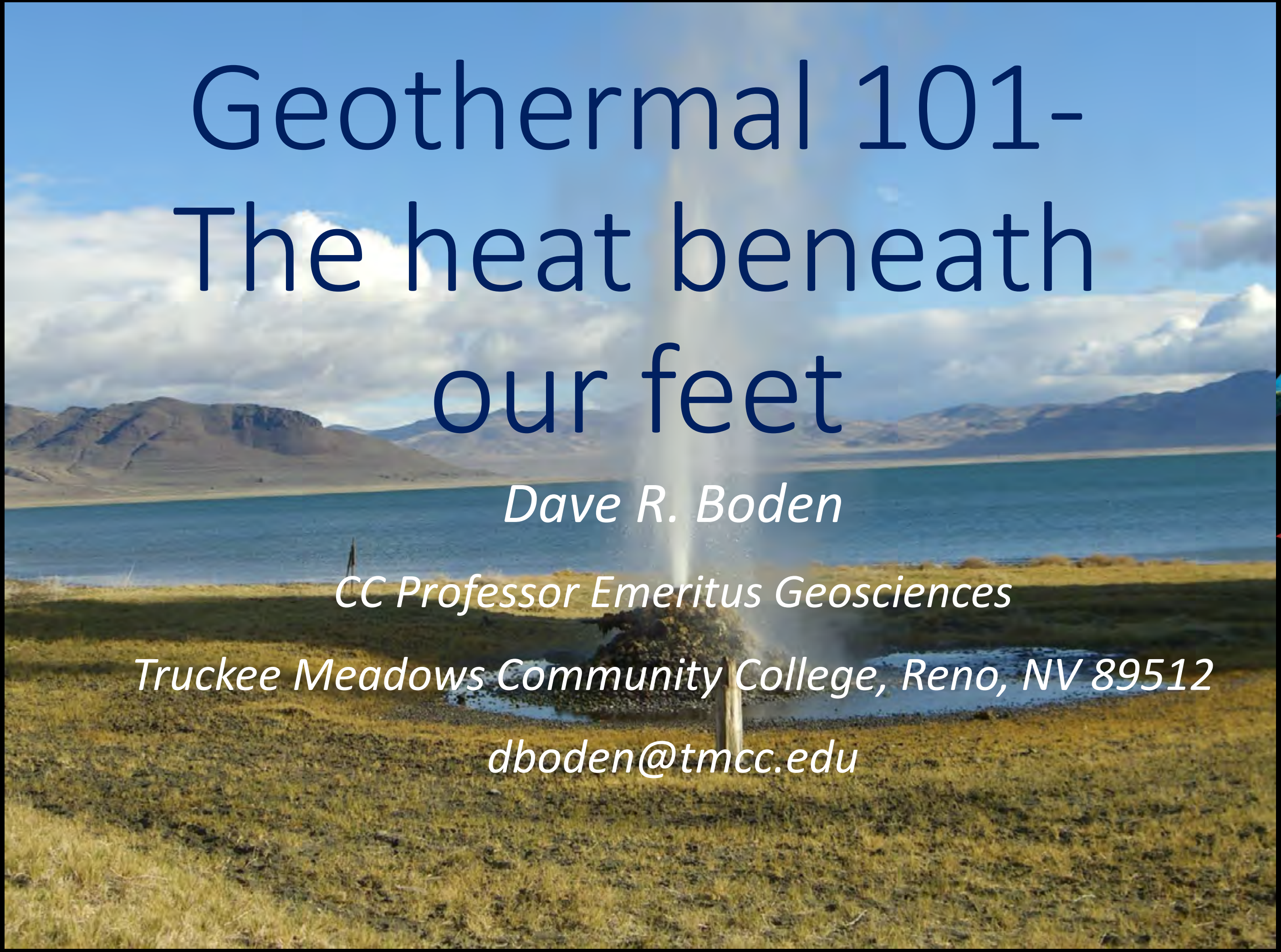
GEOTHERMAL RISING CONFERENCE



Geothermal 101- The heat beneath our feet

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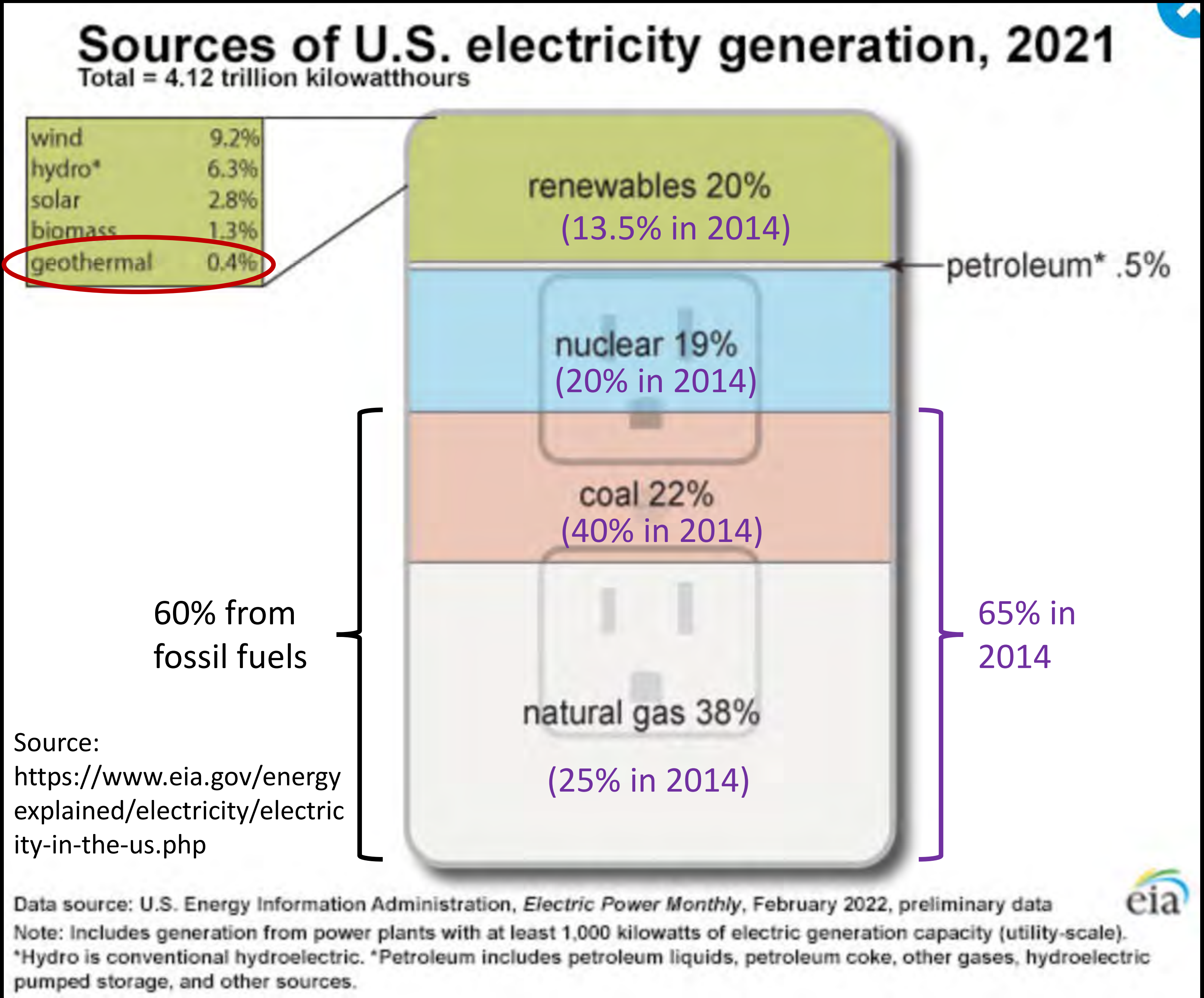
Agenda

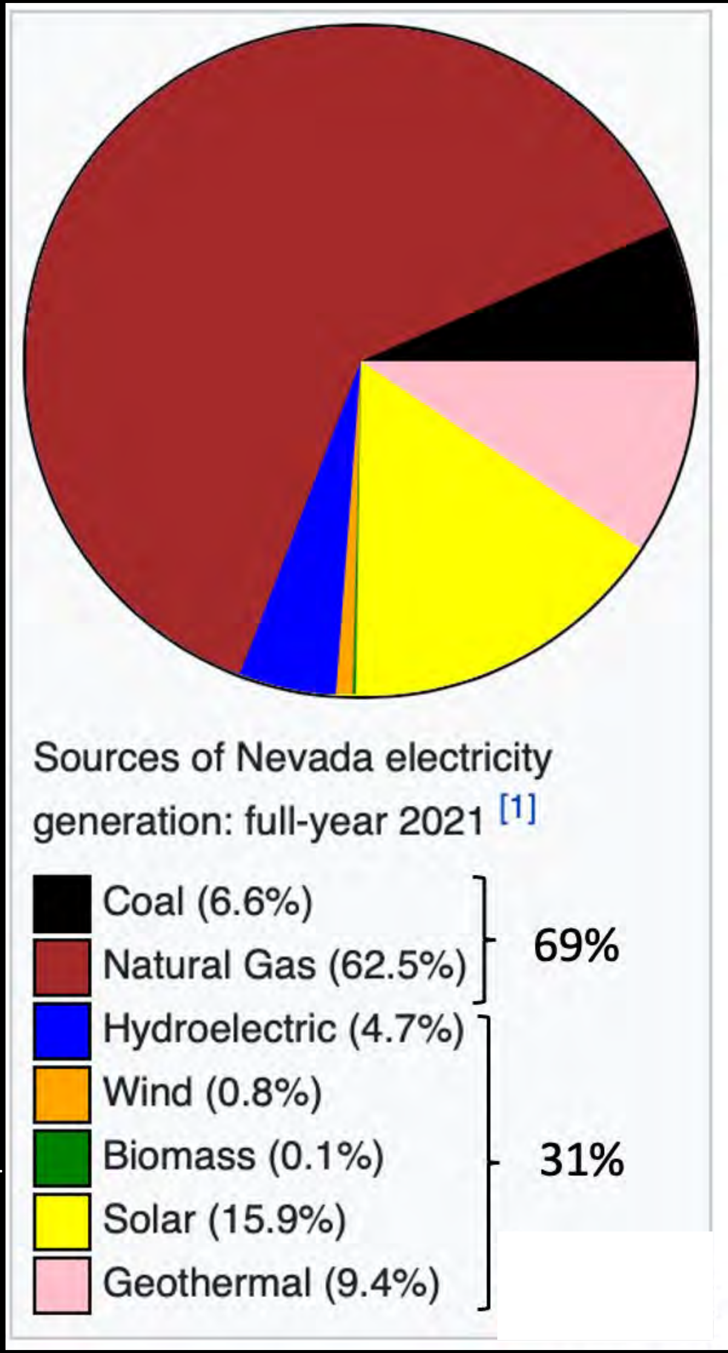
- What is geothermal energy and where does the heat come from?
- How is geothermal energy used?
- How are energy and power related?
- What are some key attributes and challenges for using geothermal energy?
- What criteria are needed to make a geothermal system viable for power generation?
- What makes Nevada attractive for development of geothermal resources?
- What are some exciting new technologies for expanding availability of geothermal energy and recovery of minerals?

Current and Recent Past Sources of Electricity Generation

- In CA, geothermal electricity accounted for about 6% of state's electrical production (CEC report, 2020)
- In Nevada, geothermal accounted for ~10% of state's electrical generation (Highest per capita usage of geothermal energy in the U. S.!)



Nevada Sources of Electricity



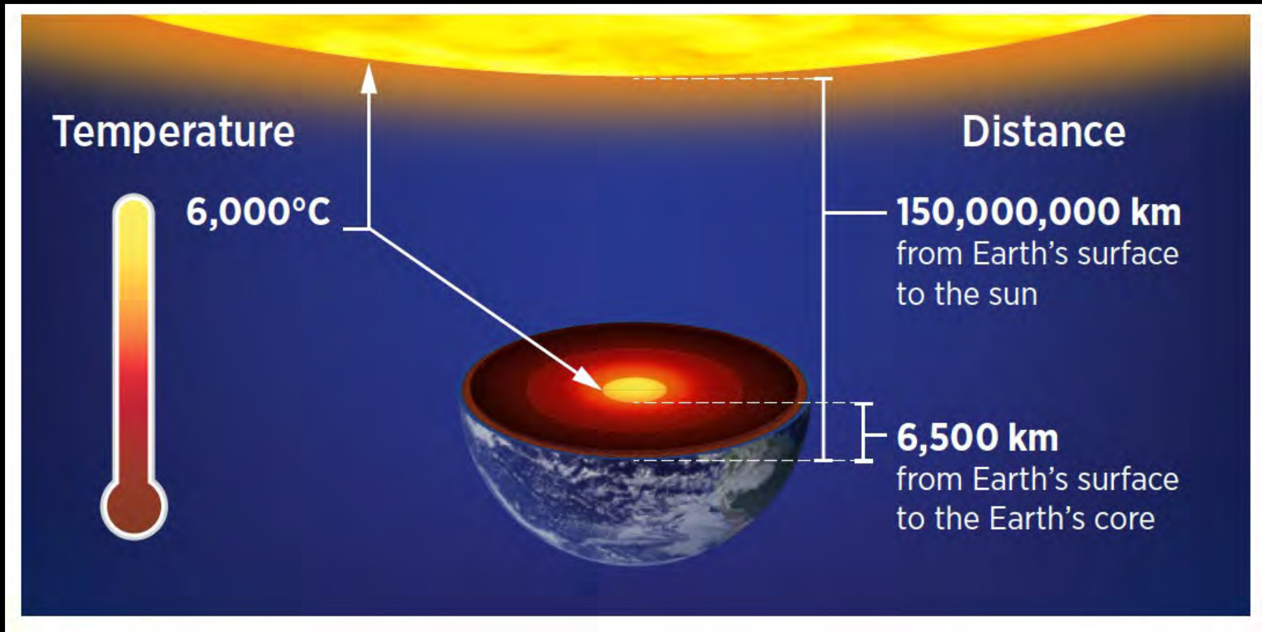
Source: https://en.wikipedia.org/wiki/List_of_power_stations_in_Nevada

Earth's Interior Contains Heat

- Earth is a giant heat engine→ ability to do work
- What might be examples of this work?
  - Erupting Volcanoes
  - Earthquakes
    - 2011 9.0 M Tohoku EQ moved ~1500 km of ocean floor 50 m (*released enough energy in a few seconds to power the U. S. for almost 2 months!*)
    - But wait that's not all: the 1960 M 9.5 Chilean EQ released enough energy to power U. S. for almost 1 year!
  - Continually moving great chunks of Earth's crust and upper mantle over great distances for a long time (heat energy that drives plate tectonics)
- Thermal energy is vast!
  - Tapping <1/1000th of one percent of thermal energy of upper crust would equal the US energy consumption in a given year

Where Does the Earth's Heat Come From?

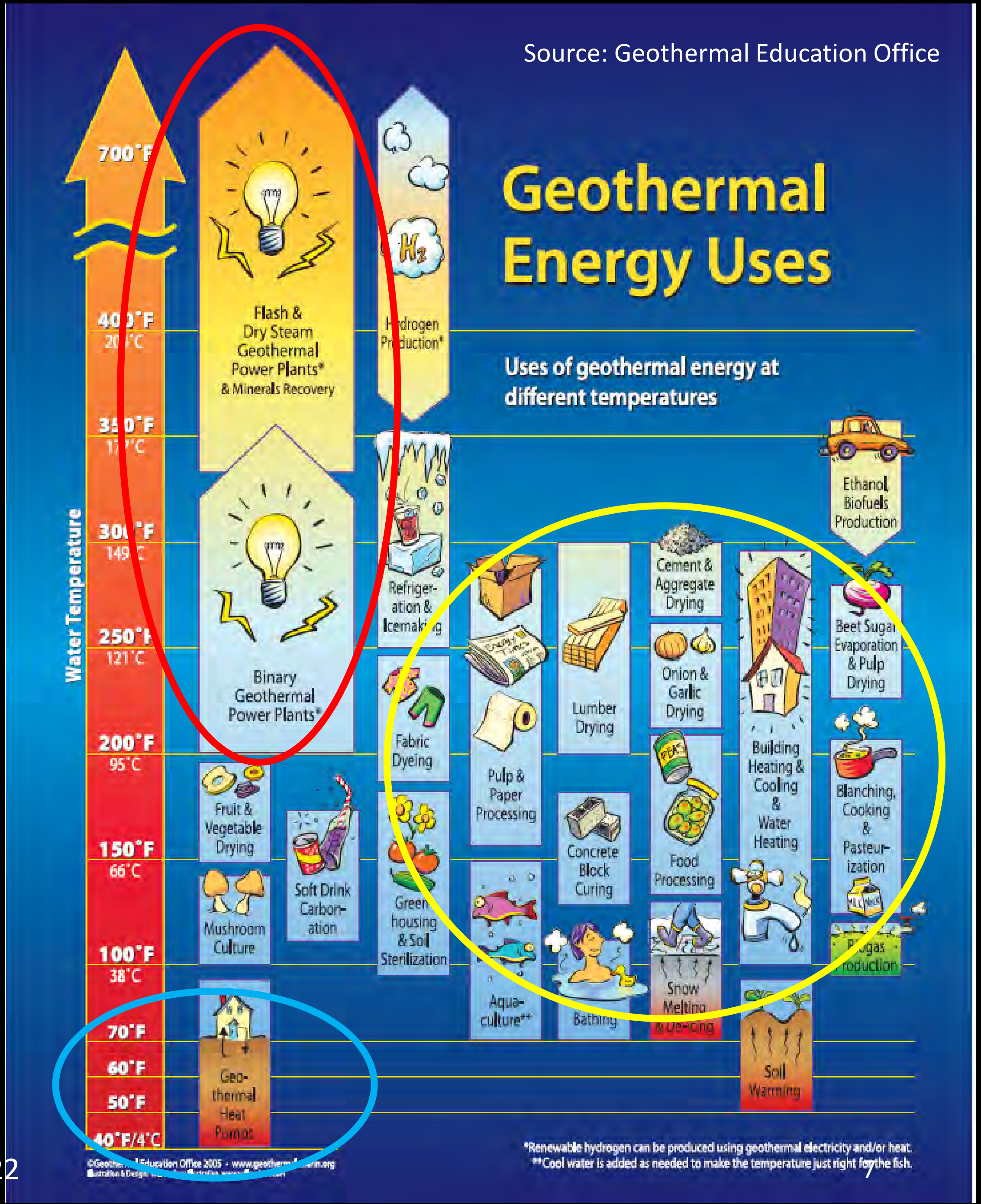
1. Residual heat left over from Earth's formation 4.6 Ga
    - Earth grew from accretion of debris, where kinetic energy was converted to thermal energy
    - Earth's core is about the same temperature as the surface of the Sun (~6000°C)
2. Radioactive decay of U, Th, and K
3. Gravitational pressure



Source: https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

What is Geothermal Energy?

