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HORIZONTAL STRAIN, $^3He/^4He$ RATIO AND INTRA-PLATE EARTHQUAKE SWARMS

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ABSTRACT
In the West Bohemian region, Central Europe, the volcanic activity appeared in late Tertiary, the Miocene. The present intra-plate magmatic activity makes itself felt by flows of gaseous and liquid fluids, enhanced geodynamic mobility of geological structures and generation of earthquake swarms. Position data of two permanent Global Navigation Satellite Systems (GNSS) stations located in the region were used to calculate the time variations of the horizontal strain field that were compared with the $^3He/^4He$ ratios and earthquake swarm occurrences. The strains and $^3He/^4He$ ratios displayed a positive relation supported by the earlier opinions on the dependence of the dynamics of the region on the fluid occurrence. Analysis of these quantities observed in 2006-2007 period indicated when the compressions calmed and the $^3He/^4He$ ratios grew then the earthquake events occurred. It presumes the detected variations relate to compressions and extensions in the region. The strain field changes monitored during the 2008 swarm proved the relation found above. The observed connections could be applied in future at selected regions in earthquake forecast procedures.

KEYWORDS: horizontal strain, $^3He/^4He$ ratio, intra-plate earthquake swarms, West Bohemia

1. INTRODUCTION

Recently, studies of earthquake swarms have become more detailed and complex. The origin of intra-plate swarms is closely linked to intra-plate magmatic processes, i.e. to motions of magmatic masses and fluids under lithospheric plates and to their ascents into the Earth's crust. One of the regions where these processes can be observed is the western part of the Bohemian Massif in Central Europe. In this region in recent years, apart from monitoring earthquake swarms (Horálek et al., 2000) also changes in the content of fluid escapes (Weinlich et al., 2006; Weise et al., 2001; Bräuer et al., 2009; Faber et al., 2009) and changes in the motions of local geological structures (Schenk et al., 2009 and 2010) have been studied.

The analysis of the GNSS data from the permanent stations enables the changes of the distance in time between these stations to be determined. The origin of these regional and/or local changes of distance is attributed to the presence of geodynamic forces, the time variability of which necessarily also causes changes in the strain field of the region, in this particular case in its horizontal direction between the monitored GNSS stations. It is assumed that the dynamics of the West Bohemian area is affected by intra-plate magmatic activity simultaneously with the effects of post-orogenic pressures of the Alps.

2. SEISMOTECTONIC PATTERN OF THE CHEB BASIN IN WEST BOHEMIA

The Bohemian Massif is located in the central part of Europe, and in view of its geological evolution belongs to the fundamental cratogenic units of the European Variscides. The tectonic motions, which now occur in the Massif, are affected by the dynamic processes caused by the most recent Alpine orogenic phase in the Miocene. The sedimentation cycle in the latter generated Cheb Basin in West Bohemia began in late Tertiary. In the Early Oligocene, volcanic activity appeared in the region and lasted to the Middle Pleistocene of the Quaternary (Kopecký, 1978; Wagner et al., 2002; Mrlina et al., 2009). Although its eruptive manifestations ended several hundred years ago, the mobility of the fault systems of West Bohemia is still affected by present magmatic processes which are associated also with earthquake activity and occurrence of mineral springs.

The recently most active seismogenic zone, the Nový Kostel zone (Horálek et al., 2000), is located in the crystalline units of the Krušné hory Mts. near the eastern border of the Cheb Basin. Its boundary with the crystalline units is formed by the Mariánské Lázně fault zone (Malkovský, 1976). The region is conspicuously affected by this fault zone, running NW-SE to NNW-SSE (Fig. 1). Faults running N-S, which are part of the regional tectonic Regensburg-Leipzig-Rostock zone (Bankwitz et al., 2003),

