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GROUNDWATER LEVEL VARIATIONS IN THE SEISMICALLY ACTIVE REGION OF WESTERN BOHEMIA IN THE YEARS 2005–2010

Renata GAŽDOVÁ *, Oldřich NOVOTNÝ, Jiří MÁLEK, Jan VALENTA, Milan BROŽ and Petr KOLÍNSKÝ

Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, v.v.i., V Holešovičkách 41, 182 09 Prague, Czech Republic
**Corresponding author's e-mail:* gazdova@irsm.cas.cz

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ABSTRACT
The western part of the Bohemian Massif (Vogtland/West-Bohemia region at the Czech-German border) is characterized by relatively frequent intraplate earthquake swarms and by other manifestations of current geodynamic activity, such as mofettes, mineral and thermal springs. In this study we analyze variations of groundwater level in four hydrological wells in the region during the years 2005–2010. Monitoring during the previous time interval of 2000–2004 is also mentioned and used for comparison. Two of the wells are located in the epicentral region of Nový Kostel, and the other wells are more distant. The time interval includes the 2008 earthquake swarm when all the wells displayed a noticeable drop in the water level. This effect was observed up to epicentral distances of nearly 30 km, which exceeds the distances of hydrological changes observed during previous earthquake swarms. Moreover, it seems that a small rise in the water level preceded the intervals of increased seismic activity, which could represent a certain precursory phenomenon. On the other hand, the hydrological changes in the Nový Kostel area were relatively small, indicating that this epicentral area is not hydrologically linked with the seismically active fault at depth. Consequently, more suitable localities for hydrological monitoring should be sought in a broader vicinity of Nový Kostel.

KEYWORDS: Western Bohemia, earthquake swarm, groundwater level

1. INTRODUCTION

The Vogtland/West-Bohemia region in the western part of the Bohemian Massif is known for the occurrence of e arthquake swarms with earthquakes of intermediate magnitude ($M_L < 5$). The active part of the region is located in the western part of the Krušné hory Mountains (Ore Mts., Erzgebirge) at the Czech-German border. The seismically active area is delimited approximately by the towns of Kraslice, Aš, Cheb and Sokolov (Fig. 1). Swarm earthquakes are usually recognized as a common feature of continental volcanic regions and mid-ocean rifts (Hill, 1977; Sigmundsson et al., 1997; Dahm et al., 2008).

Historical macro-seismic reports confirm seismic events in the Vogtland/West-Bohemia region as far back as 1198 (Kárník, 1963). Since the end of the 19th century, the most intensive earthquake swarms exceeding the local magnitude of 4.0 occurred there in the years 1896/1897, 1903, 1908/1909 and 1985/1986 (Bormann, 1989; Neunhöfer and Hemmann, 2005). Since 1985/1986, most hypocentres have been concentrated near the village of Nový Kostel (50.24°N, 12.44°E). This seismically active zone is located at the intersection of the N-S-trending Nový Kostel-Počátky-Zwota zone with the NNW-SSE-striking Mariánské Lázně Fault zone (Bankwitz et al., 2003; Fischer and Horálek, 2003; Neunhöfer and Meier, 2004; Geissler et al., 2005).

The strong earthquake swarm at the turn of the years 1985 and 1986 aroused great interest in this seismically active region. Two seismic arrays were then installed in the Czech part of the region. Thus, the subsequent earthquake swarms in the years 1997, 2000 and 2008 have already been well documented (Fischer and Horálek, 2000; Slancová and Horálek, 2000; Fischer and Michálek, 2008; Horálek and Fischer, 2008; Horálek et al., 2009; Fischer et al., 2010). Moreover, the 1985/1986 earthquake swarm also initiated various studies of hydrological, geochemical and geodetic variations, and their relations to seismic activity. In the following, some measurements of water and soil gas parameters in the earthquake area are presented.

During the strong 1985/1986 earthquake swarm, significant changes in mineral spring parameters were observed at the spa of Františkovy Lázně, about 15 km distant from the epicentral area. Several changes in discharge were very distinct, amounting up to 40 %, and had a co-seismic character (Novotny and Matyska, 1988). The changes in temperature were less noticeable, but preceded the beginning of the swarm by several months (Stejskal et al., 2008). Some hydrological changes persisted for nearly two years after the earthquake swarm. The character of the observed changes seemed to support the hypothesis of an injection of mantle fluids as the main triggering

Table 1 Parameters of the wells: code, locality, northern latitude and eastern longitude in degrees, altitude *h* in metres, depth *d* of the well in metres, *r* is the distance from well NK-1 in kilometres.

Code	Locality	Latitude	Longitude	*h*	*d*	*r*	Measured since
NK-1	Nový Kostel	50.2299	12.4430	535	23	0.0	June 2000
NK-2	Nový Kostel	50.2318	12.4472	595	23	0.4	June 2000
HM-1	Krásno	50.1067	12.7721	805	20	27.2	June 2000
S-4	Lázně Kynžvart	50.0077	12.6346	718	97	28.3	November 2006

mechanism of the earthquake swarm and the main cause of the observed anomalies (Novotný et al., 1987; Babuška and Plomerová, 2008; Horálek and Fischer, 2008; Stejskal et al., 2008).

