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FLOW RATE DECLINE AND PRESSSURE TRANSIENT IN THE LARDERELLO GEOTHERMAL FIELD

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ABSTRACT

The production history of most of the Larderello wells, both the older ones and the recent ones, that we have produced at constant pressure, is characterised by a rapid initial decline.
In this study such a decline is interpreted as the consequence of on original flow regime of the "depletion" type being followed by a "diffusion" type regime. Such an interpretation, which does prove consistent with the phenomenology of the geothermal field, was suggested by the results of the analyses of the well-closure tests carried out in the North zone of Larderello and in the Travale field.

THE DECLINE IN PRODUCTION

The production of steam in the Larderello geothermal field depends for over one third of the total on a group of ninety wells located in the northern part, near the township the field is named after.
The analisys of the decline in production as described in this study is mainly based on measurements taken on these particular wells, for the reason that their number has remained constant over two long and quite distinct time-periods; the decline has therefore depended solely on the physical processes regulating the production of the reservoir.
This feature is not true for the other areas of Larderello.
The history of production (Fig.1) is characterised by two peaks corresponding to the years 52-56 and 65-67 due to the contribution of the wells built in those years in the areas known as Valle Secolo and Gabbro (Gennai, 1964; Celati, 1976),

Other features of the production history are:
- a uniformity of supply pressure (~ 5 bar) in the wells (1), steady over long time-spans;
- the contribution made by the reinjection of condensate waters, as of the year 1979;
- the limitations put on the flow from 1980 onwards, with the aim of increasing the pressure in the reservoir.

The fall in production has already been analysed by various authors with methods based on Arps [6] correlations and other kinds (Atkinson, 1978; Celati, 1976; Gennai, 1964). Gennai and Sestini come to the conclusion in their study that the law of decline is of a harmonic type, but such a conclusion is not very convincing due to the poor resolution of the method of graphic smoothing used.
Atkinson et al. found that the whole family of curves proposed by Arps have to be used to describe the drop in flow of some Larderello wells situated in the Serrazzano area, thus failing to come to any conclusions about the type of decline.
However in that study little consideration was given to the effects of interference between wells, which can modify the typology of the decline when they come into play.
In this analysis we are therefore considering wells or groups of wells which can be considered isolated. One example of the decline in the flow of an "isolated" well, which has produced at a more or less

(1) An exception to this is the group in the Gabbro area which produce at pressures a few bar higher.

constant pressure, is provided by Well VC 10. The law of decline turns out to be of an exponential type over the first ten years or so of production (Fig. 2). Thereafter the flow remains almost constant, with the same type of decline as the older wells have.
The entire decline can be described in a single analytical function of the type:

$$G - G_\infty = (G_o - G_\infty) \cdot Exp(-t/\tau) \quad (1)$$

which however does not satisfy the condition of zero flow at $t \rightarrow \infty$, which we would expect on the strength of plausible physical considerations.
To check if the decline of Well VC 10 were characteristic of the wells of Larderello North too, it was decided to subdivide those wells into homogeneous groups, according to their topographical location and their year of construction; this was done with the aim of overcoming difficulties of interpretation caused by interference phenomena.
In this way two groups of wells selected in Larderello North, the first being a group of seventy wells mostly in the Valle Secolo area, and built before 1956, and the second being the five wells located in the Gabbro area.
For both of wells the decline in flow is characterised initially by a law of exponential type (Fig. 3,4).
Such behaviour could to some extent be influenced by the fact that the wells under consideration began producing over a time-span which is not negligible in respect of the time constant of the decline. Noting however that the time-constants of the single wells have similar readings, we must conclude that the exponential nature of the decline is real, and not the result of a manipulation of data.
Once again we find that a function like the (1) interpolates excellently the experimental data.
Considering that an exponential decline is typical of a reservoir in depletion, the period of decline successive to it might be the manifestation of a new production phase of the reservoir. The levelling-out of the curves showing declining flow could indicate the presence of a recharging of the reservoir, manifesting when the depletion has brought about some drop in the pressure. Such a recharge could be caused by a deep water table feeding the upper part of the reservoir, (Truesdell, 1973) or by meteoric surface waters located on the outer edges of the geothermal field, as has been proposed by various authors (Celati, [7], 1976; Petracco, 1975).
But some indications provided recently by the drilling of wells more than 3000 m. deep (Cappetti, 1985) go against the previous hypotheses, whereas the results of some closure tests carried out simultaneously on groups of wells (see Ch.3 and Neri, 1985) indicate the existence of a diffusive flow regime in the pressure transients.
For this reason we have looked for the existence of such a flow regime in the history of production, plotting the flows as a function of $t^{-1/2}$.
One can recognise in the decline of production illustrated in Fig. 5 that at the end of the depletion phase the flow falls linearly as a function of $t^{-1/2}$, and that the line interpolating the graph of Fig.5 satisfies the condition $G = 0$ for $t \rightarrow \infty$, as considerations of a physical nature would demand. This means that a diffusive flow regime is set up within the reservoir.
This interpretation of the decline in flow leads to a conception of a reservoir behaving firstly with a more or less constant volume (depletion phase) and then continually variable (diffusion phase).
The diffusive condition seems moreover to manifest in a vertical direction, for the second group of wells under consideration - the one which started up production a few years later than the first group - possesses the same features.
But over and beyond these considerations, which may have a great importance in the elaboration of a conceptual model, we are also interested in

