AN UPDATE ON TRAVALE - RADICONDOLI GEOTHERMAL FIELD

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ARSTRACT

Travale-Radicondoli field can be subdivided into five reservoirs with little interconnections and particular features.
Reservoir A, drilled in the early 1950s, is the shallowest and was watered out very soon by pound water. The pressurc distribution was, and still is. hydrostatic.
Reservoir B, with an initial pressure of 6 MPa at 600 m depth, was in equilibrium with reservoir A. Its production, exceptionally high in the beginning, underwent a substantial decline. Later, a preponderant contribution of meteoric water stabilized the prduction.
Reservoir C wits drilled in the 1980s at 1.3-2.5 km depth. Pressure distribution was vaporstatic although must wells have been pmducing somc liquid water. The initial pressure was 5.5 MPa, while reservoir B had declined by that time from 6 to 2 MPa. In spite of *these* favorable aspects, production declined more rapidly than expected.
Reservoir D, currently under development, is placed below reservoirs B and C at a depth of 3-4 km. Initial pressure was found to be in vaporstatic equilibrium with the initial pressures of reservoirs B and C. Steam is superheated in the reservoir and contains chloride. The most productive wells have initial flowrates as high as 30 kg/s.
Al the field boundary noncommercial wells were drilled. These wells are dry or produce CO_2 and/or liquid water. Static pressures are in equilibrium with the vaporstatic pressure distribution of the other reservoirs. This part of the field border will be referred to as reservoir E.

1. INTRODUCTION

The exploitation of Travale-Radicondoli geothermal field, located 10-15 km SE of Larderello, began in the early 1950s with wells drilled close to the natural manifestations, at depths of a few hundred meters.
Subsequently, drilling was extended areally and at depth, and additional condensing units were installed.
Up to now (June 1994), *71* wells have been drilled over an area of about 10 km^2 and the total installed capacity is 90 MW. Maximum drilled depth is 4604 m.
The wells tapped permeable layers at different depths separated by low permeability zones so the field can be subdivided into five reservoirs according to the structure, the hydrogeological setting and the different fluid characteristics.

2. DESCRIPTION OF THE INDIVIDUAL RESERVOIRS ANI) MUTUAL INTERACTIONS

The areal location of four of the five reservoirs is given in the map of Figure I using lower case letters; area d *is* not visible as it underlies areas b and c.
All the reservoirs are shown in the schematic geologic section of Figure 2.
Each reservoir Is described below.

2.1 Reservoir A

Geothermal exploitation began in the early 1950s with about 20 wells drilled to depths of a few hundred meters, close to the natural manifestations in a water-dominated system (area a in Figures 1 and 2). Two 3.5 MW exhausting-to-atmosphere units were initially installed

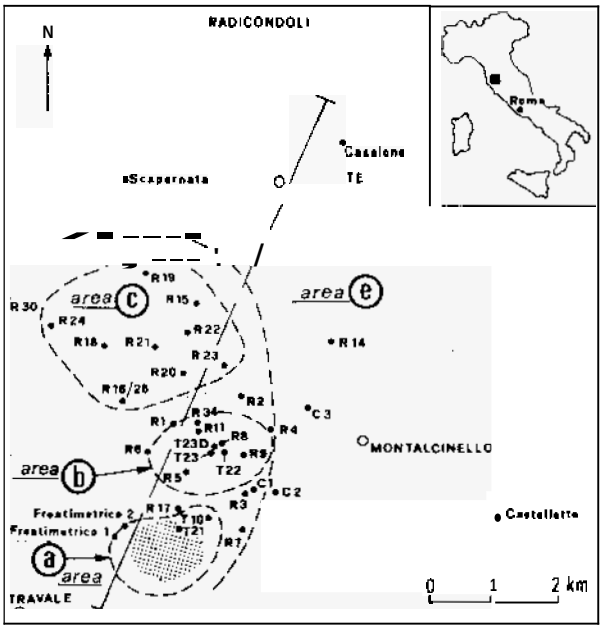

Figure 1. Location of the drilled areas. Area d approximately underlies areas b and c. (Seereservoir D in Figure 2)

