3973

THE OLD FIELD AT CERRO PRIETO CONSIDERED AS A LEAKY

Malcom A. Grant* and Michael J. O'Sullivan+
*Applied Mathematics Division, DSIR
Wellington, New Zealand
+University of Auckland
Auckland, New Zealand

ABSTRACT

Chemical and thermal changes are used to estimate the relative contributions of recharge from lateral flow and from shallower aquifers to the old field of Cerro Prieto. Pressure changes are then used to estimate the permeability of the hypothesized sealing layer overlying the reservoir. It is found that this layer is considerably less permeable than the producing aquifers; but not sufficiently impermeable to exclude flow into the reservoir of the cooler waters above. The producing aquifer is best considered as leaky rather than confined.

INTRODUCTION

Is the aquifer confined?

In the reservoir engineering analyses of Cerro Prieto, a major area of debate has been the extent to which the productive aquifer(s) is isolated by impermeable layer (or caprock or aquiclude). Some authors have made projections or models based upon confined aquifer models (eg. Liguori 1979; Molinar C. et al 1979; Tsang et al. 1979). On the other hand there does not appear to be any well-defined geological feature that forms a caprock (Elders et al 1981), and the falling chloride contents and enthalpies of the well discharges clearly indicate that the reservoir is being recharged by waters of lower salinity and temperature (Mañón M. et al. 1978; Truesdell et al. 1978; Fausto L. et al. 1979; Grant et al. 1981; Sánchez R. & de la Peña L. 1981).

For confinement

A supposition that a reservoir must be confined is sometimes carried into geothermal from petroleum reservoir engineering. It is not appropriate. As a static emplacement of fluid trapped for millions of years, a petroleum reservoir must be confined. A geothermal reservoir (other than geopressured) is part of an active hydrological system. In its natural state fluid is discharged, and replaced, continuously; and the reservoir fluid is typically replaced many times over the 10^5 - 10^6 years of life of a geothermal system. (See Donaldson et al. 1981 or Grant et al. 1982 for further comment).

The best evidence for the existence of a capping layer at Cerro Prieto is provided by the temperature distribution. Figure 1 shows an isothermal section, as drawn by Esquer (1981), showing the familiar pattern of temperature at Cerro Prieto. The top of the reservoir is marked, over most of the field, by a sharp thermal gradient, above which is a region of lower gradient. The same feature appears quite clearly in the temperature logs of many wells, for example M-48, in Figure 2. Interpreting such a temperature profile as an impermeable layer is based upon the model of Figure 3a, in which two convecting regions are separated by an aquiclude. This interpretation is probably correct in most situations. Figure 4 shows an outstanding example of this, in the peripheral well BR31 at Broadlands, where such a thermal feature coincides with an impermeable formation (Bixley, pers. comm; Grant et al. 1982). However, in some cases an alternative interpretation is possible. If there are parallel cross-flows of hot and cold water, a sharp thermal gradient will be produced without a permeability contrast. This could be appropriate to Cerro Prieto, where the extensively permeable sandstone contains a lateral flow of groundwater and the slanting upflow of hot fluid. Thus the sharp thermal gradient at the top of the reservoir may indicate a capping layer, or simply that the natural flow of both hot and cold water lies parallel to the 'cap'.

Against confinement

Against the hypothesis of a capping layer is the lack of any geological feature, and, more importantly, the changes in chloride content and discharge enthalpy. It seems now well established that the changes in chloride indicate recharge of less saline waters. Given that the salinity in the undisturbed reservoir correlate roughly with temperature, corresponding to a dilution process (Truesdell et al. 1979; Grant et al 1981), the recharge must also be of lower enthalpy. The arrival of lower temperatures will of course be delayed by heat exchange with the rock.

Enthalpy changes also indicate recharge of lower-temperature water.

Simply models in which the reservoir is confined predict a substantial and continuing rise in discharge enthalpy (Liguori 1979; Esquer P. 1981; Westwood & Castanier 1981). Discharge enthalpy did rise initially after production began, and rose to a significant excess above liquid water; but fell again. The lumped parameter model of Westwood & Castanier (1981) obtained a best match with a recharge of 260°C water, simulated discharge enthalpy then being fairly constant. The actual rise and later fall of the enthalpy indicates that the recharge has not been of constant enthalpy, but falling with time. Probably it began near reservoir values, and has fallen steadily since.

CONCEPTUAL MODEL

Figure 5 shows a simple conceptual model of the old field of Cerro Prieto. The producing aquifer (alpha) is a slanting structure, with temperatures increasing with depth to the east. Production comes from a region with average initial temperature of, say, 285°C and salinity 9000 ppm.

Above the aquifer is a layer in which there is a sharp thermal gradient - the hypothesized capping layer. Above that is permeable rock at lower temperature. Within this upper region there are flows of groundwater and warm water, the warmer waters being formed by mixing of groundwater and geothermal water. Based upon the isothermal sections, the capping layer may be up to 400m thick, and temperature drops by typically 150°C over this interval.

