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On the applicability of Dual Laterolog for the determination of fracture parameters in hard rock aquifers

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Abstract

At the present time geophysical measurement and evaluation methods developed in the 1980ies and 1990ies in the petroleum industry for fracture detection are used routinely for deep groundwater exploration. In hard rocks, methods for quantifying fracture zones are essential in order to describe their hydraulic properties. In the present paper, the estimation of fracture porosity and aperture using Dual Laterolog is presented. The separation between deep and shallow laterolog allows the estimation of fracture porosity and in high-contrast formation the calculation of fracture aperture if mud conductivity is also known. The applicability of these methods was examined in different aquifers such as carbonate, crystalline and volcanic aquifers.

The experiences in application of the methods in practice are presented using the example of the well Gabelhofen Th1 in a crystalline aquifer. The calculated fracture apertures of horizontal and vertical fractures are compared to those calculated by the parallel plate model using cubic law.

The values of calculated fracture apertures of horizontal fractures show a broad overestimate whereas the fracture apertures of vertical fractures are in a plausible range.

Die in der Erdölindustrie für die Klufterkennung in den 1980er und 1990er Jahren entwickelten geophysikalischen Messungen und Auswertemethoden werden zurzeit routinemäßig bei der Erschließung von tiefen Grundwässern verwendet. In Festgesteinen sind Methoden zur Quantifizierung von Kluftzonen erforderlich, um ihre hydraulischen Eigenschaften zu beschreiben. Im vorliegenden Beitrag wird die Abschätzung der Kluftporosität und der Kluftöffnungsweite mithilfe von Dual Laterolog vorgestellt. Die Separation zwischen dem tief eindringenden und dem flach eindringenden Laterolog erlaubt die Abschätzung der Kluftporosität und in Formationen mit hohem Widerstandskontrast die Berechnung der Kluftöffnungsweite sofern die Leitfähigkeit des Bohrschlamms ebenfalls bekannt ist. Die Anwendbarkeit der Methode wurde in unterschiedlichen Grundwasserleitern wie in karbonatischen, kristallinen und vulkanischen geprüft.

Die Erfahrungen mit der Anwendung der Methode in der Praxis werden am Beispiel der Bohrung Gabelhofen Th1 in einem kristallinen Grundwasserleiter präsentiert. Die berechneten Kluftöffnungsweiten von horizontalen und vertikalen Klüften werden mit jenen, die sich nach dem Parallelkluft-Modell unter Verwendung des kubischen Fließgesetzes ergeben, verglichen.

Die Werte der berechneten Kluftöffnungsweiten der horizontalen Klüfte zeigen eine deutliche Überschätzung, wobei die Kluftöffnungsweiten der vertikalen Klüfte in einem plausiblen Bereich liegen.

1. Introduction

In order to characterize fracture parameters in practice and to determine hydraulic properties in fractured aquifers geophysical borehole measurement methods were investigated and chosen for application. New imaging technologies, such as the Formation MicroScanner (FMS) and Formation MicroImager (FMI), can yield data for detecting and characterizing fractures (fracture porosity, aperture and dip of fractures) in the immediate vicinity of boreholes (Luthi and Souhaité, 1990; Hornby and Luthi, 1992), but where aquifer evaluation requires much deeper investigation. Furthermore, these measurements and their evaluation are expensive in comparison with others and the data evaluation requires special knowledge and specific hardware and software.

In the usual situation where water-filled fractures are much more electrically conductive than the massive rock in which they are embedded, deep-looking resistivity logging is an obvious method of choice. Furthermore, the generally high resistivity of the formation in fresh-water applications requires that active focusing techniques with focusing or guard electrodes (Laterolog) be employed instead of the conventional techniques such as long and short normal logs. For all these reasons, the application of laterolog measurements to aquifer characterization is of real practical interest to geophysicists.

Therefore, the Dual Laterolog tool (DLL) was chosen. It is routinely used in deep thermal water exploration and allows the estimation of fracture parameters in hard rocks quantitatively as well. By using the Dual Laterolog, based on resistivity anomalies and separation between shallow (LLs) and deep laterolog (LLd) and on mud conductivity, fracture zones can be detected; in addition the fracture porosity and the fracture aperture of horizontal and vertical fractures can be estimated. The applicability of the calculation methods was tested in carbonate, crystalline and volcanic aquifers.

2. Dual Laterolog resistivity measurement

The Dual Laterolog (DLL) provides two resistivity measurements with different depths of investigation: deep (LLd) and shallow (LLs). In both devices, a current beam 2 ft-thick (A_0) is forced horizontally into the formation by using focusing currents (A_1-A_2, A'_1-A'_2). Two monitoring electrodes (M_1, M_2, M'_1, M'_2) are part of a loop that adjusts the focusing currents so that in the section of the borehole between the two electrodes no current flow occurs. For the deep measurement, both measure and focusing currents return to a remote electrode on the surface at large distance. Thus the depth of investigation is greatly improved, and the effect of borehole conductivity and of adjacent formations is reduced. In the shallow laterolog, in contrast, the return electrodes which measure the bucking currents are located on the sonde. Therefore, the current sheet retains focus over a shorter distance than the deep laterolog (Fig. 1).

The Dual Laterolog response ranges from 0.2 to 40,000 Ωm, thus permitting a good characterization of highly resistive rocks. For the LLd the borehole effect is small for hole diameters up to 0.4 m, while the LLs provides good readings in holes not exceeding 0.3 m. Corrections are available for holes up to 0.6 m in diameter. The depth of investigation of the laterolog depends on the resistivity of the rock and on the resistivity contrast between the fracture zone and the unfractured formation, it can amount to max. 2.5 m. The vertical resolution of both LLd and LLs depends on the geometry defined by the focusing electrodes, which is about 0.61 m. The DLL is usually run in combination with the Natural Gamma Ray tool. The LLd and LLs curves are usually displayed on a resistivity logarithmic grid scale (sampling rate of 0.05 to 0.20 m), along with the Gamma Ray log.

Invasion and the type of water-based mud can severely affect laterolog measurements. Fresh muds cause the log measurements to be overly influenced by the resistivity of the invaded zone. Salt based muds are generally of similar salinity to formation waters, and the conductive influence does not severely retard the instrument's ability to measure beyond the invaded zone. Corrections are also required for bed-thickness and borehole size. Charts have been constructed from a series of mathematical simulations to correct the log readings for these influences (Schlumberger, 1998). Laterolog tools are generally recommended for use in salt muds, lower porosities and high-resistivity formations (Western Atlas, 1995; Fricke & Schön, 1999).