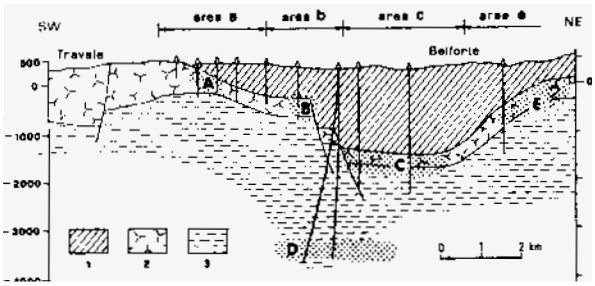

Figure 2. Section showing the locations of reservoirs A. B.C, D, E
(1) Cap rock
*(2)*Carbonate reservoir furmation
(3) Metamorphic reservoir formation

Fluid production caused the surface manifestations to disappear and triggered the inflow of meteoric water. All but one of *these* wells were soon watered out (Cataldi et al. 1970) causing the end of the power plant operation.

2.2 Reservoir B

In the early 1970s the exploration was extended northward, aiming at a deeper and hotter reservoir. Well **T22** was drilled close to the major fault bordering the southern edge of the Travale-Radicondoli graben. The permeable rocks were met at a depth of 640 m in the upthrown flank of the structure. A stem-dominated reservoir was found with a pressure of 6 MPa and a temperature of 270°C.
Well T22 wits the greatest producer ever found in Italy, with an initial flowrate of 110 kgls of dry steam (Burgassi et al., 1975).
Other highly productive wells were drilled in a small area (1 km^2) to feed a 2x15MW condensing power plant. The total reservoir flowrate history is shown in Figure 3 where the fluid has been subdivided into primary and meteoric steam, assuming that meteoric steam does nut contain gas and that primary steam gas content is constantly equal to the initial averagc (10.7% by weight).

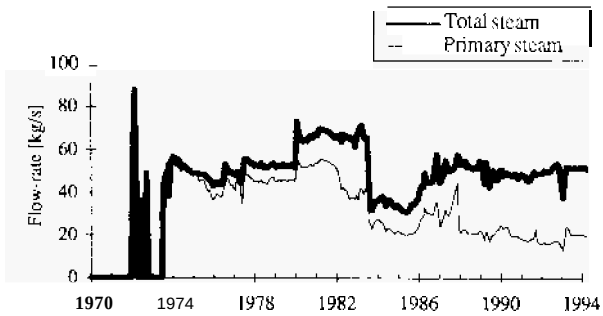

Figure 3. Steam flowrate history of reservoir B

A pressure interference test showed that all the producing wells were strongly interconnected as if they were a single well. Horizontal permeability proved to be highly anisotropic with very little resistance along the fault direction (NW-SE) (Atkinson et al., 1978).
The pressure interference test surprisingly showed that shut-in pressures were a little higher near the fault then far from it although the maximum drainage is exerted by the wells producing from the fault. There was probably a flow from the fault towards reservoir A where well T21 was still producing a two-phase mixture.
The gas flow rate and the gas/steam ratio have been decreasing (Figures 4 and 5) and the latter, starting from 12%, has reached its present value of 3%. This evolution is believed to be due to a meteoric water inflow that has been progressively replacing the original steam. The gas-steam ratio is believed to be an indicator of the mixing between original and meteoric steam. There is also geochemical evidence confirming that more than 50% of the produced steam was of meteoric origin already in 1988: the tritium content was around 5 T.U. as a result of mixing between original steam without tritium and the meteoric water containing 17 T.U.

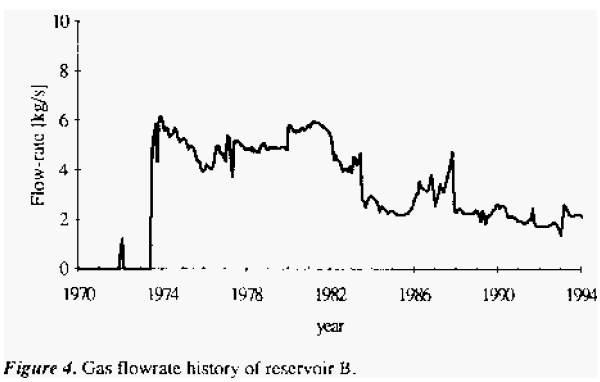

Figure 4. Gas flowrate history of reservoir B.

