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S.M. Benson and C.H. Lai

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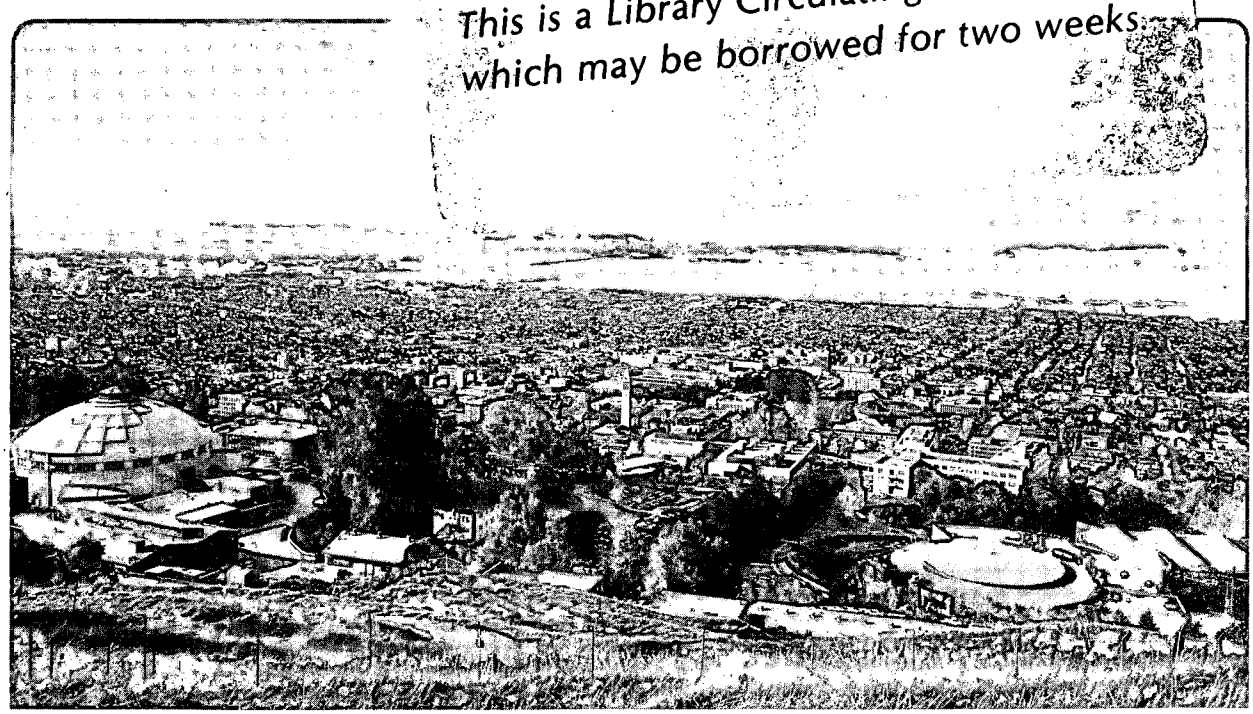

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A NEW METHOD FOR EVALUATING COMPOSITE RESERVOIR SYSTEMS

S. M. Benson and C. H. Lai

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

A simple new technique has been developed for evaluating interference test data in radially symmetric composite reservoirs. The technique is based on the realization that systematic variations in the apparent storage coefficient (calculated from semi-log analysis of the late-time data) are indicative of a two-mobility (k/μ) reservoir. By analyzing variations in the apparent storage coefficient, both the mobility and size of the inner region can be calculated. The technique is particularly useful for evaluating heterogeneous geothermal systems where the intersection of several faults, or hydrothermal alteration has created a high permeability region in the center of the geothermal field. The technique is applied to an extensive interference test in the geothermal reservoir at Klamath Falls, Oregon.

INTRODUCTION

Increased interest in complex hydrogeologic and hydrocarbon systems has stimulated the development of advanced pressure transient techniques for evaluating reservoir heterogeneity. For example, enhanced energy and fluid recovery techniques in oil and geothermal reservoirs require injection of fluid to sweep the in situ resources to production wells. Once fluid is injected, the system is nonuniform and the effects of the nonuniformity must be considered if information is to be gained by analyzing pressure transient data from such systems. Complex hydrogeologic systems are also encountered in the assessment of naturally fractured rock masses under consideration for isolation of nuclear waste, and in the evaluation of the natural state of fractured geothermal systems.

