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The Possible Explanation for Secondary Microseisms Seasonal and Annual Variations

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ABSTRACT

Annual drift is typical for microseisms. We propose a model based on thermoelastic wave generation that explains the highest microseisms during winter using higher stress level at the same time. If we remove the average influence of the background stress from the microseisms, we obtain the residual microseisms, which show the semiannual periods with maxima in March and October. The histogram of anomalous microseisms has the same form as the variations in Length of the Day (LOD). This phenomenon is recognized as a secondary order mechanism after the annual drift. The synoptic situations and earthquakes were recognized as imminent triggers of anomalous microseisms. This synoptic situation is consistent with the uplift of the northern part of Europe after ice cap melting.

Key words: Microseisms, Synoptic situation, LOD, Thermoelastic wave

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1. INTRODUCTION

It is widely accepted that microseisms are ubiquitous seismic signals generated by ocean waves (Webb 2007), especially during the winter (Zátopek 1964, 1975). The up-to-date theory anticipates that secondary microseisms (prevailing periods $T \approx 4$ - 10 s) are more likely to be generated in shallow water near the coast, as observed by many authors (Haubrich and McCamy 1969; Cessaro 1994; Bromirski and Duennebier 2002; Rhie and Romanowicz 2006; Tanimoto 2007; Gerstoft and Tanimoto 2007). The most well-known is the annual drift in microseisms amplitudes, which is explained by the annual drift of storms above the Atlantic and Pacific Ocean (Grob et al. 2011).

Holub et al. (2013) showed in their paper that there are at least three other mechanisms, which can lead to secondary microseisms excitation. The first mechanism can be connected with the atmospheric pressure variations, the second is associated with the thermoelastic waves in the rock mass (Hvoždara and Brimich 1988; Brimich 2006), and the third one is associated with large earthquakes (Kalenda et al. 2011). All of the proposed mechanisms are coupled with stress/pressure variations during the year as well as water shoaling. The maximal amplitude represents the annual variation in secondary microseisms, which were considered earlier as they are concerned with the annual trends in windstorms and cyclones (Zátopek 1964). Later Holub et al. 2013 pointed out that similar lows and extensive windstorms above the Atlantic Ocean excited in the summer season did not trigger secondary microseisms with similar intensity as those in winter. This phenomenon can be explained by the fact that the storms are not the reason for microseisms excitation, but only the triggering mechanism, which depends on the stress background, which has an annual period (compare Figs. 5, 7, and 8 in Holub et al. 2013). It can be stated that the excitation of secondary microseisms due to windstorms above the ocean is not the necessary condition for their excitation but represents only a triggering mechanism. Similarly, the third triggering mechanism connected with deformation waves after catastrophic earthquakes shows the same background as this process, i.e., excitation of secondary microseisms after catastrophic earthquakes in summer is relatively low, but the generation of secondary microseisms

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in winter is likely higher, even for less intensive earthquakes from the group of catastrophic ones (Kalenda et al. 2011; Holub et al. 2013).

This paper analyzes the physical background of annual variations in excitation mechanisms for secondary microseisms using annual thermoelastic waves. We will discuss "anomalous" secondary microseisms that exceed the normal annual distribution.

2. THE ANALYSIS OF THE BASIS FOR THE ANNUAL VARIATIONS OF MICROSEISMS

It has been shown that most microseisms anomalies are connected with atmospherics or strong earthquakes (Holub et al. 2013). But, in fact, these influences were only triggers for the anomalous microseisms and not the reason of higher microseisms during winter. Our hypothesis for the annual variations in microseisms was described for the first time in the monograph by Kalenda and Neumann (2011). This hypothesis is based on the generation of the thermoelastic waves in the depths by temperature variations at the surface. We found out that the stress in deep unweathered rock mass is maximal during the winter season when the thermal wave reaches the unweathered rocks. This explains the higher response of the massif on the external forces like air pressure variations or large earthquakes.