3. Estimation of fracture parameters

Due to the inverse relationship between resistivity and porosity, the Dual Laterolog can be used to compute the porosity of the rock according to Archie's equation (Archie, 1942), which can be applied if the sediments or rocks do not contain any clay or if the contribution of surface conduction to the signal is negligible (ODP Logging Services, 2004). The fracture porosity

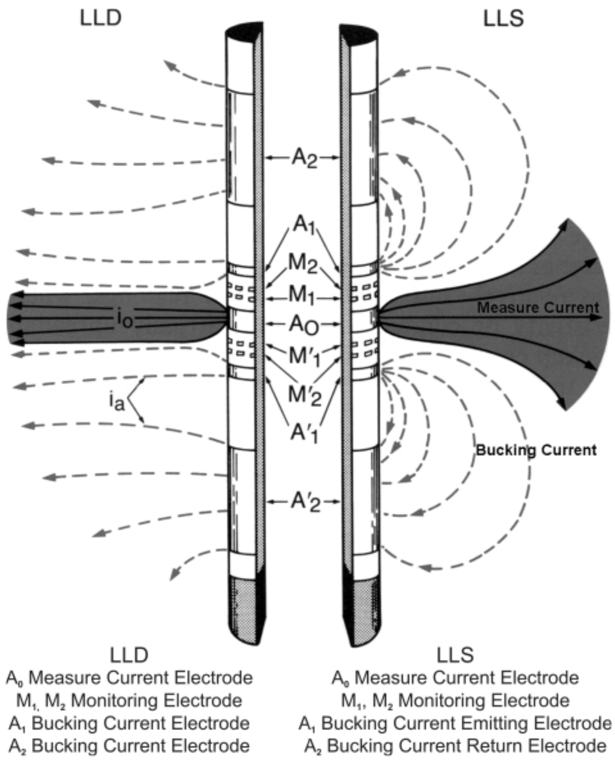

Figure 1: Schematic of the Dual Laterolog (after Schlumberger, 1991).

can be estimated from the separation between the deep and shallow measurements based on the observation that the former is sensitive to the presence of horizontal conductive features only, while the latter responds to both horizontal and vertical conductive structures.

3.1 Fracture porosity

The first equation for the estimation of the porosity (electrical connected pore space) based on measurement of core data was developed by Archie (1942). He has found a power function, which yields the total porosity of the formation depending on the relationship between the resistivity of the formation and the formation water resistivity:

$$\Phi_{tot}^{m} = \frac{a \times R_W}{R_0} \qquad (1)$$

where Φ_{tot} is the total connected porosity, R_W is the formation water resistivity (Ωm), R_0 is the resistivity of a non-shaly formation rock (Ωm), *a* is a dimensionless parameter (mostly about 1), m is Archie's cementation exponent (Fricke & Schön, 1999).

Fractured formations generally have a cementation exponent less than 2. Rule-of-thumb values of m quoted in the log analysis literature for various pore systems are given in Table 1 after John (1999).

In order to estimate the fracture porosity in hard carbonate formations Boyeldieu and Winchester (1982) developed Archie's equation further and worked out the following equation:

$$\Phi_{frac}^{m_{frac}} = \frac{C_{LLs} - C_{LLd}}{C_m} \qquad (2)$$

pore system	m
inter-granular/inter-crystalline	2.0
fractures	1.4
vugs	2.3
moldic	>3

Table 1: Cementation exponents for various pore systems (after John, 1999).

where Φ_{frac} is the fracture porosity, m_{frac} is Archie's cementation exponent (usually around 1.4), $C_{LLs} = 1/R_{LLs}$ is the conductivity measured by the shallow laterolog (S/m), $C_{LLd} = 1/R_{LLd}$ is the conductivity measured by the deep laterolog (S/m), $C_m = 1/R_m$ is the mud conductivity measured by mud log (S/m).

The real meaning of the concept of fracture porosity is to detect highly fractured zones and to characterize the jointing qualitatively also in sections where the fracture aperture can´t be calculated as described in the next chapter.

3.2 Fracture aperture

In fractured rocks large separations are observed between shallow and deep laterolog curves. In high-contrast formations the Dual Laterolog response is controlled by four parameters: the resistivity of the formation blocks, R_b, the resistivity of the invading fluid, R_m, the extent of invasion and the fracture opening. With a few simplifying assumptions Sibbit and Faivre (1985) developed a numerical finite-element model for the Dual Laterolog measurement in a borehole in order to solve the inverse problem and to determine the fracture aperture. Fig. 2 shows the configuration used in modelling. The Dual Laterolog tool is centred in a 0.203 m (8 inch) mud-filled (R_m) borehole, in turn centred in a zone of high resistivity, R_b. The high resistivity zone is a cylinder with a radius of 127 m (5,000 inches) and a height of 102 m (4,000 inches). The shoulder-beds (R_s) have a negligible effect on the Dual Laterolog response.

The resistivity of the non-fractured formation was assumed constant and high relative to the mud resistivity. For modelling a resistivity contrast of

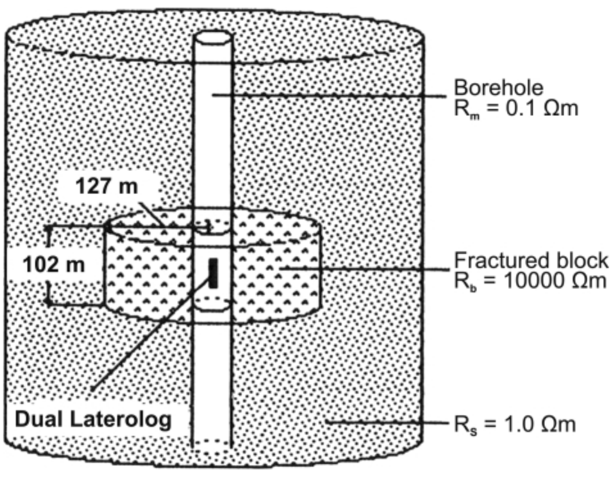

Figure 2: Configuration of tool in finite element model (after Sibbit and Faivre, 1985).

$$R_b/R_m > 10^4 \tag{3}$$

was maintained which is consistent with many reservoir models where low-porosity homogenous blocks are separated by fracture networks. In the case of fresh-water aquifers, water resistivity is in the order of tens ohm-meters and formation resistivity is in the order of thousands ohm-meters. The ratio of conductivities thus can often be out of the given range.

Fractures intersecting the borehole were discontinuous planar boundaries of infinitesimal thickness. Vertical fractures not intersecting the borehole were cylindrical boundaries. Two cases were distinguished: horizontal and vertical fractures. Qualitatively, however, it was established that horizontal behaviour is dominant for angles up to 60° with the horizontal and vertical behaviour for angles exceeding of 75°. It was also assumed that mud invades fractures and that all formation fluids would be displaced by the invading mud front. The model calculations resulted in the equation for long vertical fractures:

$$\varepsilon_v = \frac{C_{LLs} - C_{LLd}}{4 \times 10^{-4} \times C_m} \tag{4}$$

where ε_v is the fracture aperture of vertical fractures (mm), further variables see above.

For horizontal fractures was derived

$$\varepsilon_h = \frac{C_{LLd} - C_b}{1.2 \times 10^{-4} \times C_m} \tag{5}$$

where ε_h is the fracture aperture of horizontal fractures (mm); C_b is the conductivity of the non-fractured host rock (S/m); further variables see above.

