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## Water Rock Interaction [WRI 14]

### On the use of chemical geothermometry: A reactive transport modeling study of the Dixie Valley geothermal area

Christoph Wanner<sup>1\*</sup>, Loic Peiffer<sup>1</sup>, Eric Sonnenthal<sup>1</sup>, Nicolas Spycher<sup>1</sup>, Joe Iovenitti<sup>2</sup>, Burton M. Kennedy<sup>1</sup>

<sup>1</sup>Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA.

<sup>2</sup>AltaRockEnergy Inc. Sausalito, CA, USA

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#### Abstract

A 2D reactive transport model of the Dixie Valley geothermal field in Nevada, USA was developed to assess the conditions under which chemical geothermometers operate as powerful exploration tools. Model concentrations read out at the surface were processed by multicomponent geothermometry to compare inferred reservoir temperatures with true reservoir temperatures of the model. Varying reactive fracture surface areas revealed that re-equilibration does not occur if the effective fracture surface area is 1-3 orders of magnitude lower than the corresponding geometric surface area. Moreover, it could be shown that a full re-equilibration is hindered if the fluid velocity within a fracture is on the order of 1 m/day. It was concluded that such upflow rates and relatively low reactive fracture surface areas are likely occurring at a wide series of geothermal fields, confirming that geothermometers can be used as powerful geochemical exploration tools.

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**Keywords:** geothermal systems; geothermometry, reactive transport modeling, Dixie Valley, geothermal exploration.

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#### 1. Introduction

Multicomponent chemical geothermometers are an accepted exploration tool for geothermal systems [1, 2]. The concept is based on computed temperature dependent saturation indices of potential reservoir minerals using full chemical water analyses. They provide an improvement over classical SiO<sub>2</sub> and Na-K-Ca geothermometers [3] because they rely on more than a few selected chemical components. Both classical and multicomponent geothermometers ideally allow estimating the temperature of geothermal reservoirs based on chemical analysis of geothermal springs assuming that the reservoir minerals and the thermal fluid were in chemical equilibrium. If re-equilibration occurs between the reservoir at depth and the surface, then the ‘deep’ chemical signature of the fluid is lost and the obtained reservoir temperature

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\* Corresponding author. Tel.: +1-510-495-8147; fax: +1-510-486-5686

E-mail address: [cwanner@lbl.gov](mailto:cwanner@lbl.gov)

is underestimated. To assess the conditions under which solute geothermometers operate as powerful exploration tools, a 2D reactive transport model of the Dixie Valley geothermal field in Nevada, USA was developed using the computer code TOUGHREACT [4]. The Dixie Valley geothermal field, located in the Basin and Range province of the western US, was chosen as an example study since extensive geochemical and isotopic data are available [5]. For the assessment of geothermometers, a reactive transport modeling approach bears the advantage of knowing the systems reservoir temperatures while providing “synthetic” spring or well compositions that can be processed using one of the available geothermometers.

## 2. Model setup and calibration

The model was set up for a vertical NW-SE cross-section that is perpendicular to the main valley axis of Dixie Valley. The model dimensions are  $x=5400$  and  $z=4500$  m (Fig. 1). Geological units were defined according to an available geological cross-section including two major normal faults (Fig. 1). The model was discretized into  $108 \times 92$  grid blocks having a vertical extent of 50 m each. The horizontal grid block size gradually increased with increasing distance from the center of the two major normal faults where a width of 0.7 m was specified. The two normal faults were defined for 8 grid block rows resulting in a total width of ca. 23 m. A hydrostatic pressure distribution and a geothermal gradient of ca.  $7^\circ\text{C}$  per 100 m were defined as initial conditions. Fixed boundary conditions of 1 bar and  $20^\circ\text{C}$  were specified at the surface whereas no-flow boundary conditions were used for the bottom and lateral model boundaries except for the deep section of the gabbroic formation where a fixed pressure condition exceeding the hydrostatic pressure by 20 % was specified (Fig. 1b). A slight fluid overpressure was necessary to obtain upflow along both normal faults and the same shape than field derived isotherms (Fig. 1a). No heat flow was allowed for the two lateral boundaries and a constant basal heat flux was defined for the bottom boundary. Thermal and fluid flow parameters such as basal heat flux ( $90 \text{ mW/m}^2$ ), thermal conductivities ( $1.25\text{--}2.5 \text{ Wm}^{-1}\text{K}^{-1}$ ), rock permeabilities ( $10^{-16}\text{--}10^{-14} \text{ m}^2$ ) and rock porosity (0.1) were initially set to the values used by McKenna and Blackwell [6] who recently simulated the large-scale temperature and fluid field of Dixie Valley. To obtain the steady state isotherm illustrated in Figure 1b, the wet thermal conductivity of the alluvial deposits (Fig. 1) had to be modified from the McKenna and Blackwell model [6] and calibrated to  $2.5 \text{ Wm}^{-1}\text{K}^{-1}$ . The central grid block column of the eastern normal fault above an altitude of 0 m above sea level (Fig. 1) was defined using a dual continuum approach. The use of a dual continuum allowed simulating the presence of a small-scale geothermal spring located at the top of the dual continuum domain and fed by a highly permeable but narrow fracture zone. This approach bears the advantage of obtaining different upflow velocities of the spring water by changing the permeability of the fracture domain while the overall flow and temperature field remained unchanged. Simulations were run for fracture permeabilities of  $10^{-10}$ ,  $10^{-12}$  and  $10^{-14} \text{ m}^2$  resulting in upflow rates of 0.01–100 m/day.

