Influence of variation of some parameters on the HYPO-like location of seismic swarm. Synthetic study based on real data from the West-Bohemia region

JAROMÍR JANSKÝ, VLADIMÍR PLICKA AND OLDŘICH NOVOTNÝ

Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2,180 00 Prague 8, Czech Republic (jansky@seis.karlov.mff.cuni.cz, vladimir.plicka@mff.cuni.cz, on@karel.troja.mff.cuni.cz)

Key words: West-Bohemia/Vogtland, earthquake swarm, absolute location, station corrections

This is a non-peer-reviewed preprint submitted to EarthArXiv.

A B S T R A C T

The West-Bohemia/Vogtland region is well known for the occurrence of intraplate earthquake swarms. Those are monitored by the seismic network WEBNET. The relative locations, often used for estimation of the swarm time development, depend on the quality of the initial absolute location. In routine practice, hypocenters in the area are mostly located using the upper crustal 1-D velocity-depth model WEBN, composed of homogeneous layers, and the HYPO-like location algorithms. Using the P- and S-wave phase arrivals of the 156 events, selected from the 2008 earthquake swarm and recorded by 22 network stations, we demonstrate how the absolute hypocentre positions are influenced by variation of individual location parameters. These parameters include: the S-wave travel-time weight, the location starting depth, the Vp/Vs velocity ratio, the station elevation travel-time correction, and the (slight) crustal model velocity-depth variation. We locate the swarm under these variable conditions, discuss the results and derive the stations travel-time model correction to improve the location accuracy.

INTRODUCTION

Earthquake swarms represent a special type of seismic activity, often shallow, clustered in space and time, and missing a single large mainshock event (*Horálek et al., 2021*). As a rule, most attention is focused on a detailed spatial pattern of the swarms obtained by relative location methods, e.g. HypoDD (*Waldhauser and Ellsworth, 2000*), whose accuracy can be of the order of ~10 metres. Absolute locations are less well investigated. Their accuracy is lower, which means that the clusters obtained by the relative method can be actually 'shifted' as a whole, up or down, by ~100 metres. Since the final goal of seismic studies is to establish a relation of earthquakes with such features as faults, magma chambers, seismic discontinuities, temperature profiles, etc., the absolute locations and their accuracy need to be carefully examined. In this paper, we analyse a well-known European swarm region. However, the results that we derive, e.g. strategy how to improve locations with station corrections can be equally well used in other swarm areas, e.g. in the Corinth Rift, Greece (*Sokos et al., 2012*), the Reykjanes Peninsula, Iceland (*Horálek et al., 2015*), Taiwan (*Hsin-Chieh Pu et al., 2014*), to mention just a few.

The West-Bohemia/Vogtland region at the Czech-German border is well known for the occurrence of relatively frequent intraplate earthquake swarms and other manifestations of geodynamic activity, such as mineral and thermal springs, mofettes and Quaternary volcanism. The seismically active area is located in the western part of the Krušné hory Mountains (Ore Mts., Erzgebirge). The geological structure of the West-Bohemia/Vogtland region is very complicated (*Vrána and Štědrá, 1997*). The Earth's crust is broken here into a number of small blocks by several fault systems. Many seismic structural measurements of a local or regional extent have been performed in the Vogtland and western Bohemia. The respective references can be found, e.g., in *Málek et al. (2005), Hrubcová et al. (2015), Růžek and Horálek (2013)* and *Novotný et al. (2013).* Velocity models range from simple homogeneous layers to sophisticated 3-D models (e.g. *Alexandrakis et al., 2014*; *Mousavi et al., 2015*). In practice, they depend on the previous investigations performed in the region. For the routine location of a large number of events that occur in a short time span, which is the case of earthquakes swarms, often simple models are used.

Earthquake locations, beside other factors, basically depend on two factors – the location method and the velocity model. Here we use an upper crustal velocity-depth model standardly employed for swarm location in our area and focus on the travel-time locations. Most are made with various iterative linearized methods (e.g. Hypoinverse, *Klein, 1978*; FASTHYPO, *Herman, 1979*); they need a good first approximation (e.g. starting depth) and suffer often from the trade-off between earthquake depth and origin time. In this paper, we investigate a small, tightly clustered group of 156 events selected from the 2008 earthquake swarm. All the events occur at shallow crustal depths (7-11 km). We study their absolute location, based on travel times of *P*- and *S*-waves from a local network of 22 stations, using the iterative method – HYPO71PC (*Lee and Valdes, 1985*). We show how the absolute epicentre estimations are influenced by individual location parameters, like the *S*-wave travel-time weight, the starting depth, the Vp/Vs velocity ratio and the application of station elevation and model travel-time corrections.