Common types of heterogeneity can be broadly grouped as areally distributed or areally limited heterogeneities. The difference between the two groups depends on whether (1) the heterogeneity is distributed over the system, (e.g., reservoir layering and uniformly fractured rock); or (2) the heterogeneity has well-defined spacial limits, (e.g., the region behind a flood front, or an isolated fracture zone). Categorization of heterogeneity depends to some extent on the scale of the problem considered. For pressure transient testing the scale is a temporal one, governed by the diffusivity ($k/\phi\mu c$) of the rock/fluid system. In other words, during a short test period, the reservoir may behave as an areally nonuniform (or uniform) system; however, a long term test might be influenced by a nonuniformly distributed heterogeneity. Conversely, the situation may be reversed.

One of the important tasks of evaluating a geologic system is to establish the nature of its heterogeneity. The difficulty arises because many of the common types of heterogeneity have similar "pressure transient signatures" and analysis usually relies on the details of these signatures to extract information from the data. For instance, the shape of a pressure drawdown curve versus time may be nearly identical for composite reservoir systems and double-porosity systems. The pressure transient data from such heterogeneous systems can be easily misinterpreted and the actual nature of the heterogeneity may go undetected.

Conventional analysis techniques rely heavily on the shape of the early-time pressure transient response. During this time, the data are influenced by the region in the close vicinity of the active and/or observation wells. Therefore, local heterogeneities dominate the pressure transient response and if properly interpreted, can yield valuable information about the system. However, there are two difficulties when relying on this early-time data. First, as mentioned previously, the "pressure transient signature" may be nonunique. Second, early time data are strongly influenced by flow-rate variations and pressure measurement errors.

For radially symmetric composite systems (see Figure 1), these difficulties can be avoided by analyzing the late-time pressure transient response, rather than the early-time response. The late-time response is influenced by a much larger rock volume than is the early-time response. Therefore, small scale heterogeneities (far from the production and/or observation wells) have little influence on the response and the system behaves in a relatively uniform manner. However, information about the local heterogeneity is still contained in the data, but it must be extracted in a unconventional manner. The following discussion outlines a simple graphical procedure for evaluating composite reservoir systems when data from several observation wells are available. Based on the procedure, the mobility-thickness of the inner and outer regions, as well as the radial distance to the discontinuity separating the two regions can be calculated. The technique is most useful in composite systems

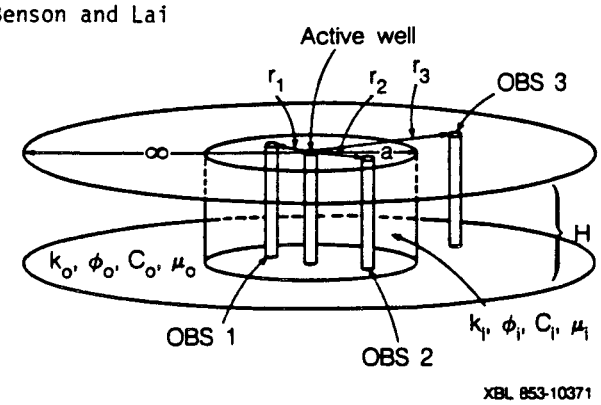

Figure 1. Schematic of a radially symmetric composite reservoir.

created by injection and production wells because it assumes the active well is concentrically located in the inner region. However, it is also applicable to natural geologic systems where the heterogeneity is roughly cylindrical, with the active well near the middle of the inner region.

COMPOSITE RESERVOIR ANALYSIS

The analysis procedure described below is developed by using the late-time asymptotic solutions presented by Ramey (1970) for drawdown (or buildup) in a radially symmetric composite reservoir. These solutions (one for the inner region, and one for the outer region) are correct to within 1% for times in seconds greater than

$$t > \frac{a^2}{0.04} \frac{1}{\eta_i} [1 - \eta_i/\eta_o] \qquad (1)$$

where a is the radial distance to the discontinuity, and η is the diffusivity ($k/\phi\mu c$). The subscripts (i) and (o) refer to the inner and outer regions respectively. The late-time asymptotic solutions (in S.I. units - mks) for the drawdown (Δp) in observation wells in the inner and outer regions are given by Equations (2) and (3) respectively;

$$\Delta p_i(r,t) = \frac{-2.303\ q}{4\pi\lambda_o h} \left\{ \frac{\lambda_o}{\lambda_i} \log \left(\frac{a}{r}\right)^2 + \log t + \log \frac{\lambda_o}{\phi_o c_o a^2} + 0.351 \right\} \qquad (2)$$

and

$$\Delta p_o(r,t) = \frac{-2.303\ q}{4\pi\lambda_o h} \left\{ \log t + \log \frac{\lambda_o}{\phi_o c_o r^2} + 0.351 \right\} \qquad (3)$$

From the form of both equations it is clear that the late-time data falls on a semi-log straight line whose slope is proportional to the mobility (λ) of the outer region. For example, Figure 2 shows a typical response for a well in the inner region. The early-time data show the influence of the inner region. The late-time transients, influenced by the outer region, eventually fall on a semi-log straight line.

