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EVALUATION OF SMALL DIAMETER COREHOLES FOR RESERVOIR INFORMATION

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1.0 Introduction

Geothermal exploration has been highly successful to date in locating targets for drilling. However, the requirements for an economically successful geothermal well are both high flow rate and high temperature. Most geophysical and geochemical exploration methods have not been highly accurate in predicting the depth and actual temperature of a reservoir, nor have they been able to locate high permeability zones. The result is that most geothermal exploration is conducted by drilling core holes to better understand the heat flow in an area followed by drilling of production diameter exploration wells which can be flow tested to ascertain the permeability.

The goal of any exploration program is to determine reservoir economics. The cost of wells makes up between one quarter and one half the total cost of producing geothermal power. The number, design, depth of wells and placement of injectors are important to the optimal exploitation of the reservoir. Although early efforts at development have focused on rapid plant construction to begin cash flow, the history of producing fields emphasizes that understanding reservoirs can reduce the risk of rapid temperature or pressure declines and increase the success of step out drilling following initial exploitation. The high cost of large diameter production wells makes the collecting of exploration data on the reservoir through some less expensive method desirable.

Geothermal developers are still drilling resources with surface expression, hot springs and surface mappable fractures and faults. As these obvious resources are developed and as the obvious targets in productive fields are exhausted, new exploration tools are needed. One possibility is the use of deep core holes drilled for temperature gradient data to provide more reservoir information. Two methods not previously applied to geothermal reservoir assessment are suggested to augment other data obtained from coreholes.

2.0 Reservoir Information

To date only a part of the information needed for assessing reservoir economics has been obtainable from narrow diameter core holes. Even deep core holes yielded at most information about lithology, temperature and occasionally if a fluid sample was possible, fluid chemistry.

The information we need most about the reservoir, such as well productivity, reservoir size and storage, hydraulic conductivity and fluid chemistry is obtained by flow testing production diameters wells. Small diameter core holes or stratigraphic wells generally would not flow due to large frictional pressure drops. If slim holes did flow the rates were often to low to stress the reservoir as at Mt. McKushin on Unalaska Island in the Aleutions. Injection yielded some information, but in fractured formations, injectivity can be twice to five times the productivity of the same well due to increased fracture aperture due to thermal contraction of the rock and pressure propping, and due to density related changes in head.

3.0 Retrieving Reservoir Information from Slim Holes

Since coreholes have always been drilled for exploration purposes to obtain temperature logs, heat flow data and lithology, it seems appropriate to obtain as much information as possible from them. The idea of obtaining reservoir information from narrow diameter holes has been neglected due to the lack of success at flowing the wells and the lack of correlation between injection tests and later production. A suite of testing methods is suggested for improving the quantity and quality of reservoir data obtained from coreholes.

4.0 Earthtide and Barometric Induced Pressure Changes in Reservoirs

Earthtides have frequently been suggested as a means of obtaining useful reservoir information through relatively inexpensive passive pressure measurements. Jacob first described the effect of barometric pressure changes on water levels in confined aquifers and developed the mathematics for calculating the storage coefficient from such measurements. Several other researchers have used tidal methods for reservoir analysis over a long period including Bredehoeft (1967), Van der Kamp and Gale (1983), Arditty (1978), Kanehiro (1979) and Axelsson (1980). Hanson describes the collection and analysis of earthtide data from the Raft River geothermal field in his 1984 report for Lawrence Livermore. More recently, Evans, et. al. (1991) used earth tides and barometric fluctuation methods to evaluate permeability and storage coefficients of sands near the Asswan dam in Egypt.

4.1 Parameters

There is some discussion about the parameters which can be evaluated using earth tide and barometric responses in aquifers. The total compressibility thickness product, ϕch or specific storage, S_s can often be calculated more accurately than through flow testing using such methods, particularly if flow test data from a single well test is considered. This can be of some significance in the long term prediction of reservoir behavior since many geothermal reservoirs are in fractured igneous or metamorphic rock with large variation in storage coefficient and which differ to a high degree from the typical sedimentary rocks of petroleum reservoirs or groundwater aquifers. If barometric effects are also considered, the average porosity of the reservoir can also be determined in combination with earth tide analysis (Bredehoeft, 1967).

