TOOL FOR FINITE SEISMIC SOURCE PARAMETERS DETERMINATION - STOPPING PHASES METHOD, VER. 2

P. Kolář

Institute of Geophysics, Czech Acad. of Sci. of Czech Rep.

Abstract

A special (interactive) Tool for particular processing of seismograms from West Bohemian seismic region has been already presented (TCP2011); the purpose of the study is to determine the parameter of (simplified) seismic source model. In the present contribution we inform about code current stage, processed data and obtained results (seismic swarms from 2000 and 2008 years were investigated), as well as about particular improvements and development, namely incorporation of (i) more precise onset time determination (with use of signal over-resampling), correction of effect of (ii) anisotropy and (iii) attenuation; the graphical appearance of the Tool has been also tuned.

1 Background and motivation

West Bohemian region is definitely the most seismo-active region on the territory of Czech Republic. The seismic activity is one of the features of geodynamics processes which perform in this region. West Bohemia seismic events are clustered in so named seismic swarms. Such type of seismic activity is known also in other regions (e.g. Iceland, Sultz in France, north Italy), but it has been firstly investigated just in West Bohemian region in 19th century.

West Bohemian swarm activity can be traced back to middle ages, instrumental observation can be dated to beginning of 20th century. Local network of (analogues) seismic stations was build up in Germany part of the region in 1962. The modern, i.e. digital, observations were started during pronounced seismic swarm which occurred in 1985/86. At that time it was established WEBNET - a network of digital seismic stations (Horálek et al., 2000), Fig. 1a, b. The WEBNET network continuously operates; of course during the time it was enlarged (up to contemporary number of about 20 stations), the equipment is permanently modernized, the network shape was tuned to optimum. Data transfer from selected stations is now continuous and on-line.

At the beginning of digital seismic observations, the main effort was concentrated on basic data processing, e.g. routine pre-processing, event identification, location, magnitude determination. Lately, the investigated tasks were enlarged to time-spatial distribution study, seismic source mechanism of larger events determination (at the beginning only double couple model was considered, lately full 6 component seismic moment tensor are determined). Together with these tasks there were performed also some structural studies. During approximately last decade, such studies become a little bit routine (even if still they are of significant importance and by far not all the problems has been solved yet) and it has arisen a highly specialized studies, as e.g. determination parameters of a finite source mode. This is also the case of our study.

The observed data are permanently subject of various studies – see e.g. Stud. Geophys. et Geod., (2000, 2008 and 2009). Actual information about the West Bohemia activity can be found on wwwWEBNET (2011a, b).

