DETAILED ANALYSIS OF (SELECTED) WEST BOHEMIAN EARTHQUAKES – RESULTS AND POSSIBLE GEOLOGICAL CONSEQUENCES

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Abstract

At TCP 2011 and 2013 we informed about Interactive tool for determination of parameters of finite seismic source model using Stopping Phases method. Now the crucial part of software is developed and the Tool is in routine operation: events are analysed, values of investigated parameters are obtained and in addition the harvested results seem to yield also information about detailed geological structure in the foci area - such knowledge cannot be obtained by another way unless the exhaustive and expensive prospecting geophysical methods are applied. Namely we processed sets of events from pronounced seismic swarms which occurred in West Bohemia in yrs. 2000, 2008 and under the investigation are 2011 data (2014 data are the challenge for the future).

The contribution describes technical details of latest software development, give list of so far gained scientific results (incl. their publications); some software problems and limits are mentioned; the future plans and perspectives of the method or of the Tool respectively are discussed.

1 Motivation

The West Bohemian region (Fig. 1) is among others known for its seismic activity or occurrence of seismic swarms respectively. This activity is part of numerous natural effects which can be observed in the region (e.g. mineral water sources and consecutive spa activities, etc.). Naturally these seismic phenomena are under the scientific interest for a long time. Contemporary studies range from fundamental seismic activity observation, records interpretation, events identification and location (i.e. determination of events origin time and foci coordinates), bulletin compilation, etc. Such works are now more or less routine (and at least partly automatized) and these results are usually presented in form of bulletins. On the other side of variety of performed studies there are highly specialized works, which are often multidisciplinary and deal usually with sets of selected events. This is also the case of our work: we model in details finite seismic sources of selected events from West Bohemia region; for the analysis is used a Tool created mostly in MATLAB platform. The paper gives more details about this work. The paper also updates and extends information which were presented about this topic at TCP11 and TCP13 (Kolář 2011; Kolář 2013). A more general overview about variety of investigated topics can be obtained e.g. from recent review study (Fischer et al. 2014).

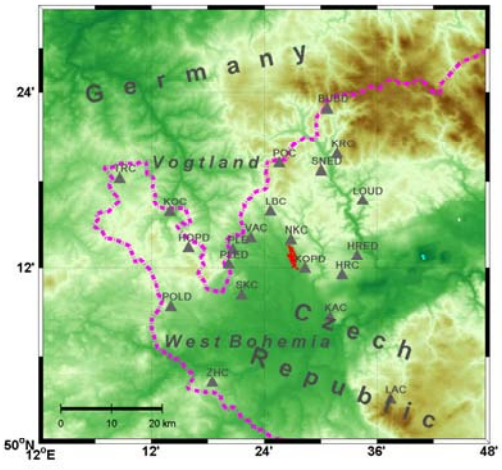

Figure 1. Standard topographic map of the West Bohemian region. State border (dashed line), WEBNET stations (triangles) and epicentres of investigated events (cloud of red crosses southerly from station Nový Kostel – NKC; swarm 2008) are plotted. The figure is overtaken from (Kolář 2015).

2 Data and region under the interest

The West Bohemia seismic activity (seismic swarms) is clustered in time and space. The modern history of seismic observation in the region can be dated back to 1985 year, when the two first digital stations were deployed in the region. It was the origin of seismic network WEBNET (wwwWEBNET) which since then continuously monitors local seismic activity. Currently the network operates about 20 stations. The WEBNET network yields outstanding data and practically any study about West Bohemia topic cannot be performed without using WEBNET data. This is also the case of our work.

3 Method

In our work we are searching for parameters of seismic source; we suppose finite circular source model. This is widely used extension to a point source approximation, especially for weak and moderated events as it is also the case of events under our interest. The method is based on older theoretical works performed in last century (Bernard and Madariaga 1984), which was brought to practical use by (Imanishi and Takeo 1998; Imanishi and Takeo 2002; Imanishi et al. 2004). The values of finite source model parameters are retrieved from time arrivals of so called "stopping phases" (which give also the name to the whole method). Stopping phases are generated on the edge of finite seismic source and practically cannot be directly seen in the seismograms. But these stopping phases can be identified by certain correlate relations, which is the property used also in our approach – see Fig. 2.

