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GEOCHEMICAL CHANGES IN RESPONSE TO PRODUCTION AND REINJECTION FOR PALINPINON-I GEOTHERMAL FIELD, NEGROS ORIENTAL, PHILIPPINES

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ABSTRACT

Chemical changes observed for production wells since the commissioning of the 112.5MWe Palinpinon-I power station (May, 1983) have been attributed to reinjection fluid returns and in some cases, localised pressure drawdown. Although there is clear evidence for a mass front of reinjection fluid to the production sector, no thermal front has as yet been confirmed. A field management strategy has developed in an attempt to minimise reinjection fluid returns.

Chloride concentrations in separated water have been successfully used to trace. and quantify reinjection fluid returns on an individual production well and field basis. The magnitude of this and other sources of recharge depend upon power station load, production and reinjection well configurations and production well status or discharge history. Silica concentrations have remained controlled by quartz solubility despite large increases in reservoir chloride. Calcium and sulphate responses indicated dissolution of Ca-bearing minerals within the reinjection sector and re-deposition of anhydrite as fluid migrated away from the reinjection sector.

INTRODUCTION

The approach taken to geothermal development in the Philippines has been well documented (Malixi, 1982). A summary of exploration and early development for Palinpinon-I (Paln-I) has been given by Maunder, et al., (1982). A brief outline of the operating system is included here.

The surface reticulation system for two-phase fluid, separated steam and liquid is shown in fig. 1. The insert in fig. 1 illustrates in plan, the production and reinjection well tracks. Twenty-two production wells are located over four pads, twenty-one being commercial; of this total, eighteen were deviated, the remainder, vertical. Deviated wells were required to adequately access the exploitable reservoir due to terrain constraints and also to maximise intersection with identified fracture permeability. Ten deviated reinjection wells collared to the northeast at lower elevation, were drilled to dispose of separated liquid. To maximise fluid dispersal and reheating, wells were drilled deep and as distant as practicable from the production sector.

Production wells were drilled to an average measured depth (MD) of 3020m or 2865m vertical depth (VD). Reinjection wells averaged 3010m (MD) or 2890m (VD). Permeability was encountered at various depths over the open interval of hole for all wells. As such, nearly all production wells are multi-zone and produce two phase fluid from a single phase liquid reservoir. A total electrical equivalent output of 144MW(e) at a production separation pressure of 0.70MPa(abs), (165°C), is available under wellhead. Although the load and hence steam demand is variable, the production separator pressure is maintained at a constant 0.70MPa(abs).

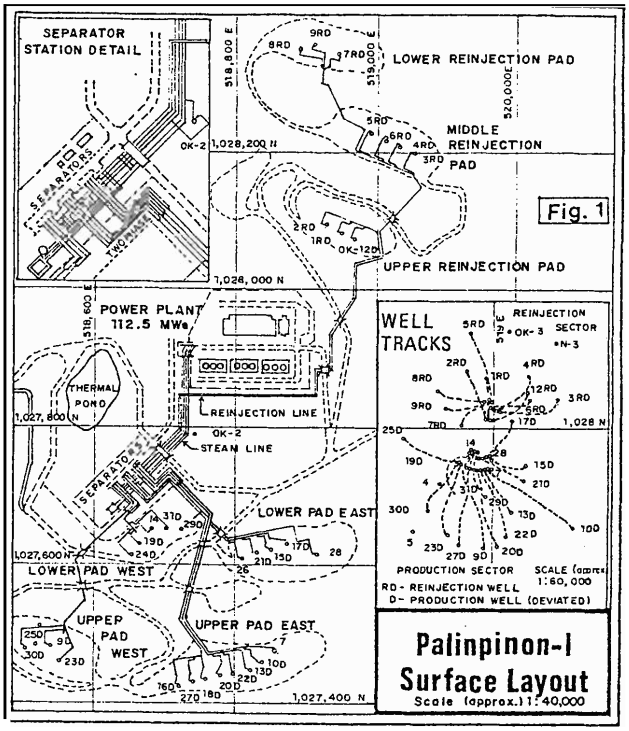

Fig. 1

Baseline, pre-exploitation chemistry has been previously reported (Jordan, 1982). Baseline data referred to in text and figures for this paper are from stabilised discharge chemistry during three month output tests (MTD), completed prior to exploitation. An intensive geochemical monitoring programme developed for Paln-I, the primary objective being to provide maximum geochemical input to assist with the formulation and subsequent review of field management policy. Early in the production history it became obvious that geochemistry would play a vital role in providing important operational guidelines for production and reinjection. Chemical monitoring parameters were chosen to reflect processes believed to be occurring within the reservoir. These were $[Cl]_{RES}$[1], $[Cl]_{ATM}$, $[SiO_2]_{RES}$, $TSiO_2$(°C), pH, $[SO_4]_{RES}$, $[Ca]_{RES}$, $[CO_2]_{TD}$[2], $[H_2S]_{TD}$, CO_2/H_2S (molar ratio). Total discharge enthalpy (h_t) was also monitored. Chemical changes were correlated with those of the operation e.g. fig.2. Selected examples which typify the chemical changes observed are presented in the following text and figures.

