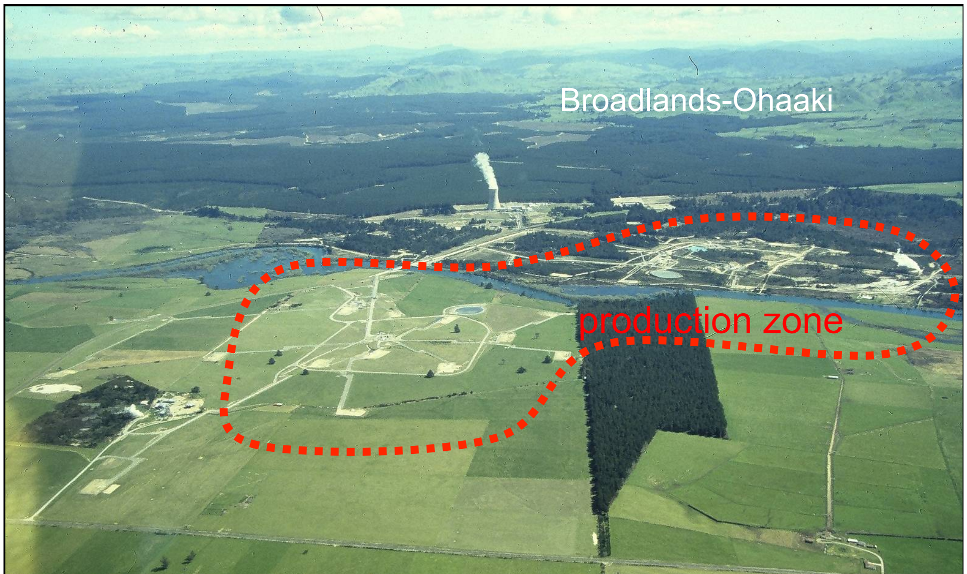


Resource Assessment

Stored heat estimate
Boundaries of reservoirs

Stored Heat

Volumetric assessment of the total amount of heat stored in a reservoir

Need to know reservoir volume, porosity and temperature

Estimate the proportion of exploitable heat-Recovery factor

Consider simple example:

1 km^3	reservoir volume
250°C	reservoir temperature
15°C	reject temperature
15%	porosity (water filled)

Stored Heat

Numerical expressions, constants & thermodynamic data

Rock density (ρ_r)	2500 kg/m^3
Water density (ρ_w)	800 kg/m^3
Rock specific heat (C_r)	1 Kj/kg°C
Volume (V)	10^9 m^3
Enthalpy water (H_{250})	1086 Kj/kg
Enthalpy water (H_{25})	63 Kj/kg
Porosity (Φ)	0.15
Temperature drop (ΔT)	235°C

thermal energy rock = $V \cdot (1 - \Phi) \cdot \rho_r \cdot C_r \cdot (\Delta T)$

thermal energy water = $V \cdot (\Phi) \cdot \rho_w \cdot (H_{250} - H_{15})$

Stored Heat

thermal energy rock

$$5 \cdot 10^{17} \text{ joules} = V \cdot (1 - \Phi) \cdot \rho_r \cdot C_r \cdot (\Delta T)$$

thermal energy water

$$1.2 \cdot 10^{17} \text{ joules} = V \cdot (\Phi) \cdot \rho_w \cdot (H_{250} - H_{15})$$

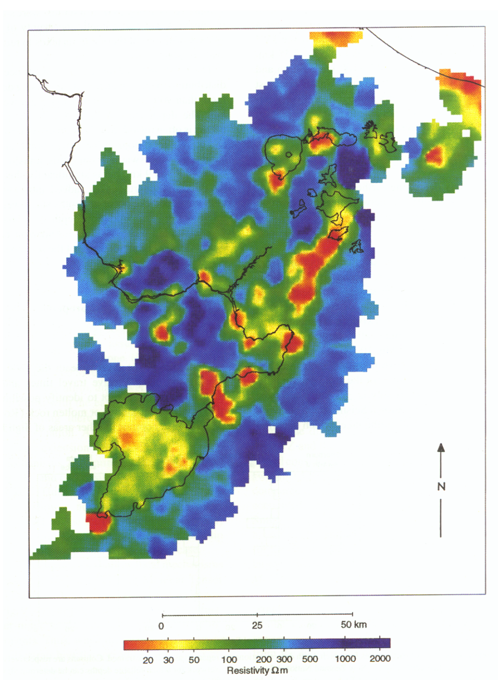
- more thermal energy contained in rock than water
- very simple assessment (no recovery factor)
- consider useable energy & mode of utilization

Boundaries of Geothermal Reservoirs

Resistivity-MT data are used to identify the lateral extent of conductive zones (layers) that are clay rich or filled with hot chloride water. In NZ, dipole-dipole resistivity measurements have revealed the limits of known geothermal plumes, but the margins need to be confirmed with well measurements.

Hydrothermal alteration zonation patterns reflect the flow & extent of hot water. Surface alteration can provide clues, but the best information is obtained from geothermal wells in which subsurface zonation patterns are determined. This includes identification of the top of the reservoir.

Fluid chemistry is used to distinguish upflow from outflow. Geothermometers and tracers (Cl concentration) are used in conjunction with the above information to interpret reservoir boundaries.



Taupo Volcanic Zone

Shallow geophysical surveys – hot water/ clay altered rocks.

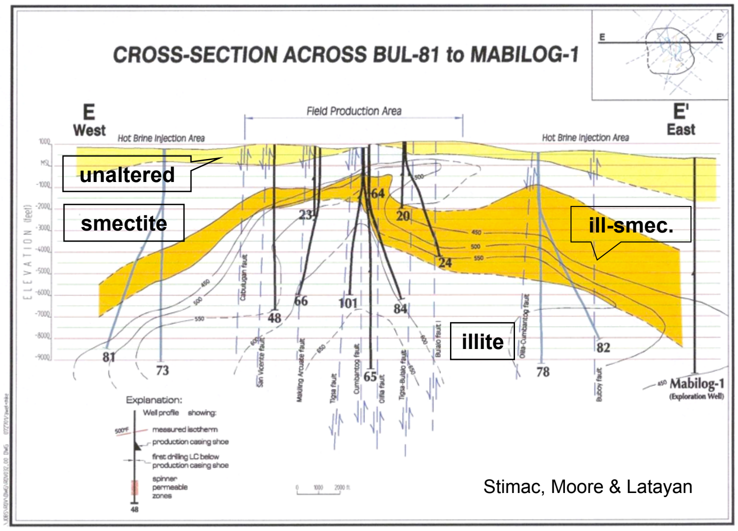
Revealed the location of Mokai, which had been omitted from earlier resource assessments.

