Acta Geodyn. Geomater., Vol. 4, No. 4 (148), 59-76, 2007

RESULTS OF TWO-YEARS' SEISMO-HYDROLOGICAL MONITORING IN THE AREA OF THE HRONOV-POŘÍČÍ FAULT ZONE, WESTERN SUDETES

Vladimír STEJSKAL [1)]*, Lumír SKALSKÝ [2)] and Ladislav KAŠPÁREK [3)]

[1)] *Institute of Rock Structure and Mechanics, v.v.i., Academy of Sciences of the Czech Republic, V Holešovičkách 41, 182 09, Praha 8, Czech Republic*
[2)] *Geophysical Institute, v.v.i., Academy of Sciences of the Czech Republic, Boční II/1401, 141 31 Praha 4, Czech Republic*
[3)] *T. G. Masaryk Water Research Institute, v.v.i., Podbabská 30, 160 62 Praha 6, Czech Republic*
**Corresponding author's e-mail:* stejskal@irsm.cas.cz

(*Received* June 2007*, accepted* September 2007*)*

ABSTRACT

We present first results of the study of possible relations between the seismic activity and crustal fluids (groundwater and carbon dioxide) in the area of the Hronov-Poříčí Fault Zone (HPFZ), situated on the NE margin of the Bohemian Massif. Local seismic monitoring and observations of groundwater levels in deep wells and concentrations of carbon-dioxide in the mineral spring at Třtice was started in 2005. Since then, more than 30 local seismic events were observed in the area of the HPFZ. The two strongest earthquakes with macroseismic effects were recorded on August 10, 2005 (M = 2.4) and October 25, 2005 (M = 3.3). Most of the epicentres were situated along the central part of the HPFZ. Only some weak events from February and March 2006 were concentrated along the SE termination of the HPFZ. Results of the hydrological monitoring show that water level fluctuations are affected mainly by the precipitation, snow-melt, air pressure changes, and tidal deformations of the Earth's crust. The effects of seismo-tectonic activity were detected only in one out of five water wells, where we observed several step-like water level anomalies with amplitudes of 4 to 15 cm. Two of them preceded the August 10, 2005 and October 25, 2005 earthquakes. Three other anomalies seemed to originate independently of the seismic activity. We therefore suppose that they were induced by aseismic movements along the HPFZ. Contrary to the water level fluctuations, CO_2 concentrations in the mineral spring seem to be dependent on water temperature; no evident seismic-induced changes have been observed yet.

KEYWORDS: seismic activity; Hronov-Poříčí Fault Zone; earthquake precursors; groundwater; crustal deformation; Earth tides

1. INTRODUCTION

Bohemian Massif - one of the most prominent Central European Variscan structures – belongs to the areas with relatively low intraplate seismic activity. Seismoactive zones are limited to its marginal parts, where young tectonic movements (Late Tertiary – Early Quaternary) caused the uplift of marginal crustal blocks forming the mountain chains which frame the almost aseismic central part of the massif (Procházková et al., 1986). The broader area of the Hronov-Poříčí Fault Zone (HPFZ) situated on the NE margin of the Bohemian Massif is known for its episodic seismic activity, characterised by the occurrence of relatively strong shocks with magnitudes up to M = 5 and epicentral intensities up to 7° MSK. First historical records of seismic activity are dated back to the 11th century (Kárník et al., 1958).

The present work summarizes the results of the first two years of the project aimed on the study of relations between the seismic activity in the HPFZ area and the dynamics of the groundwater regime. For this purpose we started local seismic monitoring using small aperture seismic array (Brož et al., 2006) and hydrological observations in selected sites distributed along the HPFZ.

Hydrogeological effects of seismic activity are the results of anomalous migration of fluids or pore-pressure variations in the Earth's crust due to seismo-tectonic processes. These effects are observable as fluctuations of various quantitative as well as qualitative hydrogeological parameters, such as water well level, spring discharge, chemical or isotopic composition, gas flow rate, temperature, electric conductivity, turbidity and others. Seismic-induced fluctuations of groundwater parameters were described by many authors from different seismoactive regions of the world (see e.g. Gavrilenko et al., 2000; Koch et al., 2003; Akita and Matsumoto, 2004; Elkhoury et al., 2006). These changes are generally believed to reflect stress variation in the Earth's crust (e.g. Kümpel, 1992). Based on the mutual temporal relation between the earthquake origin and groundwater level anomaly, we distinguish pre-, co-, and post-seismic groundwater level changes. From the point of view of earthquakes prediction, the

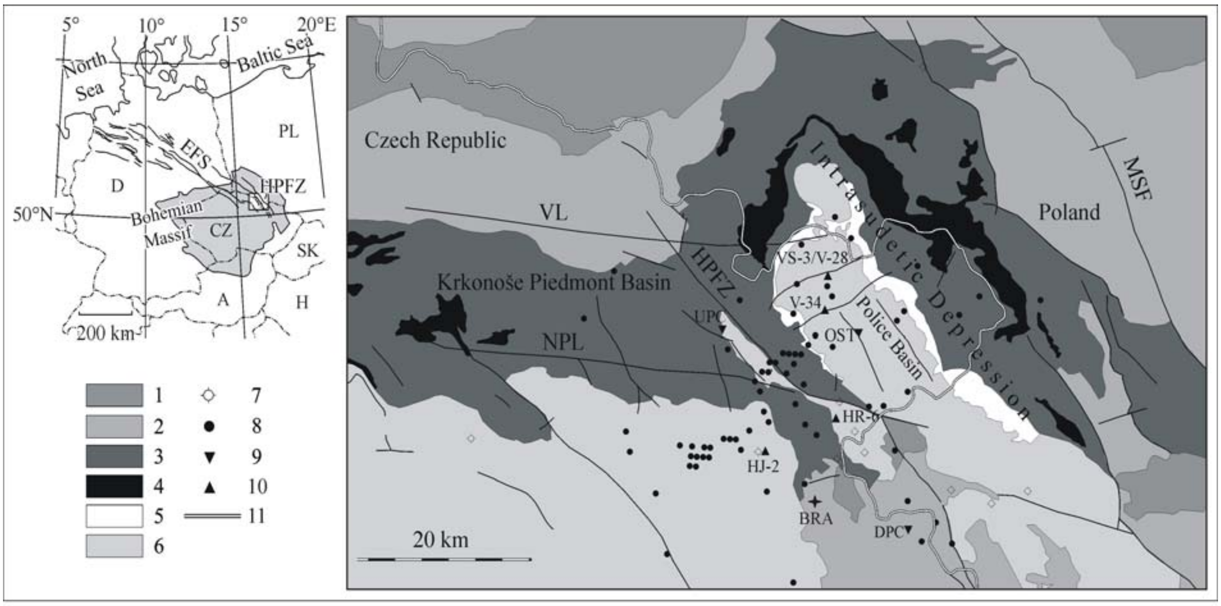

Fig. 1 Geology and tectonics of the study area (after Biely et al., 1968; Jetel and Rybářová, 1979; Schenk et al., 1989; Scheck et al., 2002; Cymerman, 2004). 1 - plutonic rocks (granites, granodiorites), 2 – metamorphites (gneisses, schists, granulites, migmatites), 3 – Permian and Carboniferous sediments, 4 – Permian volcanics, 5 – Triassic sediments, 6 – Cretaceous sediments, 7 – CO_2-rich mineral springs, 8 – epicentres of seismic events recorded from 1985 to 2005, 9 – seismic station, 10 – observation well, 11 – state boundary. HPFZ – Hronov-Poříčí Fault Zone, MSF – Marginal Sudetic Fault, EFS – Elbe Fault System (see the small-scale map in the upper left corner), VL – Vrchlabí Lineament, NPL – Nová Paka Lineament, BRA – pluviometric station Bražec.

most important are the pre-seismic anomalies which can serve as earthquake precursors. Many of the reported precursory anomalies were reviewed by Roeloffs (1988), Kissin and Grinevsky (1990) or King et al. (2006). These papers summarize basic characteristics of pre-seismic groundwater level changes, like the size of the anomaly, lead time of the occurrence and possible relations between the earthquake magnitude, epicentral distance and the amplitude of the anomaly. Reported amplitudes of the anomalies range from several centimeters to several meters and, similarly, the precursor times range from less than one day to several months or even years. The epicentral distances at which the seismic-induced hydrogeological effects are observed may reach several hundreds of kilometers. In general the groundwater level anomalies are associated not only with strong earthquakes. For example Kissin et al. (1996) or Leonardi et al. (1997) reported pre-seismic and co-seismic well level changes induced by seismic events with magnitudes $M < 3$.

In the area of the HPFZ, hydrogeological effects of seismicity have never been systematically monitored. Their occurrence has been mentioned only in connection with the assessment of macroseismic effects of strong seismic events. The most significant changes of groundwater parameters were described by Woldřich (1901) in connection with the January 1901 earthquake ($M \sim 4.6$). Anomalous fluctuations of water level and turbidity were observed in dug wells at distances of up to 60 km from the earthquake epicenter. The reported changes sustained for several hours or even days after the main shock.

2. GEOLOGICAL AND TECTONIC SETTINGS OF THE STUDY AREA

The HPFZ belongs to the broader seismoactive area of the NE margin of the Bohemian Massif which spreads between the Krkonoše Mts. and the front of the Carpathian nappes. This area is represented by a generally NW-SE-striking zone approximately 40-60 km wide and 150 km long, which comprises a number of NW-SE- and NNW-SSE-striking faults. This zone forms the SE termination of the important Central European tectonic structure – the Elbe Fault System (EFS – see Fig. 1) extending from the North Sea to the eastern margin of the Bohemian Massif (e.g. Scheck et al., 2002; Špaček et al., 2006). According to Scheck et al. (2002) the most intense crustal deformation along the EFS took place during the late Cretaceous-early Cenozoic time, when the EFS responded to regional compression with an uplift of up to 4 km.

In comparison with the well-known West Bohemia/Vogtland seismoactive zone (e.g. Bankwitz et al., 2003), the seismoactive region of the SE termination of the EFS is characterised by less frequent occurrence of seismic events. Smaller earthquake swarms in this area were reported by Špaček et al. (2006) from the Jeseníky Mts., but these micro-swarms do not include more than 50 weak events ($M \leq 1.3$). The strongest earthquakes occur on the NW margin of this seismoactive region and are connected with movements along the Hronov-Poříčí Fault Zone (Kárník et al., 1984; Procházková et al., 1986).