making forecasts for production based on past records.
With this aim in mind it may be useful to describe the decline with a single analytical function that nevertheless satisfies the conditions

$$G \equiv Exp(-t/\tau) = 1-t/\tau \quad \text{for } t << \tau$$

$$G \equiv 1/\sqrt{t} \qquad \text{for } t >> \tau$$

The most simple function to satisfy these conditions is

$$G \equiv \sqrt{\emptyset} \ / \ \sqrt{(1 + t/\emptyset)} \qquad \emptyset = \tau/2$$

which is up to describing the entire decline in production of the wells being considered and has been put forward by A. Barelli (2) as a solution to a flow problem in which the reservoir and the production pressures are constant, but the resistance to flow increases in linear fashion with the mass produced.
An analytical funcion describing the decline in flow, and with the correct boundary conditions, can acquire the significance of an influence function, at constant pressure, of the linear flow equation - if one exists - governing production.
If we admit the existence of an equation of this kind, at least in that period of production with a diffusive condition, then the function

$$Fp(t) \equiv \beta/\sqrt{t}$$

can be considered an influence function of the reservoir.
We shall therefore write that the flow G(t), at constant supply pressure P_f, is rendered by

$$G(t) = (P_o^2 - P_f^2) * \beta/\sqrt{t}$$

where P_o is the initial static pressure.
From the slope of the line in Fig. 5 we have

$$(P_o^2-P_f^2)*\beta \simeq 3 \cdot 10^5 \ (tons/\sqrt{h})$$

Along with the influence function at constant pressure, can be considered the analogous function $F_G(t)$ at constant flow defined as

$$(P_o^2-P_f^2(t)) = G \cdot F_G(t)$$

From the theory

$$F_G(t) = \alpha\sqrt{t} \ ; \ \alpha = 2/(\pi*\beta)$$

Knowing about the two influence functions allows us to describe the evolution of the reservoir in the two possible management scenarios of imposed flow or pressure. Assuming that $P_o^2-P_f^2$ is in the order of 10^3 bar^2 we can calculate

$$\alpha \simeq 2 \cdot 10^{-3} \quad (bar^2 \cdot \sqrt{h}/tons)$$

and the response function at constant flow turn out to be

$$P_o^2-P_f^2(t) = 2 \cdot 10^{-3} \ G\sqrt{t}$$

This result can be used to forecast the recovery of pressure in the reservoir, caused by a closure of the wells for a time δt, small with respect to the production time preceding the closure, and during which the flow can be held to be constant.
Applying the principle of superposition, and indicating with t^* the time the closure occured in, measured as from the start-up of production, the reservoir pressure P(t) for $t>t^*$ is given by

$$P^2(t)-P^2(t^*) = 2 \cdot 10^{-3} \ G(t^*) \ \sqrt{t-t^*}$$

Putting

$$G(t^*) = 950 \ t/h, \ P(t^*)=6.5 \ bar$$

we get approximately

$$\delta P = P(t)-P(t^*) \simeq -15\sqrt{t-t^*}$$

THE FLOW REGIME AND PRESSURE TRANSIENTS

From the year 1980 onwards, closure tests have been carried out for entire groups of wells. The first of such testings concerned the Travale field (Neri, 1985), and the second the Larderello North field - this carried out with the aim of assessing the possibility of managing the reservoir at a

(2) Private communication.

pressure higher than the one at present.