We also show by one example of a variation of the velocity-depth distribution (relative to the model WEBN) that we can get practically identical swarm location for some another crustal models due to the fact that all the hypocentres are vertically and horizontally tightly clustered and lie practically in the centre of the seismic network.

STATIONS, MODEL AND DATA

The 2008 seismic activity has been concentrated close to the Nový Kostel village (seismic station NKC, near the group of epicentres in Fig.1**)**, where earthquake swarms occurred in the years 1985/1986, 1997, 2000, 2008, 2011 and 2014 (e.g. *Dahm at al., 2008; Fischer at al., 2014; Hainzl et al., 2012; Horálek and Fischer 2008; Horálek and Šílený 2013; Horálek et al. 1996*).

Different authors have already studied some special aspects of the 2008 earthquake swarm in western Bohemia; see the references in *Novotný et al. (2016)*. The stations of the network WEBNET, which is run by the Institute of Geophysics, Czech Academy of Sciences (CAS), are shown in Fig.1, and their geographic coordinates are given in Table 1. In this paper, we also use the Cartesian coordinate system with the origin [0, 0] of X and Y axes at the point 12.4^{o}E and 50.2^{o}N. The axis X is positive to the East, the axis Y positive to the North. The origin of the axis Z equals 0 at 500 m above the sea level, thus the axis starts practically at the level of the station SKC (501 m).

The swarm was monitored by all the 22 seismic stations of the WEBNET network. Out of several thousands of recorded earthquakes, we selected 156 events that had local magnitudes $M_L \geq 1.5$, all close to station NKC. The events were recorded with distinct onsets of *P* and *S* waves. The selected events occurred between October 6 and November 2, 2008, and the largest event magnitude in the selection reaches the value of 3.8. All selected events were recorded by at least 18 seismic stations and all the epicentral distances are less than 25 km. The total number of the couples of *P*- and *S*-wave onset readings in our data set is 3306. Important is that the *S*-wave onsets represent practically one half of the total onset numbers. For the earthquake location in the given region, a 1-D *P*-wave crustal velocity-depth model (WEBN), composed of horizontal homogeneous layers and developed from the WB95 model (*Novotný, 1996*), is routinely used for seismic activity monitoring. The velocity-depth distribution of the WEBN model is given in *Novotný et al., (2016)* and is shown in Fig.2. The model uses the Vp/Vs ratio of 1.70 through the whole crustal depth range.

The relevance of the event locations is influenced by many factors, the most important among them being the phase onset reading accuracy, reflected by the phase weight, the location method and the velocity model. We locate the given data by the HYPO71PC algorithm (*Lee and Valdes, 1985*) - marked below as HYPO, which is one of the iterative algorithms suitable for the quick absolute event location. The quality of location for a given event is characterized through the following parameters: (i) the time residuals, representing the fit between measured and calculated phase arrivals, expressed by the root mean square error (in sec) - RMS, (ii) the standard estimate of the formal focal depth error ERZ, and the standard error of the epicentre ERH (both given in km). Here ERH = $\sqrt{(SDX^2 + SDY^2)}$, with SDX and SDY being the standard errors along the X and Y axes, respectively.

Program HYPO, and its input data, allow for the introduction of the station travel-time correction. One type of correction is the elevation correction that can reduce the effects of the elevations varying across the network. Because all events of the investigated swarm are distributed near the station NKC (Fig.1), we can assume that the elevation travel-time corrections are independent of the particular hypocentre. Further, because of the relative large swarm depth as compared with the epicentre distances, the seismic ray approaching each station is almost vertical. The elevation correction for each station then approximately equals the station elevation divided by velocity in the first layer (*P*-wave velocity = 4.3 km/s). The *S*-wave elevation station corrections are then derived from the *P*-wave corrections via the Vp/Vs ratio. To minimize the influence of the adopted approximation, we shortened the vertical part of each ray by defining the reference Z=0 at the elevation of 0.5 km above sea level. The elevation travel-time corrections are given in Table 1.

