TIDAL PRESSURE RESPONSE WELL TESTING AT THE SALTON SEA GEOTHERMAL FIELD, CALIFORNIA, AND RAFT RIVER, IDAHO

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The use of tidal strain induced well pressure fluctuations for the estimation of reservoir elastic and hydraulic characteristics of single-phase fluid confined aquifers has received considerable attention over the past decade.[1-6] Well-aquifer models used in these investigations fall basically into two categories, the "static" solution proposed by Bredehoeft[1] and the "dynamic" solution proposed by Bodvarsson.[2] In the limit of very large transmissivity, the dynamic solution becomes identical to the static solution. The estimation of site-specific values for the storage coefficient and formation porosity has been carried out in several instances.[1,3,6] In most of these cases, however, little or no information on the values of these parameters as determined by conventional methods was available to compare with the tidal results in order to test the model. We are currently analyzing the tidal pressure response at two wells, Elmore 3 and Sinclair 3, at the Salton Sea Geothermal Field (SSGF) in California. Considerable geophysical and geological information in addition to conventional well testing results is available for this area. We hope to use these data to more rigorously test existing tidal response models. This paper presents some preliminary results of the estimation of the effective compressibility of the reservoir rock at Elmore 3.

In addition to the work outlined above, we are also investigating the possibility of using tidal pressure response to better understand the nature of the geothermal resource at Raft River, Idaho. This system is structurally complex, and existing models for tidal response of homogeneous and isotropic aquifers are not applicable. Work is currently in progress on defining an appropriate model for this system. We have analyzed records from six wells at Raft River: RRGE-1, RRGE-2, RRGE-3, RRGE-4, RRGI-6, and RRGI-7. The tidal admittance has been calculated for these wells and the results are presented here.

Well-Reservoir Model for a Single-Phase Homogeneous and Isotropic Aquifer

A cylindrical well penetrates a confined homogeneous and isotropic aquifer of infinite extent. The equation governing the fluid perturbation pressure p in the reservoir rock due to tidal strain is given by

$$\nabla^2 p - \frac{1}{a}\partial_t p = \frac{\alpha}{aC}\partial_t b \qquad (1)$$

where C is the effective compressibility[7] of the formation and $a = k/(\nu\rho C)$ is the hydraulic diffusivity. k, ν, and ρ are permeability, kinematic viscosity, and fluid density, respectively. The tidal dilatation b is considered spatially constant, and α is an empirical constant depending on the effective and grain bulk moduli of the rock.[8] For loosely bound formations, $\alpha \simeq 1$. The boundary condition at the well-reservoir interface for an open well system takes the form

$$\partial_t p = \frac{2g\rho T}{r_w}\partial r p \qquad (2)$$

where g and r_w are the acceleration due to gravity and well radius, respectively. $T = kL/\mu$ is the formation transmissivity, where L and μ are the completion interval length and absolute viscosity, respectively. Rigorous derivations of equations (1) and (2) are given elsewhere.[2]

