Analysis and Interpretation of NDS Tracer Test Results at the Olkaria West Geothermal Field, Kenya

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Keywords

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ABSTRACT

The Olkaria III geothermal field has been under development by ORMAT since 1998. A 12 MWe binary plant was commissioned in July 2000. Long term stability of the reservoir and the well output suggested that the field is able to sustain a larger load; therefore ORMAT continued field development by drilling new wells and increased power output by an additional 36 MWe by early 2009. A series of well tests have been carried out in Olkaria III since the commissioning of the new power plant, including down hole pressure and temperature measurement, continuous reservoir pressure monitoring, geochemical sampling and tracer tests to define the hydrologic flow paths and rate of return/inflow in the Olkaria III geothermal reservoir. Around 3 x 100 kg of liquid-phase tracers were injected in July 2009: 2,6-NDSA, 1,5-NDSA and 2,7 NDSA into wells OW-401, OW-307 and ORP-B1 respectively. Of the nine production wells monitored for tracer recovery during eight months, only two wells show positive tracer responses from two injection wells. The tracer mass recovered to date is however only about 3-5 % of the total tracer mass injected. The TRINV computer software program was used to calibrate properties of two flow channels connecting wells ORP-B1 and OW-301. The analysis suggests that around 5 kg/s of the total 80 kg/s injected into ORP-B1 flow towards OW-301. A small cross section area for the two flow channels (5 m^2) is modeled and relatively high longitudinal dispersivity (280-300 m). Average flow velocity from ORP-B1 to OW-301 is about 15 m/day for the bulk of the injected mass, to be compared with total distance of 1000 m. Such a slow flow velocity, high dispersivity and long distance imply that immediate cooling effects are not of concern for this well dipole. To verify this conclusion, a simple parallel plate fracture model, of the same cross section area as the larger tracer flow channel, implies that maximum cooling of production well OW-301 is about 15 ºC over 10 years of continuous injection. The study therefore concludes that injection to ORP-B1 should eventually terminate and be transferred to a more southerly location. When coupling the minimal tracer recovered with the observed lateral pressure gradient from North to South, it appears evident that most of the injected tracer is flowing straight south and consequently out of the ORMAT production sector. This is highly unusual for most high temperature geothermal reservoirs, in particular for Olkaria West where 100 % reinjection has been practiced from the onset of power production. The outer reservoir margins therefore must respond to the current mass production by a healthy and strong inflow of hot fluids from the North.

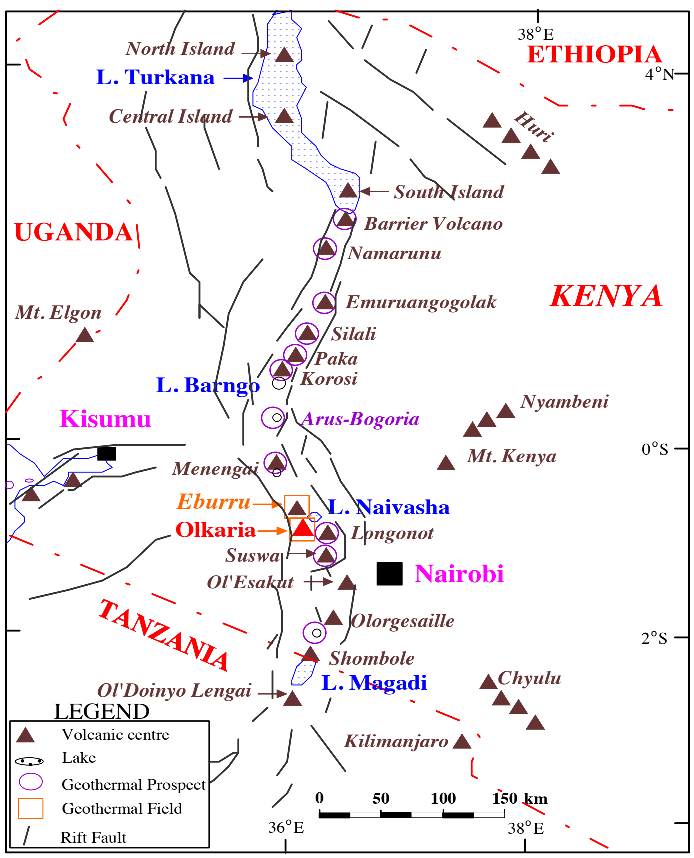

Figure 1. Olkaria Geothermal Field (after Mwangi, 2010).