As with all iterative locations, the HYPO algorithm needs the first hypocentre approximation which might influence the results. Code HYPO automatically generates the first epicentre approximation, while the first depth approximation must be specified in the input data. Because most of the previous swarms in the NKC area had events depth between 7 and 11 km, we have used the starting depth of 9 km for most of our locations.

Another important input parameter is the relative phase weighting. In HYPO, five discrete levels are considered, formally called "weight" 0, 1, 2, 3 and 4. Actually, these numbers represent the 100%, 75%, 50%, 25% and 0% weight of the phase onset arrival time, respectively. In our area, good *P*-onsets and good *S*-onsets are usually used with formal weights of 0 (100%) and 2 (50%), due to the worse estimation of the *S*-wave arrival time. (The absolute accuracy depends, of course, on the sampling frequency, which equals to 250 Hz for the WEBNET network.) The hypocentres of the 156 events located in model WEBN with the starting depth of 9 km and the interpreter listed weights (mostly 100% for the P-wave and 50% for the S-wave) are shown in Fig.1. More details are provided in Fig.3. In the latter, the hypocentres are given in Cartesian coordinates. The average location values (from all the 156 events) are given in Table 2, including RMS, ERH, and ERZ, and are denoted as location No. 1. For this location, we also show ERZ and ERH for the individual events (Fig.4, Panel A), demonstrating that these values are rather stable and do not differ much from their average over all 156 events.

In the synthetic study we always use the weight of 100% for the *P*-wave onsets. To be sure with the suitability of the weight 50% for *S* waves, we run the location of the swarm with four other *S*-wave weights: 0%, 75%, 25% and 100%. The average values of hypocentre position and the RMS, ERZ and ERH parameters for all these locations are also given in Table 2. The values of ERH and ERZ are too high for weight 0% (location No. 5 in Table 2), as expected, because in this case, the *S*-wave constraint of the hypocentre position is lacking. The values of RMS are too high for S-wave weights of 100% and 75% (location No. 4 and 3), caused by over-weighting of the uncertain *S*-wave onset times so where the onsets cannot be well fitted. The *S*-weight of 25% (location No. 2) gives slightly better ERH and RMS and slightly worse ERZ than the weight of 50%. Both these weights are usable in the location of our swarm data. The depth (red dots) and epicenter (black dots) differences between the locations using the *S* weight of 50% versus 25% are given in Fig. 4, Panel B. Here, and also in the next Panels of Fig. 4, we show with lines the average values of ERZ (red line) and ERH (black line) from Panel A, to compare the location difference with the average of standard errors for location 1. Panel B shows that location differences both in depths and epicentres are significantly below the corresponding standard errors. Thus we use the *S*-wave weight of 50% in the following locations. The locations that use this *S*-wave weight, the elevation travel-time corrections, starting depth of 9 km and Vp/Vs = 1.70, model WEBN and no stations model travel-time corrections, will be called further as the " basic" locations (location No. 1 in Table 2).

In the next paragraph, we will show the differences (absolute values) in depths and epicenters of the swarm events between the "basic" values and the values obtained in the case that some of the input parameters have been varied. We will compare the differences with the average values of ERZ and ERH obtained for the basic location to see if the differences are in the range of standard errors. We change mostly only one of the location parameters and all others keep on the values for the basic location.

SWARM LOCATIONS FOR VARIED INPUT PARAMETERS

Starting depth To illustrate the influence of the starting depth we give in Table 2 (as location 6) the average values of the hypocentre positions, RMS, ERH, and ERZ for the location that uses the starting depth of 7 km. The differences against location No. 1 are practically only in the shift of 0.1 km to the larger X. But the RMS average is higher. The differences between these locations and the basic ones for individual events are given in Fig.4, Panel C. The change of the starting depth influences more the epicenters (black diamonds), which lie in Fig. 4 mostly above the line of the average ERH for the basic location (black line). The depths are significantly less influenced and are mostly well under the level of basic ERZ average value. Let us note that the change in starting depth was modest only. The polarity of the depth differences is marked in Table 3**.**