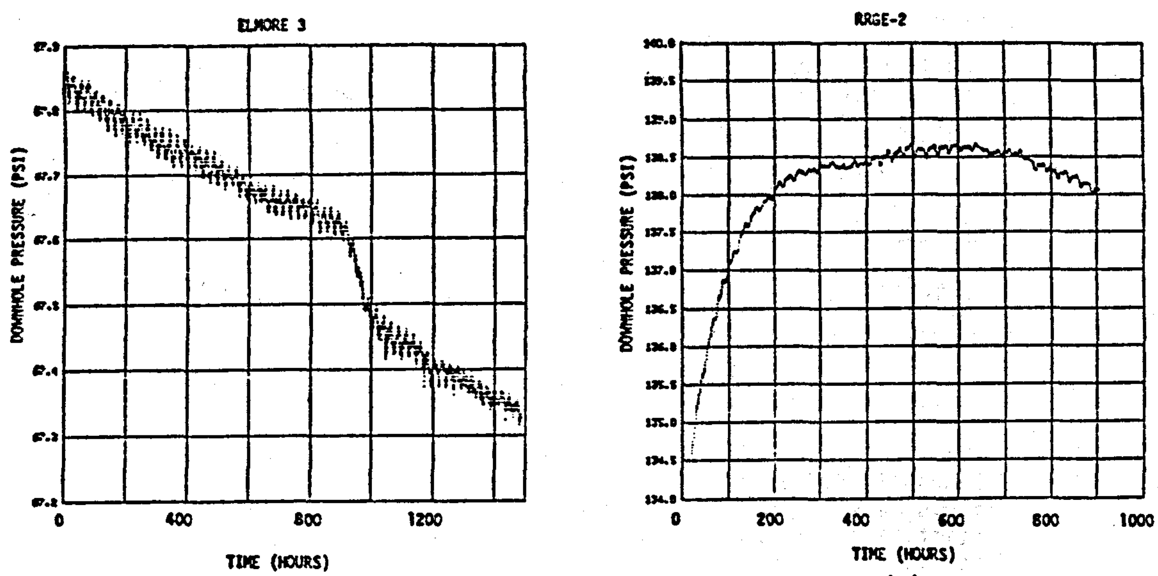
Assuming an oscillatory tidal strain of the form $b = b_0 \exp(i\omega t)$, the solution of equations (1) and (2), evaluated at the well is given by

$$p(r_w,t) = -\frac{\alpha b_0}{C}\cos(\phi)e^{i(\omega t - \phi)} \qquad (3)$$

where $\phi = \tan^{-1}(\omega/\beta)$ and $\beta = 2g\rho T/(r_w)^2$. The assumption that $\omega r_w^2/a \ll 1$ has been made in equation (3). This assumption has been shown[2] to be very good for most cases involving tidal frequencies. The tidal dilatation amplitude b_0 can be approximated by the relation $b_0 = 0.5W_2/(r_e g)$, where W_2 is the tidal potential and r_e is the radius of the earth.[1] This relation makes the assumption that Poisson's ratio σ and the whole earth Love numbers $\bar{h}$ and $\bar{l}$ are representative of the reservoir. This approximation has previously been used to estimate local tidal dilatation[1,3,6] but should be used with care in view of recent work regarding the effect of local inhomogeneities in the elastic properties of the earth's crust.[9]

Detrending, Spectral Analysis, and Error Estimation

Most of the tidal pressure response records were taken during periods when nearby wells were undergoing conventional well testing. In addition, long period pressure fluctuations, probably due to air mass movement, were present on the records. As a result, pressure excursions of a non-tidal origin were superimposed on the records (see Fig. 1). Most of these unwanted signals were eliminated by appropriate polynomial regression detrending and optimal high-pass filtering.[10]



(a) (b)

Figure 1. Tidal pressure response records from Elmore 3, SSGF, for the period 5/23/78-7/23/78, and RRGE-2, Raft River, for the peiod 11/20/77-12/27/77. The Geothermal Loop Experimental Facility (GLEF) began testing roughly 900 hours into the Elmore 3 record, resulting in the observed pressure excursion.

The least-squares best estimate of the detrended pressure response was then evaluated at six tidal frequencies: O_1 and K_1 in the diurnal band, N_2, M_2, and S_2 in the semidiurnal band, and M_3 in the terdiurnal band. Estimates of error in pressure response amplitude and phase at these frequencies were made based on the assumption that the noise in the signal was a stationary ergodic time series with uniform energy density (i.e., "white"). With this assumption, variances in the real and imaginary parts of each spectral line estimate can be computed. If the additional assumption is made that the real and imaginary parts of the estimates obey a bivariate normal distribution, confidence bounds can then be placed on the line amplitude and phase. A Fisher statistics test[11] was also applied to the detrended data to determine which spectral lines were significant at a given confidence level.

An identical procedure to that outlined above was applied to the theoretical tidal gravity signal over the same time intervals as the well pressure records.

