Methods of well logging used for borehole correlation in the granite stock, Podlesí granite, Bohemian Massif

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Abstract. The main results from the final well logging measurement of the PTP4A borehole are presented. The correlation of selected logging methods from the boreholes PTP3 and PTP4A, drilled 10 m apart, is shown. A combination of hydraulic stress tests in PTP4A and simultaneous fluid resistivity logging in PTP3 confirmed the presence of a subsurface hydrogeological connection through water-permeable fractures between both boreholes. Despite the short distance between the boreholes, the water from some horizontal fractures was redirected through highly permeable vertical ones.

Key words: well logging, fractured granites, groundwater cross-connection, correlation of curves

Introduction

Well logging methods were applied in boreholes PTP3 and PTP4A during an evaluation of methods appropriate for the geological exploration of future radioactive waste disposal sites. The boreholes, with depths 350 m and 300 m, are situated in the small Podlesí granite stock in the western part of the Czech Republic (Breiter 2002). The main goal of this study was to determine the degree to which the relatively hard granite rocks are fractured. Other aims were the hydrogeological evaluation of the boreholes, and testing the hydrogeological connection between them through a system of fractures. Borehole PTP3 was measured by the Czech company AQUATEST, a. s., and by the Hungarian company Geo Log Ltd., Budapest. The main results of Geo Log's measurements have been published (Zilahi-Sebess and Szongoth, 2002). The present article therefore concentrates on borehole PTP4A, on the correlation of logging methods performed in both boreholes by AQUATEST, and on testing the degree to which the boreholes are connected.

The well logging equipment and probes used by AQUATEST in both boreholes were manufactured by the ELGI Institute, Budapest, Hungary. The graphic interpretation of the well logs was performed with the gdBase software, recently developed by the company GDSOFTWARE in Prague, Czech Republic.

Well logging measurement of borehole PTP4A

Borehole PTP4A was drilled with the same wire-line technology as borehole PTP3 (Maros et al. 2002). The first 30 m were drilled at a diameter of 112 mm, cased by a steel casing, and cemented. The rest of the borehole had a diameter of 76 mm. During the drilling, three measurements of several logging methods were carried out for checking the inclination and hydrogeological conditions of the borehole. The following set of methods was applied when the final depth was reached:

NATURAL GAMMA RAY LOG	NEUTRON LOG
GAMMA DENSITY LOG	ACOUSTIC LOG – VELOCITY + ATT
ELECTRICAL RESISTIVITY LOGS 16" + 64"	CALIPER LOG
TEMPERATURE LOG	FLUID-RESISTIVITY LOG WITH TRACER
INCLINOMETER LOG	METHOD OF PUMPING

