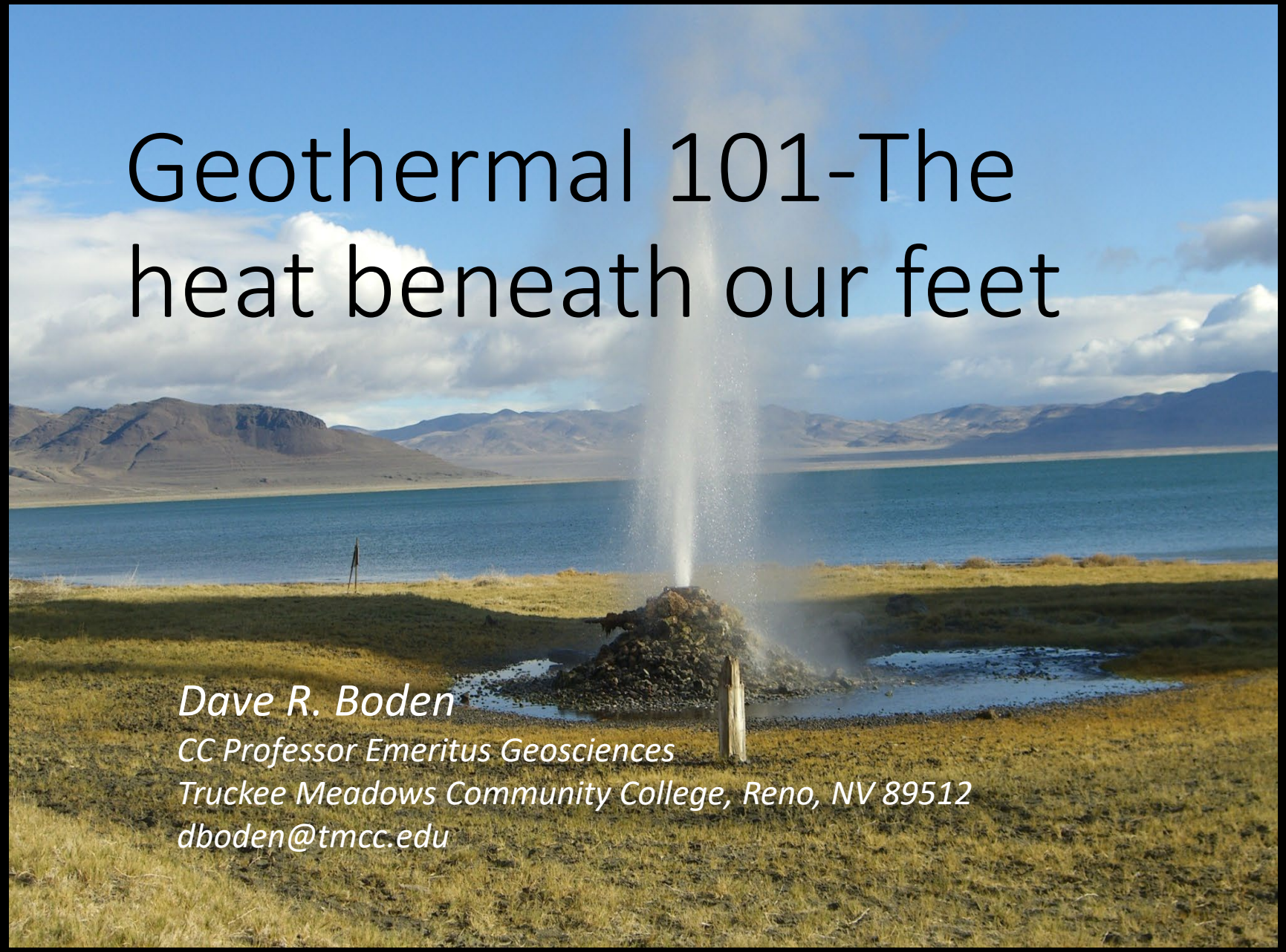

Geothermal 101-The heat beneath our feet

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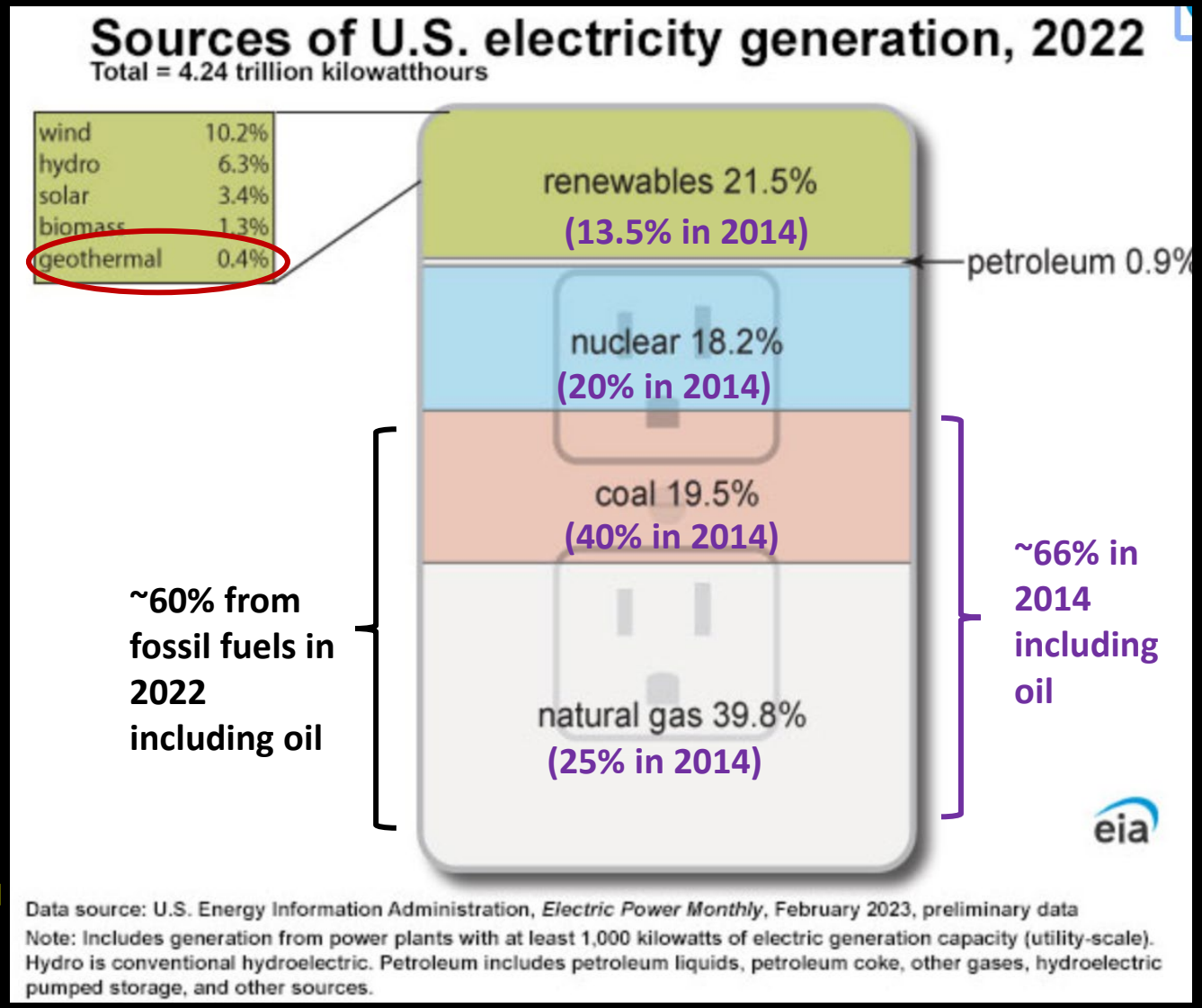
Agenda

- Some background: What are current sources of electricity and how are energy and power related?
- Where does Earth's heat come from for making geothermal energy?
- Where are most geothermal systems found?
- How is geothermal energy used?
- What are some key attributes and challenges of geothermal energy?
- What criteria are needed to make a geothermal system viable for power generation?
- What are some exciting new technologies for expanding availability of geothermal energy and recovery of critical minerals?

Some Background on 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.!)



Measuring Energy and Power

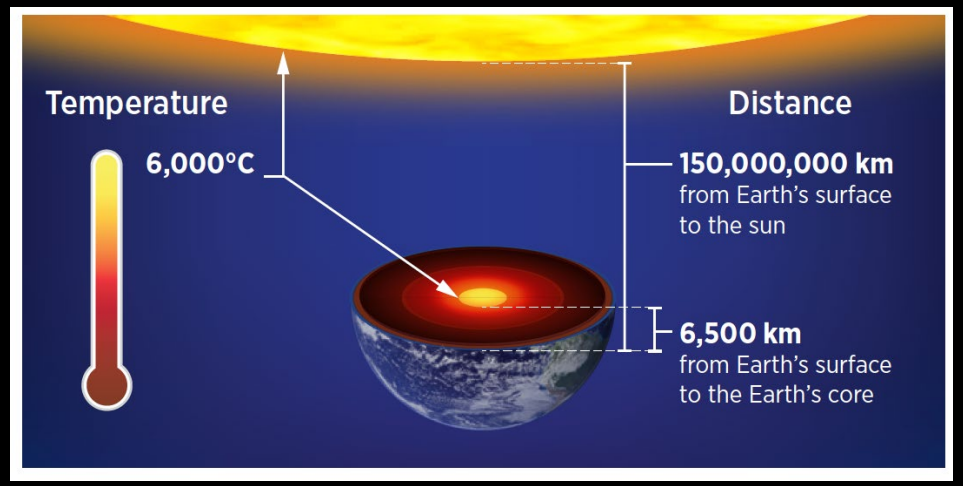
- Basic unit of Energy is Joule; basic unit of Power is Watt
- One Watt of Power = 1 Joule per second (P = E/t)
  - One kiloWatt (1 kW) = 1000 Joules/second; one MegaWatt (1 MW) = one million joules/s
  - MW is typically used in rating delivery of energy output of power plants or rate of energy output 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 in Arizona (3.9 GW x 24 hrs/day = 93.6 GWh of energy per day)

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 3 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?

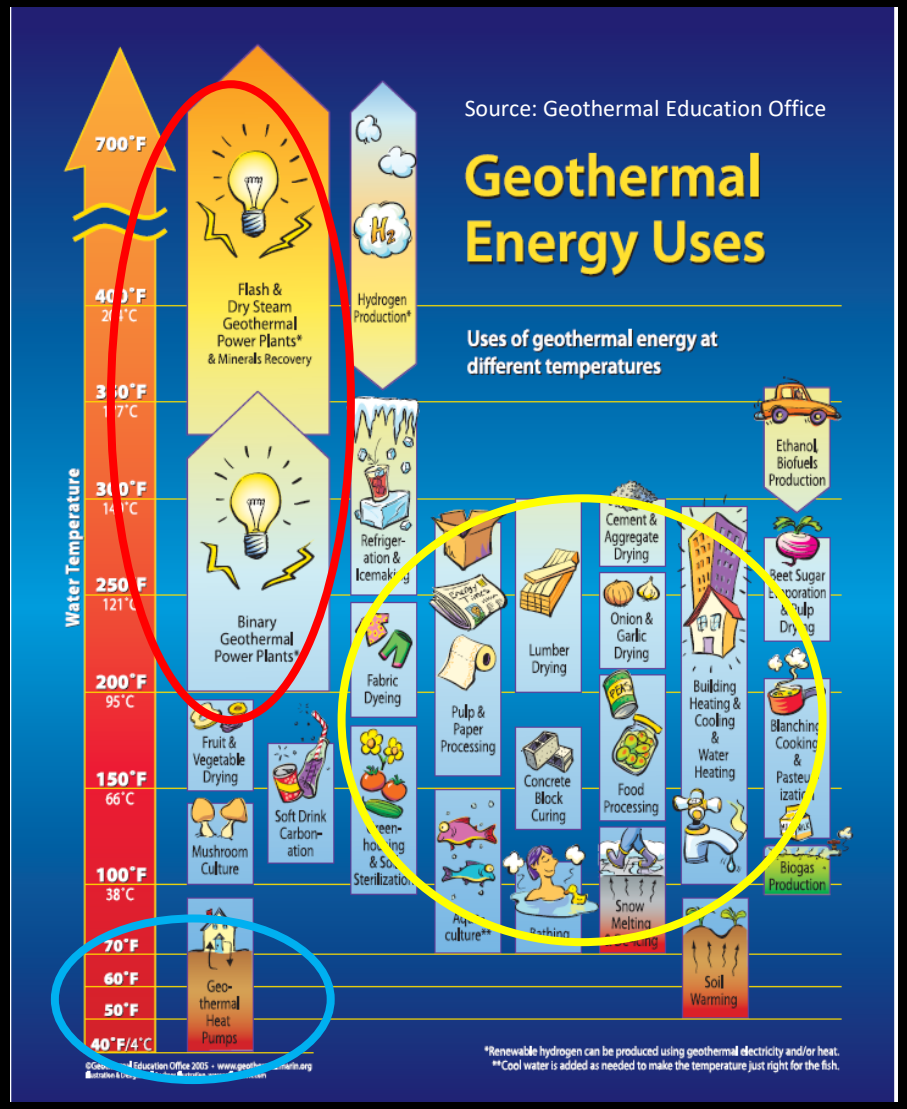
1. Residual heat left over from Earth's formation 4.6 Ga
   - Earth grew from accretion of debris, where kinetic energy was converted to thermal energy
   - Earth's core is about the same temperature as the surface of the Sun (~6000°C)
2. Radioactive decay of U, Th, and K
3. Gravitational pressure



