



## **GEOCHEMICAL RESERVOIR MONITORING – A CASE STUDY OF OLKARIA NORTHEAST FIELD IN KENYA**

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### **ABSTRACT**

The results of the geochemical bi-annual reservoir-monitoring program, of the Olkaria Northeast Field (ONEF) for the second half of 2007 are presented. The chemical changes in the reservoir have been evaluated in terms of the changes in the concentration of total discharge chloride, silica, sulphate, discharge enthalpy, calculated geo-thermometer temperatures and the variations in the gas composition of the discharge fluids.

The regions of high chloride concentration are around wells OW-714 and OW-716 to the east, OW-709 and OW-727 to the west and OW-726 at the center of the Olkaria Northeast field. The three regions indicate upflow zones within the field. The area in the vicinity of wells OW-R2, OW-710, OW-711 and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field. Recharge from the Ol Olbutot fault may be encroaching the reservoir around well OW-711. This will be confirmed in the next monitoring periods.

The Na/K geothermometer temperature distribution in 2nd half of 2007, indicate three low temperature (less than 250°C) centers around wells OW-708, OW-720 and OW-724. The rest of the area lies between 270 and 340°C. The probable cause of heating around the wells to the southwest is boiling while the increase around well OW-727 may in addition, be due to incursion of separated re-injection fluids. The CO<sub>2</sub> geothermometer temperature mark out wells that have received the separated reinjected fluid from wells OW-720 through OW-728 to well OW-714 & OW-716 in a NE-SW elongated structure.

### **1. INTRODUCTION**

The Olkaria Northeast Field (ONEF) has been under steam exploitation since October 2003. Thirty-two (32) wells have been drilled and twenty (20) of them connected to the steam gathering system in this field (Figure 1). Six (6) wells (OW-709, OW-710, OW-712, OW-713, OW-718, and OW-721), have individual separators, while the other fourteen wells have combined separators (OW-701 & OW-727, OW-705 & OW-725, OW-706 & OW-711, OW-707 & OW-715, OW-714 & OW-716, OW-719 & OW-726, OW-720 & OW-728). Six are re-injection wells (OW-R2, OW-R3, OW-703, OW-708, OW-201 and OW-204) while the other six, (OW-702D, OW-704, OW-717, OW-722, OW-723, and OW-724) are non-producers. Hot brine from the separator stations is re-injected in wells OW-R2, OW-R3,

OW-703, and OW-708. Cooling tower blowdown is injected in either OW-201 or OW-204 (currently in OW-201).

Monitoring is done in wells that are delivering steam to the power plant. At any one time, some productive wells may be shut-in or may not be monitored due to various reasons e.g. low steam demand due to machine outage. During this monitoring period the wells monitored were OW-701, OW-705, OW-706, OW-709, OW-713, OW-714, OW-715, OW-716, OW-720, OW-721, OW-725, OW-726, and OW-728.

The main objective of the steam field monitoring is to observe important changes that take place in the reservoir, which could lead to future development shortfalls. Such conditions are easily observed in advance by use of careful chemical, thermodynamic and output monitoring program. Undesirable conditions include, decrease in reservoir temperature and pressure by incursion of cold water from the periphery, which could lead to reduction in well discharge enthalpy and output resulting in decline in generating capacity. Positive changes can suggest enhanced field development and these include increase in well output as a result of wells clearing up as well as incursion of hotter fluids as a result of pressure drawdown and positive effects of re-injection which may finally lead to generation expansion.

Chemical changes in a geothermal fluid like changes in solute and gases concentration will manifest way ahead of any physical change and would give a suitable time interval for remedial action to be taken. The concentrations of various chemical constituents in both water and steam discharged from geothermal wells provide valuable quantitative information about reservoir condition and changes in response to steam exploitation. Field monitoring is therefore important in order to follow the changes and processes that influence fluid composition and thermodynamics during exploitation of the field. It also assists with calibration of the reservoir model as trends in physical and chemical parameters change.

This report presents the status on steam production and field chemistry in Olkaria Northeast Field (ONEF) for the second half of 2007.

## 2. GEOCHEMICAL CHANGES IN WELL CHARACTERISTICS

### 2.1 Monitoring procedures

During the current monitoring period, water and steam chemical data were collected from the well discharge. Water samples were collected from the weir box except for wells that share a common separator station whose water was collected using a Webre separator. Gas samples were collected from the steam line after the well cyclone separator.

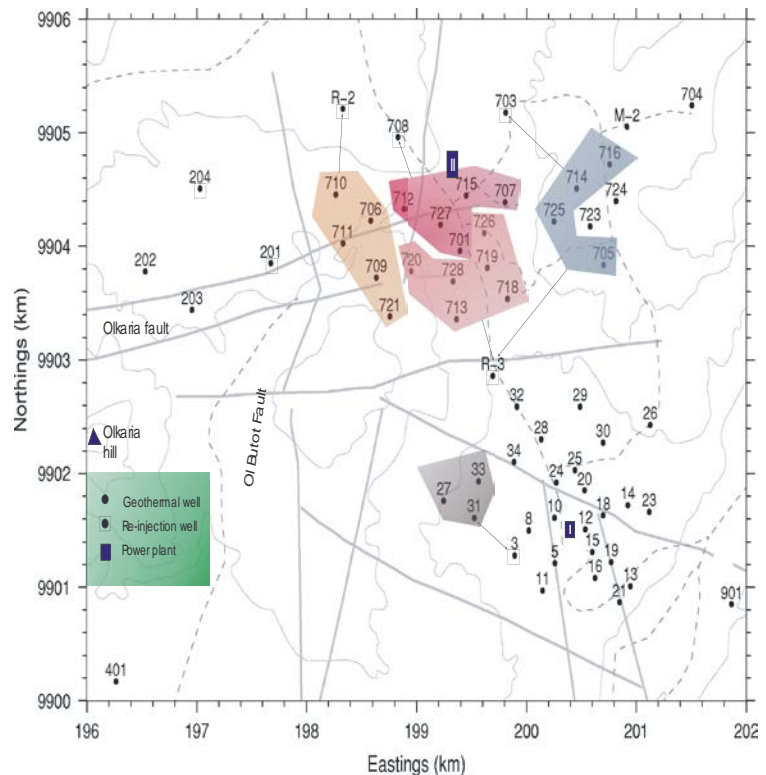


Figure 1: Well locations in Olkaria East and Northeast fields. The shaded areas show wells connected to the same re-injection well

The water samples were analysed for pH, silica, boron, sodium, potassium lithium, calcium, magnesium, carbon dioxide, sulphate, hydrogen sulphide, chloride, fluoride, total dissolved solids, and electrical conductivity. The steam samples were analysed for carbon dioxide, hydrogen sulphide, hydrogen, methane, nitrogen and oxygen gases. Some wells were not monitored, as they were not connected to the production system during the second half of 2007 due to various reasons.

## 2.2 Chemical analytical results

Results of chemical analysis for well discharge fluids for the wells monitored during this period and the previous period are presented in Table 2. Calculated solute geothermometry temperatures used here are from Fournier and Potter (1982) for quartz and Arnórsson et al. (2000) for sodium-potassium. The gas geothermometry temperatures used here are those derived from the functions of Arnórsson and Gunnlaugson (1985). The analysed data have been re-calculated to 10 bar absolute vapour pressure to remove the effects of “excess” enthalpy due to phase separation on the initiation of boiling and aid in interpretation of fluid patterns and processes that prevail in the reservoir. Solute concentration is expressed in ppm while the concentration of gases is expressed in mmol/100 moles of steam.

