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RESERVOIR RESPONSE TO TIDAL AND BAROMETRIC EFFECTS

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ABSTRACT

Solid earth tidal strain and surface loading due to fluctuations in barometric pressure have the effect, although extremely minute, of dilating or contracting the effective pore volume in a porous reservoir. If a well intersects the formation, the change in pore pressure can be measured with sensitive quartz pressure gauges. Mathematical models of the relevant fluid dynamics of the well-reservoir system have been generated and tested against conventional well pumping results or core data at the Salton Sea Geothermal Field (SSGF), California and at the Raft River, Geothermal Field (RRGF), Idaho. Porosity-total compressibility product evaluation based on tidal strain response compares favorably with results based on conventional pumping techniques. Analysis of reservoir response to barometric loading using Auto Regressive Integrated Moving Average (ARIMA) stochastic modeling appears also to have potential use for the evaluation of reservoir parameters.

INTRODUCTION

Evaluation of in situ reservoir elastic and hydraulic parameters, for example porosity-total compressibility product (ϕC_t) and permeability-thickness product (kL), requires that the fluid pressure within the reservoir be perturbed from its equilibrium state. This is typically carried out by some form of well pumping test, either by fluid injection or production, at single or multiple well ports to the reservoir. Elastic and hydraulic parameters are then estimated by interpreting the pressure response of the reservoir under nonequilibrium conditions in terms of an appropriate idealized physical model of the well-reservoir system. Historically, the effects of tidal strain and barometric pressure on the well pressure response have been classified as "noise contamination" when observed during conventional well testing. However, these small pressure fluctuations also reflect deviations of the reservoir from an equilibrium condition due to a measurable driving force (for the case of barometric pressure) or due to an estimable driving force (for the case of tidal strain). The measured pressure response from these two effects can be interpreted in terms of an appropriate well-reservoir model with the potential of extracting useful information about the reservoir. Such an approach complements conventional well testing on several points: (1) fluid production or injection is not necessary and therefore the data interpretation is not complicated by the problem of temperature dependent fluid viscosity and pressure effects, (2) the fluid flow within the reservoir is very small and turbulence which commonly occurs in fractured producing zones during conventional pump tests is unlikely, and (3) data acquisition is very simple and requires minimal downhole and surface equipment. Hence, these methods are intrinsically cost-effective.

The University of California Lawrence Livermore Laboratory Geothermal Program has initiated a project for FY 80-81 directed at investigating the potential application of tidal and barometric reservoir response evaluation for estimating in situ reservoir parameters. Downhole and wellhead pressure data from five wells at RRGF and two wells at SSGF have been or are in the process of being analyzed and some preliminary results are presented here.

WELL-RESERVOIR MODELS

At least three different approaches to the analysis of tidal strain effects on a confined aquifer have been proposed in the literature. Bredehoeft (1967) presents a simple model based on the assumption that the reservoir permeability is sufficiently large so that frictional effects can be ignored. With this approximation, a value of reservoir storage coefficient can be obtained on the assumption that the tidal dilatation can be estimated. A more general model, proposed by Bodvarsson (1970), allows for an arbitrary permeability. For the limiting case of high permeability, Bodvarsson's model reproduces that of Bredehoeft's. The most recent model for aquifer response has been proposed by Kanehiro (1979) and is directed primarily toward the analysis of reservoir pressure response for the case of a shut-in well. The latter study assumes that the well-reservoir system with a shut-in or packed off well can be classified as a purely undrained system and an expression for the storage coefficient is subsequently derived. The assumption of a purely undrained system under the stated restrictions violates the principle of conservation of mass for the general case of a compressible reservoir fluid. A reservoir undergoing an imposed strain or imposed confining stress, which is intersected by a well (either open or shut-in) does not strictly fall into either the drained or undrained categories. However, if the permeability of the reservoir is sufficiently large and the well is shut-in, the assumption that the system is undrained is very good.

We have followed Bodvarsson's (1970) approach to reservoir response modeling by retaining a finite permeability and solving the complete dynamic equations. The problem has been cast in terms of Biot's (1941) pore pressure-stress-strain formulation and the resulting pore pressure diffusion equation has been solved with the attached well-reservoir interface boundary condition. The solutions thus obtained allow for either an imposed stress (useful for the barometric loading problem) or an imposed strain (useful for the tidal dilatation problem), a compressible pore fluid, and a variety of well completion situations including shut-in, open, or shut-in with a gas cap. All of the models are analytic and assume that a cylindrical well penetrates an isotropic and homogeneous confined aquifer. In this manner, it has been a simple task to compare the tidal or barometric models to conventional well testing models (Earlougher, 1977) to see similarities and differences between the two approaches.