Is is assumed for the present purposes that there is no interaction with deeper aquifers. Since these would supply fluid of greater enthalpy and salinity, they cannot be a major source of recharge to the old field.

The reservoir exploited by units 1 & 2 is an area of about 2 km^2 of this aquifer. Recharge to this reservoir comes from two sources: lateral flow within the aquifer, and leakage downward through the capping layer. Temperature and hence average salinity changes comparatively slowly with distance within the aquifer. Both change much more rapidly through the capping layer. The next section estimates the rate of decline of chloride with cumulative mass flow, for each of these sources; and the rate of decline for the reservoir. A simple chloride balance then indicates the relative amounts of recharge from each direction.

ESTIMATE OF THE RELATIVE AMOUNTS OF RECHARGE FROM THE TWO SOURCES

Changes in reservoir salinity

Thus a decline of 500 ppm in the discharge indicated over a period of four years' production. To create such a decline, the recharge must be of lower salinity than the discharge. It is now assumed that the recharge is initially of chloride content equal to the reservoir, and changes linearly with time. This corresponds to assuming that the recharge mechanism is the sweep of water toward the reservoir, and that there was initially a distribution of temperature and salinity linearly with the volume enclosed in contours of fluid that arrive at the reservoir at the same time.

Taking the reservoir - the producing reservoir only - as covering 2 km^2, being 300m thick, having 20% porosity and negligible steam fraction in 1973 and 1977, it contains 90 Mt of water. The fall of 500 ppm in the salinity represents a total chloride loss of 9x500 (ppmxMt). With the total discharge, and assumed recharge, of 80 Mt, the recharge must average 90x500/80 = 550 ppm lower in chloride content than the discharge, or 1100 ppm lower in 1977-78 than in 1973-74, since it is initially at the same salinity. Thus the recharge falls by 1600 ppm over this period, or 20 ppm/Mt.

Lateral recharge

Figure 6, from Bermejo M. et al (1979), shows the pressure drop between 1973 and 1979. In addition, Saltuklaroglu (1979) gives data for well M-6 which extrapolate to a drop of 75 psi over the same time. A tentative completion of the 100 psi contour is drawn. The drawdown has spread much farther toward M-6 than to the east. Assuming an aquifer of constant thickness and fluid of constant properties (and no significant two-phase volume), the pattern of the isobars indicates the pattern of fluid loss from storage: the amount of flow from a particular direction is proportional to the distance of the isobars in that direction. Further, the isobaric contour is a contour of the initial position of fluid particles that enter the well at the same time.

Now consider the 100 psi contour. Original temperatures in the production field were 285°C, while near M-6 they fell to 150°C. An average over the countour is about 225°C. Corresponding chloride contents would be 9000 and 6700 ppm. The area contained within the countour is 6 km^2. Assuming the same aquifer parameters as for the reservoir, this countour contains 280 Mt of water. Thus chloride content in lateral recharge would fall by 2300 ppm after 280 Mt has flowed into the reservoir from lateral recharge, or a decline rate of 8 ppm/Mt. This estimate is even less accurate than the estimate of the changes in the reservoir.

Recharge from above

Recharge from above derives from downflow of water through the hypothesized capping layer. This is taken as 400m thick, with an assumed linear temperature drop of 150° C over it. Chloride content is similarly varying, from 9000 ppm to 4250 ppm, a drop of 4750 ppm. Assuming as a very rough first approximation that fluid flows down uniformly over the 2 km^2 of the production field (this assumption is important), this layer contains 140 Mt of water, so that the rate of chloride decline is 30 ppm/Mt.

The pressure drop is far from uniform over the production field (Bermejo M. et al. 1979). If the downflow enters over only half the production field, 4250 ppm is attained after only half as much cumulative downflow, and the decline rate is 60 ppm/Mt. As the falling enthalpy is distinctly greatest in the south, but is present everywhere, this is taken as a maximum.

The recharge source

The calculation above shows that the recharge must be falling in salinity at the rate of 20 ppm/Mt. Possible sources of recharge are lateral flow with a decline of 8 ppm/Mt, and downflow at 30-60 ppm/Mt. If the decline rate of the downflow is 30 ppm/Mt, it must represent about half the total recharge. If the decline of the downflow is 60 ppm/Mt, it must represent about one quarter of the total recharge.

Higher temperature recharge from directly below has been ignored. If present, it would have increasing enthalpy and salinity, and would require an increased amount of downflow to balance it to produce the same total recharge characteristic.

Thus, it can be concluded that one-quarter to one-half of the recharge to the old field of Cerro Prieto is water flowing down from directly above.

THE CAPPING LAYER

Recharge to the producing reservoir from above is 20-40 Mt over 1973-77, over which time the average pressure drop in the reservoir is 7 bar. Assuming that pressures above the capping layer have been maintained by groundwater flow, and so do not change greatly, a pressure drop of 7 bar is applied over 400m, or a gradient of 2 kPa/m. Applying Darcy's Law with an average kinematic viscosity of 0.15×10^{-6} m^2 gives k_v = 5-10 md.

