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Application of an Expert System for Analysis of Geothermal Well Tests

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ABSTRACT

WES is an expert system designed at Lawrence Berkeley Laboratory for interpreting well test data. The results of WES's analyses of two geothermal well tests are compared to those calculated using traditional methods. WES is well suited for analyzing well tests in geothermal systems because it is robust enough to carry out analyses of data sets that are noisy or incomplete. It also has a broad knowledge base that recognizes most of the hydrogeologic characteristics observed in geothermal systems, such as double-porosity, fractures, and leaky or sealed boundaries. Application of expert systems for analyzing geothermal well tests has several advantages, including: providing clear documentation of the procedures used in the analysis; providing on-site expertise to guide the testing program; providing a greater knowledge base than a single expert may have, and; greatly decreasing the time required for these analyses. Over the next decade expert systems will become an integral part of resource definition and development programs. This paper provides just one example of how expert systems can be used.

Introduction

At present a variety of methods are used to interpret well test data, from simple graphical solutions to sophisticated computer matching procedures (Mathews and Russell, 1967; Earlougher, 1977; Streltsova, 1988; McEdwards, 1981; Bourdet *et al.*, 1983a, b, 1984a). One common thread amongst the available techniques is the need for a human expert to assess the quality of the data, to choose the appropriate model and method to interpret the data, and finally to apply these methods to estimate the formation parameters. In recent years several expert systems have been developed to take the place of the human expert in well test analysis, to one degree or the other (Allain and Horne, 1990; Arellano *et al.*, 1990; and Mensch and Benson, 1989). These programs differ in their approach to mimicking the human expert, but all carry out the same basic tasks of model selection and parameter estimation. WES, the expert system described and applied here was developed specifically to carry out these tasks when the pressure transient data are either noisy or incomplete. For this reason, WES is a potentially valuable tool for interpretation of well tests in geothermal reservoirs, where it is often difficult to obtain high-quality well test data.

This paper is divided in three parts. First, we discuss the benefits of an expert system for well test analysis. Second, we review the procedures WES follows in carrying out a well test analysis. Finally, the system is used to interpret two well tests in a moderate temperature, liquid-dominated geothermal resource in fractured granitic rock. The results are compared to a previously published analysis of the same test data.

Advantages of an Expert System for Well Test Analysis

Advantages of expert systems fall into two categories, those inherent to any computer program and those specific to expert systems. Advantages of computer systems over manual manipulation of data are well recognized. Expert systems have special attributes that are only beginning to be recognized and exploited, including:

- They easily trace the rules and procedures they use, and therefore explain how they reach their conclusions.
- They are able to develop and manipulate higher-level symbolic representation of data, and thus are closer to human reasoning processes than numerical algorithms. For example, the shape of the pressure transient curve can be represented as a series of well-defined patterns, such as humps, valleys, and straight lines. In addition, noisy intervals in the test data can be recognized and labeled as such. These are the basic tasks that the human expert performs at the beginning of an analysis.
- They can provide expertise where it is not always available, that is, at the field test site. For example, a real-time data analysis system could propose to stop a test when enough data are collected, or to repeat it if the data are not adequate for a comprehensive analysis (e.g., noise, wellbore storage effects, uncontrolled external effects). This in-field expertise could save a significant amount of time and expense.
- There are presently no accepted standards in well test analysis, that is, two analysts, each given the same set of data, may provide different interpretations regarding the nature and parameters of a formation. An expert system would help to standardize and document the methods used to interpret data.
- They are usually easier to develop and maintain than classic programs, especially when the system tries to mimic human reasoning. For instance, expertise is usually contained in rules written in English-like syntax.

WES: General Description of the Program

Computer scientists and reservoir engineers developed WES at Lawrence Berkeley Laboratory over a two-year period. The system consists of two modules that interact with each other: a procedural program, written in C, and a rule base system using ART (Automated Reasoning Tool, from Inference Corp.), an expert system shell. The C program performs computations and graphics, and exchanges informations with both the user and ART. ART's ability to show each fact and rule used to reach a conclusion are an invaluable tool for developing the expert system. This feature can also be used at the end of each analysis to obtain a complete explanation of the reasoning followed.

WES analyzes a subset of the general well test analysis problem: it can analyze single-rate pressure drawdown and pressure buildup tests, and identify a limited number of models for the nature of the formation, including homogeneous, infinite reservoirs (Horner, 1951), bounded reservoirs (Bixel *et al.*, 1963; Gray, 1965) and leaky aquifers (Hantush and Jacob, 1955), double-porosity formations (Warren and Root, 1963; Kazemi, 1969).

The unique feature of WES is that it combines three of the most commonly used methods in well test analysis (Allain and Horne, 1990; and Arellano *et al.*, 1990). These methods include: semi-logarithmic analysis (Horner, 1951; Miller *et al.*, 1950), based on the semi-log plot (plot of the pressure drop versus the log of time); type curve matching (Agarwal *et al.*, 1970), based on the log-log plot (plot of the pressure drop versus time on log scales); and the derivative method (Bourdet *et al.*, 1983a, b, 1984a, b), based on the discrete derivative of the pressure drop, taken with respect to the log of time and plotted on log scales. By combining the advantages of each technique, WES provides a more robust analysis and a means of double-checking the results.