In addition, the authors have discovered that isolated horizontal fractures can be identified by a sharp decrease in resistivity with a total width at the inflection points of around 0.8 m and DLL may show negative separation (LLd resistivity is less than LLs).

Oilfield technology is based on the assumption that fractures and voids are filled with electrically conductive brine. Under that assumption, the electrical conductivity of the fracture filling can be taken as infinite compared to the conductivity of the massive formation. In the case of fresh water aquifers, water resistivity is in the order of tens of ohm-meters, and formation resistivity is in the order of thousands of ohm-meters. However when the conductivity of the water becomes low, variations in conductivity within the formation become important. The real issue here is the presence of alteration minerals and alteration halos around fractures. The conductivity pathway for electrical current provided by the elevated conductivity of the alteration halo could possibly overwhelm the conductivity provided by the fluid-filled fracture spaces themselves. The conductivity of the alteration zone is lower, but the thickness of that zone is probably much greater. Long et al. (1996) have suggested that electrical resistivity anomalies associated with water-bearing fractures in crystalline rocks are completely determined by alteration minerals and not open pore passages. In the openings of carbonates, residual clay infillings may be even more significant. However, clay infillings can be detected by Gamma Ray logging.

Based on a three-dimensional modelling Shaogui at al. (2006) found the judging parameter Y

$$Y = \frac{R_{LLd} - R_{LLs}}{\sqrt{R_{LLd} \times R_{LLs}}} \tag{6}$$

which defines the dip of fractures. If Y is more than 0.1, the fracture is sub-vertical; if Y is between 0 and 0.1, the fracture is a dipping fracture; and if Y is less than 0, the fracture is sub-horizontal.

In equations (2), (4) and (5) the variables C_{LLs} and C_{LLs} are measured directly by Dual Laterolog. C_m is taken from the mud log measured in the borehole. In thermal water wells the borehole is mostly filled by water or a weak mix of water and mud. R_w is measured as a log with the temperature or calculated by means of a measured value and the temperature log. The formation water resistivity may be calculated from its laboratory temperature to any formation temperature and therefore for the overall borehole by Arps' empirical formula (Arps, 1953):

$$R_{W2} = R_{W1}\frac{T_1 + 21.5}{T_2 + 21.5} \tag{7}$$

where R_{W1} is the resistivity of water at temperature T_1 (Ωm), R_{W2} is the resistivity of water at temperature T_2 (Ωm), T_1 and T_2 are temperatures (°C).

C_b, the conductivity of the non-fractured host rock is calculated from R_b, which may be different from R_t, the overall resistivity of the formation. Sibbit and Faivre (1985) suggested that in zones of non-fractured rock masses an estimate of the values of R_b the maximum values of R_{LLd} can be used. The estimated value of R_b must be greater than max R_{LLd} otherwise ε_h would be zero or negative in equation (5). This assumption leads to an approximate value of R_b and that is why the calculated horizontal fracture apertures are strongly determined by the estimate of the resistivity of the non-fractured host rock. This approach expects that the zones of non-fractured rock masses can be detected and separated from fracture zones by means of different geophysical borehole logs. Otherwise the estimate of R_b also determines the validation of the resistivity contrast criterion given in equation (3).

3.3 Fracture density

In order to estimate a further fracture parameter, the fracture density, which can not be measured by DLL directly, it was derived from the fracture porosity and aperture of horizontal fractures. Since the DLL has a vertical resolution of 0.61 m, the fracture aperture calculated by equation (5) represents an average value of the measured section. Therefore, the fracture density can be regarded as an apparent fracture density using equation (2) and (5):

$$d_{frac} = \frac{1000 \times \Phi_{frac}}{\bar{\varepsilon}_h} = 0.12\frac{(C_{LLs} - C_{LLd})^{\frac{1}{m}}}{C_{LLd} - C_b} C_m^{1-\frac{1}{m}} \tag{8}$$

where dfrac is the fracture density (m^{-1}), Φ_{frac} is the fracture porosity (-) and $\bar{\varepsilon}_h$ is the mean aperture of horizontal fractures (mm).

However, it must not be overlooked that the calculation of fracture density by equation (8) fails, if $C_{LLd} > C_{LLs}$ ($R_{LLd} < R_{LLs}$), even in case of single horizontal fractures with negative separation (Fig. 6).

4. Cubic law for fluid flow in a rock fracture

The most common model for flow in a single fracture is the cubic law, in which the fracture is represented by two parallel

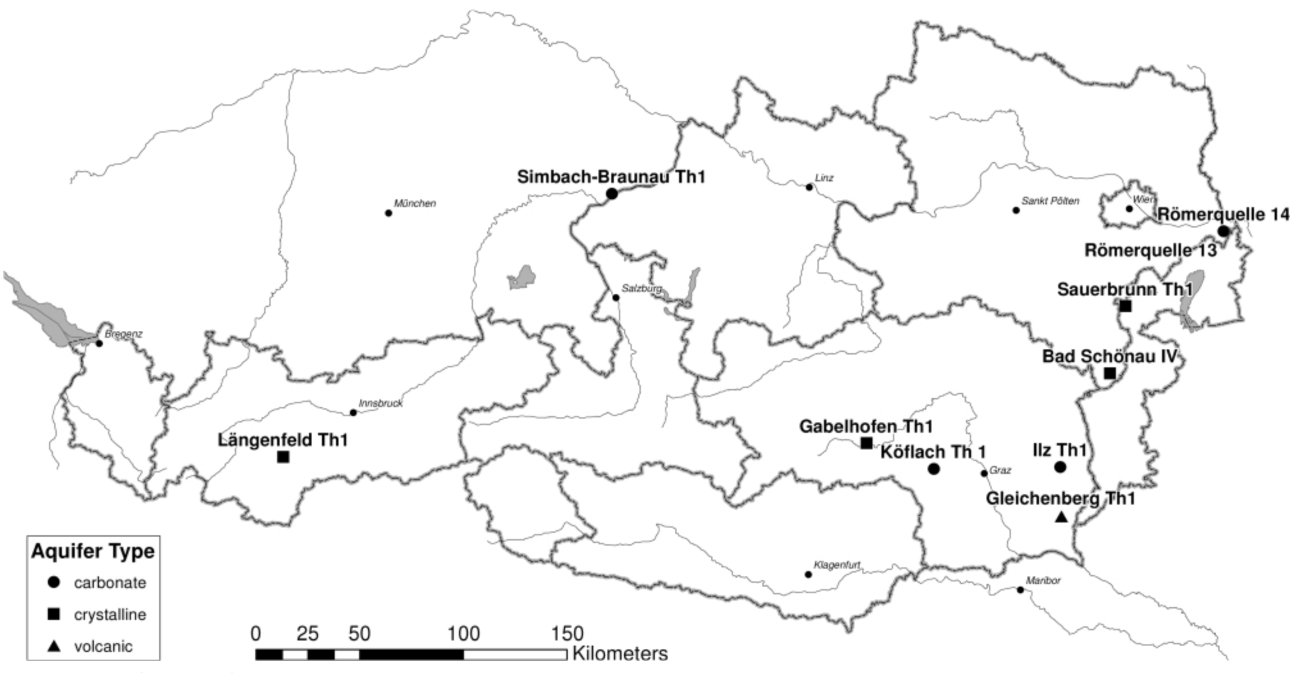

Figure 3: Site plan of the investigated wells.