## 3. WELL MONITORING RESULTS AND DISCUSSIONS

### 3.1 Geochemical monitoring

The monitoring of the wells in the producing field of Olkaria Northeast was done in the months of July to December 2007. The parameters used in the assessment of changes in the reservoir are those thought to provide significant indication of processes such as boiling, mixing and phase separation that influence fluid composition as fluids are discharged to the surface from the wells. These parameters include derived solute and gas geothermometry temperatures, gaseous concentrations of carbon dioxide, hydrogen sulphide, hydrogen and nitrogen in the steam. Others include solute concentrations of silica, sulphate, chloride and the enthalpy of the well discharge.

Water and steam samples were collected at different pressures. The water samples were collected from the weir-box and the steam samples at elevated pressures. For the purposes of interpretation of the chemical analytical data all the component concentrations were recalculated to the same pressure (10 bars absolute vapour pressure) with the assistance of WATCH, a chemical speciation programme developed by Arnórsson et al, 1983; Bjarnason, 1994). Table 2 compares derived chemical analysis results of the two most recent monitoring periods.

#### 3.1.1 Well OW-701

Well OW-701 (Figure 1) shares a common separator station with well OW-727. Sulphate levels for well OW-701 increased from 11.2 ppm to 15.9 ppm, whereas the chloride levels increased from 842 ppm to 875 ppm. Minor increase in chloride concentration during this monitoring period would indicate a possible mild mixing of reservoir fluids with reinjected separated brine from well OW-708. The solute and gas geothermometers have been erratic but generally constant. In the last monitoring period, the solute geothermometer temperatures were 233°C and 279°C for quartz and Na/K geothermometers respectively. These temperatures are comparable to the computed gases geothermometer values of 260°C, 278°C, and 286°C from T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> respectively. The temperature values are close to the previous monitoring values. This implies that the well discharges fluid from one dominant feeder zone whose fluid has attained equilibrium.

#### 3.1.2 Well OW-705

Well OW-705 was drilled to a depth of 2006 meters as an exploration well. The well shares a steam separator with well OW-725. The chloride concentration moderately reduced from 634 ppm to 579 ppm

while sulphate concentration reduced from 27.5 ppm to 10.1 ppm. The K-Na geothermometer increased by 11°C from 253°C to 264°C, which corresponds to a similar increase in T H<sub>2</sub>S and T H<sub>2</sub> gas geothermometers. This implies that the well was discharging fluid from a deeper part of the reservoir as shown by the huge reduction of Total Discharge carbon dioxide from 3294 ppm to 2002 ppm.

TABLE 2: Derived Chemical analytical results for wells monitored in first half 2007 and second half 2007

Well no.	Cl (ppm)		T Na/K		T H <sub>2</sub>		Remarks
	Second half 2007	First-half 2007	Second half 2007	First half 2007	Second half 2007	First half 2007	
OW-701	875	842	279	273	286	279	
OW-705	579	634	253	253	285	280	
OW-706	639	760	289	312	285	282	
OW-707	492	492	264	264	264	264	Assumed
OW-709	971	950	315	342	291	294	
OW-710	368	368	300	300	269	269	Assumed
OW-711	391	391	294	294	279	279	Assumed
OW-712	970	970	291	291	276	276	Assumed
OW-713	642	587	282	289	270	290	
OW-714	929	720	277	314	291	290	
OW-715	759	854	298	344	275	282	
OW-716	1091	737	288	309	293	285	
OW-718	381	381	256	256	277	277	Assumed
OW-719	357	357	273	273	271	271	Assumed
OW-720	485	630	239	257	296	292	
OW-721	546	433	268	288	285	281	
OW-725	663	615	257	270	287	280	
OW-726	877	883	288	302	276	263	
OW-727	837	890	292	303	291	291	Assumed
OW-728	780	808	285	297	291	290	

Note: In the remarks column, the well with the remark “Assumed” implies that the well was not monitored in the last monitoring period and therefore the respective values have been assumed constant.

### 3.1.3 Well OW-706

This well is located to the western sector of Olkaria Northeast borefield (Figure 1). It was drilled to 2099 m depth. The total discharge chloride reduced in the 2<sup>nd</sup> half of 2007 from 760 ppm to 639 ppm while the total discharge carbon dioxide reduced from 2672 ppm to 1994 ppm, which is close to the 1988 values. This implies that the well has not stabilized since it was opened in 2003. This will be confirmed in the next monitoring period. The chloride concentration reduced to the 2<sup>nd</sup> half of 2005 values of 669 ppm. The alternative explanation is that the well is receiving less mineralized recharge fluid.

The Na/K geothermometer, indicate a decrease in reservoir temperature from 312°C to 289°C, a decrease of 23°C. The gas geothermometry temperature functions of TCO<sub>2</sub> and T H<sub>2</sub>S are comparable to the T H<sub>2</sub> over the monitoring period. The temperatures values are 259°C, 284°C, and 285°C for T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> respectively. The inconsistent temperature values indicate that the reservoir fluid is mixing with re-injected fluid at depth, and hence creating a state of in-situ re-equilibration.

### 3.1.4 Well OW-707

Wells OW-707 is located in the eastern part of the field (Figure 1), it was drilled to 1802 m. Well OW-707 share a common cyclone separator station with well OW-715. During the 2<sup>nd</sup> half of 2007 monitoring period the well was shut-in.

### 3.1.5 Well OW-709

Well OW-709 is located in the western sector of the well field (Figure1). The well has an individual separator station. Total Discharge Chloride, silica, sulphate and enthalpy have been cyclic and erratic over time. The cyclic nature of the well discharge is mainly due to the well discharging from multiple feeder zones.

The Na/K ratio geothermometer decreased from 342°C, to 315°C, during the 2<sup>nd</sup> half of 2007 monitoring period. This could suggest that the well was drawing fluids from an aquifer, which is undergoing cooling. The gas geothermometers exhibit a similar pattern, with temperature values of 259°C, 281°C, and 291°C for T CO<sub>2</sub>, T H<sub>2</sub>S, and TH<sub>2</sub> respectively.

### 3.1.6 Well OW-710

Well OW-710 lies on the edge of the Olkaria Northeast field to the Northwest. The well was drilled to 1801 m deep. This well has an individual separator due to the cyclic nature of the well discharge. The well was shut-in during the last five monitoring periods.

### 3.1.7 Well OW-711

Well OW-711 lies to the western part of the Olkaria Northeast Field. The well was drilled to 1807 m and shares a common separator with well OW-706. The flow pattern in this well showed cyclic behavior and thence the fluids sampled may not be representative of the deep fluid. The well was shut-in during the monitoring period of 2<sup>nd</sup> half 2007.

### 3.1.8 Well OW-712

Well OW-712 is located to the West of Olkaria II power plant. The well has been stable in its production. The well was shut-in during the last monitoring period.

### 3.1.9 Well OW-713

Well OW-713 is located to the south of Olkaria Northeast borefield. The well has an individual cyclone separator and has been fitted with a motorized valve for steam regulation in the field hence it is mostly throttled (Mwawongo, 2005).

Chloride concentration in this well increased from 587 ppm to 642 ppm. The chloride concentration variation is erratic just like the well discharge. This implies the well has multiple feeder zones flowing into the well bore.

The gas concentrations show erratic changes over most of the production period. In the period between 1<sup>st</sup> half 2007 and 2<sup>nd</sup> half 2007, there was a increase in the total discharge carbon dioxide gas concentration from 1277 ppm to 7799 ppm. Hydrogen sulphide reduced from 46 ppm to 36 ppm implying that the well is discharging fluid that is mixed from multiple feeder zones.

Both solute and gas geothermometry temperatures could be used to infer other processes that could be at play in the reservoir near this well. Over most of the production period, the quartz equilibrium temperatures have been lower than the Na/K temperature. In 2<sup>nd</sup> half of 2007 the Na/K temperature

reduced from 289°C to 282°C. This implies dilution of aquifer fluid by less mineralized fluid. The gas equilibrium geothermometers indicate variable temperature values of 263°C, 236°C, and 270°C for T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> respectively. This is a reduction of upto 20°C when compared with 1<sup>st</sup> half values for T H<sub>2</sub>S, and T H<sub>2</sub> of 274°C and 290°C respectively.

