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Simultaneous Liquid- and Vapor-Phase Tracer Study in the Tejamaniles Area of the Los Azufres, Mexico, Geothermal Field

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ABSTRACT

Comisión Federal de Electricidad (CFE), the owner and operator of the Los Azufres Geothermal field, injects relatively cool (~40°C) produced brines in well Az-08, located in the Tejamaniles (Southwest) area of the field. The present study aims to investigate whether the injected fluid recharges nine production wells in this area, and if it does, to assess the fraction of the injected brine that that recharges each well. Five of the selected wells produce steam and water; the rest produce only steam. For this reason we designed the present simultaneous liquid- and steam-phase tracer study. All nine monitored production wells detected the steam-phase tracer, and the five wells that produce water and steam detected the liquid-phase tracer. For both tracers, all residence curves present a series of peaks, which we interpret as reflecting the fractured nature of the reservoir. These results demonstrated that the feeding areas of the nine monitored wells are recharged from the injector Az-08. The total percentages of tracers recovered in the nine wells at 302 days after the injection were 2.21% for the liquid-phase tracer and 0.0216% for the steam-phase tracer, which implies modest recharge from Az-08. However, these quantities are not final because at 302 days after injection the liquid-phase tracer was still arriving in five wells. Our results reveal upflow (and implied vertical permeability) of steam and water derived from fluid injected in Az-08 over vertical distances 700-1,000 m. This upflow implies (i) that cool injectate is heated enough at depth to convect upwards, thus preventing or at least retarding thermal interference; and (ii) injectate boils at depth generating steam upflow. This provides useful insights on reservoir properties (e.g., temperature, vertical permeability, two-phase conditions) at depth and on the circulation of the injected fluids.

1. INTRODUCTION

Comisión Federal de Electricidad (CFE), the owner and operator of the Los Azufres Geothermal field, injects relatively cool (~40°C) produced brines in well Az-08, located in the Tejamaniles (Southwest) area of the field. Before this study the destination of the injected fluid was not known with certainty.

To investigate possible effects of injection in Az-08 on the reservoir (e.g., recharge, thermal interference) it was decided to implement this tracer study in the production area most likely to be affected by this operation. Considering the structural characteristics of the Tejamaniles area and the distances involved, wells Az-08 (injector), Az-2A, Az-06, Az-16D, Az-16AD, Az-17, Az-33, Az-36, Az-37 and Az-46 (Fig. 1) were chosen to participate in this investigation.

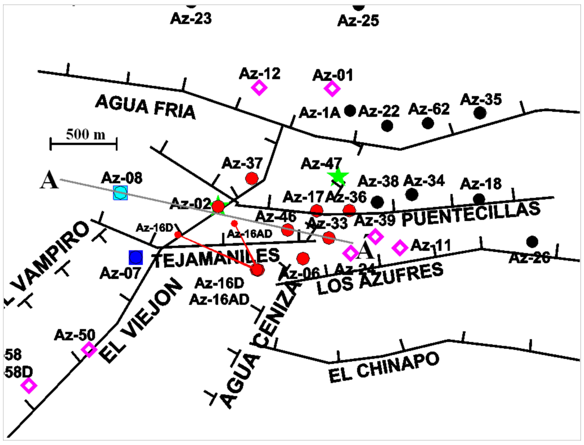

Figure 1: The Tejamaniles area where this study was conducted.

The present study aimed to investigate whether the injected fluid recharges nine production wells in this area, and if it does, to assess the fraction of the injected brine that that recharges each well. Five of the selected wells produce steam and water; the rest produce only steam. For this reason we designed a simultaneous liquid- and steam-phase tracer study.

The tracers were injected in late June 2008. Though the steam-phase tracer seems to have completed its arrival at the monitored wells, the liquid-phase tracer was still arriving at the time of this writing. However, 302 days after tracer injection there were sufficient results to infer important conclusions. For this reason we present this work as a progress report.

In the following sections we describe the materials and method used for this study, present and discuss our results and state our conclusions.

2. MATERIALS AND METHOD

As mentioned, this study took place in the Southwestern part of the Los Azufres geothermal field, in an area denominated Tejamaniles. Its name derives from a prominent fault that crosses it in the general East-West direction (Fig. 1). In this figure the injector well Az-08 is represented by a light blue square and the monitored production wells by red circles. Wells Az-16D and Az-16AD, drilled from the same pad, are deviated as shown in Fig. 1. The rest of the wells are vertical. In Fig. 2 we present a section from well Az-08 to well Az-33 (A-A´ in Fig. 1), which, taken together with Fig. 1 helps visualize the spatial relationships of the wells.

