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COLD WATER INVASION IN PRODUCING LIQUID DOMINATED GEOTHERMAL RESERVOIRS

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ABSTRACT

Pressure reduction at depth as a result of fluid withdrawal has resulted in cold water invasion in several liquid dominated geothermal reservoirs. Cool waters enter the hot reservoir by the same paths via which surface springs were fed before exploitation, and cooling is first observed in wells near such features. In some reservoirs the affected areas are restricted in depth and area. Understanding the cooling processes can provide the reservoir engineer with extra information about the reservoir structure and performance. Such cold water invasion appears now to be expected in most liquid dominated reservoirs, although this response may be difficult to separate from reinjection effects.

INTRODUCTION

Liquid dominated geothermal systems have now been developed for production in many locations around the world. In several of these fields there is evidence of cool waters from aquifers above the hot resource flooding into the hot reservoir and seriously affecting production. The basic reason for this cool influx is accepted as reversal of flow in the channels which in the natural state allowed the hot water to pass from the deep reservoir to feed the surface chloride springs. With field development and fluid withdrawal the deep pressures are reduced relative to the overlying cool groundwaters and downflow commences where suitable channels are available. This paper examines the evidence for such cooling, the implications of invasion by cool fluids on our understanding of reservoir structure and the philosophy of exploration and development of liquid dominated geothermal systems.

WAIRAKEI

In relation to other liquid dominated systems, the Wairakei reservoir is large both on terms of volume and the dynamic throughput of fluid. The area of hot reservoir is at least 15 km^2 and is hydrologically connected to the adjacent Tauhara geothermal reservoir which covers approximately the same area. The natural mass throughput at Wairakei before exploitation is estimated at 400 kg/s. Analysis of gravity changes indicates that since the mid-1970's there has been mass equilibrium in the reservoir, therefore the production flow of 1700 kg/s must be matched by a similar recharge flow (Allis, 1981). Approximately half of this recharge is attributed to increased upflow of 265°C fluid into the base of the reservoir.

Pressure effects of production were observed in 1953, almost immediately after well testing commenced (Grant, 1988). After commissioning of the first stage of the power station in 1958, mass withdrawal rate rapidly increased and temperature declines and chemical dilution effects were confirmed by 1961. Wells in the northeast, nearest to Geyser Valley (figure 1), were first affected. The cooling trend spread quickly southwest towards the highly productive wells in the Western Borefield where the major fluid withdrawal was occurring. This cool water invasion has previously been attributed to flow along fractures and faults parallel to the local faulting pattern. Detailed review of the data indicates that alternative interpretations may be possible.

A plan of the main production area at Wairakei is shown on figure 1 and a section through the Western Borefield NE to Geyser Valley is shown on figure 2. Casing depths and elevations of the feed points where cool fluid is intercepted are plotted on figure 1. This shows the cool fluid is intercepted by wells between elevations +200 and +50 masl, within the upper part of the Waiora Formation, normally considered as the main producing aquifer.

Few measurements have been made which unequivocally indicate pressures within the cooled zone. Those that are available (Bixley, 1986; Wainwright, 1970) show that these pressures are significantly higher -by about 5 bar - than the hydrostatic pressure gradient observed in the deeper hot liquid reservoir. Where a well intercepts feed points in both the shallow cool zone and the deep reservoir, this excess pressure drives a strong internal downflow within the well. Large downflows have been measured in two such wells, WK101 and 107, which had flowrates of 40 to 50 l/s (150-180 t/h, Syms and Syms, 1980), and smaller flows are present in other wells. The cool inflow levels in wells WK101 and WK107 have since been cased off and the wells returned to production.

Casing depth: With few exceptions, the cool fluid is only seen in shallow-cased wells, with production casing set between +70 and +200 masl. Where wells are cased deeper than 0 masl, only the hot reservoir fluid is found, and these deeper-cased wells even within the area showing massive cooling at shallow levels, show no excessive chemical dilution or cooling of the deep geothermal fluid. Wells cased between +200 and +250 masl, frequently produce low pressure steam with no liquid (see figure 2). Thus the "cool" zone is sandwiched between an overlying vapour-dominated zone and a lower liquid zone.

