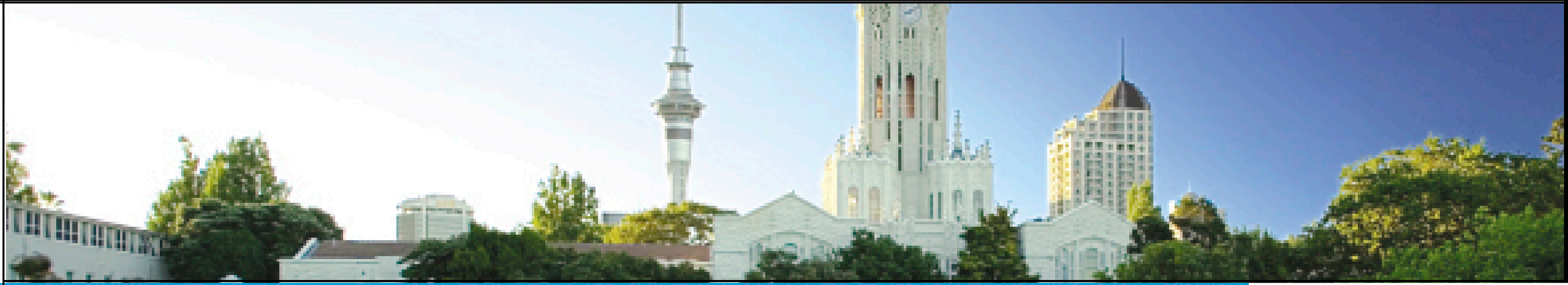


GEOTHERMAL
INSTITUTE

Introduction to geothermal science and engineering

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND
Te Whare Wānanga o Tāmaki Makaurau

John O’Sullivan, Engineering Science
University of Auckland, New Zealand

Welcome

Hola!

Kiaora!

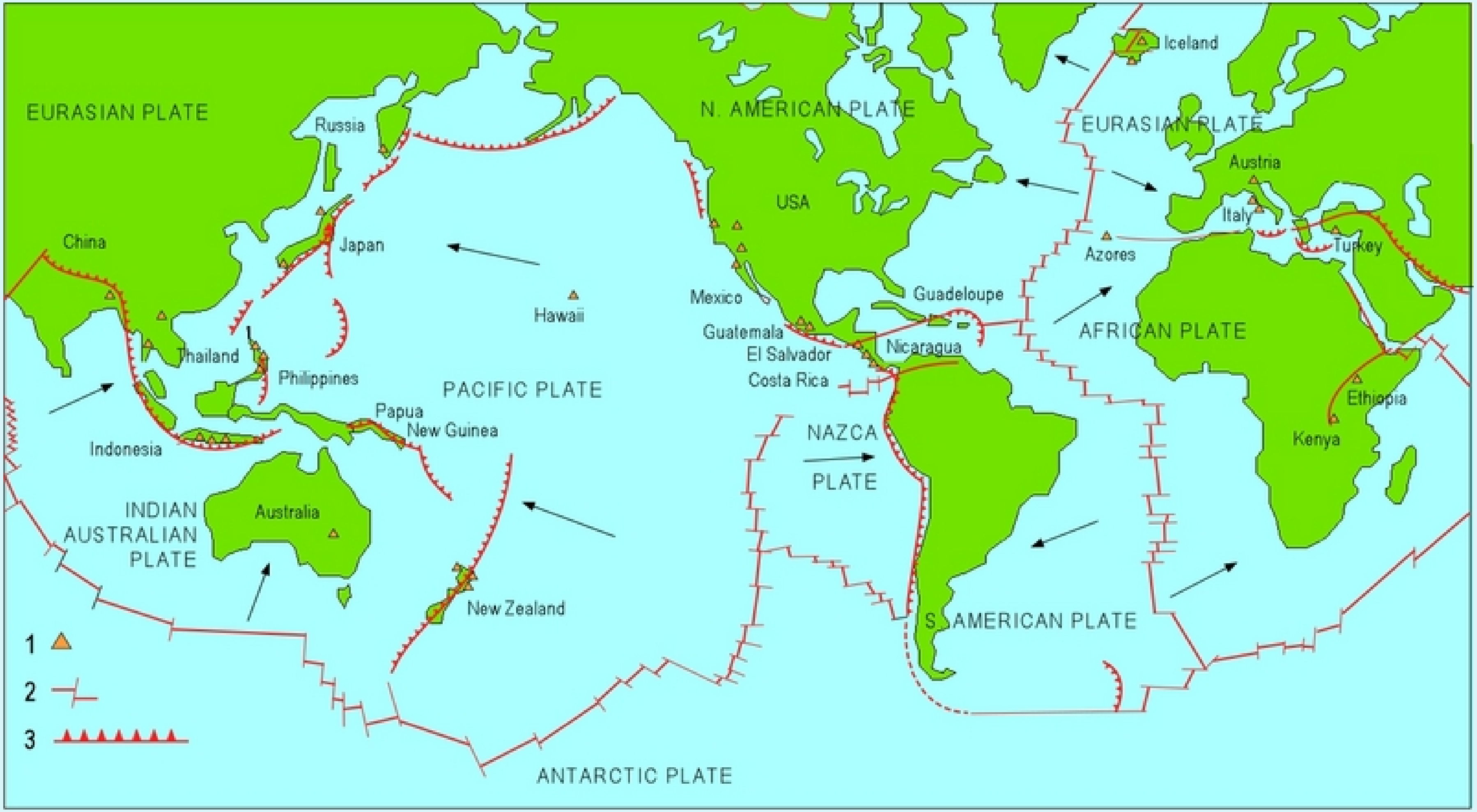
Outline

- Introduction to geothermal energy
- Types of geothermal systems
- Use of geothermal energy

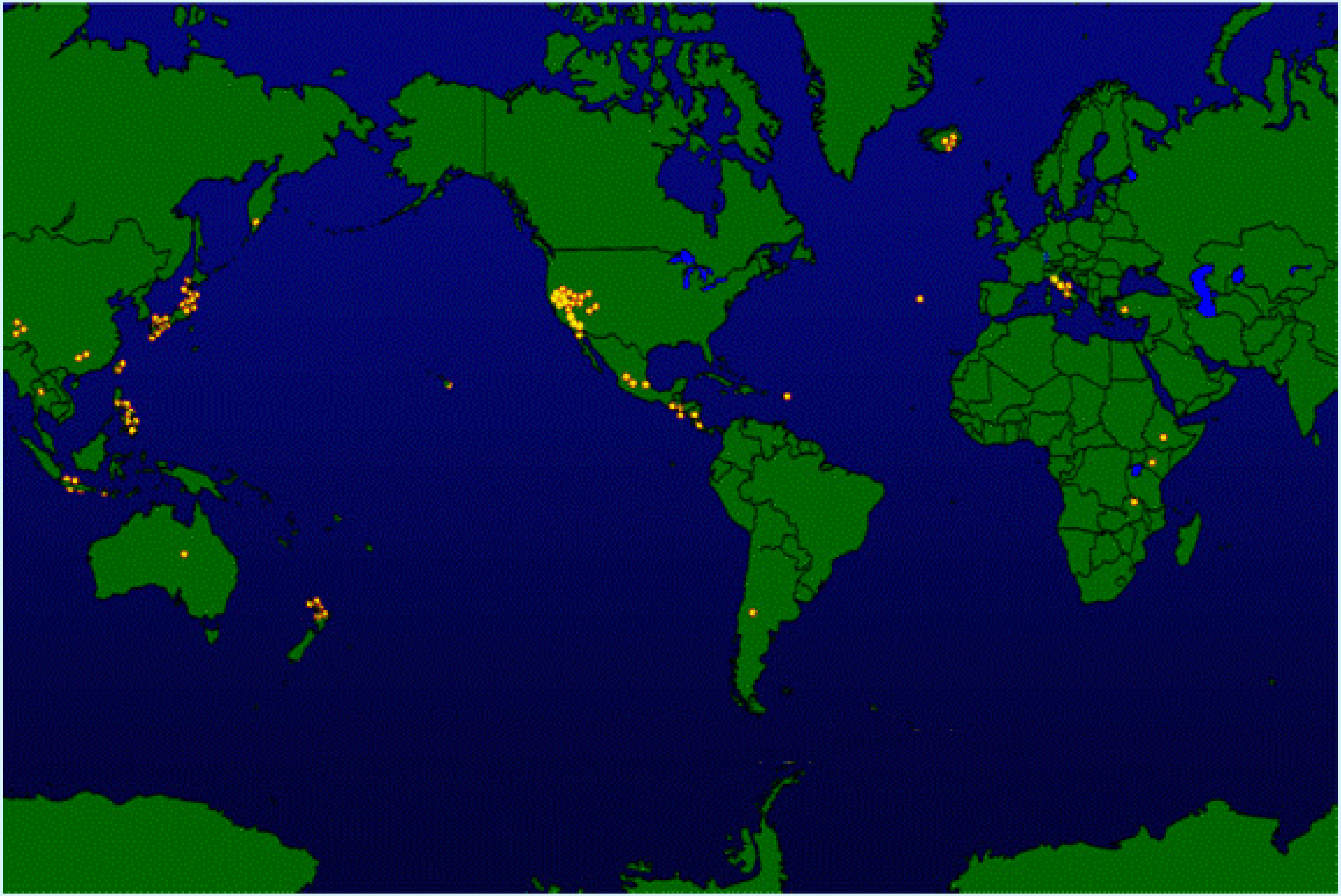
Source of geothermal energy

- Everywhere in the world there is an upward flux of heat at the surface of the earth arising from radioactive decay in the interior.
- The average value of ~65mW/m^2 corresponds to a temperature gradient of 30°C/km (depending on the thermal conductivity of the rock).
- In geothermal areas (at plate boundaries etc) the heat flow is much greater than 65mW/m^2

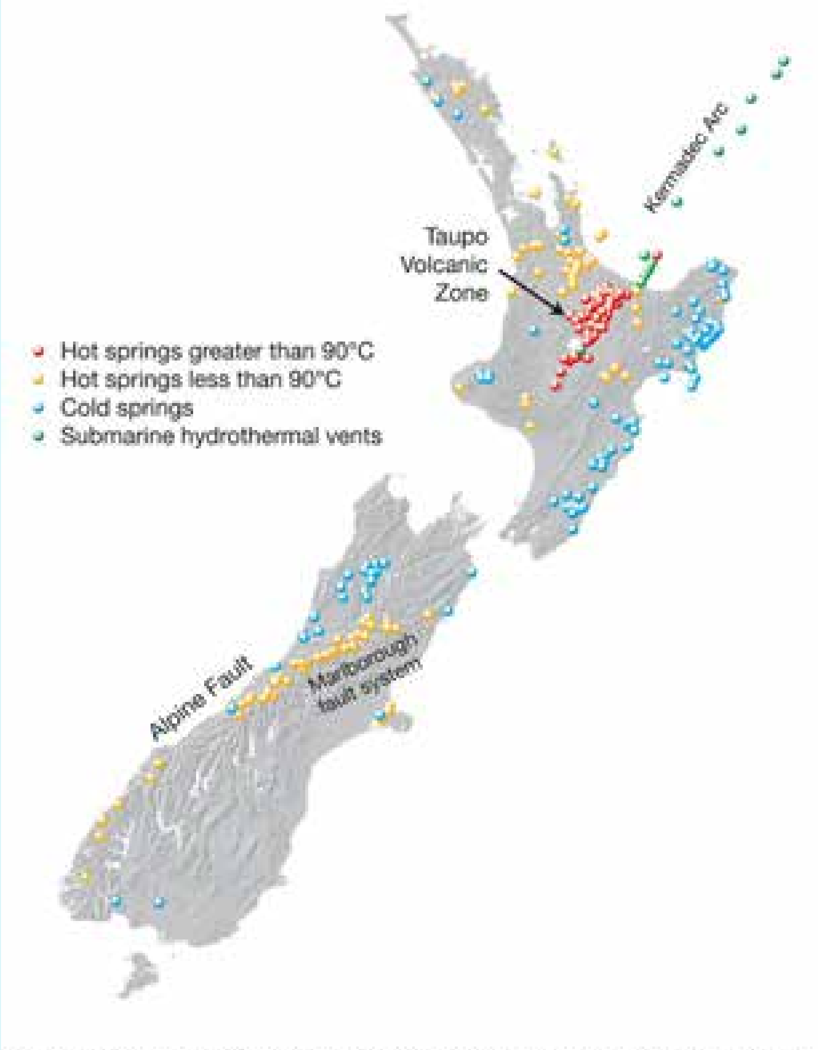
Plates, oceanic ridges, subduction zones, and geothermal fields



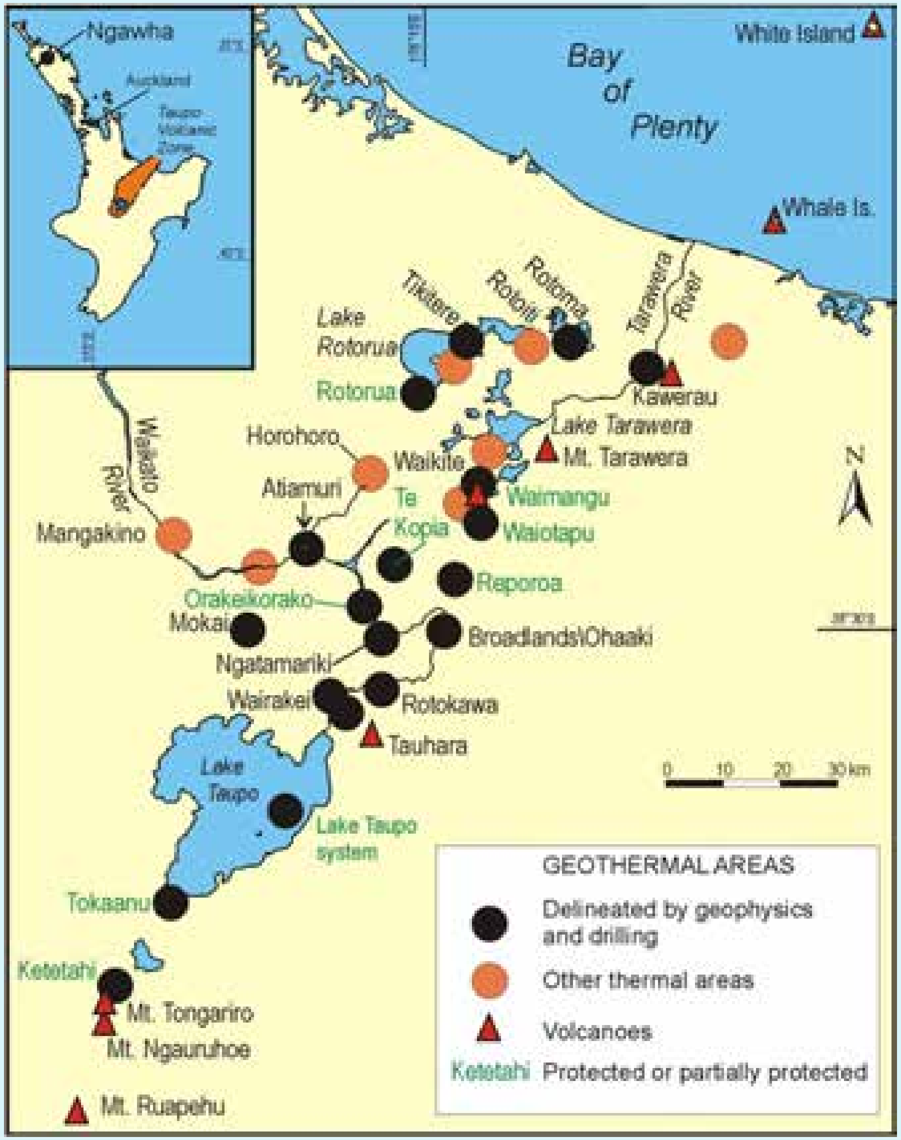
World geothermal developments



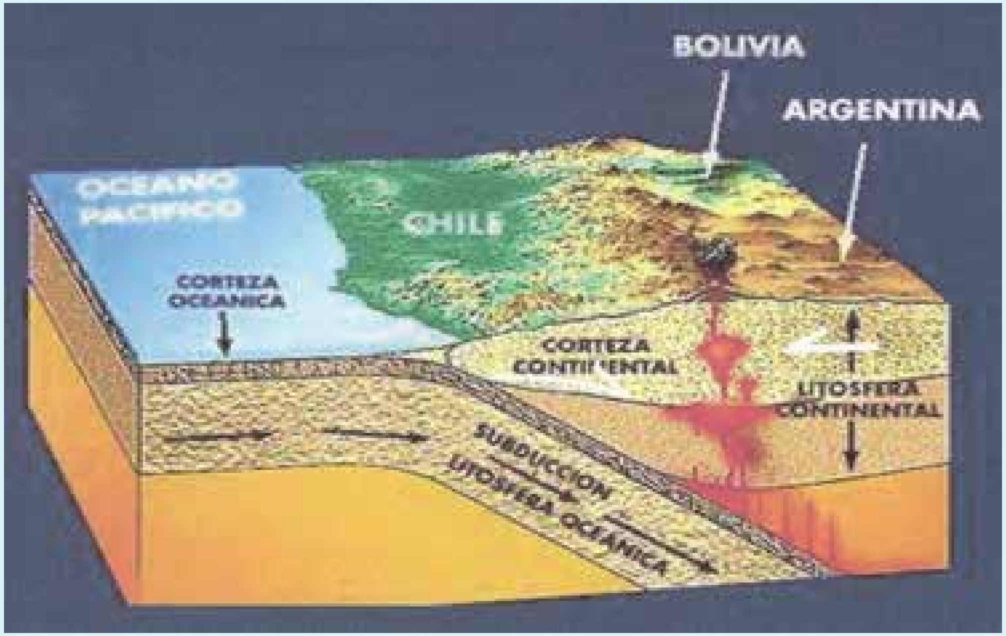
Taupo Volcanic Zone (New Zealand)



From: Reyes A.G. and Christenson B.W. (2008) Mineral waters. In: Graham I. (ed.) A
continent on the move.



