MODELLING OF PRODUCTION AND RECHARGE AT WAIRAKEI

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ABSTRACT

A distributed parameter model of the Wairakei geothermal reservoir is used to simulate production and recharge at Wairakei. The model is idealized because radial symmetry is assumed and a coarse discretization is used. However, the model does produce a reasonable steady state representation of the undisturbed reservoir, a good match to the observed behaviour and a plausible prediction of fhe future.

INTRODUCTION

The Wairakei geothermal reservoir has been used as a test case quite extensively by geothermal modellers because of readily available data and the long period of exploitation. There is a wide range of types of models (see Blakeley and O'Sullivan, 1981). The model presented here is a multi-dimensional distributed parameter one based on a reservoir simulator developed at the University of Auckland (see Zyvoloski, O'Sullivan and Krol (1979), Blakeley and O'Sullivan (1980, 1981)).

The most notable previous distributed parameter models of Wairakei are by Mercer and Faust (1979) and Pritchett, Rice and Garg (1980). Mercer and Faust (1979) use a detailed description of the Wairakei reservoir in the horizontal plane but only a quasi-three dimensional representation in the vertical direction. This is obtained by integrating through the depth of the reservoir and including vertical recharge in a manner similar to that used for leaky aquifers in groundwater modelling. Since some of the most important phenomena at Wairakei are the vertical drawdown of the boiling zone and vertical recharge, the approach used by Mercer and Faust was not adopted here. Instead some horizontal detail and realismwere sacrificed by assuming radial symmetry and the vertical dimension was fully included.

Pritchett et al (1980) use two models. The first is a 1-D vertical model similar to and pre-dating that considered by the present authors. The second is a 2-D vertical "slice" through Wairakei. The 2-D model has the advantage of having much realistic physical detail built into it. However, with a 2-D model the modelling of lateral recharge is intrinsically limited. Also it suffers from the disadvantage of including a comparatively small total volume so that the performance of the model is significantly affected by boundary recharge assumptions. This disadvantage greatly affects the reliability of long term predictions. Small changes in recharge assumptions can significantly influence the future predicted by the model. In the present model a large enough volume of the Wairakei region is included so that the inevitable recharge assumptions made at the outer boundaries do not significantly influence the behaviour of the production zone.

RESERVOIR DATA

A summary of the most significant data and its interpretation is presented here. A more comprehensive collection of Wairakei data has been prepared by Pritchett et al (1978).

a) Natural Surface Discharge

Analysis of heat flow surveys conducted in 1951-52 and 1958 shows the level of natural heat flow to be about 430 MW. Subtracting from this value the heat flow due to conduction and using a mean enthalpy of 1.026 MJ/kg, Fischer (1964) obtained a mass discharge of 440 kg/s.

More recent work (Allis, 1979), however, uses the same heat flow and deduces a mass flow of 400 kg/s. This figure corresponds to a mass inflow to the field at 260°C for an energy inflow equal to the observed surface discharge.

b) Recharge

Although the quantity of recharge to the field has been estimated from the repeat gravity data of Hunt (1977), the direction from which this recharge enters the field is in dispute. Allis (1979) believes that chemical evidence and lack of temperature change in deep bores suggest that there is very little infiltration into the field of surface meteoric water. He, therefore, assumes that the mass inflow to the field must be from increased hot water flow from depth. Conversely, it has been suggested (Grant, 1980) that the change from superhydrostatic gradients to gradients near or below hydrostatic implies that there is negligible induced upflow and water flow in the field is primarily horizontal. Cold recharge pushes the hot periphery inwards.

c) Permeability and Porosity

Laboratory measured values of permeability and porosity have proven almost useless as a means of predicting reservoir behaviour because both properties are affected by the fracture network throughout the region. Because the fracture network cannot be taken into account in the laboratory tests, they tend to underestimate values of permeability. Laboratory tests also give a higher value of porosity than that needed to explain reservoir behaviour.