Boundaries are imprecise & need to be calibrated. In general, reservoir boundaries contained inside resistivity anomaly (<10 ohm-m)

Red=conductive
Blue=resistive

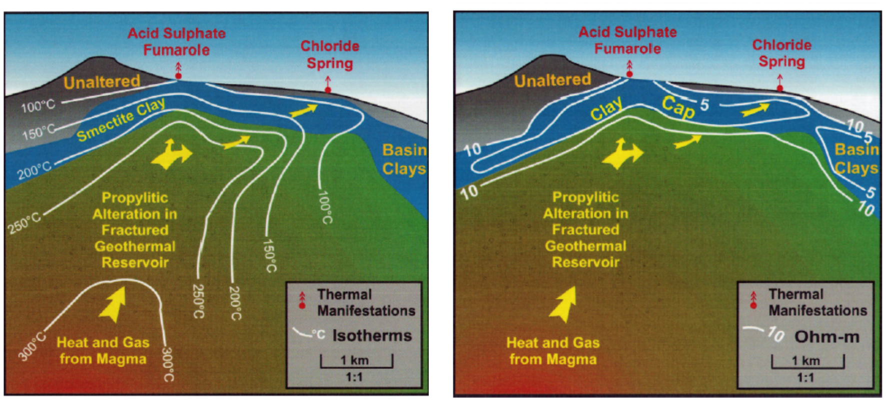
Central TVZ: DC apparent resistivity
(Stagpoole and Bibby, 1998)

East-West Cross Section Bulalo-Clay Minerals



Distribution of temperature sensitive minerals: top of reservoir

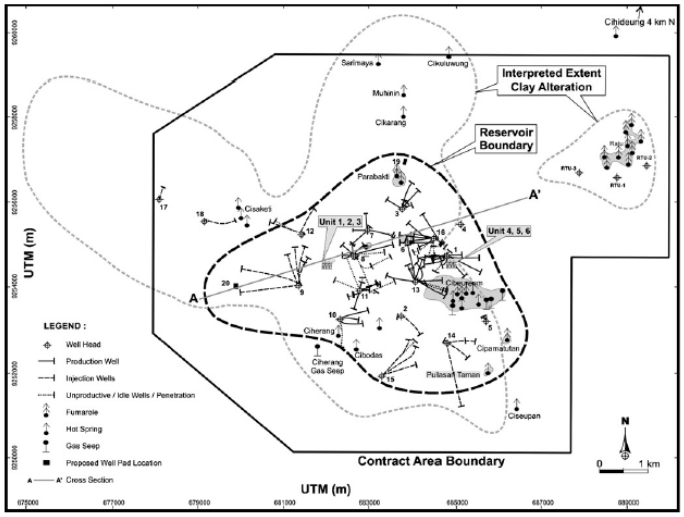
Conceptual Model: Clay Alteration & Conductivity



Stimac et al., 2008. NB Clay cap rich in smectite can be detected using methylene blue which can be applied in the field/core shed.

Reduced permeability associated with clay-layer forms a barrier to fluid movement.

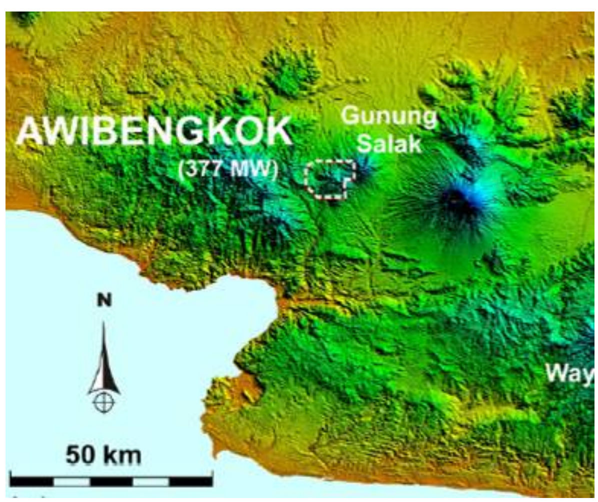
Awibengkok



Stimac et al., 2008.

Fig. 2. Map of the Gunung Salak contract area. The Salak contract area (solid black line) is shown along with the commercial reservoir boundary (dashed black line), as well as the thermal features and the interpreted extent of clay alteration based on MT-TDEM surveys (dashed grey lines). Wells are numbered based on the sequence of drill sites established. Exploration wells drilled at Ratu are also shown. Cihideung hot spring lies 4 km north of the map boundary. Lithology and alteration along cross-section A–A′ is shown in Figs. 4b and 7, respectively.

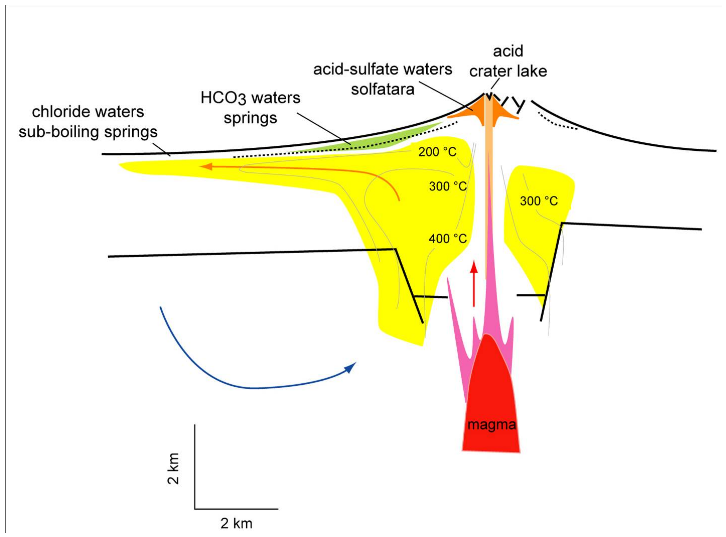
Awibengkok



Stimac et al., 2008.