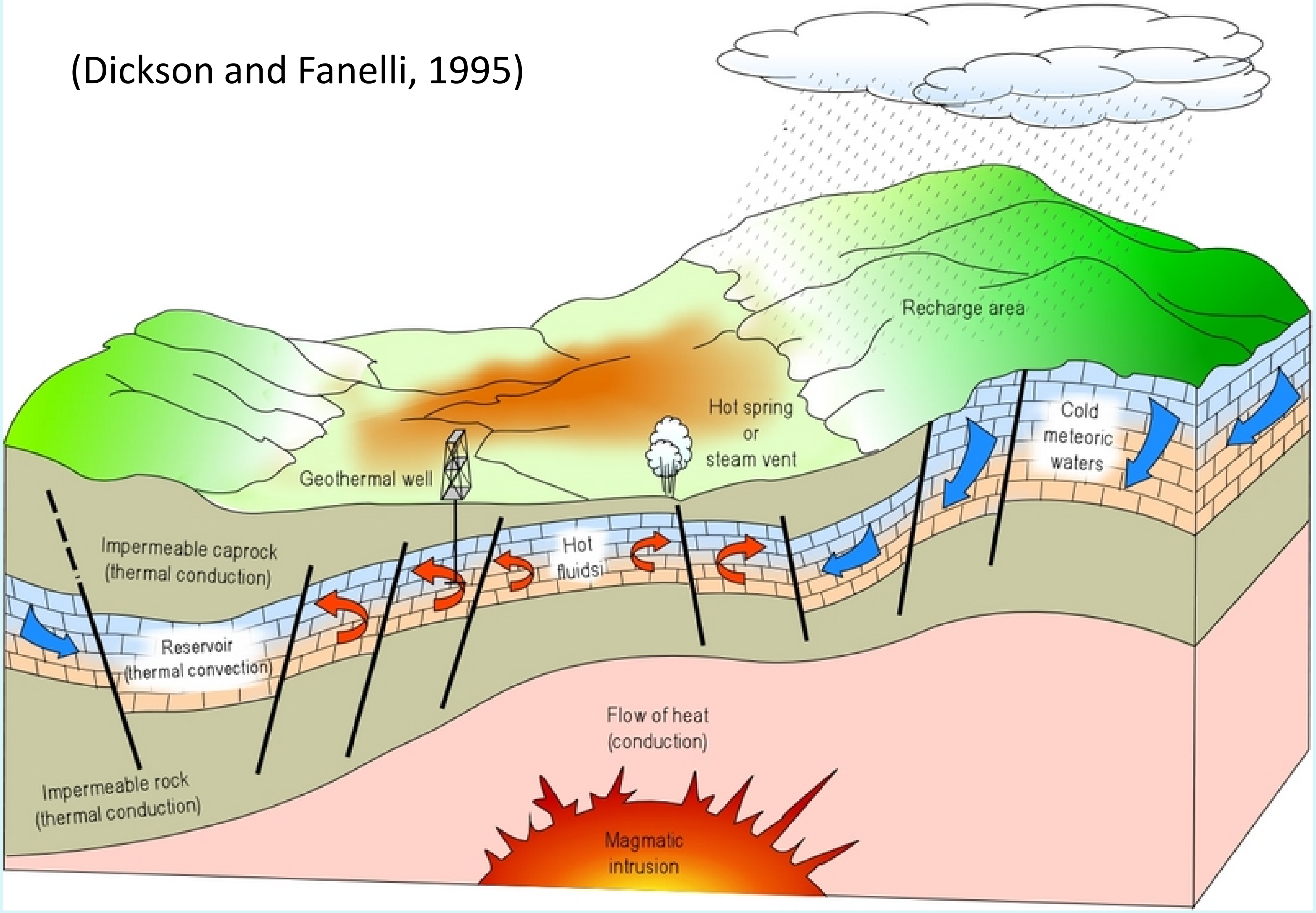
The Andes



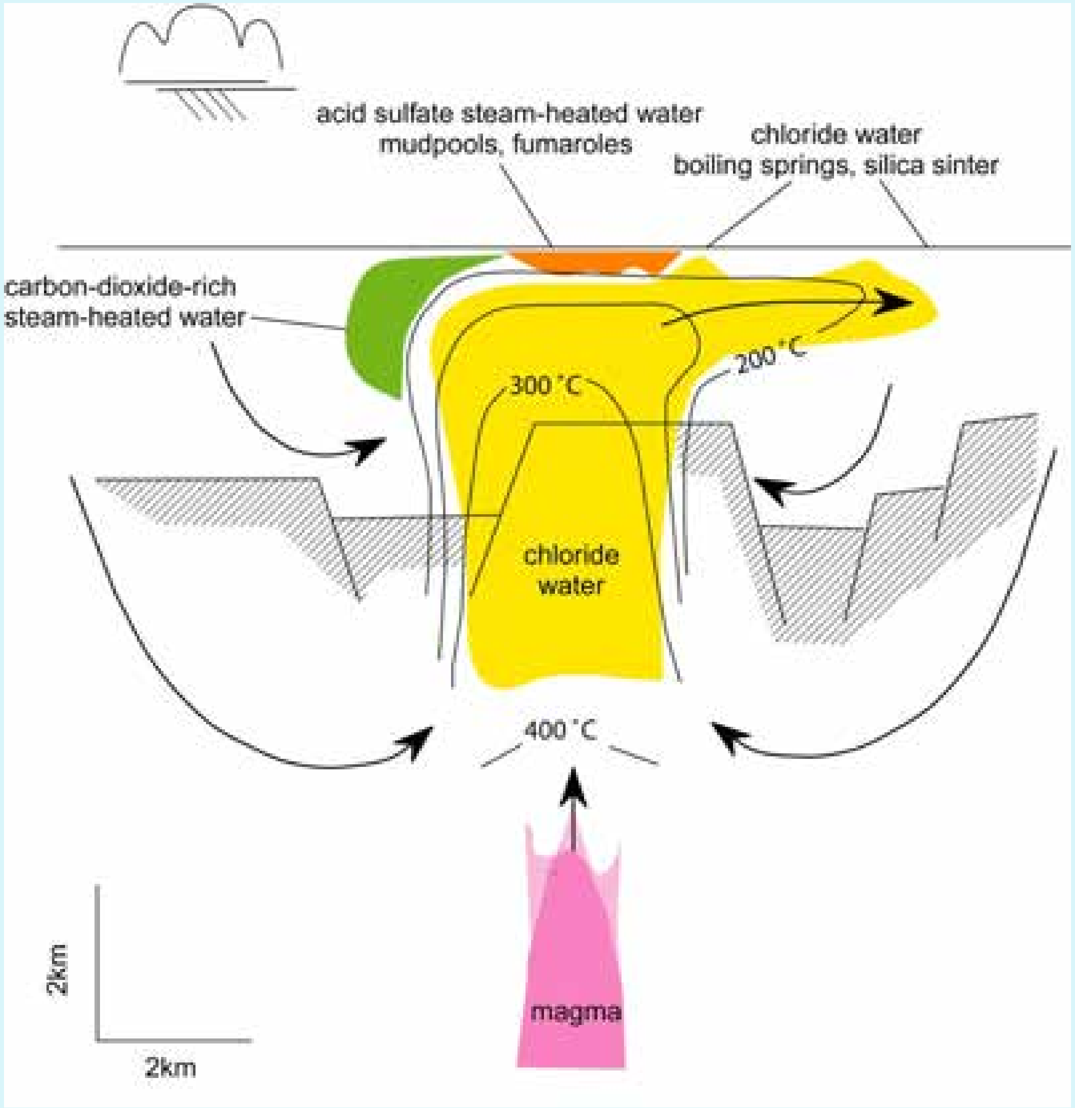
Lahsen et al. 2013

Geothermal systems

(Dickson and Fanelli, 1995)



A simple (hot) geothermal system



Types of geothermal system

- The type of geothermal system depends on the heat flow and the geological setting
- They range from warm water systems where there is no fluid movement and no boiling, up to convecting two-phase systems with lots of boiling underground

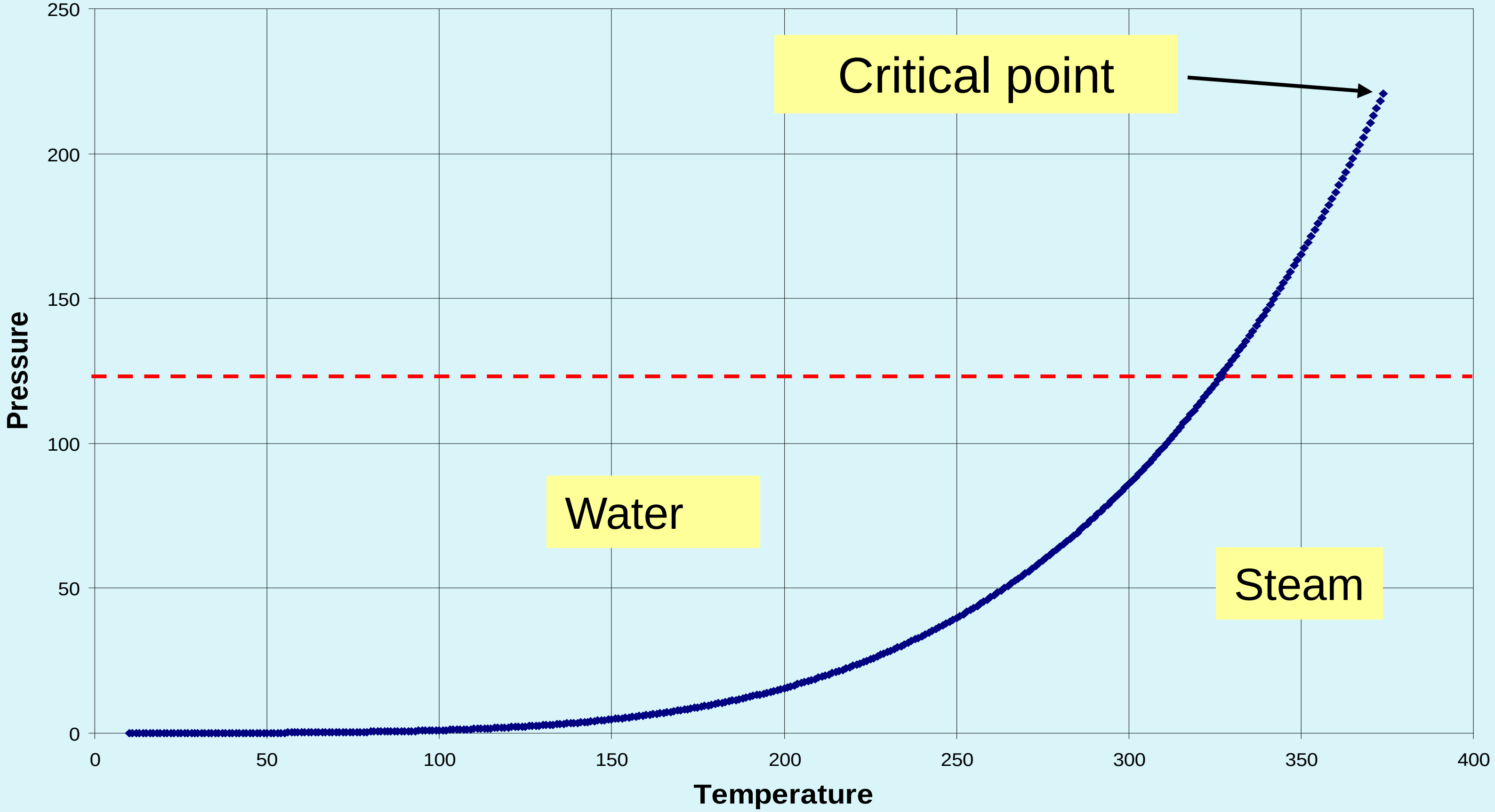
Preliminaries: definitions

- Power is the rate at which energy is being produced (or used)
- Energy is measured in Joules (J)
- Power is measured in Watts (W)
- 1 Watt = 1 Joule/second
- 1 kW = 1000 W & 1 MW = 1000kW
- Enthalpy is the measure of energy contained in water or steam (kJ/kg)

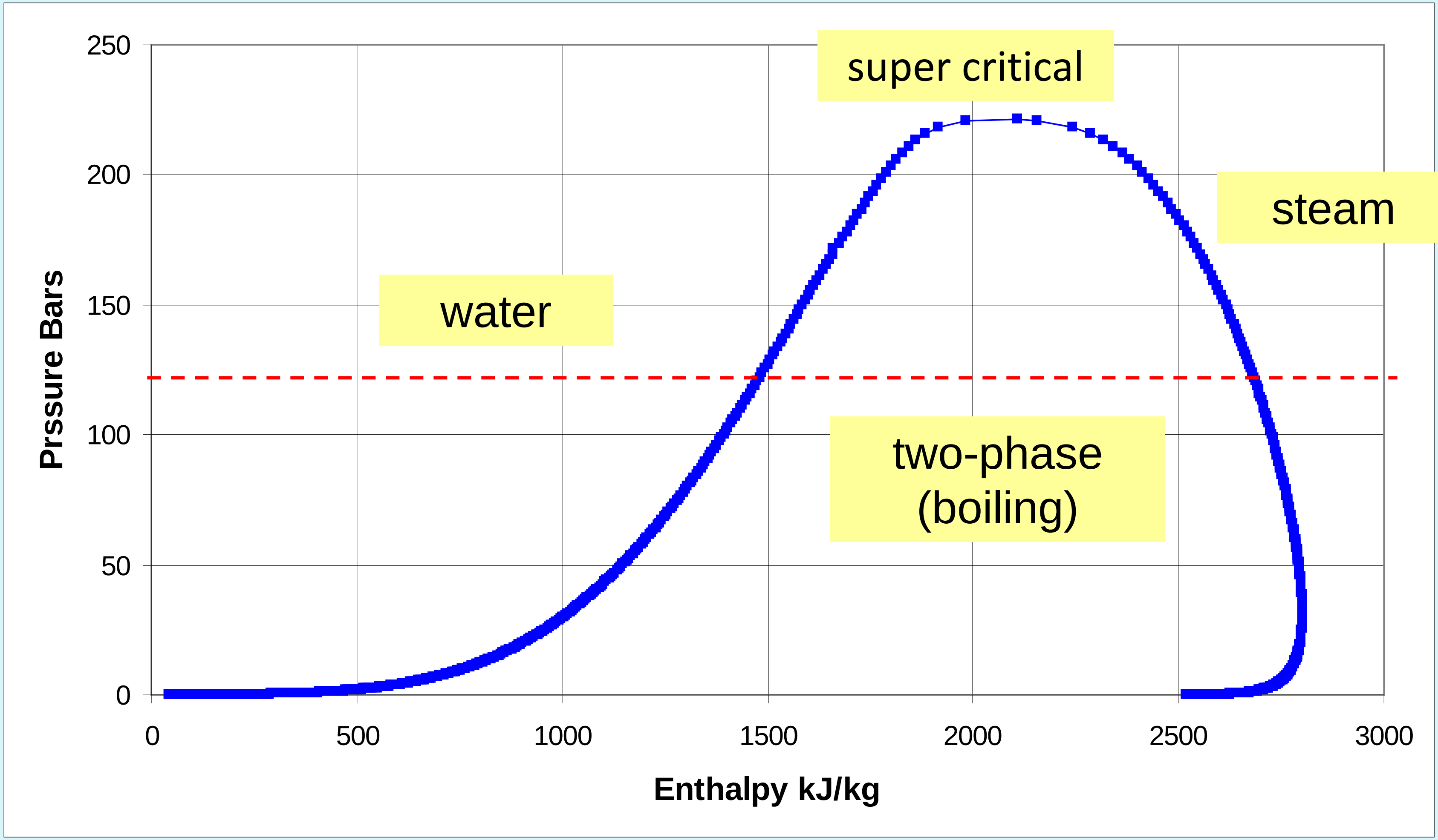
Preliminaries: properties of water

- Before discussing types of geothermal systems we need to quickly review the thermodynamic properties of water
- As liquid water is heated it changes phase by boiling to become steam (a gas phase)
- The boiling point of water depends on pressure

Preliminaries: boiling curve or saturation line for water



Preliminaries: properties of water



Heat transfer mechanisms

Before discussing types of geothermal systems we also need to review the mechanisms for heat transfer that operate in a geothermal system:

- **Conduction**
- **Convection**
- **Counter-flow**

Heat transfer mechanisms: Conduction

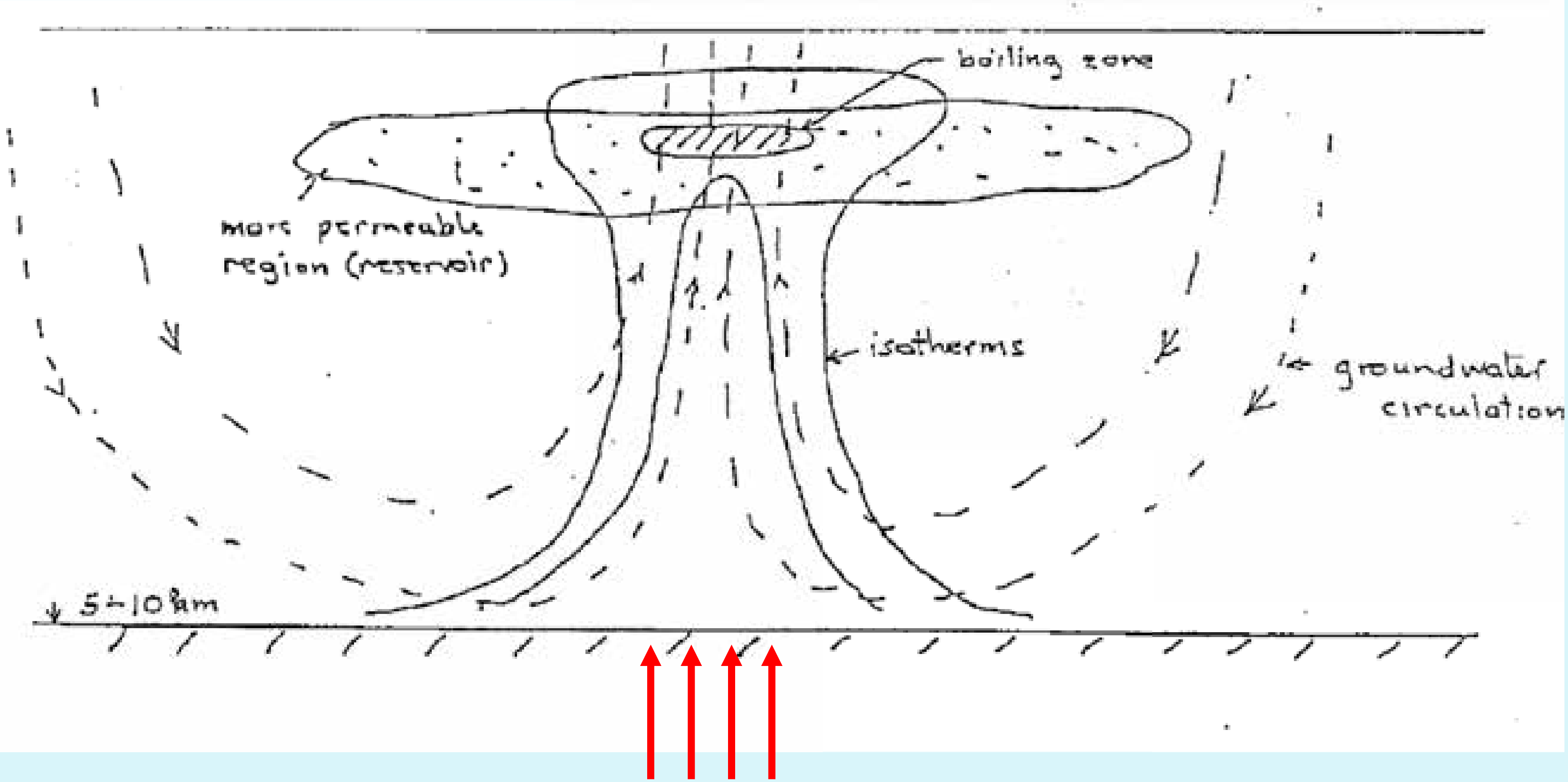
- **Conduction** – heat flows from a hot temperature to a cold temperature (no fluid movement)
- Heat flow = conductivity x temperature gradient

Heat transfer mechanisms: Convection

- **Convection** – in hot geothermal systems there is a large scale movement of water (called convection), with hot water rising. Heat moves with the hot water.
- Heat flow = mass flow x enthalpy
- Requires pathways for water to move:

<u>PERMEABILITY</u>

A convective geothermal system



heat

Heat transfer mechanisms: Counter-flow

- **Counter-flow** in some geothermal systems there is a boiling zone containing water and steam. Here water trickles down and steam rises. This process is called counter-flow
- Transfers heat (even though it may not transfer much mass) because the enthalpy of steam is higher than the enthalpy of water

- Heat flow = steam rising – water trickling down
- Also requires pathways (permeability)

Main categories of geothermal systems

Category		Temperature (T)	Production Enthalpy (h)
Warm water (low temperature)		T < 125°C	h < 600 kJ/kg
Hot water (intermediate temperature)		T < 225°C	h < 1000 kJ/kg
Two-phase (high temperature)	low-enthalpy (very hot water)	225°C < T < 270°C	1000 kJ/kg <h<1300 kJ/kg
	high enthalpy (boiling water and steam)	250°C <T< 330°C	1300 kJ/kg <h<2500 kJ/kg
	vapour – dominated (dry steam)	250°C <T< 330°C	2500 kJ/kg <h<2800 kJ/kg

Heat transfer in geothermal systems

Category		Heat transfer mechanisms
Warm water (low temperature)		Conduction
Hot water (intermediate temperature)		Convection
Two-phase (high temperature)	low-enthalpy	Strong convection Some counter-flow
	high enthalpy	Moderate convection Counter-flow
	vapour - dominated	Negligible convection Counter-flow, conduction