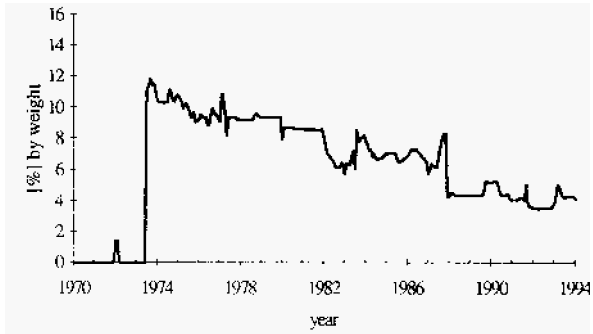

Figure 5. Gas-steam ratio history of reservoir B.

2.2.1 Reservoir B storage capacity

In order to study reservoir response io production, it is a common practice to plot reservoir pressure against cumulative mass produced. In this case, since there is no well acting as a reliable reservoir manometer, reservoir prcssurc had to be calculated using the back-pressure curve according to the following relationship:

$$P_{res}^2 - P_{fl}^2 = \alpha G + \beta G^2.$$

β was calculated assuming that turbulent flow takes place only in the borehole whilc α derives from a fitting of the experimental back-pressure curve.
The resulting values of α and β are given in Table 1.

Table I

well	laminar flow resistance α MPa^2/(kg/s)	turbulent flow resistance β MPa^2/(kg/s)^2
T22	0.17	1.0 E-3
T23D	U.22	1.2 E-3
R8	0.068	1.0 E-3
R9	0 028	1.1 E-3

The reservoir pressures P_{res} were calculated for each well using the histories of the flowing pressures P_{fl}, the flowrates G and *the* constants n and ß.
The reservoir pressures, measured or calculated for each well, were plotted against time (Figure 6) to see if thcv arc close io each other. The results seem *to* confirm the hypothesis of a single reservoir.

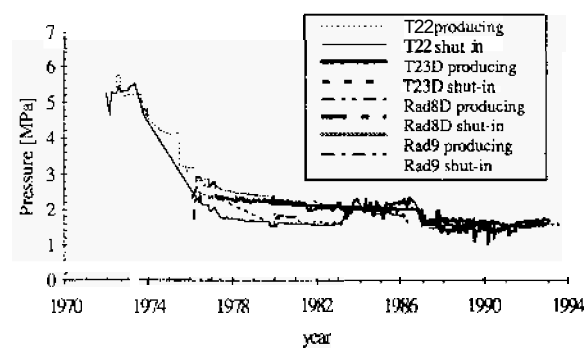

Figure 6 Individual well shut-in pressures measured or calculated from back-pressure curve.

Rcscrvoir pressure declined sharply from 6 to 2 MPa in the First *3* years *and* then almost leveled off.
To decide whether a reservoir behaves as a closed one, the average reservoir prcssurc is plotted in Figure 7 against the cumulative primary steam produced.

Two slopes are present and the relevant mass storage coefficients C_M are:

$$C_M = 1{,}300 \text{ kg/Pa}, \qquad C_M = 18{,}500 \text{ kg/Pa},$$

where C_M is the ratio between the extracted mass and the observed reservoir pressure drop in a closed system.

Assuming that the steam reservoir is superheated, the rock volume relevant to the two slopes is 10 and 150 km^3 respectively. As such large volumes are unrealistic, a different storage mechanism must be envisaged.

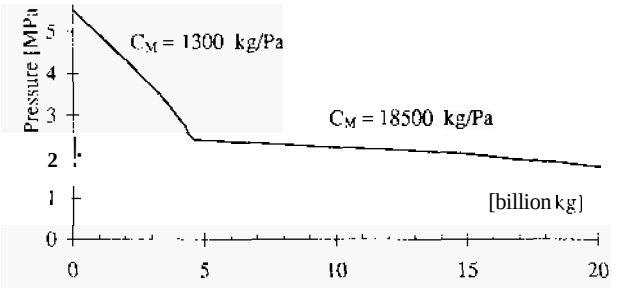

Figure 7. Reservoir pressure versus cumulative production of primary steam.

