# Insights From Unsaturated Zone Geothermal Analogues

## Rock/Water Interactions in Geothermal Systems

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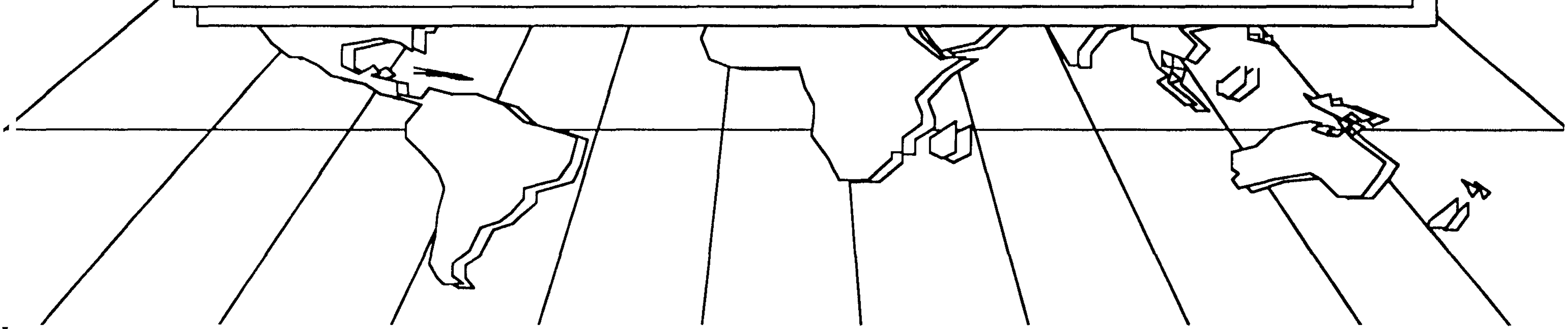
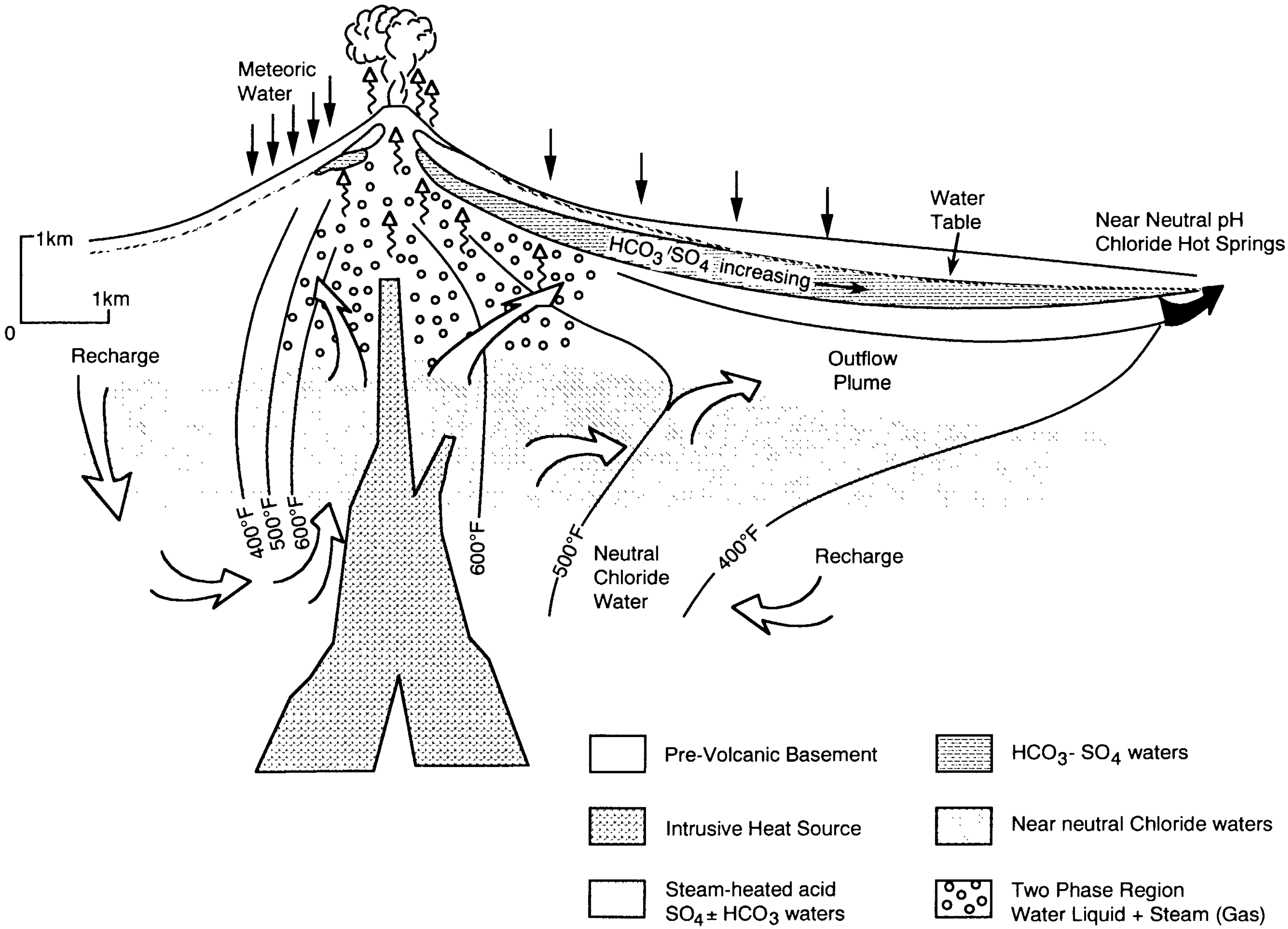
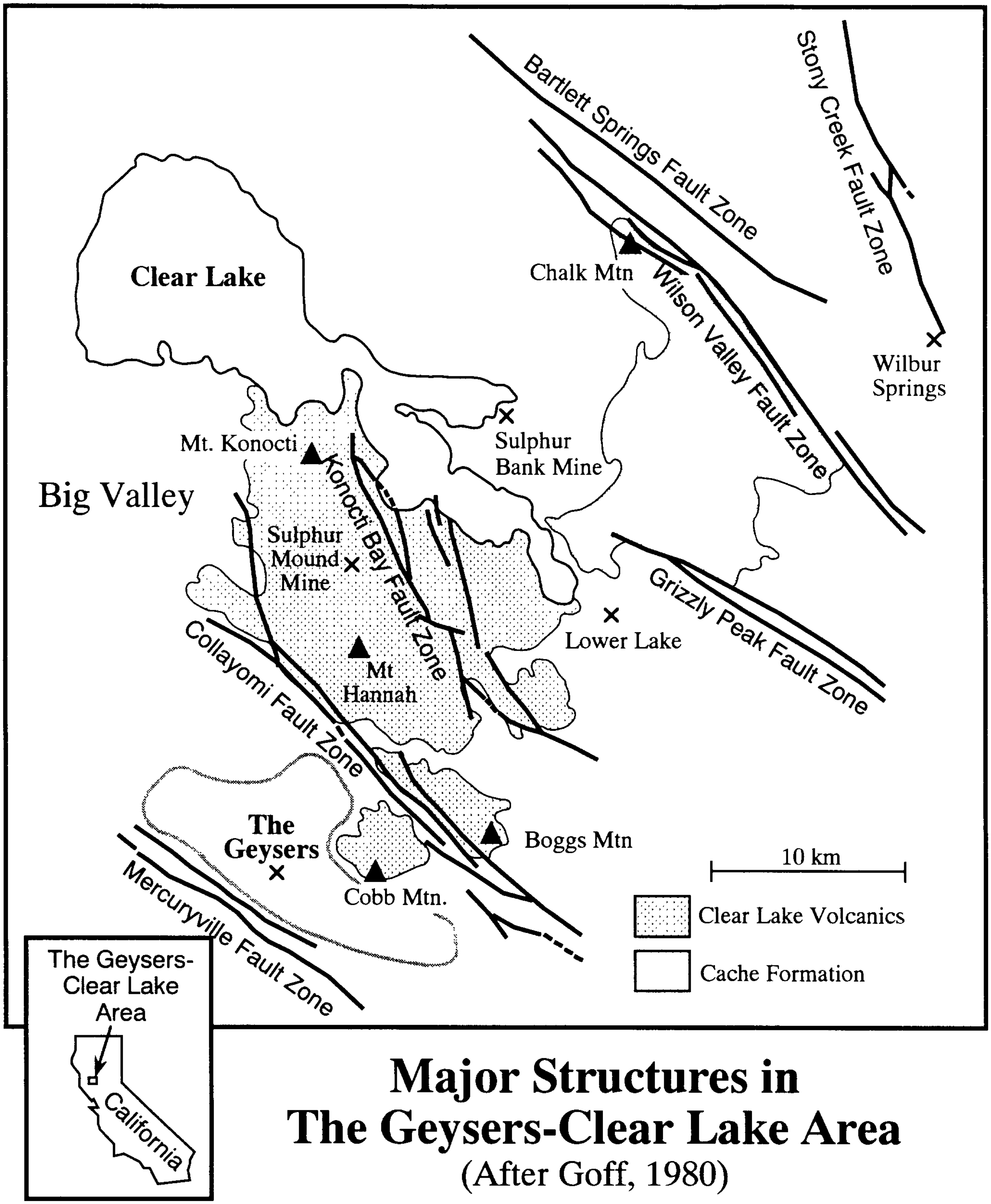