1. Introduction

The Olkaria III geothermal field is a part of the greater Olkaria geothermal system located within the East African Rift Valley at about 120 km to the Northwest of Nairobi, Kenya (Figure 1). The Eastern sector of Olkaria geothermal system has been under exploitation since 1981. In late 1999 a 13 MWe binary power plant was commissioned in Olkaria III sector, known also as Olkaria West (Figure 2). The power plant and geothermal field are managed by Orpower IV Inc., a subsidiary of ORMAT Technologies Inc. and it has been in successful and stable operation since inception. Recent additions have gradually taken the power output up to 50 MWe, the last unit being commissioned in late 2008. Monitoring of primary field parameters, such as pressure drawdown, enthalpy and total flow histories of wells have shown that the reservoir is very stable and likely to sustain even greater production load than at present. This positive field behavior led the operator, Orpower IV Inc, to consider adding new power units to the current 50 MWe plant. As part of the monitoring of reservoir response to exploitation, a tracer reservoir test was carried out to define the hydrologic flow paths and rate of return/inflow in the Olkaria III geothermal reservoir. This paper describes this tracer test, tracers selected, where injected and where recovered. The tracer recovery curves are analyzed by 1-D dispersion/advection models. Based on the geometrical cross section of these flow channels a parallel plate fracture models was used to predict cooling impact on one of the production wells in the field. Finally, the conclusions of this work are integrated into other reservoir observations made in Olkaria West.

2. The Olkaria III Conceptual Model

Bjornsson et al. (2001) proposed a conceptual model of the Olkaria geothermal fields with emphasis on Olkaria West (Figure 2). This conceptual model was built on and consistent with earlier models, and validated by Reykjavik Geothermal in 2010 (Reyjkavik Geothermal, 2010). The main features of the conceptual model can be seen in Figure 3. They are described as follows:

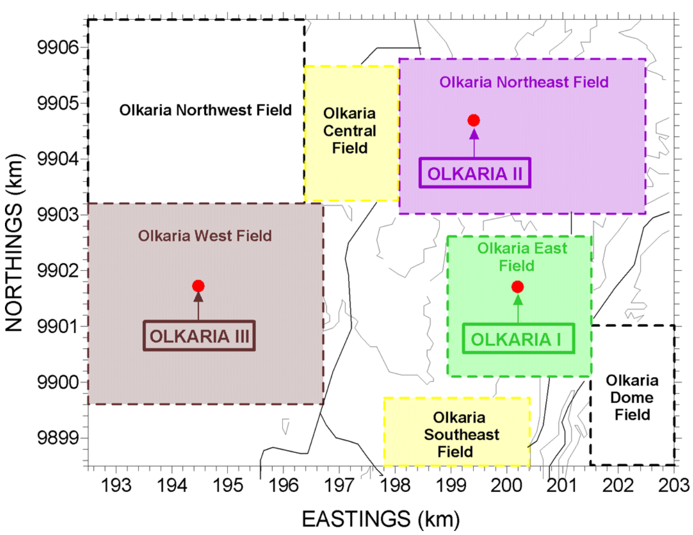

Figure 2. Sectors of the Olkaria Geothermal Field (After Mwandi, 2010).