Why are microseisms the strongest during the winter? The possible explanation could be thermoelastic waves, described, e.g., by Berger (1975); Ben-Zion and Leary (1986); by Hvoždara and Brimich (1988); by Brimich (2006) or annual hydrogenous regime period (Grillo et al. 2011). The most recent support for this proposed mechanism (of thermoelastic waves) is in monographs by Kalenda and Neumann (2011) and Kalenda et al. (2012) or by Tsai (2011). The maximum rock expansion is observed in winter, as described for example by Brimich (2006) (see Fig. 1). The water level in the deep wells has similar annual variations, but the maximum water level can be observed in spring and summer and the minimum in autumn and winter (see Fig. 1) (Zadro and Braitenberg 1999; Braitenberg et al. 2006; Stejskal et al. 2007; Grillo et al. 2011). This implies that the hydrostatic (and porous) pressure can be maximal in spring and summer, i.e., opposite to microseisms excitation.

The extensometer (strain meter) at the Vyhne tidal station is situated approximately 30 m below the surface in the granite rocks. The gallery is isolated from the surface by doors, which exclude changes of temperature due to air temperature variations on the surface. The maximum rock expansion is observed in late summer and during the winter (see Fig. 1). The maximum of noise in the rocks (difference between consequent samples) is measured at the time of maximal expansion. The noise maximum is the indication of maximum deformation velocity and/or stress maximum in the rock mass in the depths. The maximum noise occurred in autumn and winter practically at the same time as the maximum for secondary microseisms (see Fig. 2). This fact supports the explanation that both observed phenomena (secondary microseisms and noise from the strain) should have the same origin - increasing level of rock mass deformation due to changes in the stress field.

On the other hand, the water level variations are opposite to the strain in the depths with the minimum level of water during the winter. Previous interpretations of this fact were based on the minimum precipitation during winter. However, this interpretation can be different. The fissures or fractures in the upper layers can be open during the winter, when the temperature in the subsurface layers is less than average and, at the same time, the lower layers, which are expanded due to thermal waves from the previous summer, pull them and open the fissures. This interpretation of the observations can be confirmed by measuring the water level in the wells in seismic swarm areas in Western Bohemia. The seismic swarms occurred mostly during the low-level anomaly period for the water, independently of

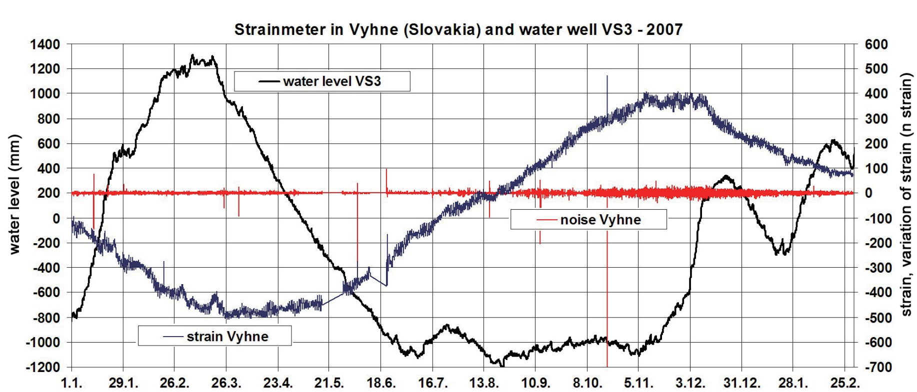

Fig. 1. The annual variations in the strain measured by the extensometer at the Vyhne tidal station in Slovakia (Brimich personal info) and the water level in the well No.VS3 in the Police Basin (Stejskal et al. 2007). (The sudden increases of the water level are the consequence of precipitations). The noise from the strain is measured as the difference between subsequent samples.