This estimated vertical permeability of the capping layer is indeed considerably less than the reservoir permeability of about 100 md. But is not sufficiently small to exclude significant flow through this layer. The conflicting interpretations for the presence of absence of a capping layer are now resolved. While there is a seal over the productive aquifer, the seal is not perfect, and the aquifer is leaky. This conclusion is consistent with all the information about the cap.

LIMITATIONS OF THE ANALYSIS

The analysis of the chloride changes, and associated reservoir structure, has been very superficial. There are a number of obvious possibilities for improvement.

Data used covers only 1973-1977, or half the exploitation history. Analysis of more recent changes would confirm, deny or modify trends in salinity and enthalpy, and the correlation between them.

The capping layer has been assumed to have uniform properties. But the falling salinities and enthalpies are not uniformly spread. No allowance has been made for the possibility of an inflow which is confined to a part of the field.

It has been assumed that pressures above the capping layer are not changing. If so much fluid has come from there, must also have been pressure change there too. A fuller analysis of Cerro Prieto would require a model which includes the response of this aquifer also. Such an analysis would be greatly helped by measurement of the pressures at this level.

Additional constraints upon possible models of the changes in the production zone would be given by the history of the non-condensable gas content of well discharges. Changes in gas content are most sensitive to the amount of boiling that has occurred, and provide the best method of quantifying changes in steam fraction in the reservoir.

MODELING STUDY

In order to further test the approximate calculations carried out above, a simple modelling exercise was performed. A reservoir of 300m thickness was considered overlain by 400m of "capping" material and then a further 400m of more permeable material. A coarse discretization was used and the model was simplified considerably by ignoring all vertical flows except above the production block. Thus the geometry of the model considered is a disk shaped reservoir, extending out to a radius of 20.5 km, connected at its centre to the ground surface by a vertical column with a cross-sectional area of 2.25 km^2. A sketch of the model geometry and calculational grid layout is shown in figure 7. The distribution of initial temperatures and pressures assumed are also shown. The temperatures were assumed to vary linearly with depth from a maximum of 295°C at the midpoint of the reservoir (950m) to a minimum of 20°C at ground level. Laterally the temperature was assumed to vary approximately linearly from 295°C in the production region down to 150°C at 3 km from the centre of the production region. The initial pressure used was hydrostatic profile corresponding to the assumed temperature distribution.

As with all other aspects of the model considered no detailed matching with field data was attempted in setting up the initial temperature distributions. The model was designed to test assumptions about the most important large-scale physical features of Cerro Prieto. The numerical values of all parameters chosen are "ball-park" approximations only. The parameters for the problem are listed in table 1.

The main parameters available for calibration in the model are the horizontal and vertical permeability. By chance the first choice of 50 md for the reservoir, 10 md for the capping layer and 100 md for the upper layer gave a good match to historical production enthalpy and chloride concentration and a reasonable match to the observed pressure decline. Decreasing the permeability values leads to an increased rise in production en--thalpy and conversely increasing permeabilities leads to a decline in production enthalpies. The vertical column is essential in the model to give enough cool recharge to lower the production enthalpy in the observed fashion. Preliminary modelling work by one of the authors in collaboration with Lippmann et al (1981) and Esquer (see Esquer (1981) showed that a single layer reservoir with horizontal recharge only was not able to match the observed production enthalpy behaviour.

The production enthalpies, chloride concentrations in the production block, pressures in the production block (see figure 8) produced by the simulation are all in reasonable agreement with observations. The corresponding temperature and vapour saturation and horizontal and vertical recharge in the production block are shown in figure 9. In this model the vertical recharge dominates. The total production for 1973-1977 was 78.8 Mt (500 kg/s) and the total vertical recharge was 39.2 mt.

The present modelling study is only a preliminary one but it has served to show that the observed behavior of the old field at Cerro Prieto can be matched with a simple model which includes the possibility of horizontal and vertical recharge of cooler water. A complete simulation study of the Cerro Prieto reservoir should include more detailed model and a more careful matching of initial data but within the context of a model which preserves the gross features of the simple model investigated here.

IMPLICATIONS FOR CERRO PRIETO

The physical mechanism controlling the response to exploitation of the old field of Cerro Prieto is cold sweep. That is, as water is withdrawn from the reservoir, it is replaced by a flow, inward and downward, of cooler water. This cooler water is heated by the rock as it advances, so that thermal changes lay behind chemical ones.

The most important consequence of this is that the resource exploited by the wells is the store fluid and heat in and above the production zone. The greater resource known to exist at greater depth can be exploited by wells producing from greater depth, such as the recently drilled E-series of wells (Domínguez A. et al. 1981).

The extent to which the behavior of the old field is also representative of the new field to the east is not yet known. Monitoring the chemical changes under exploitation should provide the first indications of the degree of similarity.

IMPLICATIONS FOR RESERVOIR ENGINEERING

The model here proposed for the old field of Cerro Prieto is of an aquifer or aquifers overlain by an aquitard whose permeability is smaller by a factor of ten. Above the aquitard is another aquifer of good permeability containing cooler fluid. With the quality data obtained in a producing geothermal field, it is practically impossible to distinguish such an aquitard from a capping layer of zero permeability, using single-well or interference tests on wells in the producing aquifer. The existing well tests, interpretable as wells producing from within a confined aquifer, cannot distinguish between a confined and a leaky aquifer.

