

# Well logging methods in groundwater surveys of complicated aquifer systems: Bohemian Cretaceous Basin

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**Abstract** Geophysical well logging methods (including borehole flow logging) can significantly contribute to a detailed understanding of hydrogeological conditions in basins with complicated sedimentary structure in studies undertaken to make optimal use of water sources, or to protect those resources from contamination. It is a common practice to delineate geological and hydrogeologic conditions at the scale used in geological maps and surface surveys. However, there is a need for more detailed descriptions of basin structure for many tasks related to water resources management and hydrologic research. This paper presents four specific examples of boreholes in complex hydrogeologic settings where useful information was provided by geophysical logging: (1) identification of large-scale upward cross-flow between aquifer horizons in an open borehole; (2) confirmation of continuous permeability throughout a long borehole interval; (3) identification of leakage into a test well via a defective casing joint; (4) evidence for downward flow in open boreholes; and (5) identification of permeable beds associated with water inflows during aquifer tests. These borehole geophysical measurements provide important

information about the detailed lithological profiles of aquifers (especially in the absence of core), enabling the optimization of groundwater monitoring, resource use, and wellhead protection activities.

**Keywords** Well logging · Borehole flow logging · Basin hydrogeology · Groundwater flow

## Introduction

Sedimentary basins often entail complex lithological and tectonic conditions, which can be associated with equally complex groundwater flow regimes. Hydrogeologists routinely characterize the large-scale structure of these basins using geologic mapping and surface surveys. However, there is a need for a generalized geotechnical approach for the detailed description of basin structure in such specific tasks as water resource management, water-quality protection, geochemical analysis, yield calculations, etc. (Hearst et al. 2003; Paillet et al. 2002; Kobr et al. 2005; Keys 1990). Geophysical well logging and especially flow logging during production can substantially contribute in these efforts, but these methods are not always used to the full extent of their capabilities in many aquifer studies.

This paper presents four interesting and instructive examples of boreholes where important information about local aquifer conditions was obtained by geophysical and borehole flow logging. These results have augmented and even modified the existing hydrogeologic understanding of the aquifer system under study, and, in one case, made hydrologists aware of a significant threat posed by borehole conditions (Fitts 2002). Clearly, this valuable experience provides useful lessons that can be used in the study of

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other complex groundwater basins. We believe that many of these specific results can be generalized to a much wider range of investigations where geophysical and hydrogeologic information needs to be integrated in the development of useful models of groundwater flow regimes in complex sedimentary aquifers (Domenico and Schwartz 1998).

The results presented here were obtained during over 20 years of groundwater research using boreholes and geophysical well logs in the study of the Bohemian Cretaceous Basin (Mares and Zboril 1970; Kobr and Krasny 2000, Kobr and Linhart 1994; Kobr and Valcarce 1989; Zboril and Mares 1971). This work included the construction of new monitoring wells in deep aquifers for the Czech Hydrometeorological Institute (within ISPA, a project of the European Union and the Czech Ministry of Environment), and the construction of other boreholes serving such purposes as exploration, monitoring, and exploitation of fresh and thermal basin groundwater. In all of this work, the application of a full suite of geophysical borehole logs contributed in a major way to the understanding of local aquifer structure inasmuch as numerous new facts were established that contributed to the improved concept of aquifer conditions and groundwater flow encountered in the basin. The four examples described in this paper come from the north-western part of the Bohemian Cretaceous Basin, a deeply subsided block of sedimentary rocks (the Benesov-Usti aquifer system) that is currently the site of extensive survey of low-temperature waters in deep aquifers.

### The Bohemian Cretaceous Basin

The Bohemian Cretaceous Basin forms the largest basin structure of the Upper Cretaceous age in the territory of the Czech Republic and takes in a major part of northern and

eastern Bohemia. The north-western part of the basin called the Benesov-Usti aquifer complex is considered the most complicated tectonic and lithological structure of this basin. This aquifer complex is an extensive hydraulically connected groundwater unit taking up an area of nearly 2,000 km<sup>2</sup> and extending to a maximum depth of 1,100 m.

Besides being the largest thermal water reservoir in the Czech Republic with an estimated yield of 300 l s<sup>-1</sup> and a present use rate of 200 l s<sup>-1</sup> for heating and pools, this is the largest groundwater resource in the Czech Republic with a potential yield of 8,300 l s<sup>-1</sup> of potable water (Hercik et al. 1999). As in other large sedimentary basins, the layered rocks within the basin form a series of several aquifer units separated by aquitard layers of varying degrees of continuity within the subsurface.

The entire aquifer system of the Benesov and Usti nad Labem areas is characterized by the distribution of aquifers illustrated in Table 1. Sedimentary units consisting of sandstone predominate in the infiltration zone located in the north-eastern part of the aquifer system near the Luzice fault zone. Layers of fine-grained sediments (mostly marlites) constitute aquitards and become more frequent throughout the sedimentary section towards the southwest. The sandstones also tend to become more fine-grained in that direction. The rate at which the thickness and degree of fine-grained material increases towards the southwest in these units varies among the different sedimentary layers (Datel and Krasny 2005; Hazdrova et al. 1968).

The basin structure indicated in Table 1 results in a layered hydrogeologic system where the thickness and permeability of hydraulically conductive units change in a lateral direction. This general large-scale structure is further complicated by local heterogeneities consisting of offsets along faults separating blocks and the occurrence of tertiary volcanics (basalts). It is necessary to have a detailed description of the local aquifer properties involved

**Table 1** Stratigraphy and lithology of the north-western part of the Bohemian Cretaceous Basin (from a regional point of view)

Age	Regional formation	Area around the Luzice fault (NE)—recharge area		Central part of the Benesov syncline		Region between Usti nad Labem and Teplice (SW)	
		Dominant lithology	Hydrogeology	Dominant lithology	Hydrogeology	Dominant lithology	Hydrogeology
Santonian	Merboltice	Sandstones	Unified Cretaceous aquifer	Sandstones, siltstones	Upper Cretaceous aquifer	Claystones, marlites	Regional aquitard
Coniacian	Brezno	Sandstones		Claystones, marlites			
Turonian	Teplice	Sandstones		Marlites, sandstones	Middle (main) Cretaceous aquifer		
	Jizera	Sandstones	Marlites	Regional aquitard	Sandstones	Basal Cretaceous aquifer	
	Bila Hora	Sandstones, marlites	Sandstones	Basal Cretaceous aquifer	Sandstones		
Cenomanian	Peruc-Korycany	Sandstones					

in order to determine groundwater yield and to understand the local groundwater flow regime as influenced by local conditions in the vicinity of production or sampling wells.

