

Geophysical techniques applied to aquifer hydrodynamics

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Abstract - The Department of Applied Geophysics, Charles University in Prague, has contributed to the solution of hydrogeologic tasks since the 1960s. At present, research on well log analysis techniques is focused on providing a basis for protection and optimization of withdrawals from both surface and ground waters. Well-logging methods applied to hydrogeologic formation evaluation provide information on the reservoir properties of the penetrated rocks, groundwater quality and groundwater flow. This manuscript presents a discussion of some geophysical techniques used for logging fluid-movement. In addition, application and verification of the methods under various geologic and hydrogeologic conditions are provided to demonstrate the effectiveness of logging for hydrogeological investigations.

1. Introduction

The Department of Applied Geophysics, Faculty of Natural Sciences, Charles University in Prague, teaches and carries out research activities in all fundamental geophysical methods. Gravimetric methods, magnetometric methods, radiometric methods and methods of nuclear geophysics, geoelectrical methods, seismic methods, geothermal methods, and logging techniques are applied to geological mapping, in prospecting for raw materials, in structural geology, hydrogeology and engineering geology, and in a wide range of studies to monitor and protect the natural environment.

Research activities performed by carrying out surface and subsurface (logging) measurements were traditionally oriented towards the exploration of raw materials, geological mapping, search for water resources and studies on the physical and technological properties of rocks. Recently, they have been enlarged to include the application of geophysical methods

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to regional and local monitoring of various fields of the natural environment: assessment of contamination risks; investigation of geological basements for the construction of nuclear power plants and other big constructions; investigation of the Earth's disturbed zones showing a relation to health risk; studies on the flow and contamination of underground water.

2. Surface geophysical methods solving hydrogeological tasks

Geophysical methods consist in the application of physical principles and measurements to record certain physical parameters which can be interpreted to determine some characteristics for sediments and the pore fluid. It is imperative to understand that all geophysical methods measure a physical parameter, and not directly any of the rock characteristics. The question is, how to translate the physical parameters into rock characteristics.

Geophysical data demand an interpretation based on empirical relations. It can be stated that geophysical methods are indirect methods. The relationships - if any - between the physical parameters and the characteristics of the rock or pore fluid, must be empirical. The mathematical interpretation model always involves some idealizations concerning the rock or sediment formation (homogeneity, isotropy, horizontal bedding, etc.). In the real Earth these assumptions are seldom fulfilled, which introduces uncertainty into the interpretation. It is often important not only to use one method but to combine the various methods in a suitable way.

The only direct access to the subsurface layers is through a borehole and careful sampling. When the drilling data and sampling data are correlated with geophysical (namely logging) data, the hydrogeological and geological evaluation becomes much more detailed.

2.1. Geoelectric methods

The wide variety of geoelectric methods as well as the dependence of the studied electrical fields on various physical parameters, make geoelectric methods potentially useful in solving a wide spectrum of prospecting and investigation problems when studying aquifers. The most frequently used methods are the following:

- DC resistivity methods are often applied in both modifications, i.e. resistivity profiling and sounding;
- the self-potential method (the spontaneous polarization method, SP) can be used to determine the amplitude of the filtration potential at the ground surface. The SP method is particularly useful in the course of investigation of fracturing and karst zones in karst regions;
- electromagnetic methods are used for shallow investigation of aquifers. It is economical to use a very low frequency (VLF) method. On the other hand, the high frequency method, namely the georadar (GPR) technique which, because of its advantages: speed, resolution and space coverage, has been widely introduced for detecting shallow karst cavities and heterogeneities as well as hydrocarbon pollution. Another high frequency method, Time

domain reflectometry (TDR), originally laboratory technique for the determination of electric permittivity of organic liquids, has been developed as a geophysical method from estimation of soil permittivity and consequently moisture content.

2.2. Seismic methods

Seismic methods are particularly useful in solving hydrogeological and engineering geological problems, investigating geological conditions at shallow depths. When studying the characteristics of bedrock, the velocity of propagation of the elastic longitudinal waves represents the principal parameter reflecting, firstly, the mechanical situation of a rock massif (stress, intensity of weathering, etc.) then, the composition of rocks, as well.

2.3. Radiometric methods

Radiometry has been primarily used for geological mapping to differentiate various types of rocks, to trace their contacts, etc. Basic rocks generally contain less radioactive elements than acid rocks. The variable overburden thickness and the weathered zone play a key role in mapping the tectonic zones. Gamma radiation penetrates only about 1 m of rocks. In places, where tectonic zones approach the Earth's surface all rocks are disintegrated, which results in greater overburden thickness, causing a more intensive shielding of gamma radiation.