- Harnessing Earth heat for use by society.
- What are some uses?
  - Produce electrical power (T >~100°C)
  - Direct use of geothermal fluid (T >~40 °C)
    - More energy efficient than power production
    - Heat (cool) buildings and homes
    - Aquaculture (fish hatcheries)
    - Greenhouses and fruit/vegetable drying
    - Spas and resorts (Peppermill)
  - Geothermal Heat Pumps (T 10°– 15°C)
    - Can be used anywhere
    - Use Earth as a thermal bank
    - Reduce energy costs by as much 40%. Why?
    - Actually largest application of direct use (71%)



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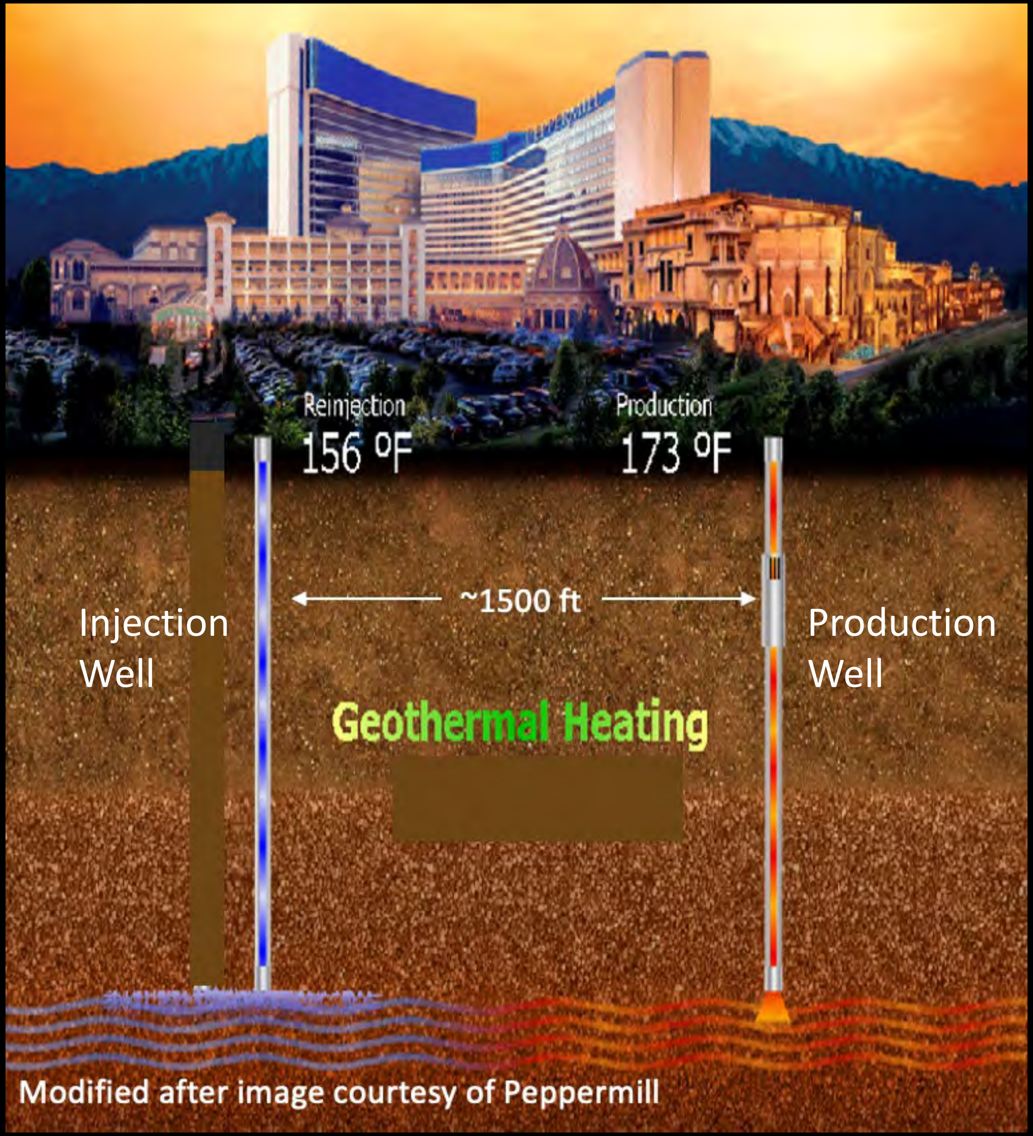
Peppermill Geothermal Direct Use

- Major conversion to direct use in 2007-2009
- Drilled two new wells, one for production and one for injection
  - Production well ~4400 ft deep produces ~1500 gpm at a T of 170°–174°F (77°-79°C)
  - Injection well ~3900 ft deep accepts 2000 gpm (pump assisted) located
- Heats entire campus
- Reduced NG consumption by ~85% saving ~$2.25M/yr in 2010
- ROI ~3.5 years!



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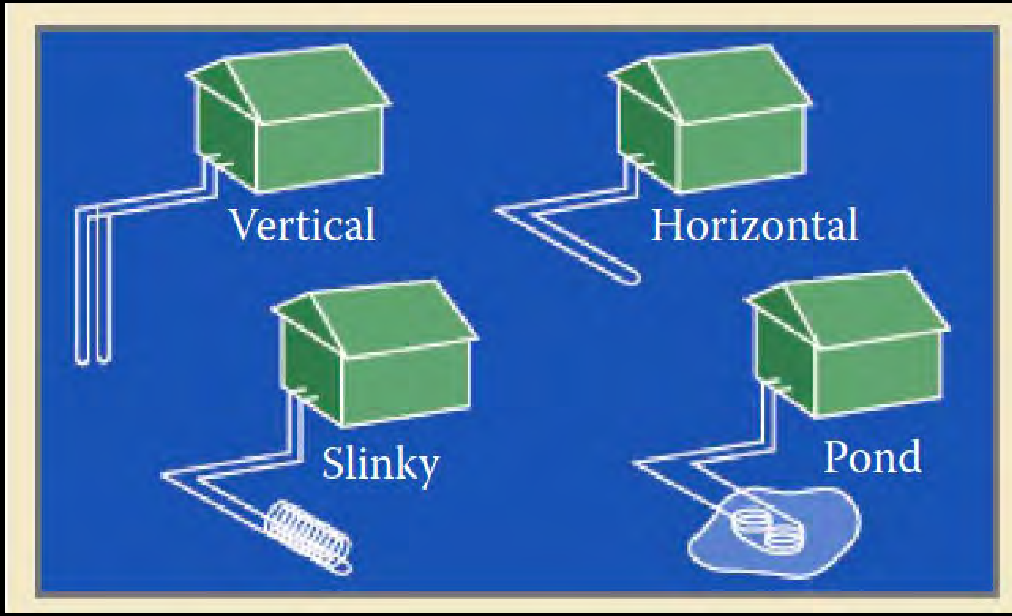
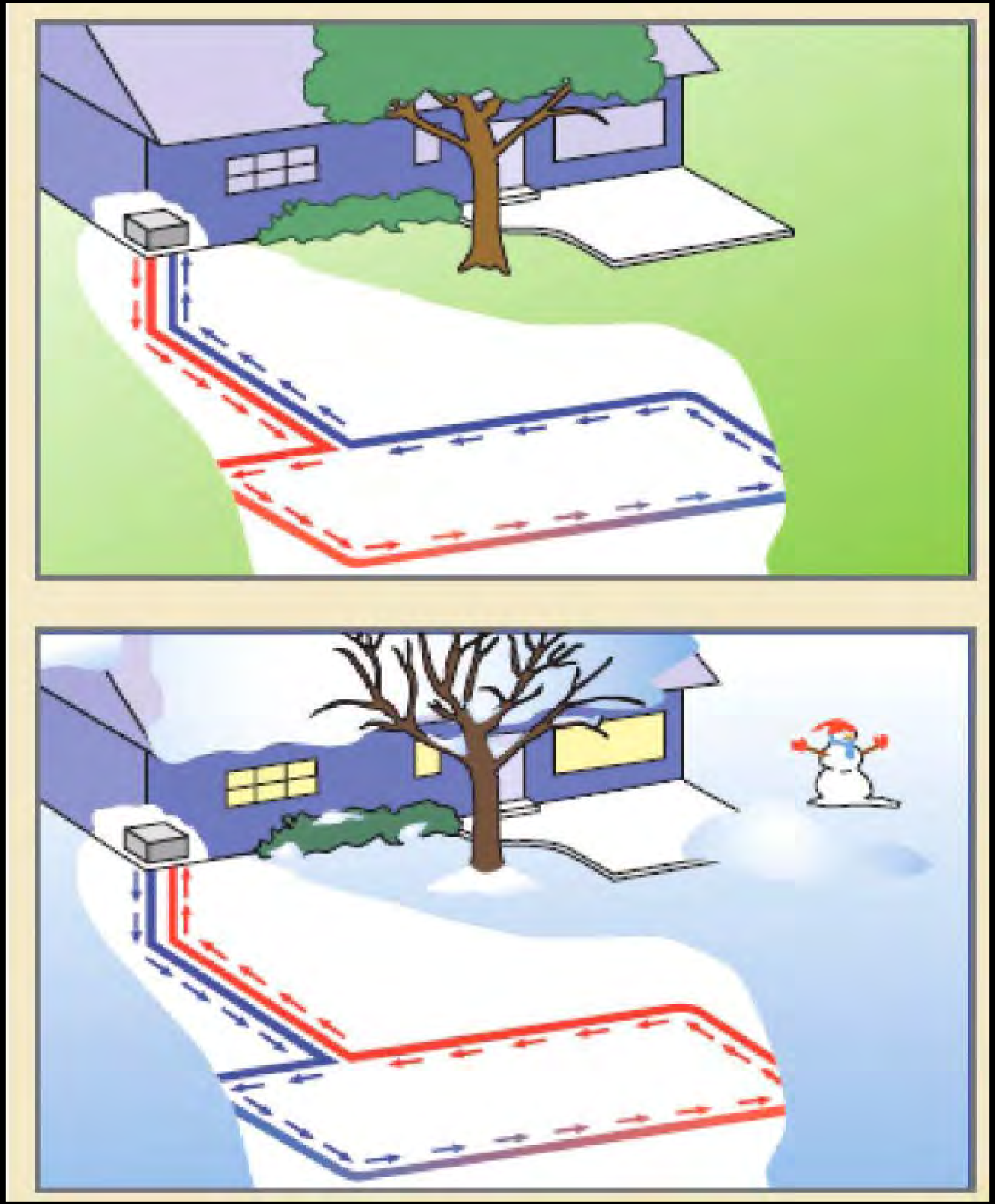
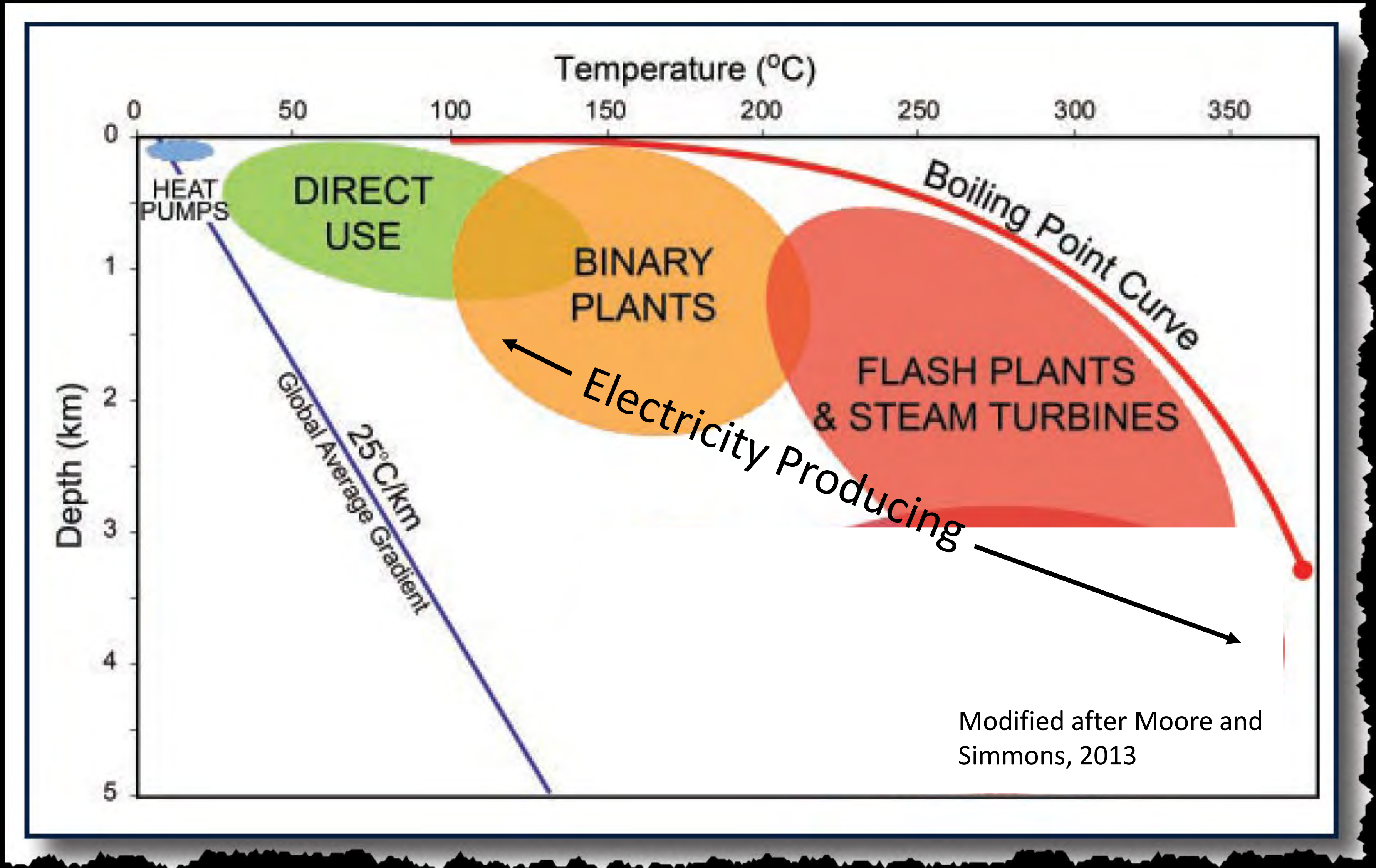
Geoexchange (heating and cooling)



Source: Duffield and Sass, USGS Circular 1249, 2003



Uses of Geothermal with Depth and Temperature



Energy and Power Are Different!

- Energy is a quantity or capacity to do work; Power is a rate at which that quantity (energy) is released
  - Power = Energy ÷ Time (P = E / T)
  - Energy = Power x Time (E = P x T)
  - Mass of wood example
- Energy can be stored; Power is an instantaneous measure
- Energy can change form; Power cannot
- Technically it’s not an Energy crisis; it’s a Power crisis

Measuring Energy and Power

- Basic unit of Energy is Joule; basic unit of Power is Watt
- One Watt of Power = 1 Joule per second ($P = E/t$)
  - One kiloWatt (1 kW) = 1000 Joules/second; one MegaWatt (1 MW) = one million joules/s
  - MW is typically used in rating delivery of energy output of power plants or rate of energy output for geothermal wells
  - One MW of power serves about 750–1000 homes
- Energy = Power x time → kiloWatt x time (in power industry unit of time is hour)→ kWh on your power bill
  - Energy generated from power plants measured in MegaWatt-hour (MWh) or GigaWatt-hour (GWh) → Palo Verde nuclear plant (3.9 GWh)

Geothermal Energy Attributes

- Premium renewable energy source – competitively priced with other renewables;
- Base load power (available 24-7 unlike wind and solar);
  - New technology allows for load following and dispatchable
  - 90%+ capacity factors (ratio of energy produced over a given time; only nuclear is comparable)
    - Solar and wind capacity factors typically 25-35%; coal- and natural-gas-fired power plants about 50-70%
- Sits on top of energy source;
  - No fuel price exposure; price certainty; insulated from price volatility;
- Promotes energy diversity;

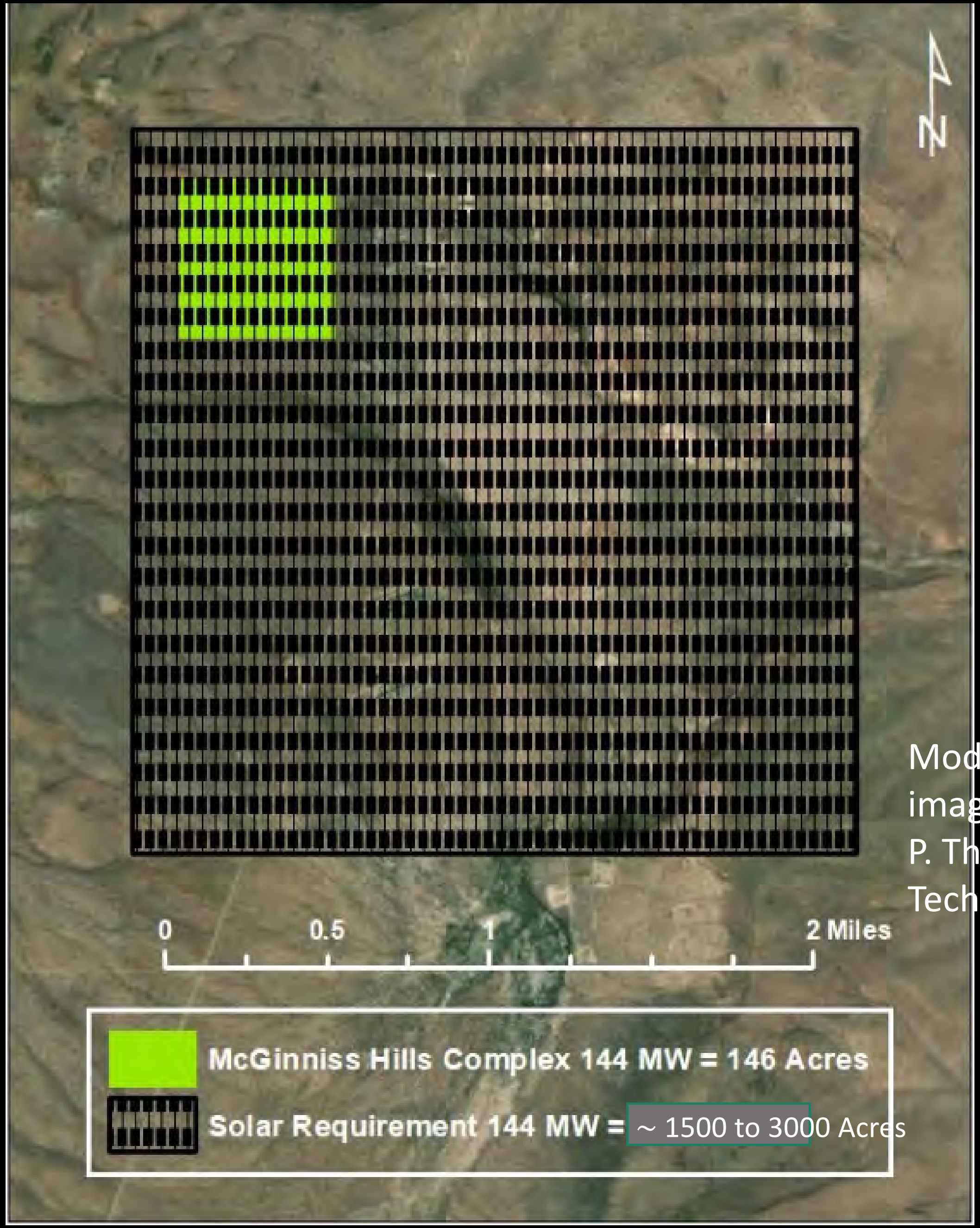
Geothermal Energy Attributes

- Proven resource, mature technology (dating back to 1913 in Italy and 1958 in New Zealand);
- Economic impact on construction/operation: number of jobs per MW;
  - CalEnergy Salton Sea: ~390 MW; ~240 employees (about 1 employee for every ~1.6 MW produced)
  - Comparably sized natural gas plant: 15 employees; commercial solar/wind plant: 10-15 employees (1 employee for every 25-34 MW produced)
- Minimal environmental impacts:
  - Minor or no greenhouse gas emissions
    - Conventional geothermal flash plant releases only 2% GHG emitted by NG-fired power plant
    - Binary plants have zero greenhouse gas emissions
  - Small footprint for power produced (1-3 acres/MW compared to an average of 85 acres/MW for wind (*NREL/TP-6A2-45834, 2009*) and about 10 acres/MW for solar (https://betterenergy.org/blog/the-true-land-footprint-of-solar-energy/)
  - Land available for multiple use

GEOTHERMAL FOOTPRINT IS SMALL

- At McGinness Hills, NV about 1 acre is required for every MW
- Solar PV requires about 10 acres/MW* (varies depending on latitude, efficiency of installed panels, time of year, and setbacks and zoning restrictions)

**Does not include storage facilities for round-the-clock power availability as with geothermal. If so, then then solar footprint increases to about 15-20 acres/MW*



Modified after image courtesy of P. Thomsen, Ormat Technologies

Land Available for Multiple Use

Miravalles geothermal field, Costa Rica. After DiPippo, 2012

Geothermal plant in Imperial Valley, CA. Source: NREL Image Gallery

Land Available for Multiple Use

Blue Lagoon Spa at Svartsengi geothermal plant, Iceland

Steamboat geothermal complex near Reno, NV. Yellow arrow points to highway traversing the producing field. Red arrow points to Galena III power plant .

