NOTICE CONCERNING COPYRIGHT RESTRICTIONS

GEOTHERMAL RESERVOIRS: PRODUCTS OF COOLING PLUTON

Principal Investigator – Denis L. Norton, Consultant
Box 310
Stanley, Idaho 83278
denis@ruralnetwork,net

Key Words – Reservoirs, dynamics, evolution, supercritical fluids, prospecting criteria

Project Purpose

Assessing the potential of a region to form and sustain a viable geothermal reservoir requires thorough understanding of how reservoirs form and the characteristics of the system that sustains them. Improvements in prospecting methods requires revisiting the process systematics that form reservoirs with this goal in mind and evaluating what parameters should be measured to optimize detection and guide intersection of the reservoirs. This goal can be achieved by a procedure that generates an ensemble of numerical/geological models depicting how source regions for reservoirs in a magma-hydrothermal system evolve.

Project Objectives

Three major targets are: 1) Synthesis of a generic models of geothermal reservoirs within the context of the regional magma-hydrothermal activity, 2) Produce a realistic set of dynamical models of the history of magma-hydrothermal activity typical of geothermal environments, and 3) Derive new and novel prospecting guides based on patterns derived from (1) and (2).

The project set out to characterize the space and time variations of fracture formation driven by progressive fluid pressure fronts as they propagate outward from a cooling pluton and to analyze the system dynamics as they occur at supercritical conditions, determine the properties of these zones that could be detected remotely. The studies focused on situations where magma-hydrothermal processes would develop conditions conducive to the formation of geothermal resources. The study drew primarily on Geysers Resource that appeared to contain evidence of how processes evolve through the near critical region of the H_2O-System.

Methods

Methods that quantitatively describe magma-hydrothermal activity have advanced to a stage that they can be used to effectively *interpret* chronological and geometric relationships amongst mineral alternation, fractures and veins, and igneous event, *map* time-space variations of transport events, and *predic*t the stage of evolutionary behavior of observed activity. A similar set of interacting processes determines the character of all systems; variability perceived amongst systems is a consequence of differences in process behavior. Consequently the theory of magma-hydrothermal activity is extensible to understanding how geothermal reservoirs form.

Behavior in magma-hydrothermal systems is studied with the aid of transport equations that represent the time dependency of any system property, here taken to be either mechanical, thermal or chemical energy, $\mathcal{G}$ among minerals and a fluid whose volume fraction (ϕ_f) and physical form of the pore space it occupies depends on space and time. The conservation of this property in a rock that contains $\hat{I}$ mineral phases plus a single fluid can be written:

$$\frac{\partial(\phi_f \mathcal{G}_f)}{\partial t} + \sum_{i}^{\hat{I}} \frac{\partial(\phi_i \mathcal{G}_i)}{\partial t} + \nabla \bullet (\phi_f \mathbf{v}_f \mathcal{G}_f) = 0 \qquad (1)$$

where t is time, ∇, the gradient operator, l^{-1}; subscripts f, fluid, and i, i^{th} mineral, $\mathbf{v}_f$, is the fluid velocity and ϕ the volume fraction of the respective i^{th} phase. The first term in Equation 1 represents local change in any system property $\mathcal{G}$ of the fluid phase with time. The second term is the local change in the level of $\mathcal{G}$ in mineral phases summed over the all phases; it is linked to the first term through kinetic and equilibrium statements. The third term on left of equation 1, advective rate of change, exerts strong control over process behavior because it depends on the local rates of change in the quantities, $\mathcal{G}$, and advection gradients, $\mathbf{v}_f$, $\mathcal{G}_f$. Integration of equalition like 1 in the context of robust material equations of state and geologic observations constitute the study methods.

Results

The 305 km^3 of magma that crystallized into the Geysers Felsite cooled to present-day conditions in about 750 *kyr*. Following emplacement of the magma a broad zone of temperature increase moved toward the surface for about 125 *kyr*; temperatures were first, perturbed at the surface somewhere between 10 and 25 *kyr* following magma emplacement. The region that straddles the contact between Geysers Felsite and its lithocap rocks resided at supercritical state conditions near the critical point for the hydrothermal fluid for about 50 *kyr*, cf. Figure 1, trajectory 1 and 2.