plates separated by a constant distance. This model assumes ideal fractures with flat, smooth surfaces of uniform aperture and of an infinitive length, for laminar flow, of a viscous, incompressible liquid. The equation for the hydraulic conductivity for one-dimensional flow between two parallel plates is (Witherspoon et al. 1980; Bear, 1993)

$$k^f = \frac{\rho \times g}{\eta} \times \frac{b^2}{12} = c(T) \times b^2 \qquad (9)$$

where k^f is the fracture hydraulic conductivity (m/s), ρ is the density of water ($kg \cdot m^{-3}$), g is the acceleration due to gravity ($m \cdot s^{-2}$), η is the dynamic viscosity of water (Pa·s), b is the mean hydraulic fracture aperture (m). Density and dynamic viscosity of water depend on temperature in depth of aquifer. Therefore in equation (9) a constant c(T) can be defined, to simplify it, which also depends on temperature.

Since the effective conductivity is related to the fracture conductivity according to

$$k = k^f \times \frac{b}{\ell} + k^r = c(T) \times \frac{b^3}{\ell} + k^r = T^f \times \frac{1}{\ell} + k^r \qquad (10)$$

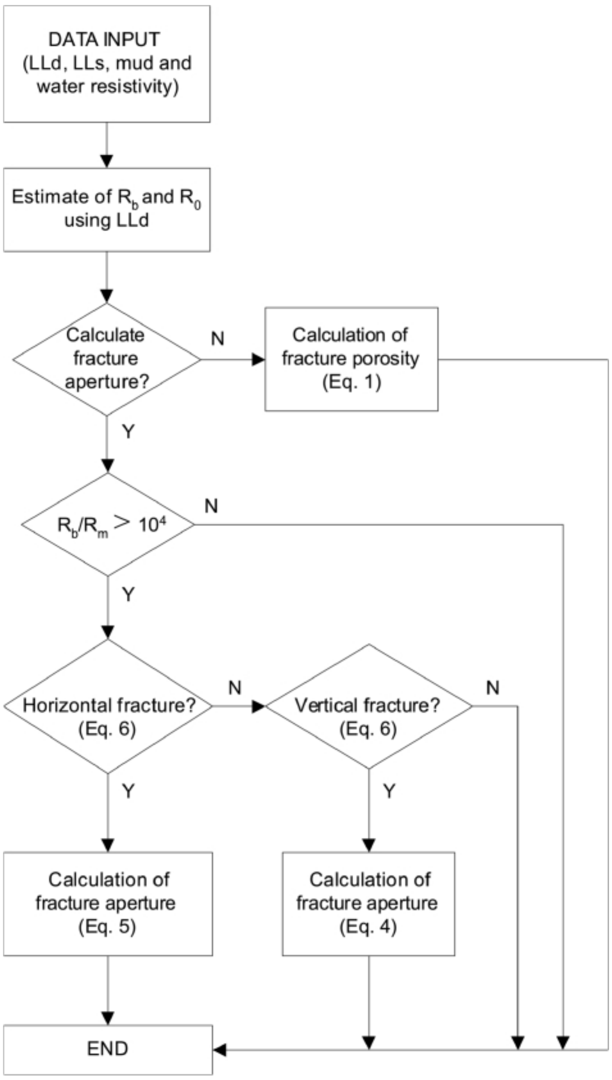

Figure 4: Work flow for determination of fracture properties.

the well-known cubic law is obtained where k is the effective hydraulic conductivity (m/s), k^r is the hydraulic conductivity of the hard rock (m/s), l is the mean fracture spacing (m) and T^f is the transmissivity of a fracture (m^2/s).

Thus the parallel plate model using cubic law allows a rough control of the “electrical” fracture aperture of horizontal fractures determined by DLL. If transmissivity or hydraulic conductivity are known by pumping test, for example, and the joint spacing can be estimated, the mean aperture can be calculated assuming laminar flow.

5. Estimation’s results

Ten wells were included in the investigations (Fig. 3). Geophysical borehole measurements and pumping tests were carried out in the wells. The hydraulic tests in the case studies were carried out as total-well tests. The well Gabelhofen Th1 is the only borehole in which Dual Laterolog was carried out and therefore it makes possible to determine the fracture apertures. In Table 2 the general information about the investigated aquifers and the main data from the wells are summarized (Vasvári, 2001). The parameters represent mean values characterizing the aquifer sections in the wells. The fracture apertures could be estimated in the well Gabelhofen Th1 only where the resistivity contrast criterion (3) measured by Dual Laterolog was given. Fig. 4 shows the work flow for determination of fracture properties from laterologs.

In the following the results of the well Gabelhofen Th1 which satisfied all the conditions are presented in detail. The tortuosity a in equation (1) was assumed to be 1. The effective hydraulic fracture aperture was calculated according to equation (10).

5.1 Gabelhofen Thermal 1

5.1.1 Geology

The well Gabelhofen Thermal 1 was drilled in the Fohnsdorf basin and is developed in the Middle East Alpine crystalline complex consisting of phyllite, quartz-rich phyllite and quartzit. The boundaries of the lithostratigraphic units were found in the depths as follows: Quarternary up to 38.5 m, Tertiary (Carpatian) up to 1096 m and crystalline basement up to 2000 m.

The crystalline basement consisting of mica slate exists in different external forms. Both in the capping bed and in the subjacent bed sections occur with phyllite-rich mica slate. At 1250 m an eight meter thick mica slate intercalation of high carbonate content was found. The acidizing test resulted in a carbonate content of 35 %. Between 1680 m and 1705 m mica schist dominates. Due to the varying quartz content quartz-rich mica slate, mica-rich quartzite and quartzite were differentiated. Until 1680 m quartz-rich sections were frequently detected, below 1680 m only mica slate and phyllite-rich mica slate was present.