A number of authors have made estimates of permeabilities from observing macroscopic features of Wairakei behaviour. McNabb et al (1975) using an analytical model estimated a horizontal permeability of 7 md. Using the temperature profile at 1 km and early pressure measurements they estimate a vertical permeability of 7.6 md. Grant (1980) estimates from the natural discharge a value at 12 md for vertical permeability, by assuming an area of 10 km² for the region of upflow in the two-phase zone. By fitting calculated values of drawdown pressure to measured pressure values in a number of wells at Tauhara, Wooding (1981) obtains an estimate of 35 md for the horizontal permeability of the aquifer between Wairakei and Tauhara.

The uniformity of pressure across the production zone suggests that horizontal permeability is high. Because this high permeability is associated with extensive faulting it is most probable that the horizontal permeability outside the faulted area is much lower.

THE MODEL

The model considered here is a radially symmetric 2-D vertical model. The grid layout and distribution of rock types are sketched in Figure 1. The rock properties used in each of the regions are shown in Table 1. Data common to all regions is shown in Table 2.

The model is designed to be a simple and obvious extension of the 1-D vertical model considered previously by the present authors (Blakeley and O'Sullivan, 1981). The 1-D vertical model produced a reasonable match to the observed field behaviour, however, its long term behaviour was largely determined by arbitrary lateral recharge assumptions In order to accurately model lateral recharge at Wairakei and to produce a model which has sensible failure modes (cold water intrusion from above or laterally) built into it an extra space dimension is essential. The circular symmetry assumed is an obvious over-simplification but allows enormous computational savings while still preserving the essential physical processes.

The model includes only a region 1050 m deep and of 10 km radius. To include the effects of flow outside this region recharge is allowed. In the centre two columns in addition to the natural throughflow a pressure dependent recharge of the form $c(p-p_0)$ is allowed into the base where c is a constant and p_0 is the initial pressure in the block. Recharge of a similar form is allowed through the side boundary. Recharge enthalpy is kept fixed at its initial value.

The model was run with only the natural throughflow (ie. without production) until a steady state was reached. This was used as the starting point for the production run.

MODEL PARAMETERS

The starting point in the choice of parameters was the previous 1-D vertical model (Blakeley and O'Sullivan, 1981). The aim in the modelling study then was to achieve a good match to the observed pressure drop in the Wairakei reservoir and the actual production enthalpy with as few changes to the basic choice of parameters as possible.

Many experimental simulations were carried out with the model and it was found necessary to change some parameters. The reasons for parameter selection are discussed below.

a) Horizontal Permeability in the Waiora Formation

The approach adopted in choosing parameters was to keep everything as simple as possible until it appeared necessary to introduce more complications. For this reason, a uniform horizontal permeability was chosen in each of the regions. It became obvious, however, that it would not be possible to get a correct history of both pressure and production enthalpy with a uniform horizontal permeability in the Waiora formation; If the permeability was sufficiently high to give a good pressure match, there was far too much cold recharge entering the production area from the surface. This large quantity of cold surface recharge is not observed. Both chemical and temperature data (Allis, 1979) suggest that there was very little infiltration of surface water during the first 20 years of exploitation. This large amount of cold surface recharge also caused numerical problems. A finer grid is probably needed to model this process. For these reasons, a relatively high permeability was chosen for the production region to give pressure support and a lower permeability for the outer region was chosen to prevent excess cold recharge.

b) Permeability in the Huka Falls Layer

Initially values of permeabilities equal to those in the Waiora formation were chosen. However, without some reduction in permeability in this layer reservoir temperatures and hence production enthalpy dropped too low.

