Geochemical changes and processes in the Olkaria East Reservoir 1984 to 2017

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Keywords

Olkaria, Reservoir, Geochemical process, production

ABSTRACT

The Olkaria East field is part of the production fields in the Greater Olkaria Geothermal area (GOGA). Olkaria is located in Naivasha, 120 Km NW of Nairobi, on the South of Lake Naivasha, on the floor of the central segment of the Kenyan Rift valley Production in this field started in 1981 when the first 15 MW unit of Olkaria I power plant was constructed. As of early 2018, 288 wells had been drilled in this field, supporting the 45 MW Olkaria I power plant and the 140 MW Olkaria IAU power plant commissioned in 2014 as well as numerous well head plants. In this paper, an assessment of chemical changes has therefore been undertaken for the initial wells that have been under production for these 37 years, to assess the effect of production to the chemistry of these wells and the possible chemical processes that might have occurred during this period.

The concentrations of dissolved constituents Si, Cl and gases CO_2 and H_2S from the production wells have been analysed. The most notable chemical changes in the fluid is that the wells have exhibited gradual increase in the concentrations of the most abundant dissolved solids (Cl and SiO_2) and gases in steam since the initial commissioning of the power plant in 1981 upto a certain period in 1993, most likely indicating progressive boiling in the reservoir. Subsequently after that, some injection was introduced stabilizing the reservoir processes. After that the concentrations of dissolved solids in the geothermal fluid has levelled off to some degree. The concentrations of CO_2 and H_2S in the discharged steam remain more or less constant with time. From correlation of these changes, with data from other disciplines, processes like cooler fluid inflow, boiling and condensation have been noticed within certain periods in the production history. This approach has helped our understanding of the changes occurring in the reservoir and helped in improving the management and sustainability of the resource.

1. Introduction

The Olkaria East field is part of the production fields in the Greater Olkaria Geothermal area (GOGA). Olkaria is located in Naivasha, 120 Km NW of Nairobi, on the South of Lake Naivasha, on the floor of the central segment of the Kenyan Rift valley The first productive well in this zone was OW 02 drilled in 1974. Production in this field started in 1981 when the first 15 MW unit of Olkaria I power plant was constructed. As of early 2018, 288 wells had been drilled in this field, supporting the 45 MW Olkaria I power plant, the 140 MW Olkaria IAU power plant commissioned in 2014, the 5.5 MW OW-37, OW 37A and OW 37B well head units, the 6.4 MW OW 43 and OW 43A wellhead units and the 5.5 MW OW 39 wellhead unit. The Olkaria east reservoir is a two-phase liquid dominated reservoir with average temperature of 250-300^{0}C with some wells recording high enthalpies of up to 2600 Kj/kg. Initial wells in this field were shallow drilled up to an average of 1600 m depth, although this changed post 2008 when the subsequent wells were drilled to 3000 m. Olkaria I had initially 33 wells that were drilled to supply steam with 31 wells being connected. Currently, about 20 wells are in production with the other wells becoming non- commercial producers due to decline whilst some were adapted to reinjection wells. The Olkaria IAU is supplied by steam from 20 wells with some steam being drawn from wells in the Olkaria North East like OW 732, OW 732A and OW 717A from the separator station SN3. The Olkaria East reservoir has been undergoing reinjection from both cold and hot reinjection wells. The design of the Olkaria I plant did not have a cold reinjection system hence only brine is reinjected to wells OW 12 and OW 21. The OIAU has a cold injection system of the condensate from the plant to OW 801 R1 and OW 801 R2 and hot reinjection to OW 13, OW 17, OW 7, OW 718 and OW 703.
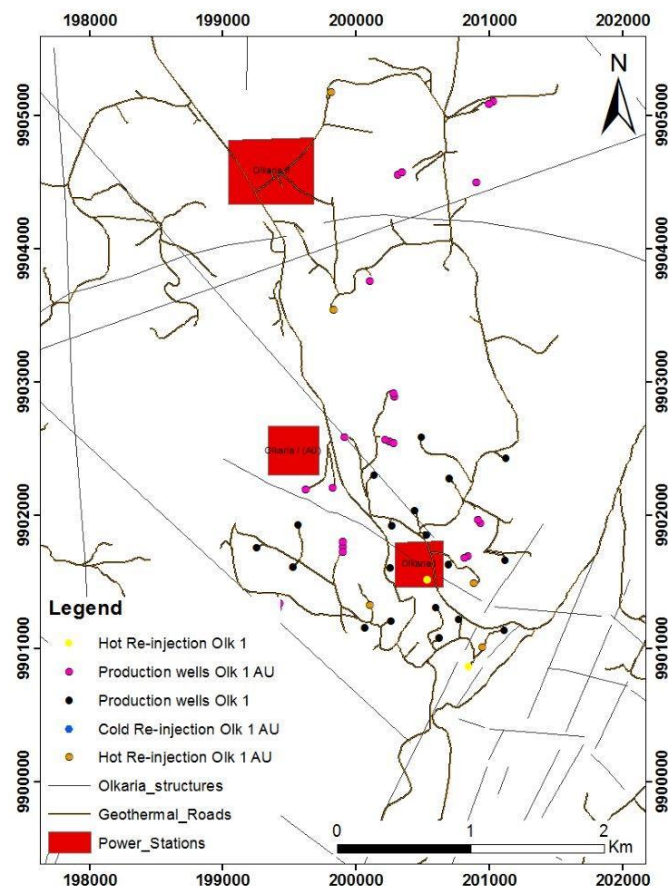

