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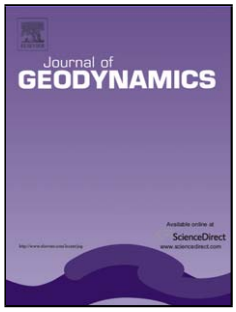

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PII: S0264-3707(10)00111-0
DOI: doi:10.1016/j.jog.2010.07.002
Reference: GEOD 1013

To appear in: *Journal of Geodynamics*

Received date: 15-1-2010
Revised date: 21-7-2010
Accepted date: 21-7-2010

Please cite this article as: Koch, U., Heinicke, J., Seismohydrological effects related to the NW Bohemia earthquake swarms of 2000 and 2008: Similarities and distinctions, *Journal of Geodynamics* (2010), doi:10.1016/j.jog.2010.07.002

Seismohydrological effects related to the NW Bohemia earthquake swarms of 2000 and 2008: Similarities and distinctions

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Abstract

For more than 20 years, seismo-hydrological investigations have been undertaken at the mineral aquifer system of Bad Brambach (Vogtland, Germany). Two strong swarm earthquake series in 2000-01 and 2008-09 at the Nový Kostel epicentre (Czech Republic, 10 km E of BB) have enabled for the first time a comparison of seismological and groundwater hydraulic features in a semi-quantitative way. In spite of their similar spatial distribution in 2001 and 2008, the earthquake foci of each swarm migrated differently through time, horizontally as well as in depth. The seismic energy of the 2008-2009 events was released predominantly within one month, in contrast to 2000-2001 when it occurred over three months. The main distinctive features of each are seen in the hydraulic pressure anomalies which accompanied the earthquake swarms: number, shape, and progression (duration) of the anomalies. The comprehensive hydraulic data, with high temporal resolution, suggest that fluid triggering dominated not only the earthquake initiating phases. In particular, the long lasting seismicity of

the 2008-2009 swarm can be attributed to a continued triggering of weak earthquakes by over-pressured deep fluids. Here, the remaining static strain was obviously not sufficient to generate strong earthquakes as at the beginning of the earthquake swarm periods. Furthermore, the enduring high fluid pressure in 2009 could also indicate a continuation of the long-term gas flow increase observed at several gas outlets in the Vogtland/NW Bohemia region between 1998 and 2008. However, it is not possible at present to derive a systematic relationship between anomaly occurrence and seismic activity, as generally proposed in the context of earthquake prediction discussion.

Keywords

earthquake swarms, NW Bohemia, mineral water aquifer, hydrostatic pressure, groundwater level, anomaly comparison

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Introduction

The Vogtland (Germany) and NW Bohemia region is well-known for the periodical occurrence of local intraplate seismicity, so-called earthquake swarms (Babuška et al., 2007; Fischer and Horálek, 2003; Horálek and Fischer, 2008). Like the Massif Central (France) and the Eifel region (Germany), it belongs to a few European seismic areas where earthquakes occur independently of strong tectonic seismic events. However, numerous CO_2 degassing mineral springs and dry CO_2 outlets (mofettes) in these regions are an indication for enduring magmatic and tectonic activity at depth. An updoming of the lithosphere-asthenosphere boundary below the Cheb Basin (Fig. 1) connected with magmatic intrusions via injection channels from the lithospheric mantle is supposed to be the source for this degassing activity (Geissler et al., 2005; Plomerová et al., 2007, Bräuer et al., 2005, 2009). Thus, an increase of the magmatic signature and the flow rate of the ascending gases were observed at several mofettes and mineral springs during the last 16 years (Bräuer et al., 2005, 2007; Koch and Heinicke, 2007; Koch et al., 2008). For more than two decades, the complicated processes of swarmquake generation have been discussed in a broad framework. Simplified, three main triggering mechanisms have been agreed: geodynamic stress accumulation, critical pore fluid pressures and hydrothermal alteration processes (Vidale and Shearer, 2006; Hill, 1977; Giammanco et al, 2008; Zoback and Harjes, 1997; Shapiro et al., 2006; King et al., 1994; Bräuer et al., 2003, 2004; Špičák and Horálek, 2001; Hainzl and Fischer, 2002; Rothert and Shapiro, 2007; Heinicke et al., 2009). Due to the high mobility of CO_2 dominated fluids below the Cheb Basin, a complex interaction of these triggering mechanisms is likely in the Vogtland/NW Bohemia region.

Since 1985/86, the most frequent epicentre zone of the NW Bohemia earthquakes has been near Nový Kostel (50.18–50.27°N, 12.35–12.48°E) in the northern part of the Cheb Basin (Fischer and Horálek, 2003; Fig. 1), on the intersection of two main tectonic elements, the NNW–SSE

trending Mariánské Lázně fault zone (MLFZ) and the N–S trending Počátky-Plesná zone (PPZ) (Bankwitz et al., 2003). The number of events within a swarmquake period can reach several tens of thousands but the magnitudes are usually < 5 and the hypocentres are located at depths of 7–12 km (Fischer and Horálek, 2003; Horálek et al., 2009). Even before the Nový Kostel earthquake swarms that occurred in 1997 and 2000 , gas flow and groundwater level anomalies had been recorded at the Seismohydrological Observatory of the Saxon Academy of Sciences at Bad Brambach, 10 km W of Nový Kostel (Fig 1). These data indicated a pre-seismic fluid overpressure due to geodynamically induced pore pressure increases in the deep aquifer (Koch and Heinicke, 1999; Heinicke and Koch, 2000; Koch et al., 2003). After a 7 year period without appreciable seismic activity, the strongest earthquake series since 1985/86 occurred in autumn 2008 at the epicentral area of Nový Kostel (Horálek et al., 2009). Seismohydrological precursor effects could also be observed on this occasion but with different characteristics than in 2000. Thus, it became possible to compare and contrast these two most important swarmquake periods of the recent past from both a seismological as well as a seismohydrological point of view. Such a comparison, however, is only by its nature semi-quantitative. Two strong earthquake swarms within a span of 8 years represent too little data to derive forecast-like predications from the analysed hydrological anomalies – such as starting time, duration, maximum magnitude or energy release distribution of the respective seismic period. Therefore, the discussion of the results is focused on the tectonic and fluid processes that could have initiated and accompanied both earthquake swarms.

Fig. 1

Locations and measurements

The high seismicity of Vogtland/NW-Bohemia is concentrated in several earthquake clusters giving evidence of recently active fault structures. The subject of the following seismological/seismohydrological comparison is focused on the epicentral area of Nový Kostel (Fig. 1) because

- it is the most frequent epicentre zone since 1985/86 (Neunhöfer and Meier, 2004; Horálek et al., 1996, 2000, 2009; Fischer and Horálek, 2003),
- only seismicity within this area induces significant anomalies in the Bad Brambach mineral water aquifer, most of them as precursors (Heinicke et al., 1995, Koch and Heinicke, 1999).

Normal and strike slip faulting are the typical focal mechanisms for these intraplate events. The occurrence of non-double-couple events has been suggested as evidence for fluid influences on focal processes (Horálek et al., 2000). The swarm earthquake series of autumn 2000 and 2008 were the strongest ones since the 1985/86 events. A preliminary evaluation of the 2008 swarm shows that it was similar to the 2000 one in respect of local magnitudes, the location of the epicentres and the temporal behaviour of focal depths and epicentral locations (Fischer and Horálek, 2003; Horálek et al., 2009).

Table 1 gives an overview of the origin of the analysed seismic data and the other subsequently used basic parameters including their temporal resolution. For the comparison of the temporal and spatial behaviour of the earthquake swarms and their relation to the hydrological anomalies, seismic events with local magnitudes of $M_L > -1$ within the Nový Kostel area were used, in each case, between September and April 2000-01 as well as 2008-09 (Fig. 2–6). Magnitudes with $M_L > 1$ were applied to characterise periods with particularly high release of seismic energy between 2000 and 2009 (Fig. 7).

Tab. 1

During the last 20 years, groundwater openings of the Bad Brambach mineral water aquifer (12.298°E, 50.239°N, about 10 km W of the Nový Kostel epicentral zone) proved to be seismohydrologically sensitive locations with respect to earthquakes in the Nový Kostel seismic zone. In particular, the mineral spring 'Wettinquelle' and a gauge well (VL4T) in the Bad Brambach Cure Park repeatedly showed anomalous behaviours before and during local earthquakes (Heinicke et al., 1995, Koch and Heinicke, 1999; Heinicke and Koch, 2003). A detailed map of the locations can be found in Koch and Heinicke (2007).

