Modeling Supercritical Systems With Tough2: Investigating The Onset of Boiling at The Geysers *

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Project Summary

- Project goal: investigate the nature and evolution of The Geysers from the time of magma emplacement, using detailed heat and water and chemical mass balances (natural state models)

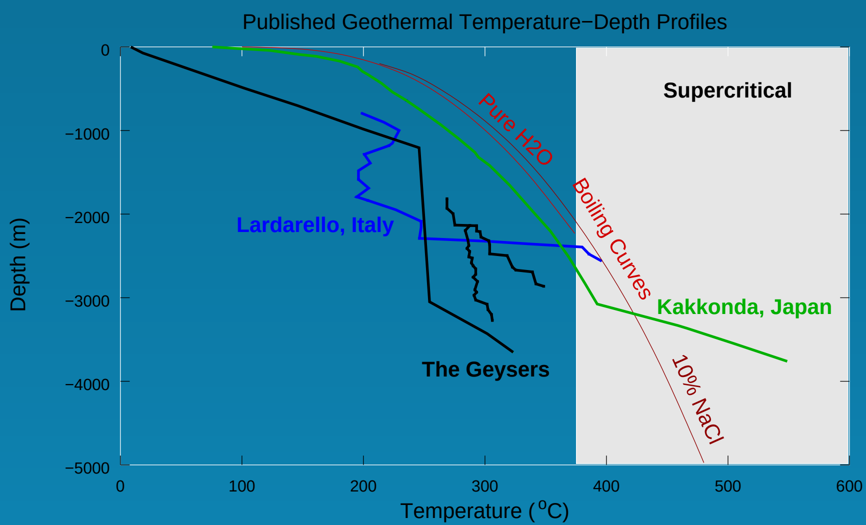
- Main issues:
  - ⋆ nature of the liquid-dominated system, as discernible from the rock alteration record (fluid inclusions and δ^{18}O)
  - ⋆ nature of the boiling "event" (transition to vapor dominated conditions)
  - ⋆ nature of interaction between geologic events (e.g. re-intrusion, faulting), fluid properties, and hydrologic events (e.g. permeability evolution)

Today's Talk

- Progress prior to May (described in various papers):
  - ⋆ development and preliminary testing of supercritical equation of state for Tough2 $EOS1sc$
  - ⋆ liquid-only supercritical flow and δ^{18}O -alteration models

- Recent progress:
  - ⋆ $EOS1sc$ redesigned to incorporate NIST-standard numerical equation of state [NIST(1999)], currently the **only** flow simulator with this feature
  - ⋆ relatively robust in testing
  - ⋆ preliminary models of the onset of boiling at The Geysers

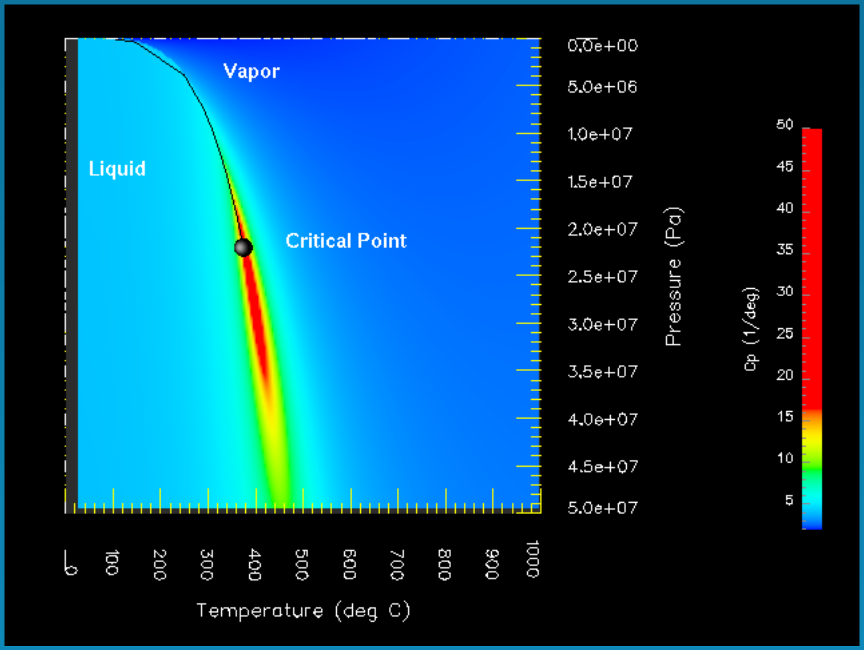
Why Supercritical?



after [Muraoka *et al.*(2000)]