Liquid water should thus be present, but even in this case, the cumularive gas produced is still too large since the amount of dissolved CO_2 in liquid water at a partial pressure as low as 0.3 MPa, is almost negligible.
Steam and gas adsorption on rock surface could be the key to the problem. Laboratory experiments are in progress tu assess the importance of this phenomenon at rcservoir conditions.

2.2.2 Interconnections between reservoir A and B

The water-dominated system of reservoir A and the stem-dominated system of reservoir B are interconnected. The shut-in pressure of reservoir B (6 MPa) was initially in hydraulic equilibrium with the aquifer of reservoir A, which has a piezometric level at +340 m a.s.l.. The connection is believed tu rake place mainly at the top of reservoir B whcrc most fractures are prcsent.
Before exploitation, pressurc in reservoir B was probably slightly higher than the hydrostatic pressurc since surface manifestations were active.
The intensive exploitation of reservoir B caused an inversion of the natural flow. At present, meteoric water flows from reservoir A to reservoir B.
The pressure interference test carried out in 1977 on reservoir B (Atkinson et al., 1978) gave an idea of the connection between these two reservoirs. The pressure transients showed a linear steam flow taking place perpendicularly from the main fault to the producing wells of reservoir B. Permeability turned out to be 0.2E-12 m^2 through a flow area of 0.3E6 m'.
Extrapolating these two values towards reservoir A, arid taking into account the existing pressurc gradient. an outflow of 10 kgls of steam was calculated to exist in 1977 toward5 well T21, which was the only producer at that time in reservoir A. This estimated flowrate is in agreement with the observed steam flowrate of this two-phase producing well.
Presently well T21 is closed and the pressure gradient is inverted (flow from reservoir A to reservoir B). The flow is driven by the pressure difference between well T21 of reservoir A (2.7MPa at the permeable horizon) and reservoir B (1.8 MPa). The above valucs d permeability nnd flow area make it possible to calculate a meteoric steam flowrate on the order of 30 kg/s. in agreement with the estimate made on the basis of the gas-stem ratio.
The evaporative process is sustained by the heat stored in the rocks. Once this heat is exhausted. the water flow could reach rcscrvoir B at a rate one order of magnitude greater than the present steam flowrate, thus watering out rcservoir B.

2.3 Reservoir C

In the early 1980s exploration was extended northwards to the graben. This reservoir covers a larger area (4 km^2), at greater depth (1300-2500 m), and involves a much thicker layer. Six productive wells were drilled; five of the six have been producing wet *stem*. Only one well (R20), the closest to rescrvoir B, has been producing superheated steam.
Gas content of the 5 wet steam producers is at present 9% by weight whilc it is 5% for well R20. Such a low value is probably affected by a meteoric contribution. The six wellc feed two power-plants, 20 MW each.
Reservoir C suffered a continuous flowrate decline without substantial changes in steam quality and gas content. The production history is givcn in Figures 8, 9 and 10.

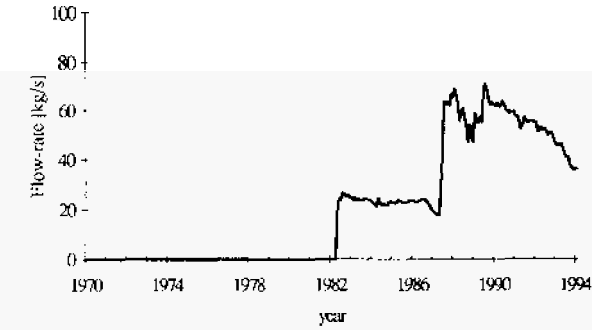

Figure 8. Steam flowrate history of reservoir C.

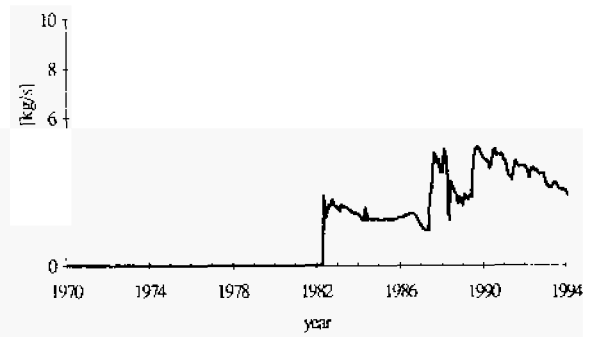

Figure 9. Gas flowrate history for reservoir C.