The Bad Brambach mineral springs are radon-bearing Na-Ca-HCO_3-SO_4 acidic springs characterised by a mineralisation > 2.5 g/L, ^{222}Rn-activities of 1.5–26 kBq/L and a gas saturation of 2.6–2.8 g/L dissolved CO_2. The isotopic signature of the free gaseous phase (99.5 % CO_2**)** indicates a crust/upper mantle origin of the spring gases (Koch et al., 2008). The 'Wettinquelle' is one of the strongest radioactive springs in the world and is used for therapeutic applications (26 kBq/l of ^{222}Rn). The spring capture is a shallow well located in the tectonically fissured Fichtelgebirge granite, about 5.5 m below the surface. A multi-parameter station recording totally 10 hydrological, hydrochemical and gas flow parameters with a temporal resolution of 2-10 minutes, including water discharge, free gas flow rate and hydrostatic pressure (Tab. 1) has operated there since April 2000. A scheme of the 'Wettinquelle' spring capture is given by Koch et al. (2003).

The other seismohydrologically sensitive location is the 15 m deep gauge well VL4T, 100 m W of the 'Wettinquelle' spring. It opens up the granitic fissured mineral water aquifer; its surface is covered by an about 5–6 m thick alluvial sediment layer. To use such a well reliably for seismohydrological purposes, it is necessary to separate meteorological influences such as

rainfall, snow melting and atmospheric pressure on the groundwater level (GWL). Besides a GWL increase during rainfall and snow melting, this effect may be observed also in times of low air pressure (deep pressure areas). Air pressure-induced GWL fluctuations are reinforced due to dissolved gas in the aquifer, in the present case CO_2. A multiple regression to separate several non-seismic influences on the groundwater level was complicated and not very convincing. A more effective way is the calculation of a GWL difference curve between the time-synchronised data series of the seismically sensitive gauge well and a shallow reference gauge that was not affected by deep originated fluid processes. The 4 m deep gauge well GW1 (10 m NW of the 'Wettinquelle'), located in the alluvial weathering zone above the Fichtelgebirge granite surface, fit this requirement. The time series of all relevant meteorological parameters are given in the respective graphs for overview and comparison. They were recorded at the climatic station Bad Brambach, 150 m W of the VL4T gauge well. Their temporal resolution is 15 min, except the precipitation data (Tab. 1). The groundwater levels in both gauge wells are measured with the same time interval by means of hydrostatic pressure probes with integrated data logger (ΔGWL= ± 0.2 cm).

Results

The 2000 and 2008 Nový Kostel seismic periods started in early September and October respectively. Thus, a temporal comparison of the seismic pattern and the accompanying anomalous hydrological effects is graphically facilitated.

Seismicity

The spatial plots of the 2000-01 and 2008-09 epicentres (M_L > -1) show an almost identical

distribution of the seismic events around Nový Kostel. Temporally, the epicentres moved on a nearly N-S directed line and the hypocentres changed in depth. Figure 2 shows the temporal trend of local magnitudes, focal depths and geographic latitudes of the Nový Kostel seismic events 2000-01 (2A) and 2008-09 (2B). Both the 2000-01 and the 2008-09 swarms started at similar latitudes (~50.20 N) and at the end of the main swarms (phases 2 in Fig. 2 A and B), the epicentres had reached 50.22–50.23 N (end of November 2000) and 50.23–50.24 (middle of December 2008), respectively. Focal depths during this time migrated from about 11.0–11.5 km to 7.0–7.5 km below the surface. The 2000-01 epicentres subsequently migrated continuously to the north (phase 3, Fig. 2A). The deeper and again more southern events after the end of March 2001 indicate that this swarm did not belong genetically to the previous ones (phase 4, Fig. 2A). The 2008-09 epicentres reached their most northern position nearly at the same time as the focal depths were shallowest (end of phase 2, Fig. 2B). From February 2009, they migrated again southward while the hypocentres moved down to 10.5–12.5 km depth (phase 3, Fig, 2B).

Despite the lower total number of events with $M_L > 1$ in 2008 (374) against 2000 (742), most of the 2008 earthquakes occurred within one month only (2000: three months). During this time, more than 80 % of the total seismic energy was released within about 4.5 days (Horálek et al., 2009). Almost 88 % of the 2008 main swarm consisted of earthquakes with $M_L \geq 1$ but this was only 22 % in 2000. Moreover, 9 single earthquakes with $M_L \geq 3$ and a maximum value of M_L = 3.8 occurred in 2008 (2000: 5 with $M_L \geq 3$; $M_{Lmax} = 3.3$). So, the 2008-09 earthquake swarm is considered to be the strongest since 1985-86 (Horálek et al., 2009).

Fig. 2 A, B

Seismohydrological anomalies

The hydrological anomalies occurring before and during the seismic periods 2000-01and 2008-09 at the Bad Brambach research station may be subdivided into

- hydrostatic pressure fluctuations in the spring capture of the 'Wettinquelle', and
- anomalous water level courses of the 15 m deep gauge well VL4T, related to the shallow GW1 well.

The capture of the mineral spring 'Wettinquelle' is hermetically closed, except for a small outlet for gas flow about 8 cm above the natural water level. Therefore, the measured pressure is the combined result of the hydrostatic pressure of the water column above the pressure probe and a gas pressure component built up by the internal resistance of the gas counter. The amount of air pressure is automatically separated by the pressure probe. Nevertheless, small air pressure induced effects on the hydrostatic pressure due to the compression of the mineral water body over-saturated by CO_2 are measurable.

Figure 3 demonstrates the hydrostatic pressure anomalies in the spring capture of 'Wettinquelle', Bad Brambach and the seismicity of 2000 and 2008. The short single failures in the pressure curves are due to regular gas sampling at the gas tap on the top of the spring capture. In 2000, one anomaly started 25 days before the earthquake period. It is characterised by high frequency fluctuations of around ±1.5 cm and a duration of 15 days, superimposed by a 1 cm increase of the total pressure, compared with the long-term pre-seismic background . The normal pressure level was reached again 12–13 days after the beginning of the swarmquake series. In 2008, two pressure anomalies were recorded: 16 days before a small swarm and 36 days before the main seismic period in the Nový Kostel zone. They lasted 5 and 6 days with water level maxima between 2.8 and 2.0 cm above the normal long-term background level, respectively.

Fig. 3

As at the Wettinquelle spring, the groundwater level (GWL) curve at gauge well VL4T shows only one pre-seismic anomaly (Fig. 4, 5) in 2000. The water level rise started 30 days before the earthquakes. Within the bounds of accuracy, this may be considered as the same precursory time as derived from the Wettinquelle hydrostatic pressure curve (Fig. 3). The calculated GWL difference line (VL4T minus GW1) reached a maximum of +25 cm above the long-term background immediately in the beginning of the seismic period. Short-term peaks in the GWL difference curve are caused by slightly shorter response times after strong rainfall and a more sensitive reaction to air pressure variations (possibly higher concentrations of dissolved CO_2) at the VL4T well compared to GW1. Twelve days after the maximum, the GWL differences decreased below the pre-seismic threshold and reached a minimum of – 7 cm within a 20 days period of relatively low seismicity. Altogether, the anomalous groundwater regime at gauge well VL4T lasted about 12 weeks, from July 28 to Oct. 18, 2000. After that, no further significant GWL anomalies occurred by the end of April 2001. By the middle of January 2001, the strongest seismicity was effectively finished.

Fig. 4

Fig. 5

In August 2008, the GWL difference line shows anomalous fluctuations of ±11 cm above the pre-seismic background beginning 12 days before a small single swarm. This small hydraulic anomaly is followed by a long-term GWL increase beginning 26 days before the main seismic period and accompanying it for 74 days (Fig. 4, 6). After a short break in a phase of lower seismicity (December 2008), the GWL difference increase proceeded steadily by the middle of

April 2009. Only in March 2009, it was interrupted by a high flood effect in the GW1 reference well, when snow melting and simultaneous ice swells in the neighbouring creek caused an over-proportional GWL rise. From the end of May 2009, the GWL difference curve dropped down again to the long-term pre-seismic background level of July 2008.

Fig. 6

At first view, the enduring 2008-2009 GWL anomaly seems to be a hydro-/meteorological seasonal effect. Figure 7 shows that such effects actually exist. They are the result of higher water retention in the deeper granitic aquifer opened up by gauge well VL4T. However, the fluctuations of the GWL difference curve scarcely exceed the +σ-level in times of low seismicity (2002-2007). The GWL difference minima 1 and 2 were caused by groundwater lowering due to underground works near the VL4 gauge. Figure 7 also demonstrates that average values are not sufficient for a reliable identification and evaluation of GWL anomalies, even though they are calculated over many years. They do not replace detailed recordings with high temporal resolution (see Fig. 5 and 6).