The system goes through four steps to complete the interpretation of a well test:

- data processing and graphical representation;
- pattern recognition;
- model selection; and
- parameter estimation.

The following sections describe these steps, along with an example showing their application. The data set selected for describing WES were obtained from a shallow well in the San Joaquin Valley, CA. This example was chosen because the data set is relatively complete and illustrates WES's capabilities nicely. Two examples from a geothermal reservoir are presented after the basic functions of WES are described.

Data Processing and Graphics Computation

Once the user has selected a well test to analyze, the C program performs four types of computations:

(1) Read the data file.

(2) Compute the discrete derivative. The algorithm used by WES is described by (Bourdet *et al.*, 1984b; Clark and Van Golf-Racht, 1985). It computes the weighted average of the slopes between the point under study and a point preceding it, and between the point under study and a point following it. These two points are not necessarily the points closest to the point of interest, but rather are defined by taking the first point outside of a given interval (I) in each direction. The smoothness of the derivative curve obtained by this method depends on the length of the interval I: increasing the length will result in a smoother derivative data, but may also hide significant patterns. Depending on the noise of the original data, the length of the interval I used by the system ranges from 0.1 to 0.5 log cycles. The derivative value is given by:

$$p' = \frac{\frac{\Delta p_1}{\Delta t_1}\Delta t_2 + \frac{\Delta p_2}{\Delta t_2}\Delta t_1}{\Delta t_1 + \Delta t_2}$$

where the time intervals Δt_1 and Δt_2 are defined on a natural log scale (since p' is the derivative of the pressure taken with respect to the natural log of time).

(3) Prepare the graphic representation of the data. Four plots are prepared: Cartesian, semi-log, log-log and derivative. A combined plot of the log-log and derivative curves is also available.

(4) Compute a new description of the semi-log, log-log and derivative curves: each curve is represented by a sequence of straight lines. The number of straight lines depends on the shape of the curve and typically 5 to 10 segments are required to adequately describe the curve. These straight lines are computed with a simple least-squares algorithm that gives the best-fit straight line for the data points contained in a given time interval.

At the end of these computations the three sets of straight lines are sent to ART. The straight line description of the data set has several advantages:

- It reduces and simplifies the data handled by the expert system shell, without a great loss of information.
- The least-squares algorithm used to compute the straight lines has an important smoothing effect.
- It represents a higher-level, symbolic description of the data, and is closer to the global image of the curve that a human expert has.

In this section and those that follow, an example of each of the steps in the analysis is provided in the italics text, as illustrated below.

Example: Figures 1–4 show the curves resulting from the initial computations, including: the raw data, semi-log, log-log, and derivative plots. Figure 1 also lists the supplemental test data needed for WES to carry out this analysis. Note that the level of random noise on the semi-log plot is relatively high. This level is typical of the range of random noise encountered in geothermal well tests. The level of noise on the late part of the derivative plot is much larger. The interval (I) used to compute the discrete derivative in this example

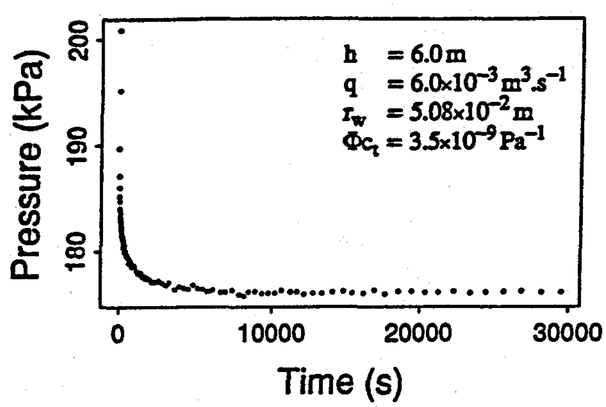

Figure 1. Cartesian plot of the pressure drawdown data.

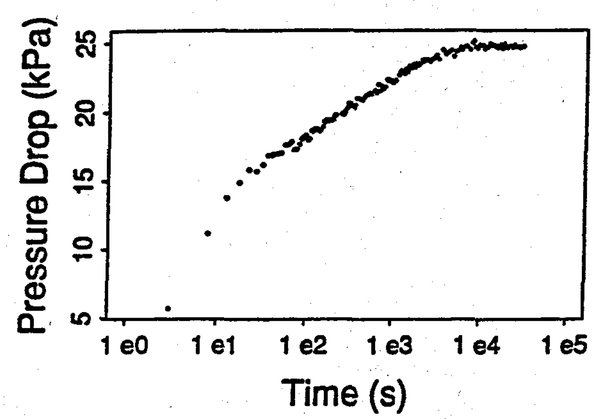

Figure 2. Semi-log plot of the pressure drawdown.