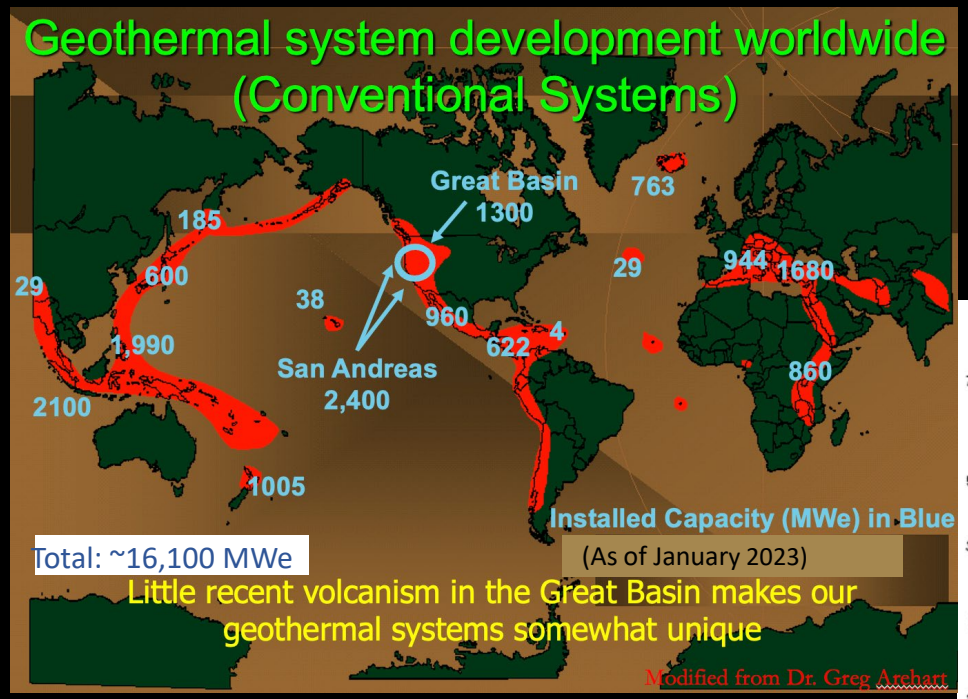
Source: https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf

What is Geothermal Energy?

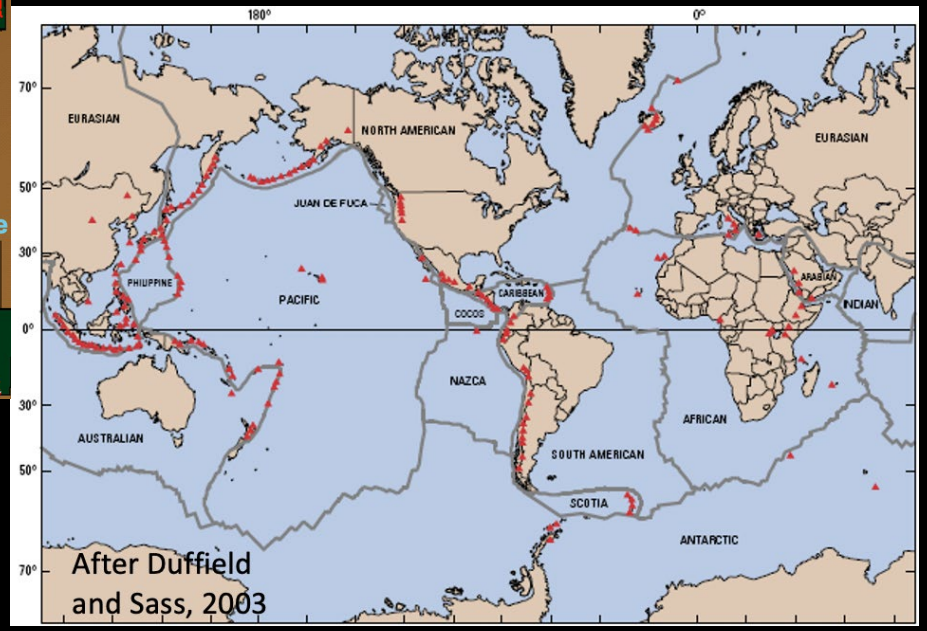
- Harnessing Earth's heat for society
- What are some uses?
  - Produce electrical power (T >~100°C)
  - Direct use of geothermal fluid (T >~40 °C)
    - More energy efficient than power production
    - Heat (cool) buildings and homes
    - Aquaculture (fish hatcheries)
    - Greenhouses and fruit/vegetable drying
    - Spas and resorts
  - 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%)



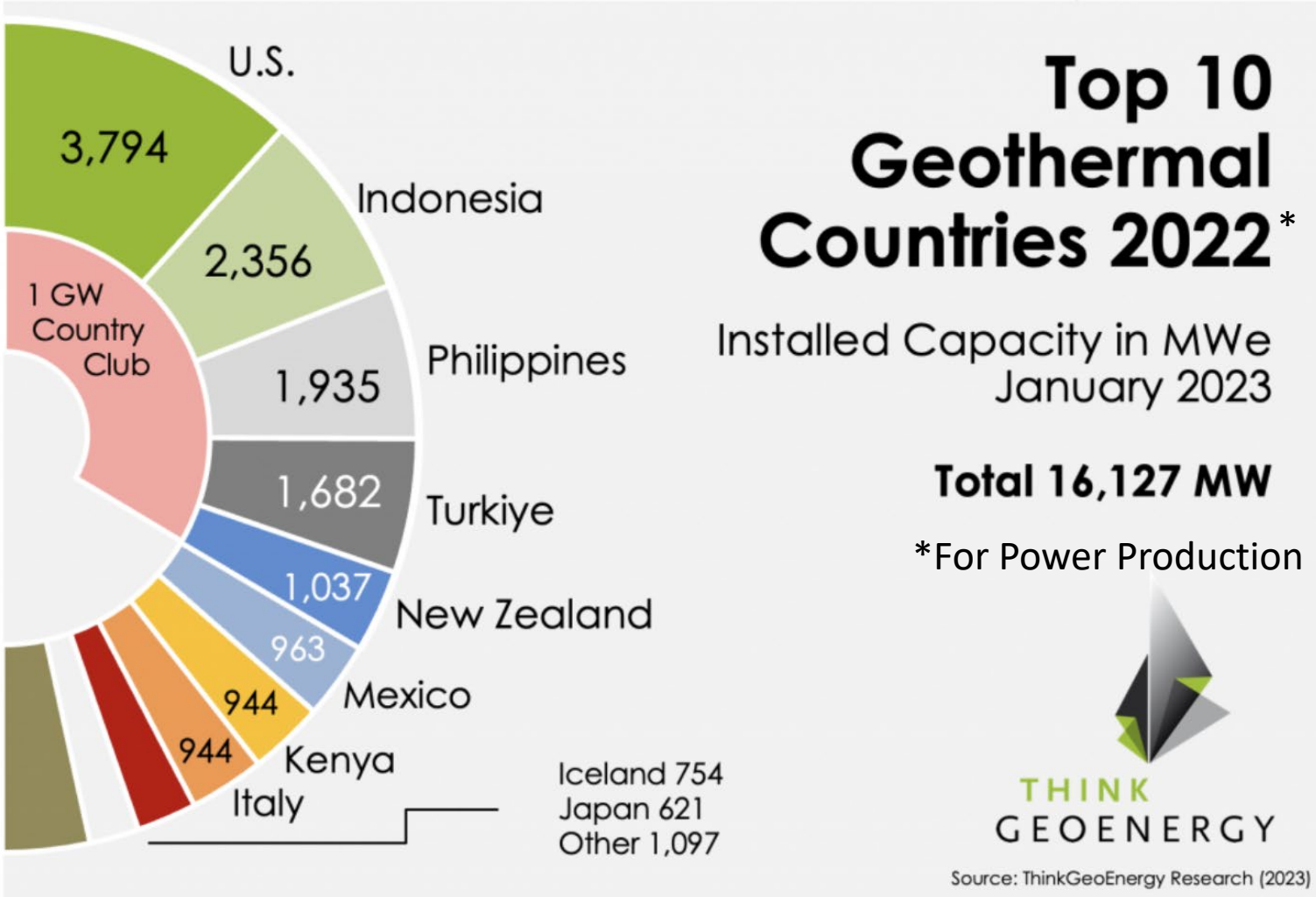
Worldwide Distribution of Geothermal Systems



Tectonic Plates

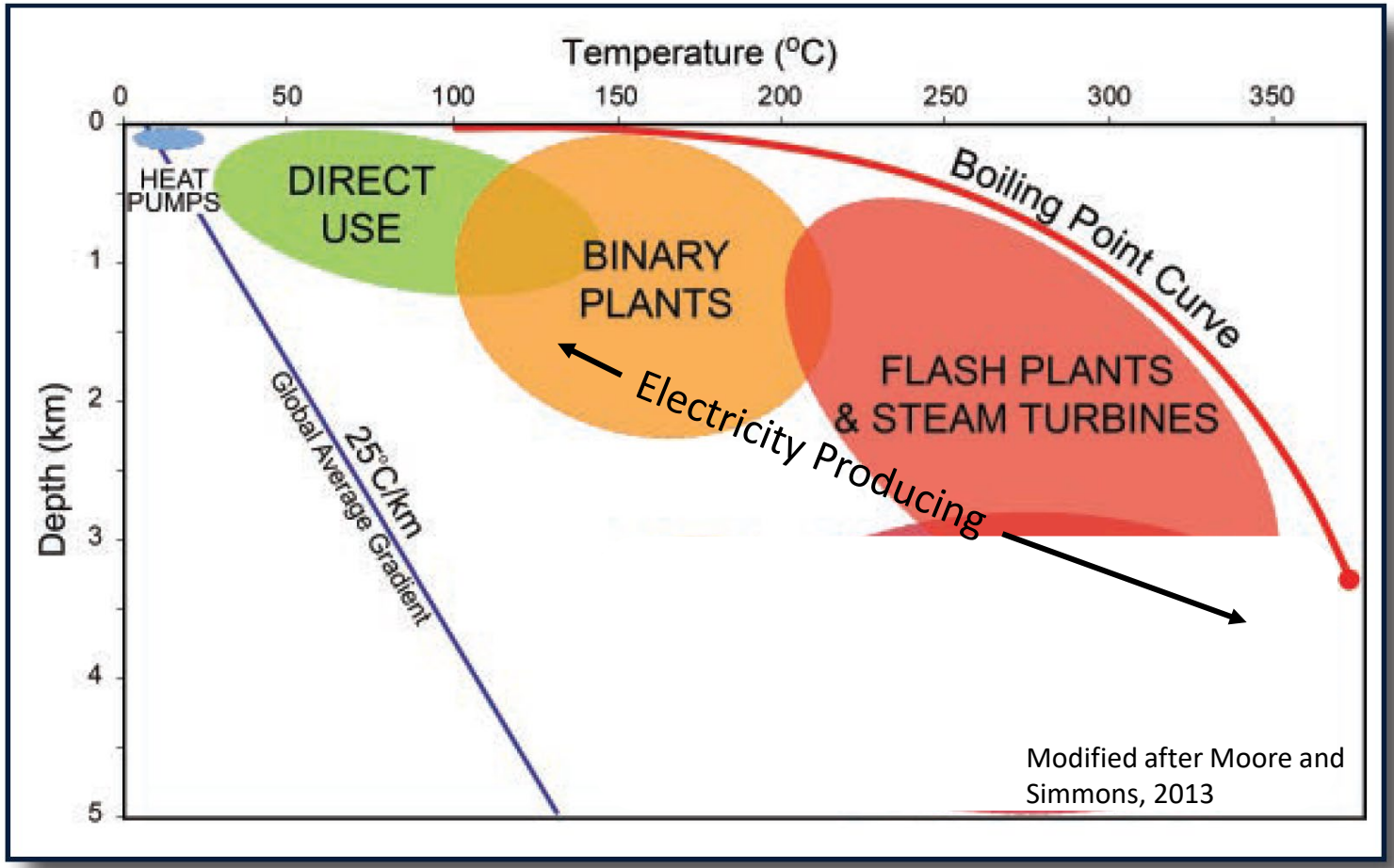


Note correspondence between distribution of geothermal systems and boundaries to tectonic plates



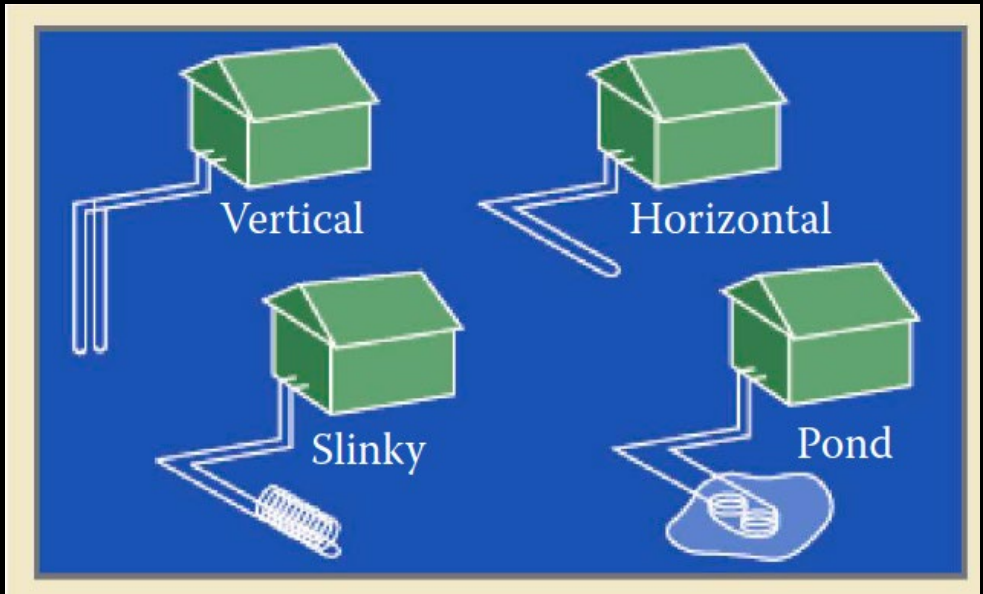
ThinkGeoEnergy Top 10 Geothermal Countries - Installed Geothermal Power Generation Capacity (copyright: ThinkGeoEnergy)

