I Overview of Geothermal Energy

II Heat Transfer

III Surface Features & Shallow Hydrology

IV Fluid Chemistry

V Resource Assessment

VI New Advances

Why use geothermal energy?

Strengths
- Clean, renewable energy
- Base load Resource/ generation
- Inexpensive (once going)
- Reliable

Weaknesses
- Long lead time: concept to production
- Large entry barriers
  - high upfront costs
  - high upfront risk
  - pre-drilling feasibility absent
- Location controlled by geology (e.g., remote)

Commercial considerations

- Resource information
- Managing risks & costs
- Location with respect to grid & market
- Availability of skilled personnel

Wairakei 2010

~235 MW capacity
1729 GWh of net generation
54.6 million tonnes geothermal fluid
60.8 petajoules thermal
>90% load factor
>50 years of production

Geothermal Resources

- What is geothermal energy?
- Where does it occur?
- How do you assess a resource?
- How long does the resource last?
- How can the resource be utilized?
- What are the engineering considerations?
- What are the geological considerations
- What are the environmental considerations?

Exploration-Development-Production
Geoscience & Engineering

Processes

Physical:	Heat & mass transfer
	Temperature-pressure gradients
	Permeability-porosity
	Hydrology & fluid flow
Chemical:	Fluid compositions
	Fluid-mineral equilibria
	Mineral corrosion/deposition
	Hydrothermal alteration

Basic Definitions

Geothermal System: A system of processes involving heat transfer to the earth's surface (convection vs conduction); from source to sink.

Geothermal Energy: An energy resource that can be utilised for heating (residential, industrial) and generation of electricity: thermal energy extracted economically

Geothermal Gradients (<5 km)

Normal	10 to 40°C/km
Anomalous	>100 °C/km

Basic Definitions

Geothermal Reservoir:

- The volume of rock from which thermal energy (heat) can be extracted
- Contains fluid(s) in fractures & pores: water & gas (steam)
- Renewable resource if:
  heat extraction = natural heat transfer
- Thermal energy stored in rock is huge (>10^{17} J)
- Heat is extracted at rate faster than natural heat transfer, this is called *heat mining*

Basic Definitions

Units:

Joule (J)* is the SI unit of energy (including heat energy)

Watt (W) is the SI unit of power (energy transfer)

$$1 \text{ W} = 1 \text{ J/s}$$

Power potential is reported in megawatt (MW; 1 MW=10^6 W)

Direct use power potential reported in MW thermal (MW_t)

* 1 calorie = 4.184 Joule

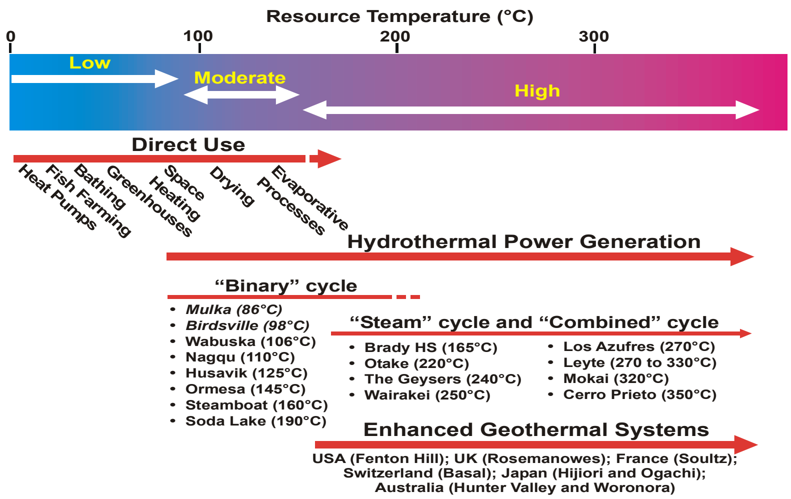
Basic Definitions

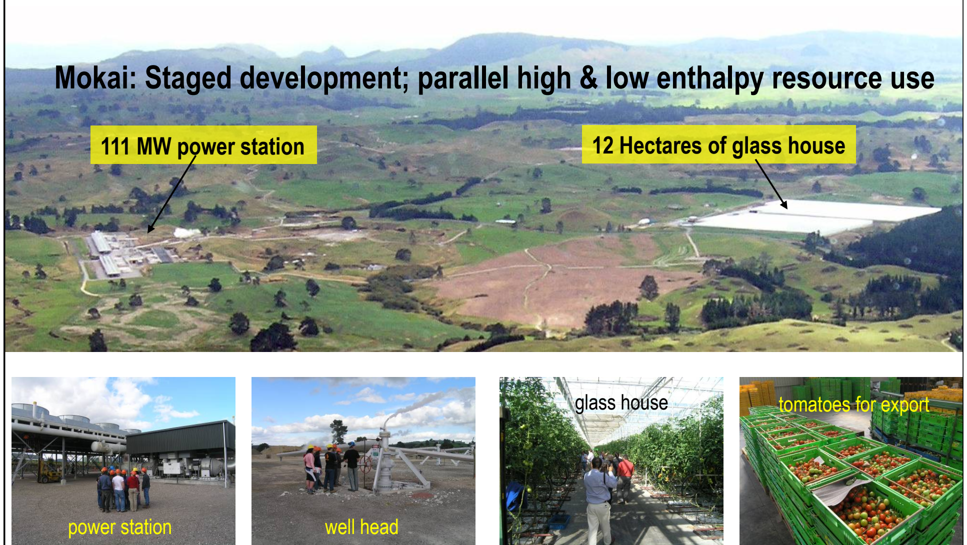
<u>Geothermal Reservoir vs Geothermal System</u>

- The reservoir represents the volume of hot rock surrounded by cold rock; both are hydraulically connected & change in pressure can be transmitted through the liquid medium

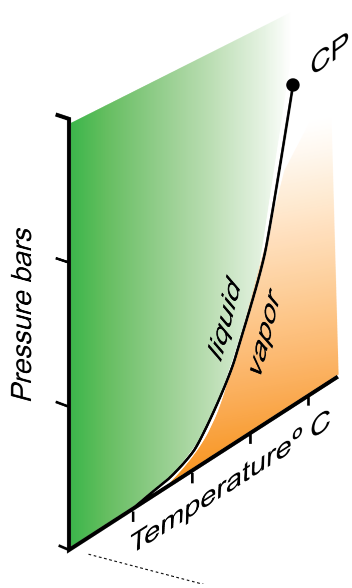
- The system comprises: heat source
  recharge (inflowing water)
  discharge (outflowing water)
  permeability structure