Geothermal Challenges

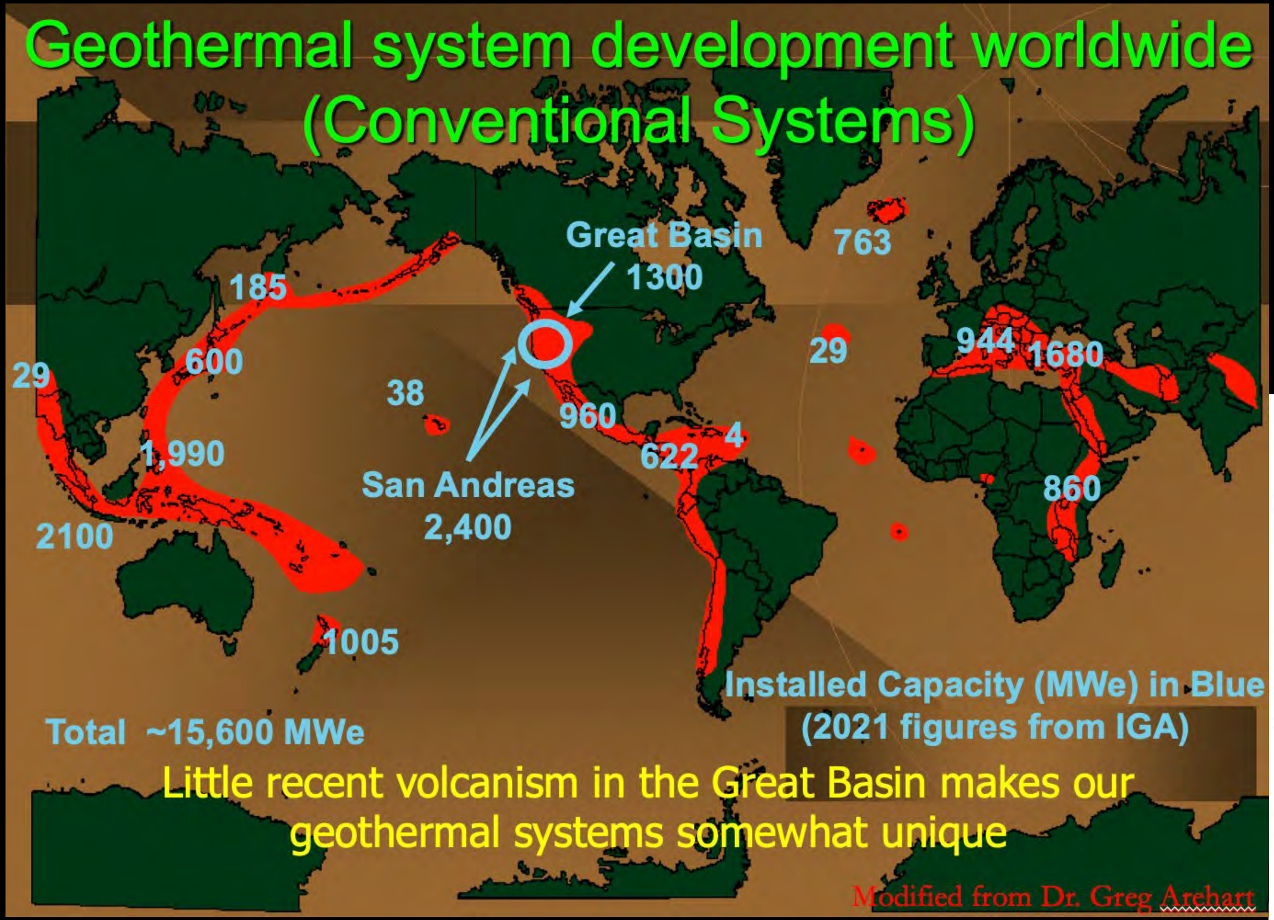
- Currently developed and actively explored systems are geographically restricted due to geologic constraints
  - Good potential to become more widespread in the future as discussed later
- Potential for induced seismicity from fluid extraction and/or injection
  - Typically most pronounced at outset of development and diminishes over time
  - Can be mitigated by adjusting rate and nature of injection
- Land subsidence from inadequate replenishing of geothermal reservoir
  - Can be minimized by injecting spent fluid
- Potential disturbance of any hydrothermal surface manifestations
  - Can also be mitigated via injection

Geyser Valley, NZ—Impact of not re-injection on geothermal surface manifestations

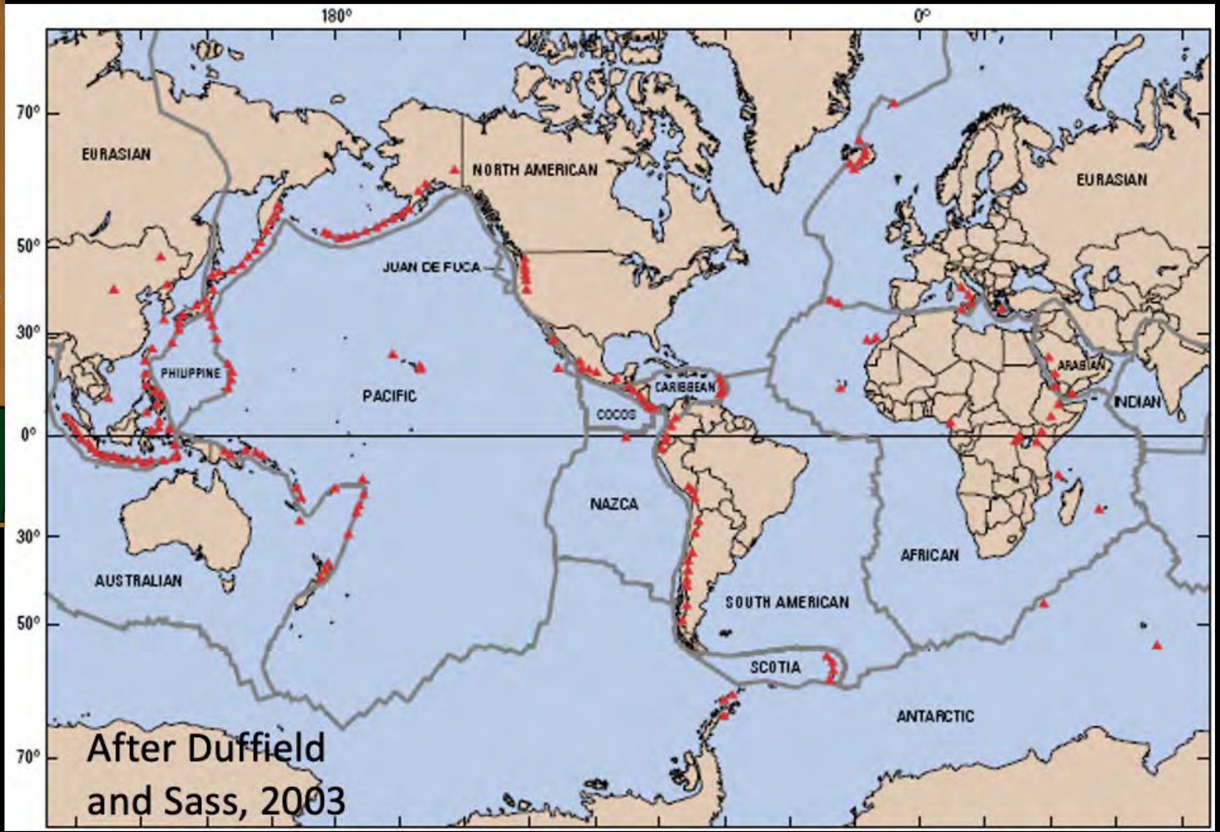
- Wairakei geothermal facility did not re-inject for about 30 years after beginning of production. Why?
  - Concern about cooling the reservoir
  - Expense of drilling new wells
- Geyser Valley prior to production (1950s)
  - https://teara.govt.nz/en/video/5437/geyser-valley-1950s

Geyser Valley Today

Worldwide Distribution of Geothermal Systems



Tectonic Plates



Note correspondence between distribution of geothermal systems and boundaries to tectonic plates

What is Needed to Make a Geothermal Resource Viable?

- Five main criteria to make a hydrothermal resource economically viable:
  1. Large heat source
  2. A permeable reservoir
  3. A supply of water
  4. A impermeable cap rock
  5. A steady recharge mechanism

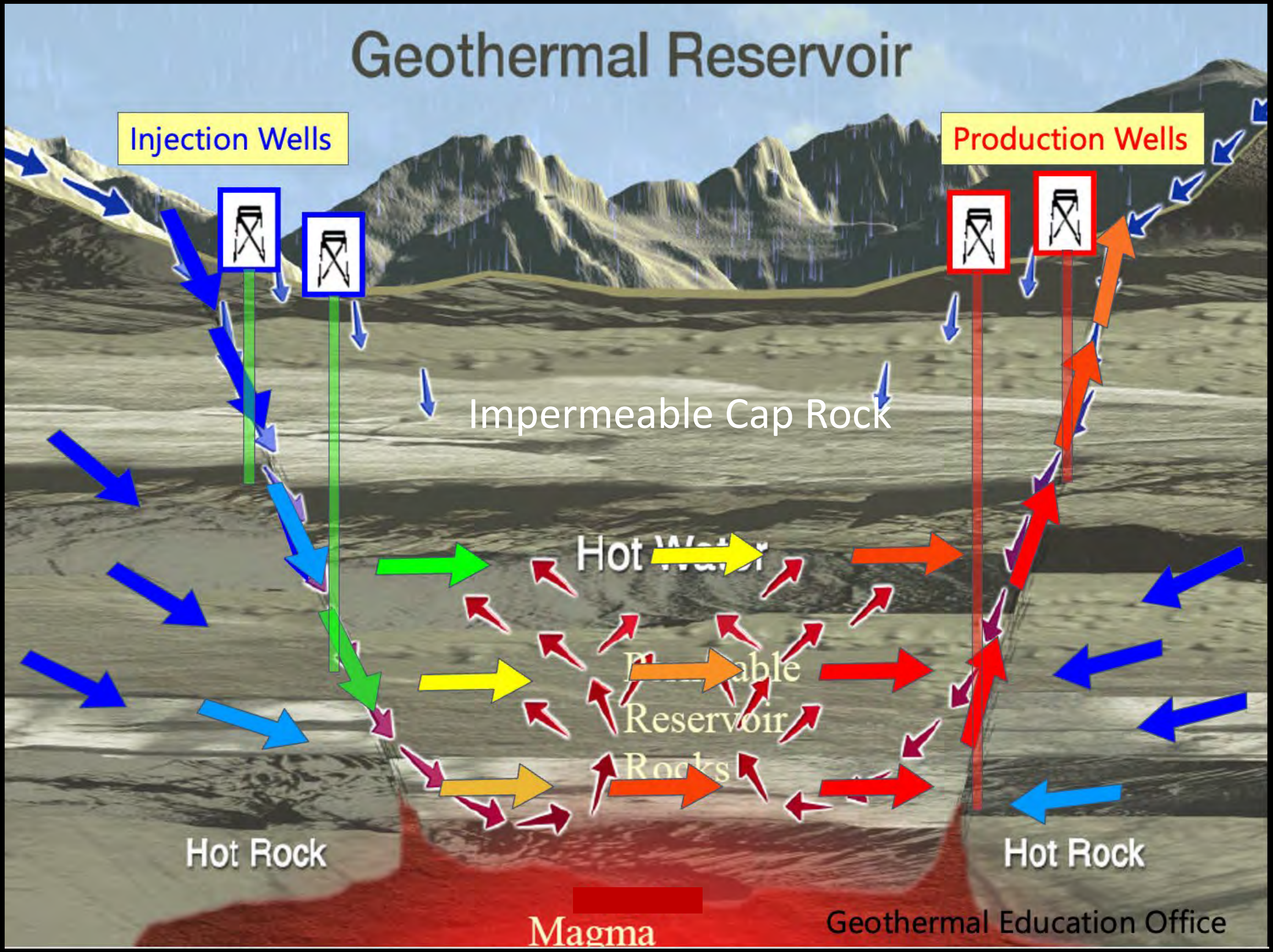
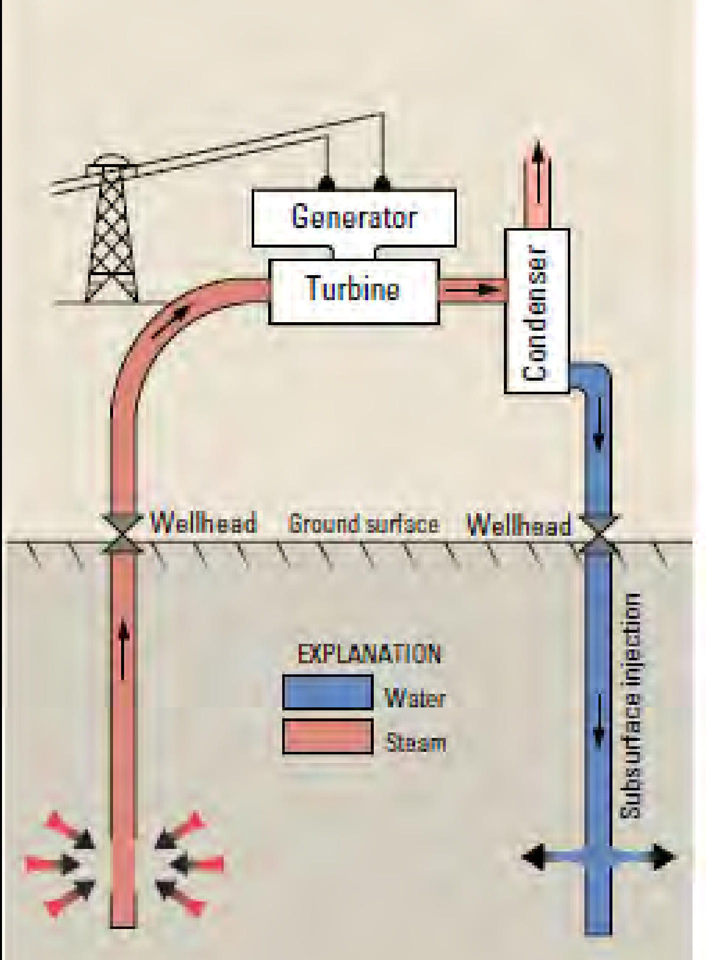


Image courtesy of M. Coolbaugh as modified from GEA

Types of Geothermal Systems and Related Power Plants

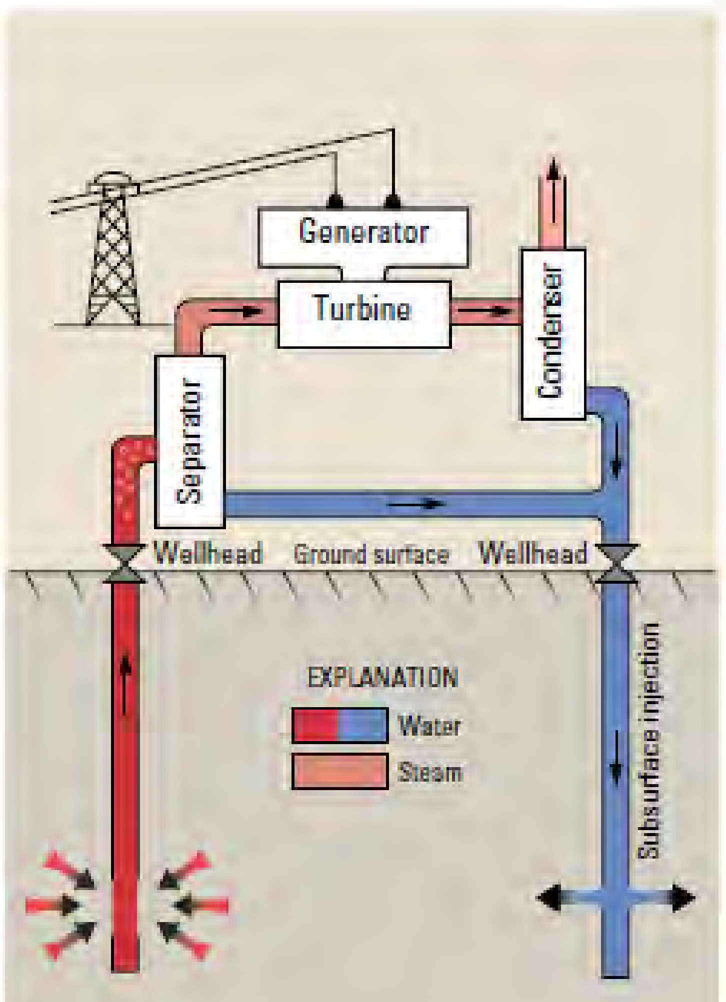
- Vapor (steam)-dominated
  - Provide greatest amount of power per mass of fluid
  - Because reservoir is already steam, all fluid mass goes to turbine
  - In order for fluid to occur as steam, reservoir is underpressured compared to surrounding rock—geologically rare conditions
  - World class examples are The Geysers, CA and Larderello, Italy (the first commercially produced geothermal reservoir for power generation in 1913).



After Duffield and Sass, 2003

Types of Geothermal Systems and Related Power Plants

- High-temperature, liquid-dominated
  - T ≥ ~180°C
  - Mainstay of the industry (flash)
  - Fluid exists as a liquid in reservoir
  - Begins to boil as pressure falls when fluid rises up well (mixture of steam and liquid—2 phase fluid)
  - From wellhead, 2-phase fluid goes to separator where steam rises to top and liquid goes to bottom
  - Only steam goes to turbine, and liquid is re-injected
  - Energy is partitioned as only steam goes to turbine



After Duffield and Sass, 2003

Well 24-5 Upper Steamboat

After shut-in and servicing, fluid in well is allowed to flow to muffler until T is high enough to bring steam to power plant.