For wells in either the inner region or outer region, this semi-log straight line can be extrapolated back to the point where $\Delta p = 0$ in order to evaluate t_o (see Figure 2). From the value of t_o, the storativity (ϕch) for the outer region, can be calculated by

$$(\phi ch)_o = 2.246 \frac{t_o}{r^2} \lambda_o h \qquad (4)$$

or

$$(\phi ch)_o = \left[2.246 \frac{t_o}{r^2} \lambda_o h\right] \left(\frac{r}{a}\right)^{2(1 - \lambda_o/\lambda_i)} \qquad (5)$$

for the inner region. From the form of Equation (5) it is clear that if $(\phi ch)_o$ is to be calculated using the late-time solution for a single well in the inner region, an estimate of both the mobility of the inner region and the radius to the discontinuity is required. Usually, this information is not available. However, if pressure transient data are available from more than one well in the inner region and one well in the outer region, the following procedure can be used to calculate the distance to the discontinuity and the mobility of the inner region.

First, calculate λ_o and $(\phi ch)_o$ for the well in the outer region. Next, calculate λ_o and the apparent storativity $(\phi ch)_a$ for wells in the inner region, where $(\phi ch)_a$ is defined by

$$(\phi ch)_a = 2.246\ \lambda_o h \frac{t_o}{r^2} \qquad (6)$$

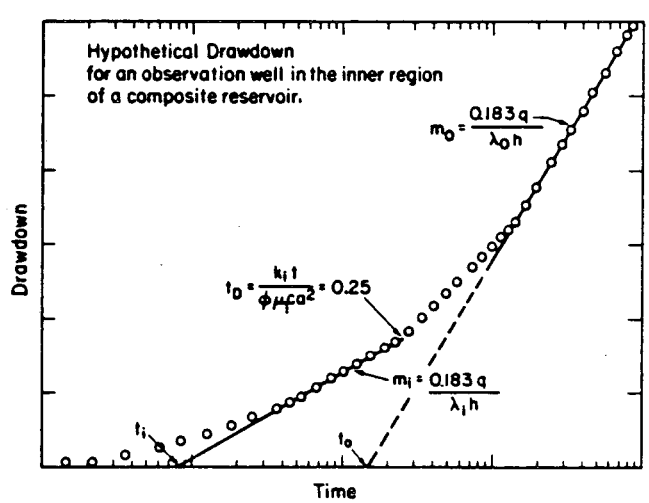

Figure 2. Semi-log plot of the hypothetical drawdown for an observation well located in the inner-region of a composite reservoir.

Next, note that by substituting Equation (6) into Equation (5) and taking the logarithm of both sides of the equation, we see that

$$\log [(\phi ch)_o/(\phi ch)_a] = 2(1 - \lambda_o/\lambda_i) \log (r/a) \quad (7)$$

This implies that on a log-log plot of $(\phi ch)_o/(\phi ch)_a$ versus the distance to the observation well (r), all of the data points from wells located in the inner region lie on a straight line with a slope of

$$b = 2(1 - \lambda_o/\lambda_i) \quad (8)$$

By preparing a graph of $\log [(\phi ch)_o/(\phi ch)_a]$ the slope (b) can be determined. Then the mobility ratio between the inner and outer regions can be calculated by

$$\lambda_o/\lambda_i = 1 - b/2 \quad (9)$$

The radius of the inner region is calculated by extrapolating the straight line drawn through the data points to the point where $(\phi ch)_o/(\phi ch)_a = 1$ and therefore, a = r.

Note that in order to evaluate the radius of the inner region, it is necessary to have an estimate of ϕch for the outer region. This can be obtained from a well located in the outer region of the reservoir or an independent source (e.g., testing in nearby wells). In practice, one rarely knows a priori if a well is located in the inner or outer region. However, if more than one well, distant from the active well, yields the same or similar values of ϕch, it can be assumed that these wells are in the outer region.

