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

3
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10
11
12 **Abstract**

13
14 For more than 20 years, seismo-hydrological investigations have been undertaken at the
15 mineral aquifer system of Bad Brambach (Vogtland, Germany). Two strong swarm earthquake
16 series in 2000-01 and 2008-09 at the Nový Kostel epicentre (Czech Republic, 10 km E of BB)
17 have enabled for the first time a comparison of seismological and groundwater hydraulic
18 features in a semi-quantitative way. In spite of their similar spatial distribution in 2001 and
19 2008, the earthquake foci of each swarm migrated differently through time, horizontally as well
20 as in depth. The seismic energy of the 2008-2009 events was released predominantly within one
21 month, in contrast to 2000-2001 when it occurred over three months. The main distinctive
22 features of each are seen in the hydraulic pressure anomalies which accompanied the
23 earthquake swarms: number, shape, and progression (duration) of the anomalies. The
24 comprehensive hydraulic data, with high temporal resolution, suggest that fluid triggering
25 dominated not only the earthquake initiating phases. In particular, the long lasting seismicity of

1 the 2008-2009 swarm can be attributed to a continued triggering of weak earthquakes by
2 over-pressured deep fluids. Here, the remaining static strain was obviously not sufficient to
3 generate strong earthquakes as at the beginning of the earthquake swarm periods. Furthermore,
4 the enduring high fluid pressure in 2009 could also indicate a continuation of the long-term gas
5 flow increase observed at several gas outlets in the Vogtland/NW Bohemia region between
6 1998 and 2008. However, it is not possible at present to derive a systematic relationship
7 between anomaly occurrence and seismic activity, as generally proposed in the context of
8 earthquake prediction discussion.

9

10 **Keywords**

11

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

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1 **Introduction**

2

3 The Vogtland (Germany) and NW Bohemia region is well-known for the periodical occurrence
4 of local intraplate seismicity, so-called earthquake swarms (Babuška et al., 2007; Fischer and
5 Horálek, 2003; Horálek and Fischer, 2008). Like the Massif Central (France) and the Eifel
6 region (Germany), it belongs to a few European seismic areas where earthquakes occur
7 independently of strong tectonic seismic events. However, numerous CO₂ degassing mineral
8 springs and dry CO₂ outlets (mofettes) in these regions are an indication for enduring magmatic
9 and tectonic activity at depth. An updoming of the lithosphere-asthenosphere boundary below
10 the Cheb Basin (Fig. 1) connected with magmatic intrusions via injection channels from the
11 lithospheric mantle is supposed to be the source for this degassing activity (Geissler et al., 2005;
12 Plomerová et al., 2007, Bräuer et al., 2005, 2009). Thus, an increase of the magmatic signature
13 and the flow rate of the ascending gases were observed at several mofettes and mineral springs
14 during the last 16 years (Bräuer et al., 2005, 2007; Koch and Heinicke, 2007; Koch et al., 2008).
15 For more than two decades, the complicated processes of swarmquake generation have been
16 discussed in a broad framework. Simplified, three main triggering mechanisms have been
17 agreed: geodynamic stress accumulation, critical pore fluid pressures and hydrothermal
18 alteration processes (Vidale and Shearer, 2006; Hill, 1977; Giammanco et al, 2008; Zoback and
19 Harjes, 1997; Shapiro et al., 2006; King et al., 1994; Bräuer et al., 2003, 2004; Špičák and
20 Horálek, 2001; Hainzl and Fischer, 2002; Rothert and Shapiro, 2007; Heinicke et al., 2009).
21 Due to the high mobility of CO₂ dominated fluids below the Cheb Basin, a complex interaction
22 of these triggering mechanisms is likely in the Vogtland/NW Bohemia region.
23 Since 1985/86, the most frequent epicentre zone of the NW Bohemia earthquakes has been near
24 Nový Kostel (50.18–50.27°N, 12.35–12.48°E) in the northern part of the Cheb Basin (Fischer
25 and Horálek, 2003; Fig. 1), on the intersection of two main tectonic elements, the NNW–SSE

1 trending Mariánské Lázně fault zone (MLFZ) and the N–S trending Počátky-Plesná zone (PPZ)
2 (Bankwitz et al., 2003). The number of events within a swarmquake period can reach several
3 tens of thousands but the magnitudes are usually < 5 and the hypocentres are located at depths
4 of 7–12 km (Fischer and Horálek, 2003; Horálek et al., 2009). Even before the Nový Kostel
5 earthquake swarms that occurred in 1997 and 2000, gas flow and groundwater level anomalies
6 had been recorded at the Seismohydrological Observatory of the Saxon Academy of Sciences at
7 Bad Brambach, 10 km W of Nový Kostel (Fig 1). These data indicated a pre-seismic fluid
8 overpressure due to geodynamically induced pore pressure increases in the deep aquifer (Koch
9 and Heinicke, 1999; Heinicke and Koch, 2000; Koch et al., 2003). After a 7 year period without
10 appreciable seismic activity, the strongest earthquake series since 1985/86 occurred in autumn
11 2008 at the epicentral area of Nový Kostel (Horálek et al., 2009). Seismohydrological precursor
12 effects could also be observed on this occasion but with different characteristics than in 2000.
13 Thus, it became possible to compare and contrast these two most important swarmquake
14 periods of the recent past from both a seismological as well as a seismohydrological point of
15 view. Such a comparison, however, is only by its nature semi-quantitative. Two strong
16 earthquake swarms within a span of 8 years represent too little data to derive forecast-like
17 predications from the analysed hydrological anomalies – such as starting time, duration,
18 maximum magnitude or energy release distribution of the respective seismic period. Therefore,
19 the discussion of the results is focused on the tectonic and fluid processes that could have
20 initiated and accompanied both earthquake swarms.