During the 1985/1986 earthquake swarm, some observers also described sudden transient changes of the water level in wells at several other sites of the region. Both the water level rises and drops were reported; see the references in Stejskal et al. (2008). All these phenomena were classified as co-seismic effects. Some authors explained them by changes in the mechanical properties of water reservoirs during ground shaking. The hydrological changes were not observed farther than 20 km from the epicentre.

Accurate measurements of some hydrological and geochemical parameters were carried out during the earthquake swarms in the years 1994 and 2000 where anomalous variations were observed (Koch and Heinicke, 1999; Heinicke and Koch, 2000; Weise et al., 2001; Koch et al., 2003; Geissler et al., 2005; Stejskal et al., 2005; Bräuer et al., 2007). Bräuer et al. (2003) assumed a captured fluid trap zone above the Nový Kostel hypocentre, which could be responsible for the fact that noticeable gas outlets and mineral springs do not exist in the Nový Kostel area. Soil gas monitoring was carried out at three localities during the 2008 earthquake swarm, which has been the most intensive earthquake activity since 1986 (Faber et al., 2009). For preceding soil gas monitoring we refer to the paper of Weinlich et al. (2006).

The groundwater level is affected mainly by hydrological, meteorological and anthropogenic factors. Moreover, it is also influenced by deformation processes in the Earth's crust including tidal forces and changes in stresses resulting from seismic activity. In the literature, one can find many reports describing effects of earthquakes on hydro-geological structures in various seismically active regions (e.g., Thomas, 1988; Igarashi and Wakita, 1990; Roeloffs and Quilty, 1997; Grecksch et al., 1999; Gavrilenko et al., 2000; Chadha et al., 2003; Montgomery and Manga, 2003; Stejskal et al., 2009). One of the best examples is the Great Geyser in Iceland whose activity depends significantly on earthquakes (Rinehart, 1968).

Kümpel (1992) also concluded that changes in the groundwater level in wells reflect the stress variations in the Earth's crust. The stress variations can cause pre-, co- and post-seismic groundwater level changes. From the earthquake prediction point of view, the pre-seismic changes play the most important role as they could represent possible earthquake precursors. Such effects have been reviewed, e.g., by Kissin (1982), Roeloffs (1988), Kissin and Grinevsky (1990), King et al. (2006). These authors have summarized the characteristics of pre-seismic groundwater level changes, such as the size of the anomaly, lead time of the occurrence, and possible relations between earthquake magnitude or epicentral distance and the amplitude of the anomaly. Possible mechanisms of earthquake triggering by increased pressure of deep fluids (after critical stress accumulation) have been analyzed, e.g., in the most recent paper by Koch and Heinicke (2011).

The present paper deals with monitoring the groundwater level in Western Bohemia during the years 2005–2010. As this time interval includes the occurrence of the earthquake swarm in 2008, some relations between earthquakes and hydrological changes will be discussed.

2. GEOLOGICAL SETTING AND LOCATION OF THE WELLS

The Institute of Rock Structure and Mechanics of the Academy of Sciences of the Czech Republic monitors the groundwater level in Western Bohemia in four observation wells (Fig. 1). Two wells (denoted as NK-1 and NK-2) are situated in the vicinity of the village of Nový Kostel. The third well (HM-1) is located near the town of Krásno and the last one (S-4) is set in the area of the Pediatric Spa at Lázně Kynžvart. Groundwater levels in wells NK-1, NK-2 and HM-1 have been measured since June 2000 and the results of these observations for the period 2000-2004 were described by Stejskal et al. (2005). Additional measurements in well S-4 started in Novemeber 2006. The main parameters of the wells are summarized in Table 1.

2.1. NOVÝ KOSTEL

Two of the wells, NK-1 and NK-2, were drilled for scientific purposes in the epicentral area of Nový Kostel. This area is situated at the NW margin of the Svatava crystalline block, which is a part of the Krušné hory (Erzgebirge) crystalline unit. The Svatava crystalline block is further divided into two blocks by the Krušné hory fault. The northern one, called the Oloví block, consists of a monotonous sequence of muscovite, garnetiferous and two-mica shists (Mlčoch et al., 1997).

The southern Kynšperk block is formed by chlorite-muscovite phyllites and schists. In contrast to the block of Oloví, the rocks of the Kynšperk block contain frequent quartzitic beds. A large part of the Kynšperk block is covered with Tertiary sediments of the Sokolov Basin.

