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Seismically induced variations in Mariánské Lázně fault gas composition in the NW Bohemian swarm quake region, Czech Republic — A continuous gas monitoring

Falk H. Weinlich [a],*, Eckhard Faber [a], Alena Boušková [b], Josef Horálek [b], Manfred Teschner [a], Jürgen Poggenburg [a]

[a] *Federal Institute for Geoscience and Natural Resources (BGR), Hannover, Germany*
[b] *Geophysical Institute, Academy of Science of the Czech Republic (GFU), Praha, Czech Republic*

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Abstract

A continuously operated gas monitoring station was emplaced within the epicentral area of the NW Bohemian swarm earthquakes overlying directly the active Mariánské Lázně fault. The recordings of 8-month continuous monitoring period are presented. The variations in radon concentrations are similarly to variations in CO_2, i.e. CO_2 is considered to be the carrier gas for radon. Very small diurnal variations in gas concentration are caused by the earth tides, as daily variations in meteorological conditions cannot explain a short daily minimum at midday times. Sudden changes in gas concentration, which clearly exceed these diurnal variations occur and are always linked with seismic activities. Decreased gas concentration may indicate compression resulting in reduced fault permeability as is implied by negative peaks following local earthquake swarms. A sudden increase in CO_2 and Rn concentration may indicate an increased fault permeability caused by stress redistribution, giving rise to opening of migration pathways. This implies a repeatedly sudden rise in gas concentration before local earthquake swarms. Several variations in gas concentration were monitored linked with remote earthquakes of ground motion amplitudes >1 μm. These seismic events are accompanied by an interference of the diurnal gas concentration–stress-cycle along the Mariánské Lázně fault. However, if shocks of remote earthquake can alter properties of the migrating fluids or the fault properties it can be suggested that these are able to trigger local seismicity, as indicated in the case of the Slovenia earthquake on 12th July 2004.

Keywords: Gas monitoring; Earthquake swarm; Rn; CO_2; Coseismic anomalies; Stress

1. Introduction

Changes in the chemical composition of the ascending fluids are linked with seismic activities and could be used as earthquake precursors providing the mechanisms are well understood. These changes can involve both, water (Tsunogai and Wakita, 1995; Favara et al., 2001) but by far more the ascending gases in mineral springs and soil gases along faults. These observations comprise changes in the contents of He (Reimer, 1990), H_2 (Satake et al., 1985; Sato et al., 1986; Sugisaki and Sugiura, 1986), the ratios of N_2/Ar, He/Ar and CH_4/Ar (Sugisaki, 1978; Kawabe, 1984;

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* Corresponding author. Present address: D-39245 Gommern, Magdeburger Chaussee 4, Germany. Tel.: +49 39200 50888.
E-mail address: falkweinlich@gmx.de (F.H. Weinlich).

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Sugisaki and Sugiura, 1986; Nagamine and Sugisaki, 1991; Ito et al., 1999; Ito, 2000) and mostly Rn (King, 1980; Hauksson and Goddart, 1981; Wakita et al., 1988; Woith and Pekdeger, 1992; Heinicke and Koch, 2000). The above mentioned investigations got additional importance as a link between earthquakes and crustal fluid migrating along faults was revealed (Špičák and Horálek, 2001; Audin et al., 2002) based on observations of earthquakes triggered by fluid injections (Healy et al., 1968; Zoback and Harjes, 1997; Seeber et al., 2004).

Within the framework of this research, two distinct investigation methods were described in the literature: monitoring of spring gases (e.g. Sugisaki and Sugiura, 1986) and soil gases (e.g. Chyi et al., 2003). Spring gases as opposite to soil gases have a considerable advantage as the former contain smaller proportions of air (Sugisaki et al., 1980). On the other hand, their disadvantage may lie in the fact, that very small gas proportions released during seismic activities can be entirely masked by the higher gas fluxes of usually CO_2 rich spring gases, which occur generally in the seismic active areas (Irwin and Barnes, 1980). The disadvantage of soil gases is linked with the gas extraction procedure, which often perturbs, with common techniques, the contents and composition in soil gases.

In the technique of soil air monitoring, predominately ^{222}Rn contents were monitored. Less interest is paid to the CO_2 contents as CO_2 is strongly influenced by biogenic activities (Ineson et al., 1998; Raich and Tufekcioglu, 2000; Andrews and Schlesinger, 2001; Maljanen et al., 2002) and meteorological conditions (Duddridge and Grainger, 1998; Toutain and Baubron, 1999; Ouyang and Zheng, 2000) resulting in diurnal and longer-period variations of the CO_2 concentration in soils. Radon concentrations show similar variations (Klusman and Webster, 1981; Koch and Heinicke, 1994; Shi and Xu, 1995; Pinault and Baubron, 1996, 1997) as it is the case with CO_2. Due to the low partial pressure Rn requires CO_2 as a carrier gas for transport (Durrance and Gregory, 1990; Ball et al., 1991). Thus, variations in radon are dependent on the CO_2 concentration and the diurnal and long-term variations in Rn concentration are not distinguishable from those of CO_2.

Toutain and Baubron (1999) reviewed and compared gas geochemical methods for earthquake prediction. The major uncertainties comparing effects of seismic events and geochemical changes in gases are often the short monitoring period, followed by a very low sampling frequency and difficulties regarding correlation of these geochemical signals with specific earthquakes.

In order to avoid above complications, for this study new equipment based on gas sensor technique (Faber et al., 2003b) designed for a continuous and long-term monitoring was utilised in the West Bohemia/Vogtland earthquake swarm area. In combination with a radon counter, temperature and pressure sensors, the monitoring system determines CO_2 contents, Rn counts, bottom-hole temperature and air pressure in 30 s intervals. Results of the first 8-month monitoring period are presented.

The station was emplaced within the epicentral area of the West Bohemian earthquakes directly overlying the active Mariánské Lázně fault. This site is in close vicinity to the seismic station Nový Kostel (NKC) operated by the Czech Academy of Science (WEBNET, e.g. Horálek et al., 2000a). The aim was to investigate the relation between seismicity and fluid (gas) transport along the Mariánské Lázně fault. In order to minimise the influence of biological processes on gas composition, gas extraction is carried out in a cellar of a building 2.5 m below the ground in a ca. half-meter deep borehole.

2. Geological settings

2.1. Geological framework

The West Bohemia/Vogtland earthquake swarm region is located in the western part of the Eger (Ohře) Rift covering an area of about 300 km^2 (Fig. 1).

The Eger Rift belongs to the European Cenozoic rift system (Ziegler, 1992). The postalpine crustal extension gave rise in the late Eocene–Oligocene to the sedimentation within the WSW–ENE striking North Bohemian Tertiary Basins (Malkovský, 1980, 1987). In a later tectonic phase, NNW–SSE striking deep faults were reactivated from Pliocene to Pleistocene and present (Špičáková et al., 2000). The tectonic evolution was always associated with an extensive alkaline basaltic volcanism taking place in several series (Ulrych et al., 2002): Oligocene–Miocene volcanic series (30.6–15.5 Ma) in the whole western Eger Rift, Middle to Late Miocene series (16.5–6.5 Ma) south of the Sokolov Basin in the Slavkovský Les and Quaternary olivine nephelinite–olivine melilitite volcanism (0.43–0.11 Ma) formed two Quaternary explosive volcanoes (Komorní Hůrka, Železná Hůrka, cf. Fig. 1) with lava flow and scoria occurring at the junction of the Eger Rift main faults and the Aš-Tachov Fault (Cheb–Domažlice Graben). The main tectonic structure of the ENE–WSW striking Eger Rift comprises the Krušné hory deep fault in the north (Erzgebirgsabbruch), the Central Fault also in the north, dipping to south, and the Litoměřice deep fault in the south, dipping to the north (Kopecký, 1979) forming a distinctive Y-structure. This structure is intersected by younger NNW–SSE striking deep faults (Horní Slavkov, Mariánské Lázně and Aš-Tachov fault), displacing the Litoměřice

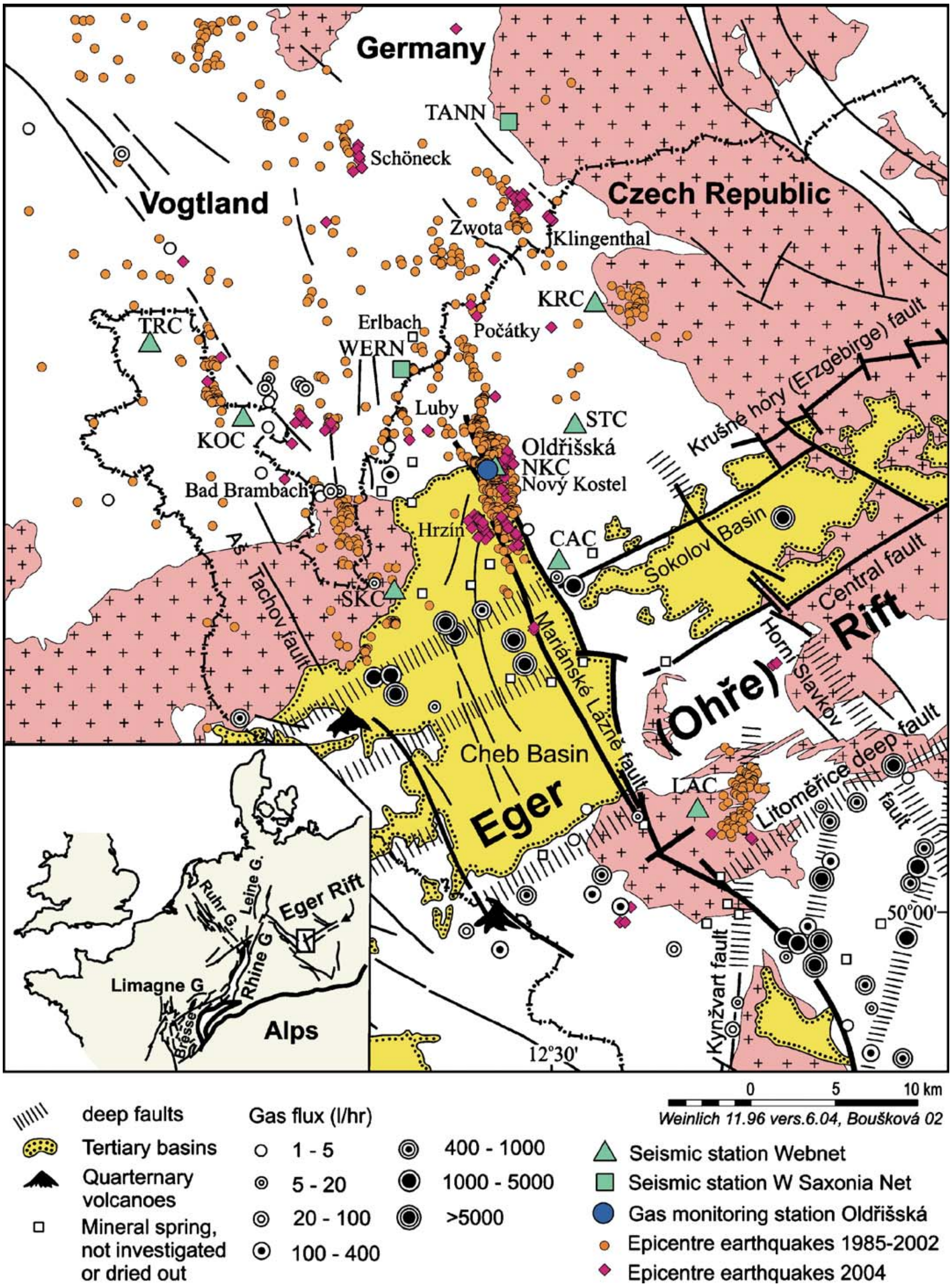

Fig. 1. Distribution pattern of swarm earthquakes and gas flux in the western Eger (Ohře) Rift. Swarm earthquakes cluster in different focal areas. Nový Kostel (NKC) is the area with highest seismic activity. The swarm earthquakes usually occur in areas with low gas (mantle CO_2) flux. This may indicate a link between unimpeded fluid migration due to high fault permeability and seismic activities caused by diminished fluid migration resulting in an increase of fluid pressure. Seismic stations: NKC — Nový Kostel, WERN — Wernitzgrün, TANN — Tannenbergsthal, Quaternary volcanoes; north: Komorní Hůrka, south: Železná Hůrka.