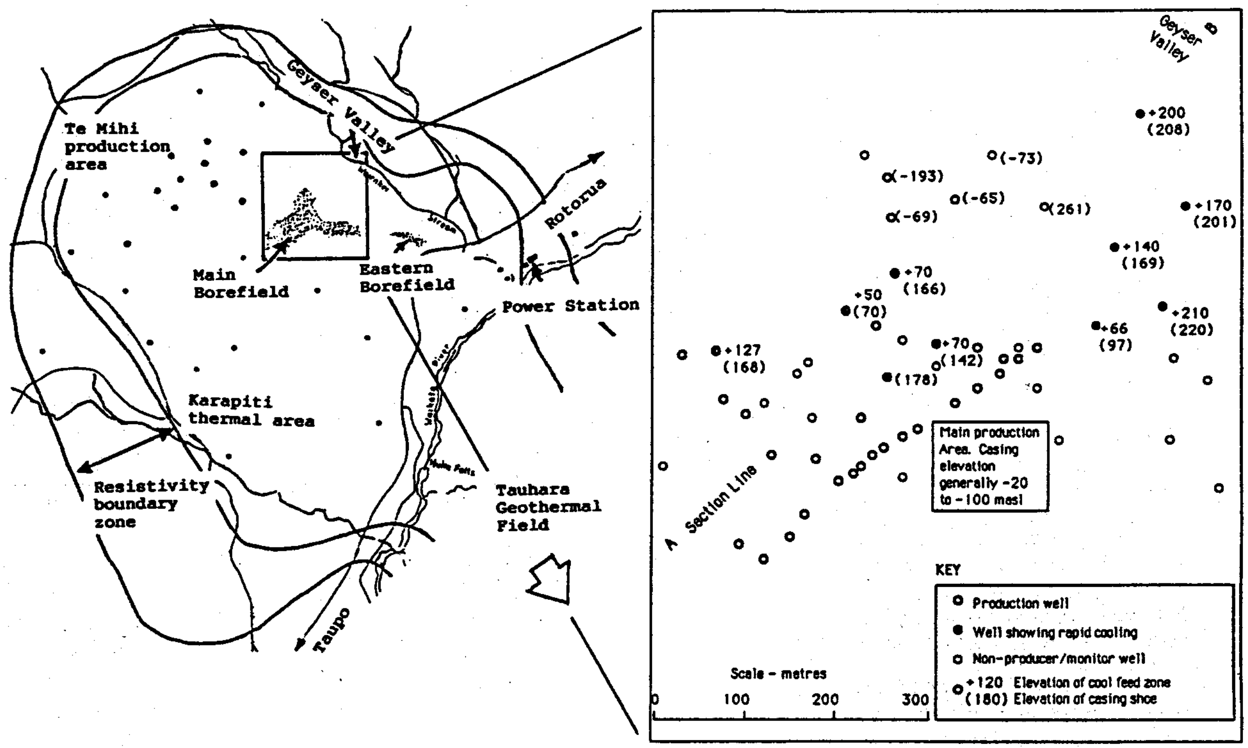

Figure 1. Wairakei geothermal field showing main production area and wells with rapid cooling.

Downhole temperatures measured in wells most affected by the cool inflows are plotted on figure 3. This shows cooling along what is essentially a single trend-line for all the affected wells, distinctly different from the normal liquid feedwater temperatures found in the reliable producing wells. Chemical data for these wells also shows differing trends: The reliable producers showing a slow decrease from original reservoir values of about 1600 ppm in 1960, to about 1500 ppm in 1981, while the cooling wells show rapid dilution , decreasing values as low as 300 ppm, indicating that mixing with cooler, lower chloride waters is occurring, for example WK21 and 31 in Glover (1977).

Interpretation: Key factors common to wells most affected by cooling at Wairakei are well location and casing depth. Location: Wells are located between the major natural outflow area and centre of major fluid withdrawal. Casing depth: The wellbore must be exposed to formation between +50 and +200 masl and for a significant internal flow to develop zones of high permeability must be intersected both in the upper cool zone and in the deep hot liquid: The cool zone is limited in vertical extent and above the main production area has spread horizontally over at least 500 metres. Fluid/formation temperatures in the cooling zone appear to have been similar throughout the whole zone as it has cooled, although chemical monitoring of producing wells indicates a cooling dilution front spreading from east to west across the main production area (where wells have suitable casing configuration to intercept the cool fluid).

