LOCATION OF PRODUCTION ZONES WITH PRESSURE GRADIENT LOGGING

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ABSTRACT

The fact that geothermal wells produce from only a limited number of discrete fractures or "feed zones" often gives rise to confusing temperature and pressure logs. This is because the wells frequently are flowing from one zone to another while the measurements are made--even though the well is shut in. Interpretation of the temperature and pressure logs is then difficult unless the location of the feed zones can be determined and the internal flows recognized. Although this may often be determined by an experienced reservoir engineer there remains considerable room for ambiguity. This paper presents a method for locating the feed zones *and* simultaneously registering upward or downward flows by comparing the measured pressure gradient with the hydrostatic gradient calculated from a simultaneously run temperature log. Demonstration of the technique in Cerro Prieto is shown.

INTRODUCTION

Two important features of most geothermal reservoirs give rise to a characteristic behavior of shut-in wells where geothermal fluid flows within the well from one level to another without ever reaching the surface. First, the reservoir fluid resides principally in fractures which form the major conduits for flow and are thus the major source of permeability. Therefore fluid enters a geothermal well only at the points where the well intersects one of the fractures--in many wells only one or two such points are found. Second, the reservoir fluid is hydrodynamically unstable in that temperatures increase and density decreases with depth. Therefore convection occurs and the net pressure gradient in the hotter part of the reservoir is greater than hydrostatic due to the very slow upward flow of water. As a result of these two situations, when a well is open to (for example) two fractures at different depths, fluid flows upward from one entry to the other because of the difference in pressure between the two. It is clear that it is in fact *impossible* for the well to be static unless the pressure gradient in the reservoir is hydrostatic. Later in the life of the reservoirs, downflows can also occur due to changing pressure/depth characteristics in the reservoir as phase separation occurs.

As a result of these upflows and downflows, the temperatures and pressures measured in *a* standard wireline log do *not* represent those of the reservoir except perhaps at the major point of fluid entry into the well. At all other points the measured pressure and temperature are only those of the fluid in the well as it flows past the instrument. In order to correctly determine *reservoir* temperatures and pressures it is clearly imperative to correctly interpret the positions of the feed points and, if possible, determine the direction and strength of any interval flows. At present there exists a body of knowledge or interpretation collected over years of field experience, for example by Grant (1979) in New Zealand and by Stefansson and Steingrimsson (1980) in Iceland. However the interpretation is based on recognition of various characteristic behaviours--for example an internal flow registers on the temperature log as a constant temperature line between the two feed zones. Such recognition relies frequently on the skill of the engineer in seeing the features of the behaviour amongst the irregularities of the log, and also often relies on his or her absorbing salient information from several sources at the same time in order to reach even a tentative answer. For example, Figure 1 shows temperature profiles in the New Zealand well Rotokawa 3 during injection testing and subsequent heating. The suggested interpretation is that the well has two major feed zones, one at 500 meters and the other at 850 meters depth--readers are invited to try thei own interpretation.

