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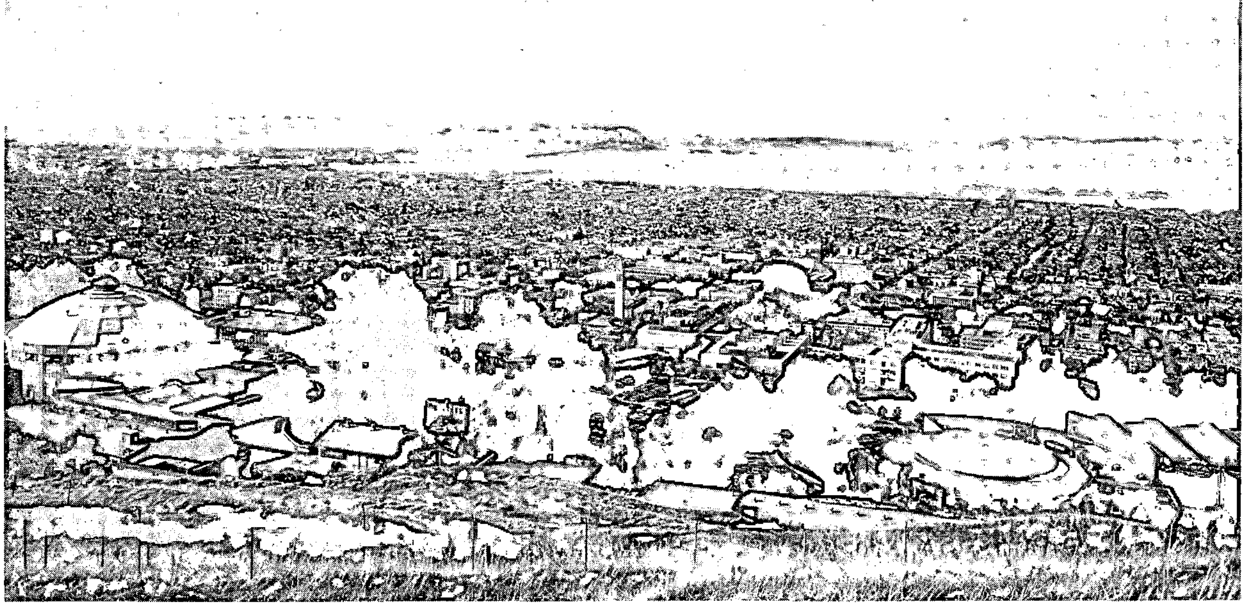

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INTERPRETATION OF INTERFERENCE DATA FROM THE KLAMATH FALLS, OREGON GEOTHERMAL RESOURCE

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ABSTRACT

Data from a seven week pressure interference test in the Klamath Falls, Oregon geothermal resource have been analyzed. The data indicate that productive wells are fed by a highly permeable fracture network and that the less permeable matrix blocks contribute significantly to the reservoir storage capacity. Detailed analysis of data from two wells is presented. Data from both of the wells yield a reservoir permeability-thickness (kh) of approximately $1.3X10^{6}$ md-ft and a storativity ($\phi c_t h$) of $6.8X10^{-3}$ ft/psi. The parameters (λ and ω), which are determined by the distribution of permeability and storativity between the matrix and fractures, vary by more than an order of magnitude. A sensitivity study shows that for these wells, the pressure transients are not very sensitive to the distribution of permeability and storativity between the fractures and matrix blocks. No hydrologic boundaries were detected during the test. This indicates that the fault which supplies hot water to the shallow hydrothermal system does not behave according to the classical model of either a barrier or constant potential boundary.