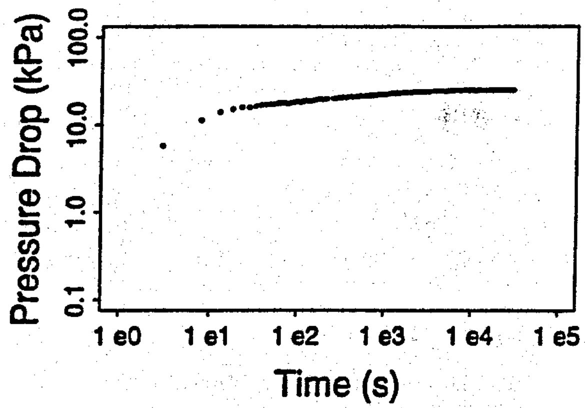

Figure 3. Log-log plot of the pressure drawdown.

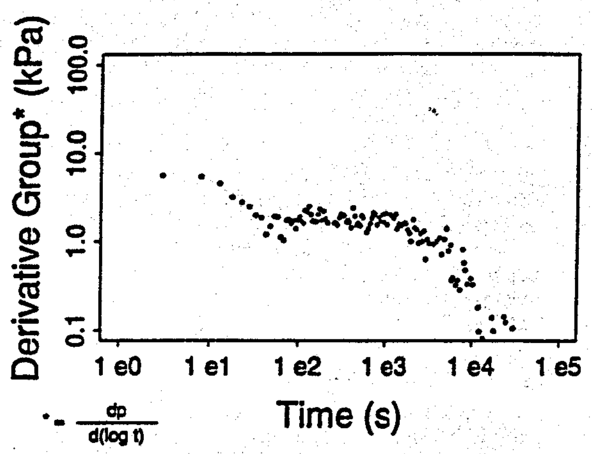

Figure 4. Log-log plot of the pressure derivative.

was 0.2 log cycles. The discrete derivative computation algorithm is very sensitive to the amount of noise present on the data. Figures 5 and 6 show the semi-log, log-log and derivative plots with their straight lines representations. All three curves are described by five or six segments, and the results demonstrate that the straight line computation algorithm is relatively insensitive to random noise: even for the derivative curve, the set of lines obtained is very close to the original curve. However, from our experience, the level of noise present on this example is close to the limit after which the straight line algorithm fails to adequately describe the late part of the derivative curve.

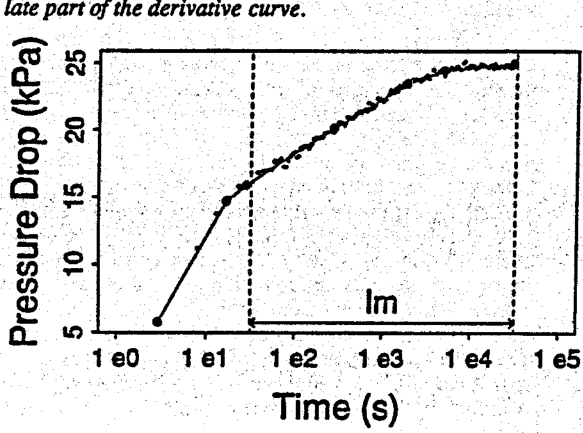

Figure 5. Semilog plot of the pressure drop with its straight line representation.

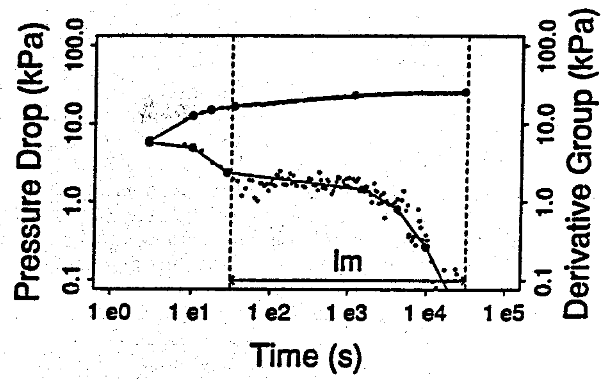

Figure 6. Combined log-log and derivative plots with their straight line representations.

Pattern Identification and Model Recognition

Using the simplified linear representation of the data set, the rule base system identifies significant patterns in the shape of the pressure drawdown curve. Significant patterns recognized by WES are: straight lines with a duration of more than one log cycle on both the semi-log and the derivative plots; a hump at the beginning of the derivative curve; and concave or convex curvatures at the end of both the semi-log and the derivative curves. Other important patterns include unit-slope straight lines at the beginning of the log-log and the derivative plots. Each of those patterns can be ascribed to a property of the well/reservoir system and are described in greater detail below.

Three time intervals are recognized in well test data (Vongvuthipornchai and Raghavan, 1988): early time, where wellbore storage is dominant, and intermediate and late time, where it is negligible. Intermediate time corresponds to the unaffected reservoir response, and late time to formation heterogeneity and outer boundary effects. WES uses these time interval concepts, but combines the intermediate and late time intervals for the purpose of pattern recognition and model selection. All three intervals may not be present in a test, and one of the difficulties of well test analysis is to determine precisely the position and duration of these intervals.