Warm water systems

Geothermal pool in Hungary

Warm water systems

- In <u>warm water</u> systems the heat transfer mechanism is conduction alone. There is no convective circulation of groundwater.
- Boiling does not occur in the reservoir even during exploitation.
- They are mainly used for direct use, non-electrical purposes. Binary plants are now being produced that can use water at ~ 90ºC
- Very common worldwide

Hot water systems

Hotwater Beach, NZ

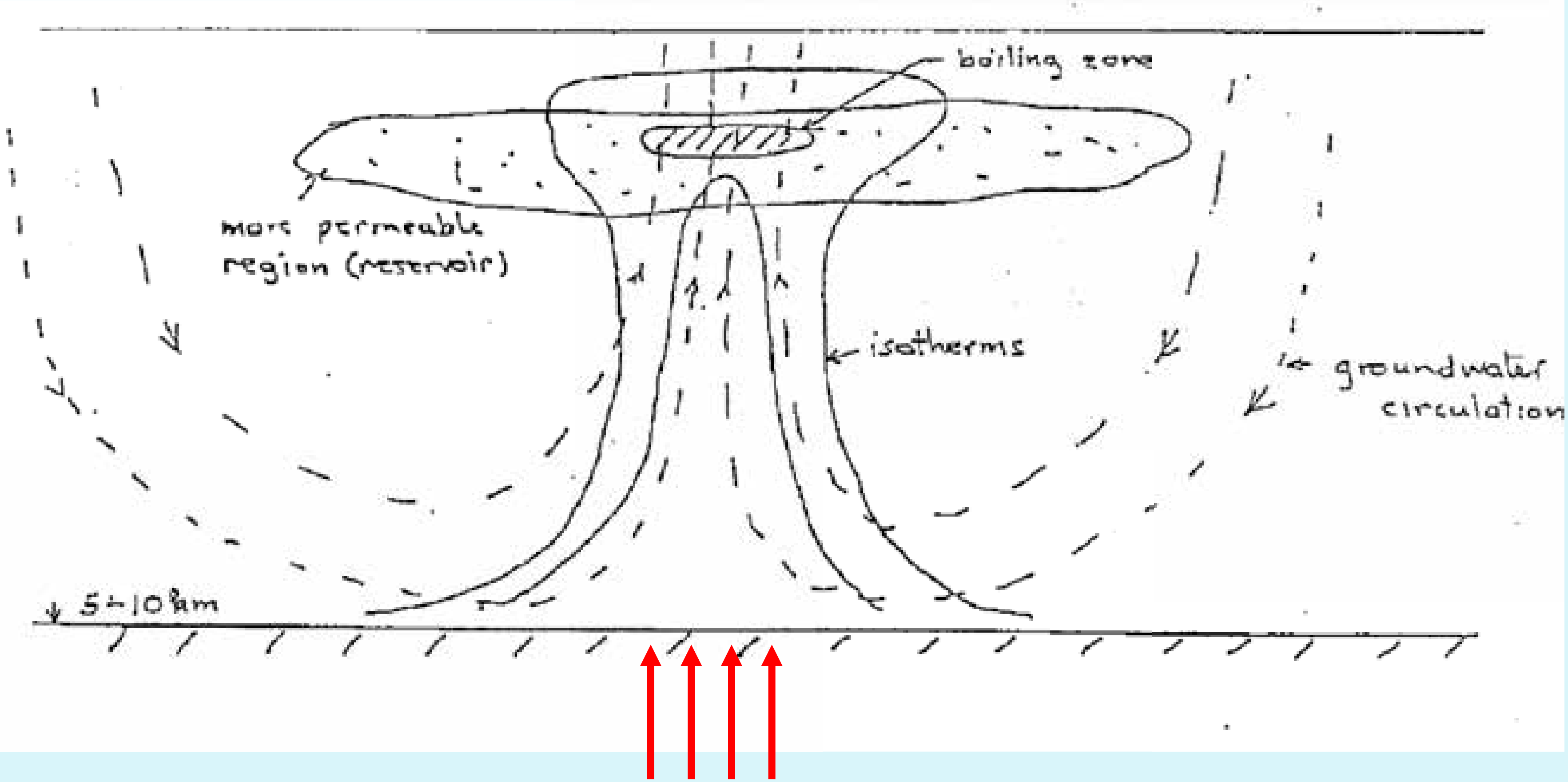
Hot water systems

- In a hot water geothermal system the local heat flux is larger than 60-70mW/m^2
- Heat from depth is transported to the surface mainly by convection of groundwater.
- Driven by buoyancy

Hot water systems

- Only liquid hot water in their pre-production state.
- Not much boiling, if any, occurs as a result of production.
- Temperatures in range 125 - 225°C
- Presence of gases may cause some boiling
- At the colder end of the range binary plants must be used for electricity generation.
- They are quite common worldwide

A convective geothermal system



heat

Hot water systems

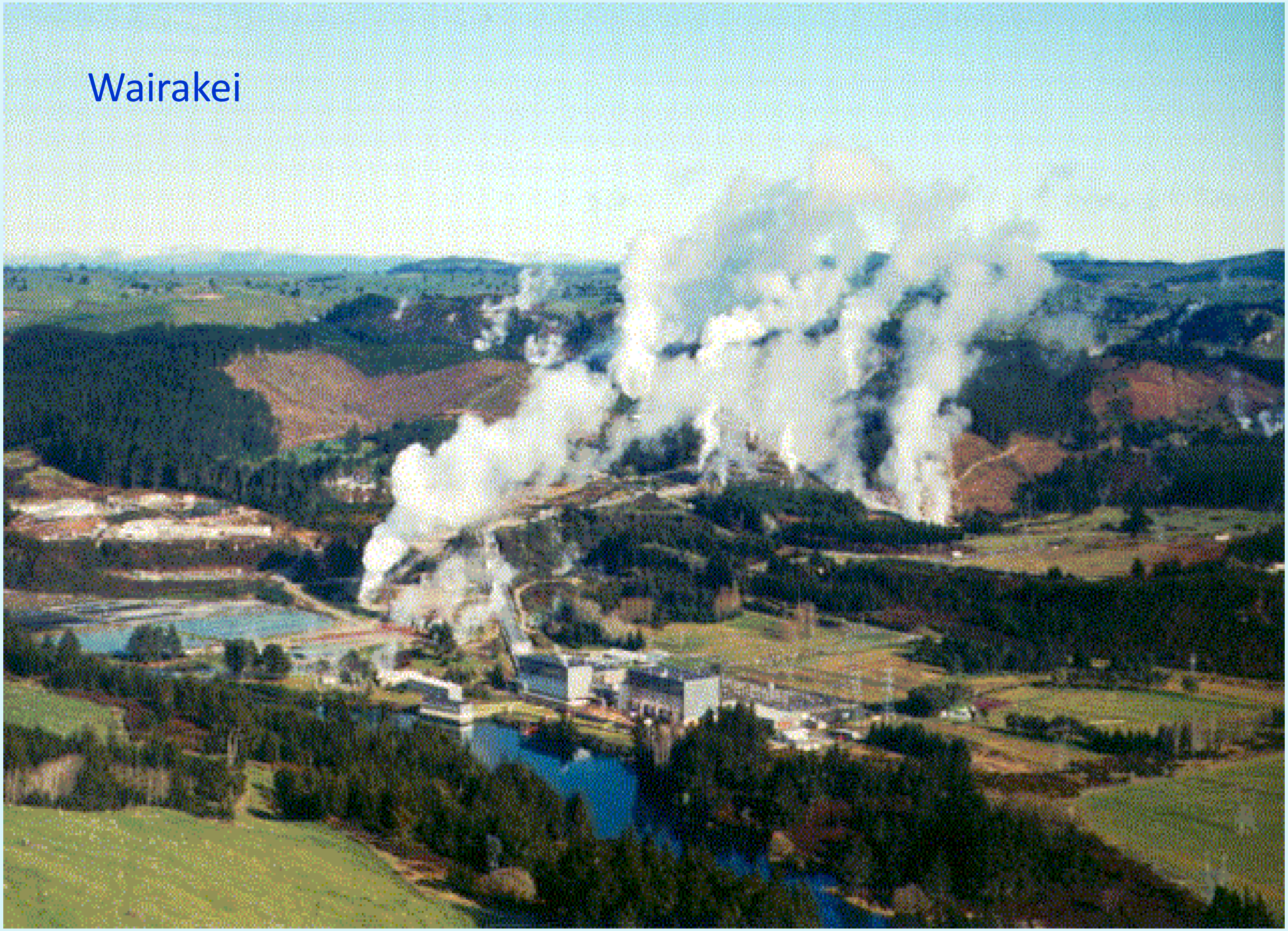
- In the sketch above a hydrothermal system is shown.
- It shows a large scale convective circulation of the ground water and the resulting plume of hot fluid.
- A small boiling zone is shown near the top of the system where the pressures are low and temperatures are high.

Hot water systems

- At greater depth the pressures are too high to permit boiling, while nearer the surface the lowering of the temperature by cold surface recharge and conductive losses prevents boiling.

- Within this overall hydrothermal system there may be a zone of permeable rock close enough to the surface to be reached by drilling. The hot part of this permeable region constitutes a <u>geothermal reservoir.</u>

Two-phase systems



Two-phase geothermal systems

- Three types: low enthalpy, high enthalpy, vapour dominated.
- In order of decreasing permeability but increasing size of boiling zone.
- In order of increasing production enthalpy
- In the boiling zone there is some heat transfer by counter-flow of steam upwards and water downwards giving a small mass transfer but large heat transfer

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Two-phase, liquid dominated systems

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- Also convective geothermal systems but are hotter than hot-water systems
- A two-phase region containing a mixture of steam and liquid water, overlying deeper hot liquid, is present in the natural state
- Not so common, they occur only in the hot geothermal areas
- Wairakei, New Zealand and Cerro Prieto, Mexico are examples

Two-phase, liquid dominated systems

- Temperatures vary (225 - 270ºC) with the presence of gas causing boiling at lower temperatures
- Some have large convective flows with many surface features (geysers, hot springs, mud pools, steaming ground) e.g. Wairakei
- Others have smaller convective flow and not many surface features. e.g. Ohaaki

Two-phase, liquid dominated systems

- It is possible to distinguish between low enthalpy and high enthalpy versions of this type of reservoir.
- A reservoir like Wairakei which is very permeable has a production enthalpy close to that of hot water (say 1100kJ/kg)

Two-phase, liquid dominated systems

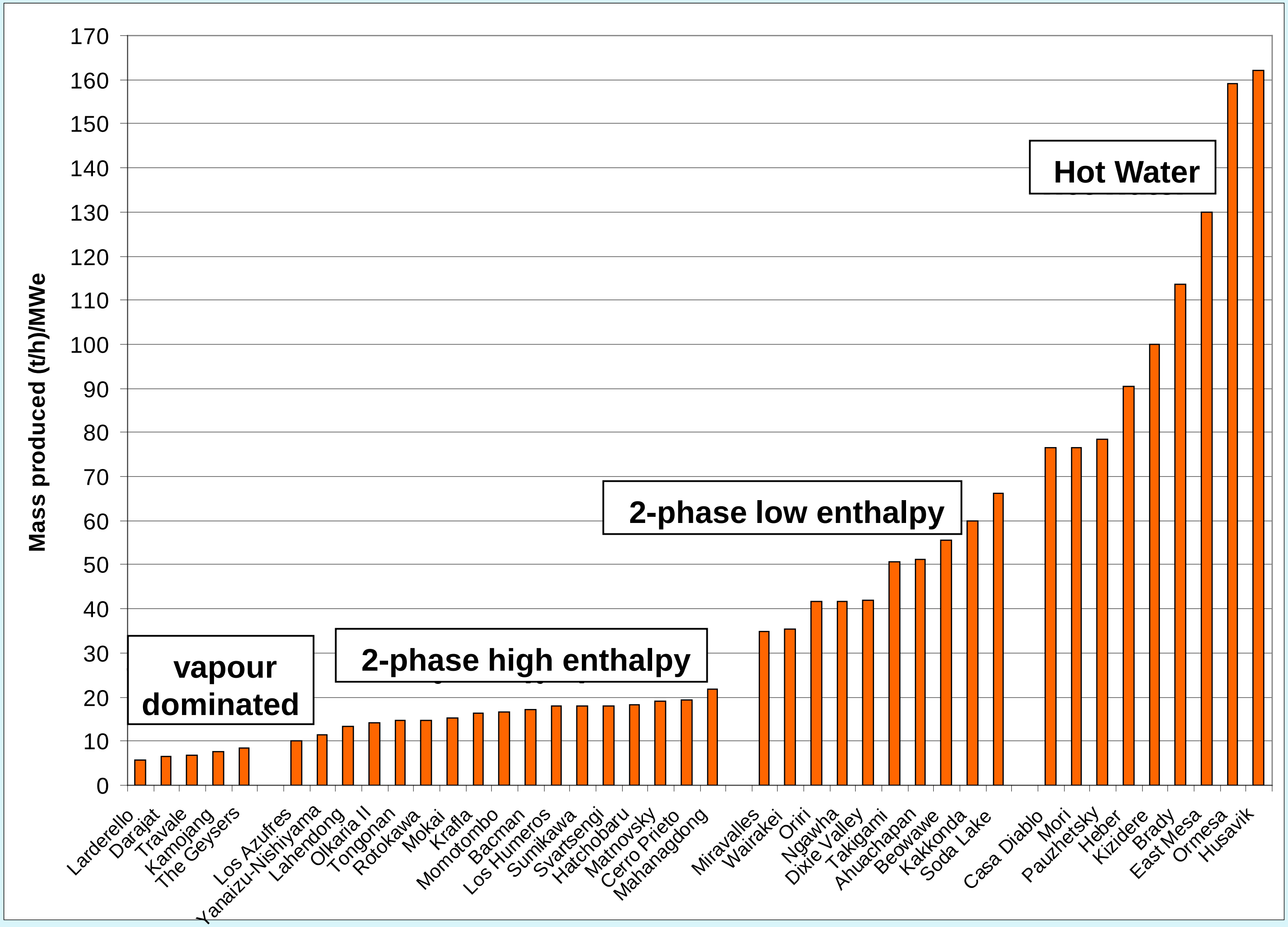
- Other systems such as Mokai which have lower, fracture-dominated permeability have a production enthalpy in the range 1500-2000kJ/kg, well above that of hot water (sometimes called “excess enthalpy”).

Champagne pool - Waiotapu

Two-phase, vapour-dominated reservoirs

- Vapour-dominated systems contain a large two-phase zone.
- Liquid phase is sparse, widely dispersed and immobile and so wells produce only steam (Geysers, Kamojang, Darajat, Lardarello).
- Temperatures vary (say 240 - 300°C) depending on depth and gas content.
- A very low permeability formation surrounding the reservoir is required to keep water out.
- Uncommon

Mass Produced per MWe Generated



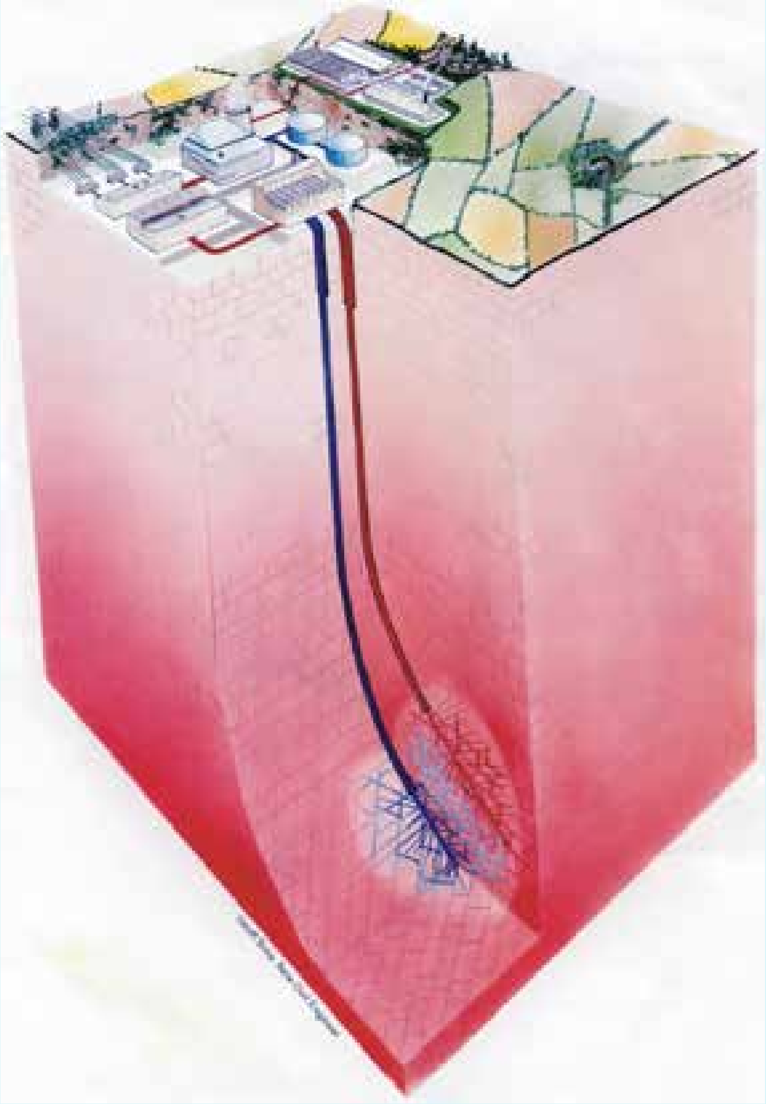
Classification

- When drilling first occurs in a geothermal reservoir it may be classified into one of the above categories quite easily.
- If it is vapour-dominated then a low downhole pressure and the production of dry steam will serve to identify it.
- The remaining categories can be distinguished by the production enthalpy and the temperature distribution with depth.