INTRODUCTION

The City of Klamath Falls, Oregon (see location map in Figure 1) is underlain by a low to moderate temperature (<110°C) geothermal resource. Although located in close proximity to the Cascade Range, the geothermal system is more typical of the fault-charged reservoirs of the Basin and Range Province to the east (Sammel, 1980). Presumably, hot water upwells along a major range front fault and flows laterally in the highly permeable near surface rocks. The subsurface geology is extremely complex; rock units are fractured, faulted and thermally altered (Peterson and McIntyre, 1970; O'Brien and Benson, 1981). Correlation of marker beds between wells is often impossible. To date, over 400 shallow wells (<400 m) have been drilled and are currently in use for space heating, domestic hot water or small scale industrial processing (OIT, 1978).

In 1979 the City of Klamath Falls drilled the first of two wells to be used to supply hot water to a district heating system. On completion of the second well, the district heating supply and distribution network were installed. Short term testing of both wells indicated that they were sufficiently productive to provide the 750 gpm peak load requirement of the heating system and that the impact on existing users would be small (Benson et al., 1980; Benson, 1982a; and Benson 1982b). Concern over the impact of pumping hot water from the resource to supply the district heating system resulted in the passage of an ordinance that prohibited pumping of geothermal fluid without returning it to the well from which it was pumped. Additionally, concern over the lack of a sufficient data base on the geothermal system resulted in a comprehensive resource study that was funded by the U. S. Department of Energy. The study, coordinated by the U. S. Geological Survey, included geochemical analysis of the reservoir fluids, tracer studies, background data monitoring and the seven week interference test that will be discussed here.

TEST DESCRIPTION

The interference test consisted of monitoring water level changes in more than 40 wells while hot water was pumped from one well for 3 weeks and concurrently reinjected into another well for an additional 4 weeks. Twelve of the observation wells were instrumented with high resolution downhole instruments that incorporate quartz crystal pressure transducers and thermistor temperature sensors (Solbau et al., 1981). Data from these twelve wells were transmitted to one of two central locations where they were processed and recorded. This allowed synchronous data recording, which resulted in the collection of very accurate early time pressure transient data. The locations of these wells are shown in Figure 2. Also shown are the locations of the production well (CW-1) and the injection well (County Museum Well). Detailed analysis of the data from the Head and Page wells (shown in Figure 2) will be discussed here.

During the first three weeks of the test well CW-1 was pumped at a rate of 43.5 kg/s. The produced water was disposed of in an irrigation canal. During the last four weeks of the test, pumping continued but the water was reinjected into the County Museum well. The back pressure at the Museum well resulted in a slightly lower and somewhat variable pumping rate (42 to 40 kg/s). The pumping rate during the test is shown in Figure 3. The injection rate during the last four weeks of the test was identical to the pumping rate.

Well Descriptions

The pumped well, CW-1, is approximately 274.3 m deep and is cased from the surface to a depth of 109.7 m. Initial testing of the well indicated that the rock units from 109.7 m to 274.3 m were of low permeability and produced very little fluid. Subsequently, the well was slotted from approximately 59.4 m to 73.1 m. A short test proved this interval to be very permeable. Essentially all of the water enters the bore between 59.4 m to 73.1 m.

The injection well, the County Museum well, was originally drilled to a depth of 376.4 m. Sinker bar runs indicate that the wellbore now has approximately 16.7 m of fill. The well is cased from the surface to a depth of 137.3 m. The remainder of the well is open hole. A spinner survey was run and showed that two intervals were accepting fluid, one between 143 - 159 m and a second between 310 - 329 m. Each interval appears to accept approximately 50% of the injected fluid. The completion data from the observation wells and the active wells are summarized in Table 1.

Interference Data

The interference data from the Head and Page wells are shown in Figures 4 and 5. Both of the wells exhibited the same basic behavior. Pressures (water levels) decreased while only the pumping well was active. The drawdown at the Head well (1.74 psi) was larger than at the Page well (1.1 psi) because it is closer to the pumped well. When injection began the water levels in both wells rose rapidly. Since the Page well is closer to the injection well than it is to the pumped well, the water level rose above its pre-test level.