# Unsaturated Conditions in Geothermal Systems

- Liquid - Dominated systems
  - above the water table
  - low permeability fractures

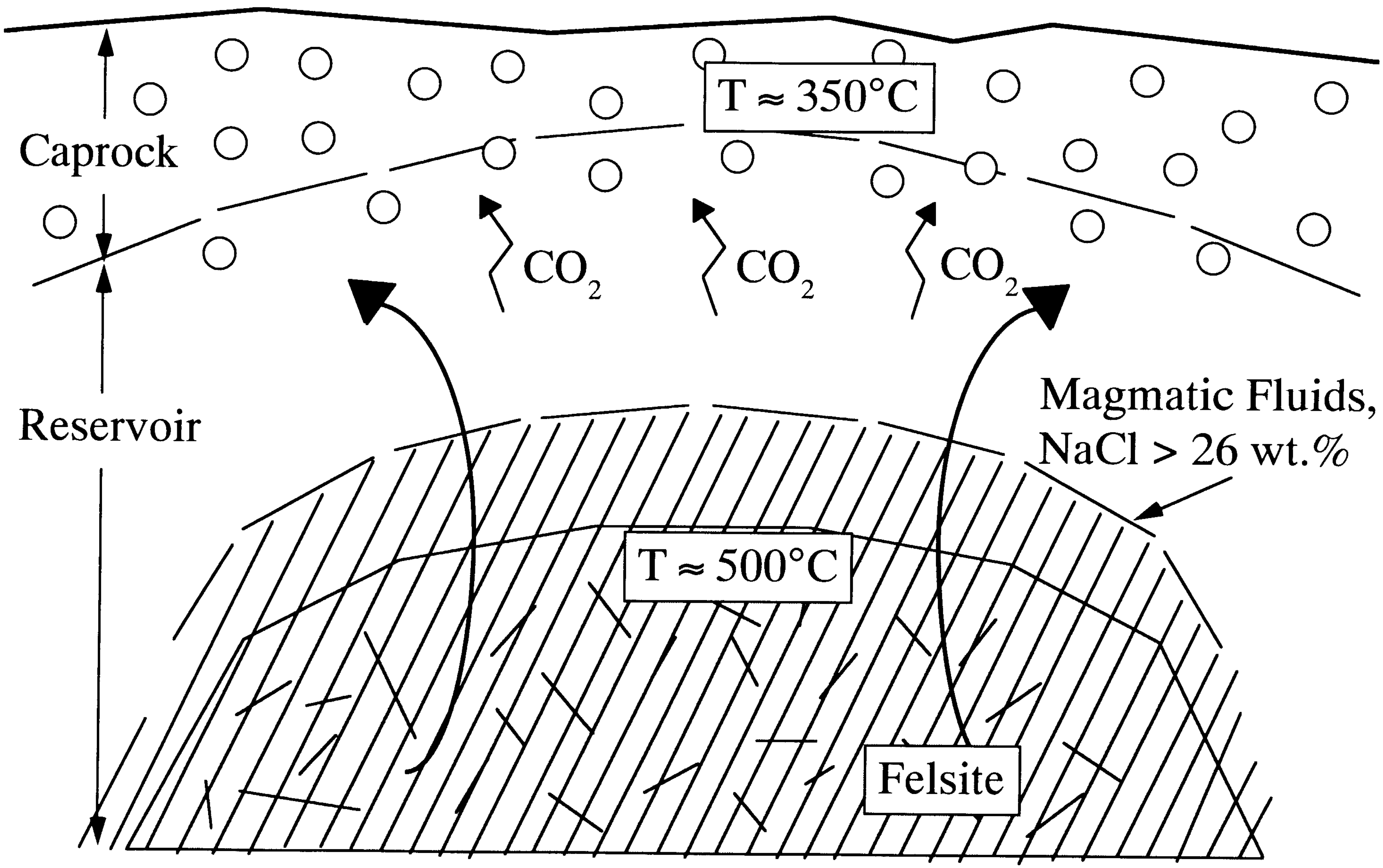
- Vapor-dominated systems


Meteoric Water
1km
1km
0
Recharge
400°F
500°F
600°F
600°F
500°F
400°F
HCO3 /SO4 increasing
Water Table
Near Neutral pH Chloride Hot Springs
Outflow Plume
Neutral Chloride Water
Recharge
Pre-Volcanic Basement
Intrusive Heat Source
Steam-heated acid SO4 ± HCO3 waters
HCO3- SO4 waters
Near neutral Chloride waters
Two Phase Region Water Liquid + Steam (Gas)