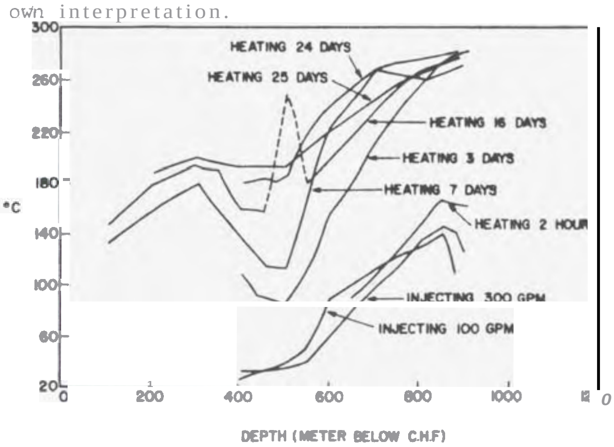


Figure 1; Rotokawa 3 temperature profiles

Thus, despite the obvious benefits of this type of interpretation, there remains a certain amount of fuzziness in the conclusions reached. A more straightforward method for daily use would be highly desirable. One obvious and direct method is the use of a downhole flow meter, as described by Syms and Bixley (1979), Syms, Syms, Bixley and Slatter (1980), and Syms, Syms and Bixley (1980). However the use of a flowmeter in geothermal wells is often problematical due to the high temperature and corrosive environment. Consequently high-priced spinner tools are usually used only during injection tests in which the well temperature is substantially reduced by the injected water: for example as described in Syms and Bixley (1979). Some success has also been obtained in New Zealand with a non-mechanical device known as a Slatter disk (Syms, Syms, Bixley and Slatter, 1980), which registers at the surface the drag on a disk placed in the flow stream downhole. The device, although ingenious and simple, is probably also best suited for injection tests (or in any configuration in which water flows *down* the well).

Thus there remains the problem of measuring the internal flow in the well in instances where the well is shut in but flowing internally (usually upwards) from one feed zone to another. This paper describes a method of estimating the magnitude and origin of the internal flow using only the standard pressure and temperature logs. The logs are to be run simultaneously, after which the pressure *gradient* determined from the pressure log is compared to the hydrostatic gradient calculated from the temperature log. This technique is demonstrated in well number M-9 in Cerro Prieto, which provides an ideal test case since the well feeds through gun perforations in the casing at a known depth.

PRESSURE GRADIENT TECHNIQUE

The principle of the technique is simple. A static (non-flowing) well will exhibit a hydrostatic pressure profile with the pressure gradient at any depth proportional to the density of the well fluid at the temperature at that depth. On the other hand, any movement of fluid in the well will result in a change in the pressure gradient--an increase above hydrostatic for upward flow and a decrease below hydrostatic for downward flow. Thus comparison of two pressure *gradient* with depth profiles (one determined from the pressure log and one from the temperature log) will effectively provide flow metering capability--enabling a direct determination of the location of the feed zones as well as the direction (and even possibly an estimate of the magnitude) of the internal flow.

FIELD EXAMPLE - CERRO PRIETO WELL M-9

Well M-9 in Cerro Prieto, Mexico, is completed to *4635* feet total depth and is cased to 3481 feet with slotted liner below *3588* feet. The well is unusual, however, in that the 11 3/4 inch casing was gun perforated between depths 2348 and 2810 feet, and these gun perforations were subsequently squeezed and a blind 7 5/8 inch liner cemented inside the 11 *3/4* inch casing to a depth of 3252 feet. A schematic from Dominguez (1978) showing the completion program is given in Figure 2.

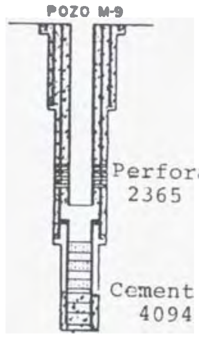


Figure 2: Cerro Prieto well M-9

The data used to test the pressure gradient procedure was collected by Lawrence Berkeley Laboratory on October 26, 1979, during a test of a combined function tool they had developed. This study uses pressure and temperature profiles from their survey number 10. Table 1 summarizes the pressure and temperature values measured during this survey, as well as the pressure gradient and hydrostatic pressure gradient calculated from those values. Figure *3* shows the two pressure gradients plotted as a function of depth. Unfortunately the frequency and accuracy of the pressure measurements in the survey are not sufficient to determine the pressure gradient closer than within two or three psia/100ft., however some features are immediately obvious. There is a clear indication of a 10 percent superhydrostatic gradient below 3100 feet, suggesting an upward flow initiating from around 3300 feet in the slotted lines, and flowing up as far as the bottom of the blind 7 5/8 inch liner. This behaviour is indicative of a cement failure subsequent to the squeeze job in the gun perforations at 2348-2810 feet and flow behind the 7 5/8 inch lines up to this level. This interpretation is more striking if compared to the pressure gradient profiles in the same well (Figure 4) just after the recompletion on July 2, 1975. At that time the actual pressure gradient follows the hydrostatic pressure gradient almost exactly, presumably because the gun perforations had been effectively plugged.