Essentially all of the wells monitored during the test had this type of response. In general the largest drawdowns attributed to pumping (2ϕ psi) occurred in the wells closest to the pumped well. The rapid pressure transient responses in all of the observation wells, to both injection and production, indicates that there are no hydrologic discontinuities (barriers, faults) within the region examined by the monitor wells. Qualitatively, all of the wells behaved in a uniform manner. This is suprising in light of the complexity and heterogeneity of both the lithology and thermal regime in the Klamath Falls geothermal anomaly.

DATA ANALYSIS

The fractured and heterogeneous nature of the system and the interpretation of previous short term tests suggested that a double porosity model would best describe the pressure transient behavior in the observation wells (Benson et al., 1980; Deruyck et al., 1982). The log-log plots of the drawdown data from the Head and Page wells (shown in Figures 6 and 7) are typical of double porosity reservoirs with transient interporosity flow. The data were matched to the double porosity type curves published by Deruyck et al., 1982. The best matches are shown in each instance. The calculated permeability-thickness products, total storativity and the double porosity parameters (λ and ω) are given in Table 2. The parameters λ and ω are those defined by Warren and Root, (1963):

$$\omega = \frac{(\phi c_t)_f}{(\phi c_t)_f + (\phi c_t)_m}$$

and

$$\lambda = \alpha r_w^2 \frac{k_m}{k_f}$$

The kh and the $\phi c_t h$ values are in good agreement with one another. The parameters λ and ω differ by more than the order of magnitude.

It is of interest to note that several other type curve matches are possible with this data. The log-log plot of the Page well data, shown in Figure 7, is a good example. In addition to the double porosity type curve match, shown by the solid line, two other type curve matches are shown. Fitting the early time data, up to approximately ten hours, with the conventional line source solution (Theis), gives an excellent match. The kh calculated from this curve is approximately three times the value obtained from the double porosity type curve match. Also, the departure of the data from this match after approximately ten hours would indicate the presence of a no-flow boundary. This illustrates the dangers of running a short term test in a heterogeneous system, and explains why interpretation of the previous short term tests overestimated the reservoir permeability (Benson et al., 1980). A second type curve match is also possible using the middle and late time data. The data from approximately 5 hours onward can be nicely matched with the line source solution (Theis). This match is also shown in Figure 7. Analysis based on this interpretation yields approximately the same kh and bulk $\phi c_t h$ as the double porosity type curve match. As the drawdowns measured prior to 5 hours are relatively small (<0.10 psi) one might feel confident in such a match by assuming the very early time data were inaccurate or unimportant. Using this approach, the correct values for the bulk system properties are obtained. This however is not always the case and ones confidence in the analysis increases if all of the data are considered. The double porosity interpretation yields an excellent match throughout the entire test period, thus lending credence to this interpretation.

Pressure transient data during the injection phase of this test were analyzed by assuming that the pressure transients due to the initial pumping period had reached steady state and therefore could be ignored in the subsequent calculations. In light of the background noise (other well users and seasonal water level changes), this assumption does not appear to create any additional ambiguity in the analysis. During the injection phase, flow rates were slightly variable (42 - 40 kg/s). This variation was also neglected in the analysis because water level changes due to other sources (barometric pressure fluctuations and other well uses) were of the same order of magnitude as those resulting from the flowrate variations and do not effect the overall data interpretation.

Log-log plots of the pressure buildup data and type curve matches at the Head and Page wells are shown in Figures 8 and 9. The matches between the observed data and the double porosity type curves are excellent. Data from the Head well can also be fit to a Theis curve if the first several hours of the tests are neglected. The results of both analyses are similar and are given in Table 2. Data from the Page well are best fit to a double porosity type curve with pseudo-steady state interporosity flow. All of the other test data are more accurately described with a transient interporosity flow model. This is probably the result of its being closer to the active well, which tends to exagerate the effects of the double porosity system. Once again, the values of kh and the $\phi c_t h$ are in good agreement but λ and ω vary substantially.