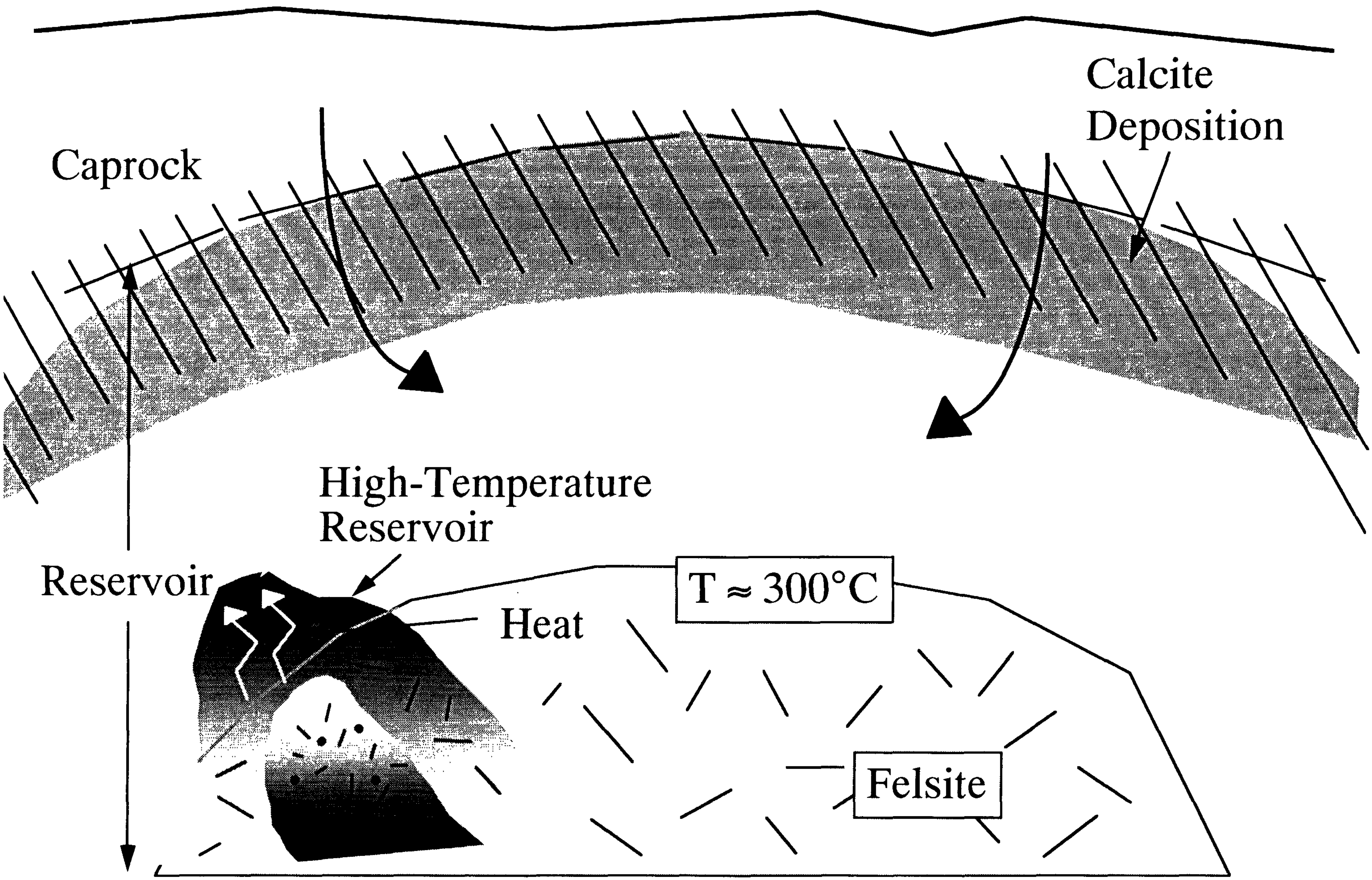


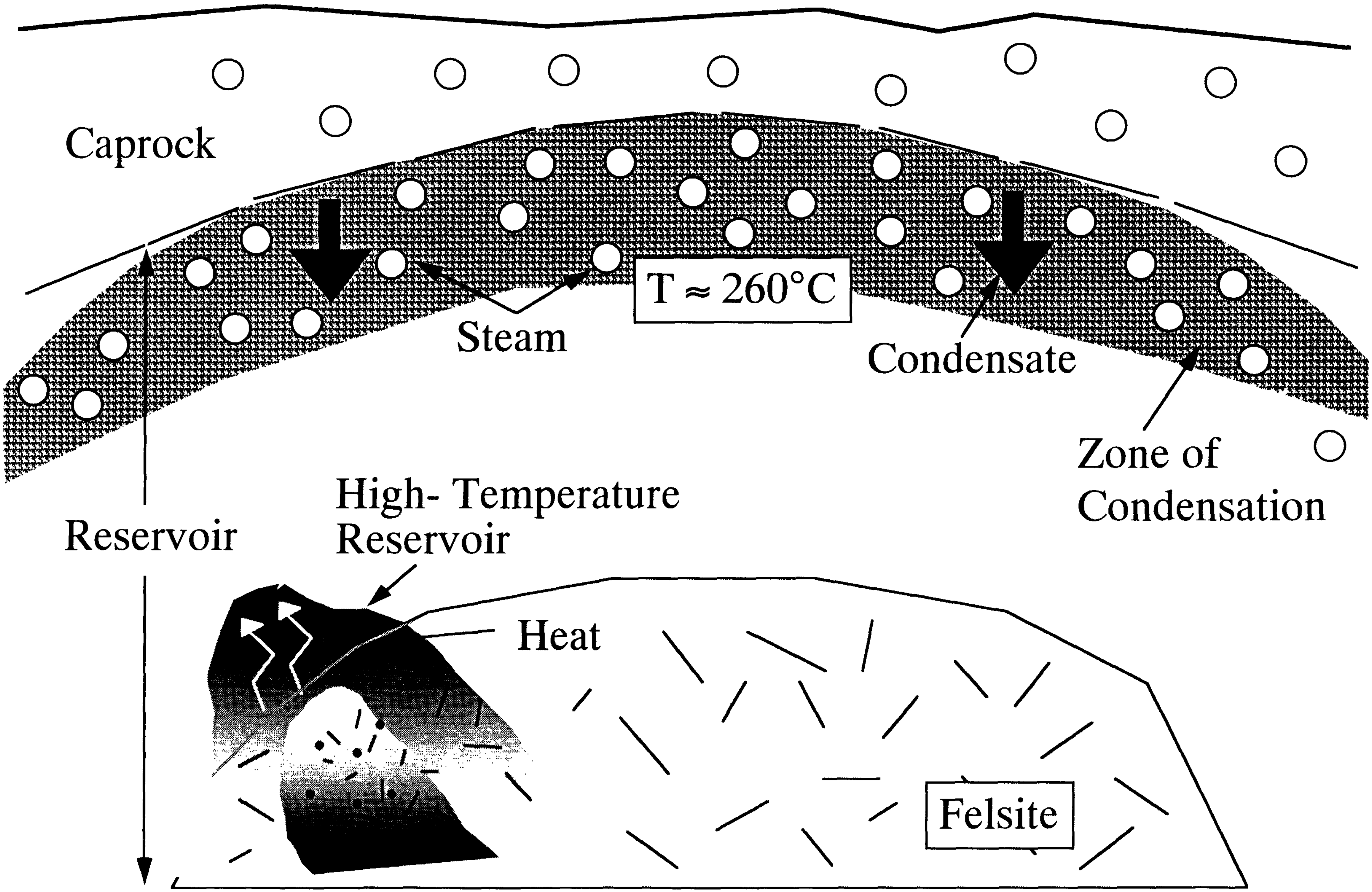

# Major Structures in The Geysers-Clear Lake Area

(After Goff, 1980)



T ≈ 350°C
Caprock
$CO_2$
$CO_2$
$CO_2$
Reservoir
Magmatic Fluids,
NaCl > 26 wt.%
T ≈ 500°C
Felsite


