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# TEMPORAL CHANGES IN NOBLE GAS COMPOSITIONS WITHIN THE AIDLIN SECTOR OF THE GEYSERS GEOTHERMAL SYSTEM

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## **ABSTRACT**

The use of nonreactive isotopic tracers coupled to a full thermal-hydrological reservoir simulation allows for an improved method of investigating how reservoir fluids contained within matrix and fractures contribute over time to fluids produced from geothermal systems. A combined field and modeling study has been initiated to evaluate the effects of injection, production, and fracture-matrix interaction on produced noble gas contents and isotopic ratios. Gas samples collected periodically from the Aidlin steam field at The Geysers, California, between 1997 and 2006 have been analyzed for their noble gas compositions, and reveal systematic shifts in abundance and isotopic ratios over time. Because of the low concentrations of helium dissolved in the injection waters, the injectate itself has little impact on the helium isotopic composition of the reservoir fluids over time. However, the injection process may lead to fracturing of reservoir rocks and an increase in diffusion-controlled variations in noble gas compositions, related to gases derived from fluids within the rock matrix.

## **INTRODUCTION**

The Aidlin geothermal field (Figure 1) is located within the northwestern portion of The Geysers geothermal system. This portion of The Geysers steamfield is characterized by higher reservoir temperatures (260–290°C) and elevated noncondensable gas contents (Klein and Chase, 1995; Hulen et al., 2001). The Aidlin reservoir rocks consist of argillite and metagraywacke of the Franciscan Assemblage (Hulen et al., 2001). Much of The Geysers geothermal field is underlain by shallow intrusions that supply heat to the overlying geothermal reservoir (Dalrymple et al., 1999; Stimac et al., 2001). Elevated helium isotope ratios ( $> 6 R_a$ ) for gas samples previously collected at The Geysers (e.g., Torgersen and Jenkins, 1982; Kennedy and Truesdell, 1996) have been interpreted to indicate a magmatic source for the helium.

Steam production at Aidlin began in 1989 and has been accompanied by varying amounts of injection, using condensate, creek water, and, most recently, reclaimed water from the Santa Rosa–Geysers Recharge Project (Stark et al., 2005). Injection of condensate water at The Geysers has increased ammonia concentrations and D/H ratios of the produced fluids, with injection-derived steam estimated to constitute between 24 and 80% for most portions of the field (e.g., Goyal, 1999). At present, steam is produced from wells Aidlin 1, 4, 6, 7, 9, and 10, with wells Aidlin 5 and 11 used for injection.

Figure 1. Location of wells at Aidlin. Condensate from the Aidlin plant and reclaimed water from the Santa Rosa–Geysers Recharge Project are used for injection into wells AD-5 and AD-11.

### **HELIUM ISOTOPE COMPOSITIONS OF AIDLIN WELLS**

Lawrence Berkeley National Laboratory (LBNL) has conducted periodic gas sampling of wells at Aidlin since 1997. Production-well fluids were passed through a condensing coil in an ice bath, and noncondensable gases (NCG) were collected in copper tubes sealed with cold welds for noble gas analysis. Sample preparation and noble gas analyses were conducted in the Roving Automated Rare Gas Analysis (RARGA) laboratory at LBNL, using procedures similar to those described in Hiyagon and Kennedy (1992) and Kennedy and van Soest (2006). Helium data are reported as R/Ra, where R is the  $^3\text{He}/^4\text{He}$  of the measured sample and Ra is the isotopic ratio in air ( $1.4 \times 10^{-6}$ ).

Helium isotopic compositions of the sampled well gases range from 5.6–7.6 Ra (Figure 2). These values overlap, but in general are lower than the range of He isotopic values previously reported for The Geysers by Torgersen and Jenkins (1982) [6.7–9.6 Ra] and Kennedy and Truesdell (1996) [6.6–8.3 Ra]. Some wells exhibit a general trend towards lower  $^3\text{He}/^4\text{He}$  values with time, such as Aidlin 5 (prior to conversion as an injector) and Aidlin 6. Other wells show both increases and decreases in He Ra values with time.

Figure 2. Changes in He isotopic compositions (reported as R/Ra) for Aidlin wells over time.