Figure 1: Production wells and reinjection wells locations as well as mapped faults in the Olkaria East field

The East field has been under exploitation for 37 years for the 45 MW Olkaria I plant and 4 years for the 140 MW OIAU. During this period, injection has been done together with tracer tests to assess the hydrology of the system and the reservoir response to production. In this paper, an assessment of chemical changes has therefore been undertaken for the initial wells that have been under production for these 37 years, to assess the effect of production to the chemistry of these wells and the possible chemical processes that might have occurred during this period.

2. Chemical monitoring

Geothermal reservoirs are known to change with time as a result of production. Geochemical methods have been applied to monitor the changes of the reservoir due to exploitation. Geochemical data obtained from producing wells can give relevant information on the reservoir condition depending on the kind of data that has been used. Geochemical data can be used to map recharge zones, cold water intrusion, boiling and most importantly in evaluation of scaling and corrosion tendencies.

The Olkaria East field is monitored biannually for the Olkaria I wells and quarterly for OAIU wells, where samples are collected from all the production wells. Sampling is done along the two phase lines using a webre separator that enables the sampling of liquid and vapour separately as described by Arnórsson et al., (2006). The liquid samples are collected using a cooling spiral into different sample bottles and treated differently based on the components. Water Samples from some wells were collected at atmospheric pressure. Samples for pH, CO_2, H_2S were untreated; samples for analysis of F, Cl, B and TDS were collected as unfiltered untreated samples; SO_4 samples were filtered and treated with zinc acetate; the metal samples were filtered and acidified; SiO_2 samples were diluted ten times after collection. The steam samples for gas analysis of $CO_2, H_2S, H_2, CH_4, N_2, O_2$ were collected into an evacuated double port glass flasks containing caustic solution. The analysis was done based on methods as described by Armansson and Pang (2006).

The concentrations of the deep liquid have been evaluated using the chemical speciation program WATCH Arnórsson et al., (1982), Bjarnason, (2010). This was based on the established reservoir temperatures at the depth of the major aquifers obtained from temperature logs. The sampling pressure was also in cooperated as well as the discharge enthalpies of the respective wells. The effect of the excess enthalpy on the deep liquid concentration was not considered. This is expected to affect some of the gas concentration in the deep liquid but with little effect on the non-volatile constituents. The discharge enthalpy was evaluated using the Russell James lip pressure method.