Fig. 7

Discussion

It should be noted that the occurrence of hydrological anomalies and seismic crises cannot be considered as having a fixed time table. Until now, no seismohydrological publication has considered two or more seismohydrologically anomalous periods separated by several years of very low seismicity *and* lacking anomalies ('zero-hypothesis') as well (Fig. 7). Differences in

the time span between the respective anomaly and seismic period and/or in the duration of both suggest that the local increase of static strain and pore pressure perturbation before the seismic events depend both on the location of the first fracture zone activated by the swarm and the strain accumulated there. The processes generating a hydraulic anomaly at 13–14 km distance from the hypocentre are exceedingly complex. The preparation process seems to be always unique and, consequently, with a different anomaly behaviour. The long lasting fracturing process during and after a swarm (preparation and relaxation) changes the elastic properties of the fault structure and the fluid transport paths (Scholz, 1990). Thus, the following seismic crisis has to be different to the previous one, both with regard to the activated fault planes and to variations in the anomaly occurrence. In the present case, this is expressed by different time spans between the hydrological anomalies and earthquakes (12 to 36 days) and the shape and duration of the anomalies (a few days to 8 months). Therefore, it is not possible at present to derive a systematic relationship between anomaly occurrence and seismic activity, as proposed within the common earthquake prediction debate (e.g. Nature, February/March 1999).

Table 2 gives an overview about the characteristics of the swarmquake periods 2000-01 and 2008-09 regarding seismicity and seismohydrological anomalies. In both cases, real hydrological precursors were registered. 'Real' means that the anomaly-generating processes in the depth *and* the appearance of the anomaly at the surface occurred before the seismic events. Anomalies appearing after the beginning of seismicity are normally denoted as 'co-seismic' effects, although they may have been generated absolutely before the earthquake period. In such a case, a pre-seismic anomaly origin is practically impossible to verify at the surface because it cannot be separated from possible hydrological effects released by the earthquakes themselves due to dynamic stress (e. g. opening of cracks due to shocks).

Tab. 2

Generally, hydrological earthquake precursors may arise in following ways:

A) Tectonic stress accumulation in the crust causes higher pressures in pores and fissures of the fluid system. Static strain accumulation can change tensile cracks and their diffusivity. The resulting pressure perturbation along tectonic structures transmits the signal to the Earth's surface where it may be observed for example as an increase of groundwater levels, a stronger water discharge at springs and/or an activation of free degassing at mineral springs and dry gas outlets, e. g. mofettes (Heinicke and Koch, 2000; Koch et al., 2003).

B) A primary pressure increase in the fluid system (with the respective surface effects mentioned before) may decrease the friction between fault planes. Together with a weakening of faults by aggressive fluids (producing alteration effects), these processes may decrease the critical failure condition along the faults resulting in a triggering of earthquakes (Parotidis et al., 2005; Koch et al., 2008; Heinicke et al., 2009).

Both scenarios imply a sufficient accumulation of tectonic stress to initiate seismicity. Otherwise, hydrological anomalies at the surface may also occur without subsequent seismicity. In the case of the hydrological anomalies observed at Bad Brambach, a decision about the priority of one of these two main processes is difficult. The GWL anomaly one month before the 2000 earthquakes and the following GWL decrease below the pre-seismic level suggest process A. However, even in this seismic period, several authors detected clues for an earthquake triggering by fluids. Parotidis et al. (2005) tested the hypothesis about the triggering of NW Bohemian earthquakes by ascending magmatic fluids and identified pore pressure diffusion to be responsible for the spatiotemporal clustering and the migration of the seismic events (see also Fig. 2). In contrast, Horálek and Fischer (2008) emphasized that the pore pressure of crustal fluids is decisive for bringing the faults from a subcritical to a critical state. This would mean that fluid triggering could occur only in the initial phase of the 2000-2001

swarm.

Huenges et al. (1997) proposed the existence of a highly permeable fracture system up to the 9.1 km deep bottom of the German Deep Drilling borehole (KTB), which could enable fluid migration at relatively low overpressures. This depth range corresponds to the mean focal depth of the Novy Kostel earthquake swarms. Injection experiments at the KTB between 2004 and 2005 showed that fluid migration into the crustal fault system induced micro-seismicity adjacent to the borehole triggered by pore pressure perturbations of only 0.01–1.0 bar at hypocentral depths (Shapiro et al., 2006). Moreover, a vertical Earth's surface uplift of 3.1 mm was caused by pore pressure changes of more than 11 MPa close to the KTB injection borehole (Jahr et al., 2008).

The 2008-09 seismic events at the Nový Kostel epicentral area were accompanied by an anomalous pressure in the deep-reaching mineral aquifer system for about 8 months. Contrary to the 2000 period, where no appreciable earthquakes occurred after January 2001, low but frequent seismic activity in 2008-09 continued to the end of April 2009, after the maximum energy release in October. Therefore, it may be inferred that fluid triggering was the crucial process for initiation and continuation of the 2008-09 swarmquake series. Only from May 2009 did the anomalous groundwater level in the deep gauge well VL4T decrease again, reaching its pre-seismic level in August 2009 (Fig. 6). The long-lasting anomalous fluid pressure of 2008-09 could also emphasize the continuation of the long-term gas flow increase observed at mineral springs and mofettes in the region since 1998 (Koch et al., 2008). This quantitative signal was accompanied by a rise of the $^{3}He/^{4}He$ ratio of ascending gases, an evidence for a possible increase of magmatic activity beneath the Cheb Basin (Weise et al., 2001; Bräuer et al., 2009).

The seismic events 2000-01 and 2008-09 obviously occurred in the same epicentral area of Nový Kostel, around the intersection of Mariánské Lázně and Počátky-Plesná fault zones (Fig.

1, 2). During the 2000 and 2008 main seismic periods, the hypocentres migrated from south of the epicentral area and depths of 11–11.5 km to the north and upward to about 7 km depth. In 2000, the hypocentres remained in the north but their focal depths moved down to 10.5–12 km only after the end of March 2001 (Fig. 2A). In 2008, the hypocentres declined from 10.5 to 12.5 km depth between January and April. Almost at the same time, they migrated southward (Fig. 2B). Taking into account that pore pressure diffusion can play an important role for the spatial and temporal behaviour of swarmquake foci (Shapiro et al., 2006), the different migration patterns of the hypocentres between the 2000-01 and 2008-09 may be related to the different shapes and durations of the observed fluid pressure anomalies. Both the 2000 and the 2008 anomalies (Wettinquelle and GWL) started between 25 and 36 days before the onset of the main seismic period, and the VL4T groundwater pressure ascended to a maximum of 25 cm above the long-term pre-seismic background level. This suggests similar earthquake initiating processes, independently if stress accumulation or fluid triggering was the primary factor. For 2008, it may be assumed that the stress drop was complete by the end of October, the month with a concentrated high release of seismic energy. Interestingly, the following phase of low seismicity (middle of November by end of December 2008) was accompanied by a horizontal segment of the GWL difference curve (Fig. 4, 6). This means that the earthquake-sensitive VL4T groundwater table persisted at a high but relatively constant level. The following GWL difference increase was accompanied by a period of frequent seismicity but low seismic energy release. Having presupposed that the stress drop was predominantly over by the end of October 2008, the 'seismic restart' in January 2009 may be attributed to fluid triggering processes under reduced friction conditions along the fault plane. Possibly, this process occurred more or less intensively until the end of April 2009. Further, the higher fluid influence for earthquake triggering might also be responsible for the differences in the migration patterns of the 2008-09 hypocentres, compared to 2000-01 (Fig. 2, Tab. 2).

In contrast to 2008, the 2000 GWL anomaly had vanished by the onset of earthquake activity, and the subsequent decrease of the GWL difference curve below the pre-seismic level indicates an opening of additional pores and cracks, possibly due to the seismic shock waves. During this GWL difference minimum, a break in the seismic activity occurred. However, the GWL difference curve also shows that the additional pore space was either closed again due to a new stress accumulation or was filled very quickly by over-pressured fluids from depth. Both processes, or a combination thereof, should have been completed within 20 days, accompanied by a new onset of seismicity lasting up to the end of 2000. In any case, the 2000 groundwater level data cannot clarify definitely if the 'post-anomaly' seismicity was mainly triggered by fluids (Parotidis et al., 2005) or if the role of pore pressure of crustal fluids was limited only to the initial phase of the 2000 swarm to bring the faults from a subcritical to a critical state. Also, they cannot verify if the further swarm activities were mainly driven by stress changes due to co- and post-seismic slips depending on the frictional state of the seismically active fault(s) (Horálek and Fischer, 2008). The rapid closing and/or the fluid re-filling of the additional pore/fissure space after the 2000 GWL anomaly indicates that the fluid pressure was sufficient for earthquake triggering as well as for keeping the active fault in a critical state and, thus, for a continuation of seismicity.