Surface thermal features have helium isotope signatures of 6 to 7 R/Ra indicating mantle helium & a magmatic intrusion. The distribution of fumaroles, acid sulfate, bicarbonate & chloride springs is characteristic of steep terrain in the vicinity of a composite andesite cone

Awibengkok



Stimac et al., 2008.

Awibengkok

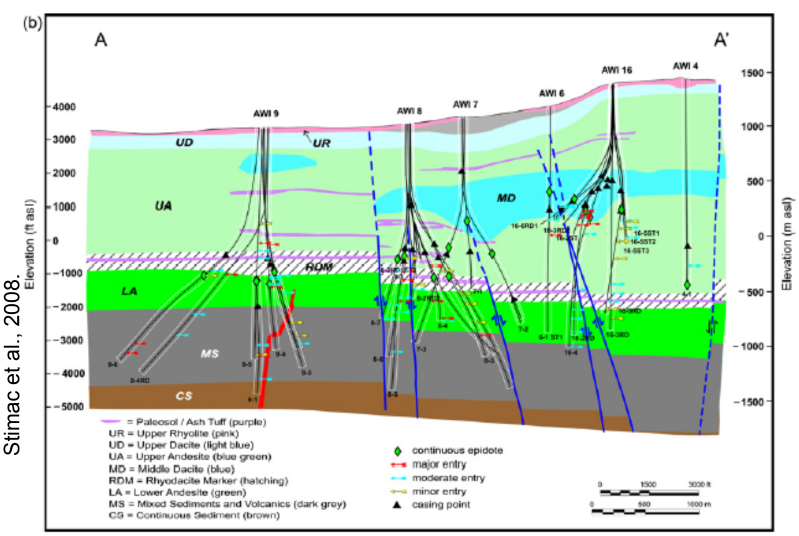


Fig. 4. (*Continued*).

Stimac et al., 2008.

Awibengkok

Stimac et al., 2008.

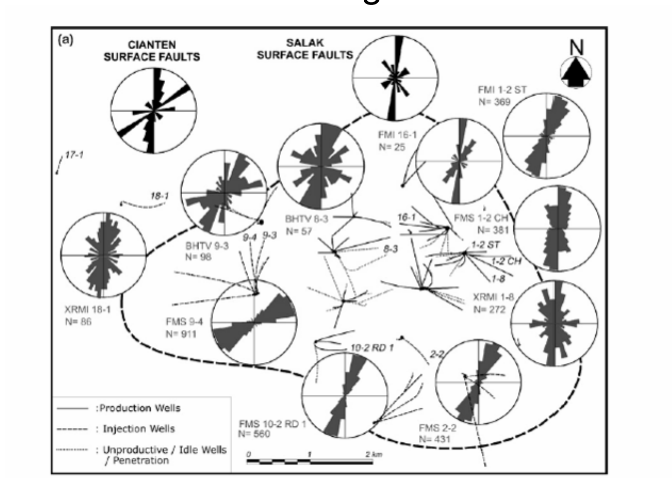


Fig. 6. Locations and orientations of surface and subsurface structures in the Awigengkok area. (a) Rose diagrams of strike of surface faults mapped in the Cianten Caldera and the Awibengkok area (black) and open fracture orientations interpreted from downhole image logs (dark gray). N refers to the number of open fractures mapped. Abbreviations for image log type are BHTV: Borehole Televiewer; FMS: Schlumberger Formation Microanalyzer; FMI: Schlumberger Formation Microimager; XRMI: Halliburton Extended Range Microimager. (b) Map of inferred subsurface faults based on offset in the Rhyodacite Marker (RDM).

Awibengkok

Stimac et al., 2008.

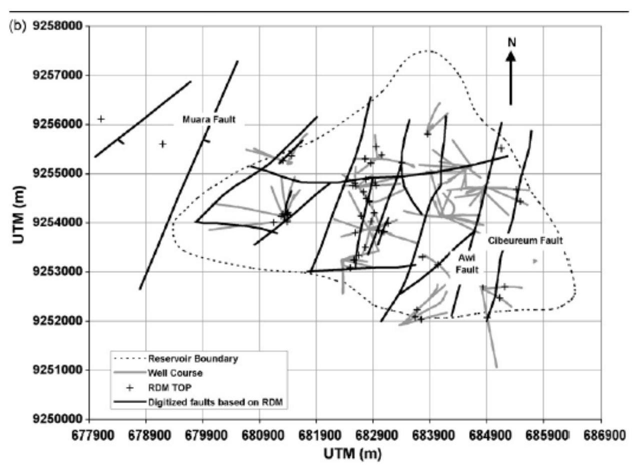
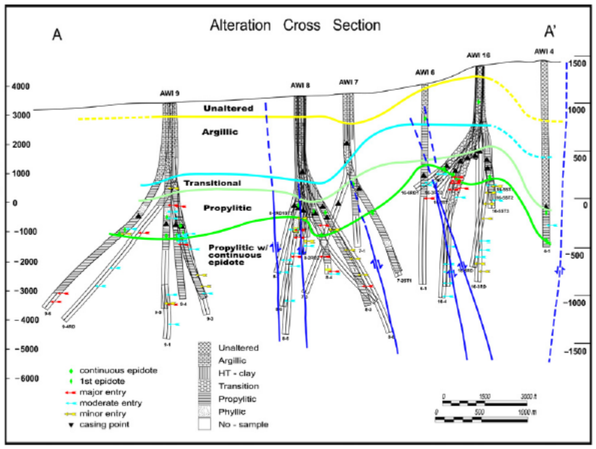


Fig. 6. Locations and orientations of surface and subsurface structures in the Awigengkok area. (a) Rose diagrams of strike of surface faults mapped in the Cianten Caldera and the Awibengkok area (black) and open fracture orientations interpreted from downhole image logs (dark gray). N refers to the number of open fractures mapped. Abbreviations for image log type are BHTV: Borehole Televiewer; FMS: Schlumberger Formation Microanalyzer; FMI: Schlumberger Formation Microimager; XRMI: Halliburton Extended Range Microimager. (b) Map of inferred subsurface faults based on offset in the Rhyodacite Marker (RDM).