Vp/Vs ratio Recently, the Vp/Vs value of 1.68 has been found in the investigated area using Wadati's method (*Novotný et al., 2016*). We used this Vp/Vs with the WEBN *P*-wave velocity model, running the locations as for the basic case. The corresponding average positions, RMS, ERH and ERZ are again given in Table 2 (location No. 7). In this case, we get a shift of 0.2 km to larger depth and larger ERH and ERZ, as compared with the basic locations. The differences in the depth and epicentre distances for individual events between this location and the basic one are shown in Fig.4, Panel D. Most of the differences in the depth coordinates (red diamonds) lie slightly above the level of the "basic" average ERZ (red) line. Just five differences exceed 0.3 km, and four of them equal to zero (these depths are less than those for basic location, note the sign in Table 3). The differences in epicentres lie significantly below the basic ERH average line. The average differences are given in Table 3. These results indicate that Vp/Vs=1.68 is not optimal for use with the WEBN *P*-wave model.

Contrarily, we find that this ratio is fully acceptable with another velocity-depth distribution model, marked here as MN. The MN model was derived from the 2008 swarm data by a variant of the conjugate gradients method (*Novotný et al., 2012*). This model, shown in Fig.2 by a solid thin line, has the same layering as model WEBN, but features lower velocities in deeper layers. With this model (starting depth 9 km, *S*-wave weight 50%, elevation corrections applied), we get even slightly better locations (see corresponding average RMS, ERH and ERZ, location No. 8 in Table 2) than for the basic location. However, due to the lower velocities in the MN model, the hypocentre depths increase by ~0.35 km (see Table 2) as compared with the basic location. The differences in depth for individual events are shown in Fig. 4, Panel E (red diamonds). On the other hand, the differences in epicentres (black diamonds) are rather low. We again show the "basic" ERZ (red line) and ERH (black line) averages for comparison. The average difference in epicentres and depth between the basic location and the location using the MN model are given in Table 3.

Variation of the *P*-wave velocity-depth distribution Since the swarm hypocentres are distributed in a relatively small depth interval, between 7 and 12 km, with a lack of sources in shallow layers, the travel-time data do not strongly constrain the velocity models. Let us here demonstrate an example, shown in Fig.2 by a dashed line, that we propose as model MH. Its uppermost part to the depth of 2 km is identical with the WEBN model, but in deeper parts, it has just one layer. We find (by a grid search with the grid step 0.01 km/s) that the *P*-wave velocity of 6.18 km/s in this layer minimizes the sum of RMS for all events of the swarm. The average of location parameters RMS, ERH, ERZ and of coordinates X, Y and Z for location in this model (location parameters the same as for the basic location), shown in Table 2 as location No. 9, are very near to that for the "basic" location. Fig.4, Panel F shows the values of the epicenter (black diamonds) and depth (red diamonds) differences for these two locations. The average values of both difference sets are very low (0.022 km and 0.035, see Table 3), so they are well below the reference average ERH (black line) and ERZ (red line) of basic locations.

Elevation station corrections (EC) The elevation travel-time corrections (EC) are easy to find in our case where epicentral distances are comparable with the swarm depth. They are worth to be used because they improve the location of the swarm. The results of the experiments with and without EC can be seen in Table 2, row No. 1 in comparison with row No. 10. We observe that without introducing the corrections, the hypocentre positions change significantly, decreasing X, Y and Z by 0.1 km, 0.15 km and 0.15 km, respectively; see also Fig.4, Panel G. Most of the depth differences are on the level of the average basic ERZ. Some of them equal to zero, a few differences increase to 0.3 km. The differences in the epicentres are even more pronounced and lie over the average basic ERH. Ignoring the elevation corrections yields also a notable increase in average ERZ, ERH and RMS, as shows the Table 2 and Table 3. To further illustrate the effect of the elevation corrections, we compare the locations with and without EC in Fig. 3. We conclude that the application of elevation travel-time corrections is a necessary prerequisite for achieving accurate seismic studies based on hypocentre locations.