### 3.1.10 Well OW-714

Well OW-714 is located in the eastern part of the Olkaria Northeast field and it has the largest output. The well was drilled to 2502 m and shares a common separator with well OW-716. The total discharge chloride concentration increased from 720 ppm in the 1<sup>st</sup> half of 2007, to 929 ppm in the 2<sup>nd</sup> half of 2007. The erratic variation of the chemical constituents is a reflection of the reservoir processes that occur in the aquifers feeding the well.

Geothermometry temperatures show erratic values and stable values from solute and gas geothermometers respectively. Quartz temperatures could give the best indication of reservoir temperatures but are mostly affected by condensation and mixing. The quartz temperatures over most of the production period show lower temperatures than those of Na/K. Quartz also responds more quickly to re-equilibration than the Na/K temperatures. The Na/K geothermometer values decreased from 314°C to 277°C for the 2<sup>nd</sup> half of 2007. During the 2<sup>nd</sup> half monitoring period of 2007 the gas temperature geothermometers gave higher or lower values of 255°C, 299°C and 291°C for T CO<sub>2</sub>, T H<sub>2</sub>S and T H<sub>2</sub> respectively. The geothermometer temperatures showed almost similar temperatures, which would suggest a probable attainment of mineral equilibria. Increase in geothermometer temperature may indicate boiling in the aquifer.

### 3.1.11 Well OW-715

Well OW-715 is located to the south of the power plant (Figure 1). The well was drilled to 2003 m depth and shares a common separator with well OW-707. The chloride concentration decreased from 854 ppm in the 1<sup>st</sup> half of 2007 to 759 ppm in 2<sup>nd</sup> half of 2007. This implies that the well is discharging from one dominant aquifer, which is also receiving less mineralized fluid and hence the decrease in chloride concentration. The gas concentration of the well discharge during the monitoring period, show mild decrease in total discharge carbon dioxide gas from 1519 ppm to 1403 ppm.

The Na/K geothermometer temperature decreased from 344°C to 298°C over the same monitoring period. The gas equilibrium geothermometers indicate highly variant values, with temperature values of 260°C, 278°C and 275°C for T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> respectively. This is a reflection of the multiple feeders flowing into the well and hence the hybrid discharge obtained during sampling.

### 3.1.12 Well OW-716

Well OW-716 is located in the eastern sector of the Olkaria Northeast field. This well shares a cyclone separator with well OW-714. The well produces at a fairly stable steam and water flow rates. The chloride contents generally remained almost constant during the discharge tests. However, the concentration increased drastically in 2<sup>nd</sup> half of 2007 to 1091 ppm from 737 ppm obtained in 1<sup>st</sup> half of 2007. This implies that the aquifer around the well may be experiencing a recharge from a deeper more mineralized aquifer.

The solute geothermometers have decreased in this monitoring period from 309°C in 1<sup>st</sup> half of 2007 to 288°C in 2<sup>nd</sup> half of 2007 for the Na/K geothermometer. This is consistent with recharge of reservoir by deep aquifer fluid. The gas geothermometers TCO<sub>2</sub>, T H<sub>2</sub>S, T H<sub>2</sub> value are 256°C, 292°C, and 293°C respectively.

### 3.1.13 Well OW-718

Well OW-718 is located on the southeastern edge of the Olkaria Northeast field (Figure 1). The well has a cyclic pattern of flow and the samples taken from this well may not reflect the true composition of reservoir fluids. The well was shut-in during this monitoring period.

### 3.1.14 Well OW-719

Well OW-719 is located to the south of Olkaria II power plant along the same alignment as wells OW-718 and OW-717 as well as wells OW-713 and OW-728. This well shares the same separator with well OW-726 and has fairly steady output. The well was shut-in during this monitoring period.

### 3.1.15 Well OW-720

Well OW-720 is located in the western sector of Olkaria Northeast field. The well shares a common separator with well OW-728. The total discharge chloride concentration decreased from 630 ppm to 485 ppm while the total discharge Carbon dioxide concentration increased from 698 ppm to 699 ppm in the 2<sup>nd</sup> half of 2007. However, hydrogen sulphide decreased from 118 ppm to 106 ppm. The increase or decrease from various chemical constituents, imply that the well is discharging fluid that is a hybrid of fluid from multiple feeders.

The Na/K geothermometer temperature decreased from 257°C to 239°C in the 2<sup>nd</sup> half of 2007. This is consistent with a well discharging fluid from multiple feeder zones. The gas geothermometers TCO<sub>2</sub>, T H<sub>2</sub>S, T H<sub>2</sub> value are 254°C, 299°C, and 296°C respectively.

### 3.1.16 Well OW-721

Well OW-721 is located in the southwestern part of the Olkaria Northeast production field. The well was drilled to 2201 m. The total discharge chloride concentration show, an increase from 433 ppm in 1<sup>st</sup> half of 2007 to 546 ppm in 2<sup>nd</sup> half of 2007. The total discharge carbon dioxide increased from 406 ppm to 763 ppm during the monitoring period. The solute geothermometry temperatures of quartz and Na/K show an erratic variation in the last four monitoring periods. The Na/K geothermometer temperatures decreased from 288°C to 268°C, a reservoir temperature decline of 20°C. This implies that recharge fluid from the Ol Olbutot fault zone has started mixing with reservoir fluid flowing into the well. The gas geothermometers show higher or equal temperatures with T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> giving 258°C, 296°C and 285°C respectively.

### 3.1.17 Well OW-725

Well OW-725 is located in the eastern sector of Olkaria Northeast field and shares a common separator with well OW-705. The total discharge chloride concentration increased from 615 ppm to 663 ppm in the 2<sup>nd</sup> half of 2007. Total discharge carbon dioxide concentration shows an increase from 437 ppm to 1000 ppm. The other chemical species variation has been erratic. This implies that the well is drawing a more mineralized fluid, from another aquifer, which was not feeding the well before. This observation will be confirmed in the next monitoring period.

The solute geothermometry temperatures of Na/K show a reduction trend between 2<sup>nd</sup> half of 2006 and 2<sup>nd</sup> half of 2007. The temperature decreased from 276°C to 257°C between the three monitoring periods. The decrease in these geothermometry temperatures with corresponding chloride increase implies that mixing of reservoir fluids with cooler (150°C) re-injection fluid is taking place. Gas equilibration temperatures in the 2<sup>nd</sup> half of 2007 were erratic at 256°C for T CO<sub>2</sub>, and 297°C for T H<sub>2</sub>S, however, T H<sub>2</sub> increased from 280°C to 287°C. This implies moderate phase segregation within the aquifer close to the well.

### 3.1.18 Well OW-726

Well OW-726 is located in the center of the Northeast production Field (Figure 1) and shares a cyclone separator with well OW-719. The total discharge chloride concentration reduced from 883 ppm to 877 ppm in the 2<sup>nd</sup> half of 2007. This has been the trend since 2<sup>nd</sup> half of 2005 with a total discharge chloride concentration of 1005 ppm. However, total discharge carbon dioxide increased from 359 ppm in the 1<sup>st</sup> half of 2007 to 2290 ppm in the 2<sup>nd</sup> half of 2007. This implies that the well has been discharging from different feed zones whose chemistry is diverse. This fact is reflected in the erratic variation in the discharge enthalpy in addition to the solute geothermometers. The Na/K geothermometer decreased from 302°C to 288°C while the quartz geothermometer remained increased from 254°C to 271°C. The temperature shift between the two geothermometers is evidence to the hybrid nature of the fluids discharged by the well. The increase in quartz geothermometer may be due to boiling in the immediate area around the well such that the Na/K ratio still remained constant. The gas geothermometers show variable temperatures with T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> giving 262°C, 267°C and 276°C respectively for 2<sup>nd</sup> half of 2007 monitoring period. This implies that the well discharges fluid from different feeder zones, which have undergone diverse reservoir processes.