5.1.2 Borehole measurements and fracture zone determination

To isolate the fracture zones and to determine the water bea-

Well	Aquifer type	Open hole (m)	T (m^2/s)	Fracture porosity	max. R_m (Ωm)	max. R_b/R_m	Comparability	Resistivity measurement
Ilz Th 1	carbonate	1469 - 1906	7.30×10^{-5}	0.012	380	180	-	Dual Laterolog
Köflach Th1	carbonate	767 – 1039	2.30×10^{-4}	0.006	*(10000)**	180	-	Dual Laterolog
Römerquelle 13	carbonate	37 – 81	5.48×10^{-4}	0.025	8000	630	core sample	Dual Laterolog
Römerquelle 14	carbonate	33 - 57	3.32×10^{-5}	0.218	25600	2,390	core sample	Dual Laterolog
Sauerbrunn Th1	crystalline	681 - 1103	5.29×10^{-5}	0.024	600	50	-	Dual Laterolog
Längenfeld Th1	crystalline	811 - 1865	8.54×10^{-5}	0.033	48000	4,000	-	Dual Laterolog
Gabelhofen Th1	crystalline	1074 - 2000	3.35×10^{-6}	0.005	23600	1.07×10^{5}	-	Dual Laterolog
Simbach-Braunau Th1	carbonate	1735 - 1848	2.40×10^{-3}	0.021	2000	200	FMS	Dual Laterolog
Bad Schönau IV	crystalline	197 - 503	4.29×10^{-7}	-	*(80480)**	1.75×10^{4}	-	Dual Induction log
Gleichenberg Th1	volcanic	545 - 1502	7.35×10^{-6}	-	*(80480)**	4.47×10^{4}	-	Dual Induction log

* upper bound for resistivity measurement

Table 2: General information about the investigated wells (after Vasvári, 2001).

ring horizons geophysical borehole measurements like Self Potential (SP), Gamma Ray (GR), Dual Laterolog (LLs, LLd), 4 Arm Caliper (CAL), Micro Laterolog (MLL), Microlog (normal and lateral resistivity, RNML, RLML), Temperature (TEMP), Acoustic (AC) were carried out in the open hole from 1074 m to 2000 m before the first aquifer test. Logs represent measuring data detected every 10 cm in the open hole.

In Fig. 5 the indicative logs (CAL, GR, resistivity as well as temperature) are shown. The specific resistivity of phyllite varies from about 1000 up to 23600 Ωm. The sections with values of the specific resistivity under 10 Ωm may show the influence of mud (R_m = 0.22 – 0.38 Ωm) and formation water (R_w = 0.40 – 0.48 Ωm). The formation temperature ranged between 47.6°C and 61.7°C. The natural gamma radiation varies between 29.2 and 223 API, the mean value amounts to 111.7 API.

The detailed investigation – evaluation and contrasting juxtaposition of all geophysical borehole measurements – resulted in 25 potential water-bearing horizons (minimum thickness of 0.2 m) with a total thickness of 18.8 m (Vasvári, 2001).

The indication for fracture zones and consequently for water-bearing horizons were positive temperature gradients, sharp decrease in resistivity with separation between R_{LLs} and R_{LLd}.

A typical fracture zone between

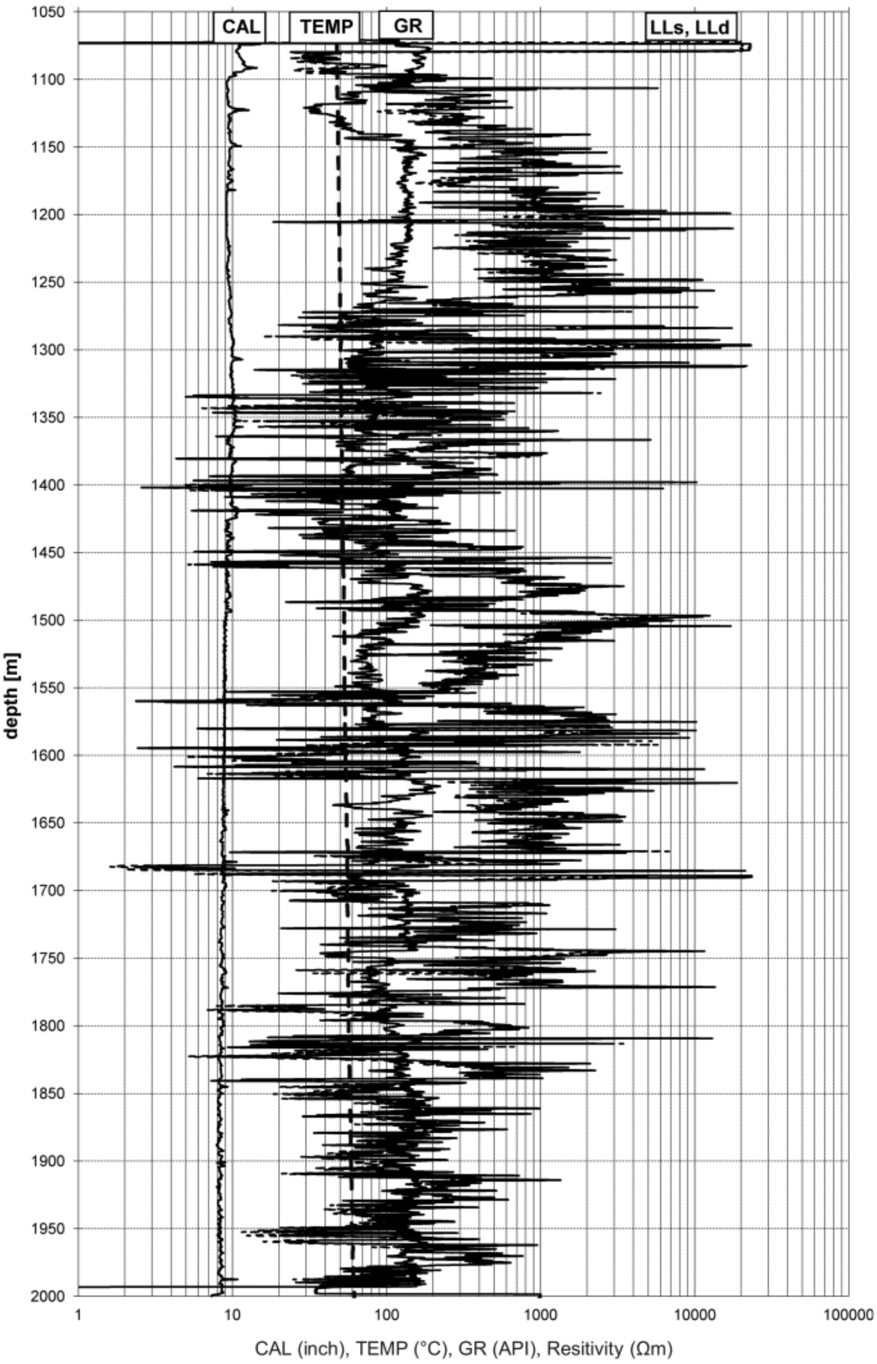

Figure 5: Caliper (CAL), Temperature (TEMP) Gamma Ray (GR) log and Dual Laterolog (LLs, LLd).