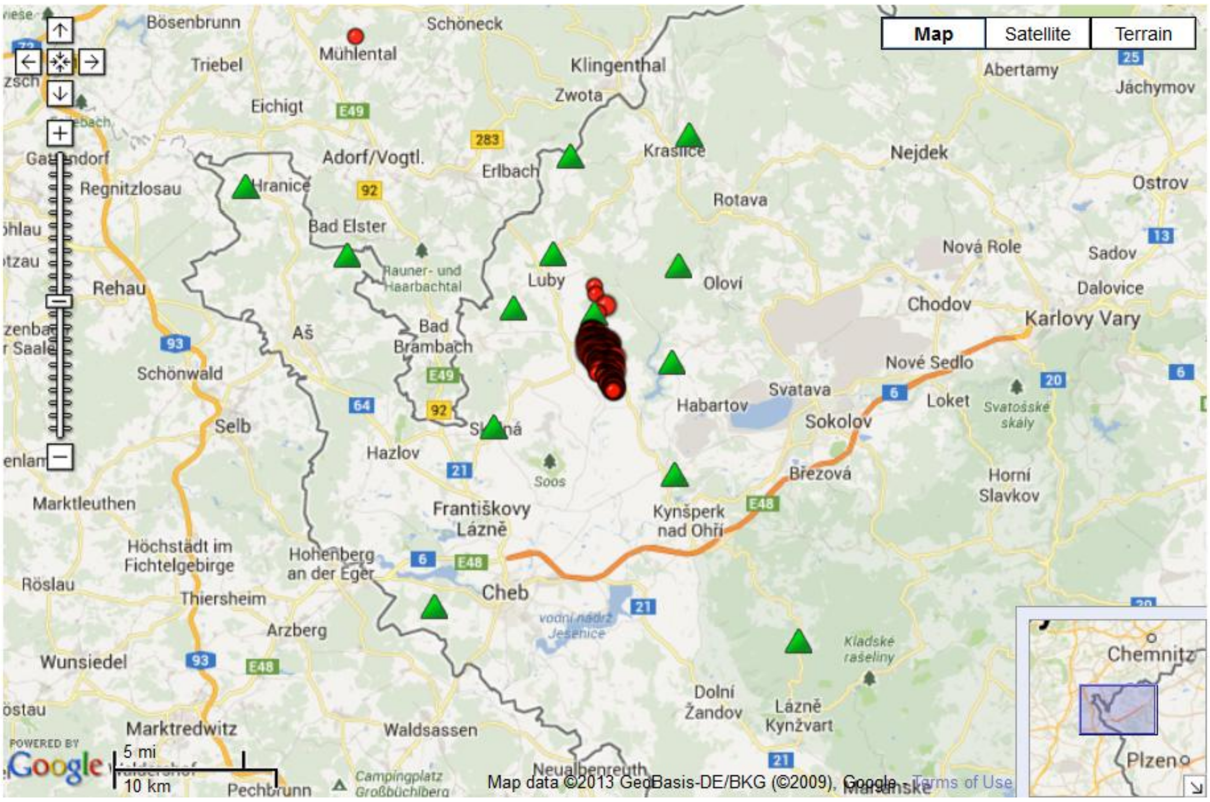

Figure 1a. Map of West Bohemian region with WEBNET stations (triangels) and the epicenters of 2008 swarm (circles) as an example of the activity – overtaken from wwwWEBNET (2011b).

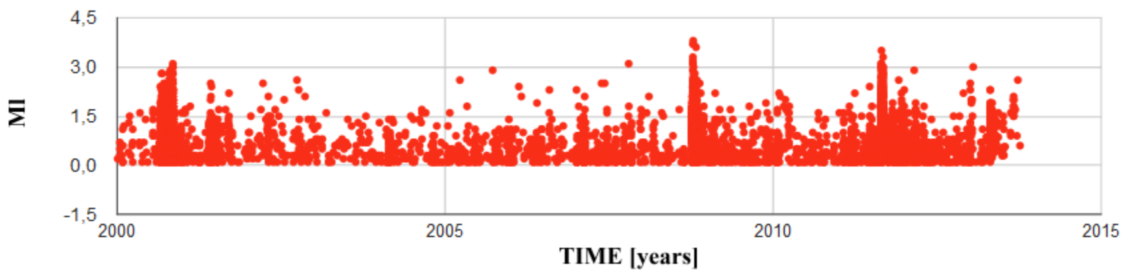

Figure 1b. Time distribution of the events versus their magnitude for years 2000- 2013; pronounced swarms occurred in year 2000, 2008, 2011 and 2013 - overtaken from wwwWEBNET (2011b).

2 Stopping phases method

We adopted Stopping phases method to model finite seismic source. The method is based on relatively simple idea: the seismic source is modeled as a rupture propagating radially from a nucleation point along the fault plane (the location of the event as well as the orientation of the fault plane is supposed to be known from previous study). The rupturing continues with constant velocity until the source boundary is reached; in our model the boundary is supposed to be of circular or elliptical shapes, respectively. Note that such models are considered to be suitable for relatively weeker events, which is definitely the case of West Bohemian events. For the rupture process can be identified in seismograms three phases: (i) onset of signal, which corresponds to the beginning of the process (i.e. signals coming from the source nucleation point) and (ii) two so named stopping phases, which correspond to stopping points situated on the edge of ruptured area. When the rupture process reach the source boundary and fade in a particular direction, such a change results in a change of slope of displacement pulse, which can be (in twice differentiate displacement signal, i.e. in accelerogram) interpreted as a stopping phase – see Appendix. We can say that the stopping phases can be understand as a change in the course of observed displacement produced by finite source. In another words the source radiation can be for our purpose reduced into three points (the two later are named critical points), while the signals from all other point are mutually destroyed by deconstructive interference. The radiation from critical points was theoretically studied by Bernard and Madariaga (1970), this theory was then used by Imanishi and Takeo (1998, 2002), who designed Stopping phases method for finite circular seismic source parameters determination.