Table 1 presents the horizontal distances of the monitored wells to the injector, and the corresponding water and steam flowrates. For the deviated wells the distance is taken from the closest point to well Az-08. As shown, five of the selected wells produce steam and water; the rest produce only steam. For this reason we designed a simultaneous liquid- and steam-phase tracer study. This has the additional advantage of allowing comparison of both tracer results in the five wells that produce water and steam.

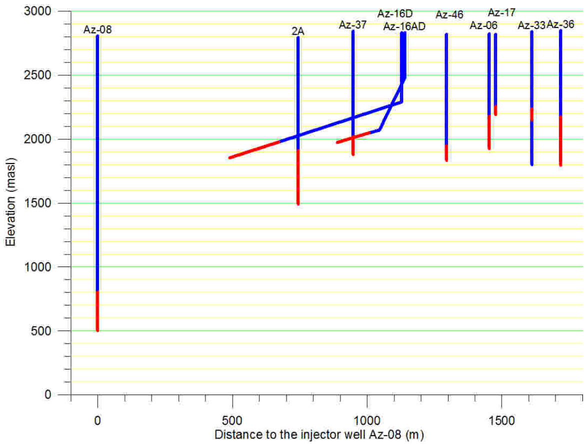

Figure 2: Spatial relations between the wells, slotted liners in red.

Table 1. Wells, distances and production

Well	Distance to Az-08 (m)	Production (t/h)	
		Water	Steam
Az-16D	537.23	11	8.5
Az-2A	745.43	76	32
Az-16AD	891.97	0	19
Az-37	998.64	0	28
Az-46	1,295.08	1	45
Az-06	1,467.11	0	29
Az-17	1,489.41	0	35
Az-33	1,611.70	28	35
Az-36	1,735.34	1	20

To choose the appropriate tracers we considered the usual requirements: negligible concentration in the reservoir fluid, thermal and chemical stability at reservoir conditions, low detection limit, negligible risk to the environment, reasonably simple logistics, commercial availability and affordable price. One important particular constraint for our choice of tracers was reservoir temperature: in the area of interest it ranges 280- 300°C, at the deep, water-dominated zone, and is lower than that at lesser depths (R.M. Barragán, 2008, private communication).

Several authors (e.g., Adams, 1995; Adams et al., 2000; Rose et al., 2001; Rose et al., 2002; and others) researched liquid-phase geothermal tracers. Many of these tracers were found to be thermally unstable at 300°C, or only marginally stable at this temperature. Thus our choices were considerably reduced. We conservatively chose the ecologically benign compound 2,7-naphtalene disulfonate (2,7-nds) as our liquid-phase tracer, for its high thermal and chemical stability (e.g., Rose et al., 2001, 2002), low detection limit, commercial availability, affordability and simple field logistics. The detection limit of 2,7-naphtalene disulfonate is approximately 0.1 ppb by conventional high-performance liquid chromatography (e.g., Rose et al., 2001). Previously we had successfully used this tracer in the Los Humeros, Mexico geothermal field (Iglesias et al., 2007).

Steam-phase tracers were researched by several authors also (e.g., Adams, 1995; Adams et al. , 2000; Adams et al., 2001). Again, many of the tracers considered were found to be unstable or marginally stable at 300°C. We chose the non-toxic, non-flammable, non-corrosive gas SF_6 as our steam-phase tracer, for its thermal stability at high temperature, chemical stability at reservoir conditions, low detection limit, commercial availability, affordability and relatively simple field logistics. The detection limit of SF_6, referred to its condensed steam carrier, is about 0.02 parts per trillion (ppt), by gas chromatography with electron-capture detector. We had successfully used this tracer in Los Azufres (Iglesias and Torres, 2006; Iglesias et al., 2006a), in the Los Humeros (Iglesias et al., 2007) and in the Las Tres Virgenes (Iglesias et al., 2006b), Mexico, geothermal fields.

On June 24, 2008 we injected 200 kg of 2,7-nds and 99.3 kg of SF_6 in well Az-08. Sampling of the production wells started the same day, several hours later. For convenience, the nine production wells were sampled with diminishing frequency: twice a day during the first week, daily during the second week, three times a week during the following seven weeks, twice a week the next two weeks, and once a week thereafter.

Steam samples were collected in Giggenbach-type glass bottles, previously filled with 50 ml of a 4N NaOH solution, and then evacuated. Depending on the facilities of each particular well, samples were obtained directly from the steam line, or from the wellhead, in this case by means of a portable separator. Liquid samples were collected in 60 cc plastic bottles, from the waste water exit at the separator.