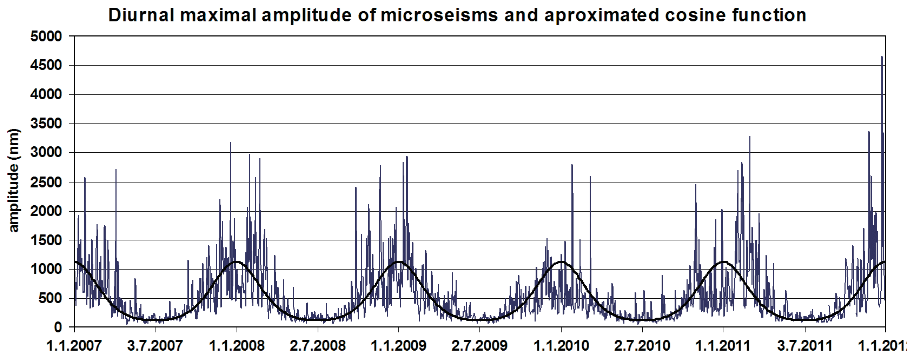

Fig. 2. Diurnal maximal amplitude of microseisms at the OKC seismic station and approximation using the cosine function (in logarithmic scale).

precipitation (Gaždová, Málek personal info).

Therefore, we can generally detect two layers in the massif - the upper, weathered unconsolidated layer, which contains most of water volume collectors and the lower layer, which is mostly unweathered and which can generate thermoelastic waves (Berger 1975; Ben-Zion and Leary 1986; Kalenda and Neumann 2011; Tsai 2011). The theoretical description of the genesis of thermoelastic waves is in the next chapter. The temperatures from the previous summer (and the temperature drop between summer and winter) can be correlated with microseisms during the winter. The mechanisms from the annual variations in stress in the solid part of the massif are the essential reason for the higher microseisms excitation in winter compared with summer.

3. THEORETICAL ANALYSIS OF THERMOELASTIC WAVES

It has been observed for quite a long time that variations in the Earth's surface temperature produce thermoelastic effects in the rock beneath (Berger 1975). While a part of the effect is relevant only to the surface (Harrison and Herbst 1977), another part penetrates deeper into the rocks. As the models show this happens even if the rock is covered by a layer of loose material (Ben-Zion and Leary 1986) and the results are supported by field measurements (Berger and Wyatt 1973; Ben-Zion and Leary 1986; Hvoždara and Brimich 1988; Prawirodirdjo et al. 2006; Kalenda and Neumann 2011; Kalenda et al. 2012). While the temperature is viewed mostly as a source of undesirable noise in thermoelastic strain and tilt measurements that must be subtracted in the analysis of other effects, the role of these thermoelastic effects remains to be fully considered as a source and a trigger factor to large-scale events, in particular earthquakes. The involved sources may seem small at first, but their consistent consequences accumulated over time and their ability to move a system already close to breaking (critical) point over the edge may easily be underestimated.

The basic notations of elasticity theory are the description of stress in a solid material through the stress tensor and the deformation of the solid material through the strain tensor [further details concerning this section may be found in (Landau and Lifschitz 1983)]. The stress tensor σ_{ij} is a symmetric tensor describing the force per area $\sigma_{ij} n_i$ in a plane with unit normal vector n_i (Einstein summation is assumed for repeated indices). The strain tensor u_{ij} is the leading term in the expansion of distance change between points in the solid due to deformations.

The relationship between strain and stress can be obtained in line with general thermodynamic principles from the free energy F:

$$\sigma_{ij} = \frac{\partial F}{\partial u_{ij}} \tag{1}$$

Under the assumption of the material isotropy, the expansion of F up to the second order, in terms of the first order variables of strain u_{ij} and temperature fluctuation T - $T_{0,}$ can be easily obtained through general symmetry arguments:

$$F = F_0 - K\alpha (T - T_0) u_{ii} + \frac{\lambda}{2} (u_{ii})^2 + \mu u_{ij} u_{ij} \\ + \text{higher order terms} \tag{2}$$

The absence of first order terms is enforced by the assumption of equilibrium at vanishing first order variables of the expansion. The second order terms are the only ones that can be formed without violating isotropy (symmetry under rotations). The constants λ, μ of the solid material are known as Lame coefficients. The split of the constant of the first term into the product of constants K, α is a physically motivated convention. Restricting to the second order in the expansion of F, we obtain from Eq. (1) Hook's law:

$$\sigma_{ij} = - K\alpha (T - T_0) \delta_{ij} + \lambda u_{kk} \delta_{ij} + 2\mu u_{ij} \tag{3}$$