The Hronov-Poříčí Fault Zone (HPFZ) is a system of parallel fractures, dividing two important structural units – Intrasudetic Depression and the Krkonoše Piedmont Basin (Fig. 1). The NW-SE-striking fault zone is approximately 30 km long and up to 500 m wide. It is bounded by the Vrchlabí lineament in the north and by the Nová Paka lineament in the south. Both E-W-striking faults are supposed to be sinistral strike slips (cf. Schenk et al., 1989). The contemporary HPFZ is a result of a complicated and long-lasting evolution which began in the late Paleozoic. Since then, several tectonic phases have taken place. The fault zone successively developed from an asymmetrical anticline whose steeply inclined SW arm was axially disrupted by a reverse fault due to the regional compression (Tásler, 1979). Along this fault, the NE block was relatively uplifted. The main reverse fault is accompanied by parallel or oblique, high angle dislocations (normal or reverse faults) grouped under the term Hronov-Poříčí Fault Zone.

The relatively frequent local seismic activity is a proof of the current mobility of the HPFZ. Macroseismic effects of historical earthquakes in this area reached the epicentral intensity $I_o = 7°$ three times during the last 300 years (30 June 1751, 11 December 1799 and 10 January 1901 – Kárník et al., 1958). The strongest historical earthquake of January 10, 1901 reached the magnitude of 4.6 and was felt over the area of 50,000 km^2 (Woldřich, 1901). The isoseists of local earthquakes are elongated mostly in the NW–SE direction – in accordance with the orientation of the HPFZ. The depth of foci is mostly between 5 and 15 km (Schenk et al., 1989). Instrumental monitoring of seismic activity focused on local earthquakes began in the 1980s. Since 1984 were recorded in the area of HPFZ more than 80 earthquakes in the magnitude range $M = 0.0–3.4$.

Another significant proof of the increased endogenic dynamics of the study area is the occurrence of CO_2-rich mineral springs. A major role in the transport of the mantle derived CO_2 play deep permeable faults like the HPFZ or some other local fractures (Jetel and Rybářová, 1979). In general, the mineral springs in the area of the HPFZ belong to a larger zone, which partly extends to the territory of Poland (cf. Fig. 1).

A possible explanation of the present mobility of the HPFZ was given by Schenk et al. (1989). According to this local geodynamic model, the HPFZ, as a reverse fault, balances the compression caused by the movements along the Nová Paka and Vrchlabí lineaments, bounding the HPFZ in the north and south. This presumption is supported by the analyses of repeated triangulation and precise levelling, performed in the broader vicinity of the HPFZ by Vyskočil (1988). Results of the repeated geodetic measurements indicate compressional tendencies across the HPFZ. More recent data on crustal deformation in the broader area of the HPFZ are available owing to GPS measurements along the Marginal Sudetic Fault (MSF), running parallel to the HPFZ along the NE margin of the Bohemian Massif (Fig. 1). Preliminary results of the GPS monitoring indicate NE–SW compression tendencies, perpendicular to the MSF and HPFZ (Kontny, 2004).

3. OBSERVATIONS

3.1. MONITORING OF SEISMIC ACTIVITY

Three seismic stations - Úpice (UPC), Dobruška-Polom (DPC) and Ostaš (OST) - are presently operated in the broader area of the HPFZ. The UPC and DPC stations belong to the Czech Regional Seismological Network and are operated by the Geophysical Institute (IG) in Prague. The data from these stations are recorded in continuous mode with sampling frequency of 20 Hz. The third station - OST is operated since 2005 by the Institute of Rock Structure and Mechanics (IRSM). This station was designed as a small aperture array containing three SM6b satellite short-periodic sensors and the Güralp CMG-40T broadband sensor as a central point. Data are recorded in a continuous mode with a sampling frequency of 100 Hz. Most seismic data (i.e. co-ordinates in Fig. 1, magnitudes and origin times of seismic events) used in this paper were taken from the Catalogue of regional seismic events, compiled by the IG (the catalogue is published in an electronic form at http://web.ig.cas.cz/en/seismic-service/catalogs-of-regional-seismic-events/).

3.2. HYDROLOGICAL MEASUREMENTS

3.2.1. MONITORING SITES

At present, the hydrological observations are carried out in five monitoring sites (see Fig 1). Three of them (HJ-2, HR-6 and V-34) were newly established by the IRSM and the Faculty of Science of Charles University in Prague in 2005, and the two remaining sites (VS-3 and V-28) have been observed by the T.G. Masaryk Water Research Institute (WRI) since 1970s and 1980s respectively. A brief description of all the five monitoring sites is given below:

- **Monitoring site HJ-2**
  Monitoring site HJ-2 is situated approximately 8 km southwest of the surface trace of the HPFZ near the municipality of Třtice. Selected parameters of CO2-rich mineral water in a shallow reservoir are observed here. The presence of the reservoir is determined by a zone of tectonic fractures in Upper Cretaceous sediments. Mineral water is artificially captured in a dug well and in the 35 m deep borehole HJ-2. The distance

between the two objects is approximately 600 m, and their hydraulic interconnection was proved by pumping tests. The observations carried out at the HJ-2 site consist of daily manual measurements of CO2 concentrations and temperature of the spring captured in the dug well and of automatic water level measurements in the HJ-2 well.

- **Monitoring site HR-6**
  Observation well HR-6 was drilled in Upper Cretaceous sediments (Turonian marlstones and siltstones) approximately 2.5 km south of the HPFZ, near the town of Hronov. The depth of the well is 100 m. It taps a reservoir of non-mineralized water at the depth of 30-100 m. Only automatic water level measurements are taken at the HR-6 site
- **Monitoring site V-34**
  The V-34 well, situated near the town of Teplice nad Metují, approximately 9 km northeast of the HPFZ is 281 m deep. It passes through the fault plane of the Skály Fault – an ENE–WSW-striking dislocation perpendicular to the HPFZ. The well taps a reservoir in Upper Cretaceous sediments (Cenomanian sandstones) in the depth of 238–281 m. Only automatic water level measurements are taken at the V-34 site.
- **Monitoring sites VS-3 and V-28**
  The deep observation wells VS-3 (305 m) and V-28 (300 m) were drilled in the valley of the Metuje River near the municipality of Adršpach, only 540 m from each other. Both wells tap aquifers in Upper Cretaceous sediments (Middle Turonian to Cenomanian sandstones, marlstones and silicites), nevertheless they differ in the vertical range of screens (i.e. open parts of the casing). The VS-3 well is opened at depths of 38.38-207.06 m and 216.65-260.13 m while the V-28 well at a depth of 157.2–211.75 m. Automatic water level measurements at these two wells are taken by the WRI since 1998. In June 2006, water level at the VS-3 well is simultaneously measured by the IRSM using DataCon sensor with a higher resolution.

3.3. *MEASURING TECHNIQUES*

Measurements of CO_2 concentrations in the mineral water spring are taken daily by a local observer using the Haertl's instrument. The declared accuracy of measurements is between 10 and 15 %. On the other hand, the water level measurements are fully automatic. All observation wells are equipped with water level sensors comprising of the measuring unit (hydrostatic pressure transducer) and the data storage unit. Two types of water level sensors are used: DataCon sensors (used by the IRSM) with a 1-mm resolution of the water column and Noel sensors (used by the WRI) with a 1-cm resolution of the water column. The sampling period of measurements is 10 minutes in the IRSM wells and 1 hour in the WRI wells. Additional measurements of air pressure, which considerably influences the groundwater level fluctuations, are taken at the OST seismic station. Data are recorded automatically with a sampling period of 10 minutes. The resolution of the measurements is 0.001 hPa. The air pressure sensor is placed in an unheated underground cellar, in order to avoid the fluctuations caused by the wind gusts.

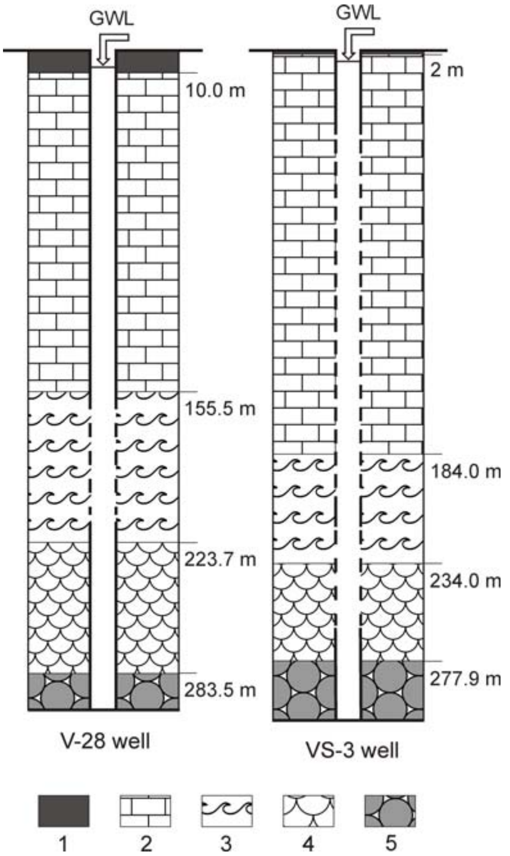

Fig. 2 Observation wells VS-3 and V-28.
1 - Quaternary alluvial deposits.
2 - Middle Turonian marlstones and silty sandstones.
3 - Lower Turonian marlstones.
4 - Cenomanian cherts (upper most Cenomanian series), marlstones and sandstones.
5 - Triassic sandstones. Broken line - open parts of the well casing, GWL = groundwater level.