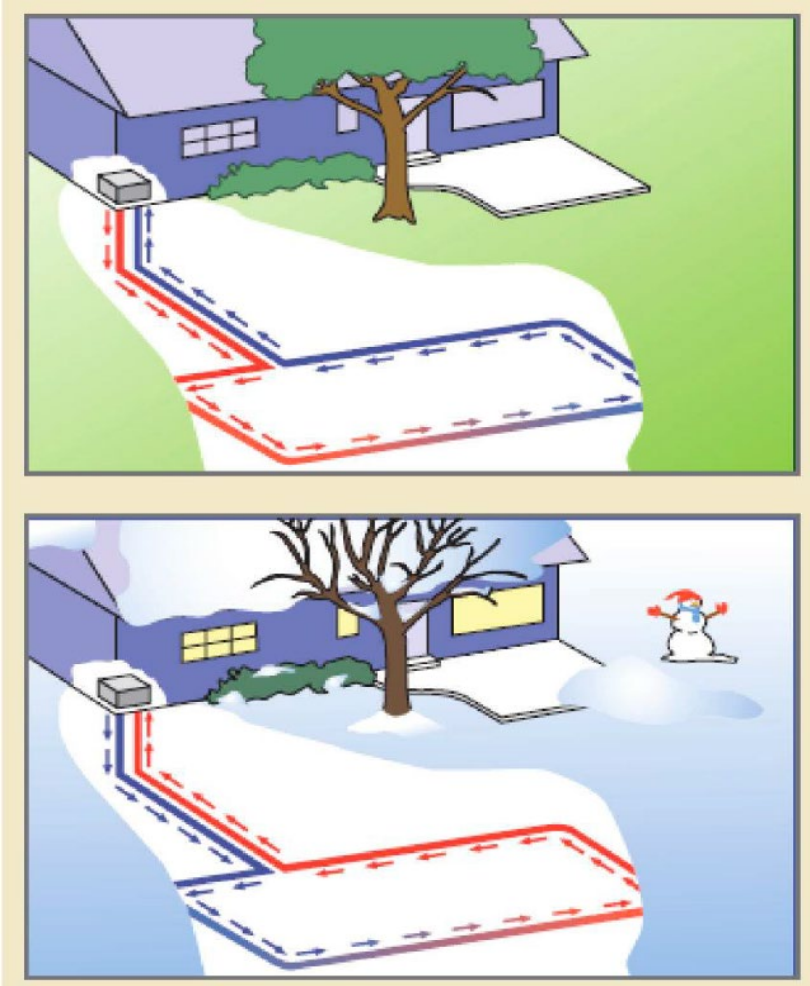
Uses of Geothermal Energy with Depth and Temperature



Modified after Moore and Simmons, 2013

Geothermal Heat Pumps (heating and cooling)





- More efficient to transfer energy than to produce energy
- For every unit of electricity used, system gleans or dissipates 3-4 units of heat
- About 40% more efficient than air-source heat pumps
- Downside: More expensive upfront costs (ROI about 3-6 years for new construction)
- Upside: 30% tax credit to defer costs

Figure Source: Duffield and Sass, USGS Circular 1249, 2003

What is Needed to Make a Geothermal Fluids Viable for Development?

- 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

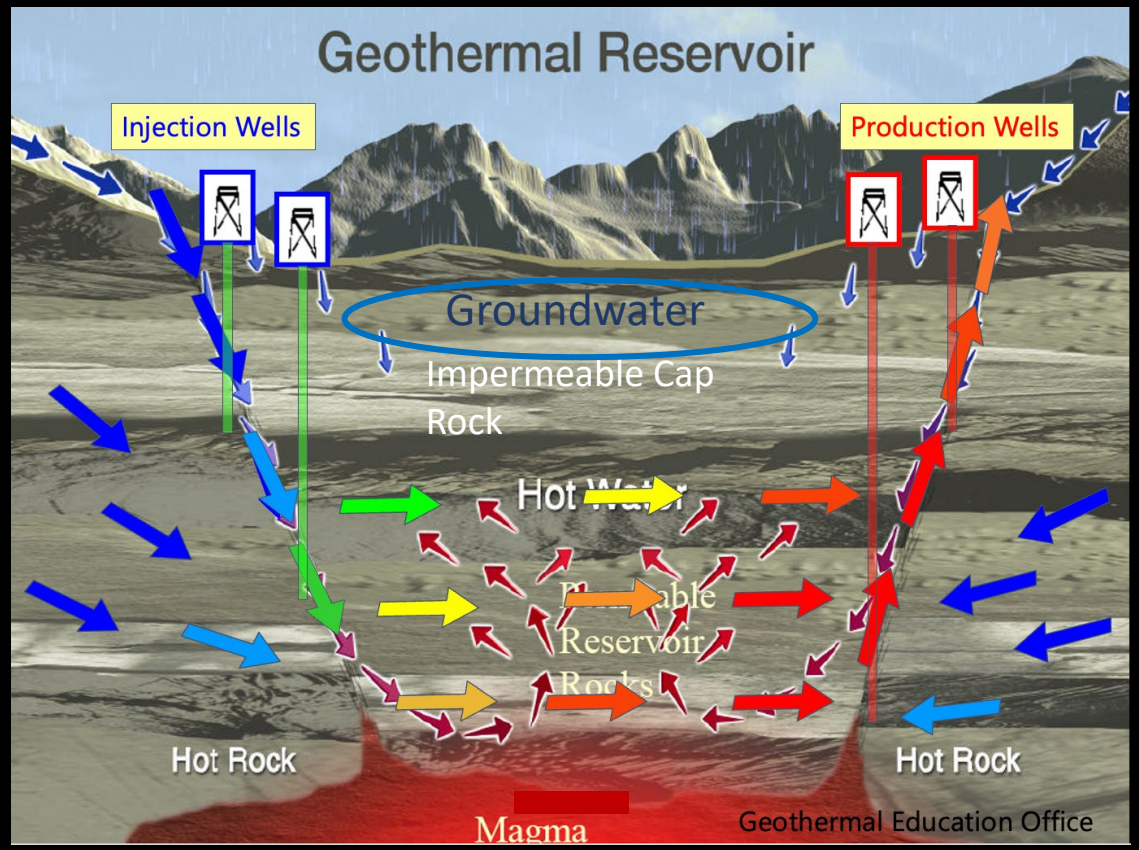


Image courtesy of M. Coolbaugh as modified from GEO

Direct Use of Geothermal Fluids

- E.g., Boise, ID district geothermal heating system
  - Largest in U. S.
  - Began in 1890
  - System now heats about 7.5M ft^2 in about 100 buildings
  - Fluid T: 72-75°C

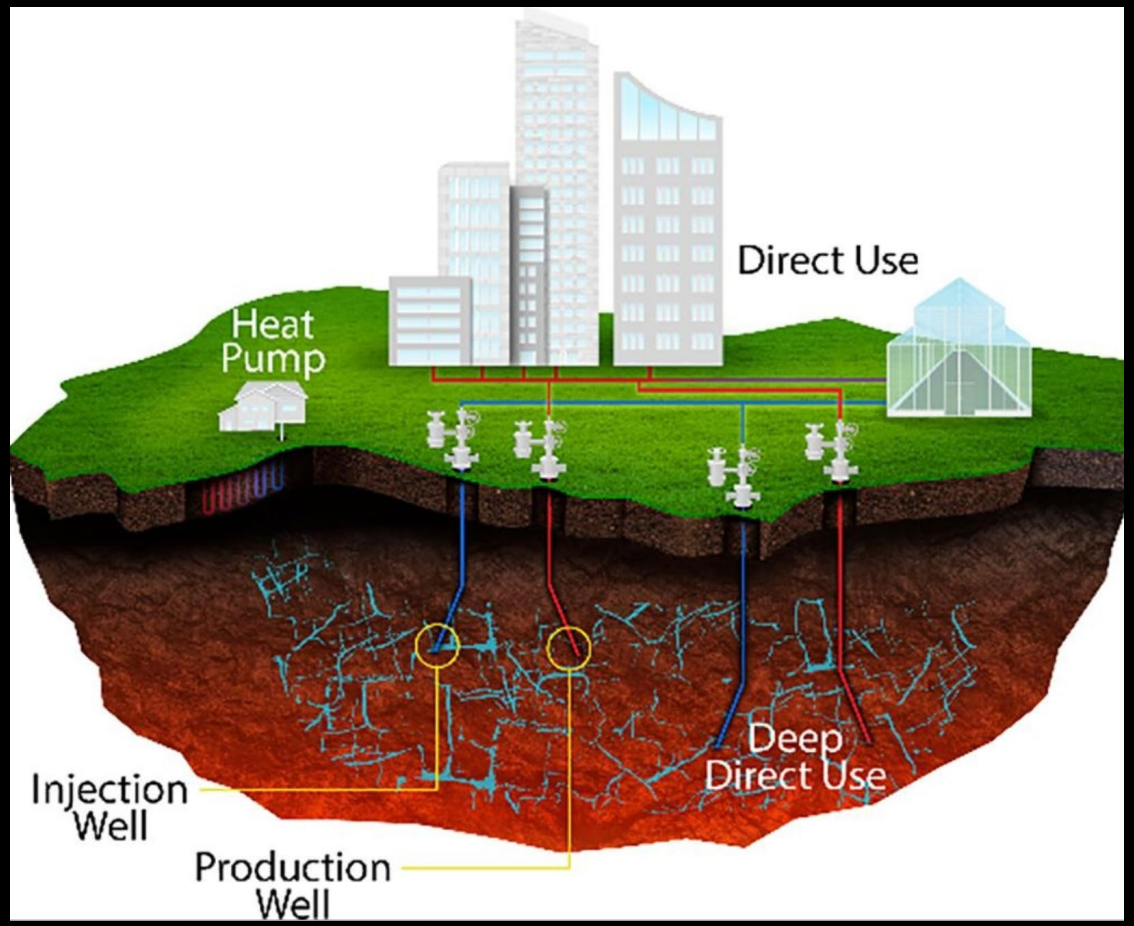
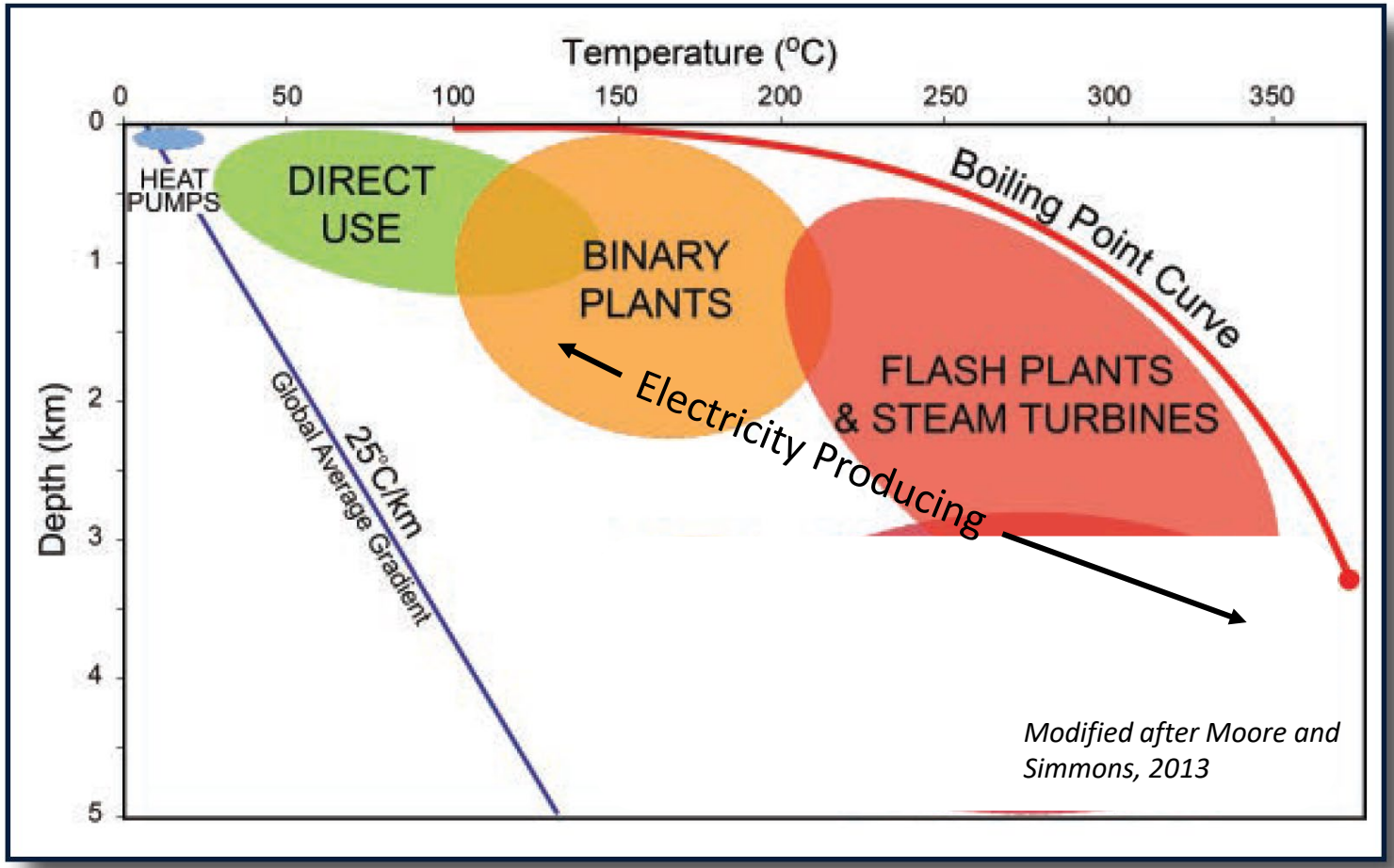