The Larderello North Well-Closure Test

The test involved the closure, within the span of two hours, of 51 wells which were producing 950 t/h of steam.
During the closure period, which had a duration of 20 days, the pressure at the head of all the closed wells was measured daily, and then measurements continued intermittently at the 19 control wells after the reopening of the producing wells.
At the reopening phase the flow was regulated at the level pertaining before closure; in some cases the well-head valves were throattled.
The pressure build-up curves of the 70 wells involved in the test (Fig. 6,7) reveal a homogeneous behaviour, with just a few exceptions due to phenomena of condensation or such.
The homogeneity of behaviour indicates the existence of a single law of pressure build-up one which has turned out to be of a diffusive type, as can be seen in Fig. 7, in which the pressures are plotted as a function of the square root of closure time.
The majority of the closure curves lie between 6 and 7 bar, with a slope of 0.05 bar/$(h)^{1/2}$, three times less of that calculated. A limited number of 12 wells lie outside these margins, with slopes of a similar value.
These are wells located further out from those with lower pressure, and a few hundred metres deeper.
The test did not point to phenomena of radial flow between the edges of the reservoir and its centre, neither did the storage capacity of the reservoir turn out to be very significant.
The test results demonstrate rather that there is a flow regime of a diffusive nature throughout the reservoir, with negligible storage, and that it is developping in a vertical direction.

Compressibility and Diffusivity

During the drilling of new wells in the Larderello North Zone, it has recently been found that there exists, in the most heavily drilled area,a vertical pressure gradient of 0.01 bar/m.
Given that the reservoir produces in a semistationary state, this gradient determines the current flow of vapour according to Darcy's law

$$q = \left(\frac{K}{\mu}\right) \cdot \mathrm{grad}\ (P)$$

Assuming a linear flow model, the increase δP of pressure during the closure of the wells, is rendered by

$$\delta P = 2q \left(\frac{\mu}{K}\right) \sqrt{\left(\frac{\eta \delta t}{\pi}\right)}$$

Combining the two equations we see that the diffusivity depends only on the pressure gradient (3) and on th slope of the build-up curves.
The value of $5 \cdot 10^{-3}$ m^2/s, coming from the calculation, is two scales lower than the previous estimates made by analyzing the build-up of single wells.
The estimation of ϕc does not come as readily as that of the diffusivity. We need to postulate a flow surface, that we will suppose equal to the topographical one (5 km^2) over which the wells are located. So we get

$$\frac{K}{\mu} \simeq 10^{-8} \text{ m}^2/\text{Pa} \cdot \text{s})$$

$$\phi c \simeq 2 \cdot 10^{-6} \text{ Pa}^{-1}$$

A figure of this kind for ϕc, is more compatible with a biphase fluid than with superheated steam.

Influence Functions at Constant Flow

The results of the closure tests show that the relationship which exists between increase of

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(3) The dependence is quadratic, and so in the calculation of η the uncertainty over the figure for the gradient gets amplified.

pressure and time of closure is of the type

$$\delta(P^2) = G \cdot F_e(\delta t)$$

were $F_e(t)$ is the influence function at constant flow, which is

$$F_e(\delta t) = .65\sqrt{\delta t} / G$$

The influence function can be used to simulate reservoir manegement scenarios, with variable flow regimes; in particular it can be used to calculate the fall in pressure during the period following the reopening of wells. Given the invariance of the flows we shall write

$$\delta(P^2) = .65[\sqrt{\delta t} - \sqrt{(\delta t - T^*)}] \; ; \; \delta t > T^*$$

T^* = Closure time

The theoretical variation in pressure which is calculated with the above equation is shown in diagramatic form in Fig. 8, together with the pressures of the control wells.

The similarity between the theoretical curves and the measurement graphs is considerable and shows the validity of the theoretical approach used.

A more detailed analysis of the various curves shows (Fig. 9) that the measured decline of pressure is not, initially, of a diffusive type, nor is it from storage. It might rather be caused by a phenomenon of evaporation of the steam condensed during the closure.