Calcite
Deposition
Caprock
High-Temperature
Reservoir
Reservoir
T ≈ 300°C
Heat
Felsite



Caprock
T ≈ 260°C
Steam
Condensate
Zone of
Condensation
Reservoir
High- Temperature
Reservoir
Heat
Felsite

# Properties of The Geysers

| | |
|---|---|
| Temperature: | 240° - 347°C |
| Pressure: | 35.45 bars msl |
| Porosity: | 1-5% |

Data from Gunderson, 1991, Walters et al, 1991, Williamson, 1991

# Fluid Characteristics

| Fluid Type | Salinity | pH | Temp. |
|---|---|---|---|
| NaCl pore fluid | Variable | Neutral (5.5-6.5) | 250°-350° |
| Acid-sulfate water | Low | Acidic (2-3) | 100-130°+ |
| $CO_2$-rich condensate | Low | Slightly acidic to neutral (5-6.5) | 150-220° |
| Acid-chloride water | Low | Acidic (1-4.5) | 100°+ |

## Usual Order of Replacement of Primary Minerals in Some Systems

| Primary mineral | N.Z. fields (TVZ) | Ngawha | Olkaria | Philippines & Indonesia | Iceland |
|---|---|---|---|---|---|
| Volcanic glass | 1 | absent | 1 | 1 | 1 |
| Magnetite<br>Titanomagnetite<br>Ilmenite | 2 | 1 | 5 | 2 | |
| Pyroxene<br>Amphibole<br>Olivine | 3 | absent | 2 | 3 | 2-3 |
| Biotite | 4-5 | 2 | absent | rare? | |
| Ca-plagioclase | 4-5 | albite present | 3 | 4 | 4 |
| Microcline<br>Sanidine<br>Orthoclase | absent | 3 | 4 | absent | absent |
| Quartz | not affected | not affected | not affected | absent | absent |

(Browne, 1982)

# Typical Alteration Replacement Products

| Original Mineral | Replacement Products |
|---|---|
| Volcanic glass | Zeolites (e.g. mordenite, laumontite), cristobalite, quartz, calcite, clays (e.g. montmorillonite) |
| Magnetite/ilmenite/ titanomagetite | Pyrite, leucoxene, sphene, pyrrhotite, hematite |
| Pyroxene/amphibole/ olivine/biotite | Chlorite, illite, quartz, pyrite, calcite, anhydrite |
| Calcic plagioclase | Calcite, albite, adularia, wairakite, quartz, anhydrite, chlorite, illite, kaolin, montmorillonite, epidote |
| Anorthoclase/sanidine/ orthoclase | Adularia |