21

22 Fig. 1

1

2 **Locations and measurements**

3

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

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

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

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

1

2 Tab. 1

3

4 During the last 20 years, groundwater openings of the Bad Brambach mineral water aquifer
5 (12.298°E, 50.239°N, about 10 km W of the Nový Kostel epicentral zone) proved to be
6 seismohydrologically sensitive locations with respect to earthquakes in the Nový Kostel
7 seismic zone. In particular, the mineral spring 'Wetтинquelle' and a gauge well (VL4T) in the
8 Bad Brambach Cure Park repeatedly showed anomalous behaviours before and during local
9 earthquakes (Heinicke et al., 1995, Koch and Heinicke, 1999; Heinicke and Koch, 2003). A
10 detailed map of the locations can be found in Koch and Heinicke (2007).

11 The Bad Brambach mineral springs are radon-bearing Na-Ca-HCO₃-SO₄ acidic springs
12 characterised by a mineralisation > 2.5 g/L, ²²²Rn-activities of 1.5–26 kBq/L and a gas
13 saturation of 2.6–2.8 g/L dissolved CO₂. The isotopic signature of the free gaseous phase (99.5
14 % CO₂) indicates a crust/upper mantle origin of the spring gases (Koch et al., 2008). The
15 'Wetтинquelle' is one of the strongest radioactive springs in the world and is used for therapeutic
16 applications (26 kBq/l of ²²²Rn). The spring capture is a shallow well located in the tectonically
17 fissured Fichtelgebirge granite, about 5.5 m below the surface. A multi-parameter station
18 recording totally 10 hydrological, hydrochemical and gas flow parameters with a temporal
19 resolution of 2-10 minutes, including water discharge, free gas flow rate and hydrostatic
20 pressure (Tab. 1) has operated there since April 2000. A scheme of the 'Wetтинquelle' spring
21 capture is given by Koch et al. (2003).

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

1 rainfall, snow melting and atmospheric pressure on the groundwater level (GWL). Besides a
2 GWL increase during rainfall and snow melting, this effect may be observed also in times of
3 low air pressure (deep pressure areas). Air pressure-induced GWL fluctuations are reinforced
4 due to dissolved gas in the aquifer, in the present case CO₂. A multiple regression to separate
5 several non-seismic influences on the groundwater level was complicated and not very
6 convincing. A more effective way is the calculation of a GWL difference curve between the
7 time-synchronised data series of the seismically sensitive gauge well and a shallow reference
8 gauge that was not affected by deep originated fluid processes. The 4 m deep gauge well GW1
9 (10 m NW of the 'Wetinquelle'), located in the alluvial weathering zone above the
10 Fichtelgebirge granite surface, fit this requirement. The time series of all relevant
11 meteorological parameters are given in the respective graphs for overview and comparison.
12 They were recorded at the climatic station Bad Brambach, 150 m W of the VL4T gauge well.
13 Their temporal resolution is 15 min, except the precipitation data (Tab. 1). The groundwater
14 levels in both gauge wells are measured with the same time interval by means of hydrostatic
15 pressure probes with integrated data logger ($\Delta\text{GWL} = \pm 0.2 \text{ cm}$).

16

17 **Results**

18

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

22

23 *Seismicity*

24

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

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

15 Despite the lower total number of events with $M_L > 1$ in 2008 (374) against 2000 (742), most of
16 the 2008 earthquakes occurred within one month only (2000: three months). During this time,
17 more than 80 % of the total seismic energy was released within about 4.5 days (Horálek et al.,
18 2009). Almost 88 % of the 2008 main swarm consisted of earthquakes with $M_L \geq 1$ but this was
19 only 22 % in 2000. Moreover, 9 single earthquakes with $M_L \geq 3$ and a maximum value of $M_L =$
20 3.8 occurred in 2008 (2000: 5 with $M_L \geq 3$; $M_{Lmax} = 3.3$). So, the 2008-09 earthquake swarm is
21 considered to be the strongest since 1985-86 (Horálek et al., 2009).

22

23 Fig. 2 A, B

24

25 *Seismohydrological anomalies*

1

2 The hydrological anomalies occurring before and during the seismic periods 2000-01 and
3 2008-09 at the Bad Brambach research station may be subdivided into

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

7 The capture of the mineral spring 'Wetтинquelle' is hermetically closed, except for a small outlet
8 for gas flow about 8 cm above the natural water level. Therefore, the measured pressure is the
9 combined result of the hydrostatic pressure of the water column above the pressure probe and a
10 gas pressure component built up by the internal resistance of the gas counter. The amount of air
11 pressure is automatically separated by the pressure probe. Nevertheless, small air pressure
12 induced effects on the hydrostatic pressure due to the compression of the mineral water body
13 over-saturated by CO₂ are measurable.

14 Figure 3 demonstrates the hydrostatic pressure anomalies in the spring capture of
15 'Wetтинquelle', Bad Brambach and the seismicity of 2000 and 2008. The short single failures in
16 the pressure curves are due to regular gas sampling at the gas tap on the top of the spring
17 capture. In 2000, one anomaly started 25 days before the earthquake period. It is characterised
18 by high frequency fluctuations of around ± 1.5 cm and a duration of 15 days, superimposed by
19 a 1 cm increase of the total pressure, compared with the long-term pre-seismic background .

20 The normal pressure level was reached again 12–13 days after the beginning of the
21 swarmquake series. In 2008, two pressure anomalies were recorded: 16 days before a small
22 swarm and 36 days before the main seismic period in the Nový Kostel zone. They lasted 5 and
23 6 days with water level maxima between 2.8 and 2.0 cm above the normal long-term
24 background level, respectively.

25

1 Fig. 3

2

3 As at the Wettinguelle spring, the groundwater level (GWL) curve at gauge well VL4T shows
4 only one pre-seismic anomaly (Fig. 4, 5) in 2000. The water level rise started 30 days before the
5 earthquakes. Within the bounds of accuracy, this may be considered as the same precursory
6 time as derived from the Wettinguelle hydrostatic pressure curve (Fig. 3). The calculated GWL
7 difference line (VL4T minus GW1) reached a maximum of +25 cm above the long-term
8 background immediately in the beginning of the seismic period. Short-term peaks in the GWL
9 difference curve are caused by slightly shorter response times after strong rainfall and a more
10 sensitive reaction to air pressure variations (possibly higher concentrations of dissolved CO₂) at
11 the VL4T well compared to GW1. Twelve days after the maximum, the GWL differences
12 decreased below the pre-seismic threshold and reached a minimum of – 7 cm within a 20 days
13 period of relatively low seismicity. Altogether, the anomalous groundwater regime at gauge
14 well VL4T lasted about 12 weeks, from July 28 to Oct. 18, 2000. After that, no further
15 significant GWL anomalies occurred by the end of April 2001. By the middle of January 2001,
16 the strongest seismicity was effectively finished.