WES performs pattern identification in two steps: the first step looks for patterns related to the wellbore storage effect, and the second step looks for patterns relevant to the reservoir model. These are always executed in this order, because the second step uses the results of the first one.

Presence of Well Bore Storage: Wellbore storage occurs at the beginning of a well test and, if present, masks the response of the reservoir during this period (Agarwal *et al.*, 1970). The major difficulty created by wellbore storage is that its presence must be recognized so that it is not mistaken for an actual reservoir response. The most diagnostic pattern created by wellbore storage is a hump at the beginning of the derivative curve. Depending on the amount of data available for the beginning of the test, this hump can be either complete or partial: in the second case, only the last part of the hump is present on the derivative curve. When the whole pattern is present, a unit-slope straight line may also appear at the beginning of both the log-log and derivative plots. These straight lines are a confirmation of the presence of a wellbore storage effect.

Once it recognizes the hump, the system is able to determine the different time intervals for the test: it first computes precisely the top of the hump (or first data point if only the downward portion of the hump is present), and defines the interval ranging from the beginning of the test to half a log cycle before the top of the hump as early time, and the interval beginning one log cycle after the top to the end of the test as intermediate/late time.

Example: Figures 4 and 6 show that only half of the hump appears on the derivative curve. The two first straight lines on the derivative represent a downward, convex pattern that is recognized by the system as the end of a hump. Presence of wellbore storage is inferred from this fact. In this case, there is no unit-slope straight line at the beginning of the test to confirm this interpretation. Since the upward portion of the hump is not present on the curve, the first data point is assumed to be the top of hump. The intermediate/late time interval (Im) begins one log cycle after this point, and the early time interval (Ie) is not defined in this case.

Reservoir Pattern: If the intermediate/late time interval is present, the response of the reservoir for this period provides information about the nature of the formation and its outer boundaries. WES uses patterns on both the semi-log curve and the pressure derivative curve to identify the appropriate reservoir model. Pressure derivative curves have the advantage that patterns are usually more uniquely represented than on the semi-log plot (Clark and Van Golf-Racht, 1985); but it is sometimes too noisy to be usable. When the data are noisy semi-log plots provide for more reliable pattern identification. Combining these two methods draws from the strength of each.

In this portion of the analysis WES computes a more accurate representation of the intermediate/late time interval determined in the preceding step. One to four straight lines are usually enough to represent this portion of the curve for tests corresponding to the models currently recognized by the system. Results of the computation are used by the rule base system to determine the shape of the curve on the intermediate/late time interval. Characteristic shapes include concave, convex and straight portions.

Example: The computation of the new series of straight lines on the semi-log curve for the Im interval (Fig. 7) returns three lines: a long first one, followed by two shorter segments with decreasing slopes, the last one being almost horizontal. WES describes such a pattern as a long segment followed by a convex portion.

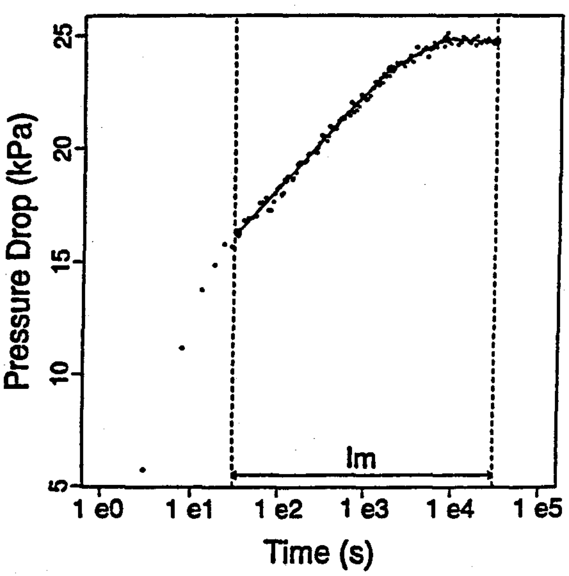

Figure 7. New straight line representations computed on the intermediate/late time interval (Im).

Model Recognition: In its present state, WES is able to identify a limited set of models, including homogeneous, vertically fractured, leaky, and double porosity reservoirs, and two kinds of outer boundaries (no flow and pressure maintenance boundaries). Each model is associated with a pattern on the portion of the curve corresponding to the intermediate/late time interval. Some of these patterns are illustrated in Fig. 8. For example, an homogeneous formation without boundaries is characterized by a long straight line on the semi-log plot and a zero-sloped straight line on the derivative plot (Bourdet *et al.*, 1983a). The semi-log plot of pressure drawdown in a double porosity formation is characterized by either a convex portion followed by a concave portion, or only a concave portion when the first pattern is hidden by wellbore storage (Gringarten, 1984). Double porosity formations are indicated on the derivative plot by valleys in the intermediate/late time interval.