The main results of the measurements are given in Fig. 1. Well logging data were processed by the gdBase software, which enables a variety of logging curves, computer interpretations, and conversions of raw data into physical units with the help of proper calibrations. The rock through which borehole PTP4A was drilled is mostly medium-grained biotite granite, very homogeneous and slightly fractured. The physical properties of this granite change due to variable degrees of alteration and fracturing. The results of these factors are physically very similar. The lithological profile was therefore differentiated according to degrees of total rock failure, which is the sum of the alteration and fracturing of the formation. Electrical resistivity logs are the most sensitive to fracturing or alteration, but this sensitivity is not always accurate. Better indications of real rock failures are given by neutron log, gamma density log, and acoustic log methods. The lithological profile in Fig. 1 therefore consists of a determination of the degree of granite disturbance. The alteration is the most extensive down to a depth of 60 m, and is combined with the fracturing of the granite. Down to a depth of 100 m the granite is partially altered and fractured. The granite in the section from 100 to 240 m is much less fractured. In the final section, from 240 to 300 m, the granite is again more fractured, though the fractures are impermeable and mostly filled with various materials. The rigidity of the granite increases significantly from approximately 100 m down to the bottom. This is apparent on curves from the neutron log and
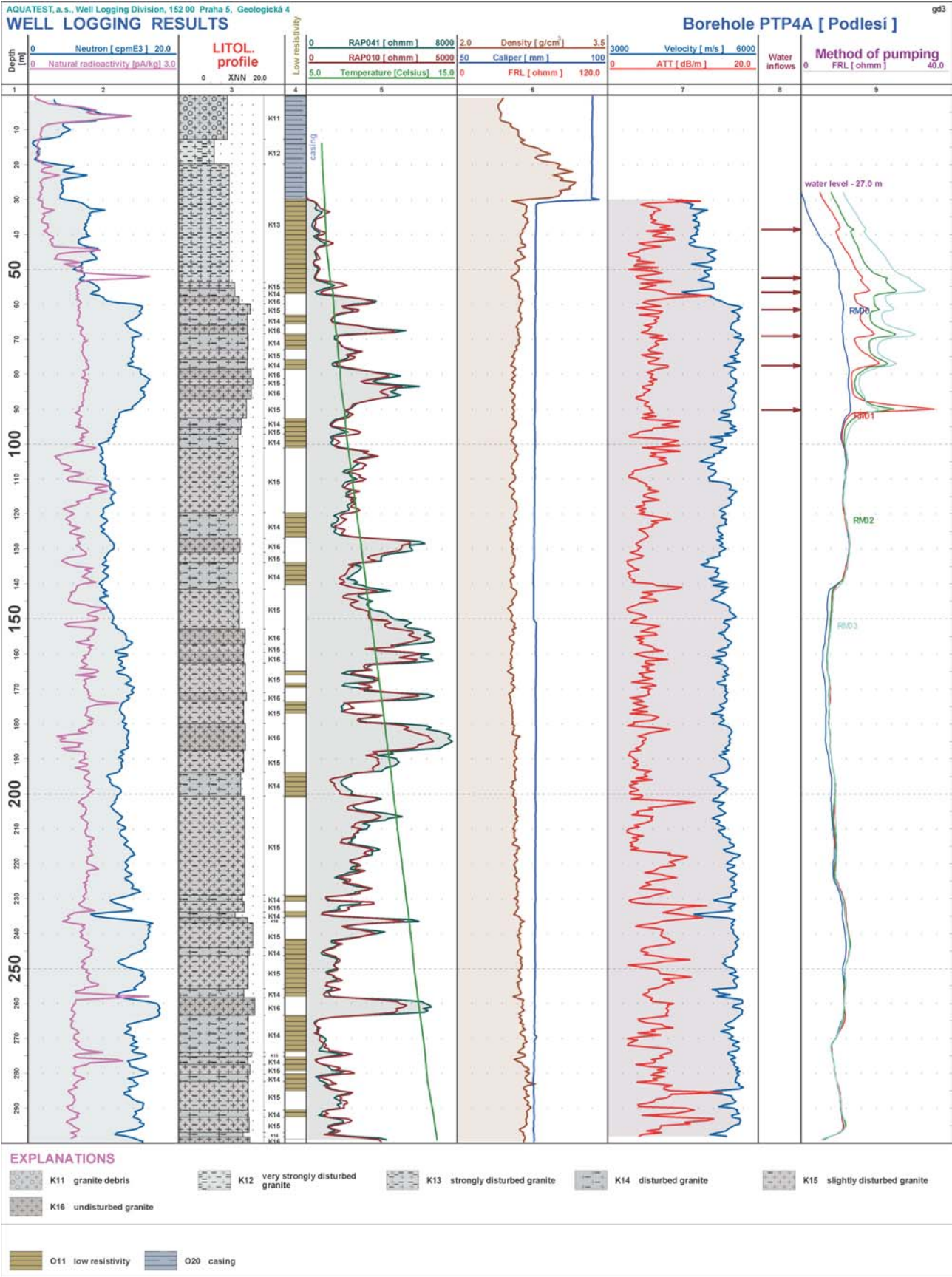
Figure 1. Well logging measurement in borehole PTP4A.

acoustic velocity log data. The permeability of granites in this section is minimal, as no water inflow was detected.