17

18 Fig. 4

19 Fig. 5

20

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

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

5

6 Fig. 6

7

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

17

18 Fig. 7

19

20 **Discussion**

21

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

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

15 Table 2 gives an overview about the characteristics of the swarmquake periods 2000-01 and
16 2008-09 regarding seismicity and seismohydrological anomalies. In both cases, real
17 hydrological precursors were registered. 'Real' means that the anomaly-generating processes in
18 the depth *and* the appearance of the anomaly at the surface occurred before the seismic events.
19 Anomalies appearing after the beginning of seismicity are normally denoted as 'co-seismic'
20 effects, although they may have been generated absolutely before the earthquake period. In
21 such a case, a pre-seismic anomaly origin is practically impossible to verify at the surface
22 because it cannot be separated from possible hydrological effects released by the earthquakes
23 themselves due to dynamic stress (e. g. opening of cracks due to shocks).

24

25 Tab. 2

1

2 Generally, hydrological earthquake precursors may arise in following ways:

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

9 B) A primary pressure increase in the fluid system (with the respective surface effects
10 mentioned before) may decrease the friction between fault planes. Together with a weakening
11 of faults by aggressive fluids (producing alteration effects), these processes may decrease the
12 critical failure condition along the faults resulting in a triggering of earthquakes (Parotidis et al.,
13 2005; Koch et al., 2008; Heinicke et al., 2009).

14 Both scenarios imply a sufficient accumulation of tectonic stress to initiate seismicity.

15 Otherwise, hydrological anomalies at the surface may also occur without subsequent seismicity.

16 In the case of the hydrological anomalies observed at Bad Brambach, a decision about the
17 priority of one of these two main processes is difficult. The GWL anomaly one month before
18 the 2000 earthquakes and the following GWL decrease below the pre-seismic level suggest
19 process A. However, even in this seismic period, several authors detected clues for an
20 earthquake triggering by fluids. Parotidis et al. (2005) tested the hypothesis about the triggering
21 of NW Bohemian earthquakes by ascending magmatic fluids and identified pore pressure
22 diffusion to be responsible for the spatiotemporal clustering and the migration of the seismic
23 events (see also Fig. 2). In contrast, Horálek and Fischer (2008) emphasized that the pore
24 pressure of crustal fluids is decisive for bringing the faults from a subcritical to a critical state.
25 This would mean that fluid triggering could occur only in the initial phase of the 2000-2001

1 swarm.

2 Huenges et al. (1997) proposed the existence of a highly permeable fracture system up to the
3 9.1 km deep bottom of the German Deep Drilling borehole (KTB), which could enable fluid
4 migration at relatively low overpressures. This depth range corresponds to the mean focal depth
5 of the Nový Kostel earthquake swarms. Injection experiments at the KTB between 2004 and
6 2005 showed that fluid migration into the crustal fault system induced micro-seismicity
7 adjacent to the borehole triggered by pore pressure perturbations of only 0.01–1.0 bar at
8 hypocentral depths (Shapiro et al., 2006). Moreover, a vertical Earth's surface uplift of 3.1 mm
9 was caused by pore pressure changes of more than 11 MPa close to the KTB injection borehole
10 (Jahr et al., 2008).

11 The 2008-09 seismic events at the Nový Kostel epicentral area were accompanied by an
12 anomalous pressure in the deep-reaching mineral aquifer system for about 8 months. Contrary
13 to the 2000 period, where no appreciable earthquakes occurred after January 2001, low but
14 frequent seismic activity in 2008-09 continued to the end of April 2009, after the maximum
15 energy release in October. Therefore, it may be inferred that fluid triggering was the crucial
16 process for initiation and continuation of the 2008-09 swarmquake series. Only from May 2009
17 did the anomalous groundwater level in the deep gauge well VL4T decrease again, reaching its
18 pre-seismic level in August 2009 (Fig. 6). The long-lasting anomalous fluid pressure of
19 2008-09 could also emphasize the continuation of the long-term gas flow increase observed at
20 mineral springs and mofettes in the region since 1998 (Koch et al., 2008). This quantitative
21 signal was accompanied by a rise of the $^3\text{He}/^4\text{He}$ ratio of ascending gases, an evidence for a
22 possible increase of magmatic activity beneath the Cheb Basin (Weise et al., 2001; Bräuer et al.,
23 2009).

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

1 1, 2). During the 2000 and 2008 main seismic periods, the hypocentres migrated from south of
2 the epicentral area and depths of 11–11.5 km to the north and upward to about 7 km depth. In
3 2000, the hypocentres remained in the north but their focal depths moved down to 10.5–12 km
4 only after the end of March 2001 (Fig. 2A). In 2008, the hypocentres declined from 10.5 to 12.5
5 km depth between January and April. Almost at the same time, they migrated southward (Fig.
6 2B). Taking into account that pore pressure diffusion can play an important role for the spatial
7 and temporal behaviour of swarmquake foci (Shapiro et al., 2006), the different migration
8 patterns of the hypocentres between the 2000-01 and 2008-09 may be related to the different
9 shapes and durations of the observed fluid pressure anomalies. Both the 2000 and the 2008
10 anomalies (Wetтинquelle and GWL) started between 25 and 36 days before the onset of the
11 main seismic period, and the VL4T groundwater pressure ascended to a maximum of 25 cm
12 above the long-term pre-seismic background level. This suggests similar earthquake initiating
13 processes, independently if stress accumulation or fluid triggering was the primary factor. For
14 2008, it may be assumed that the stress drop was complete by the end of October, the month
15 with a concentrated high release of seismic energy. Interestingly, the following phase of low
16 seismicity (middle of November by end of December 2008) was accompanied by a horizontal
17 segment of the GWL difference curve (Fig. 4, 6). This means that the earthquake-sensitive
18 VL4T groundwater table persisted at a high but relatively constant level. The following GWL
19 difference increase was accompanied by a period of frequent seismicity but low seismic energy
20 release. Having presupposed that the stress drop was predominantly over by the end of October
21 2008, the 'seismic restart' in January 2009 may be attributed to fluid triggering processes under
22 reduced friction conditions along the fault plane. Possibly, this process occurred more or less
23 intensively until the end of April 2009. Further, the higher fluid influence for earthquake
24 triggering might also be responsible for the differences in the migration patterns of the 2008-09
25 hypocentres, compared to 2000-01 (Fig. 2, Tab. 2).