Full station corrections (FC), FC accommodate departures of our model from the real structure in terms of both velocity model (MC) and station elevation (EC), FC=MC+EC. The *P*-wave model correction is defined as the *P*-wave travel-time residual at a given station averaged over all events of the swarm, obtained by the location that use the elevation corrections (location row No. 11 in Table 2). The full correction for *S*-wave is estimated as the *P*-wave correction multiplied by the Vp/Vs ratio. Let us mention that we tested also another approach where the *S*-wave correction was estimated from the *S*-wave residuals. That approach however was abandoned due to uncertain *S*-wave onsets. The effect of the full correction has been investigated in location test No. 12 of Table 2. The application of the full travel-time corrections increases the depth of individual events on average by 0.11 km. Shift of the epicenters to the north and to the east is only negligible. This location of the swarm gives significantly better results; indeed, we find noticeably lower average RMS, ERH and ERZ, each one being practically one half, compared to the basic location. These aspects are further illustrated for individual events of the swarm in Fig.4, Panel H, and in Table 3.

Model station corrections (MC) show so the deviation of the real medium between the swarm and station from the model WEBN. The seismic swarms are characterised by tight clustering, thus waves from different sources propagate to each station practically through the same part of the crust. As seen from Table 1, the MCs reach the values from -0.06 up to 0.08 sec.On Fig. 1 we can observe a NS strip of 7 stations with positive MS (marked by green triangles) that detach two groups of stations with negative (or zero) MC (marked by red triangles).

It is worth noting that there are at least three pairs of the stations (SNED - KRC, STC - LOUD and KOPD - KVC), not far from each other, but belonging to different groups. This observation manifests that the “lateral” change in velocities is rather fast, possibly related to faults of the region. The fast variation seems to be confirmed in *Mousavi et al. (2015)*, by their vertical velocity profile D in Fig 13.

DISCUSSION AND CONCLUSIONS

We investigated issues related to free parameters of absolute seismic location, such as starting depth, the *S*-phase weight and Vp/Vs value, the influence of modification of the crustal model, the influence of elevation and model station corrections. Although rather technical, the topic is important for applications where a high location accuracy is needed when relating earthquakes to structural features, such as faults.

Our results are shown as a difference between the basic, standardly used location (WEBN model, Vp/Vs=1.70, *P*-wave weight of 100%, *S*-wave weight of 50%, starting depth of 9 km) and the locations with changed conditions. First, we get that the *S*-wave weight of 50% and 25% are suitable (Fig 4, Panel B), while the other *S*-wave weights give lover location accuracy (see RMS in Table 2). The relatively small differences in the starting depth can cause an increase of the difference in epicenters (above the average of ERH for basic location), the differences in depth are (slightly unexpected) smaller than those for epicenters and about on 1/3 of ERZ average for basic location (Fig 4, Panel C).

The Vp/Vs parameter is important in the HYPO locations because is valid for the whole model. Even the small change from 1.70 to 1.68 causes the dispersion of individual epicenter differences. Their average value is about half of the basic ERH. Almost all the individual depth differences lie over the basic ERZ (Fig 4, Panel D). The average RMS, ERH, and ERZ are higher than that for the basic location. We can get low average RMS, ERH, and ERZ even for the Vp/Vs of 1.78, by evaluating another velocity model, model MN (see Fig 2). For this model, we get almost identical epicenters as are the basic ones, but the events depth increase to 0.34 km on average, i.e. to almost double the basic ERZ. This illustrates that for each *P*-wave velocity distribution we have to use a specific Vp/Vs value (or vice-versa) to get a high location accuracy. But different *P*-wavevelocity - Vp/Vs combinations might yield notably different swarm depths, even if the RMS stay low.

Since the swarm hypocentres are distributed in a relatively small depth range, and with a lack of sources in shallow layers, the travel-time data from the swarm do not constrain sufficiently well the velocity models. Therefore there are some other simple 1-D models that equally well minimize the sum of RMS over all events of the swarm. We demonstrated it by model MH, shown in Fig.2. The corresponding event locations in this model are practically identical with those in the basic model and give also so low average ERH, and ERZ (Table 2 location No. 9, Fig.4, Panel F). But the minimal sum of RMS itself, of corse, is not sufficient to guarantee the suitability of the model from point of view of other demands, e.g. generation of acceptable seismograms.

In our case, where the swarm is clustered at the depth of around 9 km, its epicenters lie inside of the station network and the larger epicenter distances are less than 25 km, the estimation of the elevation travel-time corrections might be quite accurate (all the rays propagate from the sources upwards, with relative small radiation angle). If the location algorithm allows their introduction in the input data, they should be used, because they can increase the hypocentres accuracy. For more distant stations the elevation corrections cannot be obtained in our simple way. However, they may lose their importance, because of a large incidence angle of the ray.

