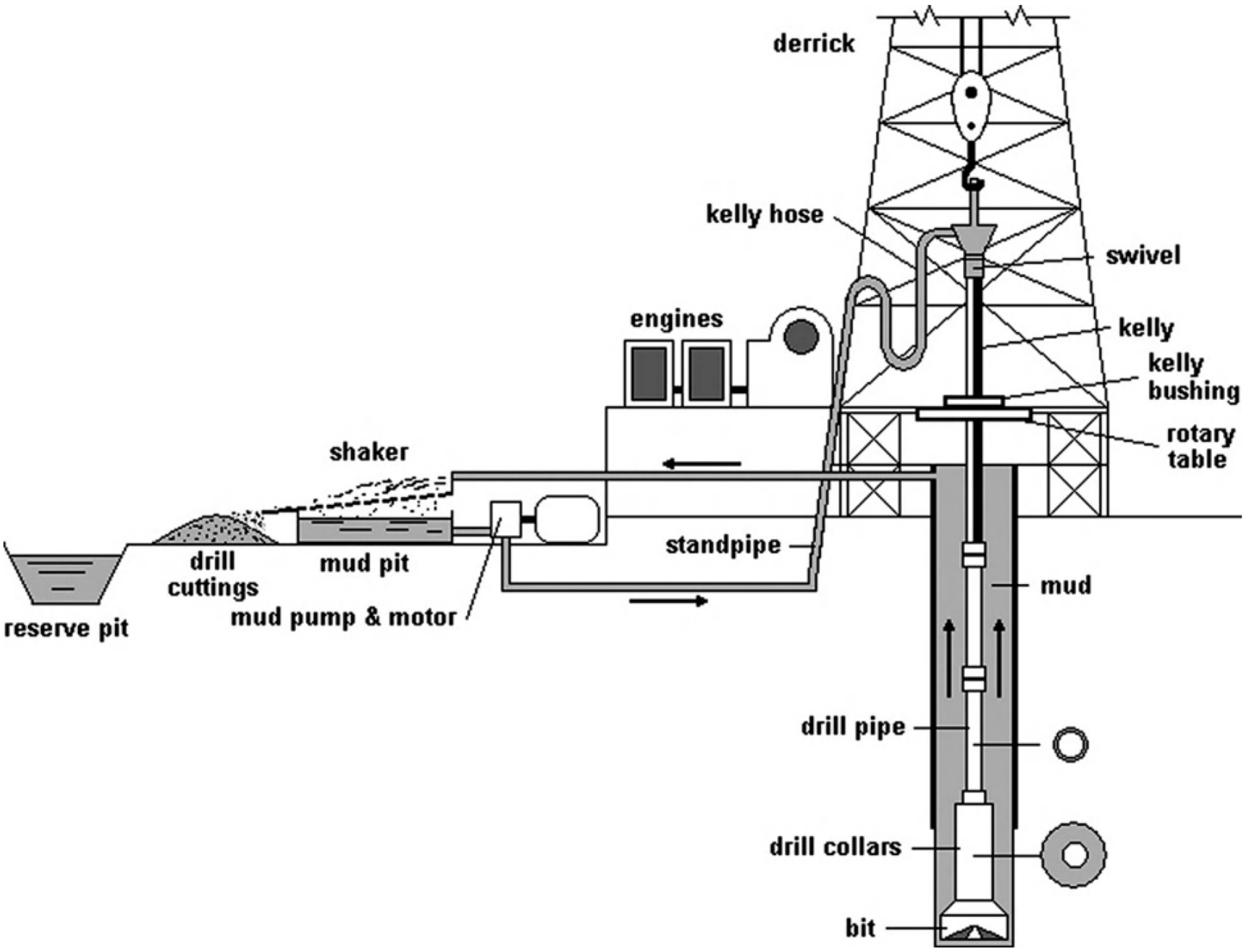


Fig. 3.4 Typical drill rig setup; not to scale.

