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GEOCHEMICAL MONITORING OF RESEVOIR RESPONSE TO PRODUCTION

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ABSTRACT

Geochemical procedures used to monitor reservoir response to production are highlighted. Case studies for Olkaria and Wairakei geothermal fields using these procedures are reviewed. Development of both fields has resulted in changes in chemistry of the discharged fluids. In both cases development induced pressure drawdown has been observed. There is pressure decline in wells located in the central part of Olkaria I field. An inflow of a cold recharge is identified to the east and southern part of the filed. In Wairakei deep pressures were drawn down by well discharge resulting in the increase in size and pressure of the shallow steam. Cold recharge was also observed in the Western Borefield.

1. INTRODUCTION

Reservoir monitoring starts with commissioning or with the commencement of exploitation of geothermal fluids for both power generation and direct utilization. The way a geothermal reservoir changes with time as a result of its exploitation has been described as the response of the reservoir to the production road and monitoring is on the effects of water/steam extraction. Most important information on geothermal reservoirs is obtained through a carefully planned monitoring program.
Changes are physical and/or chemical and manifest in pressure, temperature, enthalpy, heat flux and chemistry of geothermal fluids. The chemical and physical data from wells sunk into a boiling reservoir provide important information on the response of the reservoir to the production load in regard to recharge and enhanced boiling. The data can also provide useful information to map cold water recharge into single liquid water reservoirs and information on the quality of the fluid for the use in question. Other uses on the data is to aid in predicting undesirable processes e.g. scaling/mineral deposition, in quantifying reservoir capacity and lifespan and finally Sound environmental practices and formulation of management practices suited to a particular reservoir. In this write up, procedures followed during geochemical monitoring process are highlighted and study cases of Olkaria I and Wairakei geothermal fields discussed.

2. PARAMETERS MEASURED

The parameters measured are different from one system to another. Generally there are basic common aspects for monitoring universal to almost every reservoir and include:

- Temperature/enthalpy for liquid or dry steam wells
- Well head pressure of production well
- Water and steam flow rates
- Chemical content of discharged fluid
- Down-hole pressure and temperature of wells
- Environmental effects

3. PRESSURE AND TEMPERATURE CHANGES

When production is more than the reservoir recharge pressure drop is experienced Pressure drop can be large, small, fast or slow and causes boiling in the reservoir. The main effects of the pressure draw down as a result of excess well production (p) are increased recharge of cold water in to the reservoir from the drainage (D) above, deep recharge (R) below, lateral cooler inflow (l) and enhanced boiling in the case of reservoirs with temperatures in excess of 100ºC. This is presented in Figure 1 adopted from Glover and Bacon (2000) in a report on chemical changes in natural features and well discharges at Wairakei geothermal field, New Zealand. The natural outflow (0) was considered to be zero as the surface outflow of water ceased with continued exploitation of the field. The model was used to calculate the hydrological balance for Wairakei but its purpose here is to give a picture of what takes place at the subsurface during the exploitation of geothermal fluids.

Pressure drawdown by itself may cause wells to become unproductive but cold water recharge may also do so by condensing steam and thus reducing boiling. Pressure decline manifests in further changes such as increase of larger steam zones and heat flow. New fumaroles, boiling mud pools and increase in hydrothermal eruptions. Depressurization boiling as well as cold water inflow causes cooling in the reservoir. If the recharge is not directly into the reservoir or the depressurized zone it might not cause cooling and is good for the system.

