Conceptual Model Components

from Novi Ganefianto, 2015
Volcanic Hydrothermal System

LEGEND:
- Acid sulphate bicarbonate waters
- Mixed sulphate chloride waters
- Two phase zone (liquid, steam, gas)

modified after Nicholson (1993)

C/G-Figures/General Geothermal Geoth System
Yuliana H Jan 2005
Elements of the Natural (Initial) State:

- Upflow characterized by high temp, agreement between geothermometers, (equilibrated), high chloride, low NCG, single-phase liquid (no boiling)

- Outflow characterized by lower temps, disagreement between geothermometers, lower chloride, wide range of NCG, boiling

- Reservoir boundaries constrained by geochemistry (water type and gas chemistry distributions), surface geology (major structures, lithology), geophysics (MT base of conductor), hydrology

- Phase distributions of upflow and outflow are inferred from chloride springs (water table), boiling point for depth, fumarole locations, and gas chemistry trends

- Nature of heat source (magmatic or commercial geothermal), clay cap orientation reflects geometry of heat source
- **Initial-state (natural state) chemistry is the only stage where field-wide equilibrium is approached**

- **Once commercially developed, geochemistry of the field should be viewed as a perturbed equilibrium system** where reservoir processes (equilibrium or non-equilibrium) compete to alter the controlling chemical reactions

- **Conceptual models are an iterative approach to understanding a system.** Once developed, the conceptual model(s) will change over time due with new data. There may be more than one conceptual model in early resource development

- Analogs are instructive but often fail to capture the unique balance and/or interaction between the recharge and extraction processes at each field
Elements of the Produced (Commercial) State:

- Reservoir boundaries constrained by well lithology (base of argillic, top of propylitic, first epidote, TLC, etc.)

- Subsurface temperatures confirmed by flowing PT surveys and supported by geothermometry from production chemistry samples and enthalpy measurements

- Upflow interpreted by highest flowing temp. profiles, chloride, equilibrium between geothermometers, low NCG, little/no excess steam, and no temp reversals in temperature gradients

- Phase distributions confirmed by PT logs and geothermometry interpretations/calculations for excess steam

- Bottomhole profiles delineate base of convective upflow

- Little/no magmatic inputs
Data Quality

Analytical Data Quality

- Use reputable geothermal lab – water quality labs not always experienced with complex geothermal sample matrices
- Detection limits for Mg – geothermal reservoirs low in Mg, 0.2 ppm detection limit not good enough! Need 0.02 ppm DL for Mg
- Silica must be acidified and diluted
- Argon/oxygen separation in chromatography for NCG air corrections
- Lab QC/QA limits – calibration curve, replicate analyses, sample spike recovery, and QC standard recovery
- Charge balance for non-acidic samples

Sample Quality

- Samples collected using correct chemical preservatives and filtration techniques - HNO3 for metals, dilute HNO3 for silica, CdCl2+ NaOH for NCG, etc. (Giggenbach and Goguel, 1989)
- Gas chemistry most reliable for fumaroles at saturated/superheated conditions with high steam flux – below saturation conditions samples subjected to near-surface condensation and CO2 enrichment (evidenced on gas grids/ternary diagrams)
- NCG Air correction - low air contamination for gas samples indicate good sampling techniques

Garbage In = Garbage Out
Conceptual Model Uncertainties

- Reservoir mineralogy controlling fluid/rock interactions – typically feldspars (albite, quartz, epidote) geothermometry temps
- Degree of mixing - distance of chloride springs from reservoir
- Processes controlling fluid/gas chemistry – gas chemistry more ambiguous, degree of boiling is often uncertain, does initial state steam cap exist??
- Sources of chloride (geothermal, magmatic, connate)
- Stages of alteration
Geochemistry Objectives

- **Reservoir distribution (upflow/outflow) & processes (boiling, mixing, cooling, gas condensation, etc.)**
  - Locate neutral high – temp equilibrated fluids (upflow)
  - Predict fluid-mineral equilibration temperatures & spatial distributions
  - Water types & NCG content and spatial distribution
  - Early stage vs. late stage boiling (ammonia, H₂S)
  - Mixing trends and fluid migration
  - Fluid source (magmatic or geothermal) and evolution
  - Phase distribution (liquid level, boiling zones, boiled outflow)
  - Heat source – δ¹⁸O and δD, helium isotopes