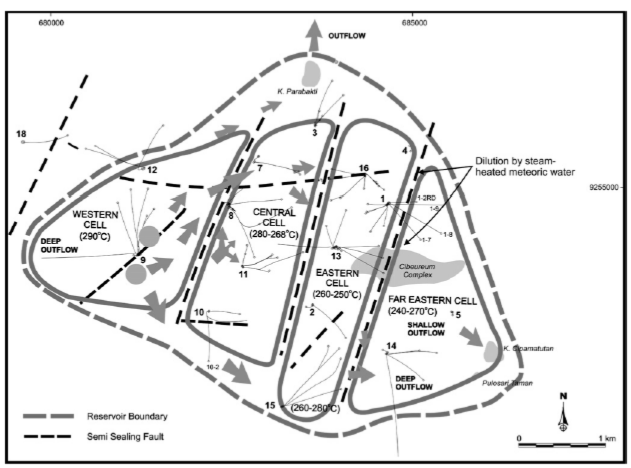
Awibengkok



Stimac et al., 2008.

Fig. 7. Cross-section A-A′ (see Fig. 2) showing the distribution of alteration mineral assemblages. Faults may play a role in localizing changes in the elevation of the reservoir top. HT-clay: hydrothermal clay (rich in smectite and associated with pyrite).

Awibengkok



Stimac et al., 2008.

Fig. 8. Sector map of the Awibengkok geothermal reservoir. The field can be divided into four sectors with distinctive temperatures, fluid chemical signatures, and tracer return patterns. Faults and fractures shown in Fig. 6 play a major role in determining sector boundaries. Arrows indicate the general direction of fluid flow under natural-state (pre-exploitation) conditions.

Awibengkok

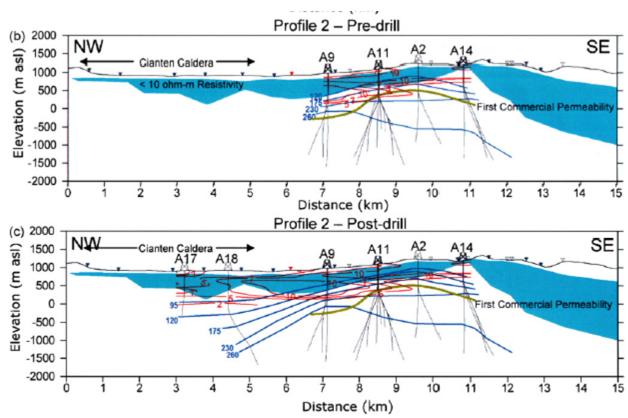
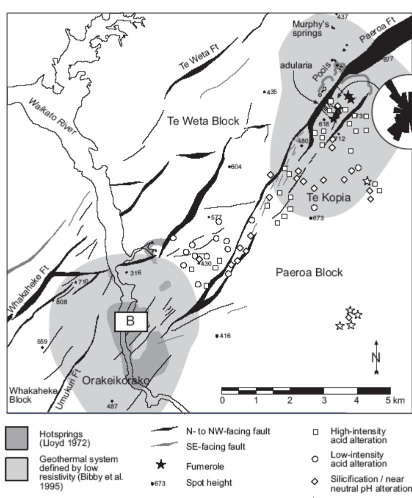
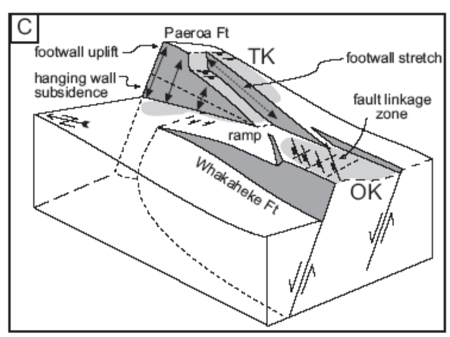


Fig. 11. Resistivity profiles of the Awibengkok area highlighting the <10 Ω-m layer defined by 1D MT models (shaded blue) temperature isotherms and methylene blue contours (in g/ml). (a) N-S resistivity cross-section showing the thickening of the low-resistivity layer south of Awi 15 and deepening of the high-temperature isotherms is consistent with a reservoir margin. A similar thickening of the low-resistivity layer is observed north of the Sarimaya chloride spring. (b) Pre-drilling NW-SE resistivity. The thickening of the low-resistivity layer SE of Awi 14 and deepening of the high-temperature isotherms is consistent with a reservoir margin. The isotherms do not show clear evidence for a margin NW near the Awi 9 pad. (c) Post-drilling NW-SE cross-section with observed temperatures (in red) and methylene blue data (in g/ml) from new wells Awi 17 and 18.

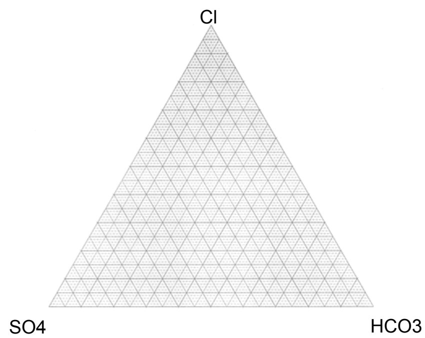
Stimac et al., 2008.