### **SOURCES OF HELIUM AT AIDLIN**

The elevated He Ra values at Aidlin indicate that the bulk of the helium contained in the geothermal fluids is derived from a mantle source. The most likely source is degassing from a high-level magma chamber or cooling intrusive body (Kennedy and Truesdell, 1996). The Geysers hydrothermal system is closely associated with silicic volcanism at the Clear Lake volcanic field (e.g., Dalrymple et al., 1999; Stimac et al., 2001; Schmitt et al., 2006). Lower crustal intrusion of basalt and assimilation of crustal metasedimentary rocks has resulted in the generation of voluminous ( $>300 \text{ km}^3$ ) silicic volcanic and shallow-level plutonic rocks over the past 2 Ma. These degassing magmas likely serve as the primary source of helium encountered in The Geysers geothermal fluids.

Air-saturated injection water represents another source of helium. Much of the steam currently being produced at The Geysers is derived from injected waters. These waters (consisting primarily of condensate from the cooling towers and reclaimed water from the Santa Rosa–Geysers Recharge Project) have equilibrated with air, and thus have a He isotopic signature similar to that of air ( $\sim 1 \text{ Ra}$ ). However, the  $^4\text{He}$  concentration in water equilibrated with air is  $\sim 2 \times 10^{-12}$  moles/g, whereas the average  $^4\text{He}$  concentration in the 2005 Aidlin production fluids is  $\sim 6 \times 10^{-9}$  moles/g. Therefore, it is unlikely that the small decreases in He isotopic ratios over time reflect an increased injection contribution to the He composition.

A simple mixing calculation can be made to evaluate the effect of mixing injectate having He concentrations and isotopic compositions that reflect those of air-saturated water (ASW) with reservoir fluids on the He isotopic composition of the produced fluids. Helium concentrations in ASW at 25°C are  $4.41 \times 10^{-8}$  cc STP/g fluid (Ozima and Podosek, 2002), and would have a He isotopic ratio of 1 Ra. We used the He concentrations and isotopic composition of the 2002 AD-7 well fluid, which has a He concentration of  $1.35 \times 10^{-4}$  cc STP/g fluid and a He isotopic ratio of 7.29 Ra, to represent the initial reservoir fluid. Using the mixing equation:

$$\frac{F}{1-F} = \left( \frac{R_M - R_R}{R_{ASW} - R_M} \right) \left( \frac{C_R}{C_{ASW}} \right) \quad (1)$$

a mixing curve (Figure 3) was generated, where F is the fraction of injectate in the mixed production fluid,  $R_M$  is the He isotopic ratio of the mixed fluid,  $R_R$  is the He isotopic ratio of the reservoir fluid,  $R_{ASW}$  is the He isotopic ratio of the injectate,  $C_R$  is the concentration of He in the reservoir fluid, and  $C_{ASW}$  is the He concentration of the injectate. The mixing relations indicate that to obtain even a small decrease in Ra from 7.29 to 7.09, 99% of the produced fluid would need to be injectate. While injectate is likely to be a significant (>20%) component of the produced fluids at The Geysers (e.g., Goyal, 1999), it is not the dominant source of fluids at Aidlin, because the volume of produced fluids has been substantially larger than the amount of water that has been reinjected back into the Aidlin reservoir. Thus, mixing of injection waters with reservoir fluids cannot be directly responsible for the observed decrease in  $^3\text{He}/^4\text{He}$  values with time.

Figure 3. Helium mixing curve for injectate and reservoir fluids at Aidlin. Note that shifts in the He isotopic composition in the resulting mixed fluid only occur with a very large (>95%) injection fraction.

An additional source of He in the Aidlin reservoir is  $^4\text{He}$  produced through radiogenic decay of the Th and U present in the reservoir rocks. Using the equation for  $^4\text{He}$  production rate from Craig and Lupton (1981) and Th and U concentrations (6.1 and 1.9 ppm, respectively) for greywacke at The Geysers reported by Schmitt et al. (2006), we find that the annual  $^4\text{He}$  production rate is  $1.81 \times 10^{-17}$  moles/g rock. Therefore, the late Mesozoic to early Tertiary reservoir greywacke could contain as much as  $\sim 10^{-9}$  moles  $^4\text{He}/\text{g}$ , representing a significant potential source given the He concentrations in the present-day production fluid. Because the helium is radiogenic, it is expected to have an isotopic composition of  $\sim 0.02$  Ra. Formation of new fractures resulting from the injection of cool water into the reservoir would expose fresh rock surfaces, and the diffusive loss of radiogenic helium from the greywacke matrix along these fracture surfaces could lower the production fluid  $^3\text{He}/^4\text{He}$  value.

