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RESERVOIR EQUILIBRIUM IN TWO PHASE GEOTHERMAL SYSTEMS

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ABSTRACT

Before exploitation in the steam dominated reservoir at Kamojang a quasistatic gas/water two phase well bore column has been measured in Kamojang Well 17, with an all gas phase standing adjacent to and in equilibrium with the permeable steam zones at those points. The apparently linear pressure gradient thus established in conjunction with evidence of phase seperation at the permeable features and an identification of permeable strata from characteristic heating profiles at Kamojang and Olkaria leads to a description of that equilibrium, and a logically constructed argument for reservoir formation.

FORMATION OF THE TWO PHASE WELL BORE COLUMN

Water injection tests in steam wells result in condensing of steam at the permeable zones, sometimes with accumulation of non condensible gas both within the wellbore and in the formation. If the well is moderately permeable, and the pump rate not too high, the gas rises buoyantly against the downflow of pumped water, which enters the formation after a condition of nearly free fall.

Steam is condensed at or close to the well bore. Since the condensing of steam does not appreciably affect reservoir pressure, the two phase column, after a short initial equilibrating period, becomes quasi stable. The column transitions from gas at the permeable feature incrementally to a nearly all water column above at each permeable interval (Fig. 1).

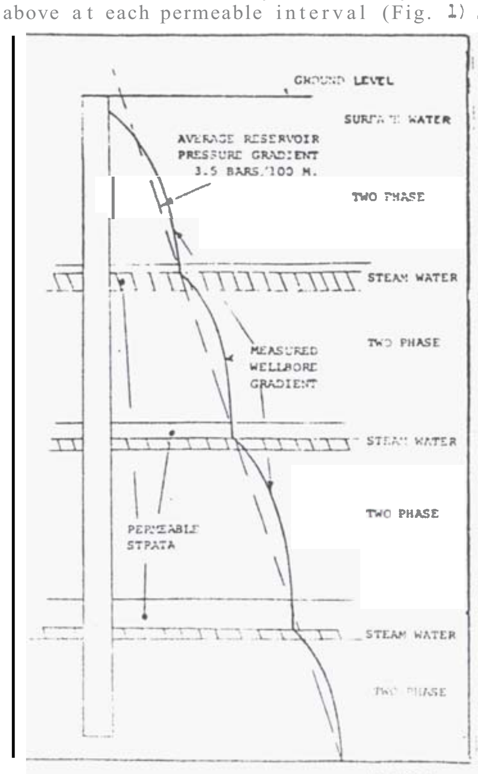

FIGURE 1

When pumping stops the column dissipates slowly as water enters the formation, becoming increasingly two phase as steam and gas flaw upward from high to lower pressure permeability above. Finally the bore is filled with up-flowing steam and gas from above the water table in the lower production zone. The transition is slow and early profiles are close to true reservoir pressure.

COMPARISON OF HEATING TEMPERATURE AND PRESSURE PROFILES AT KAMOJANG AND OLKARIA

Two interesting similarities are noted:

(i) In the heating temperature/pressure profiles
(ii) In the relationship of pressure gradient to depth of production zone at the maximum enthalpy of steam (modified slightly by the presence of gas).