The gravitational forces acting on the solid earth stress the formation, deforming the pore spaces containing the fluids. The ratio between the predicted tidal stress and the observed fluid level or pressure changes in a borehole is related to the elastic properties of the fluid, the rock and to the porosity of the rock as well as the permeability. Since the tidal stress acts over a very large area, the properties affecting the tidal response in the wellbore are averaged over a broad area.

Hanson (1984) uses the earth tide response of a well in a fractured reservoir with very low permeability in the formation to estimate the fracture direction. The high contrast between the fracture permeability and the formation permeability allows the phase shift and the admittance to vary sufficiently for different tidal periods to calculate the permeability under some circumstances. However, Hanson uses the correlation between the directional predicted stress and the observed phase lag and admittance at different frequencies to calculate fracture direction and dip. Figure 1 shows an example of one step in this method applied to data from a fractured well in the Imperial Valley. Earth tidal stresses normal to planes at various orientations were predicted using tidal software developed by Duncan Agnew (1984, personal communication). The cross correlations between the predicted tides and the observed tides were then calculated until a good match was found. This was then assumed to be the fracture dip and direction. The best match for Britz 3 was found at a strike of N42°E and a dip of 80°. The problem can be computationally reduced by generating a set of equations to be solved by a non-linear least-squares method. Hanson (1984).

4.2 Borehole Diameter Effect

Small borehole diameters, all other factors remaining constant, have the effect of increasing the tidal amplification of the borehole at tidal frequencies. The very small amounts of fluid squeezed from the formation during tidal dilatation result in large water level fluctuations for a small diameter well with a free liquid surface. In a well with a positive shut-in wellhead pressure, the well bore radius has the same effect; however, the effect of the well depth, which is to reduce the amplification, may overwhelm the affect of well radius.

Bredehoeft (1967) shows that the tidal amplification factor (which is comparable to the tidal admittance used by others) for the large permeabilities and borehole diameters less than 10 cm. (4 in.) and depths encountered in geothermal coreholes is always 1 at tidal periods. This makes it impossible to calculate permeability using earth tide analysis, since the permeability (and the transmissivity) are related to the admittance at different tidal periods. However, under special circumstances where either the permeability is low, less than 0.929 cm^2/sec for the very large well bore radius of 30.5 cm. (12 in.) or greater, the tidal admittance or amplification factor varies sufficiently to be useful for calculating the permeability at tidal periods of 12 hours to 24 hours. Hanson's more detailed analysis yields similar results.

4.3 Tool Requirements

Although pressure sensors are available which in heat shields can be left in high temperature wells (500°F) for up to 12 hours, the earth tide and barometric pressure methods require that data be collected over a period of at least two weeks, preferably longer. The pressure responses in deep bore holes are commonly of the order of 0.01 to 0.1 psid. The fact that the difference in pressure or water level is the quantity to be measured makes the resolution and repeatability of the measurement more important than the absolute accuracy of the pressure measured. For this reason it is acceptable to use a system of capillary tubing with an expansion chamber of size at least twice the tubing volume set at depths of 25 m. or greater below the water level in the well. The pressure measurement should be made with a high resolution transducer such as the Paroscientific quartz transducer. Since the absolute pressures are not high, the resolution can be improved by using a transducer with a low pressure range. The system is purged with an inert gas such as nitrogen to reduce corrosion. Helium is not recommended due the difficulty of sealing leaks in helium systems. The system is purged periodically to remove condensed liquid and ensure pressure transmission to the transducer.