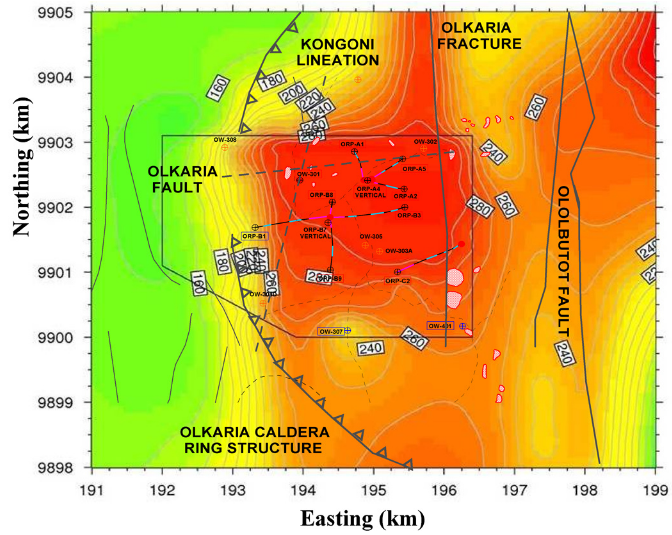

Figure 3. Temperature distribution at 1000 m a.s.l. at the Olkaria III sector (After Reykjavik Geothermal, 2010).

1. The Olkaria volcanic complex is dominated by two upflow zones, one in the East and the other in the West.
2. The eastern and western halves of the greater Olkaria resource are divided by a permeable N-S feature the Ololbult fault (Figure 3) making both sectors independent.
3. The Olkaria III sector has three major fracture zones, the W-E striking Olkaria fault, the N-S striking Olkaria fracture and a N-S striking fault zone approximately through well OW-301 (Figure 3). Figure 3 also shows part of the Olkaria caldera ring structure.
4. The upflow zone of the West field appears to be located in the NE corner of the current concession of ORMAT (Figure 4). This is the hottest spot of the West field with temperatures between 250 and 350ºC.
5. The Ololbutot fault serves as a constant pressure boundary.
6. The western boundary of the West field is characterized by low permeability and high CO_2 gas content in the geothermal field.
7. When the western field is under production, the fluid recharge to the reservoir is preferably coming from the Ololbutot constant pressure boundary and complemented by reinjection as will be discussed in next sections of this paper.

3. The Tracer Test using Naphthalene Disulfonate (NDS)

This tracer test was conducted to define the hydrological flow paths and rate of return/inflow of injected brine in the West Olkaria field considering the increase of fluid extraction and reinjected after commissioning a new power plant in fall 2008. The results of this reservoir tracer test will assist in defining long-term reinjection strategies for the current project and future expansion.

Three types of naphthalene disulfonate (NDS) tracers were used in this test: 1,5-NDS, 2,6-NDS and 2,7-NDS. The chemical

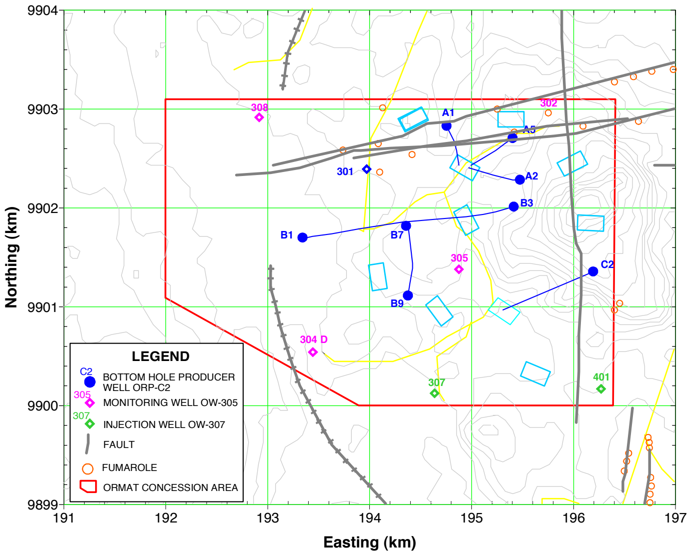

Figure 4. Well location and concession area of Olkaria III sector.

tracers were pumped as slugs into wells OW-307, OW-401 and ORP-B1 (Figure 4) respectively during normal injection service receiving plant injectate, and it was intended to follow the liquid phase in the reservoir.