Berger's model (Berger 1975) considers a half-space of elastic material with horizontal coordinates x, z, vertical coordinate (depth) y, and with a surface temperature given by a harmonic wave with amplitude τ_0, angular frequency ω, and wave number k (see Fig. 3):

$$T = \tau_0 e^{i(\omega t + kx)} \tag{4}$$

After solving the heat equation:

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T \tag{5}$$

and the equilibrium condition that becomes, in our case, of plane strain:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = 0 \text{ and } \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = 0 \tag{6}$$

we obtain

$$u_{xx} = \left(\frac{1+\sigma}{1-\sigma}\right)\frac{k}{\gamma}\beta\tau_0 e^{i(\omega t + kx)} e^{-ky}\left[2(1-\sigma) - ky\right] \tag{7}$$

$$u_{yy} = \left(\frac{1+\sigma}{1-\sigma}\right)\frac{k}{\gamma}\beta\tau_0 e^{i(\omega t + kx)} e^{-ky}\left(-2\sigma + ky\right) \tag{8}$$

$$u_{xy} = \left(\frac{1+\sigma}{1-\sigma}\right)\frac{k}{\gamma}\beta\tau_0 e^{i(\omega t + kx)} e^{-ky}\left(1 - ky\right) \tag{9}$$

with $\beta = \frac{\alpha}{3}\frac{1+\sigma}{1-2\sigma}$ and the Poisson number σ.

Since the key factor in these expressions governing the penetration depths of the considered effects is e^{-ky}, we may conclude that the surface temperature variation effects are comparable with the wavelength of variations on the surface.

The maximum stress in depths will not be at the time of minimum temperature on the surface, but at the time, when the integral

$$\varepsilon \approx \int_0^R \alpha \Delta\vartheta(h)\, dh \tag{10}$$

is maximal. ε is the lateral strain, R is the Earth's radius, α is the thermal expansibility of rock, $\Delta\vartheta(h)$ is the difference between long-term medium and instant temperature at a given depth, and h is the depth. In the ideal rocks without any cover, the maximum stress, generated by thermoelastic wave will be in late summer or in autumn (see Fig. 3d), but in real rocks, which are cracked or disintegrated to the depth of tens of meters and which are covered by the soils, the maximum of thermoelastic stress in the seismogenic depths will be shifted into the winter months depending on the thickness of the superficial layers in agreement with models by Ben-Zion and Leary (1986) and/or by Tsai (2011) or with the direct temperature measurements in wells (Mareš et al. 1990).

4. SEASONAL VARIATIONS OF MICROSEISMS

Microseisms have an evident annual period. The anomalous microseisms are observed not only in winter. Their relative amplitude could be 3 times higher in comparison with the normal development.

We used data from the OKC seismic station (Czech Republic) (ϕ = 49.8375°N; λ = 18.1472°E) for the analysis of secondary microseisms. Maximum particle velocities (nm s^{-1}) were measured daily at night, between 23:00 - 01:00 UTC, to be disturbed as little as possible by anthropogenic noise, and were subsequently converted to displacement amplitudes (nm). Observations used in this paper cover the time interval from 1 January 2007 to 31 December 2011 (see Fig. 2).

We approximated the curve of maximal amplitude for microseisms at the OKC seismic station (in log-scale) using the cosine function (see Table 1 in Holub et al. 2013 and Fig. 2) and we separated the "anomalous" microseisms, whose amplitude was at least 3 times higher than the average microseisms amplitude (defined by approximated cosine function). The value of 3 was chosen according to the normal distribution of amplitudes around the average value at the 90% significance level (see for example Fig. 3b in Holub et al. 2013). We obtained approximately 10% of the "anomalous" microseisms outside the median of the whole data set.