There were practically no cavities in the borehole wall according to the caliper log. The general dip of the borehole is about 1°, and the general direction of the dip is 247°. The deviation from the vertical at the final depth of 300 m was 5.34 m.

Borehole PTP4A intersected the water table 13.5 m below surface. The water's temperature was 6.0 °C at the water level and nearly 14.0 °C at the bottom. According to the fluid resistivity log, the water resistivity was about 100 ohmmetres. This is equivalent to very low total concentration of 70 mg/l. The so-called pumping method was used for determining the inflows of water. This method is based on the decrease of water resistivity in the borehole using NaCl as a tracer. The tracer concentration in the water should be approximately homogeneous throughout the entire borehole. The water is then pumped while fluid resistivity is recorded in appropriate time intervals. Water inflow can be easily detected in intervals during which the water resistivity is increasing. Most of the anomalies are proportional to the yield of water inflow. In borehole PTP4A there were four greater water inflows at the depths of 56.5 m, 69.0 m, 77.5 m, and 90.2 m. Three other water inflows were very small at the depths of 38.5 m, 52.5 m, and 61.5 m. All inflows are clearly visible on Fig. 1 in the last two columns. The water level during pumping was 27.0 m, and the total groundwater yield was Q = 0.05 l/s. This value is approximately the same as that calculated by the final measurement in the nearby borehole PTP3. The largest water inflows were later confirmed by a combination of well logging in PTP3 and hydraulic stress tests in PTP4A.

Correlation of logging methods in boreholes PTP3 and PTP4A

The correlation curves of the natural gamma logs, neutron logs, water inflows, electrical resistivity logs, and the velocities of longitudinal waves from acoustic logs measured in both boreholes are presented on Fig. 2. In each column curves representing the same methods at the same scale are differentiated by colour. No depth correction was made regarding the small difference between borehole levels. On the whole the correspondence between the curves is quite acceptable, though there is some variation between certain sections and methods. Although the boreholes are very close to each other, the correlation between the curves is perhaps not as high as would be expected. This is because the granite is generally fractured by three rectangular systems of fractures that intersect the boreholes at various angles. The best correlations are given by the methods that are less sensitive to small changes in the rocks, such as neutron log and the acoustic velocity of longitudinal waves. The most considerable differences appear in the electrical resistivity curves. An intermediate degree of correlation is shown by the natural gamma log and water inflow measurements. All significant water producing fractures occurred

in the upper part of the boreholes, with a maximum depth less than 100 m.

Positive differences between the curves are yellow, negative ones are grey.

Well logging in combination with hydraulic stress testing for verifying the hydrogeological connection between boreholes PTP3 and PTP4A

The surface distance between these boreholes is 10 m. The general dip of borehole PTP3 is 1.5°, and the general direction of the dip is 73°. Borehole PTP4A generally dips at 1.0°, with a general dip direction of 247°. Due to the nearly opposite directions of the borehole dips, the distance between the boreholes increases with depth. At a depth of 100 m the distance between them is 11 m, while at a depth of 300 m they are approximately 16 m apart.

The connection of fractures between the boreholes was verified by a combination of well logging measurement and simultaneous hydraulic stress testing. The existence of the connecting fractures was confirmed by the first set of hydraulic stress tests (HST) conducted in borehole PTP4A. All significant water producing fractures, determined from well logging, were tested by HST. The fact that there was a nearly immediate reaction of the water level in borehole PTP3 when the HST tests were started can be considered as proof that the two boreholes are connected by fractures. During the HST verification of the main water inflows in borehole PTP4A at depths of 56.5 m, 69.0 m, 77.5 m, and 90.2 m, the water level in PTP3 changed quickly and significantly. Packers were installed in each of these permeable fractures. Salt solution was pumped into the packer, and the hydraulic pressure was increased. In borehole PTP3, the first fluid-resistivity record was taken before the first connection test. There were no technical means for replacing the salt water in borehole PTP3. The water resistivity was high in the upper part, while from 52 m downward it dropped to lower values. The shape of the first fluid resistivity curve is a result of salting the water during the final logging of the whole complex of methods, and testing the borehole by HST.