The properties of the capping layer would be tested directly by interference testing through it - for example with a normal production well and an observation well which terminates above the reservoir. Alternatively, it is possible that drilling data (circulation losses, mud weights and levels) may be available that give information about formation pressures above the reservoir. A history of the changes of these pressures, in response to the exploitation of the field, would be very valuable.

Interference testing between E-1 and M-46 showed no response (Sánchez R. & de la Peña L. 1981), indicating some degree of isolation between aquifers alpha and beta. Interference testing across the capping layer might yield a similar result. A result of no observed response can be interpreted to give an upper bound on the vertical permeability of the capping layer. It does not imply zero response, and for this reason tests would need to be carefully designed to produce a significant response, or a significant null response.

It may be very difficult to generate good tests for interference outside the productive aquifer, and over short times no test may yield useful results. At Wairakei, all wells were completed with an adjacent groundwater hole. Numerous tests demonstrated no response of the groundwater to geothermal production. Some years after production began, there were some signs of infiltration of cooler water. These are now more widespread, and there is a marked depression of the groundwater surface. At Broadlands, pressures in Ohaki rhyolite (see Figure 4), were, in the natural state of the field, about 6 bar below hydrostatic extrapolation of the reservoir pressures. Despite this excellent evidence for a resistive layer (through which the natural flow passed, giving a measure of its resistance), there has been substantial downflow of water from the rhyolite into the reservoir during past periods of discharge. In this case a shallow well has been observed to respond to production wells. These observations from Wairakei and Broadlands show that it is difficult to design tests that will predict the extent of inflow from aquifers above a geothermal reservoir, and that is is a mistake to assume that the geothermal reservoir is isolated even when there is no evidence of a direct connection to external waters.

CONCLUSION

The producing aquifer of the old field of Cerro Prieto is best considered as a leaky aquifer. One quarter to one half of its recharge derives from cooler rock inmediately above.

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TABLE 1. MODEL PARAMETERS.

porosity	0.2
rock density	2500 kg/m^3
rock specific heat	1000 J/kg.K
conductivity	2.5 W/mK
permeability	10^{-14} m^2 (10 md) caprock
	5.0 x 10^{-14} m^2 (50 md) reservoir
production rate	500 kg/s

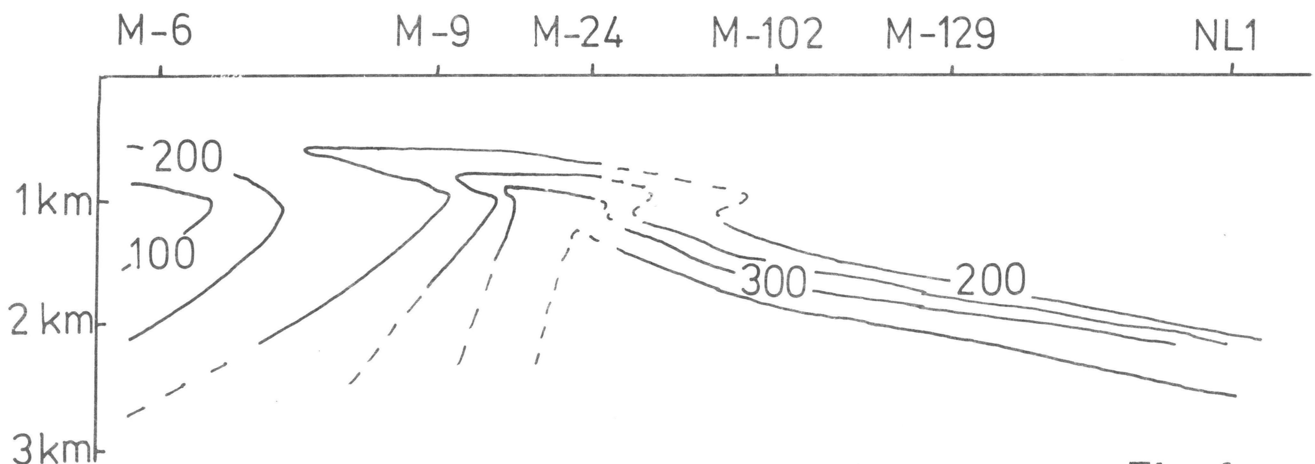


Fig. 1

(a)