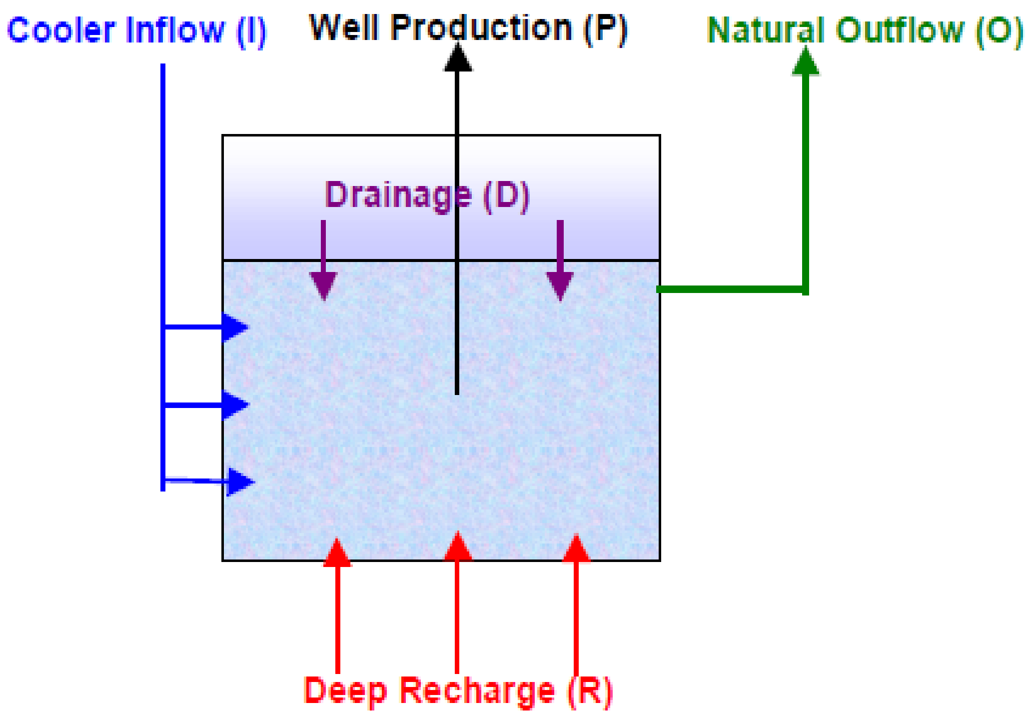


FIGURE 1: Schematic flow diagram as a result of excess well production

The temperatures are measured using various types of sensors: thermometers, probes and geothermometry. Discharge temp of a well is mainly influenced by flow-rate into the well.

4. MONITORING FREQUENCIES

Chemical and isotopic monitoring studies require regular sampling of discharged fluids. Frequency depends on the level of production and rate of steam withdrawal. As a rule sampling frequency is highest during the early stages of discharge of each well.

It is recommendable that samples for full analysis should be collected weekly for the first month, bimonthly for a year and 3 times in a year during production. With rapid changes or fluctuations more frequent sampling is required.

5. MONITORING DATA PRESENTATION

The Principle variable for monitoring studies is time. It is convenient to present chemical and isotopic data from discharged fluids as plots against time where time is on the x-axis and the chemical and physical data on the y-axis. Both primary data (analytical concentrations or ratios) and derived data (geothermometry temperatures, steam fraction) should be plotted. Plot together with discharge enthalpies &steam flows because variations in discharge enthalpy can be cause of variations in chemical and isotopic compositions of well discharges.

6. EFFECTS OF PRESSURE DROP & INCREASED IN COLD RECHARGE

The following, though not exhaustive, are the expected effects on pressure drop with a cold recharge in to the reservoir:

- Decrease in well discharge
- Changes in surface activity
- Lowered water level in wells
- Increased boiling (in high enthalpy systems)
- Increased recharge into the system (usually cold water)
- Surface subsidence –may result in damage to surface piping and equipment
- Result in changes in chemical composition of the reservoir fluid
- Changes in temperature/enthalpy of reservoir fluid
- Cold recharge may cause the reservoir to become unproductive
- Changes in temperature profiles of wells

7. DISCHARGE FLUID CHEMISTRY

Chemistry data is obtained through sampling of both steam and water from production wells and other surface discharge points with subsequent isotope, chemical analysis and data interpretation. Analyses of the partial and full analysis are recommended as follows:

Partial analysis

- Water samples: Cl, B, SiO_2, Na, K, Ca
- Steam samples: CO_2, H_2S, N_2, O_2, H_2, CH_4 & NH_3

Full analysis

- Water samples: pH, Cl, B, SiO_2, Na, K Ca, Mg, CO_2, H_2S, SO_4 and $\sigma^{18}O$ and $\sigma^{2}H$
- Steam samples: CO_2, H_2S, N_2, O_2, H_2, CH_4 NH_3 & Ar

Each of the analysed components provides its information on changes in the reservoir conditions and generally most of the Chemical data information deduced includes:

- Temperature changes in the reservoir
- Incursion of colder non-reservoir water into the geothermal reservoirs
- Fate on the re-injected brine using tracer testing.
- Scaling and corrosion tendencies.
- Brine re-injection (hot or cold)
- Where to re-inject and for how long –tracer testing
- Need to drill more replacement wells
- Need to increase installed capacity (install additional generating units) etc.

An example of data interpretation is if you observe a decrease in the concentrations of Cl and B in the liquid water phase of well discharge at a particular separation pressure are indicative of cold water recharge. Changes in $\sigma^{18}O$ and $\sigma^{2}H$ may reflect recharge from a different source into the aquifers.

Cold Water was injected in well OW-15 in the depressurized zone and dilution of the fluid with respect to chloride was observed. The cold dilute water diluted the geothermal brine as well as condensing the steam which also brought further dilution.