deep fault stepwise to the north and narrowing the Eger Rift to the west (Weinlich et al., 1998, 2003). The Mariánské Lázně deep fault is morphologically active and forms as an escarpment bounding the east edge of the Cheb Basin and the Cheb–Domažlice Graben in the Mariánské Lázně area. In addition, NNE–SSW striking deep faults are also present (Kynvart fault zone) as well as the nearly N–S trending faults (Šťovíčková, 1980; Bankwitz et al., 2003).

Associated with these tectonic and volcanic evolutions is the recent ascent of CO_2-rich magmatic gases along faults with $\delta^{13}C$-values of −2.5 up to −3‰ as well as the anomalously high proportions of mantle-derived ^3He (O'Nions et al., 1989; Weinlich et al., 1999). The gas flux distribution depicts the tectonic structure. The deep-seated Y-structure of the Eger Rift splits the ascending magmatic gases forming separate gas release centres in the Cheb Basin and in the Mariánské Lázně area (Weinlich et al., 1998). The mantle CO_2 leaches cations from the adjacent rocks and forms the HCO_3 waters in West Bohemia (Pačes, 1972). The HCO_3 formation results in an isotopic fractionation of CO_2 (Wendt, 1968). Since ^{13}C is preferred fixed in the HCO_3^- ion with a fractionation factor $\varepsilon_{\mathrm{HCO3\text{-}gas}}$ of about 10‰ at 10 °C (Mook et al., 1974; Zhang et al., 1995), the remaining CO_2 in the gas phase becomes isotopically lighter. This process is mirrored in the distribution pattern of the magmatic gases in NW Bohemia. In areas with high gas flux CO_2 is dominated by $\delta^{13}C$-values of −2.5 up to −3‰ whereas in the margin areas with low gas fluxes isotopically lighter, fractionated CO_2 is predominant with $\delta^{13}C$-values of −6 up to −10‰ (Weinlich et al., 1999).

Recent earthquake swarms are still accompanying these geodynamic activities. Earthquake swarms are sequences of numerous small seismic events, which cluster distinctively in a small area. These earthquake swarms reoccur periodically with magnitudes of predominantly of $M_L < 3.5$ at depths below 4 km, and in exception with magnitudes of $M_L > 4.5$. The most prominent swarms were reported in 1770/71, 1824, 1896/97, 1903, 1908 ($M_{\mathrm{Lmax}} \approx 5.0$), 1985/86 ($M_{\mathrm{Lmax}} = 4.6$), 1997 ($M_{\mathrm{Lmax}} = 3.0$), 2000 ($M_{\mathrm{Lmax}} \leq 3.4$) (Knett, 1910; Kárnik et al., 1957; Grünthal, 1988; Grünthal et al., 1990; Fischer and Horálek, 2003).

The majority of these most micro-seismic events are concentrated in several epicentral zones (Fig. 1), whereas 90% of the seismic events are focused in the Nový Kostel area (Horálek et al., 2000b) along the 350° striking Nový Kostel–Počátky–Zwota line (Havíř, 2000), intersecting the Mariánské Lázně fault at Nový Kostel. This fault is still active as clearly proven by vertical movements (Mrlina, 2000). Changes in the state of stress induced by fault movements or seismic activities can affect the gas migration. In response, changes in the gas concentrations can reveal changes in state of stress caused by seismic activities.

2.2. Local geological situation of the monitoring site

The gas monitoring station was emplaced in Oldřišská village located within the epicentral swarm earthquake area of Nový Kostel (Fig. 2), in a distance of about 700 m SSW from the seismic station Nový Kostel. The location of the gas monitoring station was chosen in accordance with the record of seismic events documented from 1985–2001 (Fischer and Horálek, 2003).

The Mariánské Lázně fault forms at Oldřišská a steep 40–50 m high escarpment bounding the western edge of the Cheb Basin. In addition, the course of the Mariánské Lázně fault was verified by Georadar measurements (Hubatka et al., 2004) (Fig. 2).

Several gas-bearing mineral springs located along Mariánské Lázně fault zone (in the Cheb Basin; Horní Pochlovice, Dolní Častkov, Hluboká and Kopanina, from S to N, Fig. 1) reveal fluid migration along these fault system. The ascending gases are CO_2-rich and exhibit high ^3He contents, R/R_a values from 2.6 to 4.3, and $\delta^{13}C_{CO_2}$ values of −1.9 and −2.4‰ indicating a strong mantle signature (Weinlich et al., 1999). At Nový Kostel the occurrence of CO_2-rich waters (2200 mg CO_2/l in water of the Pliocene) was also confirmed by a borehole (H15) (Kolářová, 1965). A little mineral spring located in the immediate vicinity of the monitoring building in the Opatovský stream valley exhibits fluid migration even at the Oldřišská site along Mariánské Lázně fault system. The water contains 380 mg/l TDS and is of Fe–Ca–Mg–HCO_3–(Cl–SO_4) type, which demonstrates an input of magmatic CO_2.

Apart from all these indications, a measured $\delta^{13}C$ value of −4.8‰ in the extracted gas CO_2 at the monitoring station proofs the ascent of magmatic CO_2 and therefore the successful emplacement of the monitoring station directly along the Mariánské Lázně deep fault.

North of Nový Kostel fluid migration is evidently impeded by silicification of the fault plane as it is indicated by the presence of numerous chunks of vein quartz in Oldřišská and by a Quartz–Hg mineralisation in Horní Luby (Chrt and Strnad, 1961). North of Oldřišská there are no further mineral springs of Ca–HCO_3 type (Kolářová and Myslil, 1979). Approximately 10 km to the NNW of Nový Kostel, in Erlbach a mineral spring of NaCl type occurred with about 10,000 mg/l TDS (Göhler, 1928). This mineralisation

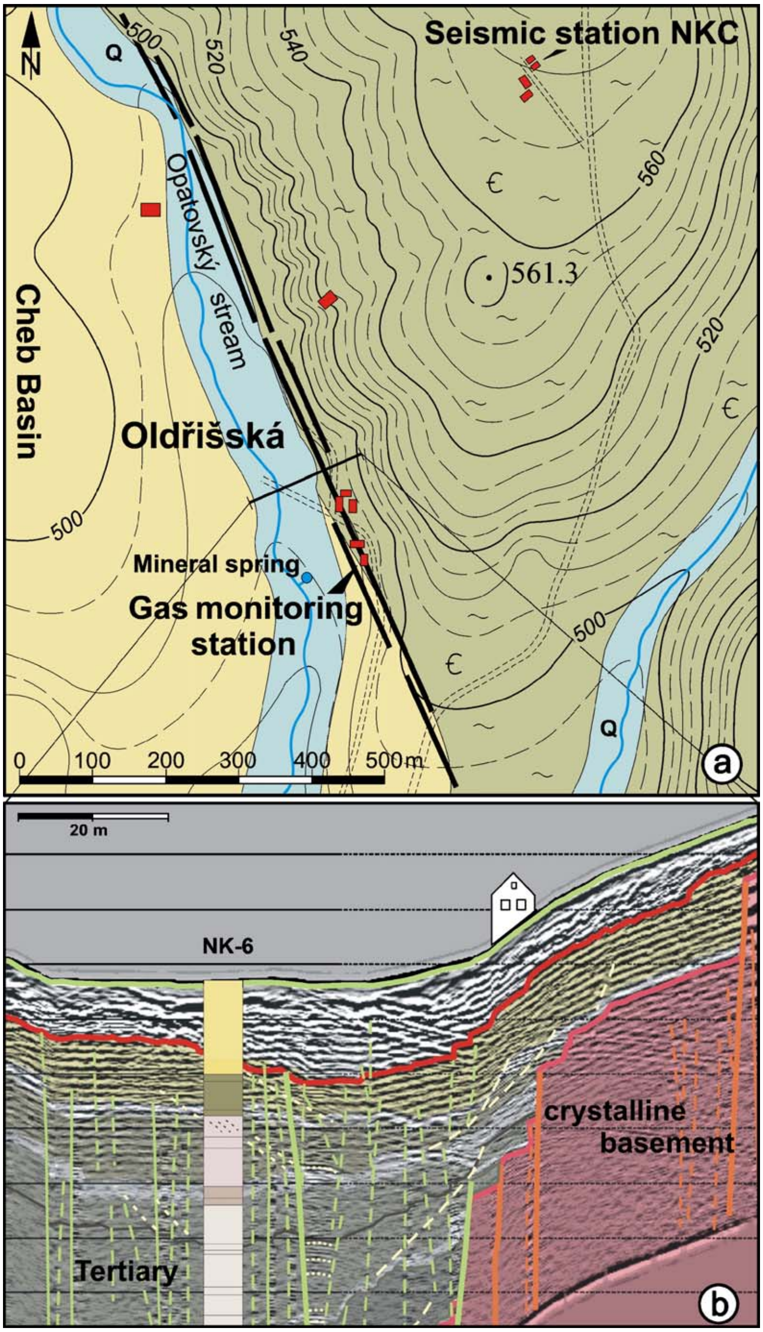

Fig. 2. Detailed map of the location of the gas monitoring station at Oldřišská, Nový Kostel, on the escarpment of the Mariánské Lázně fault (a) with the Georadar profile (Hubatka et al., 2004) of this location (b). The migration of deep-seated, magmatic CO_2 is evident by a $\delta^{13}C_{CO_2}$ value of −4.8‰ in the extracted gas and the occurrence of a mineral spring of Fe–Ca–Mg–HCO_3–(Cl–SO_4) type. Є — Cambrian phyllite of Erzgebirge/Krušné hory crystalline, Cheb Basin — Pliocene below Pleistocene, Q — Holocene.

type indicates Zechstein derived NaCl waters encountered in the north, i.e. in the Vogtland and western Saxony (Altensalz, Zwickau; Carlé, 1966). It is thus not comparable with the mineral waters of the Cheb Basin, confirming an impeded fluid migration in this area.