Some patterns can correspond to more than one model (Gringarten, 1984). In such a case, WES will continue the analysis using each of the different possibilities, or hypotheses, until it is able to resolve the conflict (by the use of geological information, specialized plots, and subsidiary information from other wells in the area). The system is designed to generate as many hypotheses compatible with the facts as possible, to ensure that the correct model is included in the set of hypotheses.

Example: The pattern determined in the preceding step is interpreted by the system as characteristic of an homogeneous formation with a pressure maintenance boundary. WES recognizes two models corresponding to this pattern, a homogeneous reservoir with a constant pressure fault and a leaky aquifer.

Parameter Estimation

Once a model has been selected, the last step of the analysis consists of calculating the properties of the formation. Calculated parameters include the reservoir permeability (k), the skin factor of the well (s), the wellbore storage coefficient (C), and the distance to boundaries (when applicable). For double-porosity reservoirs, the parameters λ and ω are also calculated (Warren and Root, 1963). WES uses three methods to calculate these parameters. Here again, redundancy improves the robustness of the parameter estimation procedure, although it is not always possible to apply all three methods to a data set. The methods used include semi-log analysis (Horner, 1951; Miller *et al.*, 1950), an approximate type curve matching procedure (combined log-log and derivative) and a numerical curve-fitting routine. The semi-log and approximate type curve matching procedure are only applied to the early and intermediate time intervals where boundary and reservoir heterogeneity effects are negligible.

The approximate type curve matching procedure of the combined log-log and derivative plots provides a quick estimate of the formation parameters and an "educated" first guess of k, s and C for the automated curve-fitting routine. The procedure follows two steps: (1) the system computes the ratio between the ordinate of the top of the hump and the ordinate of the horizontal straight line that appear on the derivative plot; this result is compared to values stored in a table to select the appropriate type curve to use (e.g. for different values of C_De^{2s}); (2) the selected type curve is adjusted to the data by computing the necessary x and y shifts to match the pressure derivative plot. Values of k, s, and C_D are calculated from conventional type-curve matching procedures (Ramey, 1970). This algorithm provides fairly good results for simple models and complete data, and good initial "guesses" for the numerical curve-fitting routine.

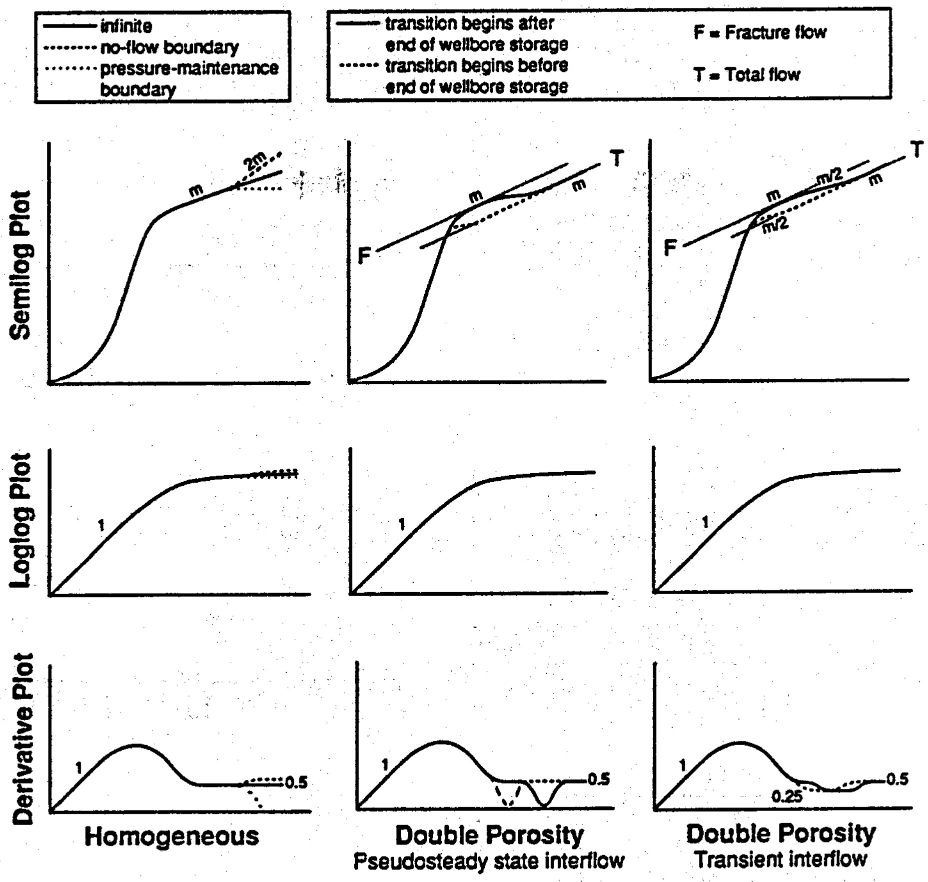

Figure 8. Characteristic curves for selected reservoirs.

