INTERPRETATION OF FLUID PRESSURE MEASUREMENTS IN GEOTHERMAL WELLS

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ABSTRACT

Static fluid pressure profiles measured in wells are frequently quite different from those occurring naturally in the ground. Normally, true aquifer pressures will be measured only at the levels of greatest permeability.

Careful interpretation of downhole pressures, measured in a group of wells penetrating various zones in an Indonesian geothermal field, confirmed that a 400m thick, water-filled formation overlies a vapour-dominated reservoir - although clearly no single well could reflect such a pressure distribution.

MEASUREMENTS

While very sophisticated and accurate instruments are now available for downhole pressure measurements of wells at quite high temperatures, there is sometimes a lack of understanding of the use and meaning of the more usual techniques employed in geothermal work. This paper describes examples of actual field observations to demonstrate some of the ways in which such measurements can reveal reservoir conditions.

The special instruments developed fairly recently record the pressure at the surface with a sensitivity of better than 0.001 bars. However, the instrument in common use is hung on a wireline, it scribes the pressure values detected by a helical bourdon tube sensor, and has a sensitivity of only 1 in 2000 - that is, it is readable to 0.1 bars in a deep well. It is with observations from the second type that we are concerned here.

Amongst other factors, the pressure profile in a petroleum or geothermal reservoir depends upon : (a) the permeabilities of the formation materials; (b) the types and states of the fluids present; and (c) the temperatures. Even cold ground water systems often contain several aquifers at different horizons, between which there is no effective connection and no simple hydrostatic pressure relationship - hence the occurrence of "perched water tables" and pressure inversions.

Geothermal systems tend to be much more complicated than cold water aquifers, as a consequence of the following factors:

(a) Liquid water, steam and gas (mainly carbon dioxide) may all be present, allowing a range of densities of up to 2000 to 1.

(b) Non-turbulent flows of water (of different temperature) do not mix readily.

(c) Heat is transferred at a faster rate by the flow of water through permeable rocks than by conductive heating.

As a result, temperature inversions are common, particularly away from the source of heat, and the corresponding pressure gradients can vary considerably throughout a vertical section. Figure 1 is a simple two-dimensional example of the distribution of temperature in a geothermal system.

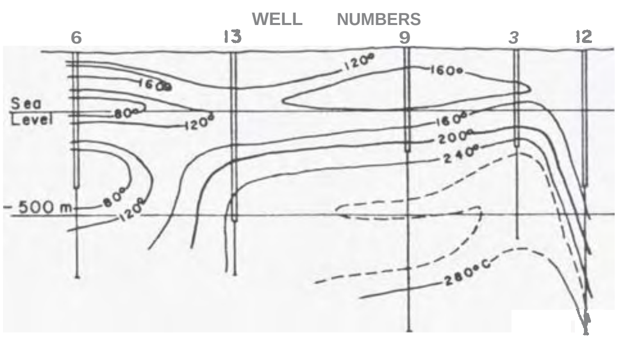

Fig. '1 Temperature inversions in south-north vertical section at Ohaki, NZ.

Drilled holes do not necessarily provide simple means for observing the pressure distribution in a reservoir. Firstly, they introduce very permeable vertical connections between horizontal aquifers, and therefore are likely to alter the flow patterns. Secondly, ready circulation within the bores themselves will mask differences of density which could be sustained in the pores of the formations. It follows that :

(a) the diameter and cased depth of a well is important in determining the degree of disturbance to the natural state; and

(b) the section of the well opposite the most permeable zone is likely to approach most closely to the original condition in the reservoir.

The examples described later illustrate these points.

For consistency, the metric unit for pressure throughout this paper is the "bar". Confusion can be avoided if all measurements are identified as being above absolute zero ("a") or above atmospheric or gauge pressure ("g"). To allow conversion between the two, and to permit the employment of the standard steam tables (which quote absolute values), it is necessary to know the atmospheric pressure. This of course varies with altitude, approximately as shown in Figure 2, and also with local geography.