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

18

19 **Conclusions**

20

21 In spite of their similar spatial distribution in both seismic periods, the epicentres of the Nový
22 Kostel earthquakes migrated differently through time: S→N in 2000-01 and S→N→S in
23 2008-09. In both cases, the shallowest focal depths were observed when the epicentres reached
24 their most northern positions.

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

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

20

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22

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3

4

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15
16

17 **Figure captions**

18

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

24

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

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

7

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

12

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

18

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

24

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

1 Brambach and seismicity in the Nový Kostel area from July 2008 to August 2009. Two
2 anomalies were recorded in 2008: 12 days before a small event and 26 days before the main
3 seismic period. The second anomaly lasted ~74 days accompanying the main seismic period.
4 After a short break at the end of December (constant GWL difference), the seismicity continued
5 and the GWL difference increased again steadily by the middle of April 2009. Only from the
6 end of May 2009, the groundwater level differences decreased again reaching the 2008
7 pre-seismic background level approximately at the end of August 2009. The high flood effect in
8 2009 occurred due to a different response of the gauges VL4T and GW1 to a ice swells in the
9 neighbouring creek.

10

11 **Figure 7:** Monthly averages of groundwater levels and GWL differences at Bad Brambach
12 versus the number of earthquakes with magnitudes > 1 at Nový Kostel between May 2000 and
13 August 2009. The number of earthquakes in 2008 (374, B) is approximately a half as against
14 2000 (742, A). But, in 2008, the total seismic energy was practically released within one month.
15 The periodic seasonal fluctuations of the GWL differences are the result of higher water
16 retention in the aquifer opened up by gauge well VL4T. The GWL difference minima 1 and 2
17 were caused by groundwater lowering due to underground works near the VL4 gauge.

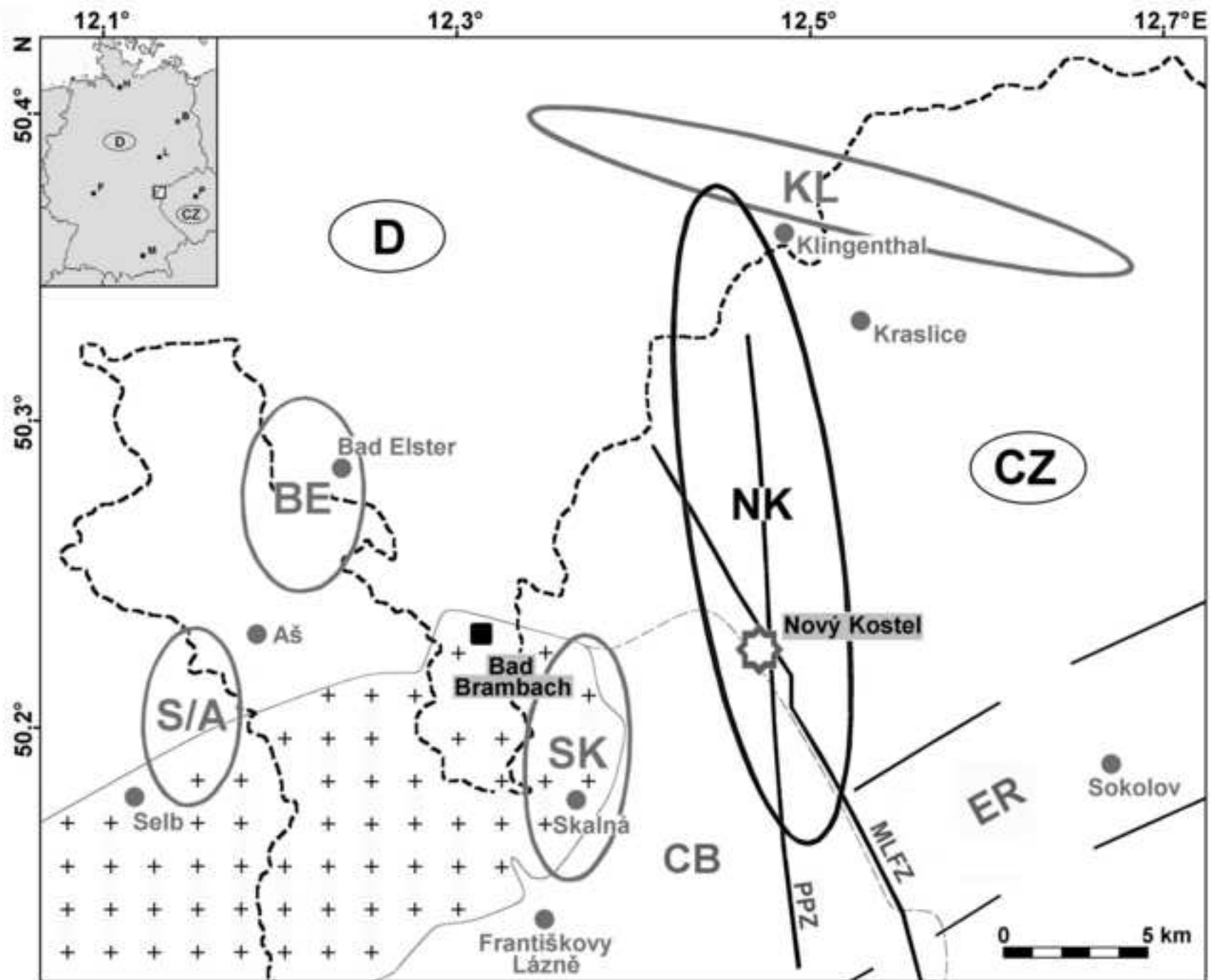
Table 1: Applied basic data and their temporal resolution