The numerical matching routine is a non-linear least-squares optimization that uses a modified Gauss-Newton algorithm (Gill and Murray, 1978). The minimization procedure uses the parameters x, x_1, and x_2, where:

$$k = k_0 e^{x}$$

$$C = C_0 e^{x_1}$$

and

$$s = s_0 + \frac{x_2}{2}$$

where k_0, C_0, and s_0 are the initial guesses of these parameters. This change of variables was chosen to improve the performance of the optimization routine and ensures that k and C remain positive during the optimization process. Bounds are set on these parameters to ensure that they remain physically realistic.

Example: The chosen model depends on four parameters: k, C, s and the nature of the pressure maintenance boundary. For this example, pressure maintenance is created by leakage from an overlying pond, therefore only this interpretation will be described. WES uses all three analysis methods to interpret this test. The semi-log and approximate type curve method are used on the early and intermediate time portions of the test and provide estimates of k, s, and C. The automatic matching routine uses all the test data and provides estimates of these parameters and the leakage factor B *(*$B = kHH'/k'$*, where the primed values refer to the properties of the leaky caprock). C can also be estimated independently by computing its geometrical value (that is, the value obtained from the geometrical dimensions of the wellbore, assuming that it is cylindrical). Figure 9 shows the log-log and derivative curves, with the two closest type curves (obtained from a table), and Table 1 gives the numerical*

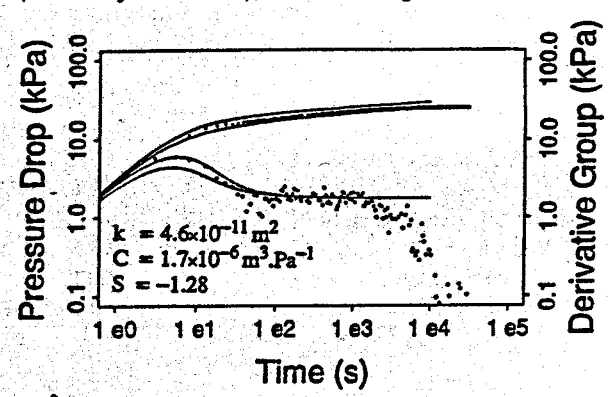

Figure 9. Approximate type curve match of the infinite-acting part of the data. The two closest type curves are illustrated (e.g. for values of $C_D e^{2s}$).

values of the calculated parameters. In this case, the early part of the hump is missing, therefore the type curve match may not be very reliable. However, comparison with the results from the semi-log analysis indicates that similar values are obtained with both types of analysis. The curve match from the automated matching routine is shown in Fig. 10. As indicated in Table 1, parameter estimates from all

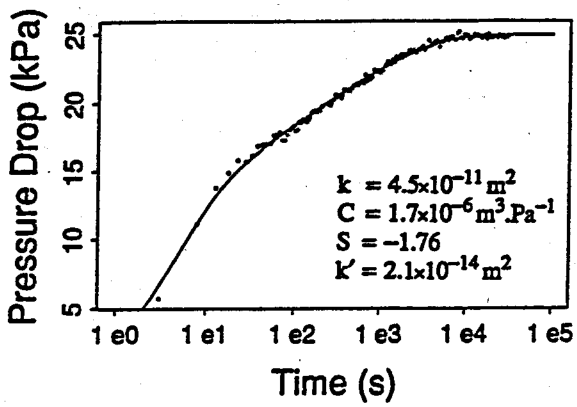

Figure 10. Automated curve fit for a leaky aquifer model.

three methods are in excellent agreement. Good agreement between the results of the different analysis methods gives a high degree of confidence in the validity of the analysis.

Table 1. Results of the Parameter Estimation.

Method	k (m^2)	C (m^3/Pa)	s	k′ (m^2)
Semi-log	$4.5\cdot10^{-11}$		-1.7	
Type curve	$4.6\cdot10^{-11}$	$1.7\cdot10^{-6}$	-1.3	
Numerical	$4.5\cdot10^{-11}$	$1.7\cdot10^{-6}$	-1.8	$2.1\cdot10^{-14}$
Geometrical		$8.3\cdot10^{-7}$		

Application to Geothermal Well Tests

WES was applied for interpretation of two pressure buildup tests in a fractured granitic reservoir in Wendel, CA (Benson, 1982). The test well, WEN-1, was drilled to a total depth of 1780 m, and cased to 1545 m with 0.24 m diameter casing (9 5/8 inch). The entire open interval is completed in granitic basement rock. Maximum measured downhole temperature is 120°C. Eighty percent of the produced fluid comes from one major fracture zone. Supplemental data for these two tests are provided in Table 2.

Table 2. Supplemental Data for WEN-1.

Flow rate, buildup No. 1	$4.3\cdot10^{-2}$ m^3/s
Flowing time, buildup No. 1	$4.86\cdot10^{4}$ s
Flow rate, buildup No. 2	$3.9\cdot10^{-2}$ m^3/s
Flowing time, buildup No. 2	$3.64\cdot10^{5}$ s
Viscosity	$2.3\cdot10^{-4}$ Pa·s
Wellbore radius	0.12 m
Porosity-compressibility-thickness product	$2.0\cdot10^{-8}$ m/Pa

Horner plots of the two pressure buildups are shown in Figs. 11 and 12. Each of these plots is characterized by rapid initial pressure recovery (note that time increases from right to left in these plots). Following this period the rate of pressure buildup decreases for a period of about 1/2 of a log cycle. The late-time pressure buildup is characterized by a semi-log straight line of at least one log cycle on both plots.

