Preliminary Results on a Depletion Model for the Gabbro Zone

(Northern Part of Larderello Field)

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INTRODUCTION

One of the tasks in the ENEL/DOE joint agreement includes the development of reservoir evaluation methods which will be applicable to both United States and Italian steam reservoirs. To this end, the Gabbro Reservoir data have been studied and a new lumped parameter model of the reservoir has been developed. This report summarizes the preliminary results of our modelling efforts.

RESERVOIR PRESSURE AND PRODUCTION DATA

In the Gabbro Zone there are four wells which provide the major production volume; Wells G-1, G-3, G-6 and G-9. Three additional wells supply minor production volumes; Wells G-7, SD-2 and N-155.

A study was made of the original pressures of eleven wells in the Gabbro Zone. From these data it was clear that an original pressure trend existed in the reservoir. The pressure decreased in the south-southeast direction. We mapped the Gabbro Zone initial pressures and drew pressure contours. From this map it appeared that the pressures in Wells G-4, G-9 and SD-2 were very close to the average reservoir pressure, Wells G-1 and G-7 appeared to be about 0.6 Kgm/cm^2 above the average, and Well SD-4 appeared to be about 3.4 Kgm/cm^2 above the average. Wells G-3 and G-8 appeared to be about 1.9 Kgm/cm^2 below the average pressure, and Well 155 was about 3.8 Kgm/cm^2 below the average. There was a long history of pressure data from Wells G-4, G-8 and SD-4 and these differences in pressure have persisted throughout the producing life of Gabbro.

The production and average pressure data are shown in Table 1 and are graphed in Fig. 1. Notice that after 1965 the average pressure drops smoothly with production. Early in the life, from 1960 to 1965, the three data points behave in an erratic manner. It appears there is some error in these early data.

TABLE 1: DETAILED PRODUCTION DATA, GABBRO ZONE

Date	Average Flow Rate (10^3T/Mo)	Cumulative Production (10^6 Tons)	Average Pressure (Kgm/cm^2)
1960	0.0	.0	30.0
1961	41.2	0.49	
1962	81.8	1.48	26.6
1963	100.7	2.08	
	154.2	3.01	
1964	198.2	4.20	
	232.2	5.59	24.85
1965	244.8	7.06	
	243.0	8.52	22.28
1966	247.3	10.00	
	228.5	11.37	21.27
1967	216.7	12.67	
	221.7	14.00	20.03
1968	271.7	15.63	
	261.7	17.20	18.79
1969	263.3	18.78	
	270.0	20.40	18.02
1970	255.0	21.93	
	248.3	23.42	17.45
1971	240.0	24.86	
	238.3	26.29	17.08
1972	231.7	27.68	
	228.3	29.05	16.52
1973	223.3	30.39	
	223.3	31.73	16.07
1974	220.0	33.05	
	225.0	34.40	15.85
1975	213.3	35.68	
	213.3	36.96	15.18
1976	205.0	38.19	
	215.0	39.48	15.28
1977	206.7	40.72	
	218.3	42.03	14.97

RESERVOIR MODELLING

During the past ten years the number of producing wells in the Gabbro Zone has remained constant, and during this time both the producing rate and the Gabbro Zone pressure have declined continuously. Thus there is strong evidence that the Gabbro Zone is undergoing depletion.

The paper by Celati et al[1] clearly shows that the producing interval at Gabbro is brecciated carbonates associated with evaporitic deposits, with a flysh cap rock. Beneath this permeable horizon lies quartzites and phyllites which are somewhat fractured and which are likely to contain liquid water at some great depth which supplies steam to the producing interval. This sequence of rock types is similiar to the geology seen in the main part of the old Larderello field.

A conceptual model which fits with this geologic picture and with the pressure trend toward Larderello is to assume a large deposit of boiling water lies at some depth. Depletion of this deposit can occur due to leak off toward Larderello and due to production of steam from Gabbro wells. Also we can assume that the pressure seen in the producing zone is less than it is in the boiling zone due to vertical frictional pressure losses through the fractures in the deep quartzites and phyllites.