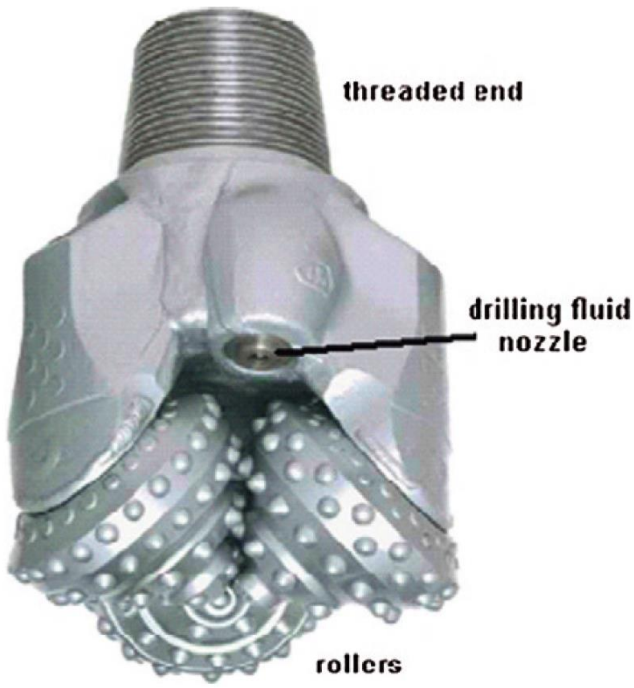
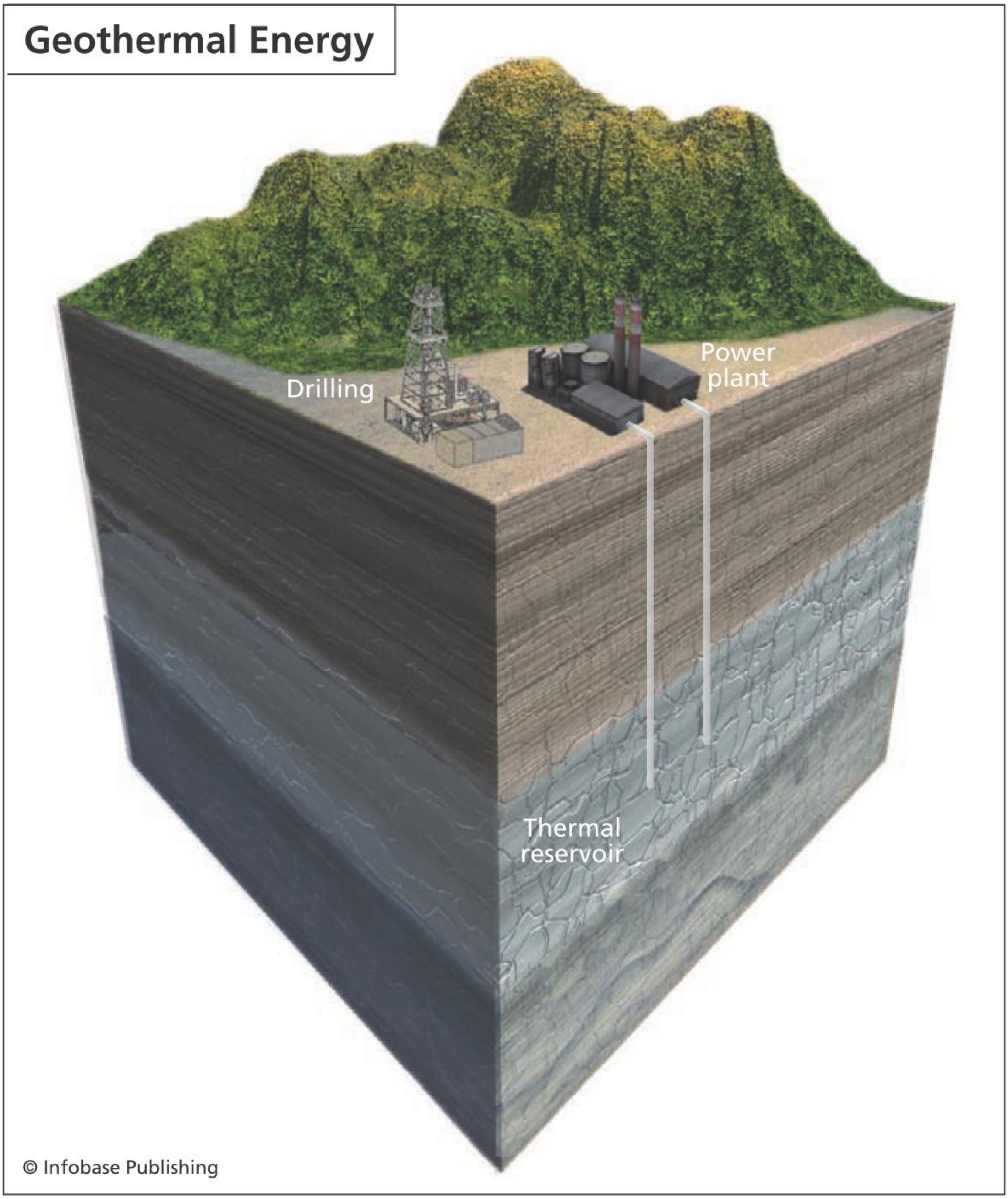