CHEMICAL CHANGES IN RESPONSE TO EXPLOITATION

Seventeen of twenty-one production wells have shown an overall increase in $[Cl]_{RES}$ as of May 85' (refer fig.2) The variable nature of the $[Cl]_{RES}$ responses have largely been accounted for in terms of operating conditions of individual production wells, reinjection (RI) load and the configuration of RI wells in service at any one time.

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[1] $[Cl]_{RES}$. RES denotes reservoir constituent concentrations; this better reflects the multi-zone nature of fluid production and replaces the commonly used term, "aquifer."

[2] TD = concentration in total discharge

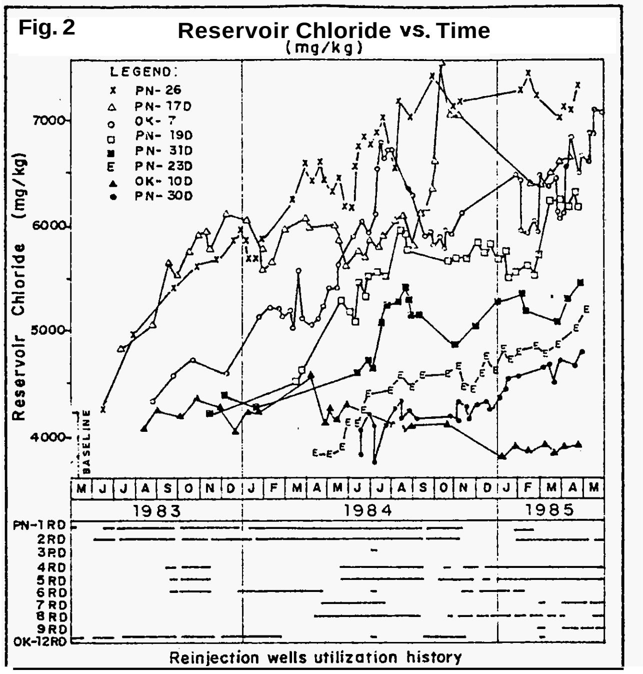

Fig. 2 Reservoir Chloride vs. Time (mg/kg)

Several processes would result in increased mineralisation:

1) extensive boiling and steam separation within the reservoir, resulting in increased [Cl] RES for residual liquid.
2) natural recharge of higher mineralised fluid,
3) reinjection fluid returns.

Discharge enthalpies and pressure-temperature profiles showed that extensive reservoir boiling had not occurred. Flashing near the well-bore and two phase conditions were corrected for excess steam when calculating [Cl] RES. Natural recharge of significantly higher mineralised fluid would be expected to originate from a higher enthalpy source, but there is no evidence to support this.

RI returns were therefore concluded to be the principal cause of increased mineralisation. Chloride ion is a relatively non-reactive ion, under reservoir conditions and is concentrated at the surface when "flash" separated. Useful information concerning the dispersal of RI fluids has been obtained using chloride as a natural tracer.

It was recognised at an early stage that RI returns were significant(fig. 2). Furthermore, since fluid containing a RI component was produced and flashed again, a method to evaluate returns,which accommodated recycling was necessary. A plot of [Cl] RI[3] vs. time for both reinjection lines is presented in fig. 3. This shows an overall increase in [Cl]RI, in response to RI returns, across the production field. Fluctuations reflect changes in production well utilisation. The large amount of [Cl] RI data available enabled accurate assessment of the percentage RI fluid being discharged by an individual well, using the following relationship:

$$X = \frac{Cl_1 - Cl_2}{Cl_3 - Cl_2} \quad \text{------------} \quad (1)$$

Where X = fraction of RI fluid in the total discharge
Cl_1= monthly mean [Cl] RES for the production well
Cl_2= mean baseline [Cl]RES for the production well
Cl_3= monthly mean [Cl]RI.

Cl_3 represents the weighted monthly mean [Cl]RI calculated on the basis of separated liquid flows for the two main RI lines. A plot of % RI returns vs. time for selected wells is presented in fig. 4. This approach takes recycling into account, hence the affect of RI wells on individual production wells can be more clearly identified.