Hot dry rock - EGS

- Japan (Hijiori, Ogachi)
- France (Soultz Sous)
- Australia (Cooper Basin)
- US (Fenton Hill, NM)
- England (Rosemanowes)
- Sweden (Fjallbacka)
- Russia (Tirniauz)
- Germany (Neustadt-Glewe)

2007 - MIT Releases Major Report on Geothermal Energy. Group leader: Jeff Tester



Hot dry rock - engineered geothermal systems

The idea:

- Drill two wells
- Use hydraulic-fracturing to create a permeable zone connecting the wells
- Pump cold water down one well and produce hot water from the other
- Many problems, no-one has got it working well

Geothermal reservoirs

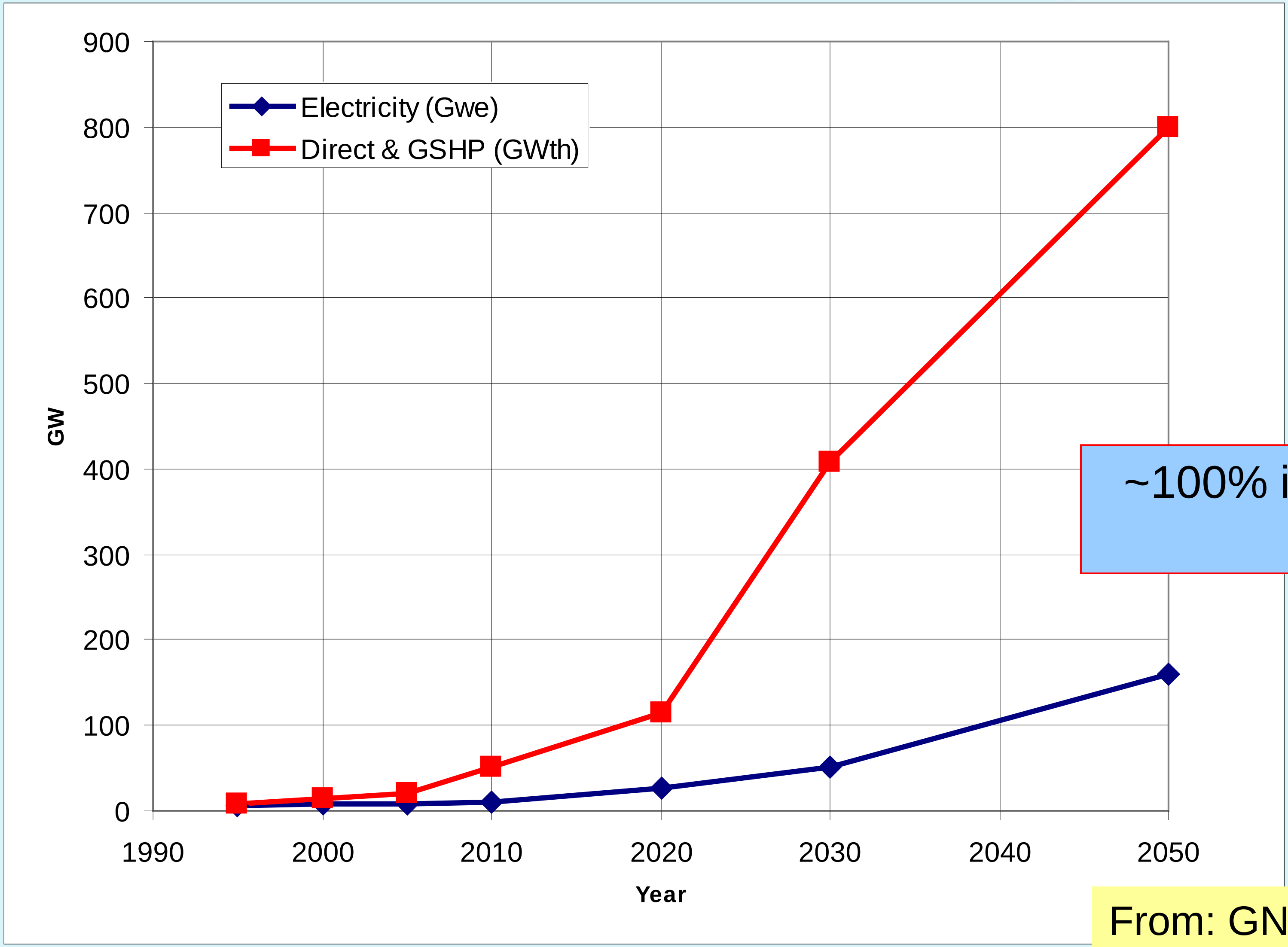
- A geothermal reservoir is quite different from an oil or gas reservoir, or even a ground water reservoir.
- A geothermal reservoir is usually not a clearly defined highly permeable region confined by low permeability strata.
- The quantity to be extracted, namely heat energy, is not contained entirely in the reservoir fluid. In an oil reservoir, once the oil has been extracted the reservoir is exhausted.

Geothermal reservoirs

- The production of water and steam from a geothermal well is replaced in the reservoir by surrounding cooler water which is heated by the reservoir rock and then becomes available for production.
- This process of <u>recharge </u>is very important in the behaviour of geothermal reservoirs.
- In convective geothermal systems the fluid is moving. In an oil reservoir the fluid is stationary.

Uses of geothermal energy

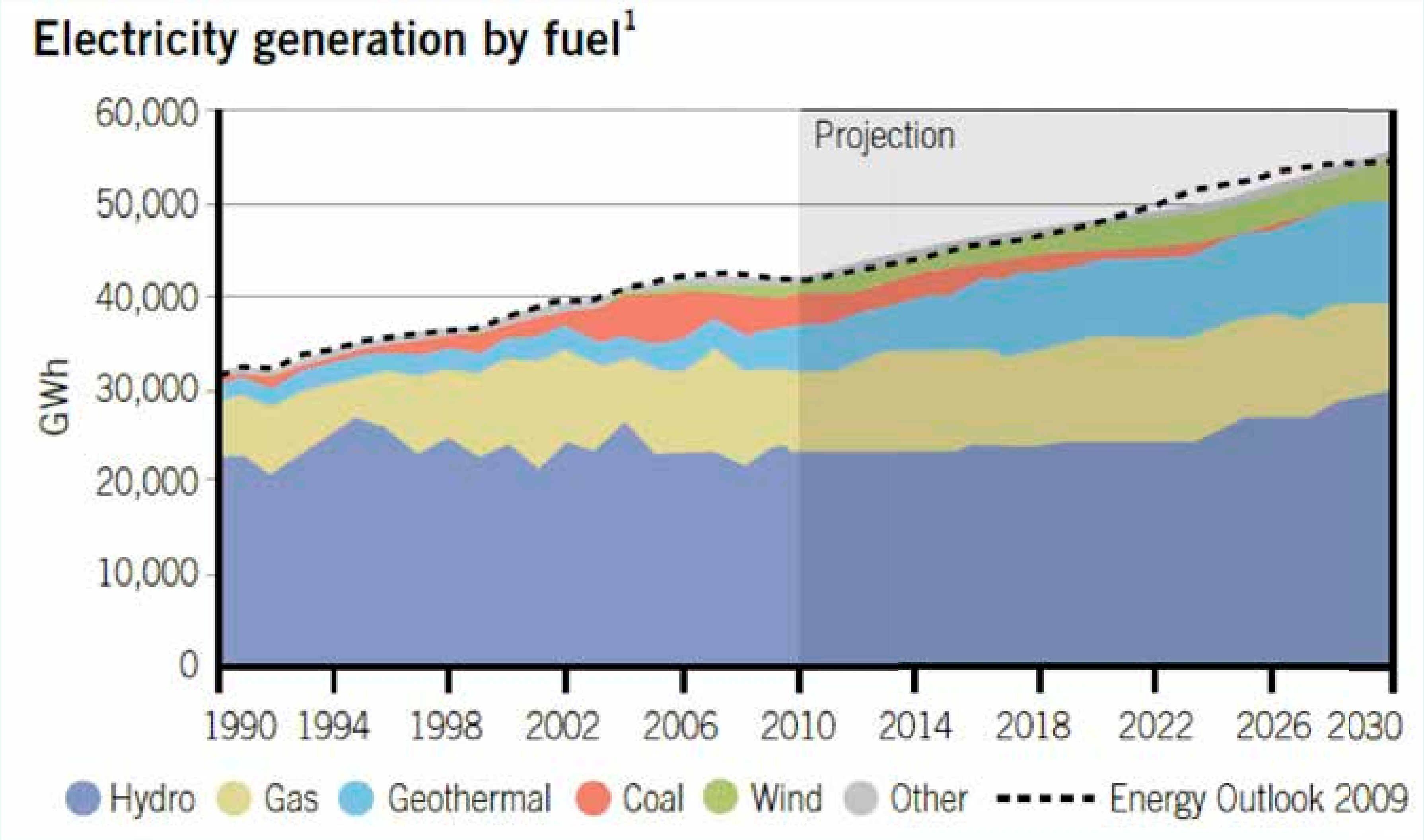
World geothermal capacity



~100% increase by 2020

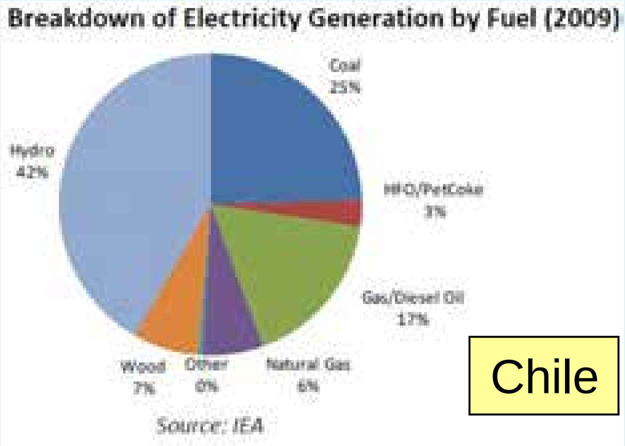
From: GNS Science

Future electricity generation in New Zealand



From : “Developing our Energy Potential …”, Ministry of Economic Development Report 2011

Current electricity generation in the Andes



Breakdown of Electricity Generation by Fuel (2009)

Source: IEA

Chile

OFERTA DE GENERACION 2011

Bolivia

Source:
Vera Ruiz, 2013

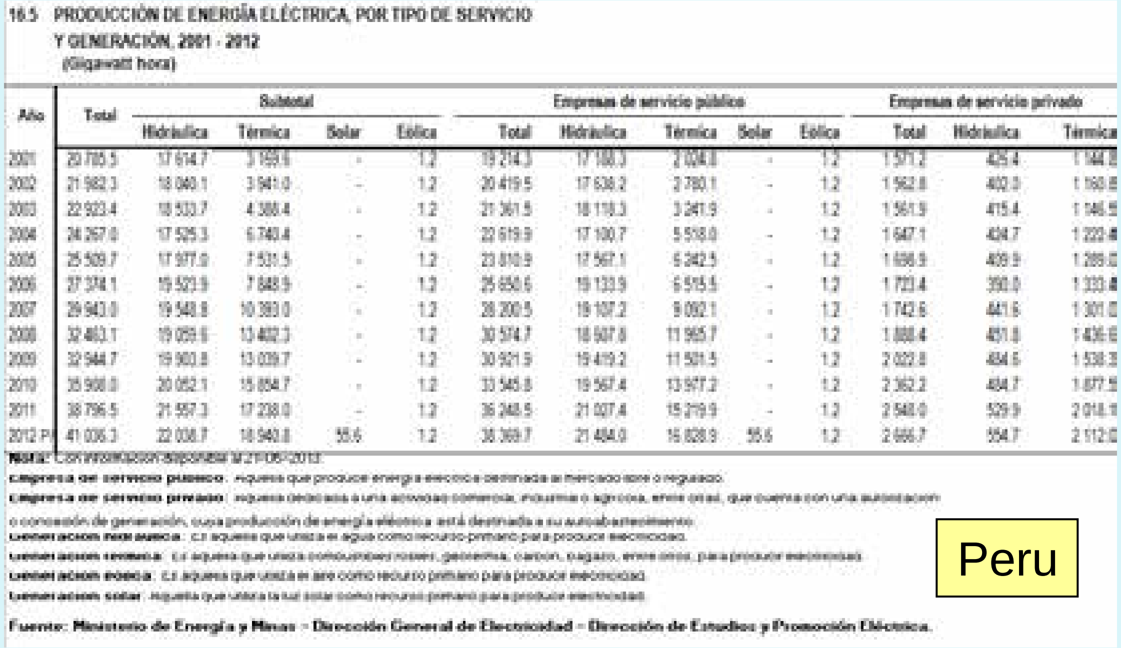
Ecuador (2012)

Source: REEEP Policy Database

Energy sources

Total installed electricity capacity (2010): 4.761,39 MW.

Thermo-electricity: 52,17%
Hydro-electricity: 42,37%
Wind power: 0,02%
Biomass: 1,16%
From interconnection with Colombia: 4,28%.



16.5 PRODUCCIÓN DE ENERGÍA ELÉCTRICA, POR TIPO DE SERVICIO Y GENERACIÓN, 2001 - 2012
(Gigawatt hora)

Año	Total	Subtotal				Empresas de servicio público					Empresas de servicio privado		
		Hidráulica	Térmica	Solar	Eólica	Total	Hidráulica	Térmica	Solar	Eólica	Total	Hidráulica	Térmica
2001	20 785.5	17 614.7	3 169.6	-	1.2	19 214.3	17 188.3	2 024.8	-	1.2	1 571.2	425.4	1 145.8
2002	21 982.3	18 040.1	3 941.0	-	1.2	20 419.5	17 638.2	2 780.1	-	1.2	1 562.8	402.0	1 160.8
2003	22 923.4	18 533.7	4 388.4	-	1.2	21 361.5	18 118.3	3 241.9	-	1.2	1 561.9	415.4	1 146.5
2004	24 267.0	17 525.3	6 740.4	-	1.2	22 619.9	17 100.7	5 518.0	-	1.2	1 647.1	424.7	1 222.4
2005	25 509.7	17 977.0	7 531.5	-	1.2	23 810.9	17 567.1	6 242.5	-	1.2	1 698.9	409.9	1 289.0
2006	27 374.1	19 523.9	7 848.9	-	1.2	25 650.6	19 133.9	6 515.5	-	1.2	1 723.4	390.0	1 333.4
2007	29 943.0	19 548.8	10 393.0	-	1.2	28 200.5	19 107.2	9 092.1	-	1.2	1 742.6	441.6	1 301.0
2008	32 463.1	19 059.6	13 402.3	-	1.2	30 574.7	18 607.8	11 965.7	-	1.2	1 888.4	451.8	1 436.6
2009	32 944.7	19 903.8	13 039.7	-	1.2	30 921.9	19 419.2	11 501.5	-	1.2	2 022.8	484.5	1 538.3
2010	35 908.0	20 052.1	15 854.7	-	1.2	33 545.8	19 567.4	13 977.2	-	1.2	2 362.2	484.7	1 877.5
2011	38 796.5	21 557.3	17 238.0	-	1.2	36 248.5	21 027.4	15 219.9	-	1.2	2 548.0	529.9	2 018.1
2012 P/	41 036.3	22 038.7	18 940.8	55.6	1.2	38 369.7	21 484.0	16 828.9	55.6	1.2	2 666.7	554.7	2 112.0

Nota: Con información disponible al 21-06-2013.
Empresa de servicio público: Aquella que produce energía eléctrica destinada al mercado libre o regulado.
Empresa de servicio privado: Aquella dedicada a una actividad comercial, industrial o agrícola, entre otras, que cuenta con una autorización o concesión de generación, cuya producción de energía eléctrica está destinada a su autoabastecimiento.
Generación hidráulica: Es aquella que utiliza el agua como recurso primario para producir electricidad.
Generación térmica: Es aquella que utiliza combustibles fósiles, geotermia, carbón, bagazo, entre otros, para producir electricidad.
Generación eólica: Es aquella que utiliza el aire como recurso primario para producir electricidad.
Generación solar: Aquella que utiliza la luz solar como recurso primario para producir electricidad.

Fuente: Ministerio de Energía y Minas - Dirección General de Electricidad - Dirección de Estudios y Promoción Eléctrica.

Peru

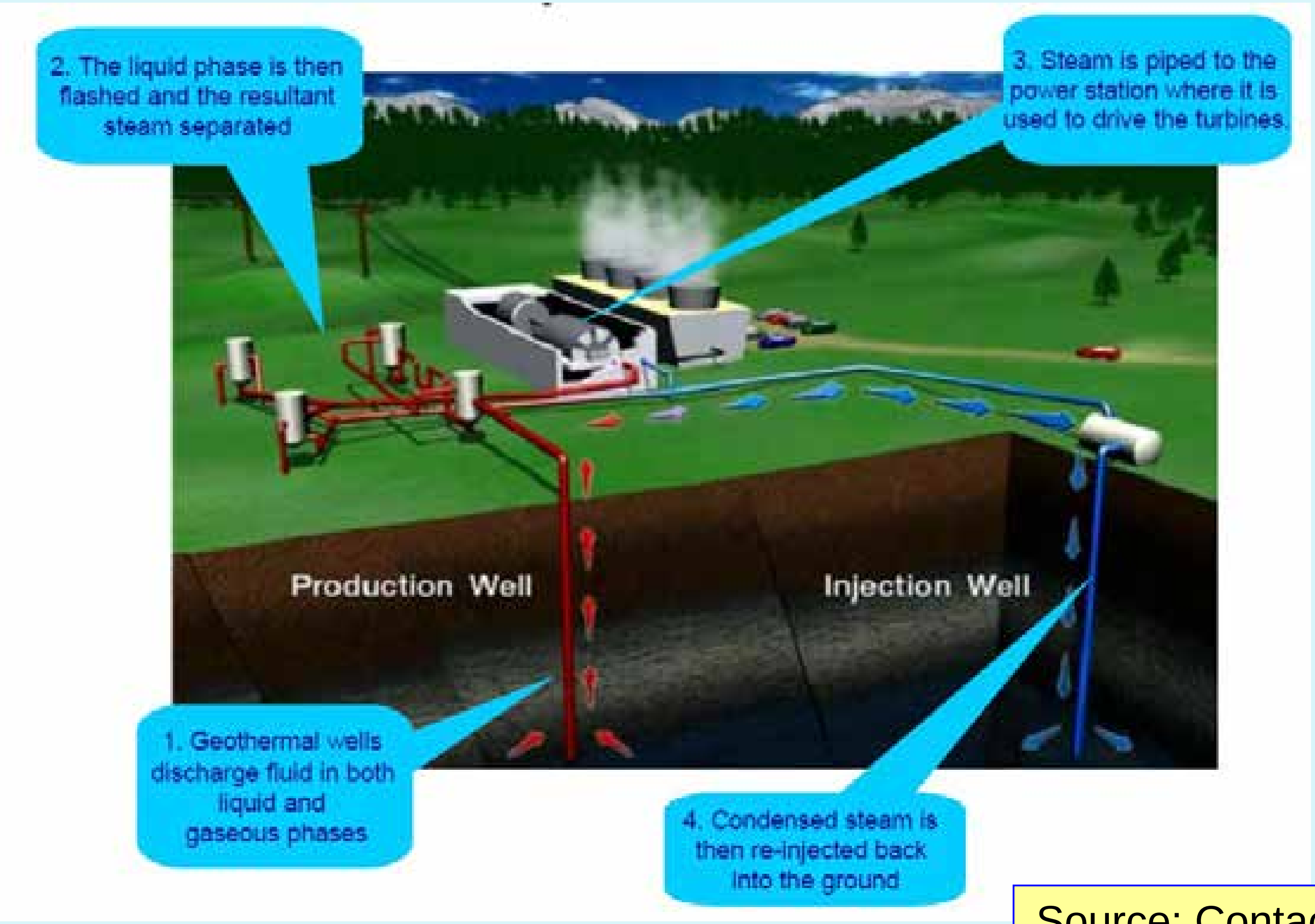
Colombia (2012)

Source: REEEP Policy Database (contributed by SERN for REEEP)

Energy sources

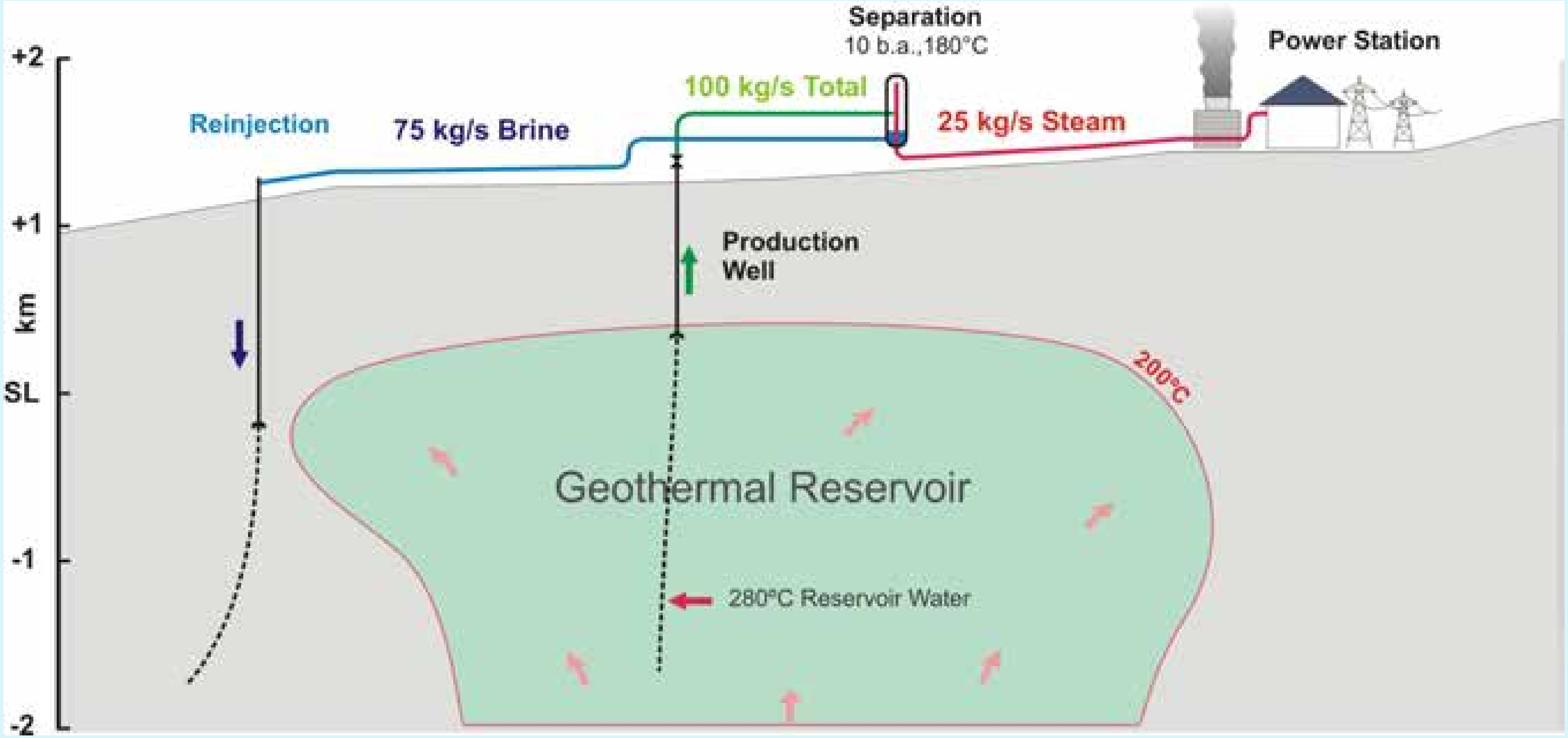
Total installed electricity capacity (2010): 13.531 MW
Hydro-electricity: 68%
Fossil fuels (coal and natural gas): 32%.