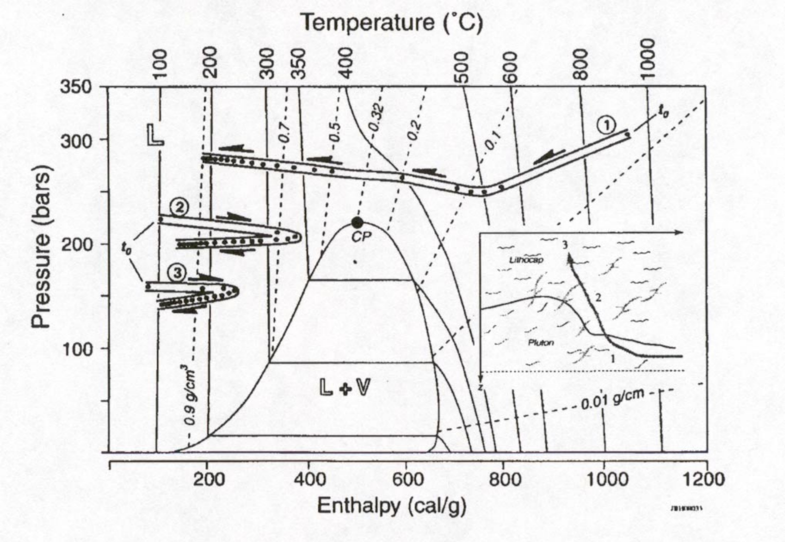

Figure 1. Enthalpy-Pressure project of the H_2O-System, showing the 2-phase "dome", L+V, liquid, L and vapor, V regions. Above critical end point, CP, the phase is a supercritical fluid. Isotherms, °C and isochores, g/cm^3 are depicted respect phases. The hydrothermal history of rocks typical of locations shown within insert of generic section through Felsite are shown from initial intrusion of the felsite, t_0, for 1 My in 50,000 yr increments. Based on an ensemble of detailed numerical models, Norton and Hulen, 2001.

The thermal, mechanical and chemical processes that combined to dissipate the energy from the felsite interacted in an oscillatory manner. Such behavior is partially attributed to their interconnectedness through feedback relations, and because each feedback depends on hydrothermal fluid properties. The properties are demonstrably non-linear near critical points of the fluid. The tendency for lithocap rocks to be shifted in state conditions from t_0 toward the 2-phase dome is well know, but the shift to near critical conditions, cf trajectory 2 has previously unexplored consequences as does the decay of state conditions from within the pluton, cf trajectory 1. In all other magma-hydrothermal systems in the upper crust studied to date, vigorously flowing fluids are similarly attracted to extrema in transport, thermodynamic, and solvation properties of the fluid. The consequences of this process evolution are reflected in geothermometric, mineral and fracture data, from the Geysers rocks.

Geothermometric Data (Fluid Inclusions)

The distribution of fluid inclusion filling temperatures from locations adjacent to the felsite-lithocap contact from Moore and Gunderson, 1995, are correlated with the theoretical trajectories of similar locations in the numerical models, Figure 2. The abundance of inclusions are mapped onto the pressure-enthalpy section with state trajectories of rock from the sample locations. The values from quartz in the felsite, left-hand figure, formed late in the cooling history, circa, 300–400 kyr, whereas those in the lithocap, right-hand figure, formed early, circa 10–30 kyr, as required by progressive thermal states in the lithocap.