Well OW-307 is the best injection well of the field (Figure 4). It was located at South of the wellfield and drilled vertically down to 2020 m. A PTS survey ran in 2001 suggests that the well has a main pay zone at 950-1000 m and minor one below 1000 m (PB Power, 2001). It has been estimated that the well can accept over 700 t/h of fluid by gravity only. Well OW-401 is another vertical well drilled down to 2402 m and located to the SE of the ORMAT concession. It has been receiving fluid since 2001 by a main feed zone at 1250-1400 m and a minor one at 1650 m (PB Power, 2001). Injection capacity has been estimated to be 20 t/h/bar. ORP-B1 was drilled by Orpower IV directionally to the West from wellpad "B", located a few meters south of the power plant. Main feed zones of the well are between 1300 and 1600 m depth. Initially, it was drilled as a production well. Due to limited capacity of the pipeline to OW-401, it was decided to connect ORP-B1 to the injection gathering system in 2009 as a temporary solution.

The injection of NDS tracers was conducted on July 28th, 2009. Table 1 shows the injection sequence and Data Summary of the tests. The 2,6 NDSA tracer was injected in well OW-401. To help accommodate tracer injection the flowrate of the injection well was throttled slightly to reduce wellhead pressure. The tracer was delivered while the plant injectate was entering the well at a rate of 62 t/h. The tracer was injected directly into the 2" side valve at the wellhead, over a short time interval, resulting in a concentrated slug of tracer passing into the wellbore.

The 1,5-naphthalene disulfonic acid was injected into well OW-307. The wellhead pressure during injection was approximately 2.2 bar-g. Throttling of this well was impossible, due to plant injection requirements. The tracer was delivered while the plant injectate was entering the well at a rate of 71 t/h. As for well OW-401, the liquid tracer was injected directly into the 2" side valve at the wellhead, relevant data are outlined in Table 1.

Table 1. Injection sequence and Data Summary.

	OW-401	OW-307	ORP-B1
Tracer type	2,6 NDSA	1,5 NDSA	2,7 NDSA
Tracer quantity (kg)	95	95	96
Final concentration (w/v)	10.5%	10.5%	10.0%
Well injection flow rate	62	71	35
before/after tracer injection (t/h)			
Wellhead pressure (barg)	1.30	2.18	3.00
Tracer injection time (min)	8	11	24
Average tracer injection rate (l/min)	119	86	38
Initial tracer concentration (%)	1.08	0.72	0.64

The 2,7-naphthalene disulfonic acid was injected in well ORP-B1. To help accommodate tracer injection, the flowrate of the injection well was throttled to less than 10% of the normal injection rate in an attempt to reduce wellhead pressure. In spite of the throttling, the wellhead pressure remained in the region of 2.7-3.0 bars-g. The tracer was delivered while the plant injectate was entering the well at a rate estimated on 35 t/h. The liquid tracer was injected into a newly installed port on the 2" warm-up line at the wellhead.

A total of nine wells (ORP-A1, ORP-A2, ORP-A4, ORP-A5, ORP-B3, ORP-B7, ORP-B9, ORP-C2 and OW-301) were monitored for tracer returns. Monitoring for tracer returns to the production sector was originally programmed from the day of injection to five weeks after, but due to the slow recovery the monitoring is still ongoing. The sampling schedule was as follows:

Week 1- Sample all wells daily, starting the day of injection.
Week 2- Sample all wells daily.
Week 3- Sample all wells every 2nd day.
Week 4- Sample all wells every 2nd day.
Week 5 and beyond- Sample wells every 4th day.

Since January 2010, it was decided to continue sampling once every month in production wells ORP-B7, B9, C3 and OW-301.

In each of the monitored wells, the two-phase discharge line was tapped by a cooling coil. The two-phase sample was condensed and collected as pure liquid at the end of the coil. Correcting the tracer concentration for well enthalpy is therefore considered unnecessary.