3. RESULTS AND DISCUSSION

In what follows we present our results for the monitored wells in order of increasing distance to the injector well. Steam sampling in wells Az-16D, Az-17, Az-33, Az-36 and Az-37 was discontinued on 15 January 2009 because by that time it seemed certain SF_6 had completed its arrival in those wells, and for economic reasons. Steam sampling continued in the rest of the wells to monitor possible late arrivals of the tracer.

Well Az-16D is the closest to Az-08 (Table 1). Figure 3 presents the residence and recovery curves of 2,7-dsn for this well. Within 95 days from injection of the tracer the residence curve reveals a number of narrow peaks with significant maximum concentrations. We interpret these peaks as reflecting the existence of a similar number of pathways for liquid flow between the injector and production well. This is consistent with the known fractured nature of the reservoir. After this set of early narrow peaks appears a long hiatus, of about 120 days, in which no tracer return was recorded. This is followed by the onset of a much wider peak, which was still growing at the time of this writing. Considering its late arrival and wide width this peak probably results from a pathway that is much longer than the pathways associated with the early narrow peaks. So far, 302 days after injection of the tracers, the recovery of 2,7-nds in this well amounts to 1.93×10^{-2} %. Based on the recorded tendency of the late wide peak one expects that figure will be significantly surpassed in the end.

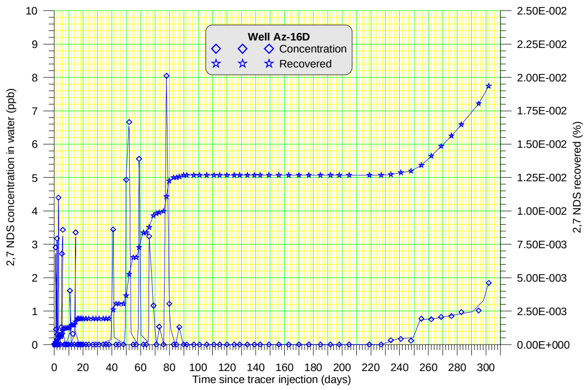

Figure 3: Residence and recovery curves of 2,7-nds in Az-16D

Figure 4 presents the residence and recovery curves of the steam-phase tracer for well Az-16D. Like for the liquid-phase tracer in this well, a set of early narrow peaks was recorded. The tracer completed its arrival 30 days after its injection (Fig. 4). No apparent temporal correlation seems to exist between the residence curves of SF_6 and 2,7-nds for this well. The final recovery of SF_6 in it was $1.5x10^{-6}$ %. Well Az-08 intercepts the Tejamaniles fault while this well seems to intercept the Tejamaniles and El Viejon faults (Fig. 1); we speculate that one or both of these faults provide the hydraulic connection between these wells.

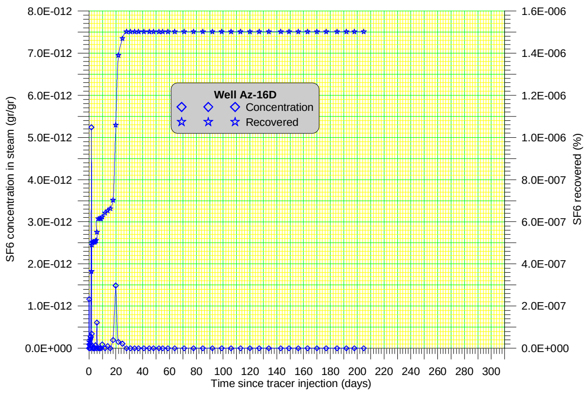

Figure 4: Residence and recovery curves of SF6 in Az-16D

Well Az-2A is next in distance to Az-08 (Table 1). It presented a very strong return of 2,7-nds, characterized by a very wide peak in its residence curve (Fig. 5). We interpret the peaks and bumps displayed by the concentration curve, as reflecting the existence of a number of pathways, of different characteristics, for liquid flow between Az-08 and Az-2A. This is consistent with the well-known fractured nature of the Los Azufres reservoir. So far, slightly more than 2.17 % of the injected 2,7-nds has been recovered in this well (Fig. 5). Note that the concentration of the liquid-phase tracer was still increasing strongly at the time of this writing. This, and the form of the residence curve suggests the width of the wide peak will increase considerably, and that therefore significantly more tracer will be recovered in the end.

Figure 6 presents the residence and recovery curves of the steam-phase tracer for Az-2A. No apparent correlation seems to exist between the residence curves of SF_6 and 2,7-nds for this well. The arrival of SF_6 has been completed in this well, as revealed by the long horizontal expanse in the tail of its recovery curve. The final recovery of SF_6 recorded in this well was $1.79x10^{-2}$ %. This well intercepts the El Viejon fault, suggesting its connection with Az-08 is via the Tejamaniles-El Viejon faults (Fig. 2).