### **MODELING OF HELIUM VARIATIONS**

A simplified reactive transport model of the Aidlin system was developed using TOUGHREACT to simulate the evolution of the He gas composition of the reservoir

over time. The TOUGHREACT simulator couples the flow of water, gas, and heat to reactive chemistry and transport for multiphase, multicomponent systems (Xu et al., 2006). The code uses a sequential iteration approach that solves the transport and reaction equations separately. Aqueous and gaseous species are transported by advection and diffusion. Reaction between mineral, gas, and aqueous species can be modeled under either equilibrium or kinetic conditions. Mineral precipitation and dissolution reactions are coupled to changes in porosity, permeability, and capillary pressure. The TOUGHREACT code has been recently enhanced to incorporate isotopic fractionation and the use of isotopes as tracers (e.g., Singleton et al., 2004). Reactive transport modeling provides a powerful tool to evaluate the integrated effects of injection on reservoir performance (e.g., Xu et al., 2004).

Heat transfer in fractured geothermal reservoirs is controlled by the effective surface area between fractures and the rock matrix, as well as by mass transfer occurring at these interfaces. Changes in fluid chemistry within the geothermal reservoir are influenced by a variety of processes, including boiling, mixing of reservoir and injected fluids, and mineral-fluid reactions.

Our conceptual model for the Aidlin system captures the processes that impact the He concentrations and isotopic compositions in the geothermal reservoir fluids. The reservoir itself is defined as a dual permeability (fracture-matrix continua) system, with fluids present in both fracture and matrix porosity. As extraction of steam from the reservoir proceeds with time, water retained in the matrix boils and flows into the fracture network. The large contrast in permeability between the low permeability metasediments (Persoff and Hulen, 2001) and the more permeable fracture network may lead to noble gas fractionations between fluid in the matrix and in fractures, resulting in the depletion of lighter-element noble gases in the matrix. The rock matrix also contains minerals containing small amounts of U and Th, which leads to the production of significant amounts of radiogenic  $^4\text{He}$  over time.

Another important component to the geothermal system is the underlying magmatic system, which supplies heat and fluids to the geothermal reservoir. This component can be represented within the model as a constant flux of heat and fluids that contain helium with a magmatic isotopic signature.

The conceptual model also captures the two main activities associated with exploitation of the Aidlin geothermal reservoir: (1) production of geothermal fluids, and (2) injection of condensate and reclaimed water. These processes lead to significant chemical and thermal changes to the reservoir (e.g., Truesdell and Shook, 1997; Goyal, 1999). Production of fluids from the geothermal reservoir leads to depletion of the original fluid composition and decreasing reservoir pressures, which result in boiling of residual fluids in the matrix and an increase in NCG contents over time. Injection of condensate and reclaimed water into the reservoir recharges the reservoir with fluid, but results in decreased fluid enthalpy. The injectate also introduces dissolved gases, and may enhance the release of radiogenic helium from fresh fracture surfaces formed from the injection of cooler fluids.

Our simplified numerical model consists of a 530 m 1-D grid with dual permeability (fracture-matrix continua). Initial reservoir conditions were set at 275°C and 3.09 MPa. Air-saturated water was injected into one end of the 1-D grid at a rate of 35 L/min, and was assigned an enthalpy corresponding to 40°C. Fluid flow through the system was controlled by injection at one end and fixed reservoir conditions at the far end. The matrix porosity was assumed to be 2%, with a fracture porosity of 0.9%. Matrix hydrologic properties were derived from measurements reported by Persoff and Hulen (2001). The initial matrix and fracture mineralogy was derived from Moore and Gunderson (1995) and Hulen et al. (2001).