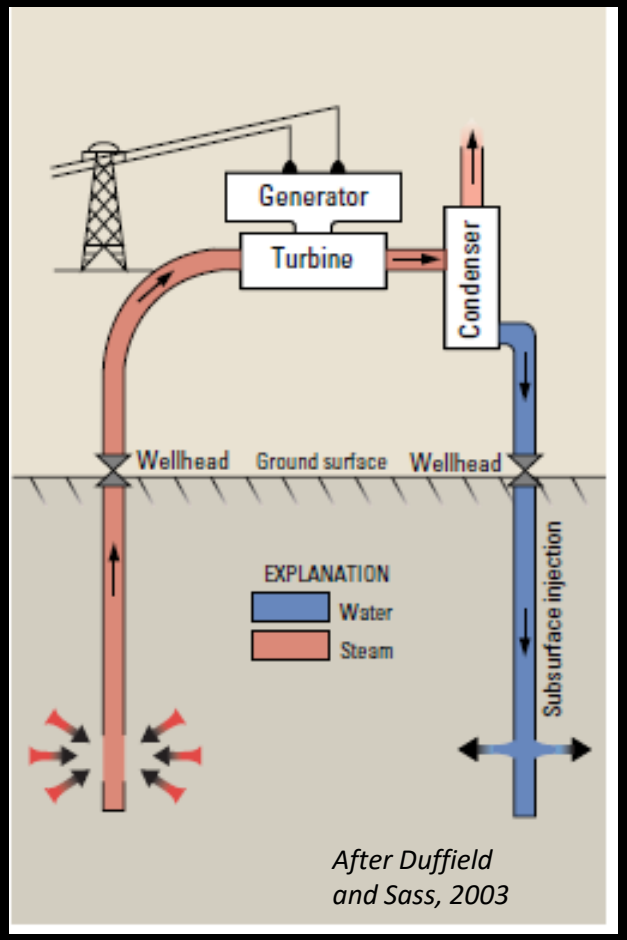
Figure source: Beckers et al., 2021

Uses of Geothermal Energy with Depth and Temperature



Types of Geothermal Systems and Related Power Plants

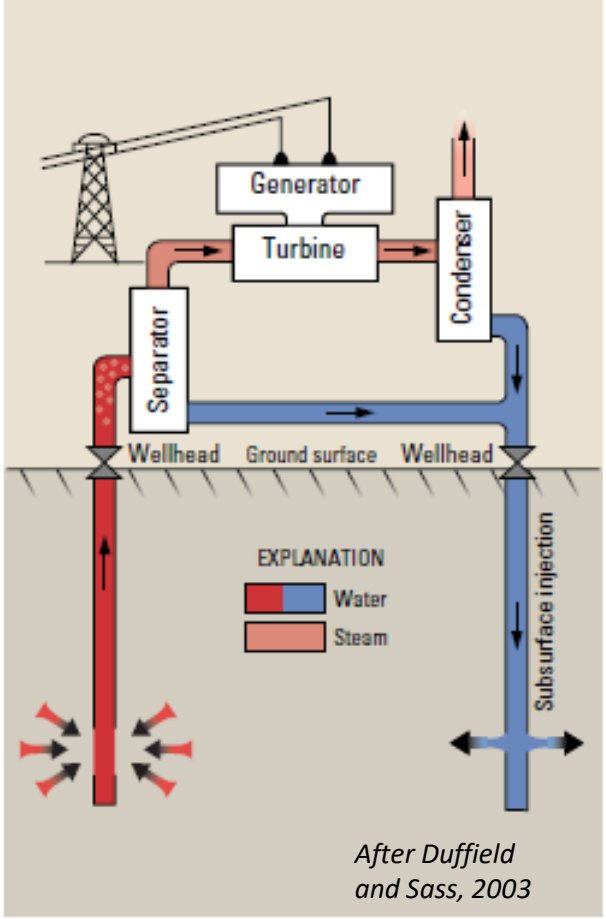
- Vapor (steam)-dominated
  - Provide greatest amount of power per mass of fluid
  - Because reservoir is already steam, all fluid mass goes to turbine
  - In order for fluid to occur as steam, reservoir is underpressured compared to surrounding rock—geologically rare conditions
  - World class examples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



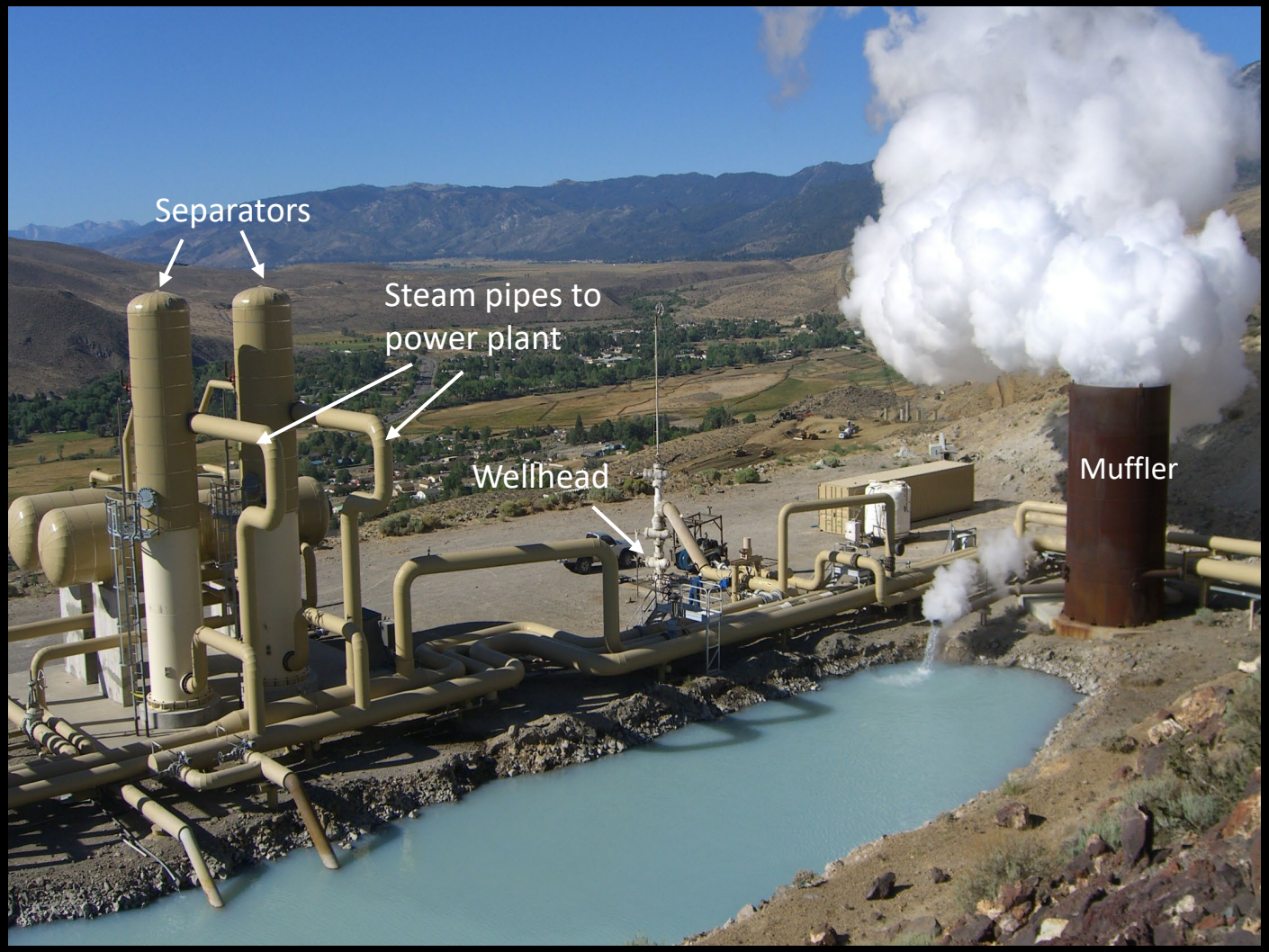
After Duffield and Sass, 2003

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

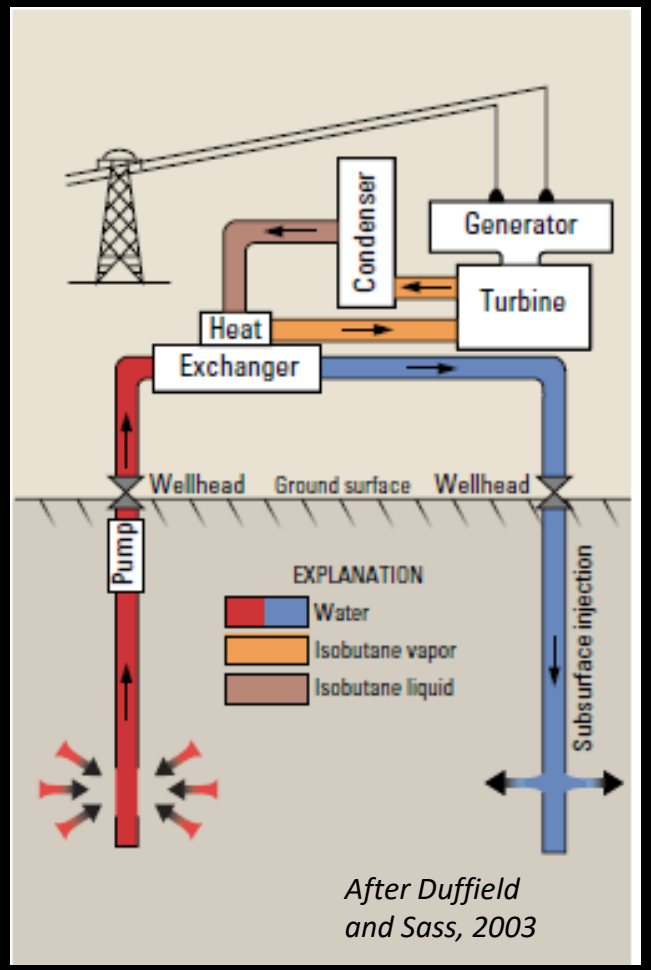


After shut-in and servicing, fluid in well is allowed to flow to muffler until T is high enough to bring steam to power plant.

Well 24-5 Upper Steamboat Field, NV

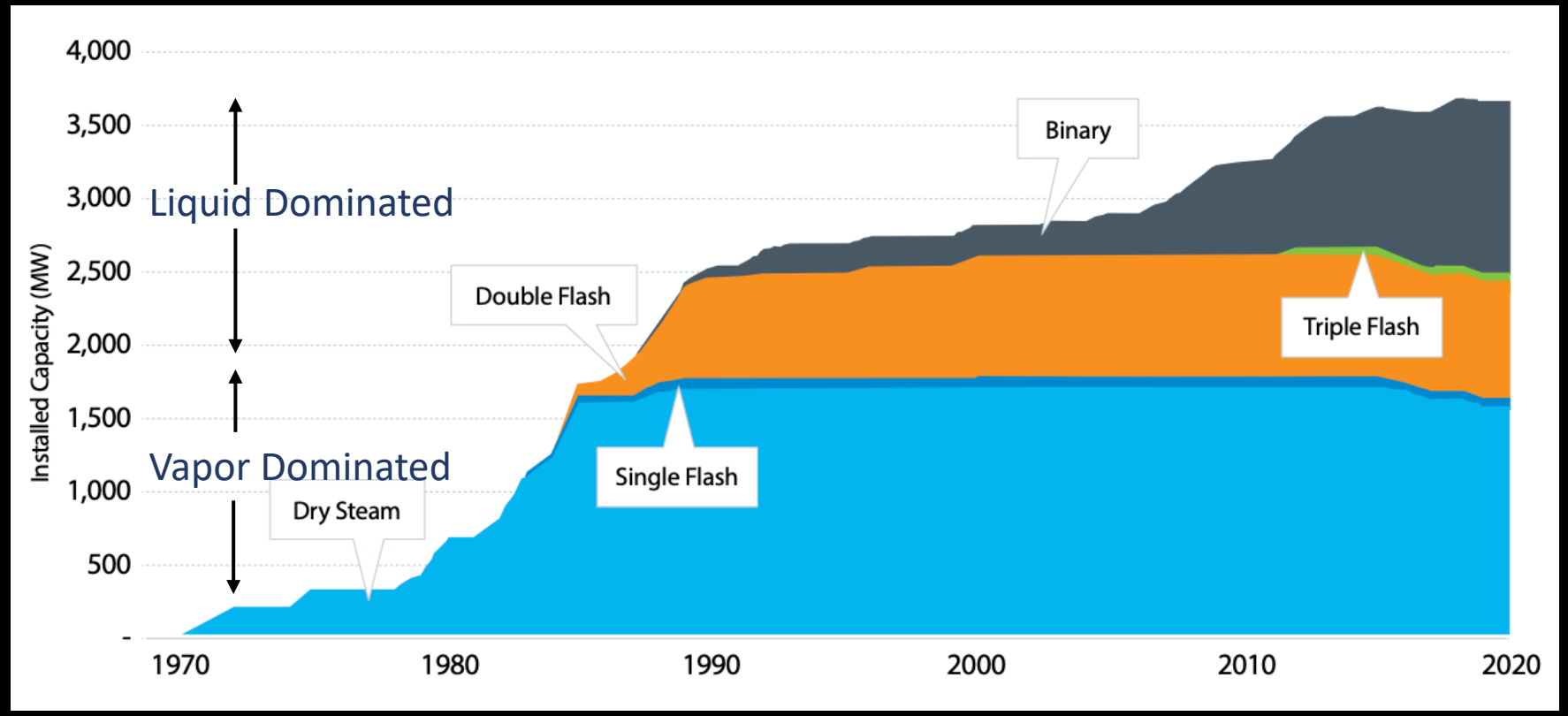
Types of Geothermal Systems and Related Power Plants