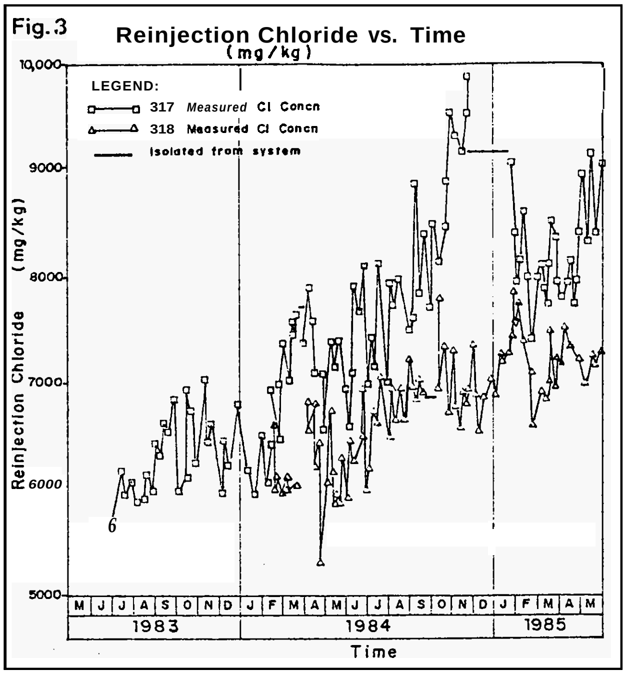

Fig. 3 Reinjection Chloride vs. Time (mg/kg)

The RI well utilisation history shown in figs. 2 and 4, provides information concerning the communication of individual RI wells with individual. or groups of production wells. Wells OK10D, PN13D, 20D and 22D have at some stage shown increased [Cl]RES but have since declined to baseline concentrations or less. From May 83' to April 84', RI wells OK12RD, PN1RD, 2RD and 6RD were utilised. Wells PN15D, 17D, 21D, 26, 28 and OK7, the first to be used for station supply, are closer to the reinjection sector than other production wells and produced significant RI fluid. The large increase in [Cl]RES and % RI fluid for PN17D, 26 and 28 demonstrated good communication (figs. 2 and 4). From May 84' to Oct. 84' a large increase in [Cl]RES and % RI fluid was observed for the westerly and central production wells PN19D, 23D, 29D, 31D, OK7 and OK9D. This occurred when RI was shifted to the western wells PN7RD and 8RD.A subsequent. recovery, i.e. [Cl]RES decline, occurred for several of these producers when PN7RD was shut. [Cl]RES has steadily increased for these same wells with PN8RD and 9RD in service (May 85').

It was considered desirable to assess mass returns on a field basis under stable operating conditions, such that when changes in individual well or field management occurred, an estimate of the response with respect

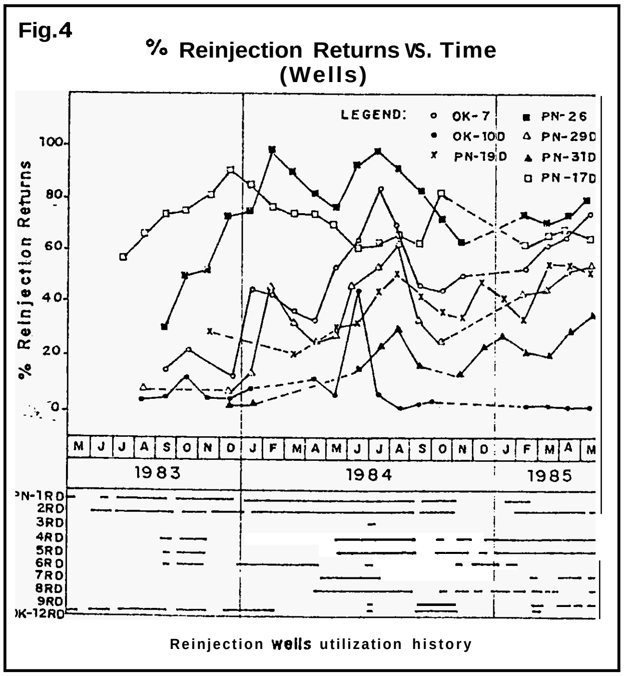

Fig.4 % Reinjection Returns vs. Time (Wells)

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[3] [Cl] RI = reinjection line chloride concentration

to RI fluid returns could be evaluated. This simplified approach involved a mass balance about the production and RI sectors with three components; production, RI and recharge, as shown in fig.5.. Eqn(1) previously given, similarly describes the mass balance around the production block. Cl_1 in this case was obtained from Cl_4 corrected for steam loss at the separator. Using a mass and energy balance about the separator it has been shown (Menzies, 1985) that :

$$Cl_1 = \left(\frac{h_5 - h_1}{h_5 - h_4}\right) Cl_4 \quad ----------- \quad (2)$$