Estimation of Effective Reservoir Compressibility at Elmore 3, SSGF

A pressure response record taken at Elmore 3 between 5/23/78 and 6/20/78 was analyzed according to the procedure outlined above. The record was 660 hours long sampled every 10 minutes by a Parascientific quartz gauge suspended from the wellhead (see Fig. 1a). The tidal admittance $\Delta p/\Delta g$, where Δg is the tidal gravity perturbation, was evaluated for all spectral lines deemed significant at the 90% confidence level by the Fisher test (see Fig. 3a). The solar tide K_1 shows a large amplitude excursion relative to the lunar tide O_1, suggesting that K_1 was contaminated by either barometric and/or temperature effects. The K_1 tide was therefore discarded in the subsequent analysis. Well logs indicate that the producing zones in Elmore 3 consist of coarse to medium grained sands of roughly 20-30% porosity. We therefore set $\alpha = 1$ in equation (3). No phase shift ϕ was seen on lines O_1, N_2, M_2, and S_2 at the 90% confidence level. We therefore set $\phi = 0$ in equation (3). A phase shift of 60°, significant at well above the 90% confidence level, was observed on K_1, lending further evidence for contamination at this tidal frequency. With the above observations, the effective compressibility is given by

$$C = b_0/|p| \tag{4}$$

Figure 2 shows the calculated reservoir effective compressibility, with 90% confidence error bars, based on equation (4). The numerical values are 6.33×10^{-6}, 2.75×10^{-6}, 6.44×10^{-6}, and $7.71 \times 10^{-6} psi^{-1}$, corresponding to the O_1, N_2, M_2, and S_2 tides, respectively. It is seen from this figure that all of the computed compressibilities, with the exception of the N_2 line, are greater than those evaluated from static compression tests of saturated sandstones with 20-30% porosity[12] (line b). This may be a result of increased compressibility due to fractures not seen in samples the size of cores. Conventional well testing results suggest that the reservoir is indeed fractured.[13] Also shown on this figure is a theoretical upper bound on reservoir compressibility (line a) evaluated on the basis of depth-porosity logs at the SSGF.[14]

Evaluation of Tidal Admittance at Raft River, Idaho

A total of seven records taken from archived data covering the time period of 9/29/75 to 6/1/79 was analyzed for the presence of tidal pressure response. Six wells, RRGE-1, RRGE-2, RRGE-3, RRGE-4, RRGI-6, and RRGI-7, were represented in the records. The longest record, that taken between 11/20/77 and 12/27/77 at RRGE-2, is given in Fig. 1b. Detrending, spectral analysis, and error estimation as

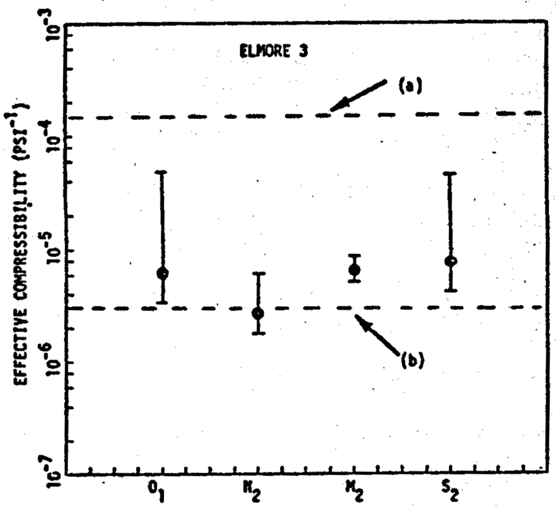


Figure 2. Calculated effective compressibilities of the reservoir rock at Elmore 3 at four tidal frequencies. 90% confidence error bars are given. (a) Theoretical upper bound.[14] (b) Static compression tests on saturated sandstone.[12]

described above were applied to the data and to the corresponding theoretical gravity over the same time periods to evaluate the tidal admittances. Figures 3b-h show the computed tidal admittances for the various wells for those spectral frequencies that were, according to the Fisher test, significant at the 90% confidence level. The uncertainty in the tidal admittances is reflected in the 90% confidence error bars.