Horizontal and vertical permeabilities were set equal. Higher values of permeability were used for the part of the Huka Falls above the production zone.

c) Vertical Permeability in the Waiora Formation

Without a lower permeability layer representing the Huka Falls formation, problems were experienced with selecting vertical permeabilities in the Waiora formation. While increasing the permeability initially raised the pressures it led later to excess cold recharge from the surface outside the production zone, which lowered production enthalpy considerably. However, the cold recharge from the surface was greatly decreased by the presence of a relatively impermeable layer representing the Huka Falls. This made it possible to use a uniform vertical permeability in the Waiora formation avoiding further complications.

d) Permeability in the Pumice Layer

Some modellers (Pritchett et al, 1980) have used a value of vertical permeability for the pumice layer that is higher than elsewhere in the reservoir. It was found that the value of permeability in the pumice layer made very little difference to the pressure and enthalpy histories. However, high values can cause computational problems when the surface flow in the outer blocks changes direction from upwards to downwards. It is probably necessary to use a finer grid to adequately model these processes. For this reason a value intermediate between that of the Huka Falls and Waiora Formation was chosen. Horizontal and vertical permeability are the same.

e) Permeability in the Ignimbrites

A value of permeability not much lower than that in the Waiora formation was chosen, consistent with the belief (Mercer & Faust, 1979) that the vertical permeability in the ignimbrites is not much different from that in the Waiora formation. Horizontal and vertical permeabilities were set equal and uniform throughout the layer.

f) Natural Throughflow

A natural throughflow of 400 kg/s was allowed entering the centre two columns at 260 C. This meant that most of the natural surface discharge occurred from these columns whose surface area is 12.57 km. However, the hot water zone extended over a greater area than this, as electrical resistivity measurements suggest it should.

g) Production

The production was assigned to the various blocks according to the historical production records and using available data on major feed zones and open intervals of the wells (see Grant (1980, 198.1) and Pritchett et al (1978)).

For simulation of the behaviour of the reservoir beyong 1977 the average 1977 production level is used.

h) Comparison with other modellers

The values of parameters chosen agree quite well with those used by other modellers. However, Pritchet et al (1980) use more rock types in their model than are used here. Mercer and Faust (1979) use a value of 0.6 md for horizontal permeability in the outer part of the Waiora aquifer. In the inner region the permeability varies from 3 to 300 md. Vertical permeability values used for the Huka Falls confining bed vary from .01 to 2 md. The porosity throughout is 0.25. These values are similar to those used here.

RESULTS

The resulting pressures at 275 m below sealevel for the rock properties in Table 1 are plotted in Fig. 2, together with the field results (taken from Fradkin et al (1980) and a private communication from Grant). While the pressures are initially a little low, the agreement is very good up until 1968. The model exaggerates the recovery on partial shutdown. From then on it gives an over-estimate of the pressure. This is accompanied by the rather high proportion of recharge to total production for this period shown in Table 3.

Fig. 3 shows the distribution of pressures horizontally at 275 m below sealevel. Pressure profiles at the beginning of 1953 and 1973 are shown for the inner five blocks. The amount of drawdown in the large outer block is very sensitive to the recharge parameter which is chosen. However, the pressures of the five blocks inside this are relatively insensitive to the choice of recharge parameter. This includes a region of 5 km radius and, therefore, the predicted behaviour of the production zone is not affected by the recharge boundary condition. The pressure drawdown extends well beyond the limits of the production region. Wooding and Grant (1974) observe that the pressure drawdown induced by Wairakei is widespread, extending through the Tauhara field to distances of order 10 km.

The resulting production enthalpies are plotted in Fig. 4, together with field results. Like the field results, the model results show considerable fluctuations. Apart from a slight exaggeration of the rise in 1963, the agreement is good.

The effects on both pressure and enthalpy of varying the horizontal permeability for the Waiora formation are shown in Figs. 5,6,7 and 8. Fig. 5 shows pressures for models which vary only in the horizontal permeability of the outer Waiora formation. Fig. 6 shows the production enthalpy for these same models. Figs. 7 and 8 show pressures and enthalpies for models which vary only in the horizontal permeability of the inner Waiora formation.

Fig. 5 shows that the main effect on pressure of increasing the permeability in the outer Waiora formation is to raise pressure after 1963. There is almost no effect before this. Increasing the Permeability in this outer region increases the recharge to the production zone. The delay in its action is consistent with the idea that the last phase of the pressure history is dominated by recharge effects.