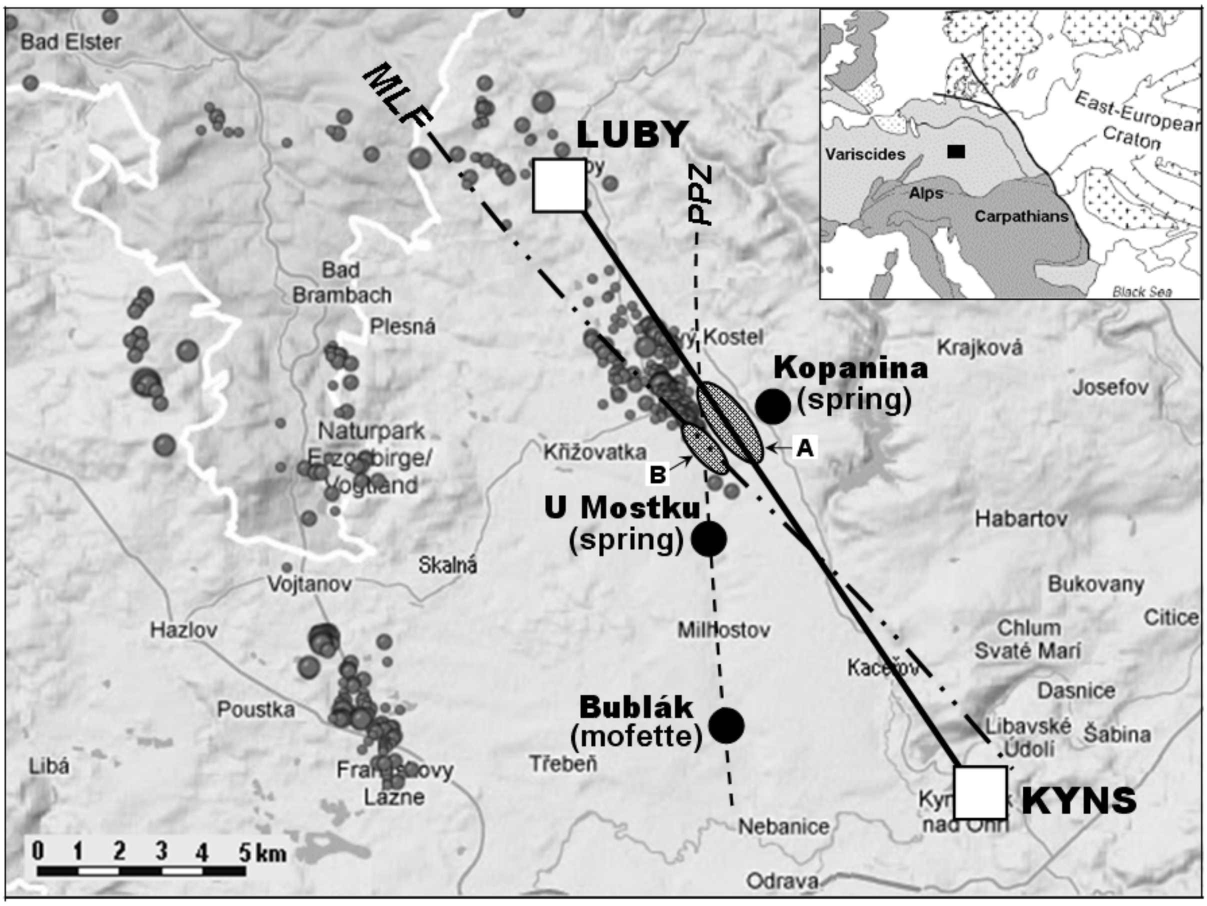

Fig. 1 The West Bohemian area with earthquake swarms; grey dots - earthquake events at depths of 12 or more km from the 1994 – 2009 period; large black dots – degassing sites, white squares – permanent GNSS stations, MLF – Mariánské Lázně fault zone, PPZ – Počátky-Plesná zone, hatched ellipses – epicentre areas of the February 2007 (A) and the November 2007 (B) micro-swarms.

approach it obliquely. The latter is identical with the Počátky-Plesná zone in the region of our interest. Figure 1 shows epicentres of the earthquake shocks which occurred in the region from 1994 till 2009 and their focal depths correspond to 12 or more km. The positions of these deeper foci demonstrate distinctly "roads of access", occurring in the fault systems in the lower part of the Nový Kostel seismogenic zone, whose fluid components use in a high probability for penetrating from the lithosphere upwards to the Earth's crust. Their distributions indicate that the roads agree well with the Mariánské Lázně fault zone. Similar distributions of the epicentres can be observed near Františkovy Lázně town continuing towards NW and in Vogtland.

3. REGIONAL PERMANENT GNSS MONITORING

The permanent GNSS stations KYNS and LUBY (Fig. 1) were established in December 2005 and form a part of the GEONAS geodynamic network (Schenk et al., 2010). The stations are equipped with Topcon GB-1000 receivers and TPSCR3 GGD CONE snow dome antennas that allow up to 18 visible American NAVSTAR and Russian GLONASS satellites to be tracked. The receivers are set for data registration with a 5° elevation mask, and the recording interval is set to 1 second. To protect the stations against power failures, they are equipped with 230/12 V power source/charges and lead/acid 12V/225Ah stand-by batteries which can power the station equipment independently for at least 24 hours (Kottnauer et al., 2003).