Leaks in the tubing and valves and fittings at the surface will cause pressure drops with time which recover dramatically after purging. Although the pressure transducer itself is not very sensitive to diurnal temperature fluctuations, heating and cooling of the tubing, valves and fittings at the surface can result in 24 hour period noise in the measured signal. If diurnal temperature changes are measured, this noise can be filtered mathematically from the signal, but ever effort should be made to reduce this noise by burying the transducer, excess tubing and associated valving in insulated boxes. Other sources of noise include high frequency atmospheric pressure fluctuations and heating and cooling cycling in the wellbore due to internal well circulation. These effects can often be removed by post processing. Radio interference can cause sharp spikes in the signal and any surface wiring should be shielded. High energy radio or other airwave transmissions such as LORAN can cause serious interference with pressure measurements of this type. Signal amplification and isolation can help to reduce these effects.

Monitoring of barometric pressure fluctuations using a transducer open to atmosphere allows for the most accurate analysis of barometric efficiency values and can be used to remove barometric effects from the data. Software for this purpose has been developed by the authors and used on data from the Philippines and Steamboat, NV. The best results are obtained when barometric pressure and water level changes are measured at the same sampling interval.

Sampling interval can be calculated from the Nyquist frequency:

$$f = n/2$$

where n is the sampling rate in $time^{-1}$ and f is the highest frequency which this sampling rate will accurately measure. However, if there is considerable energy in higher frequencies, aliasing of the data can occur. For example if a tidal period of 3 hours or 1×10^{-4} sec^{-1} is the highest frequency of interest then the sampling interval is 1.5 hours or 90 minutes. However, if barometric pressure changes are occurring at shorter than 3 hour periods or there is considerable noise from thermal cycling at periods of less than this then the data can be aliased. Most time series data is filtered during collection by building an instrument that doesn't respond to signals at higher frequencies than the Nyquist frequency. Since this isn't possible with pressure transducers, the only way to avoid these problems is to over sample and check the amplitude spectrum for high frequency noise. This might mean that ten minute sample intervals would be warranted for a few days to determine if there is significant energy at high frequencies.

4.4 Borehole Design Requirements

Since no flow of the well is needed for earth tide and barometric pressure measurements, the requirements for well construction are only that the formation of interest is isolated by casing or intervening impermeable material and that the borehole is open to the formation or fracture. Significant skin effects can affect earth tide and barometric pressure measurements, so that an open, undamaged borehole is the best completion for this type of analysis. Most temperature gradient wells are completed with sealed 1.25 in. diameter tubing for running temperature probes. The effect of the tubing on the earth tide response is complex, but it can be analyzed. (See Evans, et al, 1991) However, these methods are best in open bore holes. Decreasing borehole diameter does not affect the ability to collect the measurements since the expansion chamber on the capillary tubing system can be as small as 1 cm od. as long as the length of the chamber allows for twice the volume of the tubing.

5.0 Borehole Seismics

A promising area for more detailed investigation of fractured reservoir properties is the use of borehole seismic techniques to evaluate fracture permeability, combined fracture and matrix permeability, fracture aperture and fracture height. Under the optimal circumstances this assessment can be not only qualitative, but also quantitative.

The techniques described here are currently being used experimentally by the oil and gas industry and for evaluation of nuclear waste disposal sites in Canada. They hold promise for evaluation of fractured geothermal reservoirs if the instrumentation required can be adapted for high temperature use.

5.1 Description of Method

The original work done in the development of borehole seismic fracture characterization methods was conducted by Atomic Energy of Canada Limited for the purpose of better characterizing fractures in potential nuclear waste repositories. A seismic source either in the borehole or on the surface causes fractures to expand and contract, stimulating a seismic wave in the borehole as well as an accompanying P wave. (Figure 2) The borehole acts as a waveguide for a trapped mode called a Stoneley wave, tube wave or in some sources, a water hammer wave. The volume of fluid ejected from the fracture is the same as the tube wave volumetric strain. Beydoun, et al (1985) showed that fracture permeability could be determined from tube waves generated in a tilted borehole intersecting a dipping fracture with parallel walls. His experiments used an array of sensors in the well and a source at varying distances from the well. The fracture permeability can be evaluated from the tube wave amplitude normalized to the direct P wave amplitude in the fluid, the pressure ratio shown in Figure 3.In addition to determining fracture permeability, the fracture length could also be observed under some circumstances. However, the technique required a costly vertical array and Vibroseis (TM Conoco) truck and it has never become popular.