### 3.1.19 Well OW-727

Well OW-727 is located in the western sector of the Olkaria Northeast production field and shares a common separator with well OW-701. The chloride concentration has increased from 837 ppm to 890 ppm in 1<sup>st</sup> half of 2007. However, silica has declined from 543 ppm to 523 ppm. The quartz geothermometer reduced from 268°C to 263°C while the Na/K geothermometer increased from 292°C to 303°C. This implies that the well is discharging from more than one dominant feeder zone. The gas geothermometers show variable temperatures with T CO<sub>2</sub>, T H<sub>2</sub>S, and T H<sub>2</sub> giving 257°C, 291°C and 291°C respectively for 1<sup>st</sup> half of 2007 monitoring period. The well was not available for monitoring during the 2<sup>nd</sup> half of 2007.

### 3.1.20 Well OW-728

Well OW-728 is located in the western sector of the Olkaria Northeast production field. It shares a common separator with well OW-720. The chloride concentration decreased from 808 ppm to 780.5 ppm in the 2<sup>nd</sup> half of 2007. The total discharge concentration of hydrogen sulphide increased from 76.4 ppm to 113.5 ppm while carbon dioxide concentration decreased from 944 ppm to 821 ppm. However, other chemical constituents have erratic variation. This may suggest that the well discharges from multiple feeders in the aquifer. A similar behavior is observed in the case of the solute geothermometers, they reduced from 297°C to 285°C for Na/K geothermometer. The gas chemistry is erratic and no specific trends have been observed. The gas geothermometers (T CO<sub>2</sub> = 255°C, T H<sub>2</sub>S = 298°C) are lower or higher than the solute geothermometers including T H<sub>2</sub> whose temperature value of 291°C during the 2<sup>nd</sup> half of 2007.

## 3.2 Overall chemical changes

To evaluate the chemical changes that have occurred in the reservoir over a period of the last six months during geochemical monitoring, reservoir distribution plots of chemical constituents and geothermometry temperatures over the monitoring period of 2<sup>nd</sup> half of 2007 were made and compared with distribution plots of the previous monitoring period 1<sup>st</sup> half of 2007. These distribution plots are used to infer processes that influence fluid composition in the reservoir in response to production load. Overall total discharge chloride concentration distribution plot is illustrated in Figure 2 and Figure 3. The regions of high chloride concentration are around wells OW-714 and OW-726 to the east and OW-709, OW-727, to the west and OW-726 in the center. The three regions indicate upflow zones within the Olkaria Northeast field (Ofwona, 2002). The area in the vicinity of wells OW-R2, OW-710, OW-711, OW-718, and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field.



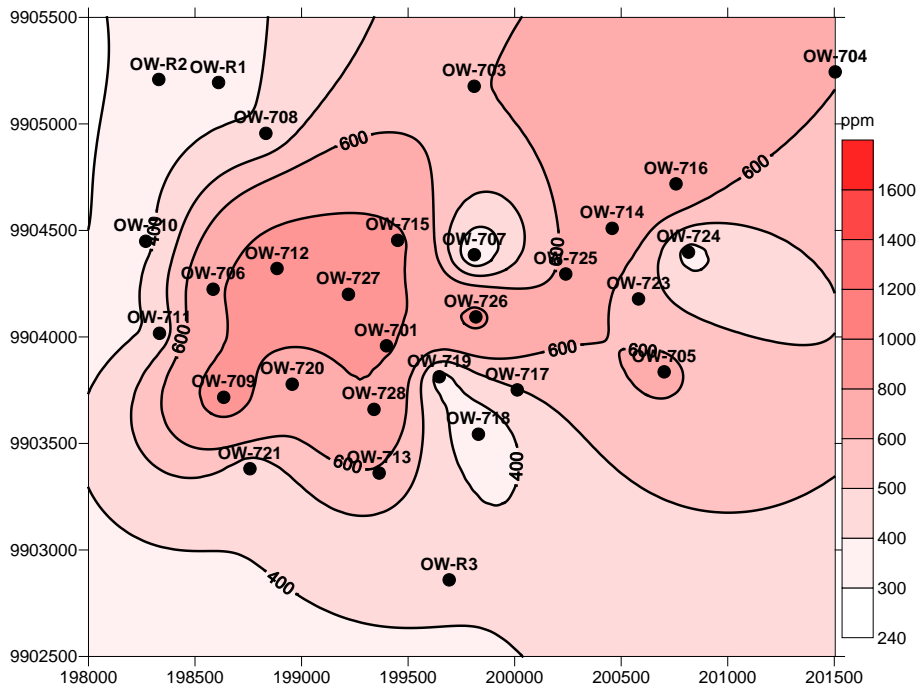


FIGURE 2: TD Chloride conc 1st half 2007 distribution plot

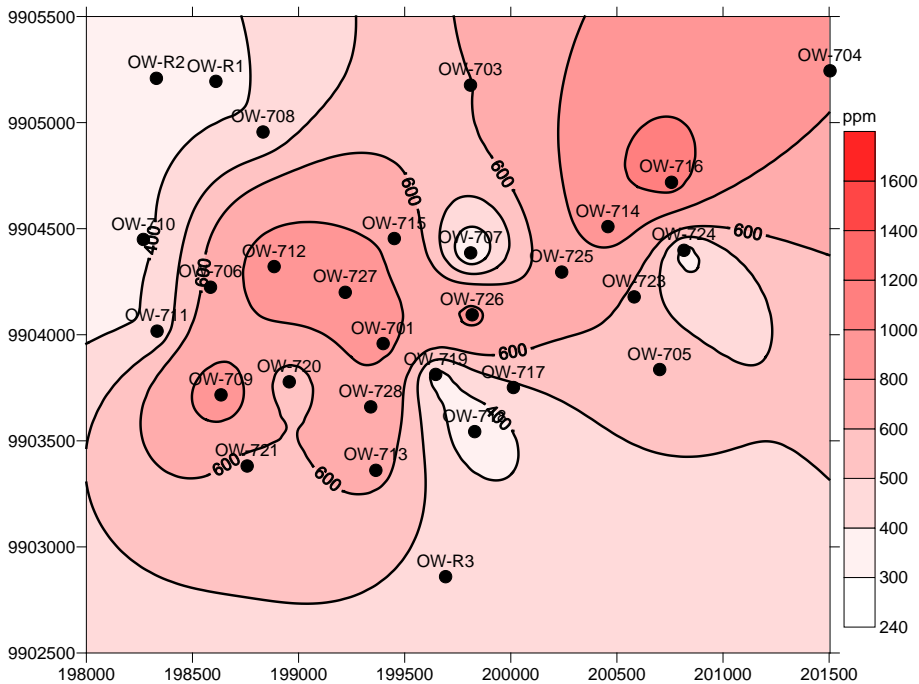


FIGURE 3: TD Chloride conc 2nd half 2007 distribution plot

Figure 4, 1<sup>st</sup> half 2007 total discharge carbon dioxide distribution plot indicate three high concentration centers around wells OW-706, OW-707, and the south east part of the field enclosed by the contour passing through wells OW-719, OW-717, OW-723, OW-724, OW-718 and OW-705 whose concentration is in excess of 1600 ppm. In the 2<sup>nd</sup> half of 2007, the distribution of the total discharge carbon dioxide changed significantly (Figure 5). The high concentration centers around wells OW-706 and OW-707 have reduced and the large southern front has shifted from the east around well OW-705 to the west around well OW-713. These centers are areas where re-injection fluid has mixed with the reservoir fluid and then discharged by the wells in the vicinity.