On the regional scale, the basin illustrated in Table 1 and Fig. 2 is divided into three main aquifers: (1) a basal aquifer in the Cenomanian sandstone; (2) a middle aquifer in the Turonian sandstone; and (3) an upper aquifer in the Coniacian–Santonian sediments just below the surface. These three aquifers are separated by regional aquitards of Lower and Upper Turonian marlstones. This general description applies to the central portion of the basin cross-section, while the situation is somewhat different towards either edge of the basin where individual aquifer units thicken or thin.

Borehole geophysics shows that the local aquifer structure in the vicinity of individual boreholes is considerably more complicated than the regionally generalized model described earlier. The thick, uniform aquifer units included in the general model are broken into thinner and more porous layers separated by low-permeability units such as claystones and marlstones. At the same time, beds of porous sandstone up to several meters in thickness are found within the thick marlstone sequences of the regional aquitards. The distinctly different piezometric water levels and the variable chemical composition from waters sampled within these subunits provide evidence for at least locally isolated flow within these individual subunits.

Geophysical well logging and production logging are useful and sometimes the only applicable method for delineating the local lithologic and hydrologic structure (zonality) of the aquifer in the vicinity of a well. Identifying the zonality, and the way this local structure is related to the larger lithologic units such as those in Fig. 2, is required to understand how the local conditions influence the measurements made to effectively determine the sustainable yield and protection measures for the surrounding water supply. (Todd and Mays 2005; Rushton 2005).

### Well logging methods

Well logging is the general term used to describe the collecting of a set of geophysical measurements to be used in assessing the physical properties of the rocks and surrounding boreholes, and of the fluid filling the pores and crevices within those rocks. Borehole logs are also used to inspect the condition of boreholes and to assess the geo-mechanical conditions of the geologic units penetrated by the drilling. Properly obtained and analyzed geophysical logs can be used to reduce future drilling costs by guiding the location, drilling, and construction of sampling, production, or disposal wells. Well logs can also be used in the

horizontal and vertical extrapolation of data derived from boreholes.

Geophysical measurements in boreholes provide continuous objective records of formation and fluid properties, giving values that are consistent from borehole to borehole that do not change with time as long as the logging equipment is properly calibrated and standardized. In contrast to continuous series of measurements provided by geophysical logs, samples of rocks, and fluids are almost never continuous. Continuous coring and subsequent analysis of enough samples to provide a statistically meaningful representation of the formation invariably costs much more than most logging programs. Geophysical logs also provide the opportunity to monitor “time-lapse” changes in a dynamic system, as in the invasion of pores by drilling fluid, or the approach to thermal equilibrium after termination of circulation. Changes in fluid and rock characteristics and even well construction in response to pumping or injection can also be monitored. Nuclear logs and occasionally acoustic measurements are unique in providing the ability to measure aquifer properties through casing. A combination of these geophysical logs can be used to construct a lithological profile of the sedimentary units surrounding the borehole, indicating the location of permeable layers, and providing estimates of porosity as controlled by grain size, cementation, and lithology (Fetter 2001).

In clastic sediments (dirty sands or dirty sandstones), the task is to define the lithological type related to the problem of determining the clay content and porosity (Hearst et al. 2003). The curves of gamma ray log, of formation resistivity, and sometimes also of spontaneous polarization and neutron–neutron log are considered to be indicators of the clay content. Porosity is often determined by neutron–neutron logging. Spontaneous polarization cannot be often used during a borehole drilling because just a very small resistivity contrast between drilling mud and groundwater (formation water) is measured. The compensated density gamma–gamma log or compensated acoustic log also can be employed to determine porosity. It is the gamma log and the neutron–neutron log which are of fundamental importance for lithology interpretations (Hearst et al. 2003; Keys 1990), especially because of frequent use of well logging in cased boreholes.

### Borehole flow logging

Borehole flow measurements are made in open or screened boreholes where drilling mud has been replaced by water after circulation or other development to allow free communication between the formation and the borehole fluid column. Under these conditions, changes in the physical

properties of the borehole fluid reflect the properties of the formation fluids. The variation in these properties as a function of depth can be obtained using various logging methods based on temperature, electrical resistivity, and fluid movement. Flow logging includes all techniques used to measure the natural (under ambient conditions) or induced (pumping or injection) flow within a borehole (Keys 1990; Hearst et al. 2003; Guerin 2005).

Fluid column logs (temperature and resistivity) often provide a preliminary idea of the distribution of flow in boreholes. Fluid column logs should be a common part of each basic logs run in any set of hydrogeological boreholes. Inflow and loss zones and intervals with vertical movement of water are usually indicated on high-resolution temperature or differential temperature logs. The intervals where movement of water occurs along the borehole are indicated by constant or nearly constant temperature. The depths where water enters or exits the borehole are indicated by abrupt changes in slope of the temperature log, which are especially evident on differential temperature logs.

The most direct measurement of flow ( $Q$ ,  $\text{m}^3 \text{s}^{-1}$  or  $\text{l s}^{-1}$ ) in boreholes is based on the impeller (also sometimes known as spinner) flowmeter (Molz et al. 1989; Williams and Paillet 2002). The measurement senses the movement of fluid in a direction perpendicular to a set of impeller blades, with the rotation rate expressed in counts per second. This rotation rate can be calibrated in volumetric flow using controlled flow in calibration tubes. Measurements can be made with the impeller aligned so as to detect vertical or horizontal flow. The measurement is applicable to the measurement of water velocities greater than  $10^{-3} \text{ m s}^{-1}$ . This sensitivity limits the use of impeller flowmeters because flow rates encountered in water wells and monitoring boreholes are usually far below this limit. For this reason, vertical volumetric flow rates are often determined using some other measurement of vertical velocity  $v$  ( $\text{m s}^{-1}$ ) and the known borehole radius  $r$  (m). The vertical velocity  $v$  is most often estimated by measuring the rate of movement of a tracer in the well. Water entering the well or water injected into the well can create an interface within the borehole fluid column that can be traced over time. The contrast in water quality is indicated by a sharp contrast in the electrical resistivity (or its inverse, conductivity), temperature, or optical clarity of the water. The movement of this interface over time is readily indicated by a series of fluid column resistivity, temperature, or photometry logs. The time series generated in this manner indicates whether there is horizontal flow across the borehole, manifested by a steady change in values at the inflow depth interval, or vertical flow, where the boundary between inflow and borehole fluid moves up or down along the fluid column. Vertical flow rates are calculated using the equation:

$$Q = \pi r^2 v \quad [\text{m}^3 \text{ s}^{-1}], \quad (1)$$

where the well radius  $r$  (m) can be taken from the caliper log and the velocity  $v$  ( $\text{m s}^{-1}$ ) is interpreted from the fluid column log time series.

The yield of an aquifer can also be determined using the dilution method (Grinbaum 1965). Increasing the concentration of a tracer in a well from the original value  $C_0$ – $C_1$  and measuring the changes of the tracer concentration  $C_t$  can be used to calculate the inflow for any 1-m interval using the equations:

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

where  $q_i$  is the inflow and  $\Delta t$  (s) is the time from the moment of tracer addition. The total yield of the aquifer  $Q_i$  is then given by the sum of the  $q_i$  throughout the inflow interval.

One specialized version of the dilution method known as photometry uses a dye introduced into the borehole column and optical measurements of the dilution of dye over time to measure inflow to the borehole (Zboril and Mares 1971; Pitrak et al. 2007). This method was not used in any of the boreholes described in this paper, but is in most ways equivalent to the application of the dilution method in our examples.

If there are differences in the dissolved solids content of inflows, the inflow depths appear as abrupt shifts in the resistivity given by fluid column logs. The inflow depths can be emphasized by introducing sodium chloride into the borehole column to decrease the resistivity of the water in the borehole and therefore enhance the contrast between inflowing fresh water and the saline borehole column. The inflow sites then appear as on the fluid resistivity curves where the higher resistivity (20–100  $\Omega\text{m}$  entering the borehole contrasts with the low resistivity (less than 10  $\Omega\text{m}$ ) of the moderately saline water in the fluid column. Since outflow zones have no effect on the properties of the fluid column, they are not detected on the resistivity logs.

Log-derived hydraulic conductivities  $K$  and consequently transmissivity  $T$  are based on the theory of steady-state water flow to the ideal water well. For a 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 Dupuit equation applies

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

where  $\Delta S$  (m) is the difference in the water level in the well between the start of the test and the asymptotic approach to steady state,  $H$  (m) is the aquifer thickness,  $r$  (m) is the well

radius, and  $R(m)$  is the radius of the cone of depression (pumping) or mound of build-up (injection).

Grinbaum (1965) showed that for small water level differences  $\Delta S$  the following equation applies:

$$K = \frac{Q}{H\Delta S} \quad [\text{m s}^{-1}]. \quad (4)$$

For the log-derived evaluation of hydraulic conductivity, the parameters  $Q$  and  $H$  are determined from the geophysical and flow logs, and  $\Delta S$  is determined by precise measurement of water levels during the hydraulic testing. The thickness  $H_i$  of the aquifer units and the yield or water loss in the interval  $Q_i$  is determined from the flowmeter log showing the changes in vertical flow over the particular interval. The thickness  $H_i$  can also be checked against the vertical extent of the corresponding porous layer indicated by the geophysical logs (gamma, resistivity, and neutron–neutron). The vertical flow rate remains constant over impermeable intervals, while permeable intervals show a change in vertical borehole flow such that

$$Q = Q_i - Q_{i-1} \quad [\text{m}^3 \text{ s}^{-1}] \quad (5)$$

corresponding to the yield or water loss  $Q_i$  the aquifer in that interval. Water level drawdown caused by pumping in the borehole  $\Delta D$  corresponds to the drawdown in the aquifer unit  $\Delta S$  only if a single confined aquifer intersects the borehole test section. If more than one confined aquifer of different piezometric levels are penetrated by the open interval, two hydrodynamic tests under different pumping or injection rates must be carried out in order to determine  $\Delta S_i$ . The piezometric level for each aquifer is taken as the limit  $\Delta D^i$  for  $Q_i^i \rightarrow 0$ , assuming that the relation between the yield of an aquifer  $Q_i^i$  and steady-state water level  $D^i$  is linear.

The transmissivity  $T$  of an aquifer is related to the hydraulic conductivity  $K$  of the aquifer and its thickness  $H$  by the relation:

$$T = KH \quad [\text{m}^2 \text{ s}^{-1}]. \quad (6)$$

Ambient flow under static conditions depends on both permeability of beds and the water level difference driving that flow. One flow profile does not contain enough data to determine the relative permeability. If for example, ambient flow connects two zones of different permeability, the inflow from one must equal the outflow from the other. The water level in the borehole equilibrates to the transmissivity-weighted average of the two to cause the inflow to equal the outflow. Definitive statements about relative permeability can only be made when data are collected in two different flow conditions to determine the two variable parameters: zone transmissivity and zone water level.

Therefore, the hydraulic parameters (hydraulic conductivity, transmissivity, etc.) were determined from the boreholes by hydrodynamic tests (the mean parameters of the open zones of boreholes). Borehole flow measurements should be taken as a very important part of the complex of hydrogeological, hydraulic, geochemical, and geophysical methods that complement and balance out each other. The results of borehole flow logging can provide more detailed information on every permeable zone (including determining of partial transmissivity values—Paillet et al. 2002; Molz et al. 1989), which could be useful for a precise description of the groundwater regime in heterogeneous environment. In certain cases, borehole flow logging using the method proposed by Molz et al. (1989) can be employed to estimate the relative zone transmissivity.