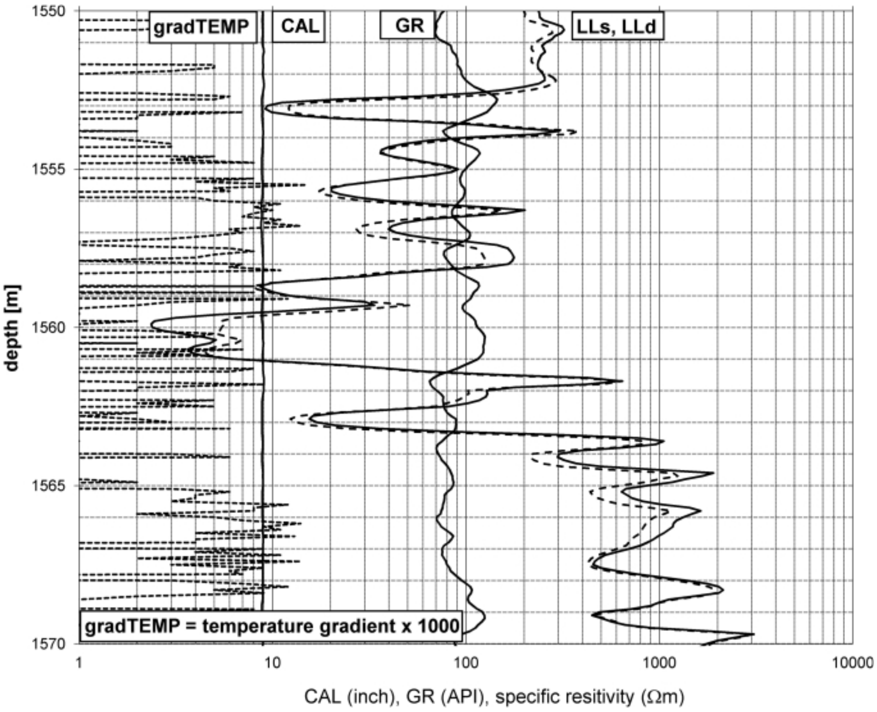

Figure 6: Fracture zone between 1552 and 1564 m.

Hydraulic test	Total duration (day)	Discharge (l/s)	Drawdown (m)	Transmissivity (m^2/s)		Notes
				Pumping	Recovery	
air slug	2	-	-	-	-	degasification, not evaluable
1. long-term pumping test	26	1.46	590	3.6 - 4.1×10^{-6}	5.0×10^{-6}	after first acid stimulation
		1.85	880			
1. overflow test	60	0.37	-	-	8.9×10^{-6}	
2. overflow test	96	0.37-0.41	-	-	9.6×10^{-6}	after second acid stimulation
2. long-term pumping test	132	1.55	431	5.3 - 5.9×10^{-6}	4.0×10^{-6}	
		2.40	775			

Table 3: Evaluation of the hydraulic tests.

1552 and 1564 m is presented in Fig. 6. The specific resistivity decreases from 2000 Ωm to 100 Ωm actually it sinks under 10 Ωm in the vicinity of fractures. The Gamma Ray log features slightly increased values in sections of low resistivity associated with fractures. Probably high uranium content can indicate fluid movement, subsequent mineral deposition, and thus a probable zone of permeability, usually a fractured zone. The temperature gradients are virtually continuous positive and indicate thermal water inflow. However significant borehole breakouts on the caliper log can not be detected in this zone.

Isolated horizontal fractures were identified by a sharp decrease (at least one order of magnitude) in resistivity with a total width at the inflection points of around 0.8 m and DLL may show negative separation and the judging parameter Y should have a negative value.

Based on the peaks of the deep Dual Laterolog measurement as recommended by Sibbit and Faivre (1985) for short borehole sections R_b could be estimated to 22,000 Ωm. In the 950 m long measuring section based on the alternate lithology described above there are areas with definitely essential lower resistivity. Often is the resistivity directly at the shoulders affected by adjacent fractures or other effects. Therefore, to estimate the resistivity of the non-fractured host rock in a certain point the maximum of R_{LLd} in an interval of 4 m (2 m upwards and 2 m downwards) about the point was used.

5.1.3 Aquifer tests

The aquifer tested in the open hole reaches from 1075 m to 2000 m, so the total thickness amounts to 925 m. In the well five hydraulic tests (pumping and overflow) were carried out and evaluated (Tab. 3).

Before the second pumping test and the second overflow test acid stimulation was performed to enhance the flow properties of the rock and to increase the well productivity, respectively, by creating conductive wormholes in the carbonatic phyllite. Therefore the aperture of hydraulic fractures calculated by evaluation of the pumping test data cannot directly compared with the result of the geophysical borehole logs because the fracture properties were modified by acid stimulation in the vicinity of the borehole. However, the late recovery data which characterise the transmissivity in a more distant aquifer area with an average value of 9.1x10^{-6} m^2/s were used for calculating the unaffected hydraulic fracture aperture. Furthermore the residual drawdown graph in Fig. 7 shows wellbore storage effect in the borehole.

The estimated transmissivity represents a total transmissivity resulting from total-well tests in the open hole. A partition of total transmissivity into fractured and matrix components was not possible.

5.1.4 Calculation of fracture porosity and fracture apertures

The average total porosity by Archie (m =1.4) amounts to 1.9 % and corresponds with the sandstone-porosity. The fracture porosity calculated from the total porosity amounts to 0.5 %. The average fracture porosity by Boyeldieu and Winchester (1982) (m = 1.4) was also calculated to 0.5 %.

In the open hole different indications for 26 single horizontal fractures were found. In Table 4 single horizontal fractures are presented, where the resistivity contrast given in equation (3) is fulfilled, thus the use of equations (4) and (5) is founded and a sub-horizontal dip of fracture is indicated by equation

(6). The fractures were identified by a sharp decrease in resistivity of at least an order of magnitude, with a total width at the inflection points of around 0.8 meters and LLs and LLd shown negative separation. An example for a typical Dual Laterolog response is shown in Fig. 8.

Nearly all values of fracture aperture are obviously out of a plausible range. The results of fracture aperture are in contradiction to the calculated aquifer transmissivitity. Assuming horizontal flow to the well in horizontal fractures only, a negligible tranmissivity of the non-fractured host rock and a mean fracture spacing of 35.6 m equation (10) results in a mean equivalent aperture size of 0.028 mm.

The sharp decrease of resistivity up the values less than 100 Ωm or even 10 Ωm determines the overestimated calculation of fracture aperture. Too high conductivities lead to implausible apertures although the resistivity measurement is not influenced by alteration effects in the horizontal fractures as it is recognisable in the Gamma Ray log. If the resistivity is low being in the range mentioned above and therefore the conductivity is high the aperture is calculated too high because the high resistivity of non-fractured rock has a negligible influence on the calculation.

The calculated fracture apertures of vertical fractures in Table 5 are in a more plausible range than those of horizontal fractures (Tab. 4). Nevertheless the values show an overestimate of the aperture size by one order of magnitude as compared with the hydraulic equivalent aperture using equation (10). Laterolog response near a vertical fracture is shown in Fig. 9. The increase of Gamma Ray (from 100 to 200 API) indicates a possible alteration in the fracture.

6. Discussion and conclusion

Fracture porosity is found accurately only by processing the formation micro-scanner curves for fracture aperture and fracture frequency. The methods for calculation of fracture porosity including the well known dual-porosity model can be extremely inaccurate. Crain (2010) stated that these models either over-estimate fracture porosity by several orders of magnitude, or cannot be applied because the log data does not fit the model.