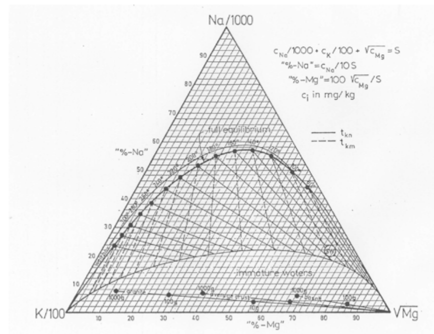
Boundaries of Te Kopia & Orakeikorako

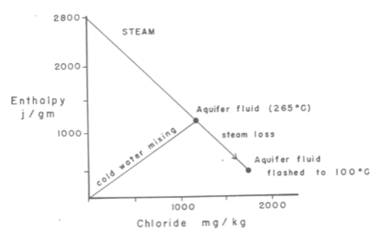




Boundaries of Geothermal Reservoirs: Chemical Indicators







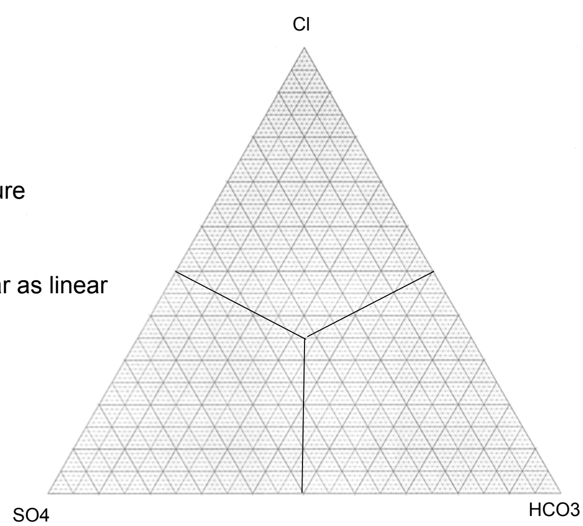
Three graphs of water chemistry used
to interpret reservoir conditions & fluid flow

Boundaries of Geothermal Reservoirs: Chemical Indicators

Cl-HCO_3-SO_4 plot used to:

- distinguish water types
- interpret chemical structure
- assess fluid flow

Mixing trends always appear as linear arrays of data

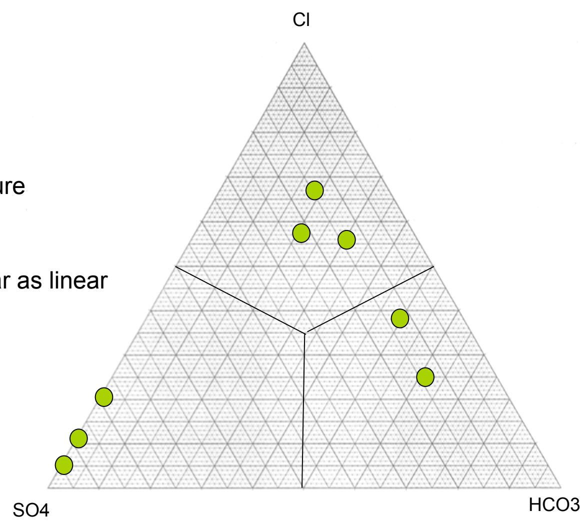


Boundaries of Geothermal Reservoirs: Chemical Indicators

Cl-HCO_3-SO_4 plot used to:

- distinguish water types
- interpret chemical structure
- assess fluid flow

Mixing trends always appear as linear arrays of data

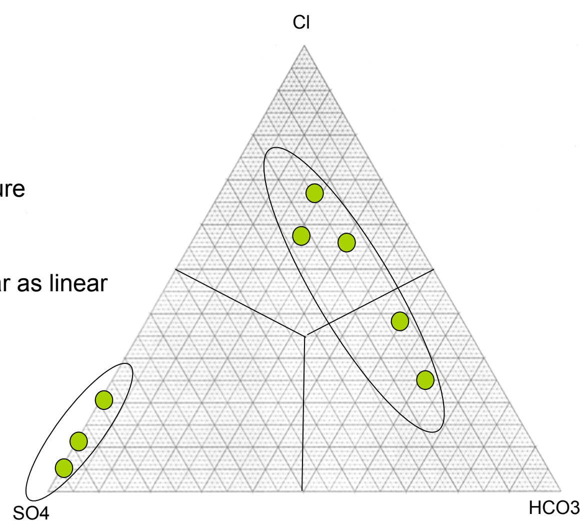


Boundaries of Geothermal Reservoirs: Chemical Indicators

Cl-HCO_3-SO_4 plot used to:

- distinguish water types
- interpret chemical structure
- assess fluid flow

Mixing trends always appear as linear arrays of data



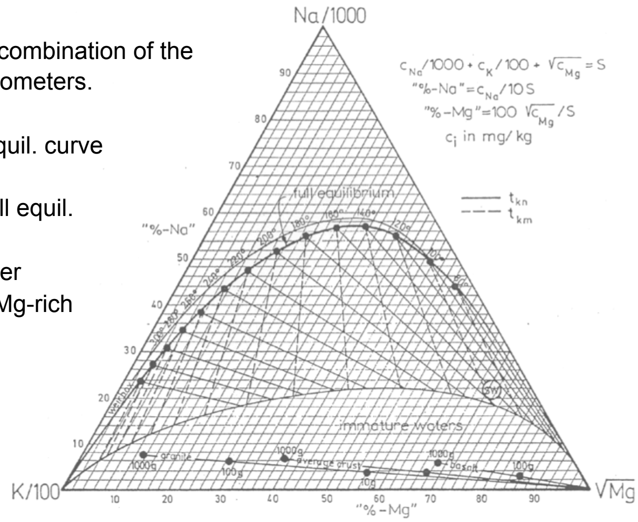
Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

$T_{KNa}=T_{KMg}$ plot on full equil. curve

$T_{KNa}>T_{KMg}$ plot below full equil.