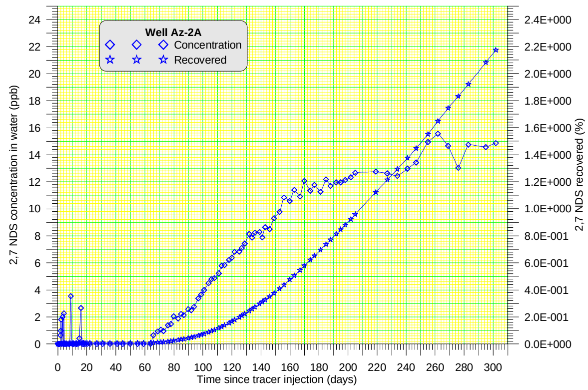

Figure 5: Residence and recovery curves of 2,7-nds in Az-2A

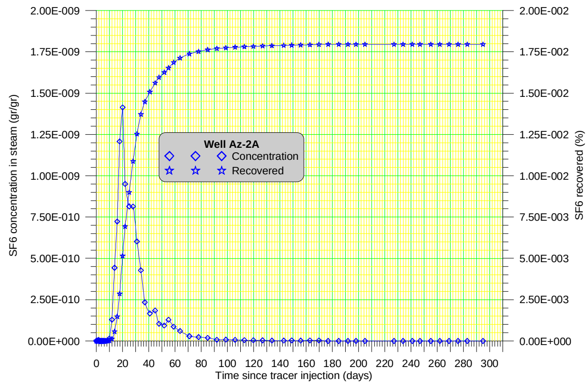

Figure 6: Residence and recovery curves of SF6 in Az-2A

Third in order of distance to the injector well is Az-16AD (Table 1). This well produces only steam, thus only steam-phase tracer results exist for it. Its residence and recovery curves are presented in Fig. 7. Unlike Az-16 and Az-2A this well kept receiving SF_6 for 239 days, much longer than recorded in the former wells. The final recovery for this well amounted to $8.57x10^{-4}$ %. These features could be associated with the fact that this well may have intercepted the Tejamaniles fault (Fig. 1), the same fault intercepted by the injector well Az-08.

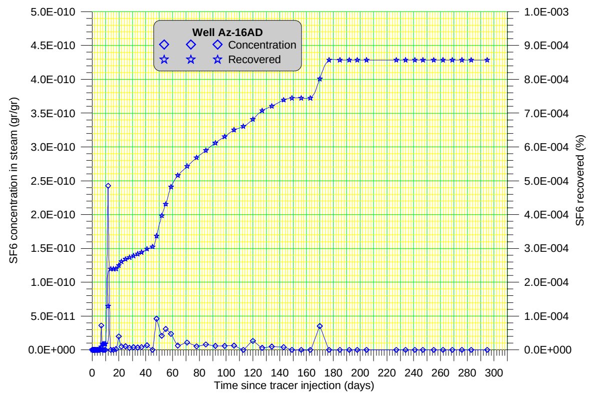

Figure 7: Residence and recovery curves of SF6 in Az-16AD

Well Az-37, fourth in order of distance to the injector, also produces only steam (Table 1). Its residence and recovery curves for the steam tracer are shown in Fig. 8. The last recorded arrival of SF_6 occurred 71 days after tracer injection. The final recovery for this well amounted to $3.28x10^{-4}$ %. This well intercepted the El Viejon fault. Therefore it may receive steam from injection in Az-08 via the Tejamaniles-El Viejon faults (Fig. 1).

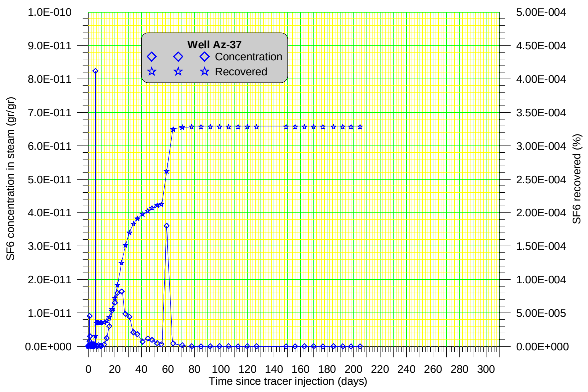

Figure 8: Residence and recovery curves of SF6 in Az-37

Next in order of distance is well Az-46; it produces water and steam (Table 1). Figure 9 presents its residence and recovery curves for the liquid-phase tracer. After recording five noticeable peaks of 2,7-nds, it stopped receiving this tracer 80 days after injection. Interestingly, much later, small concentrations of the tracer were recorded again (Fig. 9), similarly to what was recorded in wells Az-16D (Fig. 3), Az-33 (Fig. 13) and Az-36 (Fig. 15). So far, the 2,7-nds recovery in this well equals $3.14x10^{-4}$ %.