Fig. 3.5 A tri-cone roller bit designed for hard rock formations, manufactured by Hughes Christensen [4].

Geothermal well blow out in Azufres, Mexico (https://youtu.be/D-FlXDsieeY)

Breaking News Steam Blow from well IJN 6-1 (https://youtu.be/RnNAcuosIOE)



A geothermal system consists of the power plant, the thermal reservoir, and wells to connect the two.

ORCHYD project (Horizon 2020)

ORCHYD

«Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement In Deep Geothermal Drilling»

ROP = Rate of Penetration

Deep geothermal energy

Key development gateway for geothermal energy

Heat energy recovery

Geothermal electricity production

Enhanced Geothermal System (EGS)

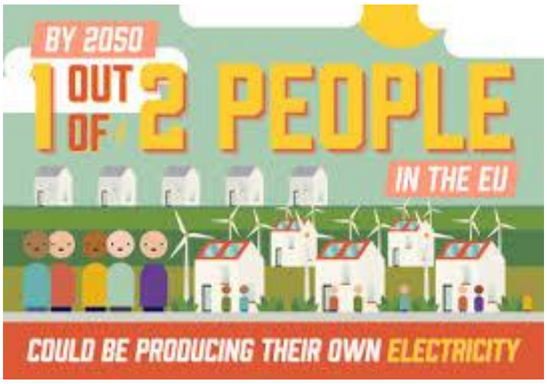
Combines electricity and heat (thermal energy) production

European Renewable Energy Council

Rethinking 2050 program

Both electricity and thermal energy production are expected to multiply

https://www.buildup.eu/en/practices/publications/re-thinking-2050-100-renewable-energy-vision-european-union



Geothermal energy

Carbon neutral

Widely available

Can provide stable supply (unlike wind and solar)

Unfilled potential

Currently geothermal supplies <2% of global energy

Viable geothermal reservoirs

Deep saline aquifers

Hot dry rocks

In both reservoirs

Heat is transported to the surface via boreholes/wells

Colder water is injected into the reservoir

This water is heated before it is returned to the surface

Reservoir permeability may be artificially stimulated to increase the fluid flow rate

Natural fracture permeability is boosted

Targeted multilateral drilling may connect to a well

Key barriers to widespread adoption of geothermal energy

- (1) Very low efficiency with which heat at depth is recovered to the surface
    - EGS demonstration projects have typically recovered 0.2~2% of available energy
- (2) Lack of versatility and viability of available drilling methods
    - Exploit multilateral and directional drilling strategies
        - Intersect fracture permeability
        - Maximize sweep efficiency (i.e. contact between cold injection fluids and hot rocks)
- (3) The showstopper remains the slow rates of conventional drilling to the greater depths of sufficiently hot rocks
    - >4 km through hard rocks