A study of boiling water systems was made by Brigham and Morrow[2] which indicated that p/Z is linear with cumulative production for such systems. This linearity does not hold for the entire life of a boiling water reservoir, but it is good approximation to the depletion history during the first 1/3 to 1/2 of the depletion. Using this assumption, the following equation is valid for the deep boiling zone.

$$(p/Z)_{deep} = A - B(Q_{prod} + Q_{Lard}) \qquad (1)$$

where $(p/Z)_{deep}$ = The value of p/Z in the deep boiling zone

Q_{prod} = The cumulative production from the Gabbro Zone

Q_{Lard} = The cumulative leak-off from Gabbro to Larderello

The leak-off from Gabbro to Larderello is not known, however it is possible to write a pseudo-steady state equation which approximates the nature of that leak-off. It has the following form

$$Q_{Lard} = C'\Sigma(p_{Gabbro} - p_{Lard}) \qquad (2)$$

A study of the main Larderello producing zone shows that its pressure has remained nearly constant at 8 Kgm/cm^2 for the past 15 years. Using this concept, Equation 2 can be combined with Equation 1 to arrive at the following equation;

$$(p/Z)_{deep} = A - B\, Q_{prod} - C\Sigma(p-8) \qquad (3)$$

Equation 3 is for the p/Z in the deep boiling horizon. The pressure seen in the producing zone is less than in the deep zone due to frictional pressure losses. This can be expressed as follows

$$(p/Z)_{top} = (p/Z)_{deep} - \Delta(p/Z) \qquad (4)$$

where $(p/Z)_{top}$ = the value of p/Z seen in the producing zone. The values associated with Figure 1

$\Delta(p/Z)_{flow}$ = the drop in p/Z due to vertical flow through the deep fractured zone

To handle the term, $\Delta(p/Z)_{flow}$ we can consider the flow to be a transient linear flow problem of the type solved by Nabor and Barham[3] and shown in Fig. 2. In the system we have envisioned here, the deep boiling interface can be treated approximately as a constant pressure boundary, which is the curve labeled $F_o\,(t_D)$ in Figure 2.

If we look in detail at the curve $F_o(t_D)$ we see that the early portion of the curve is a straight line with a slope of 1/2 on log-log paper. The $F(t_D)$ function is proportional to the pressure drop for a given flow rate and t_D is proportional to time. Thus at early time the pressure drop is proportional to the square root of time. Later in time the curve, $F_o(t_D)$, gradually leaves the half slope line and becomes constant.

A good approximation to this curve is to use the half slope until t_D is approximately 0.78, and assume the pressure drop is constant thereafter. The maximum error using this approximation is 10%. We will refer to this time as a lag time hereafter in this report. Thus when the time for a given flow rate is less than the lag time the square root of that time is used as a multiplier on the calculated flow rate with a maximum value of unity since the curve, $F_o(t_D)$, has a maximum value of unity. For example, if a lag time of 30 months is assumed; at 6 months the transient flow rate effect is $\sqrt{6/30}$ = 0.447 at 18 months it is $\sqrt{18/30}$ = 0.775, and at 30 or more months it is 1.000.

Using the above ideas it is possible to calculate equivalent flow rates for various assumed lag times. Since the reservoir parameters which make up the t_D function are not known for Gabbro, it was necessary to assume various lag times and assess the results.

Equation 4 refers to the $\Delta(p/Z)$ due to flow. The correct equation for steady state linear flow of a gas is as follows,

$$q = D' \int_{p_1}^{p_2} \frac{2pdp}{\mu Z} = D'\Delta m(p) \tag{5}$$

$$\text{where } m(p) = \int_{p_o}^{p} \frac{2pdp}{\mu Z}$$

Equation 5 is also a very close approximation to the transient linear flow behavior of a gas when the q used is the equivalent flow rate. Thus this equation can be used to calculate the $\Delta(p/Z)$ due to linear flow. Unfortunately, the terms $\Delta m(p)$ and $\Delta(p/Z)$ are not directly comparable.

To relate Equation 5 to Equation 4 it was first necessary to calculate Z and p/Z for the Gabbro Zone as a function of pressure, p for a given temperature, since the steam temperature remains constant. The next step was to calculate m(p) for Gabbro Zone. The function m(p) was proportional to p^2. Finally it was necessary to relate q and $\Delta m(p)$ to $\Delta(p/Z)$ so that Equations 4 and 5 could be related. An empirical equation was attempted of the following form

$$\Delta(p/Z) = D' \frac{(\Delta m(p))^n}{(p/Z)^m_{top}} = D' \frac{(\Delta(p^2))^n}{(p/Z)^m_{top}} = \frac{D\ (q)^n}{(p/Z)^m_{top}} \tag{6}$$

Note that all three forms of Equation 6 are identical, based on the foregoing statements.