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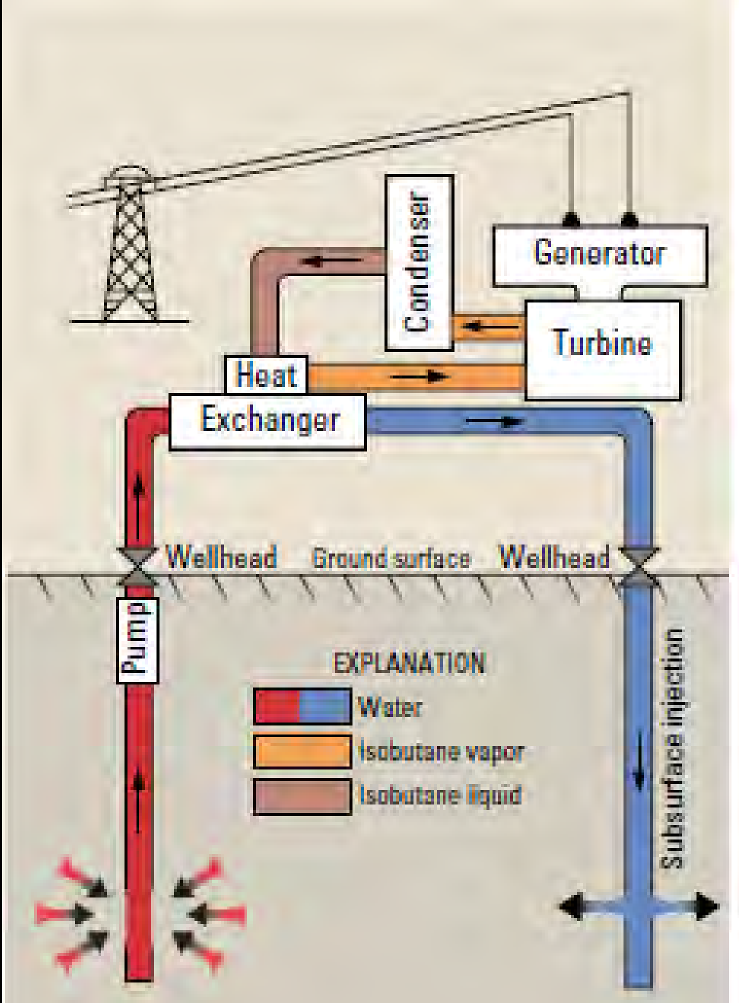
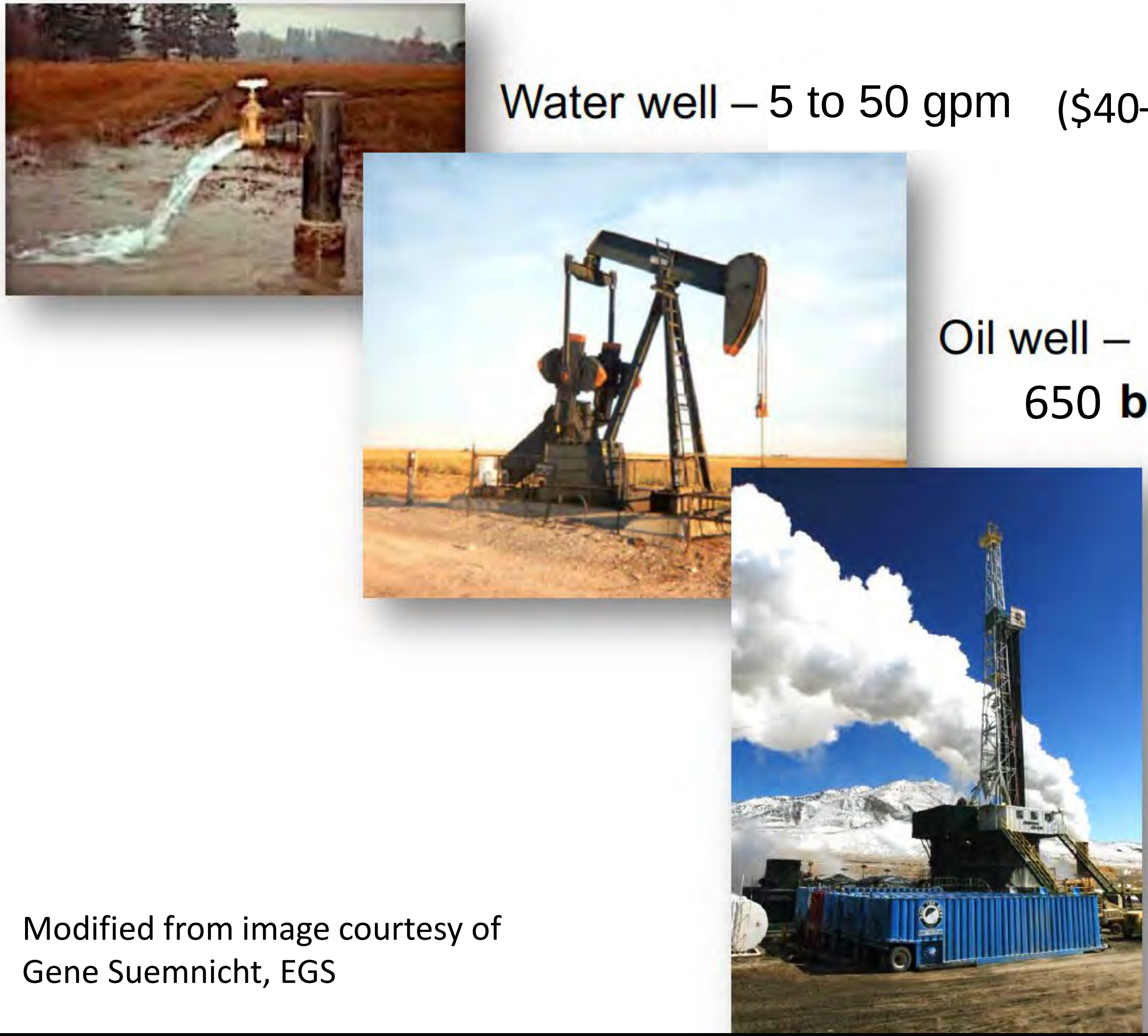
Types of Geothermal Systems and Related Power Plants

- Moderate-temperature, liquid-dominated
  - T > ~100 - 180°C
  - Provide an increasing proportion of power. Why?
    - Lower T systems are more common than high T systems
  - Binary systems
    - Two fluids—the geothermal fluid provides the heat, and a working fluid that serves the turbo-generator
    - Geothermal fluid passes through heat exchanger to flash working fluid having a low boiling point to generate more steam pressure than water
    - Both geothermal and working fluids form closed loops therefore there are no emissions of GHGs



After Duffield and Sass, 2003

Comparative Production Rates



Water well – 5 to 50 gpm ($40–$400/day)

Oil well – 20 gpm
650 **bbls/day**
(~$65,000/day)

<u>Geothermal well</u>
2000 gpm
(~$6000 – $12,000/day)

Modified from image courtesy of
Gene Suemnicht, EGS

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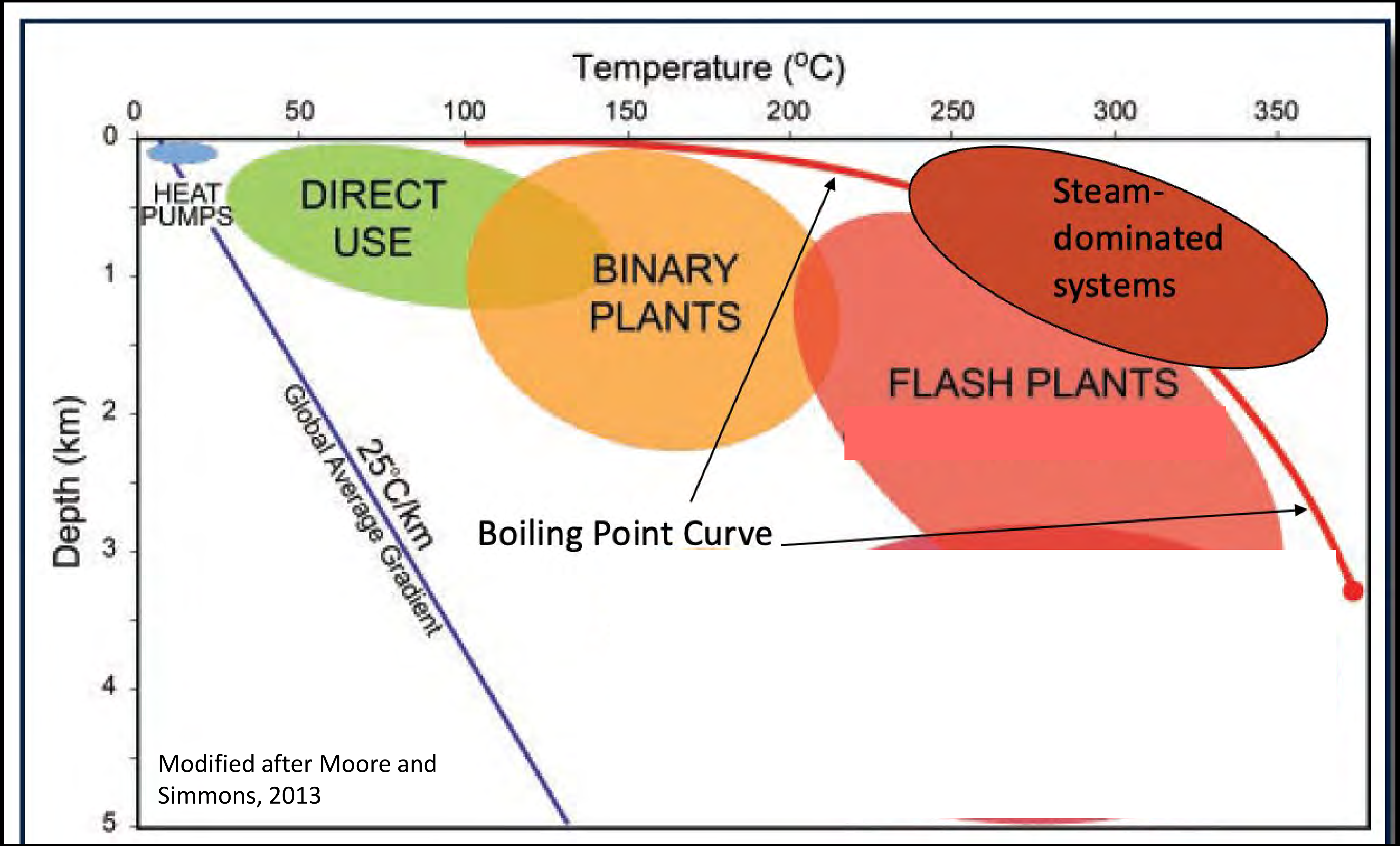
Temperature (°C)
0
50
100
150
200
250
300
350
Depth (km)
0
1
2
3
4
5
HEAT PUMPS
DIRECT USE
BINARY PLANTS
Steam-dominated systems
FLASH PLANTS
Global Average Gradient
25°C/km
Boiling Point Curve
Modified after Moore and Simmons, 2013

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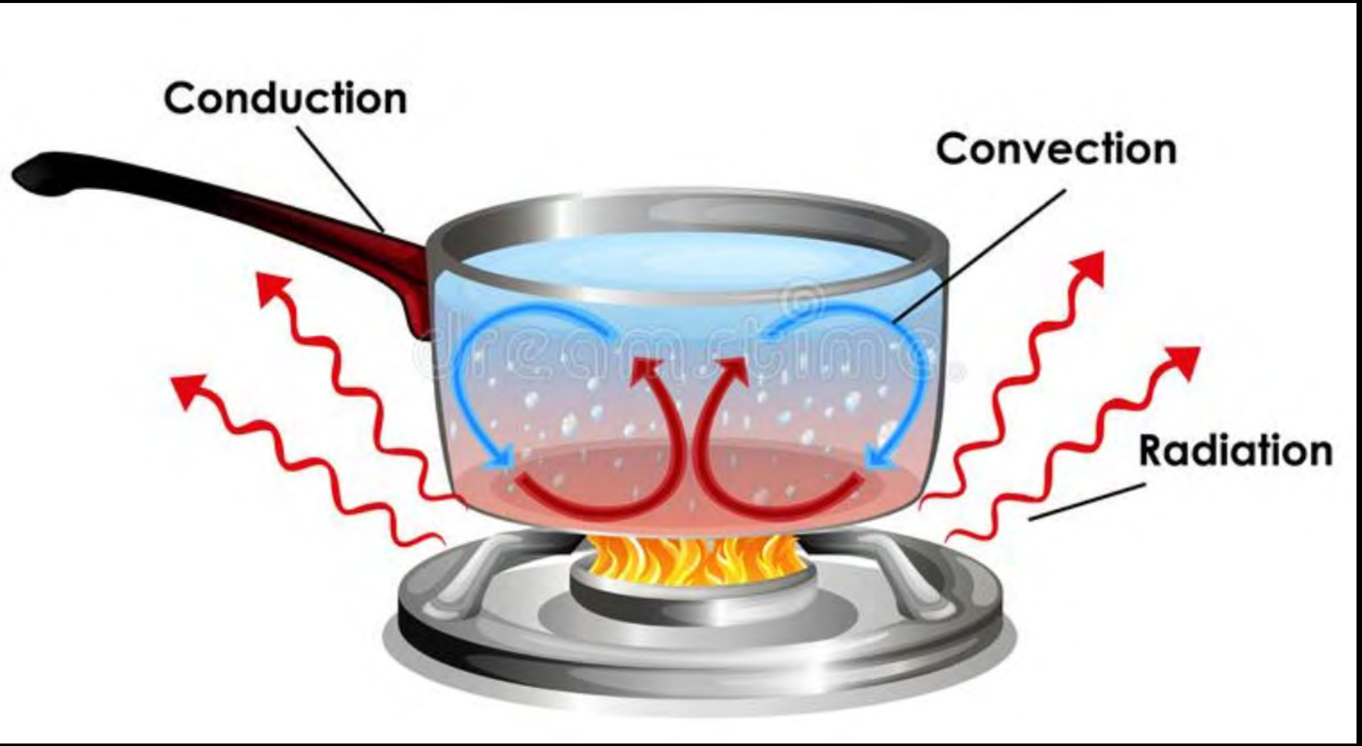
How is heat transferred?

1. Radiation–transfer of heat through space
2. Conduction–transfer of heat by contact
   - Transfer of heat through solid rock
   - Slow as rocks are poor conductors (good insulators)
   - Consistent increasing T with depth (geothermal gradient)
3. Convection–transfer of heat by motion
   - Most efficient
   - Critical for geothermal systems
   - Will T change much with depth?
     - No
   - Requires good permeability



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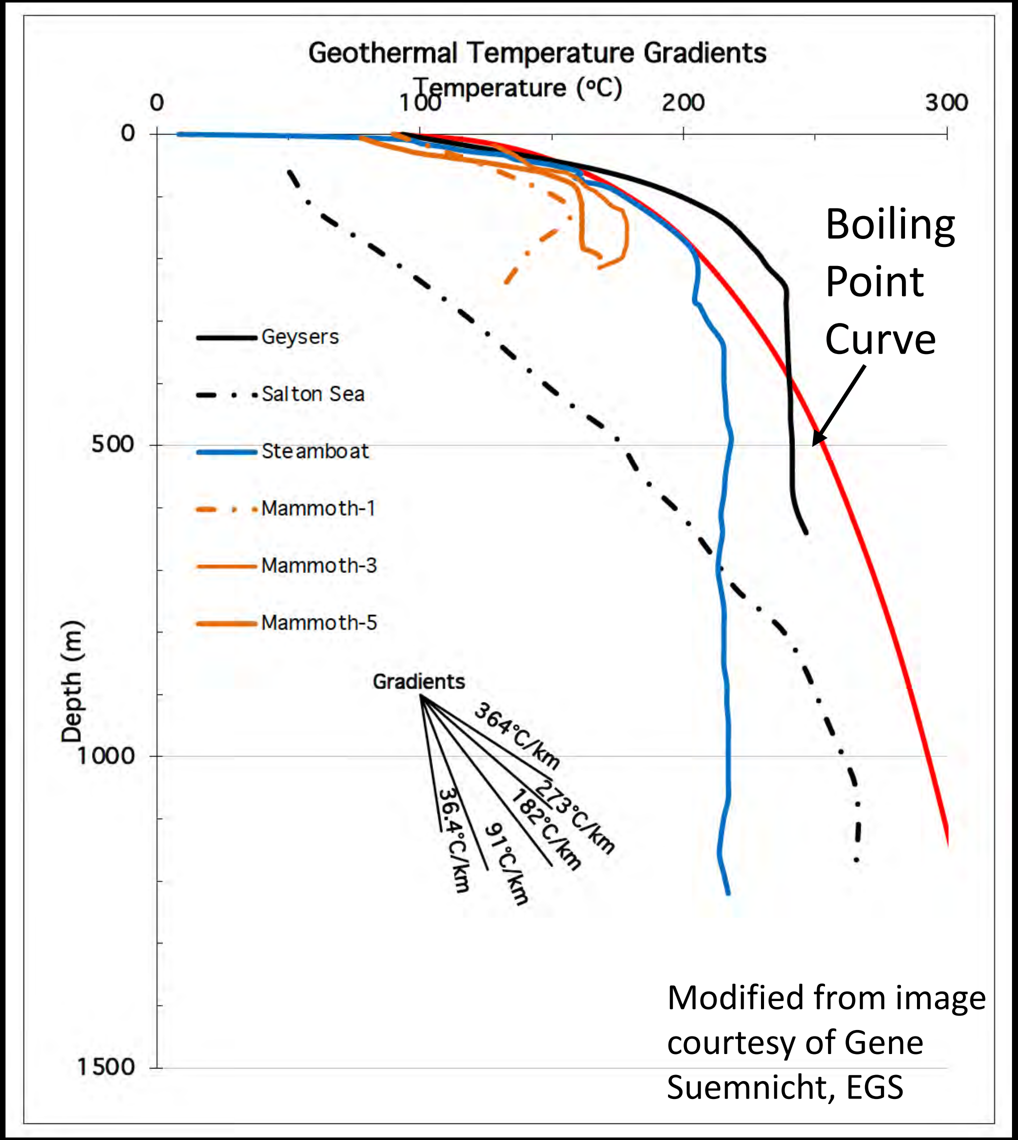
Profiles of Drill Temperature with Depth



Can you distinguish the conductive from the convective zones of heat transfer in the drill hole T with depth profiles?

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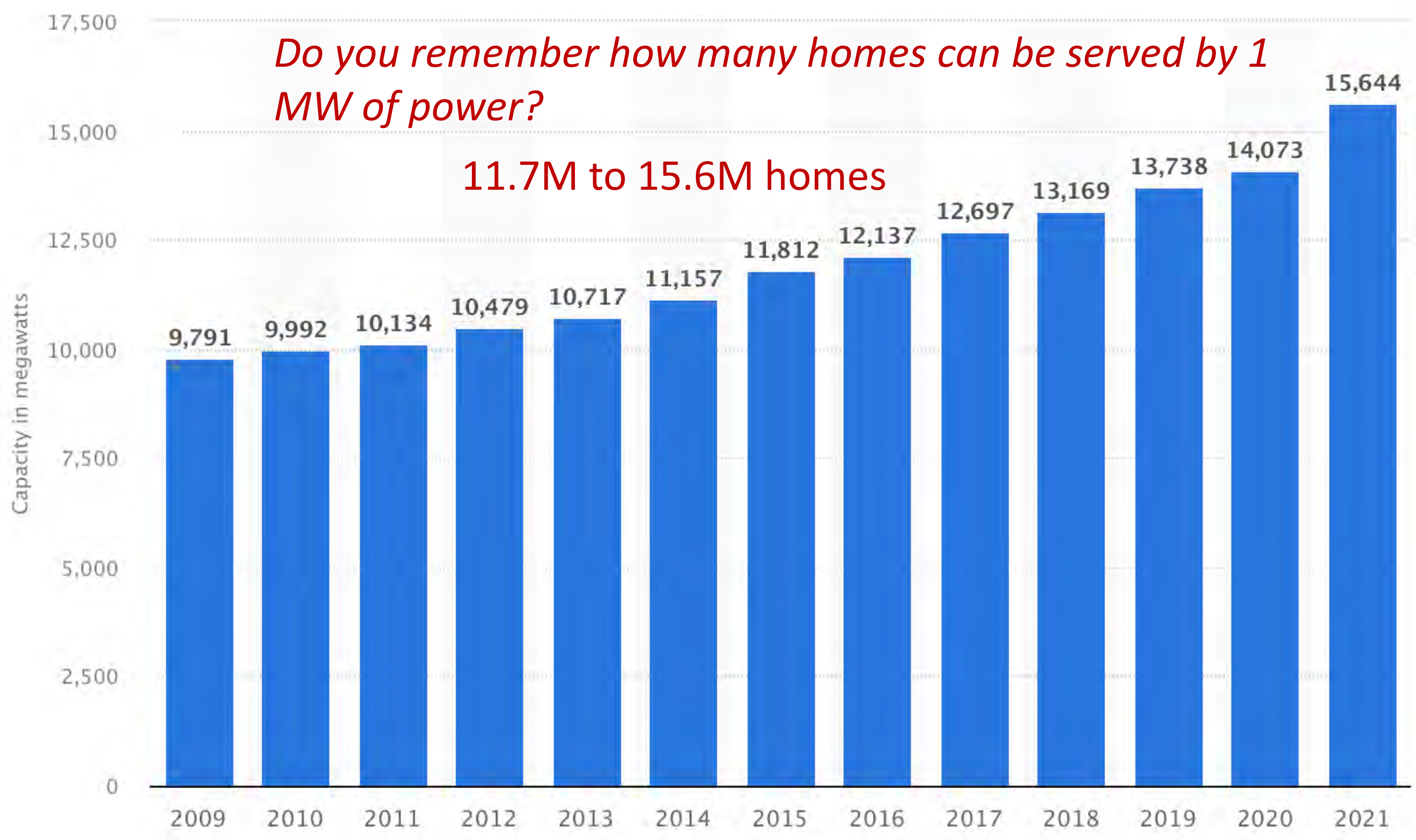
Geothermal energy capacity worldwide from 2009 to 2021

(in megawatts)

Power capacity increased by 60% over past 12 years

Do you remember how many homes can be served by 1 MW of power?