### Well logging data discussion—examples of findings of interest

All of the boreholes selected for this paper were drilled without core. The lithology profile for each borehole was based on well logging (natural gamma, neutron–neutron, density, formation resistivity, magnetic susceptibility caliper, and occasionally acoustic logs), description of cuttings produced during drilling, and regional knowledge of the local geological cross-section. The hydrogeological conditions in the boreholes under ambient and stressed conditions were determined by flow logging (fluid column temperature and resistivity and impeller flowmeter logging, and monitoring the movement of fluid during dilution and marker fluid emplacement). These measurements were supplemented by video recordings in all boreholes, providing a qualitative indication of the presence of flow as demonstrated by the movement of suspended particles in the flow field.

Quantitative interpretations are making commonly for dilution methods. Following parameters are given: vertical flow or vertical velocity (Fig. 5) and quantitative interpretation of water inflows and water outflows (presented or as relative value; percentages of total flow or as a quantitative value,  $\text{l s}^{-1}$ ). Field measurements of flowmeter can be affected by sandy grains in circulated water (Fig. 3). Therefore, quantitative interpretations are making just in wells where absence of grains in water is guaranteed. Some of grains striking to narrow slot between rotated propeller and the body of the probe are the cause of short-time retarding of propeller rotation. In these cases, the scale of flowmeter curve is often difficult to express exactly in flow units, vertical flow ( $\text{l s}^{-1}$ ) or vertical velocity ( $\text{m s}^{-1}$ ).

Lithological symbols and physical units used in the geophysical log interpretation in Figs. 3, 4, 5, 6 are explained in Tables 2 and 3.

**Table 2** Lithological symbols used in Figs. 3, 4, 5, 6

Q	Quaternary cover
M	Tertiary neovolcanites
Middle and upper aquifers (Turonian, Coniacian)	
T11	Sandstone, fine grained
T12	Sandstone, medium grained
T13	Sandstone, coarse grained
T14	Sandstone, slightly clayey
T15	Clayey sandstone
T16	Silty sandstone
T17	Marly sandstone
T18	Clayey sandstone with organic mixture
T19	Calcareous sandstone
T21	Conglomerate
T31	Clayey siltstone
T32	Marly siltstone
T33	Sandy siltstone
T34	Calcareous siltstone
T41	Sandy marlstone
T42	Silty marlstone
T43	Clayey marlstone
T44	Calcareous marlstone
T51	Sandy claystone
T52	Silty claystone
T53	Claystone with coal
T54	Calcareous claystone
T55	Clayey limestone
T70	Siltstone
T80	Claystone
T90	Marlstone
Basal aquifer (Cenomanian)	
C11	Sandstone, fine grained
C12	Sandstone, medium grained
C13	Sandstone, coarse grained
C14	Sandstone, slightly clayey
C15	Clayey sandstone
C16	Silty sandstone
C18	Sandstone with glauconite
C24	Conglomerate
C25	Sandstone with organic mixture
C31	Clayey siltstone
C32	Marly siltstone
C33	Sandy siltstone
C41	Sandy marlstone
C42	Silty marlstone
C43	Clayey marlstone
C51	Sandy claystone
C52	Silty claystone
C53	Marly claystone
K	Crystalline bedrock (gneiss)

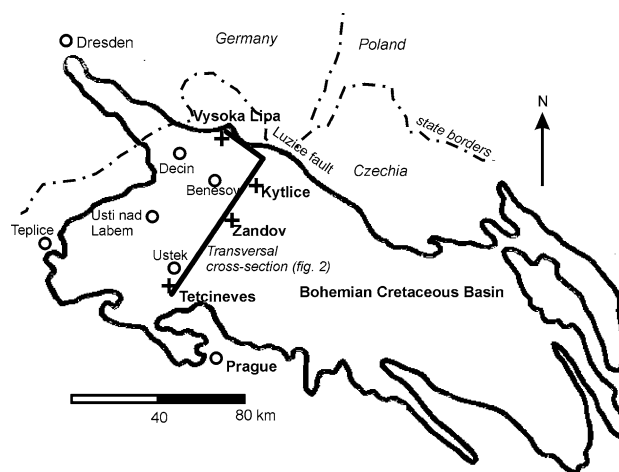
**Table 3** Units used in Figs. 3, 4, 5, 6

Ohmm	Ohm meter
°C	Celsius degree
mm	Millimeter
cps	Counts per second
cpm E3	Counts per minute (values $10^{-3}$ )
nGy/h	Nanogray per hour
l/s	Liters per second
V	Volt

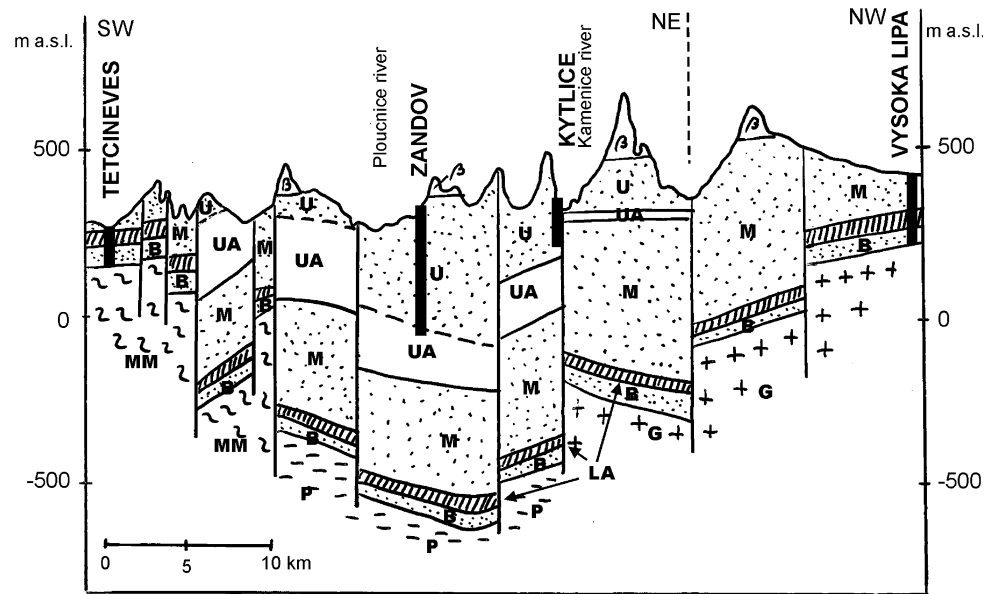
**Example 1:** A strong upward flow and an artificial interconnection between partial aquifers (Kytlice, No. 2H286, Fig. 3)

The Kytlice borehole was drilled to a depth of 77 m in Coniacian sandstone in the north-western part of the Bohemian Cretaceous Basin (Fig. 1). A very strong upward hydraulic gradient was detected at this location in the analysis of the borehole flowmeter logs (Fig. 3). This gradient is consistent with the topographic location of the well site in the Kamenice valley. The borehole is provided a communication route for upward flow which would not have occurred under natural conditions. This large flow would not have been obvious without the flow log interpretation because all of the flow exited in the subsurface. In this case, logging prevented long-term continuation of cross-influence of aquifer units because recognition of these conditions leads to grouting and abandonment of the well to insure restoration of natural conditions.

