Analysis of Water Levels and Reservoir Pressure Measurements in Geothermal Wells

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ABSTRACT

In the low-permeability, fractured formations normally forming the reservoir in Italian geothermal fields, the water levels, measured in the wells after mud drilling has ended, give quite a good indication of fluid pressures in the fractures, both in water-dominated and vapor-dominated reservoirs.

The unknown formation pressures of Larderello field for the 1940 to 1955 period, when the wells were not shut in, have been determined on the basis of these water-level data. Initial pressures ranging from 20 to 40 ata were found in Larderello, but these values were in all cases affected by the nearby producing zones as a result of the gradual spreading of the explored area.

Pressure-depth plots have shown that in different parts of the fields both water-dominated and vapor-dominated systems had existed before intensive exploitation began.

INTRODUCTION

The exploitation of the Larderello geothermal field began in the first half of the 19th century with the drilling of some shallow wells which drew from the surface permeable layers a mixture of local meteoric waters and steam which reached the surface through the few fractures in the cap rock formation.

It was only in 1926, however, that the wells reached the reservoir top, and it was also in this period that the first drilling data were gathered. These included stratigraphical profiles, loss of circulation, water-level measurements, and so on.

The productive wells were shut in for the first time in 1942, but shut-in pressures were not recorded systematically until much later (1955).

The lack of pressure data for the first period of field exploitation, which was particularly intense over small areas of the field, can be partly overcome by an interpretation of the drilling data.

GEOLOGY AND PERMEABILITY

From a geological point of view, Larderello, Travale, and Mt. Amiata geothermal fields can all be placed in a single scheme as follows:

1. A basal complex which represents the potential geothermal reservoir and is made up of a schistose-quartzitic series (Paleozoic-Triassic), overlain by a series made up of an anhydritic-dolomitic formation in its lower part, mainly limestone in the middle and sandstone in its upper part (Upper Triassic to Oligocene).
2. A cap-rock complex of prevalently shaly terms in flysch facies (Upper Jurassic to Cretaceous) lying in structural discordance over the basal complex.

This discordance between the mainly shaly complex and the underlying terrains is the result of prevalently horizontal movements caused by compressive phenomena during the Alpine orogenesis. After this compressive phase the region was affected by distensive movements which produced horst-and-graben tectonics.

The reservoir rocks are characterized by high permeability in the fractured zones only, having a very low matrix permeability (Barelli et al., 1975). Information obtained from drilling shows that the highest permeability is in the upper part of the basal complex and particularly where this is made up of carbonate layers.

Figure 1 gives, in contour lines, the elevation of the first fractured zones encountered in the wells. These form the actual reservoir top which is very close to the contact surface between the cap rock and the potential reservoir. This reconstruction leads to the hypothesis that there is a continous highly fractured horizon over almost all the field.

The fracturing in the upper part of the basal complex can be attributed to the overthrust of the flysch-facies complex on the Oligocenic to Paleozoic terrains. There is also proof of overthrusts with varying dips on the inside of the formations underlying the cap rock, causing fracture

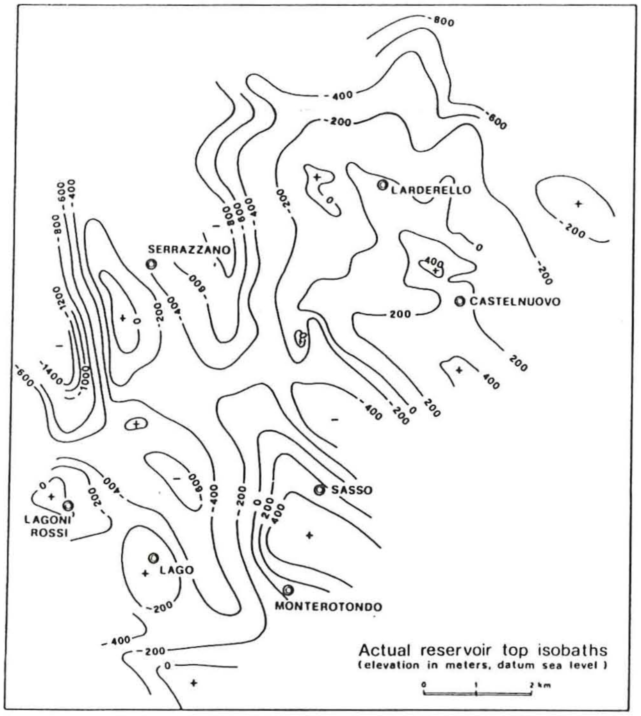

Figure 1. Actual reservoir top in Larderello geothermal area.

systems which go down to a considerable depth.

The permeability is also tied to the fracture systems caused by distensive movements. These have caused direct faults which may have affected most of the crust with the result that the volcanic or subvolcanic manifestations of Roccastrada, Montecatini V.C., and Orciatico all lie on the alignment of one of the main faults. More local direct faults may have equal importance in causing fracturation.

This structural situation is typical of all the geothermal fields in Tuscany and the same observations made for Larderello can also be applied to them.

As a consequence of this type of tectonics, fracturing is localized and the wells are generally cross-fractured zones for small depth intervals, as shown by temperature measurements and well logs. Pressure or water level measurements in these conditions can be referred with reasonable accuracy to a given depth on the inside of the reservoir.

WATER LEVELS, RESERVOIR PRESSURES

In the Italian geothermal fields drilling has always been carried out by mud circulation when crossing the cap rock and by using water when crossing the basal fractured formations. Water levels are measured when drilling operations are suspended or completed, before the well begins production.

In the steam-producing zones when the well encounters one thin fracture zone only, the water level remains constant as drilling proceeds. Where, on the other hand, the fracture zones are thicker or there are several fractures at different depths, there are variations in water levels or even sudden blowouts of the wells.

In many cases the water levels are known, but there are no data available on the temperatures of the liquid column as, for example, in the case of the old wells and where measurements were carried out while drilling operations were suspended for a short period only. In the later situation there are also sometimes doubts as to water-level stabilization.