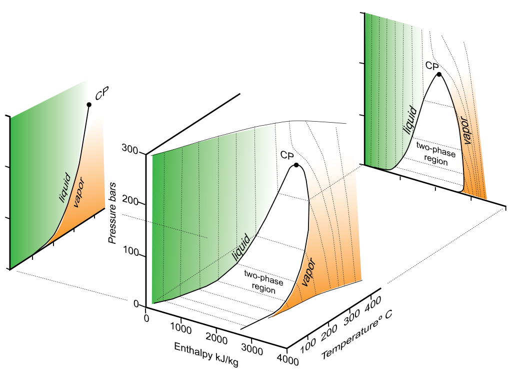
Utilization





Energy in Fluid: Vapor versus liquid H_2O

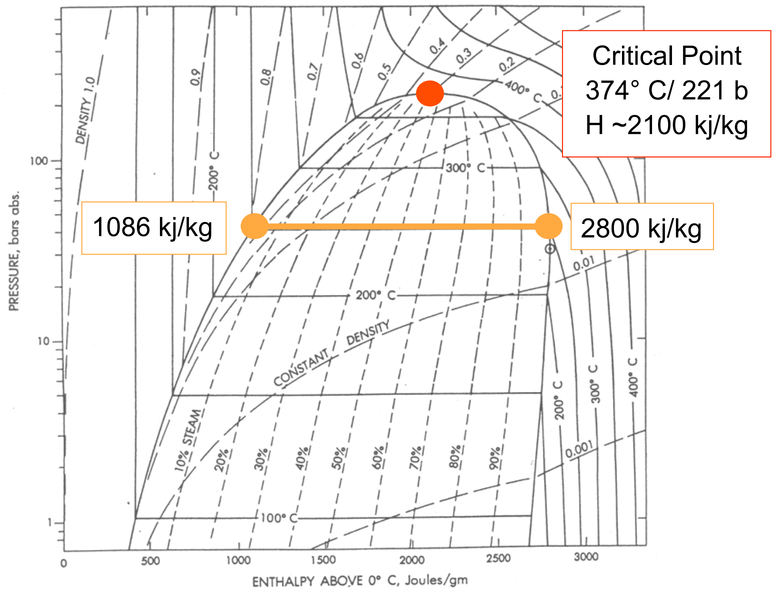




Critical Point: 374° C, 221 b
Enthalpy (H): 2100 kilojoules/kg

At 250° C H_{water}=1086 kj/kg
H_{vapor}=2800 kj/kg

Energy in Fluid: Vapor versus liquid H_2O



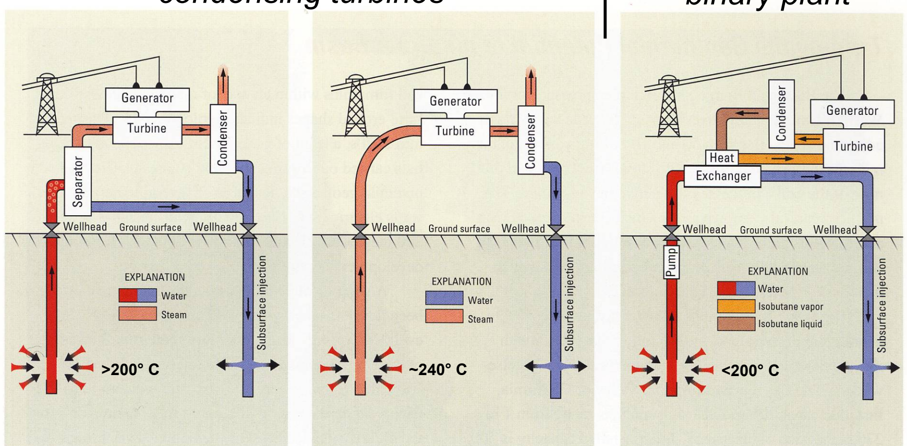
Energy in Fluid: Vapor versus liquid H_2O

Vapor contains more thermal energy/ kilogram than hot water at the same temperature and pressure.

Power stations can be run on wells producing vapor-only, a mixture of liquid and vapor, and liquid-only (under pressure).

Power Cycles & Electricity Generation

condensing turbines — *binary plant*



Graphics: Duffield & Sass, 2003

liquid-dominated reservoir | **vapor-dominated reservoir** | **liquid-dominated reservoir**

Classification

Geothermal systems are classified based on temperature & mode of heat transfer (e.g., Ellis & Mahon, 1977; Hochstein, 1992)

Hochstein (1992)	
Temperature	Low (<125 °C)
	Intermediate (125 to 225 °C)
	High (>225 °C)
Ellis and Mahon (1977)	
Cyclic	Convective heat transfer/fluid flow
	associated with volcanic activity
	hydro-pressured
Storage	Water stored in rock formation (naturally stagnant)
	sedimentary basins
	geo-pressured

Classification

Hochstein (1992)

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Ellis and Mahon (1977)

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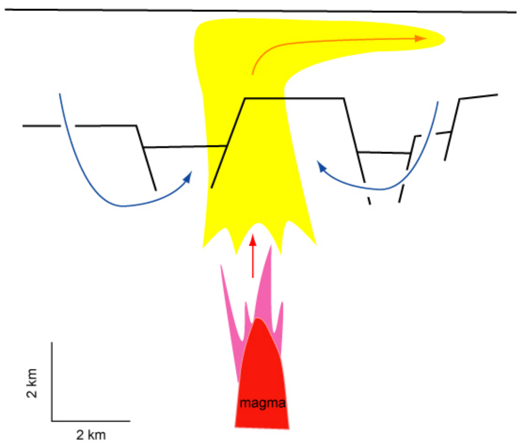
Classification

High Temperature Systems--Reservoirs

Liquid Dominated:	Common, most abundant Wells produce steam & liquid Fractures & pores filled with hot water Max temperature gradient is boiling point for depth Steam zones can develop with production
Vapor Dominated	Uncommon, but very attractive Wells produce dry steam (little liquid waste) Isothermal with depth (max ~ 235° C) Fractures & pores filled with steam (vapor) & hot water; vapor is mobile while the liquid is static

Classification

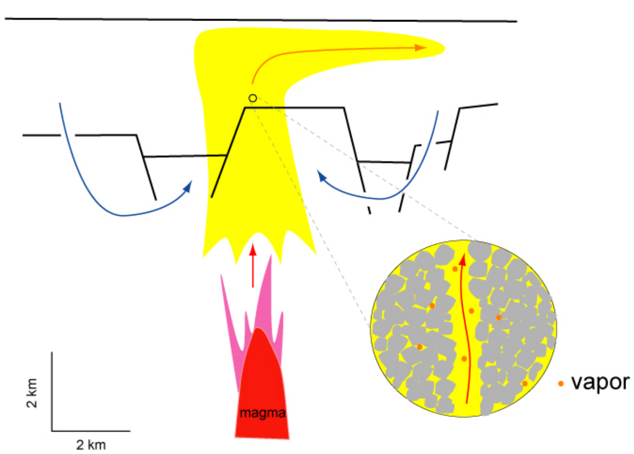
Liquid Dominated



Cartoon showing essential parts to a high temperature geothermal system, including magmatic intrusion at depth, inflowing cold meteoric water, and rising geothermal water.

Classification

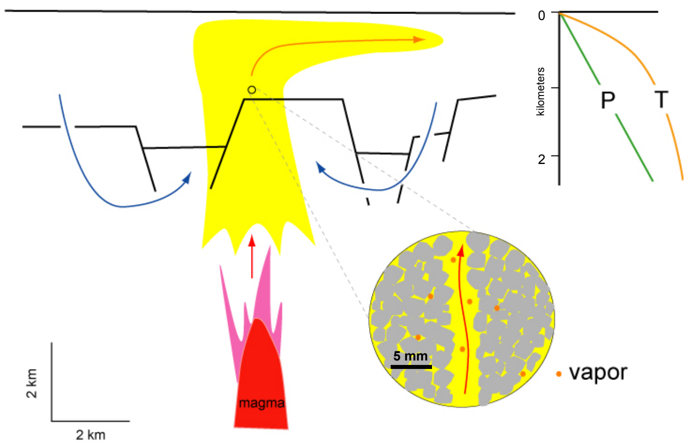
Liquid Dominated



The inset is a magnified view of the rock matrix cut by a open vertical fracture through which geothermal water rises. The small orange dots represent vapor so the fluid is just at boiling temperature.