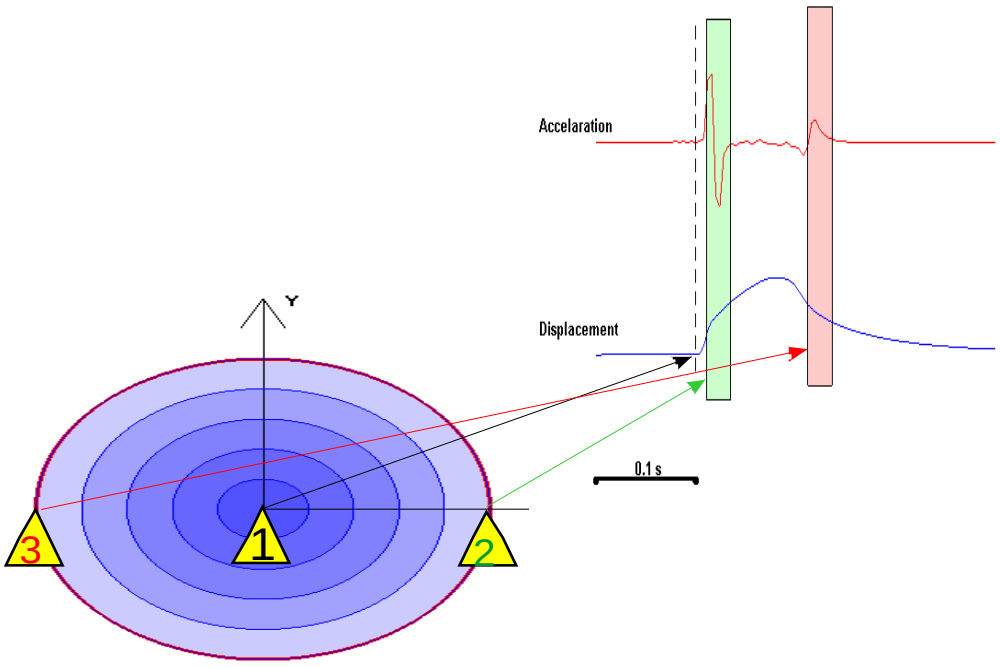

Figure 2. Schema of stopping phases generation. A finite circular source seen from a seismic station (a circular source is symbolically distorted into an ellipse by perspective). Onset of the (synthetic) signal comes at the station from the nucleation centre (marked by 1). When the rupture process stops, it is manifested in signal as a change of observed displacement curve – the onset of the first stopping phase corresponds to the radiation from the point 2 (i.e. the source point closest to the station). Radiation from the farthest point of the source (marked by 3), 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 event according to the M-model by (Boatwright 1980). Corresponding acceleration is plotted above displacement signal, the manifestation of stopping phases is obvious – adopted from (Kolář 2013).

4 Processed data

As mentioned above, the West Bohemian seismic activity is clustered in time; it is manifested by reoccurrence of aperiodic seismic swarms. The recent pronounced swarms occurred in years 2000, 2008, 2011 and 2014. These swarms were recorded by number of seismic stations sufficient for advanced studies. Our analysis (i.e. finite source parameters determination) started with set of selected events from 2000 year swarm, continued with swarm 2008 and currently the data from 2011 year swarm are under the process. Note, that Stopping phases method can be applied only if previous analysis have been performed; namely precise event locations and source mechanisms determination. The 2014 year swarm then remains a challenge for the nearby future.

5 Tool for Stopping phases method practical implementation

To interpret the stopping phase arrivals as accurately as possible is essential for the successful application of the method. Therefore the time arrivals of stopping phases definitely cannot be determined automatically. But the automatically determined times are treated as a first approximation. Then according several criterions the interpretations are modified, if necessary. To make such way of data processing usable in routine analysis of numerous events, it has been developed an Interactive tool (on MATLAB platform). The Tool was already presented at TCP11 and TCP13 (Kolář 2011; Kolář 2013). The successfully processed data sets from swarms from 2000 and 2008 years (mentioned above) or concerned published results (mentioned below) as well as the ongoing further data processing unambiguously prove that the Tool was designed successfully and effectively (see Figs. 3 - 5 placed at the end of the text).

6 Tool: current stage

Since the last presentation of the tool at TCP13 (Kolář 2013), no principal methodological changes were applied[1], but numerous small improvements were introduced. These improvements deal mainly with routine work (better or clearer graphical appearance, macro functions which make the routine operation more comfortable or reliable, etc.). Such improvements are incorporated continuously any time a requirement appears.