The recent experimental wells drilled in the central part of the Larderello area, which is also the most densely exploited, have shown that a liquid column remains above the fractured zone even when the wells are drilled in a vapor-dominated area. In this zone, for example, the well-bottom measurements show that superheated steam exists in the reservoir to at least 1000 m below the surface.

However, when the experimental wells crossed permeable horizons at about 400 m depth, a liquid column was also observed above the fracture. Thus the water levels have a different meaning in water- and vapor-dominated reservoirs.

A contour map of the water levels measured in wells in Larderello geothermal area cannot be prepared as the data in the different zones generally refer to different periods and the levels varied with the depth of the fractures even within the same well. A similar map could only be meaningful for limited areas where the available data refer to a relatively short period and correlated fracture depths.

Figure 2 represents the water-level contours for the wells in the area surrounding Serrazzano from 1967 to 1971. The variations in pressure for this period were below 3 ata in the area under study. The levels refer to the top of the actual reservoir. The maximum, in the central part of the area, cannot be explained by ordinary laws of ground-water hydrology as the recharge zones are far from this area and before 1967 production was concentrated on the top of the

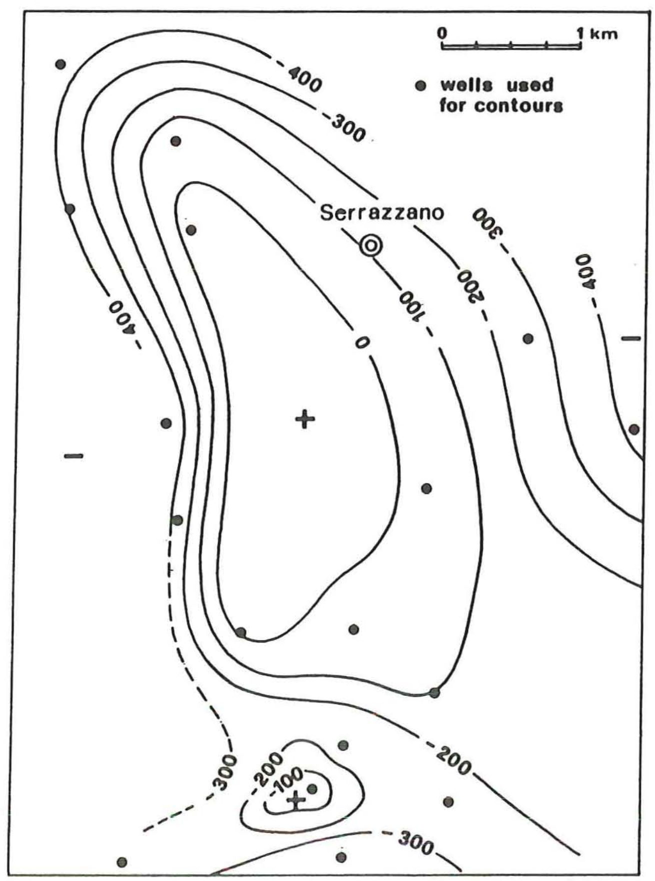

Figure 2. Water levels measured in wells drilled in Serrazzano area from 1967 to 1971 (meters, datum sea level).

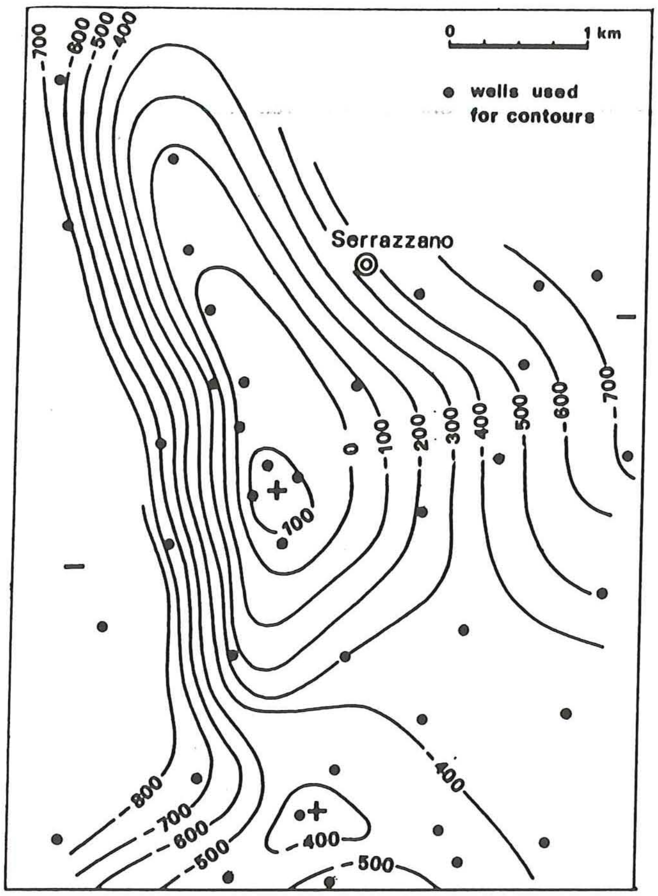

Figure 3. Actual reservoir top isobaths of Serrazzano area (elevation in meters, datum sea level).

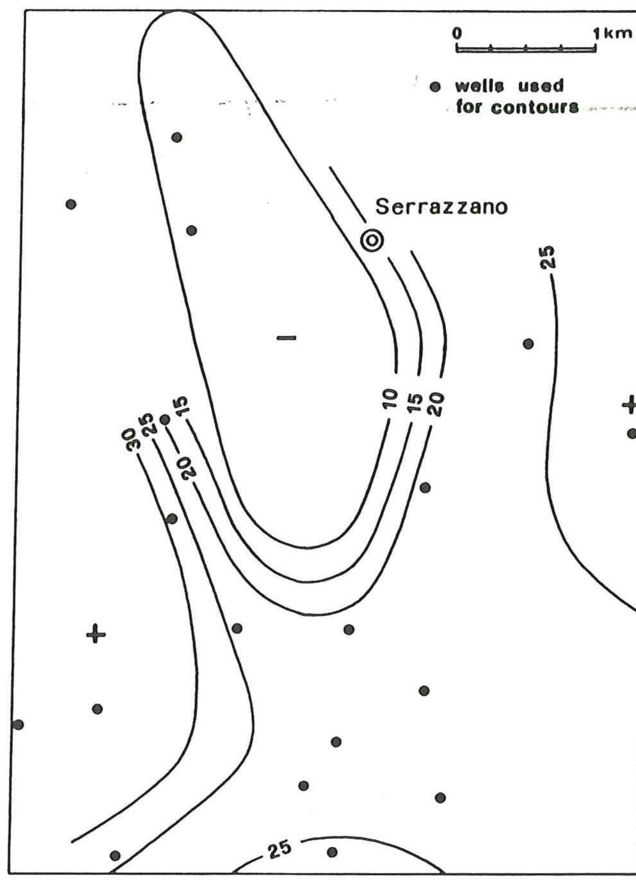

Figure 4. Pressure distribution at the actual reservoir top in Serrazzano area in 1970 (ata).