- 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

Installed U. S. Geothermal Power Capacity (Resource Type/Technology)



NREL report, 2021 (https://www.nrel.gov/docs/fy21osti/78291.pdf)

Geothermal Energy Attributes

1. Base load power (available 24-7 unlike wind and solar);
   - New technology allows for load following and dispatchable energy
   - 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%
2. Sits on top of energy source;
   - No fuel price exposure; price certainty; insulated from price volatility;
3. Promotes energy diversity;
4. Proven resource, mature technology (dating back to 1913 in Italy and 1958 in New Zealand);

Geothermal Energy Attributes

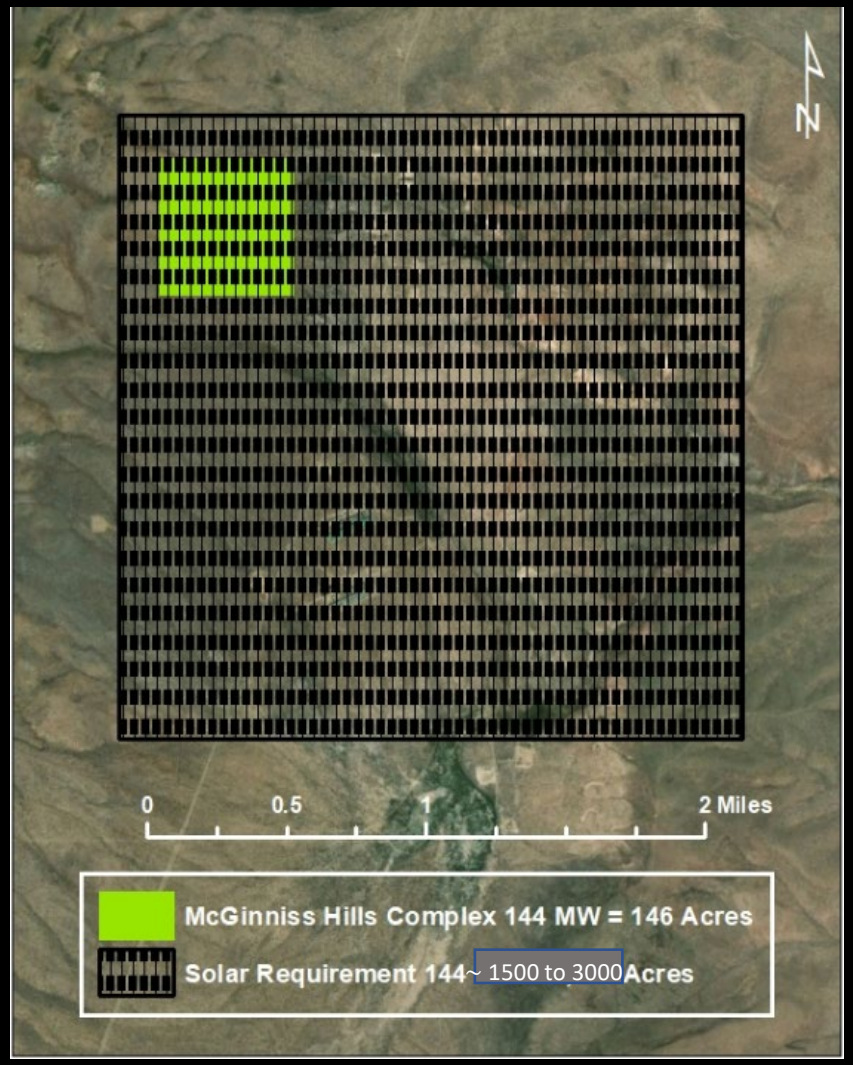
5. Economic impact on construction/operation: number of jobs per MW;
   - CalEnergy Salton Sea: ~390 MW; ~240 employees (about 1 employee for every ~1.6 MW produced)
   - Comparably sized natural gas plant: 15 employees; commercial solar/wind plant: 10-15 employees (1 employee for every 25-34 MW produced)
6. 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

7

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

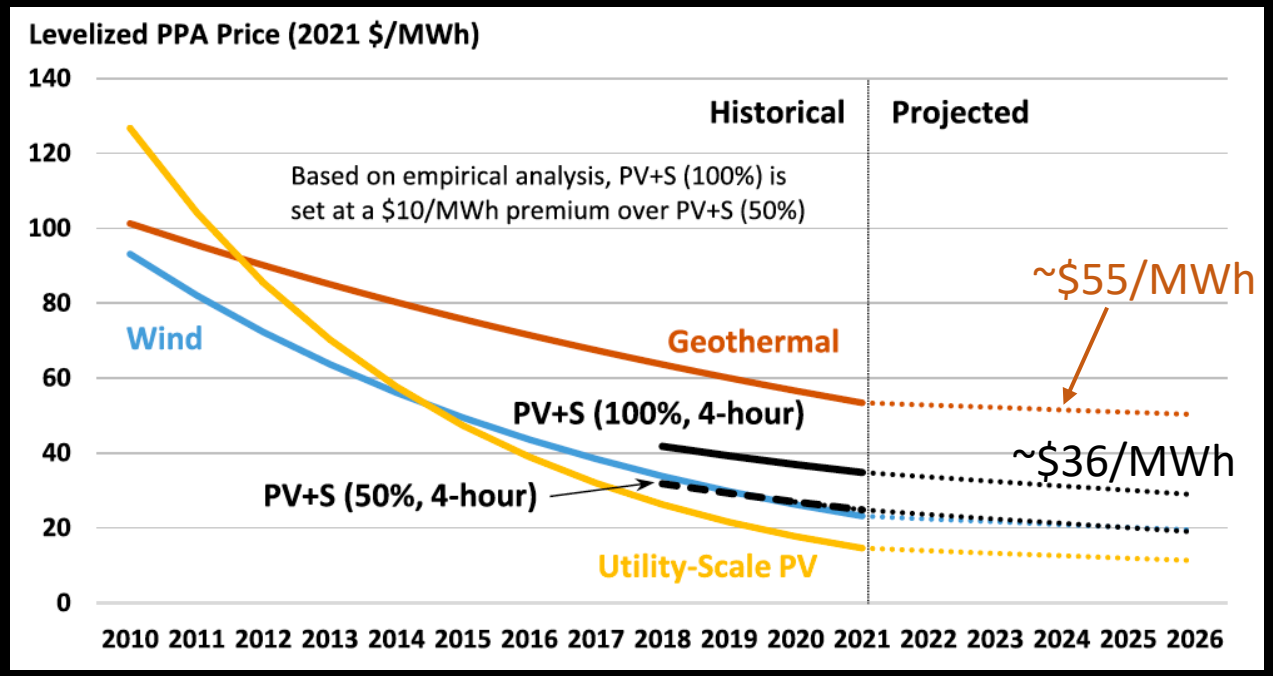
Miravalles geothermal field, Costa Rica. After DiPippo, 2012

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

Blue Lagoon Spa at Svartsengi geothermal plant, Iceland

Principal Geothermal Challenge

- Higher cost compared to solar PV and wind
  - Reflects higher risk and expense to develop



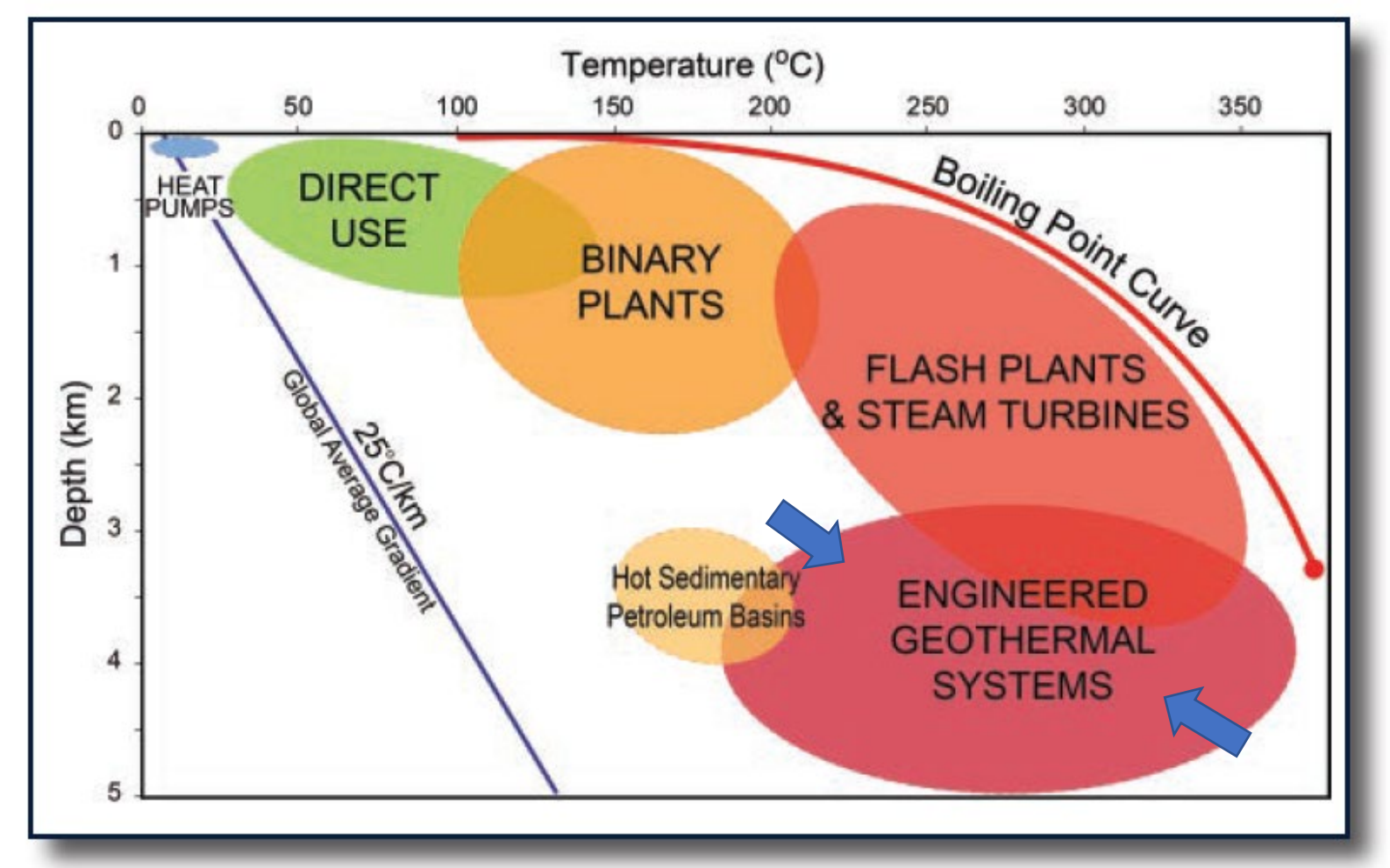
After Bolinger et al., 2023

- Policy intervention to promote non-intermittent renewable energy sources
  - e. g., 2021 CPUC Energy Procurement Order requires an additional 2000 MW of geothermal by 2035
  - Expand oil and gas exploration efficiencies that currently do not require EA or EIS under NEPA to include geothermal

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 as a working fluid
- Applying Closed-Loop Technology
- Recovering Li From Geothermal Brines

EGS



After Simmons and Allis, 2015

Engineered Geothermal Systems (EGS)

- Artificially generated convecting hydrothermal system. How?
  - By injecting water deep underground (3-5 km)
  - By improving permeability via thermal shocking (hydroshearing) and hydrofracking
    - Hot rocks contract and fracture when exposed to cold injected fluid improving permeability (hydroshearing)
    - Hydrofracking fluids pumped down under high pressure to stimulate fracture permeability
    - Fracture permeability achieved in stages via zonal isolation (using bridges and plugs) 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

EGS (DOE-Supported FORGE Venture)

- Injection well shown in blue; production well shown in red. Physical separation of two wells in reservoir ~150 m.
- Each well drilled over a period of 2.5-3 months with TD in each well of about 11k feet (~8000 ft deep with about 3000 feet lateral legs
- Bottom hole T about 230°C
- Injection well stimulated in 3 stages