If a reasonable estimate of ϕch for the outer region is not available, the mobility ratio (λ_o/λ_i) can still be calculated. For this case prepare a plot of $\log (\phi ch)_a$ versus log(r). The slope of this line will be (-b) and λ_o/λ_i can be calculated accordingly.

EXAMPLE

During the summer of 1983, a seven-week interference test, in which over 50 wells were monitored, was conducted in the Klamath Falls, Oregon, geothermal reservoir (Benson et al., 1984a). The anomaly is a shallow (< 2000 ft), moderate temperature (100°C) geothermal system that occurs in rocks of primarily volcanic origin. Both andesitic flows and lacustrine volcanic sediments contribute to the permeability and porosity of the system.

More than 450 wells have been drilled and considerable effort has been devoted to developing a geologic model of the area. However, the hydrogeologic characteristics of the reservoir remain ill-defined because correlation of individual rock units is often difficult, if not impossible, even over distances as short as 100 ft. The geologic complexity is believed to be the result of a varying depositional environment and faulting.

One of the objectives of the interference test was to determine the effect of the geologic heterogeneity on the hydrologic behavior of the geothermal reservoir. As mentioned above, interference testing can be a useful tool for detecting hydrologic heterogeneity. However, since the pressure response for many of the common types of reservoir heterogeneity are very similar, a sufficiently accurate geologic model is required before an accurate analysis of the interference data is possible. In Klamath Falls, the complexity of the system precludes development of a hydrogeologic model based on geologic data alone. Therefore, only by combining both types of data is it possible to develop a convincing model of the system.

Interference Test Description

The interference test, which covered a seven-week period during July-August 1983 consisted of measuring water level changes in 52 wells over a one-mile square area, while pumping and injection operations were ongoing in two other wells. For the first three weeks, well CW-1 was pumped at a rate of 43.5 kg/s. For the final four weeks, water was pumped from CW-1 and concurrently reinjected into the County Museum well. Figure 3 shows the pumping and reinjection schedule. The figure also shows the downhole pressure response at one of the observation wells (Head well). During the first phase of the test the pressure dropped (approximately 1.7 psi in this well). After reinjection began, the pressure gradually increased to within 0.4 psi of the original value. This response is typical of all of the observation wells. Observation, pumping (CW-1) and injection (County Museum) well locations are shown in Figure 4. Well depths range from 250 ft to over 1200 ft. However, each well penetrates the reservoir (as is evident from the test and drilling data).

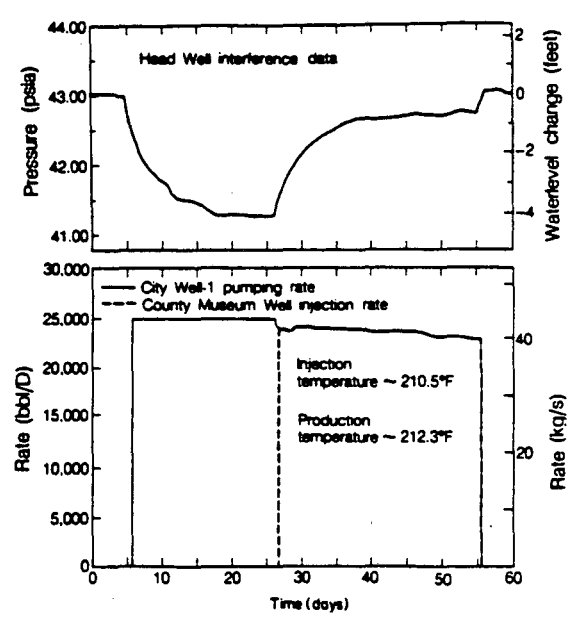

Figure 3. Pumping, injection, and observation well data from the interference test.

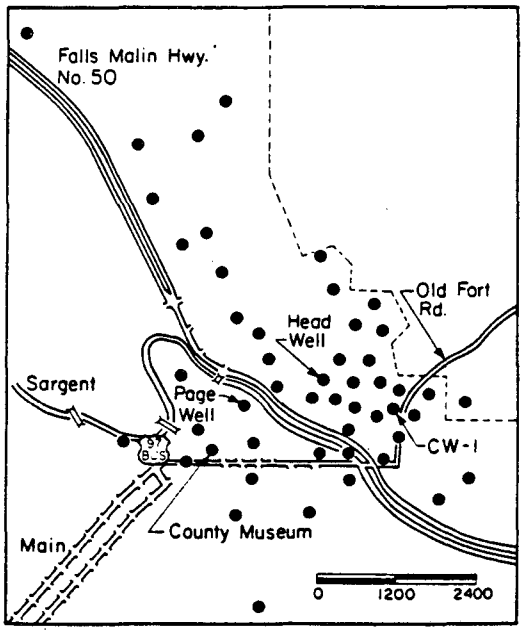

Figure 4. Observation-well location map.