To represent diffusion within our simulations, the gas phase diffusion coefficients for  $^3\text{He}$  and  $^4\text{He}$  are calculated assuming ideal gas behavior as a function of temperature, pressure, molecular weight, and molecular diameter, according to Lasaga (1998), as follows (see also Singleton et al., 2004):

$$D = \frac{RT}{3\sqrt{2}\pi P N_A d_m^2} \sqrt{\frac{8RT}{\pi M}} \quad (2)$$

where  $D$  is the diffusion coefficient ( $\text{m}^2/\text{s}$ ),  $R$  is the gas constant ( $8.31451 \text{ m}^2 \text{ kg s}^{-2} \text{ mol}^{-1} \text{ K}^{-1}$ ),  $T$  is temperature in Kelvin units,  $P$  is the gas pressure ( $\text{kg m}^{-1} \text{ s}^{-2}$ ),  $N_A$  is Avogadro's number ( $6.0221367 \times 10^{23} \text{ mol}^{-1}$ ),  $d_m$  is the molecular diameter (m), and  $M$  is the molecular weight (kg/mol). Molecular diameters for  $^3\text{He}$  and  $^4\text{He}$  were assumed to be the same ( $3.0 \times 10^{-10}$  m) and therefore diffusive fractionation occurred solely through the differing masses of the isotopes.

Transport of  $^3\text{He}$  and  $^4\text{He}$  in the gas phase takes place through advection and diffusion, with the diffusive fluxes following Fick's Law. The diffusive flux ( $F_D$ ) is therefore expressed as follows:

$$F_D = D\phi S_g \tau \nabla(\phi S_g C) \quad (3)$$

where  $\phi$  is the porosity,  $S_g$  is the gas saturation,  $\tau$  is the tortuosity, and  $C$  is the gas species concentration. Typical values were assumed for the tortuosity of fractures and the rock matrix (0.8 and 0.2, respectively).

### Initial Model Results

Three different processes were examined with these simulations: 1) the effect of injection water on helium isotope compositions, 2) the role of diffusion on helium isotopic exchange between matrix and fracture, and the impact that *in situ* radiogenic  $^4\text{He}$  production might have on helium isotope compositions. We did not assess long-term accumulation and subsequent release of  $^4\text{He}$  from the matrix with this model.

The effect of injection on the He isotopic composition of fluid within the fracture and the matrix is presented in Figure 4. For the case without diffusion ( $D = 0$ ), there is a dramatic difference between the He isotopic composition in the fractures and that of the

matrix, because the extremely low matrix permeability allows very little exchange of fluid between these two reservoirs. The injected fluid moves preferentially into the higher permeability fracture network (as steam), and thus the He isotopic composition of the matrix is only slightly affected by injection. Because of the 1-D nature of this model, injected fluid moves through the fracture elements as a plug of steam, resulting in progressive displacement of the reservoir fluid with injectate. After 1 year of injection under these conditions, the He isotopic composition for the grid blocks within 200 m of the injection well is equal to that of the injectate ( $R/R_a = 1$ ).

Figure 4. Simulated He isotopic compositions of fluids for fracture and matrix elements vs. distance from injection well for diffusion and diffusion-absent ( $D = 0$ ) cases at  $t = 1$  year.

A very different result is obtained when diffusion is enabled in the simulation. There is preferred diffusion of  $^3\text{He}$  from the matrix fluids into the fracture network, resulting in a slight increase in the  $R/R_a$  values of the fracture relative to those of the matrix. After 1 year of injection, the magnitude and distance over which the He isotopic compositions have been modified is significantly less than in the case without diffusion. Inclusion of present-day generation of  $^4\text{He}$  resulting from *in situ* radiogenic decay of Th and U in the rock had no discernable effect on model results. Changes in reservoir temperature resulting from 1 year of injection (Figure 5) are limited to a small region ( $<30$  m) near the injection well.

Figure 5. Simulated temperatures for fracture and matrix elements vs. distance from injection well at  $t = 1$  year.