As can be seen from Table 2, the parameters kh and $\phi c_t h$ all in good agreement. On the other hand, λ and ω both vary by more than an order of magnitude. To assess the significance of the variation of these parameters, a sensitivity study was conducted to determine their uniqueness. The data were re-analyzed using the method described by Lai et al., (1983). They have developed a semi-analytic solution for analyzing pressure transients in double porosity reservoirs with block-like geometry and transient interporosity flow. A semi-log plot of the data match obtained from the analysis of the drawdown at the Page well is shown in Figure 10. The same values for kh and $\phi c_t h$ were obtained. However, values of $\lambda = 1.05X10^{-6}$ and $\omega = 4X10^{-3}$ were calculated. These values differ by more than an order of magnitude from the values obtained with the log-log type curve match. Also shown in Figure 10 are the drawdowns calculated using several other values of λ and ω (varying by more than 2 orders of magnitude). It can be seen that for all practical purposes these curves are almost indistinguishable. The implication is that for observation wells far from the active well, in a high permeability reservoir, the data analysis may not uniquely determine the parameters λ and ω.

SUMMARY

Analysis of the data from a 7 week interference test show that all of the shallow geothermal wells in the Klamath Falls geothermal resource penetrate a single continuous aquifer. Local heterogeneities (rock type and temperature) do not appear to significantly affect the hydrologic behavior of the system. The responses of individual wells to pumping and/or reinjection are consistent with this observation. Detailed analyses of the data from two of the observation wells show that the aquifer behaves as a double porosity medium. The fractures and high permeability strata provide pathways along which the fluid moves easily. The less permeable matrix blocks store the bulk of the hot geothermal water. No hydrologic boundaries to the geothermal system were apparent in the interference data. However, the effects of the other users and the seasonal rise in water level may have masked the effects of a boundary in the very late time data. It can be estimated that there are no hydrologic boundaries within a 1 mile radius of the pumped well. This sheds a new light on the hydrologic properties of the fault that is known to transect the area and is the postulated source of the near surface hot water. The fault does not behave according to the classical models for either a barrier or constant potential boundary. Instead, it is essentially invisible to hydrologic testing. Several hypothesis can explain this observation. First, the hot water may upwell over a broad region rather than along a single fault zone that would be detected hydrologically. Second, the fault permeability may be on the same order of magnitude as the permeability of the near surface aquifers and hence, indistinguishable. Third, a single fault may provide the conduit for upwelling from great depth but as the fault approaches the surface, the width of the fractured zone increases which creates a diffuse upwelling region in the near surface. Without more information it is not possible to determine which one of these possibilities (or others) is the correct one.

COMMENTS

Analysis of this interference data points out some of the limitations of and provides guidelines for interference testing and data analysis in highly heterogeneous systems. These are summarized as follows.

1) Short term tests can lead to overestimation of reservoir permeability.

2) Analysis of moderate to late time data with the line source solution may yield the correct bulk values of kh and $\phi c_t h$.

3) Data from a test of proper duration and obtained with sufficiently sensitive instrumentation can be analyzed using a double porosity model to evaluate kh and $\phi c_t h$ with a high level of confidence.

4) It may not be possible to uniquely determine values for the double porosity parameters (λ and ω) in highly permeable reservoirs and/or observation wells far from the flowing well

All of these observations are consistent with theoretical results. However, the limitations of analysis methods are not always apparent by examination of mathematical solutions.

Analysis of this data demonstrates that even with a very high quality data set, there are limitations to the amount of information that can be obtained. Additional interpretation requires input from other disciplines such as well logging/or and detailed lithologic evaluation.

ACKNOWLEDGEMENTS

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Table 1. Well Completion Data

Well	Depth (m)	Elevation* (m)	Cased Depth (m)	Distance to* CW-1 (m)	Distance to Museum Well (m)
CW-1	274.3	1272	109.7**	-	838
County Museum	376.4	1252	137.3	838	-
Head	76.2	1278	18.3	320	640
Page	141.7	1256	45.4	671	259

* Distances and elevations are approximate.