4. Theory

The flow of a tracer between an injection point and an observation point can be modeled by the convection-dispersion-diffusion equation in one dimension (Axelsson et al., 2005)

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 x} - u\frac{\partial C}{\partial x}$$

where D is the dispersion coefficient (m^2/s), C the tracer concentration in the flow-channel (kg/m^3), x the distance along the flow channel (m) and u the average fluid velocity in the channel (m/s) given by $u = q/\varrho A\phi$, with q the injection rate (kg/s), ϱ the water density (kg/m^3), A the average cross-sectional area of the flow-channel (m^2) and ϕ the flow-channel porosity. Molecular diffusion may be neglected such that $D = \alpha_L u$ with α_L the longitudinal dispersivity of the channel (m). Assuming instantaneous injection of a mass M (kg) of tracer at time $t = 0$ the solution for the tracer recovery curve at any distance x is given by:

$$c(t) = \frac{uM}{Q}\frac{1}{2\sqrt{\pi Dt}}e^{-(x-ut)^2/4Dt}$$

Here $c(t)$ is the tracer concentration in the production well fluid, Q the production rate (kg/s) and x the distance between the wells involved. Conservation of the tracer according to c•Q = C•q, has been assumed. This equation is the basis for the tracer interpretation software TRINV, included in the ICEBOX software package that is used for simulation or interpretation of the tracer test results presented in this paper (United Nations University Geothermal Training Programme, 1994). TRINV is an interactive DOS-mode program, which automatically simulates the data through inversion. We have the option of defining a model with one or more flow-channels and to define a first guess for the model parameters. TRINV, consequently, uses non-linear least-squares fitting to simulate the data and obtain the model properties, i.e. the flow channel volumes ($A\phi$) and dispersivity (α_L) (Axelsson et al., 2005; Arason et al., 2004).

5. Results and Discussion

Of the nine wells monitored for more than nine months, only two wells showed positive tracer response from one or two of the injection wells, indicating the influence of the injected. The 2,7-NDSA injected in Well ORP-B1 showed positive returns in two wells (OW-301 and ORP-B7) indicating a direct hydrological connection between these well pairs. The 1,5-NDSA injected in well OW-307 showed positive returns only in well OW-301 but in negligible quantities. The recovery profiles are shown in Figure 5. First arrival of tracer in well ORP-B1 was detected 8 days after injection while in well ORP-B7 breakthrough occurred 18 days after injection.

Figure 6 shows the simulated recovery curves compared with the observed data for the injection-production dipole ORP-B1 and OW-301. Before coming up with a best model, a trial and error analysis was required to estimate what mass of water injected to ORP-B1 is flowing to OW-301. This process initially uses the 3 % recovery of tracer mass in OW-301 as the minimum flow in the channels connecting the well to ORP-B1 (i.e. 3 % of the stable 80 kg/s injected). By increasing the flow in 1 kg/s steps and estimating the total tracer recovery after an infinite time, a stable total mass recovery of 6 % was persistent for a range of flows. From this crude analysis it was decided that 5 kg/s is a best estimate for the total flow coming from ORP-B1 to OW-301. As it can be seen in the figure, the best model is assuming a two channel ("two pulse")flow path in which the faster path is channeling 1 kg/s and the latter about 4 kg/s. Table 2 shows properties of model pulses #1 and #2. Table 3 shows the flow channel properties derived by the modeling.