11.7M to 15.6M homes



Source: https://www.statista.com/statistics/476281/global-capacity-of-geothermal-energy/

ThinkGeoEnergy's Top 10 Geothermal Countries 2020 – installed power generation capacity (MWe)

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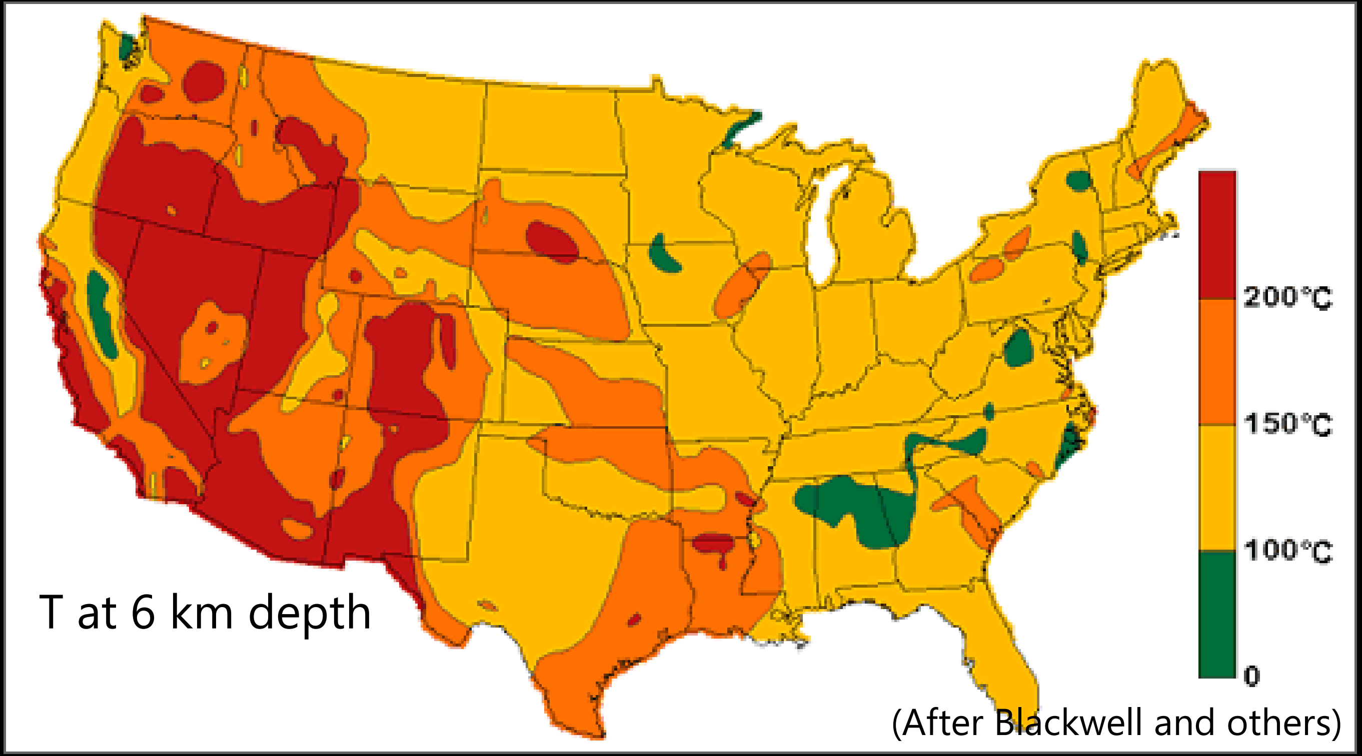
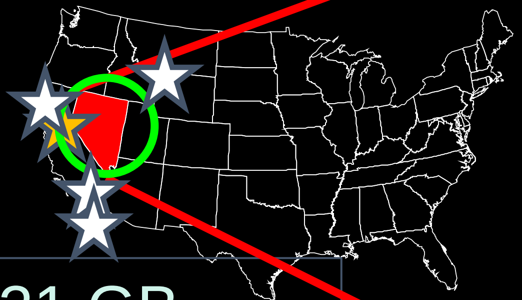
What Makes the Great Basin (Nevada) So Prospective for Geothermal Energy?

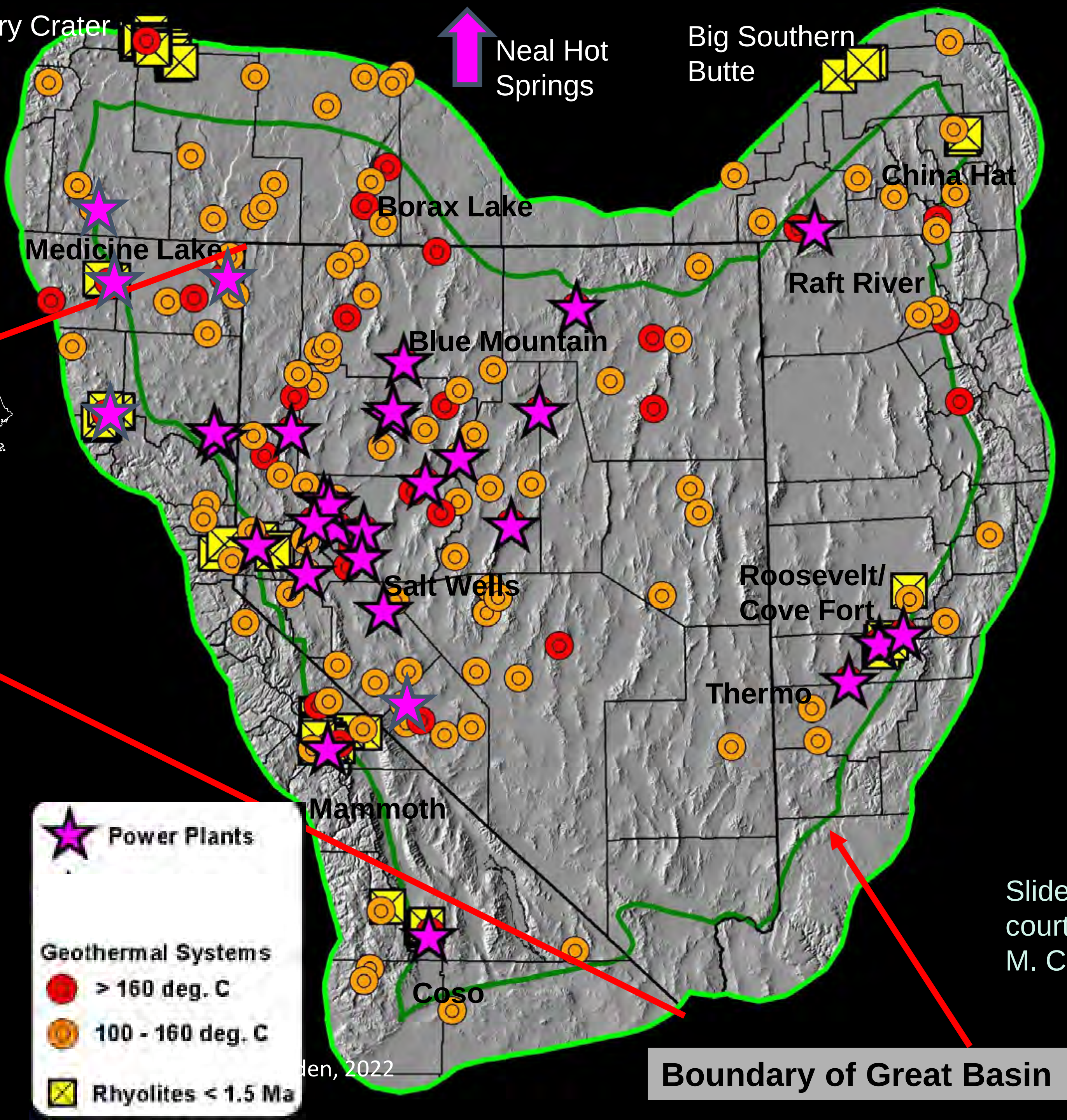
- Crust is being stretched and thinned
  - Results in high heat flow
  - Hot rocks of mantle are closer to surface
- As crust is stretched, rocks break to make fractures (faults)
  - Allows for deep circulation of fluids and conduits of good permeability



Geothermal Systems in Nevada & Great Basin, USA



2021 GB Geothermal Power Plant Capacity is ~1300 MWe
NV = 825 MWe for 26 power plants
NVnet = ~700MWe



Slide courtesy of M. Coolbaugh

Exciting Emerging Pursuits

- Generating Artificial Geothermal Reservoirs (Engineered Geothermal Systems or EGS)
- Developing Hot Sedimentary Aquifers
- Harnessing Superhot/Supercritical Geothermal Reservoirs
- Using Supercritical CO_2
- Applying Closed-Loop Technology
- Recovering Li From Geothermal Brines

Engineered Geothermal Systems (EGS)

- Artificially generated convecting hydrothermal system. How?
  - By injecting water deep underground (3-5 km)
  - By improving permeability via thermal shocking (cold water into hot rock)
    - Unlike hydrofracking used for oil and gas extraction, fluid injected under relatively low pressure (hydroshearing)
    - Fracture permeability achieved in stages via zonal isolation to maximize size of engineered reservoir
- Upside:
  - Have the potential to increase current geothermal power output by 1 to 2 orders of magnitude (10x to 100x) (Tester et al., 2006). Why?
    - Hot rock is much more widely distributed than hot rock with circulating water (currently developed conventional systems)
    - Much less restricted to specific geological favorable regions, such as along and near plate tectonic boundaries
  - Significant reduction in CO_2 emissions by displacing fossil-fuel-fired power plants by making geothermal power more widespread than currently

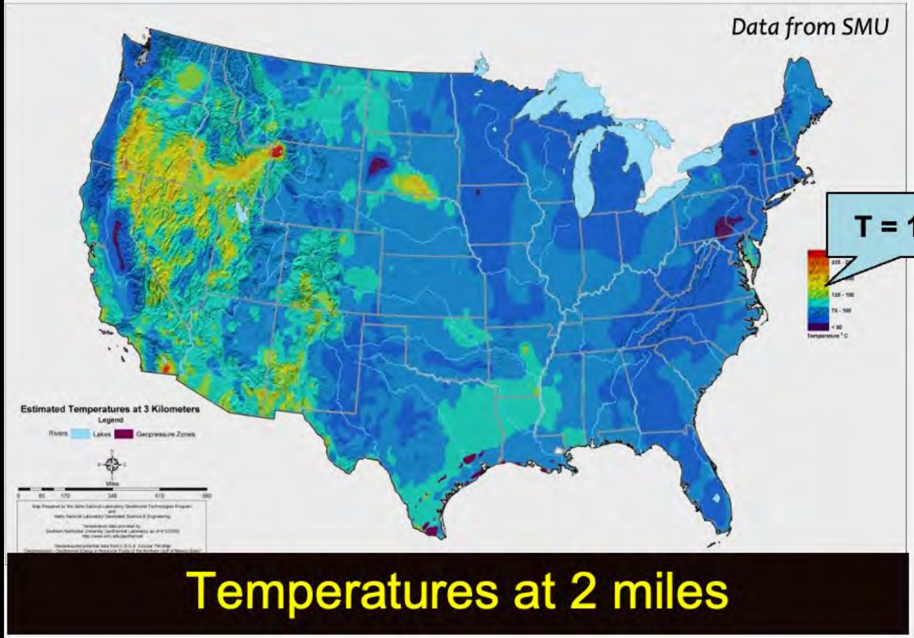
Engineered Geothermal Systems (EGS)

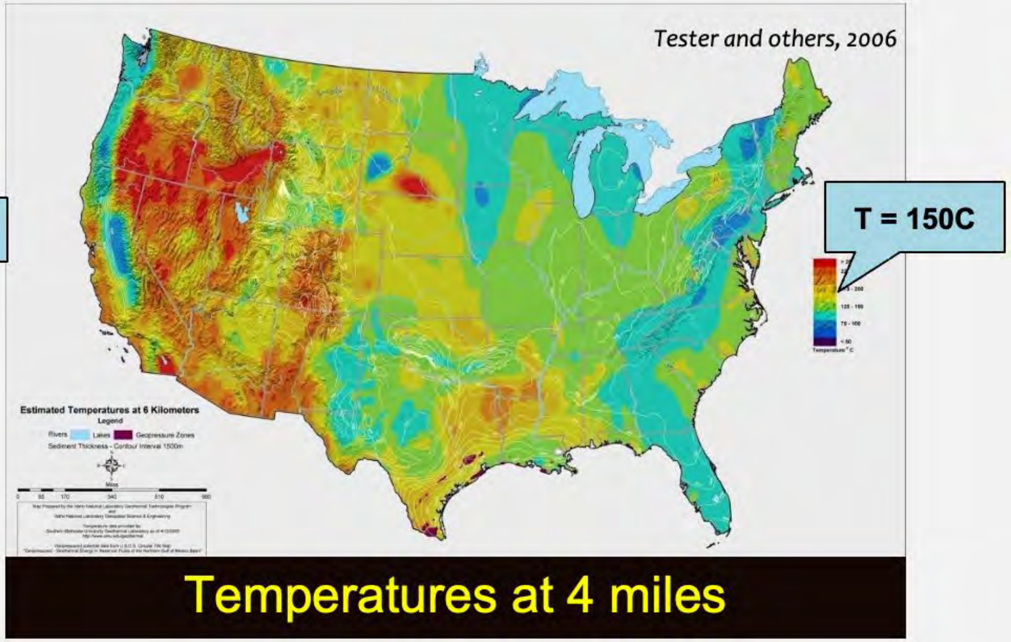
- Challenges:
  - Financial: must drill deeper with deep horizontal legs which is expensive
  - Engineering: Artificially develop a permeable reservoir where water can flow and pick up heat to fuel a power plant
  - Water: Available source of water as significant amount of injected water can be lost into the rock formations and no longer available for recirculation
  - Potential Induced Seismicity: Injecting cold water causes rock to fracture (good for permeability) but can create small earthquakes on surface

EGS Resource Base

EGS systems lack permeability for natural convection

USGS Estimated Potential in Western States = 518,000 MWe*

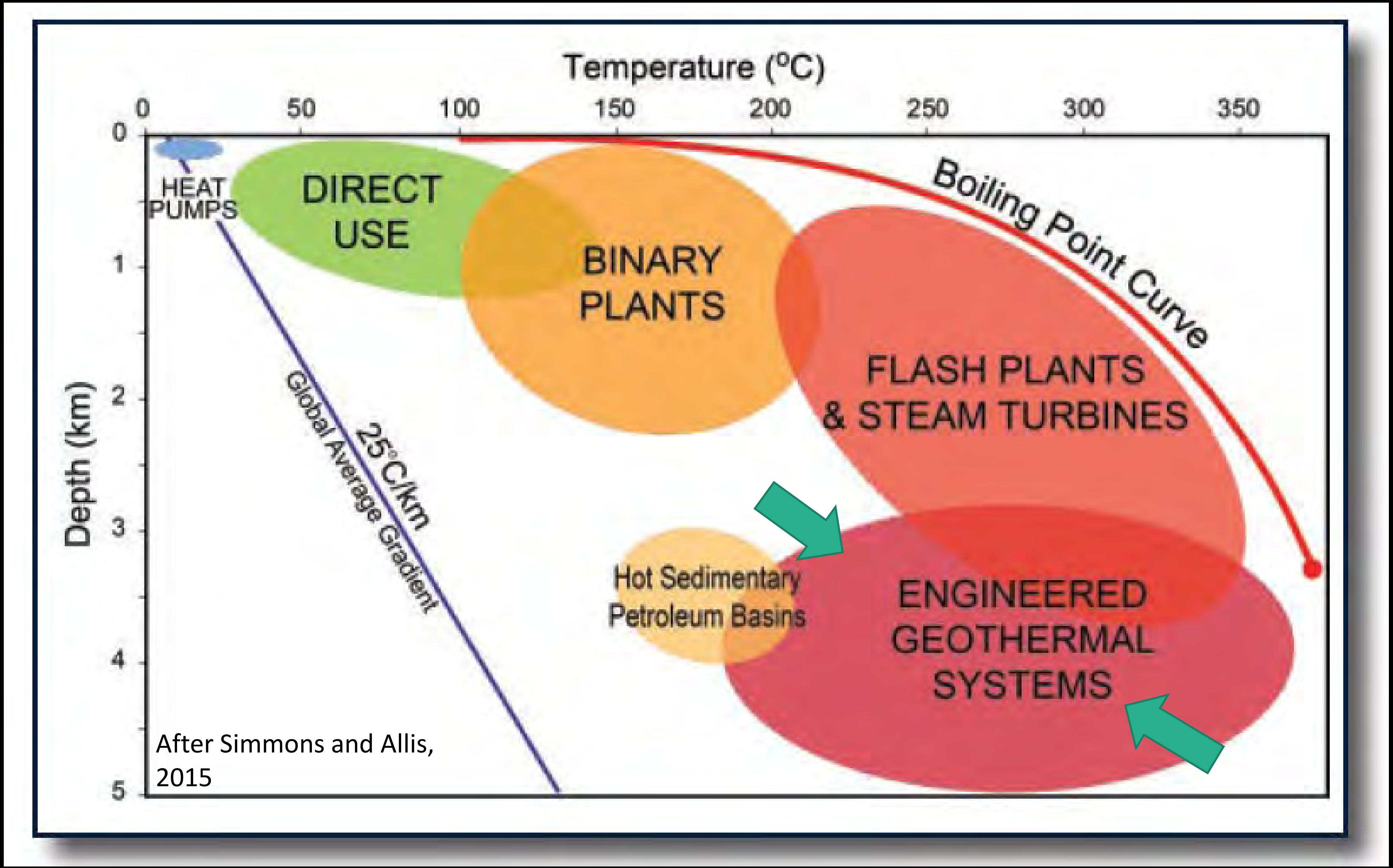




** Probably overly optimistic; 100,000 MWe would be great*

Fig. courtesy of C. Jones and J. Moore, FORGE

EGS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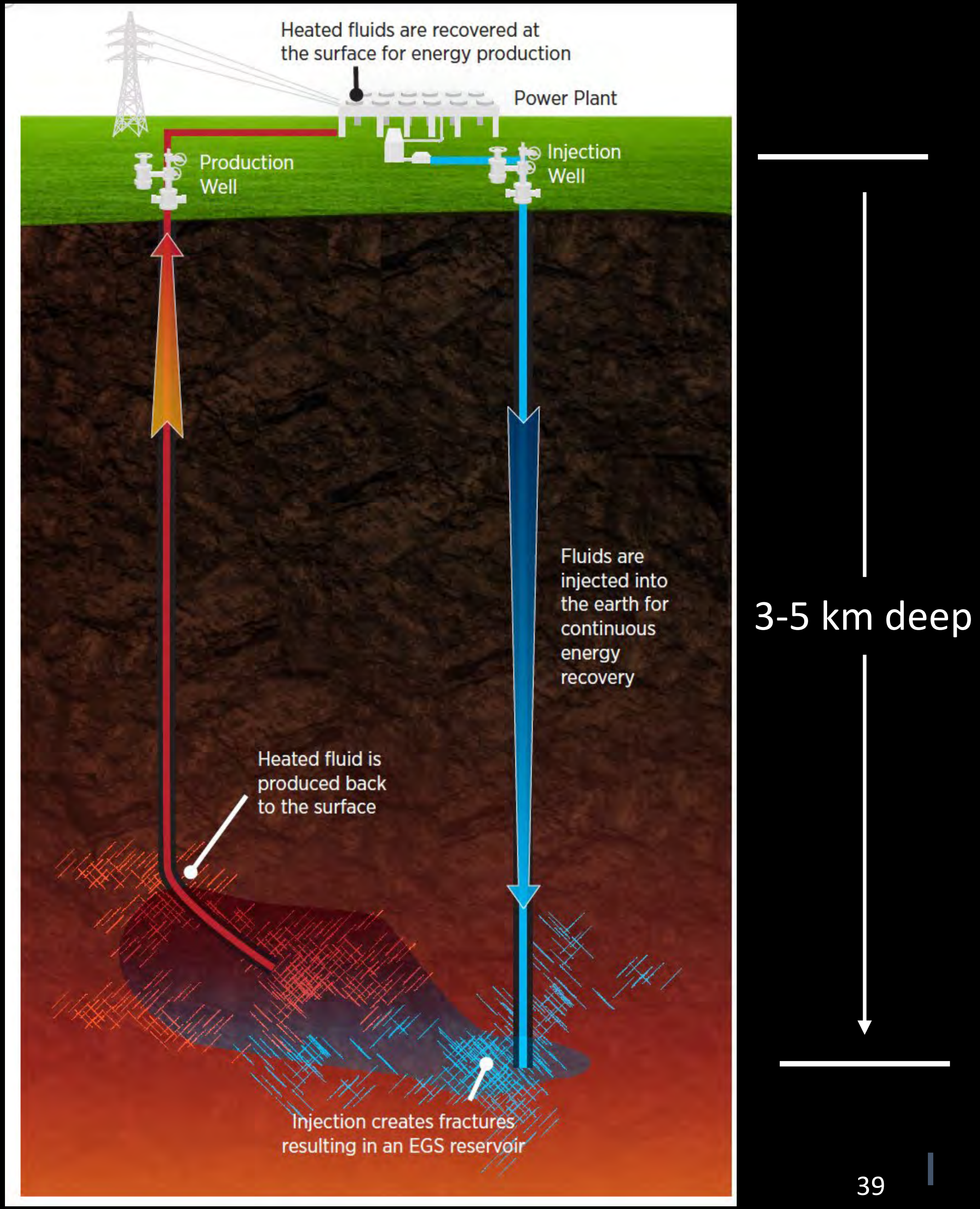
Depth (km)
HEAT PUMPS
DIRECT USE
BINARY PLANTS
Boiling Point Curve
FLASH PLANTS & STEAM TURBINES
Global Average Gradient
25°C/km
Hot Sedimentary Petroleum Basins
ENGINEERED GEOTHERMAL SYSTEMS
After Simmons and Allis, 2015