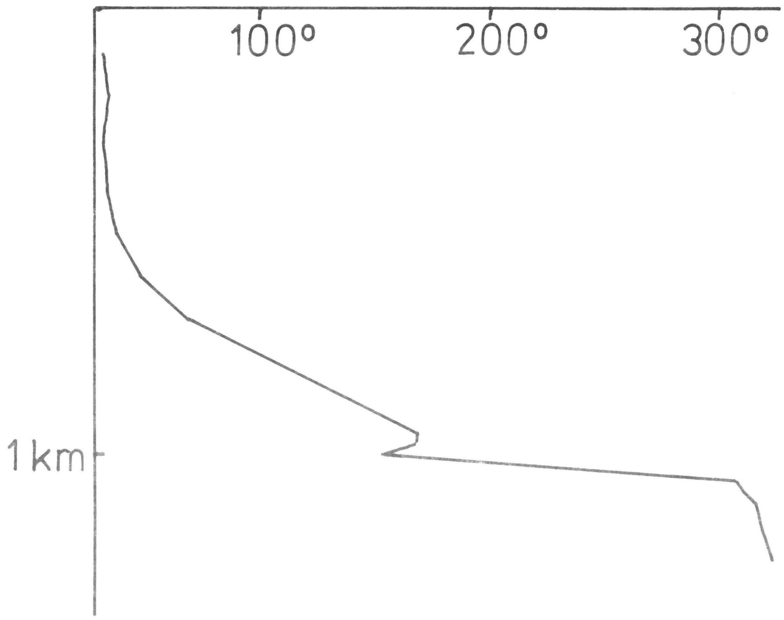


Fig. 2

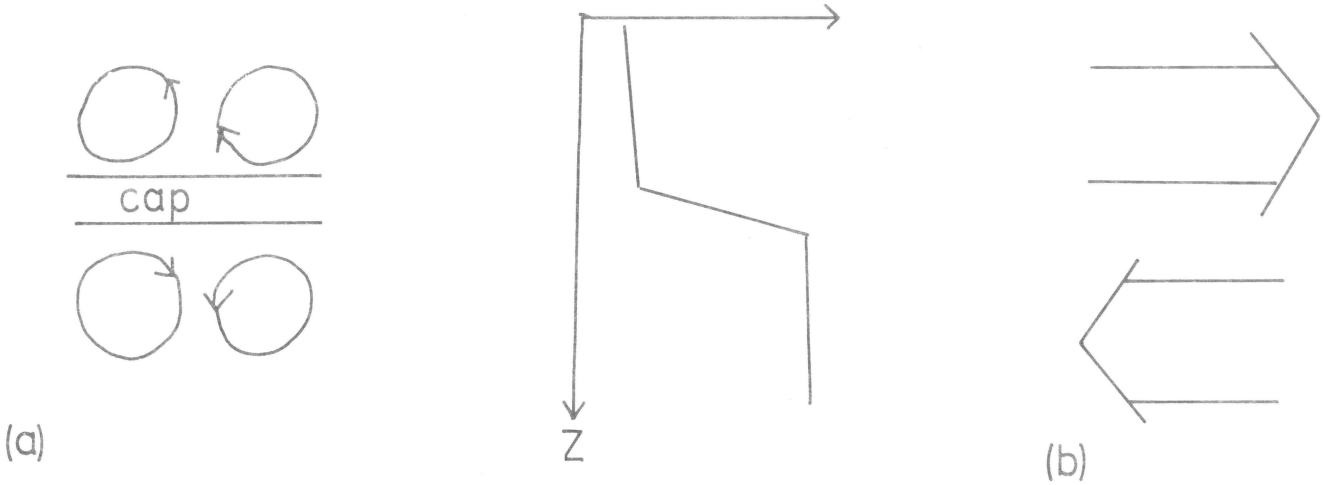


Fig. 3