Tracer test No. 1 with HST packers in the interval 76.5–78.5 m:

On the right side of Fig. 3 the results of the pumping method are given for the packer position in the interval 76.5–78.5 m. In borehole PTP4A, salt solution was pressed through the packer and into the rock under a pressure of only 0.5 MPa. In borehole PTP3 (left side of Fig. 3), fluid resistivity records were taken in 6–10 minute time intervals at the depth interval of 70–100 m, to register the arrival of the NaCl solution from PTP4A. The anomaly in the third curve, at a depth of 78.0 m and 25 minutes after the start of the test, is considerable and evidently represented salt solution coming from PTP4A. Based on the calculation of the distance between the boreholes and the time of measurement, the interval velocity of the salt solution was about
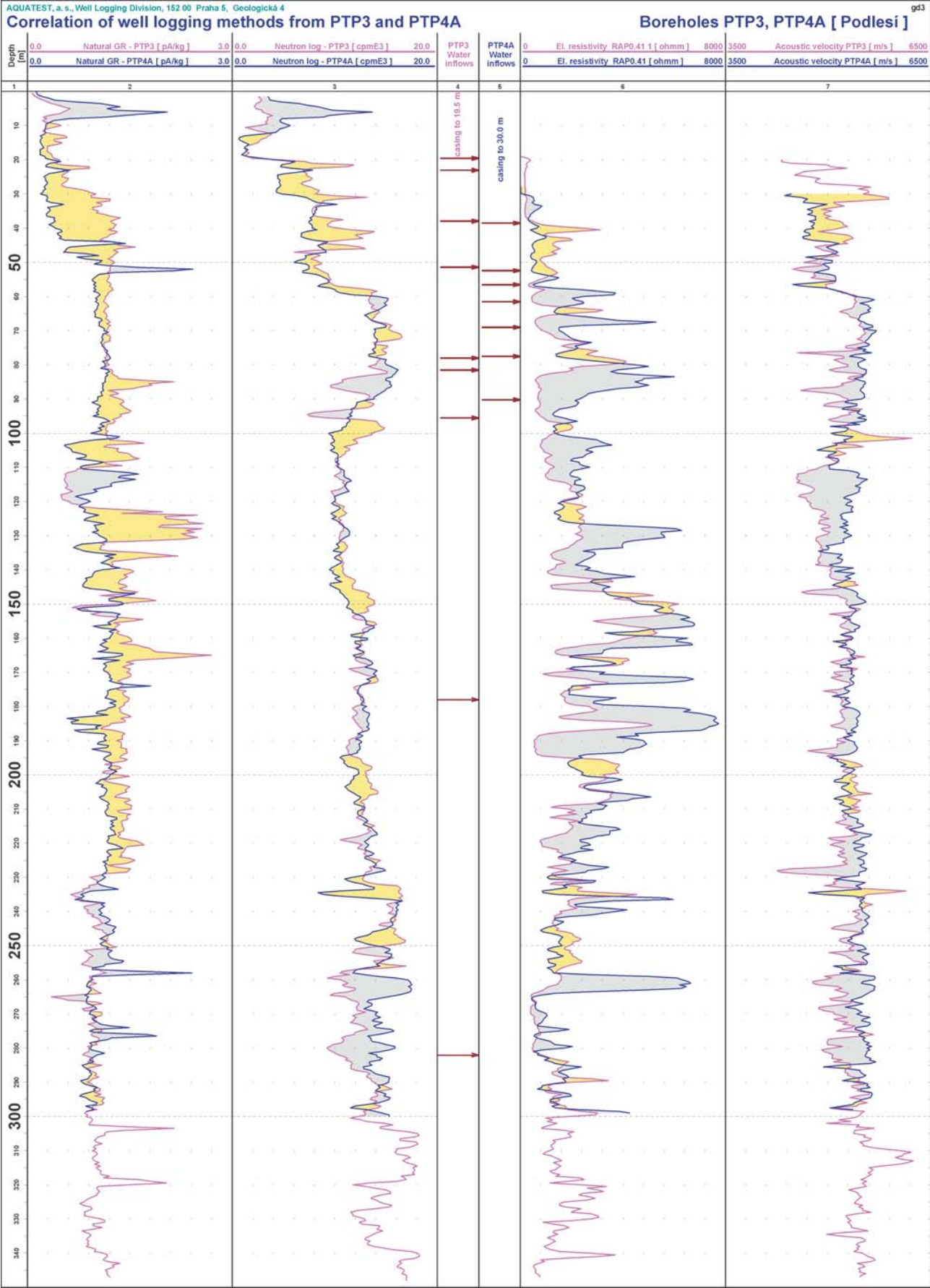
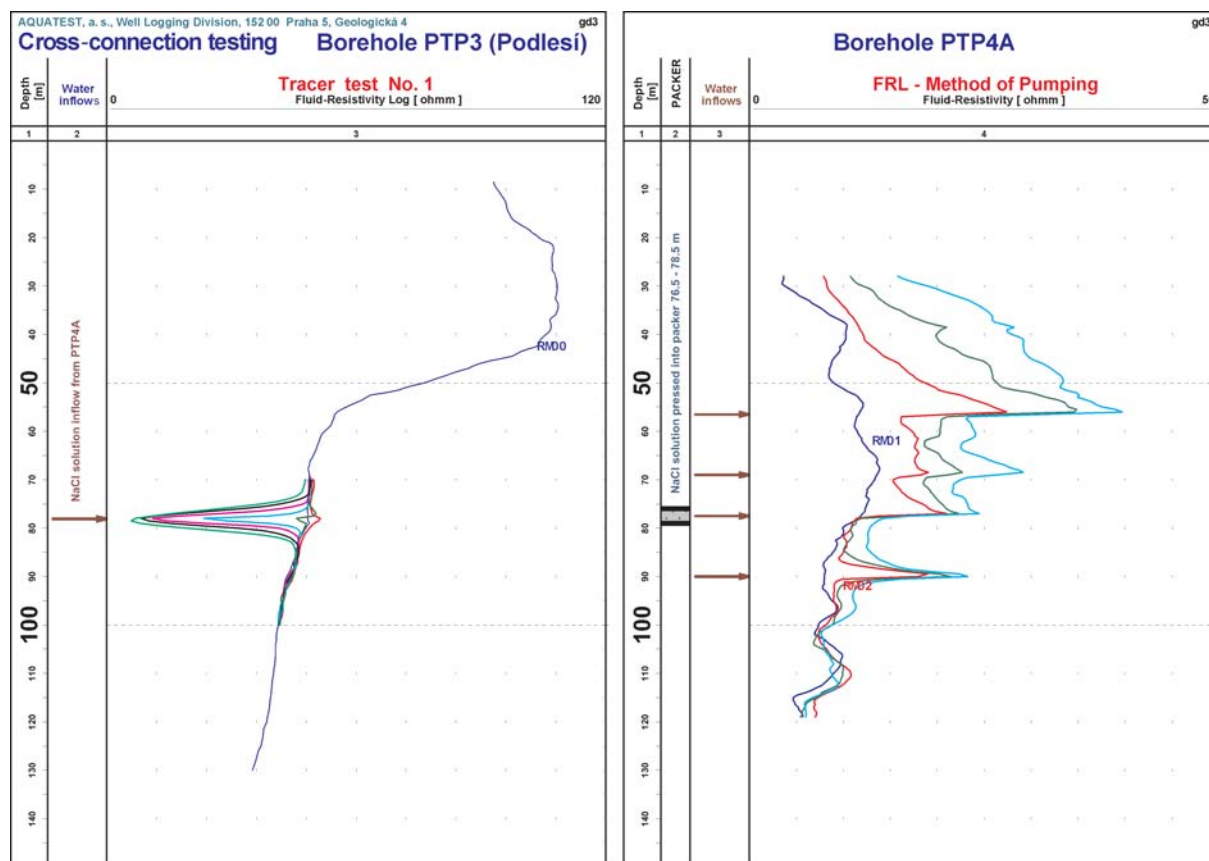Figure 2. Correlation of gamma, neutron, resistivity, and acoustic logs from PTP3 and PTP4A.