Figure 10. Noncondensable gas content history of reservoir C

The reservoir pressure history is shown in Figure 11; it was calculated with the same procedure as described earlier fur reservoir B. The relevant parameter:, are given in Table 2.

Table 2

Well	Laminar flow resistance α MPa²/(kg/s)	Turbulent flow resistance β MPa²/(kg/s)²
R15	0.7	13.9E-3
R18	0.7	7.6E-3
R 20	1.2	7.0E-3
R21	8.3	20.0E-3
R22 1st completion.	0.44	1114 E-3
K22 2nd completion.	1.2	25.5 E-3
R24	0.7	8.5 E-3

Flow resistance a in rcservoir C turned out to be almost an order of magnitude greater than in reservoir B as listed in Table 1. The larger values of β with respect to those of reservoir B are due to the smaller diameters used in the wells drilled in reservoir C.
The scheme of the interconnections between these six wells (Figure 12) has ken constructed on the basis of wellhead pressure arid flow rate histones using shut-in and opening operations.

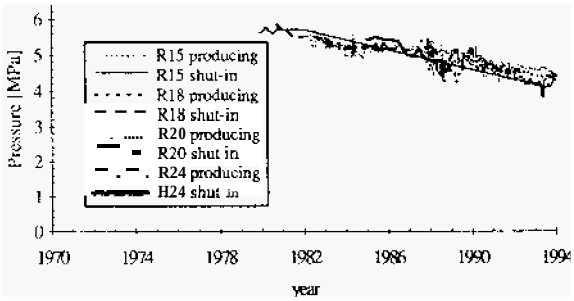

Figure 11. Reservoir pressure calculated or measured from individual well shut-in prcssure or back pressure curve.

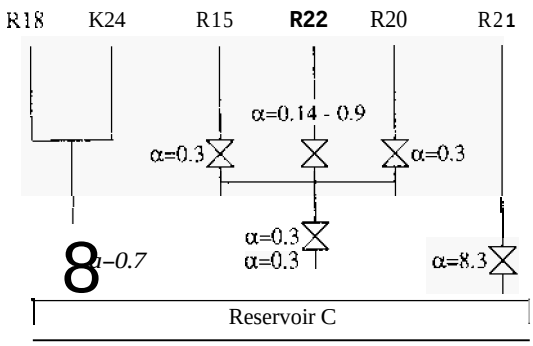

Figure 12. Well flow resistances α [MPa²/(kg/s)] and well interconnections in reservoir C.

A connection exists between wells R15 and R20. Surprisingly, these two wells are placed at the opposite reservoir boundaries (1 km apart). with a substantial elevation difference (750 m) between the producing intervals. They produce fluids of different gas content (9% and 5%) and enthalpy (wet and superheated *steam).*
Reservoir pressure is currently declining at a rate of 0.16-*0.2* MPa/year (Figure 11).
Reservoir pressure versus cumulative mass produced is graphed in Figure 13. It shows a linear depletion that is typical for a closed system; the storage coefficient C_M is 12,500 kg/Pa.

2.3.1 Discussion on reservoir C behavior.

Reservoir pressure decreased from the initial 5.5 to 4.5 MPa in 1994 (Figure 11); since it was in saturation conditions, the temperature should havc dccreased from 270 to 257°C. Employing a lumped parameter model. each cubic meter of rock should have evaporated 13 kg of water.