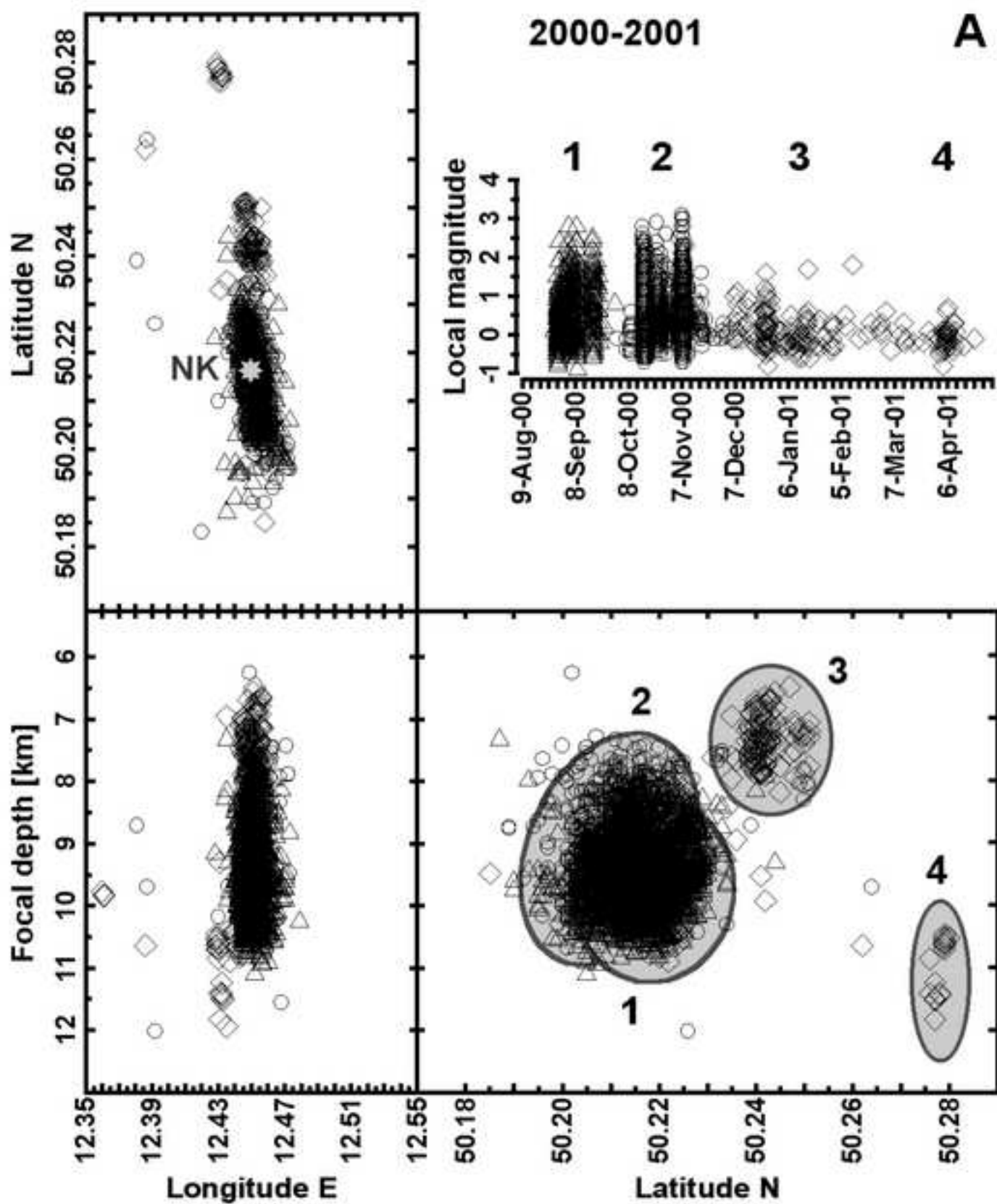
Type of data	Unit	Temporal resolution	Data source
seismic data	---	1 sec	WEBNET GFU Prague http://www.ig.cas.cz Fischer and Horálek, 2003 Horálek et al., 2009
hydrostatic pressure 'Wetinquelle' spring	m (above pressure probe)	10 min	own measurements
groundwater levels gauges VL4T, GW1	m (above sea level)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