ORCHYD aims to

- Develop and demonstrate a new generation of hybrid Hydro-Percussive drilling technology
- Extend drilling performance in very hard rock
    - From the actual range of 1-2 m/h to a range of 4-10 m/h

Design and produce a new Hydro-Mechanical Dynamic rock cutting process

- Well adapted for drilling deep hard rocks
    - Very hard, mainly crystalline, deep rocks

Redesigning and merging two mature technologies

- (1) High Pressure Water-Jetting (HPWJ)
- (2) Percussive Drilling

Reduce

- Cost of deep geothermal drilling
- Risk of investment in high-enthalpy geothermal projects (producing electricity and heat)

Improve competitiveness of a carbon-free renewable resource

Factor affecting the performance of deep drilling operations

- Difficulty of breaking deep rock formations with acceptable drilling speed (ROP)

Low efficiency of drilling into deep hard rocks

- Strong geostatic stresses
    - Weight of overlying rock mass
        - «Overburden pressures»
    - Tectonic deformation history
- Hydrostatic pressure
    - Weight of drilling mud column inside the well being drilled
- Abrasiveness and natural heterogeneity of rock matrix

These strengthening effects

- Cause intense compression keeping rock particles
    - Pressed against each other
    - Resistant to brittle fracture

Increase the time required to carry out the last deep drilling sections considerably

And therefore the associated costs

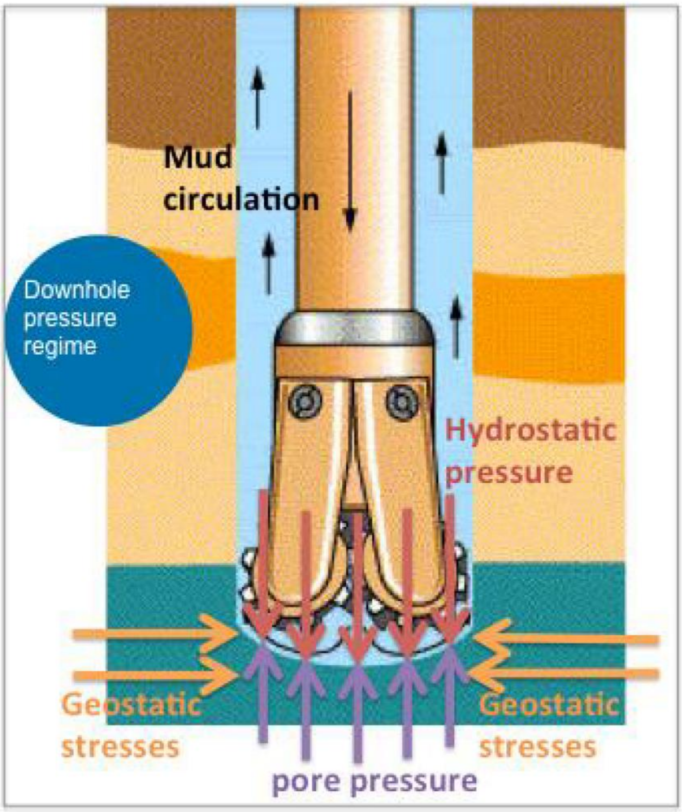


Figure 3: simplified representation of downhole pressures regime

Releasing the bottom of the borehole from high level of confining stresses

Significantly weakens the rock in-situ

Before it is attacked by the advancing mechanical drilling bit

Increases ROP considerably in deep drilling operations

ORCHYD proposes to induce the process of stress release using

High Pressure Water Jet (HPWJ)

Up to 200 MPa pressure

1 Pa = 1 N/m² (N=Newton)

200 MPa = 1973.8 Atm (https://www.asknumbers.com/atm-to-megapascal.aspx)

Cut grooves with most effective geometry to modify the stress field favorably

Optimal geometry is poorly understood for fluid-immersed hard rock under high confinement