Conclusions

In spite of their similar spatial distribution in both seismic periods, the epicentres of the Nový Kostel earthquakes migrated differently through time: S→N in 2000-01 and S→N→S in 2008-09. In both cases, the shallowest focal depths were observed when the epicentres reached their most northern positions.

Compared to 2000-01, the number of events with $M_L>1$ was approximately half in 2008-09 but

the seismic energy was released predominantly within 1 month (2000: 3 months). Also, the number of single events with M_L>3.3 exceeded that of 2000. The main distinctive features between the 2000-01 and the 2008-09 seismic periods occurred in the hydraulic anomalies recorded at the Bad Brambach seismo-hydrological observatory: anomaly number, shape, and progression (duration). Two relatively short anomalies before the 2000 earthquakes faced altogether four partly long-enduring anomalous sections before and during the 2008-09 seismic events, after which the groundwater pressure in a 15 m deep gauge well reached again its 2008 pre-seismic level only at the end of August 2009. The comprehensive hydraulic data with high temporal resolution suggest that fluid triggering dominated not only the earthquake initiating phases (Horálek and Fischer, 2008). They demonstrate that the higher release of seismic energy and the enduring earthquake activity in 2008-09 was accompanied by a long-term increase of fluid pressure. Therefore, the seismicity in 2009 could be attributed to a continued triggering of weak earthquakes by over-pressured deep fluids (Parotidis et al., 2005). But, obviously, the remaining static strain was not sufficient to generate strong earthquakes such as at the beginning of the seismic periods 2000 and 2008. Furthermore, the enduring high fluid pressure in 2009 could indicate a continuation of the long-term gas flow increase observed at several gas outlets in the region between 1998 and 2008 (Koch et al., 2008). Together with an accompanying rise of the $^3He/^4He$ ratio of ascending gases, this could be an indication for an increasing magmatic activity beneath the Cheb Basin (Weise et al., 2001; Bräuer et al., 2009).

Acknowledgements

The authors wish to thank the former director of the Sächsische Staatsbäder GmbH, Christian Kirchner, for the steady support of their investigations at the Bad Brambach mineral springs, the editor of the Journal of Geodynamics, Randell Stephenson, for his impressive engagement

in publishing this paper and an unknown reviewer for valuable recommendations, hints and comments.

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Figure captions

Figure 1: Earthquake epicentres in the Vogtland/ NW Bohemia with Cheb Basin (CB) and Eger Rift (ER). Since 1985, the most frequent epicentre is located near Nový Kostel (NK). BE – Bad Elster, KL – Klingenthal, SK – Skalná, S/A – Selb/Aš, MLFZ – Mariánské Lázně fault zone, PPZ – Počátky-Plesná zone, Bad Brambach – seismo-hydrological observatory; + Fichtelgebirge granite.

Figure 2: Spatial distribution of the 2000-01 (A) and 2008-09 (B) earthquake swarm epi- and

hypocentres near Nový Kostel (Czech Republic) together with the temporal plot of magnitudes between September and April, respectively ($M_L > -1$). The numbered ellipses highlight the migration of the hypocentres along the Nový Kostel (NK) fault plane, according to the magnitude plot above. The events after the end of March 2001 (phase 4) and the declining hypocentres at the end of phase 3 in 2009 demonstrate that these swarms obviously do not belong to the previous seismic phases (further explanations in the text).

Figure 3: Hydrostatic pressure anomalies in the spring capture of 'Wettinquelle', Bad Brambach and seismicity 2000 and 2008. In 2000, one anomaly occurred 25 days before the beginning of earthquakes while two anomalies were recorded in 2008: 16 days before a small swarm and 36 days before the main seismic period in the Nový Kostel zone.

Figure 4: The groundwater level differences between the gauge wells VL4T and GW1, Bad Brambach within the main seismic periods August–December 2000 and 2008, respectively. As with the spring capture pressure (Fig. 3), one anomaly in 2000 and two anomalies in 2008 were observed. Contrary to 2000, the anomalous high water level difference did not decline to the starting level after the beginning of the earthquake swarms.

Figure 5: Groundwater levels (GWL), GWL differences, air pressure, precipitation at Bad Brambach and seismicity in the Nový Kostel area from July 2000 to April 2001. In 2000, the anomaly started 30 days before the earthquakes. The peak is coincident with the occurrence of the first seismic events. No further significant groundwater anomalies were observed after the end of the main seismic period.

Figure 6: Groundwater levels (GWL), GWL differences, air pressure, precipitation at Bad

Brambach and seismicity in the Nový Kostel area from July 2008 to August 2009. Two anomalies were recorded in 2008: 12 days before a small event and 26 days before the main seismic period. The second anomaly lasted ~74 days accompanying the main seismic period. After a short break at the end of December (constant GWL difference), the seismicity continued and the GWL difference increased again steadily by the middle of April 2009. Only from the end of May 2009, the groundwater level differences decreased again reaching the 2008 pre-seismic background level approximately at the end of August 2009. The high flood effect in 2009 occurred due to a different response of the gauges VL4T and GW1 to a ice swells in the neighbouring creek.

Figure 7: Monthly averages of groundwater levels and GWL differences at Bad Brambach versus the number of earthquakes with magnitudes > 1 at Nový Kostel between May 2000 and August 2009. The number of earthquakes in 2008 (374, B) is approximately a half as against 2000 (742, A). But, in 2008, the total seismic energy was practically released within one month. The periodic seasonal fluctuations of the GWL differences are the result of higher water retention in the aquifer opened up by gauge well VL4T. The GWL difference minima 1 and 2 were caused by groundwater lowering due to underground works near the VL4 gauge.

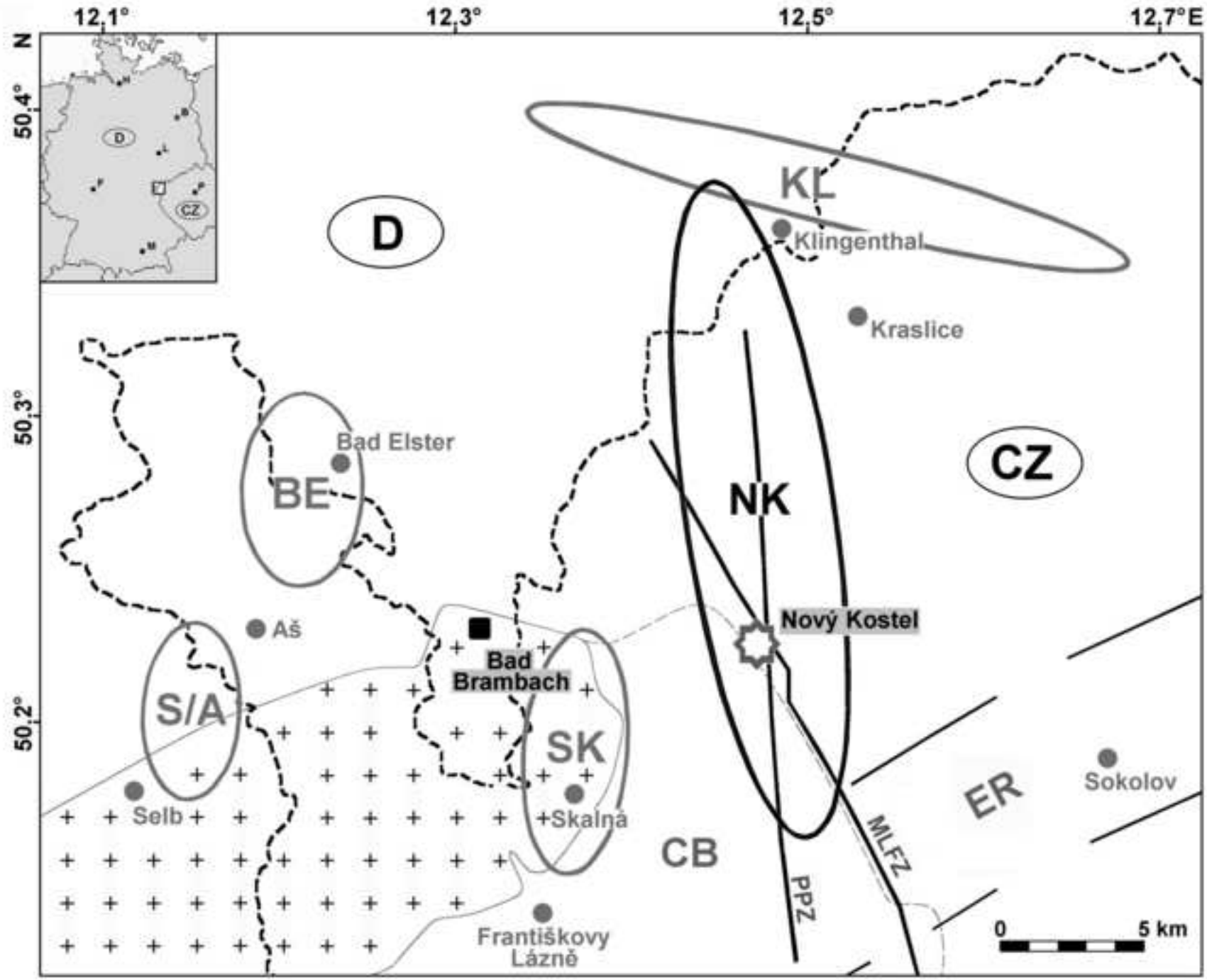
Table 1: Applied basic data and their temporal resolution