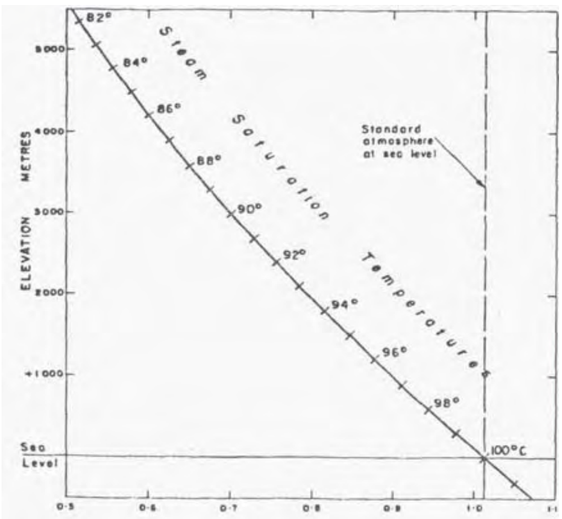

Fig. 2 Standard atmospheric pressure - effect of altitude.

The usefulness of a result is much enhanced if its accuracy can be assessed. One should also be aware of the extent to which natural variations affect the observations. Apart from the altitude difference mentioned above, regular or unpredictable changes in pressure may include: (a) barometric variations, with a possible range of 0.1 bar; (b) tidal movements, up to 0.8 bar; and (c) geyser-type fluctuations, sometimes with very large amplitude. An awareness of such time-based occurrences is important when assessing pressure trends.

The scope of measurement errors is not always appreciated, but they may involve: (a) instrument calibration, as the bourdon tube relaxes; (b) normal instrument and reading errors; and (c) error in the depth of the instrument (pressure change about 0.1 bar per metre in water).

The instrument is not wholly temperature corrected. Also, the level of the instrument in the well is dependent on: (i) the characteristics of the steel wire under load and heat; (ii) the accuracy of the depthmeter; and (iii) the reliability of the surface levelling to the wellhead. With reasonable control of all contributing factors, the probably error in absolute pressure values is likely to be in the range 0.3 to 1 bar, and is best checked by carrying out repeat tests in known stable conditions, employing different equipment and people.

If there is no wellhead pressure, and temperatures are known, the most accurate, cheap method of measuring pressure is by observing the depth to water level; then using water densities to calculate pressures at greater depths. Changes in water level provide a sensitive indicator of pressure variations.

PERCHED AQUIFERS

In geologic formations having alternate tight and permeable horizons, and lateral connections to different hydrologic conditions, the fluid pressures in successive aquifers may be unrelated. The presence of a series of perched aquifers is difficult to detect in a single well unless each permeable zone is measured for pressure, then sealed off before drilling resumes. This can be a very time-consuming and expensive exercise if done to a rigid programme.

However, the information needed can often be obtained with minimal interruption to the drilling operations if the rest level and density of the drilling fluid in the well are noted after encountering zones of lost circulation. In such cases, the drilling process is used to actually identify the zones whose fluid pressures may be important in the later planning of drilling or production.

A gross example of a perched aquifer, identified from measurements taken after circulation losses, was found during the drilling of a 1000m well near the boundary of the Olkaria geothermal field in the Rift Valley region of Kenya. The pressure at each of the loss zones was measured either: (a) in thin mud, by lowering the pressure recorder to the bottom of the hole: or (b) in viscous mud, by recording the depth to the top of the mud, and the mud density. After each recording, the formation was sealed with mud plugs before drilling resumed: so that the pressures measured at deeper loss zones were not influenced by those at higher levels.

Figure 3 shows the observed well pressures, and more boldly, the inferred formation pressures at the depths of circulation losses. As is clear, the zone from about 150 to 600m is quite separate. hydrologically, from that below about 650m. Obviously the inverse pressure gradient evident above the 600m level could not occur in the well itself.

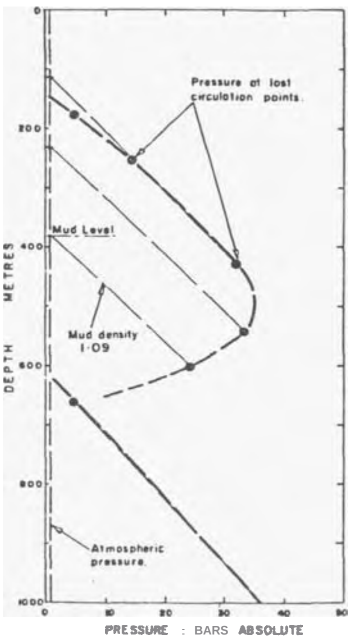

Fig. 3 Perched aquifer identified from pressures calculated during drilling phase.