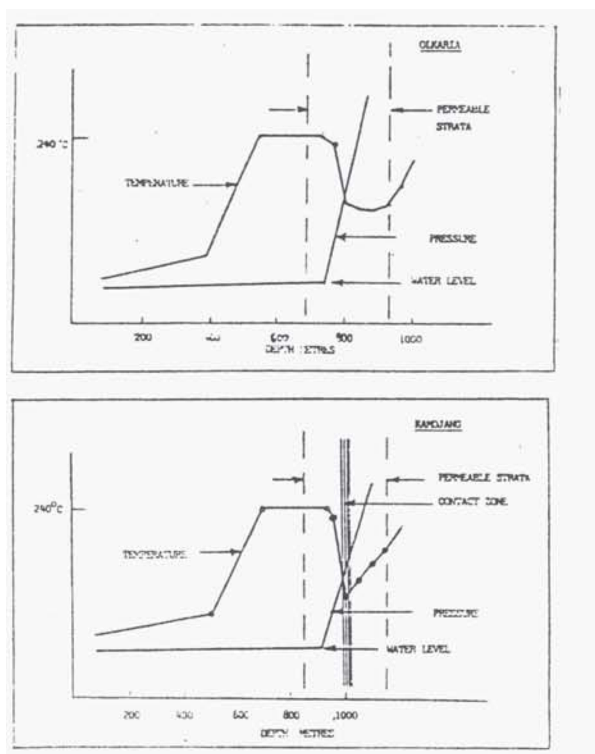

FIGURE 2

The remarkable similarity (Fig 2) indicates production from very similar formations, both are bedded strata. The strata are seen in pictorial temperature relief reflecting the degree of intrusive cooling by pumped water. The steam profile in the bed above the water table obscures that detail. The sharper inversion of the Kamojang profile indicates a narrow band of high permeability indicating a well developed contact zone. Partial drilling losses before the major loss is consistent with fracture permeability in the lava immediately above the contact, compatible with multi-stage caldera formation and reflected in the generally higher mass outputs of Kamojang wells.

Because injected water within the water table is relatively immobile the inversion remains for a considerable period conductively heating. After discharge the inversion is still present and in this instance is the result of contributory flashing from the water table to sustain well flow. The water table may be above or below the zone of maximum permeability within the permeable strata, if the stratum is not horizontal.

In both Olkaria and Kamojang the production steam zone at near maximum steam enthalpy condition occurs at the lowest known high permeability horizon within the two phase upper reservoir. Olkaria has a reported shallow steam/gas zone at a pressure of 3.5 bars and depth of approximately 100 metres, consistent with a 4.0 bar per 100 metre gradient extrapolated fram maximum enthalpy production zone at 800 metres in well OW 13. The maximum enthalpy condition production zone in the Kamojang reservoir Eastern field is at about 900 metres with a pressure gradient of 3.5 bars/100 m, suggestive of a significant correlation between permeability depth at maximum enthalpy conditions and pressure gradient in the upper reservoir.

ARGUMENT FOR METHOD OF FORMATION AND STABILITY OF TWO PHASE RESERVOIRS

The argument is constructed from the previous measurements observations and the following assumptions:

- (i) Heat and magmatic steam/gas flow are sufficient to maintain saturation conditions throughout the reservoir above the magmatic heat source.
- (ii) The structure is sealed at the margins restricting lateral water inflow.
- (iii) The reservoir has low permeability in the vertical plane except at permeable strata and is restricted vertically to the rock matrix.
- (iv) At equilibrium heat and gas flow rates upward are nearly constant.
- (v) Water downflow is constant.

During successive cycles of Caldera formation strata are created of high permeability where lava/pyroclastic flows cover existing topography of lake and sediment, accumulated in the forming caldera structural depression. The permeability so formed at the contact will depend on thickness of lava cover, and depth of depression sediments.

Initially temperature gradients are high with associated high temperature steam/gas vents at the surface and water is almost completely driven from the system. When the temperature gradient declines sufficiently for free water to form at the surface without evaporating it begins to travel downward against the upflow of magmatic steam and gas in intimate contact within the rock matrix.' The descending water will modify the gradient to one of steam saturation, while maintaining saturation conditions above with the continuous excess heat flow. Where permeability occurs steam and water phases separate, resulting in a steam cap above a perched water table. The water table will cause rising magmatic steam to condense on the underside while gas continues to bubble through and the two phase condition will re-establish, extending deeper into the reservoir. The back pressure builds below the water table and the pressure at the permeable feature falls, but saturation conditions are maintained by a continuous series of equilibria at each point in the reservoir above. The two phase progresses downward in a series of similar equilibria at each successive permeable zone. When the two phase front encounters permeability at a temperature above the maximum enthalpy of steam, reduction in pressure here due to back pressuring cannot fall below the pressure of maximum enthalpy of steam. This property of steam has been the subject of a paper by Russell James, DSIR, New Zealand.

Briefly stated under conditions of adiabatic expansion steam will tend to its maximum energy state. In the continued presence of an excess of both heat and water under adiabatic expansion once that energy state is achieved it cannot be lost.