In both Figures 3 and 4, the measured pressure gradient differs almost uniformly (with the exception of the features already described) from the hydrostatic gradient by about 2 psia/100ft. This could be due to drift in either of the instruments, or to the small bleed flow in the well. The small zig-zags in Figure *4* are due to the inaccuracies in taking differences in pressure from the pressure log. Similar-sized zig-zags appear in Figure *3;* however in neither case are these inaccuracies anywhere near as large as the change in gradient indicated in the upflow. The superhydrostatic gradient in geothermal reservoirs is commonly of order 110% of hydrostatic (as it is in this case): Tongonan in the Philippines, for example, has a similar difference (Whittome and Smith, 1979).

Depth(ft)	Pressure(psia)	Temperature(°C)	Pressure Gradient (psia/100ft)	Rydrostatic Gradient (psia/100ft)
100	153.4	138.2	---	40.21
200	195.0	138.2	41.60	40.21
300	237.1	139.0	42.10	40.17
400	279.6	139.0	42.50	40.17
500	323.4	138.2	43.80	40.21
1000	533.0	138.2	41.92	40.21
1500	744.6	138.2	42.32	40.21
2000	956.5	139.8	42.38	40.17
2500	1166.1	148.9	41.92	39.97
2560	1201.3	153.8	---	39.74
2570	1205.4	---	---	---
2580	1203.5	---	41.00	---
2590	1213.7	---	41.00	---
2600	1217.7	162.1	38.60	39.53
2700	1249.0	176.0	38.00	38.95
2800	1281.5	195.8	38.80	38.19
2900	1319.7	204.8	38.00	37.50
3000	1364.5	207.3	44.80	37.17
3100	1410.2	203.2	45.70	37.23
3200	1454.3	200.7	44.10	37.40
3300	1495.9	202.4	41.60	37.40
3400	1536.5	204.0	40.60	37.33
3500	1575.4	208.1	38.90	37.17
3600	1612.5	215.5	17.10	36.88
3675	1629.3	218.8	22.40	36.57

Table 1. Cerro Prieto Well M-9 test, October 26, 1979.