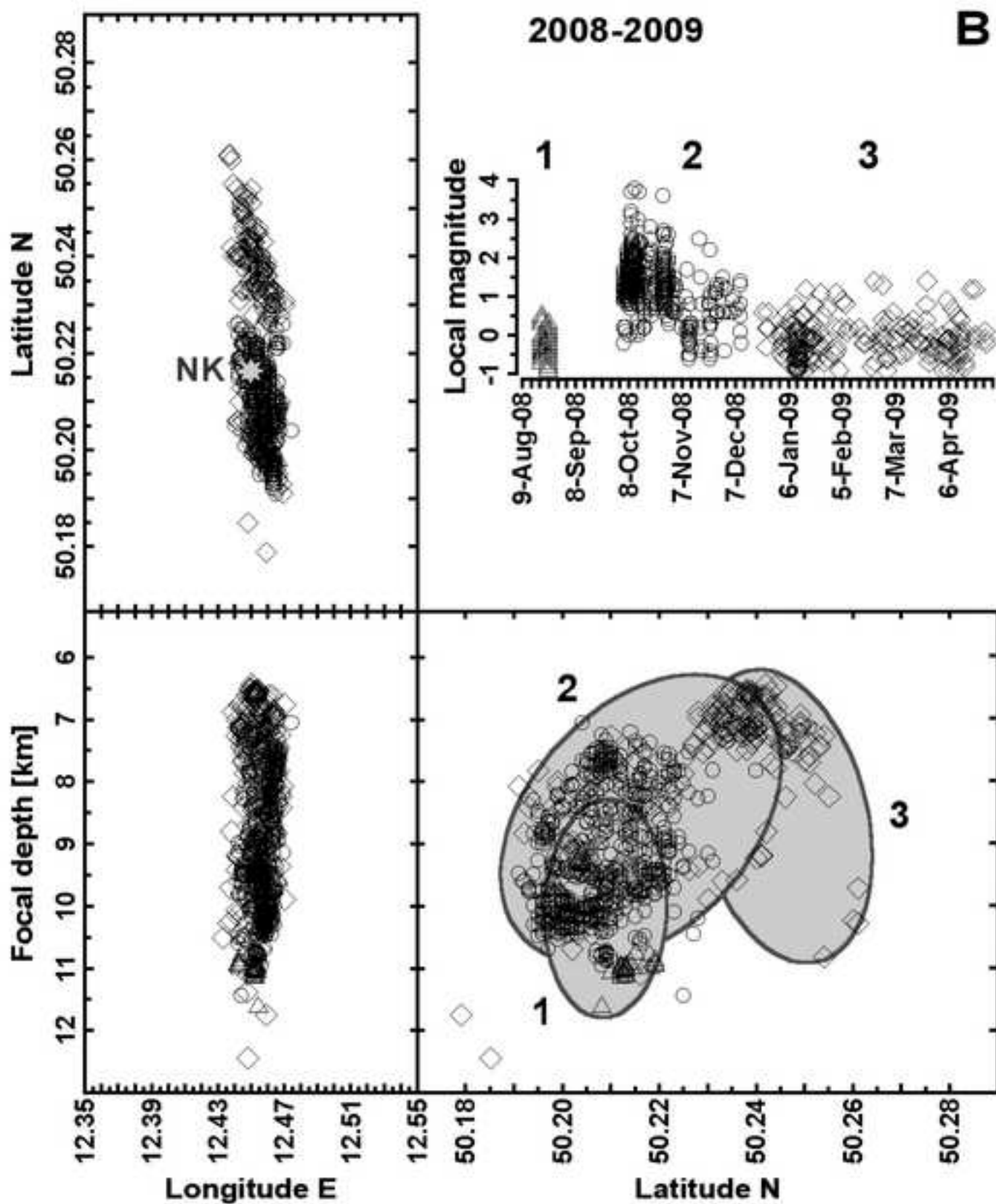
Table 2: Comparison of seismicity and anomalies between the earthquake periods 2000-01 and 2008-09

	2000-2001	2008-2009
Seismicity	<ul style="list-style-type: none"> • 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) $3.0 \leq M_L \leq 3.3$: 5 $M_L > 3.3$: 0 (max. 3.3)	374 events with $M_L > 1$ within 1 month (October 2008) $3.0 \leq M_L \leq 3.3$: 3 $M_L > 3.3$: 6 (max. 3.8)
Anomalies	1 pressure anomaly 'Wetтинquelle' 25 days before the main events	2 pressure anomalies 'Wetтинquelle' 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 (± 1 cm) 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