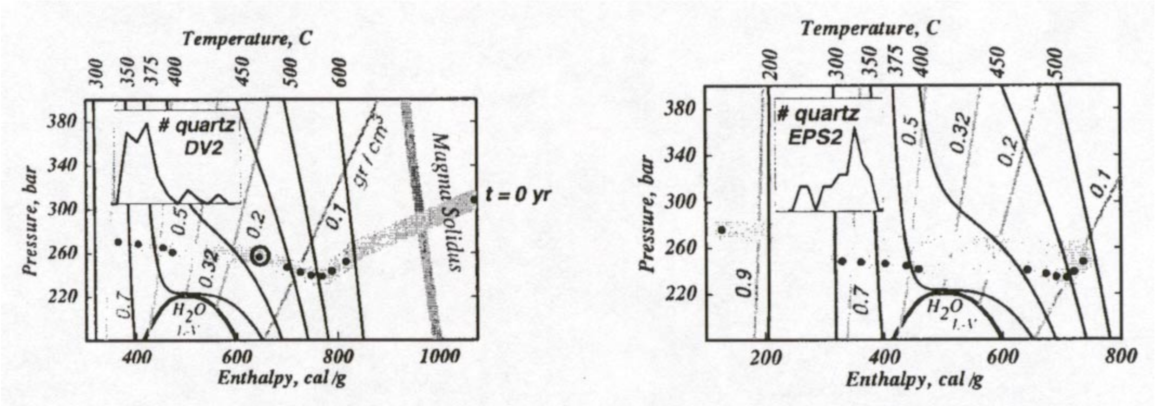

Figure 2. Time trajectory of rocks in numerical approximation of Geysers Felsite correlated with geothermocometric data from within felsite, left-hand, and lithocap, right-hand. Dots at 50 kyr increment on trajectory, see Figure 1.

The time of formation of fluid inclusions relative to the time zero of magma emplacement is useful in understanding the relative ages of hydrothermal rock units. Compilation of system wide geothermometric data in the context of numerical representations of the thermal history of the heat source is recommended to help establish system age for all geothermal prospects. This method is new also to the field of fluid inclusion studies.

.

Mineral Records of Dynamical Behavior

The Geysers is renown for enormous concentrations of tourmaline veins. The delicate zoning within some of these crystals reflects oscillations in chemical state associated typical of expectations from numerical models at near-critical conditions, Figure 3.

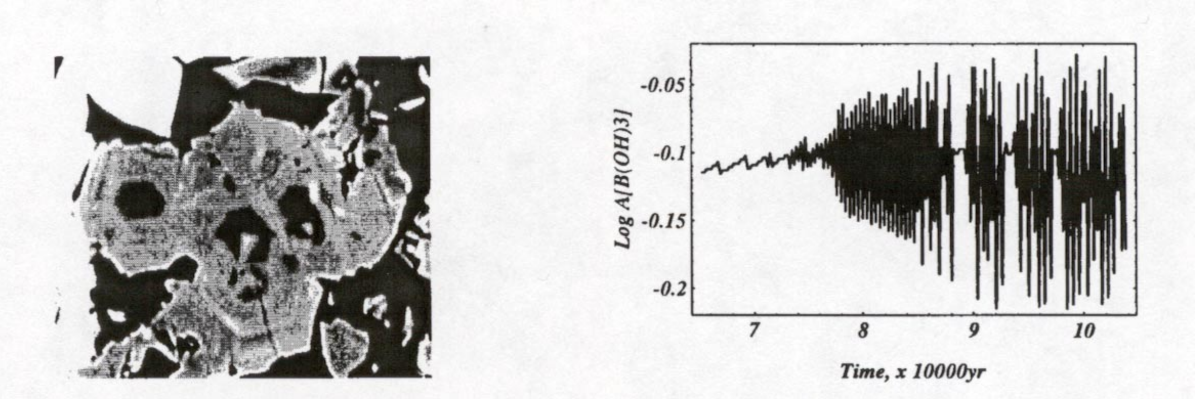

Figure 3. Left: Backscattered electron image of vein tourmalines from the carapace of the Geyser Felsite displaying oscillating chemical zones. The light gray core is dravite-like composition, (Na, Mg)-rich, $NaMg_3Al_6Si_6O_{18}(BO_3)_3(O,OH)_4$, and the rim is foitite, (☐ Fe^{2+}_2 Al) $Al_6Si_6O_{18}(BO_3)_3(O,OH)_4$, is a x-site vacant tourmaline,☐ with almost one-half of the x-site is vacant and the octahedral site is Al and Fe-rich. Field of view ~ 100 µm. Right: Log a $[B(OH)_3]$ vs. time in equilibrium with: K-feldspar, quartz, albite, dravite, phlogopite, muscovite and unit activity of H_2O.