Reservoir temperatures have also been estimated based on solute and gas geothermometers. Calculated Solute Geothermometry temperatures used here are from Fournier and Potter (1982) for quartz and Arnórsson et al., (1983) for sodium- potassium. For the purpose of monitoring the changes of the reservoir with time, specific parameters have been plotted graphically over time. This includes the concentrations of chloride, silica and the concentration of gases; carbon dioxide and hydrogen sulphide. These concentrations are also compared to the total discharge enthalpy, enthalpies due to cation geothermometers, steam and brine flow rates.

3. Monitoring results

3.1 Chloride and Enthalpy

The chloride concentrations for well OW 15, OW 16 and OW 18 have been analysed from 1984 when production from Olkaria I plant began. This has been linked to production from OW 14, OW 44 and OW 44A which came under production in the same sector of the field with the commissioning of Olkaria IAU in 2015. Figure 2 below shows the variation in chloride concentrations over this period.
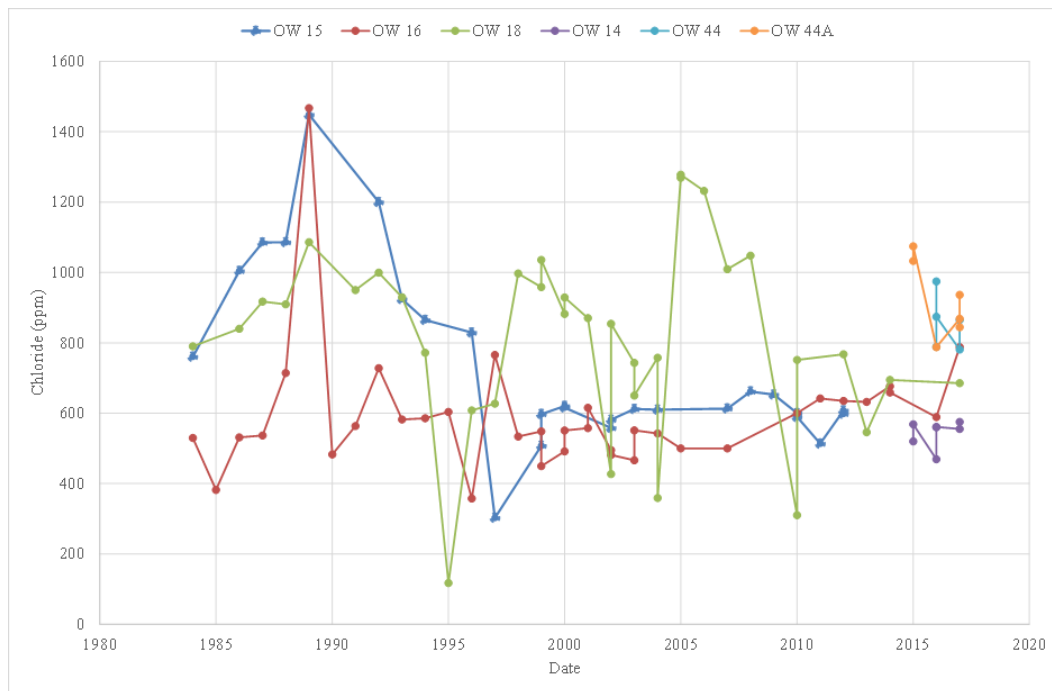

Figure 2: The variation in chloride in wells OW 15, Ow 16, OW 18, OW 14, OW 44, OW 44A from 1984 to 2017.