Liquid Dominated

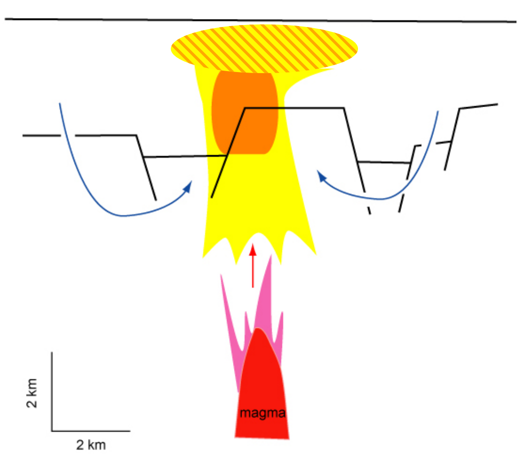
Classification



The graphs on the right show how pressure (P) increases linearly with depth due to the weight of the hot water column (hot hydrostatic); the corresponding temperature represents the boiling point for depth curve.

Vapor Dominated

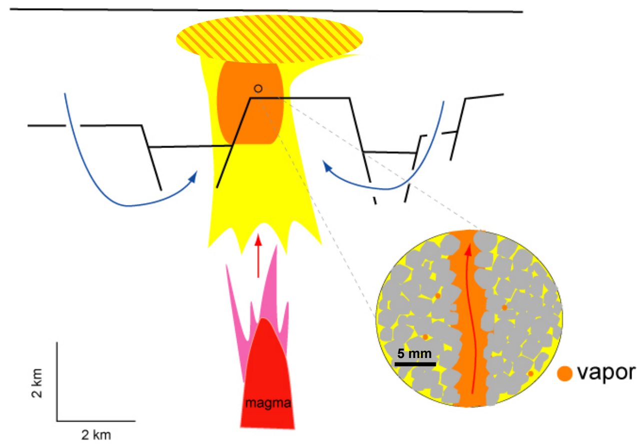
Classification



Cartoon showing essential parts to a high temperature geothermal system with a vapor dominated reservoir. Note, low permeability rocks surround the vapor zone.

Classification

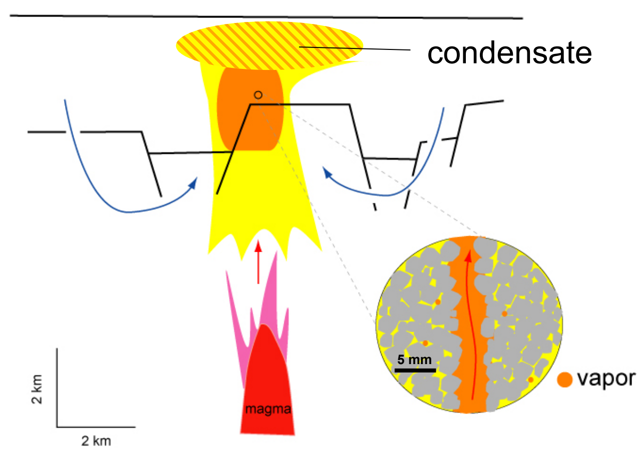
Vapor Dominated



The inset is a magnified view of the rock matrix cut by a open vertical fracture through which vapor and gases rise, while the liquid water is immobile and effectively locked into the pore space in the rock matrix.

Classification

Vapor Dominated



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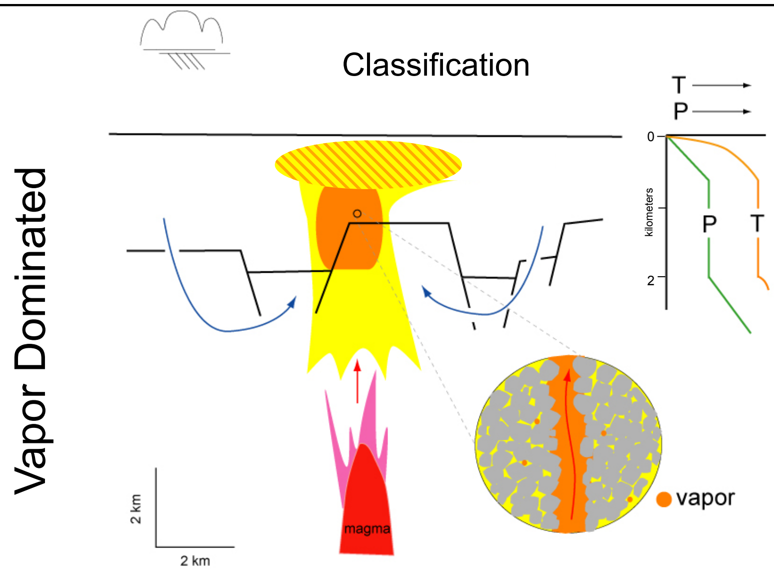
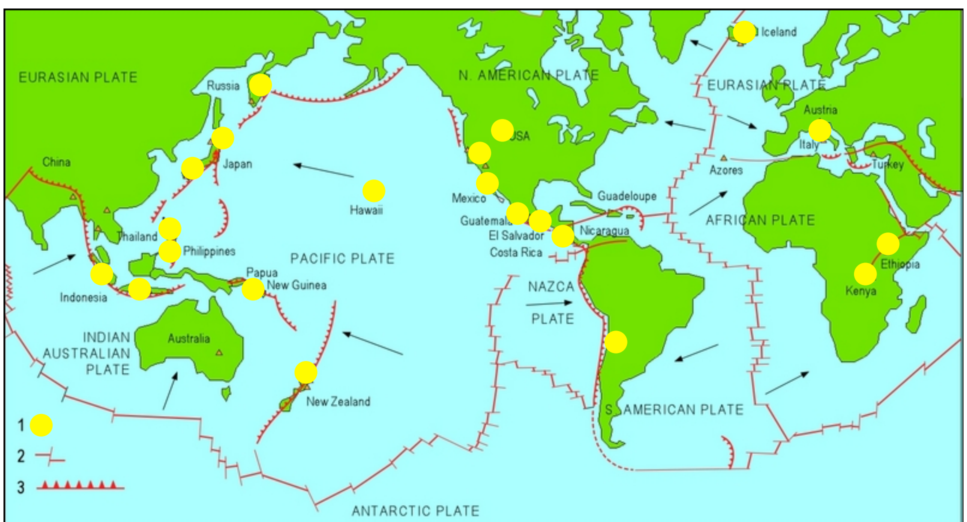
Classification



The graphs on the right show how pressure (P) and temperature (T) have vertical gradients through the vapor dominated zone, with a maximum temperature of ~235 °C.



DISTRIBUTION & OCCURRENCE

High temperature systems occur along plate boundaries, including: 1) mid-ocean ridges and continental rifts (Olkaria, Kenya; Aluto, Ethiopia) ; 2) ocean island (Hawaii, Iceland) and continental hot spots (Yellowstone, USA); 3) volcanic-magmatic arcs (Taupo Volc Zone, New Zealand, Sumatra & Java, Indonesia; Philippines; S. Kyushu, Japan; Central Mexico; El Salvador, Nicaragua, Costa Rica, Lardarello, Italy).