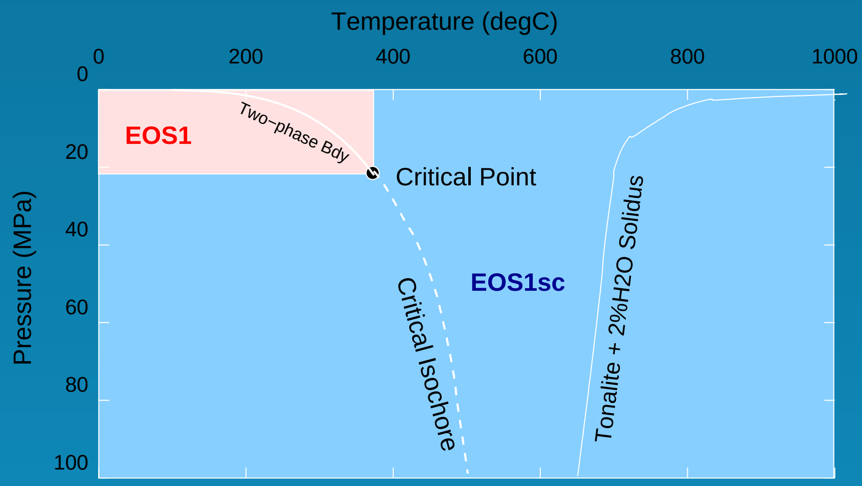
- Deep drilling magmatic geothermal systems encounters these conditions
- Models of non-magmatic systems often encounter these conditions at depth in conductive zones, e.g. the Basin and Range [Wisian(2000)]

Critical Fluid Properties



- Fluid flow and transport properties reach strong extrema at the critical point, profoundly influencing convection
- Isobaric heat capacity ($C_p \frac{1}{^\circ C}$) and isothermal compressibility ($\beta \frac{1}{Pa}$) $\rightarrow +\infty$ at critical point.
- Extrema extend beyond critical point along the critical isochore ($\rho = \rho_{critical}$)

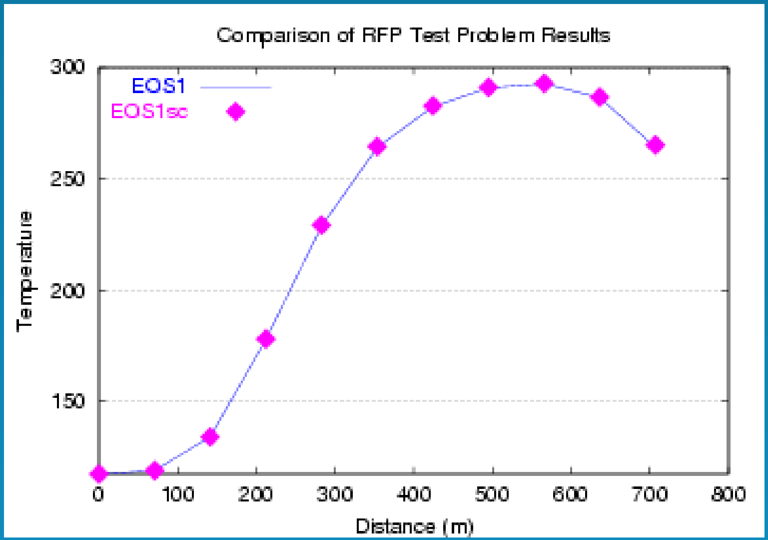
Why Tough2?



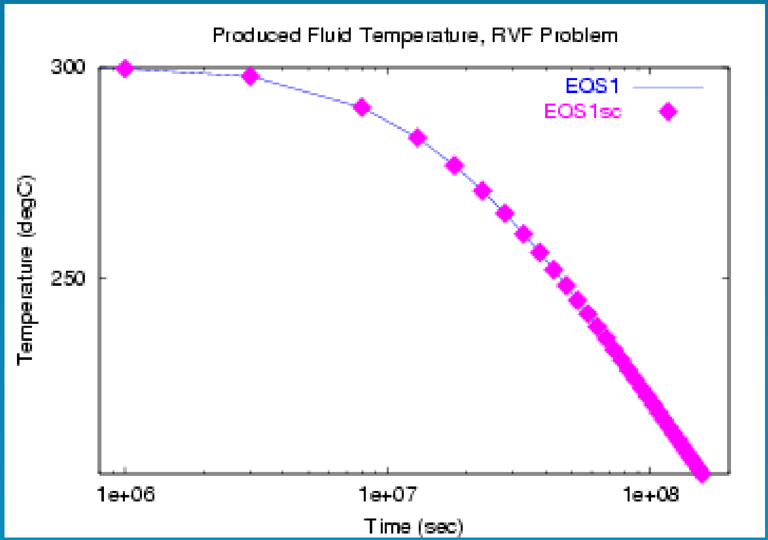
- Flexible (irregular) gridding
- Variety of choices for matrix solution
- Other capabilities needed for history matching, reactive transport modeling, etc.
- As-shipped equation of state (EOS1) limited to subcritical, needs revised EOS ($EOS1sc$) with extended range

Subcritical Tests of *EOS1sc*

- Comparison of *TOUGH2* test problem results using EOS1 and *EOS1sc* show excellent match; however *EOS1sc* run times are 5-50 times longer.