The effect on production enthalpy is, however, immediate as shown by Fig.6. For ease of comparison yearly averages of production enthalpy are plotted in each case. Higher outer permeability causes lower steady state temperatures in the production zone. Consequently, production enthalpies start off lower, and then remain lower throughout. The effect of varying permeability is most obvious during the enthalpy peak of the mid-sixties.

Changes caused by increasing the permeability of the inner Waiora act at quite different times to those caused by increases in the outer Waiora. Slight pressure changes are evident very early in the history (Fig.7) and increase only a small amount with time. This contrasts with Fig. 5 where almost no difference is seen until after 1964.

Conversely, changes in enthalpy caused by increasing the permeability of the inner Waiora are fairly negligible until 1962 at the start of the enthalpy rise (Fig.8). It is only during this rise that the enthalpies are quite clearly distinguishable.

Decreasing the recharge from the centre base by decreasing the recharge coefficient has effects on both pressure and enthalpy very similar to those obtained by decreasing the horizontal permeability in the outer Waiora formation.

Increasing the vertical permeability in the Waiora formation has effects very similar to those obtained by increasing the horizontal permeability in the inner Waiora formation.

The history of the production enthalpy shows the following trends. Enthalpy is fairly constant until 1962. Thus the production enthalpy in this initial period is very dependent on the natural state that existed before production began. The two parameters which most significantly affect this are the vertical permeability of the Huka Falls formation and the horizontal permeability of the outer Waiora formation.

Low vertical permeability in the Huka Falls formation causes high temperatures below it in the Waiora formation in the steady state. Similarly low horizontal permeability in the outer Waiora reduces the flow between the hot production area and the cooler outer area, resulting in high temperatures in the production area.

The rise in enthalpy beginning in 1962 is the result of an increased proportion of steam in the production fluid. Any property which increases the flow into the production area will increase the water saturation in the upper two phase region of the production zone. This limits the extent of the rise in enthalpy Such proporties are horizontal and vertical permeability throughout the Waiora formation and the amount of induced upflow.

The production enthalpy declines again as the increased proportion of steam in the 2-phase region caused by the drop in pressure is balanced by cooler recharge entering. The most significant properties in this case are the horizontal permeability in the outer Waiora formation and the amount of cold recharge entering the outer boundary.

There appear to be three corresponding phases in the pressure history. In the first phase fluid is drawn from close to the production wells. In the second phase drainage effects are most important. Pressures are most dependent on vertical and horizontal permeability in the inner Waiora formation. Recharge effects are most important in the last stage. Pressure is controlled by the horizontal permeability in the outer Waiora formation and the amount of recharge, both induced hot upflow and the cold recharge to the outer boundary.

Figs. 9 and 10 give the results that were obtained by simulating the future performance of the reservoir. Both pressure and production enthalpy show an extremely gradual decline. The ratio of mass replaced to that withdrawn for the last 10 years of simulation was 1.1. The hot production fluid was being completely replaced by cold recharge. Heat was mined from the reservoir in the process.

Fig. 11 shows the extent of the boiling zone and the isothermal profile for the years 1953, 1968, 1975 and 2008 (predicted changes between 1975 and 2008 are slow). During the years between 1953 and 1968 the boiling zone beneath the Huka Falls layer increases in size. There is a consequent cooling of the reservoir in this region. Most of this change occurs in the early 1960's. A similar increase in boiling zone and decrease in temperatures occurs between 1968 and 1975. However, by 2008 the boiling zone is beginning to recede. Temperatures at the top of the reservoir are dropping as cold surface water enters and formerly 2-phase areas become saturated again.

CONCLUSIONS

A 2-D vertical radially symmetric model is capable of producing a good fit to the production enthalpy at Wairakei. This was not possible in an earlier 1-D vertical model (Blakeley and O'Sullivan (1981)). However, with a 2-D vertical radially symmetric model it is possible to represent the recharge more accurately. The recharge enthalpy declines as cooler water enters the production zone laterally.