structural high, where the maximum levels are observed. By comparing Figure 2 with Figure 3, which represents the depths of the fractures to which the water levels refer, we can see that there is a strong similarity between the two trends.

If, instead of the water levels, we plot the pressure exerted by the liquid columns on the fractures (Fig. 4) we then obtain a much more realistic trend: the pressures on the fractures decrease regularly from the more outside zones toward the inner and more intensely drained ones. We thus have a clear explanation if we assume the zone to be vapor-dominated and we consider the liquid columns over the fractures to be indicative of steam pressure. This hypothesis is in accordance with the fact that in the Tuscan steam fields shut-in pressures in the wells immediately after blowout always correspond to those exerted on the fractures by the liquid columns. This is shown clearly in Figure 5 where the height Δh of the liquid column above the fracture is given as a function of the shut-in pressure P for 80 steam wells in the Larderello, Bagnore, Piancastagnaio, and Travale geothermal fields.

The scattering of data points can be attributed to:

1. The finite thickness of the permeable zone.
2. The differences in liquid density. Due to the lack of temperature measurements, the possibility of mud residue and gas in the liquid, or boiling phenomena, this factor is often unknown.
3. Errors or insufficient stabilization in water-level and pressure measurements.

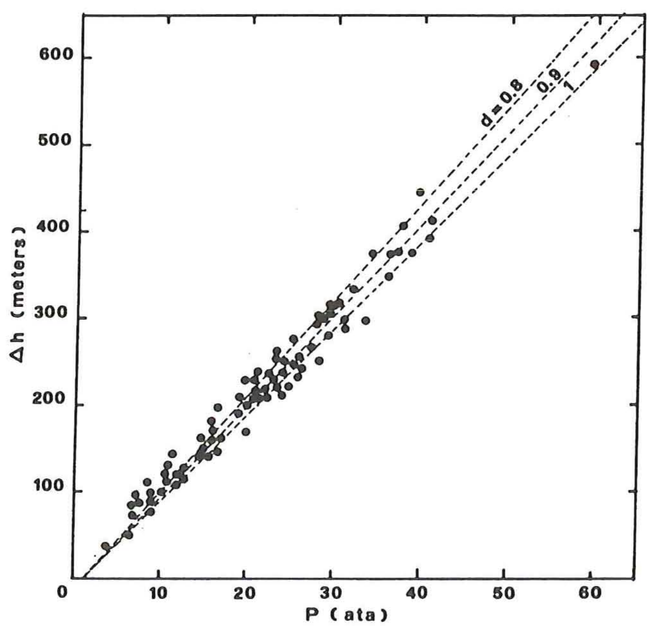

Figure 5. Comparison between height of water columns above the fractures Δh and shut-in pressure P. Data from Larderello, Mt. Amiata, and Travale fields. Dotted lines: expected curves for constant liquid density d.

Figure 5 includes all the available data. With more reliable information, differences of less than 10% are found between the measured pressure and that calculated from the level.

Useful level data have also been obtained with a thick fractured zone when the drilling was suspended and the measurements performed as soon as the top of this zone was reached. Therefore reservoir pressures can be determined with sufficient approximation from the water-level measurements both in a water-dominated and vapor-dominated system.

Some observations made during drilling and before blowout help to explain how the liquid column is maintained in equilibrium when the wells are drilled in vapor-dominated reservoirs:

1. The wells which encountered huge fractures or natural cavities blew out suddenly during drilling with eruptions that were often uncontrollable even by water injection.
2. Spontaneous blowout during drilling occurs more often in the wells which initially produce a high gas-content fluid.
3. After drilling has been completed and before blowout, there are intermittent gas exhalations and oscillations in water level.
4. High-productivity wells rapidly reach blowout conditions while long periods are necessary for low-productivity wells (Bianchi, 1965).

Consequently it may be said that the water column in a well communicating with a vapor-dominated reservoir is maintained in equilibrium as there is a continual transfer of water from the well to the reservoir and of steam from the reservoir to the well. A static equilibrium is also difficult to imagine with fractures of a certain size.

Steam condensation in the borehole heats the liquid column and causes the exhalations of uncondensable gases.

INITIAL PRESSURES

The first wells in the Larderello geothermal area to reach the reservoir in zones near natural surface manifestations, already exploited by means of several shallow wells, found steam with static pressures of about 30 ata.

After 1955 the wells were drilled far from the first exploitation zones and reached even deeper levels of the reservoir. However, the pressures were still affected by interference from the producing wells, as shown by the gradual pressure decline in the shut-in wells in the marginal areas.

The maximum pressure observed in Larderello geothermal area was 40 ata. In other geothermal fields where exploration began more recently the initial reservoir pressures have been measured. At Piancastagnaio this was about 41 ata. In the Bagnore field the shut-in pressure in the first well, after a short production period, was 22 ata, while the water level measured before blowout indicates a reservoir pressure of 33 ata. These two different values can be justified if we consider the rapid pressure decline in Bagnore field in the early phases of exploitation.

The maximum pressures in Travale field, where new wells were drilled from 1972 on, are 60 to 62 ata.

PRESSURE-DEPTH PLOTS

The pressure-depth plots provide information on the production effects at different depths and on the physical state of the fluid in the continuous phase (Fig. 6). In fact, while in a water-dominated system we must find a nearly hydrostatic pressure gradient, little increase in pressure with depth is expected in an unexploited vapor-dominated system.