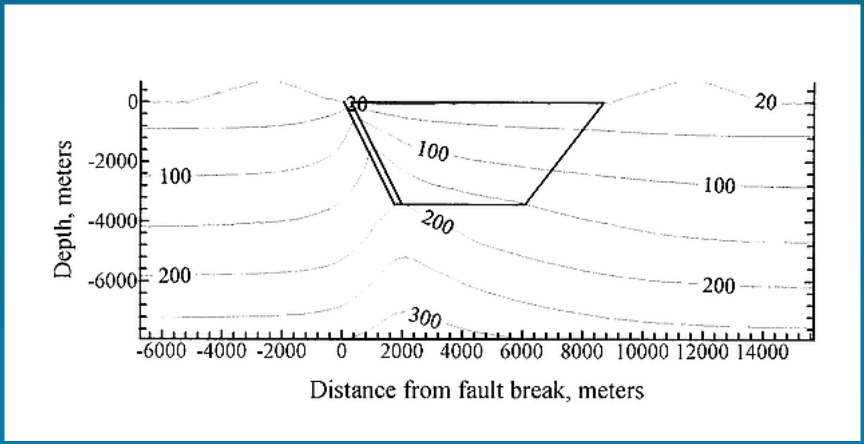


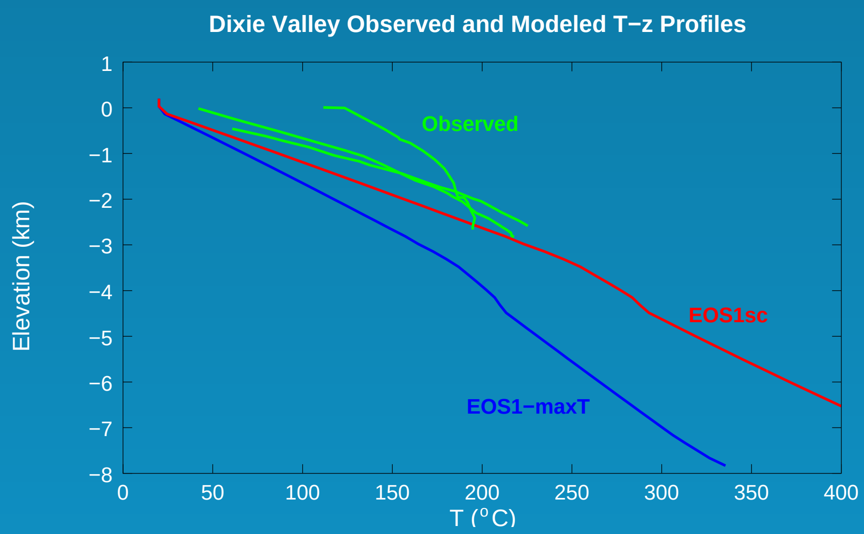
Geothermal 5-Spot



Fracture Heat Sweep

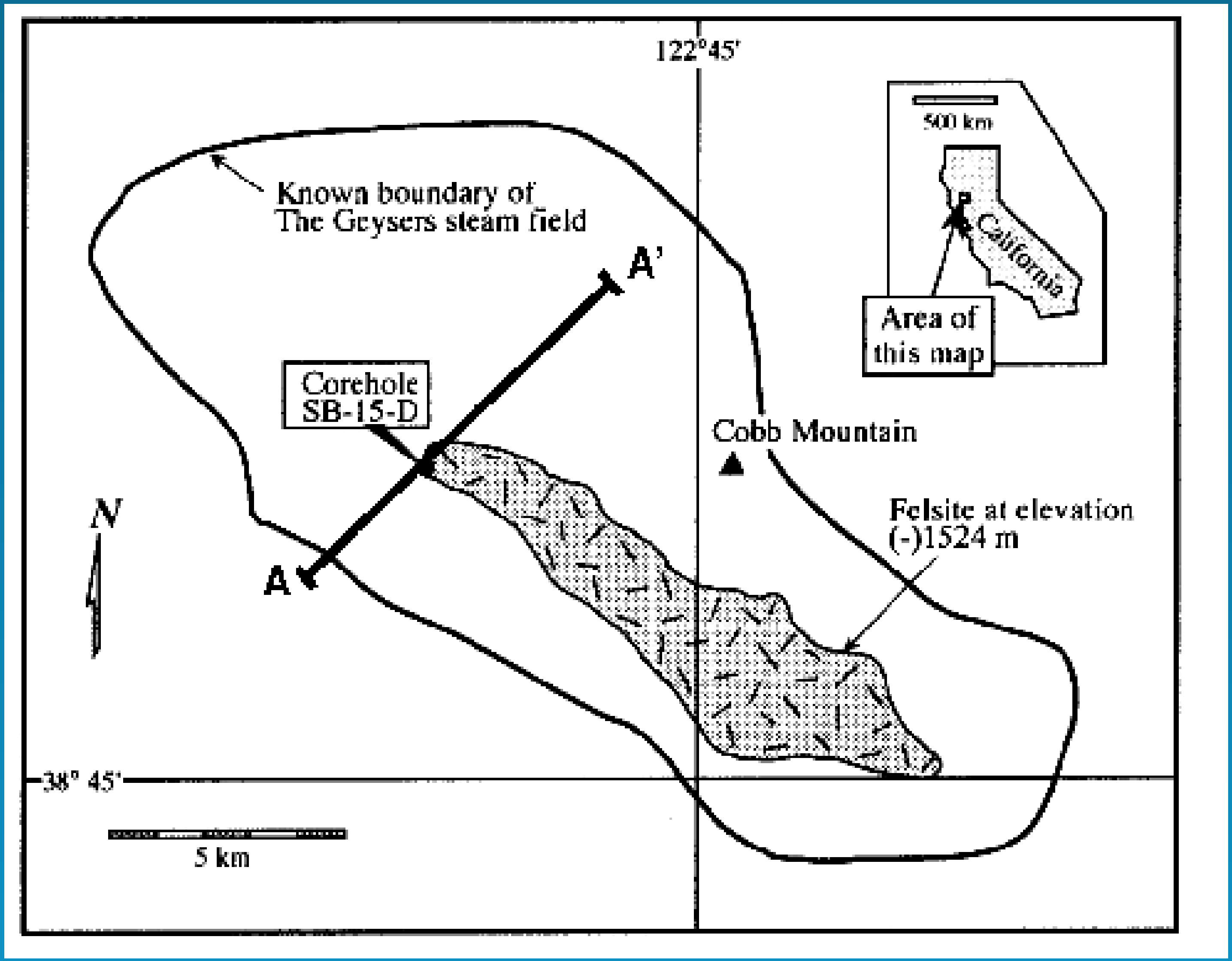
Extensional Geothermal Systems



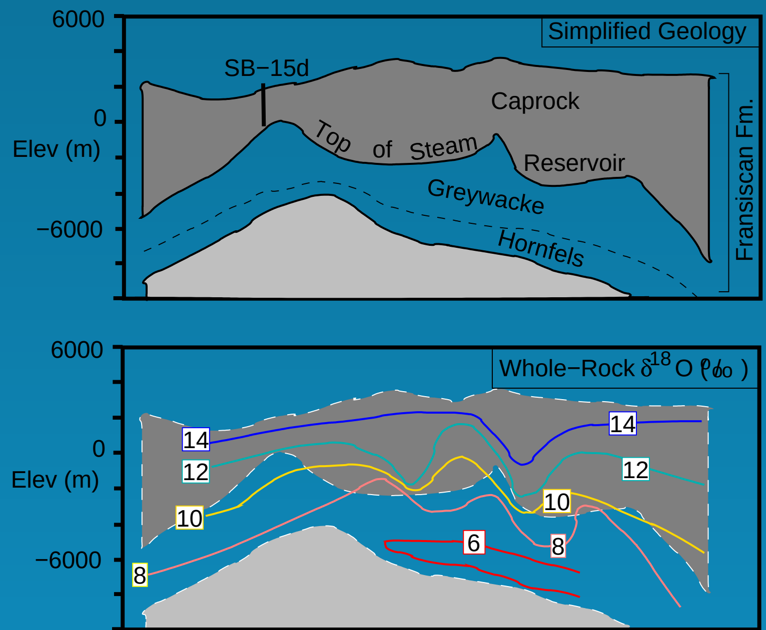


- Fluid conditions approach critical at the base of current models, model design limited by capabilities of the reservoir simulator [Wisian(2000)]
- Application of *EOS1sc* allows realistic treatment of the deep parts of the system, and simplifies matching of shallow observations