Plate Tectonic Settings

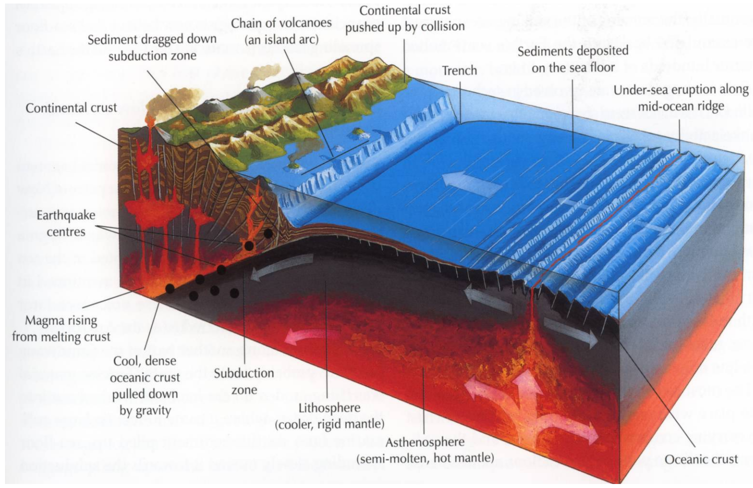


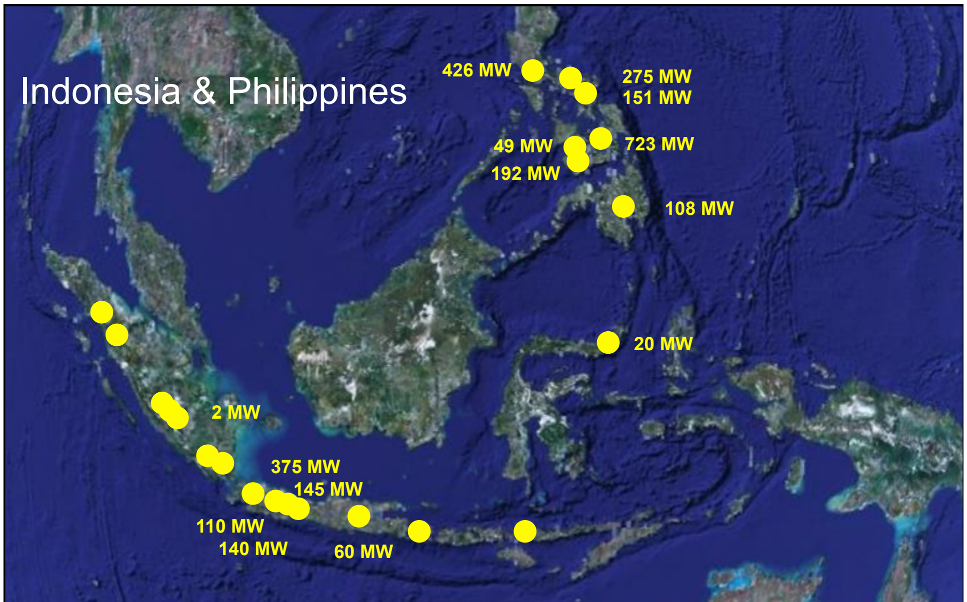
Plate tectonic setting: high temperature geothermal systems occur where magma intrudes to shallow levels in the crust and erupts through to the surface. The above diagram show a mid-ocean spreading center (divergent plate boundary) and a volcanic arc forming above a subduction zone (convergent plate boundary). Hydrothermal activity in oceanic & continental rifts is associated with mafic (± felsic) magmatism, whereas in volcanic arcs, it is more strongly associated with andesitic-dacitic composition magmas.

Note: oceanic crust ranges 5-10 km thickness and is made of mafic igneous rock; continental crust is ≥ 35 km and is made of mainly granitic composition rock.

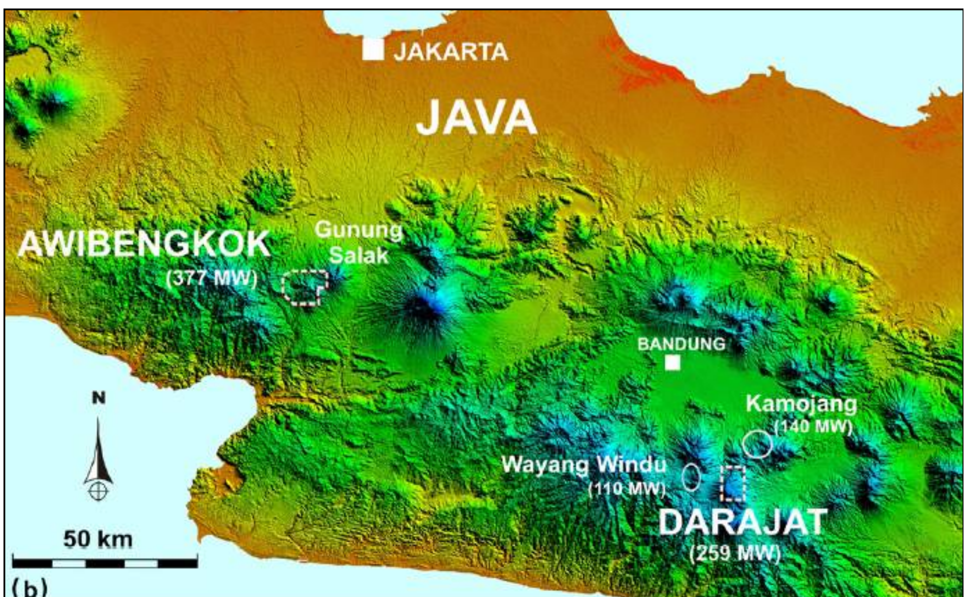
Plate Tectonic Settings

The highest and most intense heat transfer occurs along mid-ocean spreading centers, and hydrothermal activity is strongly developed throughout ocean basins along these active plate margins. However, they are mainly inaccessible to exploitation as an energy resource even though vents discharge at >300 °C on the ocean floor. The mid-ocean ridge system becomes sub-aerial in Iceland and here we can see geothermal systems convecting seawater (Rekjanes) as well as meteoric water (e.g. Krafla). The combination of mafic magmatism (which are the hottest melts at ~1100 °C) and tectonic extension are highly conducive to geothermal activity.

Heat transfer in volcanic arc is less than mid-ocean ridges and also highly variable. The Taupo Volcanic Zone (NZ) is one of the premier thermal belts in the world with 4000-5000 MW_t, but the heat flow can be considerably lower than this. The majority (~70%) of high temperature geothermal systems that are being exploited lie in this setting (e.g., Indonesia, Philippines, NZ). Systems typically have natural heat flows of 30 to 300 MW_t.

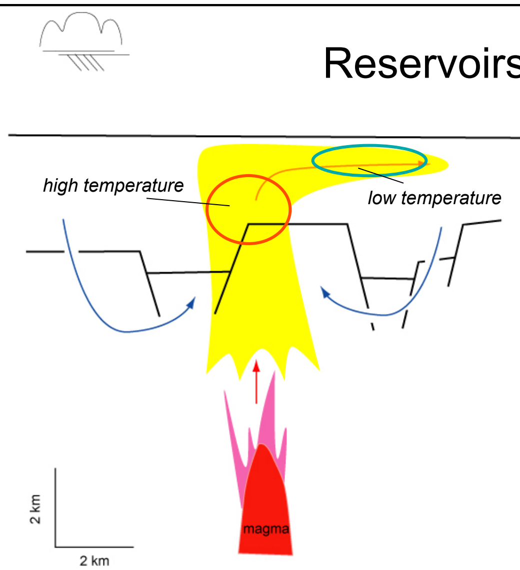


Map from Google Earth showing the Indonesia-Philippine archipelago and the locations of high temperature geothermal systems; values represent plant generation.



High temperature geothermal systems in west Java (image from Stimac et al, 2008).