As it follows from the theory (Bernard and Madariaga, 1970), the two stopping phases are in mutual relation as a pulse and its Hilbert transform, which is also the criterion for their identification. The time lags between these phases depend on source size, geometrical orientation of the finite source and also on the source-to-station path. Therefore first we have to search for the stopping phases in seismograms. The time delays between onset and these two stopping phases represent the input data, which are subject of inversion process which evaluates finite source model parameters.

3 Real data processing

During application of Imanishi and Takeo (1998, 2002) methodology on the West Bohemian data from 2000 year, it has appeared that while the above mentioned inversion is contemporary more or less routine process, the stopping phases identification is crucial. We therefore developed an interactive Tool for Stopping phases determination (written on MATLAB platform). By the Tool were successfully processed 36 selected events from West Bohemian 2000 year swarm, the results was published in Kolář and Růžek (2012), the Tool itself was referred also in Kolář (2011).

Further we processed selected events from 2008 West Bohemian seismic swarm (the next pronounced swarm after the 2000 year swarm). As the WEBNET seismic network is subject of continuous development and improvement, the data of 2008 year swarm are of significantly higher quality than the previous one, namely the events are recorded by higher number of seismic stations (including those which did not operate during swarm 2000)[1]. Higher quality of processed data enables their more detailed analysis which was connected with same software improvements and development, which are described below.

4 Interactive Tool improvements

As it is obvious from the Fig. 2, the appearance of the main Tool window is generally preserved but some new features has been added.

Signal resampling

We increase the precision of the stopping phases onsets readings. Even if the time position of a signal sample cannot be distinguish more precisely than it is signal sampling interval, the time distance of parts of signal, namely of similar shapes, can be measured more precisely. The idea of this approach is based on mutual correlation of the signal parts. This approach enables determine mutual time position of two identical or similar signals with use of their maximal correlation (see e.g. Fremont and Malone, 1987, Deichmann and Garcia-Fernandez, 1992) with higher precision than does original sampling interval. We over-resample the signal (10 times) and we suppose that the real precision of our readings is than about 0.2 of original time sample (original sampling is 0.4 ms, i.e. sampling

[1] More than 20 seismic stations operated during 2008 year swarm and the average number of processed seismograms increased from about 5 per event in set from 2000 year data to about 15 for 2008 year data.

frequency 250 Hz). Note, that the parts of signal corresponding to the stopping phase fulfill the criterion of signal similarity as it follows from their definition.