Diagram of a geothermal project – flash plant

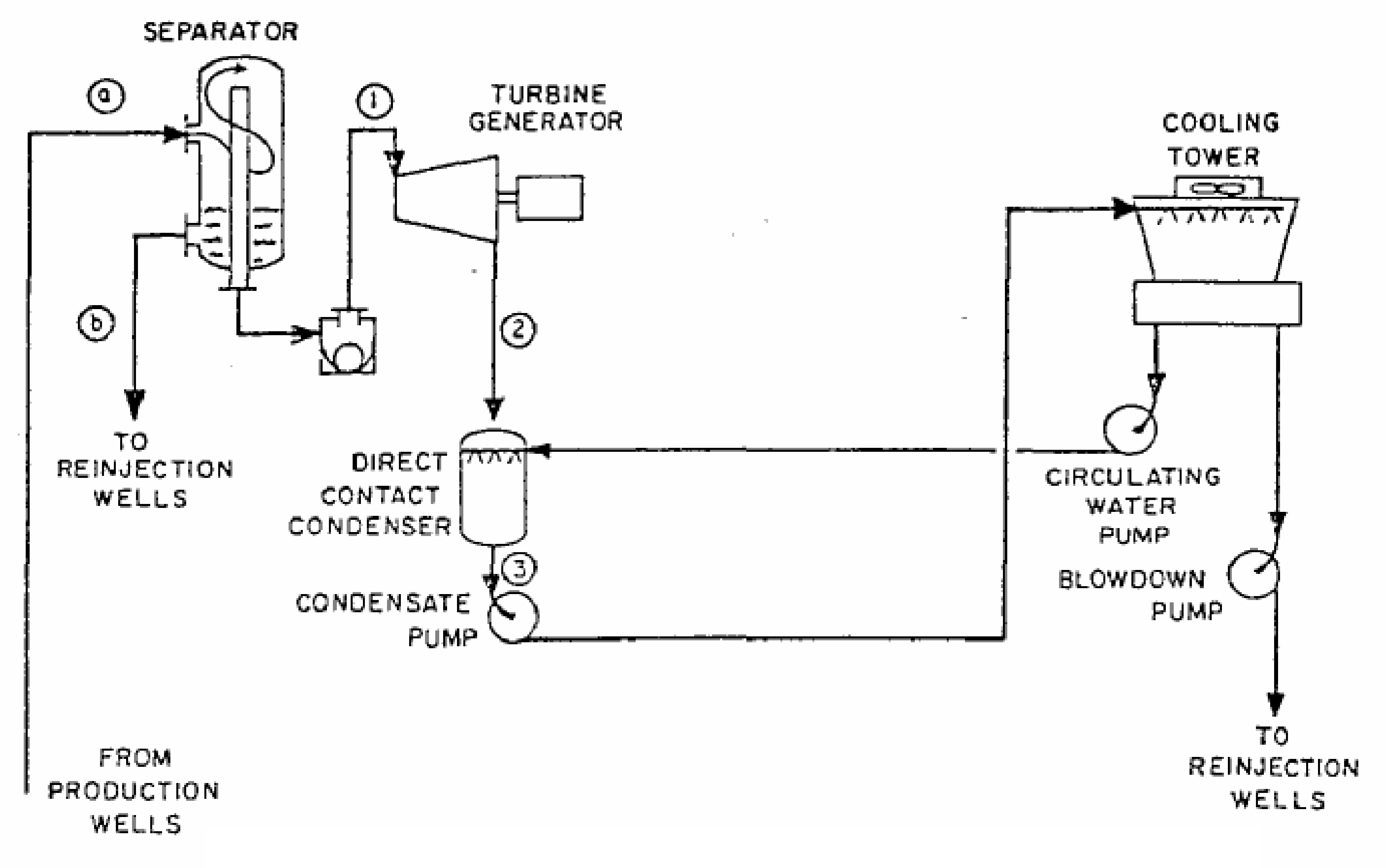


Source: Contact Energy

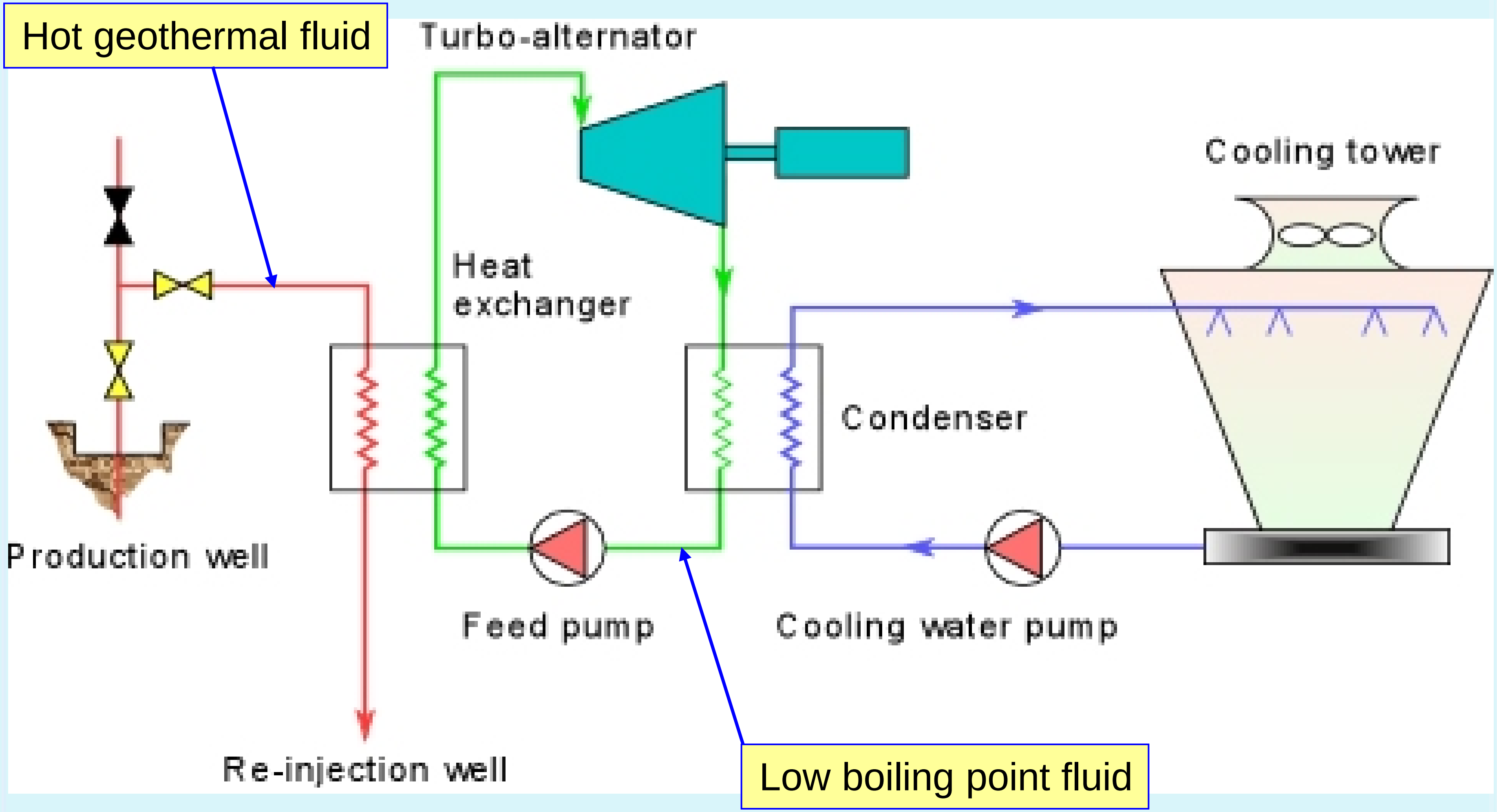
Schematic for a geothermal project – flash plant



Single flash geothermal plant



Binary plant



Hot geothermal fluid

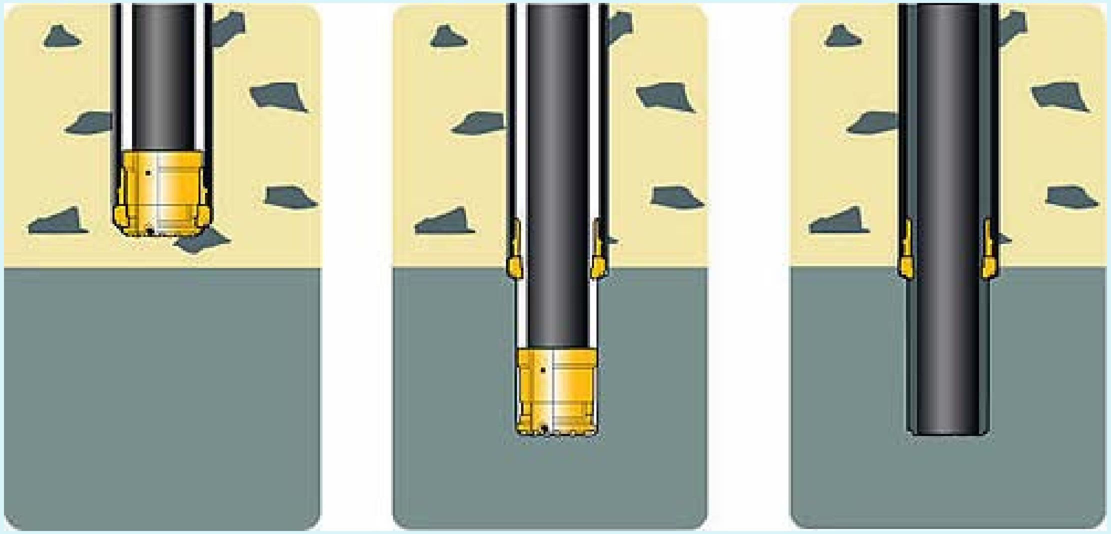
Low boiling point fluid

Plant equipment

- Geothermal drilling rigs

Plant equipment

- Geothermal drilling equipment



Plant equipment

- Geothermal well

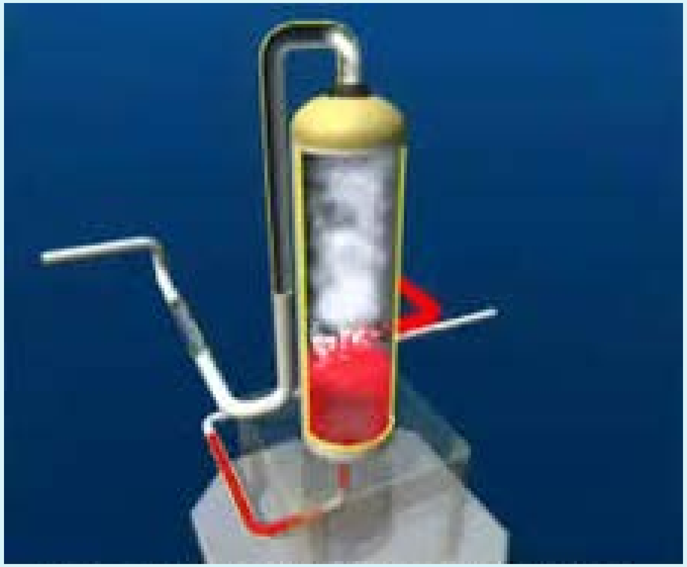



Plant equipment

- Steamfield

Plant equipment

- Separator



Plant equipment

- Wairakei power station – New Zealand
  - 220 MW

Plant equipment

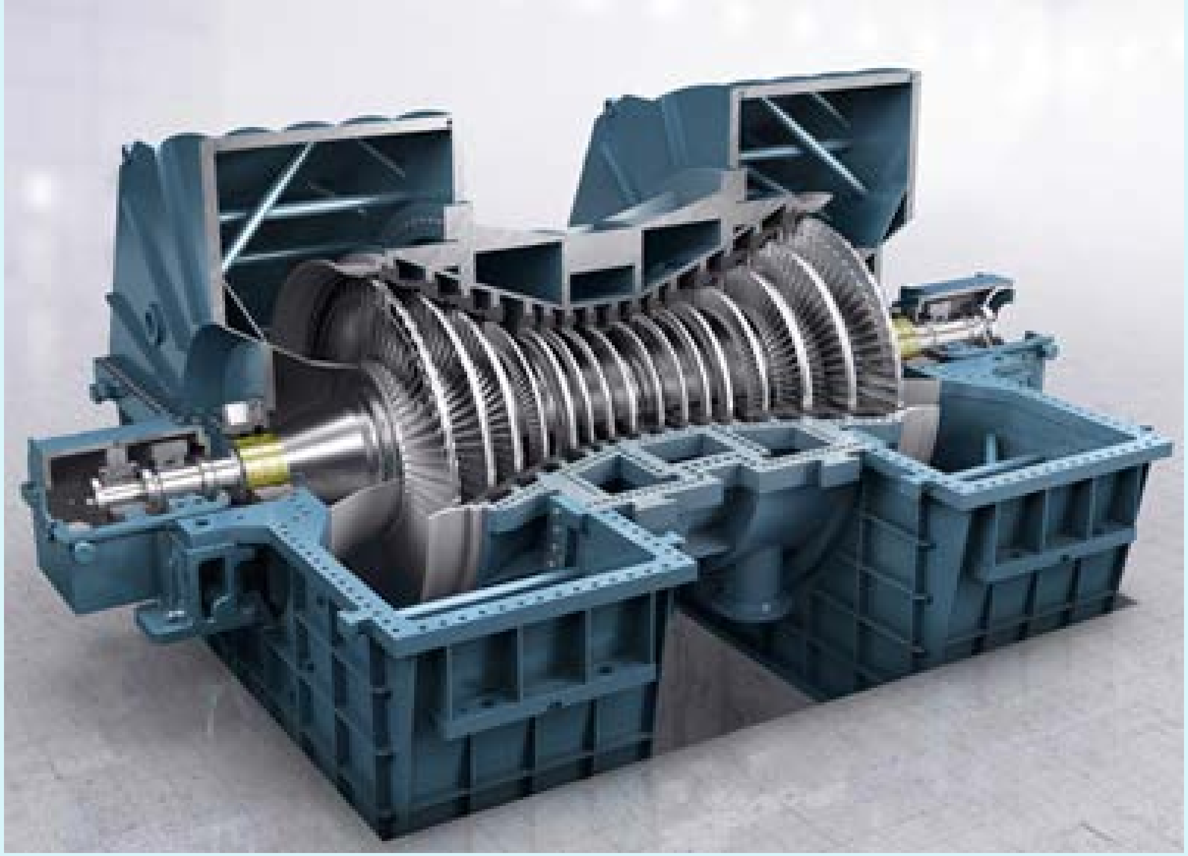
- Geysers power station - USA
  - 1517 MW
  - 22 Power stations

Plant equipment

- Ngawha power station – New Zealand
  - 25 MW
  - Binary plant

Plant equipment

- Turbine



Plant equipment

- Condenser

Plant equipment

- Cooling towers

Worldwide direct use (non-electrical)

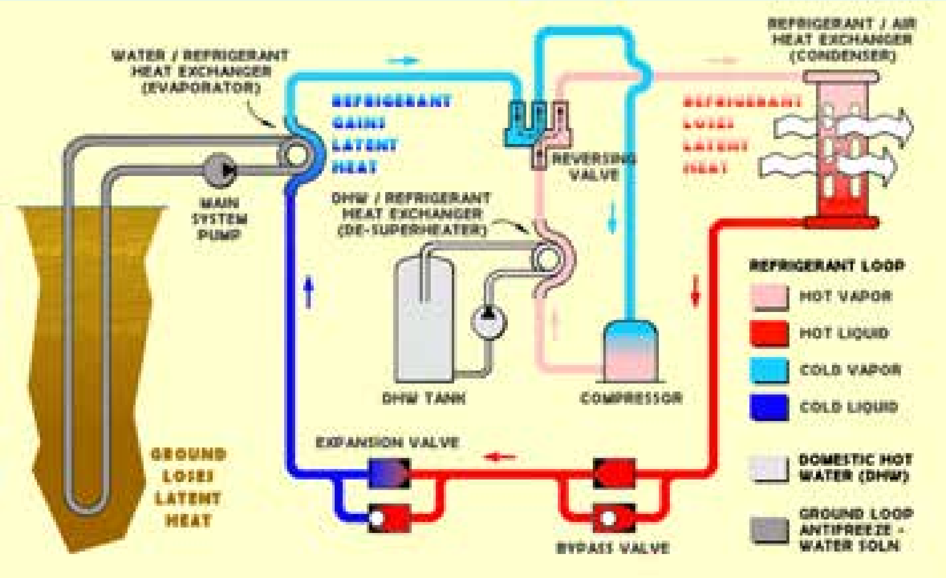
Capacity MWth				
	2010	**2005**	**2000**	**1995**
Geothermal heat pumps	35236	15384	5275	1854
Space heating	5391	4366	3263	2579
Greenhouse heating	1544	1404	1246	1085
Aquaculture pond heating	653	616	605	1097
Agricultural drying	127	157	74	67
Industrial use	533	484	474	544
Bathing and swimming	6689	5401	3957	1085
Cooling / snow melting	368	371	114	115
Other	41	86	137	238
Total	**50583**	**28269**	**15145**	**8664**

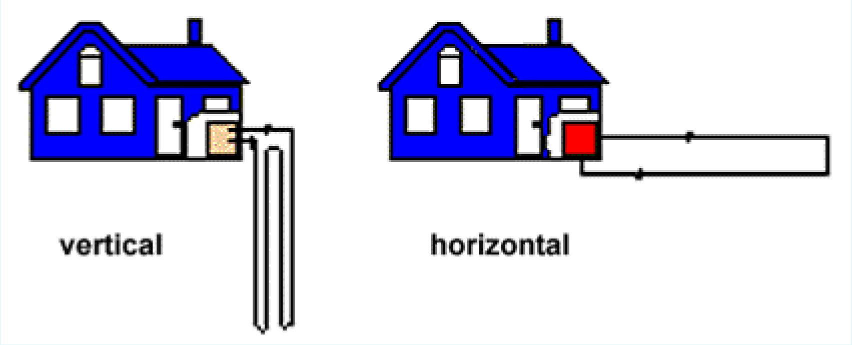
Bathing

Agriculture – geothermally heated glass house

Aquaculture - Prawn Farm, Wairakei

Geothermal heat pumps (also called ground source heat pumps)