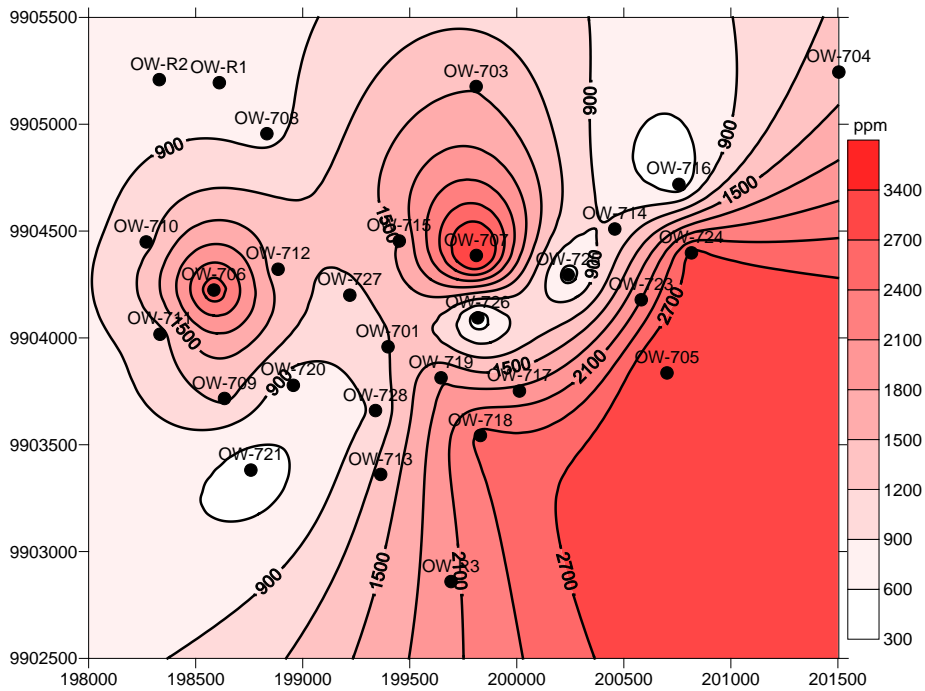


FIGURE 4: TD Carbon Dioxide conc 1st half 2007 distribution plot

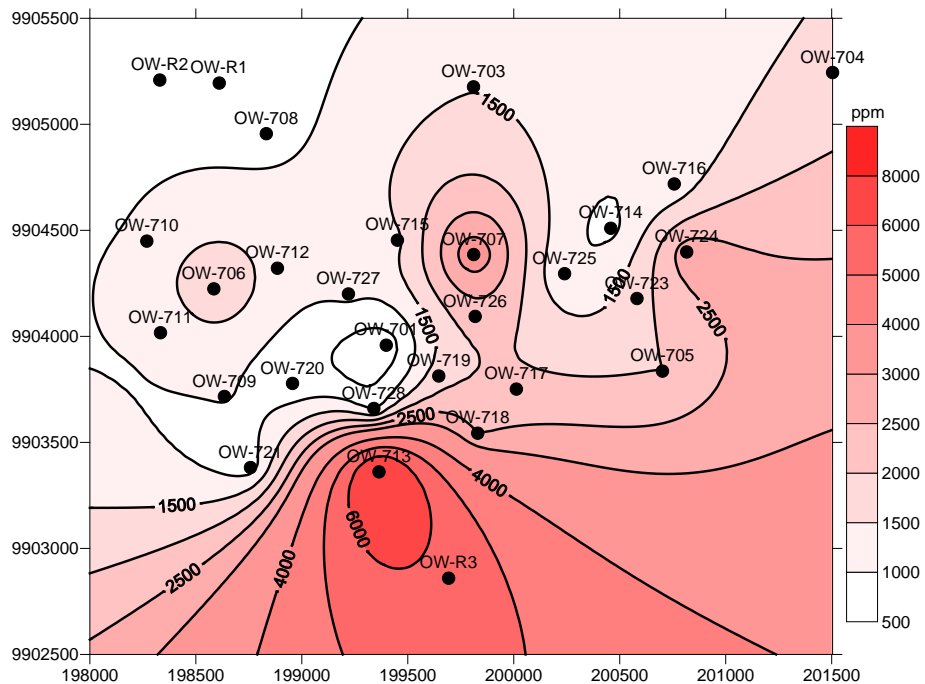


FIGURE 5: TD Carbon Dioxide conc 2nd half 2007 distribution plot

Figure 6, T Na/K temperature distribution plot 1<sup>st</sup> half of 2007, indicate two large high temperature zones; to the west around wells OW-709 & OW-706 and to the east around wells OW-714, OW-715, & OW-716. The plot in addition shows two low temperature (less than 265°C) centers, one around well OW-708, and the other near wells OW-705, OW-723 and OW-724. The rest of the area lies between 270 and 340°C. In the 2<sup>nd</sup> half of 2007 monitoring period, the cold center around well OW-708 has persisted and enjoined the region around well OW-720 (Figure 7). The other cold center around wells OW-723 and OW-724, has maintained the status quo. The area covered by the 280°C, contour line has

increased, which implies that the reservoir has cooled by about 20°C. The high temperature peaks around OW-701 and OW-713 have been eliminated. The probable cause of cooling around the wells may be due to the re-injected fluid entering the reservoir around wells OW-708 through OW-712 to well OW-720 zone. On the other hand the other wells within the Olkaria fault zone may be receiving cooler recharge fluids. This will be confirmed in the next monitoring period.