Geysers Models: Location of Cross-Section



Geology and Alteration

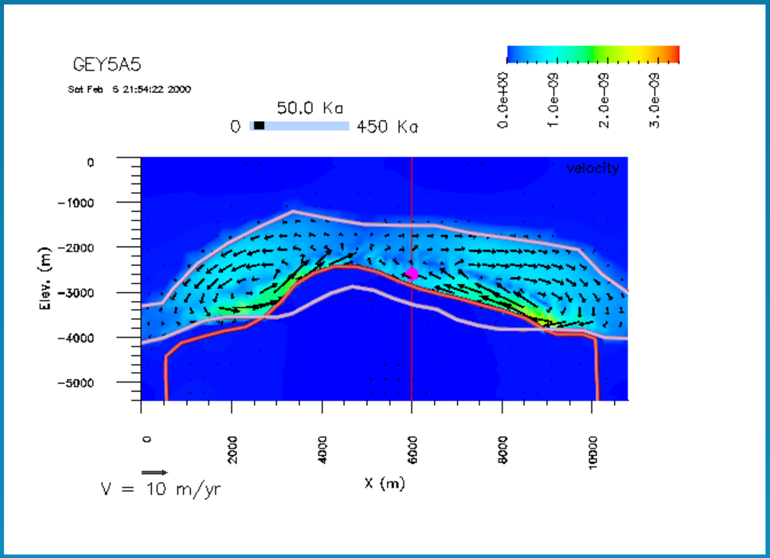


after [Moore and Gunderson(1995), Hulen and Moore(1996)]

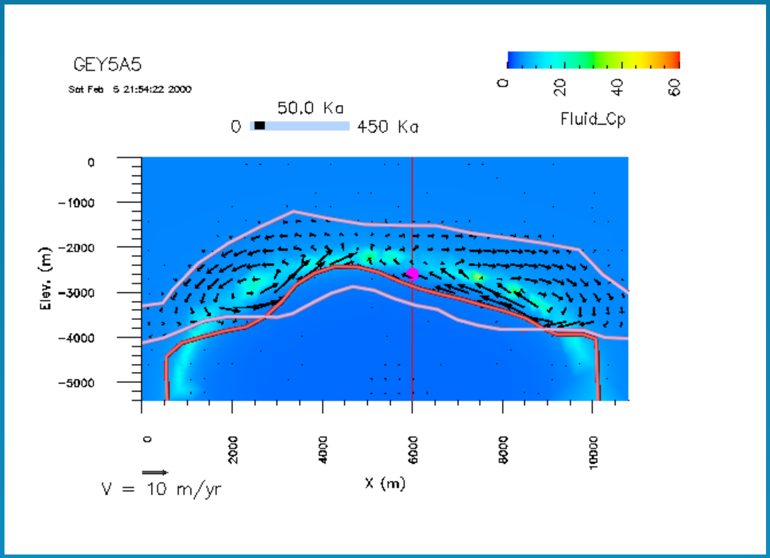
- Permeability zones
  - ⋆ caprock
  - ⋆ reservoir (lower greywacke and upper felsite)
  - ⋆ hot intrusive (deep felsite)
- Alteration zones
  - ⋆ minimal in caprock
  - ⋆ widespread moderate depletion (6-8‰) in reservoir
  - ⋆ concentrated strong (8-10‰) along low felsite flank

Geysers Supercritical Models

- Hydrothermal flow models that accurately treat critical fluid properties tend to show strong control by these properties on the deep system [Brikowski(2001)]