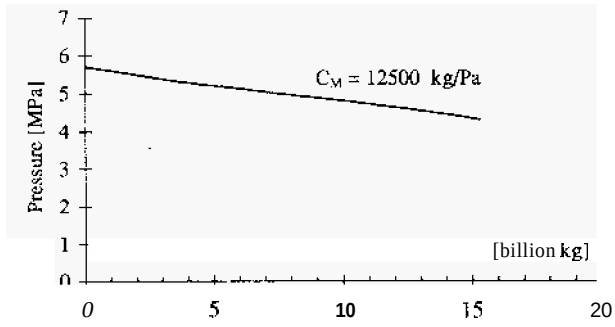

Figure 13. Reservoir C pressure versus cumulative steam production

On the other hand, pressure distribution *is* vaporstatic and thus the liquid saturation should be less than the irreducible saturation. about 30% maximum. With a porosity of 1.5% (core average), 1 m^3 of rock could hold less than 5 kg of water.
The amount of evaporated steam per unit rock volume is *thus* almost three times the amount of water that could havc been initially in place.
Moreover the reservoir should now be superheated while it is still saturated.
In addition. *the* total mass of produced gas could not have been initially stored in the reservoir volume at its low partial pressure.
In conclusion, even if the reservoir behaves as though it were closed, there should be a substantial water and gas inflow or, alternatively, adsorption might play a major role.

2.3.2 Interaction between reservoirs B and C

Initial pressure in reservoir B was 6.0 MPa in 1972 at -236 m (sea level); initial pressure in reservoir C in 1980 was *5.8* MPa at -1710 m (s.l.). Considering the vaporstatic head, the depletion caused by 8 years of production from reservoir B on reservoir C was approximately 0.6 MPa .
A further connection between reservoirs B and C was revealed by the gas content drop in reservoir B, which took place in 1987 (Figure *5)* when massive production from rcservoir C began.
It is likely that reservoir C's production has been partially depleting reservoir B which has been inducing a water inflow from reservoir A.

It is worth noting that the total gas flow of reservoirs B plus C has remained roughly constant at 5-6 kg/s from 1973 to the present (Figure 14) even though prduction shifted from one to two reservoirs and from one well in 1973 to ten wells in 1994 and despite the fact that the total steam flowrate of the two reservoirs had roughly doubled in the meantime (Figure 15).

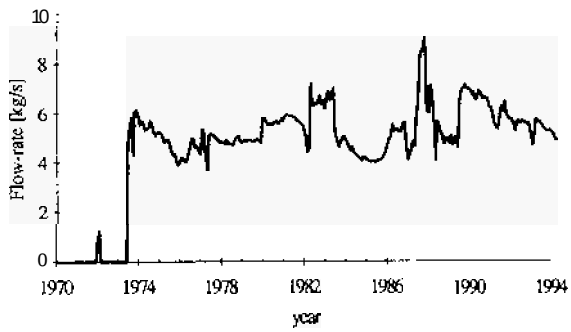

Figure 14. Gas flow rate history for reservoirs B+C

The constancy of the gas flowrate seems to suggest gas generation in the reservoir or an inflow which is independent of the reservoir pressure.



Figure 15. Total steam flowrate history for reservoirs B+C.

2.4 Reservoir D

After 1992, ten deep wells (4 km) were drilled below the reservoirs already in production (reservoirs B and C), investigating deep seismic reflecting horizons (Batini et al., 1895).
Some of these wells turned out to he highly productive (15-30 kg/s).
The reservoir fluid is superheated steam with an initial pressure of 7.3 MPa in vaporstatic equilibrium with the previously discovered reservoirs.
The reservoir temperature is about 320°C and the gas content is 6% by weight.
Most of the wells have nut yet been extensively exploited, but only the Initial tests have been performed.
At present, two wells are feeding a 20 MW power plant.
The high chloride content (5-10 ppm) requires the use of scrubbers.

2.5 Reservoir E

This is not redly a reservoir, but noncommercial peripheral wells have been put together in this category.
All these wells show a static pressure of 6 MPa at the permeable level regardless of their depth. suggesting that the vapor dominated field extends into this border area.
As their temperatures are lower (100-225°C), they produce gas or water if they are nut dry.