The model presented here gives a very good fit to the pressure decline at Wairakei during the period 1960-68. The predicted pressures before 1960 are a little low. The pressure recovery on partial shutdown is exaggerated and thereafter the predicted pressure is too high.

There are three possible sources of error. The early behaviour is affected by the choice of relative permeability factors. The factors given in Table 1 are modifications of the standard Corey formula suggested by Grant (1977). Their suitability, or indeed the suitability of the Corey formula is not really known.

The pressure behaviour from 1968 onwards is probably influence by two factors. In order to accurately represent lateral recharge the model extends a considerable distance in the horizontal direction. To economise in computation time by avoiding too many blocks a fairly coarse grid was used. This could lead to overreaction to sudden reduction in production as was seen in 1968 but also after that to a lesser degree. The fluid at the level pressure measurements are taken is all liquid and relatively imcompressible.

Another possible source of error is in the choice of recharge parameter for the centre base. The proportion of recharge entering the field laterally or vertically is unknown. Allowing too high a proportion to enter vertically could cause the pressures to be too high in the later section of the history, Further work is being carried out in these three areas.

The model predicts a slow decrease in pressure and enthalpy up to the year 2000. However, there are three factors which mean that a lifetime estimate based on this model would over-estimate the actual lifetime. The first two, the assumption of radial symmetry and the uniformity of horizontal permeability mean that the cold outer waters intrude upon the field slowly and uniformly. In fact cold water may enter some sections of the field much more quickly than others. The third factor, the assumption of a non-fractured porous medium, has a similar effect. In reality, cold water may enter much more quickly passing preferentially along fractures.

The model does indicate that cold water intrusion from above is likely to be an important factor in the future behaviour of the Wairakei reservoir.

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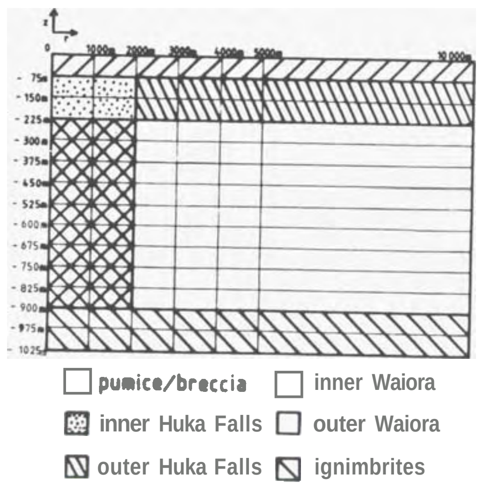

Figure 1: Grid layout and distribution of rock types.

Rock type	Porosity	Horizontal Permeability (md)	Vertical Permeability (md)
pumice/breccia	0.25	10	10
inner Huka Falls	0.20	1	1
outer Huka Falls	0.20	0.1	0.1
inner Waiora	0.20	300	20
outer Waiora	0.20	20	20
ignimbrites	0.15	5	5

TABLE 1: Rock properties

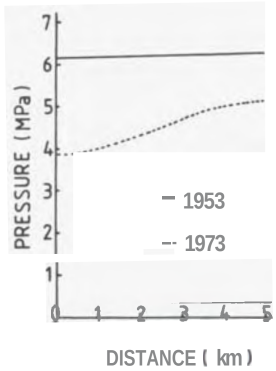

Figure 3: Distribution of pressures radially at RL-275m.