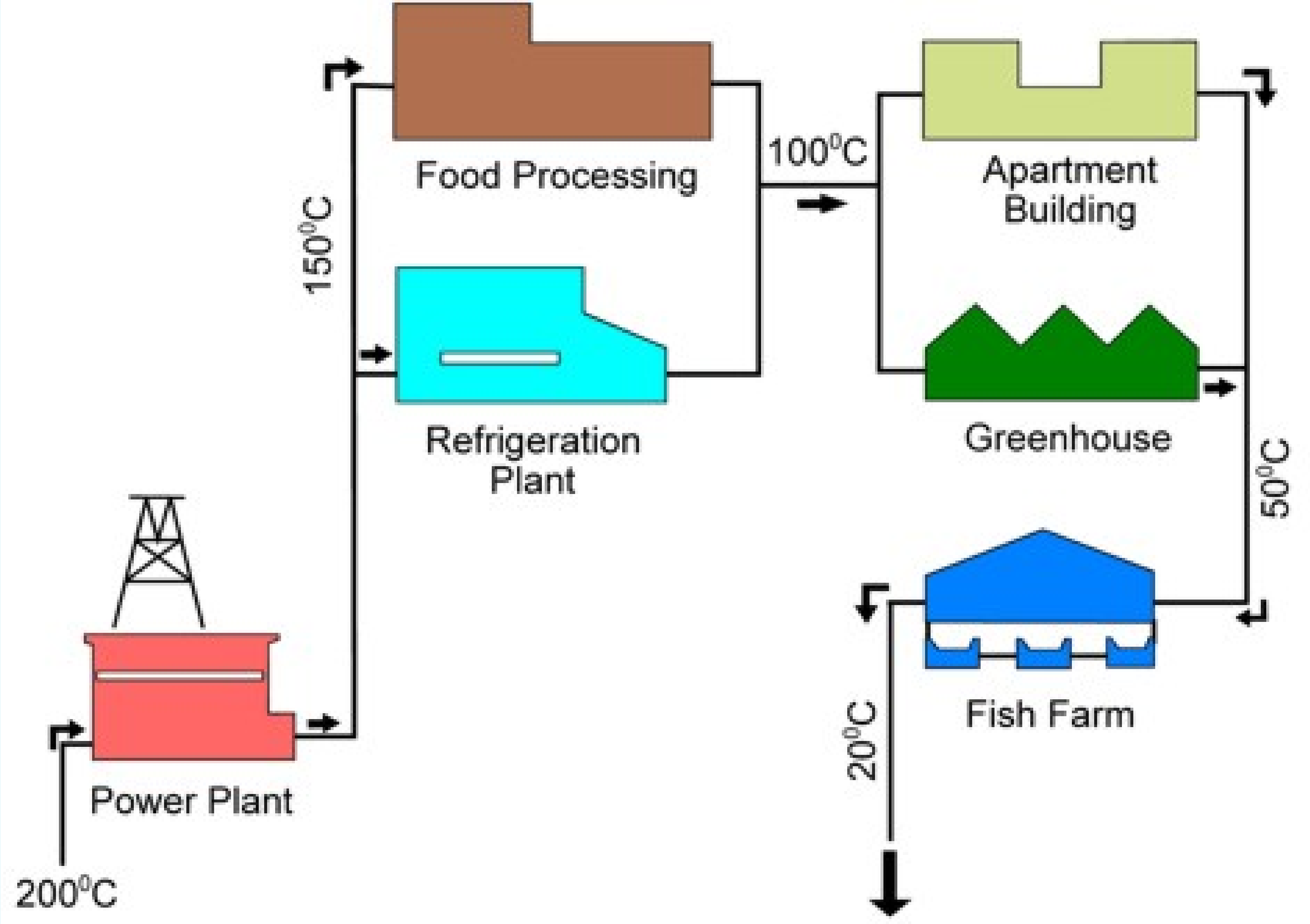




Industrial use: Kawerau paper mill

- Kawerau Paper Mill 1958: First use of geothermal steam in paper mill
- 56% of New Zealand’s direct energy usage. Largest industrial use in the world
- 2009: 122 MWe electricity generating plant

Cascade use


Food Processing
150°C
Refrigeration Plant
100°C
Apartment Building
Greenhouse
50°C
Fish Farm
20°C
Power Plant
200°C

Thank you

- Thank you to IRENA
- Questions?

Introduction to geothermal environmental considerations

The Geothermal Institute
University of Auckland

Bridget Lynne

Santiago de Chile, 26-29 May 2014

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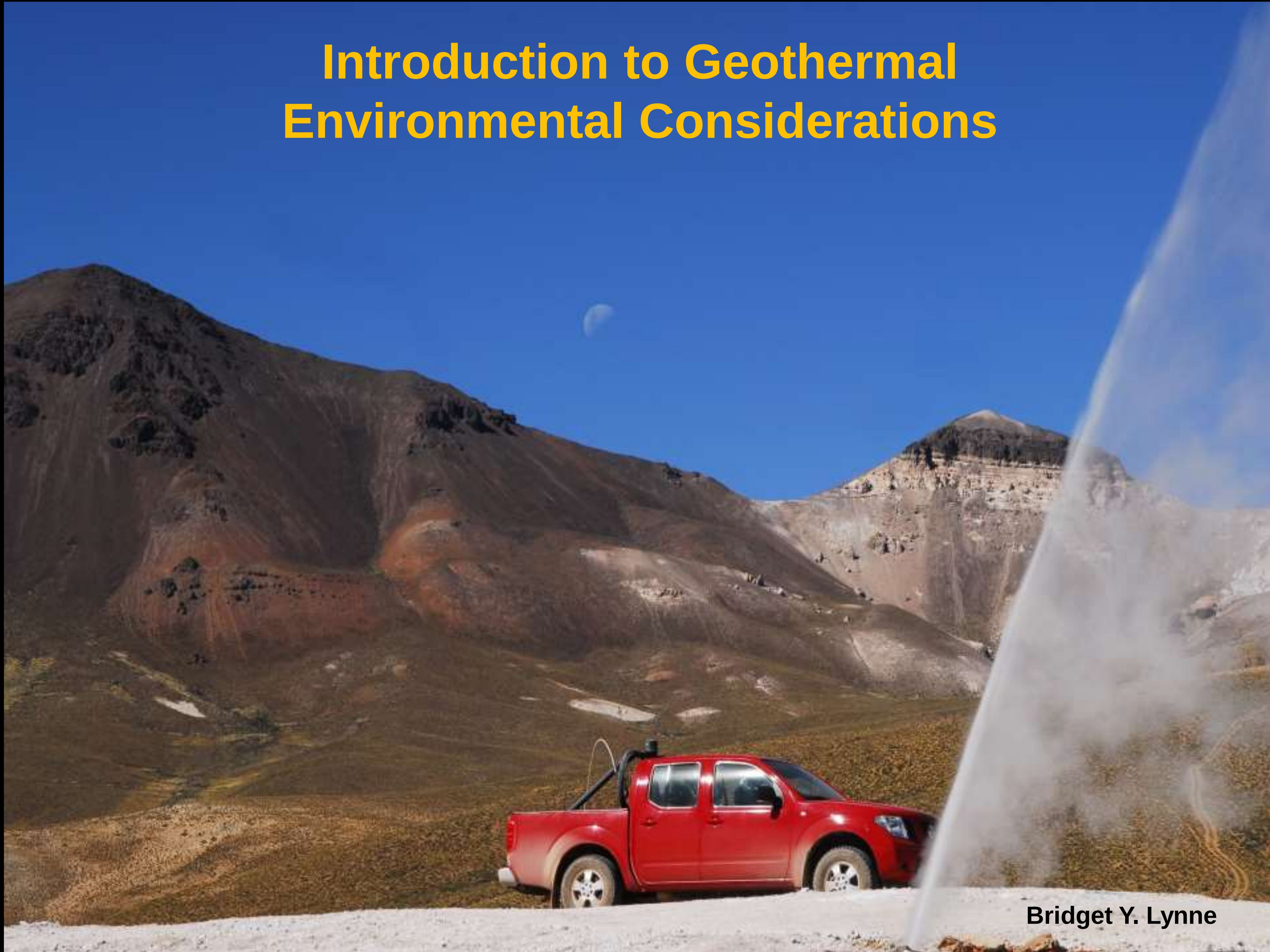
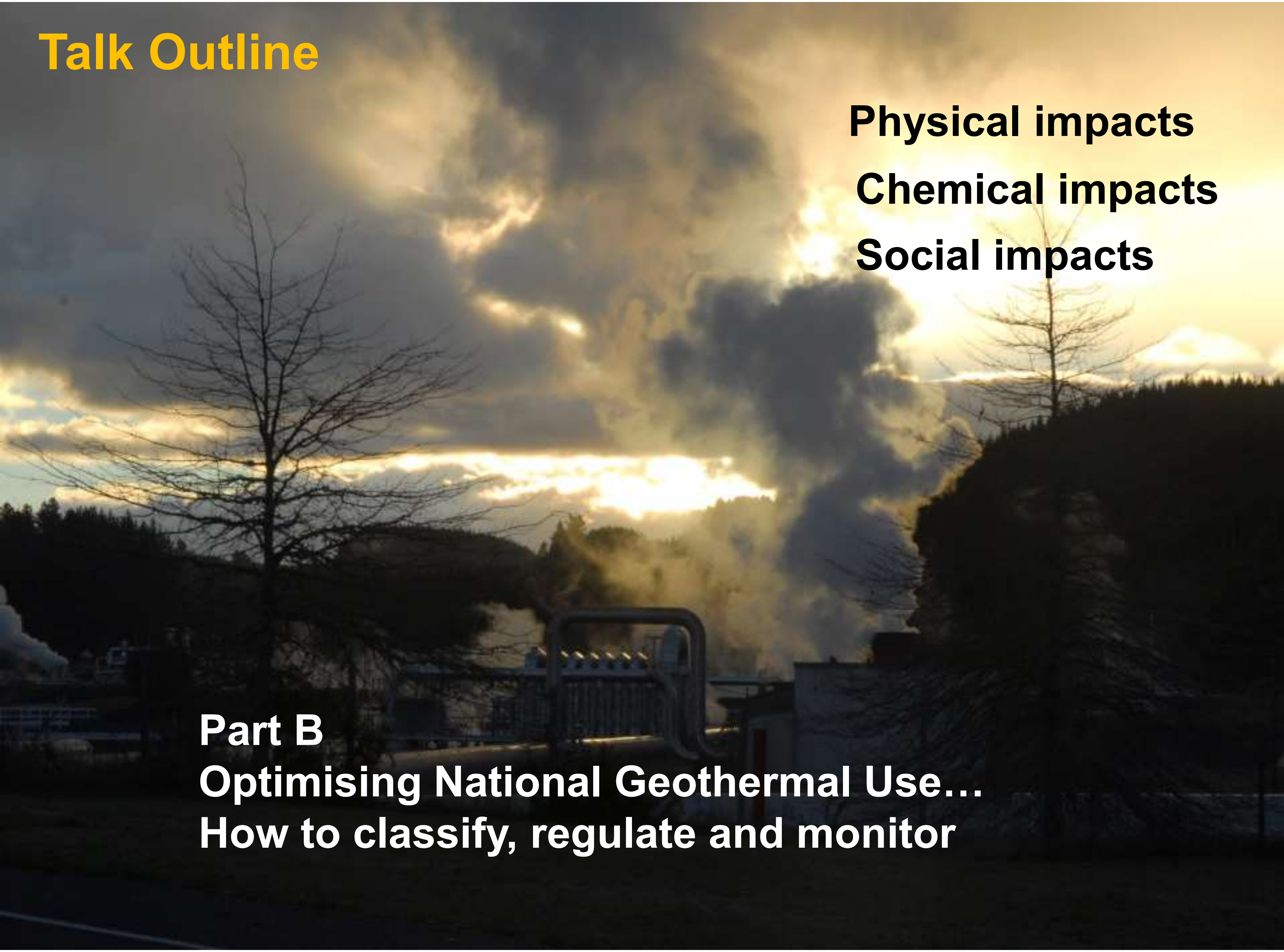
Introduction to Geothermal Environmental Considerations



Bridget Y. Lynne

Talk Outline



Physical impacts

Chemical impacts

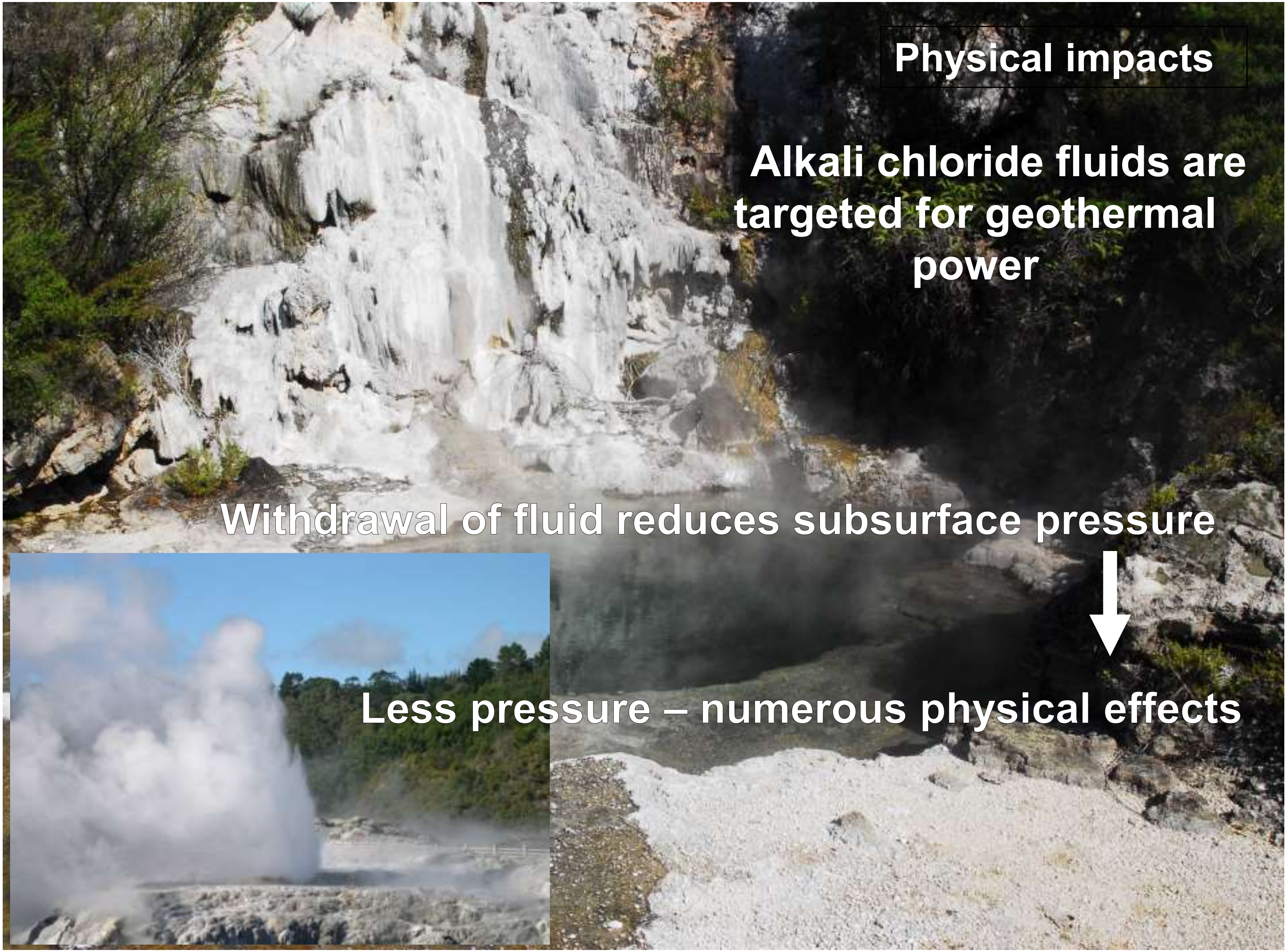
Social impacts

Part B

Optimising National Geothermal Use…

How to classify, regulate and monitor

All aspects of environmental development must be given careful consideration



Physical impacts

Alkali chloride fluids are targeted for geothermal power

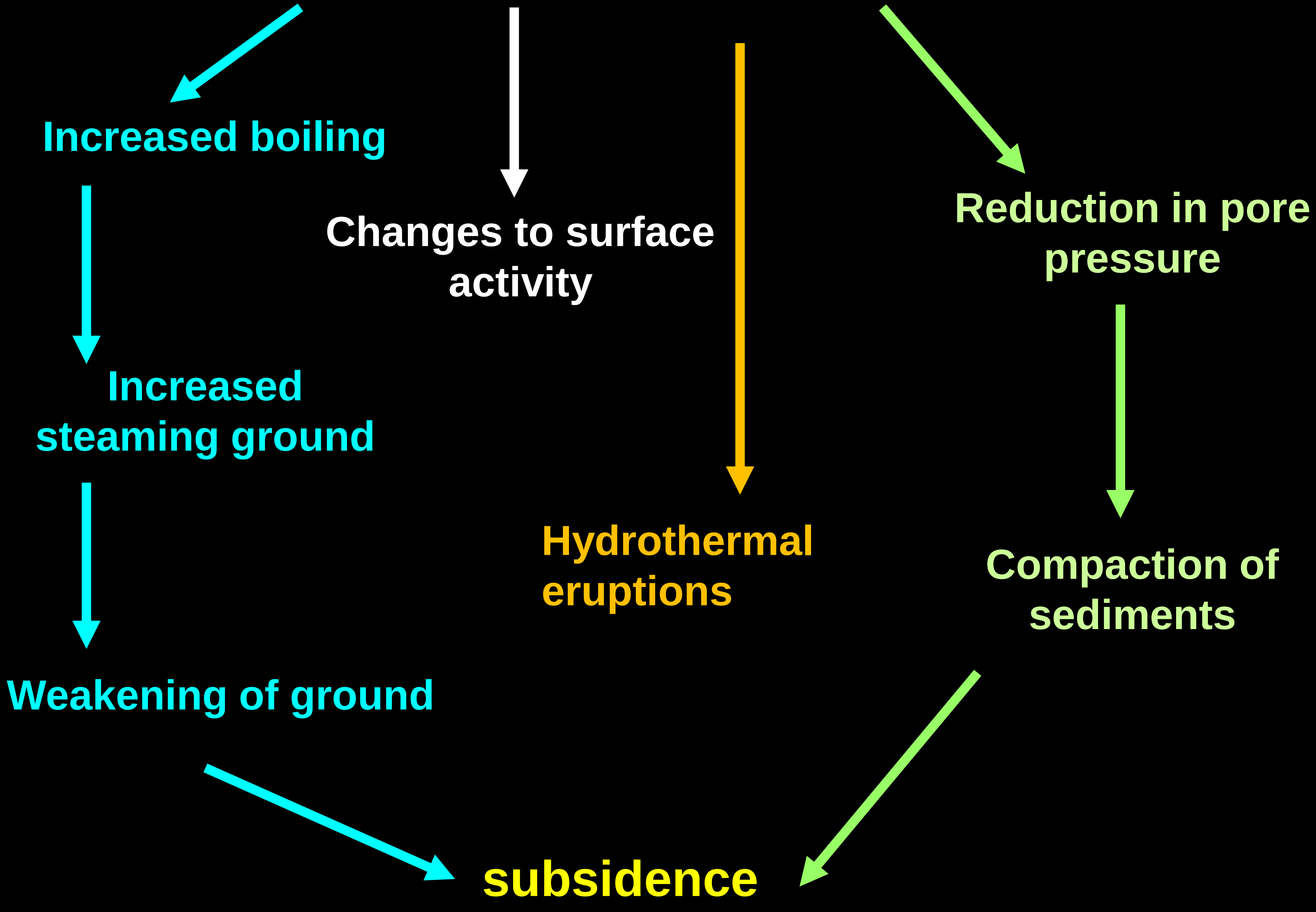
Withdrawal of fluid reduces subsurface pressure

↓

Less pressure – numerous physical effects

Physical impacts

Less pressure results in …..