Under favourable conditions tectonic dislocations and zones of fractured and disintegrated rocks exhibit positive anomalies due to higher emanation, i.e. increased concentration of radioactive elements in the soilair. Radioactive gases primarily emanate in rocks along weakened zones. The survey was conducted using emanometry and other geophysical (or geochemical) methods for which samples of soilair are pumped from 0.2 - 0.5 m deep holes.

2.4. Other geophysical methods

Geophysical methods are applied to obtain knowledge on the geological structure of the area investigated. At this stage more or less all geophysical methods are helpful.

In regional surveys, ground gravity and magnetic methods are commonly used. Micro-gravimetry (detailed gravity measurements with high precision) was used for special tasks, namely in karst regions.

If the fracture zones serve as groundwater discharge sites, then they also exhibit geothermal anomalies which are remarkably intensive in the case of thermal waters. Geothermic surveying is conducted by means of electrical thermistor thermometers. Their accuracy reaches 0.1 °C and they are introduced into holes up to 2 m in depth.

3. Well logging

The term well-logging refers to a set of geophysical methods applied to the assessment of the physical properties of rocks and fluids filling the borehole and pores and/or fractures of the rock, the technical inspection of boreholes, and the recognition of basic geological conditions in the rock complexes penetrated by drilling. Various technical and blasting operations are also often carried out by logging services. Valid well logs, correctly interpreted, can be used to reduce future drilling costs by guiding the location, proper drilling, and construction of test holes and production or disposal of wells. Well logging also enables the vertical and horizontal extrapolation of data derived from drill holes.

Geophysical well logging can provide continuous objective records with values that are consistent from well to well and from time to time, if the equipment is properly calibrated and standardized. In contrast to uninterrupted geophysical logs, samples of rock or fluid almost never provide continuous data. Continuous sampling, added to the subsequent analysis of enough samples to be statistically meaningful, costs much more than most logging programs. Logging techniques also permit time-lapse measurements to observe changes in a dynamic system. Changes in both fluid and rock characteristics and well construction caused by pumping or injection can be determined by periodic logging. Radiation logs and, under some conditions, acoustic logs are unique in providing data on aquifers through casing.

Complex logging methods are chosen to construct a lithological profile of the location of permeable layers and the determination of porosity controlled by geological conditions of the area under study (built by sediments with different degrees of cementation, by igneous and metamorphic rocks) and by the type of reservoir rock (with percolation or fracture porosity).

In clastic sediments, i.e. dirty sands or dirty sandstones, the task is to define the basic lithological type related to the problem of determining the clay content. The curves of spontaneous polarization (SP), of gamma ray log (GR), of resistivity (Ra) and sometimes also of neutron log (NL) are considered indicators of clay content.

Porosity is often determined by neutron-neutron logging. The compensated density gamma-gamma log or compensated acoustic log can also be employed to determine porosity.

4. Hydrologging approaches: fluid-movement logging

The methods dealing with borehole fluid properties are applied only in clean wells where mud has been replaced by water. Under these conditions, changes in the physical properties of the borehole fluids reflect the properties of the formation water only. The variation of these properties in boreholes as a function of depth may be obtained using logging methods.

Fluid-movement logging includes all techniques for measuring natural and/or artificially induced flow within a single borehole.

The simplest way of measuring groundwater flow rates in boreholes is by propeller flow meters. Vertical and horizontal flow meters are used to obtain data on the direction and velocity of groundwater in boreholes under both natural and forced gradient (pump-test) conditions. This

technique is applicable to groundwater velocities down to 10^{-3} m/s. Taking into account their sensitivity limit, their use is very restricted because flow rates in water wells and monitoring boreholes are usually lower. For this reason, vertical flow rates are often determined indirectly from the vertical velocity W (m/s) and well radius r (m) values.

The vertical velocity W is generally determined from temporal plots of fluid properties following the injection of a tracer into the well bore. The water entering the well or injected into the well creates a physical boundary whose vertical displacement according to the moving water can be registered perfectly on the temporal plots of fluid resistivity, photometry or temperature log.

The configuration of the measured time-series curves of fluid resistivity, photometry and temperature shows whether there is a horizontal filtration, across the borehole (which would be manifested by an increase of the measured values in time in the same depth interval), or a vertical flow; in this case, the boundary between pure and marked fluid moves in time along the vertical axis of the borehole.

Photometric measurements in wells aim to determine the attenuation of the luminous flux, between the source of light radiation and the photometric cell. The flux impinges on a photovoltaic cell after it has passed through the fluid to be measured. Cell illumination depends on the absorption properties of the fluid, i.e. on the intensity of colouring, or on the amount of the dispersed particles. The substance used for making dye marks (Brilliant Blue FCF, type E 133) has the food A-test so that it can be used in drinking water.