These plots are of use if we have pressure values for a long depth interval and small surface areas so that the

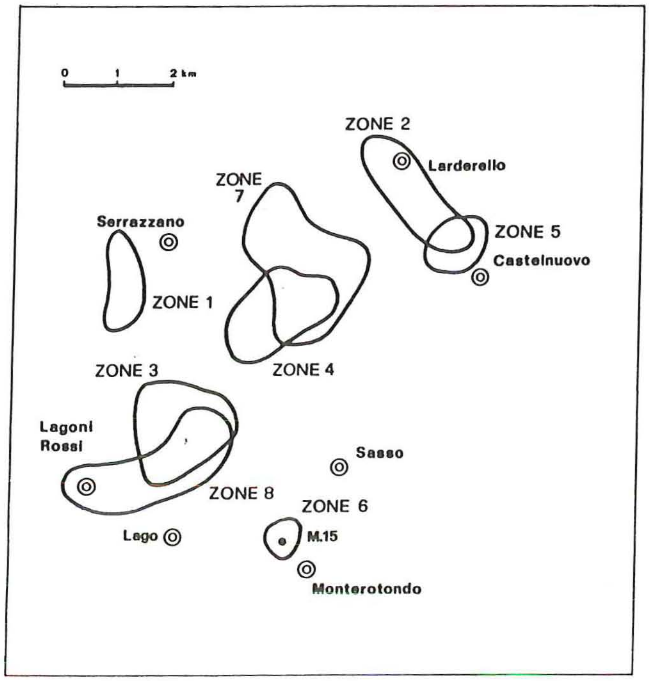

Figure 6. Larderello geothermal area. Location of the zones considered in pressure-depth plots.

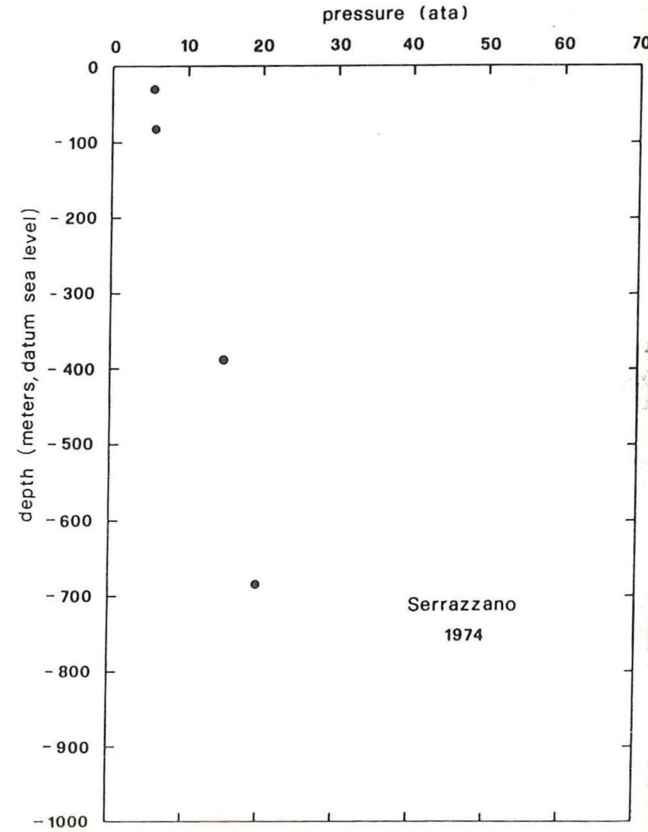

Figure 7. Pressure vs depth for Serrazzano field in 1974 (Zone 1 in Fig. 6).

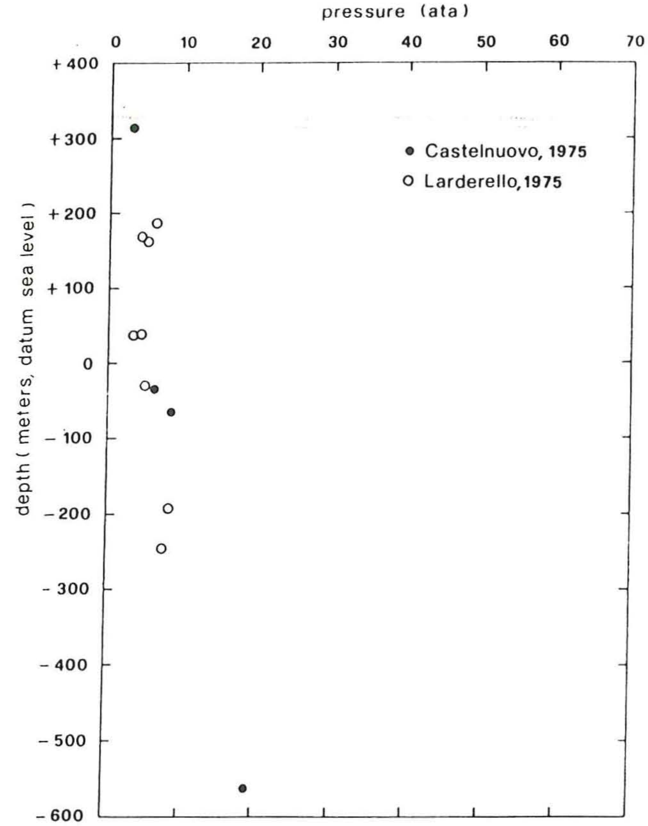

Figure 8. Pressure vs depth for Castelnuovo and Larderello fields in 1975 (Zone 2 in Fig. 6).

horizontal gradients have only a slight influence.

In the production areas of Larderello geothermal system the pressure gradient is now clearly below the hydrostatic one but above what it should be with static steam (Figs. 7 and 8). On the other hand, in some areas where production is low the plots show nearly constant pressures along depth intervals of several hundreds of meters, even though there is some scattering of points (Figs. 9 and 10).

The pressure values far below the initial ones and the gradient are a result of fluid extraction, which was especially concentrated in the upper part of the reservoir.

As these situations are common to almost all the steam-producing zones we may say that nowadays the system in this area is vapor-dominated at least for the reservoir depth explored so far.