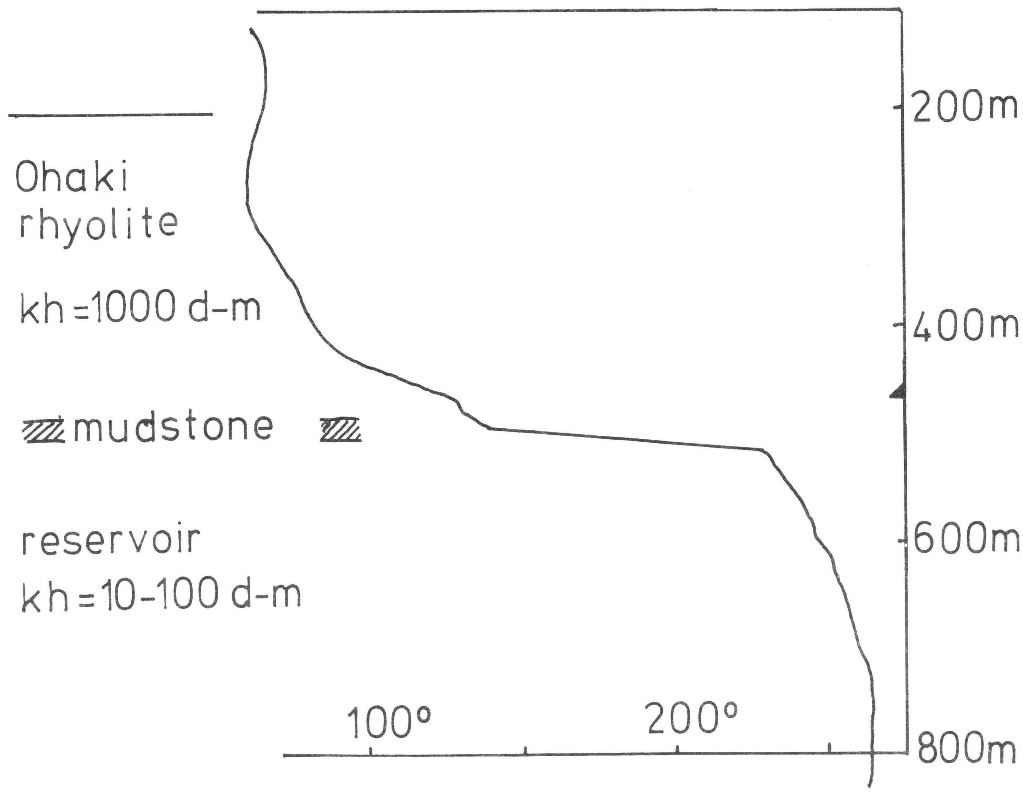

Ohaki
rhyolite
kh=1000 d-m
mudstone
reservoir
kh=10-100 d-m
200m
400m
600m
800m
100°
200°

Fig. 4