At constant separator pressure of 0.68 MPa (abs), h_4 and h_5 can be obtained from steam tables; h_4 = 692kJ/kq, h_5 = 2762kJ/kg.

$$\text{let } \alpha = \frac{h_5 - h_1}{h_5 - h_4}$$

$$\text{from (1) } x = \frac{\alpha Cl_4 - Cl_2}{Cl_4 - Cl_2} \quad ------------ \quad (3)$$

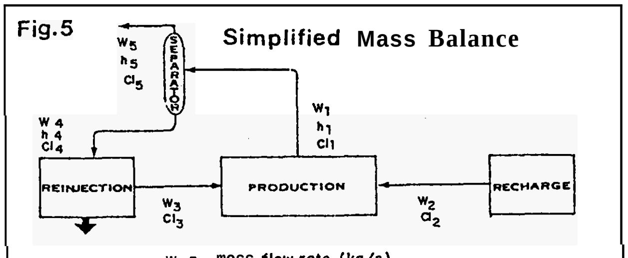
Cl_3 in eqn. (1) is assumed to approximate Cl_4 i.e. [Cl]RI. Cl_2 as recharge is assumed to be constant at 4000mg/kg based on [Cl]RES baseline data, so

$$x = \frac{\left(\frac{2762 - h1}{2070}\right) C14 - 4000}{Cl_4 - 4000} \qquad (4)$$

It was thus possible to calculate the field average monthly RI returns knowing the average field enthalpy and the average monthly [Cl]RI. Fig. 6 shows field RI returns over the period. The: strong increase noted from May to July-August 84' coincided with westerly RI to PN7RD and 8RD. A maximum of approx. 30% RI returns on a field basis has been assessed; i.e. the bulk of RI was dispersed away from the RI - production sector vicinity.

Fig. 7 shows the average % RI fluid discharged for individual production wells relative to cumulative total mass discharge. The scatter demonstrates the lack of a simple relationship. Surprisingly, several wells with low cumulative total mass discharge have shown significant RI returns e.g. PN28. This can be explained by the extended discharge of nearby wells or alternatively, the natural sweep of RI fluid to the production sector through permeable fracture paths in response to induced pressure gradients. A significant decrease in the rate of decline of measured single phase liquid pressures both in and on the edge of the production sector has been observed. This, together with the observation that several wells e.g. OK10D, (fig. 7), had low overall RI returns, indicated significant recharge from another source.

Fig.5 Simplified Mass Balance



where :
w = mass flow rate (kg/s)
Cl = chloride concentration (mg/kg)
h = enthalpy (kJ/kg)

MONTHLY AVE: % Percentage Reinjection Returns (Field Basis) vs. Time

Fig. 6

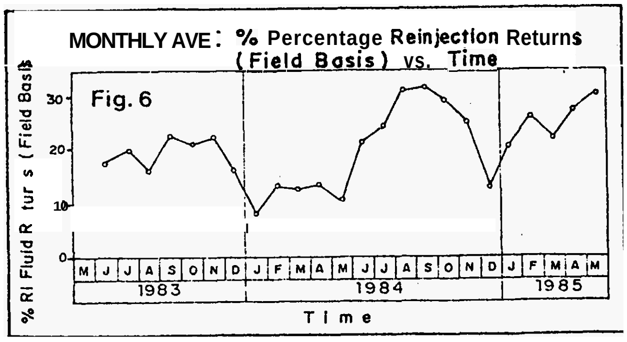
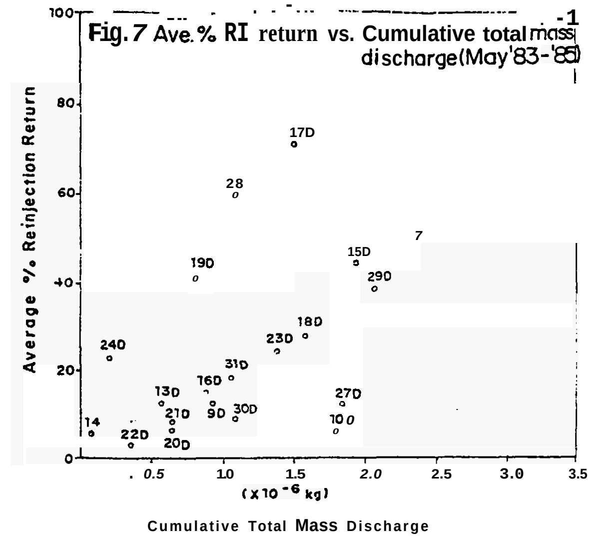


Fig. 7 Ave. % RI return vs. Cumulative total mass discharge (May'83-'85)



In view of the clear evidence that a mass front of RI fluid had reached the production sector, concern was therefore held for the thermal front which follows. No temperature decline for mixed fluid production from any well has been observed. A small decline in OK7 i.e. 310 to 300°C from a single survey awaits confirmation. Average field enthalpy has increased from a value of 1240kJ/kg prior to exploitation, to a present value of 1430 kJ/kg.

