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Earthquake swarms in West Bohemia - their onset and fade

Zemětřesné roje v západních Čechách – jak se probouzí a jak doznívají

Type of thesis

Bachelor´s thesis

Supervisor: prof. RNDr. Tomáš Fischer, Ph.D.

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Prohlášení:

Prohlašuji, že jsem závěrečnou práci zpracoval samostatně a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

V Praze, 23.08.2021

Podpis

Poděkování:

Zde bych velmi rád poděkoval vedoucímu mé práce prof. RNDr. Tomáši Fischerovi, Ph.D. za trpělivost, věnovaný čas, cenné odborné rady, připomínky, poskytování studijních materiálů a literatury. Ještě bych chtěl poděkovat Mgr. Josefu Vlčkovi, Ph.D. za pomoc s přípravou skriptu. Děkuji také své rodině za pomoc a podporu během studia.

Abstrakt

Během posledních 30 let byla v západočeské zemětřesné oblasti přístrojově zaznamenána aktivita různých zemětřesných rojů. Táto práce se zabývá časoprostorovým vývojem seismicity předcházející a následující po vybraných rojích od roku 1992 do 2020. Úvodní část obsahuje stručný popis zájmové oblasti. Rešeršní část seznamuje čtenáře s potřebnými základy seismologie a následně jsou popsány zemětřesné roje – jejich typická aktivita, možné mechanismy vzniku, příklady ze světa a ze Západních Čech. V praktické části je s použitím seismických katalogů vykreslena seismická aktivita předcházející a následující po vybraných rojích. Cílem bylo najit nějaké zákonitosti v časoprostorovém vývoji západočeských zemětřesných rojů. S použitím vizualizace aktivity vybraných rojů podle vlastního hodnocení autora nebyly nalezeny žádné zákonitosti, pro lépe podložený závěr je potřeba provést kvantitativní analýzu.

Abstract

During the last 30 years, the activity of various earthquake swarms has been instrumentally recorded in the West Bohemian earthquake region. This work is studying the spatiotemporal evolution of seismicity preceding and following selected swarms from 1992 to 2020. The introductory part contains a brief description of the area of interest. The research part acquaints the reader with the necessary basics of seismology. In the next, phenomenon of earthquake swarms is described – their typical activity, possible mechanisms of origin, examples from the world and from the West Bohemia. In the practical part, using seismic catalogs, seismic activity preceding and following selected swarms is visualized. The aim is to find some regularities in the spatiotemporal evolution of the West Bohemian earthquake swarms. Using the visualization of the activity of selected swarms and the author's own interpretation, no regularities were found. For a more relevant conclusion a quantitative analysis should be carried out.

Contents

1. Introduction

Measurements of seismic activity in the West-Bohemia/Vogtland region are available from the beginning of 20th century. However, high-quality measurements are available only from the 1985/86 thanks to the installation of first local three-component digital seismic stations VAC and TIS (Vavryčuk, 1993), and later installing of NKC station in 1989, which became the core of the WEBNET network set up in 1994 (Horálek et al., 1996). Considering available data, one can conclude that seismic activity in West-Bohemia/Vogtland is a long-term process; first seismic observations were documented in Medieval times. Using modern technologies, we can delimit present seismic activity in West Bohemia and Vogtland to the area between 49.9° and 51°N and 12.0°and 12.8°E (Fig. 1).

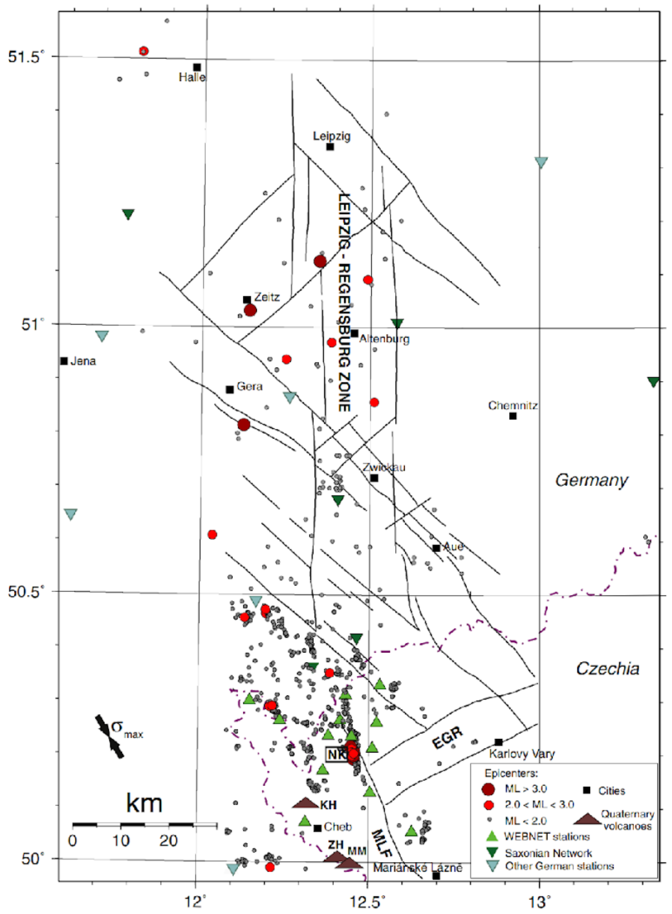


Figure 1: The West Bohemia/Vogtland earthquake swarm region with earthquake epicenters for the 1991 – 2011 period (gray and red circles). Nový Kostel zone is situated at an intersection of Eger Rift (EGR) and Mariánské Lázně fault (MLF). Quaternary volcanoes marked Komorní Hůrka (KH), Železní Hůrka (ZH), and Mýtina Maar are marked with brown triangles. The maximum compression in the region striking 145° is indicated in the lower left corner. Triangles indicate seismic stations of the (WEBNET — green, apex up, SXNET — dark green, apex down, other stations — green-blue, apex down). Black squares denote towns. The Czech–German border is marked by dashed line (Fischer et al. 2014).

Dominating focal depths are between 6 and 15 km, rarely to 25 km, the seismic activity is scattered within an area of about 3500 km^2 and several focal zones can be easily distinguished (Fischer et al. 2014). Horálek et al. (2000) delineated 7 focal zones (Fig. 4).

Prevailing among focal zones is area close to Nový Kostel where almost 90% of total seismic energy was released since 1991 (Fischer and Michálek, 2008). The whole area demonstrates strong episodic character of the activity, but a stable range of seismic moment rate 10^{12}–10^{14} Nm per month in the inter-swarm period indicates lasting seismic activity in the form of single events and microswarms (Fischer et al. 2014). The maximum hypocenter depths vary from 10 to 25 km with an increasing trend towards NW; the deepest hypocenters in the NK zone occur at 12 km.

According to available data on historic seismicity, the earthquake swarm occurrence has shown pronounced migration within the area of 15 × 15 km during the past 200 years (Fischer et al. 2014). It seems that according to the activity, the major focal zone migrates in the following way: about 1824: Hartenberg–Oloví; 1897–1962: Kraslice–Bad Brambach; and 1985–2011: Nový Kostel (Fischer et al. 2014).

The aim of this thesis is to review spatiotemporal distribution of the West-Bohemia swarms before and after swarms and microswarms and address open questions related to potential existence of patterns of swarm type seismic activity in the region. It is not clear whether any of the earthquake swarms in the area has patterns during its evolution and in this thesis, author will try to examine each episode and provide a reasoned answer.

2. Basics of seismology

In this chapter we will introduce some basic terms of seismology. It includes different magnitude scales, seismic moment, epicenter, hypocenter, and simplified explanation of location methods. They are necessary to better understand the earthquake swarms.

2.1.Magnitude

Even though earthquakes around the world are rather different from identical, seismology needs values which can describe earthquakes regardless of strength and place where they happened. For a long time in human history intensity of earthquake was measured empirically according to reported damage caused by earthquake; this way the macroseismic intensity I is defined. Main reasons for that were lack of instruments which can somehow measure intensity of earthquake and absence of a method to interpret measured parameters. First reliable seismograph was constructed by John Milne in 1892. The first magnitude scale was invented in 1935 by Charles Richter. It is called Richter magnitude scale or local magnitude scale. To define local magnitude M_L, we must measure the largest amplitude A recorded on the Wood-Anderson seismograph, distance correction is provided by offset in log A

$$M_L=\log_{10}A(X) - \log_{10}A_0(X)$$

where amplitude of the reference event is A_0 and epicentral distance is X. Richter made a table of values of A_0 and $\log_{10}$ for the different source-receiver distances. Since Richter designed his scale specifically for southern California, local magnitude has problems with portability (Shearer, 2009).

Nowadays M_L is used as magnitude for shallow local earthquakes because it underestimates deep, far, and large earthquakes. Gradual technological progress has led to more accurate instruments and over time there has been a need to measure the magnitude of earthquakes over long distances. In 1950s Gutenberg developed magnitude scale based on body-waves, which is also known as body-wave magnitude

$$m_b=\log_{10}(A/T) + Q(h, \Delta) + \text{station correction},$$

A is the maximum amplitude and T is the dominant period of measured waves, Q is calibration function based on epicentral distance in degrees Δ and event depth h. m_b is varying between stations due to radiation pattern, directivity, and local station effects, therefore station correction is needed for stations which continually give higher or lower m_b values (Shearer, 2009).