Since in Larderello before 1948 drilling was confined to very small thicknesses of the reservoir, there was no information for that period on the pressure trend in relation to depth. Between 1948 and 1952 the depths reached by drilling increased considerably and the lower part of the pressure-depth plot relative to Castelnuovo field shows that the pressures were controlled by steam down to 100 m below sea level, while the upper part of the reservoir in this zone is at 300 to 400 m a.s.l. (Fig. 11). The shallower wells were the most influenced by the producing ones. Figure 12 refers to M15 well, drilled in 1955 in a zone which had already been productive for a long time. It went far down into the reservoir and encountered fractured zones at different depths. Evidently the reservoir was vapor-dominated, at least down to 600 m below sea level (b.s.l.), while the reservoir top is at 300 m above sea level (a.s.l.).

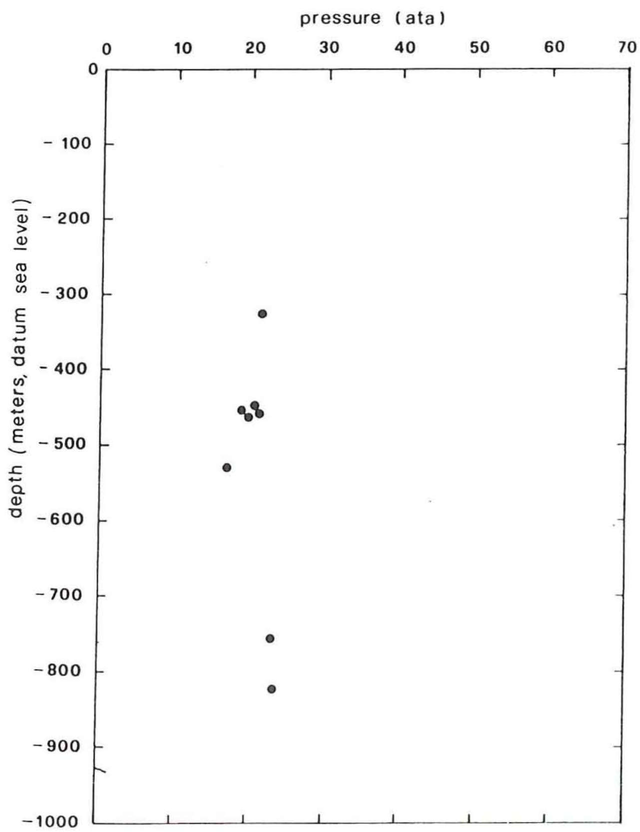

Figure 9. Pressure vs depth for wells in Zone 3 (Fig. 6) in 1974.

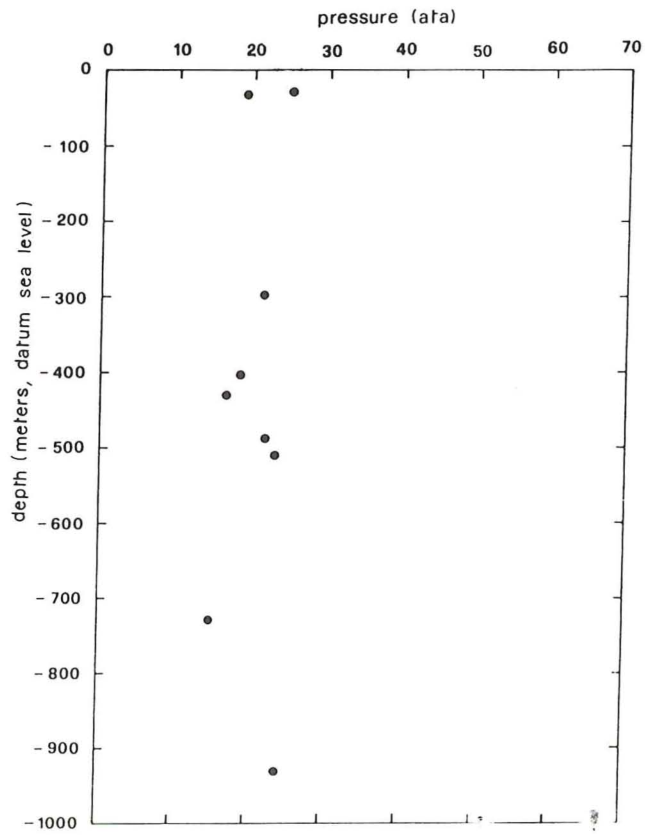

Figure 10. Pressure vs depth for the wells in Zone 4 (Fig. 6) in 1974.

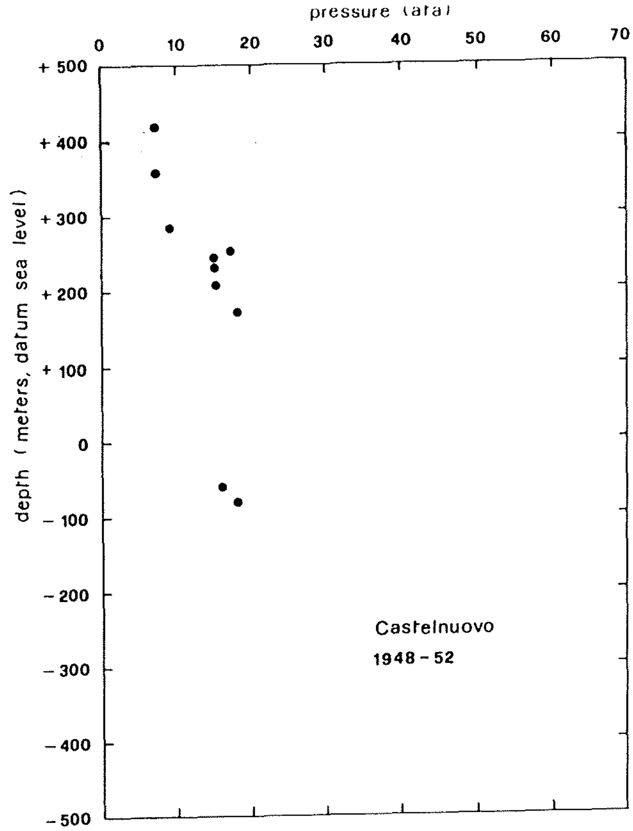

Figure 11. Pressure vs depth for Castelnuovo field (Zone 5 in Fig. 6). Data refer to the period from 1948 to 1952.