** Slotted from 59.4 – 73.1 m.

Table 2. Well Test Data Analysis Results

Observation Well	Active Well	kh(md-ft)	ϕch(ft/psi)	λ	ω
Head	CW-1	1.29×10^6	9.6×10^{-3}	6.8×10^{-9}	0.01
Page	CW-1	1.38×10^6	4.3×10^{-3}	1.8×10^{-7}	0.3
Head	Museum	1.23×10^6	5.7×10^{-3}	5.1×10^{-7}	0.3
Page	Museum	1.41×10^6	7.7×10^{-3}	2.4×10^{-7}	0.06

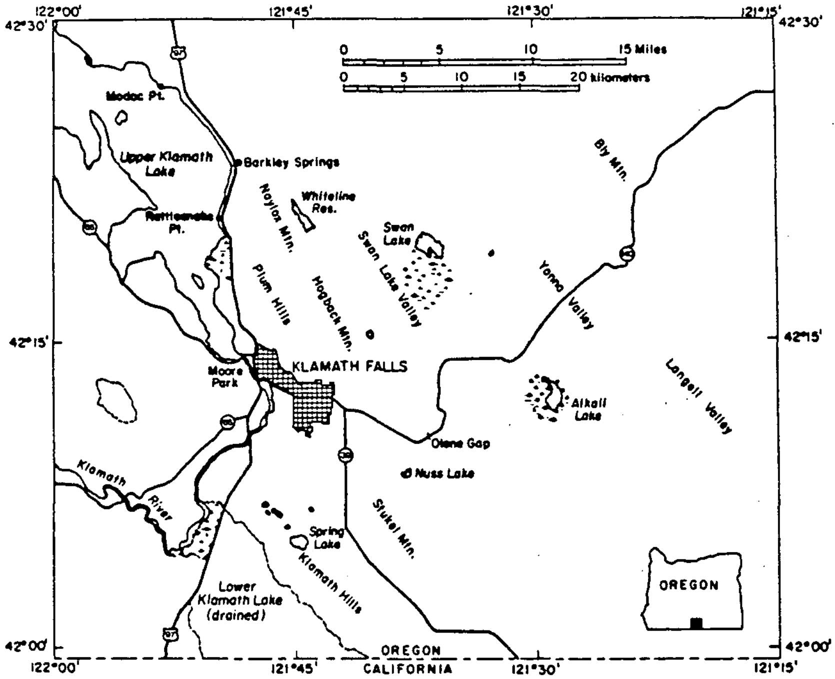

Figure 1. Location map of Klamath Falls, OR.

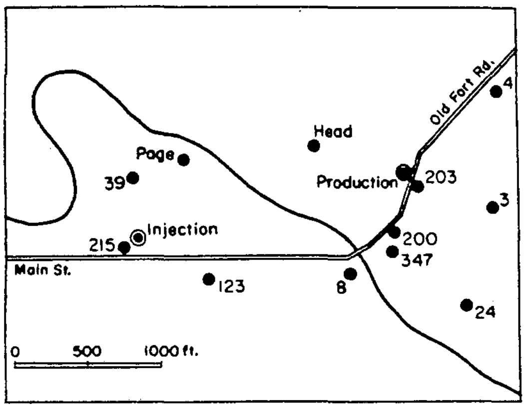

Figure 2. Well location map.