Another world-wide magnitude scale used for shallow earthquakes inducing strong surface waves is the surface wave magnitude

$$M_S=\log_{10}(A/T) + 1.66\log_{10} \Delta+3.3$$

A/T is maximum amplitude A divided by dominant period of measured waves T, Δ is epicentral distance measured in degrees.

While using body-wave or surface wave magnitude for stronger events, these magnitudes scales start to saturate. Saturation means that for events stronger than 5.5 for body waves and 8 for surface waves the magnitude is underestimated. This motivated to develop new magnitude scale based on the physical property of the earthquake source by Hanks and Kanamori in 1979 and it is called moment magnitude defined as

$$M_W=\frac{2}{3}[\log_{10}M_0 - 9.1],$$

where M_0 is the moment in Nm (see below). Since moment magnitude is established on the seismic moment of the source, it does not saturate for large events.

2.2.Seismic moment

To characterize earthquake strength from physical viewpoint, in 1966 Aki defined scalar seismic moment as

$$M_0=\mu \underline{D} A$$

where μ is the shear modulus, $\underline{D}$ is average displacement and A is the area of the fault. Scalar moment defined by Aki (1966) is the most widely used parameter to define the strength of the earthquake. Important characteristics of the equation is that it is related to the physical property of the earthquake source.

2.3.Hypocenter, epicenter, location methods

Seismic event can be described not only by its magnitude or intensity, but also by its location. Earthquake's location is one of the most wanted and desired information we can get; it is described by its position on Earth's surface and depth and origin time. Seismic activity starts on a certain area of the fault plane, even though the area of the earthquake's hypocenter could be broad, since P waves are faster than rupture propagation, we can use them to find point of initial displacement. This point is called a hypocenter. Another point directly above the hypocenter on the Earth's surface is called epicenter (Fig. 2).

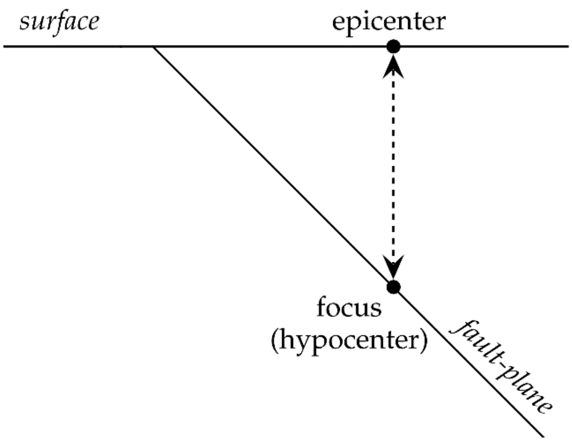


Figure 2: Vertical section perpendicular to the plane of a normal fault, defining the epicenter and hypocenter (focus) of an earthquake (Lowrie, 2009).

Earthquakes' locations around the world require a widespread network of seismic stations. For each event as much as possible data must be collected for better quality of output data. To describe the principle of any location method we can take for example, P and S waves arrival times from one seismic station. This will give an epicentral distance (distance from the station to the epicenter of recorded event), it means that earthquake's epicenter can be at any point at the epicentral distance, if we will draw all these points on the map it will look like a circle with seismic station in the center.

Usually, data from more than one station is available and seismic events can be located relatively to the position of seismic stations. If data from two seismic stations are available, using principle mentioned above, there will be two circles that intersect at two points, and earthquake's hypocenter can be any of these points. And if data from 3 stations is available, in ideal case of constant wave velocity, the circles would intersect in a single point only, and that will be the epicenter. But generally, due to observational errors, heterogeneity and anisotropy of the Earth crust, and some other reasons, the intersections of three circles would form triangle; the optimum location the earthquake's epicenter lies at the center of the triangle (Fig. 3).

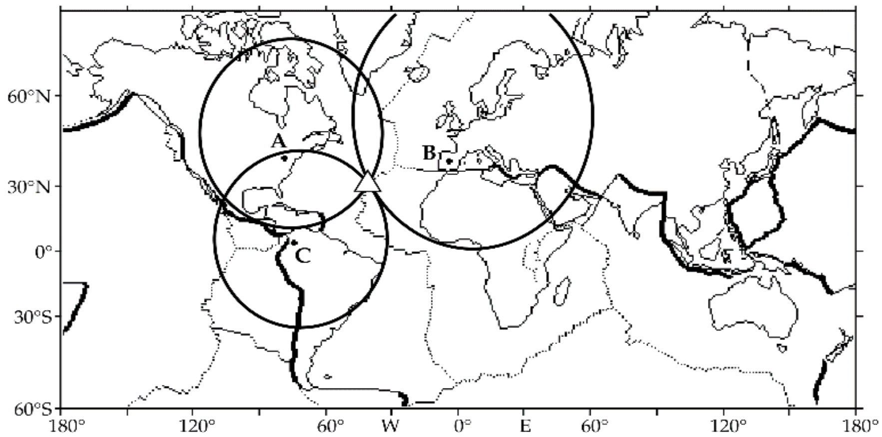


Figure 3: Location of earthquakes using data from three stations (Lowrie, 2009).

This is a geometrical interpretation of location methods. In practice localization in seismology is often considered linear as inverse problem and different methods are used to obtain precise location. For example linearization – based on method invented by Geiger (1912), starts with initial guess and using different mathematical methods problem is linearized, new model calculated and iterates until precision requirement is fulfilled (for example misfit between the observed and predicted travel-times), or direct solving of the nonlinear problem by optimization or grid search.

2.4.Seismicity (M-A, swarms)

Each year millions of different earthquakes are registered around the world. They might be very small or large, shallow, or deep. If we consider distribution of N events with magnitude greater than or equal to M, it can be simply described by Gutenberg-Richter distribution law

$$\log_{10}N=a-bM,$$

(Shearer, 2009) where a is the total number of earthquakes for M>0 and b, which is also called b-value, is equivalent to the ratio of the number of small to the number of large earthquakes. Typical global b-value is 1, which means that the number of seismic events increases 10 times with decreasing magnitude by 1.

Two main types of earthquake sequences can be identified. First is called mainshock-aftershock activity and can be described by one identifiable main earthquake with a sequence of smaller aftershock activity. Seismicity rate during this type of activity decays with Omori's law (Utsu 1961). Second type of earthquake sequence is called earthquake swarms. Earthquake swarms are sequences of seismic events distributed closely by time and space with no distinguishable main event, mostly they can last from a few days up to a few months and their activity does not regularly decay with time. It might be a consequence of a very heterogeneous stress field and/or a weakened crust without a sole well-developed fault which cannot sustain higher strain (Mogi, 1963). Swarm-like activity mostly appears at shallow depth (<10 km), appearing worldwide in various geological units at boundaries of plates, inside the plates and in subduction zones, usually connected with volcanic activity and crustal fluids, and ocean ridges (Horálek et al. 2021). One of the interesting features of swarms is that they tend to migrate during activity. When seismic energy is not enough to cause earthquakes, but enough for triggering seismic swarms then its foci during the initial stage of swarm and/or swarm phase are clustering in the surroundings of the nucleation point and slowly migrate outwards (Horálek et al. 2021). The area of migration is dependent on the activity among different fault patches on the fault plane and can be different as well as migration patterns for the same place but different swarms (Horálek et al. 2021). Migration velocity depends on the character of driving force, for example when swarms are related to dikes intrusion, they might have extremely high migration rate from 0.5 m/s to 2 m/s (Horálek et al. 2021). Because most of the swarms are occurring in the volcanic or post volcanic areas, with high activity of fluids in the crust, Horálek et al. (2021) proposed three possible processes:

a) Migration of magma in the Earth crust
b) Propagation of dike intrusion
c) Diffusion of pressurized hydrothermal fluids

Swarm-like activity in general can be of two types: volcanic and tectonic, therefore several models were proposed to explain the origin of swarms' mechanism (Horálek et al. 2021). Mogi (1963) proposed that they happen due stress concentration consequently to magma intrusion in very heterogeneous rocks. For earthquake swarms in volcanic environments Hill (1977) proposed connection between swarms and offset inflating dikes. Yamashita (1999) proposed the idea that rupturing, and fluid migration are connected.

3. Earthquake swarms

3.2. Typical swarm activity

Earthquake swarms might occur in different environments, such as plate boundaries, volcanic areas inside plates and subduction zones. Typical occurrence of an earthquake swarm is a series of overlapping sequences lasting from a few hours to a few months (exceptionally more), on shallow depth (usually less than 10 km) and with lower magnitudes ($< 5\ M_L$), sometimes with migration between different patches of fault plane.