To test this empirical equation, pressures ranging from 30 Kgm/cm^2 to 14 Kgm/cm^2 were assumed, with $\Delta(p/Z)$ values ranging from 11.98 to 4.51. The resulting equation fit was as follows

$$\Delta(p/Z) = \frac{D\ (q)^{0.904}}{(p/Z)^{0.581}_{top}} \tag{7}$$

This equation fits the data with a maximum error of less than 1%.

The final form of the lumped parameter depletion equation can now be written by combining Equation 7 with Equations 3 and 4. It is,

$$(p/Z)_{top} = A - B\ Q_{prod} - C\Sigma(p-8) - \frac{D(q)^{0.904}}{(p/Z)^{0.581}_{top}} \tag{8}$$

This is the equation we used to match the history of the Gabbro Zone

HISTORY MATCHING

As mentioned earlier there was some doubt about the validity of the first three pressure data points in the pressure/production history. For history matching we assumed the first data point at the end of 1960 was valid, and ignored the two data points at the end of 1962 and 1964. All other data were included in the history matches.

Since we didn't know what lag times would be valid for this reservoir, several lag times were assumed ranging from 30 months to 60 months and all satisfactorily matched the data. Thus there was no clear evidence as to which was the best match.

One curve fit is shown in Figure 3 for a lag time of 36 months, and the data used for the least squares equation are listed in Table 2. Figure 3 shows a considerable amount of information. First the least-squares equation fit is as follows.

$$(p/Z)_{top} = 35.460 - 0.084\,Q_{prod} - 0.039\,\Sigma(p-8) - \frac{0.304\,(q_{36})^{0.904}}{(p/Z)_{top}^{0.581}} \qquad (9)$$

Equation 9 is shown as a solid line on the figure, and the pressure data points in the producing zone are shown as circles. Note that the fit of the line is exceedingly close with the exception of the 1962 and 1964 data which were not used in the analysis and which were assumed to be incorrect.

The horizontal line near the top of the figure indicates the original reservoir pressure. The first line below shows the pressure loss in the deep boiling zone due to production (depletion) at Gabbro. The next pressure loss is depletion due to net flow from Gabbro towards Larderello. This is roughly twice the loss due to actual Gabbro production. The last space indicates the pressure loss due to vertical flow up to the producing zone. This term is a significant fraction of the total drop in pressure seen at the wells.

Finally can be seen the times when the four major wells began producing. Note, in particular, when G-9 started production the average reservoir pressure declined more rapidly and then gradually tended to level off. This can be seen in both the reservoir data and the equation curve fit. This behavior is a consequence of the lag time assumption in the model.

The fit of Equation (8) was equally satisfactory assuming different lag times. Thus we do not have an accurate picture of the size of the system, the amount of loss to Larderello nor the frictional pressure drop.

There is always a "uniqueness" problem associated with history matching. Fortunately, this problem is not as serious as we might expect. A study of extrapolations using various lag times showed that the projections to the year 1990 differ by only 7% whatever fit of Equation 8 was used. Thus, although the reservoir parameters varied widely, all projections of producing rates into the future are quite similar.

REFERENCES

1. Celati, R., Manetti, G., Marconcini, R. and Neri, G. "A Reservoir Engineering Study in Gabbro Zone (Northern Part of Larderello Field)" ENEL and CNR Report, 1976.

2. Brigham, W.E. and Morrow, W.B. "P/Z Behavior for Geothermal Steam Reservoirs" Soc. Pet. Engr. Jour. Vol. 17, No. 6 (Dec. 1977) pp. 407-412.

3. Nabor, G.W. and Barham, R.H. "Linear Aquifer Behavior" Jour. Pet. Tech. (May 1964) Trans. AIME Vol. 231 pp. 561-563.

Table 2

Data for Least-Squares Equation

for Gabbro Zone (t_{lag} = 36 Mo)