This consideration would explain also the difference between the coefficient α as mesasured, and that as estimated from the production decline.

CONCLUDING CONSIDERATIONS

The decline in production of the Larderello reservoir is interpreted is this study as the consequence of two production regimes, defined as the depletion and the diffusion regimes. The diffusive vertical-flow regime has been experimentally confirmed by the simultaneous closure tests of some fifty wells. The results of that testing, along with the measurements of the vertical pressure gradient made possible by the recent drilling of deeper wells then those currently in production, have enabled us to establish figures for the diffusivity and compressibility of the reservoir fluid.

Regimes of depletion and diffusion had already been considered by W. Brigham and the author (1980) to elaborate a production model for one part of the Larderello reservoir, getting some excellent concordance between calculations and measurements. Hovever, in that study the major factor contributing to the depressurization at the top of the reservoir was seen to be mainly due to a diffusion process ongoing since the start-up of production. In this present analysis, on the other hand, the initial depressurization is held to due to a depletion production regime.

The studies that we have described were motivated by needs of an industrial nature.

If we consider from this point of view the results which have been obtained, some useful indications can be extracted for the management of the geothermal field's exploitation.

First of all, as far as the practical problem of production forecasts is concerned, the Arps family of analytical equations is of limited use. A family of equations of this kind bears upon the exponential decline wich occurs during the depletion production regime, but cannot describe the decline that occurs once the regime becomes a diffusive one.

The equations that we have proposed do have a more general utility.

As far as the implications involved in a diffusive flow regime are concerned, one of the main ones is the existence of a vertical pressure gradient, as has indeed been experimentally verified.

It follows that a considerable increase of production pressures might be obtained by deepening the present wells.

Another feature of a diffusive production regime with a biphase fluid is the existence of an evaporation surface which is steadily receding from the top of the reservoir with the passing of time.
Therefore the upper part of the reservoir is no longer contributing to production now, since the reserve of liquid water which was initially there has run out. And so there should be large volumes of dry rock still at high temperatures (Cappetti, 1982).
Thus, when a diffusive regime is well under way, conditions exist in the reservoir which are particularly favourable for reinjection. Such conditions do not exist when a reservoir is producing in a depletion phase though, when water exists in a liquid phase in the neighbourhood of the well.

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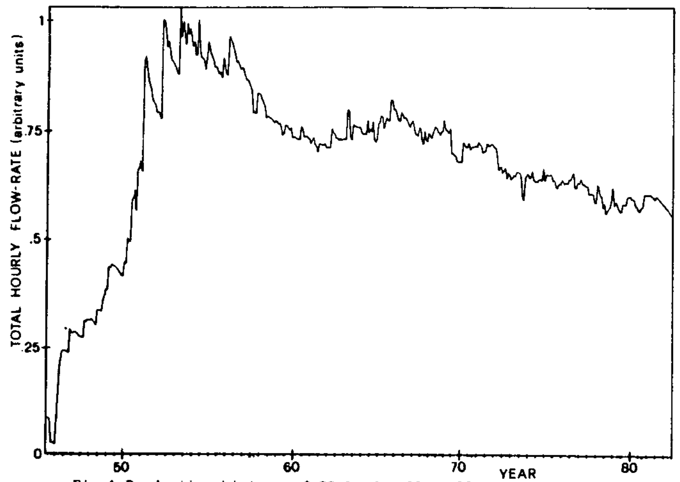

Fig.1 Production history of 89 Larderello wells

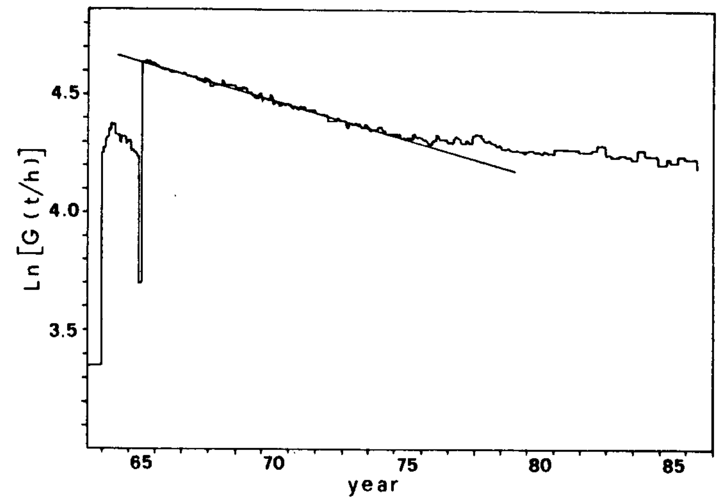

Fig.2 Production history of well VC10 represented by the natural logarithm of flow.