Current extension of the Tool concerns capability to be able to work with data not only from West Bohemia region as it has recently appeared foreign data possible suitable for the Stopping phase method. The newly programed Tool's capabilities concerns mainly: (i) raw data/seismograms organization, (ii) capability to work with different coordinate systems and (iii) with different medium velocity models.

The principal part of the Tool was designed couple of year ago and consecutive development has rather maintained and improvement character. But recently it has step by step arisen problems with MATLAB graphical outlook, when a new MATLAB release uploaded (namely for R2014 and R2015). These problems remain open to the future solution as also speed of computation is important when the same computations are performed repeatedly and routinely (namely evaluation of seismogram correlations and visualization of so called correlation maps).

As the Tool is subject of continuous improvements (even if currently not cardinal), the code has partially "working" feature: some its parts/functions are not used any more (as these ways were not found usable), some parts are in testing regime so far, some parts may be finalized into more effective way of computations, etc. These features prevent the Tool (the code) in a current stage from open distribution. If it appears such requirement, these questions or problems respectively will have to be handled somehow and the code will have to be purified.

7 Results and perspectives

Selected events from pronounced West Bohemia seismic swarms from 2000 and 2008 years were successfully processed and the results were published in (Kolář and Růžek 2012; Kolář 2015; Kolář and Růžek 2015). It is realistic to expect, that also data from years 2011 (currently under the process)

[1] The last methodological improvement was implementation of correction for effect of attenuation. Even if such correction is relatively simple from point of view of programming, it has appeared as a significant improvement namely for processing of weaker events as it has been documented in (Kolář 2015); this option was already mentioned in previous presentation of the Tool at TCP13 (Kolář 2013).

and 2014 (a plan) will be successfully processed and the results will be published. Examples of so far obtained results are given in Figs. 6 and 7.

As other perspective it has appeared processing of data from other seismic regions, whereas some technical steps in this direction have already been launched.

As an co-result it can be mentioned study based on the above quoted outputs, i.e. an attempt of detailed model of geological structure in the foci area (Kolář and Bouškova 2015). Note, that such information cannot be obtained by another way unless the exhaustive and expensive exploratery geophysical methods are applied. Unfortunately, such type of studies cannot be performed over 2000 year data due to low number of operated stations at that time. Nevertheless, processing of the 2000 year data confirms ability of the Stopping phases method and its potential for West Bohemian data processing. Meanwhile (from 2000 to 2008 when the next pronounced swarm occurred) the WEBNET network has been significantly extended which positively influenced obtained results and their accuracy.

Another item for future study also remain possible interpretations of other correlation observed in the processed data, which cannot be interpreted in term of stopping phases and which has not yet been investigated.

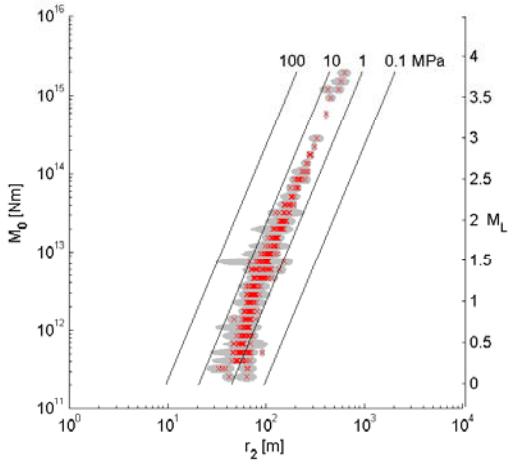

Figure 6. Scalar seismic moment M_0 (or magnitude M_L respectively) versus source radius r_2 for events from West Bohemian 2008 year earthquake swarm (events are marked by red dots, estimated errors by grey area). The figure confirms world-wide hypotheses about constant stress drop during earthquake for fairly wide magnitude range (M_L 0.1 – 3.8); *published in (Kolář 2015).*

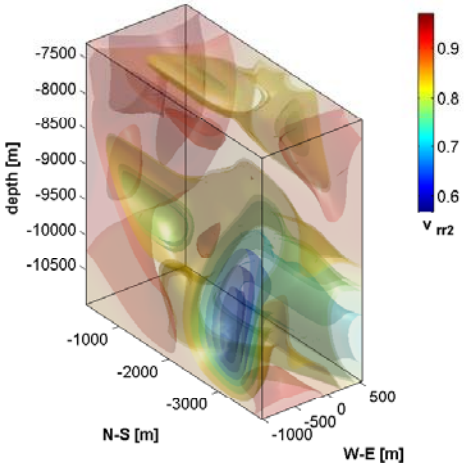

Figure 7. Possible 3D spatial model of relative velocity distribution in 2008 year earthquake swarm foci zone. View from SW to NE, elevation 30° above horizontal plane; distances are given in [m] relative to NKC station; *published in (Kolář 2015).*