The data shows that the cool fluid is quite extensive laterally, but over a very limited depth interval. Although there is a significant over-pressure in the shallow zone, there does not appear to be massive cool invasion of the deep reservoir, except via wells which link the two levels. If vertical faulting is present, it does not appear to play a significant part in the hydrology controlling the distribution of this cool water, except to provide channels between the surface and the base of the Huka formation. Also, there must be near horizontal aquicludes within the Waiora Formation to restrict access of the cool fluid into the deeper reservoir. Grindley (1965) describes the Member 5 unit of the Waiora Formation as "interbedded ignimbrites, tuffs and minor breccias with several thin siltstone bands". The presence of layers with poor vertical permeability is also indicated by zones of mobile vapour which are often encountered in the main production area within the Waiora Formation just beneath such features. Without a direct link between the deep hot reservoir and the overlying cooled zone it is difficult to explain the pre-exploitation conditions of high temperature fluids (220°C) immediately beneath the Huka "caprock". Perhaps mineral deposition since exploitation commenced has sealed off the natural flow paths. Extensive calcite deposits have formed just below the inflow point in all wells with measured downflows.

Source of the Cooling Water: At Wairakei there is an extensive network of shallow wells used to monitor changes in groundwater levels. A large depression has

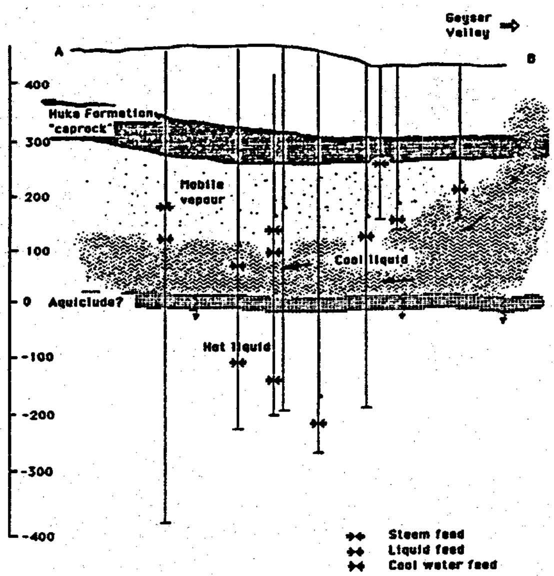

Figure 2. NE-SW section through main production area to Geyser Valley. Location of section shown on figure 1.

developed in the groundwater table above the area where cooling was first observed (Allis 1982a). Thus while the groundwater may not be the direct source of the cool fluids, fluid drainage from intermediate depths is drawing down the surface water.

KAWERAU

Field development and production commenced at Kawerau over much the same period as at Wairakei. The first exploration wells were drilled by Government Departments in 1952, and a series of seven production wells were completed on a grid approximately 200 by 500 metres by private developers in 1956-57. The production wells were drilled to supply process steam for a paper mill then under construction. The wells were initially highly productive, producing considerably more steam than had been anticipated. But after a two-year extended production test, flowrates had declined to such an extent that they could not supply the design steam load. In 1960-61 the wells were worked over to remove calcite scale, and downhole temperature profiles showed temperature declines of as much as 20°C in four years, with temperature reversals in most wells at their producing depths. One well showed gross cooling of more than 50°C (Dench, 1962).

All of these wells were originally completed to about 580 m, with a single string of 8-5/8 inch casing, cemented from surface to about 300 m, and slotted from there to bottom (typical well design is shown on figure 4, together with later modifications). Bottomhole temperatures were 240 - 260°C before production commenced. It was concluded from the 1960 investigations that the primary cause of the decline in production rates was temperature decline, with the calcite scaling as a secondary factor. In 1962 the wells were deepened to about 1000 m and uncemented liners placed across the original perforated sections to restrict access to the well by cool water. All wells showed temperature, pressure and flowrate increases following the remedial work which had been very successful: Production from one well increased to 60 t/h of separated steam, with an average of 30 t/h per well.