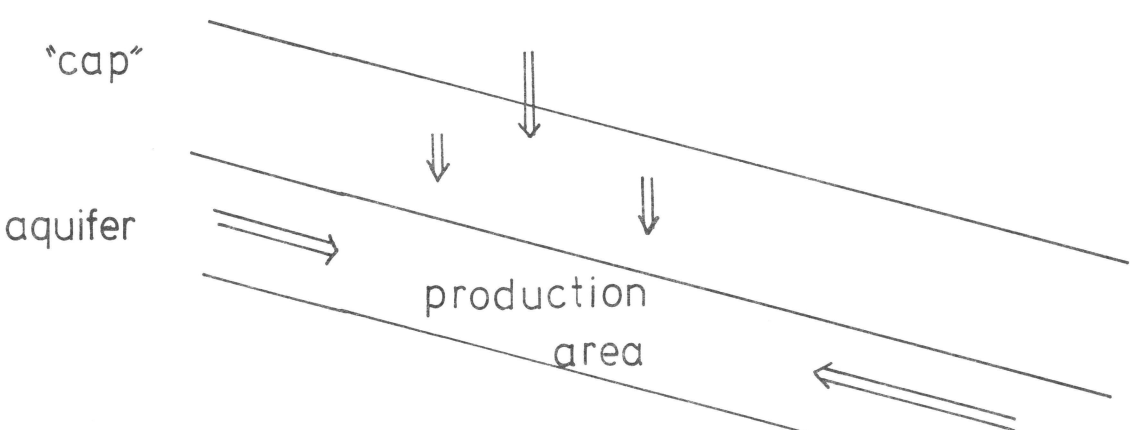
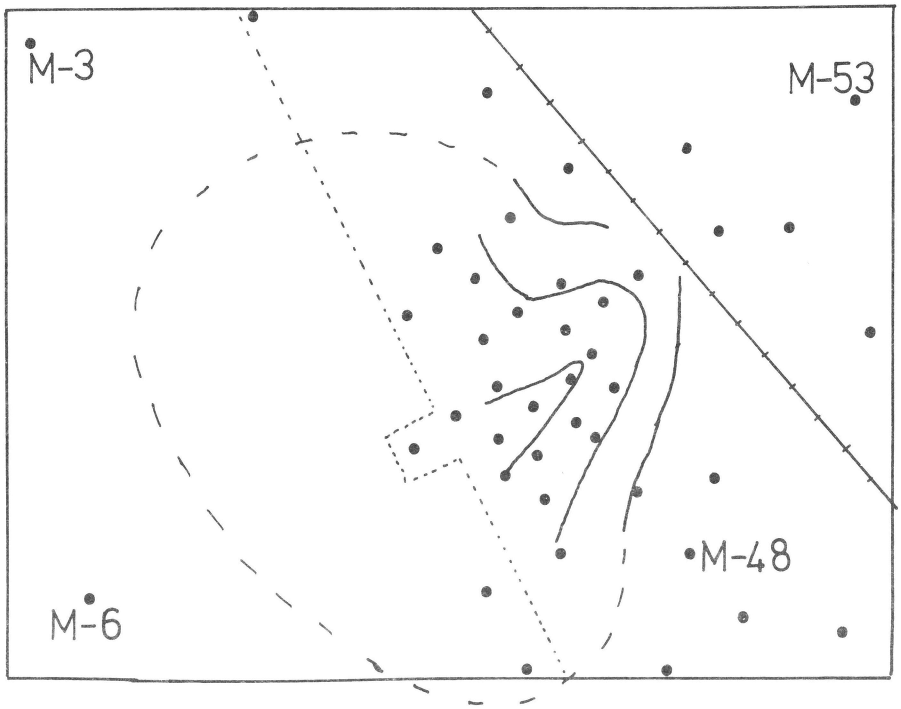
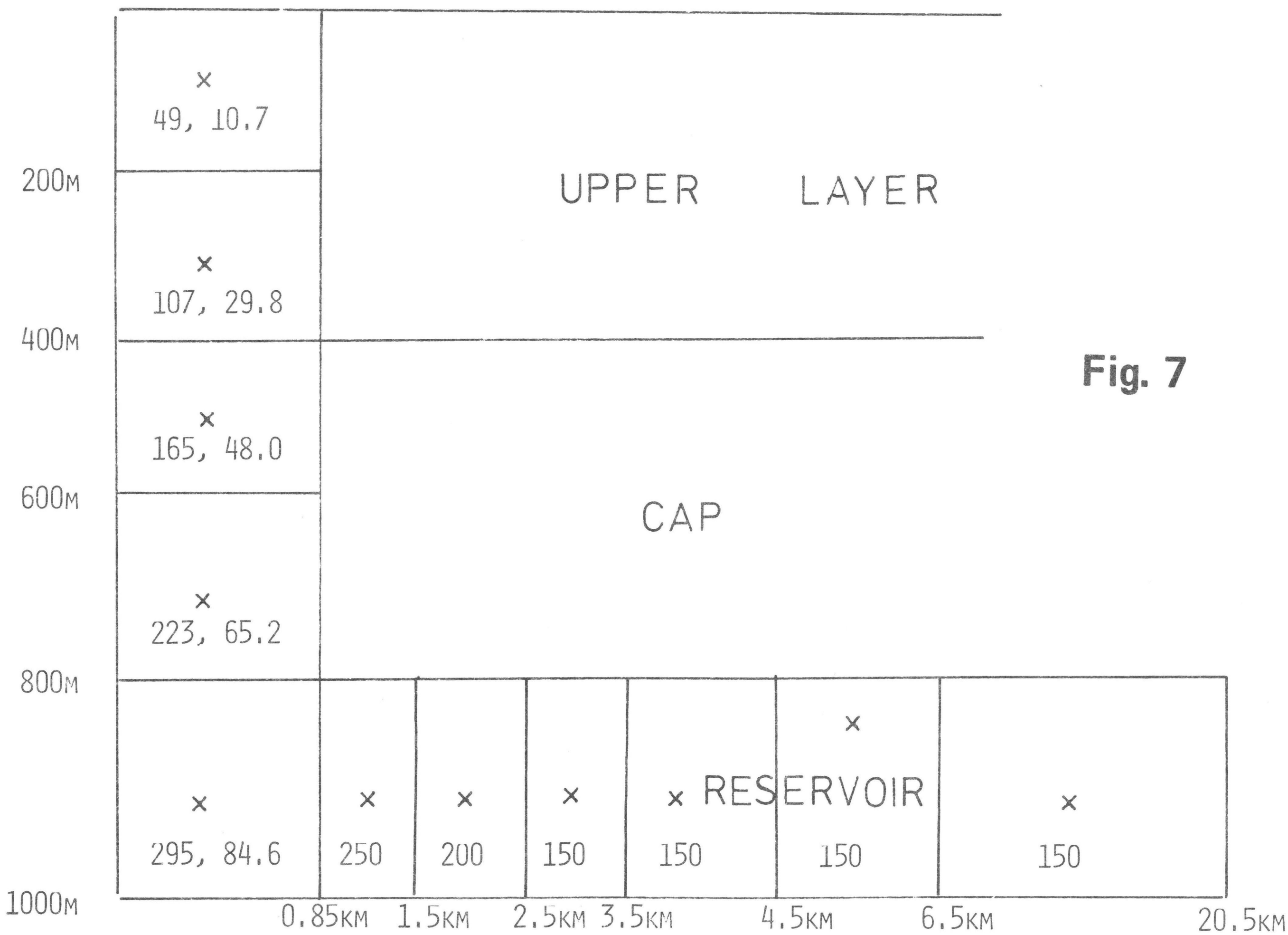