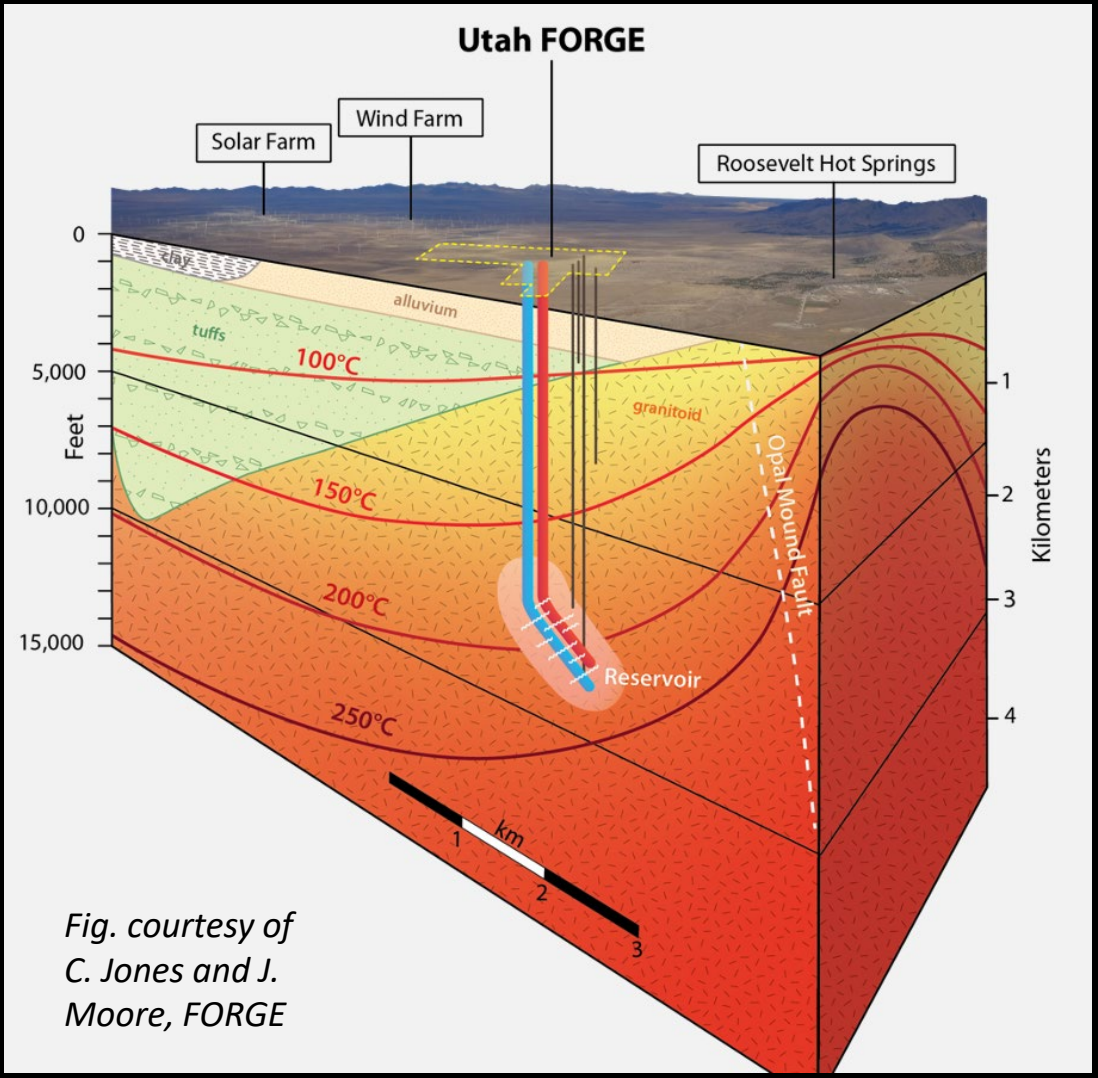


Fig. courtesy of C. Jones and J. Moore, FORGE

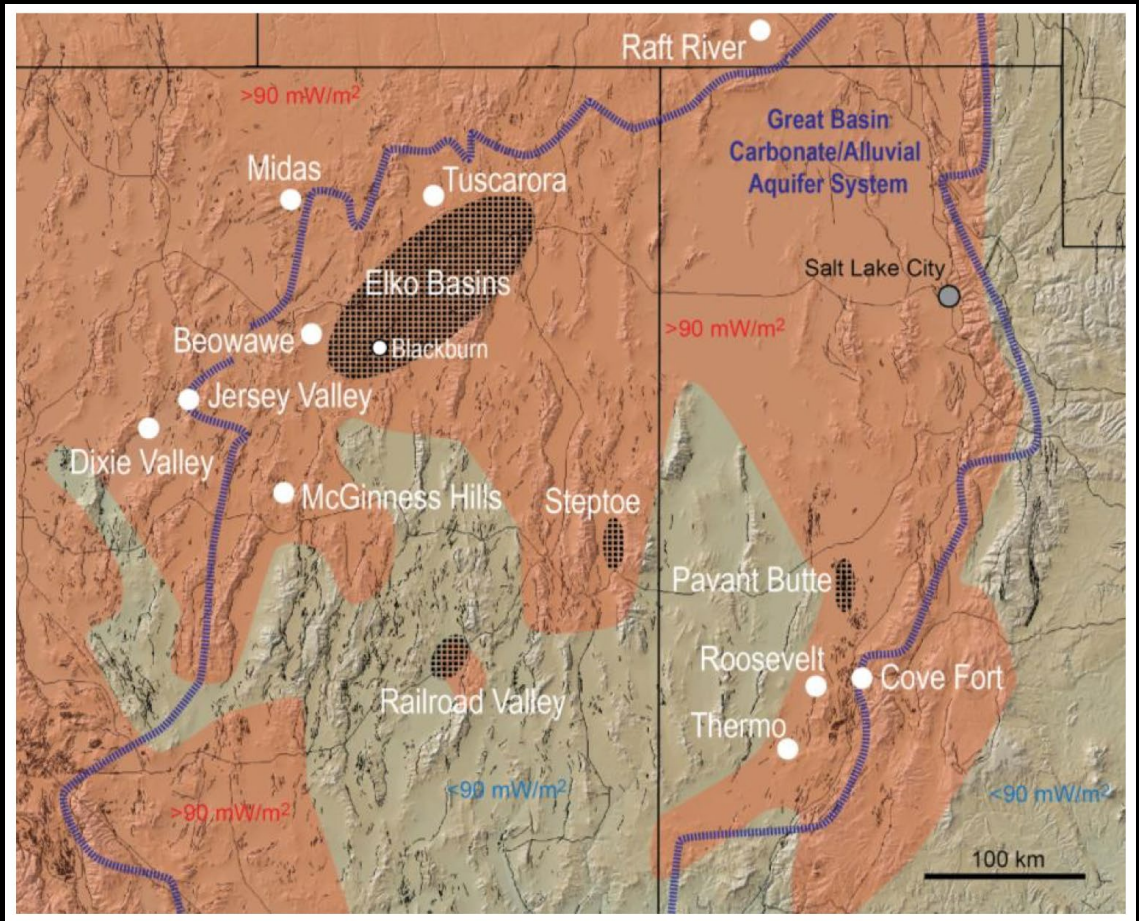
Engineered Geothermal Systems (EGS)

- Challenges:
  - Financial: Must drill deeper with deep horizontal legs which is expensive
  - 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 hot rock to fracture (good for permeability) but can create small earthquakes felt on surface
  - Heat Recovery Over Time: Imperfectly known on the time frame how repeated injection of relatively cool water will lead to cooling of the reservoir
  - Changes in Permeability Over Time: Changes in pressure and temperature can cause fluids to precipitate minerals in fractures as they circulate from injection to production wells

Boden, 2023

Hot Sedimentary Aquifers

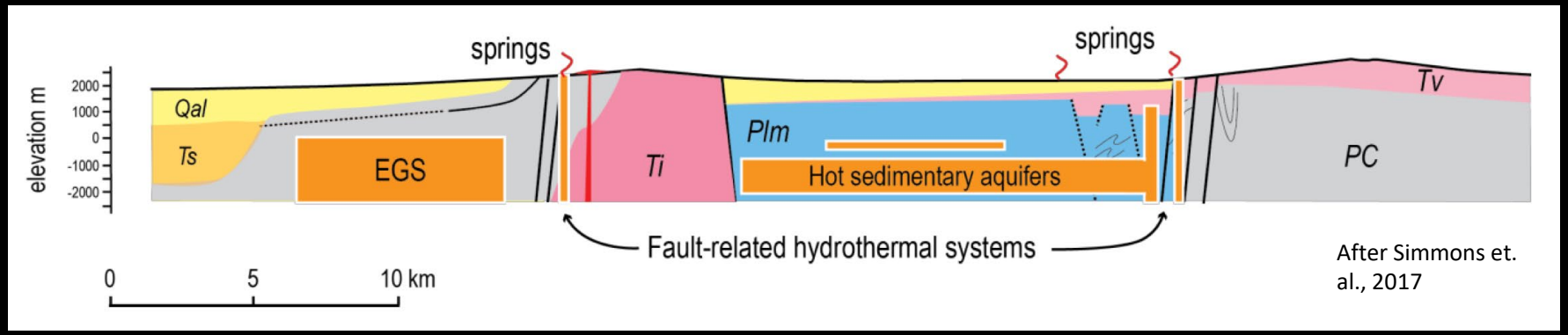
Require permeable sedimentary layers at depths of 3-5 km in regions of elevated heat flow (>90 mW/m^2) to achieve power generation temperatures of 150° to 200°C.



After Simmons et. al., 2017

Hot Sedimentary Aquifers

- Schematic Cross Section of Great Basin system

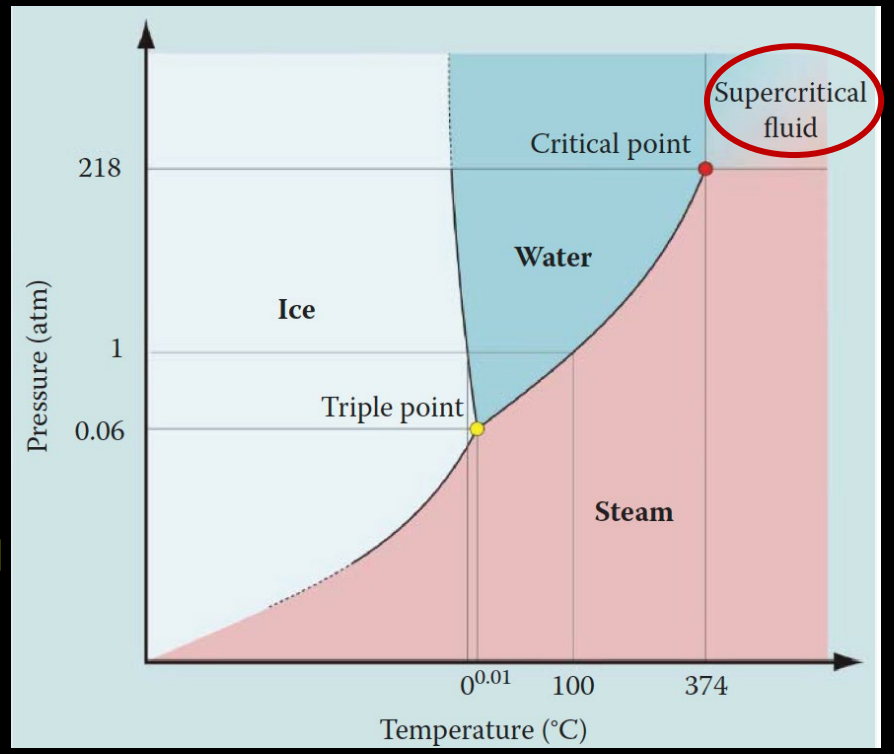


Note the large surface area of hot sedimentary aquifers compared to fault-related geothermal systems developed by current geothermal power facilities in Nevada

- Direct Use of HSA (Paris basin)
  - 65-85°C fluid in Dogger aquifer at depth of 1.5–2.0 km
  - Over 150,000 buildings served by systems from 40 geothermal sites
  - Fluid flow rates of 900-2500 gpm
  - Little or no degradation in T from 50 years of production

Superhot/Supercritical Geothermal Systems

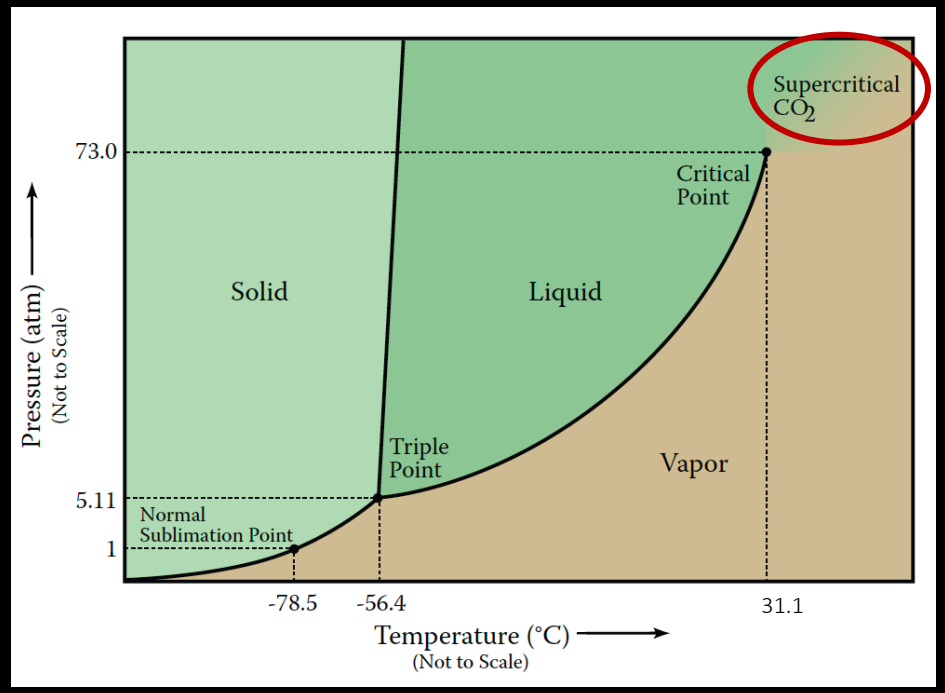
- Being explored by Iceland Deep Drilling Project (IDDP), Japan Beyond the Brittle Project (JBBP), and Hotter and Deeper Exploration Science (HADES) in New Zealand.
- What is supercritical water?
  - Fluid with properties intermediate between liquid and gas (density of liquid but mobility of gas)
  - 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, 2023