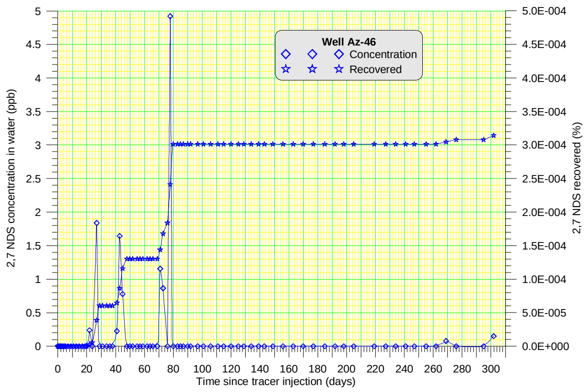

Figure 9: Residence and recovery curves od 2,7-nds in Az-46

Figure 10 shows the residence and recovery curves of the steam-phase tracer for well Az-46. The long tail of the recorded peak lasted at low concentrations until 149 days after injection. It is interesting to note that 295 days after tracer injection a small concentration of SF_6 was detected again in this well (Fig. 10). So far, SF_6 recovery in this well amounts to 2.12x10-3 %. This well, like the injector Az-08 intercepts the Tejamaniles fault (Fig. 1), which probably provides the hydraulic connection between them.

The next well in order of distance is Az-06; it also produces only steam (Table 1). Its residence and recovery curves for the steam tracer are shown in Fig. 11. Tracer recovery ended in this well 156 days after injection. Total SF_6 recovery in Az-06 equals $2.85x10^{-4}$ %. This well intersects the Los Azufres fault; thus Fig. 1 suggests its hydraulic connection with injector Az-08 is via the Tejamaniles-Agua Ceniza-Los Azufres faults.

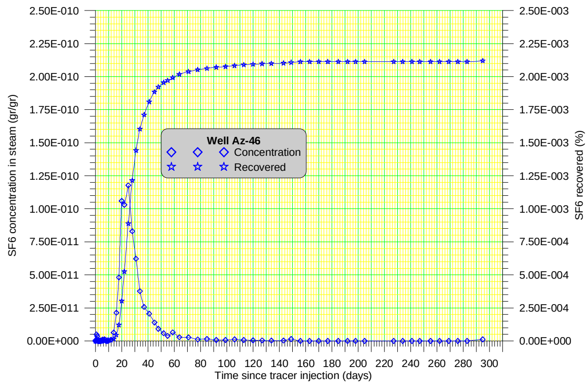

Figure 10: Residence and recovery curves of SF6 in Az-46

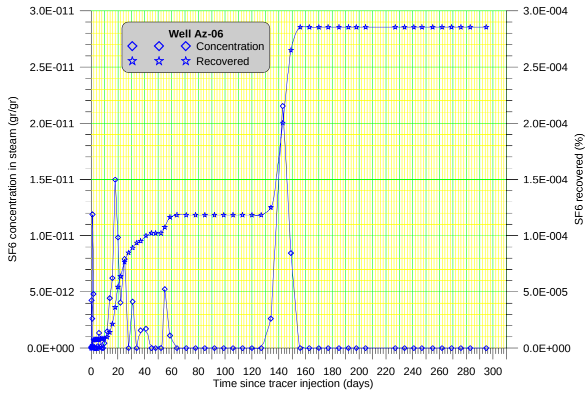

Figure 11: Residence and recovery curves of SF6 in Az-06

Well Az-17, next in distance, also produces only steam (Table 1). This is the shallowest well of the set (Fig. 2). Its residence and recovery curves for the steam tracer are shown in Fig. 12. It recorded SF_6 arrival only until 12 days after injection. Its total tracer recovery resulted $2.14x10^{-6}$ %. This well intercepts the Puentecillas fault (Fig. 1), suggesting its connection with Az-08 may be via the Tejamaniles-El Viejon-Puentecillas faults. Its shallow depth and the suggested convoluted connection with the injector may be related to the scarce recharge received by this well.