"cap"
aquifer
production
area

Fig. 5



M-3
M-53
M-48
M-6

Fig. 6



49, 10.7
200M
107, 29.8
400M
165, 48.0
600M
223, 65.2
800M
295, 84.6
1000M
UPPER LAYER
CAP
RESERVOIR
250
200
150
150
150
150
0.85KM
1.5KM
2.5KM
3.5KM
4.5KM
6.5KM
20.5KM

Fig. 7

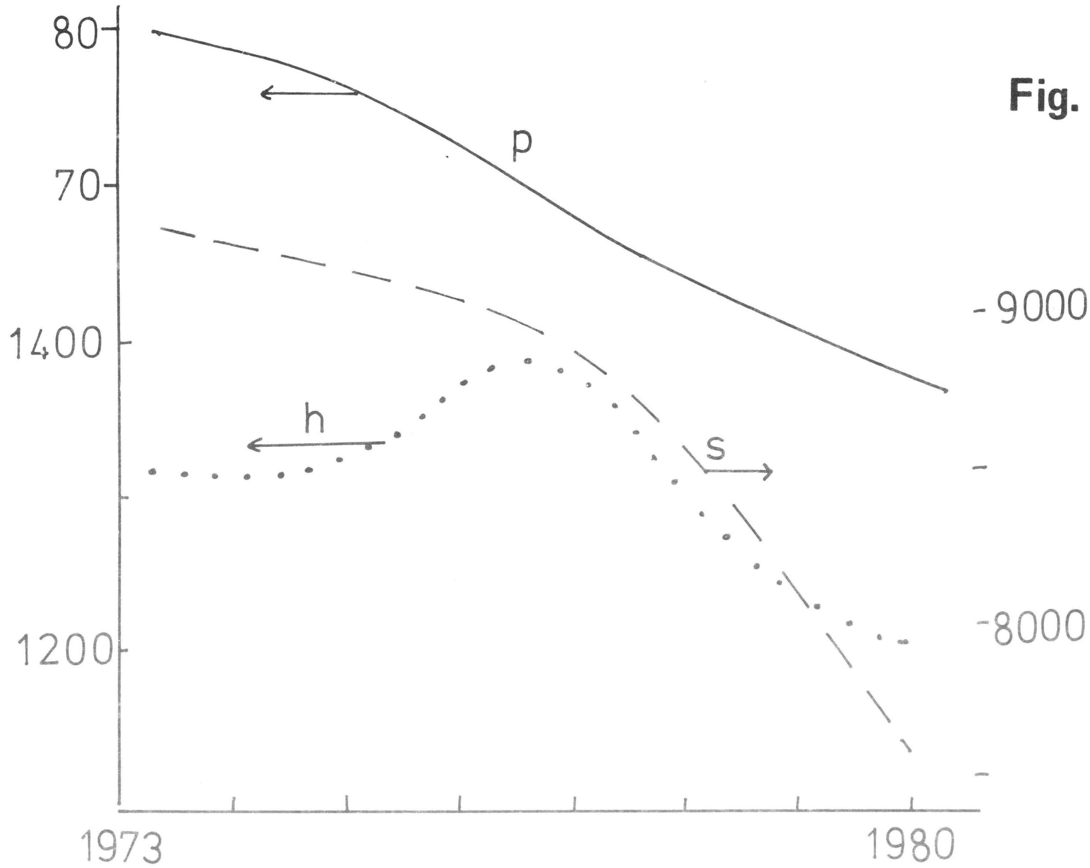


Fig. 8

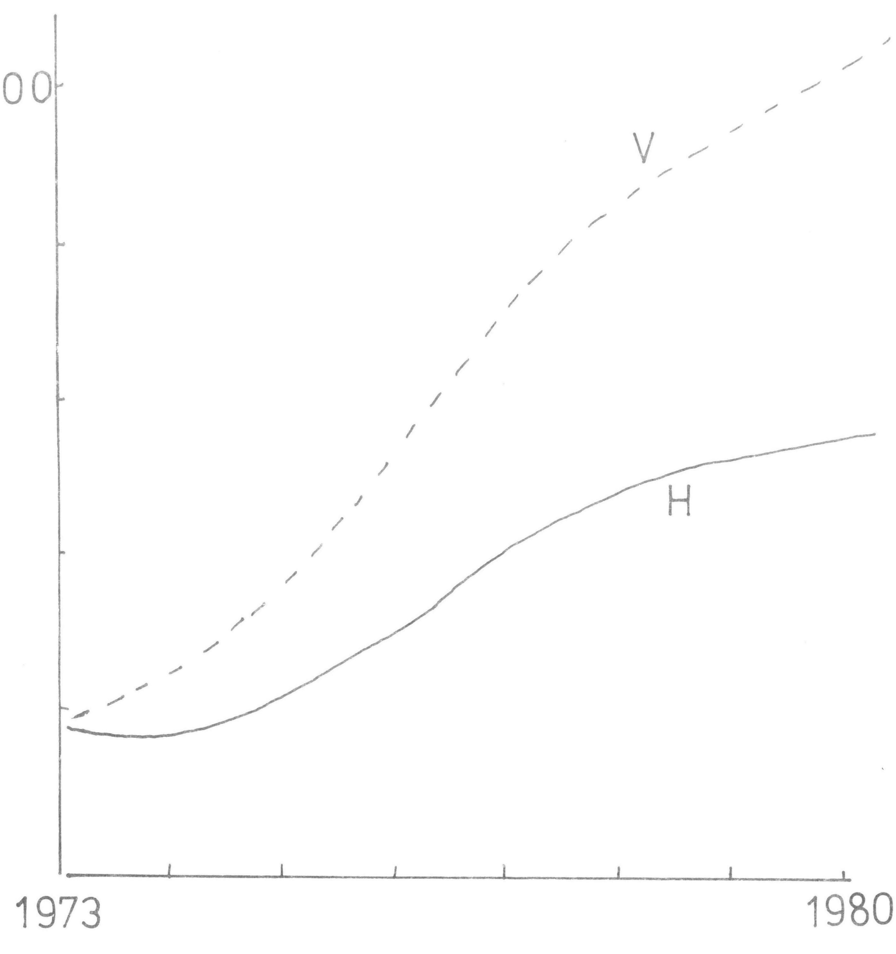


Fig. 9