Date	$(p/Z)_{top}$ Kgm/cm^2	Q 10^6Ton	$\Sigma(p-8)$	$\frac{(q_{36})^{0.904}}{(p/Z)_{top}^{0.581}}$	Calculated $(p/Z)_{top}$ Kgm/cm^2
1960	34.55	-0-	22.00	-0-	34.60
The 1962 and 1964 data were not used in the analysis					
1962	29.99	1.48	61.00	5.36	31.33
1964	27.74	5.59	95.55	15.41	26.58
1965	24.55	8.52	109.83	20.08	24.36
1966	23.40	11.37	123.10	22.12	22.98
1967	21.76	14.00	135.13	22.67	22.12
1968	20.40	17.20	145.92	25.41	20.61
1969	19.40	20.40	155.94	27.10	19.43
1970	18.80	23.42	165.39	27.45	18.70
1971	18.40	26.29	174.47	26.79	18.30
1972	17.70	29.05	182.99	26.27	17.90
1973	17.20	31.73	191.06	25.91	17.47
1974	16.95	34.40	198.91	25.79	16.98
1975	16.20	36.96	206.09	25.71	16.50
1976	16.30	39.48	213.37	25.29	16.13
1977	15.90	42.03	220.34	25.57	15.57

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3. Nabor, G.W. and Barham, R.H. "Linear Aquifer Behavior" Jour. Pet. Tech. (May 1964) Trans. AIME Vol. 231 pp. 561-563.

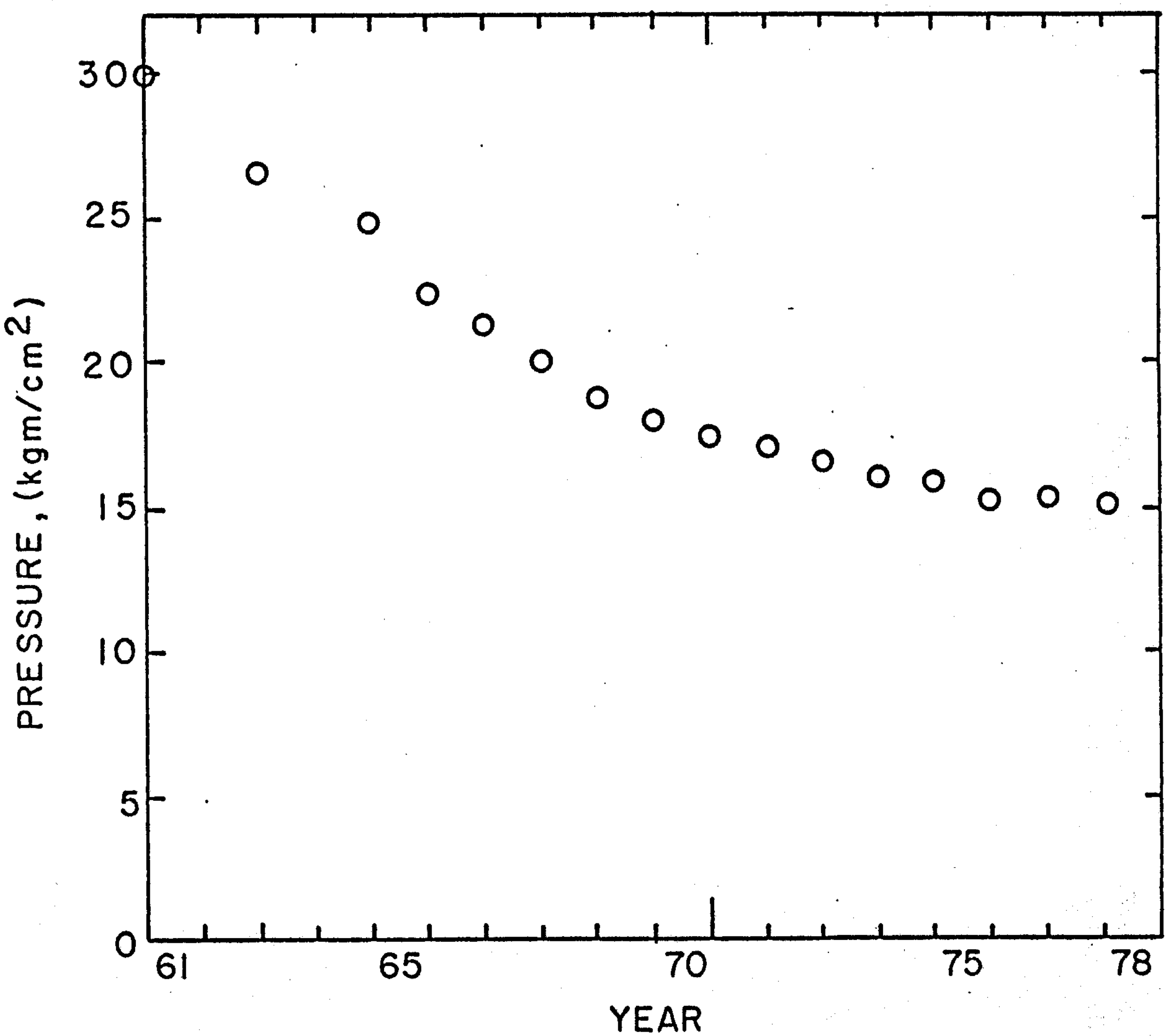

FIGURE 1 GABBRO ZONE AVERAGE RESERVOIR PRESSURE (YEAR END)