Figure 3. Tracer test No. 1 in PTP3, combined with HST in PTP4A, packer in 76.5–78.5 m.
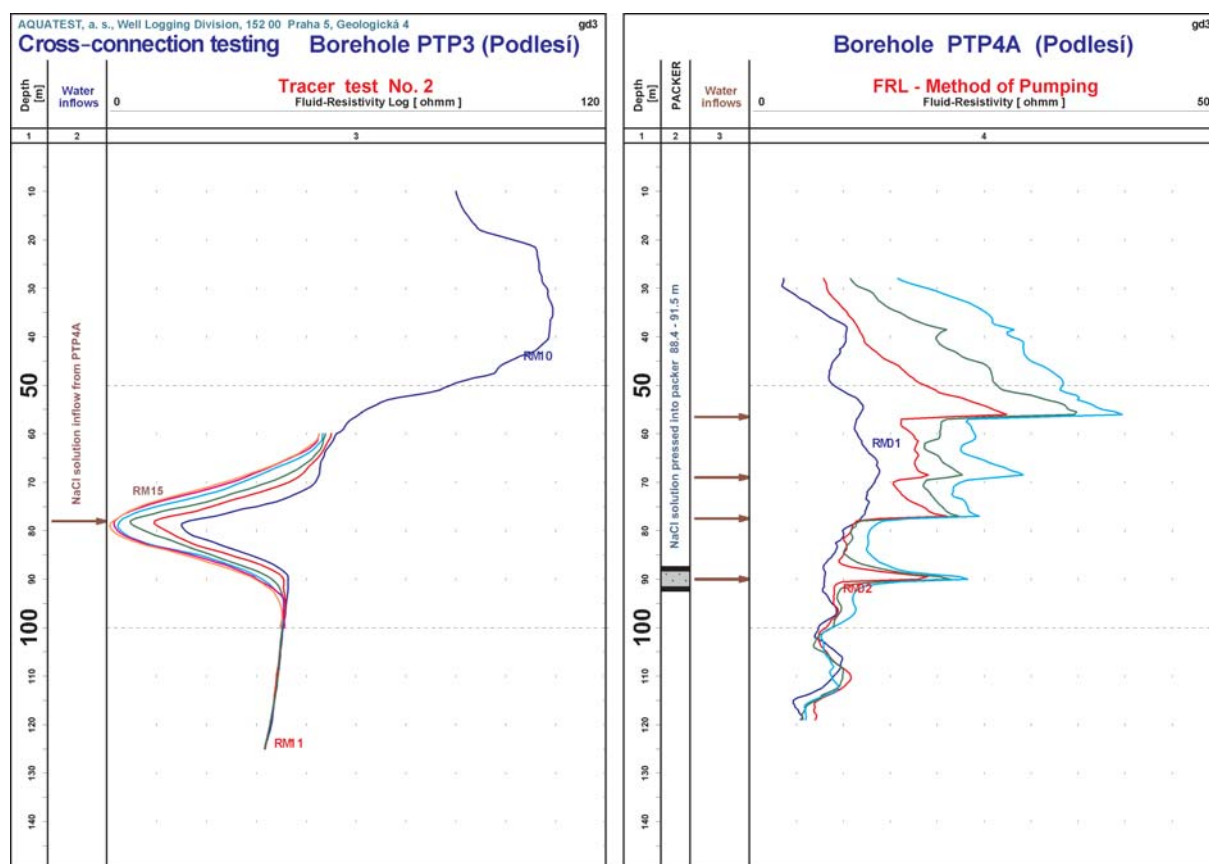