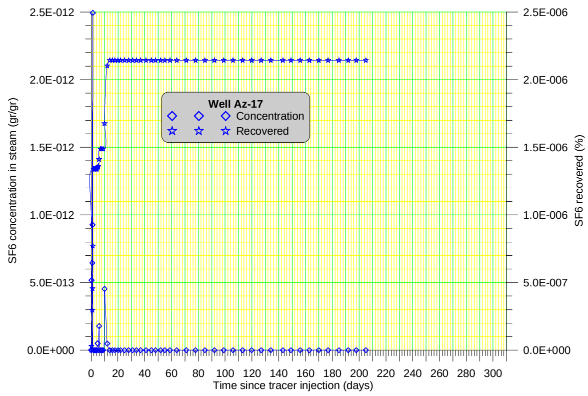

Figure 12: Residence and recovery curves of SF6 in AZ-17

Next in order of distance is well Az-33; it produces water and steam (Table 1). Figure 13 presents its residence and recovery curves for the liquid-phase tracer. It recorded five early narrow peaks in its residence curve in the 73 days following tracer injection. Then, after a long hiatus (182 days) a wide, low concentration peak was detected. So far 2,7-nds recovery equals 1.10×10^{-2} %.

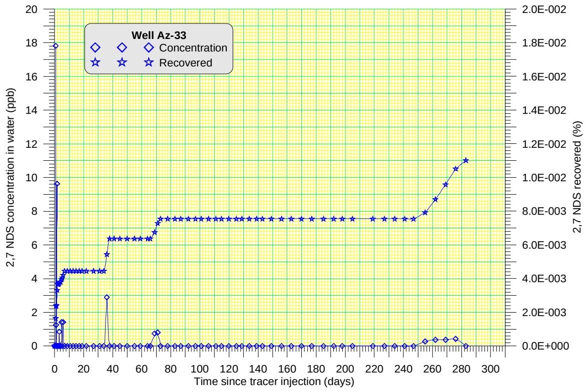

Figure 13: Residence and recovery curves of 2,7-nds in Az-33

Figure 14 shows the residence and recovery curves for the steam-phase tracer. This well received SF_6 in a series of narrow peaks that lasted 13 days after tracer injection. Its total recovery was 1.51×10^{-5} %. This well, like the injector Az-08 intercepts the Tejamaniles fault (Fig. 1), which probably provides the hydraulic connection between them.

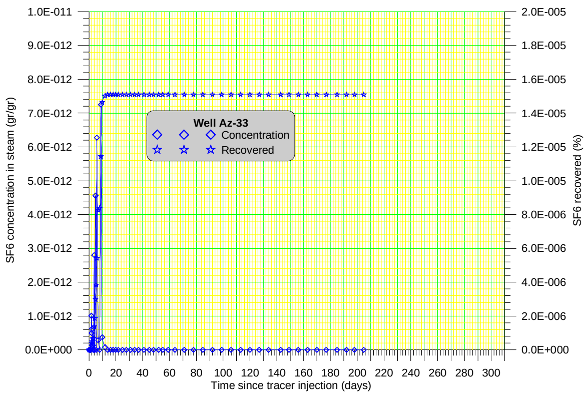

Figure 14: Residence and recovery curves of SF6 in Az-33

Well Az-36 is farthest from the injector; it produces water and steam (Table 1). Figure 15 presents its residence and recovery curves for the liquid-phase tracer. It recorded a series of narrow peaks in its residence curve in the 90 days following tracer injection. Then, after a long hiatus (193 days) a low-concentration detection was made again. So far the total recovery of 2,7-nds in this well was 1.78×10^{-3} %.

Figure 16 depicts the residence and recovery curves for the steam-phase tracer. As in wells Az-17 and Az-33, a series of narrow peaks of SF_6 were recorded within a relatively short period of, in this case, 14 days. Total recovery was 2.93×10^{-6} %. This well intercepts the Puentecillas fault (Fig. 1), suggesting its connection with Az-08 may be via the Tejamaniles-El Viejon-Puentecillas faults.

Our results demonstrated that the nine well producers monitored during this study are recharged from injection of cool brine in well Az-08. In Table 2 we have summarized the recovery results and the aggregated recovery for each tracer, so far. As indicated by the corresponding figures just presented, at the time of this writing the steam tracer seems to have essentially completed its arrival at the monitored production wells, but the liquid tracer had not yet completed its arrival to them. Therefore, the aggregated recoveries (Table 2) demonstrate that recharge by liquid is at least two orders of magnitude greater than recharge by steam in the nine monitored wells.