- **Integrated conceptual model development**
  - Combine w/ geology, geophysics, hydrology, reservoir engineering
  - There may be more than one initial model
  - Iterative models
Constructing a Basic Geochemistry Model:

**Step 1:** Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

**Step 2:** Delineate reservoir boundaries by plotting gas chemistry parameters on topographic maps with major geologic structures. Plot major gas chemistry trends (i.e., total NCG, ammonia, R/Ra)

**Step 3:** Define the geochemical parameters to distinguish upflow vs. outflow

**Step 4:** Construct geochemical cross-sections with manifestation types, water table, known or inferred structures, temperature isotherms, arrows showing flow directions, and possible boiling zones
Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

- **Mature chloride waters** – neutral pH, chloride is dominant anion. Only water type suitable for geothermometry

- **Acid sulfate (volcanic) waters** - form by condensation of geothermal gases such as H$_2$S & CO$_2$ into well-oxygenated near-surface waters

- **Bicarbonate waters** - form by gas and steam condensation into poorly-oxygenated groundwater

- **Meteoric waters & groundwater**

- **Mixing between water type end-members** plot as linear trends

*Figure 1* Relative Cl, SO$_4$ and HCO$_3$ contents of thermal waters on weight (mg/kg) basis. (Giggenbach, 1988)
Mixing – One of the most common processes of geothermal fluid modification. Deep reservoir fluids may mix along fluid flow pathways with cold groundwater, steam-heated waters, or shallow thermal waters.

- Linear trends in conservative components for a group of springs
- Presence of high Mg
- Inconsistent geothermometry
- High silica vs. discharge temp
- Mixing trends may follow a number of different trajectories
Boiling (adiabatic) cooling – gases and other volatile species partition into steam phase and separate from the residual liquid. The loss of mass (steam loss) results in a concentration of dissolved aqueous constituents at a lower enthalpy.

Conductive cooling – slowly ascending fluids may lose heat by conduction. If no steam is lost, chloride will not change, but other fluid-rock interactions or mixing may occur along long fluid flow paths.
Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

- Water level in liquid reservoir can be determined approximately by the highest elevation chloride hot spring
- Reservoir pressure determined by hydrostatic pressure gradient
- Important feature for cross-sections!!
### Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

<table>
<thead>
<tr>
<th>Quartz – no Steam Loss</th>
<th>Quartz – max Steam Loss</th>
<th>Na-K-Ca &amp; Na-K-Ca-Mg (NKC &amp; NKCM)</th>
<th>Na/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use in sub-boiling systems</td>
<td>Use in boiling systems, steam loss = 35%</td>
<td>Ca (epidote) Sensitive to high CO2 – loss of Ca-CaCO3 dep</td>
<td>Less sensitive to high CO2, but may predict higher temps</td>
</tr>
<tr>
<td>Quartz is ubiquitous in geothermal reservoirs</td>
<td>Quartz is ubiquitous in geothermal reservoirs</td>
<td>Albite feldspars abundant in geothermal reservoirs</td>
<td>Na &amp; K feldspar equilibrium</td>
</tr>
<tr>
<td>Effects of boiling/mixing are significant</td>
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<td>Less effected by boiling/mixing b/c ratios</td>
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<td>Slow Re-equilibration in rapidly rising fluids</td>
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Quartz (t>100°C): no steam loss

- Fluid-mineral equilibria
  \[ \text{SiO}_2 + 2\text{H}_2\text{O} = \text{H}_4\text{SiO} \]
- Temperature dependent equilibrium; experiments and theory.
- Quartz (SiO\(_2\)) is common in hydrothermally altered volcanic rocks & also many sedimentary, igneous & metamorphic rocks
- Re-equilibration in rapidly rising waters tends to be slow
- For fluids following long flow paths, re-equilibration may occur at lower temperatures
- Effects of boiling (steam loss) & mixing/dilution are significant
- Only used in low enthalpy (sub-boiling) geothermal systems

\[ t^\circ\text{C} = \frac{1309}{5.19 - \log c_{\text{SiO}_2}} - 273 \]

\( c_{\text{SiO}_2} \) is concentration in mg/kg (ppm) units
Quartz (t > °150 C): maximum steam loss

Fluid-mineral equilibria \( \text{SiO}_2 + 2\text{H}_2\text{O} = \text{H}_4\text{SiO}_4 \)

Temperature dependent equilibrium; experiments and theory.