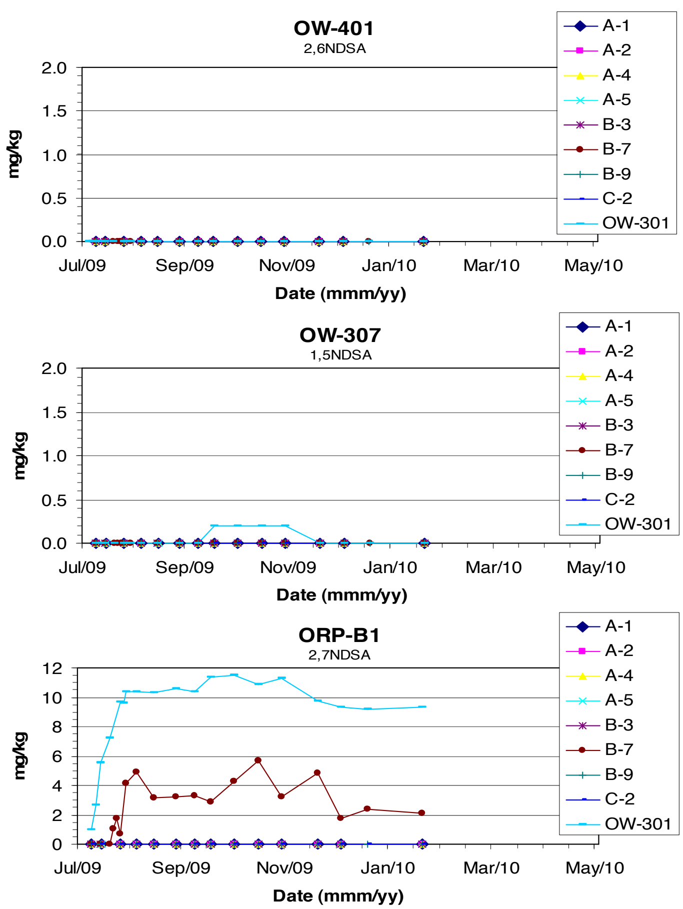

Figure 5. Tracer recovery profiles.

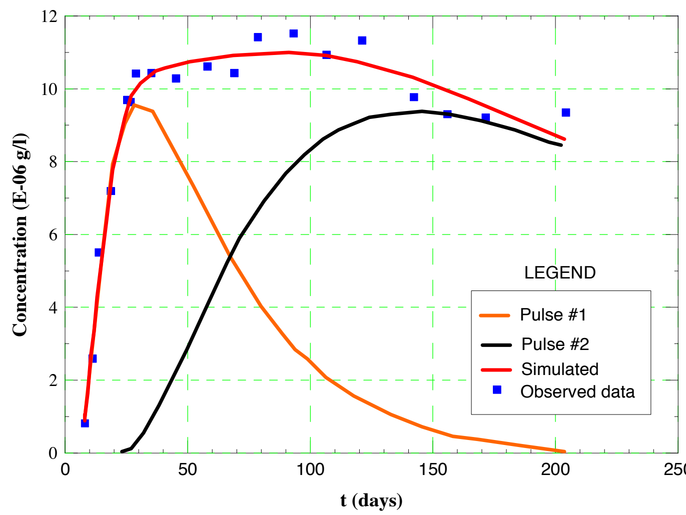

Figure 6. A two pulse tracer model for the duplet ORPB-1 to OW-301, assuming all the 18 kg/s produced from OW-301 arrive from ORP-B1.

Table 2. Properties of model pulses # 1 and # 2.

MODEL DATA	
N, Number of data points	19.0
t, last timepoint of input data (s)	0.17 x 10^8
A, integral (kg s/m^3)	167.32
Q, production rate (kg/s)	18.0
q, injection rate (kg/s)	5.0
M_t, total injected mass of tracer (kg)	96.0
M_c, recovered mass of tracer (kg)	3.0
M_r, mass recovery (%)	3.14%
rl, Lab water density (kg/m^3)	998.3
rr, in situ density (kg/m^3)	800.0

The model assumes that the distance along the flow path is 1000 m with two 1-D flow channels connecting wells ORP-B1 and OW-301. The analysis suggests very small cross section area for the two flow channels (5 m^2) and relatively high longitudinal dispersivity (280-300 m). Average flow velocity from ORP-B1 to OW-301 is about 15 m/day for the bulk of the injected mass, to be compared with total distance of 1000 m. Such a slow flow velocity, high dispersitivity and long distance imply that immediate cooling effects are not of concern for this well dipole. To verify this conclusion, a simple parallel plate fracture model, of same cross section area as the larger tracer flow channel, implies that maximum cooling of production well OW-301 would be about 15 °C over 10 years of continuous injection (Figure 7). Therefore, it can be concluded that injection to ORP-B1 should eventually terminate and be transferred to a more southerly location.