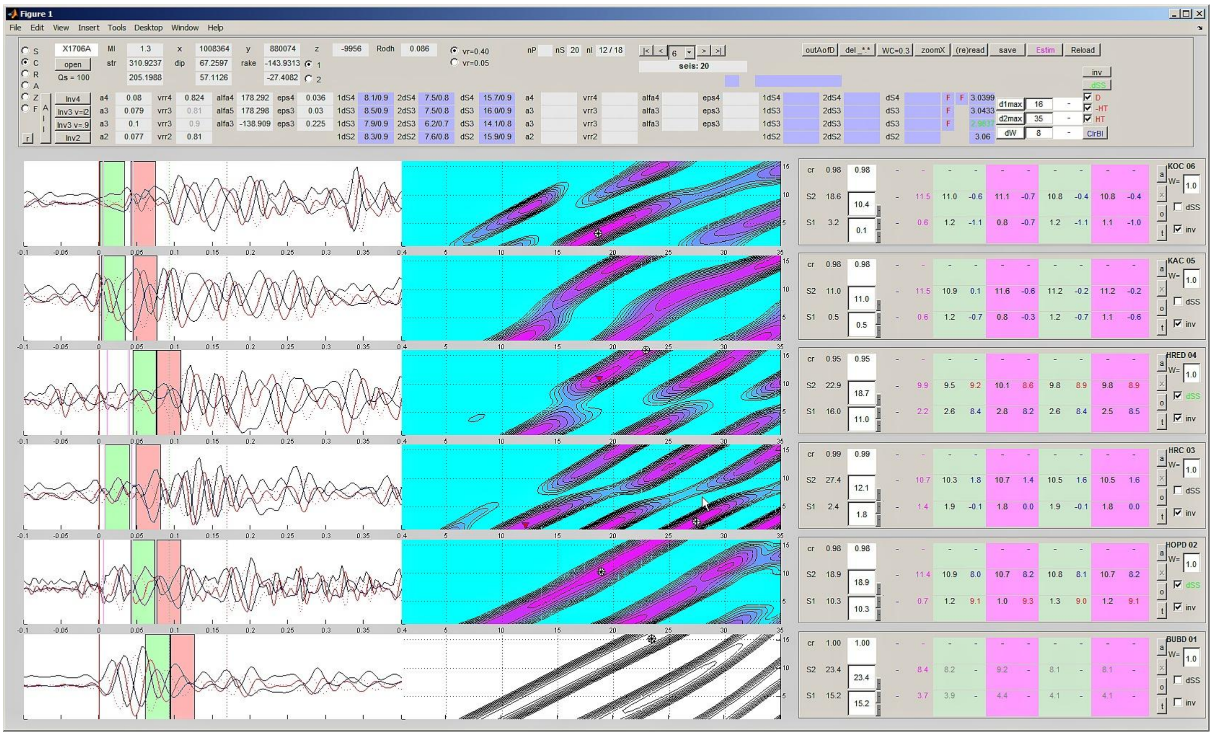

Figure 2. Tool main control window. There are displayed: (i - header) general event information and results of inversion performed for particular stopping phase interpretations, general user-interface controls, (ii – left column) processed seismograms (displacement, acceleration, its Hilbert transform distinguished by colors), (iii – middle column) correlation maps for stopping phases interpretation and (iv – right column) numerical values of stopping phases onsets, theoretical values and user-interface controls for individual events (for another details see Kolář, 2011).

Using of Stopping phase time difference

The inversion input data are time delays between S wave onsets and arrival times of stopping phases S_1 or S_2 respectively – i.e. 2 data for each station. However in some cases, when the S wave onset may not be well determined, we have unrealistic values of time differences, while time difference S_2-S_1 is realistic. Precise interpretation of S wave onset can be problematic especially when there is small amplitude of S/SH wave, the signal is spoiled by noise or by interference phases. In such cases we reformulate the inversion input and use optionally only S_2-S_1 stopping phases time difference. Such modification decrease number of inversion input data (to only 1 per station), however enable to keep in the inversion data from injured station(s) which could not be used otherwise.

Secondary window extension

To offer more information for stopping phases interpretation we extended the information displayed in the secondary windows – Fig. 3. Now there are displayed following information: (i) map of the region with the stations which are distinguish whether they are included or excluded from the particular inversion. Note that also projections of the fault planes to the surface are marked. (ii) radiation pattern of the P waves of the processed event including standard stations low hemisphere projection, (iii) radiation pattern of the SH waves and (iv) radiation pattern of the S waves (absolute amplitude), (all the radiation pattern formulas are taken from Aki and Richards, 1980). As another secondary criterion are also used waveforms of displacement which are plotted in main window (left column). All this information can serve as secondary criterions for stopping phases interpretation.