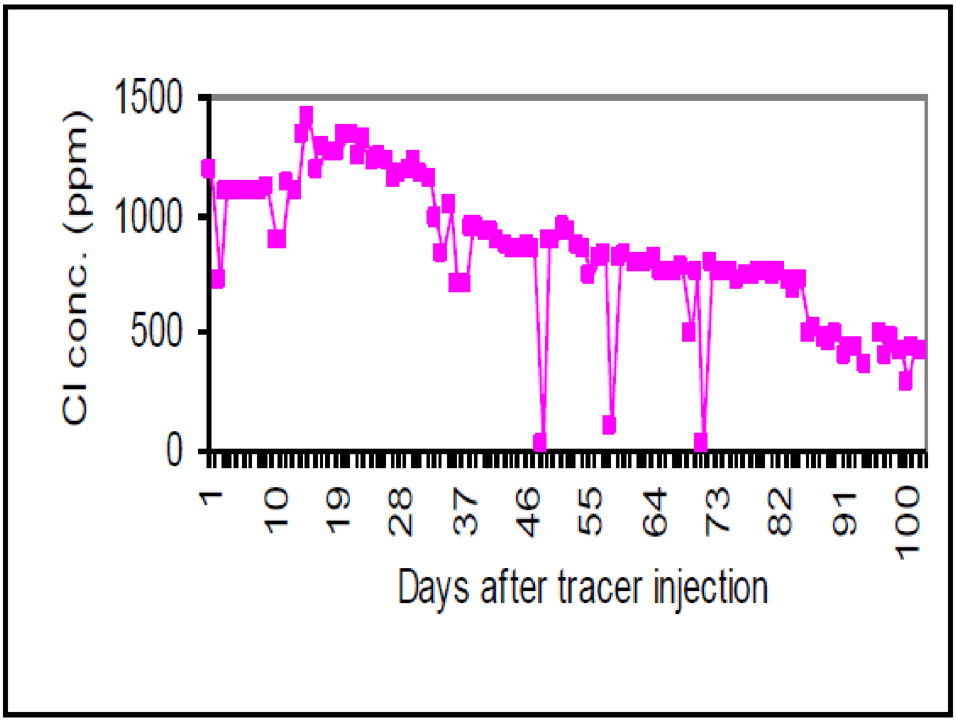


FIGURE 2: Chemical changes in well discharge

8. CASE STUDY – OLKARIA I FIELD

Olkaria I geothermal field has been in operation for the last 31 years. Initially it used to be monitored 4 times a year for both chemical and physical changes. However minimal changes were noted and monitoring was reduced to the current 2 times in a year.

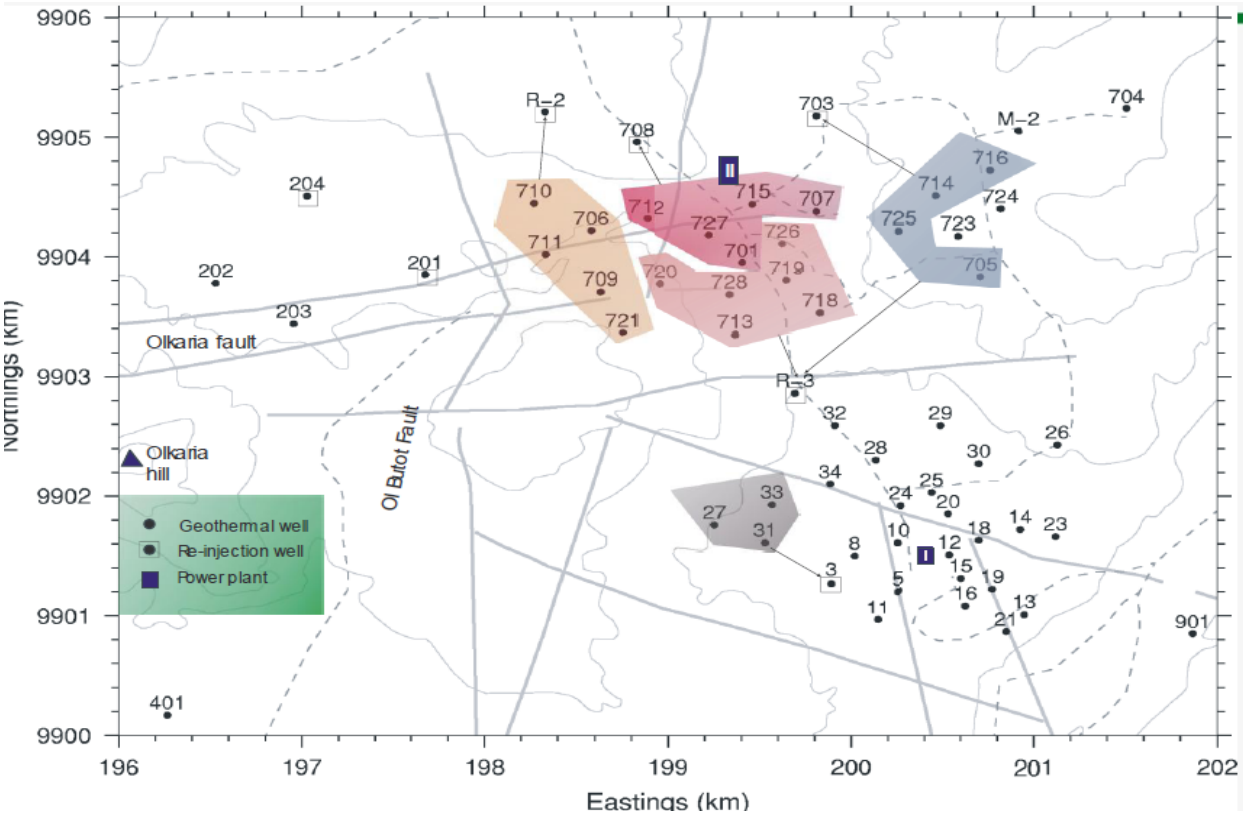


FIGURE 3. Olkaria field I well location

8.1 Pressure changes in Olkaria I

There has been noted pressure decline in wells located at the central part of the Olkaria I field (Figure 3) which is associated with depressurization as a result of excessive extraction of geothermal fluids. There has been an observed decline in enthalpy and down-hole temperature values observed at the eastern and southern part of the field. This has been interpreted as being due to inflow of cooler fluids at depth to create a hydrological balance. Geochemical changes at Olkaria I were evaluated in terms of reservoir Cl, SiO_2, SO_4, geothermometry, variations in gas content of discharge fluids (Figures 4 to 8). The Chemistry indicate boiling effects at central part of the field and an inflow of cooler fluids from the south and the eastern part as supported by lower Cl and high N_2 gas content.