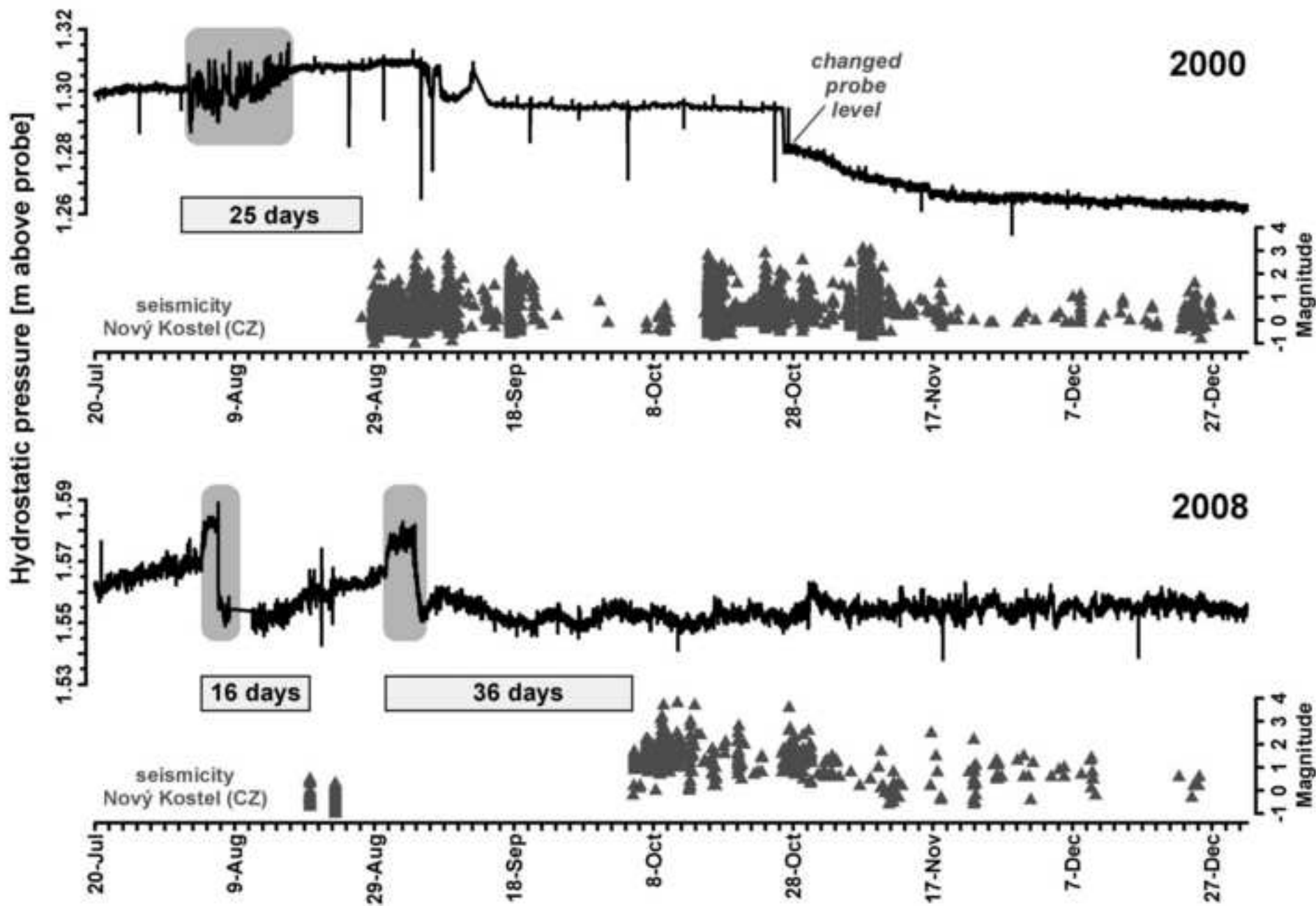
Figure



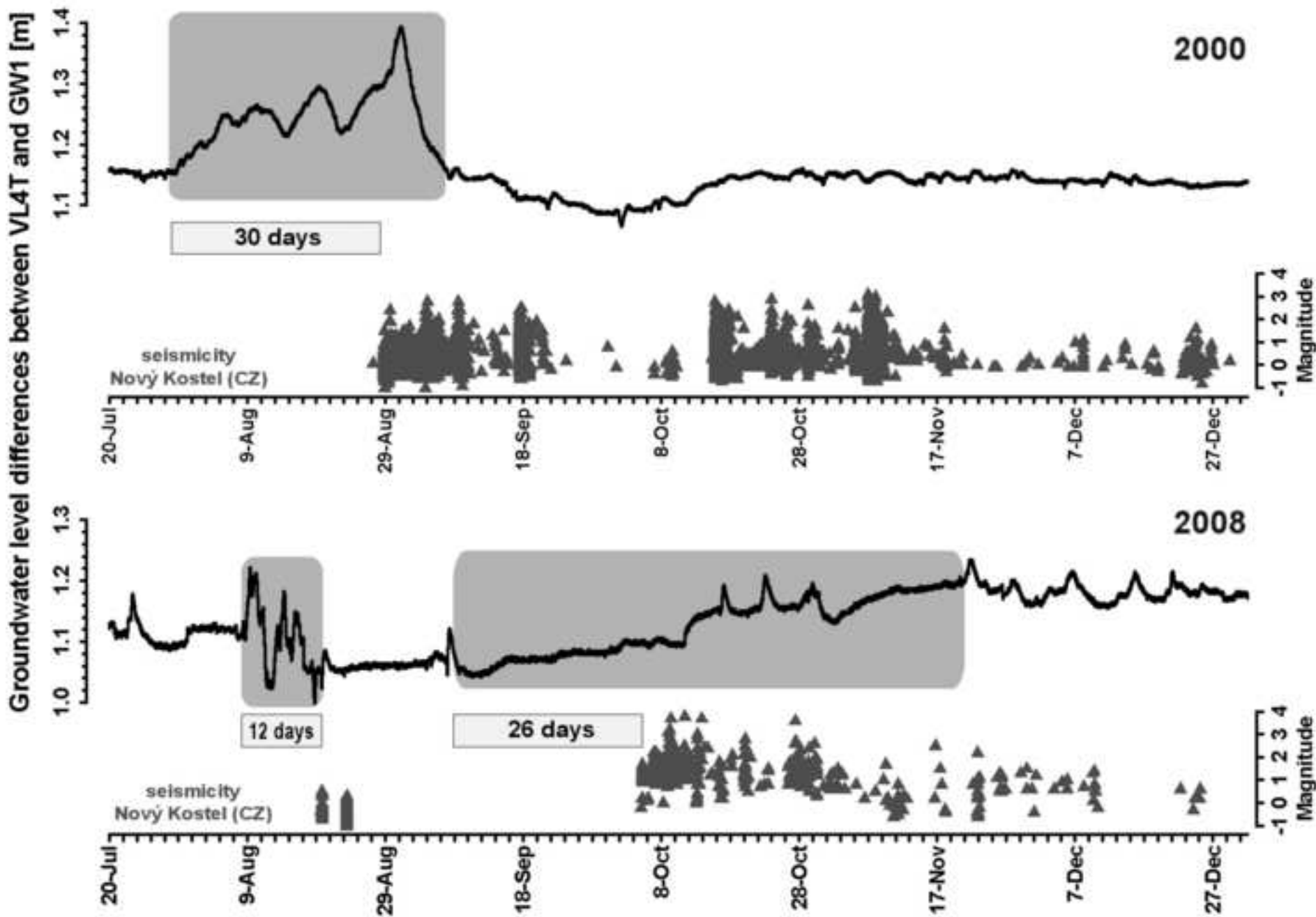




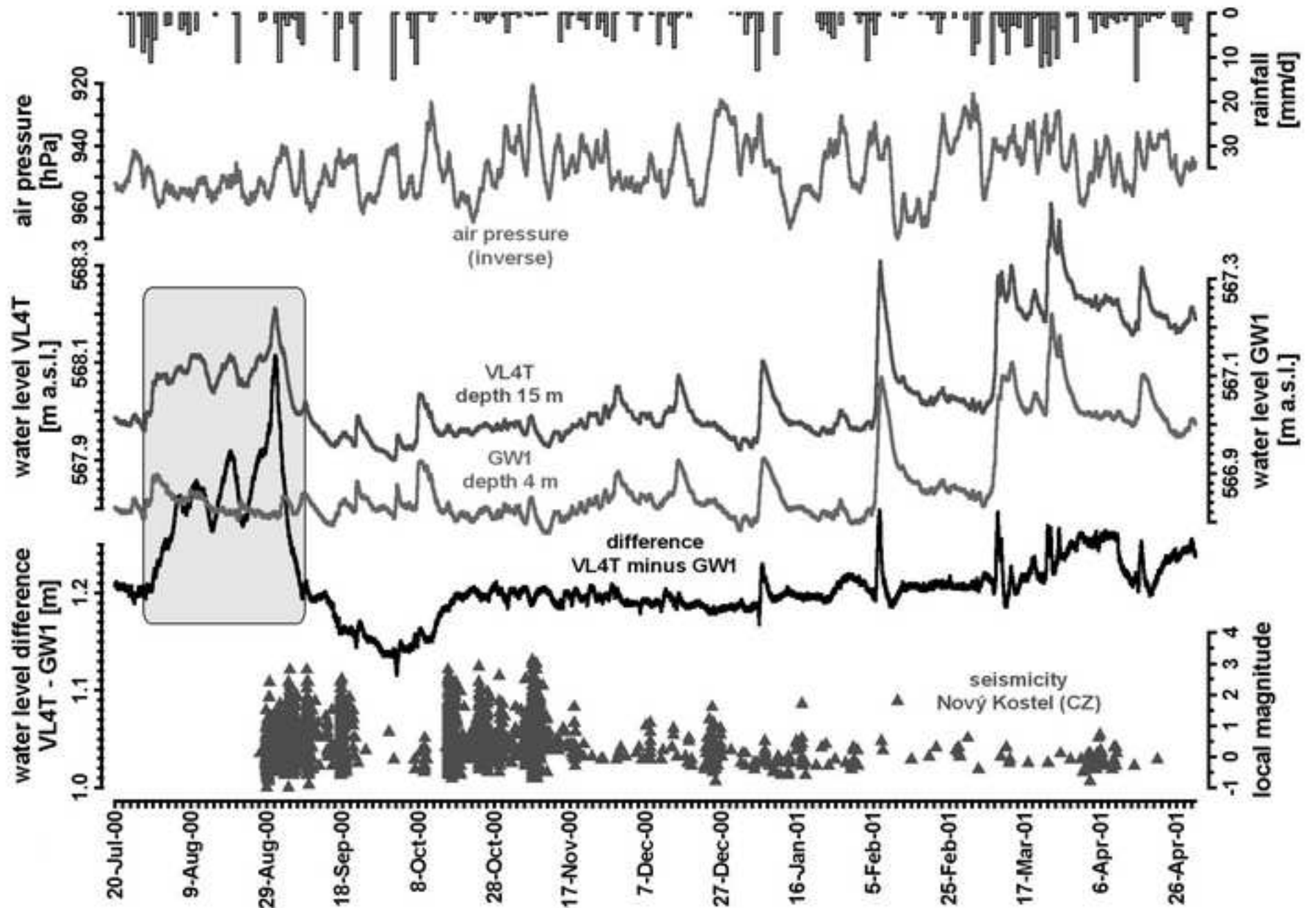
Figure