3.3. Examples worldwide

There are many different examples existing worldwide due to different environments where swarms occur. Swarms related to volcanic activity are for example Yellowstone volcanic field, Alaska, Japan, New Zealand, and Canary Islands. These swarms usually have M_L less than 5 with few up to 6, an extraordinary example is volcanic eruption on Miyakejima in Japan in 2000 with M_{Wmax}=6.4 and a lot of M_w>5 (Minson et al. 2007). Another interesting example from Japan is the earthquake swarm Matsushiro in 2000. During that swarm one of the biggest amounts of energy was released, a series of more than 700000 events with M_{Wmax}=5.4 (Cappa et al. 2009).

Interplate swarms are related to boundaries of tectonic plates. Iceland lies on mid-Atlantic ridge, between Eurasian plate to the east and North American plate to the west, and it is a great example of interplate swarms. Bárðarbunga volcanic eruption went along with an earthquake swarm that started in August 2014 and lasted for 8 months with largest magnitude M_W=5.6 and more than 70 events exceeding magnitude M_W=5 (Horálek et al. 2021). Other examples in Europe are western Alps and a few areas in the Apennines and Greece.

Quaternary volcanism areas with its geodynamic unrest and phenomena like diffuse degassing, geothermal anomalies, and chemical or dissolution anomalies are good conditions for intraplate earthquake swarms (Horálek et al. 2021). These areas are French Massif Central, Colorado, Longvalley in California, and West-Bohemia/Vogtland region.

3.4. West-Bohemia swarms, fluids

As was mentioned above, the West-Bohemia/Vogtland region is an example of intraplate swarms connected with Quaternary volcanism. Present seismic activity is delimited to the area between 49.9° and 51°N and 12.0°and 12.8°E, it is about 3500 km^2 of area with several focal zones and prevailing focal depths between 6 and 15 km (rarely to 25 km) and magnitudes usually are $M_L<4$ (Fischer et al. 2014). This seismoactive region is located in the western part of the Bohemian Massif, where three tectonic units meet: Saxothuringian, Teplá-Barrandian and the Moldanubian. Neotectonic structure Eger rift is trending ENE-WSW and crossing NNW-SSE striking Mariánské Lázně fault (Jakoubková et el. 2018). Volcanic activity in the region is represented by two Quaternary volcanoes Komorní hůrka and Železná hůrka (estimated age 0.3 Ma; Wagner et al. 2002), and the Mytina maar (Geissler et al., 2004; Mrlina et al., 2007, 2009; Proft, 1894; Seifert and Kämpf, 1994). According to different measurements age of Quaternary volcanism was determined to Middle Pleistocene 0.78-0.12 Ma ago (Mrlina et al., 2007; Šibrava and Havlíček, 1980; Ulrych et al., 2003; Wagner et al., 2002). Vylita et al. (2007) studied travertine samples from Karlovy Vary applying ^{230}Th/^{234}U method and discovered that escape of magmatic CO_2 dates back to 0.23 Ma ago, this fact gives another evidence of magmatic reservoir existence beneath West Bohemia.

Within the area of seismic swarms' activity Horálek et al. (2000) outlined 7 focal zones (Fig. 4). Dominating area among focal zones is Nový Kostel which released more than 80% of seismic moment (Fischer and Michálek, 2008).

Fischer (2005) used Green's function (EGF) to study seismograms of 80 selected events of 2000 swarms and discovered that many of them display complex source-time functions composed of several pulses. Later seismogram modeling showed that some of these events were caused by a fast stick-slip rupturing process composed of several episodes separated in time and space. Relative position of the sub-events respecting their orientation shows that most of them occurred on the same fault plane (Fischer 2005). The stick-slip rupturing of the earthquake swarm 2000 might be explained by stress and/or structural heterogeneities which prevented propagation of rupture and generation of larger events; absence of large events is typical behavior for earthquake swarms (Fischer 2005). Applying different methods and its modifications Fischer et al. (2014) discovered that the prevailing focal mechanisms in the Nový Kostel focal zone strikes about 170°, which is parallel to the orientation of the fault plane defined by hypocenter clustering. Orientation of less frequent linked focal mechanisms also matches the macroscopic fault plane, which means that the individual ruptures represent a stepwise rupturing of a major fault plane going along with a system of minor associated faults (Fischer et al. 2014).

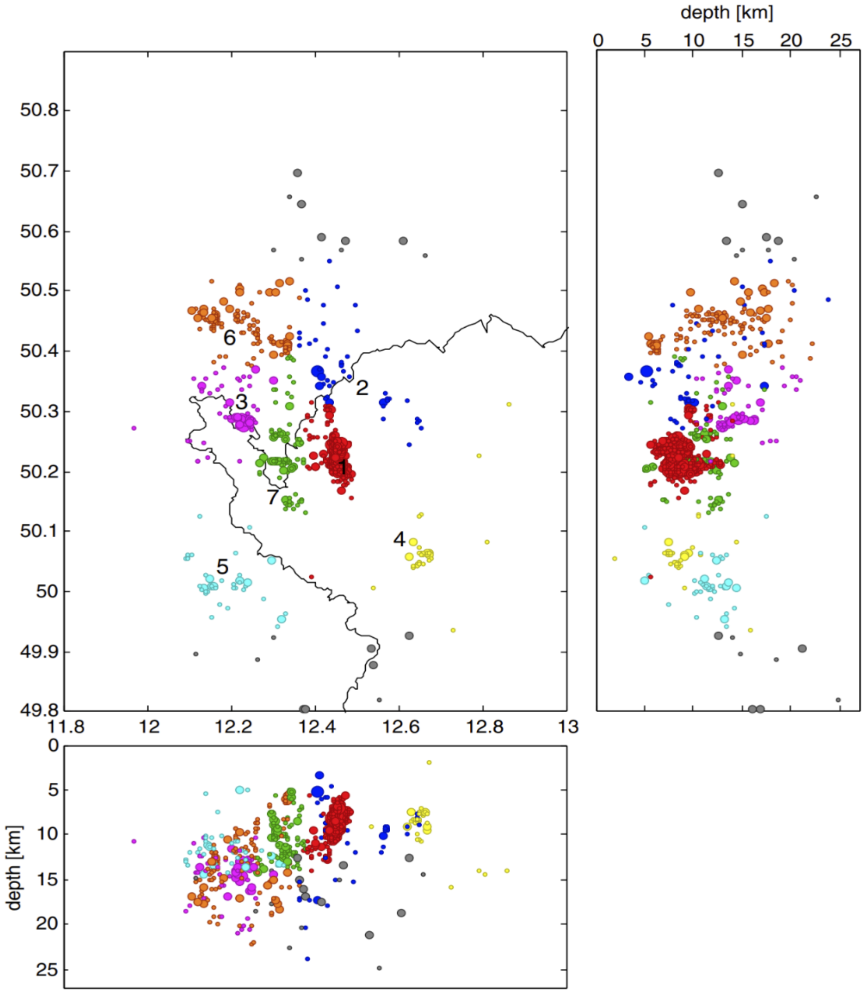


Figure 4: "Hypocenters in the West-Bohemia/Vogtland region from the period of 1991–2012. Individual focal zones are indicated by colors (1 — Nový Kostel (NK), 2 — Klingenthal, 3 — Kopaniny — Adorf, 4 — Lazy, 5 — Marktredwitz, 6 — Schöneck, 7 — Plesná) according to Horálek et al. (2000). Gray epicenters are not associated with any focal zone; the size of the circle is proportional to the event magnitude (Fischer et al. 2015). "

Fluids are important participants in complex geodynamic processes and investigating their role can help better understand mechanisms of these processes. The West-Bohemia region is famous for its mineral water springs and wet and dry mofettes. They are caused by massive CO_2 degassing; the total gas flow is more than 500 m^3/h, and it is mostly concentrated in three degassing areas: 1) Cheb basin 2) Mariánské lázně and its eastern surroundings, and 3) Karlovy Vary (Fischer et al. 2014). These areas are defined by high gas flow with CO_2 concentrations of more than 99 vol.% with about 2-4% of $\delta^{13}C$, and high mantle-derived helium contents (Fischer et al. 2014). Moving away from these areas, gas flow, CO_2 concentration and $^3He/^4He$ ratio decreases (Fischer et al. 2014). CO_2 acts as transport for minor mantle-derived components such as helium. Helium isotopes ratio is a helps to understand if fluids are crustal or mantle origin (Bräuer et al. 2004). Higher compared to the atmosphere, the 3He/^{4}He ratio indicates its mantle origin. As well as the helium isotopes ratio, $\delta^{13}C$ values in CO_2-rich gas escapes also indicate the origin of fluids in the upper mantle (Bräuer et al., 2004; Weinlich et al., 1999). The highest amount of mantle-derived helium was found in the Cheb basin where R_a is up to 6 (R_a is the ratio of ^{3}He/^{4}He in the atmosphere), in the Mariánské lázně up to 4.9 R_a, and 2.5 R_a in the Karlovy Vary (Fischer et al. 2014). Lower R_a (for example <6 R_a) most probably caused by mixing of mantle-derived He with crustal-derived He during its transportation along fluid pathways (Bräuer et al., 2008). Different isotopic studies of ^{3}He/^{4}He ratio and $\delta^{13}C$ of CO_2 in mineral springs and mofettes in West Bohemia/Vogtland shows that three degassing centers are probably supplied by magmatic fluids from separated magmatic reservoirs at the Moho depths (for detailed information see review Fischer et al.2014). The observed pre-seismic decrease of the ^{3}He/^{4}He ratio and increasing the CO_2 emission rate together with groundwater level changes is probably related to strain changes of the rock during the preparatory phase of earthquake swarms (Fischer et al. 2014). The co-seismic change of helium and CO_2 isotopes ratio is possibly connected with a release of crustal-derived volatiles due to fracturing and their admixture to the steadily ascending mantle derived flow (Fischer et al. 2014).