On the other hand, the estimation of the model station travel-time correction (MC) (and the estimation of the model full travel-time corrections (FC) as FC = EC + MC can be derived only for swarm concentrated in the vicinity of the network center. They are caused by travel-time differences (along the whole ray path event – station) between the model and the real crust velocities averaged over all swarm events. Here we suppose that the rays from all swarm events to a given station are very similar. The latter is not the demand in the case of elevation corrections. The application of the station FC-s might increase the accuracy of the swarm location in terms of RMS, ERH and ERZ. A new MC (and therefore new FC) should be computed if another swarm has a different position in the area.

Although the ultimate stage is 3-D models, many seismic studies still need a good 1-D approximation, such as simple locations, determination of the focal mechanism from polarities, fast calculations of the Green functions for full-wave inversions, etc. Therefore, for the location of the earthquake swarms in the West Bohemia/Vogtland area, we recommend the use of WEBN model, supplemented by “full” station corrections, or at least by the elevation stations corrections.

ACKNOWLEDGEMENT

The station data are taken from https://www.ig.cas.cz/. We wish to thank Alena Boušková (Inst. of Geophysics, CAS) for providing her manual phase data readings. Jiří Zahradník provided critical comments that improved the text.

REFERENCES

Alexandrakis, C., Caló, M., Bouchaala, F. and Vavryčuk, V.: 2014. Velocity structure and the role of fluids in theWest Bohemia Zone. Solid Earth, 5, 863-872.

Dahm, T., Fischer, T. and Heinzel, S.: 2008. Mechanical intrusion models and their implications for the possibility of magma-driven swarms in NW Bohemia Region. Stud. Geophys. Geod., 52(4), 529-548.

Fischer, T.,Horálek, J., Hrubcová, P., Vavryčuk, V., Bräuer, K. and Kämpf, H.: 2014. Intracontinental earthquake swarms in West-Bohemia and Vogtland: a review. Tectonophysics, 611, 1-27.

Hainzl, S., Fischer, T. and Dahm, T.: 2012. Seismicity-based estimation of the driving fluid pressure in the case of swarm activity in Western Bohemia. Geophys. J. Int., 191, 271-281.

Herman, R. B.: 1979. FASTHYPO – a hypoceter location program, Earthquakes Notes, 50, 25-37.

Horálek, J. and Fischer, T.: 2008. Role of crustal fluids in triggering the West Bohemia/Vogtland earthquake swarm: just what what we know (a review), Stud. Geophys. Geod., 52, 455-478.

Horálek, J. and Šílený, J.: 2013. Source mechanisms of the 2000-earthquake swarm in the West-Bohemia/Vogtland region (Central Europe). Geophys. J. Int., 194(2), 979-999.

Horálek, J., Boušková, A., Hampl, F. and Fischer, T.: 1996. Seismic regime of the West-Bohemian earthquake swarm region: preliminary results. Stud. Geophys. Geod., 40, 398-412.

Horálek, J., Fischer, T., Einarsson, P. and Jakobsdótir, S.S.: 2015. Earthquake Swarms in: Encyclopedia of Earthquake Engineering. Eds. Baer M. Kousioumtzoglou, Pateli M., I.A., Au S-K; pp 871-885. ISBN: 978-3-642-35343-7.

Horálek, J., Fischer, T., Einarsson, P. and Jakobsdótir, S.S.: 2021. Earthquake Swarms in: Encyclopedia of Earthquake Engineering. Springer-Verlag Berlin Heidelberg. Doi 10.1007/978-3-642-36197-5_294-1.

Hrubcová, P., Vavryčuk, V., Boušková, A. and Bohnhof, M.: 2015. Shallow crustal discontinuities inferred from forms of microearthquakes: Method and application to KTB Drill Site and West Bohemia Swarm Area. J. Gephys. Res. Solid Earth, 121, doi: 10.1002/2015JB012548.