Using Supercritical CO_2 ($ScCO_2$)

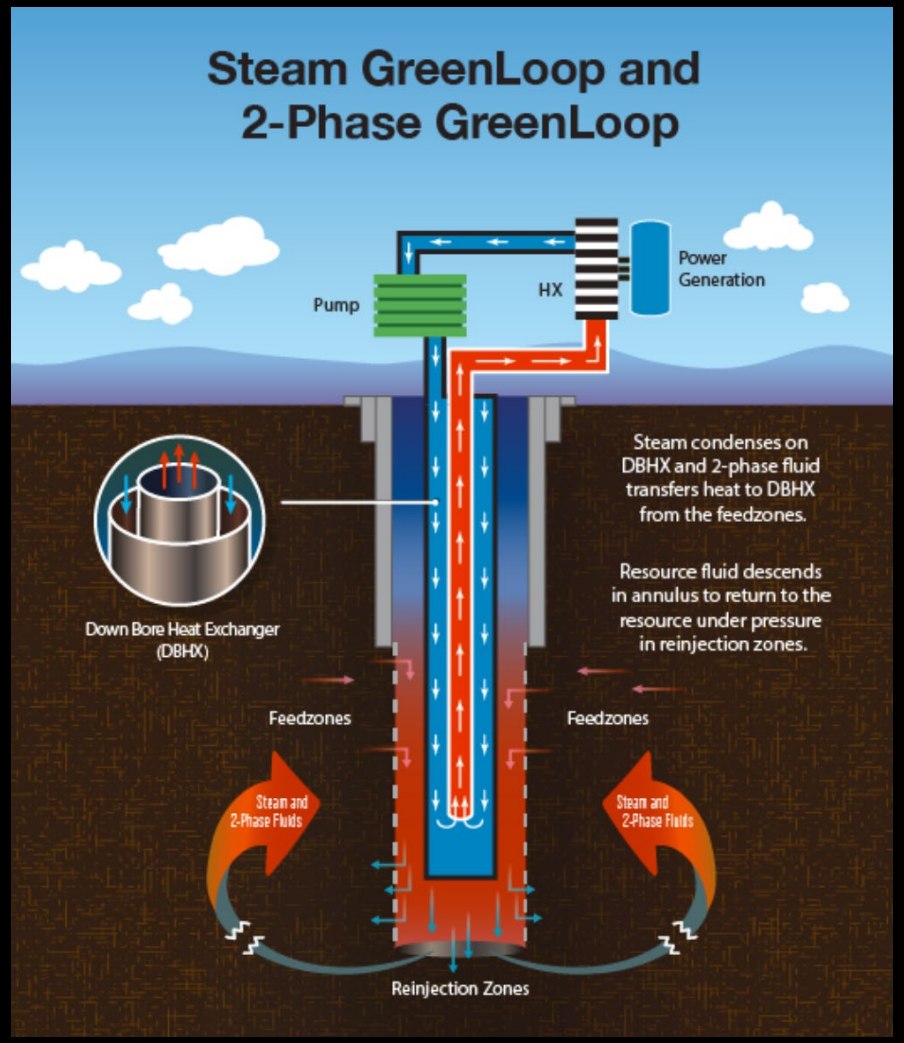
- Advantages:
  - 3x–5x higher mass flow rates than water (makes up for lower heat capacity compared to water)
  - Large density contrast between cold and hot $ScCO_2$ means strong buoyant forces reducing power consumption for pumping
  - Can help sequester CO_2 produced from fossil-fuel fired power 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



Boden, 2023

Closed-Loop Technology

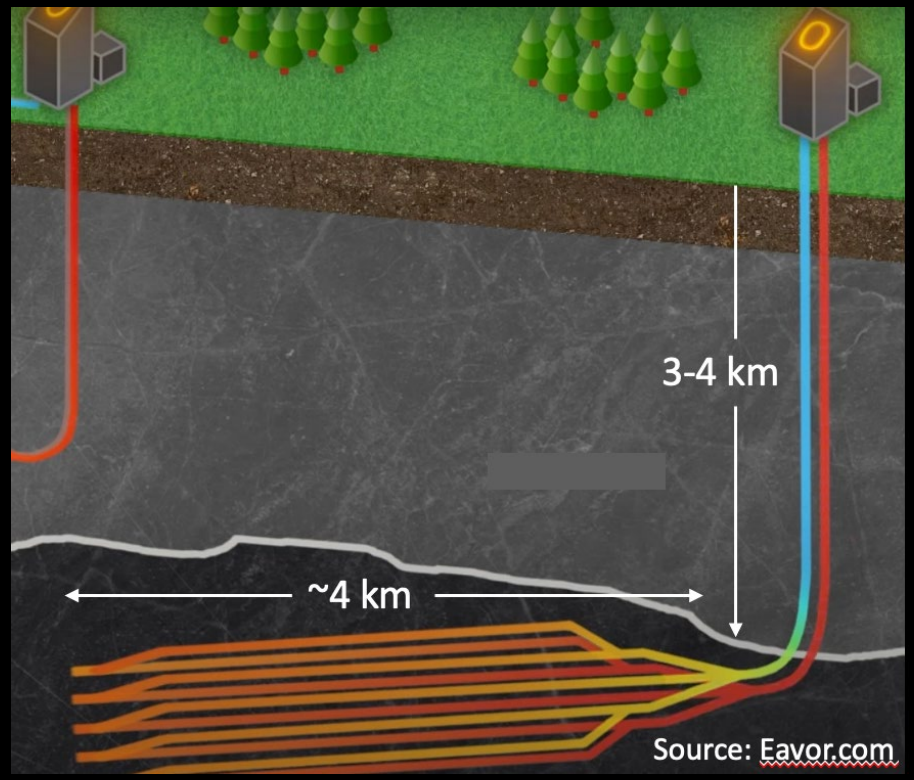
- Two different configurations being explored:
  - 1. Modify existing nonproductive wells (GreenFire's GreenLoop technology)
  - 2. Drill deep well with multiple laterals at depth to extract heat (Eavor technology)
- GreenLoop Technology
  - Utilizes down borehole heat exchanger
  - Induces convection outside of borehole
  - Steam condenses on outside of borehole transferring additional heat to injected fluid from that provided by conduction
  - Mainly for steam-dominated and 2-phase geothermal reservoirs



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

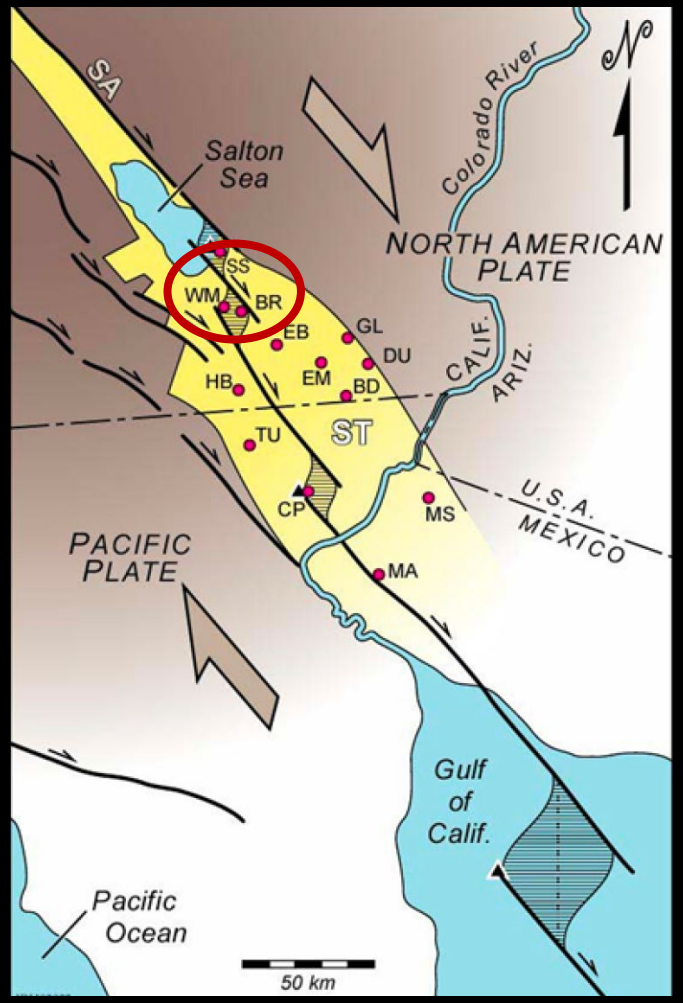
Closed-Loop Technology

- 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

- 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)

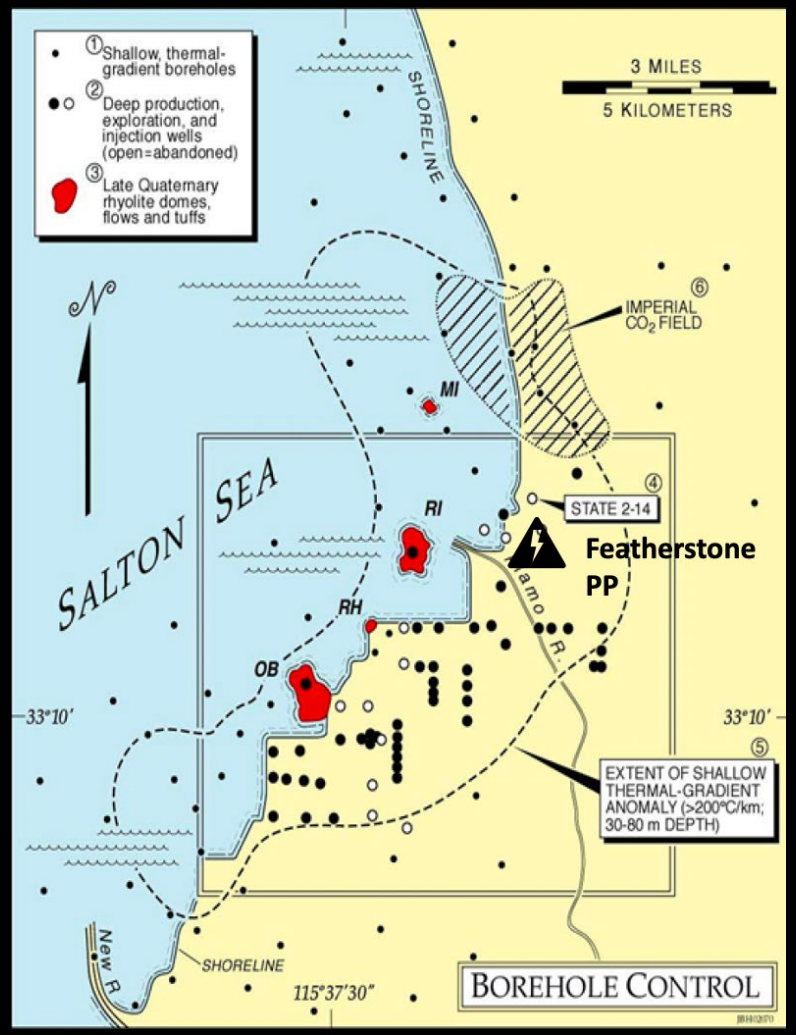
- What is geothermal energy and where does the heat come from?
- How are energy and power related?
- How is geothermal energy used?
- What criteria are needed to make a geothermal system viable for power generation?
- What are some key attributes and principal challenge for using geothermal energy?
- What are some exciting emerging technologies for harnessing geothermal energy including recovery of critical minerals from geothermal brines?

Image credit: GeoGlobal Energy Corp.

Slides in reserve

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 $30k/ton→gross revenue $600M!
    - 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

Comparative Production Rates

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

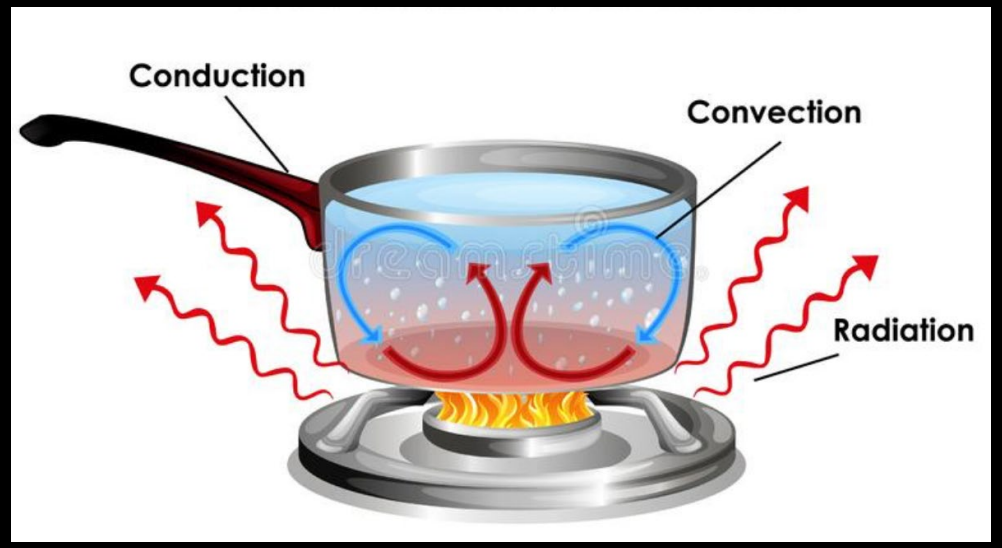
Oil well – 20 gpm
650 barrels/day
(~$58,000/day at $90/barrel as of 09/06/23)

Geothermal well
2000 gpm
(~$6000 –$12,000/day depending on T)