The chloride in well OW 15, OW 16 and OW 18 increased from onset of production in 1984 from values of between 400 mg/kg and 800 mg/kg respectively to high concentrations of between 1200 and 1400 mg/kg in discharge fluids. According to Mburu, (2004), this period was characterized by a drop on steam output of about 8% with discharge enthalpies increasing by an average of 600 kj/kg. There was some pressure decline during this period contributing to boiling conditions that possibly contributed to this increasing chloride within the wells. This increase in chloride increased steadily up to 1992, where its starts stabilizing. According to Ambusso and Karingithi, (1993), the steam decline rate began reducing in 1988 from 4% to less than 4 % post 1992. This matches the period when the Chloride concentration in 1992 was stabilizing. There was probably less boiling at this particular period especially since new make-up wells had been connected to help curb the declining steam output put from the initial wells. The chloride concentration fell sharply between 1995 to 1997 with all the three wells recording concentrations at below 300 mg/kg, way below their initial values. This drop in chloride actually matched the period when reinjection was being tested in the field to stabilize the pressure draw down in the field. From Mburu, (2004), 136,886 tonnes of cold water was injected into OW 12 between July 1996 and August 1997. This immediately resulted in mass in the three wells. This contributed to dilution of the reservoir fluid and hence the drop in the chloride. Since the reinjection was being done as a response to pressure decline, it's possible

that since the chloride had begun dropping just pre-injection, there might have been an onset of inflow of cooler water into the filed due to the declining pressure. The injection was stopped after the enthalpy of the wells also declined in response. The Chloride concentrations have been related with the enthalpy variations in the total discharge to collaborate the changes happening in the reservoir fluid from these wells. Figure 3 below shows three enthalpy values; total discharge enthalpy (H TD), enthalpy calculated from sodium potassium temperature using steam tables and considering a two phase fluid (H Na/K) and enthalpy calculated from silica temperature (H SiO$_2$).
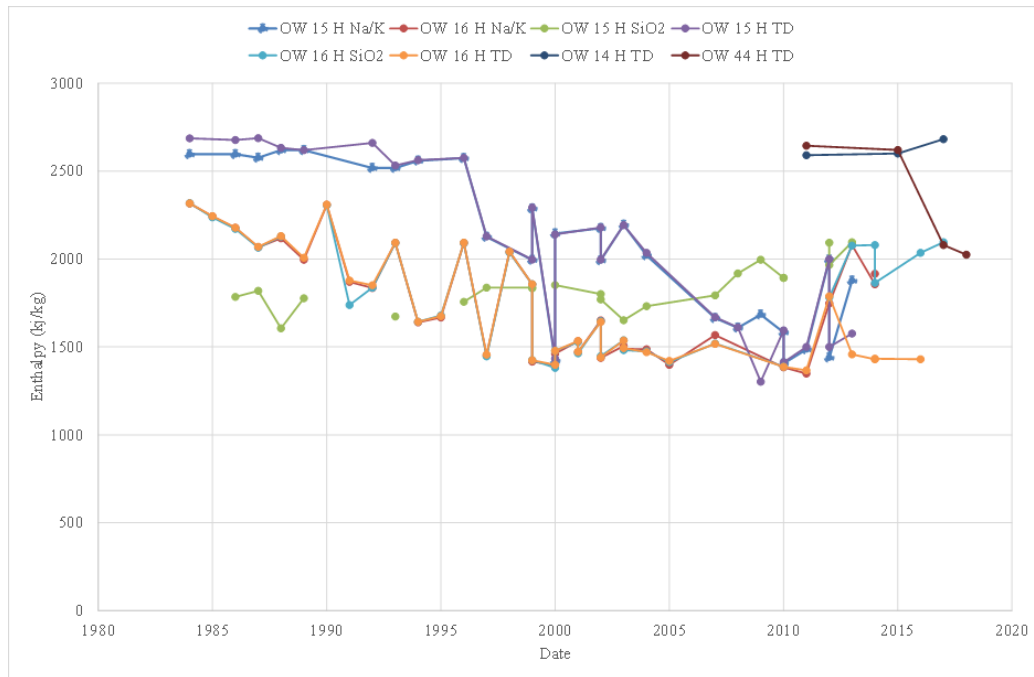

Figure 3: The enthalpy variations for OW 15, OW 16, and OW 44. Three enthalpies are plotted; enthalpy of total discharge (measured at wellhead), enthalpy calculated from Na/K and silica geothermometers and considering a saturated two phase fluid.