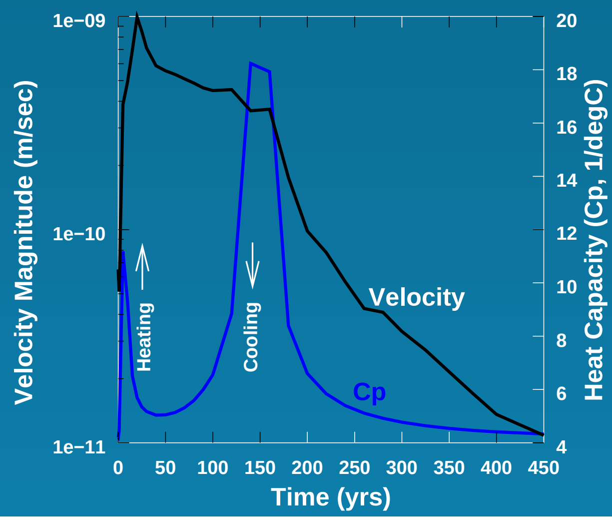


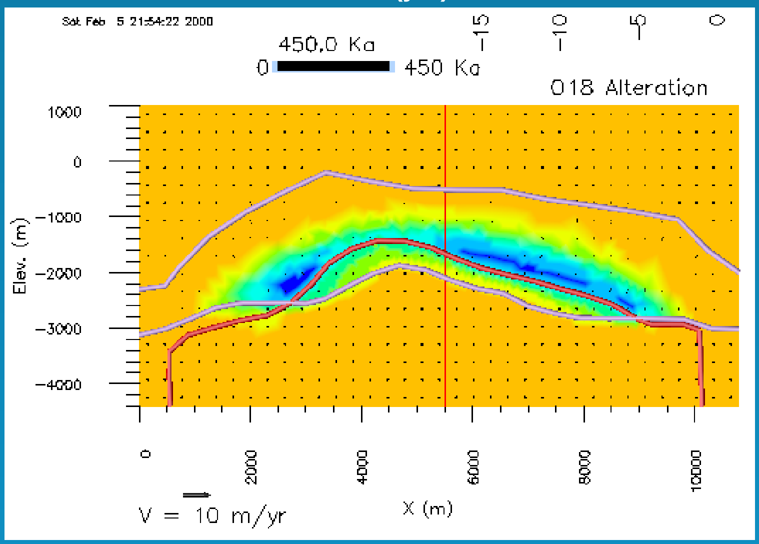
Fluid Velocity



Fluid Cp

Principal Liquid-Phase Model Results

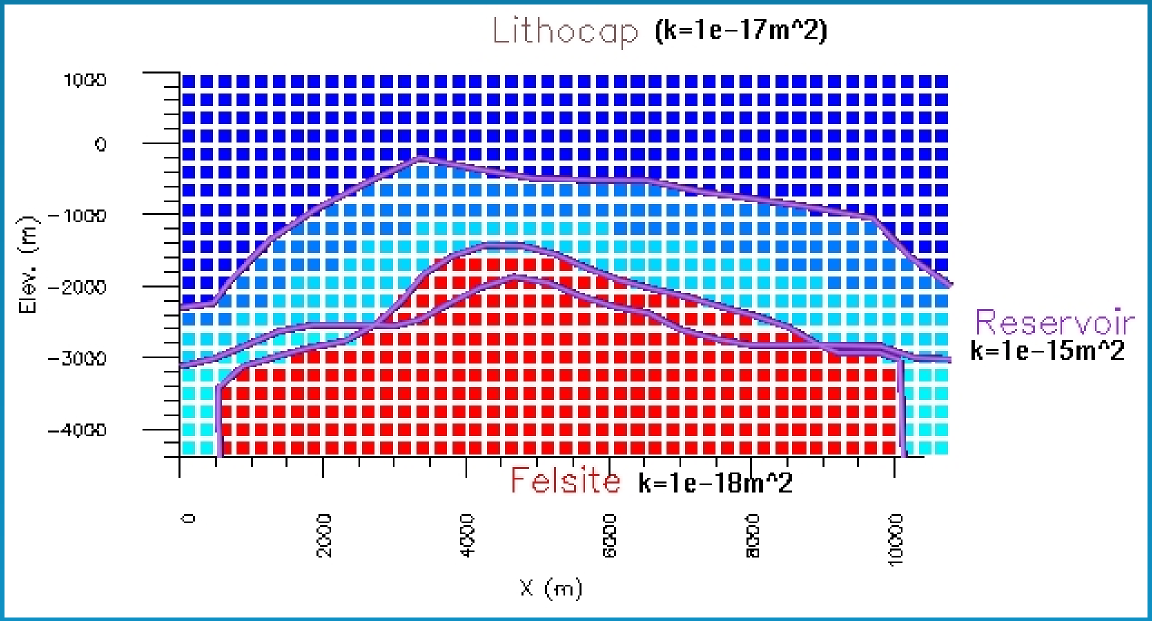




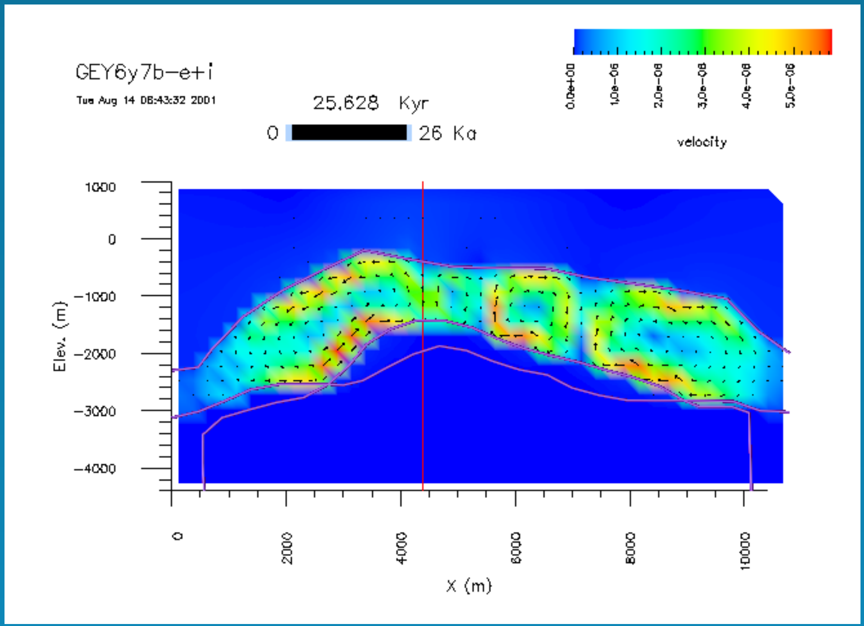
- Zone of critical conditions "drives" the pre-boiling flow system at The Geysers
- System cools in approximately 500 Kyr, despite low reservoir permeability ($10^{-17} \mathrm{m}^2$)
- Alteration distribution indicates persistent deep horizontal permeability throughout liquid-dominated stage