The vertical flow rates Q are then calculated by the relation:

$$Q = \pi \cdot r^2 \cdot W \quad (m^3 \cdot s^{-1}), \quad (1)$$

where the well radius r can be obtained from the caliper log.

The yield of an aquifer can also be determined using the dilution method, originally published by Grinbaum (1965). Increasing the concentration of a tracer in a well from the original value C_0 to C_1 and measuring the time changes of the tracer concentration C_t we can calculate the specific yield q_i for any 1 m interval of an aquifer using the relation:

$$q_i = (\pi \cdot r^2 / \Delta t) \ln \{(C_1 - C_0) / (C_t - C_0)\}, \quad (m^3 \cdot s^{-1}), \quad (2)$$

considering the well radius r (m) and the time Δt (s) from the moment of tracer addition. The total yield Q_i of an aquifer is then given by the sum of q_i through the inflow interval.

4.1. Evaluation of the fluid movement log

Inflow sites, loss sites and sections with vertical movement of water are usually clearly indicated on high resolution temperature logs, and even striking on temperature gradient logs (differential temperature logs). The depth intervals, where natural movement of the water occurs along the borehole axis, are manifested on temperature logs by a constant or nearly constant temperature.

If the mineralization (and thus also the resistivity) of individual inflows is not the same, the inflow sites appear on the fluid resistivity logs, and often on the photometry logs because of insufficient cleaning of the borehole from the original mud. The sites of inflows and losses can be emphasized by introducing sodium chloride into the borehole in order to decrease the resistivity of the water in the borehole. The inflow sites then appear on the fluid resistivity log curves as sudden increases of fluid resistivity, as pure groundwater usually exhibits resistivities in the range of 20 – 100 ohm·m.

Log-derived hydraulic conductivities Kf , and consequently transmissivities T , are based on the theory of the steady-state water flow to the ideal water well. For the homogeneous, confined aquifer penetrated by a water well, and for steady-state radial flow to the well during constant pumping or from the well during constant injection, the following relation of Dupuit is valid:

$$Kf = [Q \cdot \ln(R/r)] / [2\pi \cdot H \cdot \Delta S] \quad (m \cdot s^{-1}), \quad (3)$$

where ΔS [m] is the difference in the water levels in the well before the start of the hydrodynamic test and during the test, r [m] is the well radius and R [m] is the radius to the (injection) cone contour effect.

It was deduced (Grinbaum, 1965) that for a small water level difference ΔS the following relation (4) is also valid for both confined and unconfined aquifers:

$$Kf = Q / (H \cdot \Delta S) \quad (m \cdot s^{-1}), \quad (4)$$

For the log-derived evaluation of the hydraulic conductivity of an aquifer, the parameters Q , H , and ΔS occurring in the Eq. (4) have to be determined. The knowledge of ΔS conditioned by precise measurement of the water level in the water, well before and during the hydrodynamical test, is relatively easy. The thickness H_i and the yield or water loss Q_i of individual aquifers are evaluated from the diagram representing the depth changes of vertical flow rates Q during the hydrodynamic test. The vertical flow rate constant remains within impermeable intervals; within a permeable horizon linear changes in the vertical flow rates are observed (if the horizon is homogeneously permeable), then $Q = Q_i - Q_{i-1}$ corresponding to the yield or water loss Q_i of the aquifer.

Water level drawdown ΔD caused by the pumping test corresponds to ΔS only if one confined aquifer appears in the borehole section. If, more confined aquifers with different piezometric levels are penetrated by the water well, two hydrodynamic tests under different yields of pumped or injected water must be carried out in order to determine ΔS_i . The piezometric level of each aquifer is taken as a limit of ΔD^j for $Q_i^j \rightarrow 0$ supposing that the relation between the yield of an aquifer Q_i^j and steady state water level D^j during the pumping test is linear.

Transmissivity T of an aquifer is tied to its hydraulic conductivity Kf and thickness H through the relation:

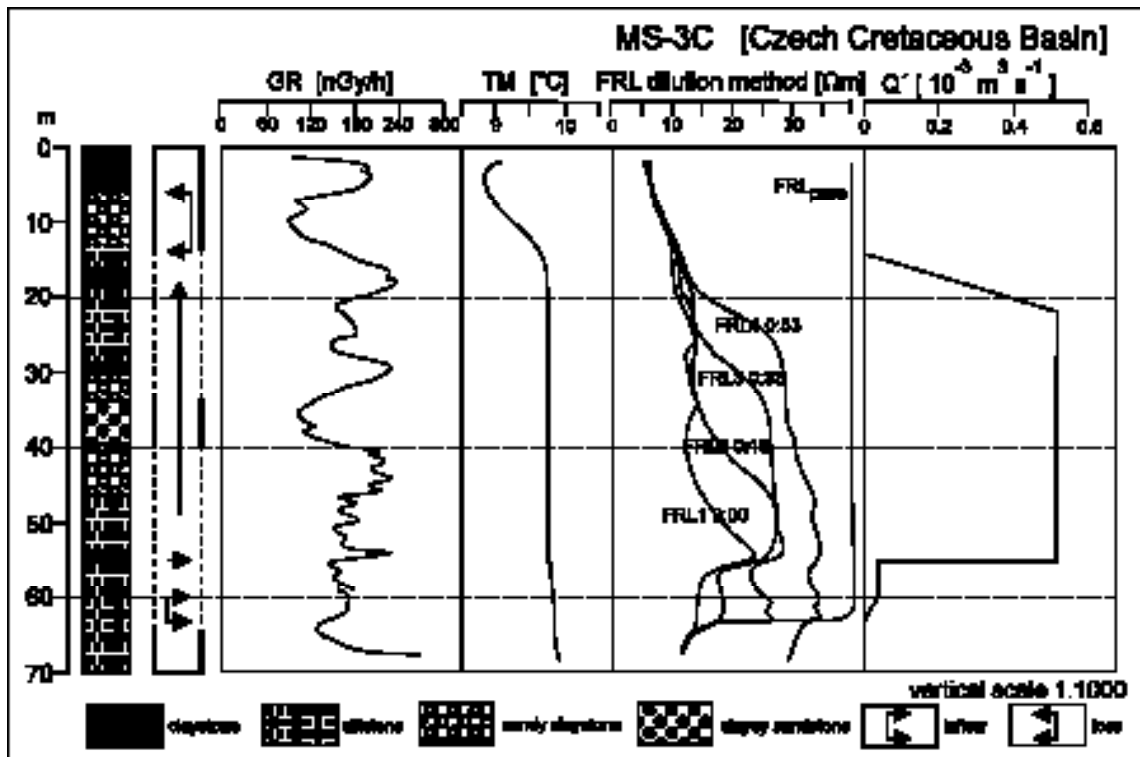
$$T = Kf \cdot H \quad (m^2 \cdot s^{-1}). \quad (5)$$

5. Examples of application

5.1. Hydrologic prospecting in sedimentary formations

The fluid circulation system in well MS-3C was studied using the tracer dilution method (Fig. 1). The tracer used was NaCl and temporal fluid resistivity logs FRL were recorded. Their configuration shows the water enters the casing at depths of 53 - 55 m and of 60 - 62 m with yields Q , prior to leaking under the shoe casing of the well and into the outside space at a depth interval 6-14 m (see also the TM log). This illustrates the poor cementing of the casing shoe.