The well pressure response, for both the applied stress and applied strain models, at a particular frequency takes the general form:

$$p = \frac{T}{1 + T} X \qquad (1)$$

where p is the well fluid pressure perturbation (system output), X is the appropriate driving force (system input), and T is a complex (i.e. defined in the complex plane) function depending on the permeability-thickness product, frequency, hydraulic diffusivity, and well completion configuration. X depends on the storage coefficient and either tidal dilatation or barometric pressure, depending on the type of analysis under consideration. The term T/(1+T) can be considered the system "transfer function". Since the tidal spectrum consists of a set of discrete frequencies (e.g. diurnal, semidiurnal, etc.), equation (1) can be used directly, in conjunction with appropriate spectral analysis signal processing, to obtain values of the reservoir parameters. The barometric pressure fluctuations and the resulting reservoir pressure response, on the other hand, are typically continuous spectra, and equation (1) is not directly appropriate for extracting information. We have found that a transformation of equation (1) from the frequency domain to the time domain and then analyzing the result in terms of a stochastic model seems to be a useful approach. The ARIMA class of stochastic models seem ideally suited for this procedure (Box and Jenkins, 1976).

RESULTS

A. Tidal strain induced pressure response at Elmore 3, SSGF.

Approximately 660 hours of downhole pressure data taken during the interval 5/23/78 - 6/20/78 and sampled every 10 minutes at Elmore 3 in the Salton Sea Geothermal Field were analyzed for tidal strain response. A Paroscientific quartz pressure gauge, having a resolution of 10^{-2} psi, was used to obtain the data. The well was shut-in and the pressure gauge was suspended approximately 100 feet below the water level. A 50 foot gas cap occupied the space between the water level in the well and the wellhead. Using data filtering and least-squares spectral analysis methods, a large signal contamination at the K_1 tide was easily observed, corresponding to the heating and subsequent expansion of the gas cap at a 24 hour (daily) period. Consequently, this frequency was discarded from further analysis. Four other tidal frequencies, corresponding to the O_1 (diurnal lunar), N_2 and M_2 (semidiurnal lunar), and S_2 (semidiurnal solar) tides, were easily resolved at a 90% confidence level. These tides had no measurable contamination from temperature effects. The M_2 tide, having the smallest estimated uncertainty, was used in the subsequent reservoir parameter calculations. Figure 1 shows the calculated value of C_p + C_f for Elmore 3, where C_p is the pore compressibility and C_f is the formation compressibility. These compressibilities are defined (Chilingarian and Wolf, 1975) as follows:

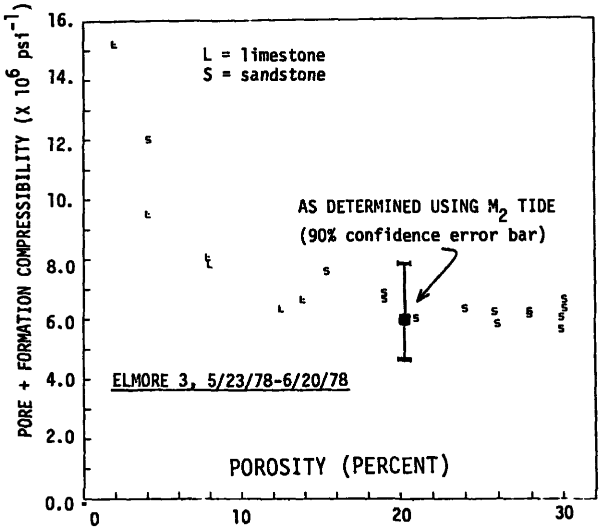

Figure 1. Comparison of C_p + C_f between core tests (Hall, 1953) and tidal evaluation.

$$C_p = -\frac{1}{V_p}\frac{\partial V_p}{\partial \sigma}\bigg|_p , \quad C_f = \frac{1}{V_p}\frac{\partial V_p}{\partial p}\bigg|_\sigma$$

where V_p is pore volume and σ is confining stress. The porosity of the predominantly sandstone reservoir formation was taken to be 20% (Tewhey, 1977). Unfortunately, no core compressibility data from this reservoir was available for comparison. The compressibility information derived from pump tests on nearby wells was of such an uncertain nature (Morse and Stone, 1979) that we resorted to using "typical" compressibilities of similar rock types for a comparison with the tidal method. Superimposed on figure 1 are the values of $C_p + C_f$ for limestones and sandstones with varying porosities. These measurements were derived on the basis of core testing (Hall, 1953) from a variety of different reservoirs. The estimates of $C_p + C_f$ based on tidal analysis is seen to be quite consistent with representative core data.