Determine optimal jetting process to cut such grooves

Adopt optimal geometry of drilled bottom-hole

By designing the best drilling bit profile

Adopt a new percussive dynamic bit-rock cutting process

Existing air hammers cannot be used at great depths

Propose new hydraulic percussive hammer technology using drilling mud fluid

This technology is mastered and about to be marketed

DrillStar (https://www.drillstar-industries.com/)

A couple of videos on DrillStar (partner to ORCHYD)

Drillstar Industrial know how (https://youtu.be/IwMrRCbYlgA)

Prix de la vocation féminine 2016 Marjolaine Destandau de Drillstar Industries (https://youtu.be/LAvVRSobuPM)

ORCHYD and DrillStar

Sensors in the laboratory cannot observe the progressive breakup of different rock types for representative rock drilling conditions

There has remained a poor understanding of the actual processes driving the fracture and comminution of the rock microstructure

At the jet-weakened bit-rock-mud interaction zone down the hole

Virtual experiments will be carried out

Advanced numerical modeling technology

The following four processes will be addressed in ORCHYD

(1) Stress release in deep boreholes

(2) HPWJ of slots

(3) Percussive drilling under downhole pressure conditions

(4) Combining (1), (2) and (3) at scale to represent drill penetration performance in an integrated hydro-mechanical dynamic drilling process

ORCHYD will develop, test (in pilot drilling with full scale bit), and deliver prototypes of the new integrated drilling system

HPWJ up to 200 MPa

In-situ stress regimes corresponding to drilling depths up to 5000 m

The HPWJ will exploit the axial vibrations of the drillstring as activation energy

Will be adapted to the new drilling system using a percussive hammer

This technology has the advantage of damping detrimental vibrations in deep hard rock

The **University of Piraeus** research team

Environmental and social acceptability

Geothermal energy and public policy

Proposed geothermal power plants

Complex requirements

Political issues

Various stakeholder groups have interest or concern about the future of geothermal energy development

E.g. business owners of hot springs

Judgment on science and technology is involved

Environmental impacts are a central issue

- NIMBY and PIMBY issues

Environmental impacts of geothermal leases

- Impact to groundwater drilling ~ short-term
  - Test wells may go 2,000 to 3,000 feet (600 to 900 m) deep
- Noise ~ short-term and intermittent
- Loss of vegetation, habitat, and soil ~ long-term
- Visual impacts ~ long-term
  - Disruption of natural beauty
- Increase in residential development
- Provision of long-term jobs

Town Council meetings

- Position papers
- Support (or not) of use of public lands
  - Leasing subsurface land to private industry

The Rock Station Town Council has been considering geothermal energy use for the last two decades but because of strong local opposition, approval of a geothermal power plant has repeatedly been put on hold. Opposition includes local hot springs resort owners and a vocal homeowner's group.

Now, however, new technologies as well as strong support from the Colorado State Governor's office and the U.S. Department of Energy make the construction and location of this power plant more appealing.

Your responsibility will be to listen to all sides of this proposal and to either approve or disapprove of a Memorandum of Agreement with the Colorado State Governor's office. This memorandum is the last hurdle that developers need before building the geothermal power plant in Rock Station.

If you reject the plant proposal, you must use the Position Paper handout to provide the voting public with a position thesis and specific supporting evidence.

If you approve the plant proposal, you must figure out how to mitigate (lessen the impact of) the concerns of homeowners and resort owners.

Requirements

1. Instead of researching and producing a PowerPoint, each of your group's members must complete the accompanying "Pro and Con" handout with research.
2. Additionally, each member of the council must come up with five questions to ask the presenters during the Town Council meeting.
3. Make a decision; not all council members need to agree. A simple majority is necessary for approval or rejection.

Sources

DiPippo, R. (2012). *Geothermal power plants: Principles, applications, case studies and environmental impact*. Elsevier.

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US Department of Energy (n,d.). *Geothermal energy: A geothermal teacher guide for grades 9-12*. Geothermal education office, Tiburon, California.