Figure 4. Tracer test No. 2 in PTP3, combined with HST in PTP4A, packer at 88.4–91.5 m.
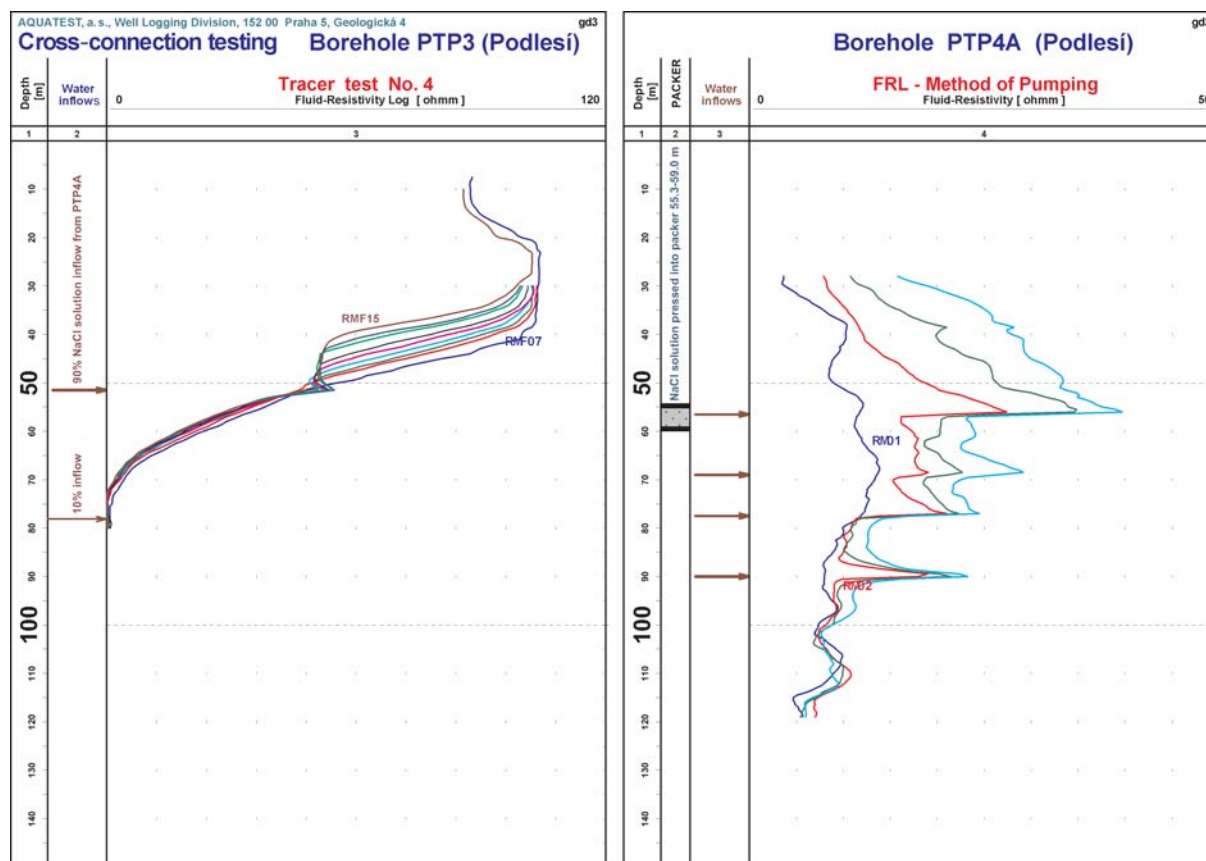
Figure 5. Tracer test No. 4 in PTP3, combined with HST in PTP4A, packer at 55.3–59.0 m.

0.5 m/minute. During this first tracer test the water level in PTP3 increased quickly, reaching a maximum speed of 0.04 m/minute. The connection between the boreholes was approximately at the same depth level.