A series of tracer tests has been designed with the following objectives:

1) to assist [Cl]RES monitoring in quantification of RI returns and,
2) to assess the optimum injection well configuration based on the interpretation of tracer results.

One I-131 radioactive tracer test has been completed using OK12RD for tracer injection. A strong return to PN17D was confirmed, this being consistent with the observed chloride response in PN17D with OK12RD in service. Other small 1-131 returns were not quantifiable.

Three slus injections of di-sodium fluorescein have also been conducted for wells OK12RD, PN1RD and PN9RD. Althouqh returns can only be interpreted qualitatively, these tests have proved useful as precursors in designing the more expensive 1-131 tracer tests. Disodium fluorescein may not be thermally stable in the long term at formation temperatures, but sufficient activity remained for returns to be detected under UV liqht using a crude gradinq system €or intensity. on the basis of di-sodium fluorescein tracer tests, a strong hydrological. connection exists between OK12RD and PN6RD.

Silica Chemistry

Despite large increases in [Cl]RES for many production wells-, none have shown increased $[SiO_2]$RES, i.e. no silica breakthrough. Silica concentrations remain controlled by quartz solubility, in agreement with measured discharge enthalpies, where single phase, and flowing measured temperatures.

Separated liquid for Paln-I has an amorphous silica saturation index ranqe, from ≲ 1.0 tc 1.3 (under to oversaturated).

The fact that silica concentrations have not increased despite a mass RI return, particularly for wells with a high RI fluid component in discharye e.q. OK7, PN17D, 26 and 28, suqqested that:

(a) solutions supersaturated with respect to quartz rapidly attained equilibrium with quartz, or,

(b) rapid re-equilibration with respect to an intermediate silica mineral phase occurred upon available quartz and other mineral surfaces, with all silica above quartz saturation being deposited

Re-discharge of a RI well in Tongonan (IR5D) after more than a year of service at an injection flow rate of approx. 60 kg/s, showed that silica concentrations agreed closely with that expected for B-cristobalite equilibrium. This indicated that B-cristobalite was the silica phase deposited. (Solaña and Harper, 1985) Discharge enthalpies of approx. 850 kJ/ kg indicated that saturated liquid temperatures were approx. 200°C.

Referenced literature (Weres <u>et al</u>., 1980) indicated that fluid slightly supersaturated with respect to amorphous silica, re-equilibrated to amorphous silica saturation for a given temperature and that this fluid remained highly supersaturated with respect to quartz. Furthermore, once amorphous silica saturation was achieved, the fluid re-equilibrated to a form of silica, intermediate between amorphous silica and quartz.

The absence of a silica breakthrough in Paln-I production wells was best explained therefore, by the mechanism outlined in (b) above. This suggested that a silica breakthrough would not occur until fracture paths became lined with an intermediate silica mineral phase.

Separated liquid is supersaturated with respect to quartz by about 200mg/kg (SiO_2) at formation temperatures which obtain in the RI sector. This is equivalent to a solid volume of approximately 1.70m^3/day using a typical RI flow rate of 250kg/s and an assumed density of 2600 kg/m^3 for silica deposited. To date, this has not significantly reduced the total injection capacity for the RI sector. Negative impact due to deposition may only be realised in the long term.

An initial tracer return time of 22 hours to PN17D from OK12RD during the 1-131 radioactive tracer test provided a maximum time within which, complete silica re-equilibration occurred.

<u>Calcium and Sulphate Chemistry</u>

$[SO_4]_{RES}$ for production wells has remained essentially constant despite its concentration in injected liquid. This implies that. sulphate has been removed from the mixed reservoir fluid. Calculations of the anhydrite saturation state of the injected fluid, indicated that supersaturation would have occurred upon reheating in the reservoir. For example, using typical $[Ca]_{RI}$ of 230 mg/kg, $[SO_4]_{RI}$ of 23mg/kg and equilibrium log K data for anhydrite (KRTA, 1983) at 0.2m NaCl, the saturation index (SI) for RI fluid with respect to anhydrite is as follows; SI = **log** K (fluid) - log K (equilibrium). At the RI fluid temperature (165°C) the log activity product (**log** K) for RI fluid was - 7.30; for equilibrium, - 6.09 or a SI of - 1.21 (undersaturated). At 260°C (RI fluid re-heating), log K (fluid) was - 7.86; **log** K (equilibrium) was - 8.08, or a SI of 0.22 (supersaturated). Hence anhydrite deposition would be expected to occur far injected fluid reheated to formation temperatures.