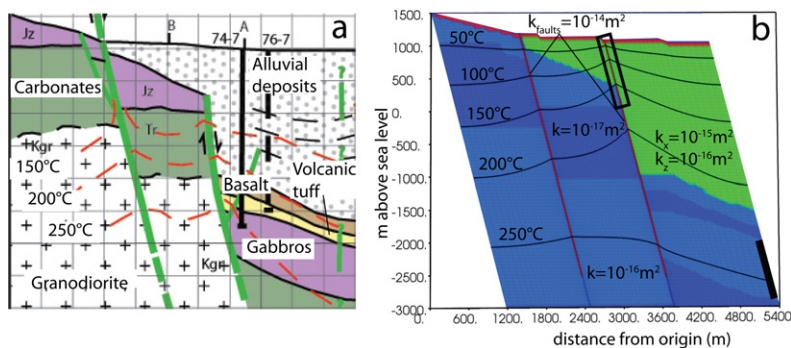


Fig. 1. Model setup and calibrated temperature field: **a.** Geological cross-section used to constrain the model with field-derived isotherms. **b.** Specified geological units of the model illustrated in terms of rock permeabilities, obtained isotherms and locations for which a fixed overpressure of 20% (filled rectangle) and a dual continuum was defined (open rectangle).

Mineralogical compositions of the different geological units (Fig. 1) were defined according to XRD analysis of well-cuttings. Mineral precipitation and dissolution reactions were formulated as kinetic reactions using a transition state theory type rate law [7]. Reaction rate constants were defined according to Palandri and Kharaka [8]. Reactive surfaces area of the fracture domain of the dual continuum were defined according to

$$A = \frac{\Pi \cdot A_{fm}}{2\phi} \quad (1)$$

where  $A$  is the reactive surface area ( $\text{m}^2_{\text{reactive surface}}/\text{m}^3_{\text{fracture medium}}$ ),  $A_{fm}$  refers to the fracture-matrix interface area ( $\text{m}^2_{\text{reactive surface}}/\text{m}^3_{\text{total fracture-matrix medium}}$ ) and  $\phi$  is the true fracture porosity of the rock. Simulations were run for three different fracture surface areas (220, 2.2 and  $0.022 \text{ m}^2/\text{m}^3$ ).  $220 \text{ m}^2/\text{m}^3$  corresponds to the value obtained by equation 2 assuming a fracture porosity of 0.01 and using the geometric fracture-matrix interface area of  $2.8 \text{ m}^2/\text{m}^3$ . Aqueous speciation reactions were calculated based on thermodynamic data tabulated in the SOLTHERM.H06 database [9]. Initial water compositions for the whole model domain except for the deep section of the gabbroic formation (east of the two normal faults) were specified according to a chemical analysis of a shallow groundwater sample collected in the Dixie Valley area [5]. A moderately saline water composition was specified as initial composition for the deep section of the gabbroic formation corresponding to the observation that geothermal reservoir fluids of the Dixie Valley area show elevated  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations [5]. By specifying a fixed, slightly overpressured boundary condition within the gabbroic formation, the model results in a constant injection of the moderately saline water into the geothermal system (Fig. 1b).