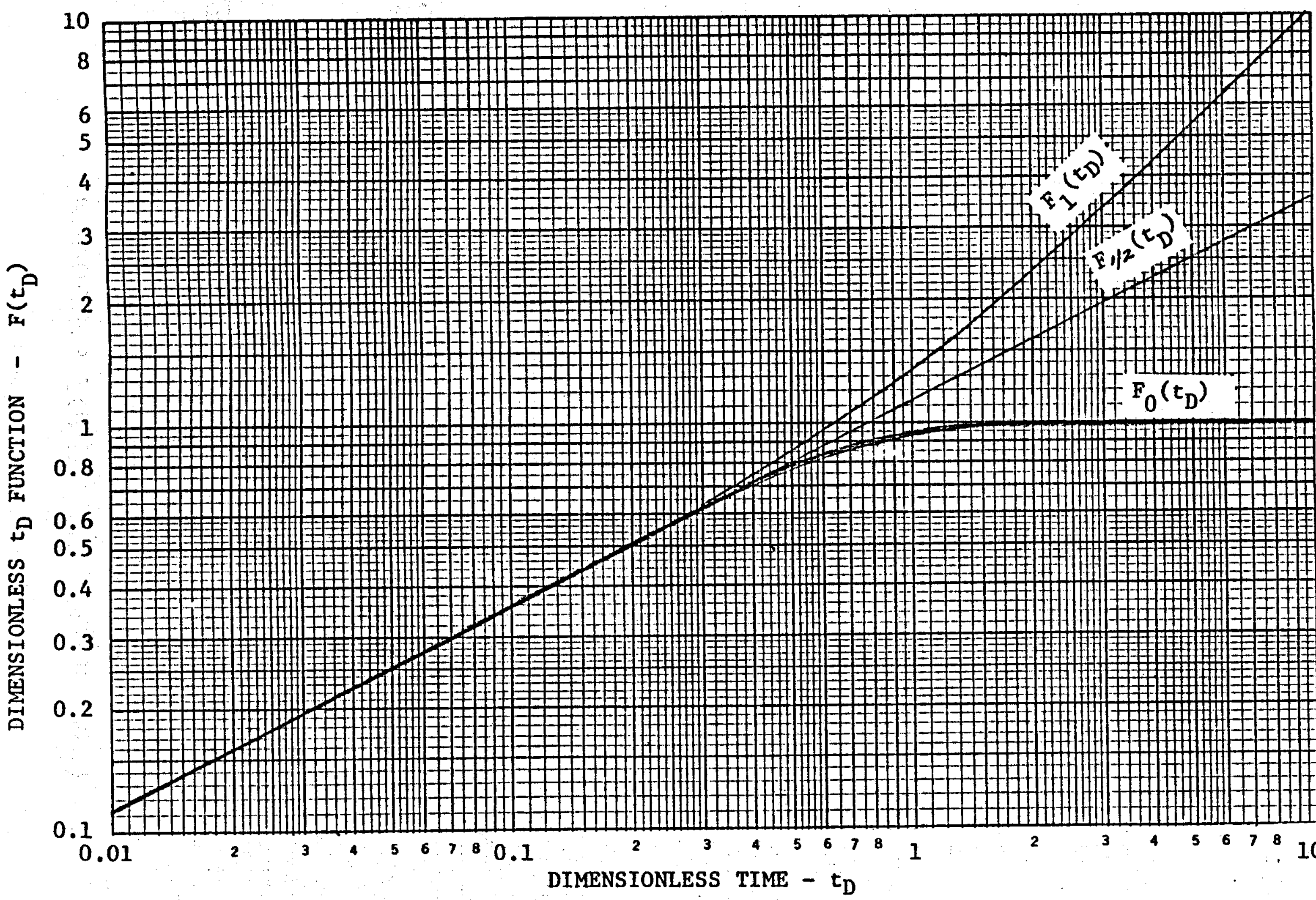

FIGURE 2. DIMENSIONLESS PRESSURE CHANGE and EFFLUX FUNCTIONS - LINEAR AQUIFERS

Ref: Nabor and Barham