Tracer test No. 2 with HST packers in the interval 88.4–91.5 m:

The results of the pumping method are given on the right side of Fig. 4 for the packer positioned in the interval 88.4–91.5 m. In borehole PTP4A, salt solution was pressed through the packer into the rock under a pressure of only 0.5 MPa. In borehole PTP3 (the left side of Fig. 4), the fluid resistivity records were taken in the depth interval of 60–125 m. Salt water came into PTP3 by the same fracture at the depth of 78.0 m as in the first test. This seems to confirm the existence of highly permeable vertical fractures that short-cut the horizontal ones. Soon after starting the HST test, high concentrations of salt solution entered borehole PTP3, as the connection between the boreholes is partly based on the same fractures. During a second tracer test, the water level in PTP3 went up more slowly than in the first test, at a maximum speed of 0.02 m/minute.

Tracer test No. 3 with HST packers in the interval 66.5–70.4 m:

In borehole PTP4A, salt solution was pressed through a packer and into the rock under a pressure of only 0.5 MPa.

In borehole PTP3, fluid resistivity records were taken at the depth interval of 40–90 m in 6–15 minute time intervals. All records show a shifting of the curves from fractures at 78.0 m and upwards. The reaction of the curves was again very fast for the same reason as in the previous test. During this third tracer test the water level in PTP3 increased with a maximum speed of 0.04 m/minute.

Tracer test No. 4 with HST packers in the interval 55.3–59.0 m:

The results of the pumping method are given on the right side of Fig. 5 for the packer positioned in the interval of 55.3–59.0 m. In borehole PTP4A salt solution was pressed through the packer and into the rock under a pressure of only 0.5 MPa. In borehole PTP3, fluid resistivity records were taken at the depth interval of 30–80 m, in 8–25 minute time intervals (the left side on Fig. 5). All records show the shifting of the curves from fractures at 51.5 m upwards. Approximately 90% of the pressurized salt water entered the borehole through a fracture at a depth of 51.5 m. The remaining 10% entered the borehole again by a fracture at 78.5 m. The changes in the logging curves were again very fast, which indicates the fast movement of the solution in the fracture system. The connections between the boreholes were mostly at the same depth level, and only partly through the system of vertical fractures to a depth of 78.5 m. During the fourth tracer test, the water level in PTP3 again increased quickly with a maximum speed of 0.04 m/minute.

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Conclusion

Well logging conducted in boreholes PTP3 and PTP4A brought informative results about the physical properties of the granite formation in which they are drilled, such as the depth ranges of the fractured parts of the granite, the water inflows, and the degree of hydraulic connection between the boreholes. The degree of correlation between both boreholes is less than expected, in contrast to the relatively homogenous character of the granite. The main reason for this is that the fracture system intersects the boreholes at various angles, which is characteristic of granites. Some methods, such as electrical resistivity log, were more influenced by the presence of fractures than others like neutron log, gamma log, and acoustic log.

The four most important water inflows, identified during the initial logging of borehole PTP4A, were tested by hydraulic stress testing in combination with well logging measurements in borehole PTP3. Salt solution was used as a tracer for identifying the connecting fractures between the boreholes. The quick communication of underground water was proven during the combined hydraulic stress test measurements in PTP4A and the simultaneous well logging in PTP3. The average velocity of the groundwater flow was approximately 0.5 m per minute under slightly increased pressure during HST. The boreholes are connected by horizontal and vertical fractures. The fracture connection between the two boreholes was confirmed at two main water-producing fractures at depths of 51.5 m and 78.5 m. The results of these tests provide proof of the existence of highly permeable vertical fractures within the short distance between the two boreholes. Such information could not be easily gained from other types of testing. The existence of highly permeable vertical fractures must be considered in the construction of mathematical models of fractured rock formations. At the end of these measurements we recommended replacing the salt water in both boreholes with pure water.

Combination of tracer logging method with hydraulic stress tests proved to be competent and can be used in similar geological formations. In the locality Podlesí is another borehole PTP-5 planned and we suppose simultaneous tracer logging in PTP-3 and PTP-4A together with hydraulic stress tests in PTP-5.

References

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