EGS—Basic Concept



Source: DOE, GeoVision Report, 2019

EGS (DOE-Supported FORGE Venture)

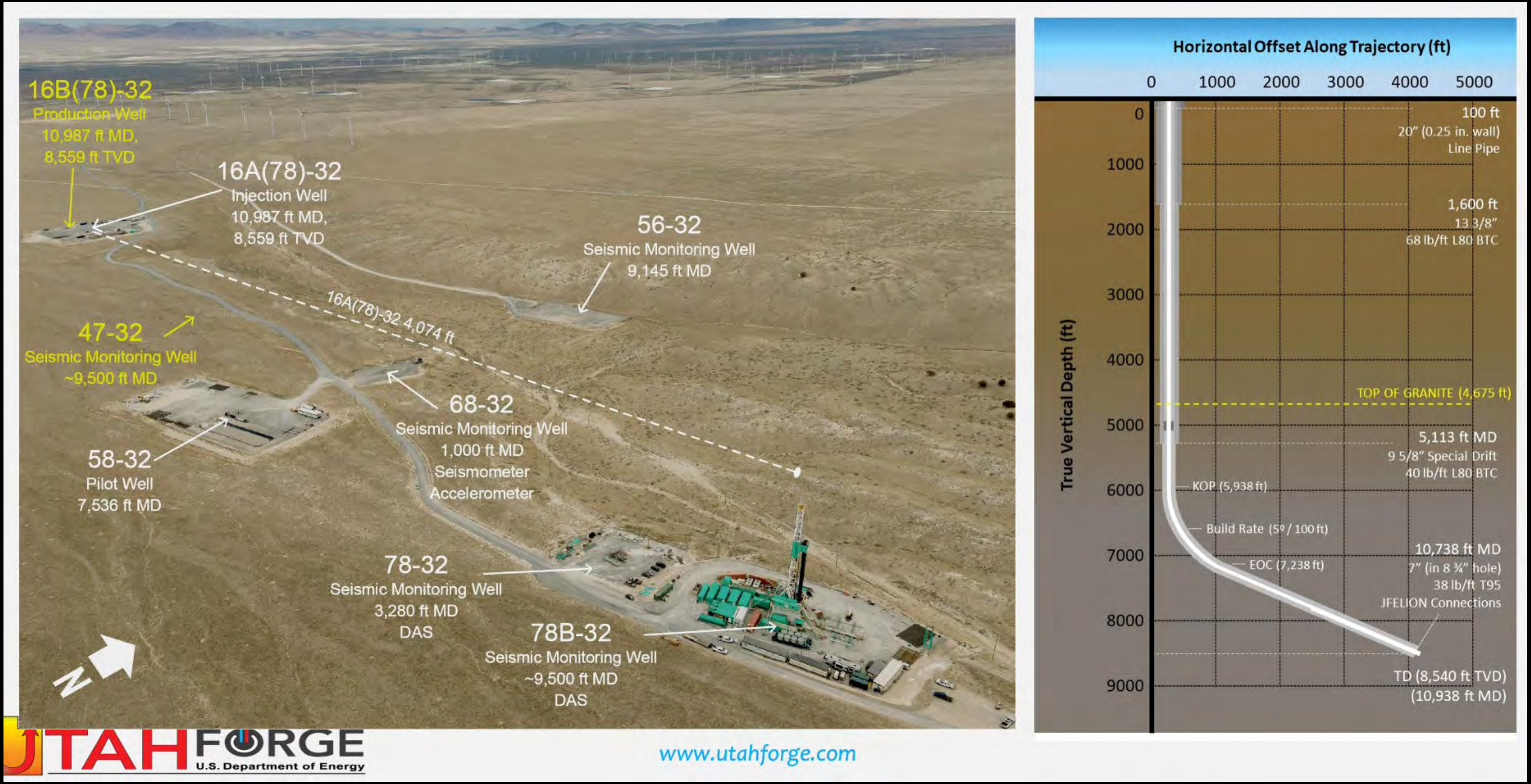


Fig. courtesy of C. Jones and J. Moore, FORGE

EGS (DOE-Supported FORGE Venture)

Injection well shown in blue; production well shown in red. Physical separation of two wells in reservoir ~150 m.

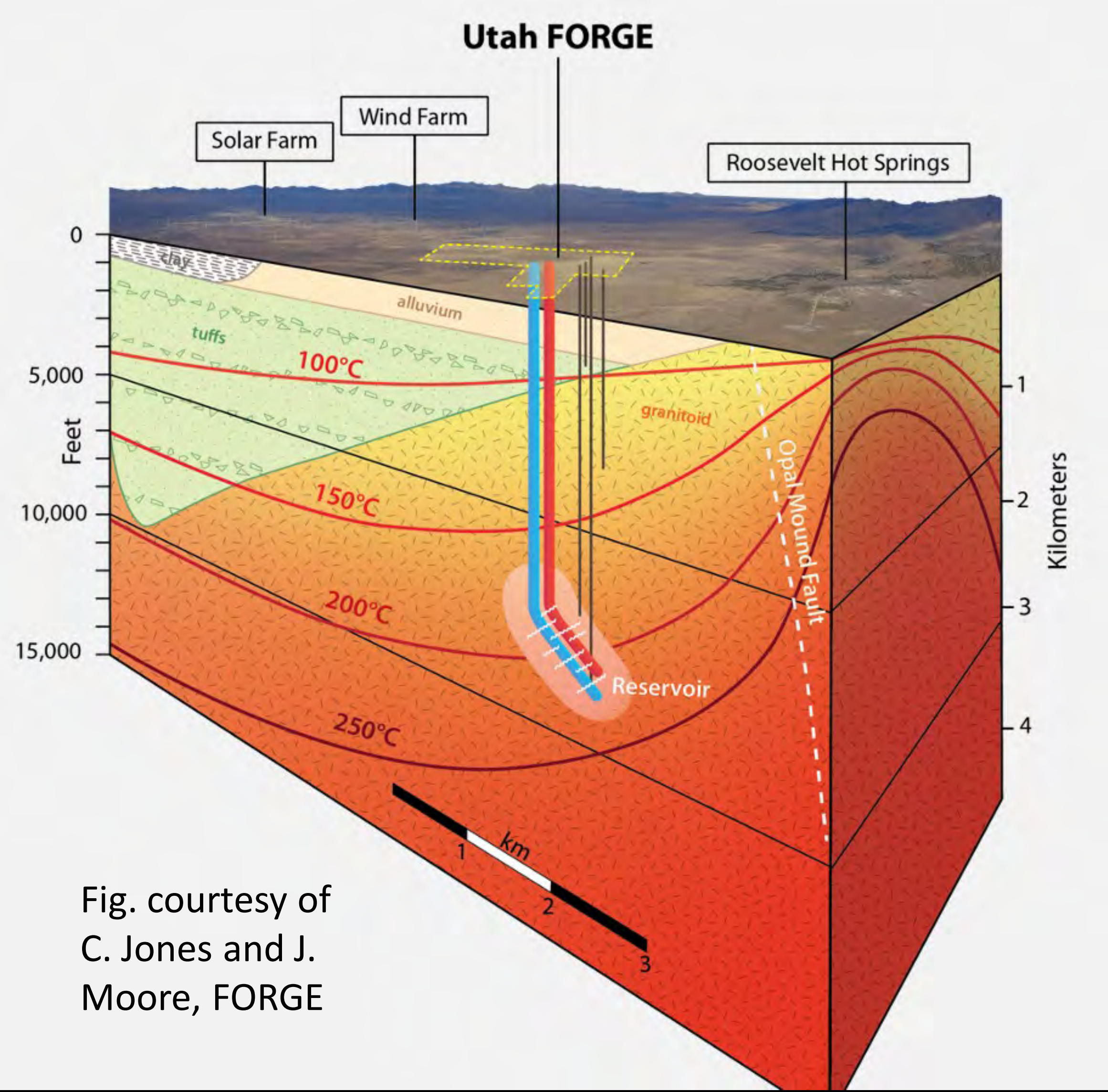


Fig. courtesy of C. Jones and J. Moore, FORGE

Hot Sedimentary Aquifers

- Deep (3-4 km) rock layers having good permeability
- Occur in areas having elevated heat flow (>90 mW/m^2)
- Have large surface areas of >100 km^2 compared to <10 km^2 of currently producing fault-controlled systems in Nevada
- May serve as a bridge between conventional systems and EGS
- Potential to provide hundreds of MWs of power

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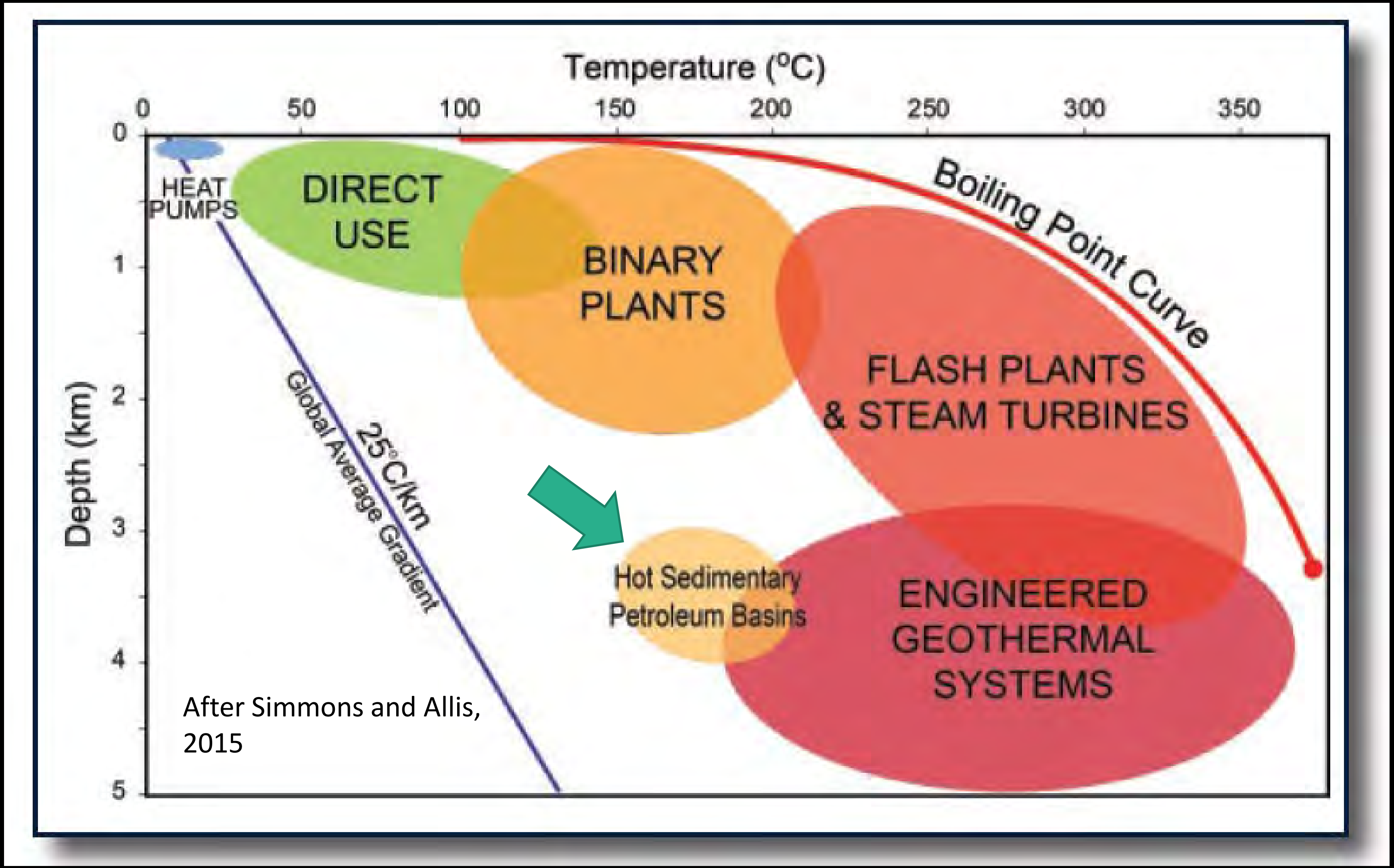
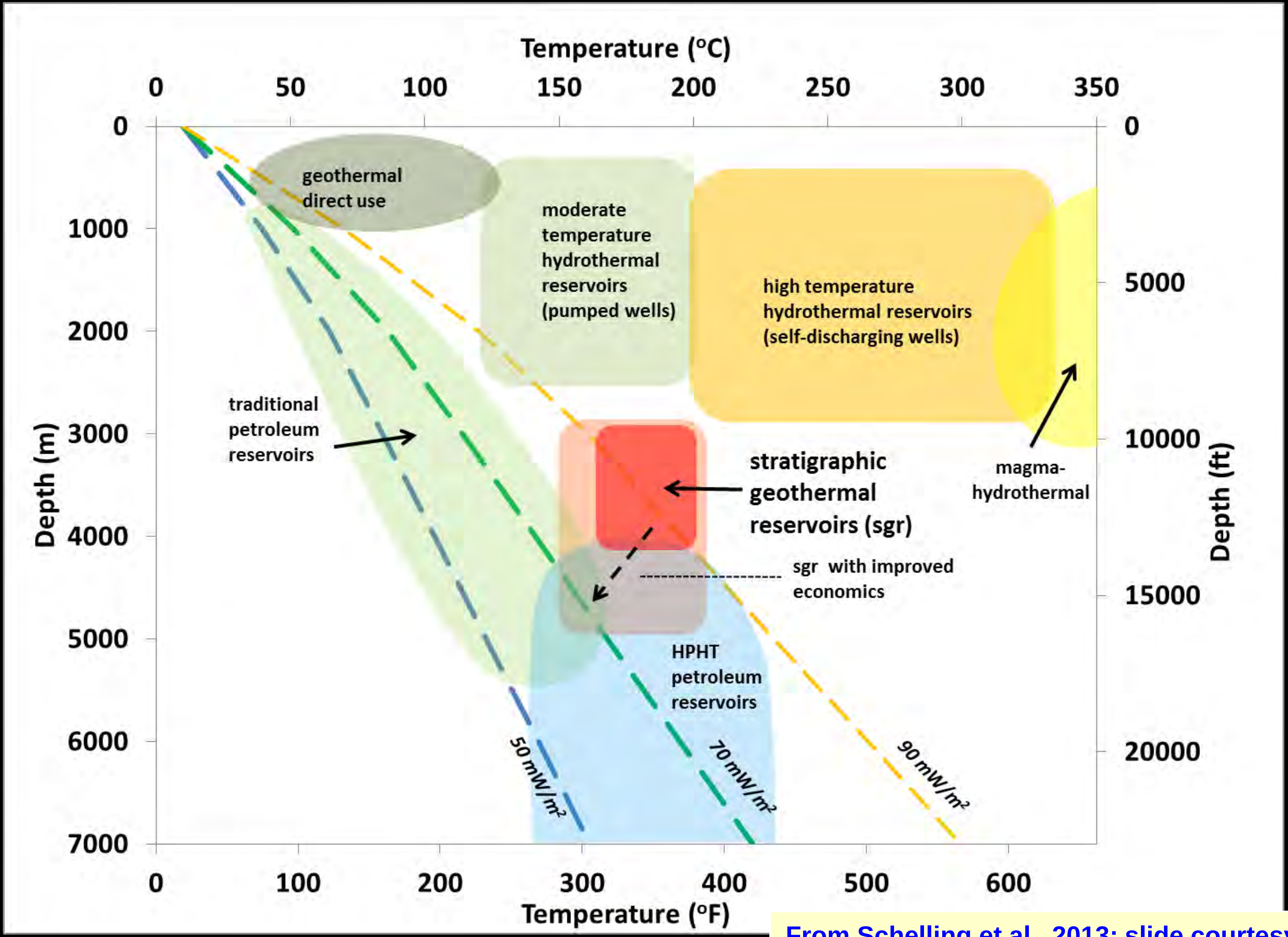
Hot Sedimentary Aquifers



Hot Sedimentary Aquifers

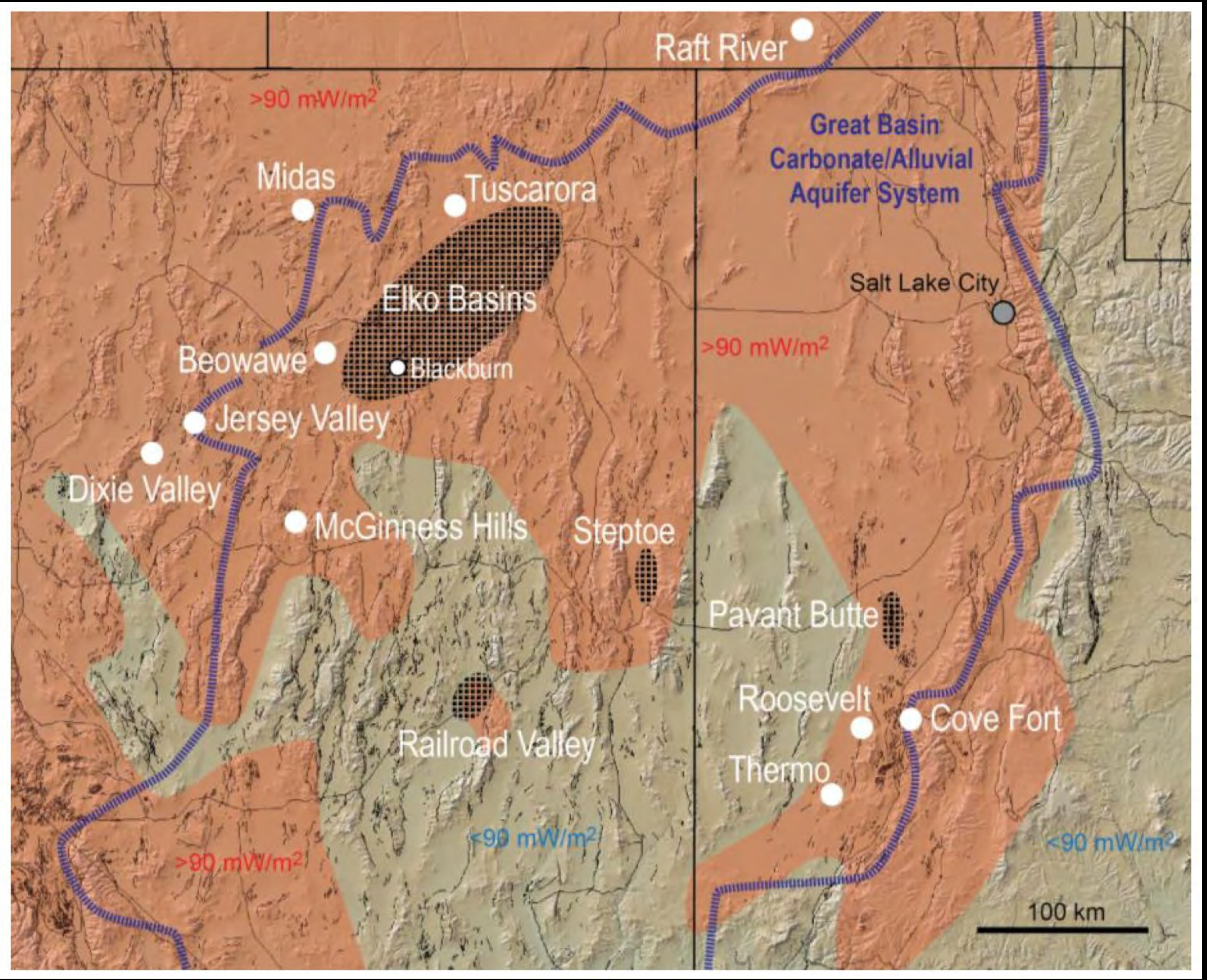
Developing hot stratigraphic geothermal reservoirs is analogous to water flood in secondary oil recovery – except we are sweeping heat, not oil.