The total discharge enthalpy of well OW 15 and OW 16 showed an increase between the periods 1986 to 1992, this being period the pressure decline and boiling within the reservoir were elevated within this well. From a discussion by Barragan, et al., (2016) adapted from methods by Truesdell et al., (1995), a comparison can be made between total discharge enthalpy and calculated enthalpies from cationic geothermometers for specific time periods within wells or over a production period. This is based on the fact that the cations silica and Na/K respond differently to temperature variations within a well. The silica concentration in the fluid adjusts immediately with temperature variations; hence the silica temperature gives an enthalpy value of the fluid close to the well. Na/K temperature re-equilibrates slowly giving a temperature that characterizes fluid far from the well. In this case some comparisons of the enthalpies have been established. $H_{TD}>H_{NaK}>H_{si}$ is one such comparison that represents near well boiling. An initially localized boiling contributes to reservoir boiling if it continues for long periods without equivalent recharge either by reinjection or natural recharge. From figure 3, it can be seen that in OW 15 and OW 16 for example, in the period between 1986 to 1992 we have the $H_{TD}> H_{NaK}> H_{Si}$ indicative of near well boiling that is occurring in this wells hence the chloride patterns. From 1992 to around 1995, the pattern in these wells becomes $H_{TD}>H_{si}=H_{NaK}$, which constitutes a boiling reservoir, given that the reservoir recharge was minimal and the intensity of localized boiling was increasing.

From figure 2 above , the chloride concentrations in the three wells increases after 1997, when the cold injection was stopped and is seen to stabilize in OW 15 and OW 16 at 600 mg/kg , though a little erratic in OW 18. These stable values are seen even up to 2015 when OIAU was commissioned. In this period we look at the variations in OW 14, OW 44 and OW 44A. It can be seen that immediately after commissioning in 2014, there was a drop in the concentrations of chloride in the wells OW 14, OW 44 and OW 44A. This concentration increased again post 2015. It should be noted that at this period, early 2015, injection of brine also began in OW 12 where about 75 t/hr of brine is being injected from wells OW 29/30, OW 24/28, OW 25, OW 20, OW 18 and OW 26. A tracer test was conducted in OW 12 from October, 2016, Koech, et al., (2017). From the tests it was seen that there is a major connection between the well OW 12 and OW15 where a tracer mass recovery of 77. 59 % was recorded within three months. Other wells like OW 14, OW 14A, OW 38, OW 18, OW 19 among others were also seen to be impacted with this injection. Looking at these figures, it means that the initial state of the wells responded to the mass withdrawal of the fluid during the commissioning hence the drop in chloride. But since reinjection from brine began immediately the wells recovered, especially given that the brine comes from high chloride brine wells, contributing to this immediate increase in chloride. The enthalpy variations from 1997 to 2015 and subsequently after 2015 have been shifting between two conditions; $H_{TD}=H_{NaK}>H_{Si}$ that suggests mixing close to the well of equilibrated liquid with cooler diluted water and $H_{Si}>H_{NaK}=H_{TD}$ representing a breakthrough of cooler water with Na/K enthalpy re-equilibration. It's noted that this has probably been influenced by the injections that began happening in the field in this period as well as the increase in pressure difference between the hot and cold aquifers, allowing entry of cooler water from neighbouring aquifers.