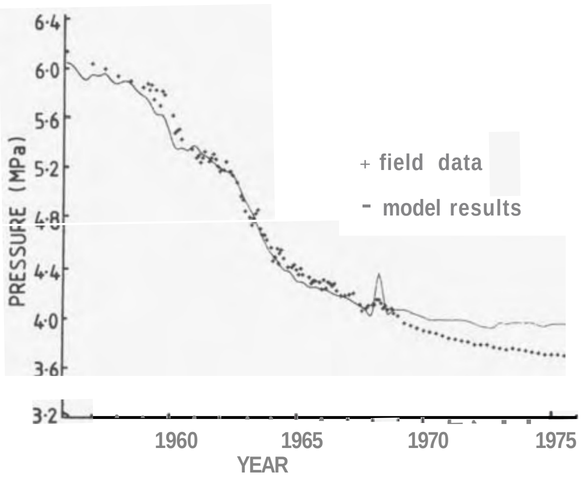

Figure 2: Pressure decline at RL-275m for the rock properties shown in Table 1.

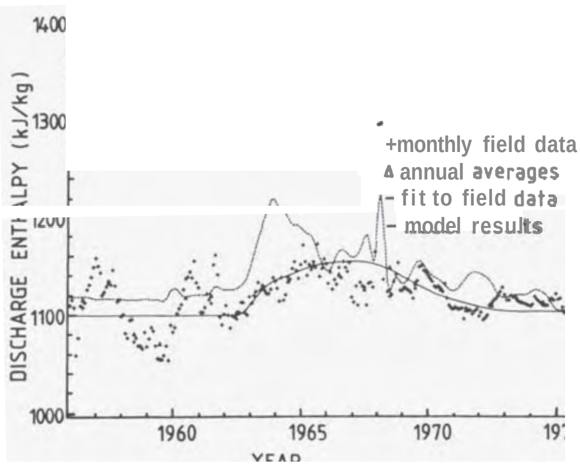

Figure 4: Production enthalpy history for the rock properties shown in table 1.

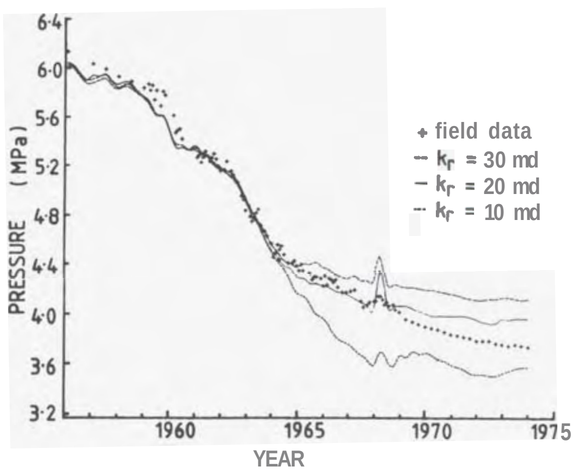

Figure 5: Pressure decline at RL-275m for varying values of horizontal permeability in the outer Waiora formation.

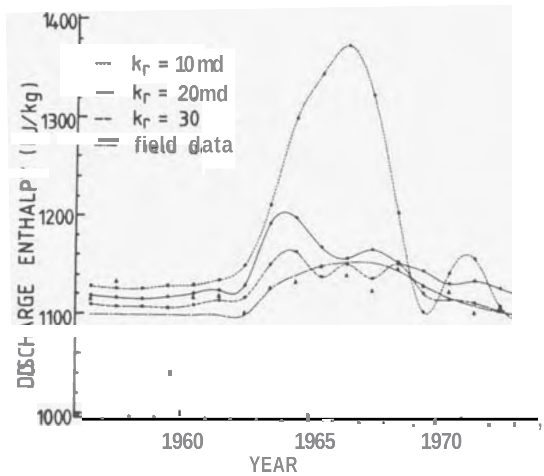

Figure 6: Production enthalpy history for varying values of horizontal permeability in the outer Waiora formation. Model results are year averages. Field results are a 'best fit' line to data.