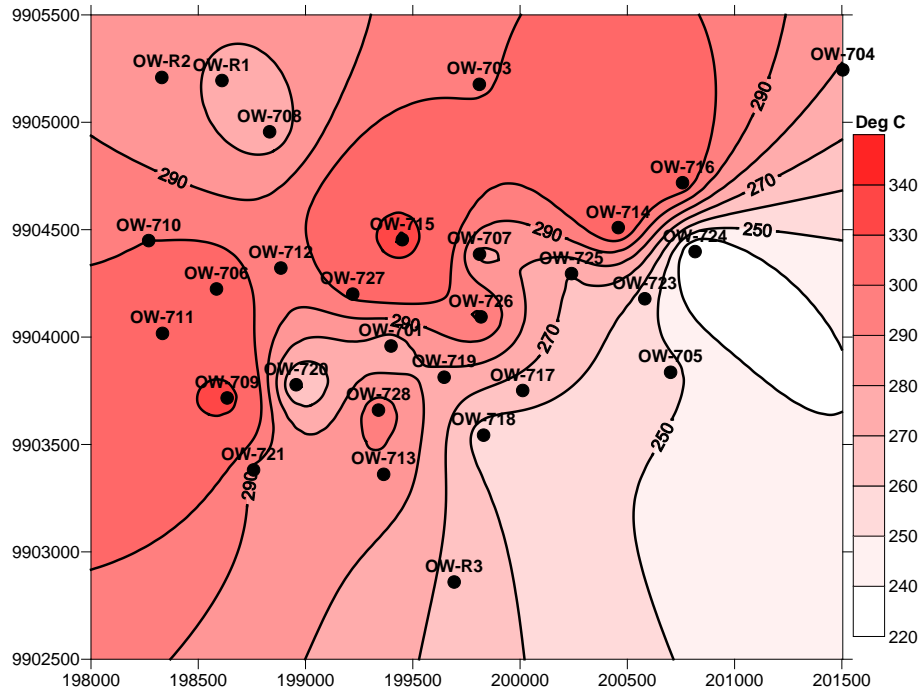


FIGURE 6: Na/K geothermometer temperature 1st half 2007 distribution plot

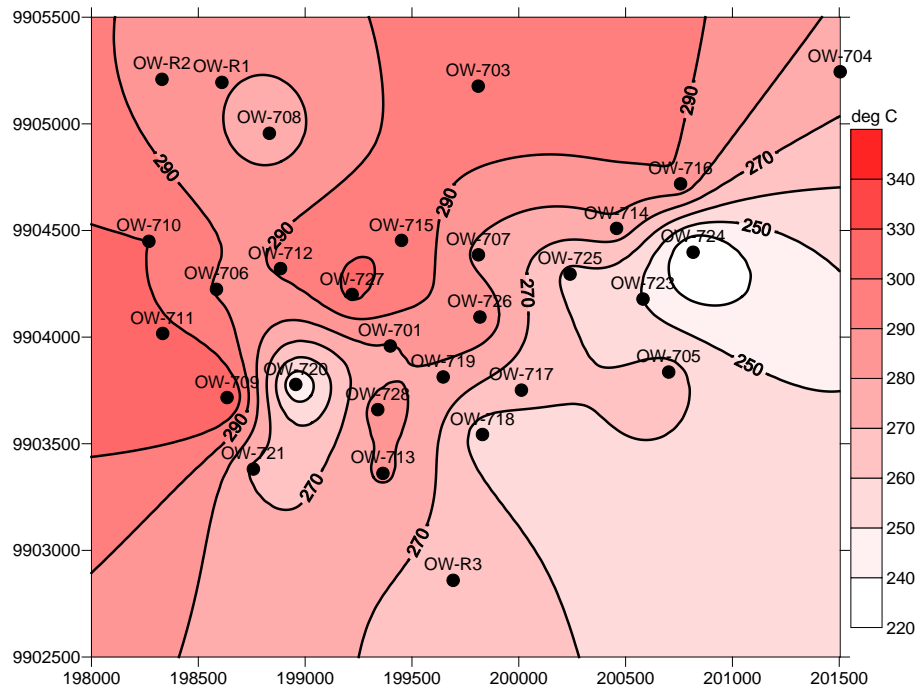


FIGURE 7: Na/K geothermometer temperature 2nd half 2007 distribution plot

In the 1<sup>st</sup> half of 2007 monitoring period, the hydrogen geothermometer temperatures Figure 8, are lower compared to the solute Na/K geothermometer values, Figure 6. In sharp contrast, the lowest temperature zone from the hydrogen geothermometer is around wells OW-707 and OW-726. Other low temperature centres can be observed around wells OW-710 and OW-R2. Two high temperature centres can be observed around wells OW-709 & OW-720 to the west and wells OW-714 & OW-716 to the east. Figure 9, hydrogen geothermometer 2<sup>nd</sup> half of 2007 temperature distribution plot, the area under the 280°C contour has reduced and a central zone of 270°C running from OW-R2 through OW-707 to OW-718 has emerged as distinct. The area under the 280°C contour indicates reservoir cooling to account for the reduction in temperatures possibly from the re-injection fluid.

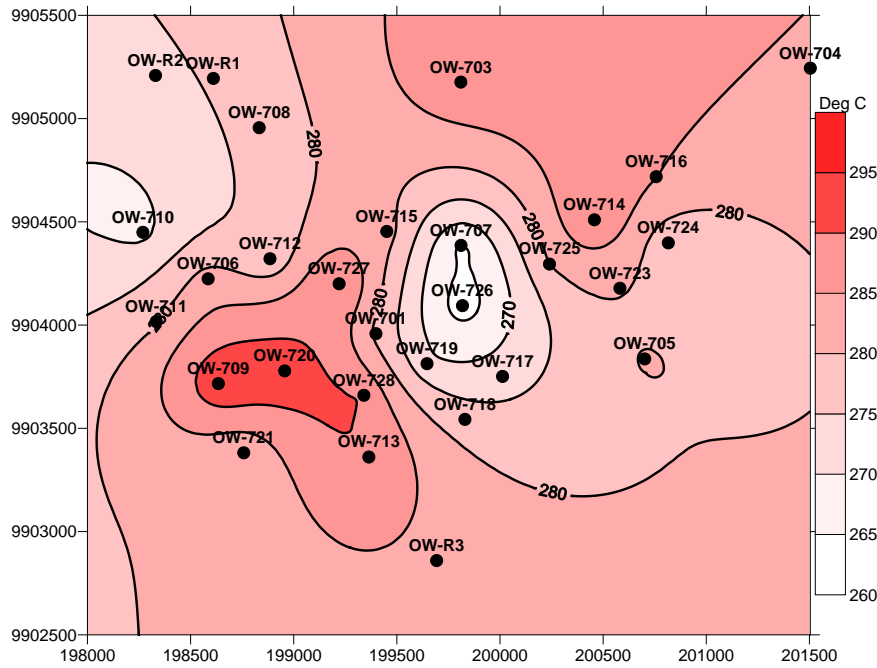


FIGURE 8: Hydrogen geothermometer temperature 1st half of 2007 distribution plot

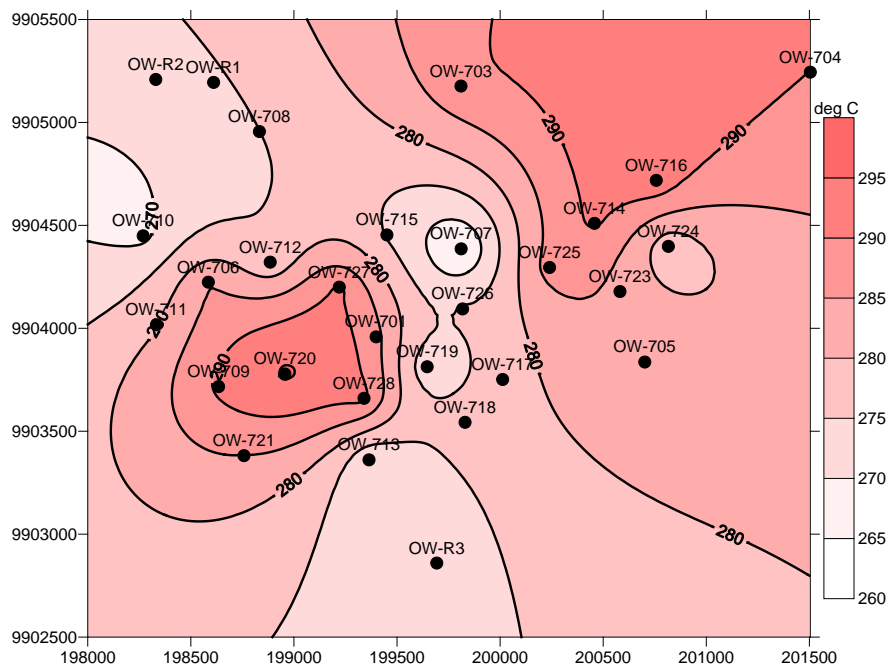


FIGURE 9: Hydrogen geothermometer temperature 2nd half of 2007 distribution plot

Figure 10, CO<sub>2</sub> geothermometer temperature 1<sup>st</sup> half of 2007 distribution plot, highlights a unique NE - SW temperature regime, with a cooler front of less than 260°C, entering the production field in the area near wells OW-712, OW-720 and OW-721. In the 2<sup>nd</sup> half of 2007 monitoring period, the CO<sub>2</sub> geothermometer temperature distribution. Figure 11, shows that temperatures have decreased across the entire field with two low temperature centers near wells OW-716, OW-720 and OW-727. This implies that the aquifer feeding these wells has received reinjected fluid, which has low gas content and hence reduces the concentration of carbon dioxide in the discharged fluid. This is confirmed in Figure 3 (total discharge chloride concentration 2<sup>nd</sup> half 2007 distribution plot), which shows corresponding regions of high concentration in the total discharge chloride. Separated brine will have high concentration of solutes, which when mixed with the aquifer fluid will result in a fluid enriched with residual chemical species.