Further information on the formation and fracture such as the fracture aperture and the bulk rock permeability can be obtained using the full waveform obtained during acoustic logging. (Tang, Cheng and Toksöz, 1991) In this method the source and multiple receivers are in the same borehole and can be on the some tool. Energy from a broad band source is absorbed by the fracture or permeable formation. Tube waves generated by the vibrating fracture are used to calculate fracture aperture.

More recently, Schlumberger has used full waveform sonic logging to evaluate permeability in a sandstone reservoir in the North Sea (Hornby, et al, 1991). Theoretical work by Chang, et al (1988) showed that velocity and attenuation of borehole Stoneley waves or tubewaves is dependant on the frequency, borehole radius, and the impedance in the permeable borehole wall. This impedance is inversely proportional to the formation permeability, but is also affected by the fluid viscosity. The largest difference in Stoneley wave velocity and attenuation occurs at low frequencies, below 10 kHz, making it necessary to use a source with energy in these frequencies and receivers which can respond to them.

Laboratory experiments currently being conducted at MIT, (Tang, et al, 1991) have applied similar methods to determination of fracture permeability in vertical and horizontal fractures. Energy absorbed by the fracture opens and closes it, moving a fluid volume in and out of the borehole which is seen as a Stoneley wave on the full wave form acoustic log. The fracture aperture is proportional to the velocity and attenuation of the

Stoneley wave. At low frequencies there is significant difference in the predicted Stoneley wave velocities and attenuation at different frequencies.

5.2 Borehole Diameter Effect

The generation of tube waves is integrally dependent on the borehole diameter. The smaller the diameter the larger the amplitude of the generated wave, since in a large diameter well more water is moved around and energy dissipated in its motion. However, petroleum well diameters are generally around 4-5 in., so this size is not considered a slim hole for them. Figure 4 shows plots of Stoneley wave response in three borehole sizes ranging from 1.5 to 4 in. Note that not only the wave amplitude, but the arrival time for the borehole stonely wave is altered by the diameter. This requires that analysis of data be modified by the borehole diameter information.

5.3 Tool Requirements

The experimental tool being using by Schlumberger has 11 receivers and a single transmitter 4.8 m. from the first receiver. The receivers are spaced at 15 cm. intervals. The source is fired every 7.5 cm as it is run with data recorded on magnetic tape. The tools are designed to run in holes as small as 3.5 in. diameter. However, the added thickness of heat shielding for operation in high temperatures, and the need for redesign of the tool to accommodate source and receiver pass through preclude the use of such tools in high temperature, narrow diameter holes without further development. The receivers and source are fairly robust for use in high temperature environments if appropriate materials are selected. Only the data collection and preprocessing electronics would be likely to require heat shielding. Such development from the private sector is unlikely in the present economic climate. However, an increase in demand for such services could stimulate development.

5.4 Borehole Design Requirements

Since flow is not required for borehole seismic methods, and the method itself determines the depth of fractures or permeable zones and their separate permeability, the completion requirements for seismic methods are even less difficult than for earth tide methods. Since the tool is long, 10 to 60 ft depending on the number of receivers and their separation, lubricators suitable for the tool length are required.

6.0 Recommended Slim Hole Exploration Program

Figure 5 shows a core hole which is suitable for use with shielded borehole seismic logging tools which can be envisioned for the immediate future. This well is also designed to accommodate flow without jeopardizing fresh water aquifers or risking subsurface blowout should very high temperature fluids be encountered at shallow depths. The well could also be used for injection testing. The design depth for cost estimation is 1640 m. (5000 feet). Lost circulation problems which can be severe in very large diameter production wells are somewhat reduced by the smaller hole size.

