A FIELD EXAMPLE OF FREE SURFACE TESTING

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Introduction

Theoretical results on free liquid surface dynamics presented by Bodvarsson (1978, this volume), provide the basis for a technique of reservoir probing and testing which can yield results that are supplementary to conventional well testing data. The Laugarnes geothermal area in Iceland which is one of the sources of the Reykjavik District Heating System is a case where both methods are applicable and appear, interestingly, to yield quite different results. A brief account of the free surface results will be presented below.

The Laugarnes geothermal source area

The Laugarnes geothermal area (see Fig. 1) has been described in some detail by Thorsteinsson and Eliasson (1970). The active reservoir underlies an area of 5 km^2 within the city of Reykjavik and has a base temperature about 145°C. The reservoir is embedded in a flood basalt series of more than 3 km thickness. Fluid conductivity is mainly along the contacts of lava beds and up through dikes and fracture zones. Evidently, the permeability is quite heterogeneous and anisotropic.

Several dozen production wells have been drilled in the area during the past decades. The maximum depth is now of the order of 3 km. The productivity of individual wells obtained with the help of submerged pumps placed at depths up to 100 meters varies from 1 to 50 kg/s with well-head temperatures mostly in the range of 125°C to 135°C. The main production is obtained from an aquifer extending between the depths of 730 and 1250 meters. The pumping load is governed by the demand on the heating system during the course of the annual cycle and varies from about 100 to 300 kg/s. As a consequence of the varying production rate, the elevation of the piezometric surface fluctuates in a quasi-periodic way with the year as a basic period. Thorsteinsson and Eliasson (1970) have during the period 1965 to the end of 1969, collected a considerable amount of water level data from 60 observation wells in the area. Fig. 2 gives an example of their water level data on a day in November of 1967. Moreover, Fig. 3 illustrates the relation between the integrated production rate and the water levels as observed in two centrally located wells. These data furnish a quite interesting picture of the hydrological characteristics of the reservoir.

Very few quantitative data are available on the permeability and porosity characteristics of the Laugarnes reservoir. Using conventional well interference test techniques in field experiments of 10 to 20 hours duration, Thorsteinsson and Eliasson (1970) have estimated the permeability of the. reservoir to be of the order of 10 darcys.

Bodvarsson (1975) arrived on the basis of water level recovery data from one well at a permeability value of a few darcy. No results were obtained on the porosity but field observations on outcrops indicate very low values, perhaps a few parts per thousand.

Relevant theoretical results presented by Bodvarsson (1977a & b, 1978) permit an analysis and interpretation of the available observational data in terms of estimates of the more global permeability and porosity characteristics of the reservoir. Two different procedures are available for carrying out this analysis, namely, 1) the production data can be taken to represent a periodic process with an approximately sinusoidal input/output, or 2) short sections of the graphs can be analyzed individually as independent processes.

On the first approach, input-output amplitude and phase relations for the annual cycle can be estimated with the help of the production rate and water level data in Fig. 3. Unfortunately, the present observational material is deficient in that the peak-to-peak input-output phase lags are small and quite poorly defined. Nevertheless, on the available data, estimates of roughly 1.5 months equivalent to a phase angle of 45 degrees are indicated.

Carrying out a numerical evaluation of the complex integral for the frequency response as given by equation (13) in the paper by Bodvarsson (1978 , this volume) for the case of various values of the sinking velocity parameter w, and comparing the results with the observational data, we obtain on the basis of the phase difference a best fit for a value of $w = 4 \times 10^{-4}$m/s. With the help of the amplitude ratio, permeability estimates of roughly 10 millidarcy and porosity estimates of 10^{-3} are obtained.

An alternative approach to the periodic input/output data based on a simple lumped system model is discussed in the Appendix. The resulting estimates of the permeability and porosity are of the same order of magnitude as the data given above.

On the individual event analysis of the water level responses to the changes in the production rates, we obtain quite similar results. The theory is based on the following results by Bodvarsson (1977b) for the response of the free water surface to sinks at depth in homogeneous and isotropic Darcy type solids. First, let the initial free surface be at equilibrium and a point-sink of volume rate V be placed at the depth d and start production at $t = 0$. The initial rate of drawdown of the free surface vertically above the sink is then

$$u = V/2\pi\phi d^2 \tag{1}$$

where ϕ is the porosity. Moreover, let k be the permeability of the solid, ν the kinematic viscosity of the fluid and therefore $c = k/\nu$ the fluid conductivity. The long term stationary value of the free surface drawdown vertically above the sink is then found to be

$$h_s = V/2\pi gcd \tag{2}$$

where g is the acceleration of gravity.