The best indicator of incursion of atmospherically contaminated fluid in the reservoir is N<sub>2</sub> gas and O<sub>2</sub> in the steam. Figure 12 and Figure 13 present the N<sub>2</sub> gas concentration distribution during the 1<sup>st</sup> half of 2007 and 2<sup>nd</sup> half of 2007 monitoring periods. Generally, high concentration is observed around wells OW-708, OW-715, and OW-724. Similarly, during the 2<sup>nd</sup> half of 2007 monitoring period the high nitrogen concentration centers have remained intact. This implies, fluid that has had atmospheric contamination is being discharged through these wells. The high nitrogen gas concentration may be as a result of mixing the reservoir fluid with natural shallow recharge and re-injected separated brine in wells OW-R2, OW-R3 and OW-708 with the reservoir fluid being discharged by the wells monitored.

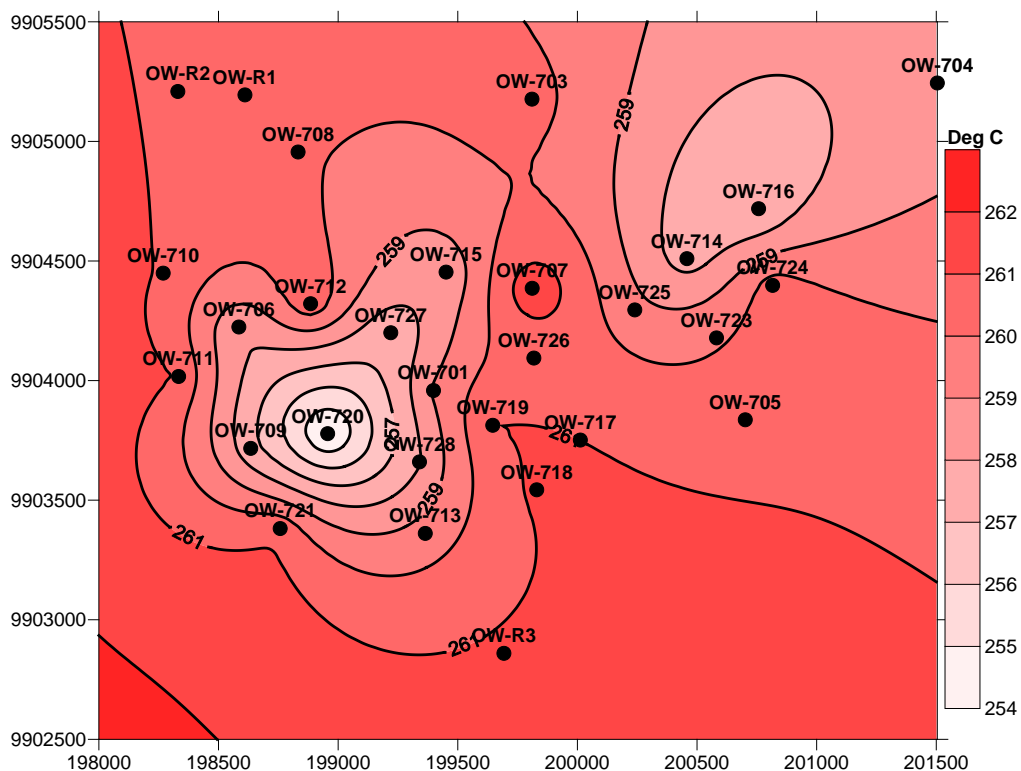


FIGURE 10: CO<sub>2</sub> geothermometer temperature 1st half of 2007 distribution plot

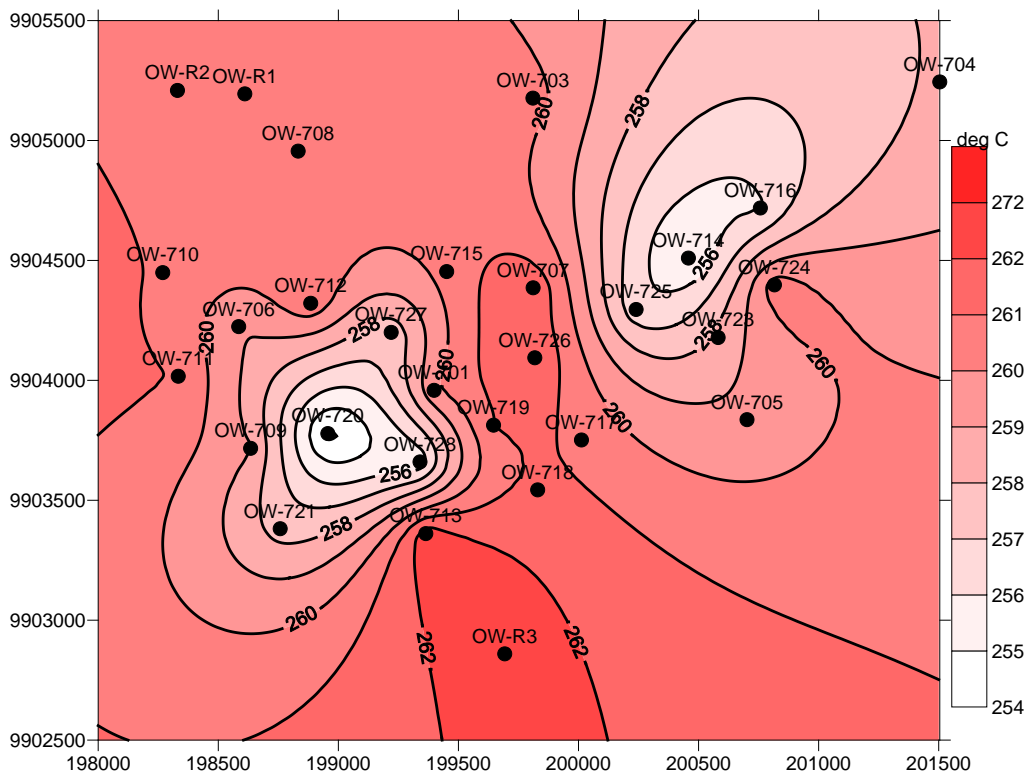


FIGURE 11: CO<sub>2</sub> geothermometer temperature 2nd half of 2007 distribution plot