<u>Trans</u> AIME (1964) 231, 561

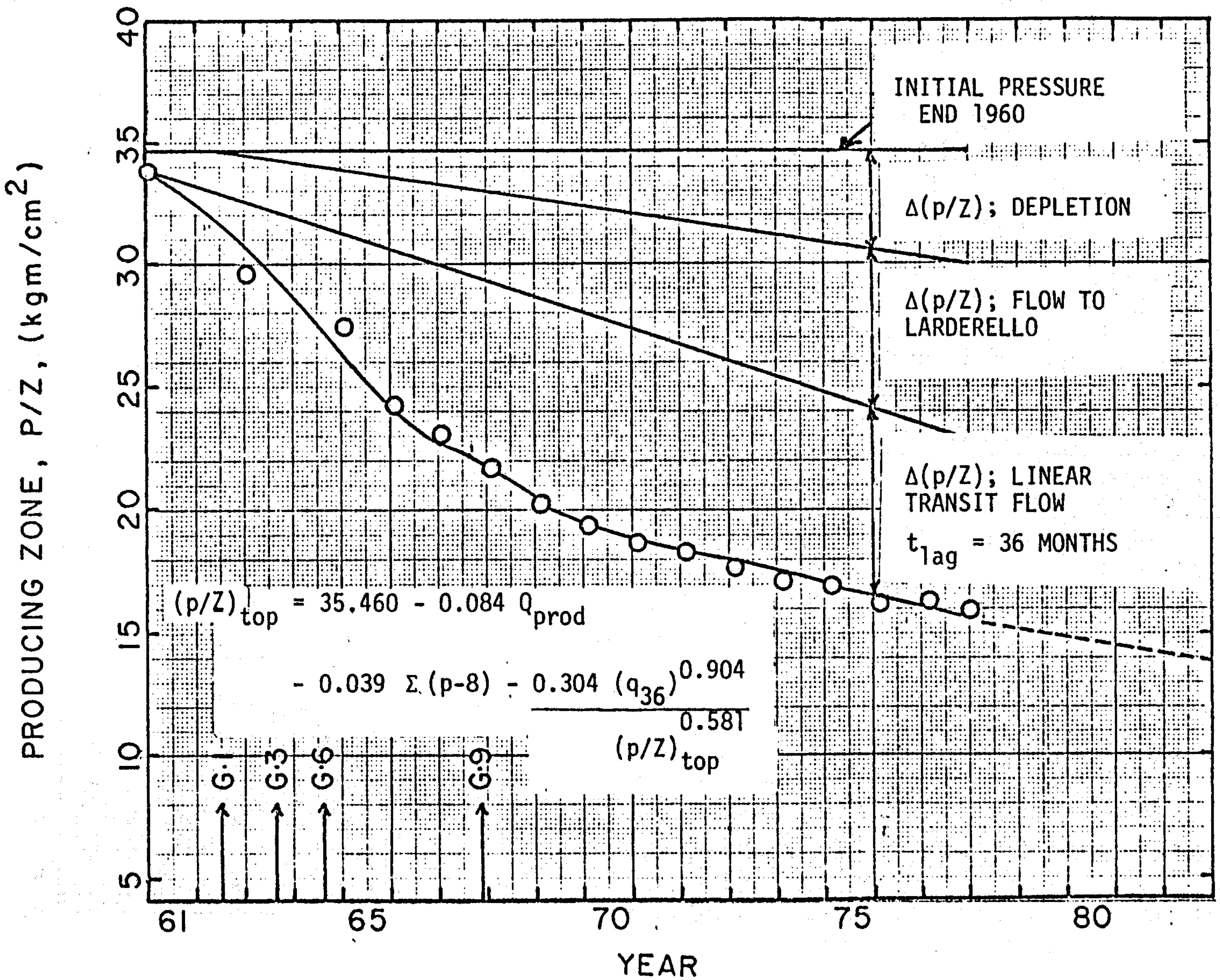

FIGURE 3. GABBRO ZONE PRESSURE-PRODUCTION HISTORY MATCH, LAG TIME = 36 MONTHS