3. Experimental setup

In the cellar of a building, a 50 cm deep borehole (5 cm diameter) was drilled down though a half-meter scree (weathered phyllite) into the in situ bedrock. A permeable tube (Gut et al., 1998) was lowered down into this hole. Gas from the borehole diffuses into the membrane tube and then flows to a trap where water/moisture is fixed by $CaCl_2$. Then the gas passes a dust filter, flows to the CO_2 and Rn sensors before it circulates back to the membrane driven by a pump (Fig. 3). For CO_2 determination a NDIR sensor (model AGM10, Sensors Europe, Ratingen, Germany), and for radon a Pylon AB 5 system equipped with a Lucas cell are used.

Supplementary, external parameters such as temperature in the borehole and atmospheric pressure are measured by a thermocouple and by a piezoresistive transducer, respectively. The analogue voltages are digitised by A/D converters while the Rn pulses are counted. The container with the sensors and the electronic system is thermally isolated to protect against the low winter temperatures.

A computer with a software developed by BGR (Faber et al., 2000, 2003a) is used in Oldřišská to run the system and to store data every 30 s. The system is connected to a mobile phone to transfer daily data and to setup parameters if required.

Gas for isotope analyses was extracted via a T-piece with rubber septum close to the membrane.

Information on air temperature, atmospheric humidity and precipitation was available from meteorological stations at Luby and Cheb of the Czech Meteorological Survey and from a station at Bad Brambach owned by the Bad Brambacher Mineralquellen GmbH.

Following the emplacement of the Oldřišská monitoring station in November 2003 and after an initial optimising phase, reliable and continuous gas monitoring started on the 1st February 2004 (Fig. 4).

4. The monitored data

4.1. Origin and transport of CO_2 and radon

From February to September 2004 CO_2 values range on the average between 0.2 to 0.4 vol.%. These CO_2 values are essentially higher then those in the atmosphere, however, lower than the typical levels of biogenic CO_2 in soils, which commonly range between 2 and 6 vol.% during the growing season, depending on the type of vegetation (Buyanovsky and Wagner, 1983). These small average values monitored at this site indicate the absence of a significant influence of biogenic CO_2.

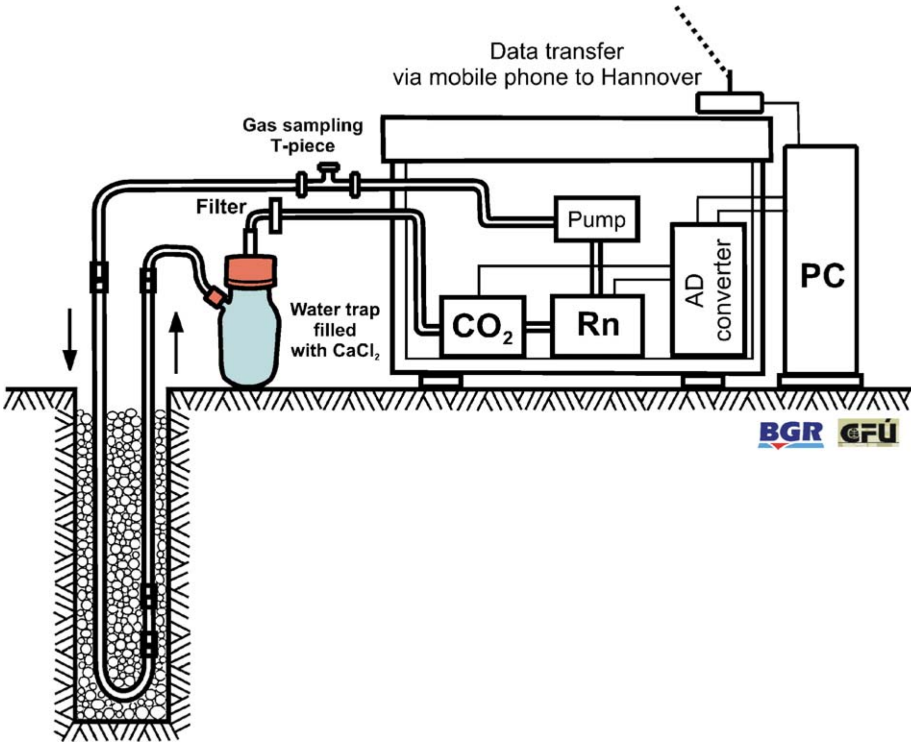

Fig. 3. Monitoring equipment installed in the basement of a building with almost no variation in the daily temperature and air moisture. The monitored parameters (CO_2, Rn, bottom-hole temperature and air pressure) are stored locally as data file and conveyed by mobile phone to Hannover.

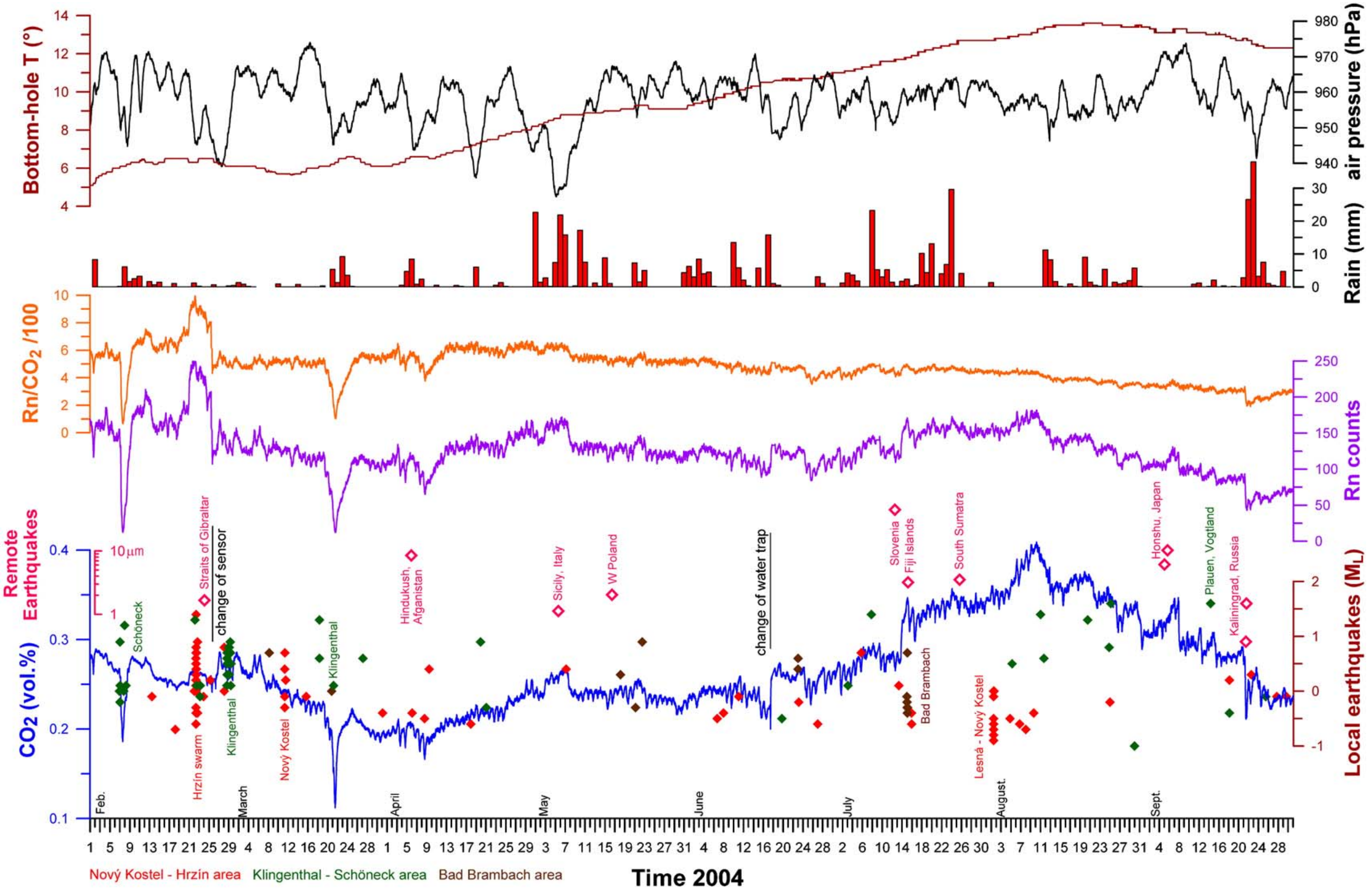

Fig. 4. Plot of the monitored CO_2 and Rn concentration and the meteorological parameters (air pressure, precipitation and bottom-hole temperature at the gas extraction point). From 1st February until the 25th February CO_2 content is corrected due to exchange of CO_2 sensor according to gas analysis. Rn and Rn/CO_2 ratio plotted as running average ($n=51$). Solid diamonds — local earthquakes, open diamonds — all remote earthquakes in this period with amplitudes of ground motion (Z-component) > 1 µm, calculated for Nový Kostel and Wernitzgrün (Sicily, Poland).

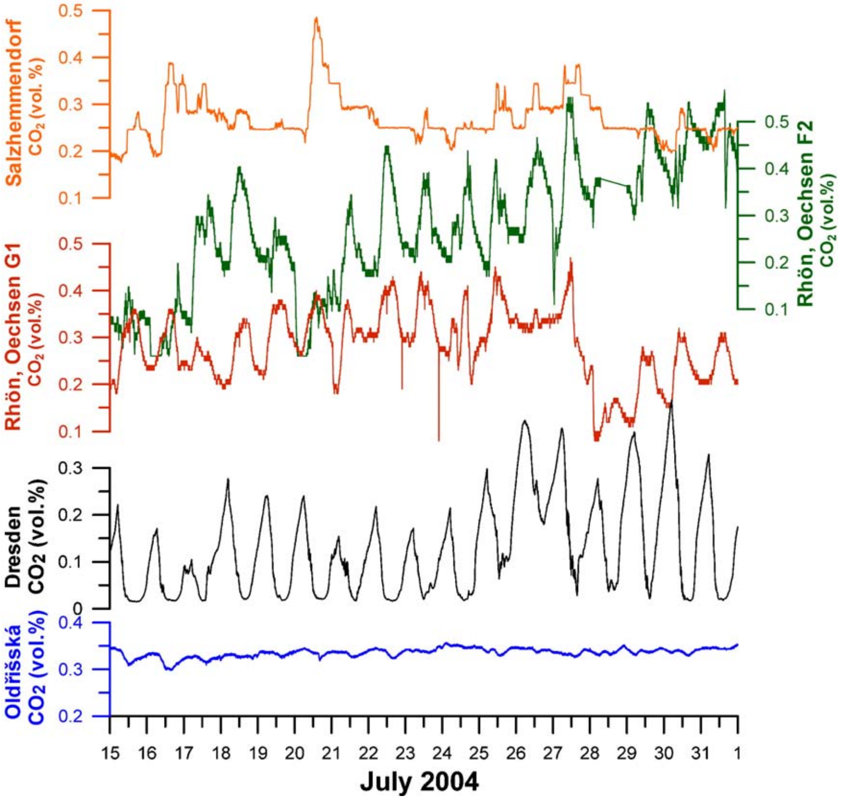

Fig. 5. Comparison of diurnal variations in CO_2 recordings at the monitoring station Oldřišská (gas extracted 2.5 m below ground) with typical diurnal variations recorded at stations with a shallower gas extraction depth, (Salzhemmendorf — 1.2 m, Dresden — 1.5 m, Rhön — 0.8 m).