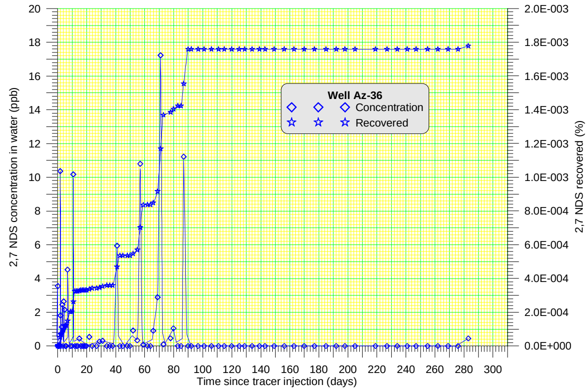

Figure 15: Residence and recovery curves of 2,7-nds in Az-36

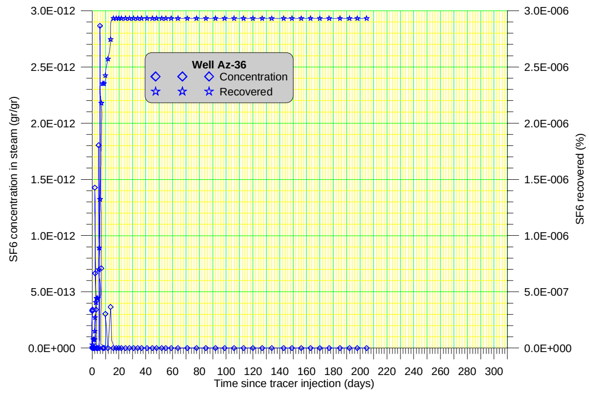

Figure 16: Residence and recovery curves of SF6 in Az-36

Table 2. Tracer recovery

Well	Tracer recovery (%)	
	2,7-nds	SF6
Az-16D	1.93E-02	1.50E-06
Az-2A	2.17E+00	1.79E-02
Az-16AD		8.57E-04
Az-37		3.28E-04
Az-46	3.14E-04	2.12E-03
Az-06		2.85E-04
Az-17		2.14E-06
Az-33	1.10E-02	1.51E-05
Az-36	1.78E-03	2.93E-06
Total	2.21E+00	2.16E-02

Well Az-2A presents the highest recovery of both tracers, by far (Table 2). This is probably related to its proximity to the injector well (745 m); to its relatively high mass flowrate, the highest by far of all nine wells (Table 1); and to the fact that the vertical distance of its producing interval to the injection interval of Az-08 is the shortest of the set (Fig. 2).

Considering that the top of the injection interval in Az-08 is 700 m below the bottom of the production interval of Az-02, the deepest production well monitored, and at least 1,000 m below the bottoms of the production intervals of the rest of the monitored wells (Fig. 2), our results reveal upflow (and implied vertical permeability) of steam and water over the vertical distances just mentioned. This upflow implies (i) cool injectate is heated enough at depth to convect upwards, thus preventing or at least retarding thermal interference; and (ii) injectate boils at depth generating steam upflow. This provides useful insights on reservoir properties (e.g., temperature, vertical permeability, two-phase conditions) at depth and on the circulation of the injected fluids.

As shown in the corresponding figures above, the residence curves of both tracers present series of peaks. We interpret this as reflecting the fractured nature of the reservoir.

3.1 Effects of Distance between Injection and Production Intervals

We investigated the effect of horizontal distance to the injector well on recovery of SF_6 and found there is a relatively strong correlation, with R = -0.827083, as indicated in Fig. 17. There is a nice exponential fit to the data, as indicated by the 95% confidence interval shown in this figure. This correlation does not include well Az-16D, because it does not follow the general trend. We concluded that, for the wells studied, with the exception of Az-16, steam derived from injection at Az-08 tends to decrease exponentially with increasing horizontal distance to the injector.

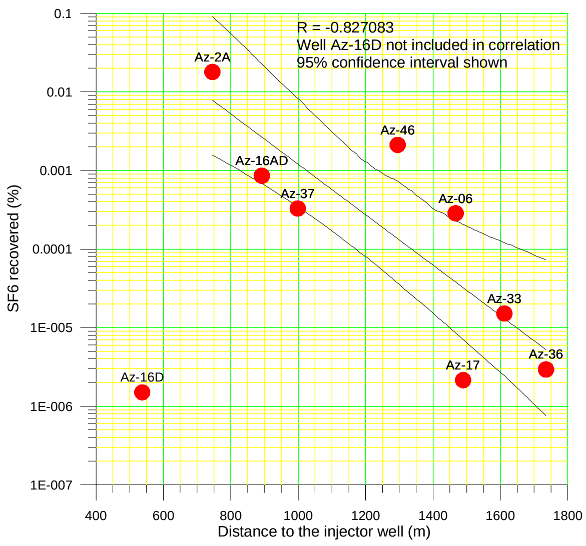

Figure 17: Correlation SF6 recovery vs. horizontal distance

We also investigated the effect of vertical distance from the injection interval to the production intervals, represented by the corresponding mid-point elevations, on the recovery of SF_6. We found a stronger correlation, with R = -0.960537. There is a good exponential fit to the data, as indicated by the 95% confidence interval shown in this figure. As stated in Fig. 18 this correlation does not include wells Az-16D and Az-36, because they do not follow the general trend. We concluded that vertical distance from the injection interval to the production intervals tend to strongly affect recovery of steam derived from injection in Az-08. Therefore we conclude that, for the studied wells, with the noted exceptions, steam recovery from injection at Az-08 generally tends to decrease exponentially with increasing vertical distance.