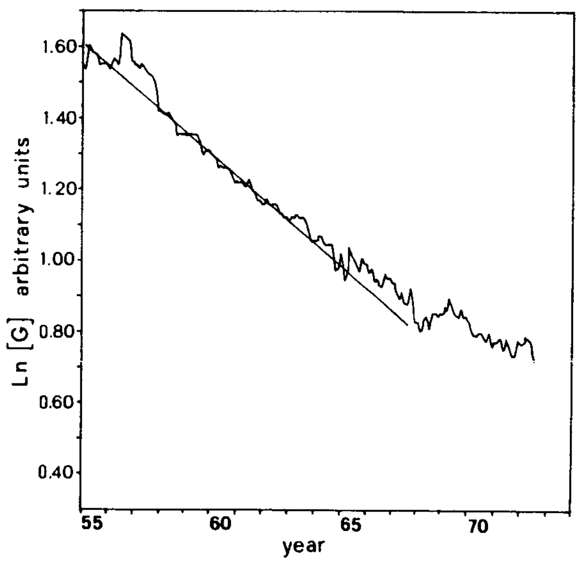

Fig.3 Production history of 70 wells located mostly in the Val di Secolo area.The se gment drawn in on the figure does not represent any interpolation.

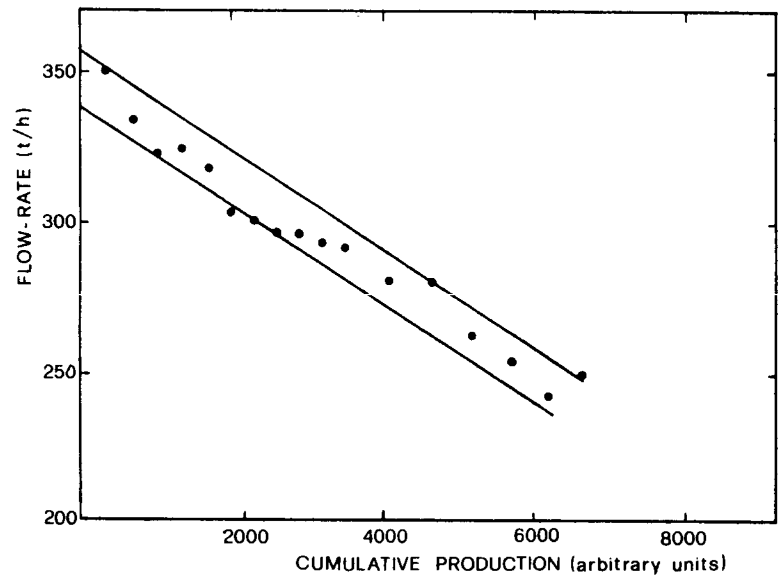

Fig. 4 Production of the wells of the Gabbro area from June '69.