Measured $\delta^{13}C_{CO_2}$ values range from −4.8 to −9.9‰ in December 2003 showing a strong magmatic signature. From January to June 2004 the $\delta^{13}C_{CO_2}$ values between −13.7 and −18.7‰ may indicate an admixture of biogenic CO_2 (in soils $\delta^{13}C_{CO_2}$ values are between −24 to −30‰, Andrews and Schlesinger, 2001). However, these $\delta^{13}C_{CO_2}$ values associated with low CO_2 concentrations of 0.2 to 0.4 vol.% could point rather towards an entirely fractionated magmatic CO_2 ascending along the Mariánské Lázně fault by HCO_3^- formation (Wendt, 1968; Weinlich, 2005).

The Rn counts range between about 100 and 220 with an average of 150 counts per 30 s (measuring interval). Furthermore, the monitoring records demonstrate, that both CO_2 and radon show similar variations and mostly constant Rn/CO_2 ratios (Fig. 4). This indicates that the radon concentration is depending on the CO_2 flux.

The natural radioactivity of rocks owing to their U and Th content results in a natural Rn content of the soil air. However, if all radon is to be derived from the weathering cover/scree (weathered, slightly limonitised Cambrian phyllite with haematitic spots) higher CO_2 flux would then dilute the Rn concentration and will result in lower Rn counts and vice versa. The monitored Rn/CO_2 ratios show an opposite behaviour as these ratios decreases with decreasing CO_2 content (Fig. 4 e.g. events on 1st and 7th February and 21st March 2004). This indicates an input from ascending deep-seated gases, CO_2 and radon. The source of radon can be U (Ra)-bearing mineralisation or gouge clay in the Mariánské Lázně fault system, as e.g. observed in Bad Brambach (U. Koch, pers. communication). In this case (Toutain and Baubron, 1999), the ratio of relative short-living ^{222}Rn ($T_{1/2}$ 3.8 d) to CO_2 ($^{222}Rn/CO_2$) could be an expression of the fluid transport velocity, i.e. the ascent time. Heinicke et al. (1993) reported an increase of Rn contents, measured as specific γ-activity, in the spring water of the Wettin spring in Bad Brambach with increasing water discharge and vice versa. An increased water discharge results in lower retention periods, less decay of radon and increased Rn recordings.

A general relationship between both the air pressure and the gas geochemical data is not ascertainable. For example, strong air pressure fluctuations occurred in the period from April to end of May (Fig. 4) without any recognisable effects on the CO_2 content. The bottom-hole temperature increased continuously from about 5 °C in February to

14 °C in August, however, there is no a correlation with the gas content, although the CO_2 content is in tendency higher in August.

Alongside with those general trends of the CO_2 and radon data, diurnal variations were monitored. However it is apparent that several peaks and shifts significantly exceeded these diurnal variations, which are thought to indicate geogenic events.

4.2. Diurnal variations

As seen in Fig. 4 diurnal variations occur in the monitored gas data. The amplitudes range from 0.02 to 0.03 vol. % independent on the season of the year and the weather conditions. Diurnal variations even occur in January and February when the soil was covered with 40 cm of snow.

The diurnal variations in published gas monitoring sets, e.g. Pinault and Baubron (1996, 1997) and Teschner et al. (2004) as well as in data sets recorded in our reference stations (Salzhemmendorf, Dresden and Oechsen in the Rhön, Germany) are partly ten times higher than those recorded in the Oldřišská monitoring station (Fig. 5). The reason of the very low diurnal variations at Oldřišská site can be related to the depth of gas extraction which is as mentioned in chapter 3 in the cellar of a building 2.5 m below grass roots over the in situ bedrock but not only 1 m in soil as at the stations mentioned above. Additionally, at Oldřišská, gas is extracted direct from the in situ bedrock and the extraction point is shielded by this building. The microbiological CO_2 production abates with depth (Richter and Großgebauer, 1978) as it is a temperature controlled process (Risk et al., 2002). Therefore, a recognisable influence of microbiological processes can be excluded at the Oldřišská site.

Fig. 6 displays in detail a typical time section of these small diurnal variations in May 2004 compared with

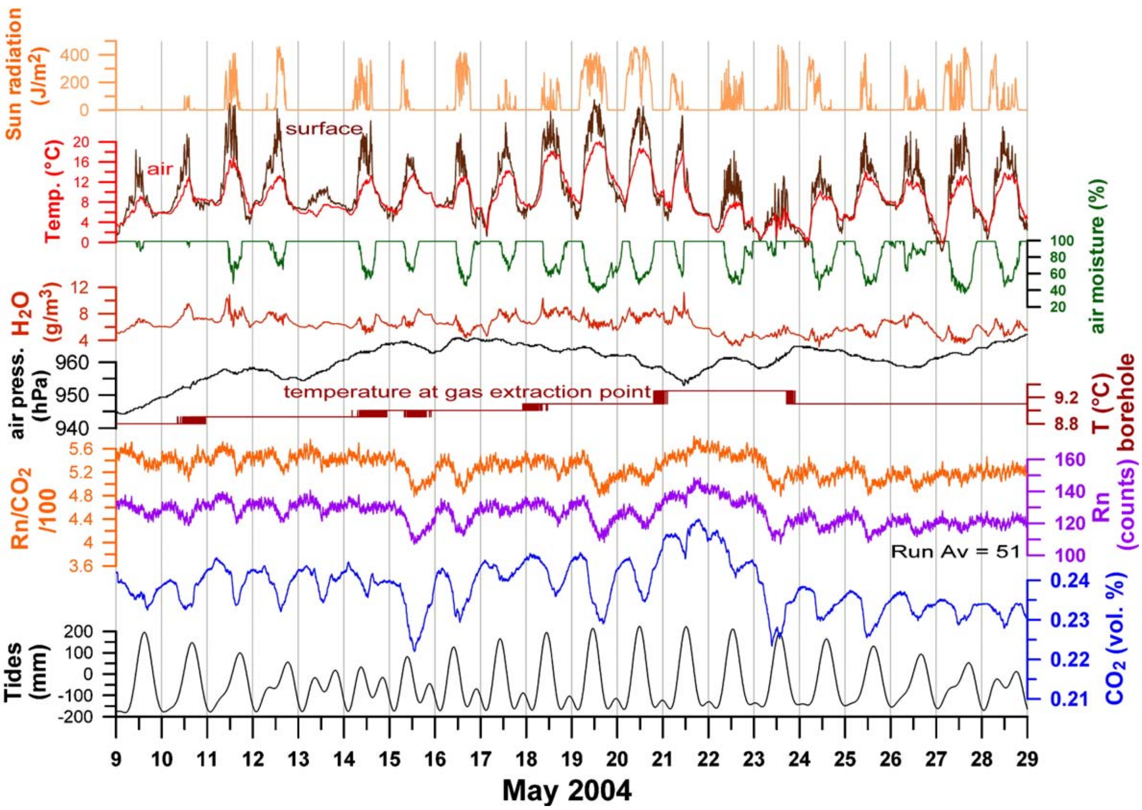

Fig. 6. Detailed plot of the minor diurnal variations in CO_2 and radon in Oldřišská compared with meteorological parameters and the sun radiation. The calculated absolute water content of the air (in g H_2O/m^3 air) and the nearly constant temperature on the bedrock clearly indicate no influence on the gas data. Note also the low temperatures, lack of sunshine and the absence of the daily minimum in air moisture on the 13th May without any effect on the CO_2 concentration. In addition, a daily minimum of CO_2 concentration at noon is impossible to be explained with atmospheric parameters or biogenic production (see text). These diurnal variations are caused by the earth tides, which became visible as the influence of meteorological conditions and biological production was restrained by the shielding effect of the building. The Rn/CO_2 ratios, as an expression of transport velocity indicate a daily cycle of stress in the Mariánské Lázně fault. The absence of these variations in periods following possibly reduction of fault permeability may be caused by seismic events (Fig. 9) and support this interpretation.

meteorological data acquired at the closest meteorological station at Bad Brambach. The highest CO_2 concentrations occur at Oldřišská usually at night times from about 23.00 h to about 10.00 h next morning. A sharp minimum in CO_2 values occurs periodically in the afternoon time between about 12.00 and 16.00 h time with a subsequent general rise in CO_2 and radon.

Air pressure dependency is not recognisable at the monitoring station in Oldřišská. In general, the diurnal minima peaks in CO_2 and radon correlate with the maxima of the air temperature, surface soil temperature, sun radiation and the minima of the air moisture. All these meteorological parameters are known to be linked and con-trolled by the daily cycle of the sun activity. Noteworthy is the 13th May characterised by low temperature differences, lack of sunshine and the absence of the daily minimum in moisture, but with typical diurnal CO_2 variations. Similar variations occur in winter under snow cover. The temperature at the gas extraction point in the borehole is not affected by the daily cycle of the sun (Fig. 6). A correlation between the absolute water content of the air, calculated from air temperature, air moisture and air pressure, is not detectable.

In soils the biological CO_2 production is enhanced at mean daytime, showing a maximum around mid-day and minimum in the night (Maljanen et al., 2002). The findings in the gas at Oldřišská are contrary to that; a sharp negative peak in CO_2 and Rn concentration during daytime is associated with maximum air temperatures. A lateral CO_2 migration could cause a time delay of maxima or minima concentration peaks. This can only take place by diffusion and cannot cause sharp minima peaks. Therefore, it can be concluded for the Oldřišská station that there is no correlation between gas data and the meteorological parameters.