We apply these results to the production event from September 1968 to March 1969 and assume that the point source model can give reasonable estimates of the parameters of interest. During the event in question, the flow rate was increased quite abruptly from 2.5 to $7 \times 10^5 m^3/month$, that is, by about 0.17 m^3/s. To correct for local precipitation we assume that the increased input flow to the local reservoir is'0.15 m^3/s. From the initial slope of the water level graph given in Fig. 3, we derive an initial rate of drawdown in response to the increased production of $u = 1.1 \times 10^{-5} m/s$. Assuming that the production depth is about 10^3 m we find on the basis of equation (1) an estimate of the porosity of about $\phi = 2 \times 10^{-3}$.

Since equilibrium was not approached during the present event, we are unable to apply equation (2) to obtain a numerical estimate of the fluid conductivity c. However, since the graph in Fig. 3 furnishes us with a lower bound h_m for the stationary drawdown h_s, we can convert equation (2) to an inequality

$$c \leq V/2\pi g h_m d \tag{3}$$

and obtain an upper bound for c. Takins on the basis of the graph h_m = 60 m, we obtain the upper bound of 4×10^{-8} s. Assuming the kinematic viscosity to be $3 \times 10^{-7} m^2/s$ (100°C) we obtain that the permeability $k \leq 1.2 \times 10^{-14} m^2$ = 12 millidarcy.

The above estimates of the global permeability turn out to be two to three orders of magnitude lower than the values quoted above as the results of the short-term well interference tests. There appears to be an inverse relation between the time scale of the test signal and the magnitude of the estimate. The longer the time scale, the lower the estimate.

Although a much more elaborate analysis of the Laugarnes data is indicated, the above discrepancies may be quite real and reflect the very considerable heterogeneity and fracturing of the reservoir. Due to local interconnection by fractures, the short-term interference tests performed on adjacent wells give much higher permeability estimates than the more intergrated global values obtained with the help of the total production rate and well data. The result indicates that considerable caution is called for in the interpretation of relatively short-term well interference tests on complex reservoirs.

Appendix

In processing the periodic data, we can also base our estimates on a lumped model as shown in Fig. 4. The model is characterized by a single input conductance K and a single capacitance S. In the physical sense, the capacitance simply represents the effective pore area of the container shown in Fig. 4. Let f be the volume rate produced from the container, h be the average liquid level in the container counted positive down and assuming that the ambient water level is zero, we arrive at the following equation governing the lumped system

$$S(dh/dt) + Kh = f \tag{4}$$

In the case of periodic flow $f = F\exp(i\omega t)$ where F is the amplitude and w the angular frequency. Let the response of the liquid level be $h = H\exp(i(\omega t-\alpha))$, and inserting in equation (4) the resulting output-input amplitude ratio is found to be

$$H/F = (K^2+S^2\omega^2)^{-\frac{1}{2}} \tag{5}$$

and the phase angle

$$\alpha = \tan^{-1}(S\omega/K) \tag{6}$$

From the graphs in Fig. 3, we find that we can on the average take F = 0.07 m^3/s, H = 19m and α = 0.78 radians. Solving equations (2) and (3) for the system parameters we obtain

$$K = 2.7\times10^{-3}m^2/s = 2.5\times10^{-4}Kg/sPa, \quad S = 1.4\times10^4m^2 \tag{7}$$

To translate these results into estimates of the average permeability k and average porosity ϕ we observe that the ground water level depression in Fig. 2 has the shape of a slightly elongated flat disk with an area of approximately A = 4 km^2. For the present purpose we replace this disk by a circular one with a radius R = 1.13 km. On the basis of simple potential theoretical relations (Sunde, 1968), we find that the contact conductance of a flat circular disk of radius R immersed in a porous medium of fluid conductivity c is simply 8cR. In the present case, where the disk is placed on the surface of the half-space the contact conductance is consequently 4cR. Since the value of K given in (4) above is to be taken as an observed value of the actual contact conductance, we obtain the estimate for c as

$$c = K/4R = 2.5\times10^{-4}/4\times1.13\times10^3 = 5.5\times10^{-8}s \quad (8$$

Since $c = k/\nu$ where k is the permeability and ν the kinematic viscosity, and moreover, the porosity $\phi = S/A$, we obtain by assuming $\nu = 3\times10^{-7}m^2/s$ (100°C) the following estimates

$$k = 1.7\times10^{-14}m^2 = 17 \text{ millidarcy and } \phi = 3.5\times10^{-3} \tag{9}$$

which is of the same order of magnitude as the results given above.