Model Grid

- Coarse grid, 43x21 elements sized 150m x 250 m
- Assume very high permeability reservoir ($k = 1$ md)
- Seek to encourage boiling by developing isothermal low pressure zone throughout reservoir, similar to present-day conditions

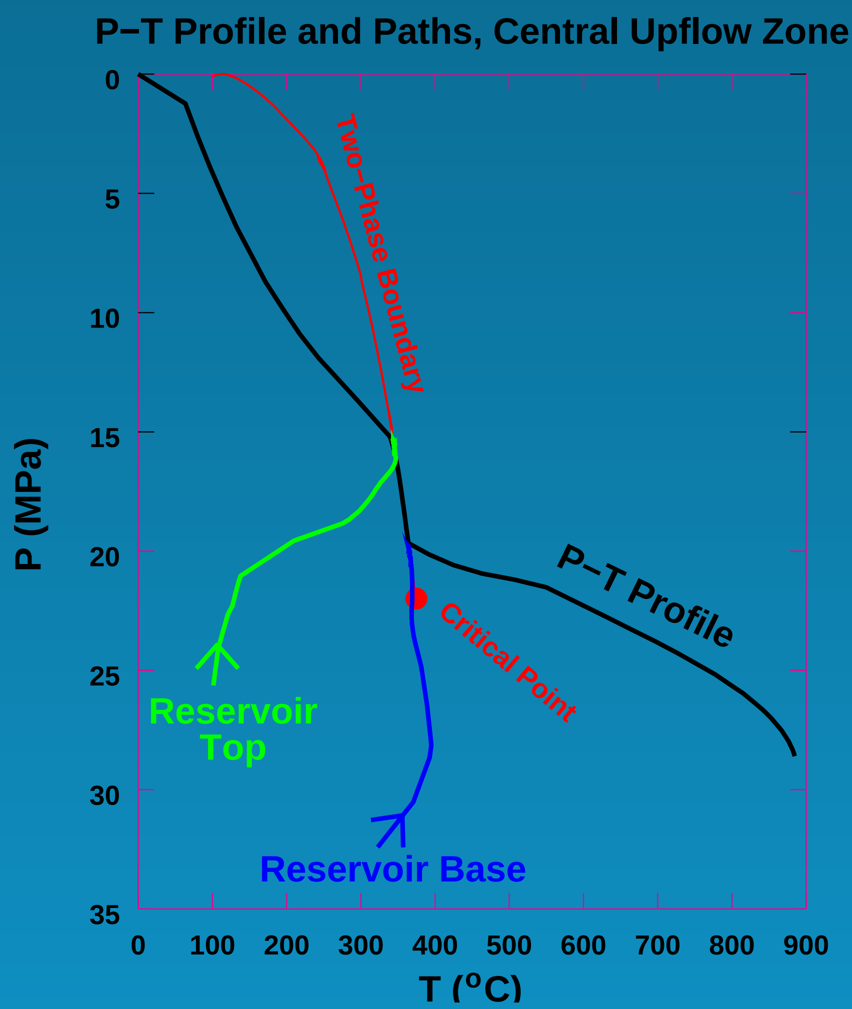


Liquid-Dominated Stage



- Model begins with intrusion of felsite at 890°C
- Reservoir rapidly develops several vigorous convection cells
- Strongest cell upwells over the apex of the felsite, near the location of well SB-15d
- red line is location of P-T section on next slide