B. Tidal strain induced pressure response at RRGI-7, Raft River

Two data sets, representing the intervals 3/24/79 4/9/79 and 5/1/79 - 6/1/79, were analyzed for tidal strain response. In both cases, the well was shut-in with positive wellhead pressure. The pressure was sampled every hour at the wellhead using a Paroscientific quartz pressure guage. Figure 2 shows $\phi C_t/\alpha$ evaluated for all tidal components resolved at the 90% confidence level which also exhibited no temperature effect contamination. α is a rock parameter relating the change in pore volume to the rock dilatation (Nur and Byerlee, 1971). For loosely bound rock and soils, α is unity to good approximation. For crystalline rocks, alpha can vary between approximately 1/2 and 1. As is evident from figure 2, there is good consistency between the independent $\phi C_t/\alpha$ estimates at different tidal frequencies as well as consistency between the two data sets. Conventional well pumping tests (injectivity) were performed on RRGI-7 during August and November of 1978 (Ahmed et al., 1978) and these results are compared with the averages of the tidal analysis results in Table 1. The tidal response analysis is consistent with the conventional well pumping tests and the differences between the two can be accounted for by a value of α not equal to unity.

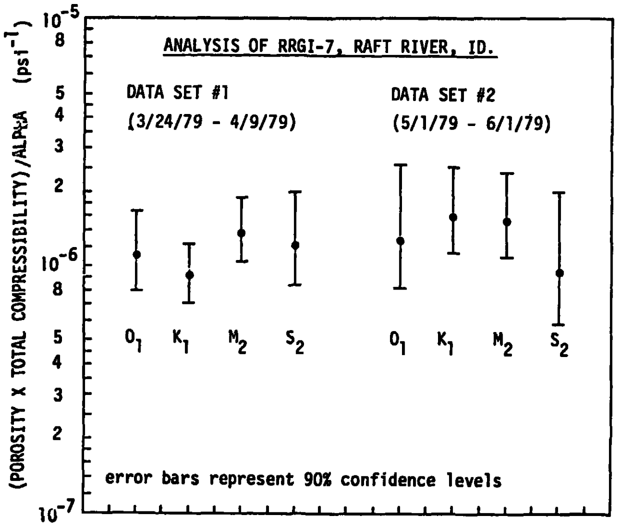

Figure. 2. Computed $\phi C_t/\alpha$ using tidal analysis for two data sets at RRGI-7.

C. Barometric pressure response at RRGI-7

During the period 3/24/79 - 4/9/79, the injection well RRGI-7 at Raft River was serving as a moniter well in a long term pump test. After removing the effects of the pump test from the data by detrending and then removing the tidal strain response by a least-squares spectral analysis method, the wellhead pressure was found to still contain a significant fluctuation. When compared with barometric pressure recorded over the same time period at the Pocatello Airport, the nearest station to Raft River that records weather information on a 24 hour basis, a remarkable correlation was observed (see figure 3). Such a correlation has been noted many times in the literature and we have observed a similar correlation at other wells at Raft River. Analysis of barometric response of a reservoir using a stochastic modeling approach is currently in progress. We are evaluating the system transfer function T/(1+T) by applying an ARIMA stochastic model to the input (barometric

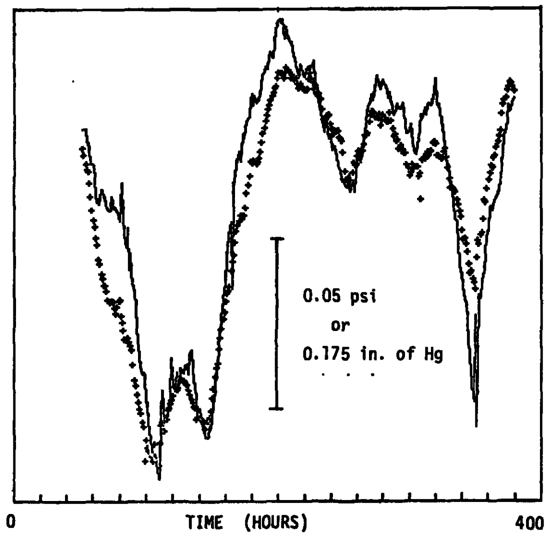

Figure 3. Correlation between barometric pressure and well-head pressure at RRGI-7. Solid line is barometric pressure (inches of mercury) recorded at Pocatello Idaho. Pluses are measured wellhead pressure (psi).

Table 1. Comparison of tidal method with conventional method

Well	Tidal $(\phi C_t/\alpha)$	Conventional (ϕC_t)
RRGI-7 (data set #1)	1.16×10^{-6} psi^{-1} (average)	0.82×10^{-6} psi^{-1}
RRGI-7 (data set #2)	1.33×10^{-6} psi^{-1}	0.82×10^{-6} psi^{-1}

pressure) and output (well fluid pressure) of the system. Results of this modeling effort are in such a preliminary state at present as to preclude their presentation here. However, the results obtained to date indicate that such an approach may be very productive. This is a consequence of the fact that, unlike solid earth tidal strain, barometric pressure is a broad-band driving force and as such may allow for the evaluation of frictional effects (e.g. kL) at the higher frequencies where these effects are typically manifested.

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