The $[Ca]_{RES}$ increase for wells affected by RI returns was initially greater than the corresponding increase in $[Cl]_{RES}$, as shown by decreasing Cl/Ca ratios with time, in fig. 8. As anhydrite would **also** remove calcium from solution, dissolution of other calcium mineral phases was required to explain the net increase in $[Ca]_{RES}$.

Calcite is prevalent as a secondary mineral within the RI sector. Calcite dissolution was considered the most likely explanation for the net increase; this on the basis of the initially undersaturated state of the injected fluid. Furthermore, decreased fluid and formation temperatures and increased salinity within the RI sector have enchanced the solubility of calcite.

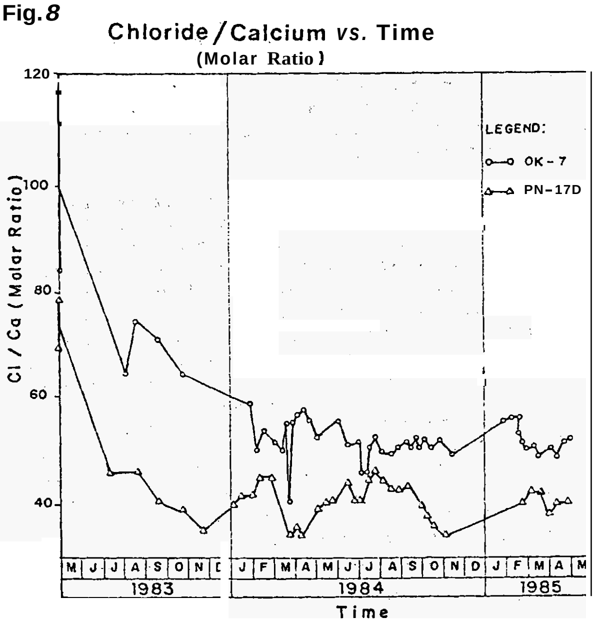
The quasi-stable minimum Cl/Ca ratio for **wells** most affected by RI returns, ranged from 40 to 50 (fig.8). This was considered to reflect either physio-chemical control **over** the rates of dissolution or the attainment of near equilibrium calcite saturation, as fluid re-heating occurred. Gross changes in $[Ca]_{RES}$ and $[CO_2]_{TD}$ **have** occurred for discharge fluid in response to RI returns. Geochemical modelling techniques (Truesdell and Singers, 1971; **KRTA**, 1983) were applied to determine **the** reservoir fluid calcite saturation state and whether this changed as RI returns increased. Emphasis was not placed on the absolute saturation state of the fluid, recognising that. modelling is at best an approximation of the fluid-mineral system under study.

The equilibrium constant for calcite is described *by:*

$$K_c = \frac{a_{Ca^{2+}} \cdot a^2_{HCO_3^-}}{P_{CO_2}}$$

(Ellis and Mahon, 1977). *An* increase in log K **for** reservoir fluid would be expected with RI returns as these have produced; increased $a_{Ca^{2+}}$, increased $a_{HCO_3^-}$ (due to a pH increase) and decreased P_{CO_2}. The saturation index (SI) has been defined as for anhydrite, i.e. SI = log K '(fluid) - log K (equilibrium), (KRTA, 1985) Results showed that for increasing RI returns there was a positive shift towards calcite saturation or supersaturation. **For** example, data for OK7 gave the following; OK7 baseline data, SI of -0.16 to SI of 0.96 when RI returns were 80%. These results also suggested that re-equilibration to calcite saturation 'was not achieved as RI fluid re-heated. Although no 'further problems with well-bore calcite deposition have occurred, evaluation of calcite saturation for reservoir fluid relative to RI returns has continued.