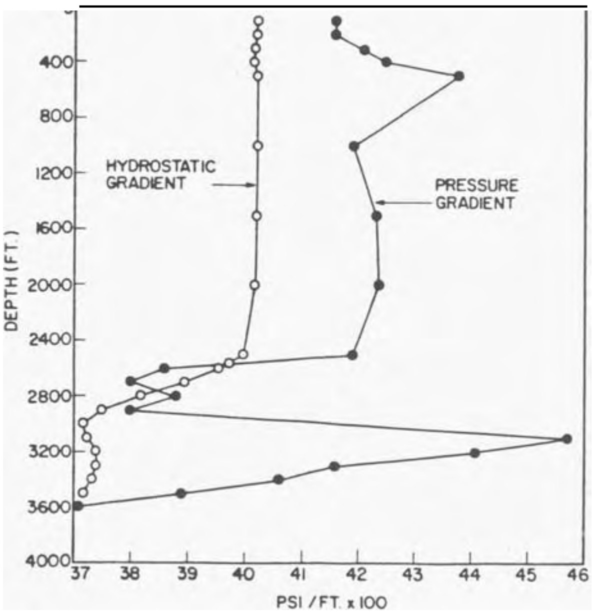


Figure 3: Cerro Prieto well M-9 pressure gradient profiles, October 26, 1979

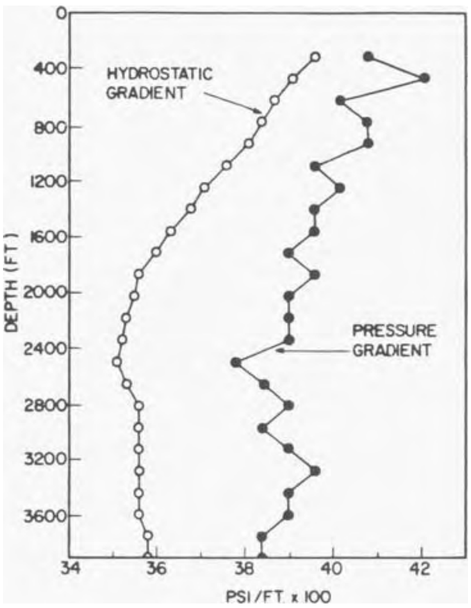


Figure 4: Cerro Prieto well M-9 pressure gradient profiles just after recompletion July 2, 1975

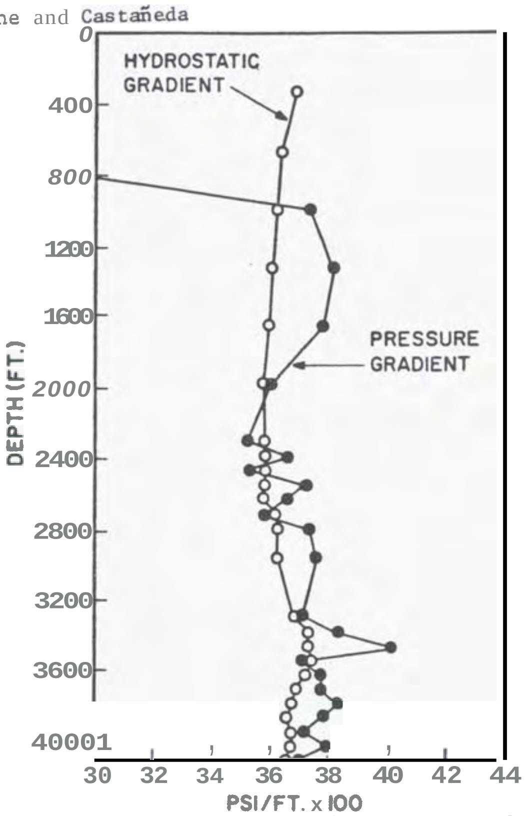


Figure 5: Cerro Prieto well M-9 pressure gradient profiles 2 years after recompletion, June 18, 1977.

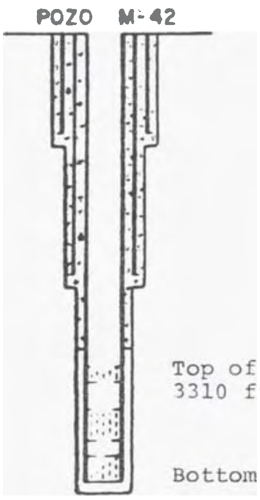
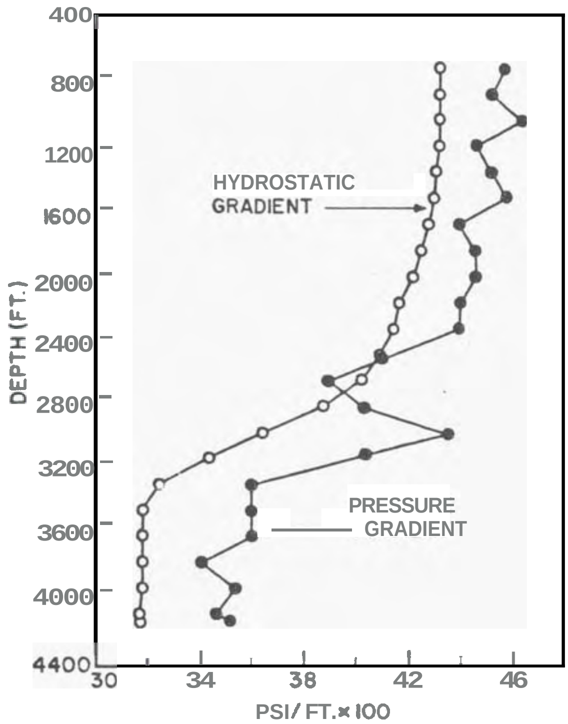


Figure 6: Cerro Prieto well M-42 completion (from Dominguez 1978).