4. WATER LEVEL DATA PROCESSING

Groundwater level data processing is based on the decomposition of the initial measured signal (i.e. directly observed groundwater level) into four components: barometric response (*BAR*), diurnal and semidiurnal tidal response (*TID*), low-frequency component (*LFC*), and high-frequency non-tidal residuals (*HFR*). The observed water level *OBS* is decomposed as the following form:

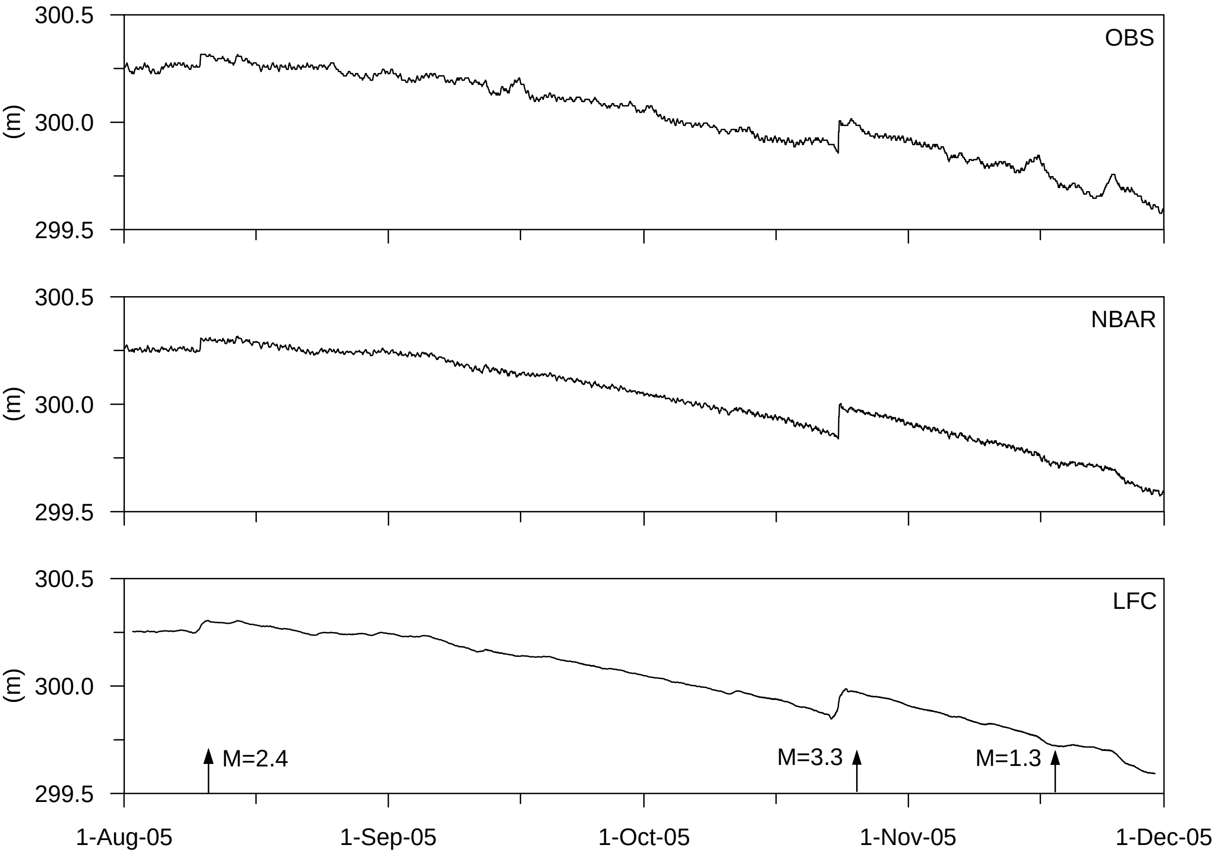

Fig. 3a Decomposition of the observed groundwater level in the VS-3 well: *OBS, NBAR* and *LFC* components. Period: August 1, 2005 to December 1, 2005. Arrows indicate the times of local earthquakes (M = earthquake magnitude). Note the pre-seismic steps recorded before the August 10 (M = 2.4) and October 25 (M = 3.3) earthquakes.

$$\begin{aligned} &OBS = BAR + NBAR \qquad (1)\\ &NBAR = LFC + HFC\\ &HFC = TID + HFR\\ &OBS = BAR + TID + LFC + HFR \end{aligned}$$

where *NBAR* is the groundwater level after removing the effects of air pressure and *HFC* is the high-frequency component of *NBAR*. The decomposition of the observed water level is shown in Figs. 3a and 3b. For detection of short term non-periodic anomalous variations the HFR component is the most suitable (see Fig. 3b). On the other hand potential long-term variations are expected to be easier detected in the LFC component.

The effects of air pressure fluctuations on the observed groundwater level variations can be removed or at least substantially reduced by means of different methods. Frequently used are the techniques based on the least squares method (e.g. Davis and Rasmussen, 1993) or the frequency dependent transfer function between the water level and air pressure variations (e.g. Quilty and Roeloffs, 1991; Lyubushin, 1994). In this paper, the recently published method of Rasmussen and Toll (2007) based on regression deconvolution method was used. The advantage of the procedure is that it accounts for the delayed response of the groundwater level to air pressure changes. To estimate the unknown response function between the air pressure and water level changes the following equation is established:

$$\Delta W(t) = \sum_{i=0}^{m} \alpha(i)\Delta B(t-i) \qquad (2)$$

where $\Delta W(t)$ is the change in water level at time t, $\Delta B(t-i)$ is the change in barometric pressure i time steps before t, $\alpha(i)$ is the unit response function at lag i and m is the maximum time lag. The response function is found using an ordinary least squares linear regression. Then, using the known response function, correction can be implemented for a series of observations starting with m-th data point.

After removing barometric effects, the water level data are split into a low frequency component LFC (below 0.8 cpd) and a high-frequency component HFC (above 0.8 cpd) by numerical filtering. For this purpose we use the Pertsev (1959) low-pass filter of

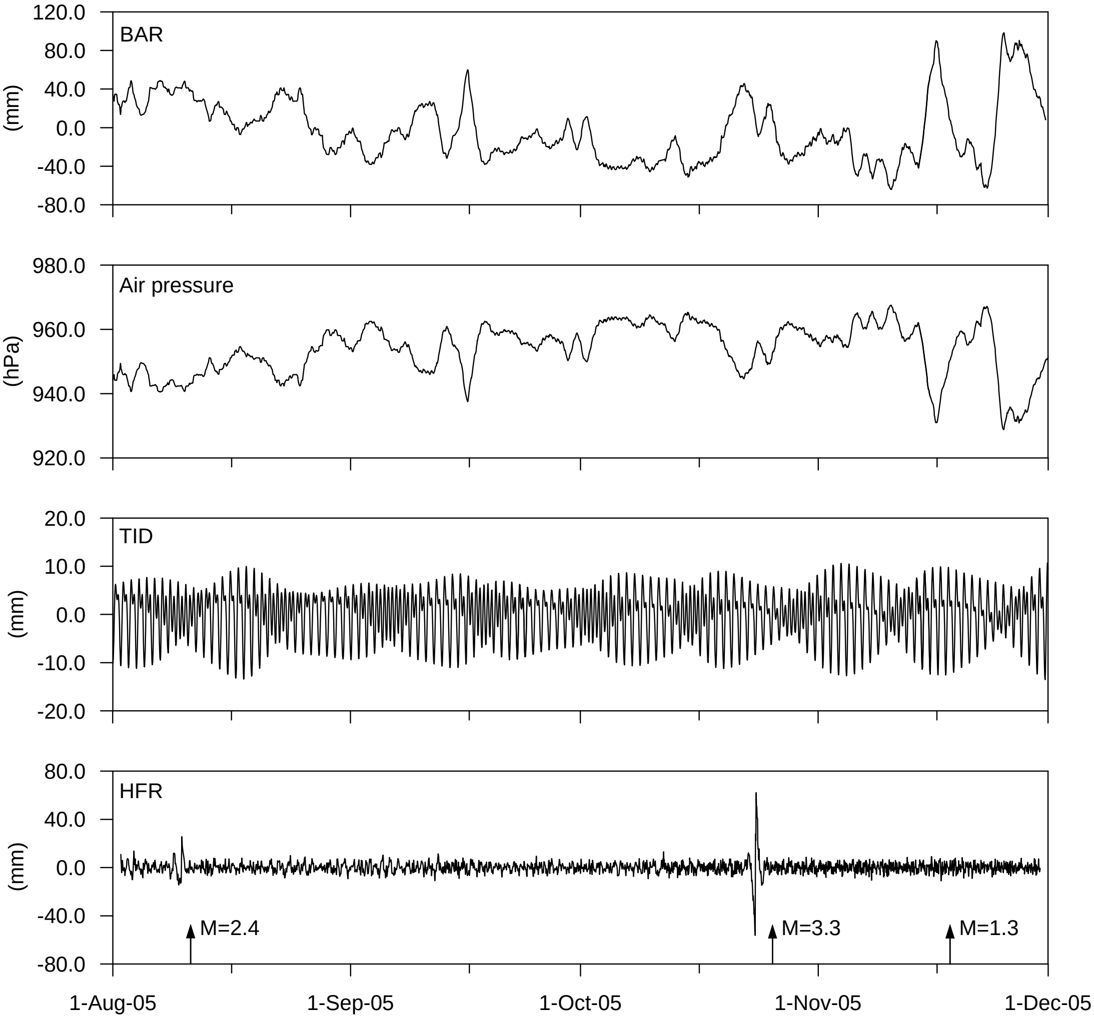

Fig. 3b Decomposition of the observed groundwater level in the VS-3 well: air pressure and *BAR, TID* and *HFR* components. Period: August 1, 2005 to December 1, 2005. Arrows indicate the times of local earthquakes (M = earthquake magnitude).

51 hours length. Finally the high-frequency component HFC is split into the tidal constituent TID and non-tidal high-frequency residuals HFR. The tidal constituent of the groundwater level signal was determined based on a tidal analysis of the high-frequency component HFC. The tidal analysis was carried out for five main wave groups (O1, K1, N2, M2, S2) according to Tamura's (1987) development with 1200 waves, using modified ETERNA 3.0 program (Wenzel 1993). The global tidal model of an ellipsoidal, rotating, elastic and oceanless Earth "Wahr-Dehant-Zschau", considering the imperfect elasticity of the Earth's mantle, was used (for details see Wahr, 1981; Dehant, 1987; Zschau and Wang, 1981). Based on this model, theoretical values of the relative volume tidal strain were calculated in order to determine the amplitude factors and phase differences between the theoretical and observed tidal waves (for result of tidal analyses see part 5.1.). The tidal constituent *TID* represents the sum of all tidal waves in the frequency range of 10.822–32.743 deg/h, whose frequencies are given by the used tidal model, and the amplitudes A_o and phases Φ_o are calculated using formulas:

$$A_o = A_m A \, \mathrm{A_f} \tag{3}$$

$$\Phi_o = \Phi_m + D_f \tag{4}$$

where A_m and Φ_m are the amplitudes and phases of the model values of volume tidal strain, A_f is the amplitude factor and D_f is the phase difference calculated for each analysed wave group. The expression for the tidal constituent *TID* is then given by:

$$TID(t) = \sum_{i=286}^{1121} A_{oi}[\cos(f_i t + \Phi_{oi})] \tag{5}$$

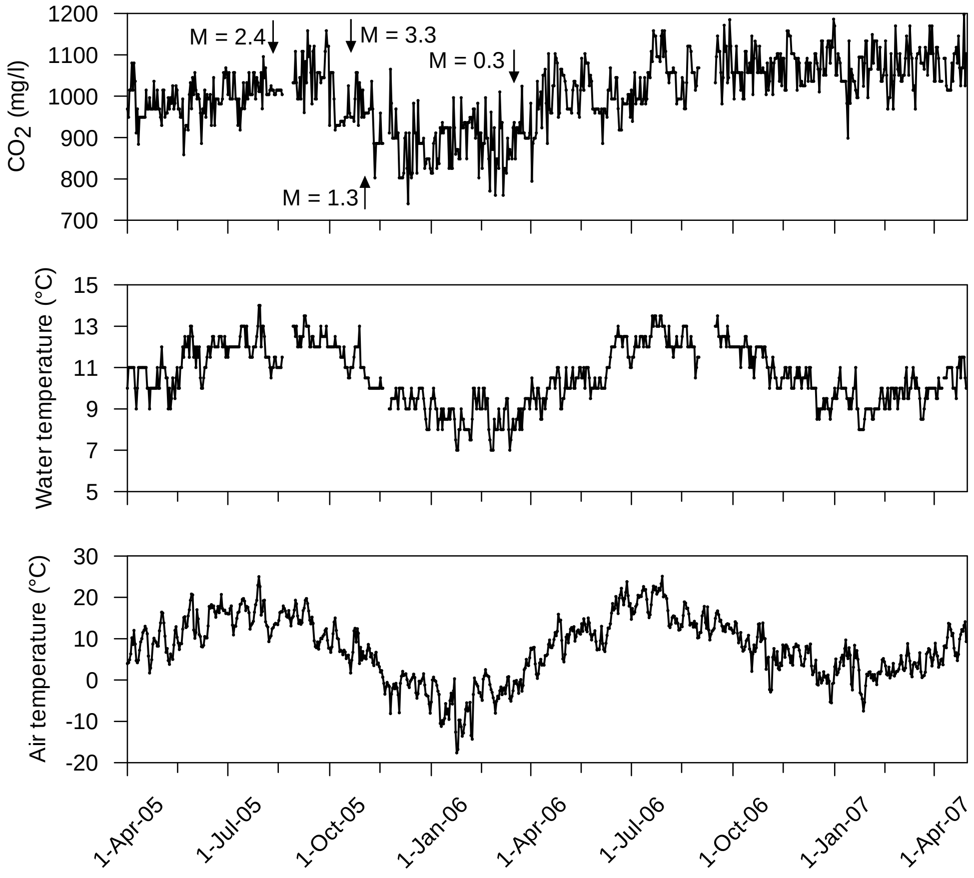

Fig. 4 CO_2 concentrations and temperature of the mineral spring Třtice. Air temperature is measured at the pluviometric station Bražec – approximately 7 km SE of the monitoring site Třtice.

where t is time in hours, f is the frequency of the wave in deg/h and i is the order of the wave according to the Tamura's development. Since we use only the waves from the above mentioned semidiurnal to diurnal frequency range in the *TID* constituent, the index i in (5) ranges from 286 to 1121. The effects of long-period tides, which are difficult to remove from such short observation series, are included in the low-frequency component (*LFC*).

5. RESULTS

The directly observed groundwater level and CO_2 concentration data are shown in Figs. 4 - 5. Here, it is obvious that the groundwater level variations in all the five observation wells generally follow the uniform seasonal pattern driven by the aquifers' replenishment due to rainfalls and melting snow cover. The best apparent common features in water level changes are the April 2006 peaks caused by the rapid snowmelt accompanied by rainfalls, which resulted in local floods. As already discussed above, the groundwater level variations are also strongly influenced by air pressure changes and Earth tides (see Figs. 7 and 8). The effects of seismic activity were identified only in one of the observation objects - the VS-3 well. The barometric and tidal response of groundwater level fluctuation and the effects of seismic activity are discussed more in detail in parts 5.1. and 5.2..

Variations in CO_2 concentrations in the Třtice mineral spring exhibit changes in the range of 700–1200 mg/l, mostly dependent on the air and thus also the water temperature. An interesting feature is the transient drop in CO_2 concentration in the period October 2005 – March 2006, which follows the period of increased seismic activity in the second half of the year 2005 (see Fig. 4). Even though there was no such drop observed at the turn of years 2006 and 2007, we suppose the 2005/2006 drop to be the result of extraordinary low air temperatures during the winter season 2005/2006 (see Fig. 4).

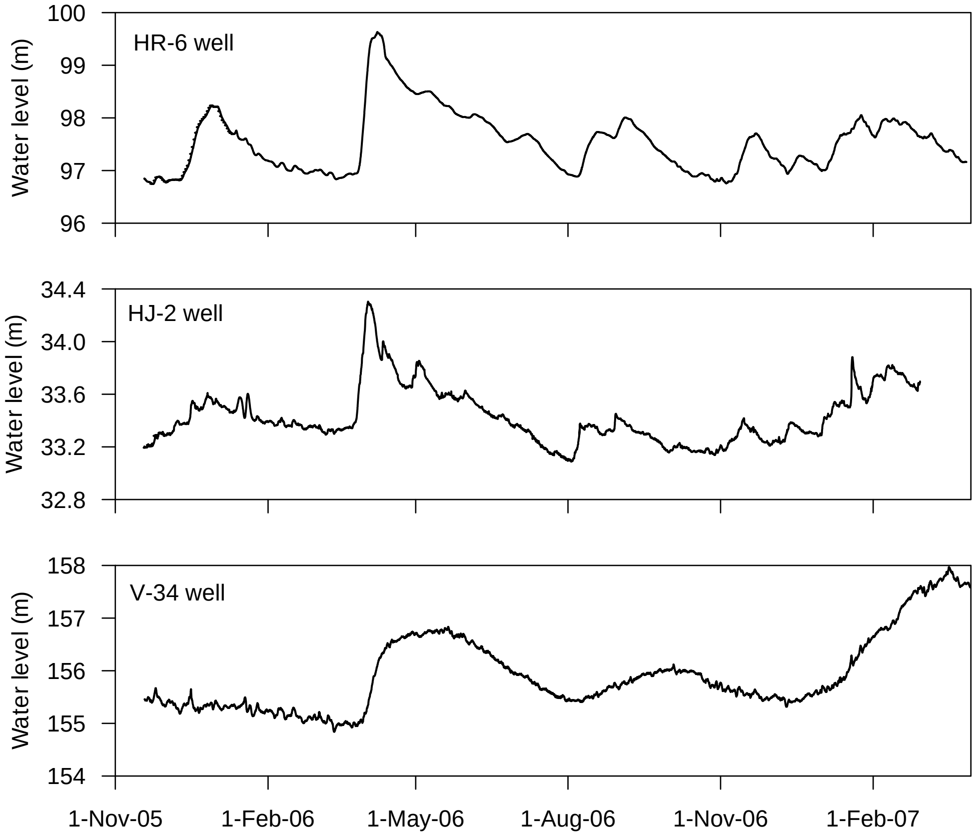

Fig. 5 Groundwater level variations in the HR-6, HJ-2 and V-34 wells. Period of observations: November 1, 2005 – April 1, 2007.

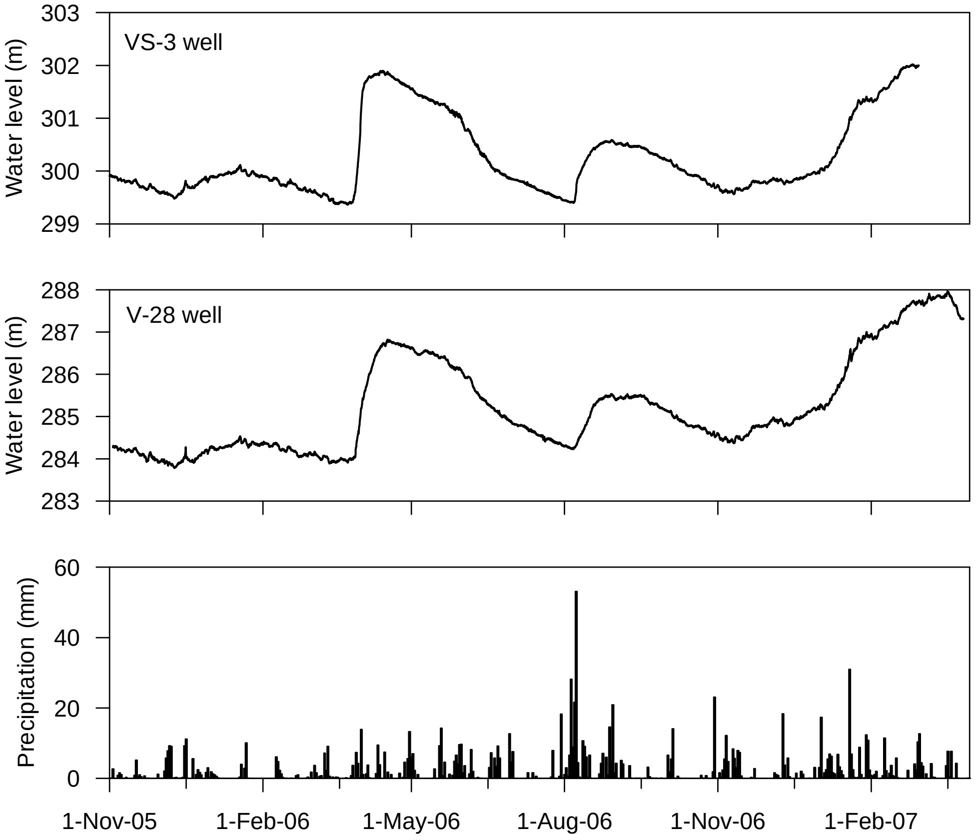

Fig. 6 Groundwater level variations in the VS-3 and V-28 wells and precipitations recorded at the pluviometric station Bražec. Period of observations: November 1, 2005 – April 1, 2007.