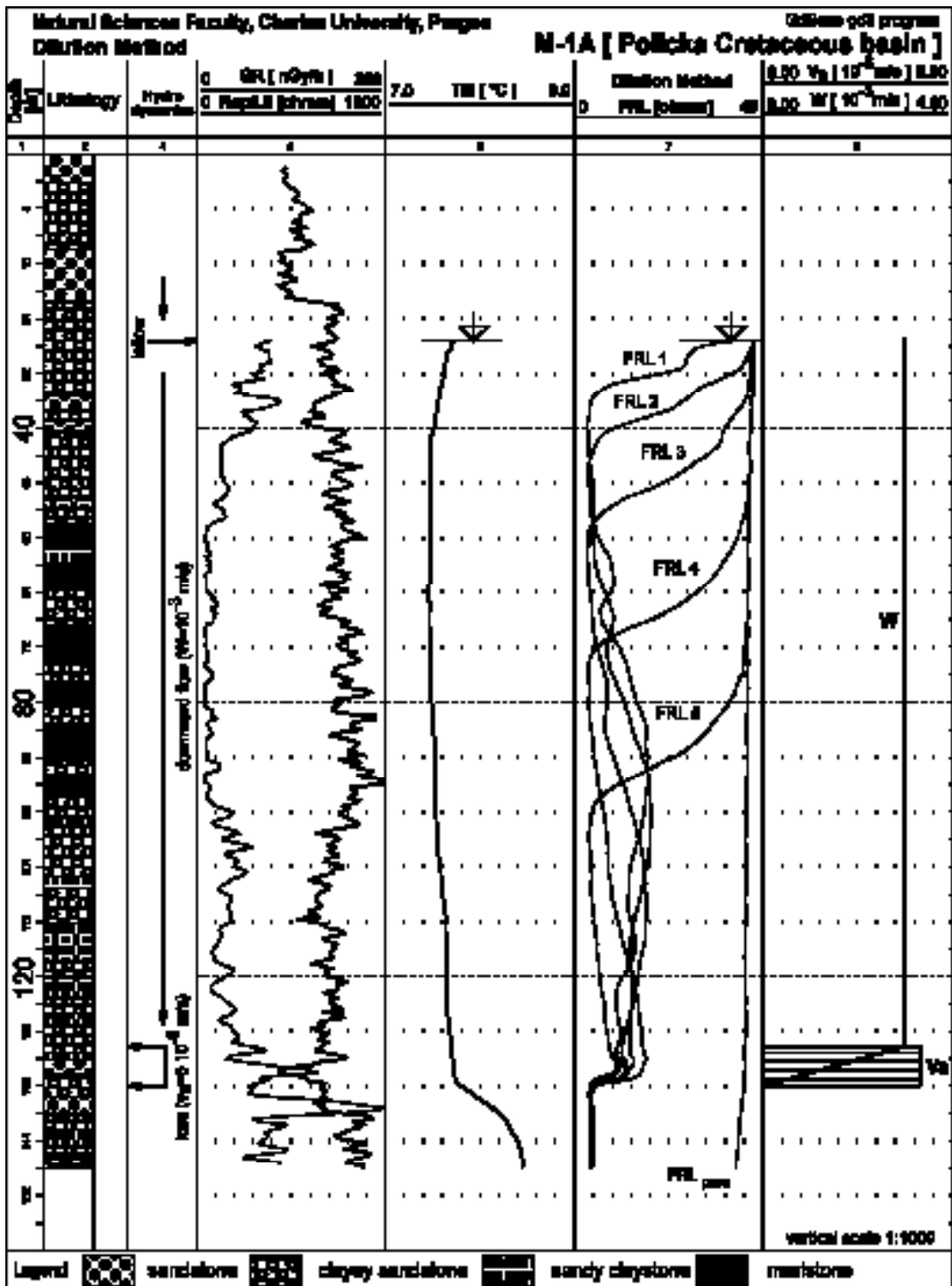
The second example illustrates another case in water circulation systems (Fig. 2). In the well M-1A an intensive downward flow with an inflow above the water table was observed after tapping the aquifer A2 at the depth of 128 - 136 m. The temporal set of fluid movement log (dilution method using salt as a tracer) exhibits both water movements: the horizontal at a depth of 130 - 136 m and the vertical from the water table at a depth of 28 m down to the horizon at 130 - 136 m, where it is absorbed.



Legend:

GR - gamma ray log, TM - temperature log, FRL - sets of the time sequence of fluid resistivity logs (Nos. 1-4: records after the fluid had been marked by sodium chloride in the well), $FRL 1$ - downwards, $FRL 2$ - upwards, Q - graph of the volumetric flow rate.

Fig. 1 - Well-log analysis in the MS-3C (Miletínek) well (Cretaceous of Bohemia).



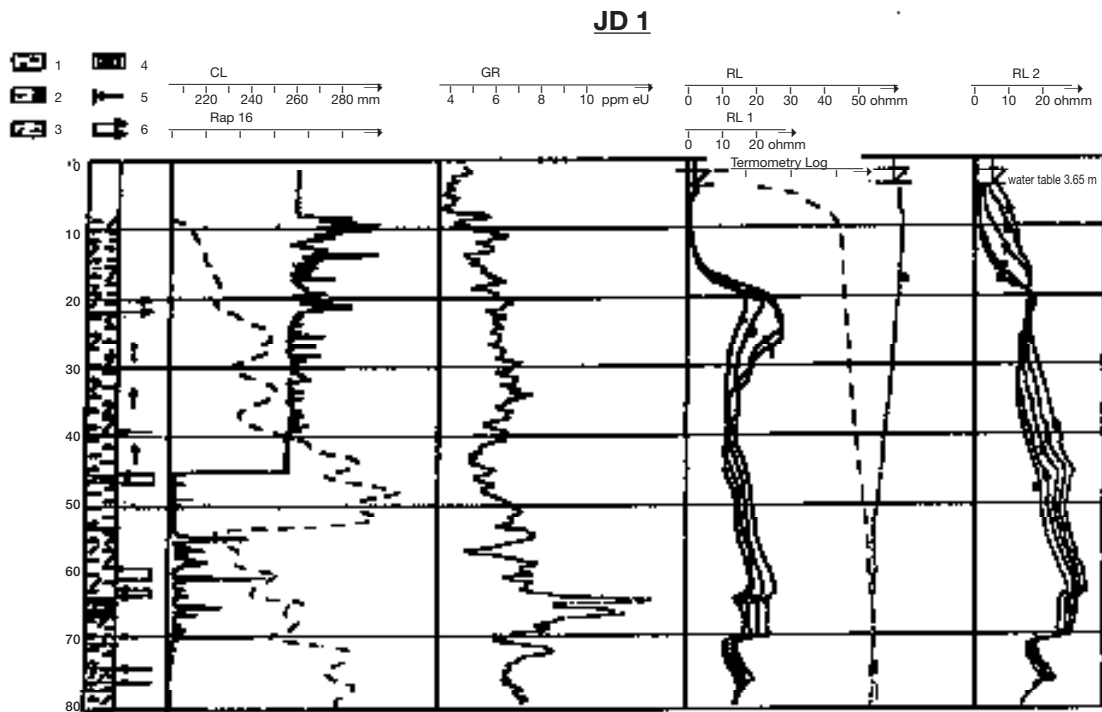
Legend:

GR - gamma ray log, Rap 0.8 - resistivity log, TM - temperature log, FRL - set of the time sequence of fluid resistivity log, Va - apparent velocity of horizontal water flow, W - velocity of vertical movement of water in the borehole.

Fig. 2 - Well-log analysis in the M-1A borehole.

5.2. Hydrologic prospection in hard rocks

Fig. 3 presents an example of geophysical logs for a borehole penetrating gneiss. Quaternary sediments occur in the cased depth interval 0 - 12 m. The two aquifers have been in the gneiss unit: one at a depth of 20 - 22 m and the other is identified by water entering the well at the depths of 77 m, 75.5 m, 69 m, 63 m, 60 m and 45 m. The deeper aquifer has the higher piezometric head. This explains why the water flows upward through the borehole at a flow rate of 0.1 l/s. Pumping yield for this well is 1 l/s. The agreement between hydrogeological tests and geophysical measurements is exceptionally good.



Legend:

CL - caliper, *GR* - gamma ray log, *Rap 16* - resistivity log carried out by normal probes with spacing 16", *TL* - temperature log, *RL* - fluid resistivity log under natural conditions (record 0), *RL 1* - sets of the time series of fluid resistivity logs after treating the water in the well with sodium chloride, Nos. 1 - 4 without pumping, *RL 2* - sets of the time series of fluid resistivity log during pumping (Nos. 5 - 9).

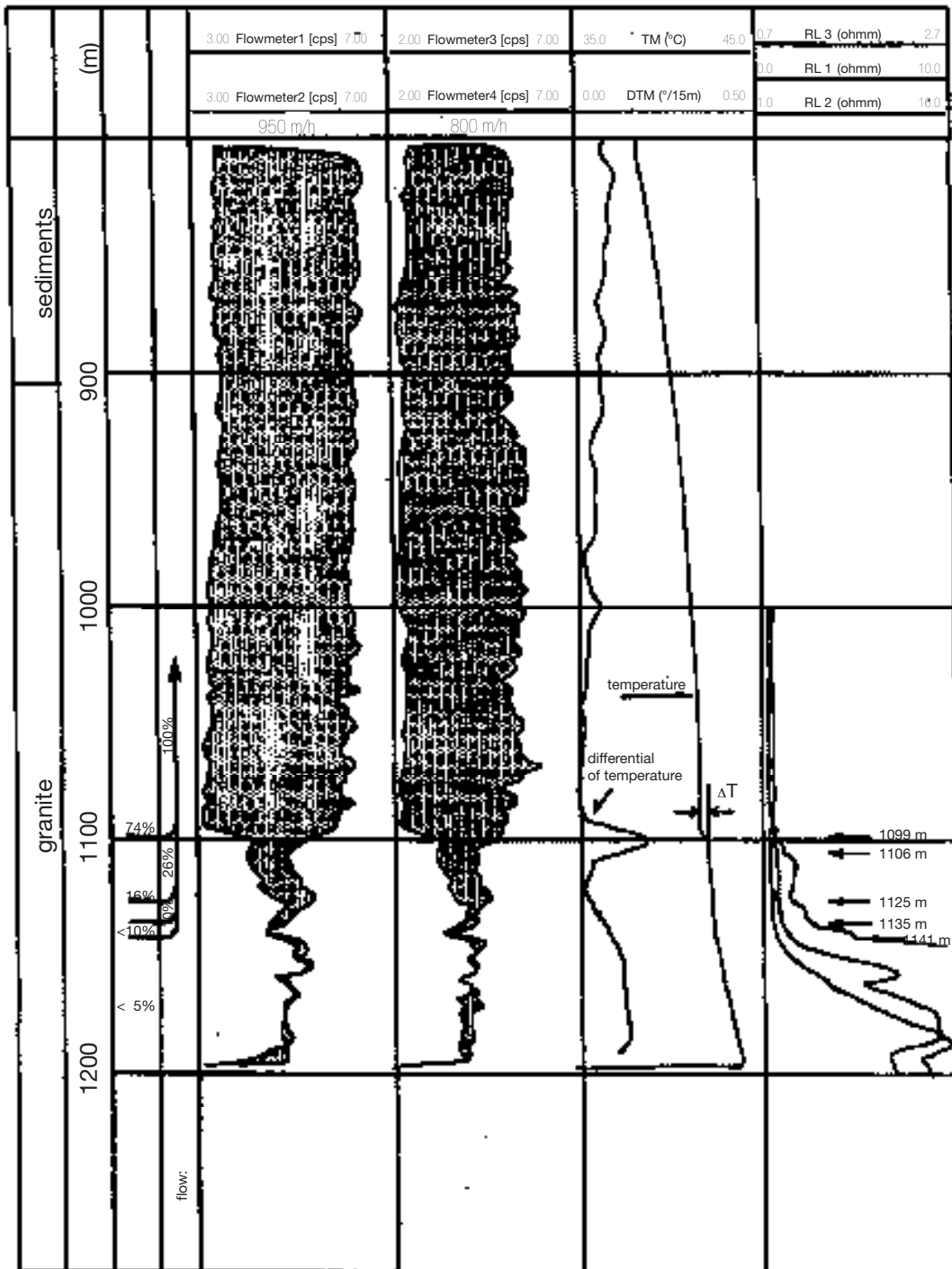
1 - gneisses, 2 - silicified gneisses, 3 - low fractured gneisses, 4 - pegmatite, 5 - water inflow, 6 - interval of water leakage.