### **COMPARISONS WITH OTHER GEOTHERMAL SYSTEMS**

Helium isotope variations at Aidlin can be compared with those observed at other geothermal systems. Within the Ohaaki-Broadlands geothermal system, Hulston and Lupton (1996) observed a range of helium isotope ratios, with values near 6  $R_a$  in the western portion of the field contrasting with values as low as 3  $R_a$  in the eastern portion of the field. They attributed this variability to the presence of two distinct helium sources: mantle helium and radiogenic helium derived from Mesozoic graywackes that form the basement of the geothermal system. Both temporal and spatial variations in He isotopes were observed for thermal features sampled from the Long Valley geothermal system (Hilton, 1996). Within a given thermal feature, He isotope ratios varied up to 25% over the three-year sampling period. Increases in He  $R_a$  values were attributed to magmatic intrusion, while decreases were attributed to  $^4\text{He}$  release from crustal rocks facilitated by hydrothermal activity.

Similarly, we interpret that the variations in He isotope compositions observed at Aidlin are also related to the presence of two distinct He reservoirs, (1) a mantle component related to the degassing of a magma body that provides heat to the geothermal system and (2) a radiogenic He component derived from the Mesozoic metagraywacke reservoir rocks. Injection within the reservoir serves to fracture these rocks, exposing new surfaces that enhance the release of radiogenic helium into circulating geothermal fluids.

## **CONCLUSIONS**

Helium isotope compositions of production fluids from wells at the Aidlin sector of The Geysers geothermal field (5.6–7.6 Ra) indicate that the helium is derived primarily from a magmatic source. However, these values are generally lower than those measured earlier at The Geysers, and we observe a trend in some wells towards slightly lower Ra values in produced Aidlin fluids with time. This trend could reflect the accelerated release of radiogenic helium from the matrix of reservoir rocks caused by fracturing associated with injection, thus lowering the  $^3\text{He}/^4\text{He}$  values of the resulting reservoir helium, which is dominated by a magmatic He component. Numerical modeling using TOUGHREACT was conducted to evaluate how magmatic gas input, *in situ* radiogenic production of  $^4\text{He}$ , and the withdrawal and injection of fluids into and out of the reservoir impact the He composition of reservoir fluids over time. The initial results of this modeling indicate that diffusion of helium between fluid in the matrix and fracture network is an important process.