Many geothermal areas have attractive thermal features such as hot springs, geysers or fumaroles. It is often of interest to the community to protect such features. In order to do this the effect of geothermal production on these features needs to be predicted. Interference testing while monitoring thermal features and wells penetrating thermal aquifers can provide useful data for determining long term effects of production on thermal features. Coreholes drilled as part of an exploration program often are used for long term monitoring of the field. It becomes increasingly important to plan their construction for such uses. The design well has a sufficiently long mechanical life to be suitable for long term monitoring of the field.

Although temperature gradient wells are frequently left uncased, they are generally abandoned after less than a year and are for the most part of shallow depth. The well design presented here is intended to penetrate reservoirs with high temperature fluids and can accommodate accidental flows of high temperature fluids with reduced danger of subsurface blowout if the flow is contained.

6.1 Estimated Cost

The design well should cost about $600,000 in a typical metamorphic or igneous geothermal field with lost circulation problems in the first 2500 ft. For comparison, a production diameter well would cost between $1,200,000 and $1,400,000. The upper portion of the well is drilled with conventional rotary technology using a rig capable of both rotary drilling and coring. Rig costs are about $3000/day with $10/foot for coring.

Significant cost savings can be realized by designing holes for short lifetimes before abandonment and not using the holes for flow or injection. The hole can be cased to a shallower depth, smaller diameter surface casing and smaller core diameters can be used. This further reduces the risk of lost circulation. This type of well can not be flowed, and may not be suitable for long term monitoring.

7.0 Conclusions

A suite of test methods run on coreholes drilled for temperature and lithology information into geothermal reservoirs can yield reservoir data useful for prediction of future well behavior. Cores yield lithology for understanding reservoir geology and as input for elastic parameters in seismic methods. Temperature with depth and heat flow data can be collected by repeated temperature logging of the well. Fluid sampling can yield information about reservoir chemistry. Long term collection of small scale pressure variation with time in the static well bore coupled with surface measurement of barometric pressure fluctuations can be used to calculated average reservoir storage, porosity, fracture direction and under some circumstances permeability.

Development of seismic logging tools for high temperature environments could further improve reservoir information from coreholes. Seismic methods allow the measurement of bulk formation permeability as well as the depth, permeability and fracture aperture of individual fractures. These reservoir parameters can be used to predict reservoir behavior with time under production conditions. Combining this information with well bore flow models can predict well productivity. The coreholes can be used for long term monitoring of reservoir drawdown during production, interference effects and injection/production well interference. Further development work is needed before the current experimental tools can be run in high temperature wells. However, if a market for such tools existed, the development needed is not extensive and could be rapidly accomplished.

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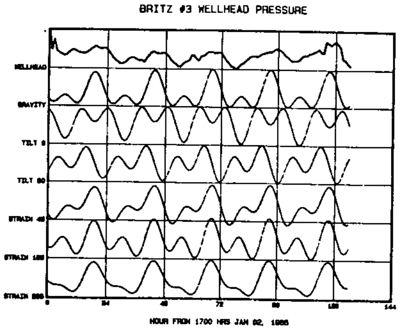

Figure 1 Britz 3 earth tide response and predicted directional tidal strain. Tilt 0° - Stress on horizontal plane, Tilt 90° - Stress on vertical plane. Strains are shown for vertical planes with orientation in degrees from north.