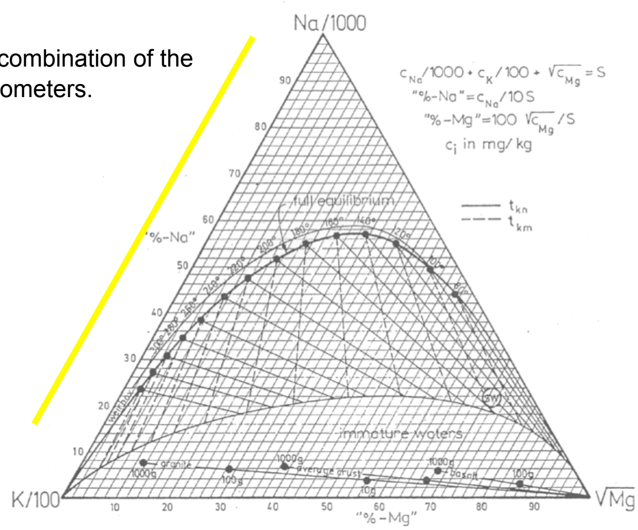
Mixing with Mg-rich water forms linear trend with Mg-rich water



Giggenbach, 1988; 1992

Boundaries of Geothermal Reservoirs: Chemical Indicators

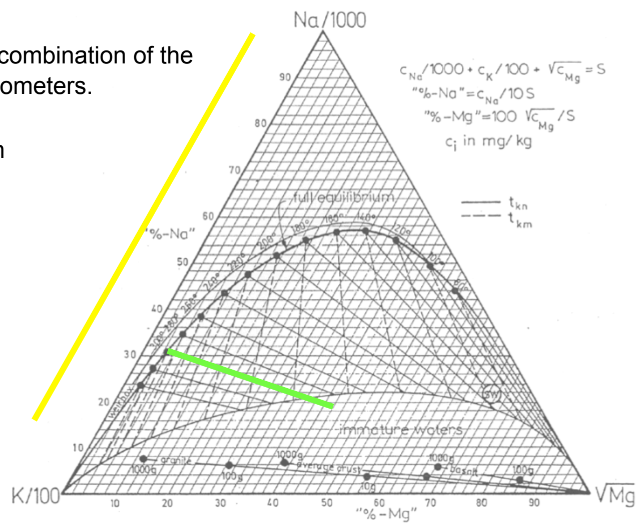
Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.



Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

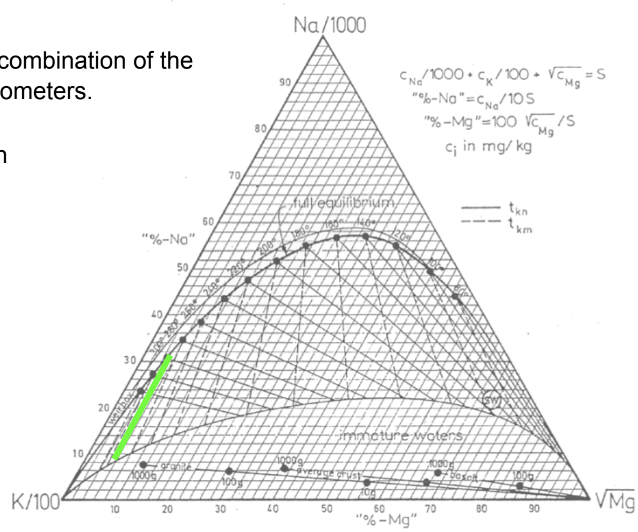
Observe Na-K ratio with T_{KNa} = 300 °C



Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Observe K-Mg ratio with T_{KMg} = 300 °C

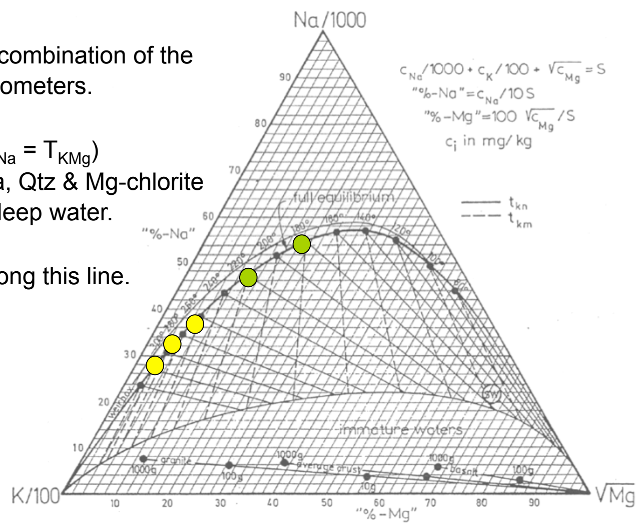


Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Full equilibrium line ($T_{KNa} = T_{KMg}$)
Na-spar, K-spar, K-mica, Qtz & Mg-chlorite are in equilibrium with deep water.

Production wells plot along this line.



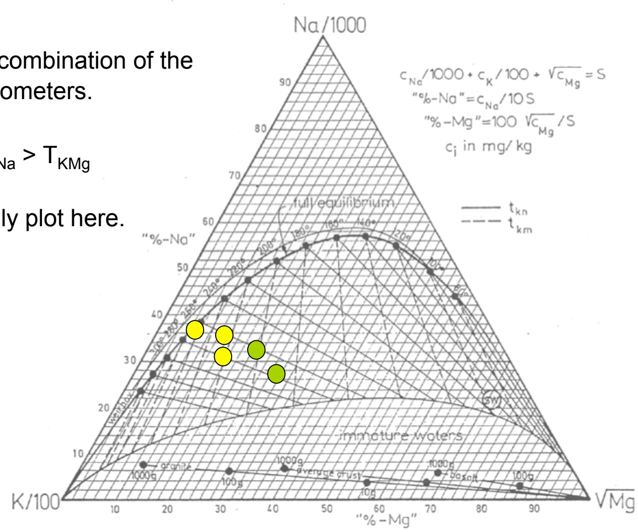
Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Note the field where $T_{KNa} > T_{KMg}$

Hot spring waters usually plot here.