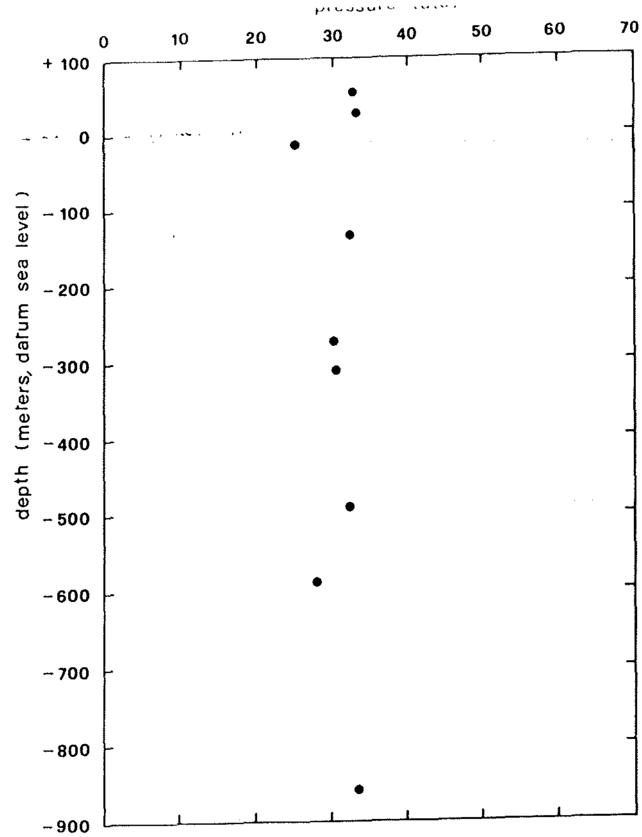

Figure 13. Pressure vs depth in Zone 7 of Fig. 6. Data refer to the period from 1955 to 1960.

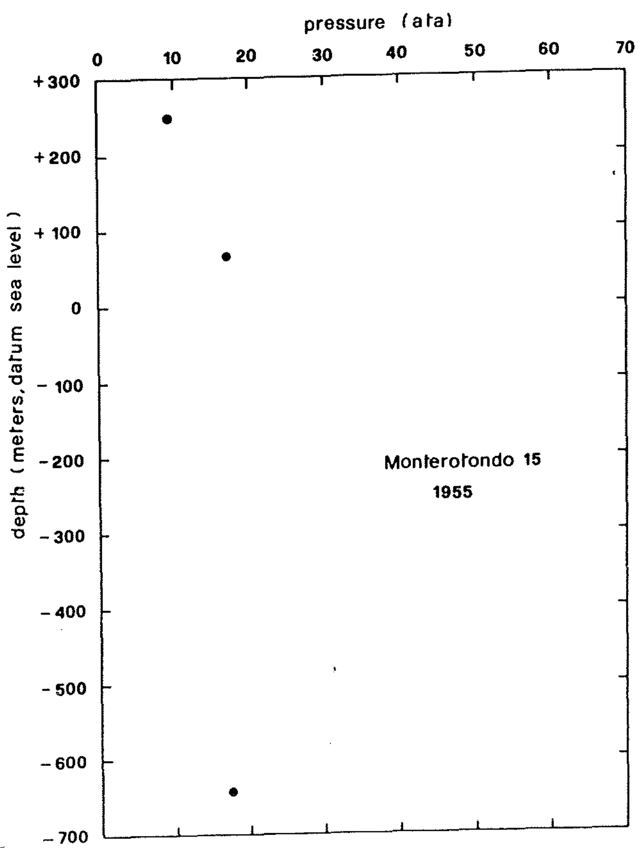

Figure 12. Pressure vs depth observed in M. 15 well (Zone 6 in Fig. 6).

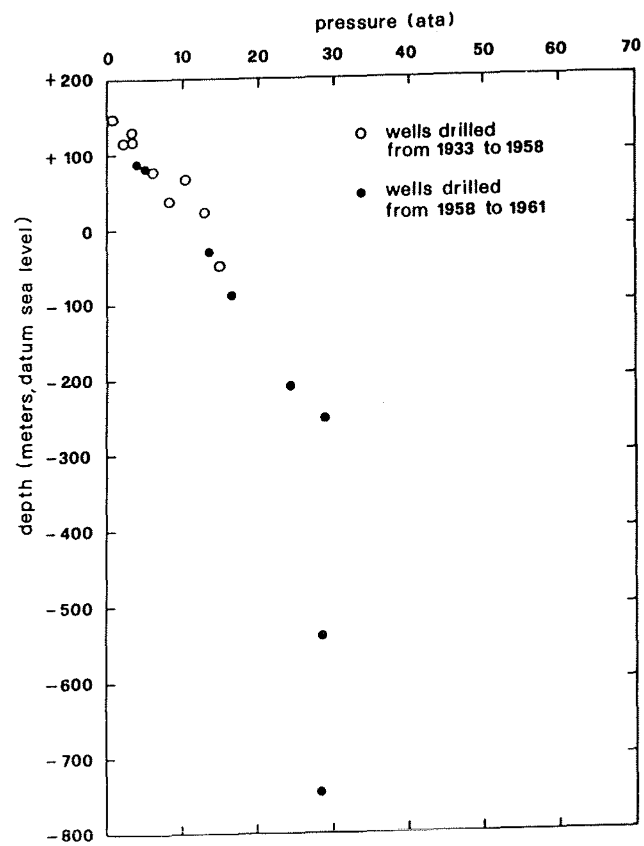

Figure 14. Pressure vs depth in Lagoni Rossi (Zone 8 in Fig. 6).

Other interesting data were also provided by wells drilled far from the exploited areas. Figure 13 refers to the wells drilled in the 1956 to 1960 period in an area which corresponds to a structural low of the reservoir, lying between Larderello and Serrazzano structural highs. Once again the system seems to be vapor-dominated down to 850 m b.s.l.