Pressure derivative plots of these two buildups are provided in Figures 13 and 14 (note that again time increases from right to left). Both plots have similar features, although the derivative plot from buildup test No. 1 (Fig. 13) is noisier, particularly near in end of the recovery period. Significant features on these two graphs are the large value of the derivative at early times (indicative of wellbore storage), a valley in

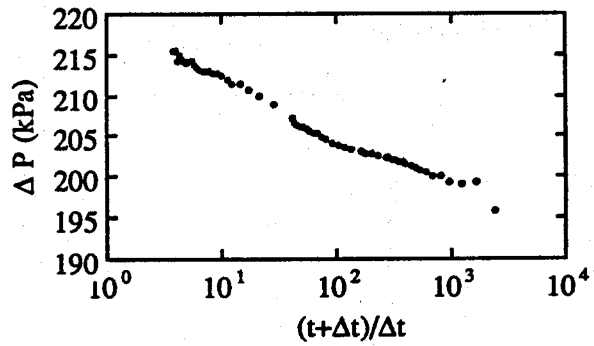

Figure 11. Horner plot of pressure buildup No. 1.

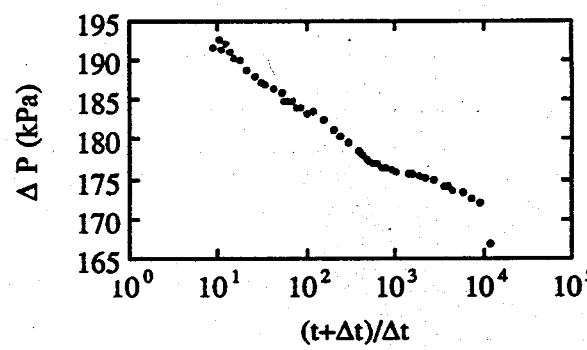

Figure 12. Horner plot of pressure buildup No. 2.

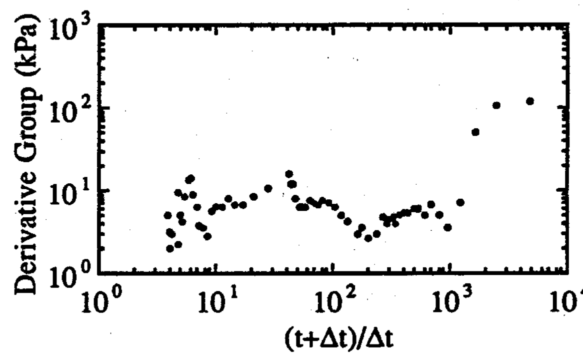

Figure 13. Pressure derivative plot of buildup No. 1.

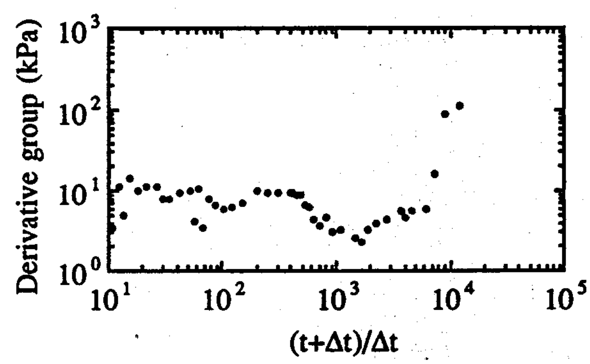

Figure 14. Pressure derivative plot of buildup No. 2.

the derivative following the initial period (indicative of a double-porosity formation), and a near-constant value of the derivative at later times (for buildup No. 2 only, Fig. 14). The noise in the derivative plot of buildup No. 1 (Fig. 13) makes it difficult to recognize significant patterns at the end of the recovery. Based on the patterns identified in the semi-log and pressure derivative plots WES recognizes two reservoir models that are consistent with pressure buildups No. 1 and 2.

The reservoir models chosen for both buildups are: (1) homogeneous reservoir with a linear sealed boundary and (2) double-porosity reservoir with no boundaries. WES identified the model "homogeneous reservoir with a sealed linear boundary" because it recognized two straight lines on the semi-log plot, with the later slope being twice the value of the earlier one (see Fig. 15). The double porosity model was identified from the valley that separated two constant-value straight lines on the pressure derivative plot (see Fig. 13). Note that these interpretations are possible even though there is considerable noise in the data, particularly on the pressure derivative plot. Selection of multiple models is desirable to ensure that the correct model is amongst the list of choices. Following model selection, WES provides numerical estimates of the parameters for each model identified using one or more of the three analysis techniques described previously (e.g., k, s, ω, λ, C).