Reservoirs



The reservoir represents the volume of rock from which thermal energy can be extracted economically. If you have a direct use application, then the low temperature outflow zone might be adequate; for electricity generation the reservoir occupies the higher temperature upflow zone.

Exploration & Development

The discovery of permeable zones containing hot water is a difficult task, considering the huge cost of drilling (>$5 million/well). Sometimes, you have the thermal energy but the permeability and flow are lacking; other times you have the permeability (circulation losses) but cool temperatures. There is no single tool, other than drilling, that provides the answer. Geoscientists provide information that guide drilling activities, which is can be revised once initial wells are completed and tested

To be effective in the discovery and management of geothermal resources, geoscientists work together and build up an interpretive model of the permeability structure and the flow of hot water, using all the available information. They include reservoir engineers in their discussions when appropriate, especially after a few wells have been drilled and first order numerical simulations can be run computed.

Heat transfer by convection

Life expectancy of a geothermal system is 50,000 to 500,000 years

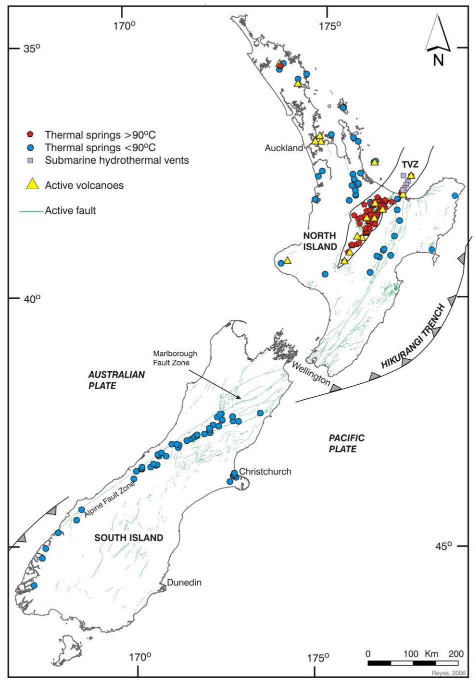
Hot spring 60° C : Low temperature-Cyclic System

High temperature resources:

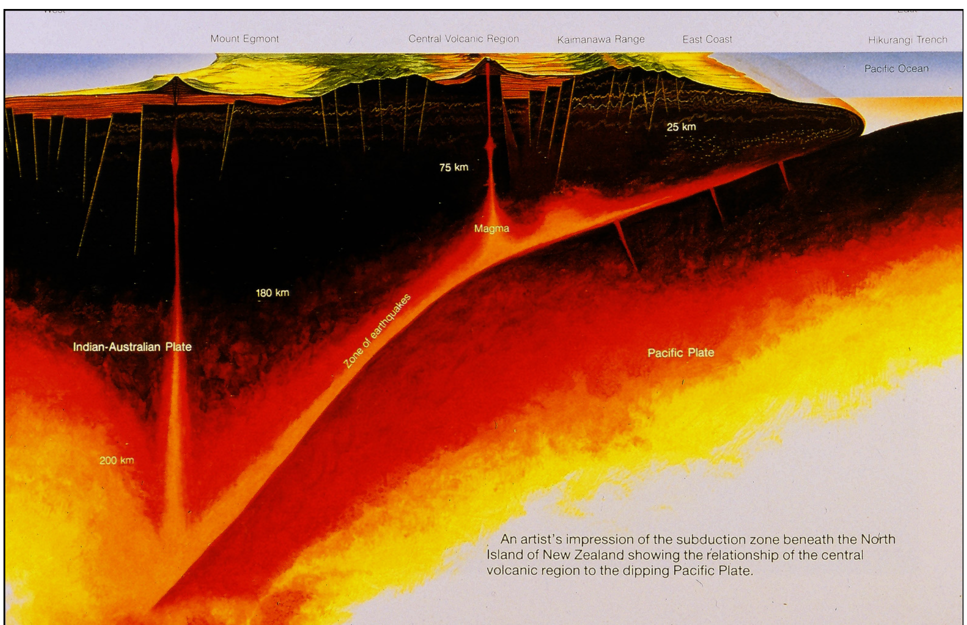
Taupo Volcanic Zone
Northland

Low temperature resources:

Northland
Waikato
East Cape
Alpine Fault



map: Reyes and Jongens, 2003



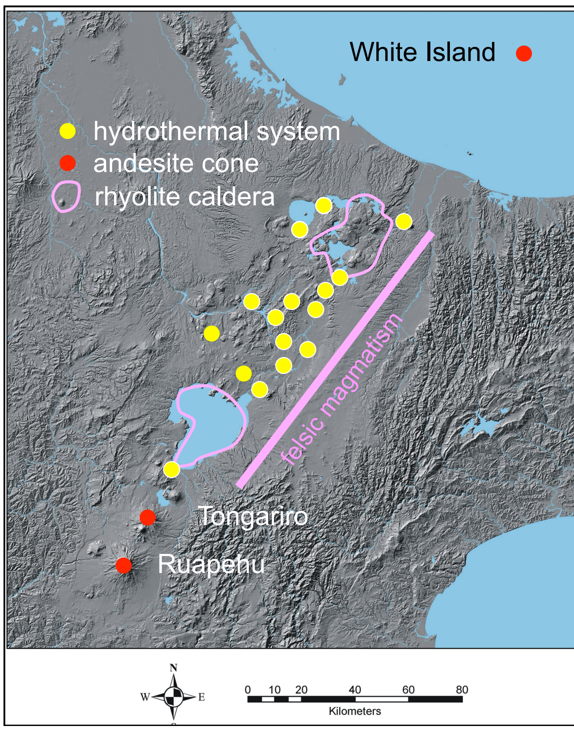
An artist's impression of the subduction zone beneath the North Island of New Zealand showing the relationship of the central volcanic region to the dipping Pacific Plate.