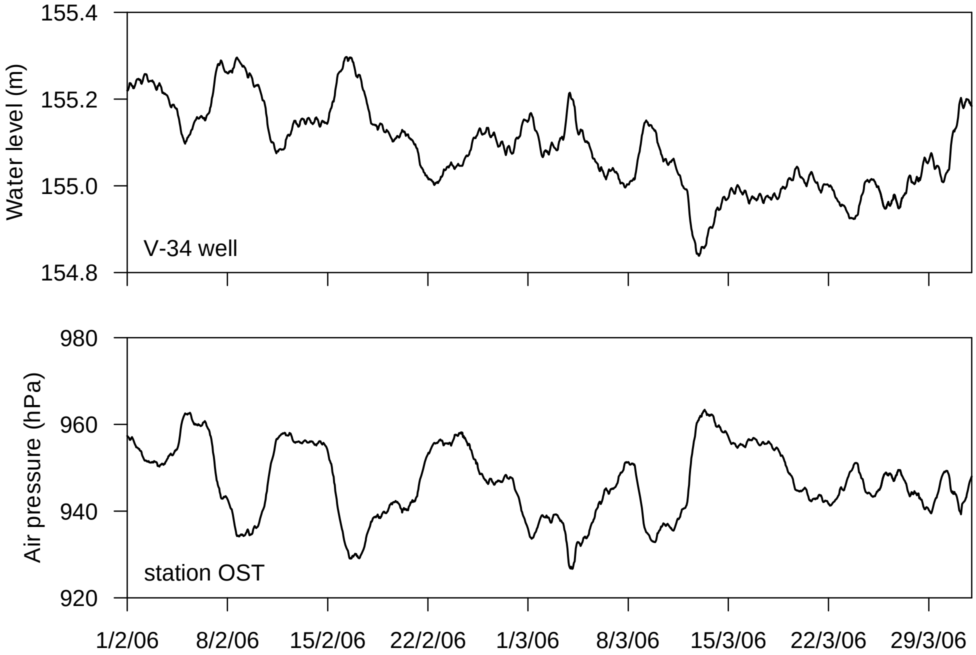

Fig. 7 Comparison of the groundwater level in the V-34 well and air pressure variations measured at the OST seismic station.

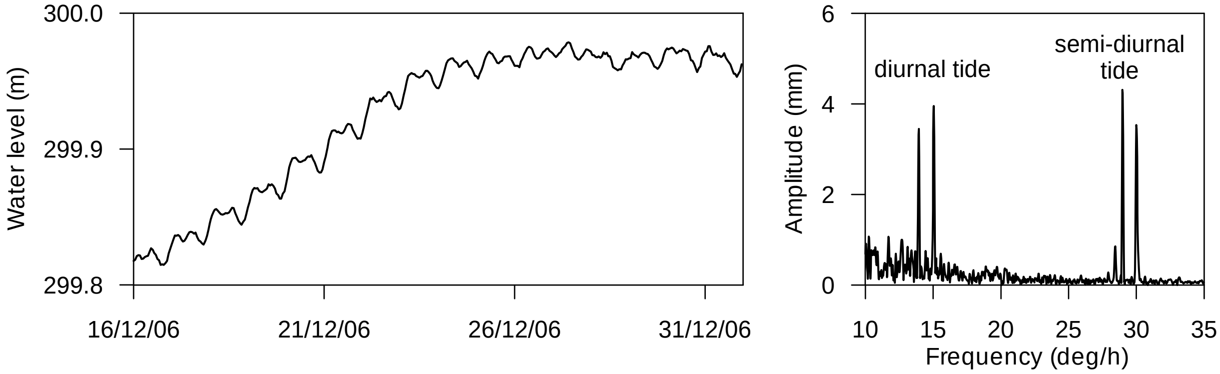

Fig. 8 Tidal variations in the VS-3 well (air pressure corrected data) and the Fourier amplitude spectra of the groundwater level data.

5.1. SENSITIVITY OF WATER WELLS TO CRUSTAL STRAIN CAUSED BY SOLID EARTH TIDES AND AIR PRESSURE LOADING

Fluctuations in water level due to atmospheric loading and Earth tides are commonly observed in many wells. The barometric and tidal response of water level is usually opposite in phase to air pressure and tidal strain changes. This means that high tide and air pressure increases cause declines in water level and vice versa. These fluctuations show that the water wells are sensitive indicators of crustal strain and also reflect material properties of aquiefers tapped by the well (e.g. Rojstaczer and Agnew, 1988).

The tidal response is of a particular importance for us because it is generally assumed that the groundwater level responds to tidal strain in the same way as it responds to crustal strain of tectonic origin (e.g. Roeloffs, 1996). Moreover, Dobrovolsky et al. (1979) assume that earthquake precursory phenomena can be observed up to the distance from earthquake epicentre where deformation ε = 10-8. Thus the water well level variations responding to volume tidal strain of the order of 10-9 (for amplitudes of the five main tidal waves see Table 1) may also reflect potential seismic-induced crustal deformations. The results of the tidal analysis (for method see part 4) are listed in

Table 1 Results of tidal analysis - model values of the volume tidal strain (in units of nstr = 10^{-9} of the relative deformation) for the five analysed tidal waves.

Tidal wave	Period [h]	Amplitude [nstr]			
		HJ-2	HR-6	V-34	VS-3/V-28
O1	25.819	6.801	6.800	6.795	6.794
K1	23.934	7.119	7.118	7.114	7.113
N2	12.658	1.335	1.333	1.326	1.325
M2	12.421	6.971	6.963	6.926	6.918
S2	12.000	3.243	3.240	3.222	3.219

Table 2 Results of tidal analysis - amplitudes of tidal variations of groundwater level for the five analysed tidal waves.

Tidal wave	Amplitude [mm]				
	HJ-2	HR-6	V-34	VS-3	V28
O1	1.176±0.245	0.651±0.109	2.136±0.217	2.789±0.617	3.260±0.508
K1	1.086±0.245	0.546±0.109	2.522±0.217	3.799±0.617	4.785±0.508
N2	0.264±0.797	0.066±0.038	0.701±0.109	0.770±0.338	1.518±0.335
M2	1.250±0.797	0.280±0.038	3.495±0.109	4.647±0.338	6.427±0.335
S2	0.711±0.797	0.043±0.038	2.625±0.109	2.145±0.338	2.251±0.335

Table 3 Results of tidal analysis – amplitude factors representing ratio between observed values of tidal water level variations (see Tab. 2) and model values of the volume tidal strain (see Table 1).

Tidal wave	Amplitude factor [mm/nstr]				
	HJ-2	HR-6	V-34	VS-3	V28
O1	0.173±0.036	0.096±0.016	0.314±0.032	0.411±0.091	0.480±0.075
K1	0.153±0.034	0.077±0.015	0.354±0.030	0.534±0.087	0.673±0.071
N2	0.198±0.060	0.050±0.029	0.529±0.082	0.581±0.255	1.146±0.253
M2	0.179±0.011	0.040±0.006	0.505±0.016	0.672±0.049	0.929±0.048
S2	0.219±0.025	0.013±0.012	0.815±0.034	0.666±0.105	0.699±0.104

Table 4 Results of tidal analysis – time shifts between observed values of tidal water level variations (see Table 2) and model values of the volume tidal strain (see Table 1).

Tidal wave	Time shift [h]				
	HJ-2	HR-6	V-34	VS-3	V28
O1	-0.893±0.857	-4.376±0.688	2.426±0.417	1.844±0.908	1.292±0.640
K1	-2.231±0.860	-4.205±0.761	2.751±0.327	0.925±0.619	-0.021±0.405
N2	0.064±0.608	-3.181±1.166	1.123±0.312	-0.007±0.884	0.037±0.444
M2	-0.409±0.126	-2.723±0.270	1.149±0.061	0.085±0.144	0.025±0.103
S2	0.354±0.214	1.310±1.684	-0.331±0.079	-0.470±0.301	-1.015±0.284

Table 5 Tidal strain sensitivity and barometric efficiency of observation wells in the area of the HPFZ.

Well	**HJ-2**	**HR-6**	**V-34**	**VS-3**	**V-28**
A_s [mm/nstr]	0.179	0.040	0.505	0.672	0.929
E_b [mm/hPa]	1.57	3.19	7.90	4.20	7.15
A_s/E_b	0.114	0.013	0.064	0.160	0.130

Table 6 Parameters of seismic events recorded in the period of 1998–2005 in the area of the HPFZ. N – number of seismic events, M – magnitude of the main event, d – distance between the epicentre of the main event and the VS-3 well, E – seismic energy of the whole group derived according to Tobyáš and Mittag (1991) as log E = 1.2 + 2.0 A M. * - earthquake magnitude calculated from seismograms at the OST station according to Scherbaum and Stoll (1983).

Group of events	**N**	**M**	**d [km]**	**E [J]**
24.6. 1999	1	2.2	14.9	3.98×10^{5}
5.9. 1999	1	1.0	12.6	1.58×10^{3}
2. - 5.12. 2003	15	1.7	21.7	4.33×10^{4}
10.8. 2005	24	2.4	11.3	1.05×10^{6}
25.10. 2005	6	3.3	16.8	6.31×10^{7}
7.11. 2005	1	1.3	12.6	6.31×10^{3}
12.2. 2006	1	-0.7*	8.0	6.31×10^{-1}
20.3. - 21.3. 2006	5	0.3	10.0	1.26×10^{2}

Tables 2-4 for all the five observation wells. The highest amplitudes of tidal fluctuations are observed in the V-28 well, whereas the lowest in the HR-6 well. The maximum variations are induced by the semi-diurnal M2 wave (V-28, VS-3, V-34 and HJ-2 wells) or by the diurnal O1 wave (HR-6 well). The time shifts of tidal groundwater level variations are relatively low compared to the model values of volume tidal strain however, the relatively high error of the estimate must be taken into account (cf. Table 4). The time shifts fall into the range of approximately from -4.4 to 2.8 hours. The negative values of the time shifts indicate a delay of the observed tidal variations of groundwater level behind the theoretical values of the volume tidal strain, whereas the positive values indicate that the observed values precede the theoretical ones. The positive time shifts, reaching the highest values in the V-34 well, are difficult to explain. Considering the relatively high errors in estimate of the time shifts, one possible reason can be that longer time series (more than 495 days used in our study) are needed to obtain more plausible results.

The response of the groundwater level to Earth tides and air pressure variations is generally defined by the tidal strain sensitivity A_s, and the barometric efficiency E_b (cf. e.g. Roeloffs, 1988):

$$A_s = -\Delta h / \varepsilon_t \tag{6}$$

$$E_b = -\Delta h / \Delta p_b \tag{7}$$

where Δh is the water level change, εt is the volume tidal strain and Δpb is the change in barometric pressure. The values of As and Eb derived for all the five observation wells in the area of the HPFZ are listed in Table 5. In accordance with Igarashi and Wakita (1991) or Roeloffs (1996), the amplitude factor F_A for the M2 wave, estimated by means of the tidal analysis (see Table 3), is herein taken as the value of the tidal strain sensitivity A_s. The barometric efficiency E_b is expressed as a linear regression coefficient between the air pressure data and the barometric response *BAR* of the water level variations.