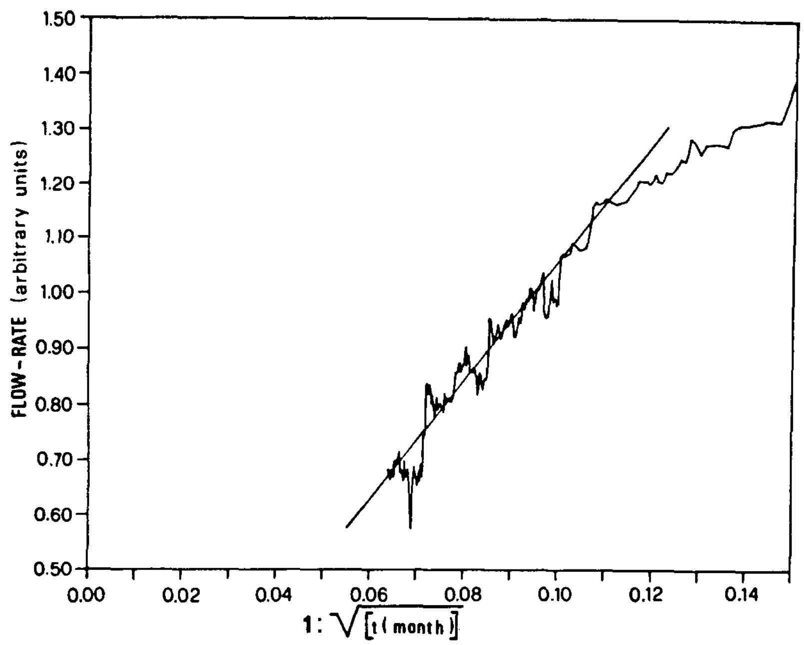

Fig. 5 Graph of the flow of the Fig. 3 wells as an inverse function of the square root of production time,measured as of Aug. 1956.

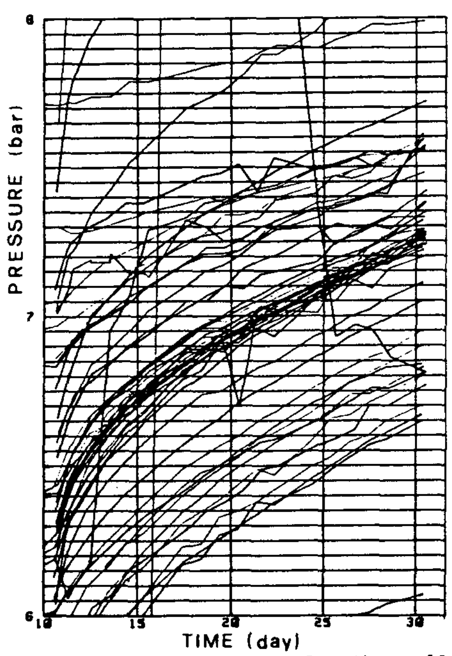

Fig. 6 Pressure graphs for the wells closed during the June '85.

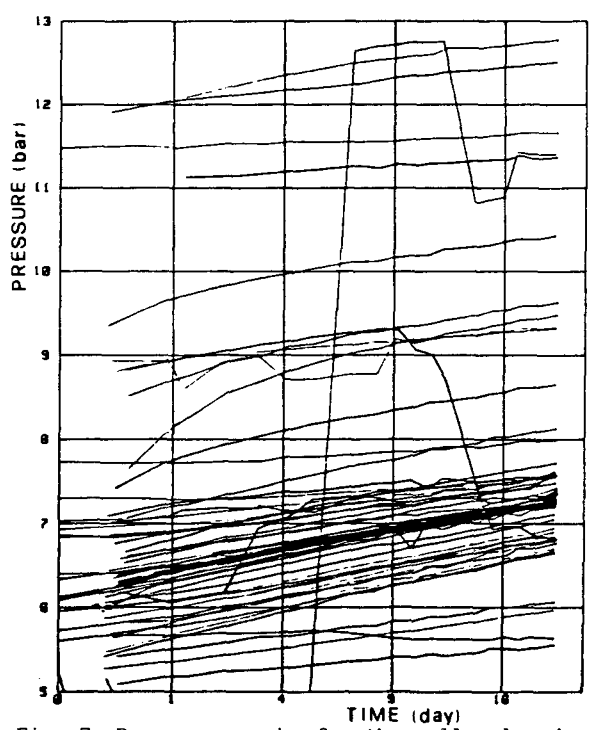

Fig. 7 Pressure graphs for the wells closed during the June '85 tests,as a function of the square root of closure time.