Figure 5 shows the pressure gradient profile for the same well M-9 on June 18, 1977, 2 years after the recompletion. In this case similar "zig-zags" appear as in figure 4 but there is no clear deviation of the pressure gradient from hydrostatic, suggesting that at this time the cement plugging the perforations was still sealed. Interestingly the pressure gradient very clearly shows the flash point in the well (at around 1000 feet or 300 meters).



'igure 7: Cerro Prieto well M-42 pressure gradient profiles.

In another example, Cerro Prieto well M-42 shown in Figure 6 has slotted liner set from 1000 m depth to total depth (1327m). The temperature profile is almost constant over this same interval, indicating internal flow, however the pressure gradient log, Figure 7, indicates that the rate of this flow is small compared to that in well M-9.

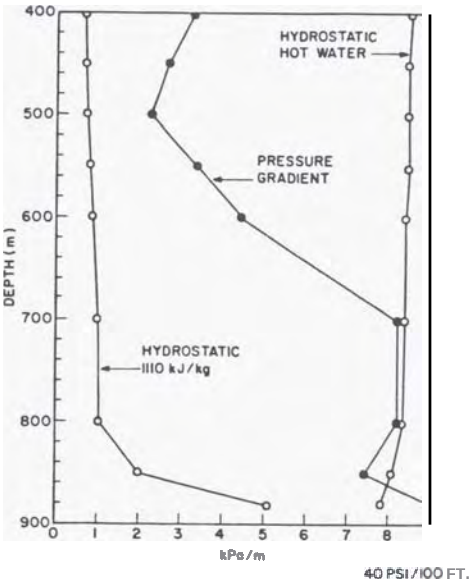


Figure 8: Rotokawa 3 pressure gradient profiles, discharging 160 tonnes/hour of 1110 kJ/kg fluid. July 17, 1978.

In a different application of the technique, Figure 8 shows the pressure gradient logs for the well Rotokawa 3 shown in Figure 1 while it was discharging 150 tonnes/hour of 1110 kJ/kg enthalpy fluid. Three alternative interpretations are possible in this case:

(1) The well is producing fluid with an enthalpy higher than 1110 kJ/kg from depth 700m. This however is not consistent with the observed permeable zones in the pump tests.

(2) The well is static below 500m andproduces fluid at a higher quality than 1110 kJ/kg from 500m depth. Boiling occurs above 700m.

(3) The well flows essentially 1110 kJ/kg fluid from 880m depth with major flashing occuring above 700m. There is a suggestion of someinjection into the permeable formation at 500m.

DISCUSSION

1. This work has basically demonstrated the use of simultaneous pressure and temperature logs as a crude flowmeter, which is nonetheless able to distinguish upflows and indicate feed zones in geothermal wells.

2. There is much room for improvement in the procedure. Readings taken at closer depth intervals would be beneficial, however the use of a pressure ***differential*** gauge run simultaneously with a temperature gauge would be a much better way to proceed. Such instruments are available in the petroleum industry (for example Schlumberger's' gradiomanometer--Schlumberger 1973); however to our knowledge none has been developed for geothermal environments. Work on acquiring or modifying an instrument for this purpose is continuing in this project.

3. The procedure has been shown to work in wells flowing liquid only, and (in field examples shown in this summary) has also proved capable of locating flash points with a high degree of resolution. The method will probably also work in wells flowing steam or two phases if the steam fraction does not change too rapidly with depth.

4. Actually, Cerro Prieto is unusual in that it is not a highly fractured reservoir, and in fact M-9 is probably unusual at Cerro Prieto in having an internal flow which arises because of its two production levels with blind casing between. For well M-42 at Cerro Prieto no internal flow was recognisable. In most other geothermal reservoirs in the world fractures are more prominent and internal flows are commonly observed.

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