For the first estimation of fracture porosity calculated for water bearing horizons the cementation exponent of 1.4 in equation (2) yields values in a plausible field (Table 2). But the investigations showed that the exponent can range from 1.1 to 1.7 at similar rocks and fracture systems. The exponent can be adjusted by core samples and it is valid for the fractured rock in the borehole only. In practice, the application of the equations (1) and (2) is recommended to estimate the fracture porosity of fractured aquifers with an acceptable accuracy.

Several references (Long et al, 1996; Paillet, 1998) demonstrate local estimates of fracture density or fracture aperture made at the borehole wall using calliper or televiewer image data have no correlation with hydraulic test results. In the usual situation where water-filled fractures are much more electrically conductive than the massive rich in which they are embedded, deep-looking resistivity logging is an obvious method of choice. The generally high resistivity of the formation in fresh-water

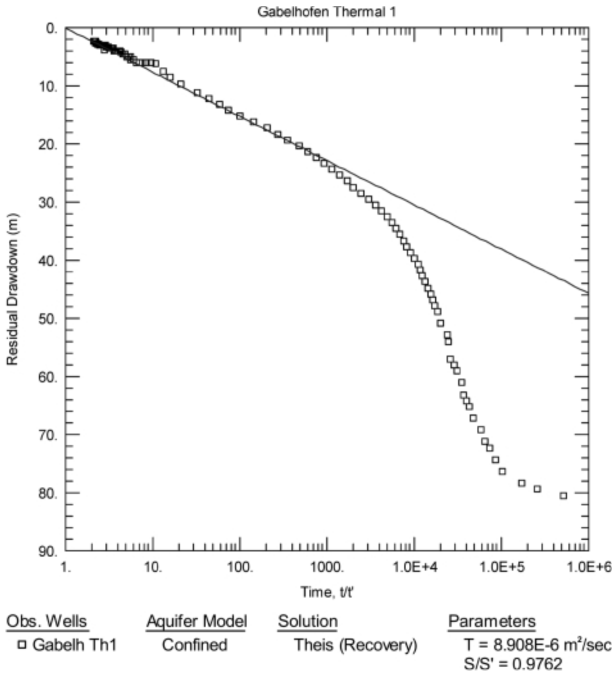

Figure 7: Recovery after the first overflow test.

Depth (m)	LLd (Ωm)	LLs (Ωm)	R_b (Ωm)	R_m (Ωm)	Y (-)	ε_h (mm)
1098.4	63.19	65.82	485	0.378	-0,041	43.4
1104.3	63.46	72.83	1015	0.378	-0.138	46.6
1150.5	108.11	115.99	2116	0.375	-0.070	27.4
1161.7	200.12	203.52	1581	0.374	-0.017	13.6
1183.1	211.39	214.99	2408	0.372	-0.017	13.4
1194.4	227.42	238.47	3427	0.372	-0.047	12.7
1205.5	18.43	28.74	18432	0.370	-0.448	166.9
1249.4	433.11	438.63	11277	0.367	-0.013	6.8
1265.4	103.21	111.04	660	0.367	-0.073	25.0
1314.9	13.91	14.07	10842	0.365	-0.011	217.9
1346.6	7.47	7.84	678	0.363	-0.048	400.3
1432.1	20.22	20.92	681	0.358	-0.034	143.0
1492.7	57.11	63.99	2237	0.352	-0.114	50.1
1503.8	194.02	214.08	17169	0.352	-0.098	14.9
1505.5	321.27	358.50	17169	0.352	-0.110	9.0
1518.0	73.97	88.80	808	0.350	-0.183	35.9
1553.1	9.18	12.16	304	0.350	-0.282	308.4
1574.7	221.12	234.89	10249	0.349	-0.060	12.9
1608.4	4.20	4.62	11550	0.346	-0.095	686.6
1617.1	6.00	6.57	9923	0.345	-0.090	478.7
1671.7	9.63	15.10	4529	0.237	-0.454	204.3
1728.0	20.74	26.64	3065	0.236	-0.251	94.3
1735.0	50.01	52.16	500	0.237	-0.042	35.5
1765.4	136.72	145.85	1381	0.236	-0.065	12.9
1816.0	9.33	10.96	453	0.232	-0.160	202.7
1879.1	34.12	36.40	326	0.230	-0.065	50.2

Table 4: Single horizontal fractures.

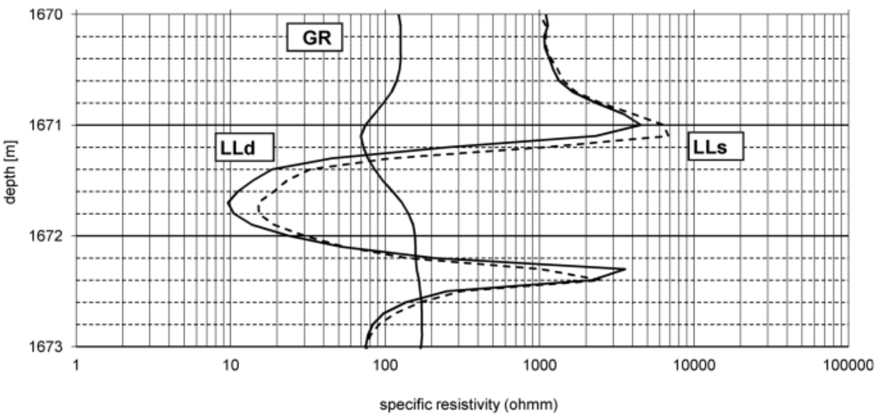

Figure 8: Typical Dual Laterolog response near a single horizontal fracture.

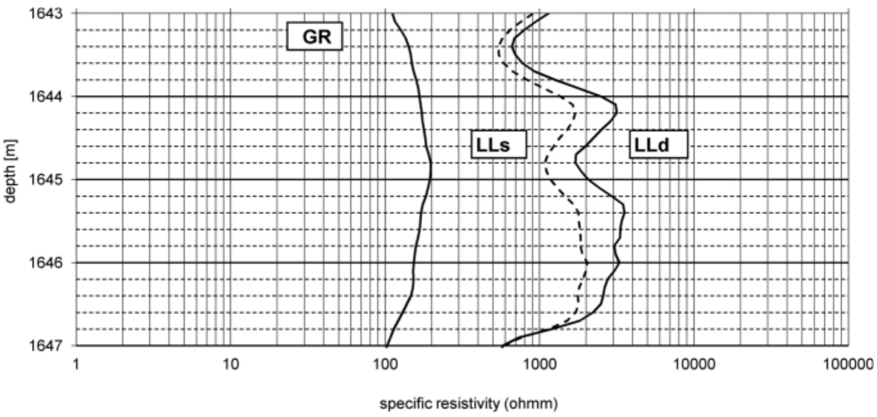

Figure 9: Typical Dual Laterolog response near a vertical fracture.

applications requires that active logging methods with focusing electrodes be employed instead of the passive techniques. For all these reasons, the application of laterolog measurements to aquifer characterization is of real interest.