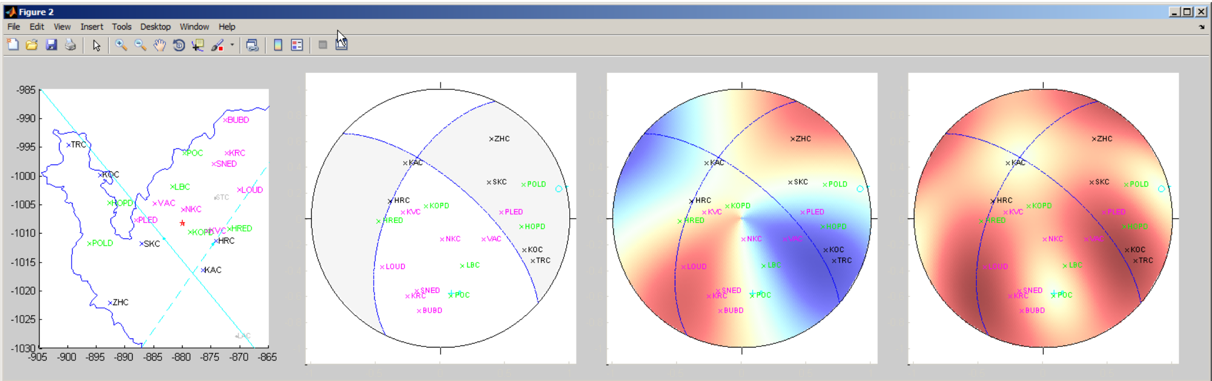

Figure 3. Tool second window. There are displayed: (i) map of the region – stations included into inversion are marked by blue color, excluded stations by violet color, station where only time difference is available by green color, the cyan lines are projection of the source fault plane on surface, (ii) standard radiation pattern (for P waves; the projection of the station is also displayed), (iii) the same as in {ii} but for SH radiation pattern, (iv) the same as in{ii} but absolute amplitudes of S waves are plotted; lower amplitudes of SH/S waves may implicate lower reliability of the data or of stopping phases interpretation, respectively.

Compensation of effect of anisotropy

It is known that the West Bohemian medium has also anisotropic properties, which causes splitting of S waves (Vavryčuk, 1993, Vavryčuk and Boušková, 2003). We optionally try to compensate effect of anisotropy for those cases when the stopping phases interpretation were difficult or ambiguous. Horizontal components of seismogram were rotated and time shifted (reasonable values of the rotation and time shift were considered) and we were searching for the simplest shape of the composed signal (approach designed by Silver and Chan, 1991). The method required maximal value of determinant D

$$D = \begin{pmatrix} C_{FS} & C_{FS} \\ C_{FS} & C_{SS} \end{pmatrix},$$

where C stands for correlation of fast (F) or slow (S) components, which are tested through all the considered values of component rotation and time shifting. If the operation simplifies stopping phases interpretation, we accepted it, but we simultaneously switch the inversion data only into S_2-S_1 mode (see above) to avoid problems with possible shifting of S wave interpretation for the station.

The process of anisotropy compensation is also designed as interactive, and the suggested correction are displayed in a temporary window – Fig. 4; the compensated signal can be either accepted or rejected, the parameters of compensation can be interactively modified if needed.

Compensation of effect of attenuation

To describe effect of attenuation we use formula

$A_{(t)} = A_{(0)} \exp(- \omega\, t / 2Q_s)$,

or its inversion form, respectively, for effect compensation; *t* stands for S waves travel time, *Qs* is the quality factor for S waves (see e.g. Aki and Richards, 1980). We put $Q_s = 100$, i.e. $Q_p = 200$ (in agreement with Kanamori, 1967), which corresponds to values used by Horálek and Šílený (2013) or also derived by Michálek and Fischer (2013). Compensation of effect of attenuation has appeared significant especially for weaker events (Ml < 1.2).

Other Tool’s functions, as well as inversion evaluation, remain unchanged and are described already in Kolář (2011).

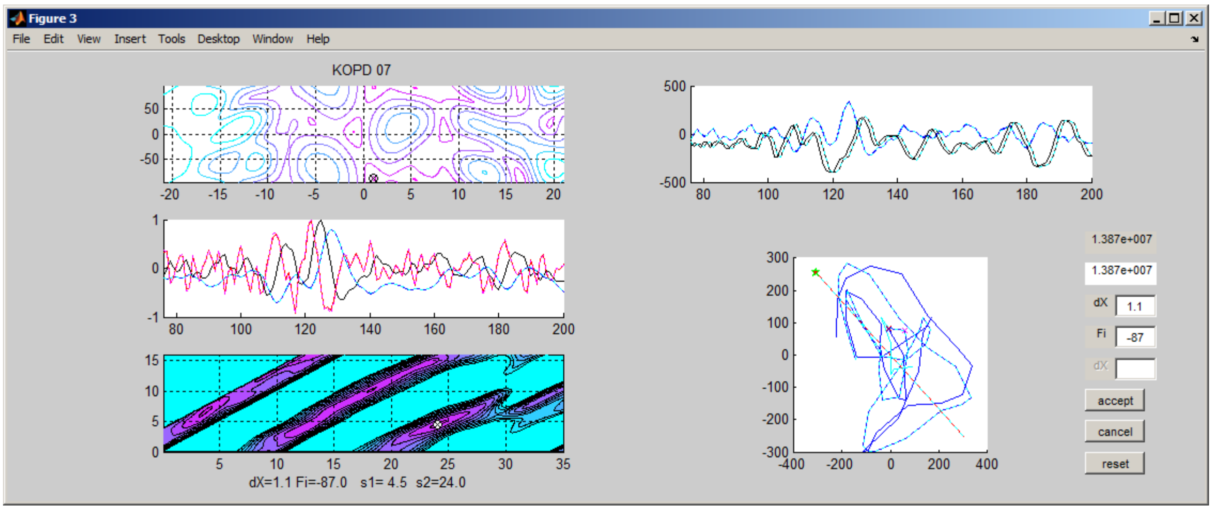

Figure 4. The anisotropy compensation window. There are displayed: values of determinant D, original and new seismograms, new correlation map, original and new displacement signals, horizontal particle motion and function user-interface controls.