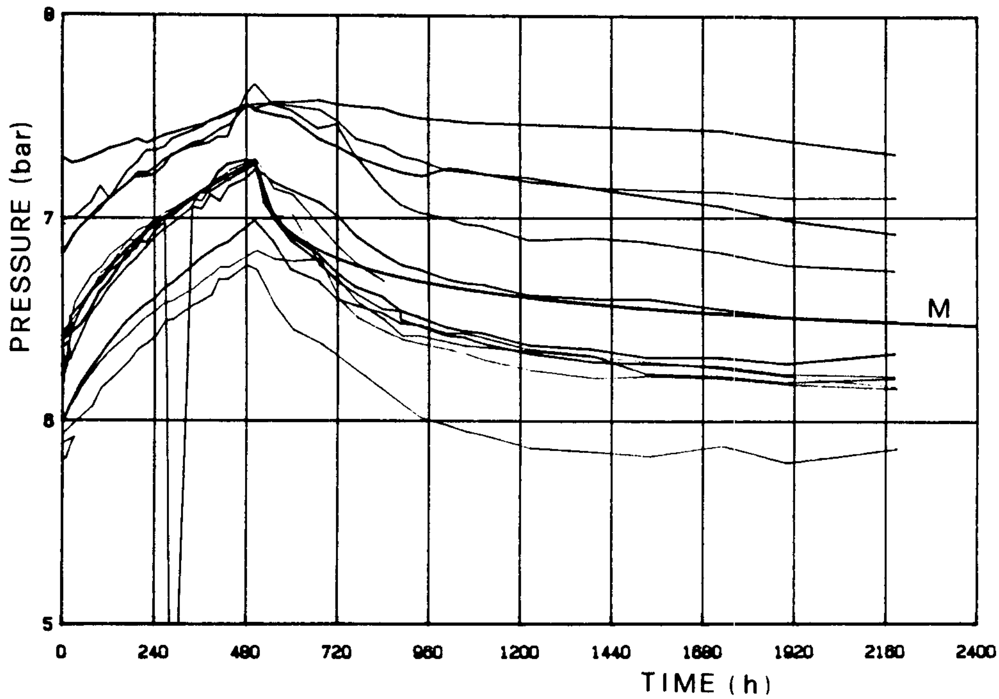

Fig. 8 Pressure graphs of the control wells during the June '85 closure of the production wells and in the period following their reopening. The curve marked M was calculated using the influence function of Well 85.

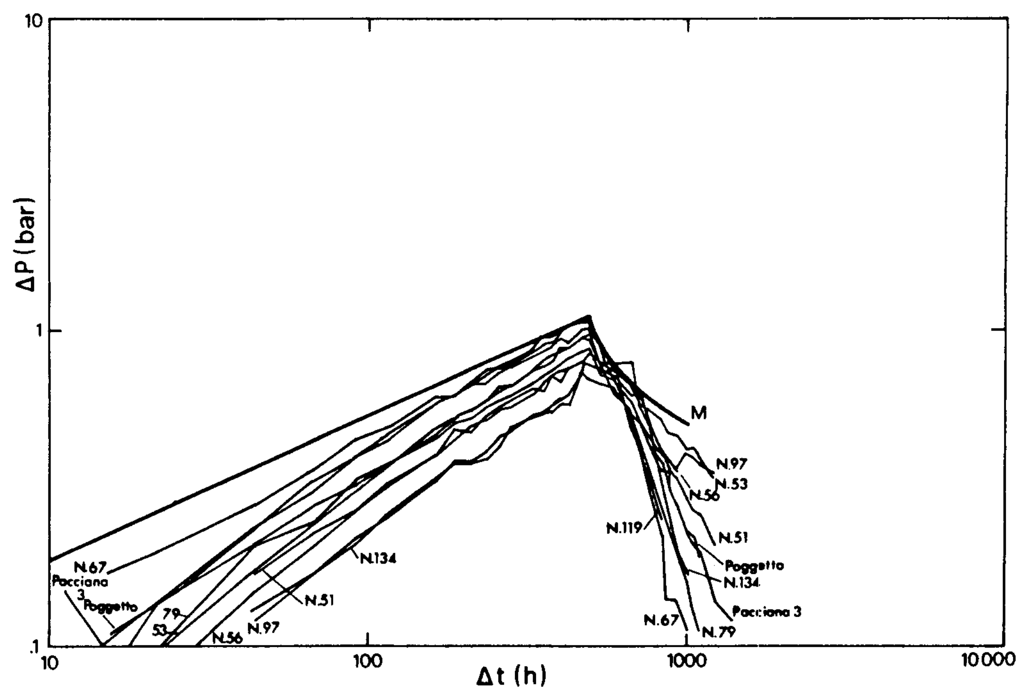

Fig. 9 Bilogarithmic pressure graph of some of the control wells. The curve M was calculated as in Fig. 8.