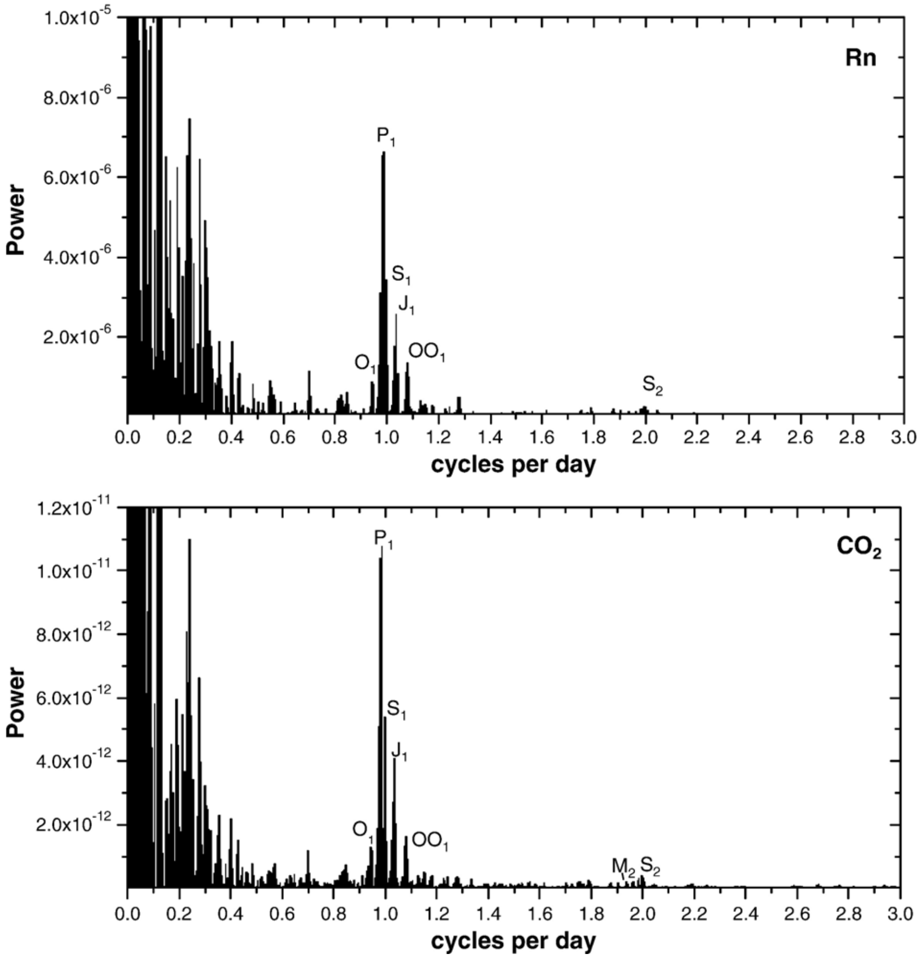

Fig. 7. Power spectra of CO_2 and Rn concentrations of the period April to September 2004. Next to low frequencies maxima cluster also in frequency bands around the diurnal earth tide constituents.

4.3. Influence of earth tides

The nearly 24 h cycle of negative CO_2 and Rn concentration peaks, which are obviously coupled with the sun cycle, depict the earth tides.

Barnet et al. (1997) observed a correlation between diurnal Rn variation and earth tides in mines excluding an influence of biogenic processes. The power spectrum of the CO_2 and Rn concentration (Fig. 7) exhibit relative maxima close to periods of 24 h (and small indications at 12 h), which coincides with earth tide constituents (e.g. S1, P1, J1 and O1 and M2). As similarly Millich et al. (1999) reported a prominent S1 peak in the Rn spectrum of radon measurements inside a gypsum mine we conclude that the 24 h cycles observed in the gas data of the Oldřišská site are based on earth tides.

Calculated earth tides of Nový Kostel (using a computer programme developed by H. G. Wenzel, 1999) show a tidal amplitude of the earth crust of max. 52 cm. In a rigid metamorphic rock complex pervaded with systems of fissures and faults, the earth tides generate a daily cycle of stress in these faults by the movements of the earth crust. This may inhibit the migration of gas along those faults for a short time. The fault structures would act like hinges between the rigid blocks of metamorphic and magmatic rocks. This diurnal cycle of stress could affect the velocity of fluid migration via fault permeability, expressed as a diurnal cycle of Rn/CO_2 ratio (Fig. 6) and result in diurnal gas concentration minima. Kies et al. (1999) also assume that the tide induced radon variations could indicate changes in state of stress resulting in opening of pathways for gas migration.

This idea is supported by the absence of diurnal variations in periods following negative peaks of CO_2 and Rn concentration which we think are caused probably by seismic events (see February and March events, Figs. 8 and 10), which could gave rise to decreased fault permeability, inhibiting the fluid migration. The lack of diurnal variations following these seismic events is by no means explainable with meteorological conditions.

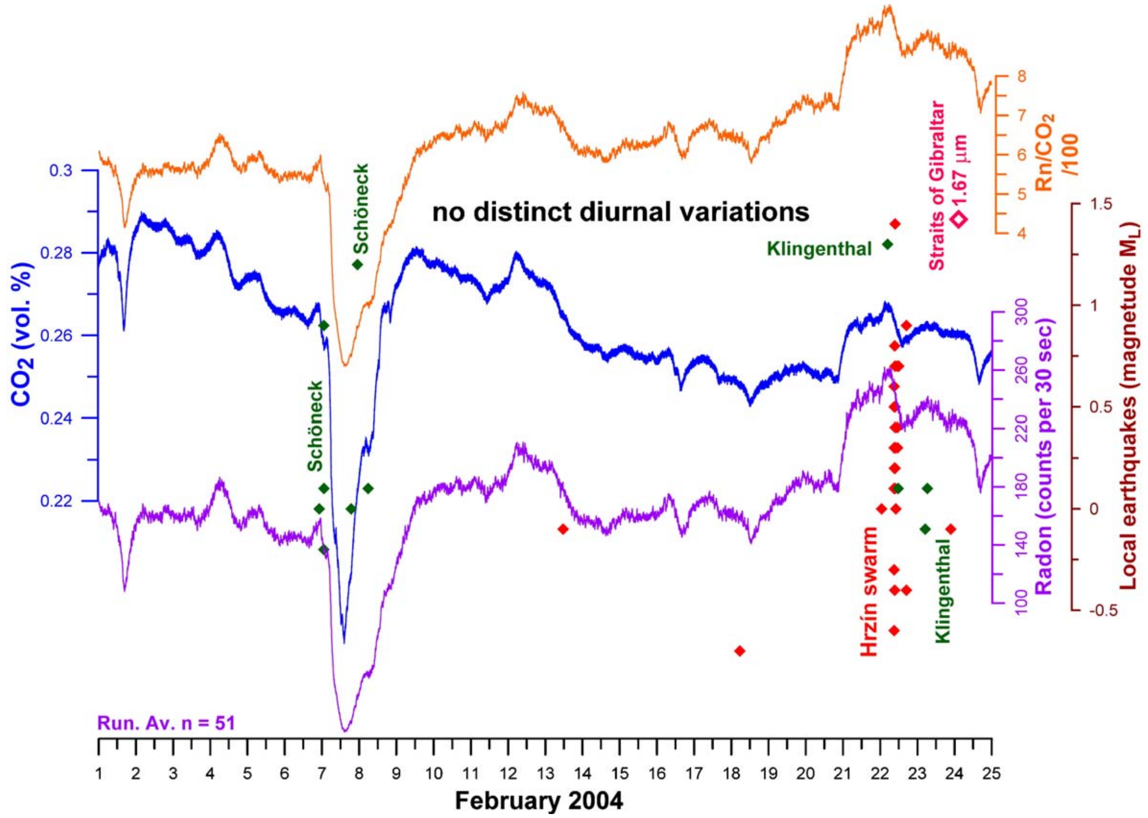

Fig. 8. Time series of gas concentration recorded in Oldřišská in February 2004. The Schöneck swarm earthquake could have given rise to a reduction of fault permeability caused by stress impeding the fluid migration along the Mariánské Lázně fault as also indicated by the Rn/CO_2 ratios (see chapter 4.1). It could have resulted in a redistribution or increase of stress along the Mariánské Lázně fault and a release of stress by triggering the earthquake swarm at Hrzín. Open diamond — remote earthquake with ground motion amplitude calculated for Nový Kostel.

Mrlina et al. (2003) investigated the fluctuation of groundwater levels associated with swarm quakes in two boreholes. In a well overlying a granitic body in the Cheb Basin ca. 6 km distant from the Mariánské Lázně fault (close to Plesná, H3) there was no influence of the water table by the earth tides. However, a strong influence of earth tides on the water table does exist in a borehole located in the direct vicinity of the Mariánské Lázně fault system (near Lesná, P1A), which proofs a daily cycle of state of stress. Doan and Cornet (2005) report a tidal pressure cycle along the Aigio fault, Gulf of Corinth, Greece.

However, if fluctuations of state of stress caused by tides affect the fluids along faults, a complete coincidence between tide and gas geochemical data does not necessarily have to exist. The stress caused by tectonic movements has to be considered in addition and will superimpose the effects of tides.

Beyond these diurnal variations changes in the CO_2 and Rn concentration occur which clearly exceed these variations and are thought to have a geogenic source.

5. Geogenic signals

Several distinct alterations beyond the diurnal variations in the gas composition occur on the recordings (Fig. 4), which cannot be explained by changes in meteorological parameters or precipitation. These alterations could but indicate variations in the state of stress of the fault, as the daily stress cycle of the tides is reflected in the CO_2 and Rn concentration, the gas concentrations should also inevitably reveal stress variations caused by seismic activities.

In most cases these peaks or shifts are accompanied by seismic activities in the area of Nový Kostel or by the seismic signals of remote earthquakes, which were recorded in the seismic station Nový Kostel. This coincidence indicates a relationship between the changes in the geochemical data and the seismic events, although observations were made in a time of relative seismic quiescence. The small seismic events with magnitude $M_L < 0.4$ are not mirrored in the geochemical data.

5.1. Local seismicity

5.1.1. 1st to 10th February period

In the night from 6th to the 7th February 2004 four earthquake shocks with low local magnitudes of max. M_L 0.9 (Fig. 8) occurred between 22.14 and 1.17 h UTC (local time −1 h) close to Schöneck (Fig. 1). This area is located in the direct prolongation of the Mariánské Lázně fault, ca. 21 km distant from Nový Kostel. From about midnight to 14.00 h (UTC) simultaneously both the CO_2 and Rn concentration decreased rapidly for the period of about two days, forming sharp negative peaks. Along with the gas concentration the Rn/CO_2 ratio decreased, indicating a lower transport velocity of fluids (see 4.1). Renewed seismic shocks occurred in the following night in Schöneck with a maximum magnitude M_L 1.2 at 22.50 h.

5.1.2. 10th to 25th February period

Following a relative smooth declining trend of the CO_2 concentration, marked by the absence of regular diurnal variations, an increase in CO_2 and Rn contents started on 20th February. at 21.30 h UTC until the early morning hours of the 22nd February. It was followed by a subsequent decrease of the CO_2 and Rn values (Fig. 8). The Rn/CO_2 ratio has a similar pattern. Precisely on 22nd February at 00.41 h an earthquake shock of M_L 1.3 occurred at Klingenthal followed by an earthquake swarm with an epicentre at Hrzín continuing from 8.55 to 16.47 h UTC. Another swarm followed on 28th February with an epicentre at Klingenthal (not shown in Fig. 8 because the CO_2 sensor was changed on 25th February).