### 3. Results and discussion

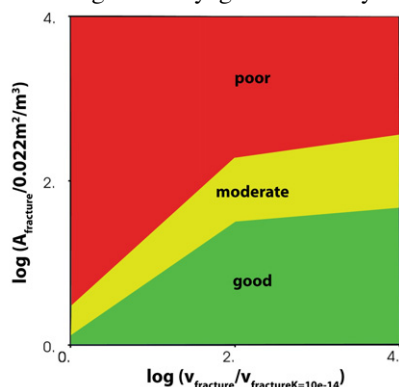
Resulting steady state concentrations in the uppermost cell of the fracture part of the dual continuum domain (“synthetic spring”) varied slightly as a function of the specified fracture surface area and flow velocity within the fracture (Table 1). Comparison with chemical analyses of water samples collected from geothermal wells and springs at Dixie Valley [5] showed similar concentration ranges for most aqueous species. Accordingly, it is inferred that the model reasonably simulates most of the relevant fluid flow and water-rock interaction processes. Synthetic spring compositions for the different model runs were then processed using the automated geothermometer GeoT [2] to compute the temperature at which these synthetic fluids were in chemical equilibrium with the specified minerals of the dual continuum domain (e.g., quartz, albite, microcline, montmorillonite, calcite, clinoptilolite). These temperatures were compared to the steady state temperature of the first grid block located below the dual continuum domain because this grid block corresponds to the fluid reservoir of the “synthetic spring”. The general observation was that the difference between reservoir temperatures inferred from GeoT ( $95\text{--}179^\circ\text{C}$ ) and the true model reservoir temperature ( $180^\circ\text{C}$ ) depends highly on the reactive fracture surface area as well as on the fluid flow velocity within the fracture domain of the dual continuum (Figure 2). Figure 2 also semi-quantitatively defines the degree of applicability of geothermometers as a function of the reactive

Table 1: Spring water composition for two selected model runs and chemical compositions observed in wells and springs at Dixie Valley (in mg/L).

Sampling	pH	$\text{Na}^+$	$\text{Cl}^-$	$\text{SiO}_2$	$\text{Ca}^{2+}$	$\text{Mg}^{2+}$	$\text{HCO}_3^-$	$\text{K}^+$	$\text{Al}^{3+}$	$\text{SO}_4^{2-}$	$T_{\text{sampling}}$
Model run <sup>1</sup>	7.2	519	270	154	8.8	0.07	913	25	<0.01	107	65
Model run <sup>2</sup>	7.1	564	195	155	4.05	0.07	1229	30	<0.01	104	91
Wells	8.7-9.6	370-518	320-624	417-642	1-10	<0.0	140-334	40-77	<1.5	149-243	143-174
Springs	7.4-8.6	141-357	28-228	32-134	11-79	0-30	76-735	5-26	<0.13	66-199	28-84

<sup>1</sup> $A=0.022 \text{ m}^2/\text{m}^3$ ,  $v=0.01 \text{ m/d}$ ; <sup>2</sup> $A=2.2 \text{ m}^2/\text{m}^3$ ,  $v=100 \text{ m/d}$

surface area and upflow velocity. Our simulations suggest that a minimum upflow velocity of about 1 m/d ( $\log(v_{\text{fracture}}/v_{\text{fractureK}=10^{-14}}) = 2$ ) is needed to avoid re-equilibration during upflow, which is most likely occurring in many geothermal systems. They also reveal that, depending on the upflow velocity, the



effective fracture reactive surface area has to be 1-1000 times lower than the corresponding geometric surface area ( $\log(A_{\text{fracture}}/0.022 \text{ m}^2/\text{m}^3)=1-3$ ) for a successful (moderate-good) application of geothermometers. It is inferred that such low reactive surface areas are likely to occur as geothermal wells and hydrothermally active fractures are subject to significant mineral coating/alteration as a result of the precipitation of secondary minerals such as calcite, clays, and amorphous silica. Overall, our simulations confirm that multicomponent chemical geothermometers can be a powerful geochemical exploration tool for many geothermal systems, given an understanding of the fluid fluxes and specific geochemical reactions taking place.

Fig. 2. Geothermometer applicability as function of fluid upflow velocity and reactive fracture surface area. The y-axis was normalized to the lowest simulated fracture surface area while a value of 4 corresponds to the geometric surface area of  $220 \text{ m}^2/\text{m}^3$ . The x axis was normalized to the velocity at a permeability of  $10^{-14} \text{ m}^2$  (0.01 m/d). “Good” denotes the reactive surface vs. upflow velocity domain where obtained GeoT temperatures and true model reservoir temperatures differ by less than  $10^\circ\text{C}$ . For the “moderate” domain the difference was  $10\text{--}20^\circ\text{C}$  and for the “poor” domain  $>20^\circ\text{C}$ .

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