Multiple studies of the West Bohemia/Vogtland region shows that earthquake swarms' activity in the area is caused by stress transfer and external driving force. Fischer et al. (2014) studied occurrences of the earthquake swarms in the whole West Bohemia/Vogtland region and found that they are correlated at interevent times below 11h, that implies a common triggering force. Omori-type decay, ETAS analysis, and the Coulomb stress analysis of the 2000 and 2008 swarms indicates that activity in the Nový Kostel area is driven by stress transfer among individual earthquakes and latter two methods also show that there was repeated external force (possible fluid injection) at the beginning of the 2000 and 2008 activity, which might initially have triggered the activity (Fischer et al. 2014). Another role of pressurized fluids is keeping near-critical loading of the focal zone to decrease the effective normal stress and make stress triggering possible, despite the tiny stress change compared to the running activity (Fischer et al. 2014). Hypocenter spreading provided better understanding of the high fluid pressure. It agrees with pore pressure diffusion models and fits even better in the model of hydraulic fracture the preferential growth in the up-dip direction (Fischer et al. 2014). Low V_P/V_S ratio found in the focal zone independently indicates that gaseous fluid phase was involved, and it leads to a high fluid pressure model (Fischer et al. 2014).

4. Analysis of migration of West Bohemia swarms

4.2. Data on selected swarms - catalogs

Analysis of earthquake swarms requires data from multiple stations and from the broad area. For this thesis due to technical reasons the seismic catalog was formed by two parts provided by the supervisor and WEBNET. The first part provided by the supervisor contains data from 1992 to 2005 with magnitude M>0. The second part provided by WEBNET contains data from 1995? to 2020, magnitude not limited from bottom. The second part contained some gaps before 2006, which was the reason to join the catalogs in 2006 to make the magnitude M>-1 part as long as possible; this is illustrated in figure 5. Because no statistical analysis is carried out, the varying magnitude of completeness does not matter.

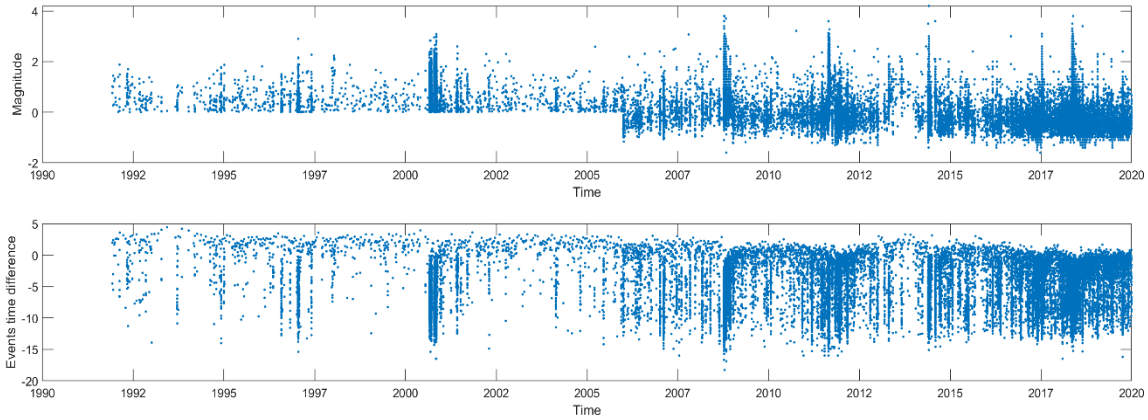


Figure 5: Magnitudes and events time difference (interevent time) of seismic events in West Bohemia/Vogtland. Catalog due to technical reasons was formed from two parts, the first part (1992-2005) contains data with magnitudes M>0, the second part (2006-2020) contains data with magnitudes M>-1.

4.3. Methods used – space-time plots – maps

After preparing data for visualization, the next goal was to identify well known and less known swarms in West Bohemia/Vogtland. Earthquake swarms are clustered in time and space. Using interevent time and magnitude graphs it is easy to visually identify sequence clustered in time, it will look like a column in the graphs, this sequence is potential earthquake swarm due to clustering in time (Fig. 6).

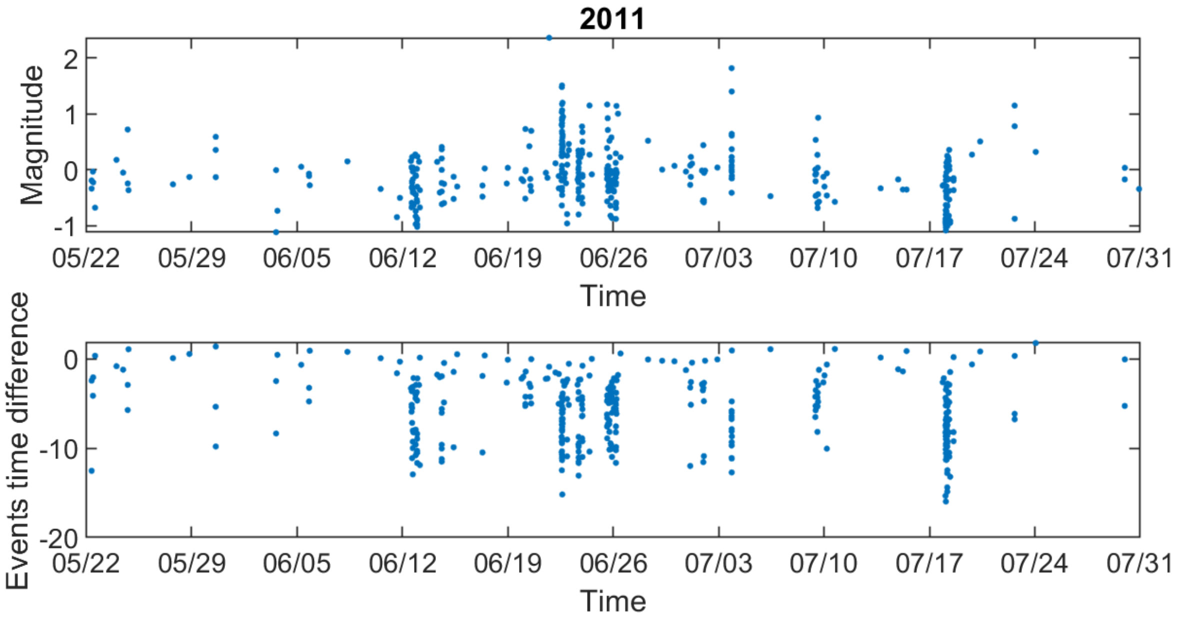


Figure 6: Magnitudes and interevent time graphs in 2011 in West Bohemia/Vogtland

Potential swarms identified by clustering in time (Fig. 6), must be further verified. For this purpose, MATLAB (by MathWorks) script is used to verify clustering in space for potential earthquake swarms. The script is drawing events on the map, it was prepared by a supervisor and consultant, the script allows to choose the date of the interested sequence and the time window for the event. When the date and time window for the event are set, the script provides a graph of the magnitudes versus time where earthquake swarms are visually identifiable and there can be limited in the beginning and the end of the swarm by clicking on the graph. After swarm's boundaries are set, MATLAB highlights events before swarm with red color, after swarm with blue color, and plots their epicenters on the map (Fig. 7). Same script and principle were used to study events from 1992 to 2020 and visualize swarms. The purpose of this method is to find interesting swarms' occurrences in time and/or space, to show what happened before and after the swarms, and potentially find interesting microswarms.

Filtering of the catalog was used to verify whether some distant events are caused by location errors. Filtering parameters are root mean square of the location (RMS) and sum of errors in X, Y, and Z directions. Histograms of root means square (RMS) of the location and sum of errors in X, Y, and Z directions histogram were used to set filtering level(Fig. 8) Initially filtration started at 4000 meters for sum of errors (in X, Y, and Z directions) and 0.1 second for RMS. Gradually filtration level of RMS and sum of errors (in X, Y, and Z directions) was shifted to 1000 meters and RMS 0.05s. Comparing maps before and after filtration revealed that filtration does not significantly affect outlier events occurrence displayed by the script mentioned above.