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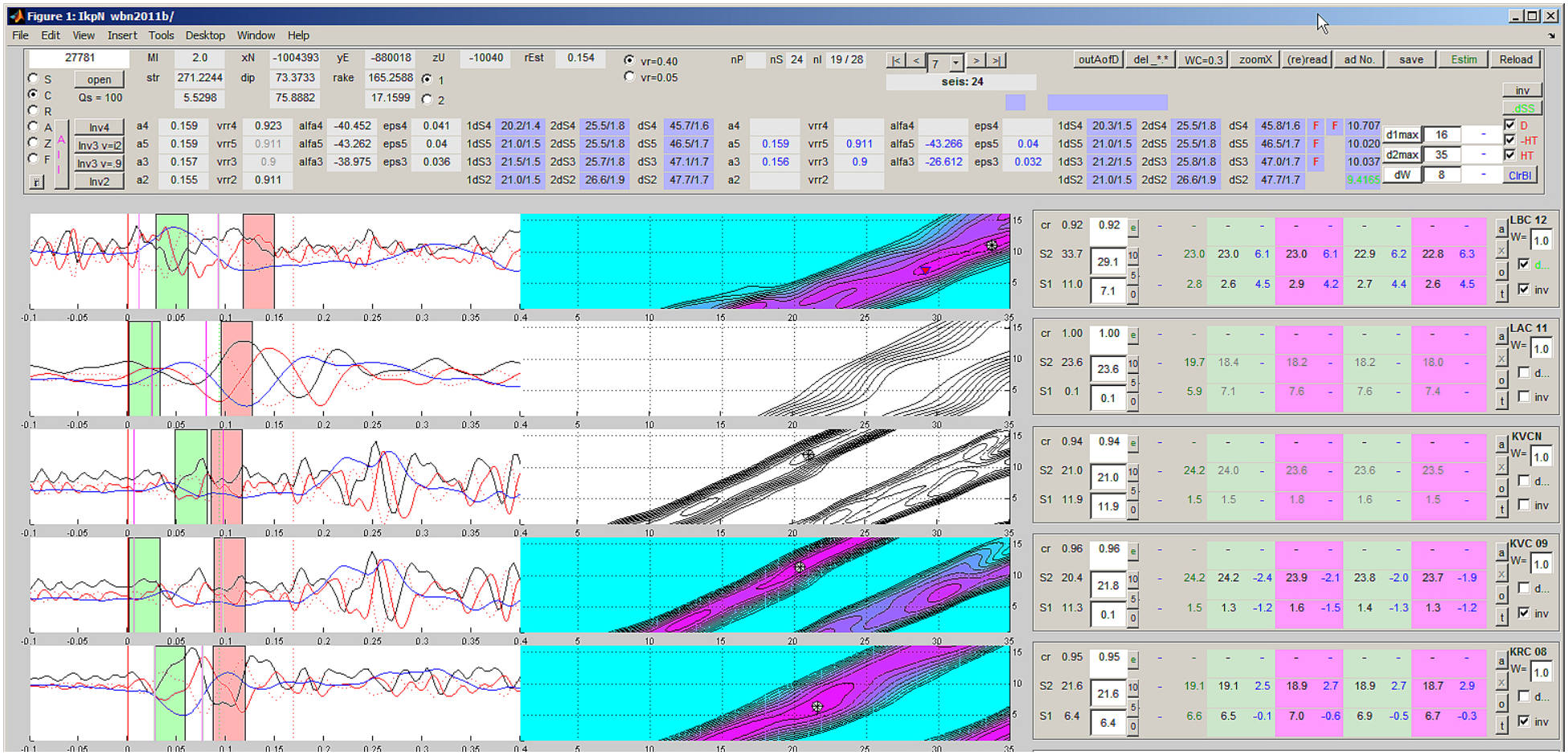
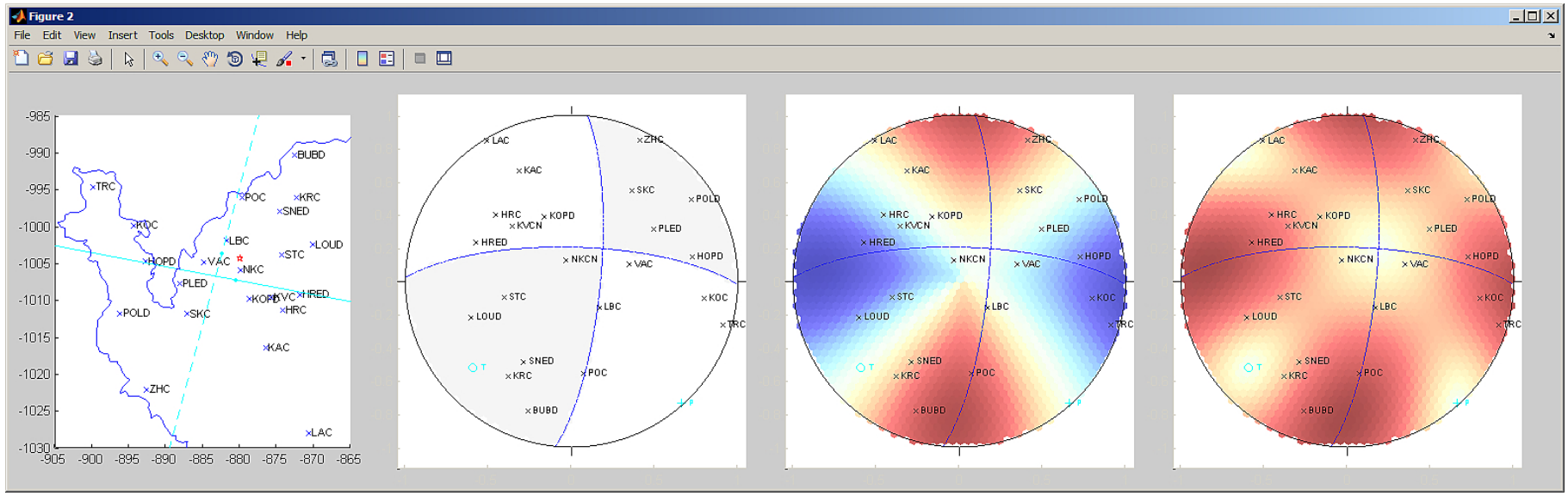