Increased boiling

Increased steaming ground

Weakening of ground

Changes to surface activity

Hydrothermal eruptions

Reduction in pore pressure

Compaction of sediments

subsidence

Physical impacts

Changes in surface activity

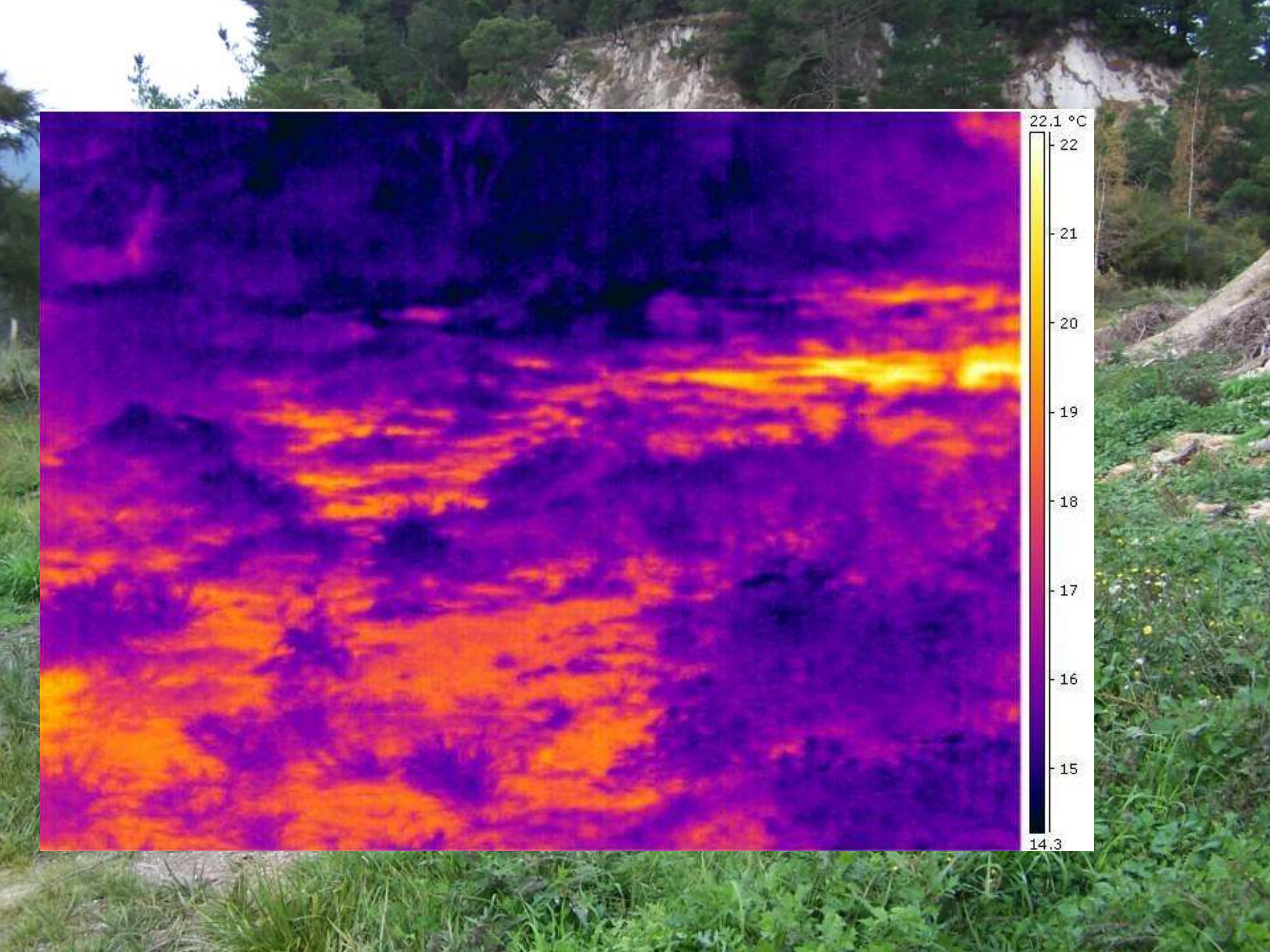
due to changes in subsurface pressure

Physical impacts

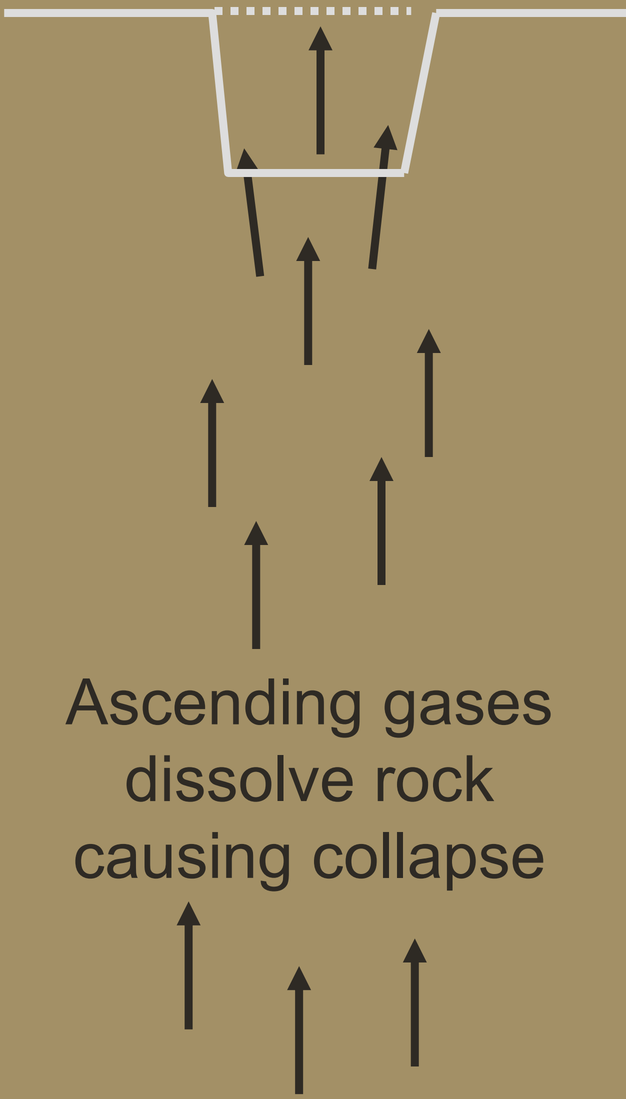
Thermally stressed grass = warm ground

Appearance of new thermal features

Not always where we want them


22.1 °C
22
21
20
19
18
17
16
15
14.3

Dissolution or collapse craters (no volcanism)



Ascending gases dissolve rock causing collapse

Waiotapu

LANDSLIDES

Acidic steam condensate overprinting


Rainbow Mountain, Waiotapu

-thermally stressed vegetation
-kaolinite clay

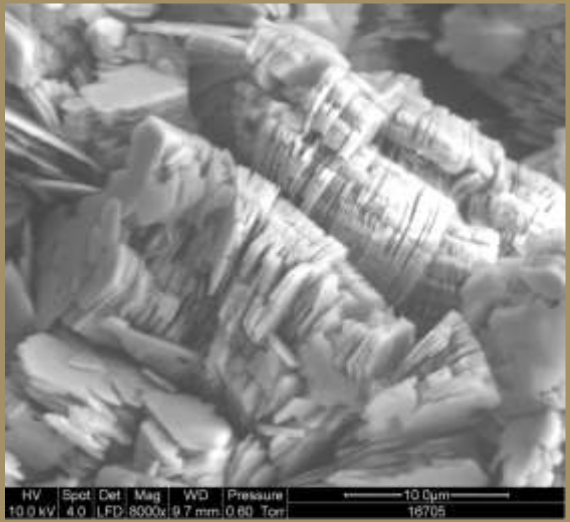

Te Kopia landslide

ALTERATION via ACIDIC STEAM CONDENSATE

- Road Cut Taupo

Acidic steam condensate overprinting

pH 3-4
Temp < 120 °C



Physical impacts

Changes in pressure can result in …

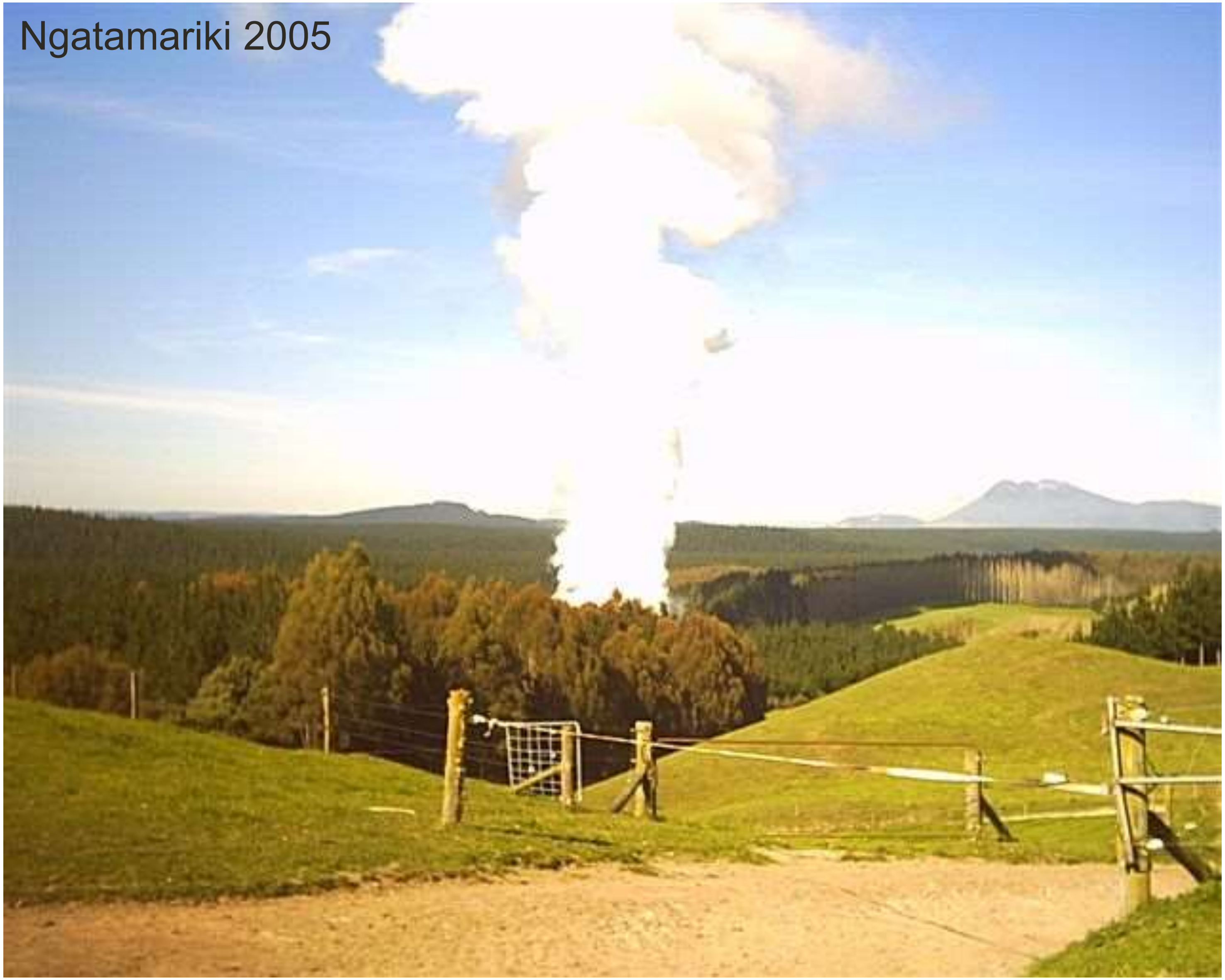
Hydrothermal eruptions

Physical impacts

Hydrothermal eruptions can occur anywhere

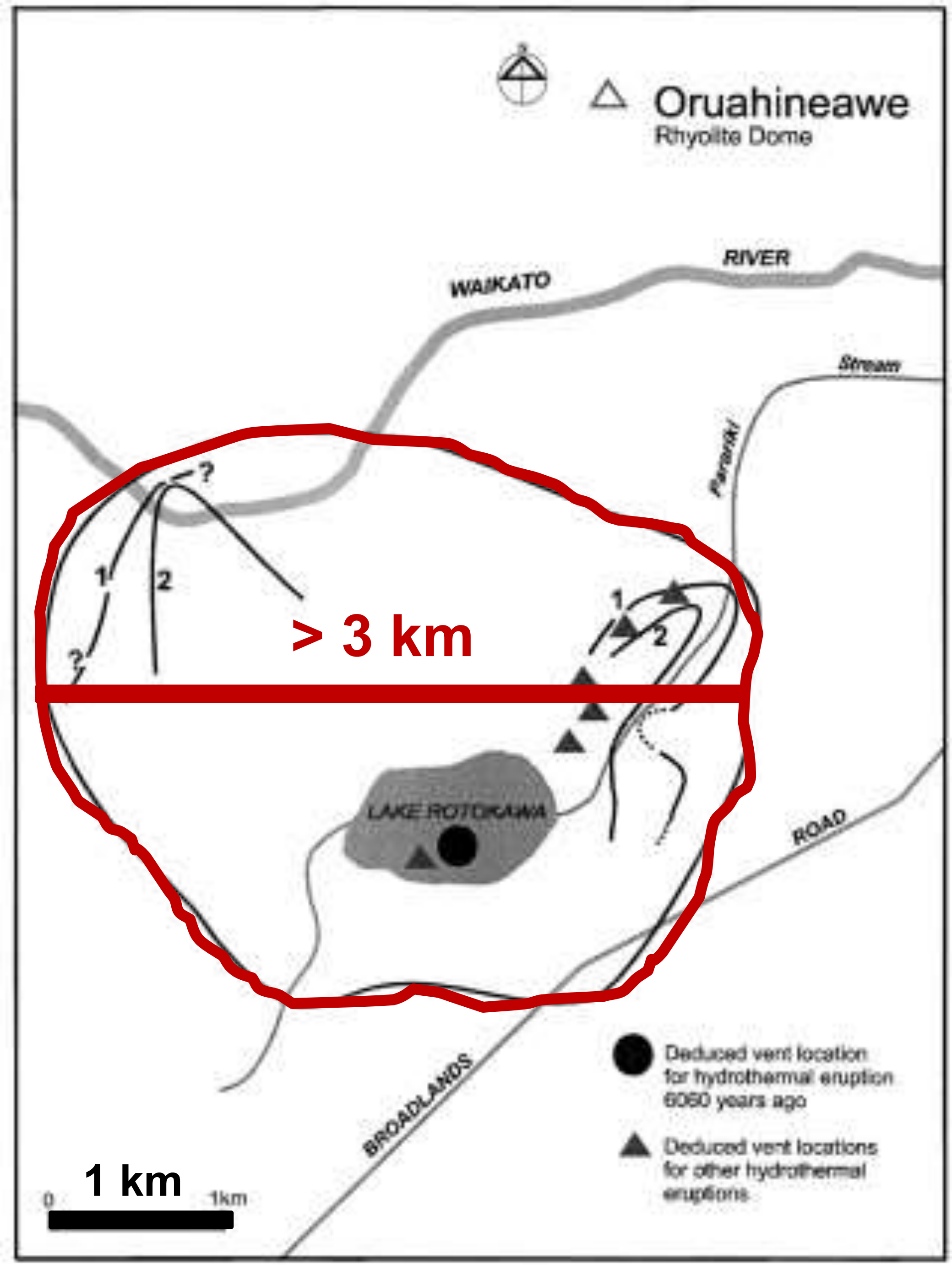
Hydrothermal Eruptions occur ….

- Without warning
- No magma involved
- Sudden change in subsurface pressure
- Flashing to steam and steam provides uplift of rocks for eruption
- Can be catastrophic


Ngatamariki 2005

Ngatamariki 2005

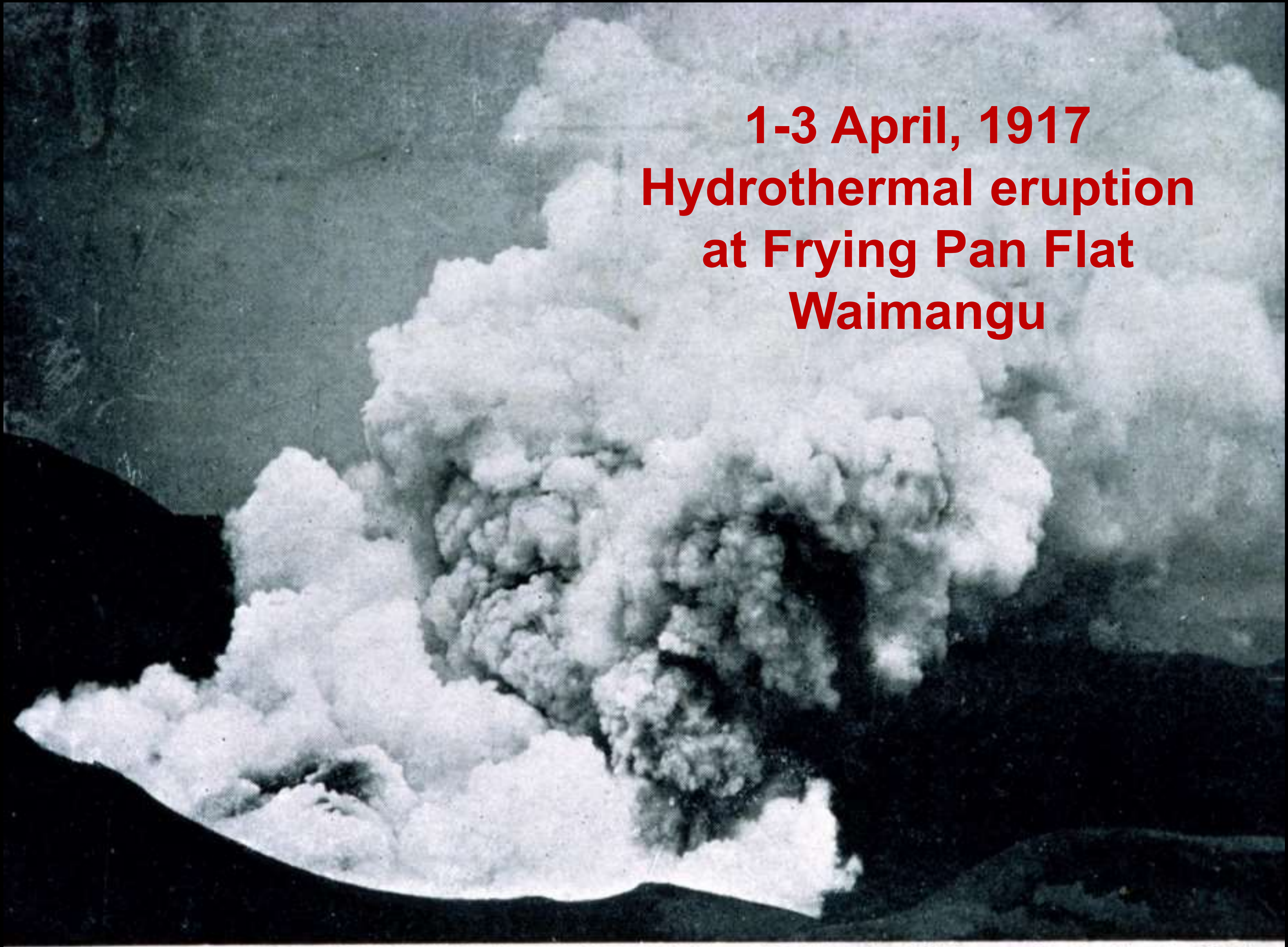
Ngatamariki 2005



Rotokawa:

Extent of deposits from hydrothermal eruption 6060 years ago

1-3 April, 1917
Hydrothermal eruption at Frying Pan Flat Waimangu



THE WAIMANGU ERUPTION APRIL 1 1917 R. G. Marsh, Photo.