The NK-1 and NK-2 wells are located in the close neighbourhood of the Mariánské Lázně (Marienbad) fault in the Oloví block, approximately 2 km north of the village of Nový Kostel. Both wells, drilled to a depth of 23 m, pass through the weathered zone and end in the two-mica schists (Stejskal et al., 2005). The technical parameters of the wells are given in Brož and Bělař (2002). The inner diameters of the tubes are 10 cm. The casings are open at the bottom of the boreholes. The wells are situated on the slope above the local drainage base, represented by the valley of the left-hand side tributary of the Lubinka brook. The altitude difference between the two wells is 60 m. The monitored aquifer is the zone of loosening of the two-mica schists. The aquifer tapped by the NK-2 well is confined. The groundwater of the NK-2 well is affected by another domestic well situated approximately 10 m away and causes abrupt non-periodic changes, which causes problems in interpreting the obtained measurements. The NK-2 well is situated 60 m south of the Nový Kostel seismic station (code NKC), which plays the key role in the WEBNET seismic network (Horálek et al., 2000) and is also a part of the Czech Regional Seismic Network – CRSN.

2.2. *KRÁSNO*

The third well, HM-1, is located near the town of Krásno at the southern margin of the Slavkov complex. This complex has a complicated dome structure and is divided into two parts – the older core and younger cover series.

The core of the crystalline complex is probably of Proterozoic age, and is formed by highly metamorphosed rocks – biotite paragneisses, two-mica gneisses, migmatites and orthogneisses. The core is covered by younger, less metamorphosed rocks of the Upper Proterozoic age. The most common rocks in the cover are sillimanite-biotite paragneisses, two-mica paragneisses and mica schists.

The whole crystalline complex is penetrated by various granitic plutons of Variscan age, belonging to the southern part of the Krušné hory batholith. The youngest intrusions are associated with the Sn-W-Li mineralization, which made the old mining history of the region (Beran and Sejkora, 2006).

There are two directions of fault systems disrupting the crystalline complex – the NE-SW system following the direction of the Eger Rift and the perpendicular NW-SE fault system.

The HM-1 borehole was drilled in the orthogneisses of the core of the Slavkov crystalline complex (Fig. 1). It is used for monitoring the groundwater level during excavation in nearby granite quarry. The depth of the well is 20 m and it follows an unconfined aquifer in the surface zone of a fissure disjunction and the rock mantle (Stejskal et al., 2005). The inner diameters of the tubes are 8.9 cm. The casing is perforate between depths 6.0 – 19.5 m. The distance of the well from the Nový Kostel epicentral area is 27 km (Table 1).

2.3. *LÁZNĚ KYNŽVART*

In November 2006, the fourth monitoring well located in the spa of Lázně Kynžvart was added to our measurements. The spa area is situated within the Lesný-Lysina Massif in the SW part of the Western Krušné Hory Mts. composite pluton, consisting of different types of Variscan granites (Klomínský et al., 2010). The massif is disrupted by the NW–SE fault system.

The S-4 borehole was drilled at the SE margin of the Lesný-Lysina Massif where several isolated bands of amphibolites are present. The borehole is located within one of these bands. The depth of the borehole is 97 m, and it passes through several fractured zones within the amphibolite block. The distance of the S-4 well from the Nový Kostel epicentral area is 28 km. The borehole was drilled for mineral water abstraction in 1956. The casing has a diameter of 19.5 cm. The perforation is between depths of 40.5 and 92 m. At present, the well is used only for monitoring purposes.

3. WATER LEVEL DATA PROCESSING

The groundwater level is recorded by means of DCP-PLI03 pressure sensors produced by the company DataCon Co. Ltd., Prague (Stejskal et al., 2005). The sensors are connected to digital data loggers with a capacity of 32 000 measured values. The data were recorded with a sampling interval of 6 minutes until November 2006. Afterwards the sampling interval was set to 10 min. The accuracy of the measured values is 0.1% with the immersion depth of the sensor amounting to 10 metres. The deduction step is 1 mm. The recorded data are regularly transmitted using a laptop linked with a RS232 serial port.

The proper interpretation of the groundwater level changes crucially needs precipitation and air pressure data. In figures shown hereinafter the daily amount of precipitation and variations of air pressure (recorded with a sampling interval of 1 hour) are given. Both data series refer to the meteorological station Cheb operated by the Czech Hydrometeorological Institute (CHMI).

First of all, for each locality, the groundwater-level heights were averaged over the whole period 2000-2010. By subtracting the mean value from the measured values we arrived at the relative heights of the groundwater level, which are considered in this

Table 2 The strongest earthquakes during the 2008 earthquake swarm: date, origin time (UTC, hour:minute:second), northern latitude and eastern longitude in degrees, focal depth *h* in kilometres, local magnitude M_L (only the events with $M_L \geq 3.0$ are included), epicentral region.