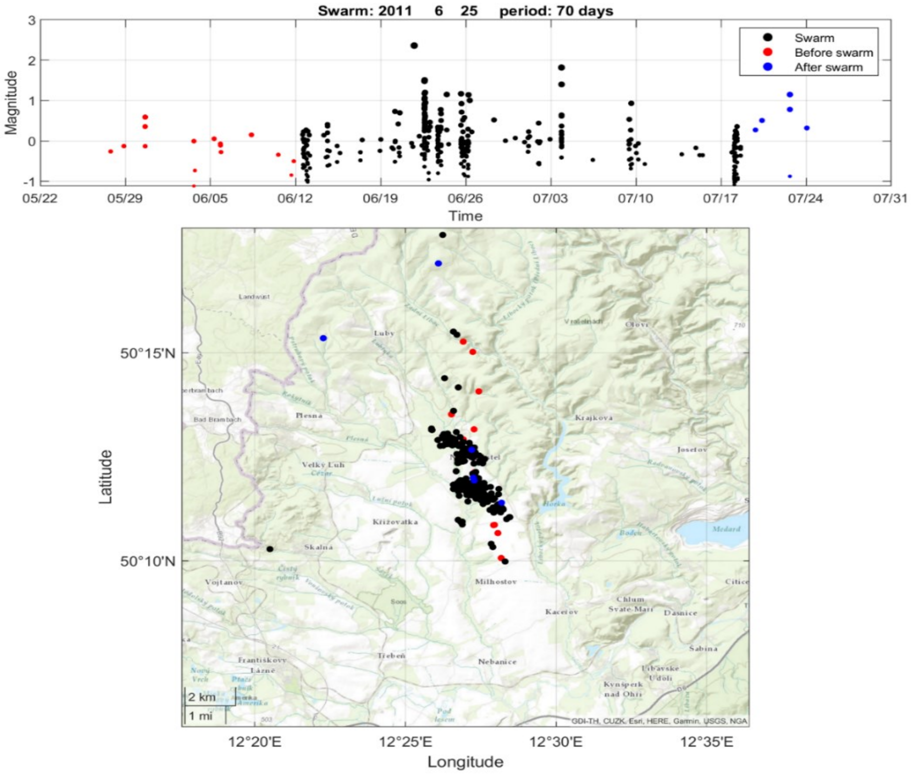


Figure 7: Example of map generated by MATLAB script, red dots are events before the swarm, black dots are events during the swarm, and blue dots are events after the swarm. The period of 70 days was chosen to include the main swarm activity

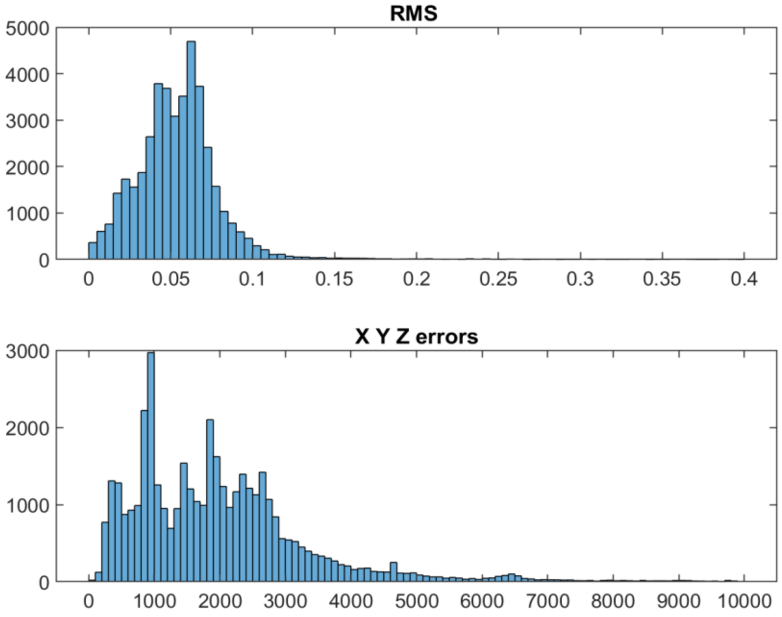


Figure 8: Histogram of RMS and sum of XYZ errors for the whole catalog.

4.4. Interaction between swarms - categorization

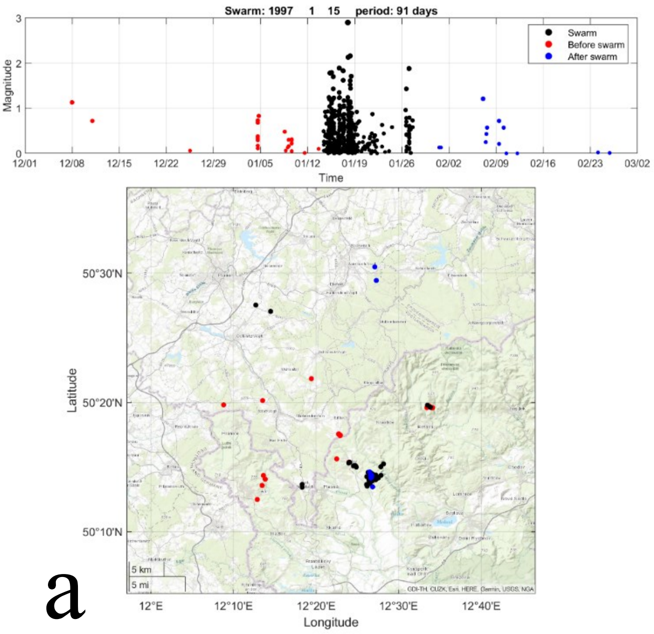
Gathered maps of earthquake swarms in the area exhibit different behavior. For better understanding and illustration of different swarms' behavior I decided to divide them to three categories:

1. Major swarms - their precursors and echoes
2. Minor swarms switching between different areas
3. Minor swarms in Nový Kostel area only

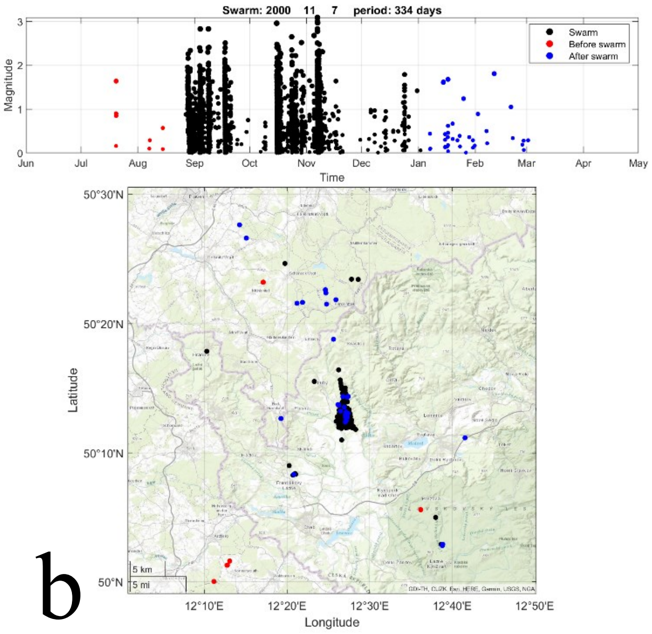
Although earthquake swarms are already categorized to three categories, swarms in the same category still show different behavior. It appears that more detailed categorization would be useful but it is out of scope of this thesis.

4.4.1. Major swarms, their precursors and echoes

Activity in 1997, 2000, 2011 and 2014 was not characterized by any visible precursor, there was minor activity before and after the swarm (Fig. 9). On the other hand, activity in 2017 (Fig. 10) was preceded by microswarms in Plesná, Lazy, Kopaniny – Adorf, and Klingenthal areas (see fig. 3). Swarm itself appeared in Nový Kostel area, activity faded in Kopaniny – Adorf and Lazy areas.