Post-hydrothermal eruption-tourist house 1917

~1925: aerial view looking NE

1917 hydrothermal eruption crater as it looks today

Small but dangerous hydrothermal eruptions behind residential property, Kuirau Park

Hydrothermal eruption breccia deposit

Physical impacts

Changes in pressure can result in …

Subsidence

SUBSIDENCE

CAUSES

1. Acidic steam condensate –corrosive, weakens ground
2. Extraction of fluids – reduces pore pressure = compaction

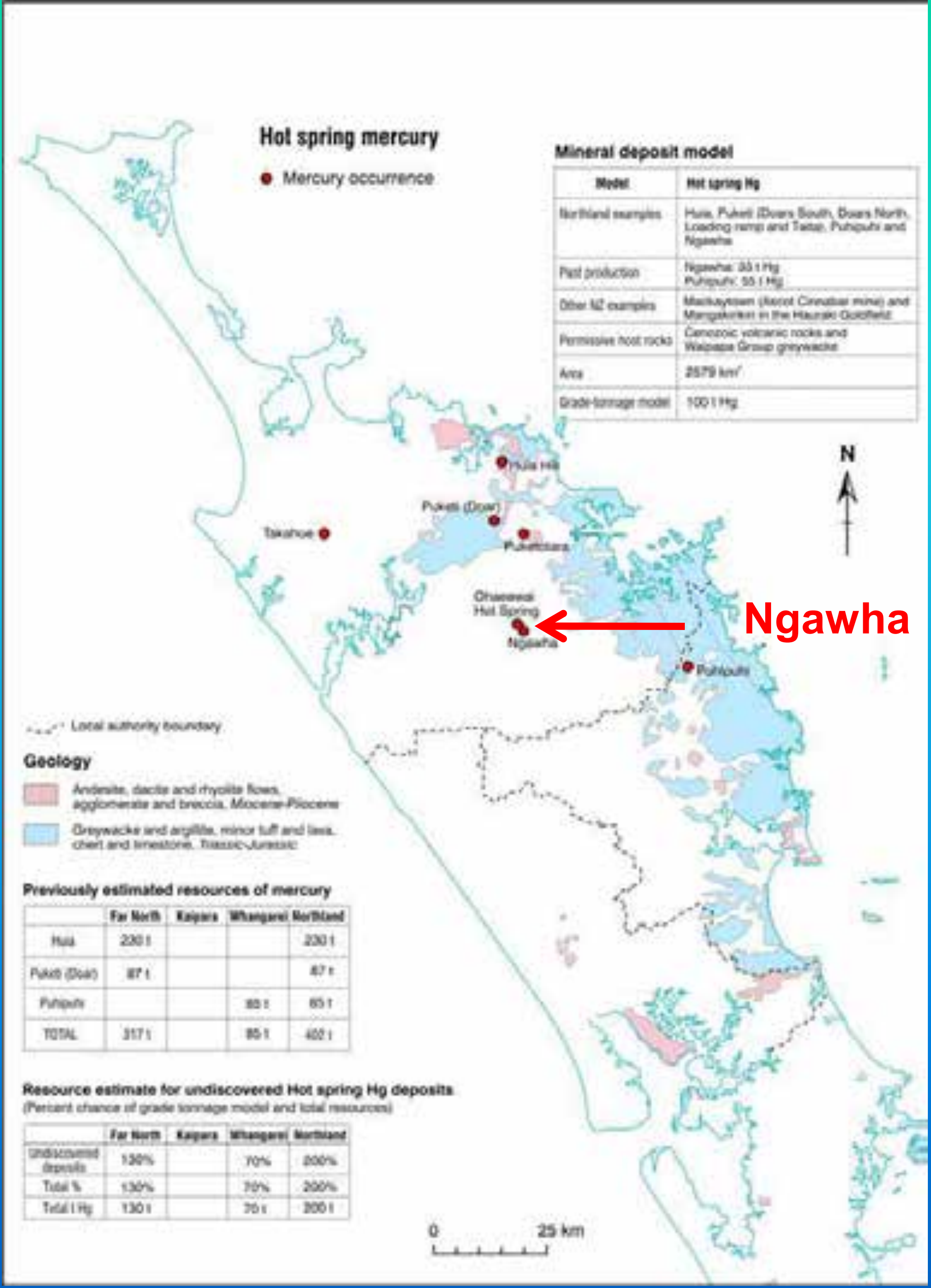
Even minor subsidence is a problem
Kawerau pulp and paper mill has zero tolerance for ground subsidence

Physical impacts

Subsidence of a netball court, Rotorua

2000

Chemical Impacts



Mineral deposit model

Model	Hot spring Hg
Northland examples	Hula, Puketi (Doars South, Doars North, Loading ramp and Taitai), Puhipuhi and Ngawha
Past production	Ngawha: 33 t Hg Puhipuhi: 55 t Hg
Other NZ examples	Mackaytown (Ascot Cinnabar mine) and Mangakirikiri in the Hauraki Goldfield
Permissive host rocks	Cenozoic volcanic rocks and Waipapa Group greywacke
Area	2579 km²
Grade-tonnage model	100 t Hg

Previously estimated resources of mercury

	Far North	Kaipara	Whangarei	Northland
Hula	230 t			230 t
Puketi (Doar)	87 t			87 t
Puhipuhi			85 t	85 t
TOTAL	317 t		85 t	402 t

Resource estimate for undiscovered Hot spring Hg deposits
(Percent chance of grade tonnage model and total resources)

	Far North	Kaipara	Whangarei	Northland
Undiscovered deposits	130%		70%	200%
Total %	130%		70%	200%
Total t Hg	130 t		70 t	200 t

Chemical impacts

Geothermal sources of mercury

Not common

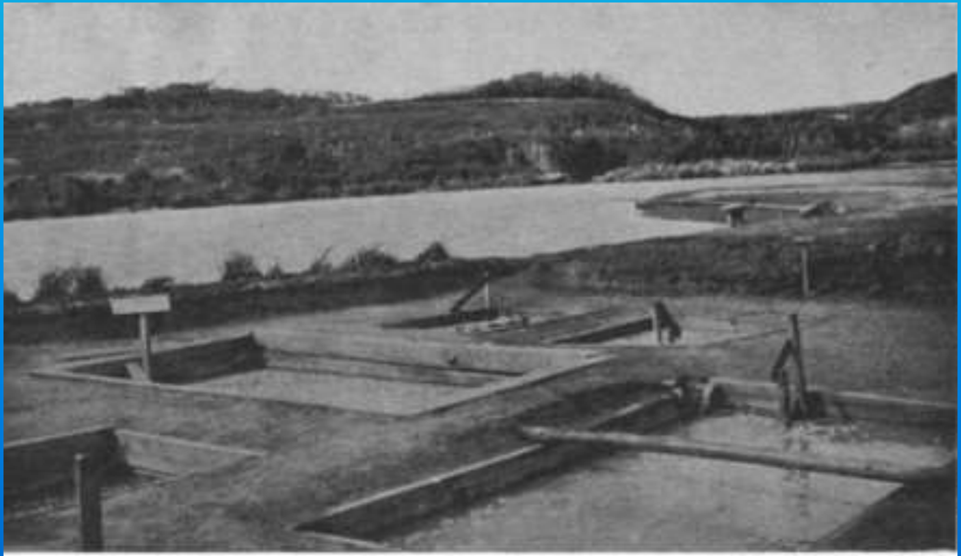
Hazard:
Inorganic mercury accumulates in river sediments, soil etc

- Food chain
- Ecological systems

Reported that:

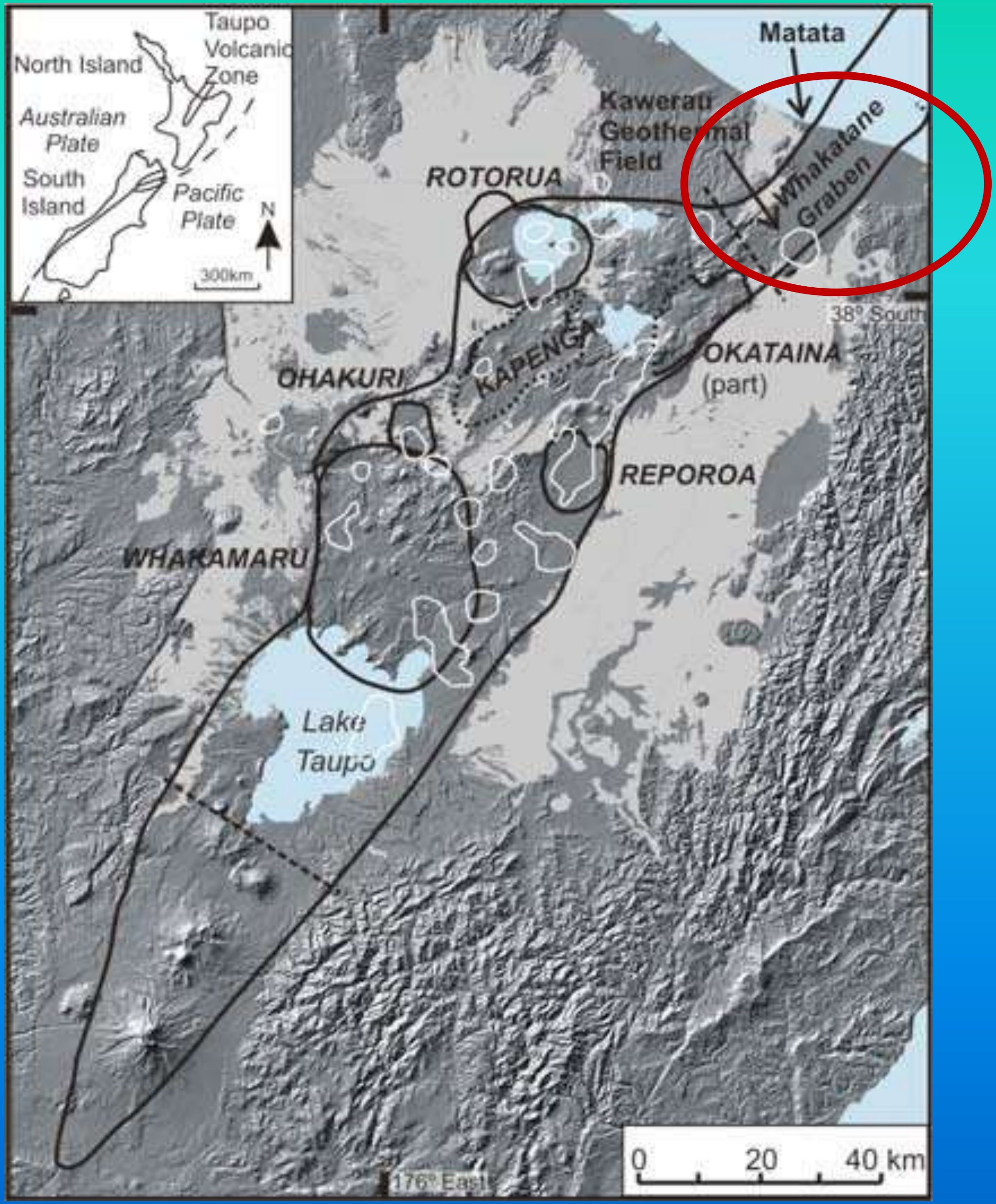
Iron spades held in fumes become covered in metallic mercury after a few minutes exposure.

Lead and zinc house gutterings become coated with metallic mercury on cool nights



(Rly. Publicity photo.)

A recent view of the Ngawha Hot Springs, North Auckland, New Zealand.



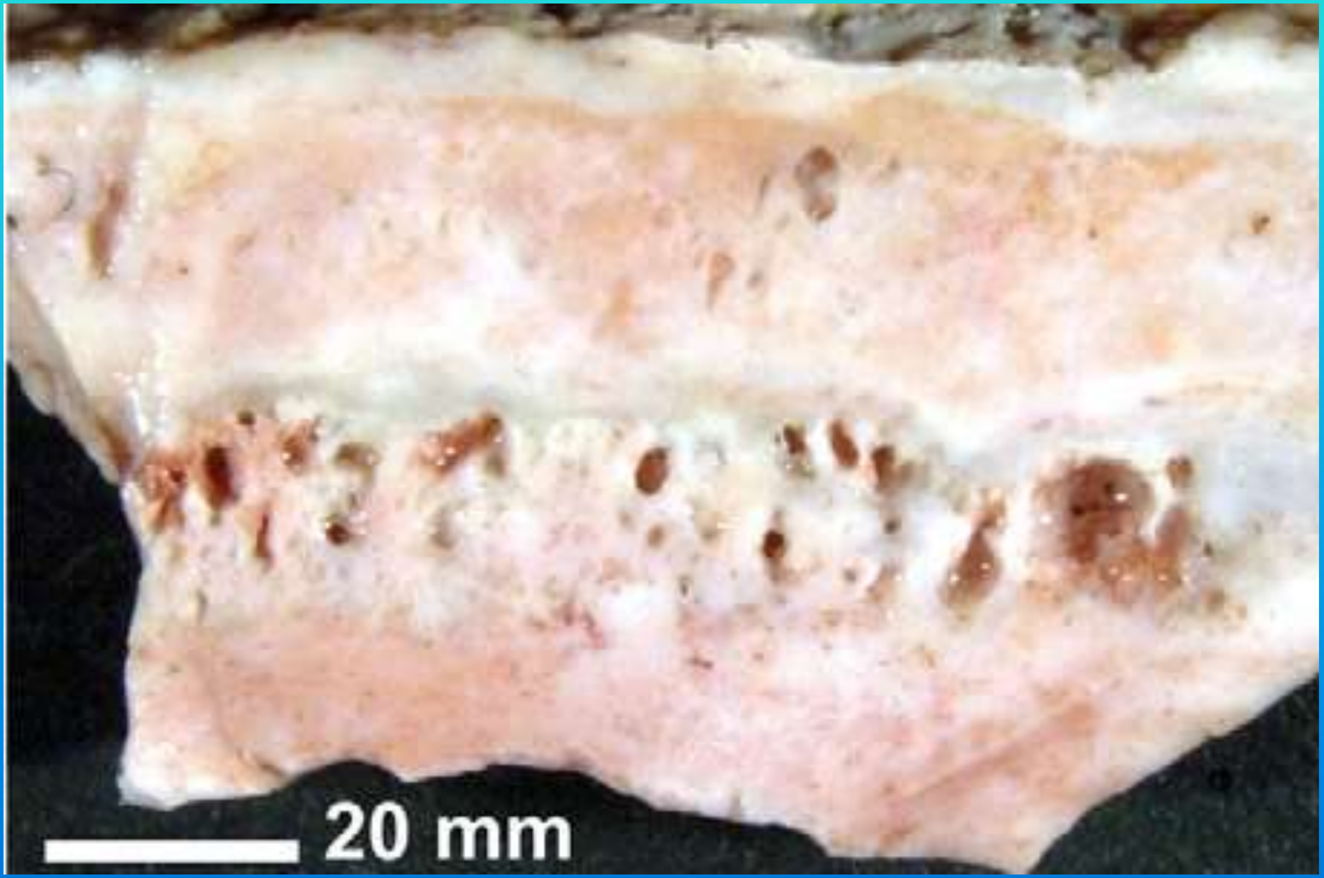
Whakatane Graben

Offshore hot springs

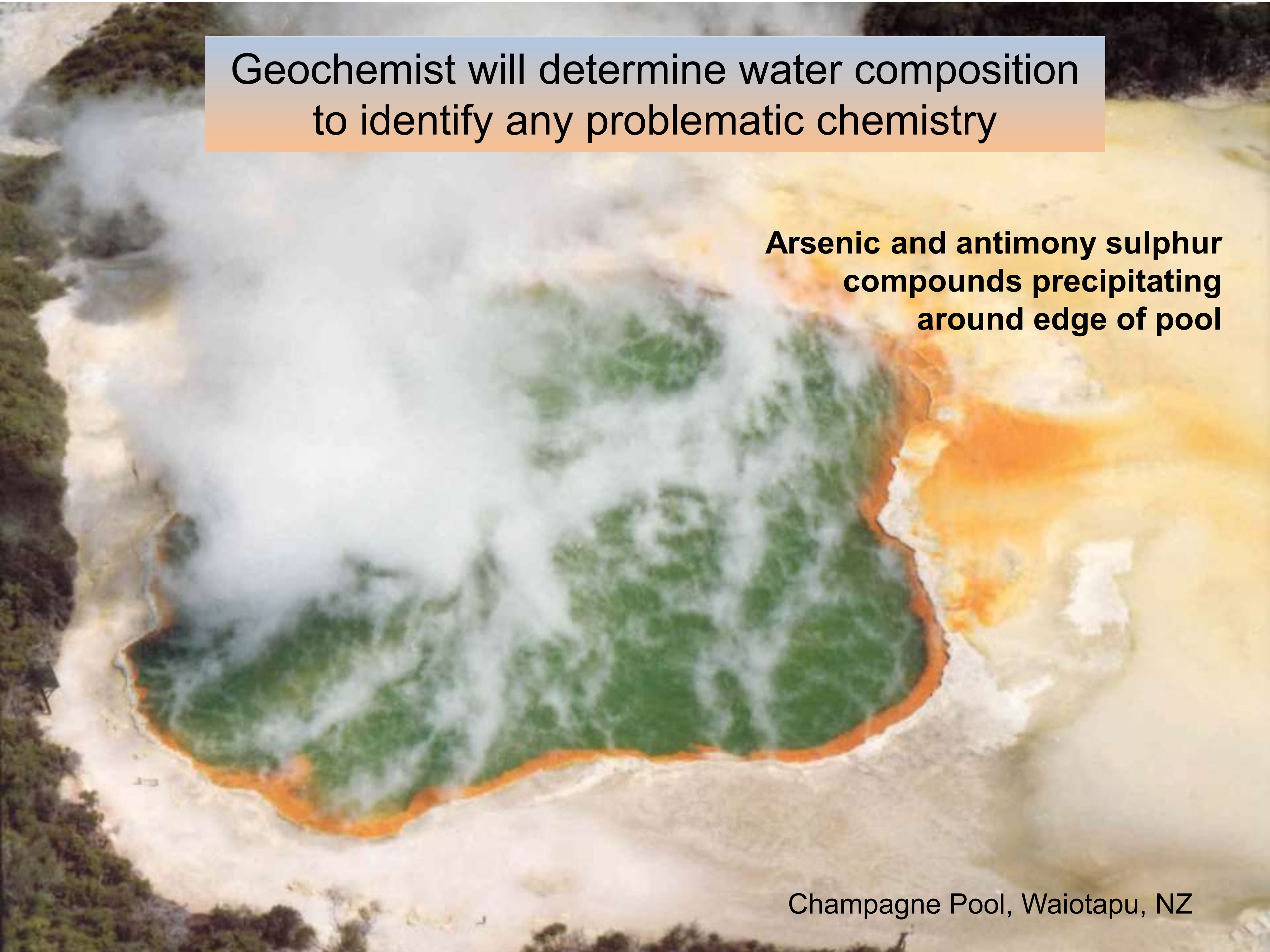
Globules of liquid mercury in discharging hot springs on the sea floor in the Whakatane Graben, NZ

Mercury droplets on cinnibar-rich (red) amorphous silica (Hg/silica hot spring rock)

Mercury-rich hot spring rock from Steamboat Springs, USA



Geochemist will determine water composition to identify any problematic chemistry



Arsenic and antimony sulphur compounds precipitating around edge of pool

Champagne Pool, Waiotapu, NZ

Geochemistry can determine if any nasty chemical constituents are going to be a problem for the development of the power plant

Chemical impacts

Disposal of drilling mud
Pipe scale
Other drilling products

Social Impacts of development

Loss of tourist features

Social impacts

Social impacts

Many features have cultural significance

Noise pollution

ap of surface activity

ENTIAL

which features change

Ongoing monitori

Enables early detec

Next talk….

Optimising National Geothermal Use…

How to classify, regulate and monitor