3.2 Silica

The changes in silica concentration in the well discharges were monitored over the period 1984 to 2017 to check for variations in reservoir temperature. The solubility of silica is controlled by temperature, and since silica has a quick response to temperature, then the variation is fluid temperature could affect its concentration. Figure 4 below shows the variations in silica for the wells analysed.
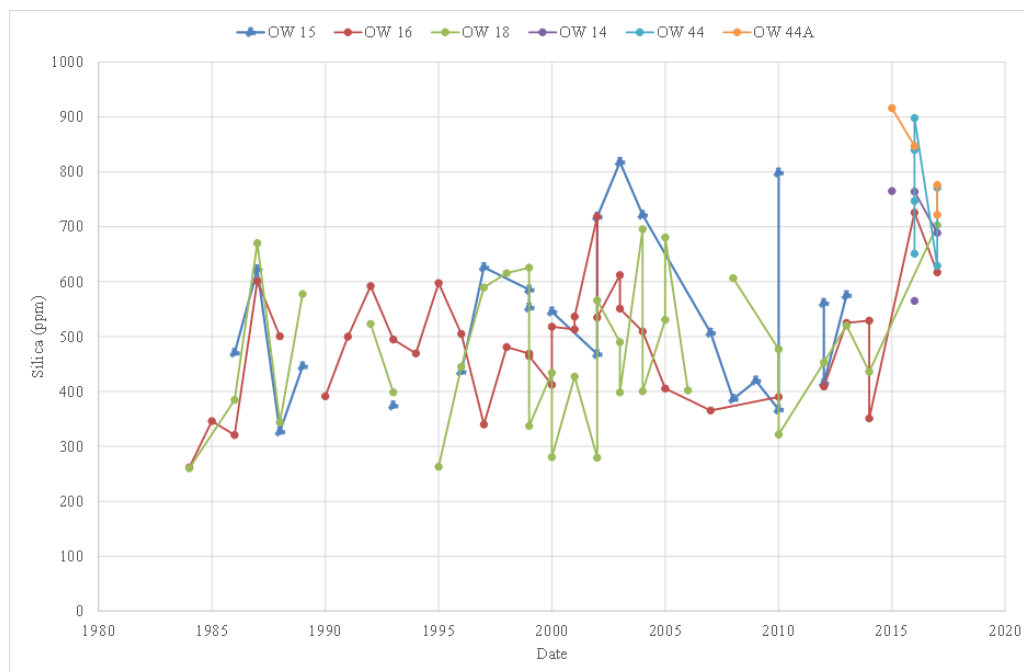
Figure 4: Silica concentrations monitored in the wells from 1984 to 2017

Silica concentration increased in the wells from the period 1984 to 1992 aligned with the period when the enthalpy was increasing. From the graph of mass flow changes (figure 5), there was an increase in steam flow and a reduction in brine flow during this period hence the increased analysed silica in fluid. The increase in the silica concentration in the wells however did not necessarily correspond to an increase in reservoir temperature. The silica concentration stayed generally stable from the period 1994 to 2015 with minor increase or decrease being contributed to be by some precipitation during sampling. An analysis of the Silica temperature has shown a generally stable temperature with margins of 10 degrees Celsius. The inflow of fluids has probably not been sustained enough to extremely cool the reservoir temperatures within specific periods.
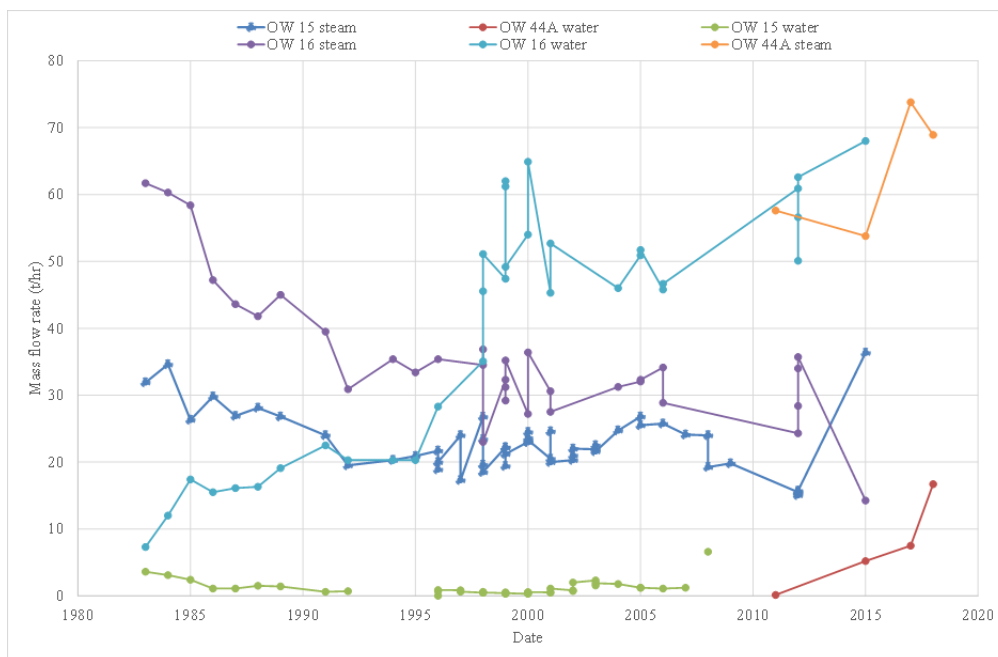
Figure 5: Mass flow changes in OW 15, OW 16, OW 44, OW 44A 1984-2015