The only productive area with a hydrostatic pressure distribution found in Larderello is the small Lagoni Rossi field (Fig. 14). Until 1958 drilling was concentrated on a small area on the top of a structural high of the reservoir near a small absorption area of meteoric waters. The pressures measured in this zone lie on the straight line corresponding to the hydrostatic pressure of a liquid with an average density of 0.8 kg/dm^3 (kilograms per cubic decimeter). The wells in this area have in general produced a little wet steam. Drilling after 1958 over a wider area northeast of the preceding one reached much greater depths, and the pressure trend shows vapor as the dominant phase.

A similar situation can be seen in the Travale field. The wells, drilled before 1962 in a zone with natural manifestations near an important absorption area, produce a two-phase mixture. Figure 15 clearly shows that these wells have reached a water-dominated reservoir.

The wells drilled since 1972 in a zone lying some kilometers from the absorption area, without any natural manifestations or previous drillings (Burgassi et al., 1975), show that a vapor-dominated system exists in this zone.

In Mt. Amiata region, where no surface manifestations existed, a fluid with a very high initial gas content was found (Cataldi, 1967).

The pressure values found in the wells drilled in the Bagnore field (Fig. 16) seem to reveal the existence of a gas and steam deposit in the upper part of the reservoir.

However, the rapid pressure decline, the spontaneous well blowouts with the consequent lack of water-level data, and the fact that the shut-in pressure values were sometimes modified by the presence of liquid over the fractures, all prevent us from drawing any final conclusions.

Figure 17 gives the pressure vs depth plot for the Piancastagnaio field. The data for 1961 to 1963 at the beginning of exploration show that a steam and gas deposit existed in the reservoir down to at least 100 m b.s.l., while the upper part of the reservoir is at about 200 m a.s.l.

The wells drilled after this period show a pressure decline and a wide scattering of data points, which may be attributed to field exploitation and areal well distribution. It must be noted that well PC/22 has a much higher pressure which may indicate the presence of a water table above the fracture depth. Figure 18, representing the Poggio Nibbio field

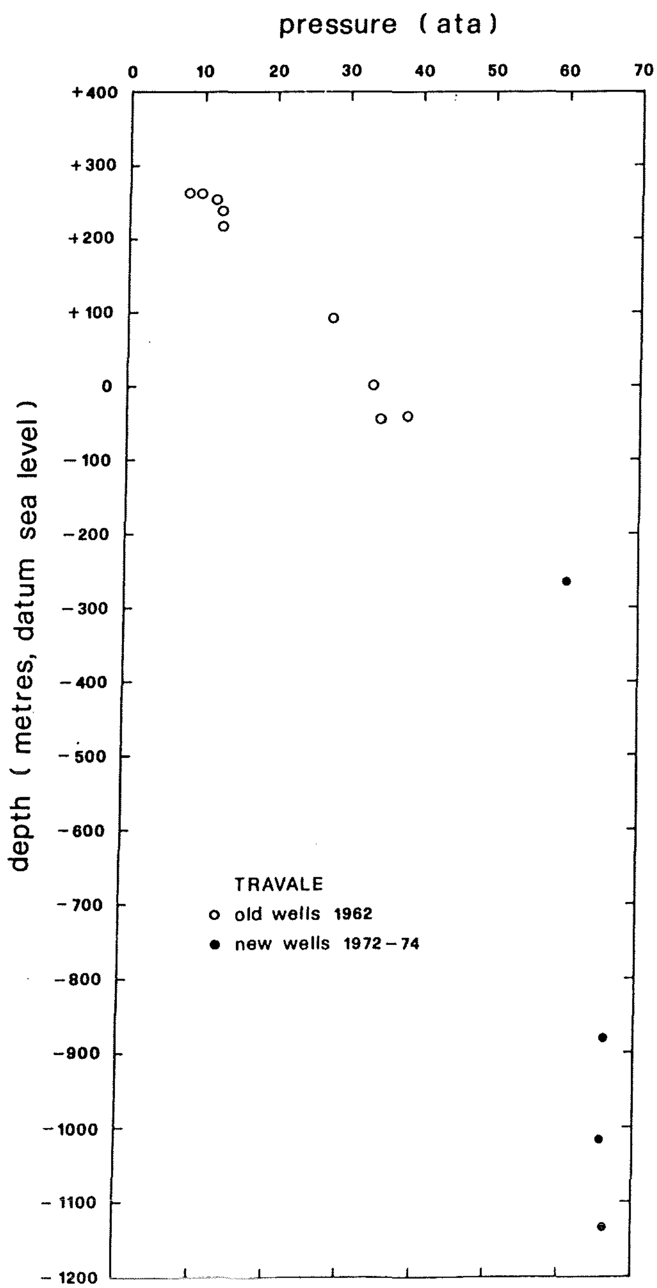

Figure 15. Pressure vs depth for Travale field.

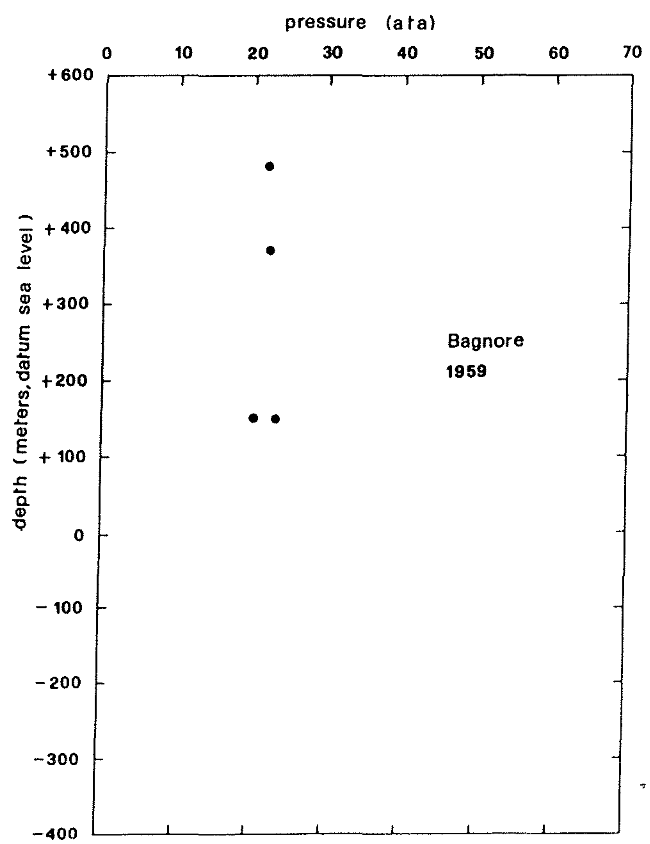

Figure 16. Pressure vs depth for Bagnore field in 1959.