8.2 Cold water

Effects of cold water inflow into the reservoir are clearly seen in Figures 4, 5, 6 and 7.

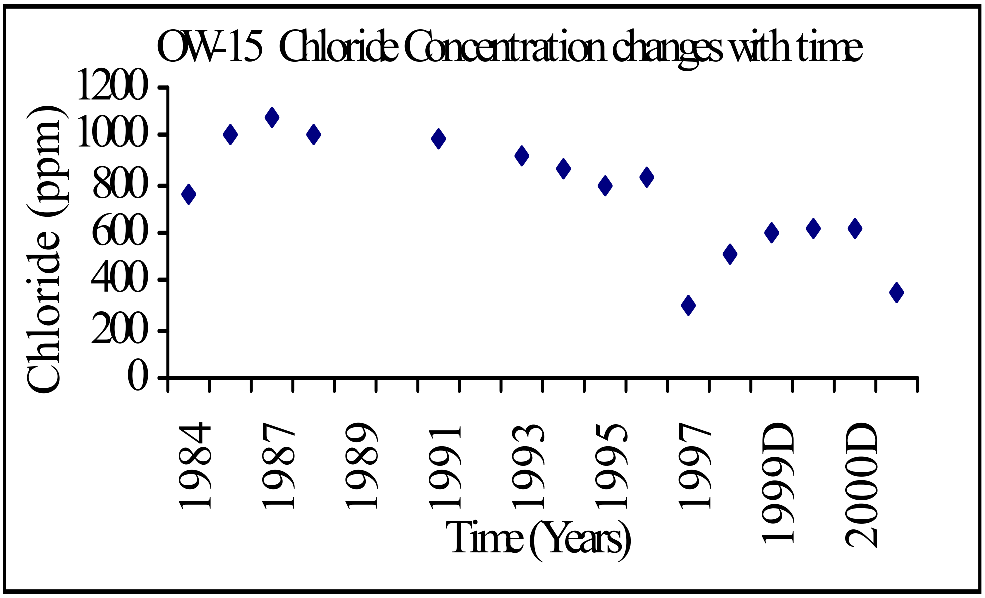


FIGURE 4: Chemical changes in well discharge OW-15

Well OW- 15 had a gradual decline for over 10 years as a result of cold water intrusion and later a gradual recover due to reservoir heat up.

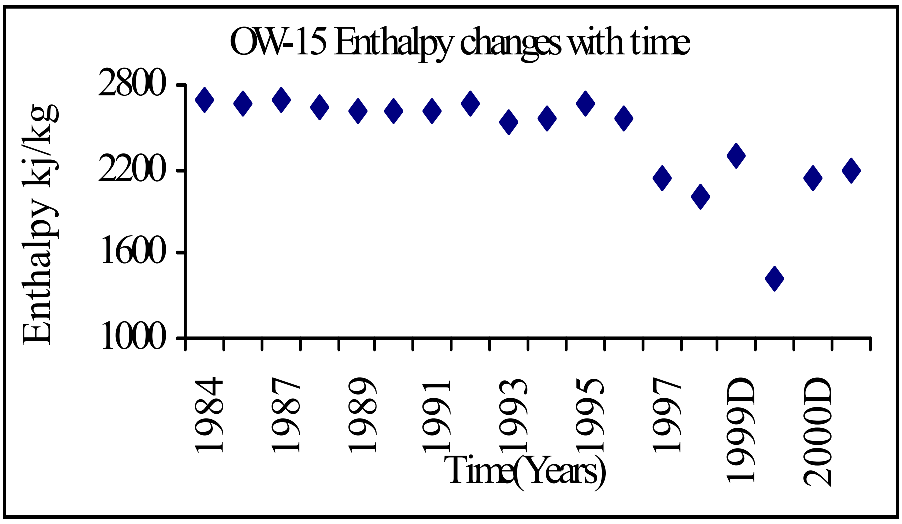


FIGURE 5: Enthalpy changes in well discharge OW-15

The enthalpy change for OW- 15 is similar to the tread exhibited by chloride concentrations due to cold water inflow. The overall effect is a reduction in heat capacity as well as generation capacity.

Both mass output and the enthalpy declined sharply since 1982 until 198 when well OW 12 could not produce anymore.

Figure 7 shows change in silica temperature in Olkaria east production field with time. A dilution effect from NE and S of field is easily identified. Generally there was temperature reduction leading to generation reduction.