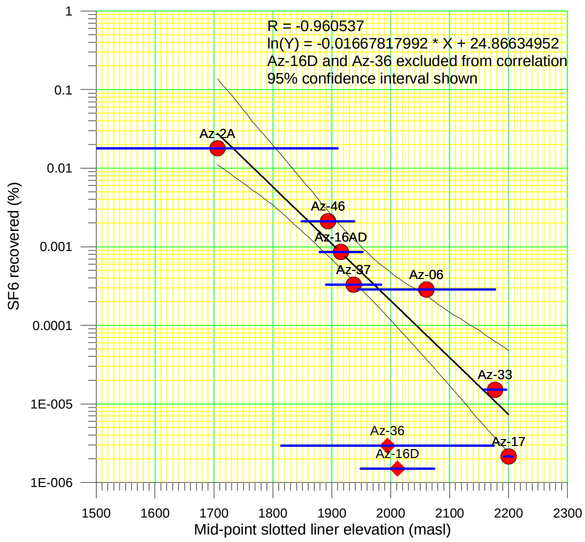

Figure 18: Correlation SF6 recovery vs. vertical distance. Slotted liners indicated in blue

Similar investigations were not attempted for 2,7-nds recovery at this time because the liquid tracer recovery was not completed. Under these conditions no reliable conclusions regarding the influence of horizontal or vertical distance between the injection interval and the production intervals could be inferred from the data.

4. SUMMARY AND CONCLUSIONS

All nine monitored production wells detected the steam-phase tracer, and the five wells that produce water and steam detected the liquid-phase tracer. Our results demonstrated that the feeding areas of the nine monitored wells are recharged from the injector Az-08. For both tracers, all residence curves present series of peaks, which we interpret as reflecting the fractured nature of the reservoir. For every studied well we suggested likely hydraulic connections with the injector well via faults or combinations of faults.

At the time of this writing, 302 days after the injection, the steam tracer seems to have completed its arrival at the monitored production wells. But the liquid tracer had not yet completed its arrival to them; recovery was still increasing strongly in well Az-2A. Furthermore, the rest of the water-producing wells were still recording arrival of 2,7-nds.

The aggregated recoveries in the nine wells are 2.21% for the liquid-phase tracer and 0.0216% for the steam-phase tracer. This implies modest recharge from Az-08, so far. A significantly higher final recovery of liquid tracer is to be expected, as indicated by the data at 302 days after injection.

Well Az-2A presents the highest recovery of both tracers, by far. This is probably related to its proximity to the injector well (745 m); to its relatively high mass flowrate, the highest by far of all nine wells; and to the fact that the vertical distance of its producing interval to the injection interval of Az-08 is the shortest of the set.

Considering that the top of the injection interval in Az-08 is 700 m below the bottom of the production interval of Az-02, the deepest production well monitored, and at least 1,000 m below the bottoms of the production intervals of the rest of the monitored wells, our results reveal upflow (and the implied vertical permeability) of steam and water over the vertical distances just mentioned. This upflow implies (i) cool injectate is heated enough at depth to convect upwards, thus preventing or at least retarding thermal interference; and (ii) injectate boils at depth generating steam upflow. This provides useful insights on reservoir properties (e.g., temperature, vertical permeability, two-phase conditions) at depth and on the circulation of the injected fluids.

We investigated the effect of horizontal distance to the injector well on recovery of SF_6. Excluding well Az-16D, which does not follow the general trend, there is a relatively strong correlation (R = -0.827083) between these variables. For the studied the wells, with the noted exception, steam derived from injection at Az-08 tends to decrease exponentially with increasing horizontal distance to the injector.

We also investigated the effect of vertical distance from the injection interval to the production intervals on recovery of SF_6. Excluding wells Az-16D and Az-36, which do not follow the general trend, there is a strong correlation (R = -0.960537) between these variables. For the rest of the wells steam recovery from injection at Az-08 generally tends to decrease exponentially with increasing vertical distance.

Similar investigations were not attempted for 2,7-nds recovery at this time because the liquid tracer recovery was not completed.

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