In the interval below the bottom of casing (16–77 m), the lithology shows sandstone with claystone layers increasing in abundance towards the bottom. None of these claystone layers are very thick but they play an important

**Fig. 1** Situation of the Bohemian Cretaceous Basin, logged boreholes and a cross-section

**Fig. 2** Geological cross-section of the Benesov and Usti nad Labem aquifer system with four presented boreholes (partially after Hercik et al. 1999). Explanations: B, basal aquifer (Cenomanian sandstones); M, middle aquifer (Turonian sandstones; U, upper aquifer (Coniacian and Santonian sandstones, siltstones, marlstones); LA, lower aquitard (Lower Turonian marlstones); UA, upper aquitard (Upper Turonian marlstones, siltstones and sandstones);  $\beta$ , neovolcanites (basalts); bedrock: MM, metamorphites; P, Permian sediments; G, granitoids



role in the hydrogeologic context by acting as aquitards separating the sandstones on either side of them. The borehole has established a hydraulic connection between the discrete sand beds previously isolated by these aquitards, causing a strong upward flow within the borehole and significantly changing the local groundwater flow regime. At the time of logging, the borehole was lined with a perforated tube below the depth of 16 m. Static water level in the perforated section was at an elevation of about 0.5 m above ground surface. This water level represents the transmissivity-weighted average of the water level in each of the individual aquifer units connected to the open borehole, and not the piezometric water level in any one of the aquifer units contributing flow to the borehole.

The seven separate zones contributing inflow or outflow to the Kytlice borehole are indicated on the flow logs shown in Fig. 3. The individual aquitards separating these flow zones appear as relatively inconspicuous claystones with thicknesses of only a few tens of centimeters. Although simple inspection would not indicate the presence of significant piezometric level differences across such thin layers, the upward flow is in excess of 12 l/s ( $1,000 \text{ m}^3 \text{ d}^{-1}$ ). The flowmeter logs show water is entering the borehole via a clean sandstone layer near the bottom of the borehole (71.4–74.8 m). Several claystone aquitards intersect the borehole just above this depth interval. Another inflow is associated with relatively thick and clean sandstone (58–63.2 m). There are several more claystone beds above this level. Above this aquitard unit there is a long interval of mostly sandstone. Water leaves the borehole under ambient conditions in a stepwise fashion through five additional outflow zones (42–46 m, 34–36 m, 30.5–32.5 m, 20–26 m, and near the bottom of steel casing

at 15.5–17.5 m). Overflow at the top of casing was negligible in comparison to the much greater vertical flow between units in the subsurface. Pumping of the borehole at a rate of  $0.58 \text{ l s}^{-1}$  produced almost no change in the flow conditions, confirming that subsurface flow was much greater than the pumping rate, and that the water level differences driving the flow in the borehole were far greater than the 1 cm of drawdown observed at the surface. Almost none of this would have been apparent without running borehole flow logs as part of the geophysical logging program.

Example 2: Confirmation of an open aquifer interval and partial leaky connection of different borehole casings (Vysoka Lipa, No. VP8462 N, Fig. 4)

The Vysoka Lipa borehole is 296.4 m deep and located in the northernmost part of the Bohemian Cretaceous Basin (Fig. 4). The Turonian and Cenomanian rocks composing the Cretaceous sediments at this location are around 300 m thick. An interval of nearly pure Turonian sandstone lies beneath the Quaternary sediments, with only a few thin silt and clay beds below 177 m. Sandy siltstone occurs in the 191.9–198.5 m interval. A geophysically distinctive layer of marly sandstone in the 223.3–226.3 m interval constitutes the stratigraphic boundary between Turonian and Cenomanian sediments. The underlying Cenomanian sediments are composed of sandstone with varying amounts of clay and silt components indicated by the gamma and neutron–neutron logs. Coarse sandstones predominate below a depth of 265.5 m. Below 294 m in depth the appearance of breccia in the drill cuttings indicated an approach to the bottom of the sedimentary sequence. The