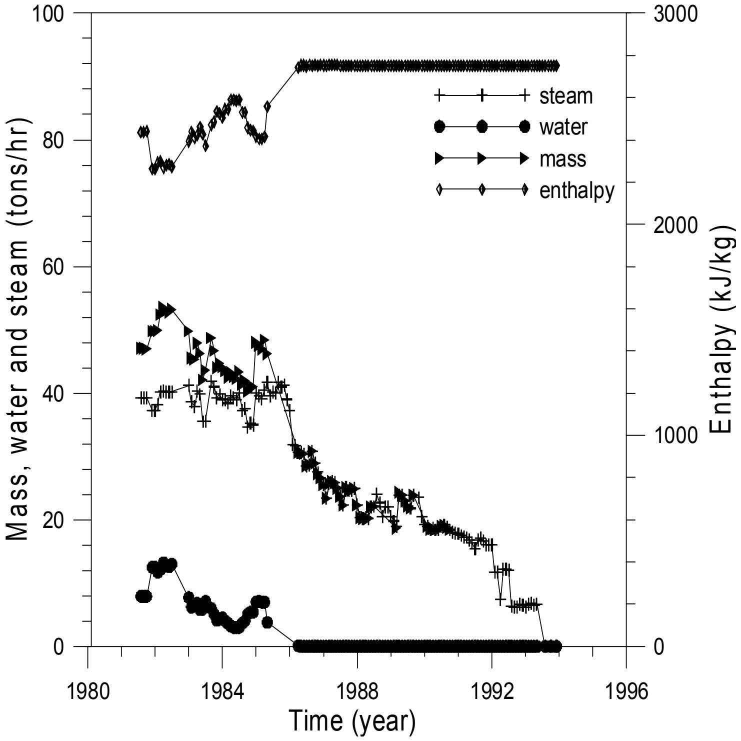


FIGURE 6: Production decline in reservoir (OW-12)

Well OW- 02 output declined initially up to 1995 when hot separated brine was re-injected in nearby well OW-03. From then on well output stabilized. The water, steam flow rate increased and this demonstrates that proper monitoring brings out a good understanding of the field leading to good management options.

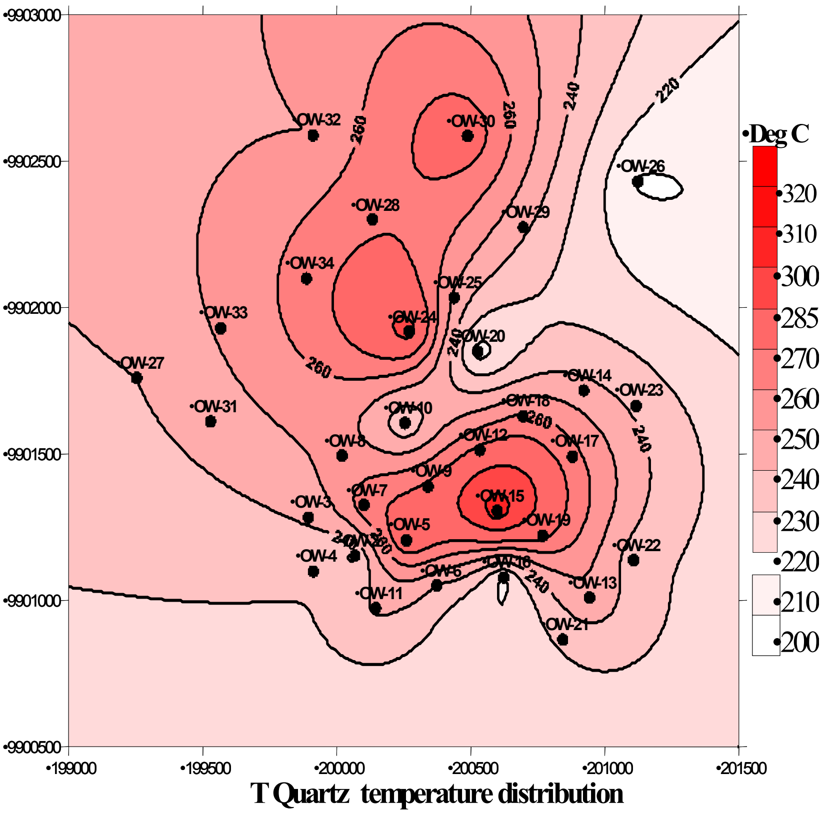


FIGURE 7: Silica geothermometry temperature distribution (2004)