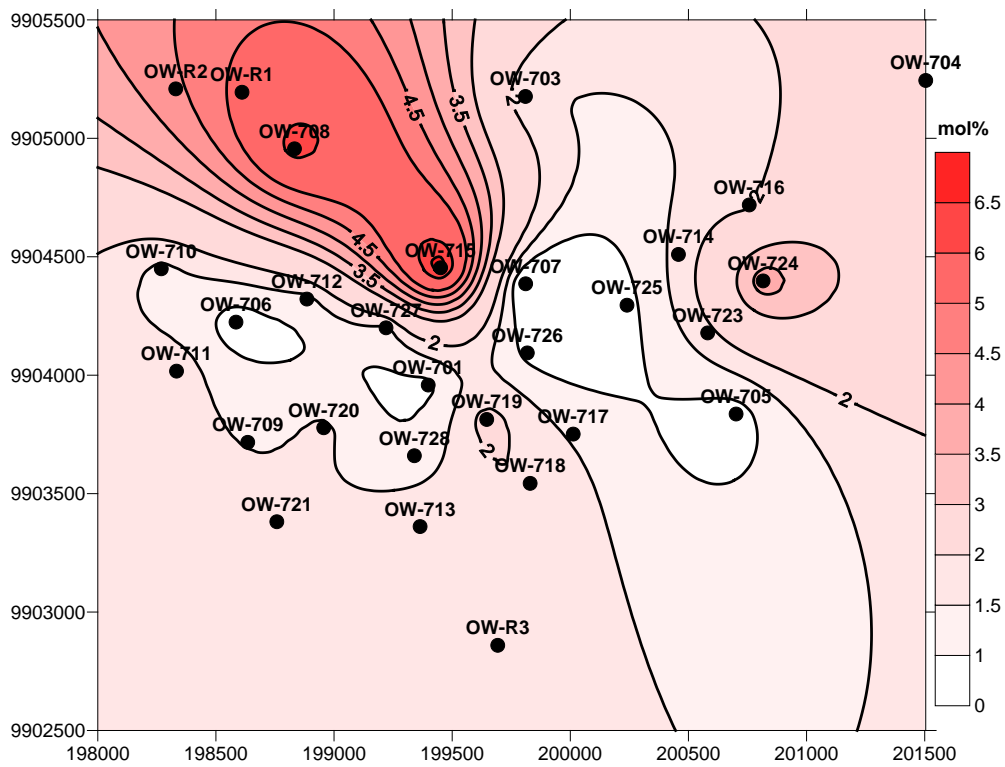


FIGURE 12: Nitrogen gas concentration 1st half of 2007 distribution plot

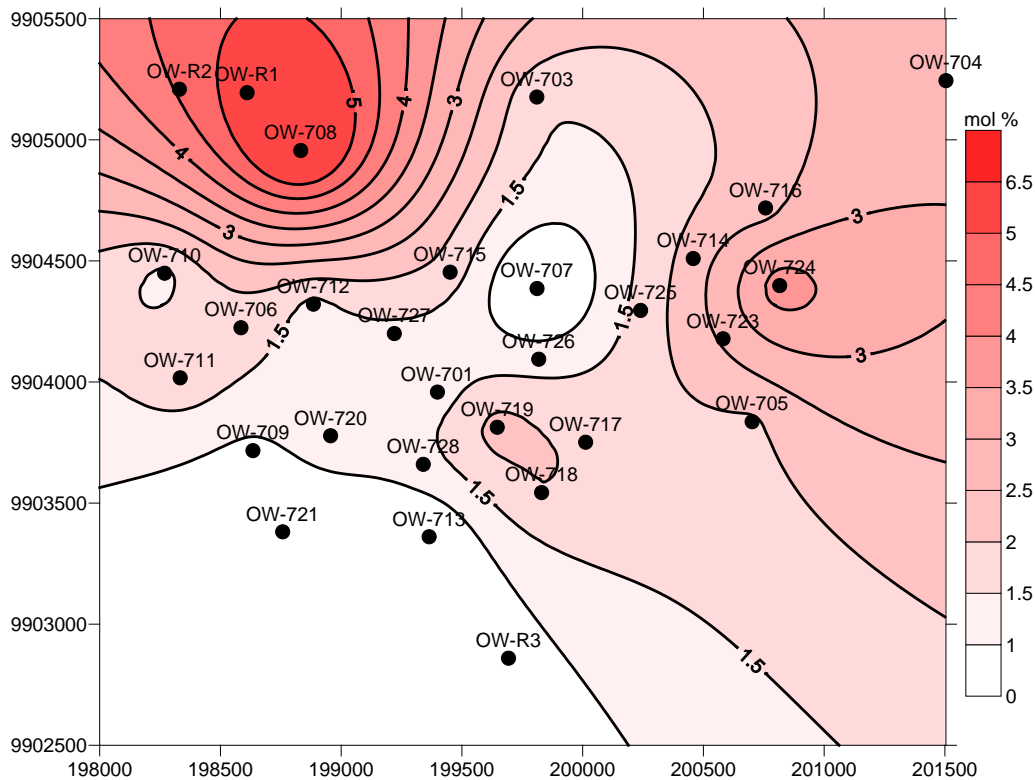


FIGURE 13: Nitrogen gas concentration 2nd half of 2007 distribution plot

#### 4. CONCLUSIONS

The regions of high chloride concentration are around wells OW-714 and OW-716 to the east, OW-709 and OW-727 to the west and OW-726 at the center of the Olkaria Northeast field. The three regions indicate upflow zones within the field. The area in the vicinity of wells OW-R2, OW-710, OW-711 and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field. Recharge from the Ol Olbutot fault may be encroaching the reservoir around well OW-711. This will be confirmed in the next monitoring periods.

The Na/K geothermometer temperature distribution in 2<sup>nd</sup> half of 2007, indicate three low temperature (less than 250°C) centers around wells OW-708, OW-720 and OW-724. The rest of the area lies between 270 and 340°C. The probable cause of heating around the wells to the southwest is boiling while the increase around well OW-727 may in addition, be due to incursion of separated re-injection fluids. The CO<sub>2</sub> geothermometer temperature mark out wells that have received the separated re-injected fluid from wells OW-720 through OW-728 to well OW-714 & OW-716 in a NE-SW elongated structure, Figure 11. When steam separates from a liquid during boiling or flashing, gases like CO<sub>2</sub>, H<sub>2</sub>S, H<sub>2</sub>, N<sub>2</sub>, and CH<sub>4</sub> move preferentially into the vapor phase. Therefore, the wells that have received separated re-injected fluid may possibly show elevated CO<sub>2</sub> geothermometer temperatures.

High Nitrogen gas concentration is observed around wells OW-708, OW-712, OW-719, OW-724, and OW-716. During the 2<sup>nd</sup> half of 2007 monitoring period the nitrogen concentration has increased across the entire field. However, the high concentration centers have remained intact. This implies, fluid that has had atmospheric contamination is being discharged through these wells. The high nitrogen gas concentration may be as a result of mixing the re-injected fluid in wells OW-R2, OW-R3 and OW-708 with the reservoir fluid being discharged by the wells monitored.

The bi-annual monitoring is adequate as a reservoir management tool. The re-injection fluid appears to move rather fast into the production field aquifer and the re-injection wells should be moved further away from the production field.

## 5. RECOMMENDATIONS

Further work need to be done in order to determine the optimum re-injection flow rate into well OW-708 so as to minimize negative effects on well OW-712.

Well OW-711 and OW-712, need to be online to enable monitoring of their output as well as any possible effects of cold re-injection at OW-201 and OW-204 since the wells are closest to the re-injection wells.

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## REFERENCES

- Arnórsson S., 1990: Gas chemistry of geothermal systems In: Augustithis, S.S. (editors), *Geochemistry of gaseous elements and compounds*. Theophratus Publications. S.A., Athens, 187-222.
- Arnórsson S., Björnsson, S., Muna Z.W. and Bwire-Ojiambo, S., 1990: The use of gas chemistry to evaluate boiling processes and initial steam fractions in geothermal reservoirs with examples from the Olkaria Field, Kenya. *Geothermics*, 19-6, 497-514.
- Arnórsson, S. and Gunnlaugsson, E., 1985: New gas geothermometers for geothermal exploration-calibration and application. *Geochim. Cosmochim. Acta*, 49, 1307-1325.
- Arnórsson S. Gunnlaugsson, E. and Svavarsson, H., 1983: The chemistry of geothermal waters in Iceland. III. Chemical geothermometry in geothermal investigations. *Geochem. Cosmochim. Acta*, 47, 567-577.
- Bjarnason, J.Ö., 1994: *The speciation programme Watch, version 2.1*. Orkustofnun, Reykjavik, 7pp
- Henley R. W., Truesdell A. H., Barton, Jr., and Whitney J. A., 1984: *Fluid – mineral equilibria in hydrothermal systems*. Volume 1, 267 pp.
- Karingithi, C.W., and Ofwona, C.O., 2006: *Status report on steam production first half 2006. Assessment of the reservoir in Olkaria Northeast and steam status*. Kenya Electricity Generating Company Ltd, internal report.
- Mwawongo, G.M., 2005: *Status report on steam production 2005. Assessment of the reservoir in Olkaria Northeast and steam status*. Kenya Electricity Generating Company, Ltd., internal report.
- Ofwona, C.O., 2006: *Status report on steam production 2005. Assessment of the reservoir in Olkaria Northeast and steam status*. Kenya Electricity Generating Company, Ltd., internal report.