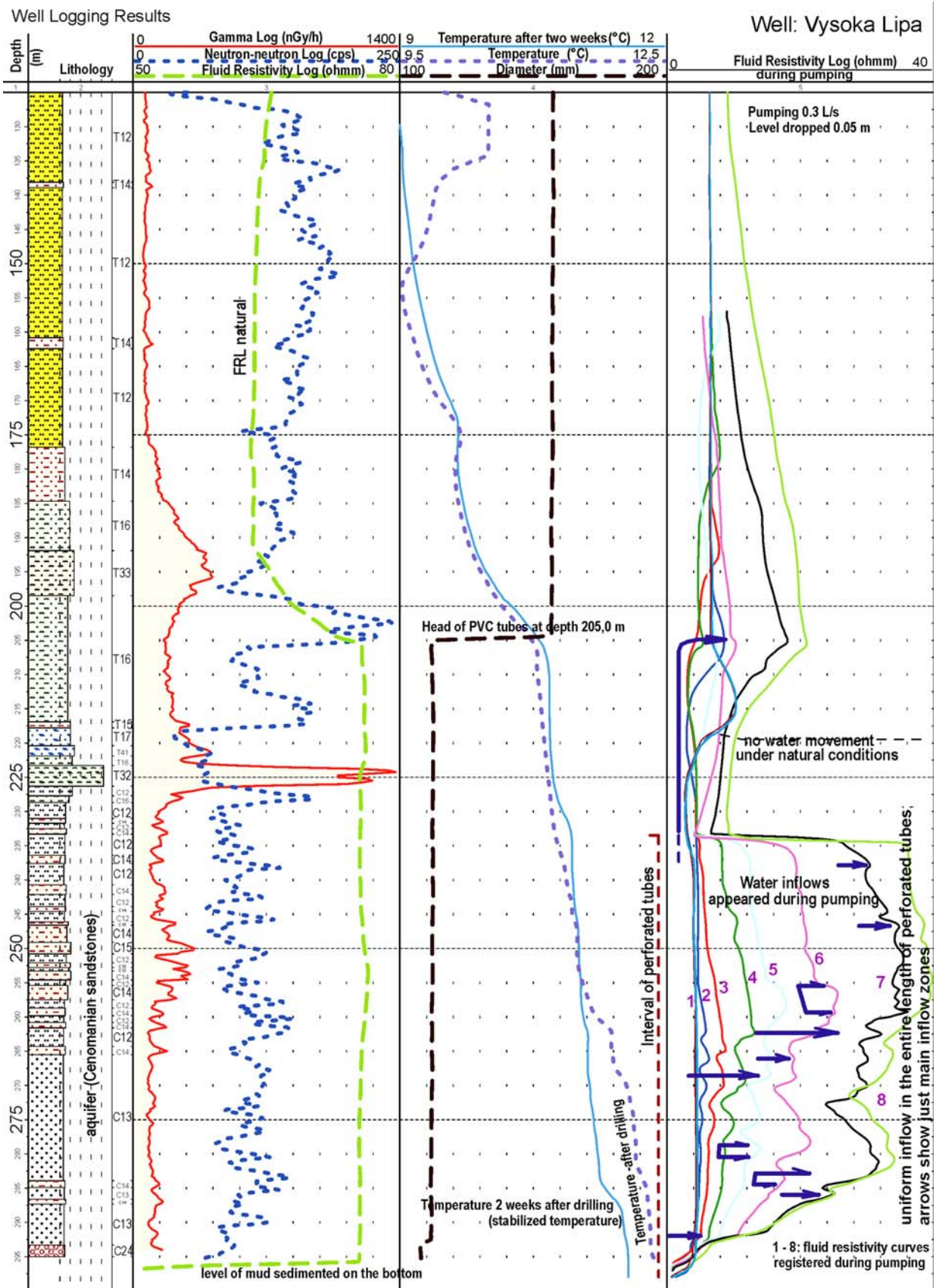


Fig. 4 Borehole Vysoka Lipa

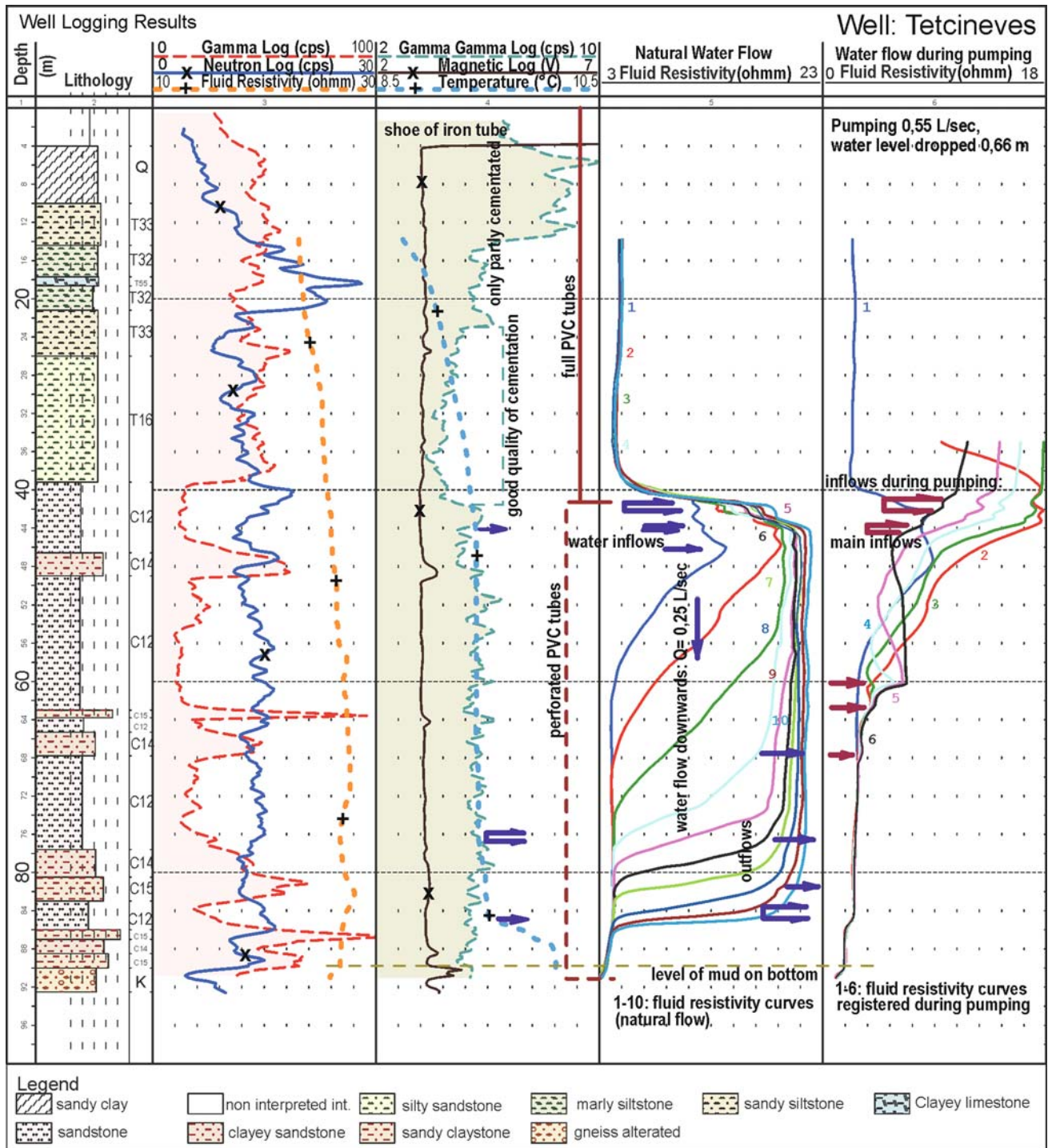


Fig. 5 Borehole Tetcineves

borehole was cased with perforations over the Cenomanian sandstone interval (235–296.4 m). The entire open interval is considered to be a single aquifer. Water level in casing was at 39.25 m below ground level and indicated confined aquifer conditions.