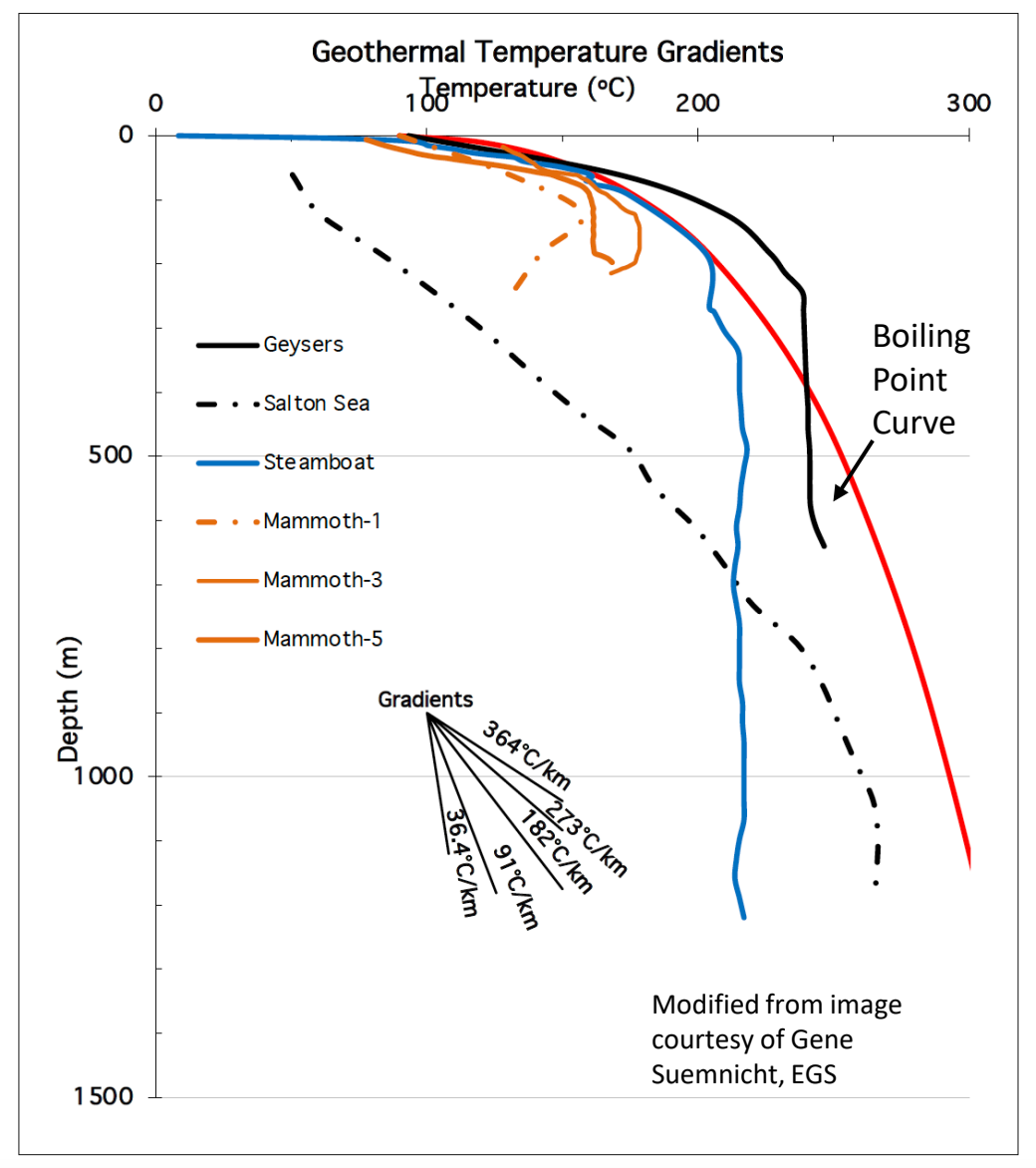
Modified from image courtesy of Gene Suemnicht, EGS

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 exploitable geothermal systems
   - Will T change much with depth?
     - No
   - Requires good permeability



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?

Fervo Energy: Blue Mountain EGS Project, NV

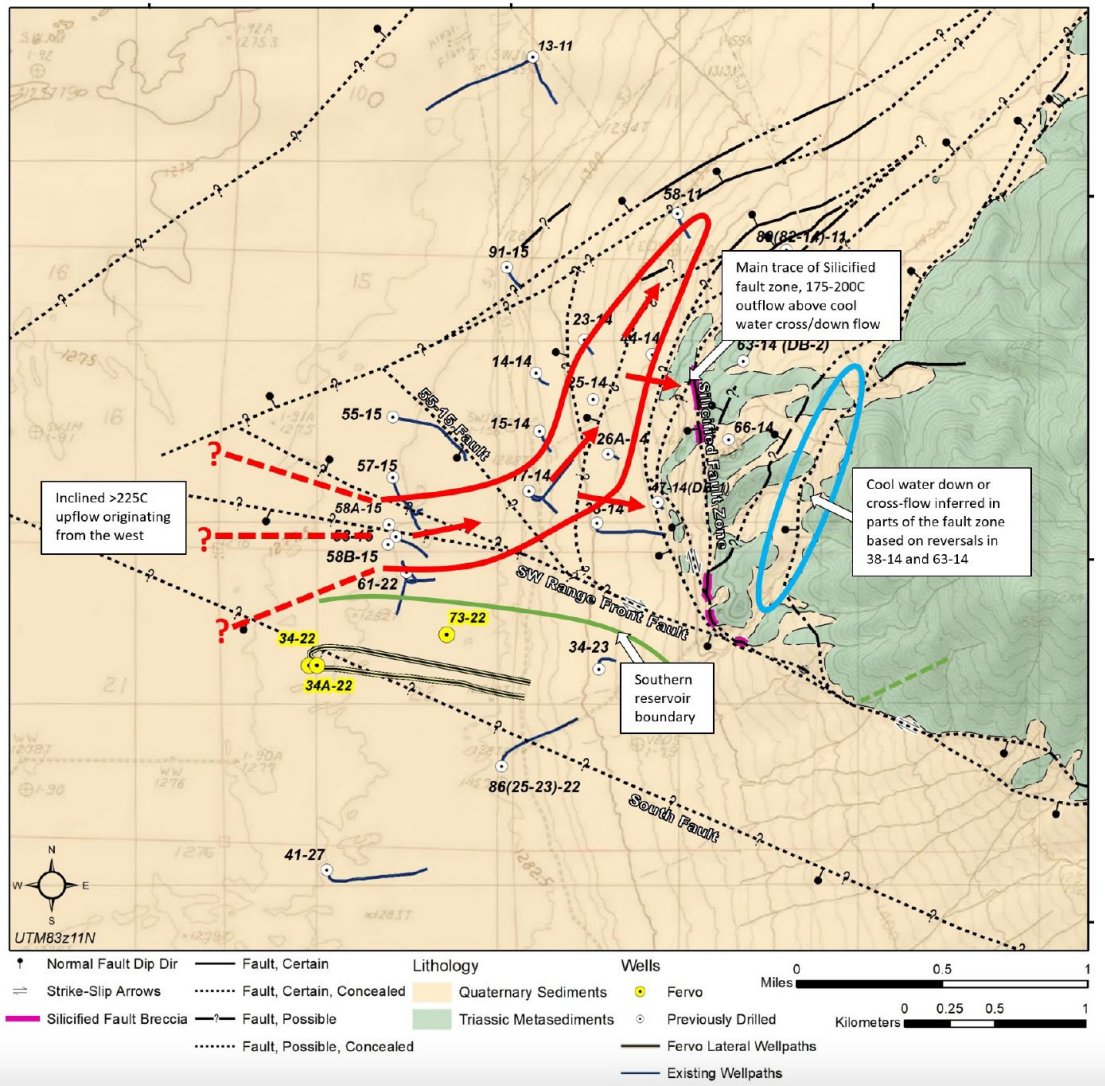
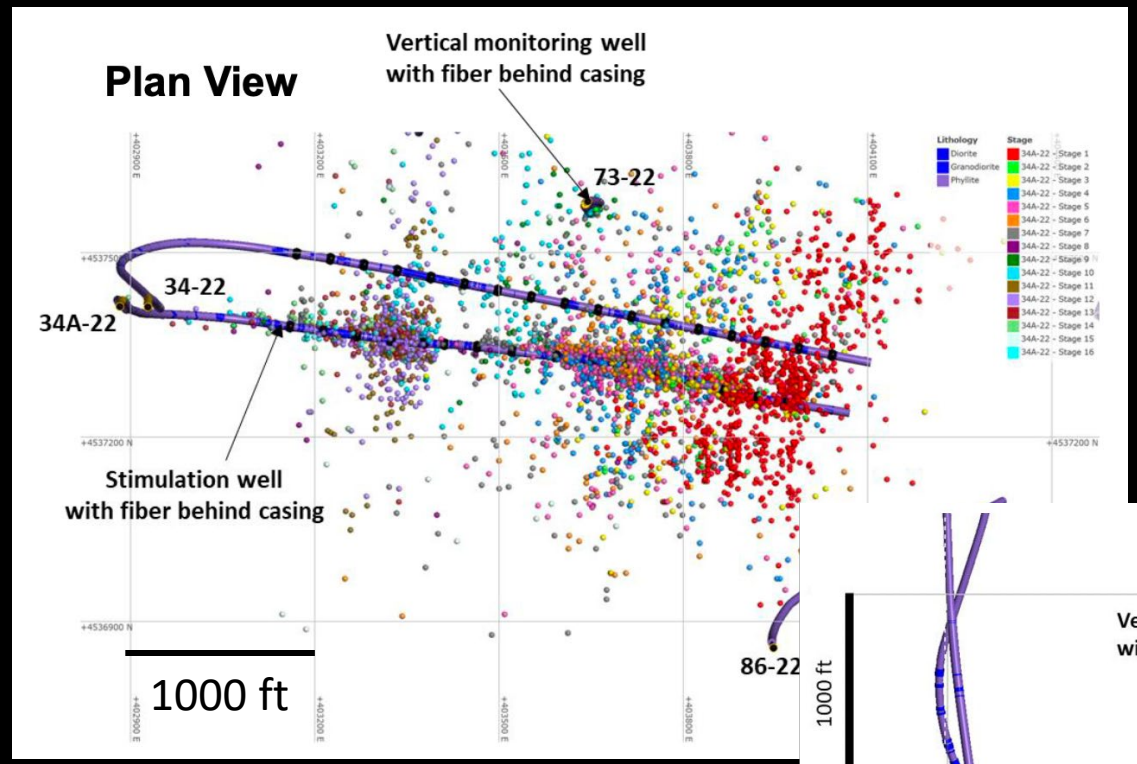


Figure after Fercho et al., 2023

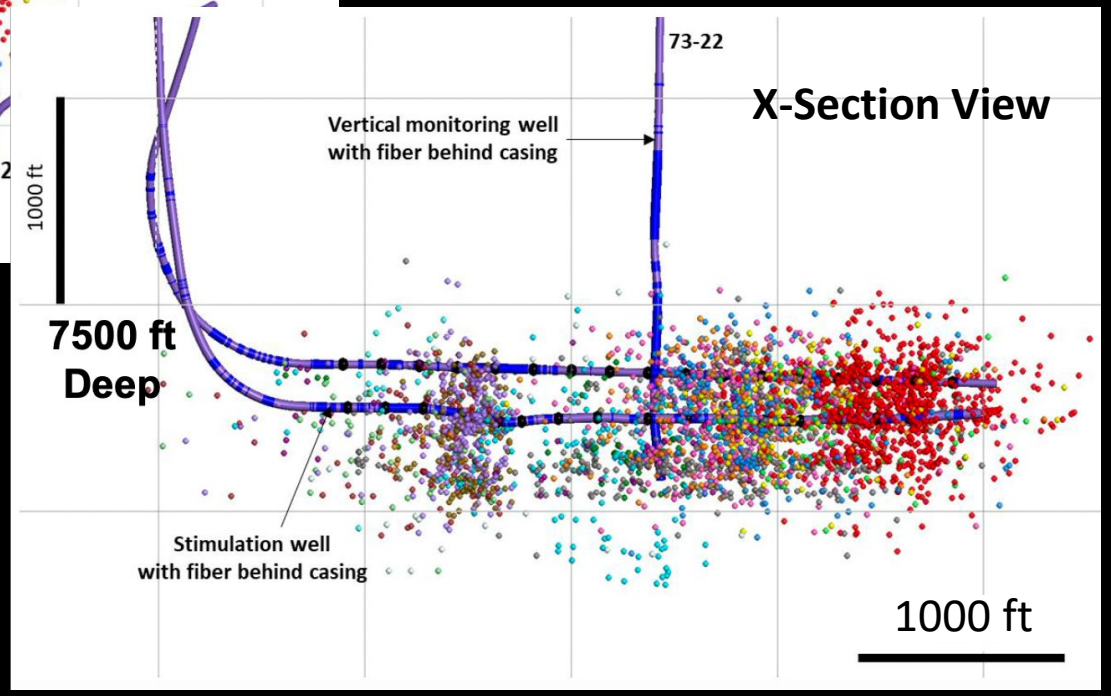
- Successfully drilled injection/production well doublet (7700 feet vertical and 3200 feet lateral legs) outside of extant hydrothermal system in about 6 months
- Stimulated both injection and production wells in multiple stages to artificially create a fracture controlled permeable reservoir
- Pair of wells capable of producing 80kg/s of fluid at 175°C to 190°C which yields about 5.1 MWe
- Thermal modelling studies suggest about a 10 year lifespan at the current rate of injection and production

Boden, 2023

Fervo Energy EGS Project



- Injection well stimulated in 16 stages
- Dots are microseismic events color coded to the stage of stimulation
- Resounding technical success
- Economic success not yet (~$12M/MW v. ~$1M/MW)



Figures after Norbeck et al., 2023