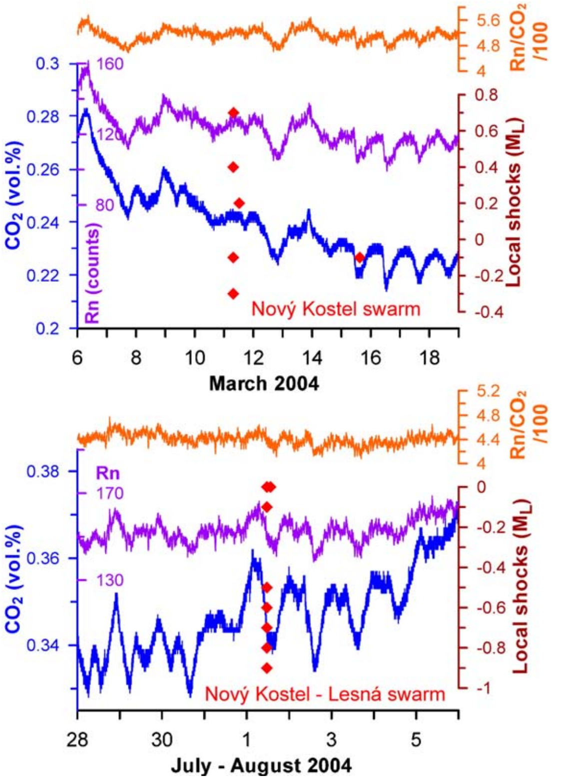

Fig. 9. The 11th March 2004 Nový Kostel swarm. Two days before this earthquake swarm there are no diurnal variations and subsequently only irregular variations were observed. The normal diurnal concentration (stress) cycle returned not before the 14th March, which indicates an interference of state of stress along the Mariánské Lázně fault by this event. Similarly the 1st August swarm is accompanied by a lack of the diurnal variations one day before.

5.1.3. 9th to 15th March period

On the 11th March, an earthquake swarm has occurred at Nový Kostel between 7.42 and 12.23 h with a maximum magnitude of M_L 0.7. This period is marked by the absence of diurnal variations for an overall time interval of 2 days prior to the occurrence of the earthquake swarm and it is followed by 3 days of irregular variations. The normal diurnal cycle has not begun again until the 14th March (Fig. 9). Similarly, a Nový Kostel swarm on the 1st August which is a far weaker and marked by a lack of diurnal variations one day prior to the earthquake swarm.

5.1.4. 18th to 29th March period

Earthquake shocks with magnitudes M_L 0.6 and 1.3 happened on 18th March in Klingenthal.

On 19th March the CO_2 and radon values decrease as well the Rn/CO_2 ratios forming a sharp negative peak (Fig. 10) on 21st March. The following period until 28th March with increasing CO_2 and Rn values is marked by the complete absence of diurnal variations.

5.2. Remote seismicity

In addition to the local seismicity, the Oldřišská site is affected by the transient of seismic waves of remote earthquakes. The gas geochemical data were compared with the seismic data of the seismic station Nový Kostel (NKC) of the Geophysical Institute Prague and with the station Wernitzgrün (WERN) of the Geophysical Observatory Collm. The majority of these remote seismic events generate only small signals characterised by low ground motion velocities with ground motion amplitudes lower than 0.1 μm (calculated for Wernitzgrün, Fig. 1; personal communication S. Wendt, Collm) and minimal ground accelerations lower than 50 $\mu m/s^2$. However, several large seismic events with ground motion amplitudes higher than 1 μm were recorded at Nový Kostel (calculated by Z. Hudová) and Wernitzgrün,

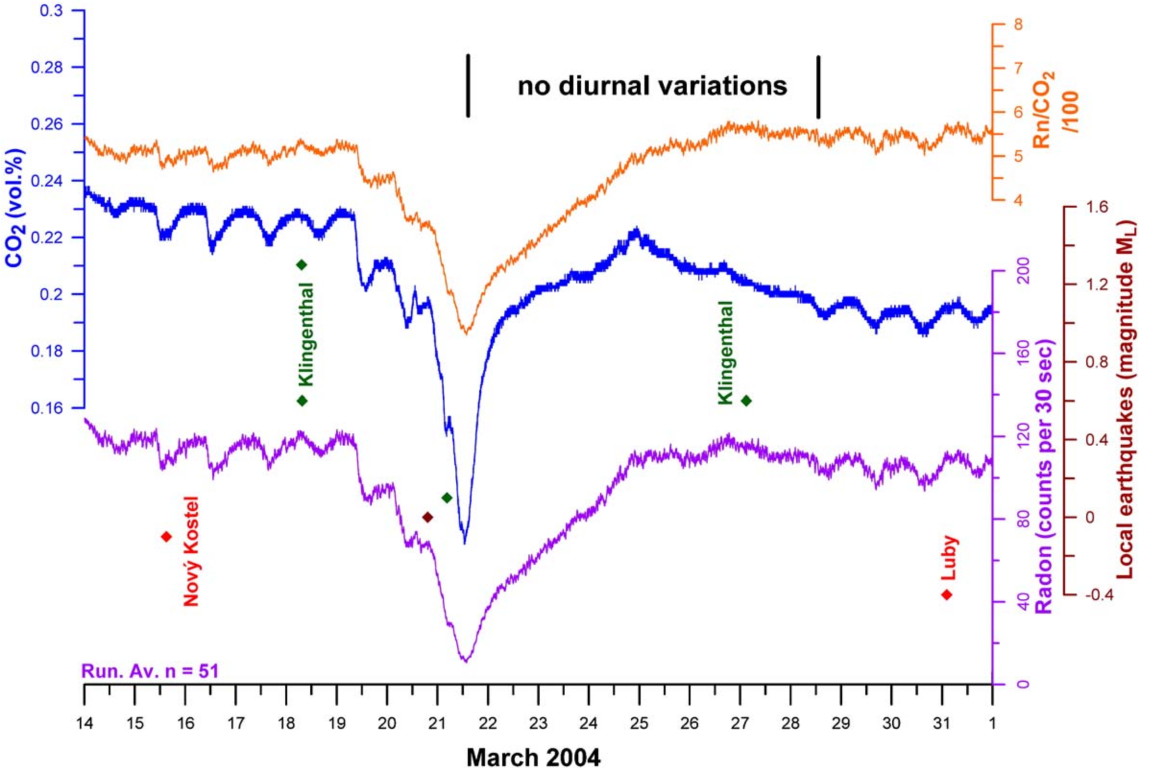

Fig. 10. CO_2 and Rn anomaly in March 2004 and seismic activity. The typical diurnal variations in CO_2 and Rn concentration occur before the Klingenthal seismic events took place. Following this event, the diurnal variations are absent until 28th March. This indicates both, the daily cycle of stress by the earth tides is interfered and Klingenthal seismic shocks could have had an influence on the state of stress along the Mariánské Lázně fault. A decrease in CO_2 and the lack of diurnal variations are impossible to be explained by decreasing air pressure (see Fig. 4) or by meteorological conditions, respectively. The accompanied decrease in the ratio of short-living ^{222}Rn to CO_2 also indicates a lower transport velocity by impeded fluid migration.

which may have had an impact on the gas monitoring data, i.e. the gas migration along the Mariánské Lázně fault.

Remote earthquakes can induce comparable ground motion, -velocity and -accelerations as local earthquakes. The maximum M_L 1.4 event of the local earthquake swarm at Hrzín on the 22nd February 2004 is characterised by prevailing frequencies of seismic waves of 8 to 14 Hz, ground motion of 0.18 μm, ground velocity of the S-wave of 6.6 μm/s (NS) and ground acceleration of 840 μm/s^2. The S-wave of the Slovenia shock on 12th July 2004 (see Fig. 11) recorded at NKC had a dominant frequency of 2.5 to 3 Hz, maximal ground velocity of 260 μm/s (NS), ground motion amplitude of 45 μm and a ground acceleration of 1900 μm/s^2 and is in this way comparable with a local earthquake of magnitude M_L 2.0. Although a remote earthquake will not result in a long-term redistribution of stress, it can cause a pressure pulse on the fluid systems. Pressure changes at the Aigio fault, Gulf of Corinth, Greece induced by remote earthquakes (Rat Islands, 2003; Sumatra, 2004) were reported by Doan and Cornet (2005) which clearly indicate an effect on the state of stress even in remote fault systems.

In Fig. 4 all events of remote seismicity with ground movement amplitudes of >1 μm are incorporated, 4 of these 9 events are accompanied by changes and shifts in gas composition.

5.2.1. 5th to 7th May period

On the 5th May at 13.42 h the seismic signals of an earthquake in Sicily were recorded (Fig. 4) at NKC. From about 10th April CO_2 and Rn continued to increases until the 7th May when the values suddenly dropped down and remained lower but relatively

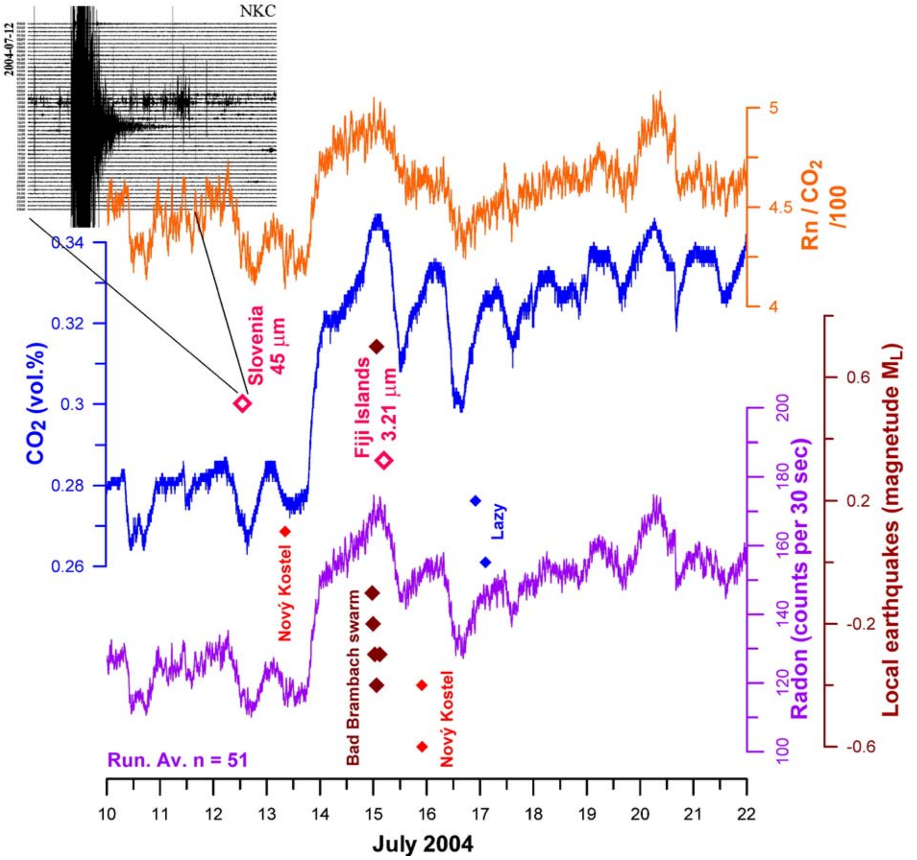

Fig. 11. The Slovenia shock monitored at Nový Kostel on 12th July 2004 at 13.05 h UTC. A day later followed a sudden increase in CO_2 and Rn at Oldřišská and an earthquake swarm in Bad Brambach at 15th July 2004. The pressure pulse of this seismic event on the fluid system at the Mariánské Lázně fault could have increased the fault permeability and/or led to a gas exsolution forming gas bubbles, respectively. This could have caused an increase of transport velocity, mirrored in the Rn/CO_2 ratio and an increase of the CO_2 and Rn concentration along the fault. If the gas exsolution took place in greater depth, this would explain the time delay between the seismic shock and the detected changes in gas concentration. This event may initiate an interference of the state of stress and could have triggered the Bad Brambach swarm. Open diamond — remote earthquake with ground motion amplitude and seismogram of the station Nový Kostel, NKC.

constant in the following days, apart from the diurnal variations. In contrast to other increase or decreases of the gas recordings, e.g. in August 2004, this is an abrupt change (Fig. 4) in gas concentration but also in the Rn/CO_2-ratio.