All the five observation wells exhibit relatively wide range of A_s and E_b values, which is a result of different mechanical properties of aquifers (especially the porosity and compressibility of the solid matrix) and the different degree of confinement of the aquifers (see e. g. Rojstaczer and Agnew, 1989; Kopylova and Boldina, 2004). Contrary to our expectations, no sign

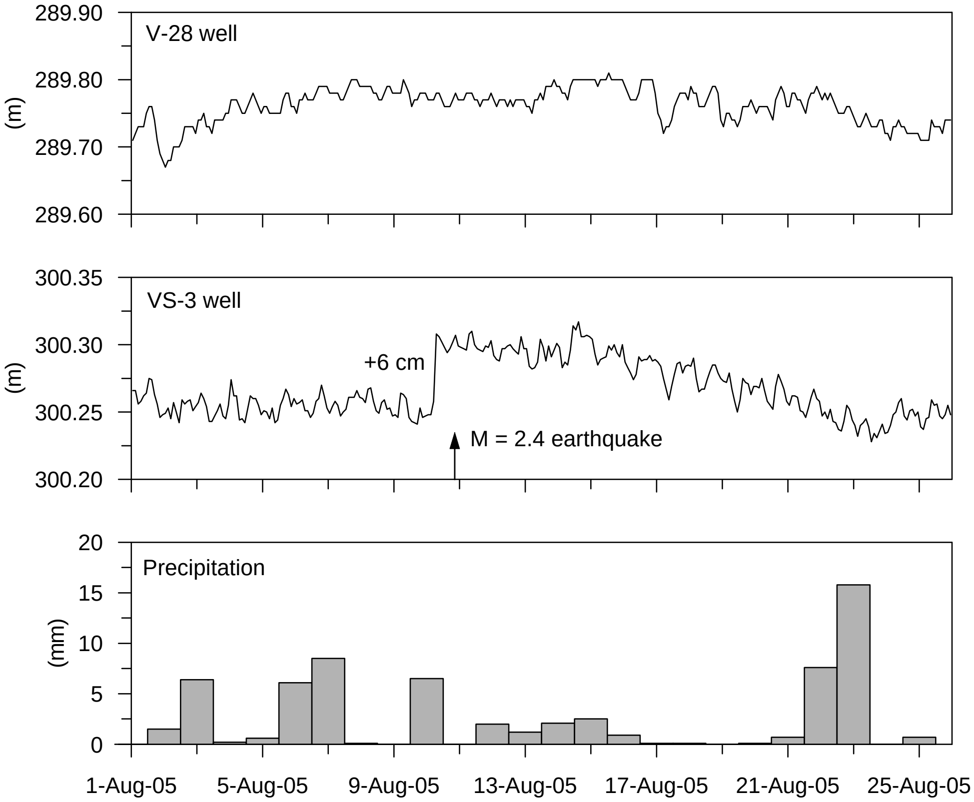

Fig. 9 Pre-seismic water level change recorded in the VS-3 well before the August 10, 2005 earthquake. The groundwater level is plotted against the precipitation daily amounts and the water level in the V-28 well. The air pressure-corrected water level data are shown.

of correlation was found between the A_s and E_b values (see A_s/E_b ratios in Table 5). It is therefore probable that the water level response is driven by the frequency of the applied strain. This possibly means that some wells are more sensitive to tidal strain with periods mostly between 10 and 30 hours while other wells exhibit higher sensitivity to air pressure loading variations with relatively longer periods (mostly above 30 hours). Wels V-28 and V-34 may serve as a good example: the values of barometric efficiency are very similar (E_b = 7.15 and 7.90 respectively), but the tidal strain sensitivity is more than 1.8 times higher in the V-28 well.

5.2. *SEISMIC-INDUCED GROUNDWATER LEVEL CHANGES*

The observations of groundwater level in HJ-2, HR-6 and V-34 wells were not fully optimized due to initial problems with measuring technique until the half of November 2005. Thus the monitoring overlaps only a relatively short period with weak seismic activity, when only few M<1 events were recorded. Considerably more interesting results are available from the monitoring of VS-3 and V-28 wells, which was launched back in 1998.

Since 1998, 54 local events have been observed in the area of the HPFZ (see Table 6). The two strongest earthquakes recorded on August 10, 2005 at 18:54:34 UTC (M = 2.4) and on October 25, 2005 at 10:51:57 UTC (M = 3.3) were preceded by distinct step-like water level rises in the VS-3 well. Both events were accompanied by several weak shocks (Table 6). Nevertheless, the first foreshock before the August 10 main event did not precede the water level anomaly, and the October 25 main event was not accompanied by any foreshocks, only by a series of five aftershocks. The observed anomalous groundwater level changes can be therefore considered to be the earthquakes' precursors. Precursory changes were recorded only in the VS-3 well and were not followed by any detectable co-seismic or post-seismic water level variations. It is interesting that the water level in the nearby V-28 well did not show any anomalous behaviour at the same time (see Figs. 9 and 10).

Amplitudes and lead times of the observed precursory groundwater level changes were +6 cm and 11-15 hours for the August 10, 2005 earthquake and +15 cm and 29 - 32 hours for the October 25 earthquake. These parameters indicate the existence of a possible relation between the earthquake magnitude and the amplitude and the lead time of the anomaly. The stronger October 2005 earthquake was preceded by an anomaly with the amplitude 2.5 times higher,

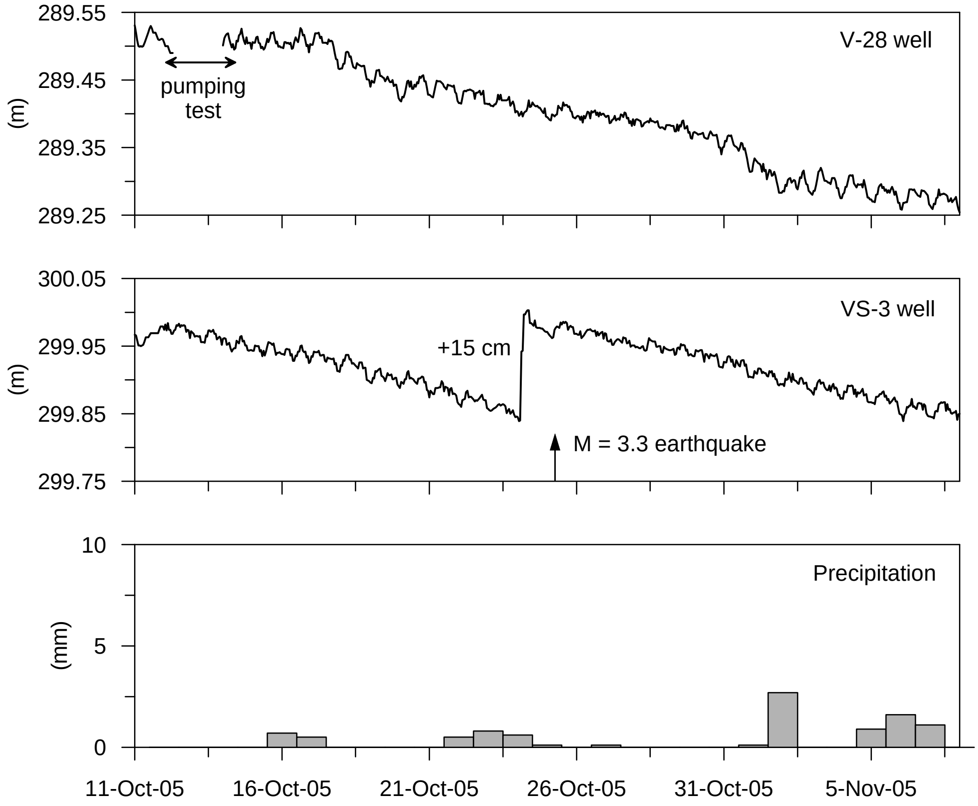

Fig. 10 Pre-seismic water level change recorded in the VS-3 well before the October 25, 2005 earthquake. The groundwater level is plotted against the precipitation daily amounts and the water level in the V-28 well. The air pressure-corrected water level data are shown.

and the lead time of the anomaly occurrence was more than two times longer. These relationships have, however, only weak statistical significance for the presence because no other examples of the precursory groundwater level changes are available.

In addition to the two above mentioned precursory groundwater level anomalies related to the two strongest earthquakes, another three sharp step-like changes with amplitudes 4–8 cm were identified in the VS-3 well during February and March 2006 (see Fig. 11). Nevertheless, these anomalies recorded on February 17 and 26 and on March 15 do not exhibit a similarly clear connection with the local seismic activity. As for the February 17 anomaly, it can be put into association only with the weak February 12 event (February 12, 2006, 19:00:56 UTC, M = -0.7). The February 26 anomaly does not exhibit any plausible time coincidence with seismic activity at all, and the March 15 anomaly can be related to the sequence of five events recorded on March 20 and 21 (the strongest M = 0.3 event was recorded on March 20, 21:45:36 UTC). Analogous to the August and October 2005 precursory anomalies, no anomalous fluctuations were observed in the V-28 well during February and March 2006.

6. INTERPRETATION AND DISCUSSION

The above presented overview of relations between anomalous groundwater level changes and local seismicity in the area of the HPFZ gives birth to the three following questions:

1. Why were the anomalous step-like groundwater level changes observed in the VS-3 well but not in the V-28 well situated at the same locality?
2. What is the mechanism of the origin of anomalous water level changes?
3. Why does not the groundwater level exhibit a response to all seismic events recorded during the period of the monitoring?