Apart from a few short-term technical blackouts, the GNSS equipments on the KYNS and LUBY stations have recorded satellite signals continually since 2005. None of the GNSS antennas was changed, i.e. no corrections for variety in antenna phase centre positions have to be introduced. This all guarantees high mutual homogeneity and compatibility of the recorded data. The recorded RINEX data were post-processed off-line at daily intervals using Bernese GPS software version 5.0 (Dach et al., 2007; Beutler et al., 2007). The precise satellite orbits, the Earth orientation parameters, clock corrections and the global ionospheric model, etc., were adopted from the CODE European regional centre in Bern, which offers

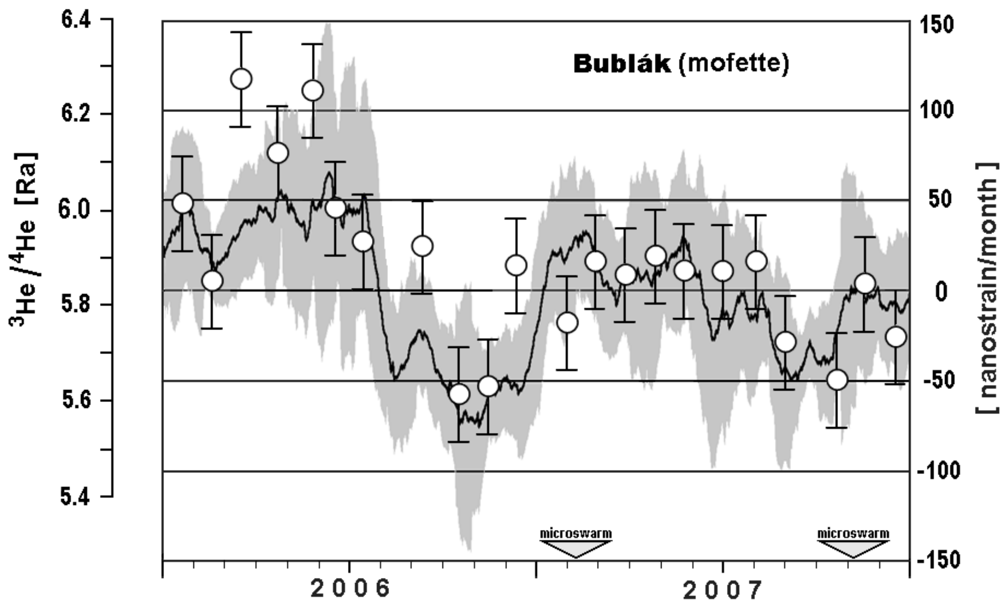

Fig. 2 The $^{3}He/^{4}He$ ratios observed at the Bublák degassing site and strain changes calculated for this area; circles and bars - $^{3}He/^{4}He$ ratios with their standard deviations (after Bräuer et al.,2009), line and gray zone – horizontal strains determined for 28-day periods with their standard deviations.

products for both the NAVSTAR and GLONASS satellite systems. Only a few outliers that appeared in the time series of station positions were removed manually.

However, it is necessary to realize that still one subject can substantially diminish an accuracy of the distance determination between KYNS and LUBY stations: possible iono- and/or tropo-spherical variations. They affect the GPS signals and the site position determinations can be influenced. In our case, the distance between our stations is some 20 km only and thus, if any variations occur, the monitored GPS signals alter similarly, and affect identically the site position calculations. It causes that these variations are unable to interfere the diurnal determinations of the relative distance between both stations.

Although nobody disputes the importance and irreplaceableness of the permanent GNSS observations in motion active regions, it is necessary to touch on a question how much site movements detected by the satellite position techniques reflect deep dynamic motions ongoing in the Earth's crust. The plausibility of the kinematic data of the geodetic satellite position systems increases not only with the number of GNSS stations, but also with the density of stations that monitor area under study. The larger the distance between the stations, the more reliably the changes of their positions detect the dynamic processes of larger depths. This fact has been proved by the interpretation of the GPS measurements carried out over large regions (Jackson et al., 2002; Reilinger et al., 2006, etc.). Thus, changes in site positions of more distant stations depend more on the dynamics of the deeper parts of the Earth's crust than on the dynamics of the local structures.