Date	Time	Latitude	Longitude	h	M_L	Locality
9.10.2008	22:20:37.91	50.215	12.445	9.63	3.5	N. Kostel
10.10.2008	03:22:05.26	50.213	12.446	9.44	3.6	N. Kostel
10.10.2008	03:22:06.88	50.209	12.442	9.20	3.2	Lesná
10.10.2008	08:08:46.24	50.213	12.444	9.68	3.3	N. Kostel
10.10.2008	08:08:46.40	50.214	12.443	9.70	3.7	N. Kostel
10.10.2008	11:18:41.62	50.221	12.443	9.60	3.3	N. Kostel
12.10.2008	07:44:56.31	50.213	12.447	9.38	3.8	N. Kostel
14.10.2008	04:01:36.31	50.217	12.444	9.64	3.0	N. Kostel
14.10.2008	19:00:33.10	50.213	12.448	8.85	3.7	N. Kostel
28.10.2008	08:30:11.39	50.212	12.452	8.03	3.6	N. Kostel

paper. In addition to these uncorrected data, barometric pressure corrections were also introduced. The pressure corrections were computed using the regression deconvolution implemented in the BETCO program (Toll and Rasmussen, 2007). The barometric pressure corrections were applied at a sampling interval of 1 hour.

4. LONG–TIME MONITORING OF THE GROUNDWATER LEVEL

Stejskal et al. (2005) analyzed the results of groundwater monitoring in Western Bohemia in the interval between June 2000 and December 2004. In the present paper, we extend this analysis to December 2010. Since some properties of the groundwater variations have already been described by Stejskal et al. (2005), we shall mention them only briefly.

Figure 2 shows the variations during the whole monitoring interval 2000–2010. The vertical dashed line divides the figure into two parts: 1) the left-hand side showing the observations till the end of the year 2004, described by Stejskal et al. (2005); 2) the right-hand side containing new observations since the beginning of the year 2005.

The upper four panels of Figure 2 show the relative heights of the groundwater level in the individual wells. No corrections were applied to these values. The fifth panel contains the local magnitudes of the earthquakes in the region, taken from the WEBNET Catalogues of Local Earthquakes, produced by the Institute of Geophysics of the Academy of Sciences of the Czech Republic. The last panel contains the daily amounts of precipitation measured at the Cheb meteorological observatory.

The NK-1, NK-2 and S-4 wells display distinct seasonal variations in the groundwater level with the maximum heights usually in spring. This spring culmination is associated with snow-melting, as the maximum precipitation usually appears later in summer. The seasonal variations in the HM-1 well are less obvious. This phenomenon is probably due to different topographies around the boreholes.

Two earthquake swarms with macroseismic effects occurred in the region during the monitoring period, the first one in August – December 2000 and the other in October – November 2008. During the earthquake swarms, the groundwater level dropped remarkably in all wells. We interpret this anomaly as a co-seismic phenomenon. The decrease was distinct even in the distant wells HM-1 and S-4. Detailed description of the observations during the 2008 earthquake swarm will be given in Section 5.

We do not have adequate explanations for the deep drops in the water level at the turn of the years 2003 and 2004. The systematic decrease in the NK-1 after the 2008 earthquake swarm could have been caused by the opening of new fluid pathways during the swarm.

The variations caused by barometric and tidal effects have smaller amplitudes and, therefore, we do not analyze them in detail. They were systematically studied by Stejskal et al. (2005).

The variations in the close wells NK-1 and NK-2 are similar, but some differences can be distinguished. This is not a surprising phenomenon as, in some regions, even greater differences were observed at close mineral springs or hydrological wells (Stejskal et al., 2008, 2009). Nevertheless, the measurements in the NK-2 well contain disturbances, caused by water withdrawal in a nearby domestic well (Stejskal et al., 2005). These disturbances obscure potential seismically induced anomalies.

5. GROUNDWATER LEVEL ANOMALIES DURING THE 2008 EARTHQUAKE SWARM

Table 2 contains the parameters of the individual earthquakes during the 2008 earthquake swarm with the local magnitudes $M_L \geq 3.0$. The strongest earthquake occurred on October 12 with $M_L = 3.8$. In this section we shall compare the individual stages of the earthquake swarm with specific hydrological changes.