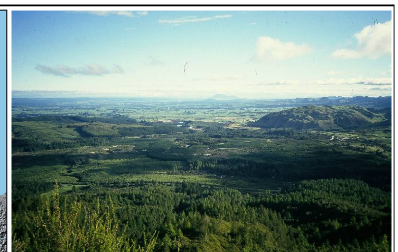
Ngauruhoe eruption, 1975-76

Edgecumbe
Earthquake 1987

M 6.3

Broadlands-Ohaaki





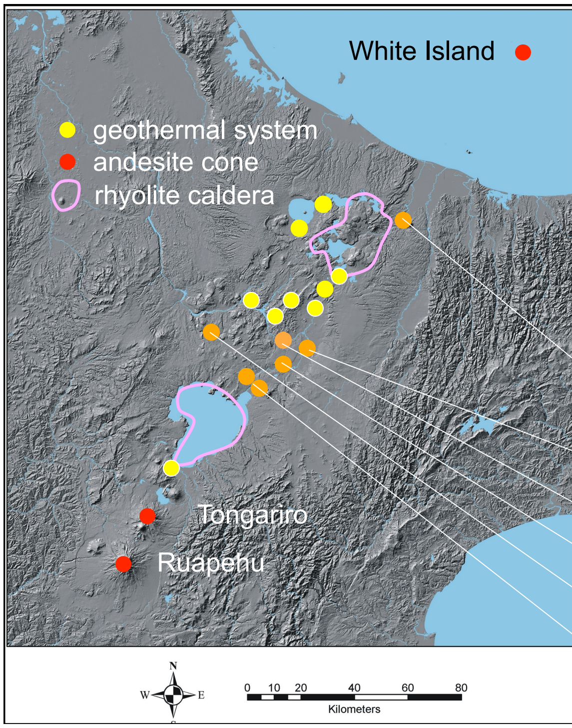
Taupo Volcanic Zone

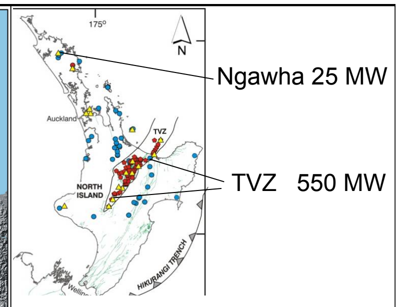
>20 geothermal systems

70% of heat transfer by hydrothermal convection

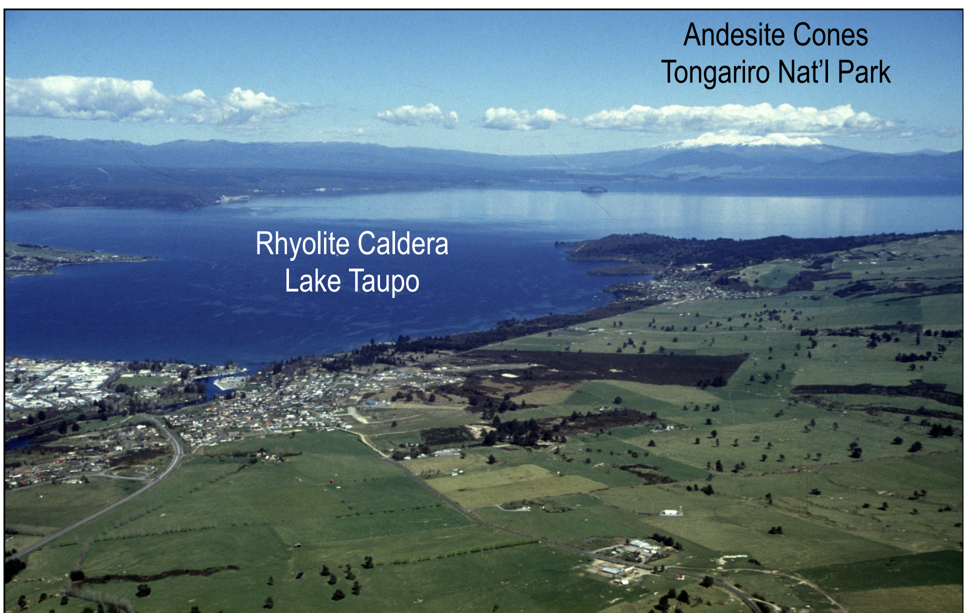
2000 kg/s total fluid flow

Exceptional heat flow

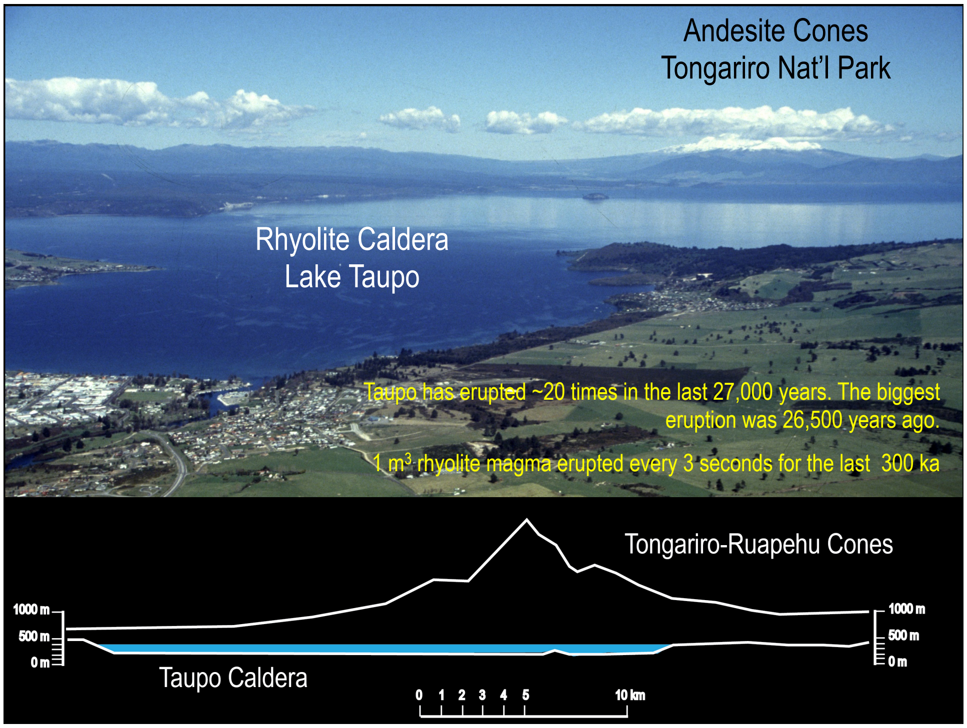


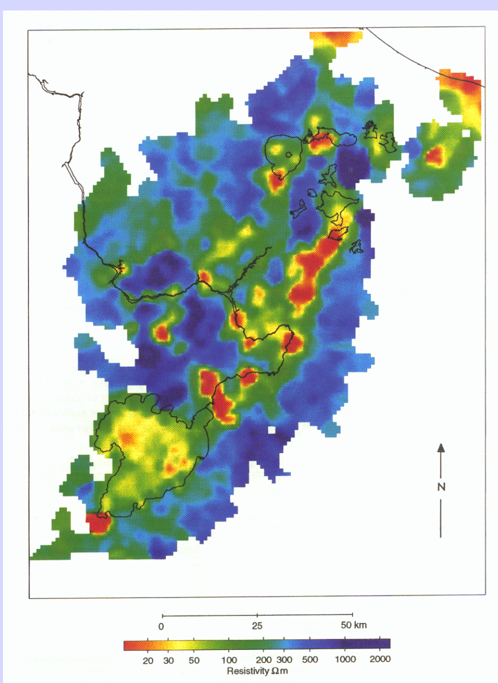


TVZ generation	MW
Kawerau	147
Ohaaki	45 (114)
Ngatamariki	82
Rotokawa	175
Mokai	111
Wairakei-Tauhara	250 (166)



Contrasting volcanic environments & processes





Taupo Volcanic Zone

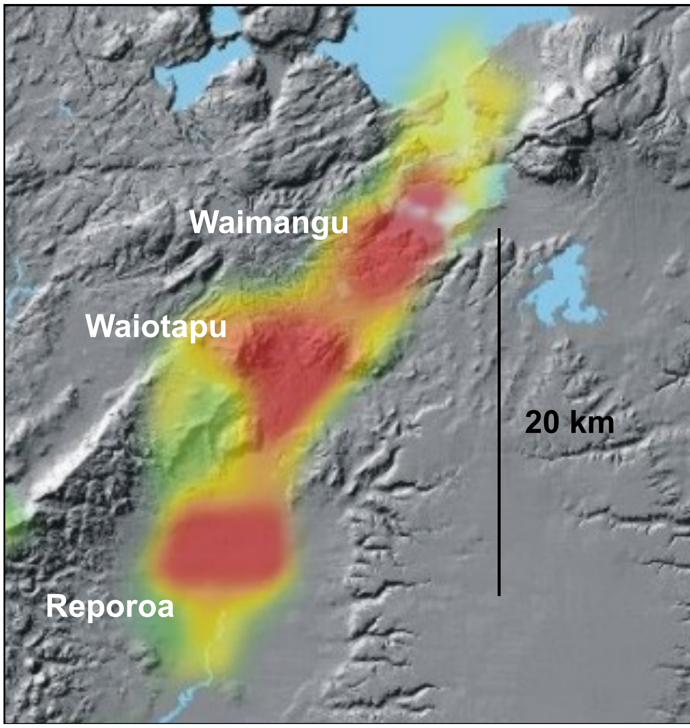
Shallow geophysical surveys – hot water/ altered rocks.