a



b

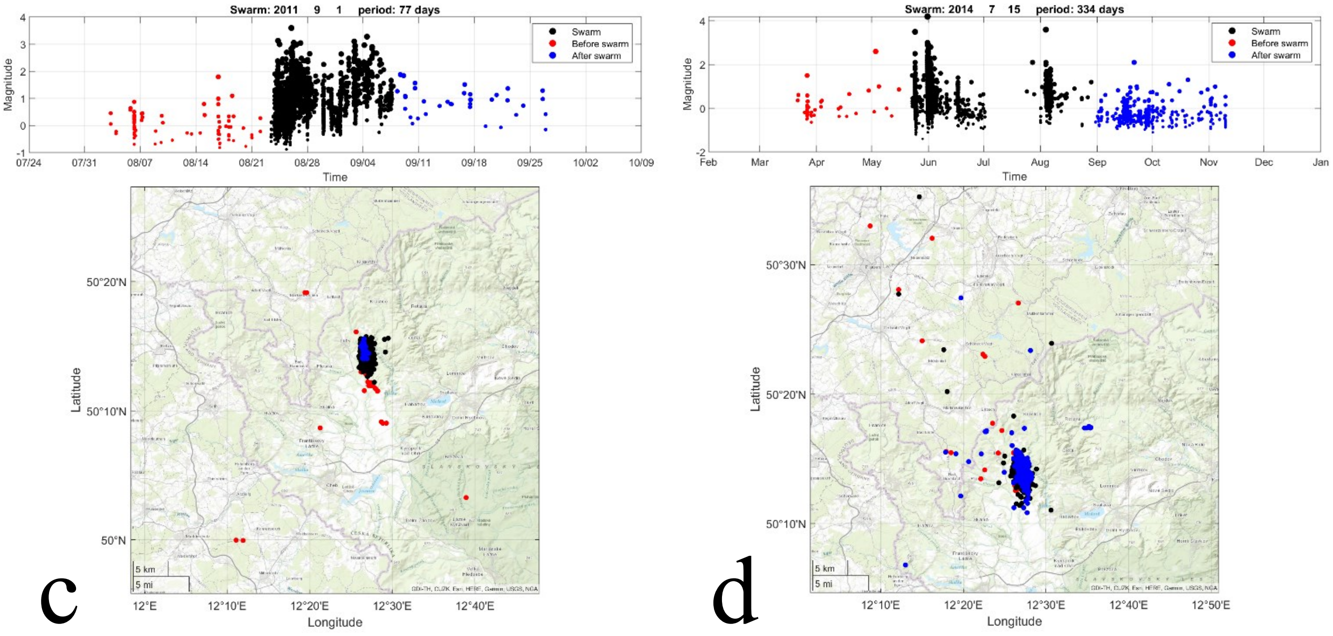


Figure 9: Earthquake swarms in 1997 (a), 2000 (b), 2011 (c) and 2014 (d), see Fig.7 for meaning of the symbols.

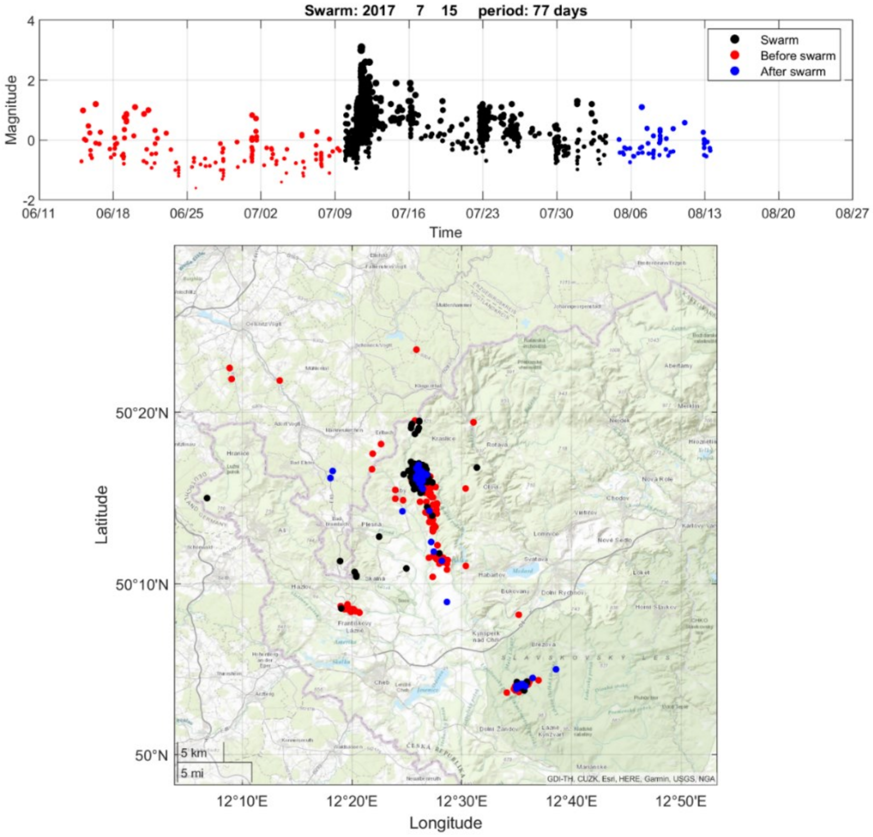


Figure 10: Earthquake swarm in 2017, see Fig.7 for meaning of the symbols.

4.4.2. Minor swarms switching between different areas

The second category contains minor swarms that switch between different areas; they have relatively faster interactions (period <42 days). 1996 swarm shows weak swarms with very fast (<14 days) interaction between Nový Kostel and Plesná zones (Fig. 11). Interesting distant swarm interaction appeared in 2015, in the Nový Kostel zone and Karlovy Vary, that didn't appear before or after in the studied catalog (Fig. 12).

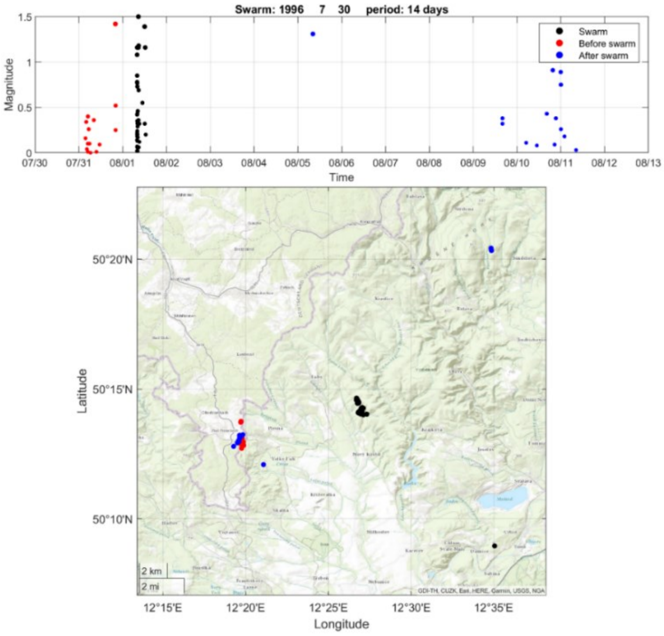


Figure 11: Swarm 1996, fast interaction between Nový Kostel and Plesná zones, see Fig.7 for meaning of the symbols.

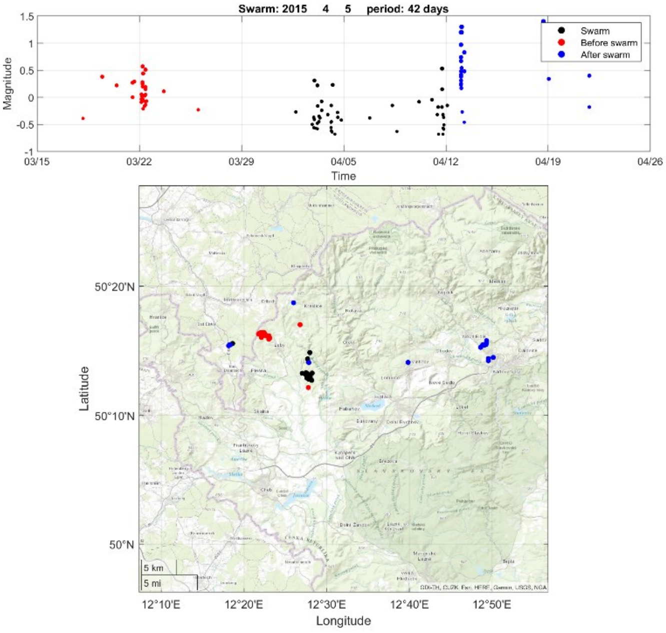


Figure 12: Distant swarm, near Karlový Vary in 2015, see Fig.7 for meaning of the symbols.

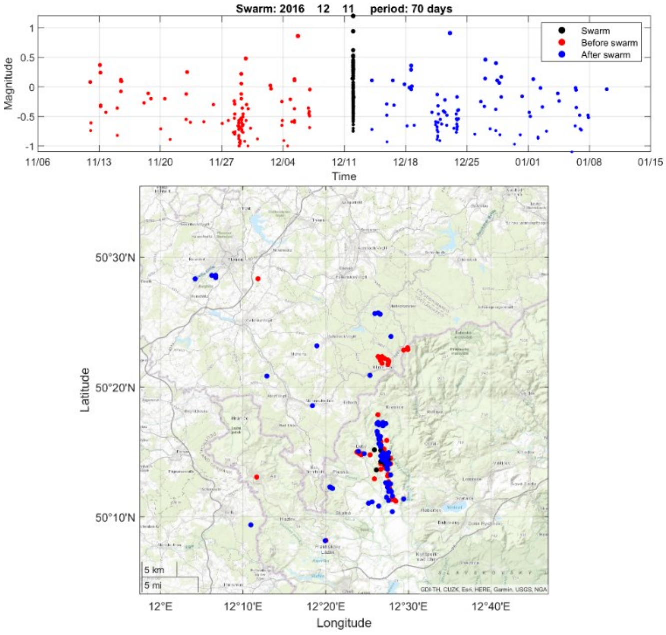


Figure 13: Earthquake swarm activity throughout the whole fault zone in 2016, see Fig.7 for meaning of the symbols.