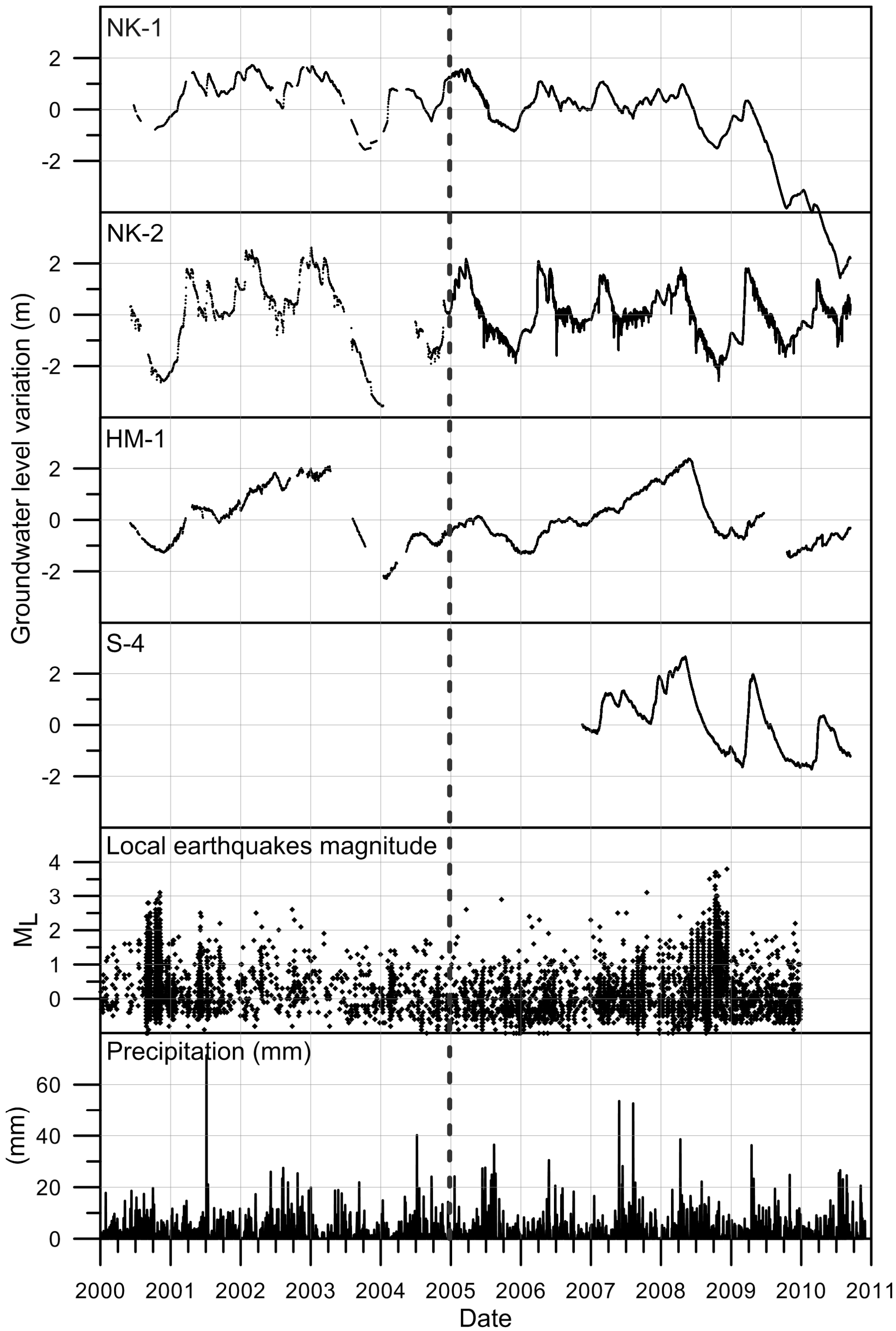

Fig. 2 Variations in groundwater level in the NK-1, NK-2, HM-1 and S-4 wells, seismic activity and precipitation in the years 2000–2010. The groundwater levels are given in metres, relative to their long-term means. M_L stands for local magnitude, derived from the-WEBNET Catalogues of Local Earthquakes.

Figures 3 and 4 show the detailed behaviour of the groundwater level and barometric pressure during the 2008 earthquake swarm in the time interval October – November 2008. The solid bold lines show the uncorrected relative heights of the groundwater level in the individual wells. The dashed line identically in Figures 3 and 4 shows the barometric pressure at the Cheb meteorological station. The thin solid lines represent the heights of the groundwater level corrected for the air pressure. The dots and diamonds show the seismic magnitudes of the individual earthquakes.

The variations of the groundwater level in the NK-1 well (Fig. 3a) are moderate and relatively smooth, without short-term effects and without noticeable relations to the variations in seismic activity. The level in the NK-2 well varies more (Fig. 3b). Several drops in the water level can even be observed prior to the intervals of increased seismic activity, in particular before October 6, 12 and 28. Nevertheless, the measurements in the NK-2 are disturbed by the pumping of water in a nearby house (Stejskal et al., 2005).

The variations in the groundwater level in the distant wells HM-1 and S-4 are surprisingly similar (Fig. 4). Small rises can be observed before some periods of increased seismic activity, e.g., before October 6, 8 and 28. We interpret this behaviour as a possible precursory phenomenon. Attention should also be paid to the "oscillatory" pattern during the main phase of the earthquake swarm between October 6 and 14.

In general, one should expect much greater groundwater level variations in the epicentral area than at distant localities. However, this phenomenon has not been observed, the amplitudes of the variations being comparable in all wells. This probably indicates that the NK-1 and NK-2 wells are not hydrologically linked with the seismically active fault at depth. Note that the concentrations of carbon dioxide and radon in soil gas of the epicentral area did not display significant relations to the 2008 earthquake swarm either (Faber et al., 2009).

These controversies lead us to formulate the preliminary hypothesis that the Mariánské Lázně fault probably does not represent the true outcrop of the deep seismically active fault, which is now commonly accepted in seismological community (e.g., Fischer and Horálek, 2003). This means that the NK-1 and NK-2 wells are not close to this outcrop.