Individual geothermal fields range from 5 to 50 km^2

Resistivity boundaries mark the margins of the resource

Information for land use planning & development

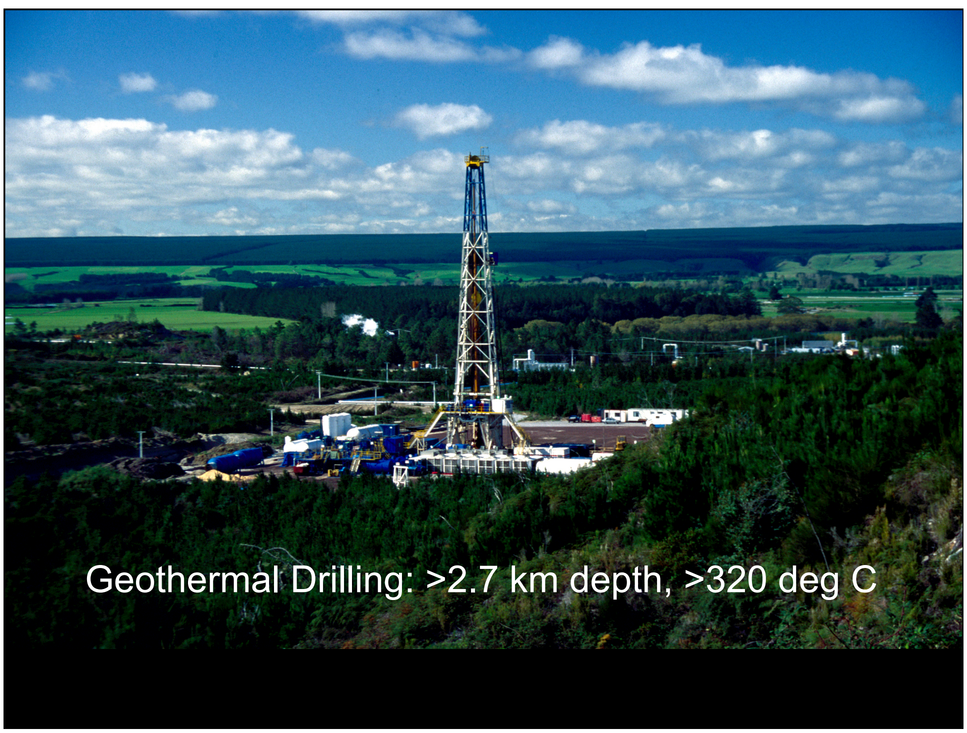
Central TVZ: DC apparent resistivity
(Stagpoole and Bibby, 1998)



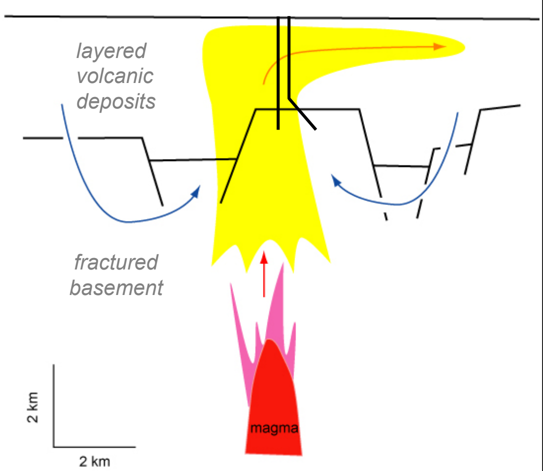
Resistivity pattern:
3 separate centers

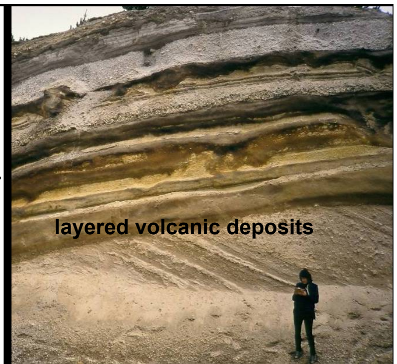
Waimangu
Waiotapu
Reporoa

At what depth
are they
interconnected?

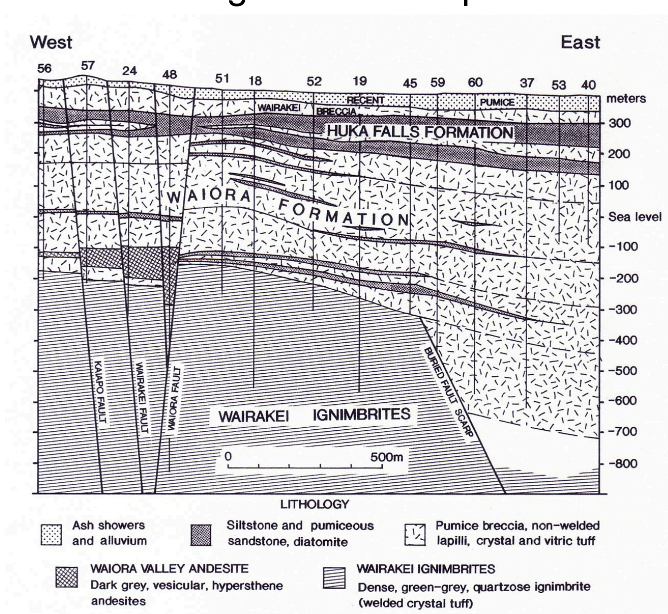


Stratigraphy



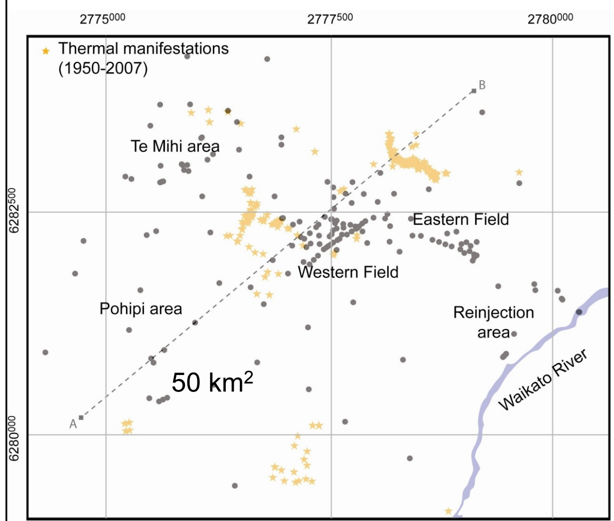


Wells drilled to target faults and permeable strata

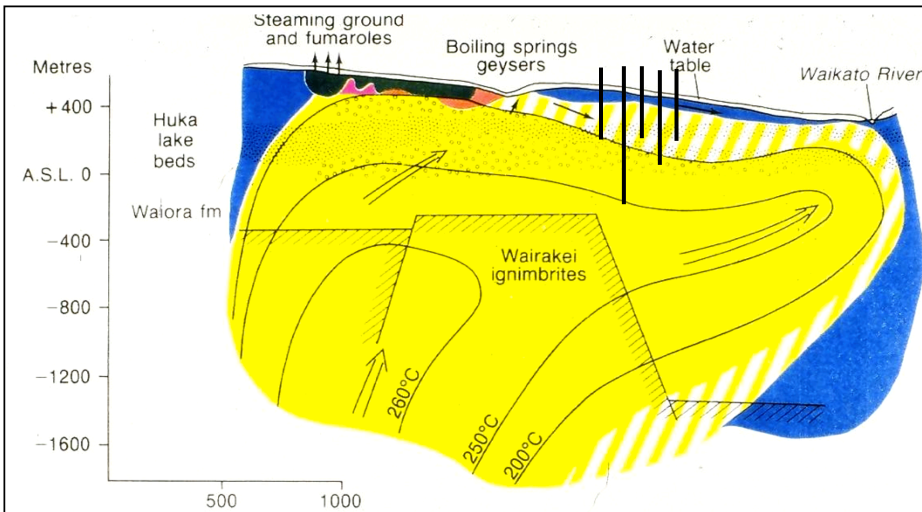


After Grindley (1965)