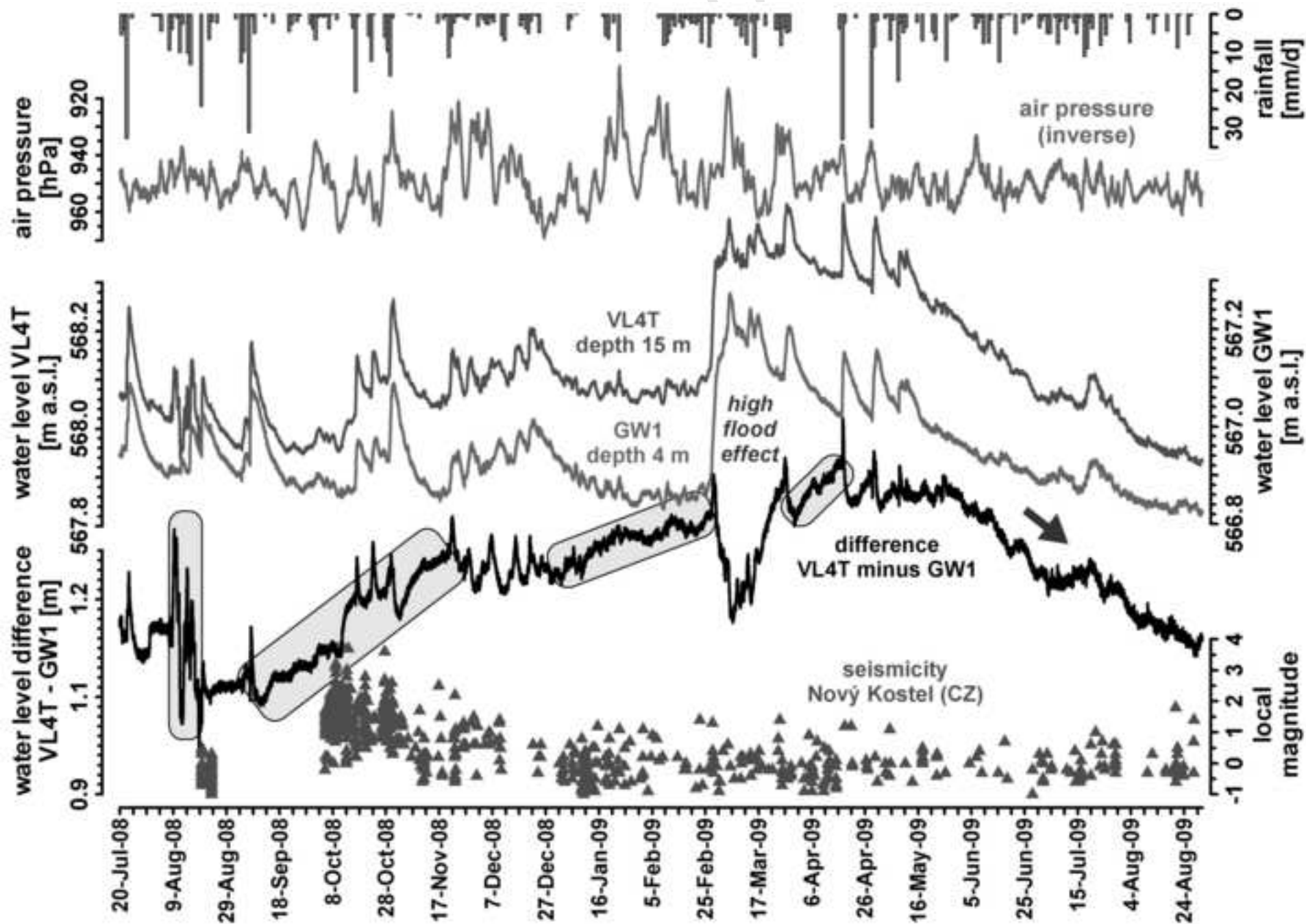
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Figure



Figure



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