A more convenient locality for hydrological and geochemical monitoring and for deep drilling should be sought in the broader vicinity of Nový Kostel. According to some geodetic measurements, a broad belt between Cheb and Kraslice should be considered (Mrlina and Seidl, 2008), and seismic refraction measurements point to the central parts of the Oloví crystalline unit (Málek et al., 2004, 2010).

6. CONCLUSIONS

The Institute of Rock Structure and Mechanics of the Academy of Sciences of the Czech Republic started monitoring the groundwater level in Western Bohemia in three observation wells in June 2000. Two of the wells, NK-1 and NK-2, are located in the epicentral area of Nový Kostel at the margin of the Oloví crystalline unit and close to the Mariánské Lázně fault. The third well, HM-1, is located near the town of Krásno in the Slavkov crystalline complex. Monitoring in the fourth well, S-4, started in November 2006. The latter well is located at the spa of Lázně Kynžvart in the Western Ore Mts. pluton.

Wells NK-1, NK-2 and S-4 display distinct seasonal variations in the groundwater level. The highest water levels are usually observed in spring, which is associated with the seasonal thaw. The seasonal variations in the HM-1 well are less obvious. The variations caused by barometric and tidal effects are significantly smaller and we have not studied them in detail. They were systematically analyzed by Stejskal et al. (2005).

During the monitoring period of 2000–2010, two earthquake swarms with macroseismic effects occurred in the region, the first one in autumn 2000 and the other in autumn 2008. During the earthquake swarms, the groundwater level in all wells dropped remarkably, which we interpret as a co-seismic phenomenon. This decrease was distinct even in wells HM-1 and S-4, whose distance from the epicentral area is nearly 30 km. Note that the hydrological and geochemical changes during the previous earthquake swarms were observed only to epicentral distances less than 20 km. Moreover, during the 2008 earthquake swarm a small rise in the water level preceded the intervals of increased seismic activity, which could represent a certain precursory phenomenon.

Seismic monitoring around Nový Kostel is absolutely indispensable as this locality lies in the epicentral region. However, the hydrological changes in wells NK-1 and NK-2 during the earthquake swarms were relatively small in comparison with the changes in the distant wells. This probably indicates that the NK-1 and NK-2 wells are not hydrologically linked with the seismically active fault at depth, i.e. they are not close to the outcrop of the fault. For this reason, a more convenient locality for hydrological monitoring should be sought in the broader vicinity of Nový Kostel.

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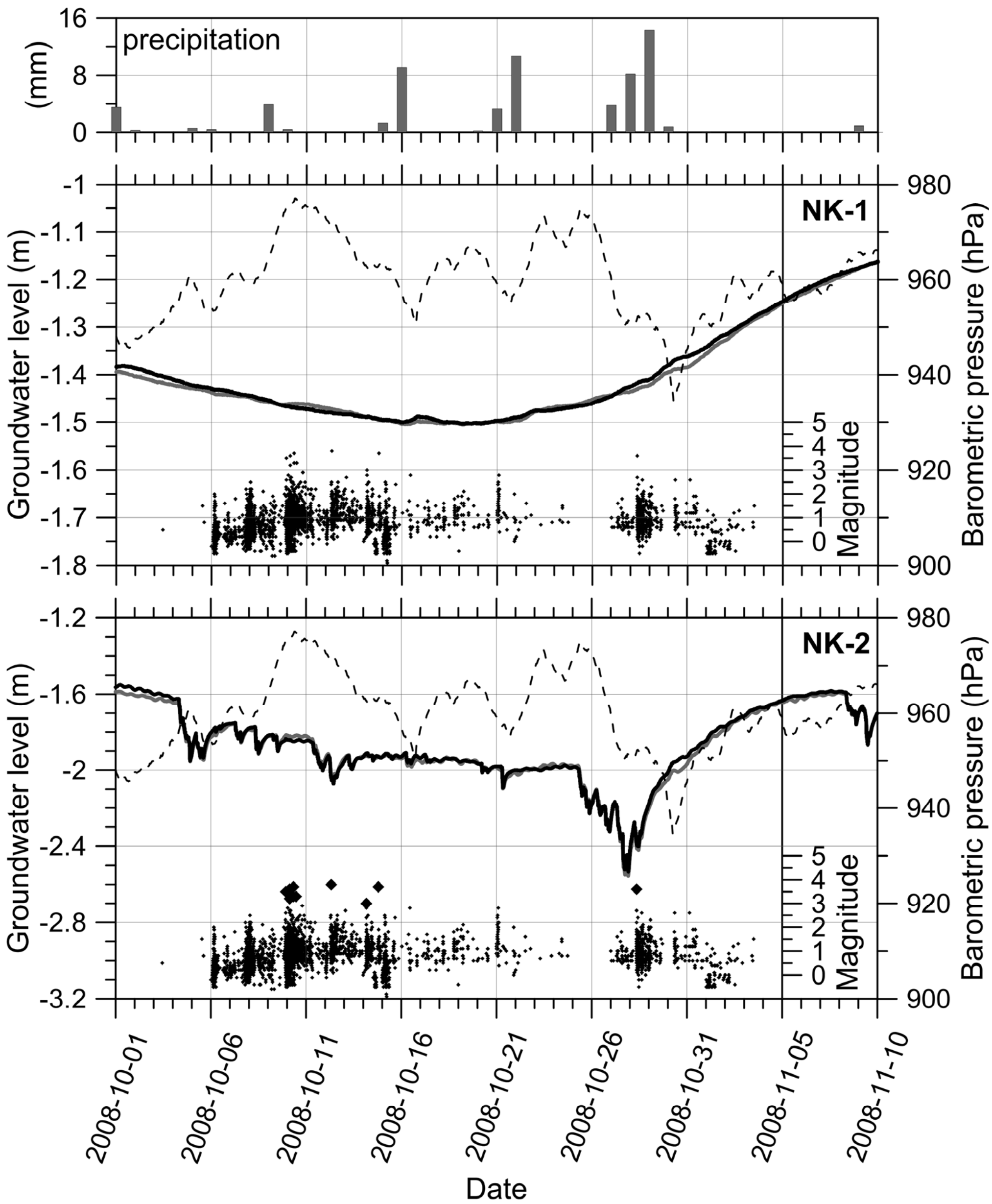