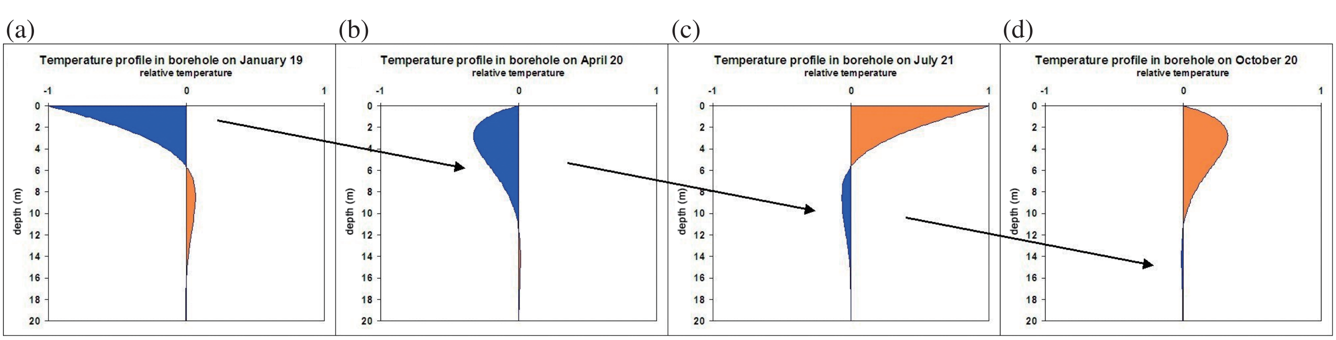

Fig. 3. The theoretical temperature profile in the borehole on January, April, July, and October according to relation (4) and average material parameters.

When we analyzed the histogram of anomalous microseisms occurrence during the year (see Table 2 in Holub et al. 2013 and Fig. 4 here) we can see two local extremes. The first extreme is at the beginning of March and the second between October and December). The histogram correlates well with the Length of the Day (LOD) variations with the regression coefficient $R = 0.59$. Both anomalous microseisms maxima occur in the period of longest days (and the slowest Earth's rotation). The subsurface discontinuities (interlayer boundaries, sub-horizontal faults) are stressed as much as possible at these periods, when the upper layers creep to the west in comparison with the lower layers as shown, e.g., Ostřihanský (in Kalenda and Neumann 2011 and Kalenda et al. 2012). Therefore, the western drift, as was described by many authors (Ostřihanský 2004; Scoppola et al. 2006; Crespi et al. 2007) can be generated in these periods. We can suppose that microseisms are one of the results of this western drift of the continents, which are triggered on the sub-horizontal discontinuities by many various forces (e.g., atmospherics, earthquakes, etc.).

The maximal microseisms are excited in periods, when the optimal conditions for them are fulfilled, i.e., the stress is maximal and/or the Coulomb criterion is fulfilled. The maximum stress in the lithosphere due to thermoelastic waves occurs in winter and the upper part of the lithosphere is pulled to the west due to speeding of the Earth's rotation. The small increments in the stress due to external forces, like air pressure variations or earthquakes, can then excite large microseisms. Why are the largest microseisms observed mostly during the time of low air pressure above the northern part of Europe? This phenomenon can be easily explained by the additional stress field generated by the melting of the northern Europe ice cover 15000 years ago (see Fig. 5a). The northern part of Europe tended to rise up

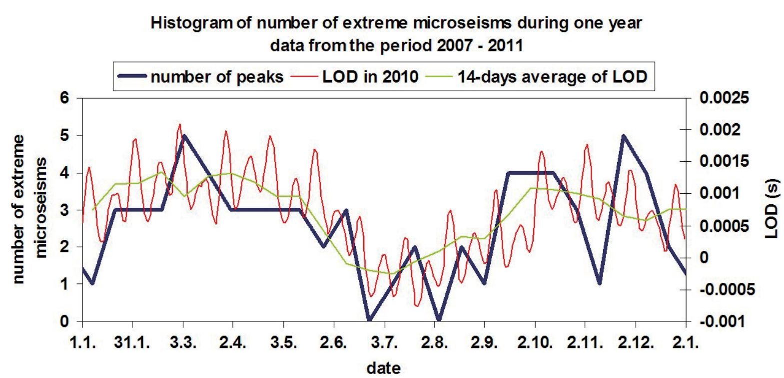

Fig. 4. Histogram of the number of anomalous microseisms during the year (peaks) and annual variations of the Length of the Day (LOD).