This permeable horizon, therefore, becomes a control point for the two phase equilibrium above. If a major permeable horizon exists below the permeability where maximum enthalpy conditions first appear then conditions here will tend toward maximum steam enthalpy with consequent adjustment of phase density between the two. Since under hydrostatic balance the same pressure cannot occur at a lower level the major permeability must dominate and the upper reservoir control point must move down to the lower level. The necessary density phase change between the two zones effected by changes in velocity of the descending water, draining the upper bed until only single phase steam exists at which point the appropriate gradient saturation condition can establish. If this then is the lowest point of major permeability between surface and heat source it becomes the final permanent control for the total reservoir. The two phase front continues to travel downward 'to heat source modifying the gradient to saturation conditions.

At equilibrium the gradient aligns to its closest possible approximation to linearity between the fixed points of pressure at reservoir free surface and the control permeability at maximum enthalpy. Intermediate permeabilities exist at pressure coincident with the gradient.

The two phase equilibium conditions are maintained by a continuous upflow of magmatic gas in the presence of a conductive heat gradient. The total water downflow is sufficient to maintain two phase control from the reservoir surface, exiting at natural surface/subsurface outflows, removing above static equilibrium energy inputs from magma source. Permeable zones in the upper reservoir will contain increasingly higher proportions of gas and water as the steam phase fraction decreases. When all steam is condensed the water/gas phase transitions from steam saturation to ambient at reservoir surface. When gas reaches the surface unconfined it emanates quietly and unobtrusively from the ground surface. CO_2 is found filling surface soil excavations in geothermal fields above the magmatic source. Where the CO_2 becomes trapped pressure builds, in direct analogy to the gas pressure that builds in shut in wells. Equilibrium is re-attained by periodic eruption from otherwise quiescent vent sites when gas pressure exceeds local hydrostatic/lithostatic. A good example is found in the Dieng field Central Java where gas eruptions of large and catastrophic proportions occur at intervals of several years.

CONSEQUENCES OF RESERVOIR MODIFICATION BY FRACTURING

Water dominated systems can be considered as two phase systems where extensive vertical fracturing of the permeable beds of the upper reservoir create effectively one composite penneable feature. In explanation first consider the caldera structure. The upper permeable beds are formed by infilling of the sinking core, consisting of sediment/lava contacts and pyroclastic material. Below lies the pre caldera impermeable rock of the original ground surface. At the lowest extremity is the intruded pluton. The vertical permeability of the system will depend on the radial tension fracturing of the impermeable rock and the permeable beds above the pluton formed in rejuvenation cycles. If the intrusion is shallow and the fractures extend through the permeable beds, the high vertical permeability of the propped fractures so formed will allow steam water separation in the fractures, and free draining of the permeable bed water tables. The depth to which water penetrates will depend on the depth to which the fractures remain open. The water table will form in the fractures and in the adjacent rock matrix with a steam/gas cap above. If meteoric water availability is high the reservoir will fill with water and become water dominated. If water availability is low, permeability and fractures deep, the steam cap may extend deep into the reservoir. Infilling of the factures by surface sediments will allow the two phase equilibria to establish. Some water dominated upper reservoirs may transition back to two phase conditions in the lower impermeable rocks. This would become evident in a tendency to isothermal conditions in deep drilled wells. Where fractures and water extend to heat source measured well temperatures approach the critical point.

Where the intruded magma source is deep and sequential permeable beds not significantly fractured production is from the steam cap of the permeable beds.

Within the framework of the discussion it would seem reasonable that the described equilibrium is the mechanism by which many geothermal systems control their heat flow to the surface. Renewed volcanic activity may occur locally within an established reservoir, temporarily disrupting that equilibrium with resultant transient surface thennal activity and non equilibrium temperature and pressure distribution in the reservoir below.

The extension of the discussion to fractured systems does not include those systems with only fracture permeability, although the confines of un-fractured rock on the periphery of such a system would effectively impose the same lateral permeability constraints as a caldera structure.

CONCLUSIONS

Because the measured pressure gradients in wells drilled into two phase conditions are unable to duplicate the pressure gradient in the adjacent reservoir, uncertainty exists as to the nature of the two phase distribution.
The measured pressure gradient is a unique phenomenon not previously reported and is the first relatively unambiguous evidence for two phase pressure distribution.
Although the reservoir in which the gradient is measured may not be representative of reservoirs in general and the' constructed equilibrium speculative and oversimplified it is hoped that the discussion may in some measure contribute to the further understanding of two phase systems.