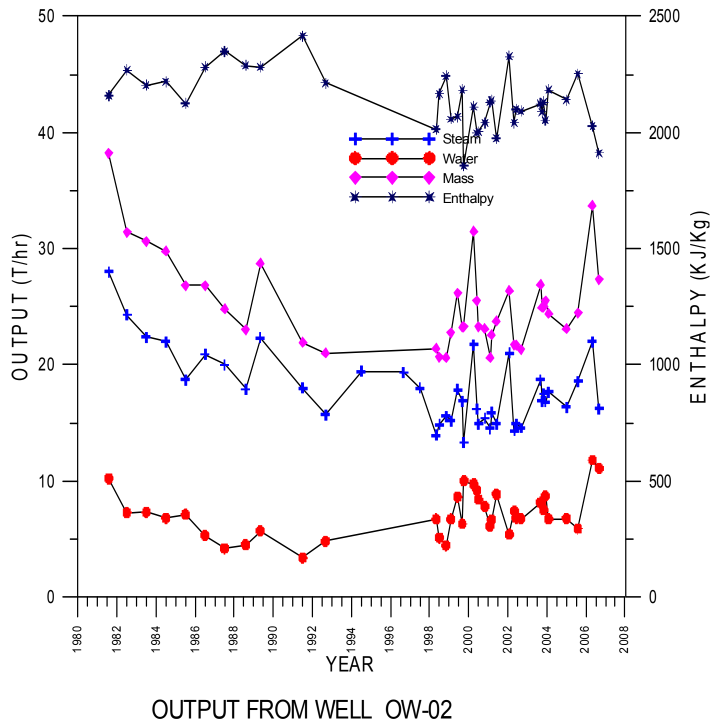


FIGURE 8: Effects of hot fluid re-injection

9. CASE STUDY - WAIRAKEI GEOTHERMAL FIELD NEW ZEALAND

Figure 9 is the map of Wairakei geothermal field showing the main thermal areas, location of borefields and power stations. The main discharge of hot water was in Geyser Valley near the northern edge of Wairakei field. Water also discharged through springs near Waikato River. Steam discharged from Karapiti thermal area to the south and Waiora Valley in the centre of the field. There are three centres of borefields, the eastern, western and Te Mihi. There are two power stations Wairakei power station commissioned in 1958 and McLachian power station commissioned in 1997.

Glover and Bacon (2000) udertook a study on the changes in natural features and well discharge at Wairakei, New Zealand since the onset of exploitation in 1952. The Wairakei bores began significant discharge in 1953 and in a period of 10 years the natural discharge increased six times (12.6 MWt to 74 MWt) the natural discharge prior to explotation. As a result there arose a large imbalance between the discharge and recharge. The consequence of this was a drawdown of pressure and a decrease of mass fluid in the field. Boiling created an enlargement of a steam zone and hence a greater flow of steam to the surface.

Dramatic changes in thermal activity have occurred in the thermally active areas of Wairakei. In Karapiti thermal area formation of a new fumarole and expansion of thermal ground was observed. There was a new hydrothermal eruption every 1 to 2 years. Heat flow increased in the steam discharge at Karapiti area from 40MWt in 1950 to 420MWt in 1964. This dramatic rise was due to the pressure drawdown in the Wairakei reservoir. The increased mass discharge and the pressure drawdown also stimulated an increase in mass recharge to the reservoir. The increased recharge and discharge resulted in a reduction of the residence time of the fluid in the reservoir. The effects of these physical changes on the chemistry are better explained in the plots that follow.

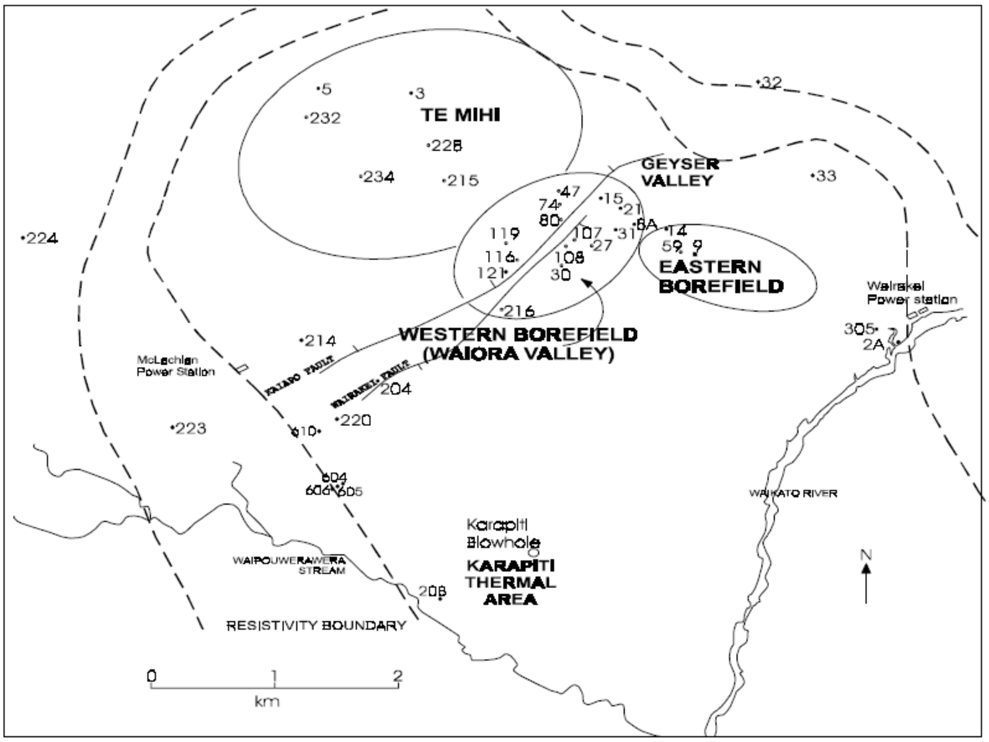
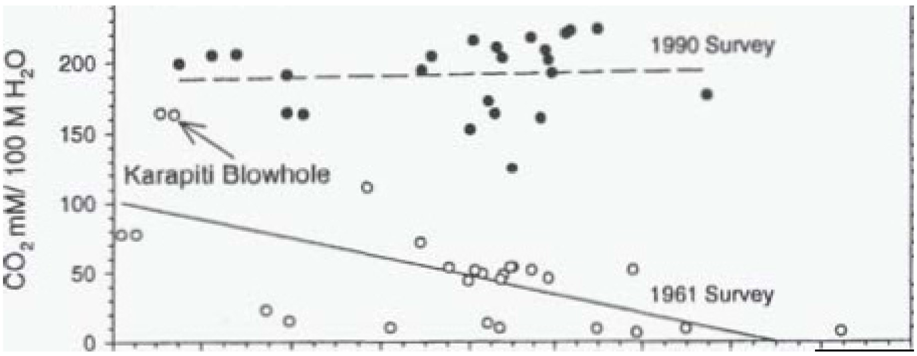