5.2.2. 11th to 19th July period

On the 12th July at 13.05 h UTC, seismic waves of the Slovenia earthquake (M_L 5.1, felt in South Bohemia and Prague) arrived at Nový Kostel and shacked this area with a ground acceleration of 1900 μm/s^2 and a maximal amplitude of 45 μm (S wave). On 13th July at 19.03 h starts a rise in the CO_2 and Rn concentration as well in the Rn/CO_2 ratio (Fig. 11). From the 14th at 23.27 h to the next morning at 2.50 h an earthquake swarm occurred in Bad Brambach. This pattern is similar to the pattern of the Hrzín swarm in February 2004 presented above.

5.2.3. 5th to 9th September period

On 5th September at 10.19 h and 15.09 h UTC the seismic station Nový Kostel recorded two relatively strong earthquake shocks of the Honshu earthquake, Japan (M_L 7.2 and 7.4). This marks the start of an increase of the CO_2 and radon concentration (Fig. 12). The first Honshu shock caused maximal ground motion amplitude of 6.1 μm (first P wave) and 27.2 μm (second P wave, both with period of about 4 s) and was followed by a prolonged period of surface waves with amplitudes of 200 μm and period 13 s. Two days later, on the 7th September the CO_2

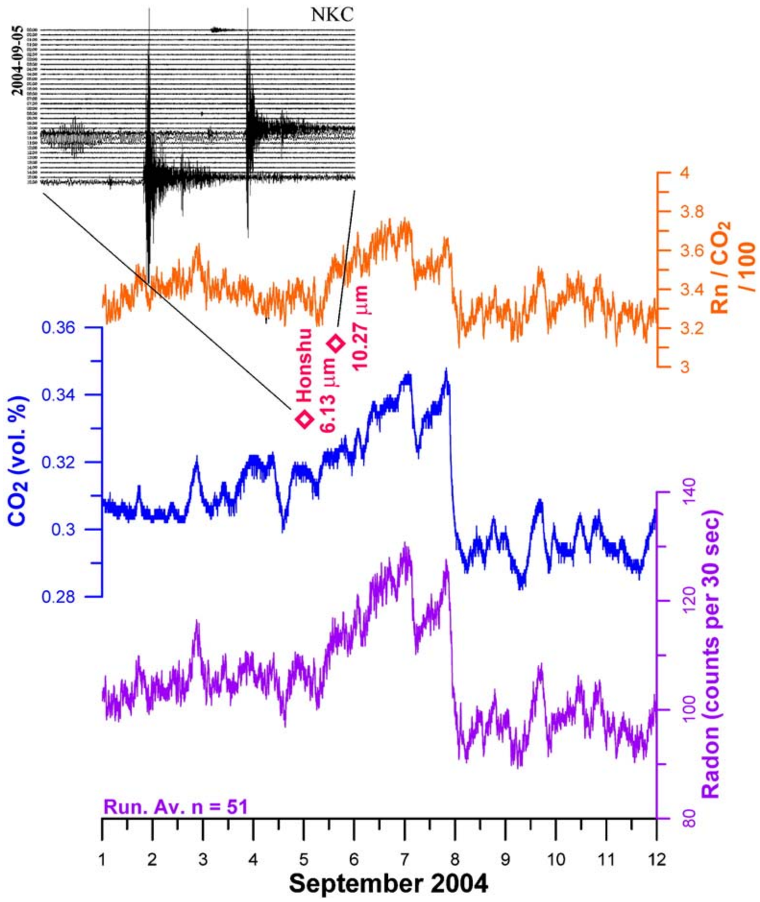

Fig. 12. The Honshu shocks registered at Nový Kostel on the 5th September 2004 with its subsequent surface waves, compared with the CO_2 and Rn monitoring data. Like in the case of the Slovenia shock a formation of gas bubbles in the fluid system could have taken place resulting in a faster upward directed gas transport to the surface. Afterwards, as the liberated gas arrived at the surface the concentration of CO_2 and Rn fell down again (superimposed by diurnal variations) and the fluids migrate slower upwards, indicated also by a decrease of the Rn/CO_2 ratio on 7th Sept. Additionally, the seismic waves might have induced a fault movement decreasing fault permeability partially closing migration paths. Open diamond — remote earthquake with ground motion amplitude and seismogram of the station Nový Kostel, NKC.

and Rn concentrations fall abruptly back to values slightly lower than recorded before this event. This period is marked by irregular and indistinct diurnal variations.

5.2.4. 21st September period

At the 21st September at 11.06 and 13.34 h UTC the signals of two earthquakes (M_L 4.8 and 5.0) with epicentres close to Kaliningrad, western Russia, were recorded in Nový Kostel with maximal ground motion amplitude of 1.49 μm (Sg wave, period 1 s). Only 4 h earlier an abrupt fall of CO_2, Rn values and Rn/CO_2 ratios was recorded (Fig. 13). Prior to this event the gas concentrations are marked by regular diurnal and subsequent by irregular variations. The heavy rainfall later on the 22nd and 23rd September (Fig. 4) could not have caused these variations.

6. Discussion

Seismic shocks potentially can cause both alterations of the physical properties of faults and/or the migrating fluids. The build-up of stress could lessen the fault permeability or a pressure pulse could open new migration paths. Furthermore a seismic shock may provoke desorption of gas or in gas bearing fluids gas exsolution. The first will result in a decrease, the latter in an increase of gas concentration.

6.1. Local seismicity

The most significant recordings are the negative peaks in gas concentrations in February and March. According to Ball et al. (1991) rainfall can affect the radon flux. The assumption that these negative peaks were caused by precipitation can be ruled out, as there was no significant

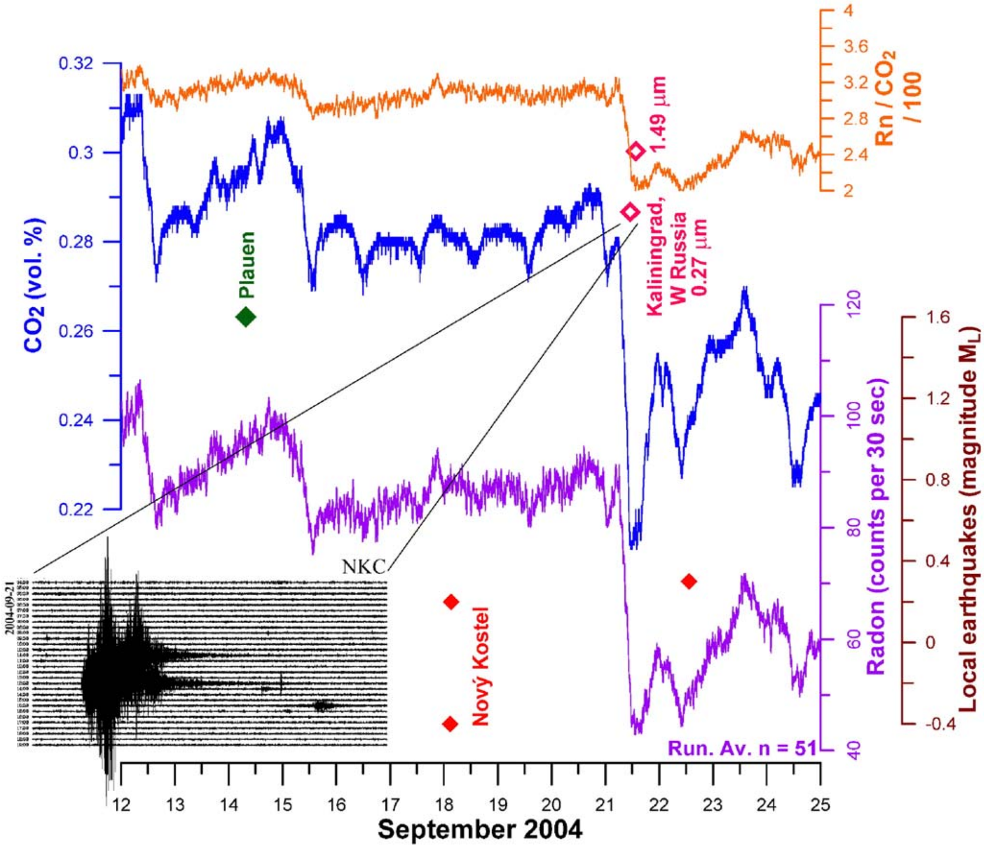

Fig. 13. The Kaliningrad shocks registered at Nový Kostel on the 21st September 2004 and the monitored CO_2 and Rn data. The shocks are recorded at Nový Kostel at 11.06 and 13.34 h (UTC). The gas concentrations start earlier to fall down at 7.02 h (UTC). However, prior to this event normal diurnal gas concentration (stress) cycle has occurred caused by earth tides. The irregular variations following this event may indicate an interference of this cycles induced by additional stress. This could in this case be caused by a local fault movement. Consequently the seismic signals of these events would have arrived at the fault in a period of anomalous stress. Thus, additional vibrations may have no effect on the fault permeability or fluids resulting in no identifiable response in gas concentration. Open diamond — remote earthquake with ground motion amplitude and seismogram of the station Nový Kostel, NKC.

rainfall. Apart from this, Ball et al. (1991) and Toutain and Baubron (1999) report an increase of the radon flux (concentration) caused by rainfall, which is opposite to the observations at Oldřišská.

These negative peaks of CO_2 and radon values are characterised by a subsequent period of the indistinctly minor (Fig. 8) or even not existing diurnal variations (Fig. 10, 21st–25th March). As the meteorological parameters preceding and succeeding to these events do not show any subsequent variations, it can be concluded, that not meteorological but geogenic processes caused the observed signal variations. A possible explanation for the strong negative peaks recognised in the geochemical signals can be related to a decreasing fault permeability of the Mariánské Lázně fault at Oldřišská due to tectonic stress caused by those seismic activities north of Nový Kostel. Changes in fault permeability caused by earthquakes were reported (Rojstaczer and Wolf, 1992) and are the reason for the many and various changes observed in mineral springs (e.g. Hoernes, 1910; Smirnova, 1971; Grecksch et al., 1999; Wang et al., 2004). The state of stress affects the fault permeability, the fluid migration and will result in different transport velocities.

Simultaneously with variations in the concentration of CO_2 and radon changes observed in the Rn/CO_2 ratio are thought to be expression for variations in the transport velocity of gas (see above). In addition, this indicates that these events were caused by a reduction in fault permeability. The reoccurrence of the diurnal variations in CO_2 and Rn concentration observed days after the negative peaks can be caused either by diminished compressive stress, further seismic shocks or by returning to the normal state of stress caused by the earth tides.