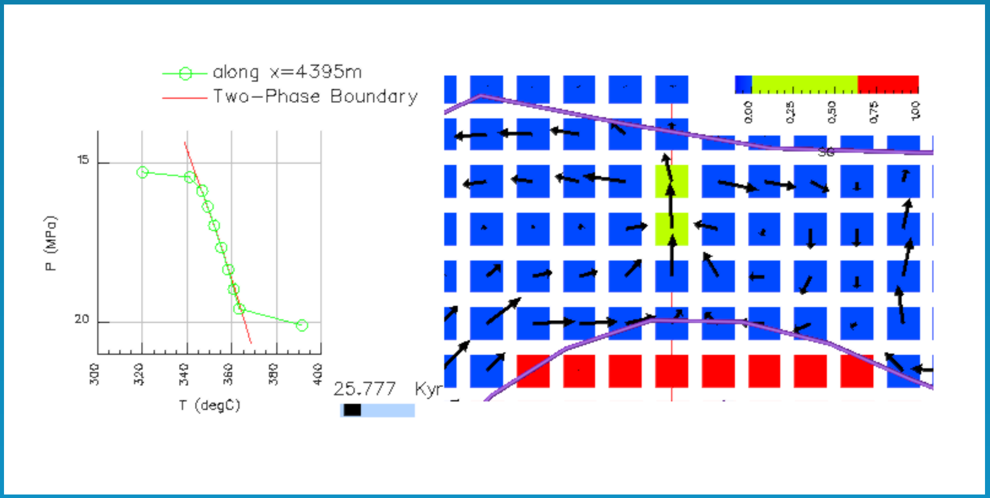
Liquid PT Path



- Points in the upflow zone (and near the felsite contact elsewhere) migrate rapidly toward the two-phase boundary, critical point, or critical isochore
- Fluid packets follow a path down the critical isochore, past critical point and then alongside the 2-phase boundary (liquid-stable)

Formation of Steam "Bubbles"

- Take closeup view of reservoir above apex of felsite intrusion
- Base of upflow zone moves onto 2-phase boundary, forming a steam packet (10% saturation "bubble", shown in green)
- This causes large P perturbation (owing to steam expansion), disrupting upflow zone
- Eventually steam packets advect upward to top of reservoir



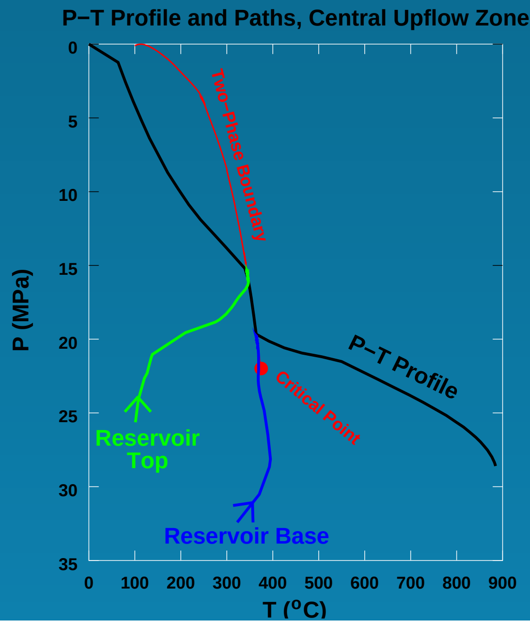
Steady Boiling

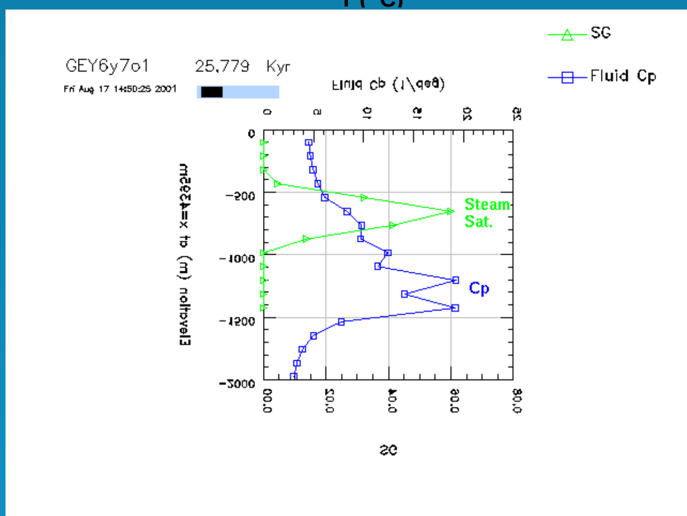
- To force continuous boiling, system must suddenly lose pressure (fracturing or drilling), or be reheated (reintrusion)
- Preliminary tests show extreme fracturing required, else metastable "simmering" conditions persist
- To date only unnatural pressure reduction using wells successfully drives upflow column to full steam saturation

Implications for Geysers

- Deep reservoir behaves much like the roots of a true geyser
- Episodic boiling occurs over extended period, potentially advecting with the flow field
- These episodes initiated at felsite contact by perturbations toward the fluid critical point
- During the metastable period, profound oscillations in flow and fracturing will occur
- These oscillations are recorded in the rock record at The Geysers, including mineral and alteration zoning, paragenetic sequences, and episodic fracturing
- System requires a significant “kick” to break out of this metastable state

Summary





- Is “simmering” a long-lived transition state to traditional boiling?
  - ⋆ Base of upflow zones in magmatic systems likely to be at critical point conditions
  - ⋆ Near-critical fluid properties encourage this behavior in high-permeability systems
- Tools like *EOS1sc* are now available to investigate such high P-T phenomena

References

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