Quartz (\( \text{SiO}_2 \)) is common in hydrothermally altered volcanic rocks & also many sedimentary, igneous & metamorphic rocks

No re-equilibration in rapidly rising waters especially production wells; in boiling chloride springs surrounded by silica sinter, amorphous silica saturation limits \( T_{\text{qtz}} \) to \( \leq 220 \°\text{C} \)

Effects of boiling (steam loss) & mixing/dilution are significant; only used in high enthalpy (boiling) geothermal systems
Na-K-Ca Geothermometer

\[
Na-K-Ca \quad t^\circ C = \frac{1647}{\log(Na/K) + \beta [\log(\sqrt{Ca/Ma}) + 2.06]} + 273.15
\]

\[\beta = 4/3 \text{ for } t<100^\circ C; = 1/3 \text{ for } t > 100^\circ C\]

- Most robust of Na/K geothermometers
- Slow equilibration for Temps > 180°C, reflects the deeper liquid temperature
- Used for well discharges
- Sensitive to high CO₂
- Correction for Mg ion (Na-K-Na-Mg) mainly for hot springs
- Difference between Na-K-Ca and Na-K-Ca-Mg may reflect groundwater contributions

Mg-correction to the Na-K-Ca geothermometer

1) Calculate the Na-K-Ca temperature, t°C, as described above. If t < 70°C no correction is required, if t > 70°C proceed as follows.

2) Calculate \(R = \frac{[Mg/(Mg+0.6)Ca+0.31K)] x 100}{\text{using concentrations in mg/kg.}}\)

3) If \(R > 50\), ignore the calculated Na-K-Ca temperature and assume that the temperature of the water at depth is approximately the same as the temperature of the water measured in the field.

4) If \(5 < R < 50\), calculate the correction from:
\[
\Delta T_{Mg} = 10.664 + 4.7415 \log R + 325.87(\log R)^2 - 1.032x10^5(\log R)^2/T_{NaKCa} - 1.968x10^7(\log R)^3/T_{NaKCa}^2 + 1.605 x 10^7(\log R)^4/T_{NaKCa}^3
\]

5) If \(R < 5\), calculate the correction from:
\[
\Delta T_{Mg} = -1.03 + 59.971(\log R) + 145.09(\log R)^2 - 3671(\log R)^2/T_{NaKCa} - 1.67x10^7 \log R/T_{NaKCa}^2
\]

6) If the value calculated for \(\Delta T_{Mg}\) is negative or <1.5, do not apply the correction.

7) Finally, subtract the value of \(\Delta T_{Mg}\) from the Na-K-Ca calculated temperature to obtain the Mg-corrected temperature.

Fournier & Truesdell (1973)
Giggenbach describes use of δD and δ18O to understand mixing between groundwater, geothermal discharges, and volcanic condensates.
Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

- Data plotted at elevation of midpoint of open hole
- Chloride is calculated from reservoir liquid (flash-corrected using enthalpy and separation pressure)
- High chloride in the east, low to the west and south

Simple contouring can be used to delineate fluid flow directions…

Reservoir Chloride (ppm) in Total Discharge
Data plotted at elevation of midpoint of open hole

Enthalpy is calculated from NKC geothermometer from reservoir liquid (flash-corrected using enthalpy and separation pressure)

High enthalpy in the east, low to the west and south

Simple contouring can be used to delineate fluid flow directions...
Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

Step 2: Delineate reservoir boundaries by plotting gas chemistry parameters on topographic maps with major geologic structures. Plot major gas chemistry trends (i.e., total NCG, ammonia, R/Ra, geothermometers)

Step 3: Define the geochemical parameters to distinguish upflow vs. outflow

Step 4: Construct geochemical cross-sections with manifestation types, water table, known or inferred structures, temperature isotherms, arrows showing flow directions, and possible boiling zones
Start by contouring major gas indicators from saturated/superheated fumaroles:

- Total NCG
- CH$_4$
- H$_2$S (CO2/H2S)
- N$_2$/Ar
- NH$_3$
- Helium isotope ratios (R/Ra, Rc/Ra)

Beware of processes affecting gas chemistry!!
Controls and processes affecting steam composition:

- Reservoir pressure and temperature
- Initial reservoir liquid dissolved gas content
- Gas solubility in liquid
- Phase distribution in the reservoir
- Degree of reservoir boiling (early formed steam contains higher proportion of gases than later formed steam)
- Steam-phase reactions – condensation, oxidation, rock buffering, mixing with air/organics
- Phase separation pressure and temperature
- Reservoir steam chemistry (if 2-phase)
- Mass of original reservoir liquid converted to steam

Step 2: Delineate reservoir boundaries by plotting gas chemistry parameters on topographic maps with major geologic structures. Plot major gas chemistry trends (i.e., total NCG, ammonia, R/Ra, geothermometers)
Reservoir P and T

- Reservoir pressure determined by hydrostatic pressure gradients with depth
- Reservoir temperature determined by thermal gradient
- Single-phase reservoir liquid rises upward in convective cell, approaches BPD and steam formation occurs
- **How does this control steam chemistry??**
- The composition of dissolved gas in initial reservoir liquid controls the steam chemistry upon initial boiling and throughout the ongoing boiling process (from early-stage to late-stage boiling)
What happens to gases as steam formation (boiling) is initiated and continues??

- Initial few percent of steam formed contains majority of dissolved gas because ~90% is CO₂.
- After boiling in the reservoir (for two-phase systems), residual liquid is depleted in gas relative to the original fluid composition (some residual gas will remain).
- Each gas has a different mass distribution coefficient, so gas ratios will change depending on the degree of boiling.
- The (less soluble gas / more soluble gas) ratio will increase in the steam because stronger partitioning of the less soluble gas into the vapor phase.
- As more steam forms, the gas ratios will decrease because steam formation dilutes gases.

Least Soluble: Ar < N₂ < H₂ < CH₄ < CO₂ < H₂S < NH₃

Most Soluble

Nicholson 1993
Gas solubility in the liquid phase determines how much will fractionate into the vapor phase during steam formation at different temperatures.

- Gas solubility in liquid increases with increasing temperature.

Boiling Processes & Gas Distribution

\[ B_i = \frac{(n_i/n_{H2O})_{vapor}}{(n_i/n_{H2O})_{liquid}} \]

\[ n_i/n_{H2O} = \text{mole ratio} \]

Fig. 1. The temperature dependence of the vapor-liquid gas distribution coefficients $B_i = x_{i,vapor}/x_{i,liquid}$. Solid lines represent data calculated by use of the equations given in Table 2.
Boiling Stages and Gas Distribution

Early Stage
- Boiling Front
  - ~250 °C @ 1.5 km
- Upflow
  - ~ 250 °C @ 2km
  - NCG dissolved in liquid phase
- high geothermometry
- some equilibrium
- high H2S
- not equilibrated

Late Stage
- Boiling Front
  - ~250 °C @ 2km
- Outflow
- minor NH3
- medium NCG
- some equilibrium

Conceptual Models of Geothermal Systems
2016 GRC Conference Workshop
Sacramento, California
October 21 & 22, 2016

Figure from Phil Molling
- Loss of low solubility gases from deep upflow on initial boiling plots as enrichment of CO2
- Mixing with magmatic fluids interpreted by increasing N2/Ar ratios (N2/Ar > 800 = magmatic)
- Mixing with air/ASW plots toward N2/Ar ratios between 84 & 38

- NH3 is a good indicator of late-stage boiling (most soluble gas)
- Trends toward CO2 on NH3-CO2-H2S ternary suggests condensation of more soluble gases (NH3 & H2S) and enrichment of CO2
Hydrogen Sulfide – Hydrogen (HSH) (py-mag) - \[ 3FeS_2 + 2H_2 + 4H_2O = Fe_3O_4 + 6H_2S \]

Gas only reaction

\[ CH_4 + 2H_2O = CO_2 + 4H_2 \]

Compare equilibrium between gas, liquid, and mineral phases…

Reactions in gas, liquid, and rock phases

Fischer-Tropsch Geothermometer (FT) - \[ \text{FT} \log (r_{CO_2}) + 4 \log (r_{H_2}) - \log (r_{CH_4}) \] (WG 1980)
Step 2: Delineate reservoir boundaries by plotting gas chemistry parameters on maps with major geologic structures