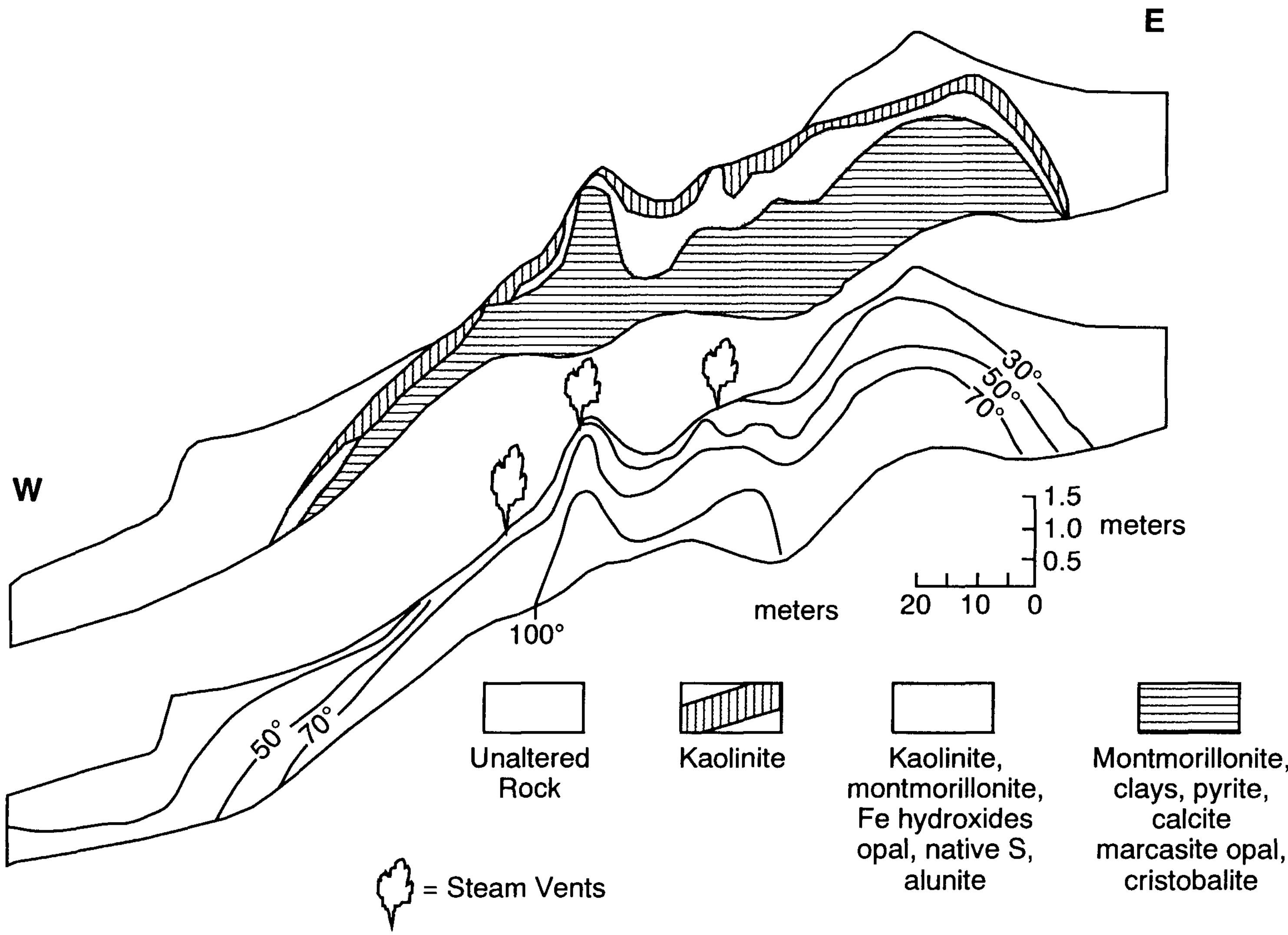
(Browne, 1982)

# Acid-Sulfate Waters

## Analyses in ppm

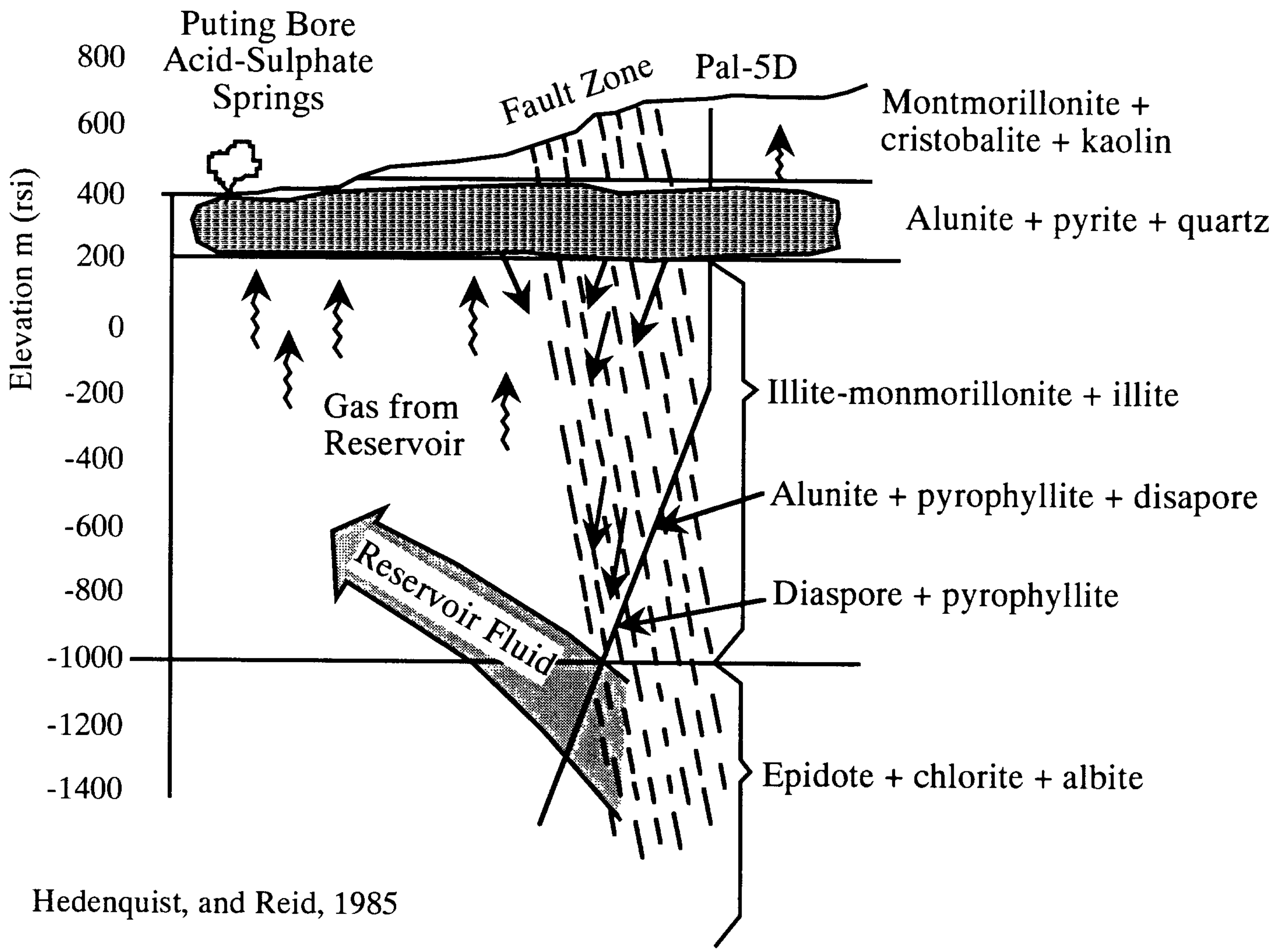
| | 1 | 2 |
|---|---|---|
| pH | 2.8 | 2.1 |
| Na | 43 | 20 |
| K | 11 | 2.4 |
| Ca | 27 | 23.9 |
| Mg | 3.5 | 21.1 |
| Fe | 8.2 | |
| Cl | 32 | |
| $SO_4$ | 347 | 2680 |
| $HCO_3$ | 0 | 0 |
| $SiO_2$ | 280 | 319.1 |
| $CO_2$ | | 660.4 |