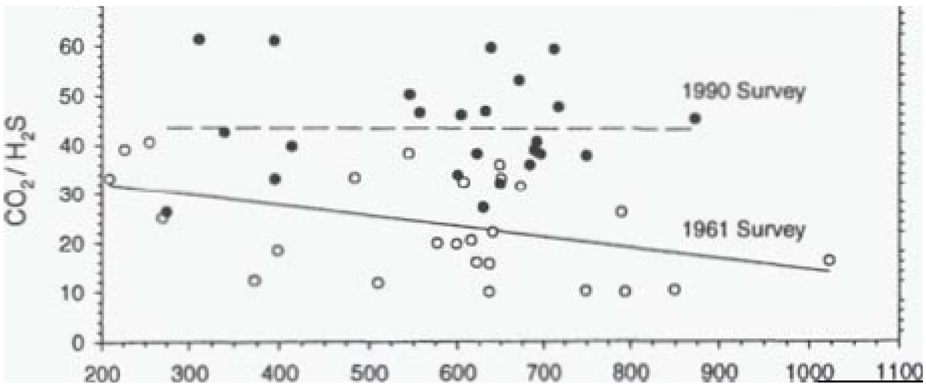
FIGURE 9: Wairakei geothermal field



200 400 600 800 1000

Distance in m from NE (left) to SW (right)

FIGURE 10: Scatter plots of 1961 and 1990 CO_2 data with the fumarole sites entered from the N end of Karapiti Thermal Area (left) to the S end (right)



Distance in m from NE (left) to SW (right)

FIGURE 11: Scatter plot for the 1961 and 1990 CO_2/H_2S data (Glover et., 1999)

The large decrease in the concentration of CO2 across the thermal area from NE to the SW is related to the loss of gas from the hot chloride water flowing under Karapiti thermal area. The hot water passing beneath Karapiti in 1961 apparently was replaced by 1969 with a steam phase drawn from the greatly expanded low pressure steam zone the Wairakei reservoir (Figures 10 and 11). This explains the 1990 CO2 concentrations and CO2/H2S ratios difference with the 1960's and is consistent with a steam zone of uniform CO2 and H2S concentrations underlying the Karapiti thermal area.

Figure 12 shows changes with time of the mass flow of chloride into the Wairakei stream in Geyser valley, the average chloride concentration of the springs, the heat gain of the stream and the mass output from the Wairakei bores. The first three parameters show an inverse relationship to the field output.

As Wairakei's development progressed, spring activity declined accompanied by dilution of the spring waters by shallow ground water. The Geysers and flowing springs of high chloride concentrations were eventually replaced by steam heated waters of low or zero discharge and by fumaroles and steaming ground.

Average chloride values for production areas show a steady decline in chloride concentrations (Figures 13a and 14) in line with the dilution and cooling of the aquifer supplying the wells. Figure 13b shows the % increase of the cold water inflow. Figure 15 shows gas flow from the bores to the power station. In the early 60's the flow rose as more wells were brought into service. From 1963 the gas flow decreased as the gas concentration in the wells decreased. The large increase in 1988 is due to the addition of the Te Mihi wells.

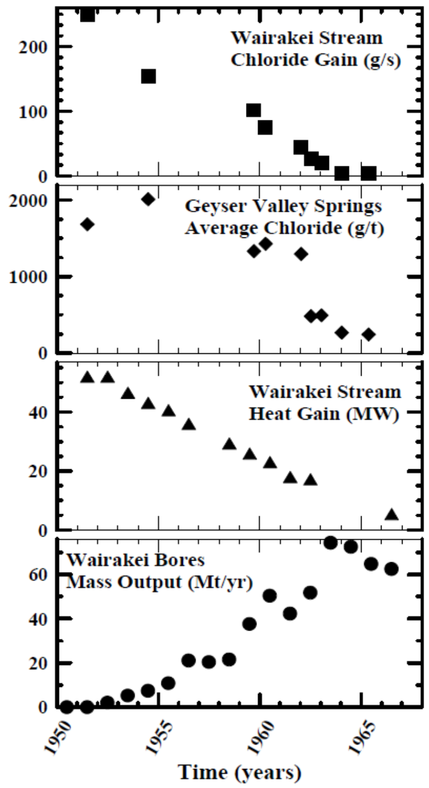


FIGURE 12: Changes in Wairakei Geyser Valley and in mass output of the Wairakei borefield (1950 - 1967)