Fig. 3 Variations in wells NK-1 and NK-2 during the 2008 earthquake swarm: relative groundwater level (bold line), air pressure (dashed line), groundwater level corrected for the air pressure (thin solid line) and seismic magnitudes of the individual earthquakes (dots for magnitudes less than 3.0 and diamonds for higher magnitudes). The uppermost panel shows precipitation.

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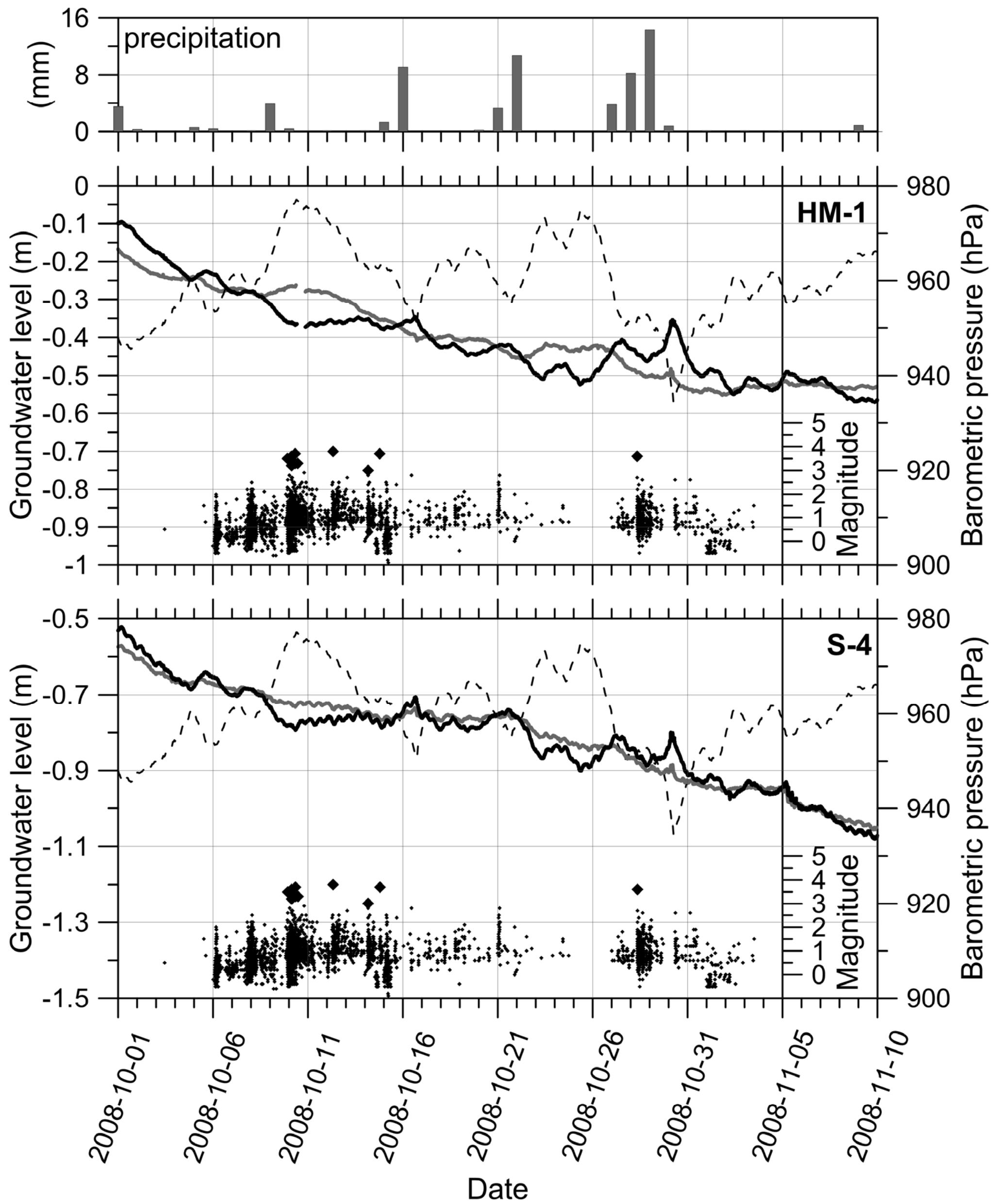