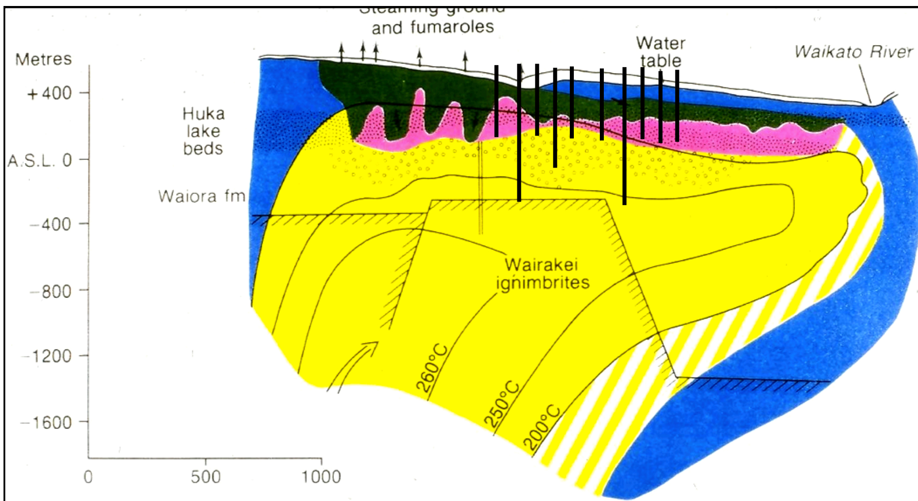
Wairakei: Production



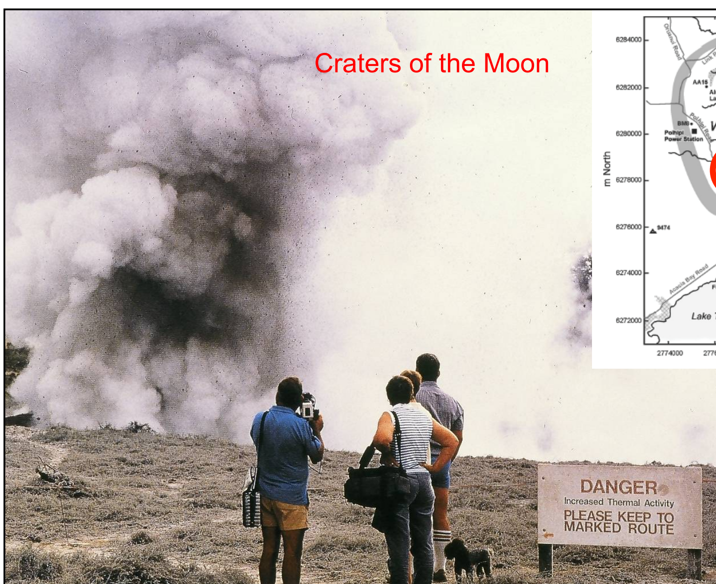
Early wells: eastern field (closely spaced)
Later wells: Te Mihi (widely spaced)

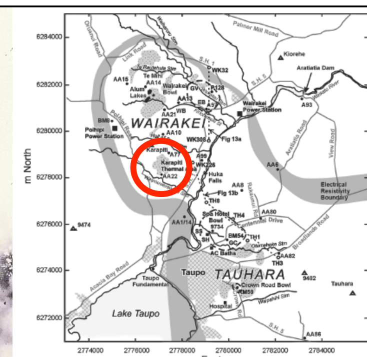


Waiora formation hosts the productive reservoir
Production proceeds without injection
Springs & geysers in Geyser Valley disappear in 1964



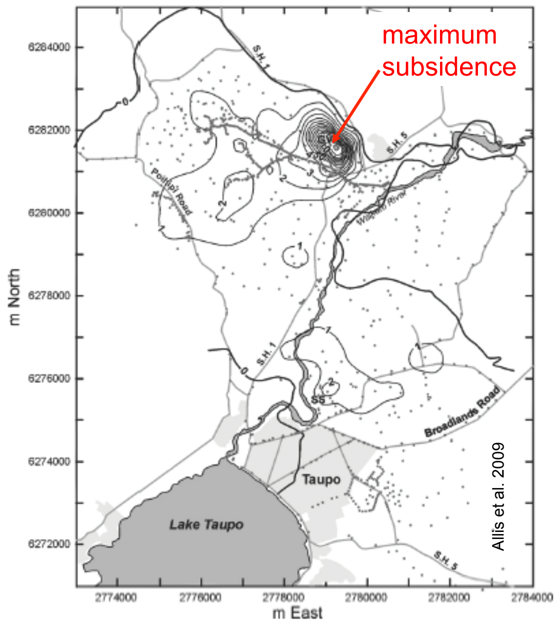
Pressure drops ~25 bar over 20 yr period
Water level drops ~200 m to form shallow steam zone
Hydrothermal eruptions and subsidence ensue





map: Allis et al. 2009
photo: C. Potton

Hydrothermal eruptions: shallow focal depths (<50 m)
unpredictable

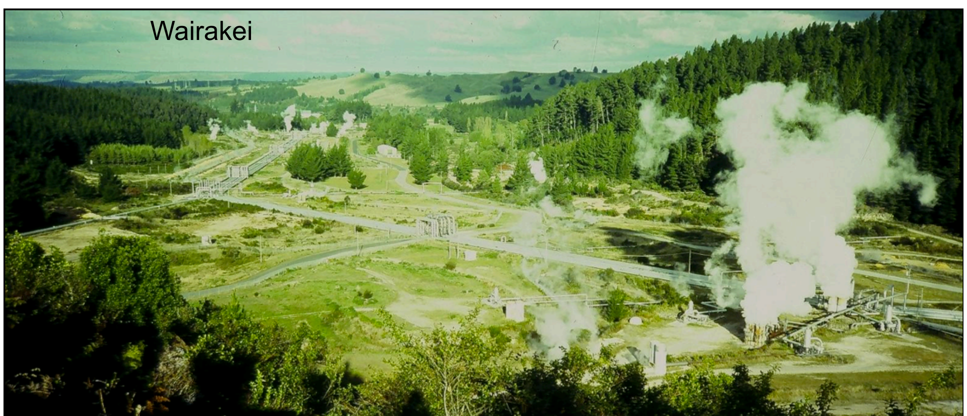


>14 m subsidence concentrated ~1 km^2

>400 mm/yr (maximum)

water loss from shallow aquifers due to reservoir production caused compaction of shallow lake sediments

subsidence rate eventually diminishes



Indigeneous

Sustainable

Renewable

Low greenhouse gas emissions

>50 years of continuous production at Wairakei (>90% load)

Geothermal System