- Data plotted at elevation of midpoint of open hole
- Low NCG in the east
- High NCG moving from east to west
- How do you know which low NCG wells are upflow vs. outflow? Compare with other field measurements and geochemistry data
Step 2: Delineate reservoir boundaries by plotting gas chemistry parameters on maps with major geologic structures

- Data plotted at elevation of midpoint of open hole
- High enthalpy in the east, low to the east and south
- Use arrows to indicate fluid flow directions
Step 1: Delineate reservoir boundaries by plotting geochemistry water types on topographic maps with major geologic structures. Plot major water chemistry trends (i.e., chloride, geothermometer temps)

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Step 3: Define the geochemical parameters to distinguish upflow vs. outflow

**Upflow:**

- Agreement or close agreement between different geothermometers (i.e., quartz, NKCM, and gas geothermometers) and highest temperatures from chloride springs
- pH neutral water chemistry
- Highest measured chloride and highest geothermometry temperatures (plot on enthalpy chloride diagram)
- Similar chemistry between different chloride springs (similar geothermometry)
- Low NCG, no magmatic gases
- Plot as thermal end-member on mixing trends
- Isotopically attained $\delta^{18}$O and high $3\text{He}/4\text{He}$ ratios
Step 3: Define the geochemical parameters to distinguish upflow vs. outflow

Outflow:

- Disagreement between geothermometers. NKCM temperatures may reflect deeper hotter reservoir liquid temps, while silica geothermometers may reflect re-equilibration at lower temperatures.
- Differences between Na-K-Ca and Na-K-Ca-Mg suggest the influence of groundwater that contributes Mg.
- Moderate to low chloride content.
- Outflow fluids plot on mixing trends towards cooler more dilute mixtures (Enthalpy-chloride diagrams, ternary diagrams, cross plots)
- May show influences of boiling from enthalpy-chloride diagrams (plot towards lower enthalpy but higher chloride from predicted reservoir temp).
- Low total NCG, high NH3 in gas chemistry, gas geothermometers/grids show non-equilibrium processes (i.e., condensation/CO2 enrichment).
- Lower 3He/4He ratios.
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Geochemistry Tools

Tools for evaluating geochemical trends:

- Surface maps and cross-sections with thermal feature water type distributions
- Surface maps w/ contoured geochemistry (Cl, geothermometers, NH3, NCG, etc.)
- Cross-plots (i.e., enthalpy-chloride, B/Cl) and ternary diagrams – Mixing trends
- Cross-sections with temperature isotherms
- Fluid chemistry reconstructions for total fluid (for exploration/production wells)

Once geochemical trends identified, start integrating other datasets:

- Geological structures (may delineate fluid flow pathways/barriers)
- MT anomalies – reservoir sides/top (base of conductor)
- Reservoir data – PT to confirm upflow trends (highest temps, convective bottom) vs. outflow trends (moderate to lower temps, may show reversals)

Conceptual model with maps and cross-sections should incorporate water type distributions, temperature contours, geological structures, fluid flow directions, mixing/boiling zones, clay cap geometry...
- 100 °C contour from saturated fumarole
- Water types delineate outflow and boiling zones
- Reservoir temps predicted using geothermometry
- Now is the time to start integrating other disciplines!!!!
Backup Slides
Gas Geothermometers

Three basic types
- Thermodynamic
  - y-temperature grids (y=steam fraction)
  - Gas ratio grids

Equilibration
- Largely occurs in the liquid phase,
  - But vapor phase equilibration also occurs

Strengths
- Gas geothermometers can be applied to steam vents/fumaroles

Weakness
- Sensitivity of gas reactions to pressure, temperature, and vapor/liquid distribution processes. Depend on knowledge of gas/steam ratio (hot water systems), which cannot be determined for fumaroles b/c gas and steam do not reach surface together
Gas Geothermometers

Fischer-Tropsch Geothermometer (FT)  
\[ CH_4 + 2H_2O = CO_2 + 4H_2 \]

Hydrogen Sulfide – Hydrogen (HSH) (py-mag)  
\[ 3FeS_2 + 2H_2 + 4H_2O = Fe_3O_4 + 6H_2S \]

Hydrogen Sulfide – Hydrogen (HSH) (py-pyrr)  
\[ FeS_2 + H_2 = FeS + H_2S \]