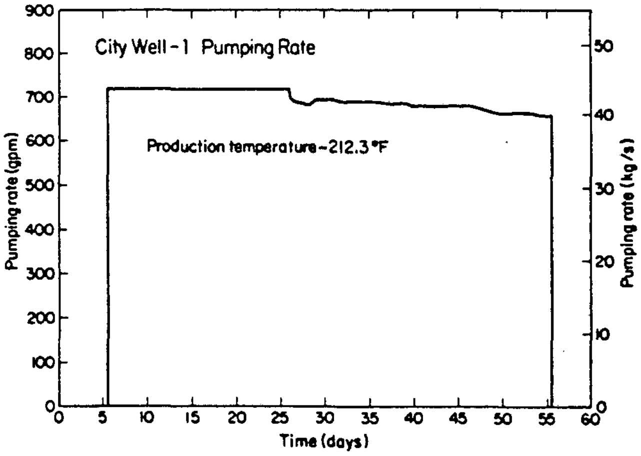

Figure 3. Pumping and injection rate during the interference test.

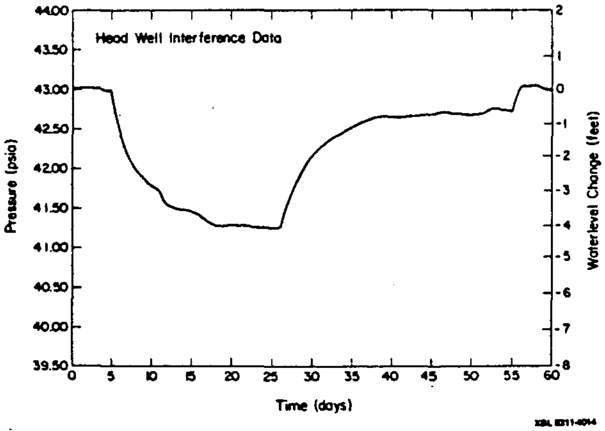

Figure 4. Head well interference data.

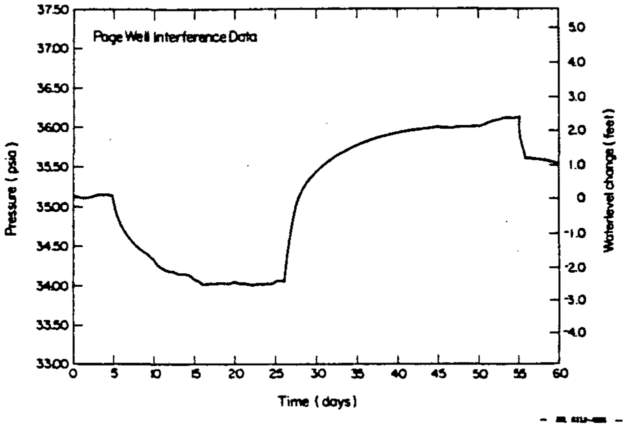

Figure 5. Page well interference data.

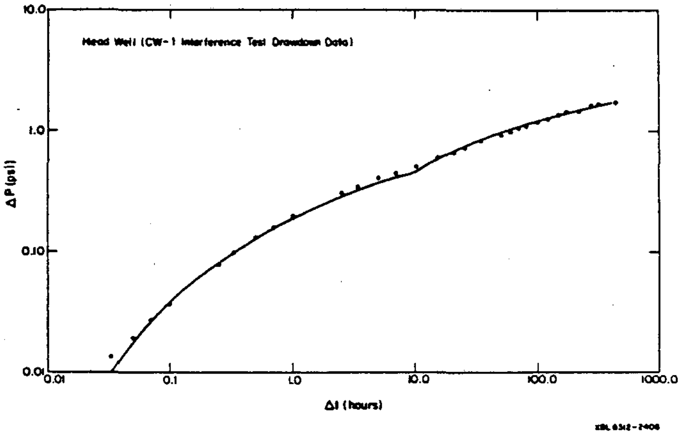

Figure 6. Log-log plot and type curve match the Head well drawdown data.