4. HORIZONTAL STRAINS AND $^{3}He/^{4}He$ RATIOS

The processed GNSS data of the diurnal positions of the KYNS and LUBY stations, their geographic latitudes and longitudes, enabled daily changes of their distances to be determined and variations of the horizontal component of the strain field between these two stations to be derived. The daily positions of both stations based on long/term observations and corrected for the motion of the Euro-Asian lithospheric plate enabled to determine the mean value of the baseline length L between these two stations. Then, the differences DL of this distance occurring between the stations during certain periods T allowed the changes in the horizontal deformations to be calculated from the relation

$$\textit{horizontal deformation}\ [\text{strain}/T] = DL\ /\ L\ .$$

Positive DL/L value corresponds to the horizontal extension deformation between the stations and the negative DL/L value to the horizontal compression deformation.

In our case, the baseline length L between KYNS and LUBY stations determined from 2005-2009 GNSS observations is round to 19 919 m. The observed (diurnal) differences DL range in millimetres

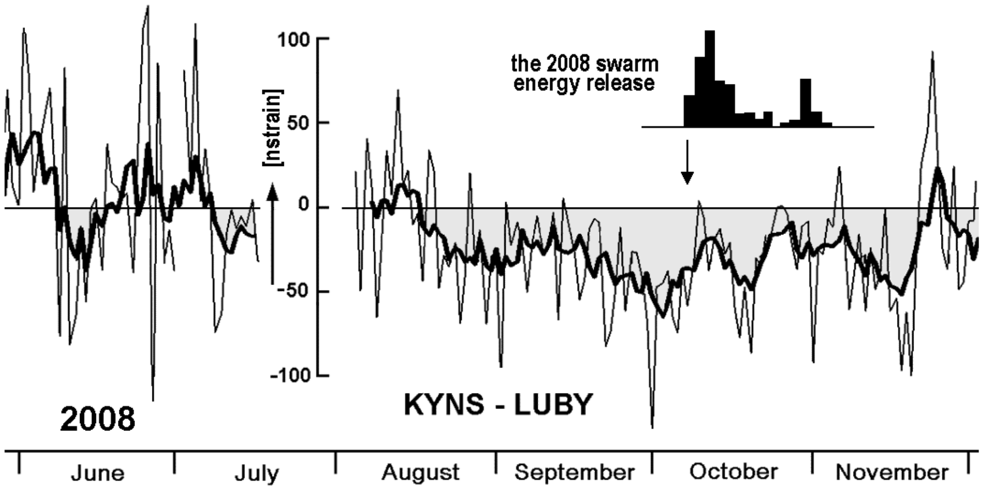

Fig. 3 Variations of the strains detected in June-November 2008 period between the KYNS and LUBY stations and their relation to intensive October 2008 earthquake swarm; thin line – diurnal horizontal strains, bolt line – the mean strains determined from 7 diurnal strain values, and the swarm energy release graph (above) given for double diurnal intervals.

reflect extensional and compressional deformations acting over the area where also the degassing locations of Bublák and U Mostku exist (Fig. 1). The horizontal deformations were calculated in nanostrains; e.g. if L = 20 km and DL = 1 mm, then the deformation corresponds to 50 nstrains.

The diurnal strain scatter reaches ± 30-50 nstrains. In order to compare these values with the $^{3}He/^{4}He$ ratios observed once per month, the mean diurnal strains and their standard deviations for 28-day periods were calculated (Fig. 2). The monthly strains manifest a deformation pattern of the area more reliably because quick and/or short-term strain variations in the medium are not presumed and, in addition, because they eliminate still vestigial scatter of diurnal values. In the period 2006-2007 the mean strains ranged approximately between -100 and +100 nstrains, i.e. *DL* varied from -2 to +2mm. In the same period the $^{3}He/^{4}He$ ratios monitored at Bublák mofette had in the main 5.9 Ra with variations from 5.4 to 6.3 Ra (Fig. 2; Bräuer et al., 2009). Besides, Bräuer et al. (2005) identified that the $^{3}He/^{4}He$ ratios from the Cheb basin are the highest ones measured in free gas samples from continental Europe to the north of the Alps.

Comparison of the strain values [strain/month] and the $^{3}He/^{4}He$ ratios patterns displays a good mutual correlation. However, it is necessary to perceive that both quantities compared have different statistical weights: the $^{3}He/^{4}He$ ratios represent monthly samples taken at Bublák degassing location (Bräuer et al., 2009), while the strains determined statistically from continuously monitored data of two GNSS stations KYNS and LUBY having thousands recorded positions. Therefore, correlation should be understood qualitatively as a relation displaying their common pattern.