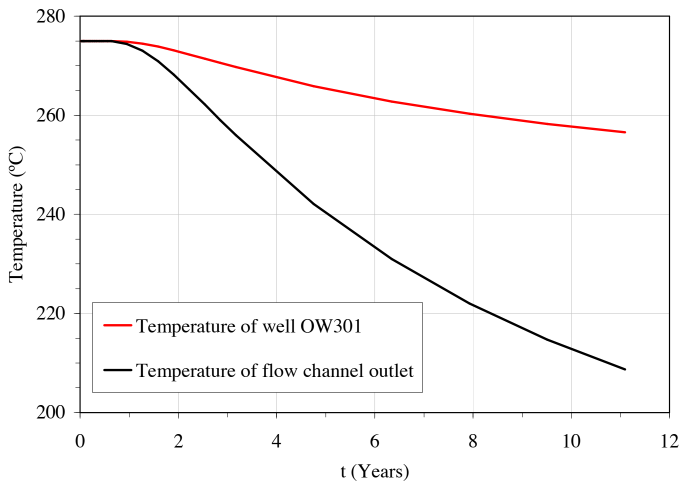

Figure 7. Estimated temperature decline in well OW-301 and channel outlet by injecting into well ORP-B1. The connecting fracture is assumed to be 100 m high and an area of 5 m .

Table 3. Simulation results and Statistics of fit.

SIMULATION RESULTS	Pulse 1	Pulse 2
x, Distance along flow path (m)	1.00×10^3	1.00×10^3
u, flow velocity (m/s)	0.29×10^{-3}	0.61×10^{-4}
D, dispersion coefficient (m^2/s)	0.82×10^{-1}	0.18×10^{-1}
m, combined mass parameter (kg/m^2)	0.17×10^{-1}	0.17×10^{-1}
$A \times \Phi$, cross section (Area x porosity) of path (m^2)	2.30×10^{-1}	0.54×10^{1}
α_L, dispersivity (m)	2.83×10^2	3.03×10^2
M_r, Mass recovery (%)	1.09	5.24
c, concentration at maximum (kg/m^3)	0.96×10^{-5}	0.94×10^{-5}
t, time at concentration maximum (s)	0.26×10^7	0.12×10^8
w, width at half height of concentration peak (s)	0.51×10^7	0.25×10^8

STATISTICS OF FIT	
Number of model parameter	6.0
Degrees of freedom	13
Mean of observed data	0.898×10^{-5}
Mean of calculated data	0.898×10^{-5}
Minimum anomaly (obs - calc)	$(-)0.667 \times 10^{-6}$
Maximum anomaly (obs - calc)	0.727×10^{-6}
Sum of squared residuals	0.35×10^{-11}
Root mean square misfit	0.429×10^{-6}
Estimate of standard deviation	0.519×10^{-6}
Coefficient of determination	97.70%

6. Conclusions

A reservoir tracer test was carried out in Olkaria III section to define hydrologic flow paths and rate of return/inflow in the Olkaria III geothermal reservoir, analysis of the test results suggest the following:

1. Of the nine production wells monitored for tracer recovery during, only two wells (OW-301 and ORP-B7) have positive tracer responses from two injection wells (OW-307 and B1).
2. The tracer mass recovered was only about 3 - 5 % of the total tracer mass injected.
3. The TRINV computer software was used to calibrate properties of two flow channels connecting wells ORP-B1 and OW-301. The analysis suggests that around 5 kg/s of the total 80 kg/s injected to ORP-B1 flow towards OW-301. A small cross section area for the two flow channels (5 m^2) is modeled and relatively high longitudinal dispersivity (280-300 m).
4. Average flow velocity from ORP-B1 to OW-301 is about 15 m/day for the bulk of the injected mass, to be compared with total distance of 1000 m. Such a slow flow velocity, high dispersitivity and long distance imply that immediate cooling effects are not of concern for this well dipole. To verify this conclusion, a simple parallel plate fracture model, of same cross section area as the larger tracer flow channel, implies that maximum cooling of production well OW-301 would be about 15 °C over 10 years of continuous injection.
5. Based on the results of the modeling, the current injection into well ORP-B1 should eventually terminate and be transferred to a more southerly location.
6. When coupling the minimal tracer recovered with the observed lateral pressure gradient from North to South, it appears evident that most of the injected tracer is flowing straight south and consequently out of the Ormat production sector. This is highly unusual for most high temperature geothermal reservoirs, in particular for Olkaria West where 100 % reinjection has been practiced from the onset of power production. The outer reservoir margins therefore must respond to the current mass production by a healthy and strong inflow of hot fluids from the North.

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