Fig. 3 - Well-log analysis in the well JD-1 Krizanov - Jakubovicky Dvùr , Moldanubicum of Bohemia.

5.3. Hydrologic investigation in deep structural wells

The structural boreholes have facilitated the evaluation of the deep-water circulation, if any exists. An example from the borehole Louny LN-1 (Fig. 4) is presented. The well penetrated 900 m of terrigenous sediments (carboniferous age) and interfered with artesian water sources at the

Borehole LN 1 - LOUNY



Legend:

TM - temperature log, DTM - differential of temperature, RL - fluid resistivity log.

Fig. 4 - Well-log analysis in the well LN 1 (Louny).

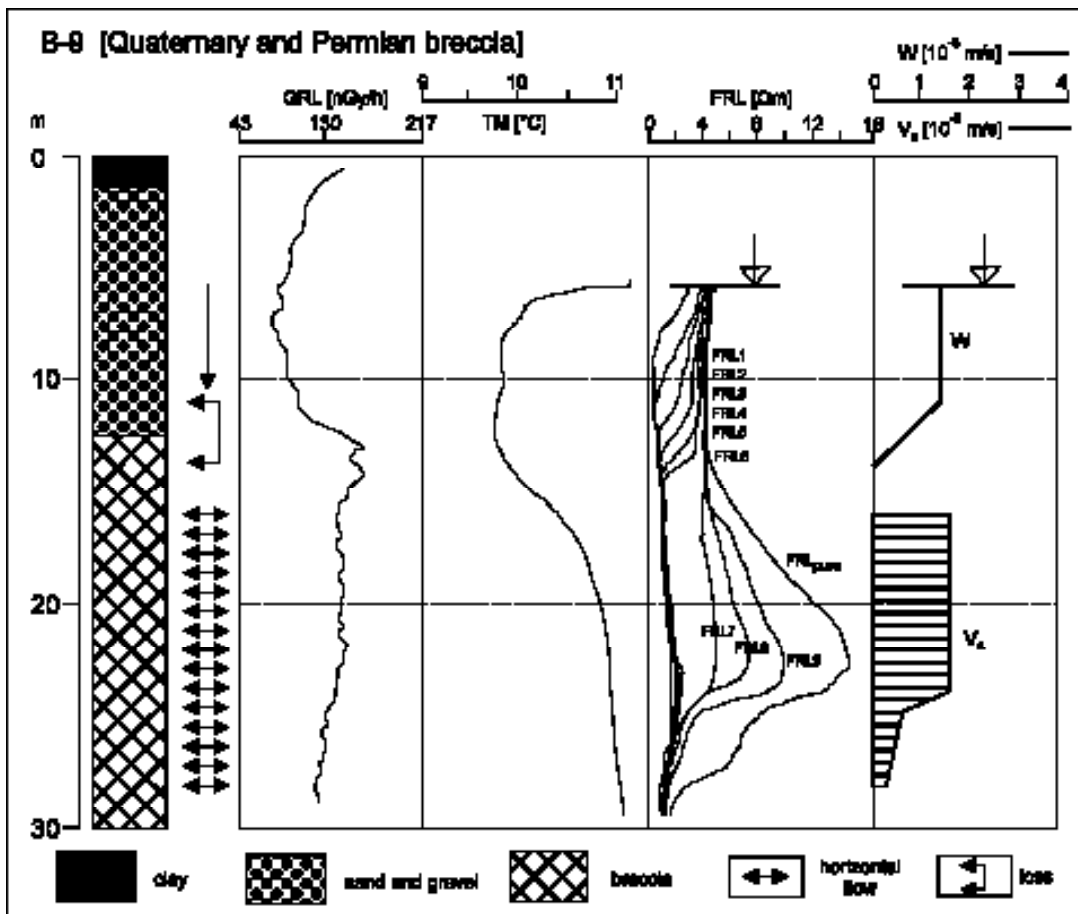
depth interval between 1100 m and 1200 m in granites. The surface between two records of flow meter (1 and 3 downwards, 2 and 4 upwards) is proportional to the yield of each inflow.