The problem formulated in the first question is met very often in the studies of earthquake-induced groundwater level changes. Completely different reactions of neighbouring wells, or substantially higher amplitudes of the anomalies not corresponding to theoretical models of the crustal strain caused by earthquakes were described e.g. by Igarashi and Wakita (1991), Kissin et al. (1996) or Grecksch et al. (1999). In our case, anomalous groundwater level changes related to seismic activity were recorded in the VS-3 well which, based on the tidal and

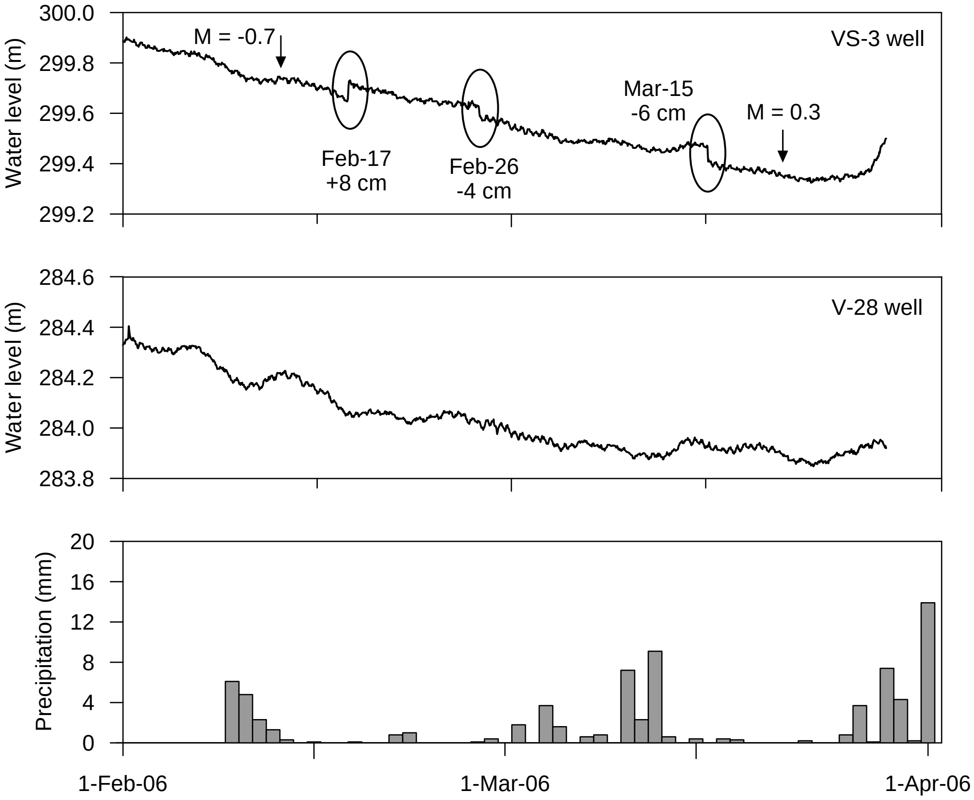

Fig. 11 Step-like groundwater level anomalies recorded in the VS-3 well during February and March 2006. The groundwater level is plotted against the precipitation daily amounts and the water level in the V-28 well. The air pressure-corrected water level data are shown.

barometric response, exhibits lower sensitivity to crustal strain than the V-28 well, where no anomalous fluctuations were observed. Thus the recorded anomalies cannot be considered a result of deformation acting universally on the upper part of the Earth's crust at the site of observation. We therefore propose an alternative hypothesis based on the presumption of the existence of a sensitive site, at which the VS-3 well is located. The existence of sensitive sites where unexpectedly high amplitudes of earthquake-related water level changes are observed is supposed by, e.g., King et al. (2006), Kissin et al. (1996) or Kümpel (1992). In all these studies, the sensitive sites are characterized as structurally weak zones often situated near tectonic faults.

If we compare the vertical sections of the VS-3 and V-28 wells (Fig. 2), we can see that the V-28 well is opened only to the Lower Turonian aquifer, whereas the VS-3 well is opened also to the underlying Cenomanian formations – namely to the chert aquifer tapped at the depth of 234 m. The chert aquifer is the most important water-bearing sedimentary unit of the Police Basin. It is characterised by the highest permeability (hydraulic conductivity k = 1.10^{-4} to 1.10^{-3} m/s) and hydraulic continuity over a large area of the northern part of the basin, which was proved by pumping tests (Krásný et al., 2002). The aquifer consists of silty-sandy silicites (cherts) with permeability of fracture type, and its thickness reaches maximum 15 m. Krásný et al. (2002) further suggest the presence of so-called preferential zones of groundwater flow within the chert aquifer. These zones are represented by a dense system of highly permeable fissures, permitting the flow of considerably higher amounts of water than in the less permeable surrounding material. The transport velocity of water within these zones is also substantially higher. Using a numerical model of the groundwater flow, Krásný et al. (2002) estimated the transport velocity at max. 15 m/day within the preferential zones and at 0.1 m/day in less fractured silicites outside the preferential zones. Formulating now the hypothesis on the VS-3 well as a sensitive site, we must presume the connection of the well with a preferential zone in the chert aquifer. Its presence in the area of the well may result from more intensive fracturing of the aquifer in the neighbourhood of tectonic dislocations near the well (see Fig. 1).

As far as the second question is concerned, the mechanism of the origin of the observed step-like water level anomalies can be considered to be a result of seismo-tectonic induced deformation of the preferential zones in the chert aquifer. The compression results in a decrease in the volume of fluid-filled fractures of the preferential zone and a consequent water level rise in the well. On the other hand, dilatation is responsible for the rock loosening and subsequent water level drop. With respect to the regional continuity of the aquifer, hydraulic interference can be presumed over longer distances, which enables the transfer of effects of larger deformations taking place closer to the seismogenic HPFZ. The deformation effects can be also supposed to propagate along the NE-SW-striking fault (perpendicular to the HPFZ) in the proximity of the VS-3 well.

The sharp step-like character of the observed anomalies is a relatively rare phenomenon, especially for the precursory groundwater level changes. This type of short-time precursory phenomena recorded within several hours before an earthquake is often explained by aseismic creep-like movements (see, e.g., Rikitake, 1975). Similarly Lorenzetti and Tulis (1989) anticipated that the pre-seismic strain increases steeply within a few minutes to a month before the earthquake, which is caused by the acceleration of aseismic slip. Some examples of the anomalous step-like groundwater level changes were reported e.g. by Kissin et al. (1996) from the seismoactive zone of the Main Kopetdag Fault, Central Asia. Analogous to our results, he observed some of these anomalies to accompany local earthquakes, while the rest of them were recorded independently of the seismic activity. The authors explain the second type of water level changes by aseismic movements in the near fault zone.

In agreement with the above mentioned opinions, we regard the accelerating pre-seismic creep movements in the fracture system of the HPFZ as the primary source of deformation resulting in the precursory groundwater level changes recorded in the VS-3 well before the August 2005 and the October 2005 earthquakes. The other three anomalies observed in February and March 2006 seem to originate independently of the weak seismic events of February 10 and March 20. Rather than precursory or post-seismic phenomena they result from aseismic movements along the HPFZ. The existence of aseismic movements along the HPFZ is suggested by Vyskočil (1988) who identified two anomalous uplifts across the fault zone based on the analysis of repeated precise levelling at two lines crossing the HPFZ. These two uplifts with magnitudes of about 10 mm preceded seismic events of May 7, 1984 (M = 3.4) and October 20, 1985 (M = 3.0). Nevertheless, no direct evidence of the aseismic creep movements along the HPFZ is available for the time of the above described water level anomalies. To confirm the proposed conception of the origin of the seismic-/tectonic-induced hydrologic anomalies, it is necessary to correlate the water level records with data providing direct information on fault displacement (see, e.g., 1989; Rudnicki et al., 1993; Johnston et al. 2006).

In conclusion, we try to answer the last question related to the absence of anomalous response to the seismo-tectonic activity before 2005. Selected parameters of seismic events recorded in the period of 1998–2006 are listed in Table 6. These data indicate that the August 10, 2005 and the October 25, 2005 events are 1 to 4 orders of seismic energy higher than the other seismic events. This explains the presence of the precursory water level changes before both earthquakes. On the other hand, three other anomalies were observed during February and March 2006 which were probably induced by aseismic movements along the HPFZ. Excluding the assumption that these movements were unique in the period of 1998–2006, we suppose that the sensitivity of the VS-3 well is changing with time. This property of sensitive sites was already noticed by King et al. (2006). They assume that the sensitivity, characterized by some near-critical hydrologic condition (e.g., permeability highly susceptible to small stress increase), can vary with time due to local stress or permeability variations. Based on available data, we can suppose, that the sequence of 24 seismic events of August 10, 2005 acted as a starting effect for the transient increase in well sensitivity.

7. CONCLUSIONS

The analysis of continuous groundwater level data from five experimental wells situated in the area of the Hronov-Poříčí Fault Zone on the NE margin of the Bohemian Massif yielded the following main conclusions:

1. Water level fluctuations in all the five wells exhibit responses to tidal strain and barometric surface loading. Both the tidal response and the barometric response show relatively wide ranges of magnitudes, which reflects the different degree of confinement and different mechanical properties of aquifers, like porosity and compressibility of the solid matrix.
2. In connection with the relatively strong earthquakes of August 10, 2005 (M = 2.4, d = 11.3 km) and October 25, 2005 (M = 3.3, d = 16.8 km), pre-seismic step-like water level rises were observed in the VS-3 well. The first anomalous precursory change reaching the amplitude of +6 cm was observed 11–15 hours prior to the August 10 seismic event. The second precursory change with the amplitude of +15 cm was recorded 32–29 hours prior to the October 2005 event.
3. Another three sharp step-like water level changes occurred in the VS-3 well during February and March 2006. Nevertheless, these anomalies with amplitudes of 4–8 cm do not exhibit clear connection with local seismic activity. Only

several weak events (M ≤ 0.3) were recorded in the area of the SE tip of the HPFZ at the time of their occurrence. In analogy to the August and October 2005 precursory anomalies, no anomalous fluctuations were observed in the nearby V-28 well during February and March 2006.

4. We explain the origin of precursory events recorded in the VS-3 well by its connection with preferential zones of groundwater flow, which are represented by a dense system of highly permeable fissures in the Cenomanian chert aquifer. The pre-seismic water level rise can be then interpreted as a result of compression of these zones, which are, due to their regional continuity, supposed to transfer the effects of larger deformations taking place closer to the active fault. We regard the accelerating pre-seismic creep movements in the fracture system of the HPFZ as the primary source of deformation resulting in the precursory groundwater level changes recorded in the VS-3 well before the August 2005 and the October 2005 earthquakes. The other three anomalies observed in February and March 2006 seem to have originated independently of the weak seismic events of February 10 and March 20. Rather than precursory or post-seismic phenomena they are a result of aseismic movements along the HPFZ.

ACKNOWLEDGEMENT

This study was supported by the Czech Science Foundation (project No. 205/05/H020), by the Ministry of the Environment CR project No. 0002071101 and by the Research Plan of the Geographical section of the Faculty of Science, Charles University, No. MSM 0021620831. We wish to thank especially Aleš Regner and Gabriela Regnerová for their precise organization of CO2 observations in the Třtice mineral spring, Jan Kašpárek (WRI, Prague) for the servicing and maintenance of the Bučnice hydro-meteorological station and Jiří Málek (IRSM, Prague) for interpretation of the seismic data. Precipitation and air temperature data were provided by the Povodí Labe, state enterprise. The air pressure correction of the water level data was performed using BETCO 1.0 software by Toll and Rasmussen (2007), which is available as freeware.