Nitrogen-Ammonia-Hydrogen (NAH)  
\[ 2NH_3 = 3H_2 + N_2 \]

Hydrogen Sulfide (H\textsubscript{2}S)  
\[ FeS_2 + FeO + 2H_2O = Fe_2O_3 + 2H_2S \]

Carbon Dioxide (CO\textsubscript{2})  
\[ CaAl2-silicate + K-feldspar + CO_2 = CaCO_3 + K-mica \]

Carbon Monoxide (CO)  
\[ CO_2 + H_2 = CO + H_2O \]

Hydrogen (H\textsubscript{2}) or Water Breakdown Geothermometer  
\[ H_2O = H_2 + 1/2 O_2 \]
**The Holy Grail Equations**

\[ H_T = H_V(y) + H_L(1-y) \]  \hspace{1cm} \textit{Heat Balance}

\[ y = \frac{(H_T - H_L)}{(H_V - H_L)} \]  \hspace{1cm} \textit{Steam Fraction}

\[ y = \frac{(H_T - H_L)}{\Delta H_{VL}} \]

\[ \Delta H_{VL} = H_V - H_L \]  \hspace{1cm} \textit{Latent Heat of Vap.}

\[ Q_T = Q_V + Q_L \]  \hspace{1cm} \textit{Mass Balance}

\[ H_T Q_T = Q_V H_V + Q_L H_L \]  \hspace{1cm} \textit{Heat & Mass Balance}

\[ H_T = \frac{(Q_V H_V + Q_L H_L)}{Q_T} \]

**Must know separation pressures & temperatures –
Use steam tables to calculate \( H_V \) and \( H_L \)**
Excess Enthalpy Calculations

- \( H_{\text{discharge}} = H_{\text{reservoir}} \) assuming adiabatic expansion.

- \( H_{\text{discharge}} = H_{\text{reservoir}} = Y_{\text{steam}} \times H_{\text{reservoir steam}} + (1-Y_{\text{steam}}) \times H_{\text{reservoir water}} \)

- \( H_{\text{discharge}} \) is measured at the surface (TFT, Prod. Sep., James tube/weir method).

- Therefore: \( Y = \frac{(H_{\text{discharge}} - H_{\text{reservoir water}})}{(H_{\text{reservoir steam}} - H_{\text{reservoir water}})} \)
  - \( Y \) is reservoir steam or “excess steam” or \( H_{\text{discharge}} \gg H_{\text{reservoir}} \)
  - Need reservoir temperature for \( H_{\text{reservoir water}} \) and \( H_{\text{reservoir steam}} \)
  - Use liquid geothermometers to calculate enthalpy of liquid and steam at reservoir temperature.
(1) \( T_{\text{measured}} = T_{\text{nkc}} = T_{\text{silica}} \)

Fully-equilibrated reservoir fluid

(2) \( T_{\text{nkc}} > T_{\text{silica}} = T_{\text{measured}} \)

or

\( T_{\text{silica}} > T_{\text{nkc}} > T_{\text{measured}} \)

Boiling in flowing well

(3) \( T_{\text{nkc}} > T_{\text{measured}} = T_{\text{silica}} \)

Mixing with cooler water near well bore

(4) \( T_{\text{nkc}} = T_{\text{silica}} > T_{\text{measured}} \)

Mixture of equilibrated liquid with steam cap

(5) \( T_{\text{nkc}} > T_{\text{silica}} > T_{\text{measured}} \)

Cooler more dilute water with equilibrated brine

(6) \( T_{\text{measured}} = T_{\text{silica}} > T_{\text{nkc}} \)

Cooler water heated by rocks

Revised from Truesdell et al., 1995
Integrated Conceptual Model

- Geophysical boundaries
- Upflow-outflow geometry
  - Fault-hosted or distributed permeability
  - Potential upflow areas
    - Mushroom or inclined system
    - Explains all thermal features?
- Temperature contours
  - Base and top of conductor
  - Boiling-for-depth
  - Background thermal gradient
- Reservoir liquid level calculation
  - Non-smectite caps & steam zones
  - Reservoir temperature & permeability
  - Reservoir rocks and lithologic caps