This particular tourmaline is the product of hydrothermal conditions near the magmalithocap contact during the early stages of energy dissipation from the magma, these componsitional data help constrain the conditions between fluid and rock several hundred thousands of years ago. An equilibrium reaction among minerals typical of this assemblage serves to discuss the significance of aqueous boron:

$$\overbrace{NaAlSi_3O_8}^{\textbf{albite}} + \overbrace{3\ SiO_2}^{\textbf{quartz}} + \overbrace{2.5\ KAl_3Si_3O_{12}H_2}^{\textbf{muscovite}} + \overbrace{KMg_3AlSi_3O_{12}H_2}^{\textbf{phlogopite}} + 3\ B(OH)_3 \Leftrightarrow$$

$$\overbrace{NaMg_3Al_6(BO_3)_3Si_6O_{22}H_4}^{\textbf{tourmaline}} + \overbrace{3.5KAlSi_3O_8}^{\textbf{feldspar}} + 6\ H_2O.$$

The equilibrium constant for this reaction is sensitive to conditions near the critical-region because of the control exerted by the stability of the aqueous ions at those state conditions. Mapping this equilibrium constant for state conditions encountered along trajectory 2, in Figure 1 displays the correlation of observed zoning in tourmaline, left hand Figure 3, with oscillatory concentrations of aqueous $B(OH)_3$.

This relationship is typical of situations noted in other studies where always one finds that the patterns of hydrothermal alteration have geometries indicative of the temporal behavior of processes that cased them. Prospecting for resources could use this information to develop functional relationships of form and process that provide the basis for new interpretations. Similar relations undoubtedly exist in epidote compositions, which could refine criteria for detection of the reservoir top surface.

Fracture Propagation

The alteration of pore space caused by dispersion of energy from the felsite is evident in drill core of lithocap rock, Figure 4. Typical patterns noted in unaltered lithocap rock are contorted discontinuous blebs of calcite, ct, left panel. During the prograde hydrothermal event calcite is dissolved and these blebs are redistributed into elongate, narrow aperture vuggy, v, quartz, q, veins oriented roughly normal to the pluton-lithocap contact, right panel. Calcite dissolution, reformation of the pore form into an elongate percolation path, and partial filling with quartz sequentially occurred following temperature increases early, 10–50,000 yr, in the felsite cooling history.

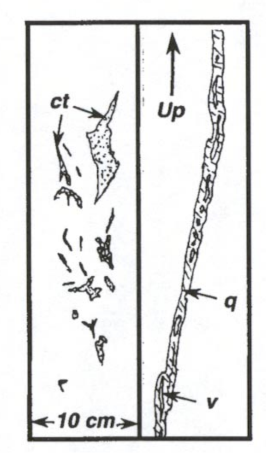

Figure 4.

The mechanical portion of the process is considered a quasi-static deformation of an isolated irregular pore into elliptical form, then extension during heating, when mechanical energy, *J*, levels in the fluid filled pore space exceeds a threshold value, *J**, the effective fracture resistance of the rock.

$$\frac{dl}{dt} = \left\{ \begin{array}{ll} \frac{\alpha(T)l}{2-\beta(T)P_f}\left(\frac{dT}{dt}\right) & J \geq J^\star \\ 0 & J < J^\star \end{array} \right\} \quad (2)$$

$$\frac{dP_f}{dt} = \left\{ \begin{array}{ll} \frac{-\alpha(T)P_f}{2-\beta(T)P_f}\left(\frac{dT}{dt}\right) & J \geq J^\star \\ \frac{\alpha(T)P_f}{1+\beta(T)P_f}\left(\frac{dT}{dt}\right) & J < J^\star \end{array} \right\} \quad (3)$$