5.4. Monitoring boreholes (situated in the surroundings of waste dumps)

Information on groundwater quality, its stratification, temperature and filtration rate served as a basis for projecting and installing an effective monitoring system.

The example presented (Fig. 5) shows logs for borehole B9, located in the vicinity of a dump. Its entire length was cased with plastic tube, 129 mm in diameter. The active part of the borehole was screened with filters.

The hydrodynamic characteristics of the borehole B 9 are very interesting and complicated.



Legend:

GR - gamma ray log, TM - temperature log, FRL - set of the fluid resistivity log, FRL_{pure} - under natural conditions, Nos.1 - 10 after treating the water in the well with sodium chloride, V_a - velocity of the horizontal flow, W - velocity of vertical movement of water in the well.

Fig. 5 - Results of logging in the monitoring well B-9.

The upper part of the borehole from 1.5 m to 12.5 m is located in Quaternary gravel, with Permian breccias occurring along the lower part from 12.5 m to 30 m. The temperature log showed differences in hydrodynamic properties between the upper part and the lower part of the borehole.

The photometry record (not shown) indicates the clean water (logging was conducted after the well was cleaned and pump tests performed), while the distribution of fluid resistivity values reflects groundwater stratification. Towards the face of the borehole the fluid resistivity increases to 14.5 ohm·m over the depth interval of 20-24 m, and then decreases to 7 ohm·m over the depth interval of 24-27 m and to 1.5 ohm·m at the bottom of the borehole.

FRL curves Nos. 1-10, obtained after injecting the NaCl tracer into the borehole fluid, demonstrate the following. Horizontal filtration of groundwater across the borehole takes place at the rate $V_a = 2.5 \cdot 10^{-4}$ m/s, i.e. 20 m/day. Water flows towards the bottom of the borehole at the rate $W = 1.5 \cdot 10^{-3}$ m/s which decreases with depth as water flows into the wall of the borehole down to 14 m. The FRL curve No. 8, measured 14 h after injection of the tracer into the borehole fluid, along with other FRL curves (No. 9 after the next 21 h, and No. 10 after another 10 h) confirmed that the shape of curves 9 and 10 conforms to the natural curve FRL_{pure} . It can be deduced from the configuration of FRL curves Nos. 8, 9 and 10 that in the lower part of the borehole, corresponding to the Permian breccia, only weak horizontal filtration takes place at a rate V_a two orders lower ($V_a = 0.15$ m/day) than at the groundwater table in the borehole as compared with the gravel collector.

The main result of the measurements is the finding that groundwaters of the Quaternary and the Permian aquifers are separated, indicating that groundwater in the borehole is stratified. In addition, the results indicate that various filtration processes appear to be taking place.

6. Conclusions

Well-log analysis for hydrogeological formation evaluation in five water wells situated under different hydrogeological environments of Bohemian massif, yields information on both the collective properties of penetrated rocks and the groundwater quality and groundwater flow, proving the efficiency of logging.

Information on sub-vertical flow rates is supplied by propeller flow meters for water flows with velocity greater than 10^{-3} m/s or by temporal fluid resistivity logs, photometric log or temperature logs, after treatment of water in the well using suitable tracers. The latter techniques cover the range of water velocities up to 10^{-7} m/s. Sub-horizontal groundwater flow in the well is detectable by dilution technique.

By repeating the measurements applicable to groundwater studies, we can monitor both the dynamic regime of underground water and/or technical parameters of the borehole. Universalism of the fluid-movement log application also for other hydrogeological studies has been reported in literature (Kobr and Valcarce, 1989; Kobr and Krásny, 2000).

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