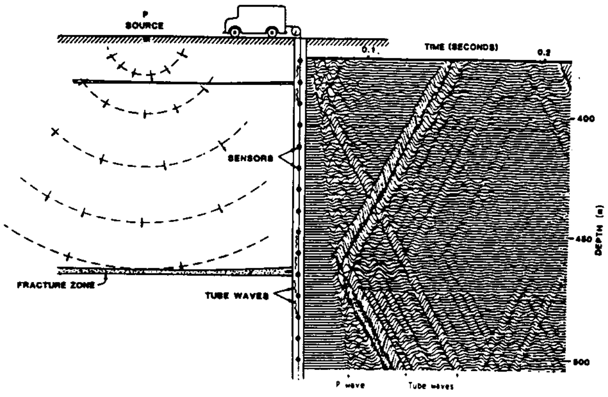

Figure 2 Schematic diagram of the mechanism of generation of tube waves (left) and an actual hydrophone VSP section. Beydoun, 1985.

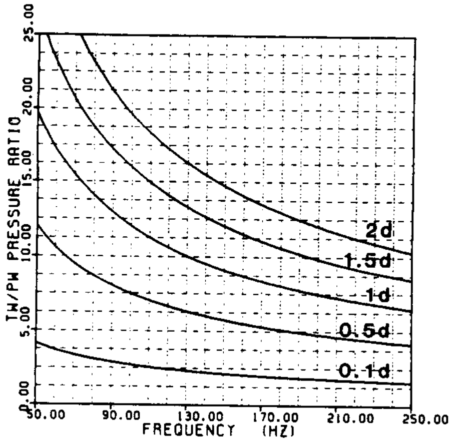

Figure 3 Tube wave to P wave pressure ratios as a function of frequency and permeability in granite. Beydoun, 1985.

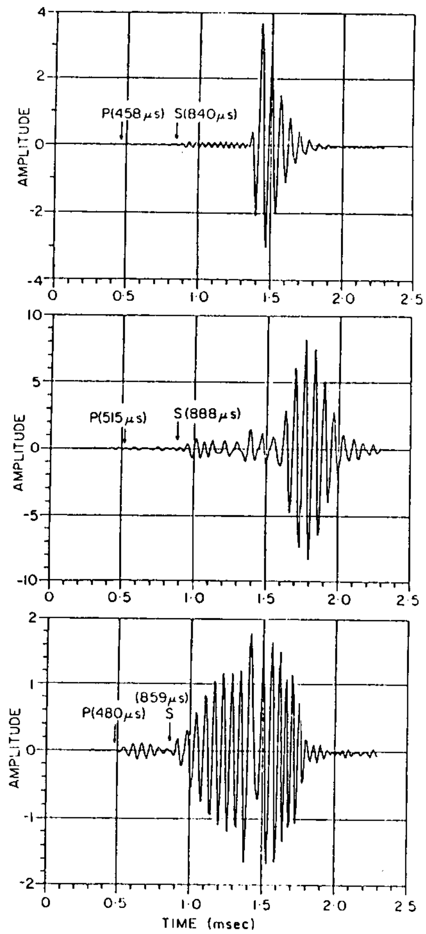

Figure 4 Synthetic microseismograms generated using identical formation and borehole parameters, but with different borehole radii. The top diagram is for a radius of 4.5 cm. (1.8 in.), The middle is for 10 cm. (4 in.), and the bottom for an intermediate size of 6.7 cm. (2.64 in.) Toksöz(1988)

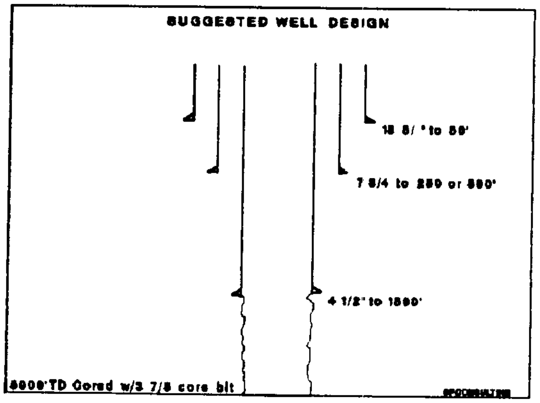

Figure 5 Wellbore diagram for typical corehole designed to maximize reservoir data, minimize cost and reduce safty risks.