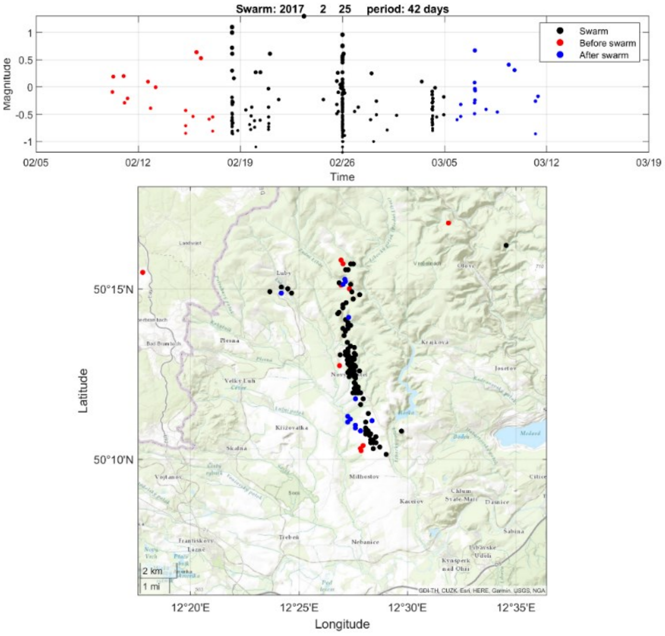


Figure 14: Earthquake swarm activity throughout the whole fault zone in 2017, see Fig.7 for meaning of the symbols.

During 2016, activity was present throughout the whole fault zone, for better illustration a longer period (70 days) is used (Fig. 13), the same phenomenon continued in 2017 (Fig. 14) and followed by major earthquake swarm in July 2017 (Fig. 10).

4.4.3. Minor swarms in the Nový Kostel area only

The third category consists of swarms occurring in the Nový Kostel area only, there is no interaction with other focal zones, swarms are weaker comparing to major swarms (strongest events are with magnitude M<2.5). For this group longer time window was used (period 49 – 98 days) to show that there are no significant events before or after swarms. Selected swarms from 2007 to 2012 show typical example for this group (Fig. 15).

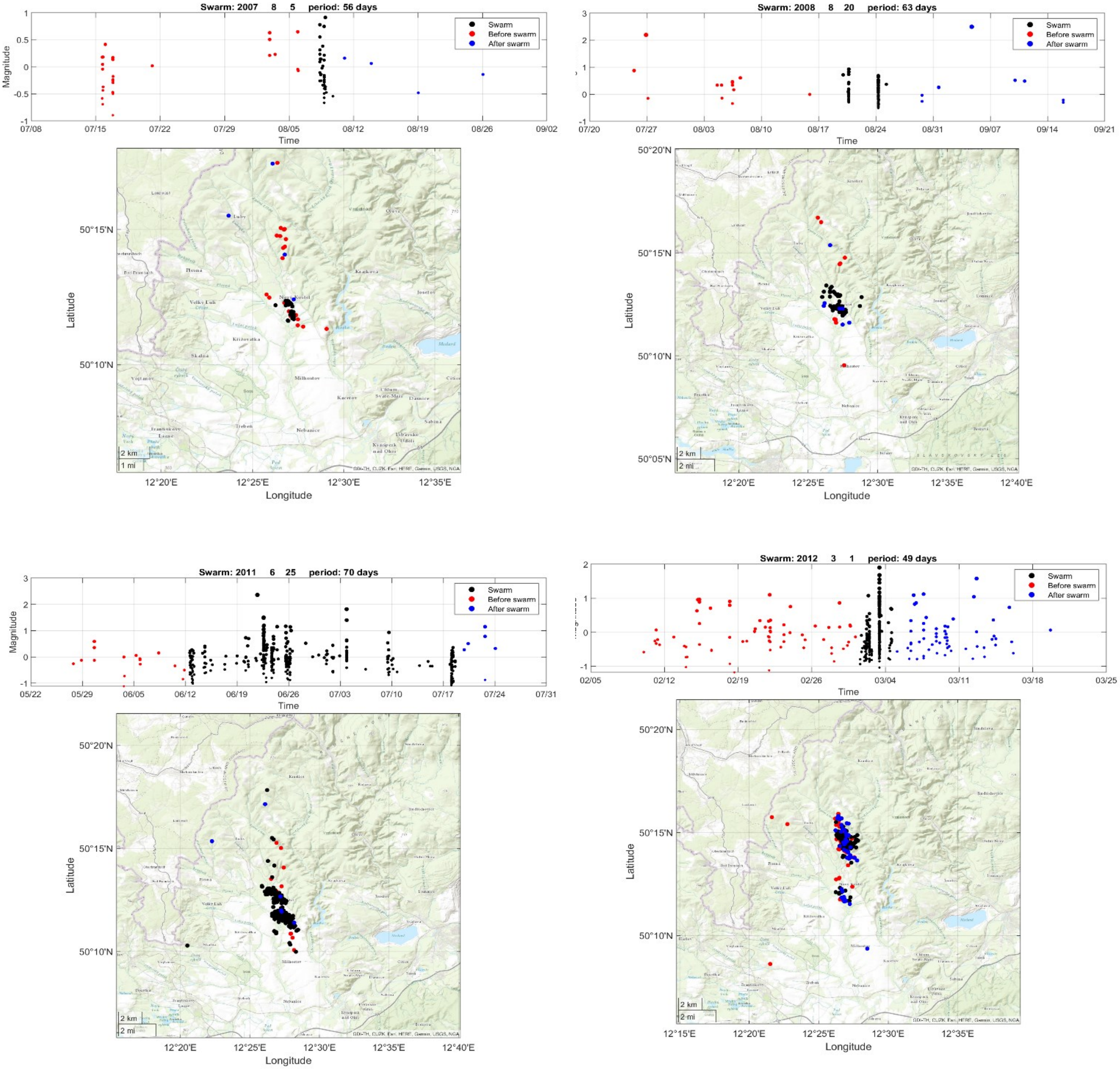


Figure 15: Selected swarms from 2007 to 2012, see Fig.7 for meaning of the symbols.

In 2013 southern and northern subclusters in Nový Kostel area were active simultaneously (Fig. 16).

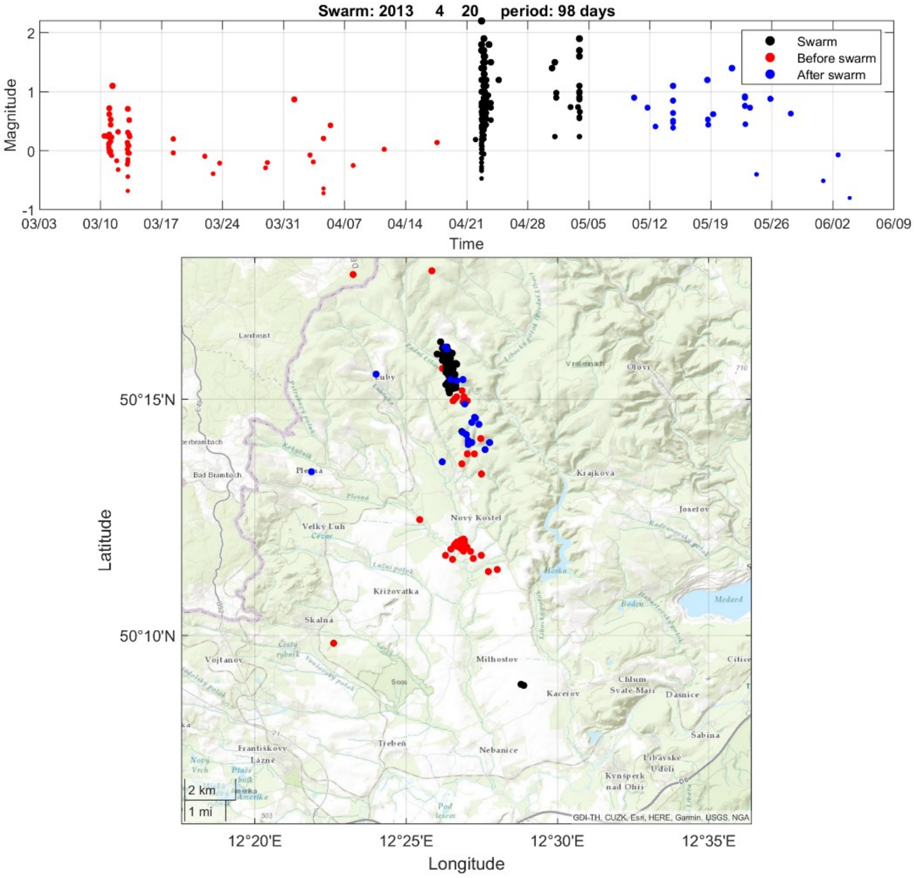


Figure 16: Activity of southern and northern subclusters in Nový Kostel area. See Fig.7 for meaning of the symbols.