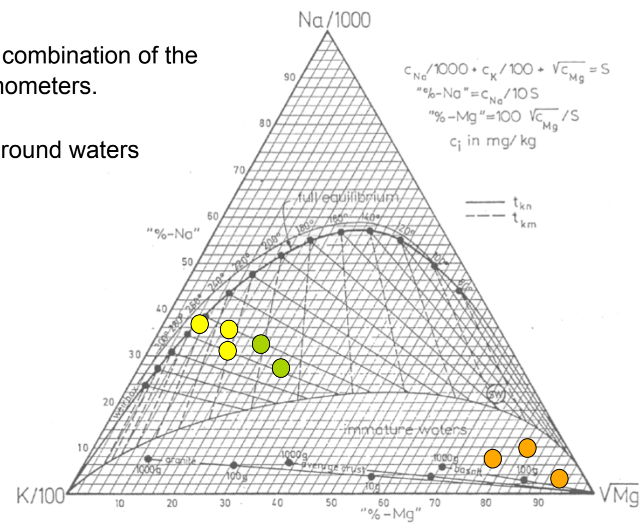
Why?



Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Cold & steam-heated ground waters plot near the Mg-apex.

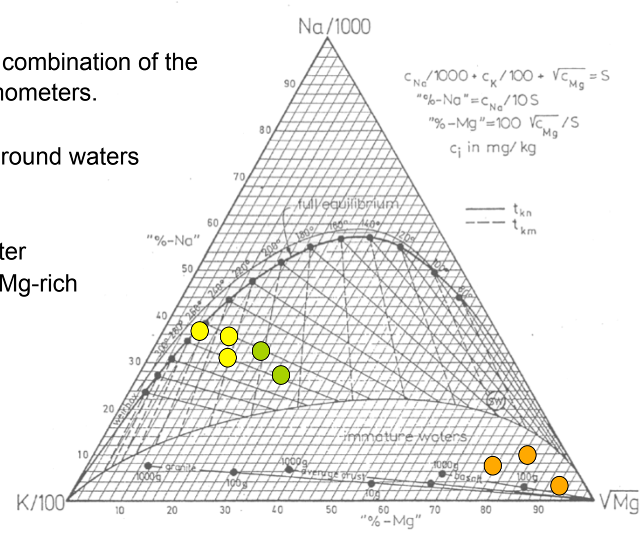


Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Cold & steam-heated ground waters plot near the Mg-apex.

Mixing with Mg-rich water forms linear trend with Mg-rich water

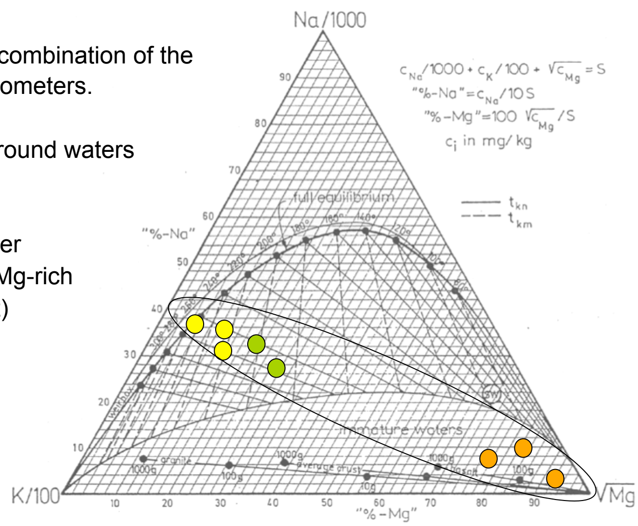


Boundaries of Geothermal Reservoirs: Chemical Indicators

Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Cold & steam-heated ground waters plot near the Mg-apex.

Mixing with Mg-rich water forms linear trend with Mg-rich water (T_{KMg} is irrelevant)

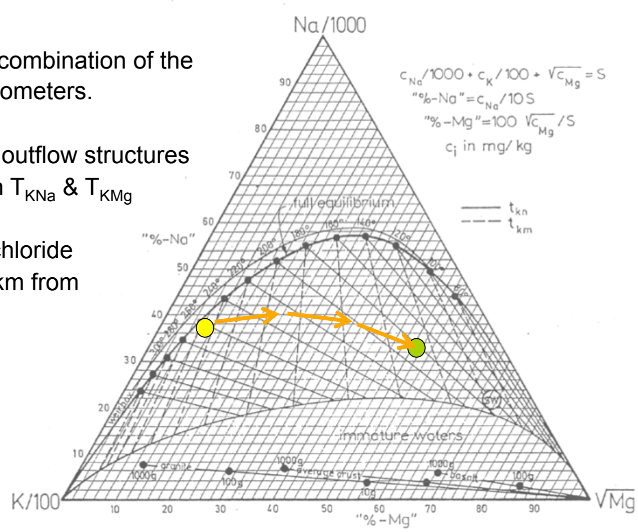


Boundaries of Geothermal Reservoirs: Chemical Indicators

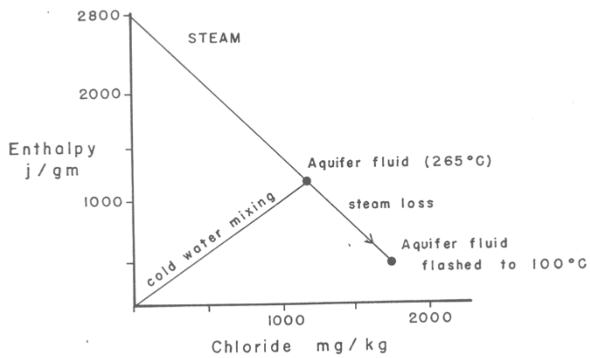
Na-K-Mg plot-powerful combination of the K-Na & K-Mg geothermometers.