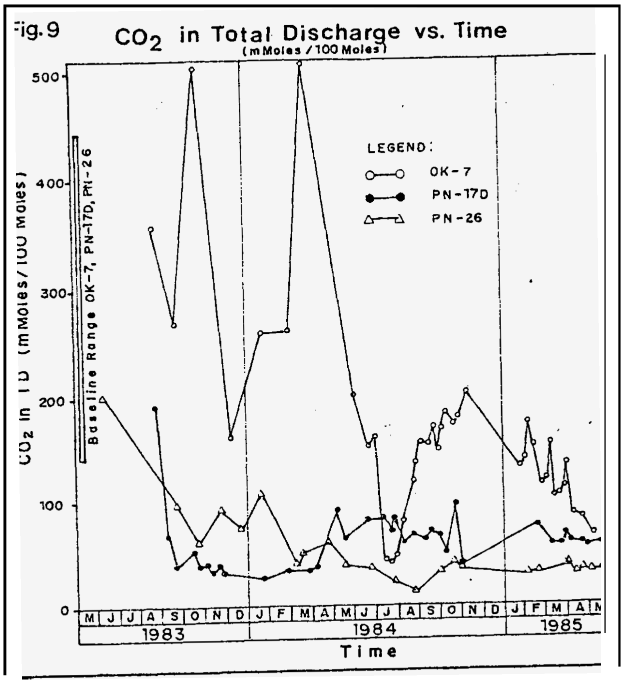
Fig.8



<u>Gas Chemistry</u>

The majority of gas is partitioned into the steam phase upon flash. Separated, liquid is depleted in dissolved gas relative to original reservoir fluid. Production wells with RI returns showed a corresponding decrease in absolute total gas concentrations, (fig.9). Well OK7 $[CO_2]_{TD}$ concentrations have decreased as much **as** 25 fold, from baseline values of approximately 360 mmoles/100 moles to 15 mmoles/100 moles. Fluid discharged by PN17D at Sept. 83' was approx. 100% RI fluid. At this level $[CO_2]_{TD}$ would be expected to approximate RI line concentrations i.e. 1.0 mmole/100 moles. However, measured $[CO_2]_{TD}$ for PN17D averaged 40 mmoles/100moles over this period. The dissolution of calcite described previously, is consistent with these higher than expected $[CO_2]_{TD}$ concentrations.

Both H_2S concentrations and CO_2/H_2S ratios have decreased for wells affected by RI fluid. The CO_2/H_2S ratio decline is consistent with the relative enrichment of H_2S over CO_2 in the remaining liquid phase after flash. CO_2 and H_2S responses have been more complex than those of the non-reactive liquid constituents. These have been clear only in those wells which have remained single phase with a high RI fluid component.

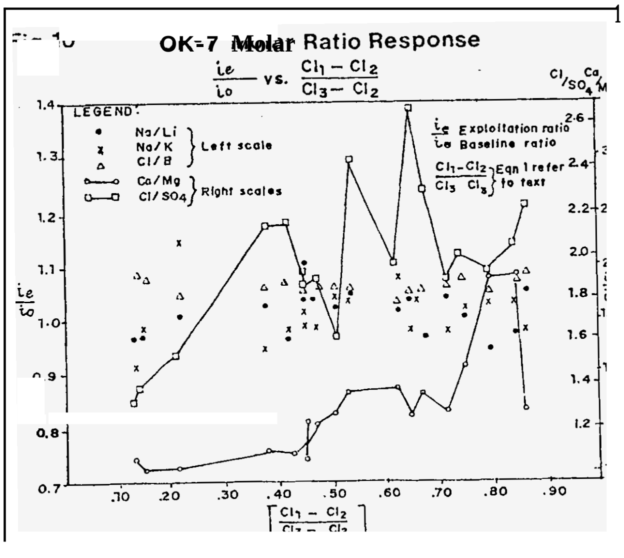


Other Parameters

A significant pH shift for reservoir fluid has been observed for wells with high RI returns. This has been explained in terms of gas depletion of reservoir fluid as RI fluid component increased. This established that RI fluid did not re-equilibrate with the feldspathic-quartz,alumino-silicate, pH controlling mineral phases prior to being re-discharged. The reservoir pH for OK7 has shown a 1.40 unit shift from 5.80 (290°C) to 7.20 (285°C) during exploitation.

Molar ratios have been plotted against chloride (fig. 10) in terms of the fraction of RI fluid as described by eqn. (1). This enabled a comparison of ion behavior with a known non reactive ion and also increasing RI returns. A ratio $\left(\frac{i_e}{i_o}\right)$ of approx. 1.0 would be expected for non-reactive behaviour. Ratios plotted in fig. 10 for OK7 data, show that Li, Na, K and B were non-reactive at all levels of RI return, within the time taken for RI fluid to be re-discharged.

This was in contrast to chances in Cl/SO_4 and Ca/Mg ratios. These changes reflected stable sulphate and magnesium concentrations but variable chloride and calcium respectively. Variations in Cl/SO_4 ratio can be explained by [Cl]RI variations. However, differences in Ca/Mg ratio for the same RI return e.g. 0.80, were thought to reflect variable rates of dissolution of calcite.