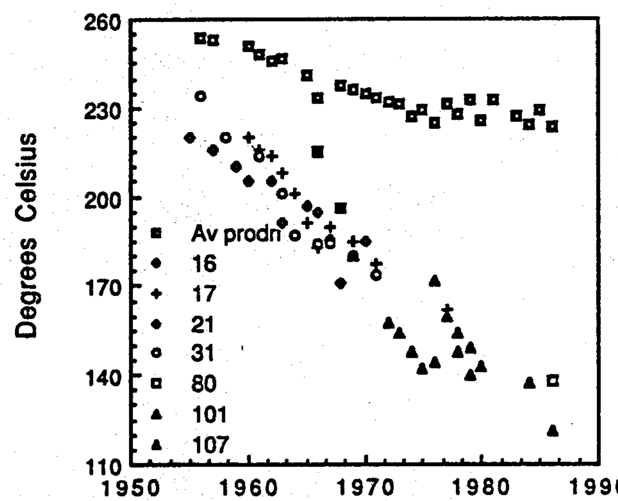

Figure 3. Downhole temperatures measured in wells showing rapid cooling. "Av prodn" temperatures is an average of feedwater temperatures in the main production area.

These reconditioned wells were again put on production, and although producing reliably, their output slowly declined and three new makeup wells in a new area of the field, cased to 500 metres, were completed in the early 1970's to maintain production rates.

Geology: The geology and structure at Kawerau is somewhat different than that found at Wairakei. The producing formations at Kawerau are fractured andesites, and there is no formation that can be described as a caprock. The initial production created a local, lower pressure boiling zone in a small area of the reservoir. But in the longer term, downhole pressures showed no significant drawdown. As there was no large natural mass throughput and the producing formations are effectively open at the top, recharge fluids must be drawn from the cooler aquifers above and around the hot reservoir to maintain pressures.

Grant (1977, fig 5) has plotted the cooling rate and cumulative mass discharge for the major producer, well KA8. Although the data is somewhat sparse, similar relationships can be drawn for other wells, some of which show cooling to less than 200°C. This data indicates a simple relationship exists between casing depth, cumulative mass produced and temperature decline.

As at Wairakei the story is not quite this simple. Casing design and installation has been one of the main factors in long term well performance at Kawerau. In the initial well designs, the production casing and slotted sections were installed as a single string, with the upper part cemented using a stage cementer, and the lower section perforated and uncemented (figure 4). While there may have been sufficient cement placed to seal the annulus initially, this was either lost to the formation or soon degraded and allowed cool fluids to flow down the casing-formation annulus in several wells (once deep pressures had been reduced relative to groundwaters, by production). Mixing of the deep hot fluids and the cool

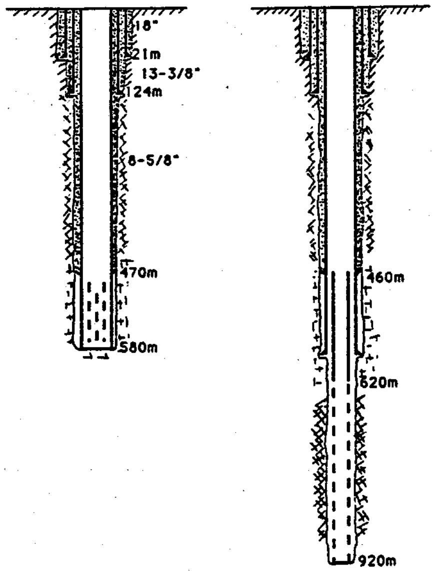

Figure 4. Typical well designs used in the Kawerau field. Original well completion on left, with single production casing string and stage cementer separating the upper cemented section and the lower uncemented and perforated section. on right, well design following 1962 workover and deepening.