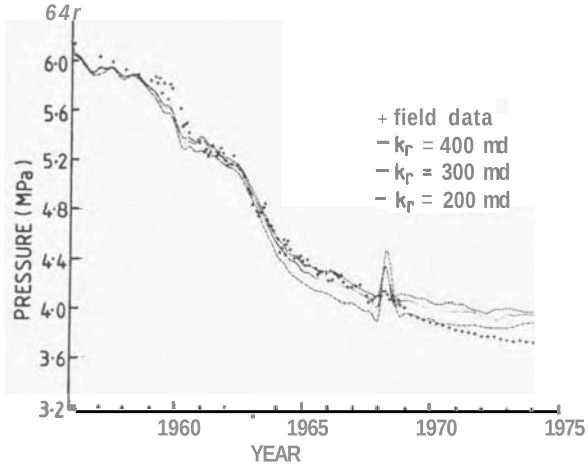

Figure 7: Pressure decline at RL-275m for varying values of horizontal permeability in the inner Waiora formation.

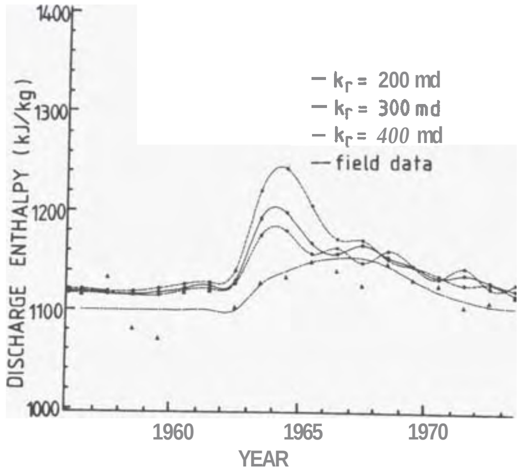

Figure 8: Production enthalpy history for values of horizontal permeability in the inner Waiora formation. Model results are year averages. Field results are a 'best fit' line to data.

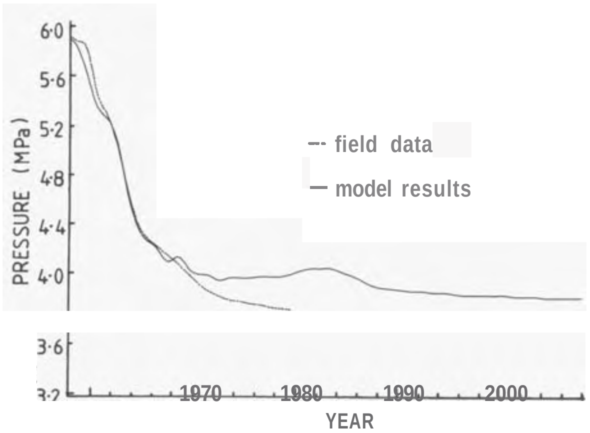

Figure 9: Past andpredicted future behaviour of pressure at RL-275m.

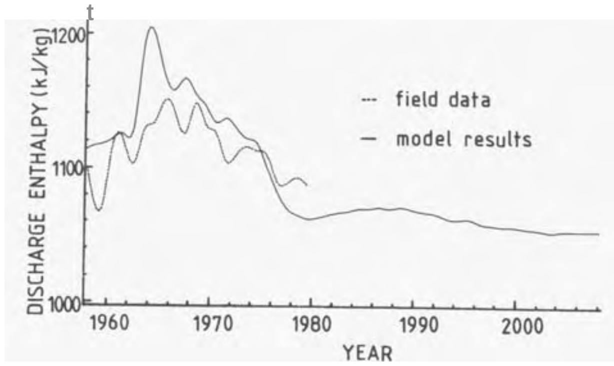

Figure 10: Past and predicted future production enthalpy.