From Schelling et al., 2013; slide courtesy Rick Allis

Hot Sedimentary Aquifers

Require permeable sedimentary layers at depths of 3-5 km in regions of elevated heat flow (>90 mW/m^2) to achieve power generation temperatures of 150° to 200°C.



After Simmons et. al., 2017

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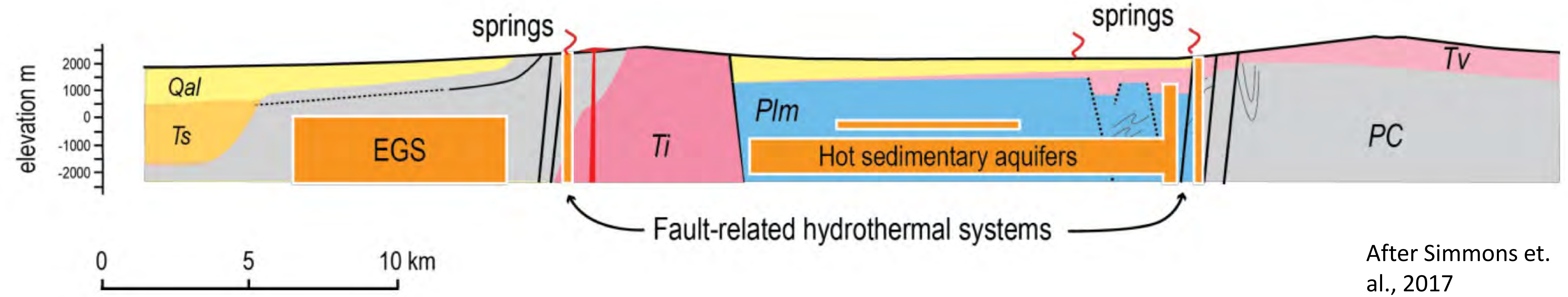
Hot Sedimentary Aquifers

- Schematic Cross Section

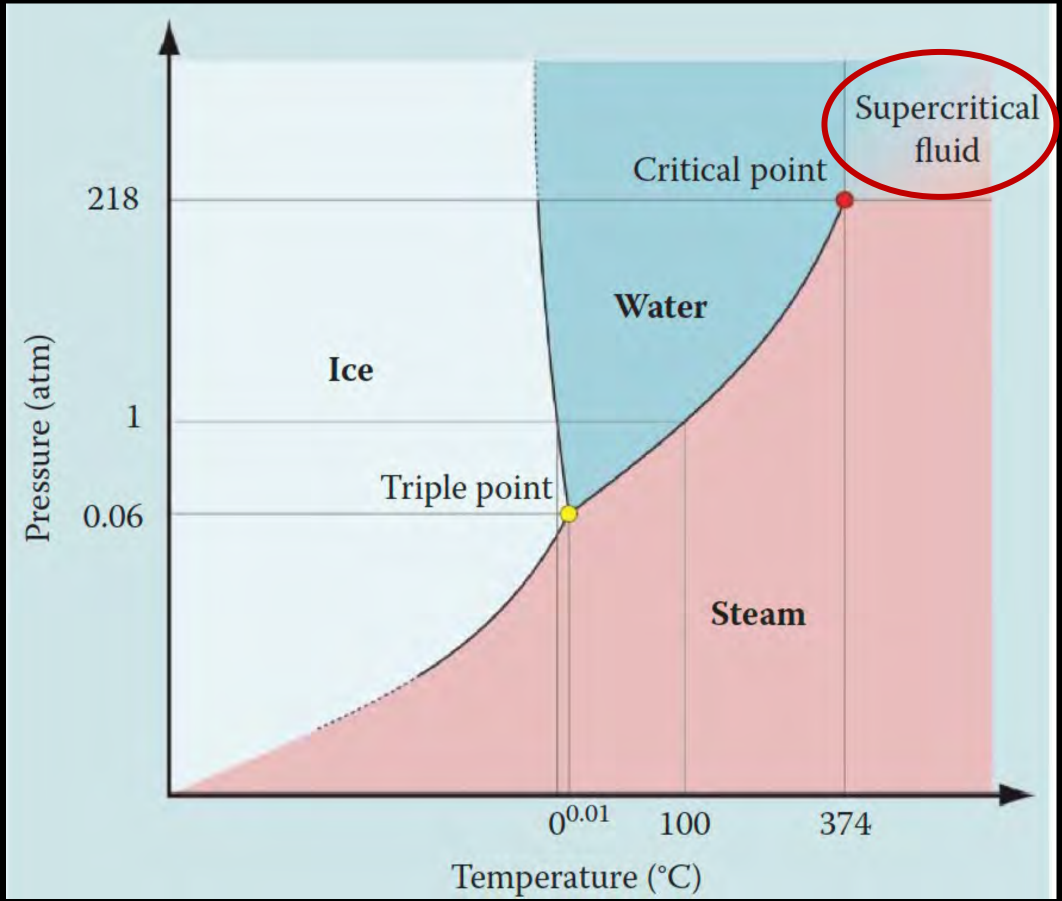


After Simmons et. al., 2017

Note the large surface area of hot sedimentary aquifers compared to fault-related geothermal systems developed by current geothermal power facilities in Nevada

Superhot/Supercritical Geothermal Systems

- Being explored by Iceland Deep Drilling Project (IDDP), Japan Beyond the Brittle Project (JBBP), and Hotter and Deeper Exploration Science (HADES) in New Zealand.
- What is supercritical water?
  - Fluid with properties intermediate between liquid and gas (density of liquid but mobility of gas)
  - Little or no acid problem because T too high (no liquid water) to form reactive H^+
  - Much greater energy (enthalpy) and mass transfer compared to conventional liquid- and vapor-dominated system
  - Well tapping supercritical reservoir would have 5x –10x power output of a conventional well
    - 5 to 10 fold fewer wells needed, saving $30M–$60M



Boden, 2022

Superhot/Supercritical Geothermal Systems

- What is supercritical water?
  - Pressure-enthalpy (energy) graph
    - Critical point of water at B on graph
    - Green region denotes two-phase condition of liquid and steam
    - Ideal path is from F→G where fluid becomes subcritical but stays superheated (no liquid)
  - Implications
    - Little or no acid problem because T too high (no liquid water) to form reactive H^+
    - Much greater energy (enthalpy) and mass transfer compared to conventional liquid- and vapor-dominated system
    - Well tapping supercritical reservoir would have 5x –10x power output of a conventional well
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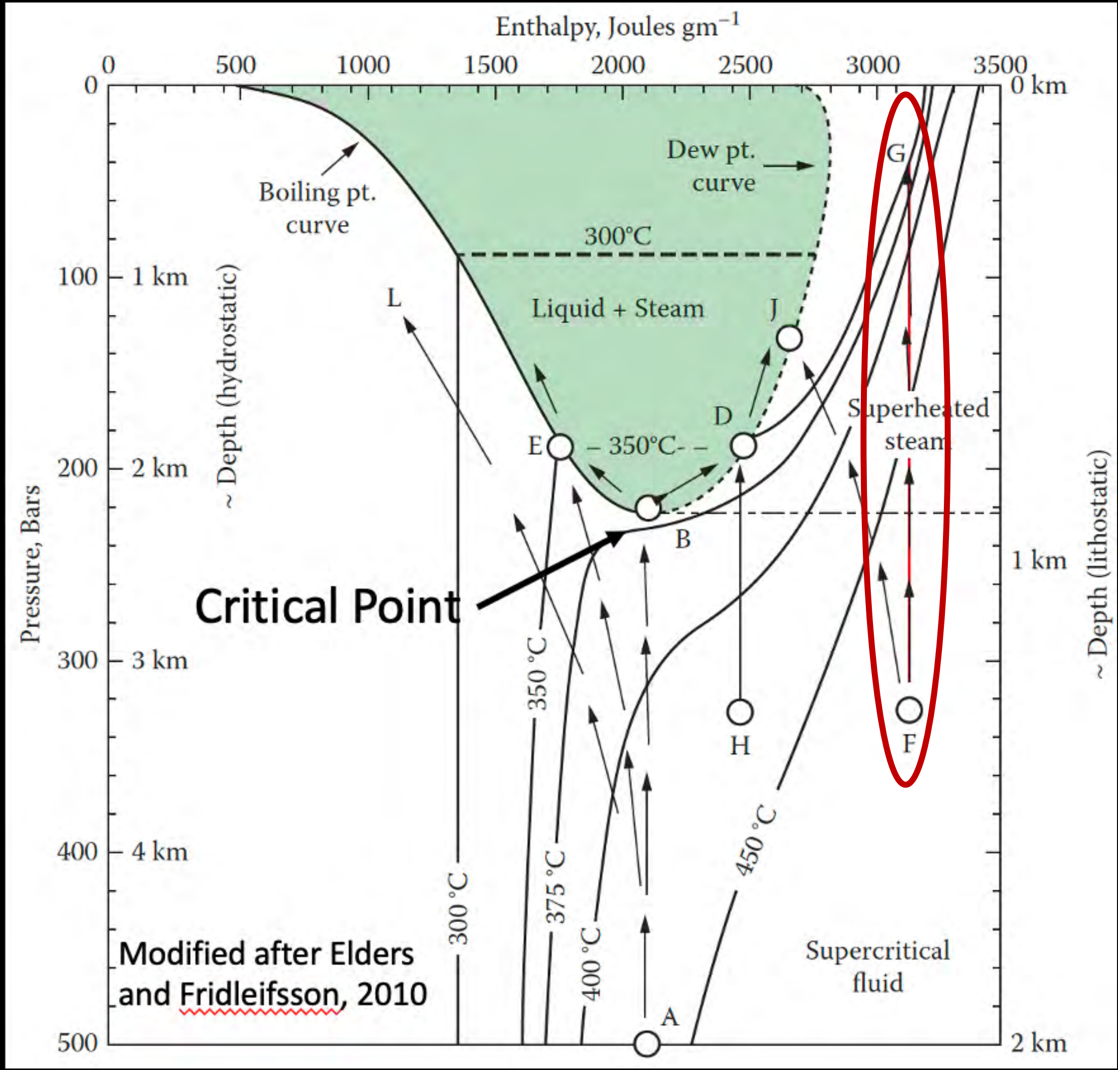

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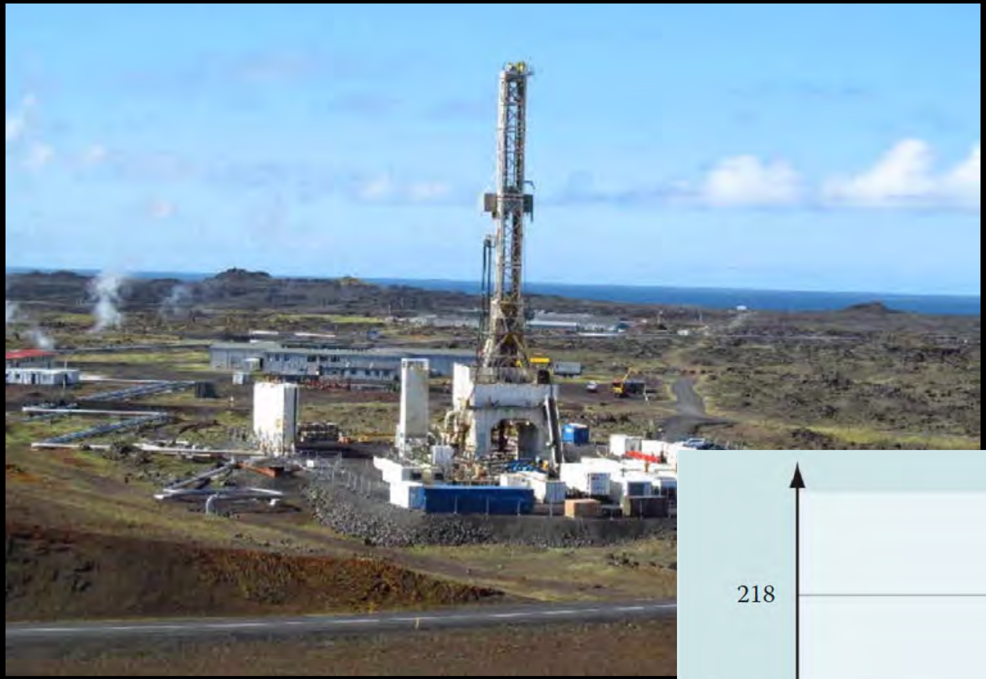
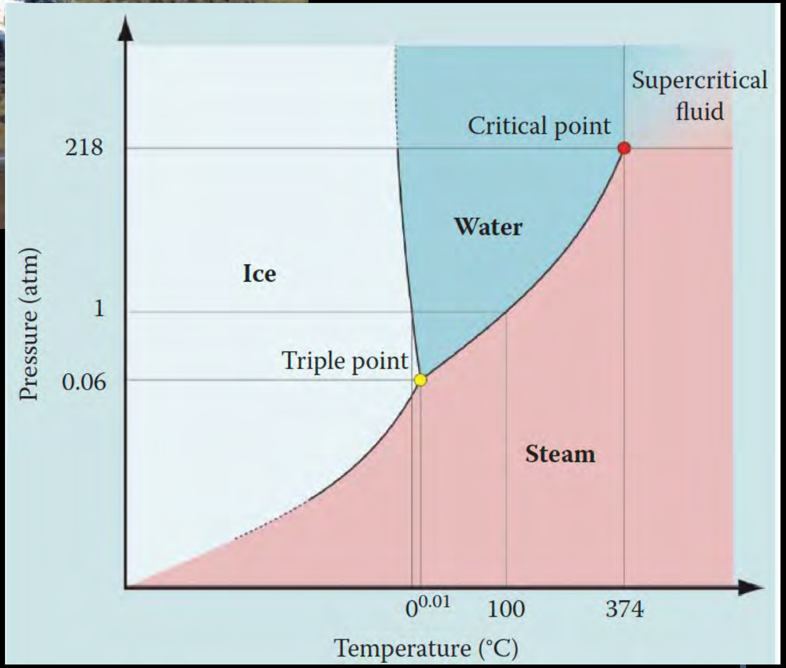
Superhot/Supercritical Geothermal Systems

- IDDP-2
  - Drilled well to 4.6 km deep
  - Bottom hole T of 427°C
  - Pressure = 340 bars (337 atm)
  - Did well intersect supercritical conditions?
  - Future uncertain as permeability limited at bottom of well





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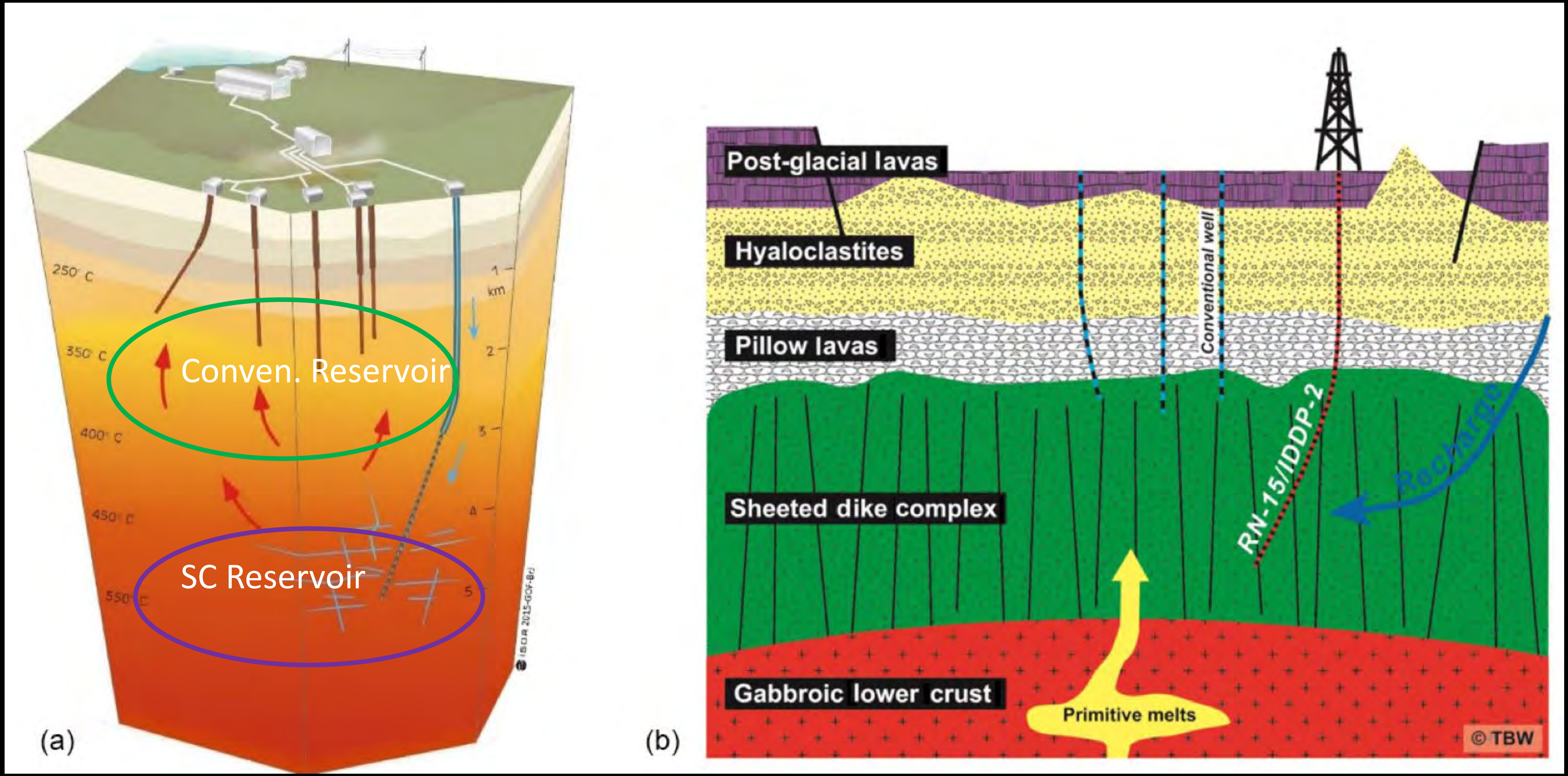
Superhot/Supercritical Geothermal Systems