1. Pool, Waiotapu, New Zealand (Wilson, 1963)
2. Maritaro Pool, Los Azufres, Mexico, Temp = 89°C (Ramirez-Dominquez, E. et al, 1988)




# Alteration Zoning: East Pauzhet, Kamchatka

(Pampura and Novikov, 1975)




Hedenquist, and Reid, 1985

# $CO_2$-Rich Waters

## Analyses in ppm

| | 1 | 2 | 3 |
|---|---|---|---|
| T°C | 75 | 44 | 190 |
| pH | | 6.6 | 5.8 |
| Na | 305 | 68.3 | 395.6 |
| K | 35.1 | 17.9 | 54.6 |
| Ca | 42.6 | 49.6 | 7.2 |
| Mg | 39.6 | 37.7 | |
| Fe | | | |
| Cl | 183 | 4.7 | 333.3 |
| $SO_4$ | 213 | 30 | 76.8 |
| $HCO_3$ | 653 | 378.2 | 8808 |
| $SiO_2$ | 205 | 167.8 | 240 |
| $CO_2$ | | 183 | |

1. Z-17, travertine depositing spring, Zunil, Guatemala, (Moore et al., 1992)
2. C.D. Cardenas, spring, Los Azufres, Mexico (Ramirez-Dominguez, E. et al., 1988)
3. Well 16, Broadlands - Oaaki, N.Z. (Hedenquist and Stewart, 1985)

# Acid-Chloride Water[1]

Analyses in ppm

| | |
|---|---|
| $CO_2$ | 3390 |
| $H_2S$ | 803 |
| $NH_4$ | 5.2 |
| Ar | 0.1 |
| N | 23.4 |
| $CH_4$ | 2.1 |
| H | 12.5 |
| Cl | 6.9 |
| B | 16.3 |
| sample gas/steam ratio (ppm) | 34700 |

[1] Analysis of superheated steam, Coso Hot Springs, California (M. Adams, unpublished data)

# Conclusions

Corrosive waters develop when:

1. the original liquid is "gassy"
2. boiling and steam loss can occur
3. steam can be channeled upward
4. steam condenses under oxidizing conditions
   (acid-sulphate waters)
   steam condenses under oxygen-poor conditions
   ($CO_2$-rich waters) or
   when superheated steam condenses
   (acid chloride waters)