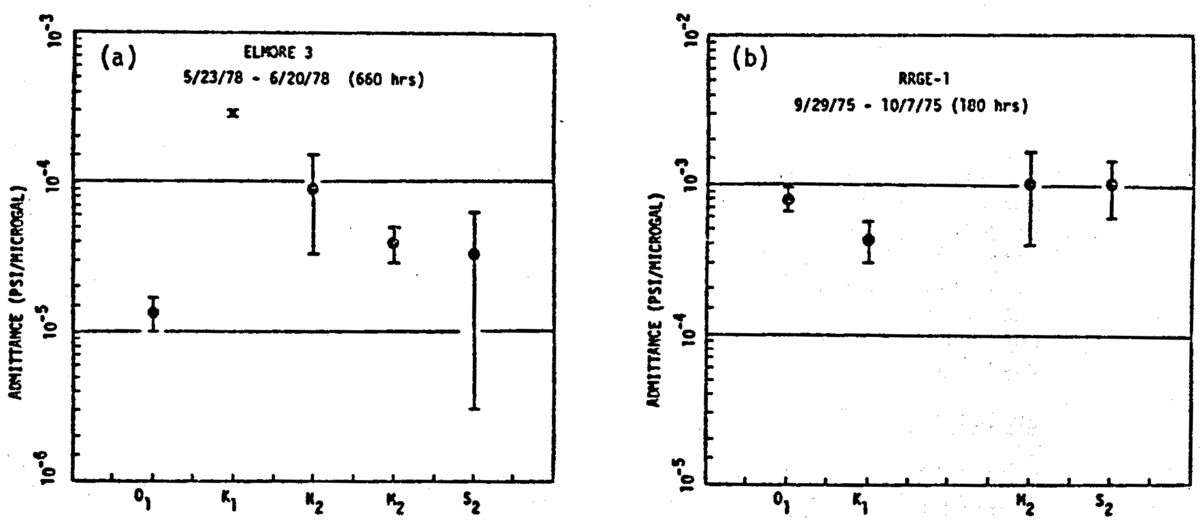


Figure 3 (a,b). Tidal admittances of Elmore 3 and RRGE-1. Error bars represent 90% confidence levels.