The possible influence of the Schöneck shocks on the fluid migration poses a question with respect to a possible link with other events in February. The earthquake shocks in Schöneck (Fig. 8) could have had an effect on the Mariánské Lázně fault as well as on the parallel striking faults located in its close vicinity. It could have triggered the earthquake swarm at Hrzín on 22nd February by impeding the fluid flux for a short time, increasing or redistributing the state of stress along a parallel striking fault which may result in a release of stress by the earthquake swarm some days later 2.5 km distant (see Fig. 1) from the location of the recorded negative gas concentration peak (stress increase). The steep increase of CO_2 and radon at Oldřišská 35 h before the Hrzín swarm (Fig. 8) could be interpreted as opening of migration paths due to a redistribution of stress. The absence of the typical diurnal variations, normally caused by the daily tidal stress cycle, may indicate an anomalous stress regime in the period of 7th to 24th February which could additionally support a link between the negative gas concentration peak on the 7th February and the Hrzín swarm at the 22nd February 2004. The non-appearance of the diurnal variations in the periods of the Nový Kostel swarms in March (Fig. 9) and indistinct in August indicate also either an interference of normal daily stress cycle caused by stress build-up or a redistribution linked with seismic events.

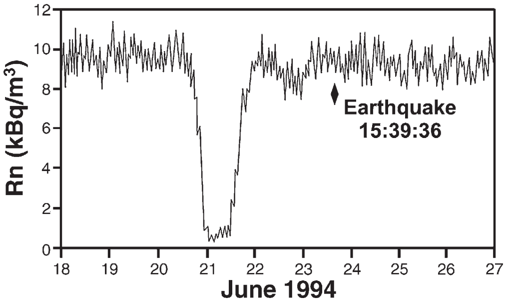

Fig. 14. Time series of Rn in soil gas recorded in June 1994 at Torre del Filosofo, Etna volcano, Sicily, Italy (Pinault and Baubron, 1997) and the earthquake at 23rd June 94 at the Etna (after data base INGV Italy, www.ingv.it/banchedati/banche.html). This pattern is similar to the February recordings in Oldřišská. A shock along a fault may have also induced here an impediment of fault permeability resulting in a release of stress by an earthquake shock.

A very similar pattern to the Hrzín swarm pattern can be seen in Pinault and Baubron (1997) at Torro del Filosofo, Etna volcano (Fig. 14). In their radon data, a negative peak on 21st June 1994 is followed by a weak decline on the 22nd June and a subsequent increase on 23rd June 1994. At 15.39 h UTC on 23rd June an earthquake of magnitude M_L 1.6 occurred in the Etna area (37.687°N, 14.796°E) (INGV, Italy, www.ingv.it/banchedati/banche.html).

6.2. Remote seismicity

Additional to the local seismicity remote earthquakes may affect fluids migrating along the Mariánské Lázně fault. This can be suggested from the Sicily earthquake (Fig. 4), interrupting a trend of increasing CO_2 and Rn values and the Honshu shocks (Fig. 12). It may also be suggested from the Slovenia shock on 12th July (Fig. 11) that a shock from a remote earthquake can alter fluid properties and/or the state of stress along faults and may be able to trigger a local swarm quake as happened on the 15th July at Bad Brambach. The pattern of the gas geochemical recordings associated with this event is nearly similar to the Hrzín swarm (Fig. 8) in February. The steep rise in CO_2 and Rn as observed at 13th July may indicate an opening of migration paths in greater depths.

Vibrations (and shocks) cause generally a gas exsolution forming gas bubbles in gas bearing fluid systems, as e.g. applied for gas extraction from fluids (Schmitt et al., 1991). In nature, vibrations related to quakes are also thought to be able to release gases from gas bearing fluid systems. Following observations in 1938, that earthquakes increased the oil production rates, the effect of vibroseismic stimulations on oil reservoirs is known and used for enhanced oil recovery (Lopuchov, 1999). The vibrations increase the gas–oil-ratios (Skovorodkin et al., 1999), among others by mobilisation of adsorbed gases. Ammosov et al. (1988) describe in detail changes in the gas composition following vibration treatment of an oil pool. Both increased gas–oil-ratios and altered gas composition exhibit clearly an increase of the bubble point pressure of these reservoir fluids, i.e. the most important feature of a gas–fluid system with respect to gas exsolution. Similarly, vibrations can cause a gas bubble formation in the CO_2 bearing waters migrating along the Mariánské Lázně fault. Such effects were observed at mineral springs, as Wang et al. (2004) explain variations in water discharge by mobilisation of gas bubbles due to vibrations caused by earthquakes. Koch et al. (2003) report a sudden rise in the gas flux in the mofettes of Bublák, 6 km south of Nový Kostel, 18 and 25 h following local seismic events of magnitude M_L 1.6 at Nový Kostel. With regard to the gas migrating along the Mariánské Lázně fault, the origin of shocks or vibrations of the ground, local or remote, is of a secondary importance. The waves of remote earthquakes have usually longer periods as local seismic events, but they are able to induce short-period waves in local structures.

Therefore, seismic vibrations of the Honshu shocks could have caused a gas exsolution at greater depths. These gas bubbles can migrate upwards faster thus increasing the CO_2 concentration along the Mariánské Lázně fault. Subsequent to this event, water with a diminished CO_2 content migrates upwards causing a decrease in CO_2 concentration later. The changes in gas concentrations are more pronounced for the Slovenia than for the Honshu shock. With respect to the Slovenia shock, its higher intensity could have in addition opened fissures supporting a faster ascent. The difference between these events may lie either in the intensity of the arriving seismic waves (see seismograms in Figs. 11 and 12) or the Honshu waves inducing fault movement along the Mariánské Lázně fault thus closing migration paths. The latter scenario would explain the mentioned abrupt fall in CO_2 and Rn concentration.

An almost similar pattern of the gas signals was observed in relation with the Kaliningrad shocks. Strongly lower gas concentrations were observed starting to fall down at 7.02 h on 21st September (Fig. 13) before the shocks arrived at 11.06 and 13.34 h at Nový Kostel. The lack of the normal diurnal variations following this event indicates an interference of the normal stress cycle and an additional stress or a pressure pulse. Fleischer (1981) supposed that changes in the strain field during the build-up of stress before an earthquake can affect the gas migration by opening or closing of fissures. However, the respective earthquake (M_L 5) is far too distant and the monitored data may reflect simply stress variations caused by fault movements. This would also support the interpretation of the effect of the Honshu waves at the Mariánské Lázně fault.

Yet another aspect of the above signal might be taken into account: if the state of stress is to be anomalous, i.e. interfered by local fault movements, an additional vibration caused by seismic events might have no additional effect on the fault permeability. This may result in periods of absence in the response of the gas concentration.

It has been demonstrated that seismic waves of local or remote events generate not one distinct but a variety of different patterns of gas geochemical signals. Those seismic events causing compressional stress will result in reduced fault permeability as it is indicated by decreased gas concentration. This implies the negative peaks in February and March 2004. Seismic events causing tensile stress, related to the monitored fault, may result in increased fault permeability, which may open additional migration paths, as it is inferred by the increased gas concentrations accompanying the Hrzín swarm. Teleseismic events could initiate a redistribution of stress increasing the permeability of the monitored fault as deduced by the Slovenia shock.

The seismic signals of blasts in coal mining in the neighbouring Sokolov Basin and in Poland, which were recorded in Nový Kostel, have no effect on the gas data. These waves probably do not penetrate deep into the crust and therefore do not influence the fluid systems.

We are aware that, with regard to stress variations, an interpretation of these monitored gas concentration data at a fault can be only tentatively at the moment. In order to investigate the relationships between gas signals, seismicity and fault permeability longer monitoring periods, possibly for a duration of several years and a net of gas monitoring stations is necessary to understand these processes. Since not all relative strong local or teleseismic events cause variations in the geochemical signals it is in addition necessary to investigate, to which kind of seismic parameters the geochemical data have the best correlation.

7. Conclusions

One of the most important aspects for a successful gas monitoring in relation to seismicity is the appropriate choice of a location for the emplacement of a gas monitoring station. The location should be directly overlying a seismically active fault and the gas extraction point must be deep enough, possibly into the in situ bedrock to avoid or minimise the influence of meteorological and biological processes. This is the most auspicious way in order to avoid masking of often weak seismic signals by the pattern of diurnal variations.

Deep-seated CO_2 with initial $\delta^{13}C_{CO_2}$ values of −4.8 to −7.7‰ is present in Oldřišská and confirms the successful emplacement of the monitoring station along the Mariánské Lázně fault. The minor diurnal variations observed are not related to meteorological conditions but are probably caused by earth tides. The daily cycle of tides of the crust, as seen e.g. in water table fluctuations in boreholes, caused evidently a daily cycle of compressive and tensile stress along faults. This can increase or decrease the fault permeability and can control the gas (fluid) migration. Additionally, tectonic stress and seismic shocks can superimpose or interrupt this daily cycle, as it is evident in the absence of regular diurnal variations associated with local earthquake swarms and seismic signals of remote earthquakes.

Although the seismic activity in NW Bohemia and the Vogtland was very low during the observation period, abrupt variations in the monitored gas concentration exceeded clearly the diurnal variations and were in all cases linked with seismic events.

A reduction of fault permeability of the Mariánské Lázně fault, caused by seismic shocks could have impeded the fluid migration in February and March. The February 2004 recordings suggest a link between seismic activities north of Nový Kostel and diminished fluid migration, build-up stress and subsequent stress release in the Hrzín swarm earthquake. The increase in gas concentrations along the Mariánské Lázně fault at Oldřišská took place 35 h before this swarm and could indicate a redistribution of stress.

The arrival of seismic signals of remote earthquakes, which are causing both, significant signals in the seismograms and ground motion with amplitudes more than 1 μm are often linked with immediate changes in the gas concentrations at the station Oldřišská. This raises the question whether remote earthquakes are able to alter the fluid properties (bubble point pressure) and trigger local earthquake swarms in NW Bohemia as suggested in the case of the Slovenia shock in July 2004 followed by a small swarm in Bad Brambach.

Owing to the location of the hypocentre of an earthquake and the anisotropy of the earth crust for seismic waves, a seismic event can generate an increase or decrease the fault permeability resulting not only in one distinct but a variety of gas geochemical signals. Furthermore it is to consider that an anomalous state of stress caused by local fault movements, reflected in the lack of diurnal variations, might create a temporary unresponsiveness to vibrations induced by seismic events. This may result in lack of non-diurnal geogenic variations in the gas composition, as sudden increase or decreases of CO_2 and Rn.

For further investigations, it is therefore necessary to install a net of gas monitoring stations. The geochemical signals of a definite seismic event monitored in more than one station with a possibly time delay could provide an understanding of the effects of seismic shocks on the gas bearing fluid systems. The coherence in the gas concentration between Rn and its carrier gas CO_2 permits, at least in part, an employment of only CO_2 or Rn sensors in order to keep a monitoring station net on an economic level. In addition, a direct comparison with simultaneously measured state of stress of the investigated fault system is necessary, e.g. by additional water table monitoring.

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