Figure 3. Main window of the Tool; as an example an event (M_L=2.0) from 2011 year swarm under the process is presented. Below header with event basic information and results of current inversion are plotted individual seismograms of processed event, correlation map and numerical values of stopping phases interpretation.



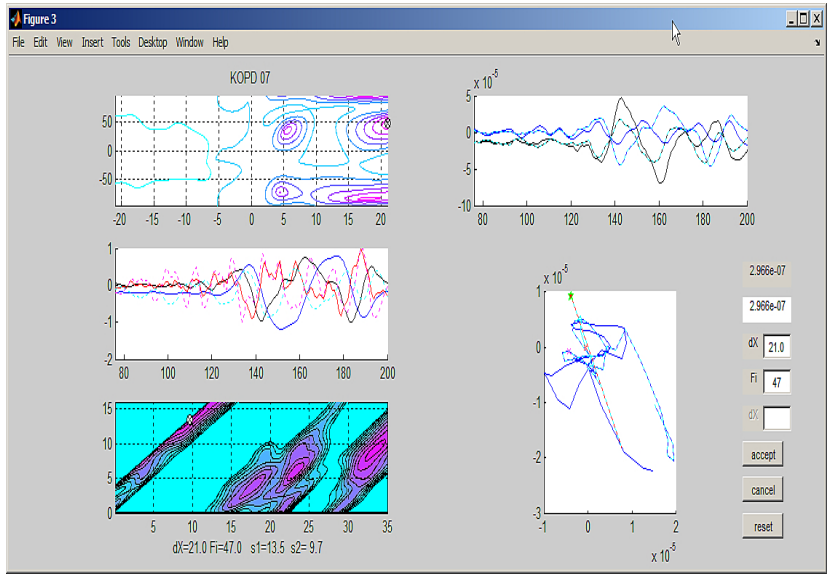


Figure 4 (above). A secondary Tool window – stations map and radiation pattern for a processed event (the same event as in Fig. 3 is displayed). This information served as a second order criteria for stopping phases interpretation.

Figure 5 (left). A window of function for effect of anisotropy correction. The effect of anisotropy correction seems to be ambiguous for the Stopping phases method and it needs a further investigation (the same event as in Fig. 3 is displayed).