From W. Cumming, Stanford Workshop 2009
**Heat Sources**

**Geothermal heat flow**
- Deep basin and Basin & Range
- Deep and old formation waters
- Lack magmatic signature (He isotopes)
- Elevated crustal radioactivity (old plutons)

**Volcanism**
- Assumed magmatic intrusion – elevated He isotopes
- Some upflow chemistry similar to epithermal porphyry
- Modelling shows only 20-50 ka pluton cooling time, so requires multiple intrusions (heat pulses)

**Source of magmatic heat**
- Upflow of gas/steam from degassing pluton & meteoric water
  - Source of chloride, sulphur and carbon
  - Hot plate from shallow intrusion
System Types

• Magma-hydrothermal
  • Distributed and fault-hosted permeability
  • Range of chemistry and fluid types
• Deep Basin (HSA)  GEOPRESSURED??
  • Sandstones or carbonates in deep basins (Europe, Australia)
  • Explore with 3D seismic surveys
  • Few successful projects (needs high electricity price!)
• Basin & Range – W. USA & E. Turkey
  • High heat flow region with deep Pleistocene basins
  • Thermal waters upwell along range-front normal faults, mostly fault-hosted systems
**Liquid Dominated Systems**

- Circulating fluid is liquid water
- Structured with upflow and outflow
- Under-pressured & over-pressured
- Upflow commonly boiling-for-depth
- May have initial steam cap
- Commonly show Cl hot springs at surface

Ngatamariki System, from Boseley et al, WGC 2010
Vapour Dominated Systems

- Upwelling vapour in fractures and counter-flow of liquid in matrix (heat-pipe)
- Very under-pressured, sealed from groundwater
- Isothermal at 240-250°C, steam pressure gradient
- Few areas of demonstrated upflow, heat sources tend to be “hot plates”
- Example: The Geysers, California
Steam Cap Systems

- Hybrid between liquid and vapour systems
- Thick steam cap with underlying liquid layer
- Few areas of demonstrated upflow, heat sources tend to be “hot plates”
- May be transition state between liquid and vapour systems
- Examples: Karaha-Telaga Bodas, Lahendong
Vapour-Cored Systems

- Poorly understood high enthalpy resources associated with young volcanic centres – now important exploration targets
- Appear transitional between liquid-dominated geothermal systems and volcanic fumarolic systems – show elements of volcanic and vapour-dominated systems
- Generally show poor hot spring chemistry, but good gas chemistry.
- Inhomogeneous liquid and gas chemistry
- Appear to be small, tight resources with significant corrosion risk.
- Common in SE Asia arc volcanoes
- Alto Peak, Leyte, Philippines example
Volcanic Systems

- High T fumaroles (some HCl-bearing)
- Local Cl & HCO3 hot springs
- Oxidising chemical conditions (RH <-2.8)
  \[ \text{RH} = \log \left( \frac{f_{\text{H}_2}}{f_{\text{H}_2\text{O}}} \right) \approx \log \left( \frac{x_{\text{H}_2}}{x_{\text{H}_2\text{O}}} \right) \]
- High H2S (SO2)
- Low atmospheric contribution – high N2/Ar
Alto Peak

- Classic 1993 Reyes, Giggenbach and others Geothermics paper

- Exploration targeted summit solfatara and shallow low resistivity of Quaternary (.38-.43 Ma) andesitic volcano with surrounding $\text{HCO}_3^-$-$\text{Cl}$ hot springs.

- 10 deep wells drilled 1990s for 77 MW development

From Reyes et al Geothermics 1993
Alto Peak Conceptual Model

- Resource around narrow vapour chimney, 1 km wide, 3-4 km deep – small system
- Chloride reservoir water formed by condensation of HCl in superheated steam mixing with meteoric water
- Hot, permeable and acidic core surrounded by cooler, tight, low pH shell
- Hot springs are re-equilibrated outflow from Cl water shell

From Reyes et al Geothermics 1993
Exploration Characteristics

- Magmatic signature to summit solfatara (HCl)
- Low resistivity clay cap under summit area
- Distal low temperature, re-equilibrated Cl hot springs
  - Diverse chemistry (i.e., major anions, Cl/B ratio)
  - Some hot springs in altered terrains show low Mg ion (!)
  - Also local neutralised Cl springs from summit fumaroles
- Solfatara fumaroles can show good gas geothermometry
- “Donut” conductor around summit sulfatara