Fig. 4 Variations in wells HM-1 and S-4 during the 2008 earthquake swarm. For the notations, see Figure 3.

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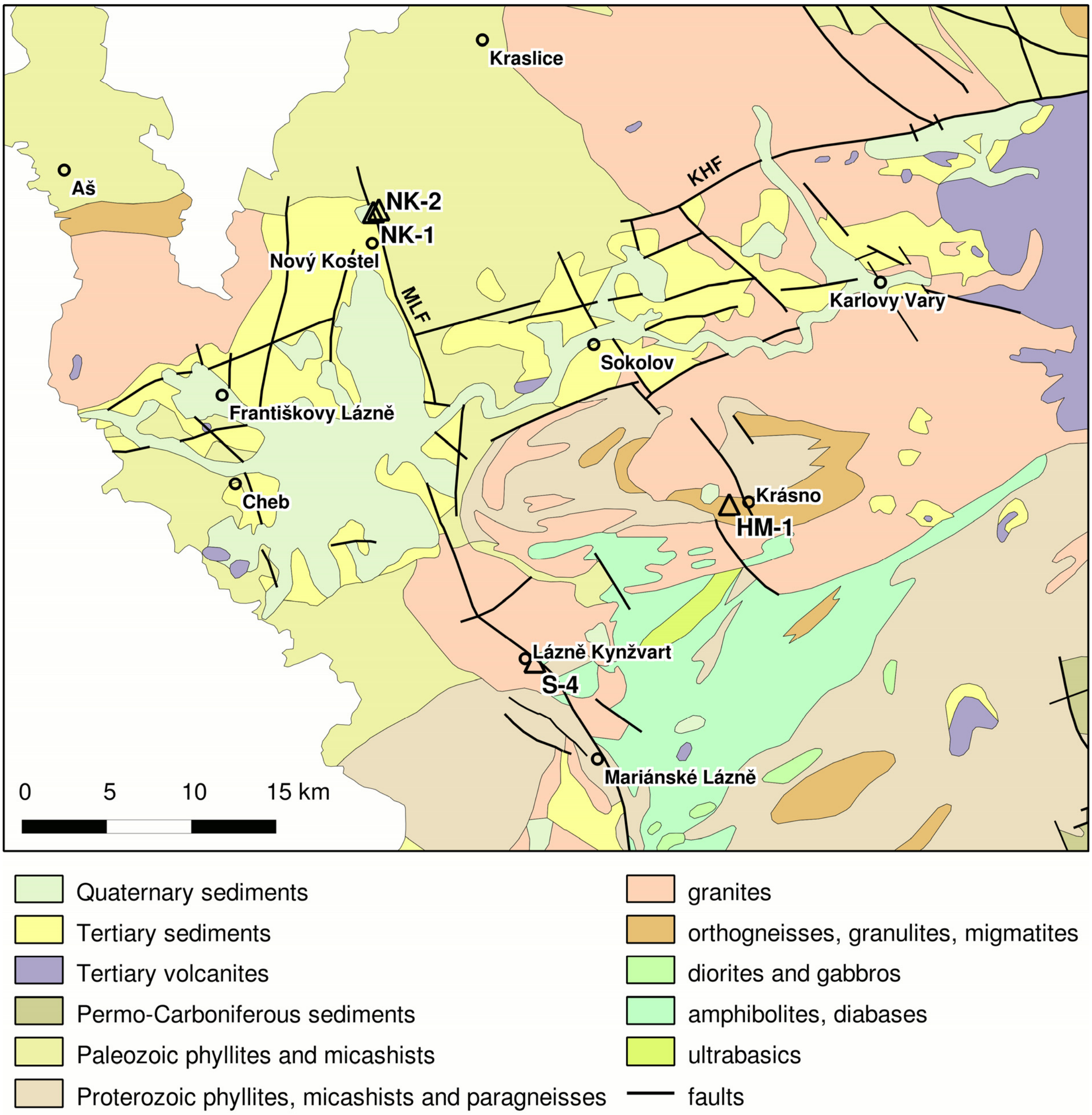

Fig. 1 Simplified geological map of Western Bohemia (adapted after Kodym, 1998). The circles show the major towns in the region, triangles denote the wells, MLF and KHF are the Mariáské Lázně and Krušné hory faults, respectively.