Hsin-Chieh, P., Cheng-Horng L., Yu-Chih H. and Yih-Hsiung Y.: 2014. The volcanic earthquake swarm of October 20, 2009 in the Tatun area of northern Taiwan. Terrestrial Atmospheric and Oceanic Sciences 25(5):625, DOI:10.3319/TAO.2014.04.11.02(T)

Klein, R. W.: 1978. Hypocenter location program HYPOINVERSE, users guide to version 1, 2, 3 and 4. U.S. geol. Surv. Open-file rep.,78-694.

Lee, W. H. K. and Valdes, C. M.: 1985. HYP071PC: A personal computer version of the HYPO71 earthquake location program, *U. S. Geological Survey Open File Report 85-749*, 43 pp.

Málek, J., Horálek, J. and Janský, J.: 2005. One-dimensional qP-wave velocity model of the upper crust for the West Bohemia/Vogtland earthquake swarm region. *Stud. Geophys. Geod.*, **49**, 501–524.

Mousavi, S., Bauer, K., Korn, M. and Hejrani, B.: 2015. Seismic tomography reveals a mid-crustal intrusive body, fluid pathways and their relation to the earthquake awarms in West Bohemia/Vogtland. Geophys. J. Int. 203, 1113-1127.

Novotný O.: 1996. A preliminary seismic model for the region of the West-Bohemian earthquake swarms. *Stud. Geophys. Geod.*, **40**, 353–366.

Novotný, O., Málek, J. and Žanda, L.: 2013. Verification of the shallow seismic crustal structure of the western Krušné Hory crystalline unit, Czech Republic. *Stud. Geophys. Geod.*, **57**, 507–519, DOI: 10.1007/s11200-012-0215-6.

Novotný, O., Sokos, E. and Plicka, V.: 2012. Upper crustal structure of the Western Gulf, Greece, infered from arrival times of the January 2010 earthquake sequence. Stud. Gephys. Geod. 56, 1007–1018, DOI: 10.1007/s11200-011-0482-7.

Novotný, O., Málek, J. and Boušková, A.: 2016. Wadati method as a simple tool to study seismically active fault zones: a case study from the West-Bohemia/Vogtland region, central Europe. *Stud. Geophys. Geod.*, **60**, 248–267, DOI: 10.1007/s11200-015-1206-1.

Růžek, B. and Horálek, J.: 2013. Three-dimensional seismic velocity model of the West Bohemia/Vogtland seismoactive region. *Geophys. J. Int.*, **195**, 1251–1266, DOI: 10.1093/gji/ggt295.

Sokos, E., Zahradník, J., Kiratzi, A., Janský, J., Gallovič, F., Novotný, O., Serpetsidaki, A., and Tselentis, G.-A.: 2012. The January 2010 Efpalio earthquake sequence in the western Corint Gulf (Greece). Tectonophysics 530-531, 299-309, doi:10.1016./j.tecto.2012.01.005

Vrána, S. and Štědrá, V. (Eds.): 1997. *Geological Model of Western Bohemia Related to the KTB Borehole in Germany*. Czech Geological Survey, Prague, Czech Republic.

Waldhauser, F. and Ellsworth, W.L.: 2000. A double-difference earthquake location algorithm: method and application to the Hayward fault. Bull. Seism. Soc. Am., 90,1353-1368.

TABLES

No:	Code	Longitude E°	Latitude N°	Elev. -500 (m)	X (km)	Y (km)	EC (s)	MC (s)	FC (s)
1	BUBD	12.5136	50.3817	246	8.081	20.222	.06	-.08	-.02
2	HOPD	12.2265	50.2238	231	-9.600	2.654	.05	-.05	.00
3	HRC	12.5367	50.1935	96	9.754	-0.716	.02	-.08	-.06
4	HRED	12.5649	50.2142	89	11.771	1.598	.02	-.07	-.05
5	KAC	12.5172	50.1436	48	8.369	-6.266	.01	.04	.05
6	KOC	12.2339	50.2642	75	-11.916	7.151	.02	-.05	-.03
7	KOPD	12.4747	50.2032	36	5.335	0.339	.01	-.02	-.01
8	KRC	12.5304	50.3316	306	9.221	14.545	.07	-.07	.00
9	KVC	12.5152	50.2059	80	7.949	0.558	.02	-.09	-.07
10	LAC	12.6250	50.0508	384	16.040	-16.697	.09	.09	.18
11	LBC	12.4123	50.2655	184	0.801	7.187	.04	.00	.04
12	LOUD	12.5745	50.2775	192	12.438	8.639	.04	-.12	-.08
13	NKC	12.4480	50.2331	110	3.358	3.598	.02	-.01	.01
14	PLED	12.3376	50.2089	56	-4.449	0.996	.01	-.03	-.02
15	POC	12.4267	50.3200	341	1.896	13.345	.08	-.02	.06
16	POLD	12.2350	50.1560	56	-11.794	-4.878	.01	-.04	-.03
17	SKC	12.3610	50.1700	1	-2.822	-3.435	.00	-.04	-.04
18	STC	12.5197	50.2591	166	8.450	6.452	.04	-.03	.01
19	TRC	12.1448	50.3032	112	-18.191	11.537	.03	-.01	.02
20	VAC	12.3772	50.2354	81	-1.688	3.838	.02	-.04	-.02
21	ZHC	12.3087	50.0706	177	-6.579	14.474	.04	-.03	.01
22	SNED	12.5013	50.3109	256	7.216	12.339	.06	.02	.08