3. CONCLUSIONS

Travale-Radicondoli field may be regarded as a single geothermal system. The subdivision into 5 reservoirs is mainly due to different depths, exploitation histories, declinc rates, stem qualities and fluid compositions.
Interconnections between reservoirs are apparent.
With the exception of reservoir A, which has a hydrostatic pressure distnbution. all the remaining 4 reservoirs have an initial vaporstatic pressure distribution (Figure 16), i.e. 6 MPa *at* -300 m arid 7 MPa at -3400 m (s.l.).
The initial field pressure was likely to be in equilibrium with the piezometric head exerted by the aquifer of reservoir A.
The natural manifestations acted as a "relief valve".
Convection extended the saturation temperature (275°C) even at shallow depth (reservoirs B and C), as can be seen in Figurc 17. In the deepest part of the field superheated steam exists with temperatures in the range of 300-350°C (reservoir D).
During exploitation, reservoir A was very soon watered out; conversely, natural water recharge stabilized production of reservoir 5, while rcscrvoir C is still declining as a closed system; the decline rate can not be explicable with the known reservoir dimensions.
Fluid production from reservoir D is still in the early stage.
At the field margins permeability and temperature decrease. Here a high gas content is present since the lower steam partial pressurc is balanced by a higher gas pressure.

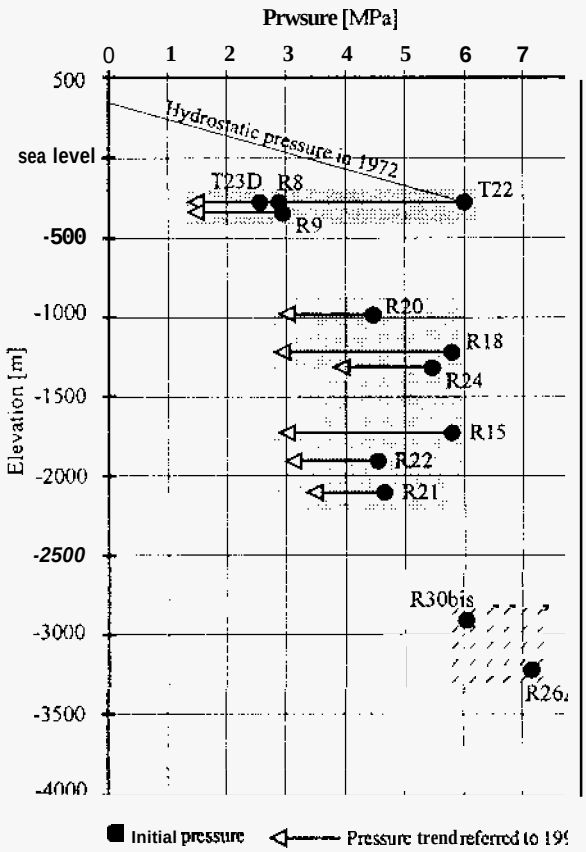

Figure 16. Pressure distribution in the field.

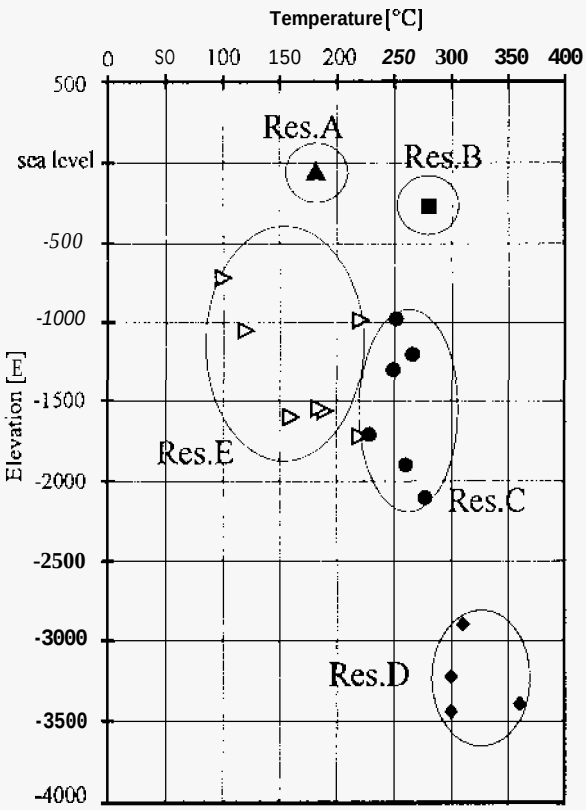

Figure 17. Temperatures in the producing intervals.

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