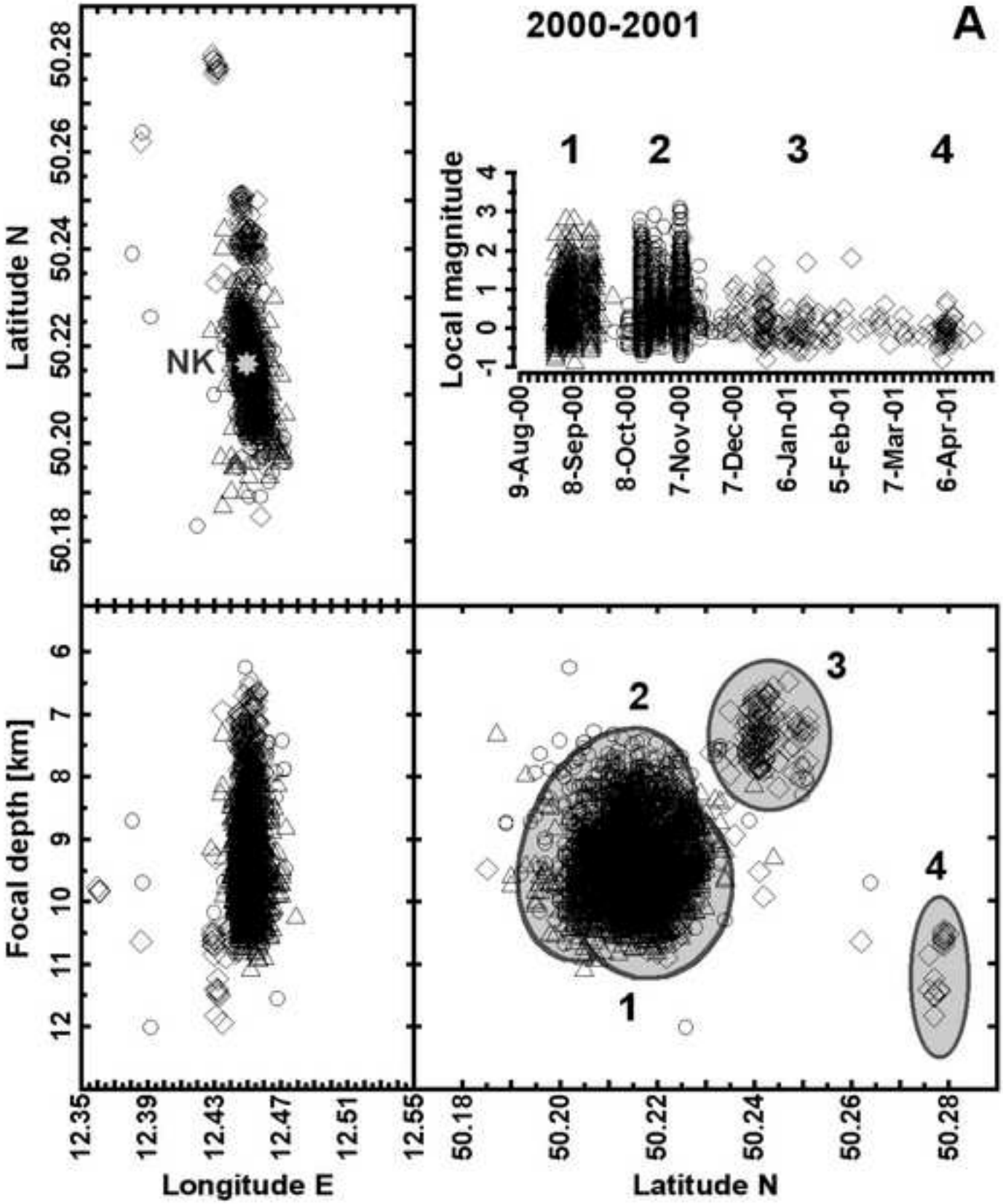
Type of data	Unit	Temporal resolution	Data source
seismic data	---	1 sec	WEBNET GFU Prague http://www.ig.cas.cz Fischer and Horálek, 2003 Horálek et al., 2009
hydrostatic pressure 'Wettinquelle' spring	m (above pressure probe)	10 min	own measurements
groundwater levels gauges VL4T, GW1	m (above sea level)	15 min	own measurements
air pressure	hPa	15 min	climatic station Bad Brambach
precipitation	mm	1 day	climatic station Bad Brambach

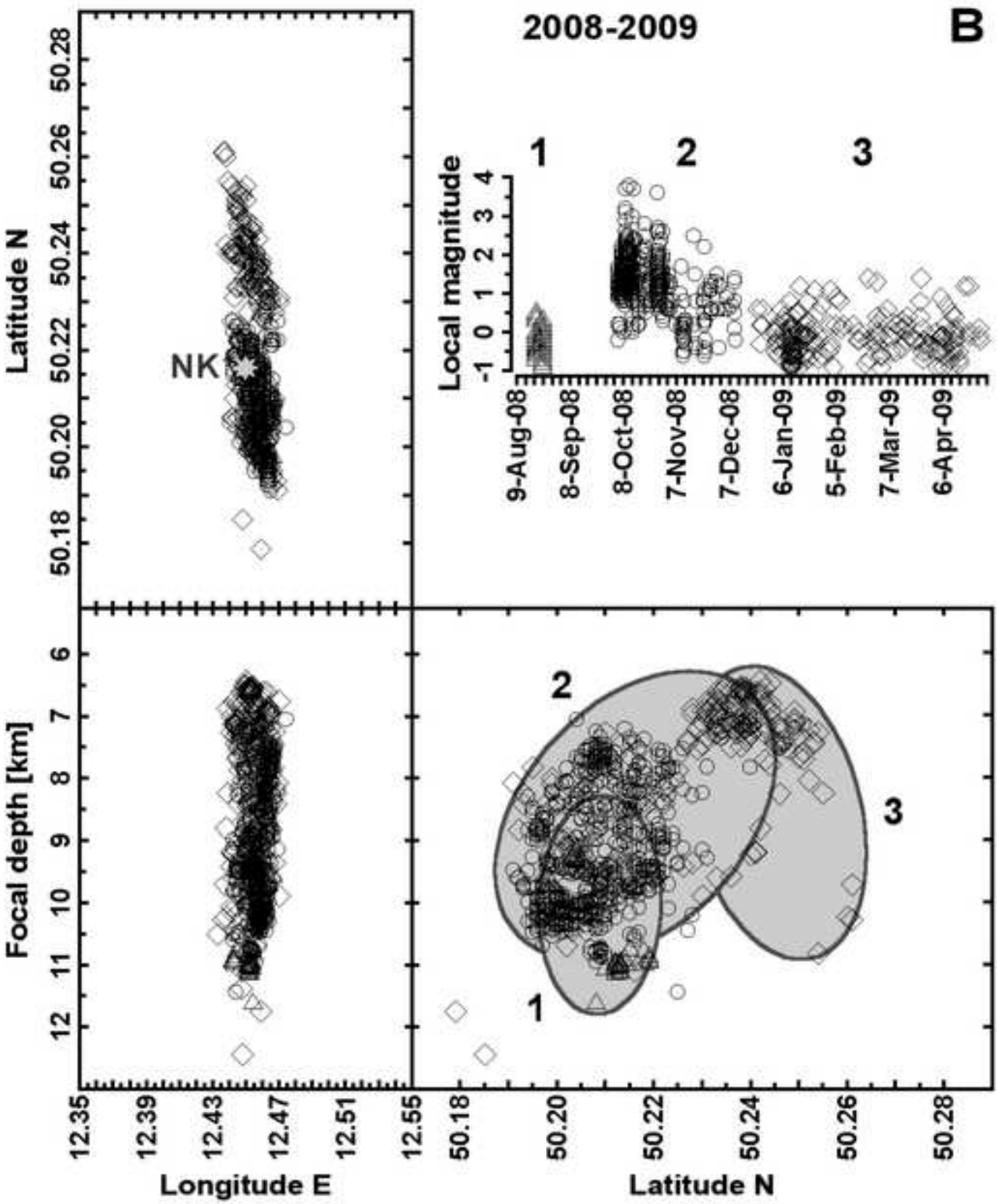
Table 2: Comparison of seismicity and anomalies between the earthquake periods 2000-01 and 2008-09