$$J = \left(\frac{4\left(1-\sigma^2\right)}{3\pi E}\right) P_f^2 l \quad (4)$$

Conservation of fluid mass and energy relationships for fracture length, *l*, and internal fluid pressure, P_f are derived as functions of fluid properties, fluid pressure, P_f, and rate of temperature change. Where *E* is Youngs modulus and σ is Poisons Ratio. Th*e* competition among expansivity, α(*T,P*), of the fluid filling the pore and its compressibility, β(*T,P*), determines the behavior of this process. Both parameters are strongly nonlinear in the super-critical region and continuously increase to +∞ at the critical point the evolution of fracture pore space, Figure 5 is sensitive to small variations in temperature and hence pressure.

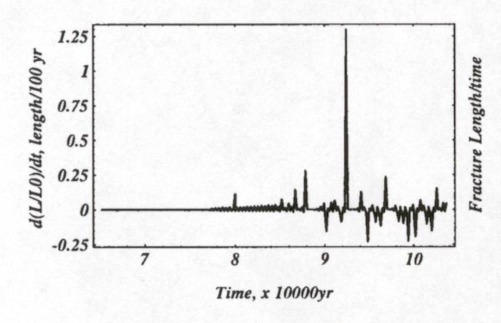

Figure 5. Change in fracture length versus time implied for convecting hydrothermal activity at location 2, inset Figure 1, near pluton-lithocap contact as derived from equations 2-4 for extension of fracture length by fluid pressure changes. Oscillatory growth is consequence of tiny pressure and temperature changes caused by fluctuating buoyancy.

Conclusions

As fluid flows tranverse from a single-phase supercritical fluid state toward a two-phase liquid-steam state their paths are determined by the dynamical behavior of process interactions "upstream". Fracture propagation deflects the flow path to low pressure-high enthalpy (vapor dominate), while mineral sealing decreases advective cooling rates and deflects the path toward low enthalphy-low temperature (liquid dominate) regions. Geometric parameters of alteration features in the Geysers rocks suggest chaotic behavior.

Interest in these patterns and constraints placed on the timing events should be of profound interest to business, the Interior Department and academics whose project goals are to audit geothermal energy resources, should they so choose.

Completion

This new perspective in geothermal resource characterization is being applied to define the parameters needed to identify the most prospective regions of a potential reservoir for development. During the final few months of this project these considerations are being summarized for geothermalists. Specific guidelines are being developed on how to apply the dynamical patterns and time constraints on evaluation of prospective regions. Perhaps the biggest impact will come to situations where regions with potentially young margmas are being prospected.

Assessment of the potential geothermal resources in the United States completed some 20 years ago did not utilize concepts and understanding of processes associated with thermal anomalies in the shallow crust. Advances in the theoretical geochemistry of rocks, minerals and fluids, dynamical analyses of process evolution, as well as improved quantative tools that permit mapping of alteration patterns in rocks in space (relative to causative thermal anomalies) and time (relative to causative thermal anomalies) coordinates were realized. This new body of information and theory offers new perspectives and opportunities, and is necessary for all future assessments. The critical concept is affording for the processes associated with the time-space dissipation of energy from thermal anomalies. The concluding work for this project outlines new methods that could greatly improve the auditing of thermal resources.

Published Results

Norton, D., 2000. Systematics of Magma-Hydrothermal Processes: Geothermal Resources Near Cooling Plutons. Geothermal Res. Council Annual Meeting.

Hulen, J.B., Norton, D.L., Moore, J.N., Beall, J.J., and Walters, M.A., 2001, Initial insights into origin, configuration, and thermal-chemical evolution of the Aidlin Steam Reservoir, Northwest Geysers steam field, Ca. GRC-Annual meeting.

Norton, D. and Hulen, Jeffrey B. 2001. Preliminary numerical analysis of the magma-hydrothermal history of the Geysers Geothermal System, California. Geothermics special issue. 30, 211-234.

Norton, D.L. and Dutrow, B.L. (2001). Complex Behavior of Magma-Hydrothermal Processes: Role of Supercritical Fluids. Geochemica et Cosmochimica Acta, v.65, pp. 4009–4017.