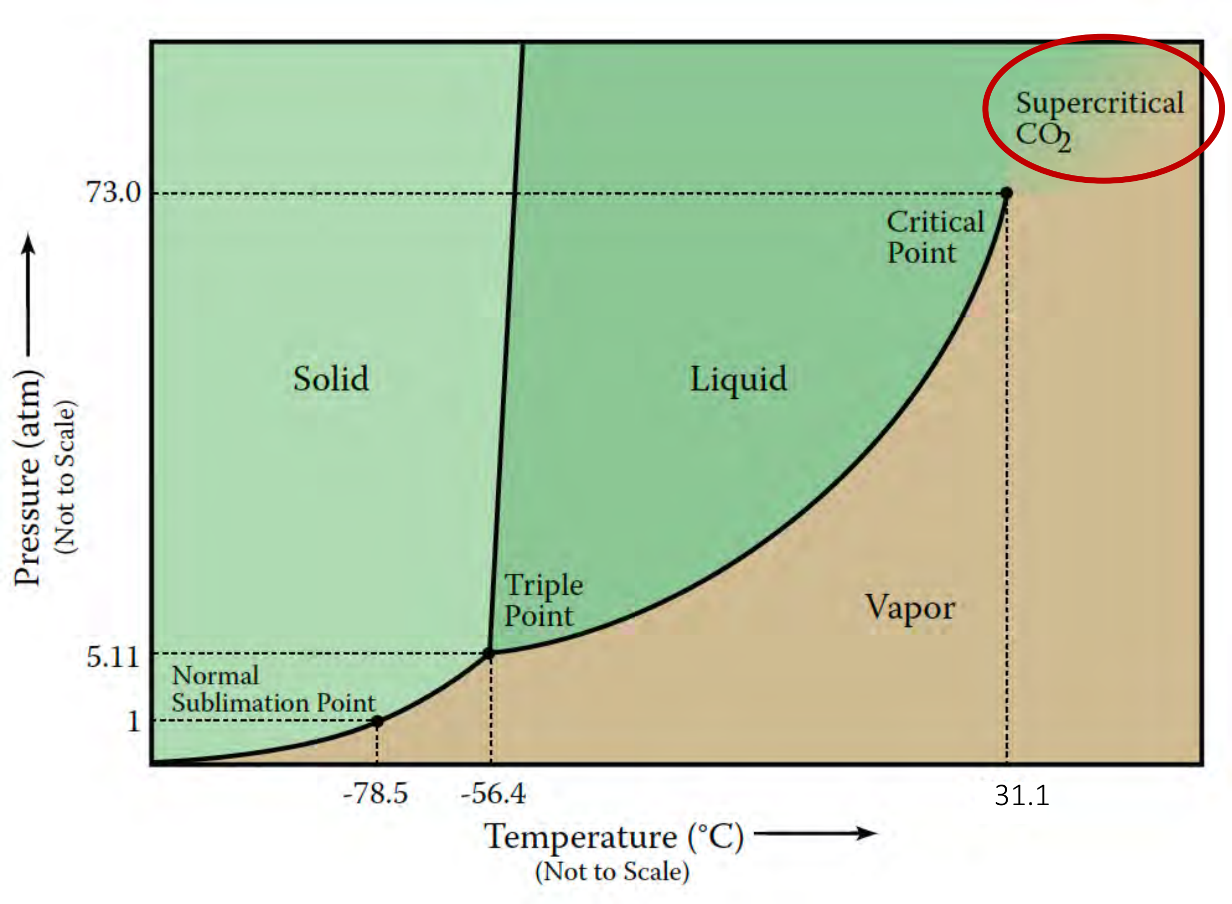
- IDDP-2



Modified after Fridleifson et al., 2017

Using Supercritical CO_2 ($ScCO_2$)

- Advantages:
  - 3x–5x higher mass flow rates than water
  - Large density contrast between cold and hot $ScCO_2$ means strong buoyant forces reducing power consumption for pumping
  - Can help sequester CO_2 produced from fossil-fuel fired power plants
  - Little or no scaling or corrosion of equipment as $ScCO_2$ is not an ionic compound
- Challenges:
  - Getting CO_2 from power plants or extraction from air is expensive
  - Unknown reactions with wallrocks at depth that could precipitate carbonate minerals reducing permeability



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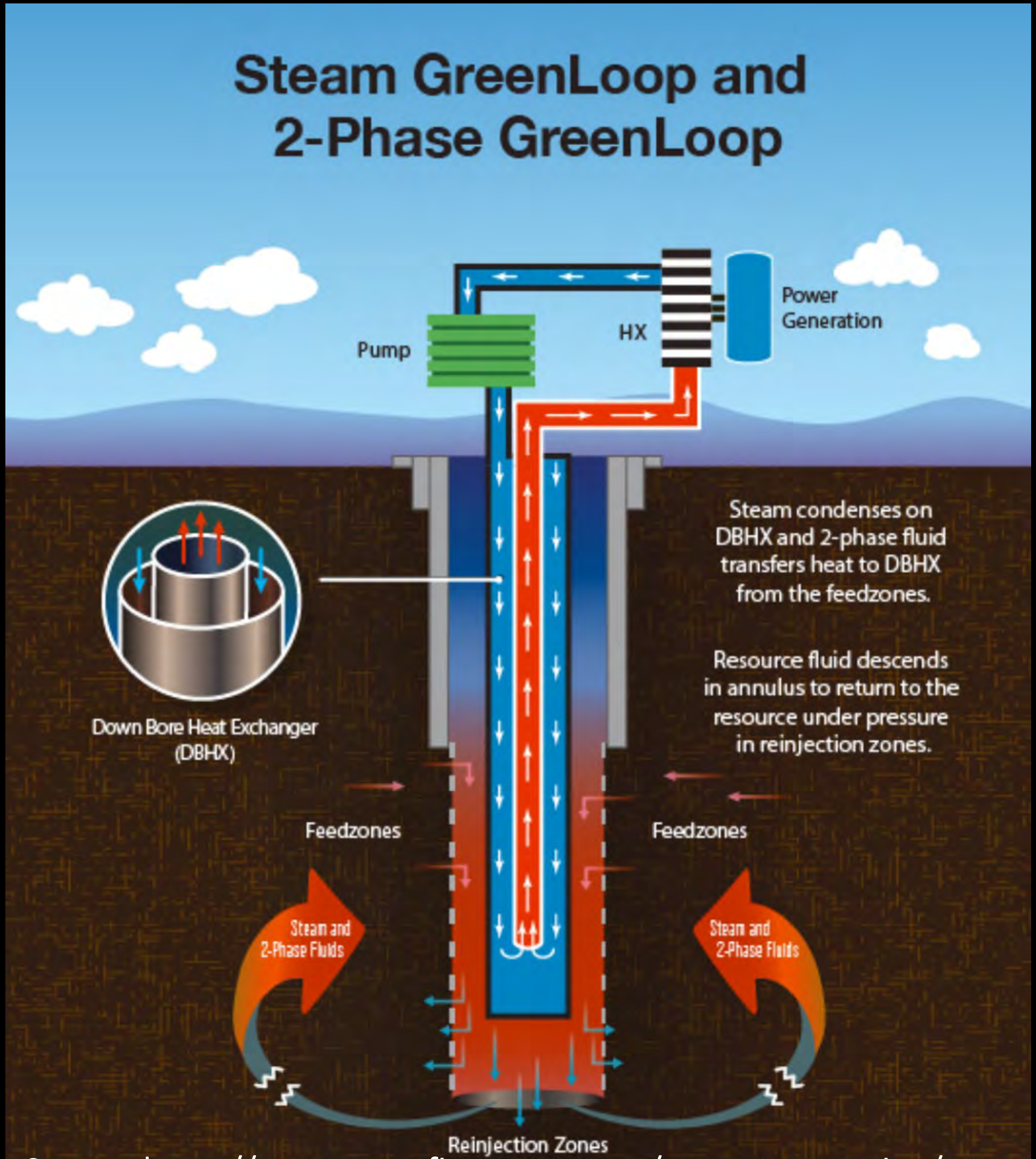
Closed-Loop Technology

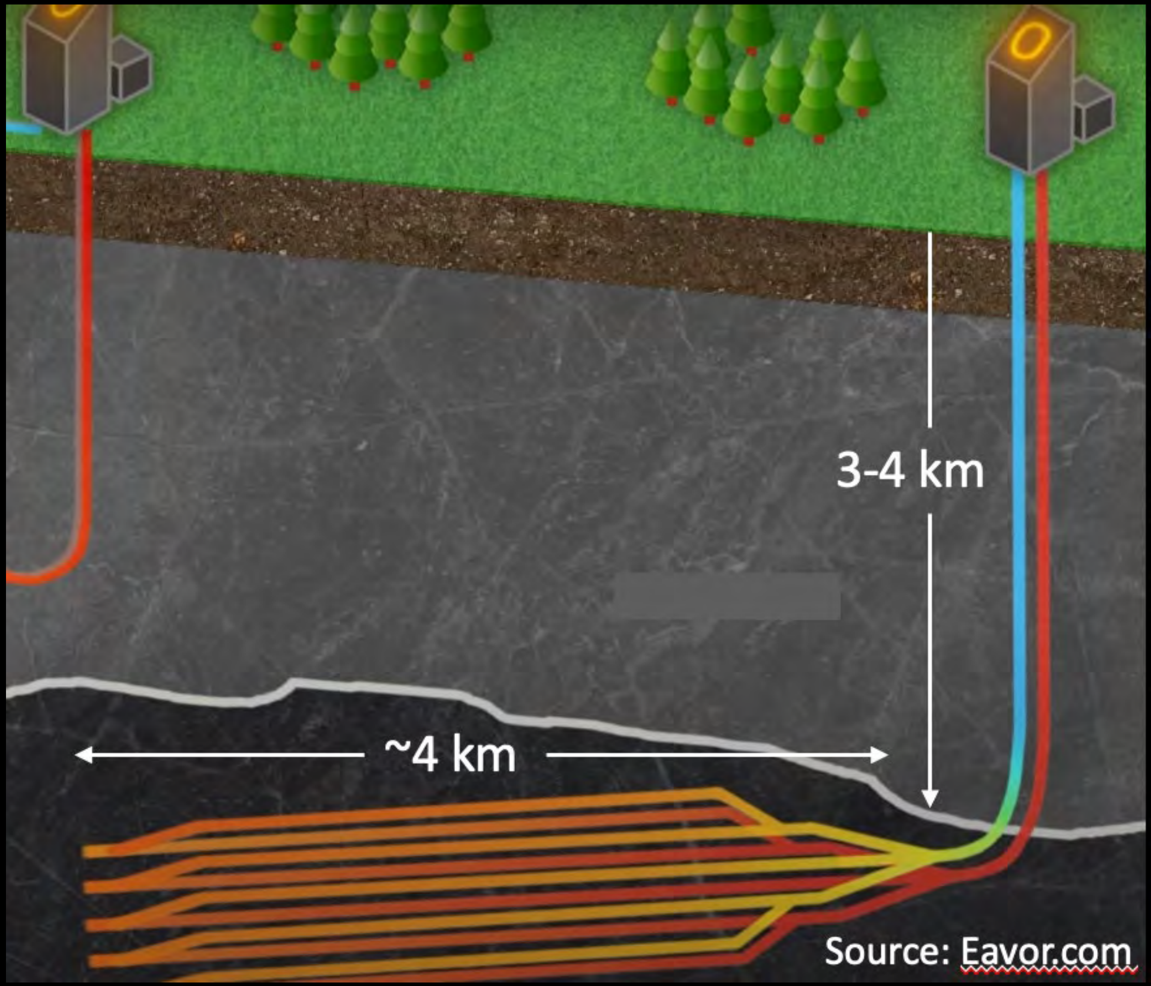
- Two different configurations being explored:
  - Modify existing nonproductive wells (GreenFire's GreenLoop technology)
  - Drill deep well with multiple laterals at depth to extract heat (Eavor technology)
- GreenLoop Technology
  - Utilizes down borehole heat exchanger
  - Induces convection outside of borehole
  - Steam condenses on outside of borehole transferring additional heat to injected fluid from that provided by conduction



Source: https://www.greenfireenergy.com/power-generation/

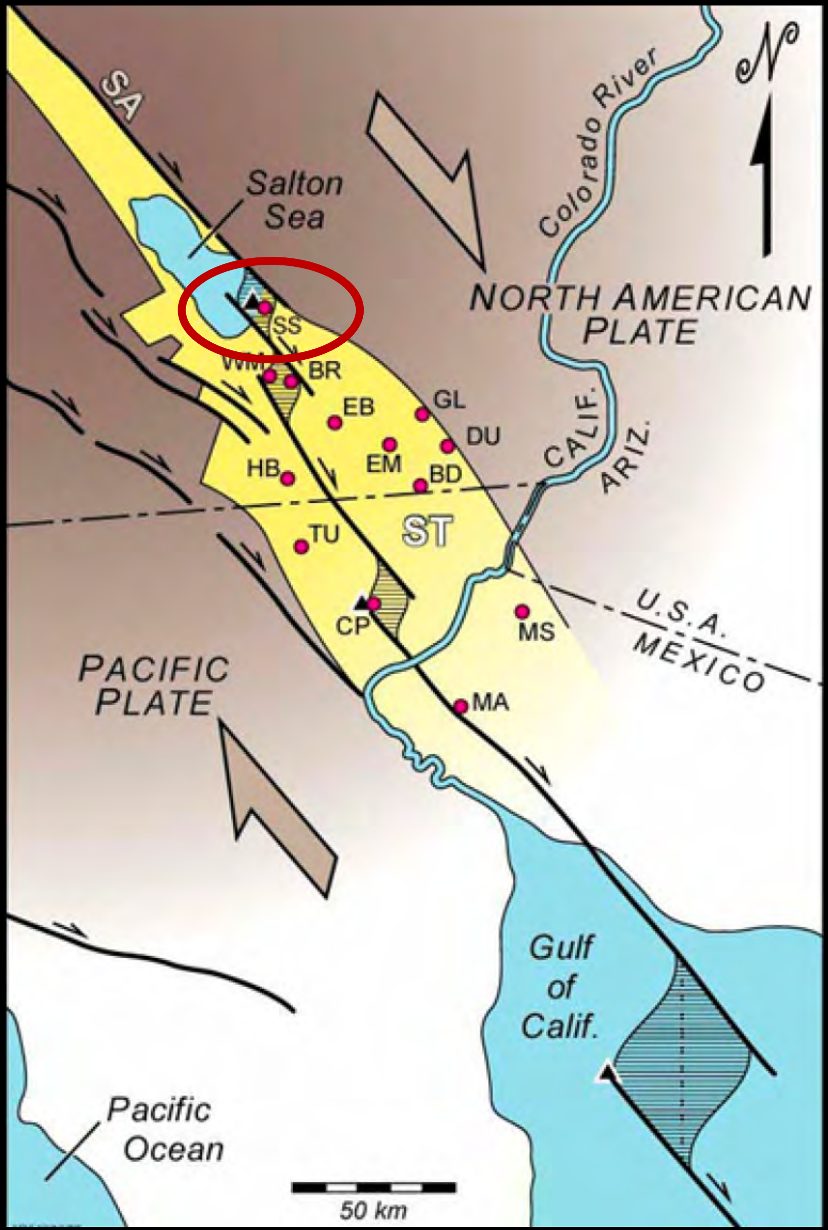
Closed-Loop Technology

- Deep Lateral Wells Configuration (Eavor Technology)
  - A fluid with a low boiling point is injected into a series of piping laterals at depth where it picks up heat to return to the surface to fuel a power plant and then reinjected
- Potential Advantages:
  - Can be applied anywhere (scalable)
  - No need to find zones of natural permeability
  - No need to artificially induce permeability via rock fracturing (EGS)
  - Avoids potential problems of producing from geothermal fluids (scaling and corrosion of equipment)
  - No added or make-up water needed
- Potential Challenges:
  - Cooling of working fluid with time (conduction v. convection)
  - Initial high cost due to technologically advanced drilling technology (deep lateral well configuration)



Li From Geothermal Brines

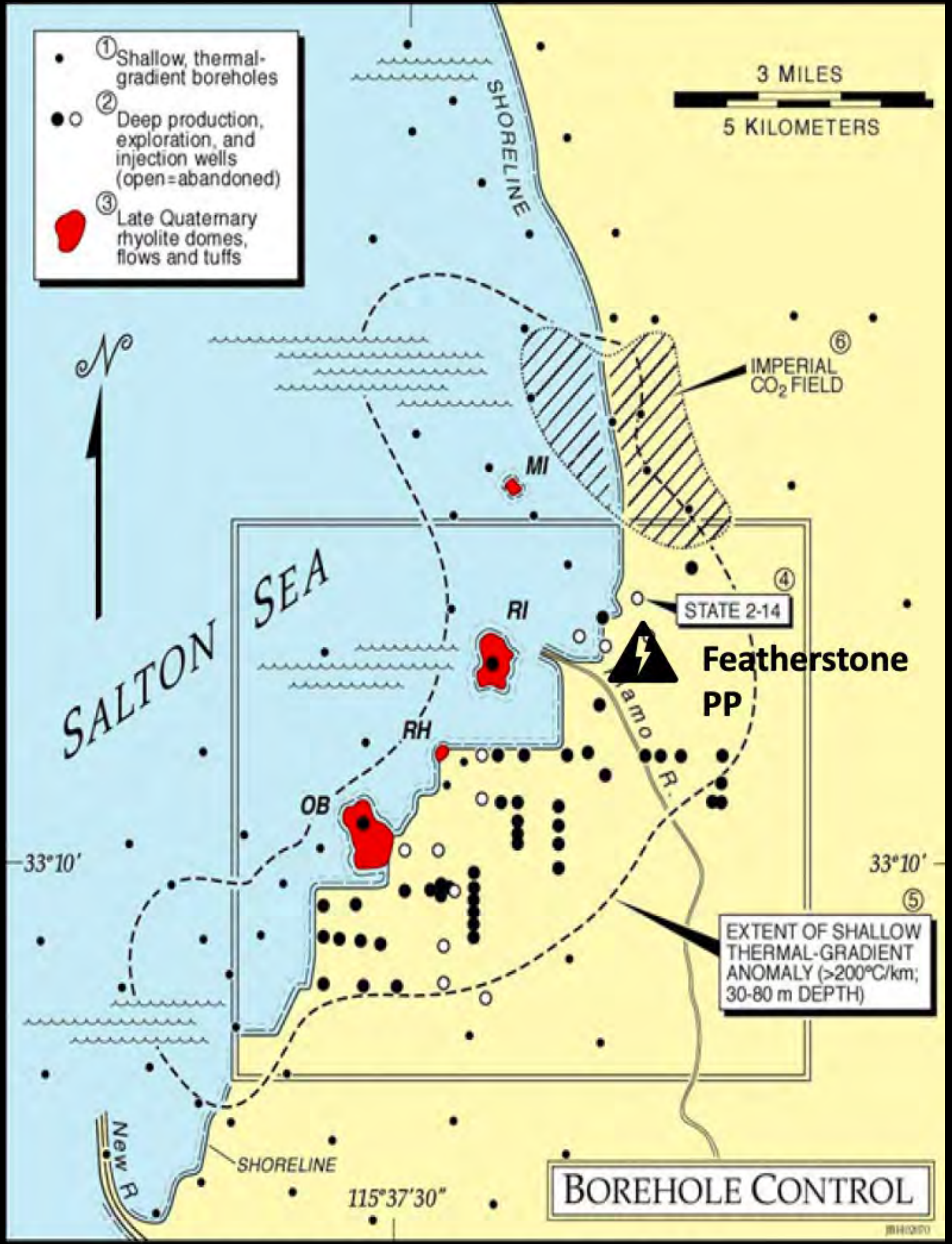
- Salton Sea geothermal field in SE CA has an installed geothermal power capacity of about 440 MW from 11 power stations
- Geothermal brines contain 250,000–300,000 ppm TDS
  - Enriched in Mn, Zn, and Li
  - Li concentration as high as 400 ppm; ave. 250–300 ppm



Modified after Hulen et al, 2002

Li From Geothermal Brines

- EnergySource 55 MW Featherstone Plant
  - Produces about 480,000 MWh/yr electrical energy
  - Gross annual power revenue \$40M–\$45M
  - Developing Li recovery plant to yield a planned 20,000 tons of LiOH/yr planned to begin operating in 2024
  - Current price of LiOH has skyrocketed to \$50k/ton→gross revenue \$1B!
    - A 100 kWh Tesla battery requires the Li content held in 50kg of LiOH → Above production of LiOH could make 360,000 Tesla batteries/yr



Modified after Hulen et al, 2002

Li From Geothermal Brines

- Salton Sea geothermal field has a resource potential of 600,000 tons/year of Li carbonate equivalent (CEC Report, 2020: https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-020.pdf)
  - Enough to make about 18,000,000 100kWh Tesla batteries/yr
  - About 5-10x the planned production of Thacker Pass Li open-pit mine (largest identified minable rock hosted Li-resource in NA)
- Depending on the price of Li carbonate of estimated resource, a potential revenue of $7B to $30B per year could be realized
  - Infusing much needed prosperity for an economically depressed region
  - Dramatically increase domestic production of Li– 90% of which is currently imported from Chile and Argentina (Source: https://www.energy.gov/eere/vehicles/articles/fotw-1225-february-14-2022-2016-2019-over-90-us-lithium-imports-came)

Agenda (Epilogue)

- What is geothermal energy and where does the heat come from?
- How is geothermal energy used?
- How are energy and power related?
- What are some key attributes and challenges for using geothermal energy?
- What criteria are needed to make a geothermal system viable for power generation?
- What makes Nevada attractive for development of geothermal resources?
- What are some exciting new technologies for harnessing geothermal energy?

Image credit:
GeoGlobal
Energy Corp.

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