Rock density	2200 kg/m³
Conductivity	1.5 W/m.K
Rock specific heat	900 J/kg.K
Mass throughflow	400 kg/s
Heat throughflow	457 MW
Surface temperature	20°C
Centre base temperature	260°C
Relative permeabilities	$kr\ell = S_\ell^4$

Time period	1958-61	1961-67	1967-74
Results from Hunt (1977)	0.3 ± 0.15	0.35 ± 0.15	0.9 ± 0.15
Model results	0.25	0.54	1.00

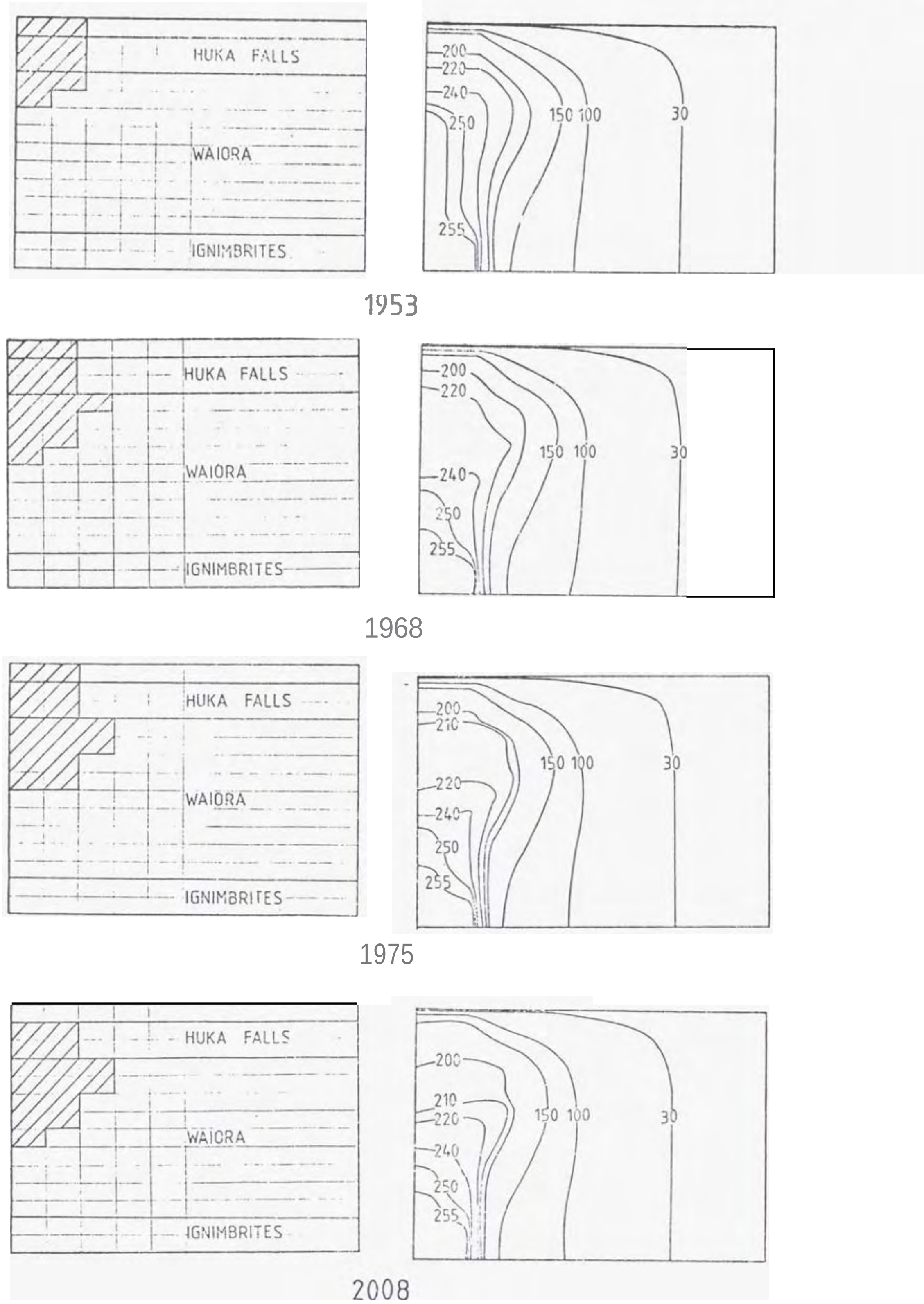

Figure 11: **Boiling zones and isothermal profiles for the years 1953, 1968, 1975 and *2008.***