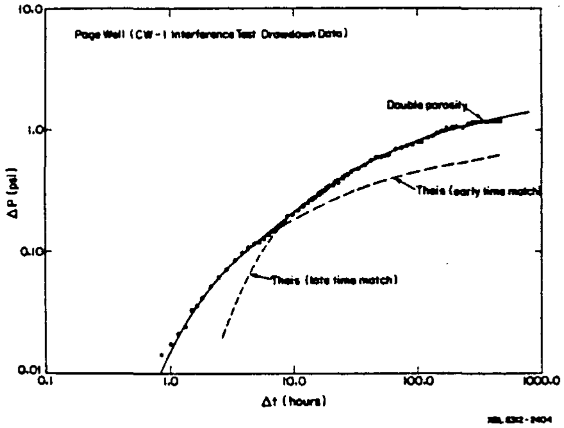

Figure 7. Log-log plot and type curve match of the Page well drawdown data.

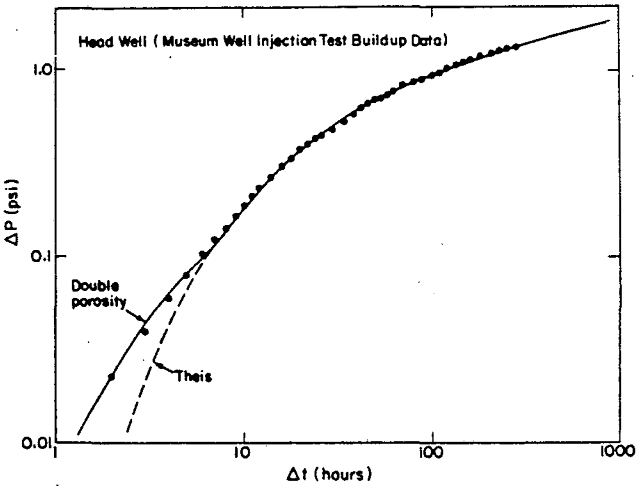

Figure 8. Log-log plot and type curve match of the Head well buildup data.

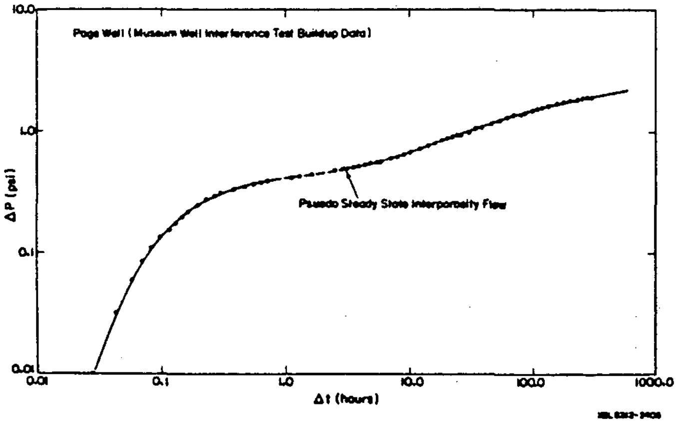

Figure 9. Log-log plot and type curve match of the Page well buildup data.

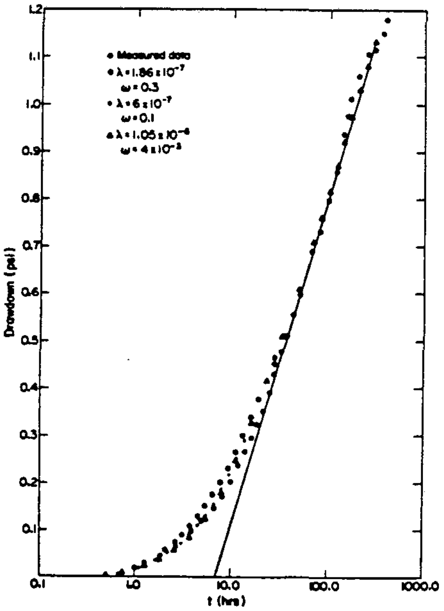

Figure 10. Semi-log plot and analysis of the Page well buildup data.