Interference Data Analysis

Interpretation of previous short-term tests and the shape of the drawdown curves (for example, see Figure 5) indicated that a double porosity or layered model described the system best. Therefore, all of the interference test data were analyzed with two techniques applicable to such systems: a type-curve matching technique developed by Deruyck et al., 1982 and a semi-log history matching technique developed by Lai et al., 1983.

The analysis showed that overall, the individual wells behaved in a remarkably uniform manner (Benson et al., 1984b). All of the interference data showed the permeability-thickness value to be approxmately 1.4 x 10^6 md-ft. On the other hand, calculated values for $(\phi ch)_t$ varied by over two orders of magnitude, from 1.1 x 10^{-3} ft/psi to 0.79 ft/psi. The high values of $(\phi ch)_t$ and the large variation cannot be explained by the double-porosity model.

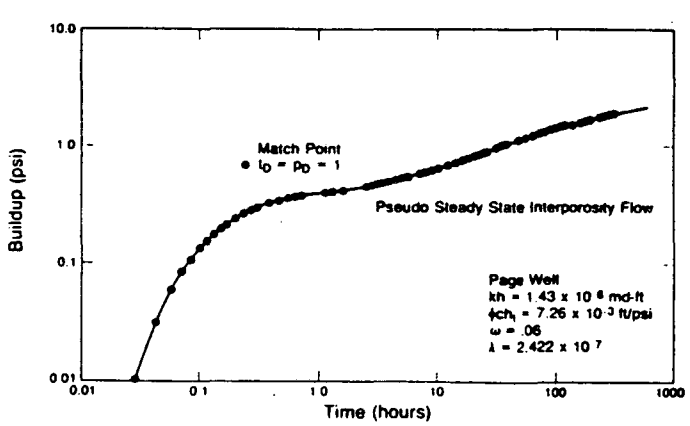

Figure 5. Log-log plot and double-porosity type-curve match for the Page well buildup data.

Closer inspection of the values of $(\phi ch)_t$ showed that they vary in a systematic manner; for wells close to the pumped well (CW-1), $(\phi ch)_t$ increases with decreasing distance to the observation well. This type of behavior is indicative of a composite reservoir system with a high mobility inner region.

The pressure data were reanalyzed using the procedure outlined here. Figure 6 shows a graph of $(\phi ch)_o/(\phi ch)_a$ versus distance from the pumped well. The data points fall on a fairly well defined straight line with a slope of 1.73. This indicates that the mobility of the inner region is 7 1/2 times that of the outer region. From the point at which $(\phi ch)_a = (\phi ch)_o$, the radius of the inner region is estimated to be 1600 feet.

Based on geologic or temperature data alone, there is no indication of the composite nature of the reservoir. For instance, the temperature distribution in the reservoir is sufficiently uniform to rule out the possibility that the entire mobility contrast is the result of fluid viscosity variations. Therefore, in light of the unanticipated results, additional evidence for the existence of a high permeability (k) region was sought. One such evidence comes from a graph of observation well drawdown vs. distance to the pumped well. For a homogeneous reservoir at semi-steady state, all of the data points should fall on a single straight line whose slope is inversely proportional to kh/μ, Figure 7 shows the drawdown at several of the wells after 336 hours of pumping. As shown, the data points do not fall on a single straight line. Instead, they fall (roughly) on two straight lines. The permeability-thickness products of these two regions, calculated from the slopes of these lines, are 1.06 x 10^7 and 1.43 x 10^6 md-ft, respectively. The permeability-thickness calculated for the outer region agrees well with the average formation permeability-thickness calculated from the pressure transient analysis. Furthermore, the ratio of the inner to outer region permeability is 7 1/2, the same value obtained from the above analysis.