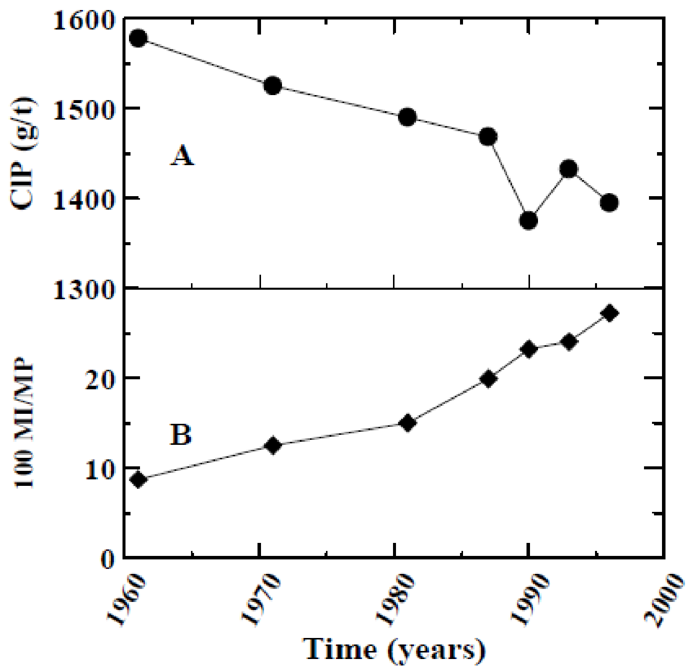


FIGURE 13a: Changes in average chloride content of the production well field Cl_p-(g/t)
FIGURE 13b: Changes in percentage of cold inflow in the production fluid (100 x M_I/M_P)

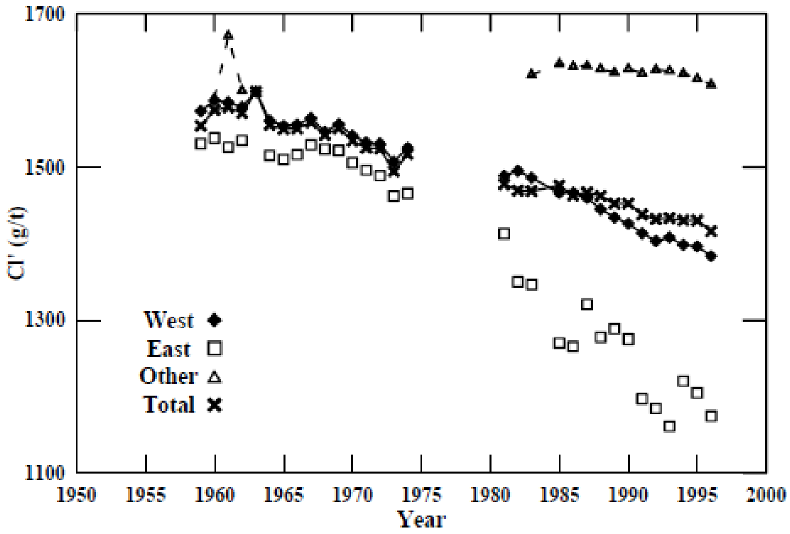


FIGURE 14: Changes in average corrected chloride (Cl′) values for the Wairakei production wells

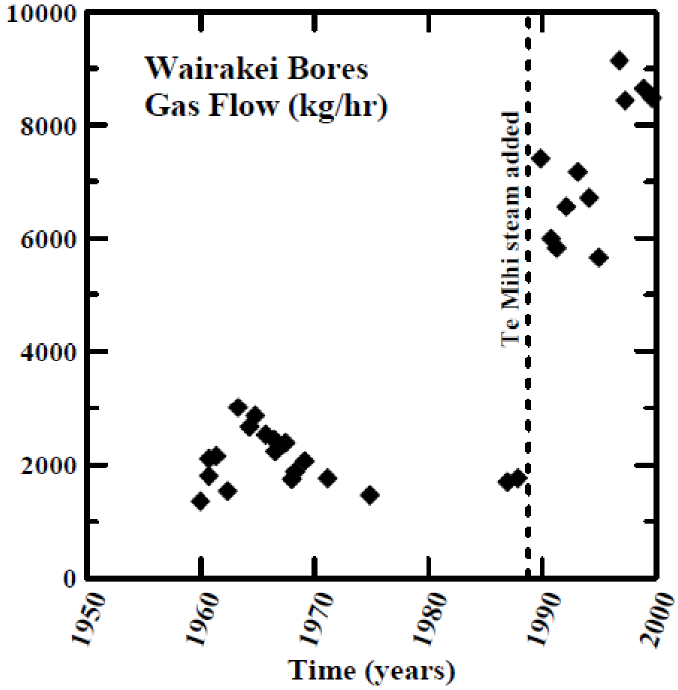


FIGURE 15: Total gas flows to the Wairakei Power Station (kg/hr)

10. CONCLUSIONS

A well planned monitoring program of producing reservoirs is vital for continued geothermal power generation and management. Major objective of monitoring is to track changes resulting from steam exploitation. Changes manifest in pressure, temperature, enthalpy and chemistry of discharge fluids. Most of these changes can be predicted using chemical data which provide information on:

- Temperature drop in the reservoir
- Incursion of colder non-reservoir water into geothermal resource
- Reinjection returns-chemical tracer testing can be used
- Scaling and corrosion tendencies

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