	2000-2001	2008-2009
Seismicity	• similar spatial distribution of the epicenters • migration along the Nový Kostel fault plane	
	epicenters migrate from S to N, remaining there after the main seismic period	epicenters migrate from S to N by the end of the main swarm and again southward from February 2009
	start at focal depths of 11–11.5 km → moving to minimum depths of ~ 7 km at the end of the main seismic period	
	focal depths decline again to 10.5–12 km only after the end of March 2001	focal depths decline again to 10.5–12.5 km between January and April 2009
	742 events with M_L>1 within 3 months (September–November 2000) 3.0≤M_L≤3.3: 5 M_L>3.3: 0 (max. 3.3)	374 events with M_L>1 within 1 month (October 2008) 3.0≤M_L ≤3.3: 3 M_L>3.3: 6 (max. 3.8)
Anomalies	1 pressure anomaly 'Wettinquelle' 25 days before the main events	2 pressure anomalies 'Wettinquelle' 16 days before a small single swarm and 36 days before the main events
	1 GW level anomaly (max. 25 cm) 30 days before the main events, ending after the beginning of the earthquakes	1 GW level anomaly (±11cm) 12 days before a small single swarm; 1 GW level anomaly (max. 25 cm) 26 days before the main events
	no further anomalies from the beginning of the earthquakes	enduring anomalous GW levels for at least 8 months from the beginning of the seismic period

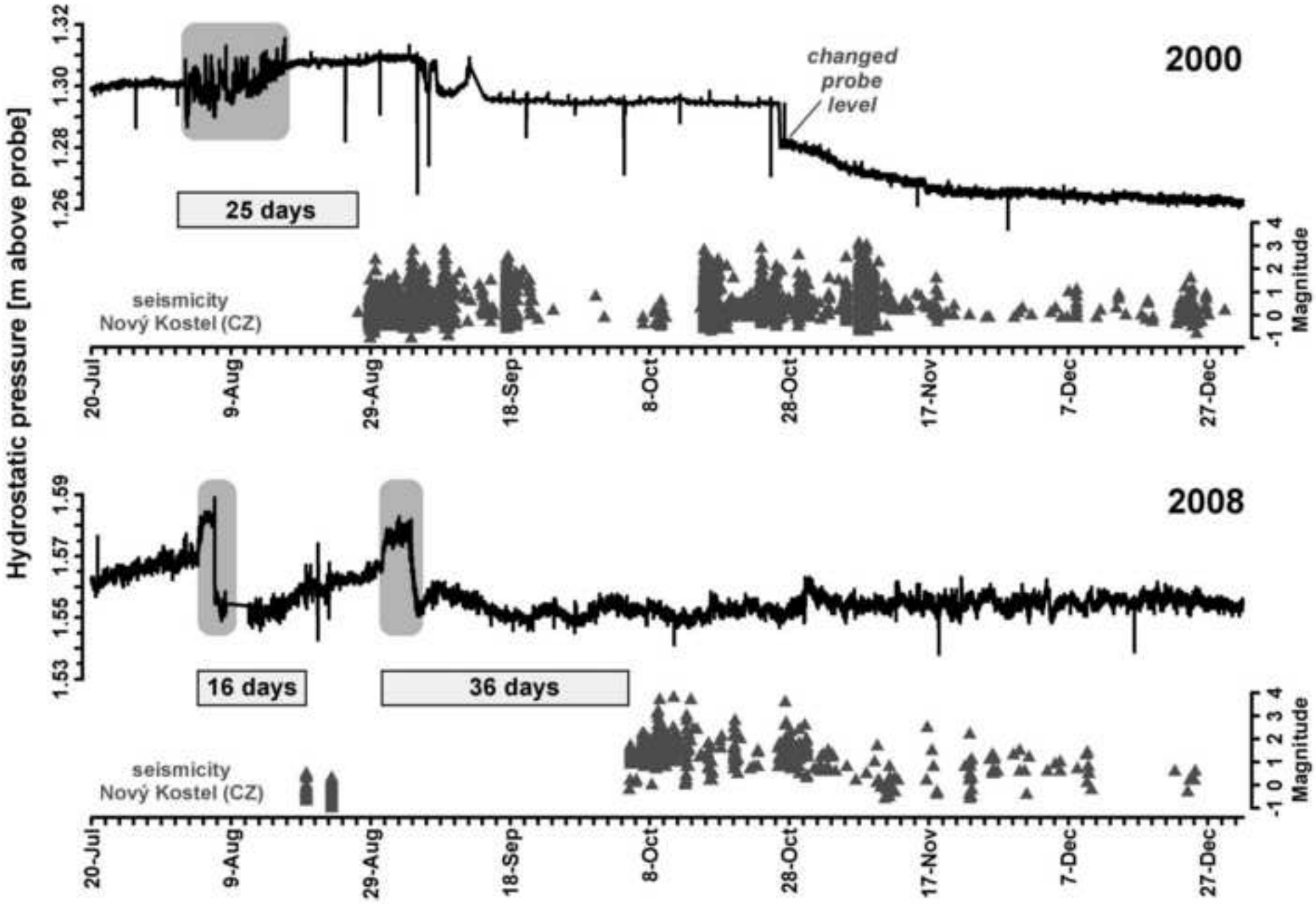
Figure


12.1°
12.3°
12.5°
12.7°E
N
50.4°
50.3°
50.2°
D
CZ
KL
Klingenthal
Kraslice
BE
Bad Elster
NK
CZ
Aš
Nový Kostel
Bad Brambach
S/A
SK
Selb
Skalná
CB
ER
Sokolov
MLFZ
PPZ
Františkovy Lázně
0
5 km