REFERENCES

Akita, F. and Matsumoto, N.: 2004, Hydrological responses induced by the Tokachi-oki earthquake in 2003 at hot spring wells in Hokkaido, Japan. Geophysical Research Letters 31 (16), Art. No. L16603.

Bankwitz, P., Schneider, G., Kämpf, H. and Bankwitz, E.: 2003, Structural Characteristics of Epicentral Areas in Central Europe: Study case Cheb Basin (Czech Republic). Journal of Geodynamics 35 (1-2), 5 – 32.

Biely, A., Buday, T., Dudek, A., Fusán, O., Kodym, O., Kopecký, L., Kuthan, M., Malkovský, M., Matějka, A., Sattran, V. and Svoboda, J.: 1968, Tectonic map of the Czechoslovakia, ÚÚG, Prague, (in Czech).

Brož, M., Stejskal, V. and Štrunc, J.: 2006, Local seismological Network Ostaš, Transactions of the VŠB-Technical University of Ostrava, Civil Engineering series, 4(2). 23-32, (in Czech).

Cymerman, Z.: 2004, Tectonic map of the Sudetes and the Fore-Sudetic Block 1:200 000, Polish Geological Institute, Warszawa.

Davis, D.R. and Rasmussen, T.C.: 1993, A comparison of linear regression with Clark's method for estimating barometric efficiency of confined aquifers. Water Resources Research 29 (6), 1849 – 1854.

Dehant, V.: 1987, Tidal parameters for an inelastic Earth. Physics of the Earth and Planetary Interiors 49 (1 – 2), 97 - 116.

Dobrovolsky, I.P., Zubkov, S.I. and Miachkin, V.I.: 1979, Estimation of the size of earthquake preparation zones. Pure and Applied Geophysics 117 (5), 1025 - 1044.

Elkhoury, J.E., Brodsky, E.E and Agnew, D.C.: 2006, Seismic waves increase permeability. Nature, 441 (7097), 1135-1138.

Gavrilenko, P., Melikadze, G., Chelidze, T., Gibert, D. and Kumsiashvili, G.: 2000, Permanent water level drop associated with the Spitak Earthquake: observations at Lisi Borehole (Republic of Georgia) and modelling. Geophysical Journal Internation 143 (1), 83 – 98.

Grecksch, G., Roth, F. and Kümpel, H. J., 1999. Coseismic well-level changes due to the 1992 Roermond earthquake compared to static deformation of half-space solutions. Geophysical Journal International 138 (2), 470 – 478.

Igarashi, G. and Wakita, H.: 1991, Tidal responses and earthquake-related changes in the water level of deep wells. Journal of Geophysical Research 96 (B3), 4269 – 4278.

Jetel, J. and Rybářová, L., 1979. Mineral waters of East Bohemian province, ÚÚG, Prague, (in Czech).

Johnston, M.J., Borcherdt, R.D., Linde, A.T. and Gladwin.: 2006, Continuous borehole strain and pore pressure in the near field of the 28 September 2004 M 6.0 Parkfield, California, earthquake: implications for nucleation, fault response, earthquake prediction, and tremor. Bulletin of the Seismological Society of America 96 (4B), 556 – 572.

Kárník, V., Schenková, Z. and Schenk, V.: 1984, Earthquake activity in the Bohemian Massif and in the Western Carpathians. Travaux Géophysiques 547 (29), 9 - 33.

Kárník, V., Michal, E. and Molnár, A.: 1958, Catalog of earthquakes in Czechoslovakia by the year 1956. Travaux Géophysiques, 69, 411 – 598, (in German).

King, C.,I., Zhang, W. and Zhang, Z.: 2006, Earthquake-induced groundwater and gas changes. Pure and Applied Geophysics 163 (4), 633 – 646.

Kissin, I.G. and Grinevsky, I.G.: 1990, Main features of the hydrogeodynamic earthquake precursors. Tectonophysics 178 (2 - 4), 277 – 286.

Kissin, I.G., Belikov, V.M. and Ishankuliev, G.A.: 1996, Short-term groundwater level variations in a seismic region as an indicator of the geodynamic regime. Tectonophysics 265 (3 – 4), 313 – 326.

Koch, U., Heinicke, J. and Vossberg, M.: 2003, Hydrogeological Effects of the Latest Vogtland – NW Bohemian Swarmquake Period (August to December 2000). Journal of Geodynamics, 35 (1-2), 107-123.

Kontny, B., 2004. Is the Sudetic Marginal Fault still active? Results of the GPS monitoring 1996 – 2002. Acta Geodynamica et Geomaterialia 1 (3), 35 – 39.

Kopylova, G.N. and Boldina, S.V.: 2004, The assessment of poroelastic properties of underground water reservoirs on data of water level observations. Complex seismological and geophysical research of Kamchatka. Petropavlovsk-Kamchatskij: Kamchatskij Pechatnyj dvor, 405 – 421.

Krásný, J., Buchtele, J., Čech, S., Hrkal, Z., Jakeš, P., Kobr, M., Mls, J., Šantrůček, J., Šilar, J. and Valečka, J.: 2002, Hydrogeology of the Police Createaceous basin: Optimisation of groundwater development and protection. Journal of Geological Sciences – Hydrogeology, Engineering Geology 22, 5 – 100, (in Czech, with English summary).

Kümpel, H.J.: 1992, About the potential of wells to reflect stress variations within inhomogeneous crust. Tectonophysics 211 (1 - 4), 317 – 336.

Leonardi, V., Arthaud, A., Tovmassian, A. and Karakhanian, A.S.: 1997, Relationships between seismic activity and piezometric level changes in the Arax basin (SW Armenia): Attempt at a typology of seismically induced piezometric anomalies. Tectonophysics 273 (3 – 4), 293 – 316.

Lorenzetti, E. and Tullis, T.E.: 1989, Geodetic predictions of a strike-slip fault model: implications for intermediate- and short-term earthquake prediction. Journal of Geophysical Research 94 (B9), 12 343 – 12 361.

Lyubushin, A.A.: 1994, Multidimensional analysis of time series for a geophysical monitoring systems. Izvestiya, Physics of the Solid Earth 29, 297 - 301.

Procházková, D., Dudek, A., Mísař, Z. and Zeman, J.: 1986, Earthquakes in Europe and their relation to basement structures and fault tectonics, Academia, Prague, 80.

Pertsev, B.P.: 1959, About the registration of the drift of zero when observing the elastic Earth tides. Izvestiya Akademii Nauk SSSR, Seria Geofyzicheskaya 4, 547 – 548, (in Russian).

Quilty, E. and Roeloffs, E.: 1991, Removal of barometric pressure response from water level data. Journal of Geophysical Research 96 (B6), 10 209 – 10 218.

Rasmussen, T.C. and Toll, N.J.: 2007, Removal of barometric pressure effects and Earth tides from observed water levels. Ground Water 45 (1), 101 – 105.

Rikitake, T.: 1975, Earthquake precursors. Bulletin of the Seismological Society of America 65 (5) 1133 – 1162.

Roelofoffs, E..: 1988, Hydrological precursors of earthquakes: a review. Pure and Applied Geophysics 126 (3-4), 177 – 209.

Roelofoffs, E.: 1996, Poroelastic techniques in the study of earthquake-related hydrologic phenomena. In: Dmowska, R., Saltzman, B. (eds), Advances in Geophysics 37, 135 – 195.

Rojstaczer, S. and Agnew D.C.: 1989, The influence of formation material properties on the response of water levels in wells to Earth tides and atmospheric loading. Journal of Geophysical Research 94 (B9), 12 403 – 12 411.

Rudnicki, J.W., Yin, J. and Roeloffs, E.: 1993, Analysis of water level changes induced by fault creep at Parkfield, California. Journal of Geophysical Research 98 (B5), 8143 - 8152.

Scheck, M., Bayer, U., Volker, O., Lamarche, J., Banka, D., and Pharaoh, T.: 2002, The Elbe Fault System in the North Central Europe – a basement controlled zone of crustal weakness. Tectonophysics 360 (1 – 4), 281 – 299.

Schenk, V., Schenková, Z. and Pospíšil, L.: 1989, Fault system dynamics and seismic activity - examples from the Bohemian Massif and the Western Carpathians. Geophysical Transactions 35 (1-2), 101 - 116.

Scherbaum, F. and Stoll, D.: 1983, Source parameters and scaling laws of the 1978 Swabian Jura (southwest Germany) aftershocks. Bulletin of the Seismological Society of America 73 (5), 1321 – 1343.

Špaček, P., Sýkorová, Z., Pazdírková, J., Švancara, J., and Havíř, J.: 2006, Present-day seismicity of the south-eastern Elbe Fault System (NE Bohemian Massif). Studia Geophysica et Geodaetica 50 (2), 233 – 258.

Tamura, Y.: 1987, A harmonic development of the tide-generating potential. Marées Terrestres Bulletin d'Informations 99, 6813 – 6855.

Tásler, R.: 1979, Geology of the Czech part of the Intrasudetic Basin, ÚÚG, Prague, (in Czech with English summary).

Tobyáš, V. and Mittag, R.: 1991, Local magnitude, surface-wave magnitude and seismic energy. Studia Geophysica et geodaetica 35 (4), 354 - 362.

Vyskočil, P.: 1988, The dynamics of the Hronov-Poříčí seismoactive fault. Proceedings of the Research Institute of Geodesy, Topography and Cartography 17, 93 – 111.

Wahr, J.M.: 1981, Body tides on an elliptical, rotating, elastic and oceanless Earth. Geophysical Journal of the Royal Astronomical Society 64 (3), 677 - 703.

Wenzel, H.G.: 1993, ETERNA 3.0, Program manual, status August 1st, 1993. Geodaetisches Institut, Karlsruhe.

Woldřich, J.N.: 1901, Earthquake in the north-eastern Bohemia on January 10, 1901. Transactions of the Czech Academy of Sciences, series II 10 (25), 1 – 33 (in Czech).

Zschau, J. and. Wang, R.: 1981, Imperfect elasticity in the Earth's mantle - implications for Earth tides and long period deformations. In: Kuo, J. T. (Ed.), Proceedings of the 9th International Symposium on Earth Tides, New York 1981, 605 - 629.