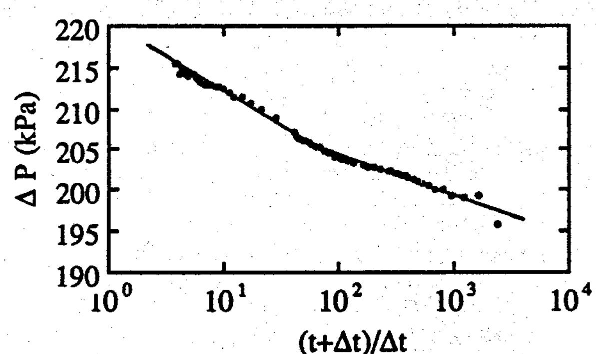

Figure 15. Plot showing two semi-log straight lines in buildup No. 1. The slope of the second semi-log straight line is twice that of the first straight line, indicating the possible presence of a sealed linear boundary.

Parameter estimates for k and s for pressure buildups No. 1 and No. 2 are provided in Table 3. Values listed were obtained from the automatic fitting routine. Double porosity parameters, λ and ω, obtained from curve-fits such as shown in Fig. 16 are $3{\cdot}10^{-8}$ and 0.2, respectively. Previous estimates of the k and s obtained using conventional Horner analysis are included in Table 3 for comparison (Benson, 1982). Note that in the earlier analysis the formation was assumed to be homogeneous and infinite (e.g., the double-porosity nature of the formation and/or the sealed boundary was not identified). The reservoir kh was calculated from the slope of the last semi-log straight line on both of the Horner plots.

As shown in Table 3, k and s for the cases where the reservoir is assumed to be infinite are in good agreement, regardless of whether or not the double-porosity nature of the reservoir is recognized. The model that includes a sealed boundary yields k values twice as high as the other methods, and skin factors from 2 to 3 times higher. Based on reevaluation of this test data, particularly the pressure derivative plots (which were not in use in 1982), the double-porosity, infinite

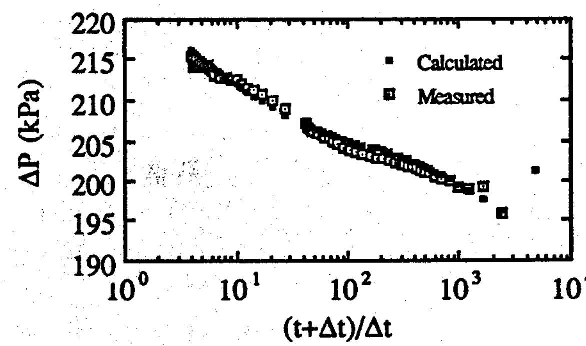

Figure 16. Match of calculated and measured pressure for a double-porosity model for buildup No. 1.

reservoir model seems to be most appropriate. WES appears to have provided a satisfactory interpretation of these tests and provided estimates of k and s nearly equal to those published previously (Benson, 1982). Moreover, by combining the most up-to-date analysis methods with conventional ones, a more thorough analysis of these data were possible, resulting in extracting even more information from the tests than was done previously.

Table 3. Parameter Estimates for Buildups No. 1 and No. 2.

Test	Reservoir Model	kh (m^3)	s
1	double-porosity, infinite	$2.0{\cdot}10^{-10}$	21
1	homogeneous, sealed	$4.2{\cdot}10^{-10}$	50
1	homogeneous*·infinite	$2.4{\cdot}10^{-10}$	24
2	double-porosity, infinite	$2.0{\cdot}10^{-10}$	20
2	homogeneous, sealed	$5.6{\cdot}10^{-10}$	64
2	homogeneous*·infinite	$2.4{\cdot}10^{-10}$	21

* From previous analysis (Benson, 1982).

Commentary

Expert systems will play an increasingly important role in carrying out routine and semi-routine tasks that rely on a combination of expertise and data synthesis. This paper has presented an example of such a system, applied for the purpose of geothermal well test analysis. The expert system described and used here, WES, was developed for the purpose of evaluating the role that expert systems can play in earth science related tasks. The challenge that became apparent almost immediately was the need for the expert system to deal with less-than-perfect quality data, incomplete data, and non-uniqueness. In dealing with these difficulties we attempted to develop a system that mimicked the way human experts manage these problems, that is, (1) by picking out the major features in the test data, (2) by having an open mind about the range of models consistent with these major features, (3) by having a broad and deep knowledge base, (4) by using redundant methods where ever possible, from rules-of-thumb to the most sophisticated mathematics, and (5) by double-checking each step in the procedure. This simple philosophy was embedded into each of the tasks that WES carries out: processing and graphical representation of the data; pattern recognition; model selection; and parameter estimation. To the extent that WES has satisfactorily been able to analyze all of the tests put to it, including the geothermal well tests described in this paper, WES is a success. However, as with human experts, we can easily foresee the time when it will fail. So, like the human expert, the expert system must continue to improve its knowledge base and learn (or be taught) from its mistakes. The expert systems of the future will make WES look very simple-minded indeed.

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