Flow measurements under ambient conditions using the dilution method indicated no measurable flow. However, the fluid column log in Fig. 4 contains an abrupt shift near 205 m indicative of fluid movement. This suggests that there is some vertical movement of water in the column

that was too small to detect with the dilution method. Because there was no significant natural flow in the well, permeable intervals were determined using the marker fluid tracer method during pumping. We used a pumping rate of  $0.3 \text{ l s}^{-1}$ , which produced a steady drawdown of 0.05 m. The relatively small drawdown at this pumping rate indicates the relatively high permeability of the Cenomanian sandstone. Numerous inflow intervals were detected in the Cenomanian sandstone, and they are distributed over almost the entire length of the perforated interval. Major inflows were found at the following depths: 255.5–259.5 m, 262.5 m, 269 m, 279–280.5 m, 285.5 m, and 292.3 m. Borehole video showed turbid water below 292.3 m confirming a stagnant column below that depth. These measurements confirm the vertical continuity of the aquifer in the Cenomanian sediments because the data indicate no hydraulic isolation between inflow zones, and a nearly continuous distribution of permeability within the section. The flow measurements also indicate small inflow (leakage) during pumping at a depth of 205 m at a casing joint.

**Example 3: Evidence of a downward flow in the borehole (Tetcineves, No. VP8216 N, Fig. 5)**

The 92-m deep Tetcineves borehole is located near Ustek in the south-western part of the Cretaceous basin and penetrates the entire depth of sediments down to crystalline basement (Fig. 5). Turonian siltstones and silty sandstones extend from just below Quaternary sediments to the Turonian–Cenomanian boundary at 39.2 m. Cenomanian sandstones interspersed with silts and clay-rich sandstones continue downwards to 90 m where the borehole penetrates the weathered gneiss of the crystalline basement.

Flow measurements in the Tetcineves borehole demonstrate the opposite situation from that of the boreholes described earlier because the flow is downward within the frame of one regional aquifer rather than upwards. Video recordings showed water inflowing at the top of the perforated interval and streaming downward, confirming the downward flow measurements shown in Fig. 5. Under ambient conditions, the flow measurements indicate inflow at about 40 m and downflow over the perforated interval to a depth of 86 m. The downflow rate remains constant at about  $0.25 \text{ l s}^{-1}$  over this interval down to the 73–86 m section, where the flow becomes steadily reduced as the water enters the sandstone over that 13 m interval.

Pumping at a rate of  $0.55 \text{ l s}^{-1}$  produced a water level decrease of 0.66 m, reversing the ambient downflow and causing the various outflow intervals to contribute inflow to the borehole. Because the deepest zones did not produce much inflow under this drawdown, we assume that the piezometric levels in the 73–86 m interval are

approximately 0.6–0.7 m lower than those in the upper part of the formation. The dilution method logs show that most of the inflow during pumping occurred in the 40–44 m interval at the top of the perforations. Lower rates of inflow were indicated at depths of 60.5, 63, and 68.5 m.

The flow logs in the Tetcineves borehole indicate a situation where water flows within a borehole drilled into a single aquifer unit in a sedimentary sequence as described on the regional scale. Impermeable or low-permeability layers of clayey sandstone within the aquifer act as aquitards and are locally breached by the borehole. The flow in the borehole indicates that a connection has been made between sandstone beds characterized by different piezometric water levels. In this case, it appears that the piezometric water level decreases systematically with depth. This information has important implications because it appears to show the impact of pumping as water extractions from the Labe River valley propagate through the aquifer system.

**Example 4: An exemplary linkage between sandstone layers and water inflows into the borehole (Zandov, No. 2H274, Fig. 6)**

The 344-m deep Zandov borehole is located in an extensive dipping and down-faulted block of Cretaceous sediments (Fig. 6). When originally drilled to a depth of 361.8 m the borehole penetrated sediments of Coniacian age composed mainly of siltstones with various proportions of limestone, clay, and sand. Two levels show Tertiary neovolcanic rocks that are probably basalts: 337.5–0342.8 m and 350.1–350.9 m. The neutron–neutron and gamma logs indicate a few thin beds of coarse sandstone within thick sequences of silty and clay-rich sediments.

The borehole is constructed with perforated casing from 42.1 to 341.9 m. With this completion, there was an artesian overflow from the borehole of about  $4 \text{ l s}^{-1}$  when the fitting at the wellhead was first opened. This overflow would then decrease to about  $3.5 \text{ l s}^{-1}$  after about 3 h of unrestricted flow. The water flowing from the wellhead had a temperature of  $10.1^\circ\text{C}$ .

The fluid column logs (temperature and resistivity) indicate abrupt shifts between intervals of nearly constant values. All of these are indicative of flow in the fluid column. The depths where these shifts or “steps” in the fluid column logs occur also correspond with sedimentary beds interpreted as coarse sandstones. The impeller flow log demonstrates that there is strong upward flow throughout much of the borehole. The video recording for this well confirmed the presence of the upward flow, with the apparent rate of upflow decreasing sequentially with depth. The video monitoring of the movement of suspended particles shows that the upward flow becomes negligible below