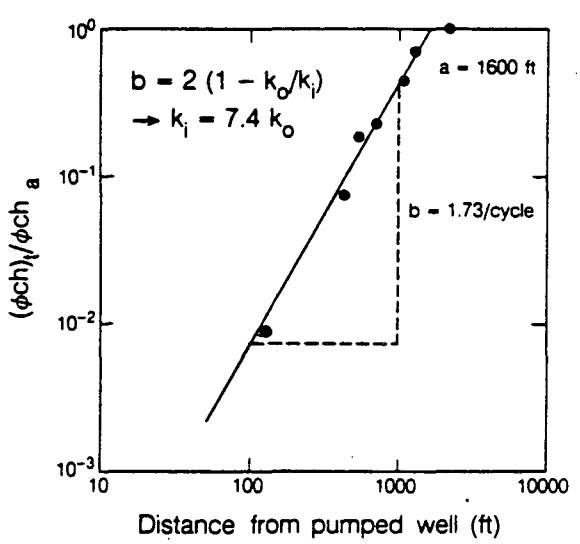

Figure 6. Composite reservoir analysis for the Klamath Falls interference data.

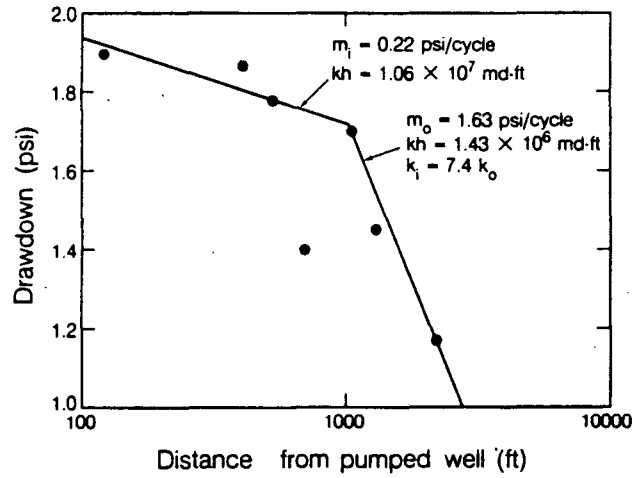

Figure 7. Pressure drawdown (at 336 hours) versus distance to the pumping well.

Consideration of the geologic setting gives additional validity to this interpretation. A major range-front normal fault is known to transect the area (Sammel, 1984). It was anticipated that the fault would manifest itself either as a constant pressure or no-flow boundary. Instead, the fault was essentially invisible to hydrologic testing. We propose here that in a limited area, the fault is not a single linear-fracture but a broad region coincident with the high permeability region detected from the interference test. The high permeability region may also be the result of the intersection of two faults; the main fault with a north-west strike and a secondary one with a north-east strike. However, the existence of the north-east striking fault is based on the interpretation of stereo-pair areal photographs, and has not been confirmed by geologic or structural studies.

CONCLUSIONS

A very simple graphical technique has been developed for evaluating radially symmetric composite reservoir systems. The technique relies on using the late-time drawdown data, thereby avoiding difficulties associated with relying heavily on the interpretation of the early-time pressure transient data. In addition to providing a new analysis technique, evaluation of the theory behind the technique shows that apparent variations in storativity can be sensitive indicators of variations in the reservoir mobility (k/μ). Thus, it provides another means for developing insight into the behavior of heterogeneous hydrogeologic systems and improving our ability to distinguish between the various types of reservoir heterogeneity.

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NOMENCLATURE

a	radius of the inner region, (m)
b	slope on log $[(\phi ch)_o/(\phi ch)_a]$ vs log (r) plot, (-)
c_i	total compressibility of the inner region, Pa^{-1}
c_o	total compressibility of the outer region, Pa^{-1}
h	reservoir thickness, (m)
k_i	permeability of the inner region, (m^2)
k_o	permeability of the outer region, (m^2)
m_o	slope on semi-log plot corresponding to the properties of the outer region, Pa/cycle
Δp_i	drawdown in the inner region, Pa
ΔP_o	drawdown in the outer region, Pa
q	flowrate, m^3/s
r	radial distance to an observation well, m
t	time since the test began, s
t_o	time intercept where m_o crosses the $\Delta p_i = 0$ axis, s
$(\phi ch)_a$	apparent storativity, m/Pa
$(\phi ch)_o$	storativity of the outer region, m/Pa
$(\phi ch)_t$	total storativity in a double-porosity reservoir (fractures and matrix), m/Pa
λ_i	mobility of the inner region, m^2/Pa.s
λ_o	mobility of the outer region, m^2/Pa.s
μ_i	fluid viscosity in the inner region, Pa.s
μ_o	fluid viscosity in the outer region, Pa.s
η_i	diffusitivity of the inner region $k_i/\phi_i\mu_i c_i$, m^2/s
η_o	diffusivity of the outer region $k_o/\phi_o\mu_o c_o$, m^2/s
ϕ_i	porosity of the inner region, (-)
ϕ_o	porosity of the outer region, (-)

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