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Figure 1

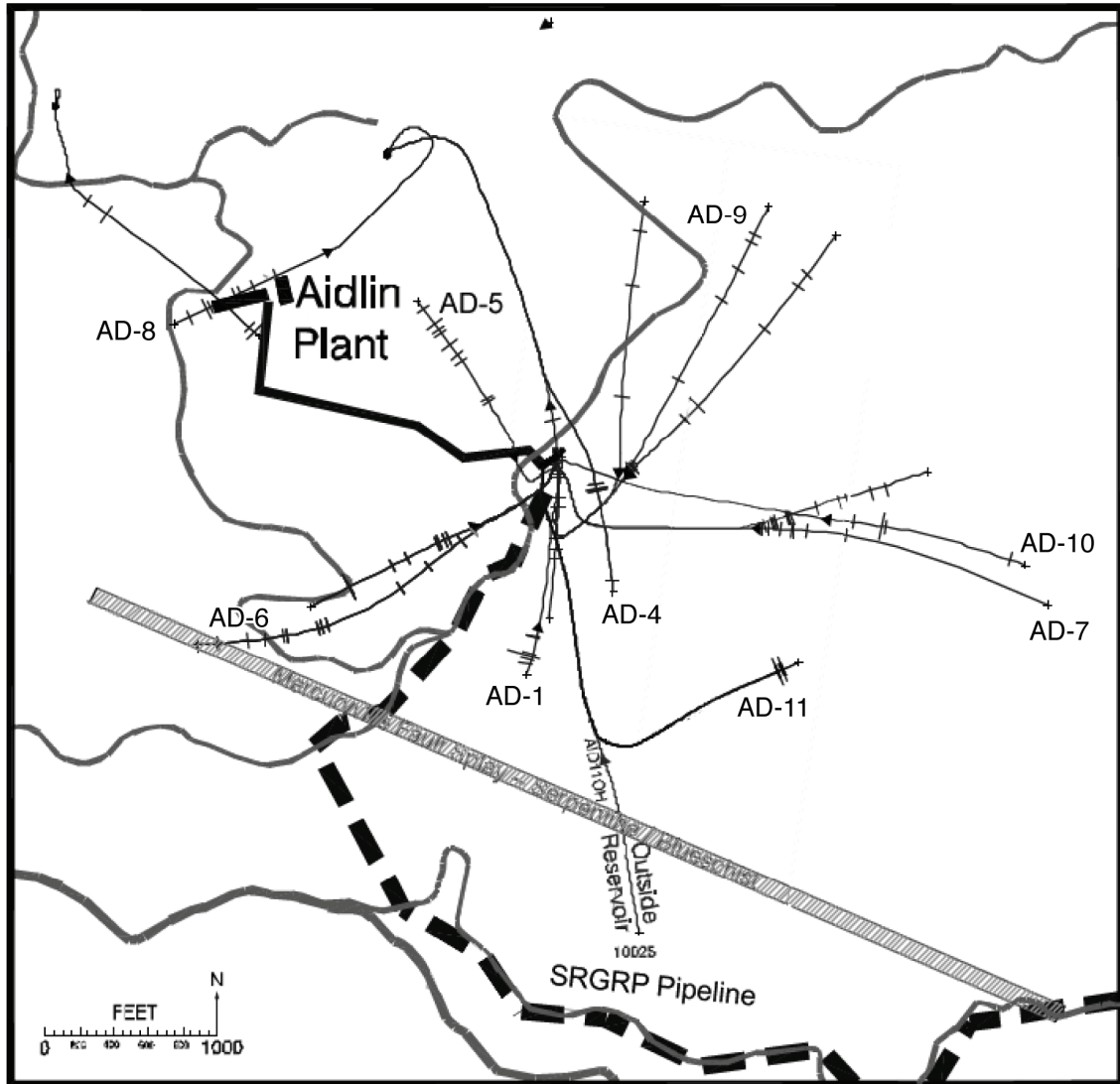


Figure 2

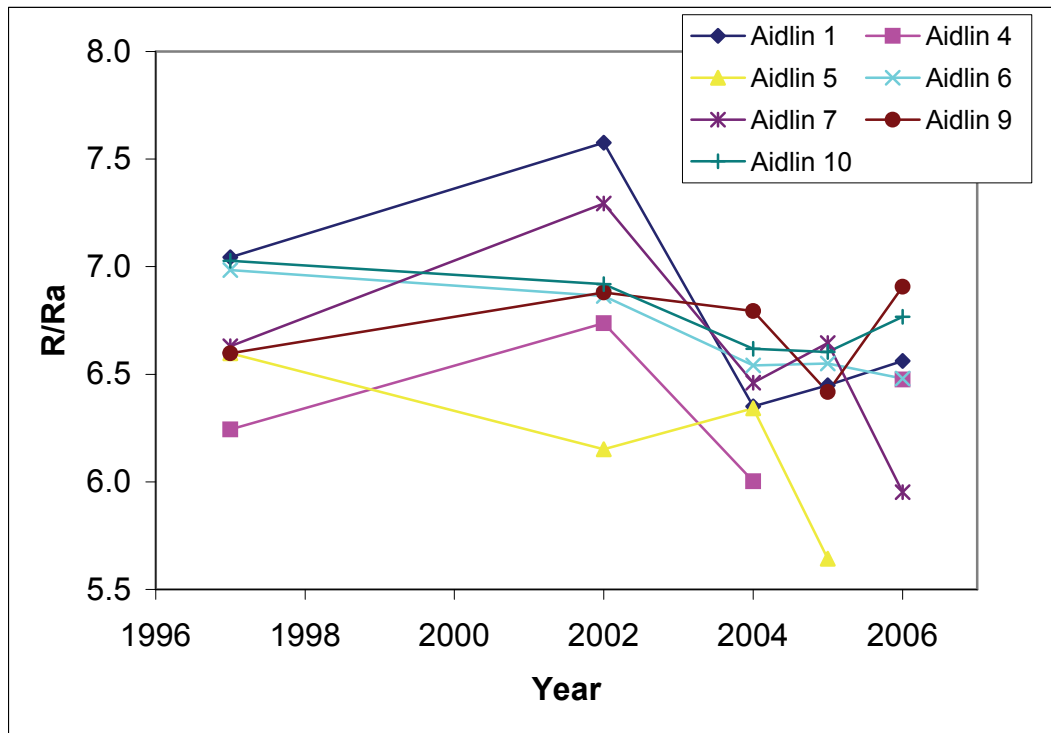