MINERAL DEPOSITION

Calcite deposition occurred early in the discharge history, at or near the flash point in wells PN13D,15D and 21D. Predictive techniques used to evaluate the degree of calcite saturation for reservoir and flashed fluid have been used with limited ~ ~ ~ cies forewarning problems resulting from calcite deposition. All wells produce from multiple feeds. Several have two-phase production above the flash-point, thus many of the basic constraints of the geochemical modelling techniques were not satisfied. In view of these limitations, a policy of restricting localised drawdown was implemented; this, in an effort to limit deposition to the wellbore. No further problems with calcite deposition have been encnuntsred.

Anhydrite deposition occurred in OK10D, PN13D, 20D and 22D. It has formed principally while the wells have been shut but was believed to have formed in some cases durinq discharge. Deposition in the shut well was due to the admixture of sulphate rich fluid which downflowed, with deeper, hotter, calcium rich neutral fluid. The small inflow of sulphate-rich fluid appeared to be more common under shut conditions. Hence, a policy of bleeding or continuous discharge of susceptible wells has been implemented.

ACIDITY

PN22D became acidic after a relatively short period of discharqe to Paln-I; PN20D has recently shown signs of an acidic, sulphate rich feed. Sulphate rich fluid was recoqnised at shallow levels in the production reservoir frcm the early discharge of the shallow exploration well, OK2. A sulphate-rich fluid component in total discharge was not detected for any dedicated prcduction well during routine output testing. Nevertheless, it was recognised that this fluid represents potential recharge under exploitation.

Data for the period Sept. 83' to Feb. 84' showed that PN22D was becoming increasingly acidic. This occurrence was the first detected in the production sector. The acidic discharge was characterised by low pH and Cl^-, and high SO_4^{2-}, Mg^{2+} and H_2S concentrations. Samples collected at atmospheric pressure showed a pH decline to 4.23 (28°C) under fully open conditions. When the well was throttled the pH declined to 3.63 (28°C).

Magnesium has proved to be a useful siqnature for acidic fluid, hecause it is more mobile under these conditions. Maqnesium concentrations in PN22D increased significzntly prior to a recognisable pH decline or $[SO_4]$ RES increases. [Mg] RES was approx. 0.15 Mg/kg under neutral conditions and increased to 2.50 mg/ kg undsr acidic conditions. Unlike all other wells, both PN20D and 22D have shown increases in [Mg]RES.

Anhydrite obstructions in both wells, are believed to have resulted in a change in the relative contribution of acidic and neutral fluids to the discharge.

PN20D is used €or reserve production. PN22D has been taken out of service pendinq the results of a study to seal off acidic-sulphate production.

SILICA DEPOSITION

The separation pressure for Paln-I,(0.70MPa. abs.), was chosen on the basis of specified turbine inlet pressure, steam supply design considerations and estimated silica concentrations for the flashed fluid. Amorphous silica saturation indeces ranged from ≤ 1.0 to 1.30 for separated liquid at 165°C. On the basis of experimental and documented field evidence (Weres et al., 1980) and measured transit times for the separated liquid to reach RI wellheads, (5-8 mins.), deposition should have been ccntrolled by the slow rate, molecular deposition mechanism. However, heavier deposition than would be expected, has been observed in RI lines. Analysis of this scale under a scanninq electron microscope has revealed that the deposits were largely colloidal in nature and cemented by molecular (amorphous) silica.

These deposits reflect deposition from a partially polymerised fluid. These observations have still to be reconciled with available experimental and field. data. Debris from early commissioning and ejected cuttings may have seeded deposition. To date silica deposition has been considered operationally acceptable.

SUMMARY AND CONCLUSIONS

The return of injected fluid to the production sector has been confirmed and quantified. Field management decisions have been made on the basis of chloride monitoring and tracer tests. These have principally concerned the choice of reinjection wells.

Wells OK12RD, PN6RD and 7RD which showed good communication with the production sector have been classified as low priority injectors. On the basis of both chemical and pressure responses the currently preferred reinjection well configuration is, PN2RD, 4RD, 5RD and 8RD.

The return of injected fluid to the production sector has had. no adverse impact on production. Pressure and chemical responses have shown significant recharge from another source.

Analysis of produced fluid has confirmed a trend of increased saturation with respect to calcite. However, calcite deposition to date has not been a major problem.

The fornation of anhydrite deposits in the well bore is avoided where practicable by continuous discharge. This is considered important strategy for the control of production from shallow acidic feeds.

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