Therefore the possibility to calculate fracture aperture by processing and evaluating the Dual Laterolog measurement was investigated more closely. Isolated horizontal fractures could be detected by Dual Laterolog, but their identification is made difficult by interpretation of a sharp decrease in resistivity. The conditions assumed at the derivation of the equations (4) and (5) for hydro-carbon differ from those for water bearing horizons. A resistivity contrast $R_b/R_m > 10^4$ between mud and unfractured host rock must also be given. This criterion strongly reduced the number of wells that could be involved in the case studies.

Depth (m)	LLd (Ωm)	LLs (Ωm)	R_b (Ωm)	R_m (Ωm)	Y (-)	ε_v (mm)
1200.0-1203.5	2498.5	1254.5	9848	0.371	0.670	0.41
1292.8-1294.1	8859.3	2483.5	14503	0.364	1.327	0.28
1295.5-1298.6	11056.4	3234.6	23276	0.365	1.117	0.21
1496.0-1501.0	6612.8	4013.3	11048	0.352	0.464	0.08
1582.0-1584.5	3381.6	1758.3	9374	0.348	0.665	0.28
1644.0-1646.5	2737.1	1602.8	3544	0.240	0.538	0.16
1689.0-1691.5	15481	2027.0	23605	0.237	2.376	0.41
1744.5-1748.0	3802.6	1731.2	9508	0.234	0.687	0.16

Table 5: Vertical fractures (values are average values in the given borehole section).

As is well known electrical fracture aperture and hydraulic fracture aperture are not directly comparable (Kolditz, 1997). Nevertheless in the case of well Gabelhofen Th1, it was the only opportunity to verify the evaluation of Dual Laterolog data. The differences between hydraulic and electrical fracture apertures, which amount to about three orders of magnitude, can be explained by the following reasons: The calculation by the parallel plate model results in an effective hydraulic aperture whereby a constant distance between the fractures and parallel and smooth fracture surfaces are assumed. The flow conditions in the fractures are laminar. The field of validity of the parallel plate model is limited for fractures in which fracture roughness in comparison to the mean aperture is small. The hydraulics of fractures weathered by chemical and hydrothermal processes or filled by minerals can not be reproduced by conventional parallel plate models. Even the higher conductivity occurred probably by alteration leads to higher values of fracture aperture in equation (5). This can be especially assumed at the investigated carbonate aquifers. The parameters f and d in equation (8) were unknown and that's why they could not be taken into account.

The estimate of R_b also has an essential influence on the results. Sibbit and Faivre (1985) suggested that in zones of non-fractured rock masses for estimate of the values of R_b the maximum values of R_{LLd} can be used. In many cases if R_{LLd} is used it results in an underestimate of R_b and that increases the fracture aperture size. If R_{LLd} is low (<100 Ωm) and the estimated value of R_b amounts to at least five times as R_{LLd} then the influence of R_b on the fracture aperture size can be neglected. That's why the fracture apertures especially of horizontal fractures in low resistivity rocks are calculated too high by this method.

However further investigations including numerical modeling are required in high resistivity water bearing formations in order to test the applicability and the validity of the methods to estimate of fracture aperture.

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References

Archie, G., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions, AIME, 146, 54-62.

Arps, J.J., 1953. The effect of temperature on the electrical resistivity of sodium chloride solutions. Journal of Petroleum Technology, Technical Note, 175, 17-20.

Bear, J., 1993. Modeling Flow and Contaminant Transport in Fractured Rocks. In: Bear, J, Tsang, C-F., Marsily, G. (ed.): Flow and Contaminant Transport in Fractured Rock, pp. 1-37.

Boyeldieu, C. and Winchester, A. 1982. Use of the Dual Laterolog for the Evaluation of the Fracture Porosity in Hard Carbonate Formations. Offshore South East Asia Conference, Singapore, 1-11.

Crain, E.R., 2010. Crain´s Petrophysical Handbook. 3rd Millennium Edition, Version 3.10, on CD-ROM.

Fricke, S. and Schön, J., 1999. Praktische Bohrlochgeophysik. Ferdinand Enke Verlag, Stuttgart, 254 pp.

Hornby, B.E. and Luthi, S.M., 1992. An integrated interpretation of fracture apertures computed from electrical borehole scans and reflected Stoneley waves. In: Hurst, A., Griffiths, C.M. and Worthington, P.F. (ed.) Geological Applications of Wireline Logs II. Geological Society Special Publication 65, 185-198.

John, H., 1999. Basics of Oil and Gas Log Analysis. Kansas Geological Survey, Doveton.

Kolditz, O., 1997. Strömung, Stoff- und Wärmetransport in Kluftgesteinen. (Flow, solute and heat transport in fractured rocks) Gerbrüder Borntraeger, Berlin, Stuttgart, 263 pp.

Long, J.C.S., Aydin, A., Brown, S.R., Einstein, H.H., Hestir, K., Hsieh, P.A., Myer, L.R., Nolte, K.G., Norton, D.L., Olsson, O.L., Paillet, F.L., Smith, J.L. and Thomsen, L., 1996. Rock Fractures and Fluid Flow, Contemporary Understanding and Applications, National Academy Press, Washington, D. C., 551 pp.

Luthi, S.M. and Souhaité, P., 1990. Fracture apertures from electrical borehole scans. Geophysics, 55, 7:821-833.

ODP Logging Services, 2004. Logging Manual. Electronic Manual, Version 2.0, Ocean Drilling Program.

Paillet, F.L., 1998. Flow modelling and permeability estimation using borehole flow logs in heterogeneous fractured formations. Water Resources Research, Vol. 34, No. 5, 997-1010.

Schlumberger, 1991. Log Interpretation Principles/Applications. Schlumberger Wireline & Testing, SMP- 7017, Sugar Land, Texas.

Schlumberger, 1998. Log Interpretation Charts. Schlumberger Wireline & Testing, SMP-7006, Sugar Land, Texas.

Shaogui, D., Xiaochang, W., Dejiang, Z., Yiren, F. and Zhen., Y. 2006. Interpreting Dual Laterolog Fracture Data in Fractured Carbonate Formation. Journal of China University of Geosciences, 17/2, 168-172.

Sibbit, A. M. and Faivre, O., 1985. The Dual Laterolog Response in Fractured Rocks. Trans., paper T, SPWLA 26th Annual Logging Symposium, 1-34.

Vasvári, V., 2001. Geohydraulische und bohrlochegophysikalische Untersuchungen in geklüfteten Grundwasserleitern. (Geohydraulic and borehole geophysical investigations in fractured aquifers.) Schriftenreihe zur Wasserwirtschaft, Technische Universität Graz, 38, 110 pp.

Western Atlas, 1995. Introduction to Wireline Log Analysis. Western Atlas International Inc., Houston, Texas.

Witherspoon, P.A., Wang, J.S.Y., Iwai, K. and Gale, J.E., 1980. Validity of cubic law for fluid flow in a deformable rock fracture. Water Resources Research, 16/6, 1016-1024.

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