5 Processes data

By the Tool is has been already successfully processed set of 36 selected events from West Bohemian earthquake 2000 year swarm - those results are described in Kolář and Růžek (2012). Note that these events were processed by the Tool ver. 1. As it is already mentioned above, the higher quality of next pronounced swarm (2008 year) enables more precise and detailed processing, which resulted in the Tool upgrade to the current stage (ver. 2). It has been already successfully processed 91 selected events from 2008 swarm (Kolář, 2013) and there is a perspective of processing of another 200 events (the selection is limited mainly by the required knowledge of source mechanism) – Fig. 5.

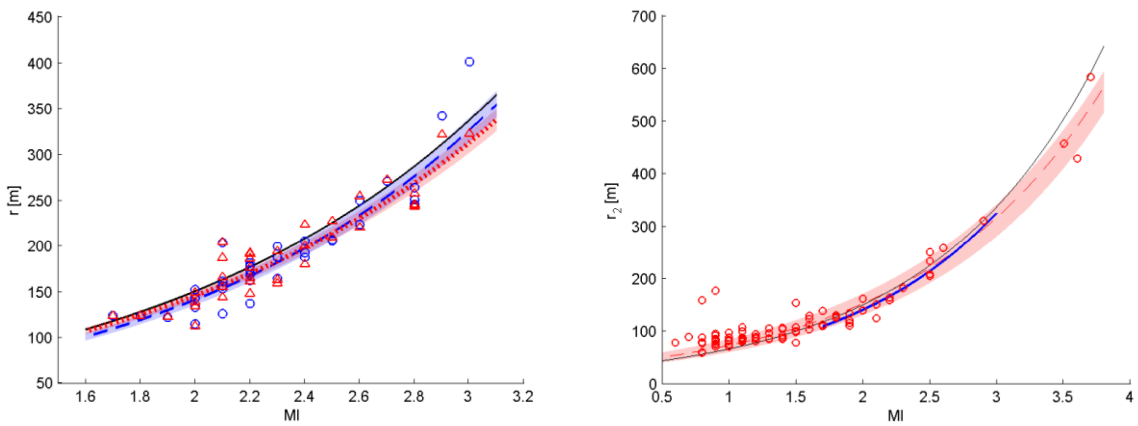

Figure 5. Results of inversion of real data. There are plotted relation of circular source radius versus event magnitude. Left: 36 selected events from 2000 year swarm. There are plotted radiuses for 2 parameters inversion (circles) and radiuses inverted with fixed rupture velocity (triangles), regressions and theoretical relation derived by Fischer and Horálek (2005) – black line; figure is overtaken from Kolář and Růžek (2012). Right: the same relation for 91 selected events from 2008 swarm; only 2 parameters inversion was performed here, the blue line is relation derived for 2000 year swarm data, the Fisher and Horálek (ibid.) relation is plotted by gray line; figure is overtaken from Kolář (2013). Mind the different scales of the figures; the magnitude range of 2008 year data is significantly wider.

6 Conclusions

The developed code appears to be an effective tool for data (selected events from West Bohemia seismic region) processing. Even if the Stopping phases methodology is rather particular, the successfully interpreted events justify their application. The developed interactive Tool is now in routine use and there is a realistic expectation of further successful processing of another West Bohemian events. As the earthquake swarm activity occurs also in other regions (namely in Iceland), it can be challenge for the method as well as for the Tool.

In addition, the correlation of parts of signals have potential to be a way to identification of other phases in seismograms which potentially can open a way for detailed interpretation of subtle medium structure (with use of the Tool capabilities).

Acknowledgement

Presentation of this work is supported by grant: P210/10/1728 of the Grant Agency of the Czech Republic (Z. Jechumtálová).