Discussions and conclusions

This thesis describes earthquake swarms which appear to me as quite interesting type of seismic sequence. Earthquake swarms occur all over the world and in various conditions. Considering that the swarms' magnitudes usually are less than that of ordinary earthquakes, in West Bohemia, the magnitude is usually $M_L<4$, high-precision recording is needed for high-quality swarm observation. The first high-precision instrumental observations in this area began from 1985/86. For this thesis was a joint catalog for the period 1992 – 2020 was compiled using data provided by the supervisor and WEBNET. To identify swarms, I studied clustering of seismic sequences in time and space. The beginning and the end of each swarm was picked according to my opinion. I selected total 28 swarms from 1992 to 2020 for more detailed research in terms of the space and time evolution with respect to the occurrence of the activity before and after the individual sequence. Maps were created with the selected swarms; the selected earthquake swarms were distributed to three categories:

1. Major swarms - their precursors and echoes
2. Minor swarms switching between different areas
3. Minor swarms in Nový Kostel area only

Total 15 maps were used as examples in this thesis to represent each category. The first category contains major swarms ($M_L<4$) with longer periods (77 – 334 days), the second category are minor swarms ($M_L<2$) with faster interactions (14 – 77 days) between different zones, the third category is about medium fast (49 – 98 days) minor swarms in the Nový Kostel area only. Categories were proposed for the better illustration of the different swarms, categorization of the swarms is performed according to author's opinion. Activity before, during, and after swarms was studied to identify any regularities in activity. Author did not find any pattern of swarms' activity using this method during mentioned period. The beginning and the end of each swarm was picked according to my opinion, also there are no strict rules for each category, and no statistical analysis was performed, so the results should be considered subjective. For this reason, detailed quantitative analysis is needed to provide more relevant conclusions.

References

1. Aki, K., 1966. Generation and propagation of G waves from the Niigata earthquake of June 14, 1964. Part 2. Estimation of earthquake moment, released energy and stress-strain drop from G wave spectrum. Bulletin of the Earthquake Research Institute, 44: 73–88.
2. Bräuer, K., Kämpf, H., Niedermann, S., Strauch, G., Weise, S.M., 2004. Evidence for a nitrogen flux directly derived from the European subcontinental mantle in the Western Eger Rift, central Europe. Geochim. Cosmochim. Acta 68, 4935–4937.
3. Cappa, F., Rutqvist, J., Yamamoto, K., 2009. Modeling crustal deformation and rupture processes related to upwelling of deep CO2-rich fluids during the 1965–1967 Matsushiro earthquake swarm in Japan. J Geophys Res 114, B10304.
4. Farrel, J., Husen, S., Smith, R. B., 2009. Earthquake swarm and b-value characterization of the Yellowstone volcano-tectonic system. J Volcanol Geotherm Res 188(1–3):260–276
5. Fischer, T., Horálek, J., 2005. Slip-generated patterns of swarm microearthquakes from West Bohemia/Vogtland (central Europe): evidence of their triggering mechanism. J. Geophys. Res. 110, B05S21.
6. Fischer, T., Horálek, J., Hrubcová, P., Vavryčuk, V., Bräuer, K., Kämpf, H., 2014. Intra-continental earthquake swarms in West-Bohemia and Vogtland: A review. Tectonophysics 611 (2014) 1–27.
7. Fischer, T., Michálek, J., 2008. Post 2000-swarm microearthquake activity in the principal focal zone of West Bohemia/Vogtland: space-time distribution and waveform similarity analysis. Stud. Geophys. Geod. 52, 493–511.
8. Geiger, L., 1912. Probability method for the determination of earthquake epicenters from the arrival time only. Bull. St. Louis. Univ 8, 60–71.
9. Geissler, W.H., Kämpf, H., Bankwitz, P., Bankwitz, E., 2004. The Quaternary tephra–tuff deposit of Mýtina (southern rim of the western Eger Graben/Czech Republic): indications for eruption and deformation processes (in German with summary in English). Z. Geol. Wiss. 32 (1), 31–54.
10. Geissler, W.H., Kämpf, H., Kind, R., Klinge, K., Plenefisch, T., Horálek, J., Zedník, J., Nehybka, V., 2005. Seismic structure and location of a CO2 source in the upper mantle of the western Eger rift, Central Europe. Tectonics 24 (TC5001).
11. Hanks, T. C., Kanamori, H., 1979. Moment magnitude scale. J. Geophys. Res. 84, B5, pp. 2348-2350.
12. Hill, D. P., 1977. A model for earthquake swarms. J. Geophys. Res. 82(8), pp. 1347–1352.
13. Horálek, J., Boušková, A., Hampl, F., Fischer, T., 1996. Seismic regime of the West-Bohemian earthquake swarm region: preliminary results. Stud. Geophys. Geod. 40, 398–412.
14. Horálek, J., Fischer, T., Boušková, A., Jedlička, P., 2000. The Western Bohemia/Vogtland region in the light of the WEBNET network. Stud. Geophys. Geod. 44, 107–125.
15. Horálek, J., Fischer, T., Einarsson, P., Jakobsdótir S. S., 2021. Chapter: Earthquake Swarms in Encyclopedia of Earthquake Engineering, Springer-Verlag, Berlin Heidelberg.

16. Jakoubková, H., Horálek, J., Fischer, T., 2018. Mainshock-Aftershock Activity Versus Earthquake Swarms in West Bohemia, Czech Republic. Pure Appl. Geophys. 175, 109–131.
17. Kämpf, H., Geissler, W.H., Bräuer, K., 2007. Combined gas-geochemical and receiver function studies, of the Vogtland/NW-Bohemia intraplate mantle degassing field Central Europe. In: Ritter, J.R.R., Christiansen, U.R. (Eds.), Mantle Plumes — A Multidisciplinary Approach. Springer-Verlag, Berlin-Heidelberg-New York, pp. 127–158.
18. Lowrie W., 2009. Fundamentals of Geophysics Second Edition. Cambridge University Press, New York, 375 pp.
19. Minson, S. E., Dreger, D. S., Burgmann, R., Kanamori, H., Larson, K. M., 2007. Seismically and geodetically determined nondouble-couple source mechanisms from the 2000 Miyakejima volcanic earthquake swarm. J Geophys Res 112, B10308.
20. Mogi, K., 1963. Some discussions on aftershocks, foreshocks and earthquake swarms — the fracture of semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena. Bull. Earthq. Res. Inst. 41, 615–658.
21. Mrlina, J., Kämpf, H., Geissler, W.H., van den Bogaard, P., 2007. Proposed Quaternary maar structure at the Czech/German boundary between Mýtina and Neualbentreuth (western Eger Rift, Central Europe): geophysical, petrochemical and geochronological indications. Z. Geol. Wiss. 35, 213–230
22. Proft, E., 1894. Kammerbühl und Eisenbühl, die Schichtvulkane des Egerer Beckens. Jahrb. Geol. Reichsanst. Wien 44, 25–85.
23. Seifert, W., Kämpf, H., 1994. Ba-enrichment in phlogopite of a nephelinite from Bohemia. *Eur. J. Mineral.* (6), 497–502.
24. Shearer P. M., 2009. Introduction to Seismology. Cambridge University Press, New York, 391 pp.
25. Šibrava, V., Havlíček, P., 1980. Radiometric age of Plio-Pleistocene volcanic rocks of the Bohemian Massif. Věstník Ústředního Ústavu Geologického 55, 129–139.
26. Ulrych, J., Lloyd, F.E., Balogh, K., 2003. Age relations and geochemical constraints of Cenozoic alkaline volcanic series in W Bohemia: a review. Geolines 15, 168–180.
27. Utsu, T., 1961. A statistical study of the occurrence of aftershocks. Geophysical Magazine. 30: 521–605.
28. Vavryčuk, V., 1993. Crustal anisotropy from local observations of shear–wave splitting in West Bohemia, Czech Republic. Bull. Seismol. Soc. Am. 83, 1420–1441.
29. Vylita, T., Žák, K., Cílek, V., Hercman, H., Mikšikova, L., 2007. Evolution of hot-spring travertine accumulation in Karlovy Vary/Carlsbad (Czech Republic) and its signifikance for the evolution of Tepla valley and Ohre/Eger rift. Z. Geomorphol. N.F. 51, 427–442.
30. Wagner, G.A., Gögen, K., Jonckhere, R.,Wagner, I., Woda, C., 2002. Dating of Quaternary volcanoes Komorní hůrka (Kammerbühl) and Železná hůrka (Eisenbühl), Czech Republic, by TL, ESR, alpha-recoil and fission track chronomertry. Z. Geol. Wiss. 30, 191–200.
31. Weinlich, F.H., Bräuer, K., Kämpf, H., Strauch, G., Tesar, J., Weise, S.M., 1999. An active subcontinental mantle volatile system in the western Eger rift, Central Europe: gas flux, isotopic (He, C, and N) and compositional fingerprints. Geochim. Cosmochim. Acta 63, 3653–3671.

32. Yamashita, T., 1999. Pore creation due to fault slip in a fluid-permeated fault zone and its effect on seismicity: generation mechanism of earthquake swarm. Pure Appl Geophys 155:625–647