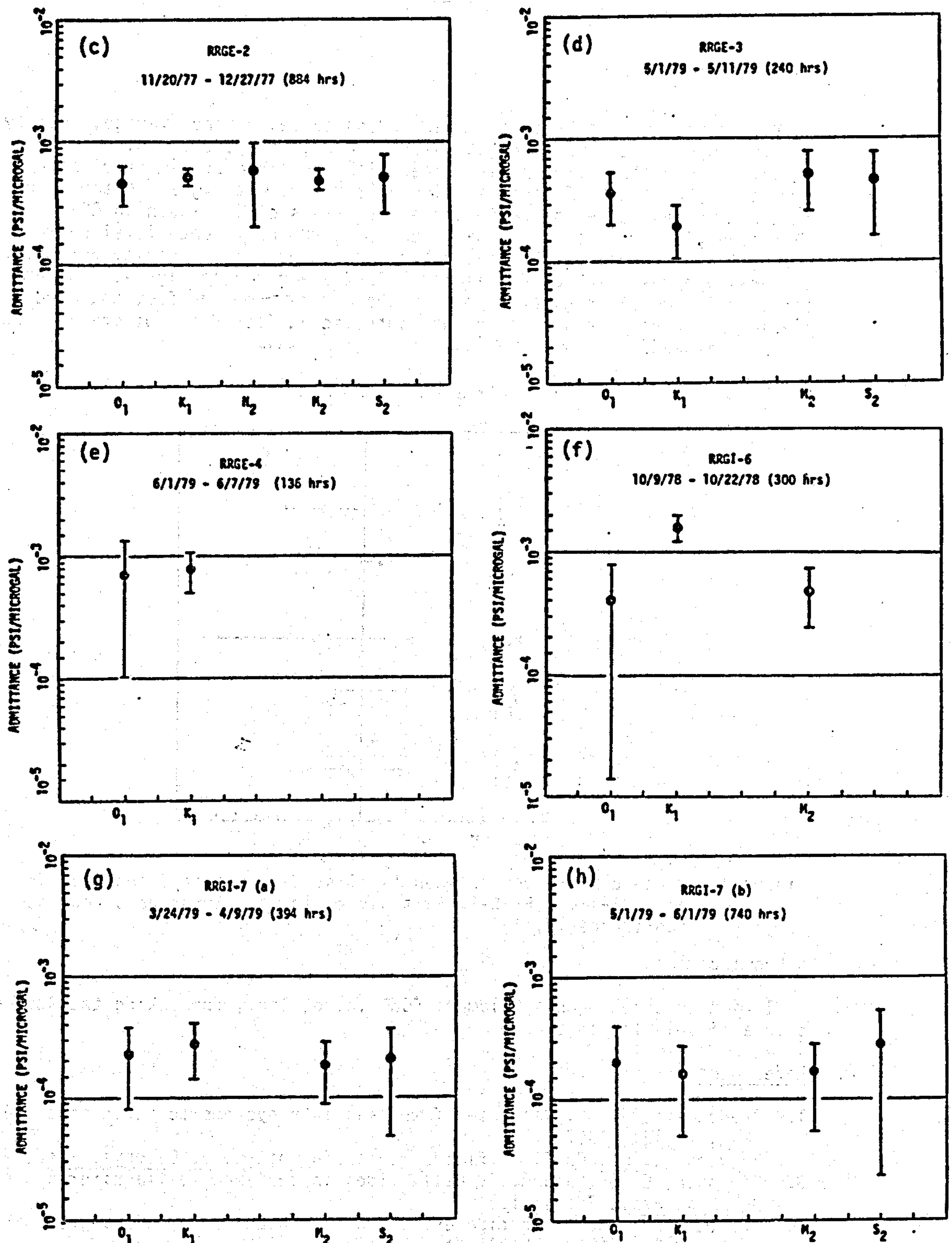


Figure 3 (c-h). Tidal admittances of RRGE-2, RRGE-3, RRGE-4, RKGI-6, and RRGI-7. Error bars represent 90% confidence levels.

The admittances at Raft River were found to be, on the average, roughly an order of magnitude larger than for that of Elmore 3 in the SSGF. This may be due in part to an enhanced tidal strain associated with the close proximity of a major fracture zone(s). The effect of contamination of the pressure signal in the diurnal energy band by barometric and/or temperature effects is clearly seen in RRGE-1 and RRGI-6, where the tidal admittance is different at a 90% confidence level between the O_1 and K_1 lines. Phase differences between the theoretical gravity perturbation and the pressure response for RRGE-1 and RRGE-2 are given in Fig. 4. The presence of structural control is clearly seen in these data from the fact that the tidal pressure response for a homogeneous isotropic aquifer does not predict the negative lag seen in RRGE-1.

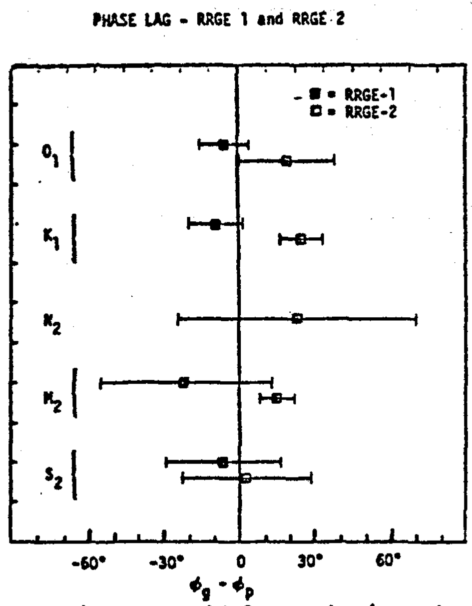


Figure 4. Phase differences between tidal strain (gravity) and pressure response at RRGE-1 and RRGE-2, Raft River, Idaho. Error bars represent 90% confidence level.

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