References

Aki, K. and Richards, P.G. (1980), Quantitative Seismology, W. H. Freeman and Co., San Francisco.

Bernard, P. and Madariaga, R. (1984), A new asymptotic method for the modeling of near-field accelerograms. *Bull Seism Soc Am* 74:539-557

Brune, J. N. (1970), Tectonic stress and the spectra of seismic shear waves from earthquakes. *J Geophys Res* 75:4997-5009

Deichmann, N. and Garcia-Fernandez, M. (1992), Rupture geometry from high-precision relative hypocentre locations of micro-earthquake clusters. *Geophys J Int* 110:501-517

Fischer, T. and Horálek, J. (2005), Slip-generated patterns of swarm microearthquakes from West Bohemia/Vogtland (central Europe): Evidence of their triggering mechanism? *J Geophys Res* 110, B05S0X, doi:10.1029/2004JB003363

Fremont, M. and Maloe, S. D. (1987), High Precision Relative Locations of Earthquakes at Mount St. Helens, Washington. *J Geophys Res* 92: B10:10223-10236

Horálek, J., Fischer, T., Boušková, A., and Jedlička, P. (2000), The Western Bohemia/Vogtland Region in the Light of the Webnet Network, *Studia Geophys et Geodet* 44, 2, 107 – 125.

Horálek, J. and Šílený, J. (2013), Source mechanisms of the 2000 earthquake swarm in the West Bohemia/Vogtland region (Central Europe). *J Int* 194, 979-999, 2013; doi: 10.1093/gji/ggt138

Imanishi, K. and Takeo, M. (1998), Estimates of fault dimensions for small earthquakes using stopping phases, *Geophys J Let* **25**, 15, pp. 287-2900.

Imanishi, K. and Takeo, M. (2002), An inversion method to analyze rupture process of small earthquakes using stopping phases, *J Geophys Res* **107**, B3.

Kanamori, H. (1967), Attenuation of P Waves in the Upper and Lowe Mantle, *Bull Earthquake Res Inst* 45, pp. 299-312.

Kolář, P. (2011), A Tool for Determination of Finite Seismic Source Parameters via Stopping Phases Method. in *Technical Computing Prague 2011*, ISBN978-80-7080-794-1, pp. 69

Kolář, P. (2013), Estimation of parameters of finite seismic source model for selected event of West Bohemia 2008 year seismic swarm, submitted to *J Seism*.

Kolář, P. and Růžek, B. (2012), Finite seismic source parameters inferred from stopping phases for selected events of West Bohemia 2000 swarm. *Acta Geodyn Geomater* 9:435–447

Michálek, J. and Fischer, T. (2013), Source parameters of the swarm earthquakes in West Bohemia/Vogtland. *Geophys J Int*, published online August 28, 2013, doi: 10.1093/gji/ggt286.

Silver, P. G. and Chan, W. W. (1991), Shear wave splitting and subcontinental mantle deformation. *J Geophys Res* 96:16,429–16,454

Studia Geohpysica et Geodetica (2000), special issue devotes to West Bohemia topics: 44, 2 – 3.

Studia Geohpysica et Geodetica (2008), special issue devotes to West Bohemia topics – Part 1: 52, 4.

Studia Geohpysica et Geodetica: (2009), special issue devotes to West Bohemia topics – Part 2: 53, 3.

Vavryčuk, V. (1993), Crustal anisotropy from local observations of shear-wave splitting in West Bohemia, Czech Republic. *Bull Seism Soc Am* 83:1420-1441

Vavryčuk. V. and Boušková, A. (2008), S-wave splitting from records of local micro-earthquakes in West-Bohemia/Vogtland: An indicator of complex crustal anisotropy. *Stud Geophys Geod* 52:631-650

wwwWEBNET (2013a), http://www.ig.cas.cz/en/structure/observatories/west-bohemia-seismic-network-webnet/ access: 17 Oct 2013.

wwwWEBNET (2013b), http://www.ig.cas.cz/en/structure/observatories/west-bohemia-seismic-network-webnet/map-epicenters, access: 17 Oct 2013.

Appendix: *WHERE* are Stopping phases generated

A synthetic example of the stopping phases generation: circular seismic source model is used, the final synthetic seismogram is calculated as a sum of seismograms generated by point seismic sources situated in a dense grid, displacement in these points is prescribed by formula proposed by Brune, (1970), source model M.