3.3 Gas concentrations

The changes in calculated gas concentrations within the period 1984-2017 have been analysed for OW 15, OW 16 , OW 18 and for 2015 to 2017 for OW 14, OW 44 and OW 44A. The analysis mainly focused on carbon dioxide and hydrogen sulphide, these being the most abundant gases in the steam with carbon dioxide being 85 % of the total gas in steam. Figure 6 and 7 below show the concentrations of CO_2 and H_2S respectively in the discharged steam. The concentrations of different gases in steam are influenced by several things including mineral assemblages as discussed by Karingithi et al., (2010), steam condensation, cooling and boiling processes within the reservoir. Entry of cold fluids usually causes oxidation of hydrogen sulphide to Sulphates hence reducing its concentration in discharge steam. Therefore huge changes in hydrogen sulphide concentration could be indicators of massive cooling in wells. Carbon dioxide changes could be influenced by calcite deposition in wells as well as changing steam fraction within the wells. For the wells considered, there have been no calcite depositions in the wells hence little variation in CO_2 in the wells due to that process. From the period 1986-1992, there was some boiling processes within these wells contributing to an increased steam fraction and hence the increased CO_2 concentration over these period for the wells OW 15, OW 16 and OW 18. A reduction in CO2 in the period 1995-1997 coincides with the period when cold water injection was done, probably resulting in dissolution and condensation of the major

soluble gas CO_2. Subsequently after that there was an increase of the CO_2 to pre-injection values and became relatively stable after that. For the H_2S concentrations, the values have been relatively stable over the entire period, probably due little condensation in the reservoir that could have oxidized our H_2S to Sulphates. For wells OW 14, OW 44 and OW 44A, there was a slight drop in the gas concentration from the values pre-commissioning and immediately after commissioning but this rose immediately after to present values.
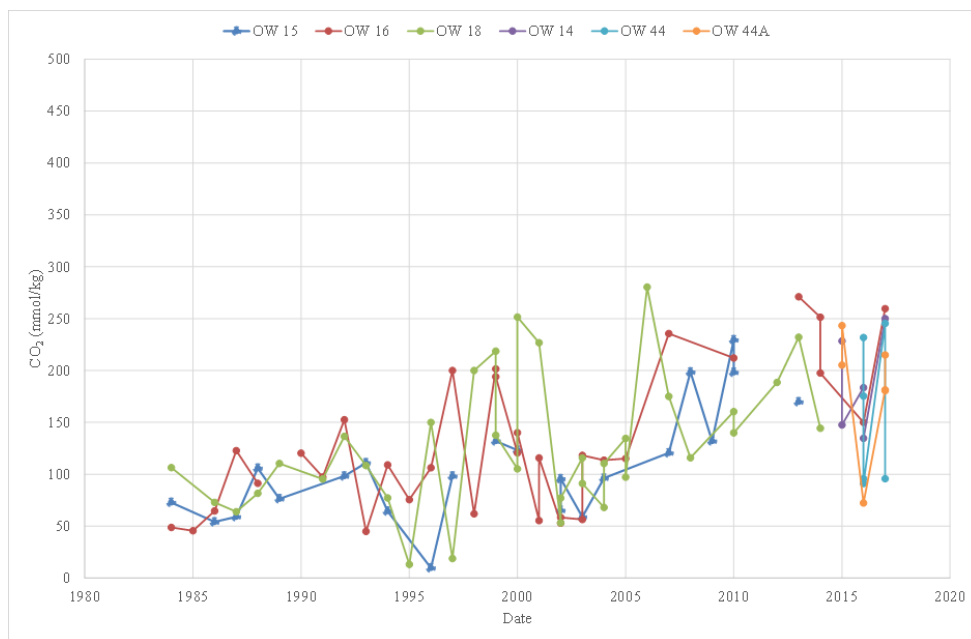