Trends associated with outflow structures show gradual change in T_{KNa} & T_{KMg}

Example: Miravalles—chloride springs discharge >10 km from upflow zone

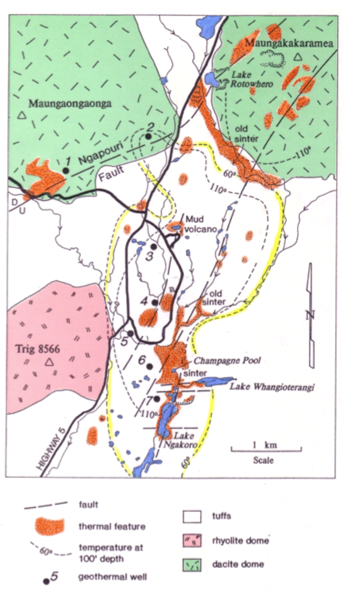


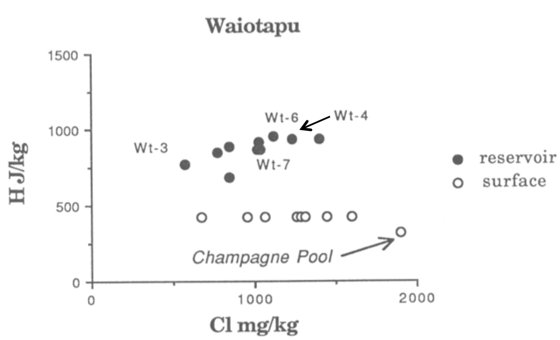
Boundaries of Geothermal Reservoirs: Chemical Indicators



Chloride-Enthalpy Plot: Distinguish mixing & boiling trends. Best applied after one or two wells have been drilled and deep water data are available.

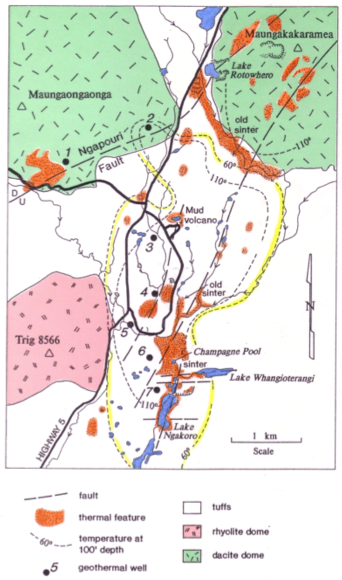
Boundaries of Geothermal Reservoirs: Chemical Indicators

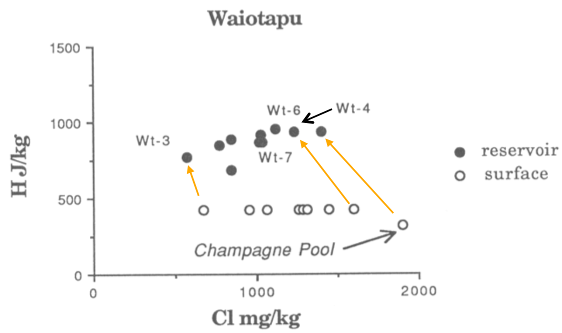




Champagne Pool contains highest Cl. Well Wt-4 has next highest.

Boundaries of Geothermal Reservoirs: Chemical Indicators

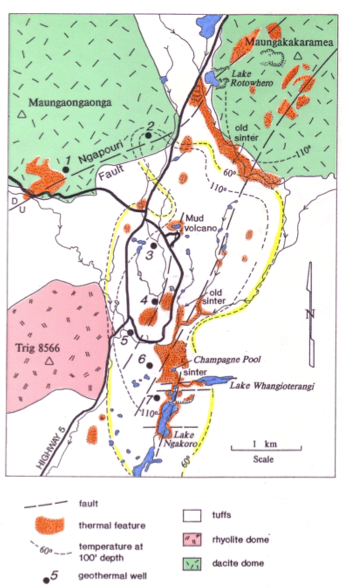


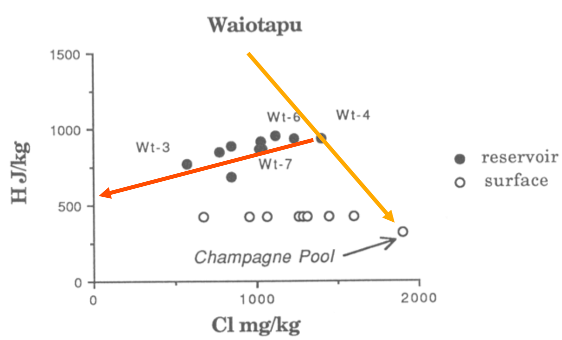


Champagne Pool contains highest Cl. Well Wt-4 has next highest.

Correcting for steam loss, the reservoir composition is computed using steam fraction.

Boundaries of Geothermal Reservoirs: Chemical Indicators



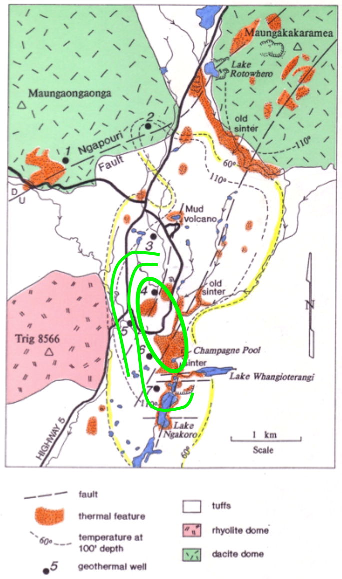


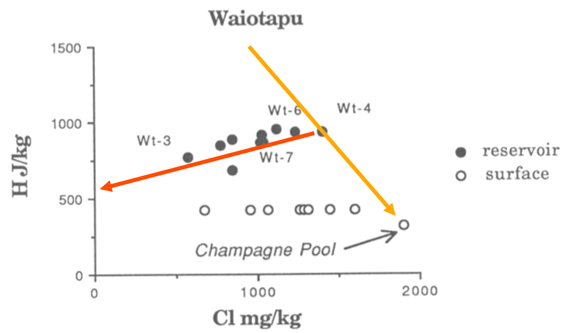
Identify boiling trend for parent or reservoir water composition.

Identify mixing-dilution trend (eyeball)

Identify end-member compositions.

Boundaries of Geothermal Reservoirs: Chemical Indicators





Interpret fluid flow on map.

Chloride contours in reservoir.

Flow direction. Compare with temperature profiles.

Summary

Determine volume of reservoir with geophysics, extent of surface thermal activity & hydrological models

Determine temperature of reservoir with aqueous geothermometers, alteration minerals & temperature gradient measurements (shallow-deep wells)

Determine heat reserves with stored heat calculation or more sophisticated reservoir modelling (numerical simulation)