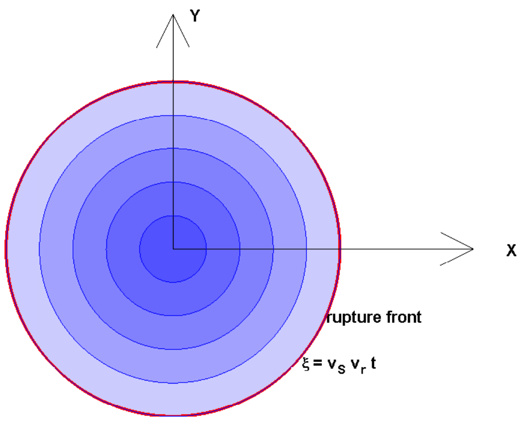

Figure 6a. Circular source model. The rupture process starts at the central nucleation point and propagates radially with constant rupture velocity until the edge is reached. Rupture velocity is conventionally given as fraction of S waves velocity $v_{ruptrure} = v_S * v_r$., where v_r stands for relative rupture velocity.

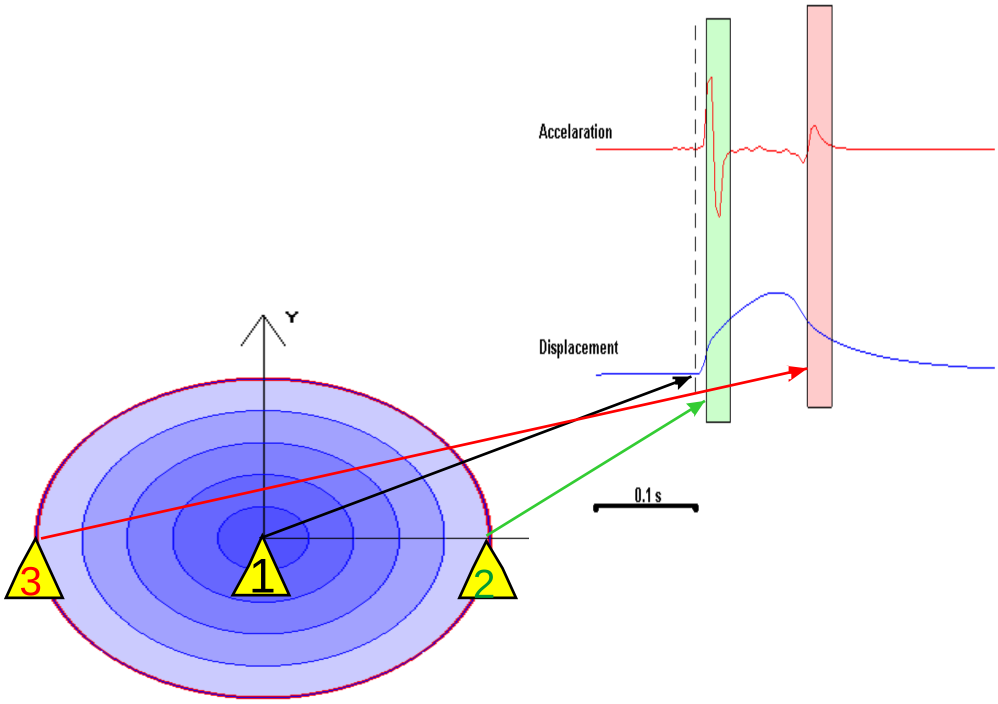

Figure 6b. The same source as in Fig 6a, but seen from a seismic station (the circle is symbolically distorted by perspective). Onset of the signal comes at the station from the nucleation center (marked by 1). When the rupture process stops, it is manifested in signal as a chance of observed displacement curve – the onset of the first stopping phase corresponds to the radiation from the point 2 (i.e. the closest source point to the station). Radiation from the farthest source point (marked by 3), it is manifested in seismogram as arrival of the second stopping phase. The rest of the signal - displacement after the second stopping phase corresponds to the healing process of the source; corresponding acceleration is plotted above displacement signal, the manifestation of stopping phases is obvious.

Contact information: P. Kolář, Institute of Geophysics, Czech Acad. of Sci., Boční II 1401, Praha 4 – Spořilov, 141 31, Czech Republic, kolar@ig.cas.cz