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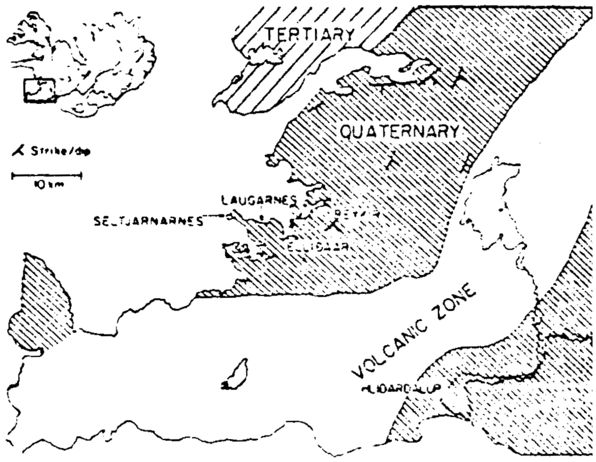

Figure 1. Geological map of southwest Iceland with index map.

From: Tomasson and Thorsteinsson (1976).

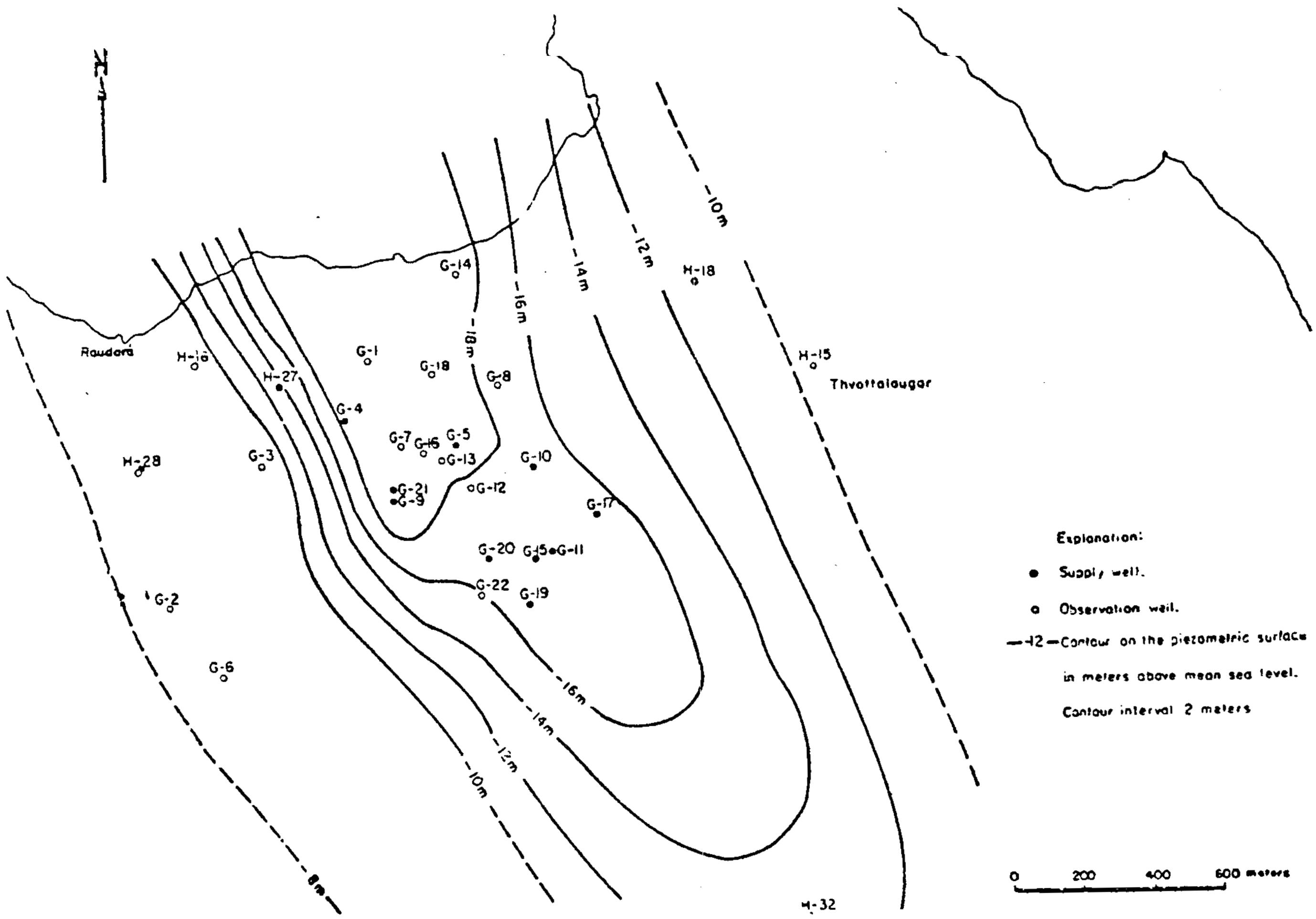

Figure 2. Elevation of the piezometric surface in the Laugarnes hydrothermal system on November 15, 1967.