If temperatures in this area of the prospect had been sufficient to justify the drilling of additional wells there, an appreciation of the reservoir fluid conditions would have proved of importance in determining casing depths, drilling techniques, and the most suitable production horizons,

WATER AND VAPOUR PHASES

When the formation supports mixed water-vapour phases, or a water phase layer above a mixed or vapour-filled zone, this situation is not reflected in well pressures, which are governed by the conditions occurring at the level of greatest permeability, and by the densities of the fluid(s) occupying the well. The application of this reasoning produced a consistent interpretation for apparently unrelated pressure plots in fourteen wells drilled in the Kamojang geothermal field in West Java, Indonesia.

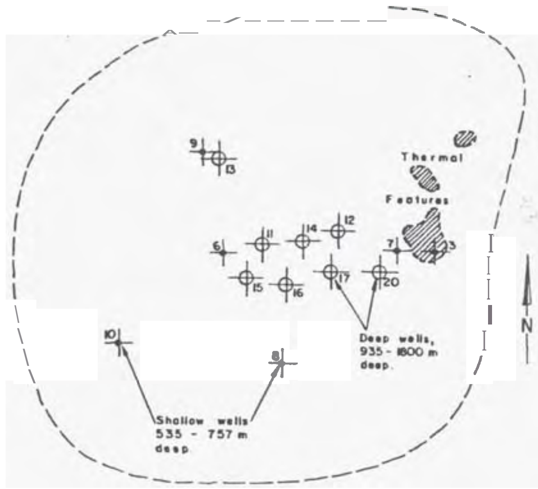

Fig. 4 Well locations at Kawah Kamojang

Figure 4 shows the locations of the wells, and Figure 5 presents selected pressure records for each well, plotted against depth below ground surface. For Wells 12 and 15, pressures measured both before and after deepening are shown. The great range of results observed does not suggest the existence of any general pattern of fluid pressures in the reservoir.