Bräuer et al. (2009) correlated the anomalies of the lower $^{3}He/^{4}He$ ratios with two earthquake swarm occurrences originated in the neighbourhood of the degassing localities; it concerned the February and November 2007 swarms (Fig. 1). Since the ratio anomalies correlated well with the negative strain values, we can claim also that prior to the micro-swarm occurrences the geological medium was in conditions of enhanced compression. It has a logical base because faults and fractures under higher pressure reduce their permeability with regard to gaseous components rising up to the Earth's crust.

5. DISCUSSION OF RESULTS

The observed time variations of the $^{3}He/^{4}He$ ratios and regional strains indicate that earthquake swarms can occur when the compressions in the upper Earth's crust decrease. One of the potential sources of generating a variety of compressions in West Bohemia has to be linked to the pressure of the Alpine system acting northwards. In a particular period, together with the motions along the Mariánské Lázně fault zone, the compressions can cause stress imbalances on faults, fractures, cracks, etc. in West Bohemia and reduce their fluid permeability. The fluid components originated by recently existing magmatic plume in the upper lithosphere cumulate themselves and gradually induce higher pressure in lower crust. It reduces progressively the compression of the medium and returns it to the condition of enhanced permeability. At this evolution stage, the fluids penetrate to the higher levels of the Earth's crust and their presence there creates conditions for the generation of earthquake swarms and the crust is turning to more stable stress and/or compression stage.

The positions of the epicentres of both 2007 micro-swarms are shown as hatched ellipses in Figure 1. Seventy-five per cent of the shocks (approx. 670 events) released during the February 2007 micro-swarm originated at depths of 9 to 10 km, whereas more than eighty-five per cent of the shocks (60 events) of the November 2007 micro-swarm originated at depths of 12 to 13km. The foci of the November swarm (Fig. 1; B) lie on the intersection of the Mariánské Lázně fault zone and Počátky-Plesná zone, at locations where the fluids from the lower crust penetrate directly to the upper parts. The foci of the February swarm (Fig. 1; A) are located about 1km NE and 3km shallower than the deeper November swarm foci.

To prove the idea that compressions of the geological medium precede to a swarm occurrence, we used the GNSS data monitored at the KYNS and LUBY stations before and during the 2008 earthquake swarm and calculated the strain variations related to its event series. Unfortunately, for the 2008 swarm period no $^3He/^4He$ ratios observed at the above mentioned degassing locations have been published. The computed strain variations between both GNSS stations (Fig. 3) showed gradual increase of compressions starting already two or more months before the swarm occurrence. As seen, the 2008 swarm occurred approximately a week after the minimum strains (maximum compression) appearance. The relation between strains and swarm occurrence displays an agreement with the above mentioned idea and proves its validity too.

A little oscillating trend of the strain pattern observed for the 2008 swarm possibly reflected still indefinite “balance of the West Bohemian medium” under recent pressure conditions. The balancing could probably relate to permeability barriers in the upper part of the Earth’s crust below that mantle-derived fluids are trapped (Bräuer et al., 2003) and laterally deflected. The barriers possibly cap the active hydraulic system (Parotidis et al., 2003), keep the permanent mantle fluid flux from further rising, increase the fluid pressure that triggers seismicity and temporarily produce variable permeability. The 2008 seismic activity was accompanied by an anomalous pressure in the deep-reaching mineral aquifer system for about 8 months which after the maximum energy release in October 2008 continued to the end of April 2009 (Koch and Heinicke, 2011). For a few months ongoing activity it may be inferred that the regional hydraulic system balanced and arising fluids triggered the 2008–2009 swarm series. Variety pattern of the hydraulic system could probably explain the repeated occurrence of decreased $^3He/^4He$ ratios after active periods of swarm-earthquake seismicity (Bräuer et al., 2008).

6. CONCLUSION

The horizontal strains, calculated for the West Bohemian region between two permanent GNSS stations, were correlated with the $^3He/^4He$ ratios determined from the monthly samples taken at the degassing locations, situated in the central part of this region. A positive correlation was found between both quantities observed in 2006-2007. In case if the strain field indicated that the compressions in the region calmed and the $^3He/^4He$ ratios grew then the earthquake events occurred. The changes in the horizontal strains and $^3He/^4He$ ratios enabled to detect intervals in that compression and extension stages act in the region and provide a probable origin of earthquake swarms. The strain field changes monitored during the 2008 swarm proved the relation between compressions and extensions and earthquake occurrences. It seems also that the observed connections could be applied in future at selected regions in an earthquake forecasting. However, it is necessary to continue in investigations of the compression and extension origin in the Earth’s crust and to specify their effects on the regional geodynamics of West Bohemia.

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