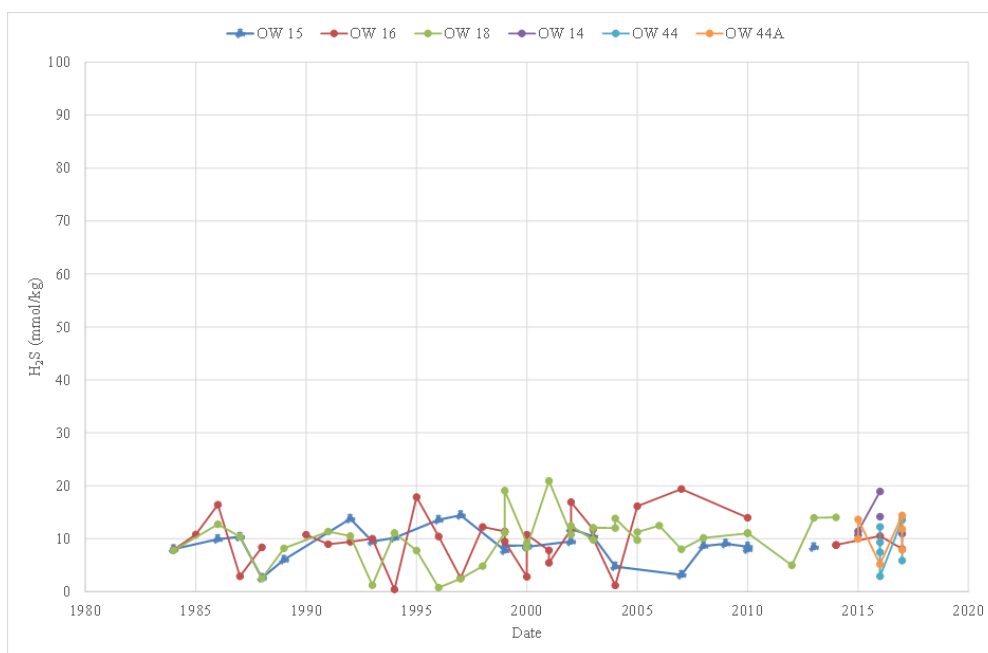**Figure 6: Concentrations of carbon dioxide in discharged steam for the period 1984-2017**

Figure 6: Concentrations of hydrogen sulphide in discharged steam for the period 1984-2017

4. Conclusion

Monitoring of the changes occurring within a geothermal reservoir can be done by collection of chemical data and correlating it with data from other disciplines like steam field data, reservoir and plant data. Chemistry data collected from wells included dissolved constituents like Chloride, silica and gas concentrations in steam and analysed over an entire production period. This data is correlated with discharge enthalpies, calculated enthalpies, total mass flow, steam flow, brine flow, reservoir steam fraction, reinjection data, tracer data and even calculated reservoir temperatures. From the results some changes in chloride, silica carbon dioxide and hydrogen sulphide concentrations for wells OW 15, OW 16, OW 18, OW 14, OW 44 and OW 44A have been seen over the entire production period 1984 to 2017. From correlation of these changes, with data from other disciplines, processes like cooler fluid inflow, boiling and condensation have been noticed within certain periods in the production history.

This approach has helped our understanding of the changes occurring in the reservoir and helped in improving the management and sustainability of the resource.

Acknowledgement

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