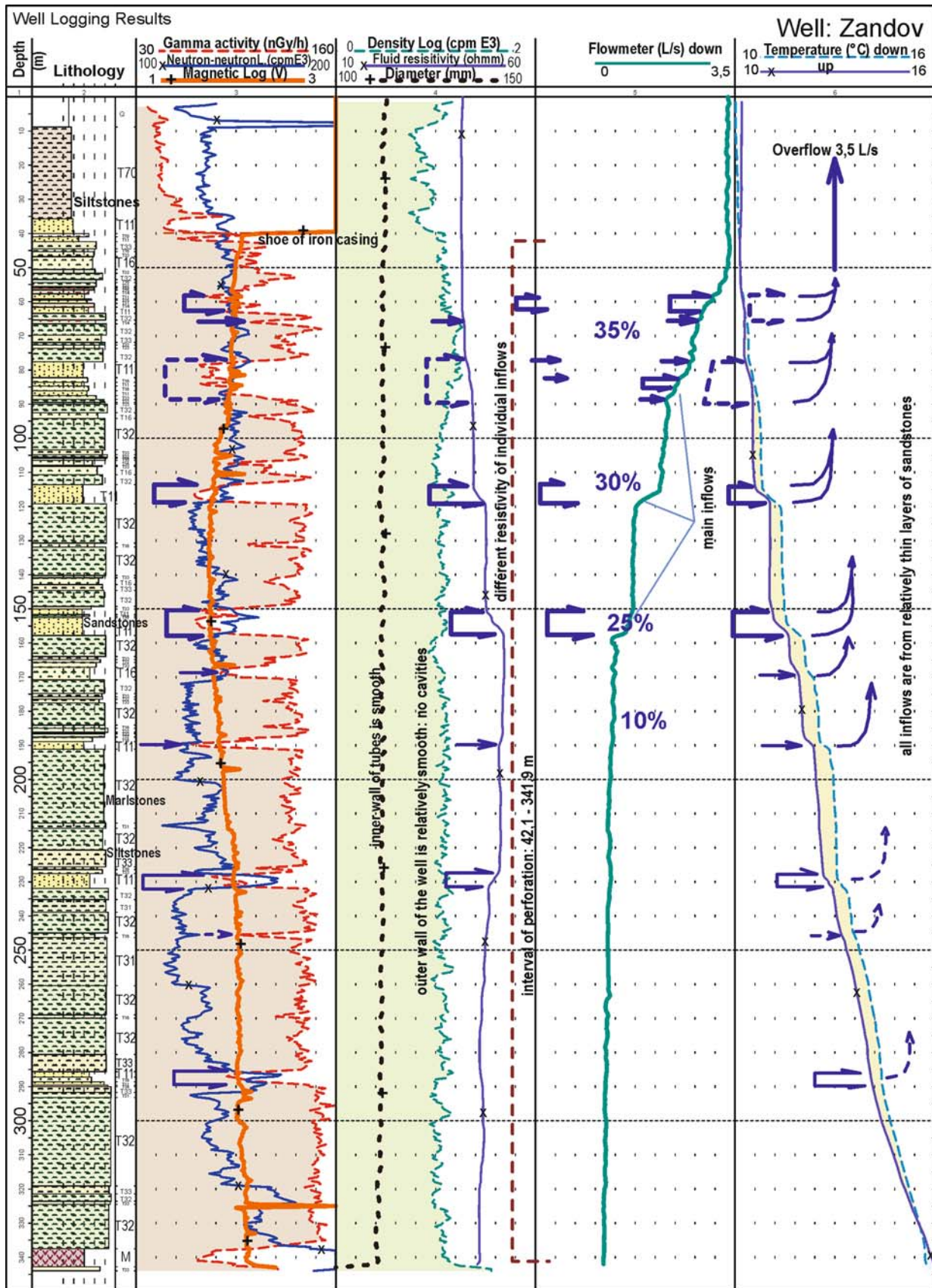


Fig. 6 Borehole Zandov

290 m, below which there appears to be no flow at all. All inflows to the fluid column are identified on the two fluid column logs and the impeller flow log in Fig. 6. Each of these corresponds to thin intervals of pure sandstone (Datel and Kobr 2007). The major inflow depths occur in the upper half of the borehole. They arise from sandstones at depths of 59–62 m, 65.5 m, 78 m, 81.5–85.5 m, 89.5 m, 112–119 m, and 150.5–157 m. These zones contribute about 90% of the entire overflow from the well. Other, less obvious flows also arise from deeper sandstone within, generally, fine-grained interval of silt and marl at depths of: 169–170 m, 190 m, 229–231 m, 245.3 m, and 285.5–290 m.

## Conclusions

Geophysical measurements in boreholes play a key role in the description of the hydrogeological environment of aquifer systems in studies related to the utilization or protection of water resources. Well-log analysis in the hydrogeologic evaluation of water wells of the Benesov-Usti nad Labem area yields information on both the properties of the rocks surrounding the borehole and the quality and quantity of groundwater flowing in the aquifers included in that geologic sequence.

Geophysical logs such as the natural gamma, neutron-neutron, and formation resistivity measurements can be converted into a continuous profile of the lithology surrounding the borehole, and these units can be qualitatively identified as aquifers or aquitards. Borehole flow measurements provide information about the movement of water into or out of the borehole under ambient and stressed (pumping or injection) conditions. Impeller flowmeter measurements can be used to detect vertical flows with velocity greater than about  $10^{-3} \text{ m s}^{-1}$ . Time sequences of fluid column resistivity logs or photometric logs can be used to monitor the movement of tracers, producing estimates of vertical flow as small as  $10^{-7} \text{ m s}^{-1}$ . Dilution techniques can be used to monitor the rate of subhorizontal movement of water into boreholes even in the absence of measurable vertical flow.

Repeat measurements under different hydraulic conditions (pumping or injection rate) can be used to monitor the dynamic performance of aquifers, indicating their connection to and interaction with regional aquifer systems. The examples presented in this paper and other studies in the literature (Kobr and Valcarce 1989; Kobr and Krasny 2000; Kobr et al. 2005) show the wide potential application of these measurements. Adjacent aquifers, separated by a thin aquitard, can have the same piezometric level and water chemistry (and thus be considered part of the same regional aquifer) or can have different levels and chemistry and thus be considered separate and distinct aquifer units as

far as monitoring and sampling are concerned (Paillet et al. 2000, 2002).

The application of geophysical well logs in aquifer studies is especially appropriate in the case of boreholes drilled without core in complex sedimentary sequences such as those described in this paper. In hydrogeological environments with a number of contributing aquifer units stacked upon each other the measurement of vertical and horizontal flow provides information to indicate which units are embedded in the same aquifer and which are effectively isolated from each other in the vicinity of the borehole. This information can be valuable in making responsible decisions regarding the projected yield from a borehole or the measures needed to protect that water resource, and can contribute to the quality of interpretations based on sampling and monitoring programs.

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