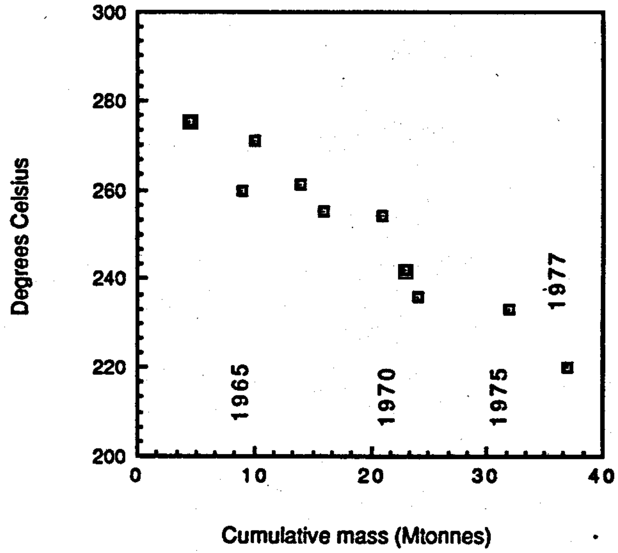

Figure 5. Kawerau KA8 feedwater temperature at 790 metres depth (after Grant 1977).

near-surface fluids not only reduced the overall quality of the well discharge, but caused severe scaling problems. Despite several attempts it has not been possible to economically repair wells with these cementing problems.

Interpretation: At Kawerau the lack of any formations to control vertical fluid movement above the producing horizons has allowed cool recharge to enter the hot reservoir by the most direct route, from above. Cooling of produced fluids was made worse by poor casing design and installation practises on several of the original wells. Clustering of production wells very close together probably made the cooling process worse than it would have been otherwise.

Since 1975 production casing depths at Kawerau have been increased to 650 metres and to date wells with this configuration have shown none of the problems of the early, shallow-cased wells, although chemical data indicates that significant dilution by cooler fluids is still occurring (Henley 1982).

As with Wairakei the serious cooling appears as a restricted invasion of part of the reservoir, rather than massive flooding of the production zone.

BROADLANDS (OHAAKI)

As yet the Broadlands field has had only a relatively short period of production (1967 to 1971 at about 30 MWe equivalent. Production for the 100MWe power station began in mid-1989). Even with this short production period, a significant drawdown of the shallow groundwater table was observed over part of the reservoir in 1971, coinciding with the area of chloride outflow before development disturbed the natural pressure regime (Allis 1982b), indicating that flow reversal had occurred in the outflow structures. Accordingly, dilution and cooling at least in this part of the deep reservoir would be expected with longer production times. As at Wairakei there are indications of lower permeability horizontal layers within the producing aquifers, thus rapid cooling should be restricted in its effects.

OTHER FIELDS

Severe cooling in parts of the reservoir has now been observed in Tiwi (Alcaraz et al, 1989) and Cerro Prieto (Grant et al, 1984). At Tiwi the cooling appears to be more pervasive than has been observed at Kawerau or Wairakei, but this may be related to the relative rates of mass withdrawal. In more recently developed reservoirs, contamination of the hot resource by reinjected waters may prevent easy chemical and physical detection of cooling by natural fluids.

DISCUSSION

It appears that conditions allowing influx of cool waters may be the general rule, rather than the exception for liquid-dominated geothermal fields. In this case suitable steps should be taken during the initial field exploration in order to have a rational approach to the potential problems or at least have the background technical material available should cool invasion become a problem later.

As the geothermal reservoir is a dynamic system, linked from the surface through to the deep upflowing fluid, a knowledge of the temperature, pressure and fluid distribution between the hot reservoir and the surface is a minimum step. During most exploration programmes such potential data is usually ignored in the rush to reach the valuable hot fluid. The desired information can be obtained by stage testing of wells prior to running the shallow casings, although this approach will usually result in considerable, and usually unacceptable, increases in drilling costs. Alternatively pressures can be measured at permeable zones as they are encountered, at minimal additional cost using the method described by Bixley and Berry (1984). Once development is committed, shallow monitor wells are necessary to determine the response of aquifers surrounding and above the hot resource to its exploitation.

Where dilution and cooling has been observed, the information may be used to better understand the structure and processes operating in the reservoir. At Wairakei the cooling pattern has provided extra information on the hydrological structure and response of the reservoir to exploitation. Apart from providing a path for the cool fluids to enter the top of the reservoir through the Huka formation "caprock", faults appear to play no part in the distribution of the cool fluids within the main producing area at Wairakei.

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