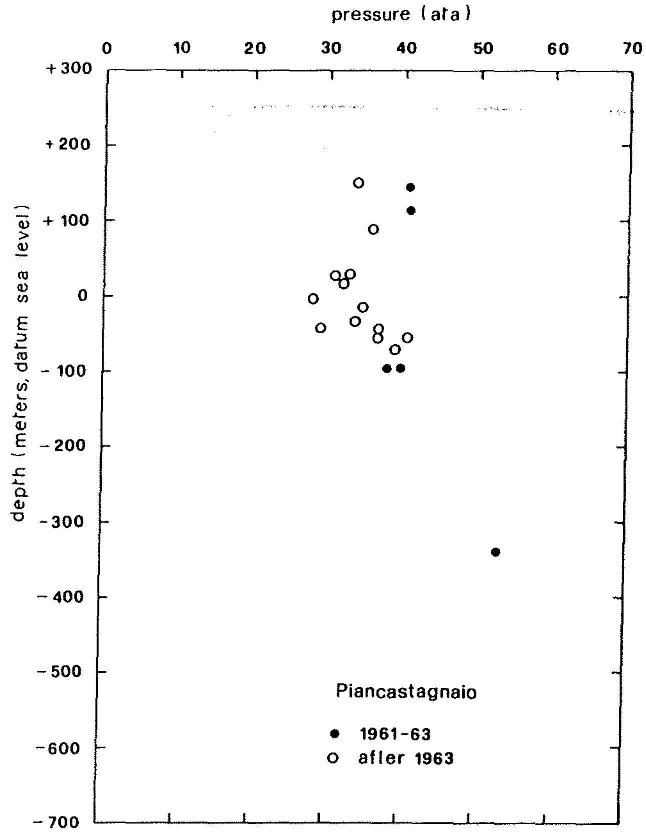

Figure 17. Pressure vs depth for Piancastagnaio field.

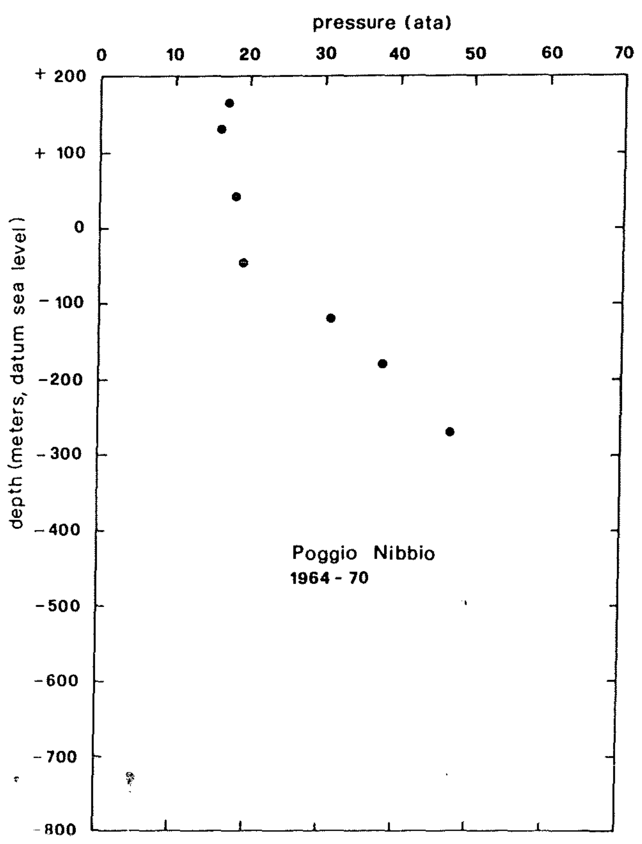

Figure 18. Pressure vs depth for Poggio Nibbio field.

(Burgassi, Calamai, and Cataldi, 1969), clearly shows the existence of a water table below the gas and steam cap.

CONCLUSIONS

Analysis of the drilling data gave information on the pressure distribution in the Larderello geothermal area for the periods when shut-in pressures were not measured. A reconstruction of the situation in this area at the beginning of exploitation was not possible as all the zones under examination had been affected by the producing wells. However, from the late 1940s on all drilling on the inside of the productive area reached a vapor-dominated reservoir. Water-dominated systems can be found on the field margins near the absorption outcrops. The Travale-area new wells, on the other hand, were drilled in an unexploited area although there are some connections between this area and the old field. Pressures obtained during shut-in of the productive wells, and water-level measurements in the nonproductive wells, show that there are almost uniform pressures in the reservoir at very different depths. Based on these data the system seems to be vapor dominated.

A study of the Travale old field (by Cataldi and others in 1970) had revealed, from an examination of the temperature distribution within the reservoir, a flow of fluids from the vapor-dominated to the water-dominated zone. Probably this flow existed even before drilling began. The old field is in the transition zone between two systems: (1) the water-dominated one which originates in the absorption zone on the western margin of the field, and (2) the vapor-dominated one in what is now the exploitation area (Burgassi et al., 1975). In this transition zone the liquid water and steam produced by the wells in a two-phase mixture may have two different origins. The old wells in Lagoni Rossi field and other marginal productive areas are probably in a similar situation.

The highest pressure found for all the Italian steam fields was measured in Travale field. Considering that Larderello is in much the same hydrogeological and thermal situation and that pressures of 40 ata were found at Larderello in zones which were already affected by production, we may deduce that Larderello, in undisturbed conditions, might also have had similar pressures.

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