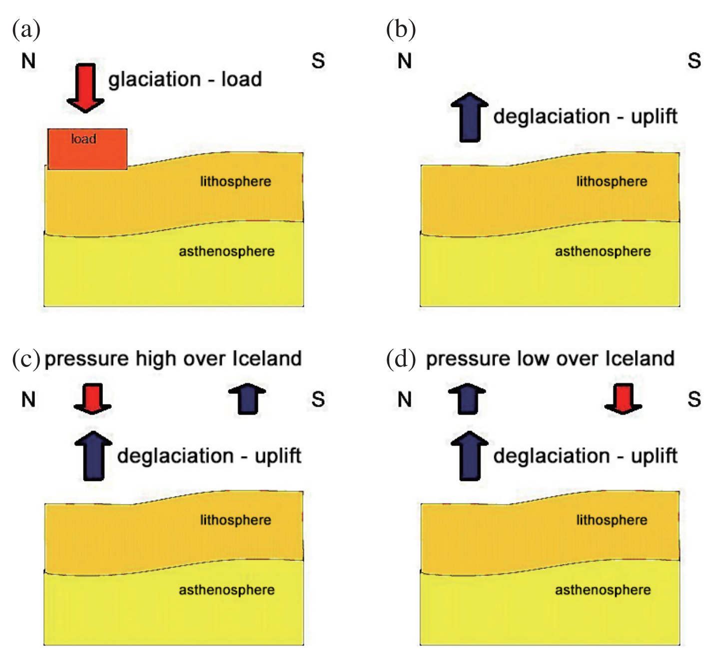

Fig. 5. The stress field model for northern and central Europe and the influence of low air pressure.

by isostasy (see Fig. 5b), which is confirmed by seacoast leveling (Mörner 1972). When we add to this stress field in Europe the part generated by meteorological conditions the primary stress field will then be attenuated during the high air pressure above northern Europe and low air pressure above central and southern Europe (see Fig. 5c) and vice versa. This field will increase during the low air pressure above northern Europe (see Fig. 5d). The highest influence of the meteorological conditions can be observed during the period when the maximum air pressure gradient will be perpendicular with the principal tectonic structures in Europe (WNW - ESE). The northern block will then be uplifted and the southern blocks will decrease (see Fig. 5d).

5. CONCLUSION

Microseisms have an evident annual period with the maximum occurring in winter. We showed using theoretical analysis that this annual period can be connected primarily with annual thermoelastic waves generated in unweathered rocks by thermal waves penetrating the depths. Such thermoelastic stress has its maximum during autumn and winter depending on the thickness of the superficial layers.

The response of massif on the external forces is nonlinear and microseisms have the same non-linear behavior. The microseisms maximum is observed during winter when stress in the rock mass approaches the strength limit of the weakest parts of the massif. Any other weak external force such as air pressure and temperature variations or the strongest earthquakes can then excite microseisms.

When we compare the amplitude of microseisms with normal (average) development (variations), which has an annual period, and when we detect anomalously high microseisms, which are at least 3 times larger than normal microseisms at the same time, we find that the time occurrence is not random, but has the same distribution as LOD variations. The occurrence maximum corresponds with the longest days, when the Earth's rotation starts speeding up. Therefore, we can surmise that the western drift of the lithosphere against the mantle also excites microseisms.

The low air pressure above northern Europe (Scandinavia, Greenland, Iceland, German Sea or Northern Atlantic) and high air pressure above central or southern Europe can be considered as imminent triggers.

The arrival of deformation waves after the strongest earthquakes, which travel mostly in the western direction (Kalenda and Neumann 2011; Kalenda et al. 2012), can be anticipated as the second order mechanism for microseisms excitation.

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