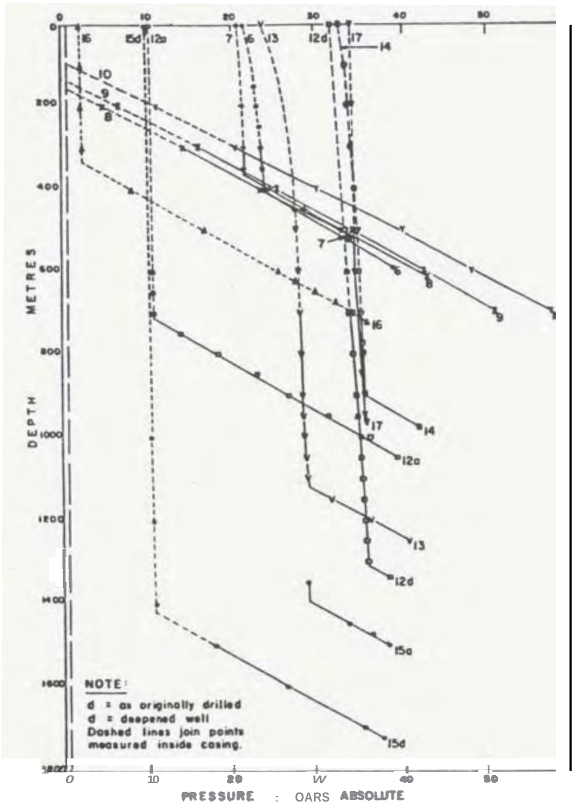

Fig. 5 Downhole pressures at Kawah Kamojang

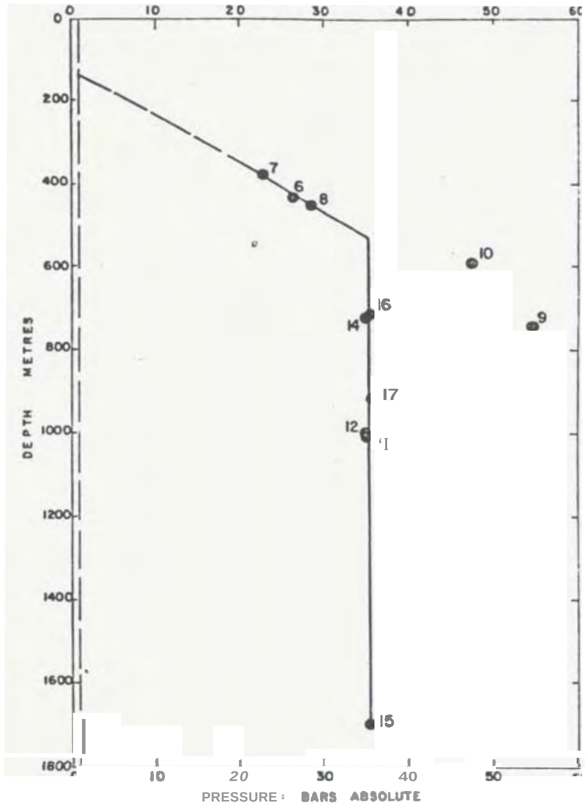

Fig. 6 Reservoir pressures at Kawah Kamojang

From detailed studies of drilling and completion test records, the depth of greatest permeability for each well was assessed, and the observed pressure was then plotted for that depth only. In the case of Well 12, the point used was the intersection of its two pressure graphs.

The result, in Figure 6, shows a remarkably consistent picture of a 400m thickness of water overlying a vapour-dominated phase which is present below 530m depth. In spite of the presence of 30 percent by volume of entrapped water, this zone has a uniform pressure of 35,4 bars absolute. The only exceptions are Wells 9 and 10, which are shallow wells near the boundary of the field where the geophysical record predicted a deep liquid zone.

Before Well 20 was drilled (in an area towards the steam-heated pools in the east of the field) a west-east section of the reservoir was drawn to help in deciding on the depth of production casing. Well 7 discharges steam from a zone having a pressure of 21.7 ba, and for more than 50 years Well 3 has blown steam from 63m depth with a temperature of 140°C, corresponding to a pressure of 3.6 ba. These data were used in constructing Figure 7, in which the thickness of the water zone was calculated from the vapour zone pressure. It will be noted that there is a difference in ground elevation of about 120m between Wells 6 and 7. The pressures for figure 5 proved more consistent when plotted against depth than against elevation, and Figure 7 shows that the upper surface of the water zone rises along with ground level.

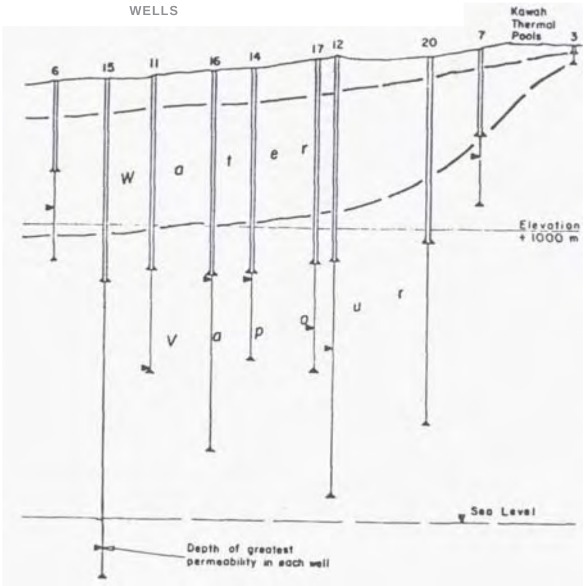

Fig. 7 Vertical section through Kawah Kamojang reservoir.

From Figure 7, the top of the vapour zone was estimated to be at about 420m depth, and this figure led to a decision to set a shorter string of production casing than was used in the more westerly deep wells. Furthermore, the thickness of the water zone scaled from Figure 7 was only 340m. The pressure exerted by this column of boiling water was calculated to be 30 ba, which later proved to be the pressure measured in Well 20's vapour zone.

CONCLUSION

Evidence has been presented to demonstrate that downhole pressure readings in closed wells should normally be equated to formation pressures only at the levels of greatest permeability. Modifications to this rule are likely to occur when, for instance, interzonal flow occurs in a well having more than one level of high permeability, but such exceptions' should be recognised from the data. Clearly, a critical attitude in the interpretation of observations is necessary if a true indication of reservoir conditions is to be obtained.