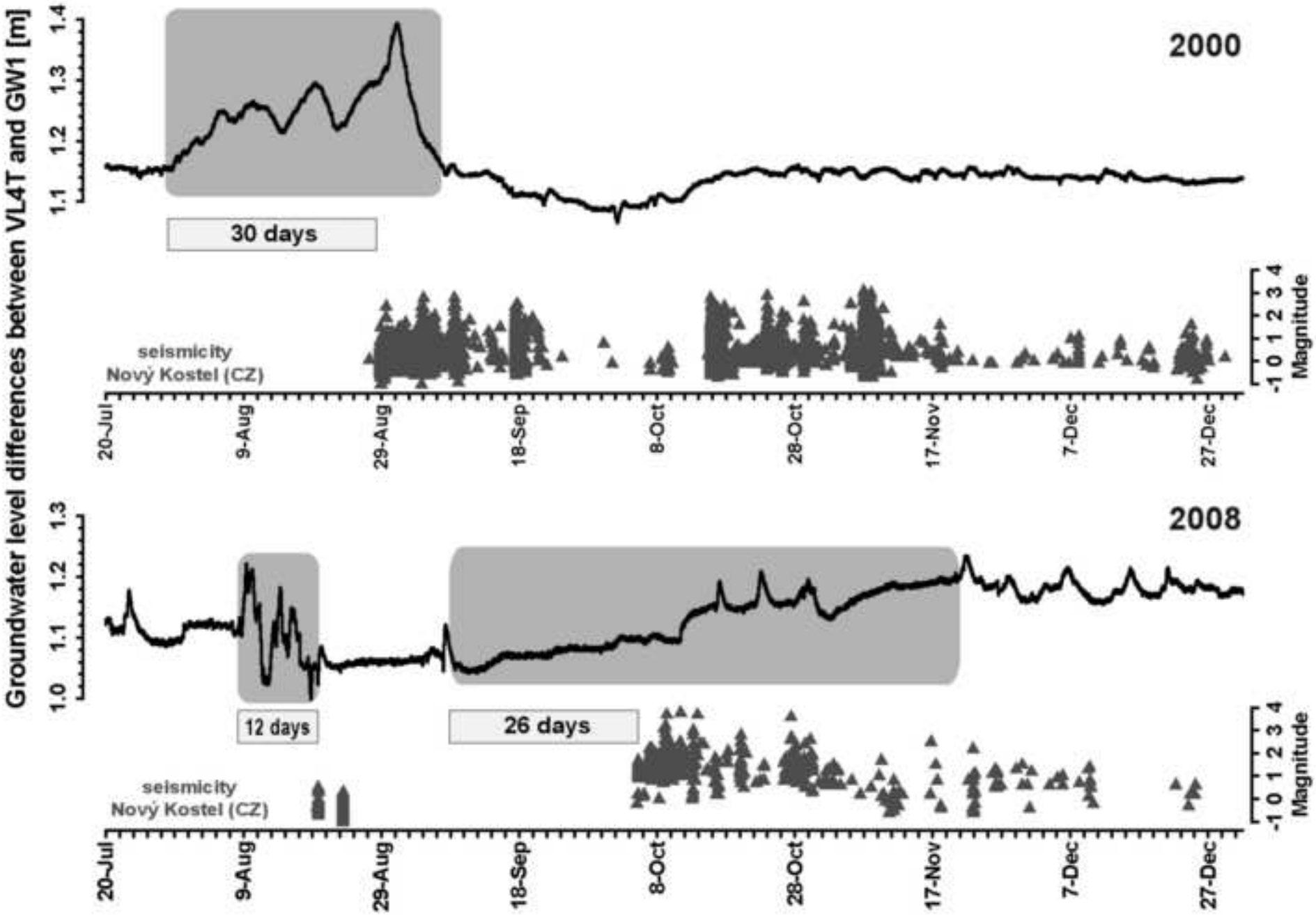




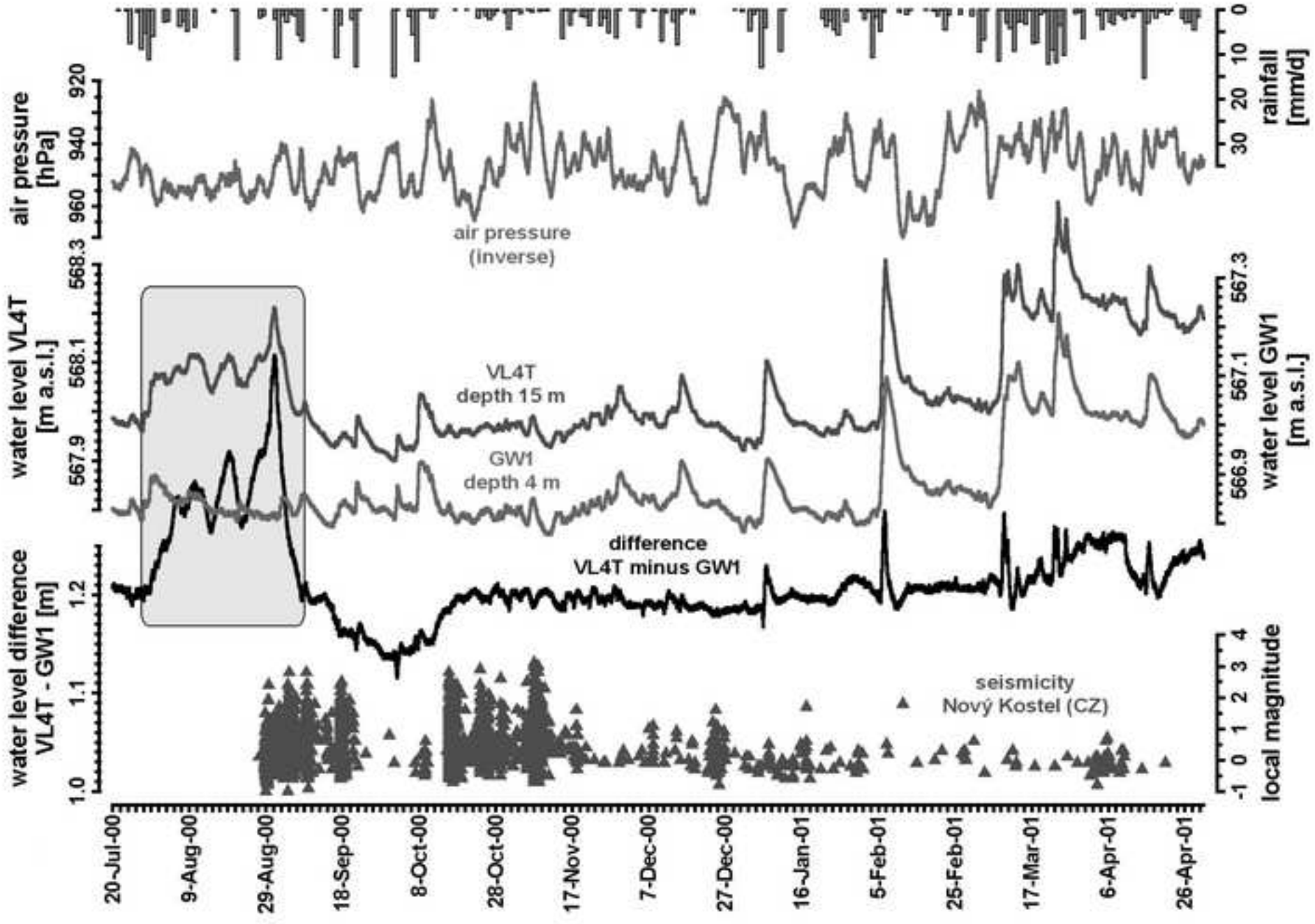
Figure


Hydrostatic pressure [m above probe]
1.26
1.28
1.30
1.32
changed probe level
2000
25 days
seismicity Nový Kostel (CZ)
Magnitude
-1 0 1 2 3 4
20-Jul
9-Aug
29-Aug
18-Sep
8-Oct
28-Oct
17-Nov
7-Dec
27-Dec
1.53
1.55
1.57
1.59
2008
16 days
36 days
seismicity Nový Kostel (CZ)
Magnitude
-1 0 1 2 3 4
20-Jul
9-Aug
29-Aug
18-Sep
8-Oct
28-Oct
17-Nov
7-Dec
27-Dec