Figure 3

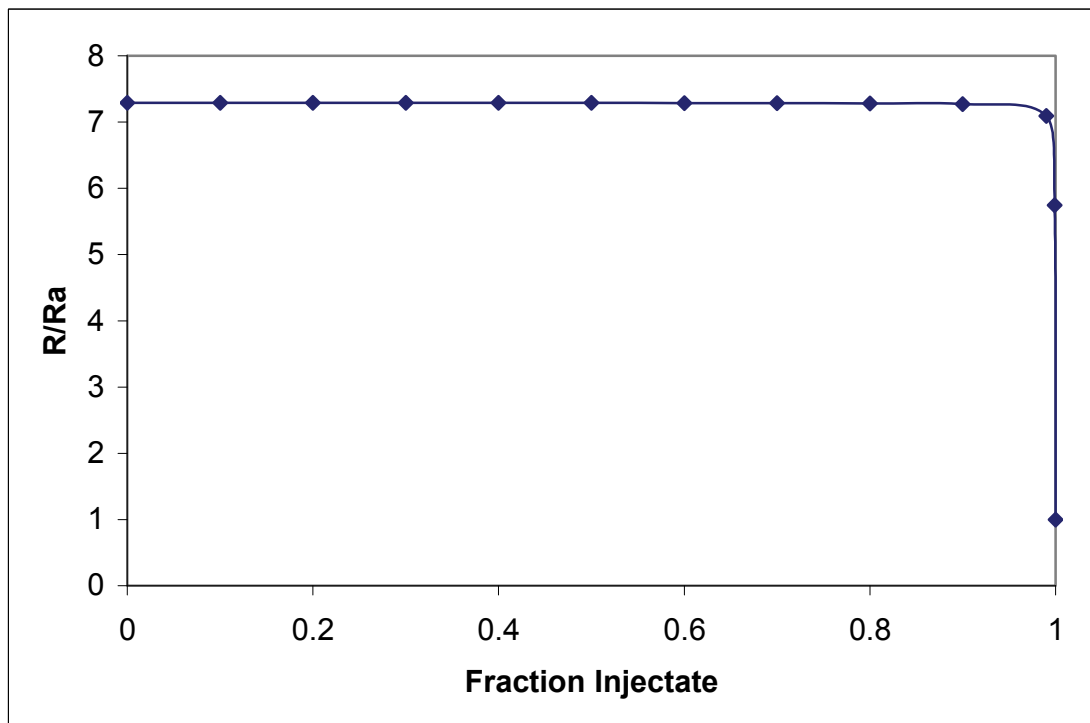


Figure 4

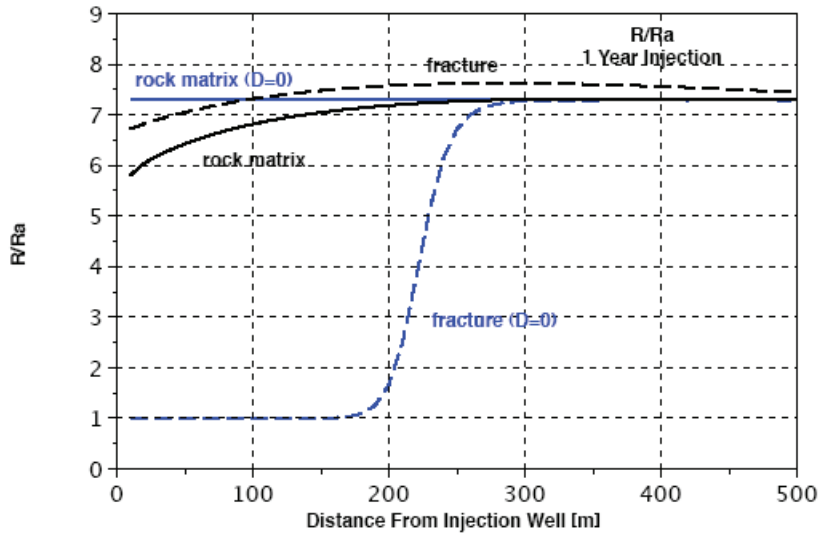


Figure 5