From: Thorsteinsson and Eliasson (1970).

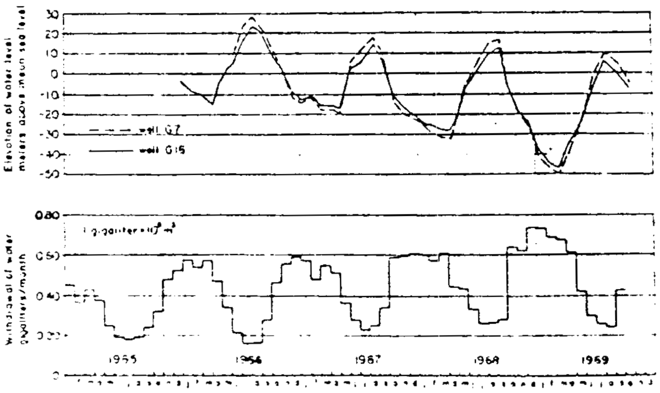

Fig. 3. Hydrographs of well!; G7 and 616 and monthly withdrawals of water from 1965 to 1969.

From: Thorsteinsson and Eliasson (1970).

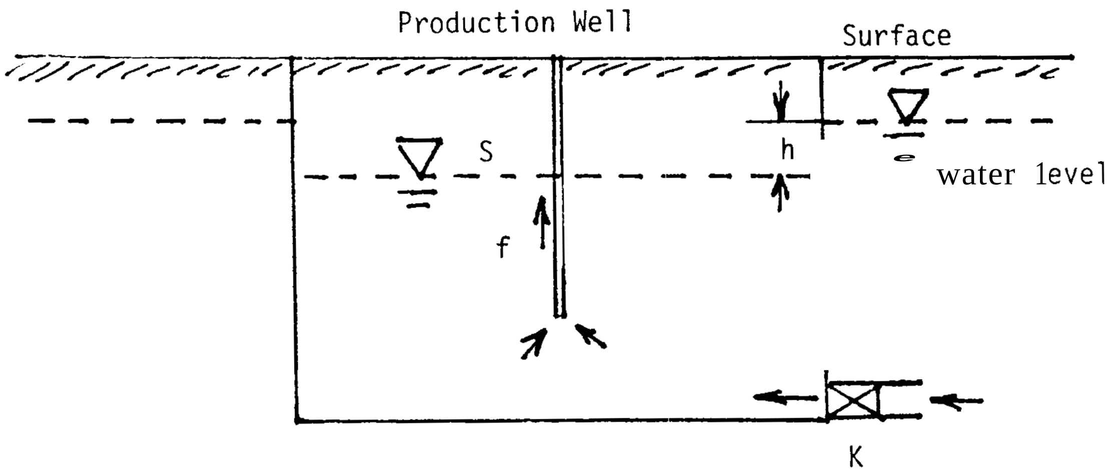

Fig. 4. Lumped model of input conductance K and capacitance S.