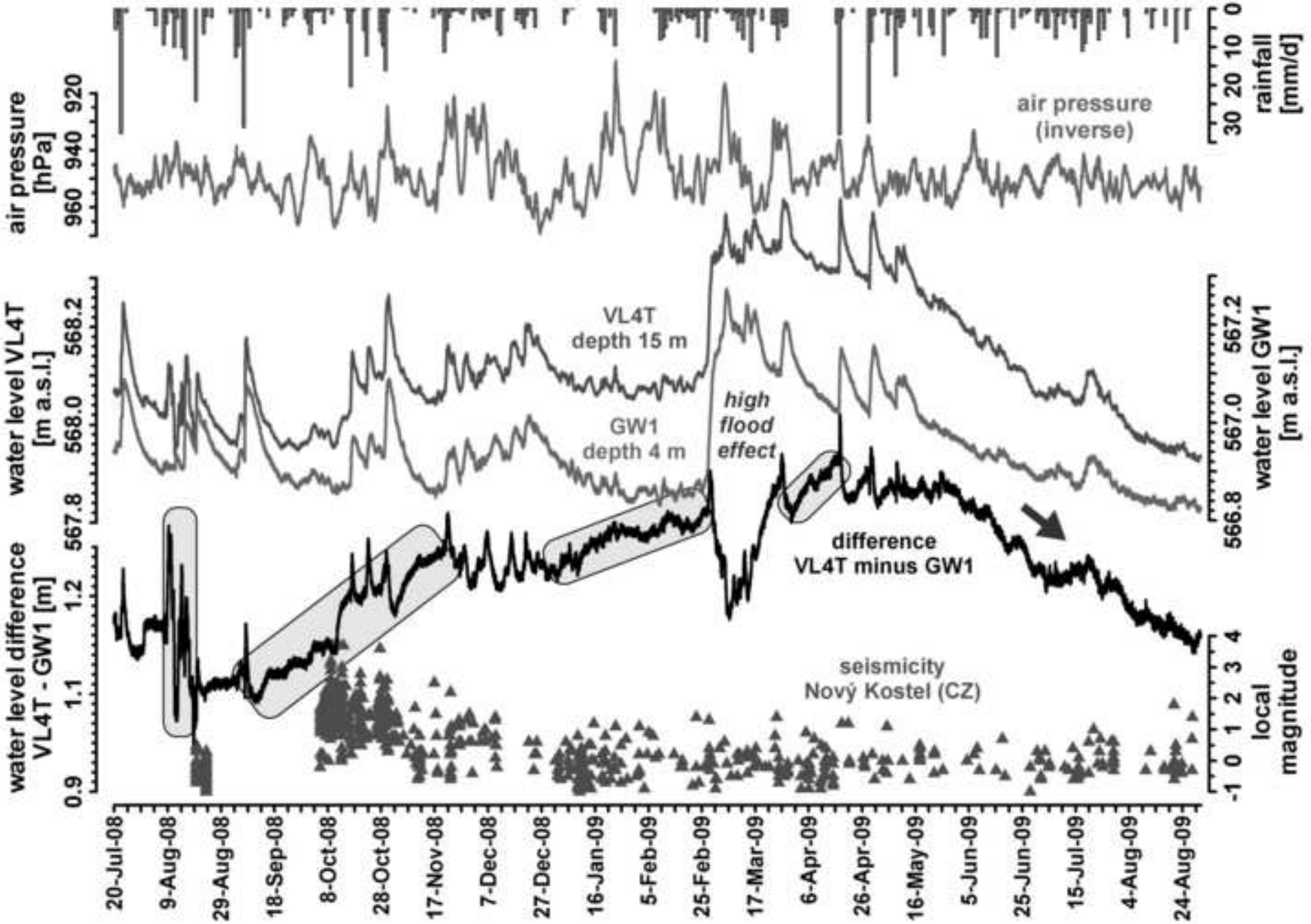
Figure


Groundwater level differences between VL4T and GW1 [m]
2000
30 days
seismicity
Nový Kostel (CZ)
Magnitude
2008
12 days
26 days
20-Jul
9-Aug
29-Aug
18-Sep
8-Oct
28-Oct
17-Nov
7-Dec
27-Dec

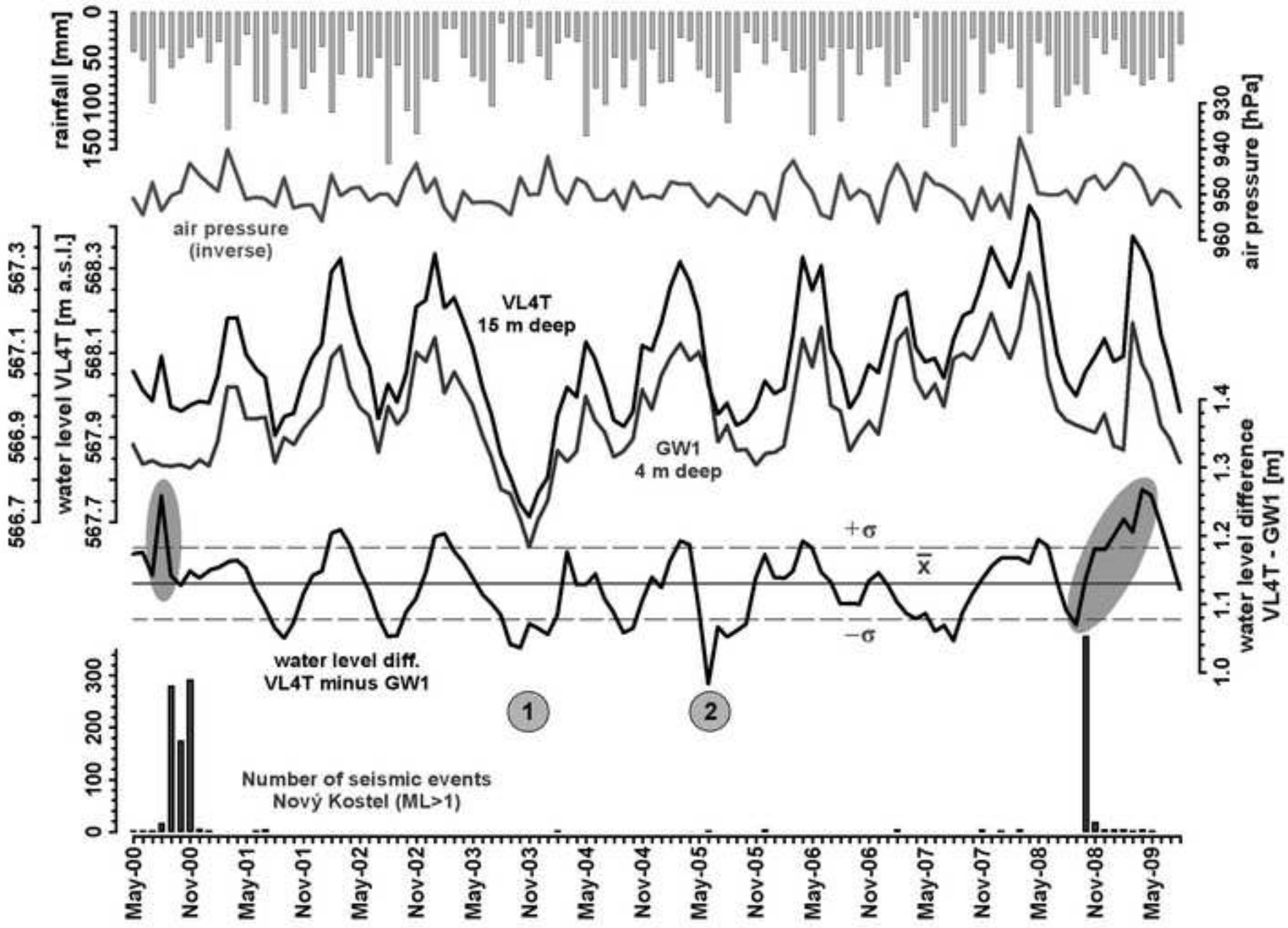
Figure


air pressure [hPa]
920
940
960
air pressure (inverse)
rainfall [mm/d]
0
10
20
30
water level VL4T [m a.s.l.]
568.3
568.1
567.9
VL4T depth 15 m
GW1 depth 4 m
water level GW1 [m a.s.l.]
567.3
567.1
566.9
difference VL4T minus GW1
water level difference VL4T - GW1 [m]
1.0
1.1
1.2
seismicity Nový Kostel (CZ)
local magnitude
-1
0
1
2
3
4
20-Jul-00
9-Aug-00
29-Aug-00
18-Sep-00
8-Oct-00
28-Oct-00
17-Nov-00
7-Dec-00
27-Dec-00
16-Jan-01
5-Feb-01
25-Feb-01
17-Mar-01
6-Apr-01
26-Apr-01

Figure


air pressure [hPa]
960 940 920
air pressure (inverse)
rainfall [mm/d]
30 20 10 0
water level VL4T [m a.s.l.]
568.2 568.0 567.8
VL4T depth 15 m
GW1 depth 4 m
high flood effect
water level GW1 [m a.s.l.]
567.2 567.0 566.8
water level difference VL4T - GW1 [m]
1.2 1.1 0.9
difference VL4T minus GW1
seismicity Nový Kostel (CZ)
local magnitude
4 3 2 1 0 -1
20-Jul-08
9-Aug-08
29-Aug-08
18-Sep-08
8-Oct-08
28-Oct-08
17-Nov-08
7-Dec-08
27-Dec-08
16-Jan-09
5-Feb-09
25-Feb-09
17-Mar-09
6-Apr-09
26-Apr-09
16-May-09
5-Jun-09
25-Jun-09
15-Jul-09
4-Aug-09
24-Aug-09

Figure


rainfall [mm]
150 100 50 0
air pressure (inverse)
960 950 940 930
air pressure [hPa]
water level VL4T [m a.s.l.]
566.7 566.9 567.1 567.3
567.7 567.9 568.1 568.3
VL4T
15 m deep
GW1
4 m deep
+σ
x̄
−σ
water level diff.
VL4T minus GW1
1.0 1.1 1.2 1.3 1.4
water level difference
VL4T - GW1 [m]
1
2
0 100 200 300
Number of seismic events
Nový Kostel (ML>1)
May-00
Nov-00
May-01
Nov-01
May-02
Nov-02
May-03
Nov-03
May-04
Nov-04
May-05
Nov-05
May-06
Nov-06
May-07
Nov-07
May-08
Nov-08
May-09