Table 1: Codes, geographical and Cartesian coordinates of individual stations of the WEBNET network. No. of events recorded by given station. Elev. is the station elevation above our Z=0 level. (Our Z axis has its origin at the level of 500 m above the sea level to decrease the influence of elevation travel-time corrections. These corrections are estimated, not computed.) So the elevation correction (EC) are estimated for these modified elevation values. Table gives also the derived model travel-time correction (MC) and the full correction (FC) that represent the sum of EC and MC.

No.	Location by HYPO					Aver. EPIC.		ERH (km)	Aver. Z (km)	ERZ (km)	RMS (s)
	Model	Cor.	Z (km)	Vp/Vs	S-weight	X (km)	Y (km)				
1	W	EC	9	1.70	0.50	3.871	1.210	0.124	9.643	0.166	0.057
2	W	EC	9	1.70	0.25	3.871	1.195	0.122	9.618	0.168	0.052
3	W	EC	9	1.70	0.75	3.870	1.219	0.126	9.663	0.169	0.061
4	W	EC	9	1.70	1.00	3.869	1.224	0.126	9.677	0.172	0.063
5	W	EC	9	1.70	0.00	3.853	1.163	0.166	9.567	0.270	0.040*
6	W	EC	7	1.70	0.50	3.994	1.174	0.126	9.621	0.172	0.061
7	W	EC	9	1.68	0.50	3.931	1.143	0.137	9.826	0.180	0.061
8	MN	EC	9	1.68	0.50	3.862	1.179	0.120	9.971	0.166	0.056
9	MH	EC	9	1.70	0.50	3.861	1.206	0.123	9.681	0.169	0.056
10	W	-	9	1.70	0.50	3.787	1.061	0.145	9.500	0.196	0.067
11	W	FC	9	1.70	0.50	3.913	1.274	0.061	9.753	0.082	0.030

Table 2. Table gives the input parameters used in 11 different locations of our 156 swarm events. W represents the WEBN crustal model, for models MN and MH see text. EC marks that stations elevation travel-time correction has been used in the location, whereas FC means that the sum of both the elevation and model travel-time correction has been used. Z gives the value for the location first depth approximations. The used Vp/Vs and S wave phase weight represent the further input parameters.
The Table gives also the averages of the locations (output) parameters: The cartesian coordinates X, Y and Z(in km), the root mean square error of time residuals (in sec) - RMS, standard error of the focal depth (in km) ERZ, and standard error of the epicentre (in km) ERH, where ERH = sqrt(SDX**2+SDY**2), with SDX and SDY being the standard errors in axes X and Y (in km), respectively. The location No. 1 corresponds to the basic location.

*)Value is from P-waves only. If corresponding locations is fixed and S waves weighted by 0.50% the RMS reaches the value of 0.079 s.

Nos:	Dif. epi	Dif. depth
1 - 2	0.015	0.025
1 - 6	0.159	0.045*
1 - 7	0.090	-0.185
1 - 8	0.032	-0.336
1 - 9	0.021	-0.035
1 - 10	0.176	0.146
1 - 11	0.048	-0. 110

Table 3. Average location difference in epicentres and depths (km) between pairs of locations marked in Table 2.
*Average from difference absolute values

FIGURES

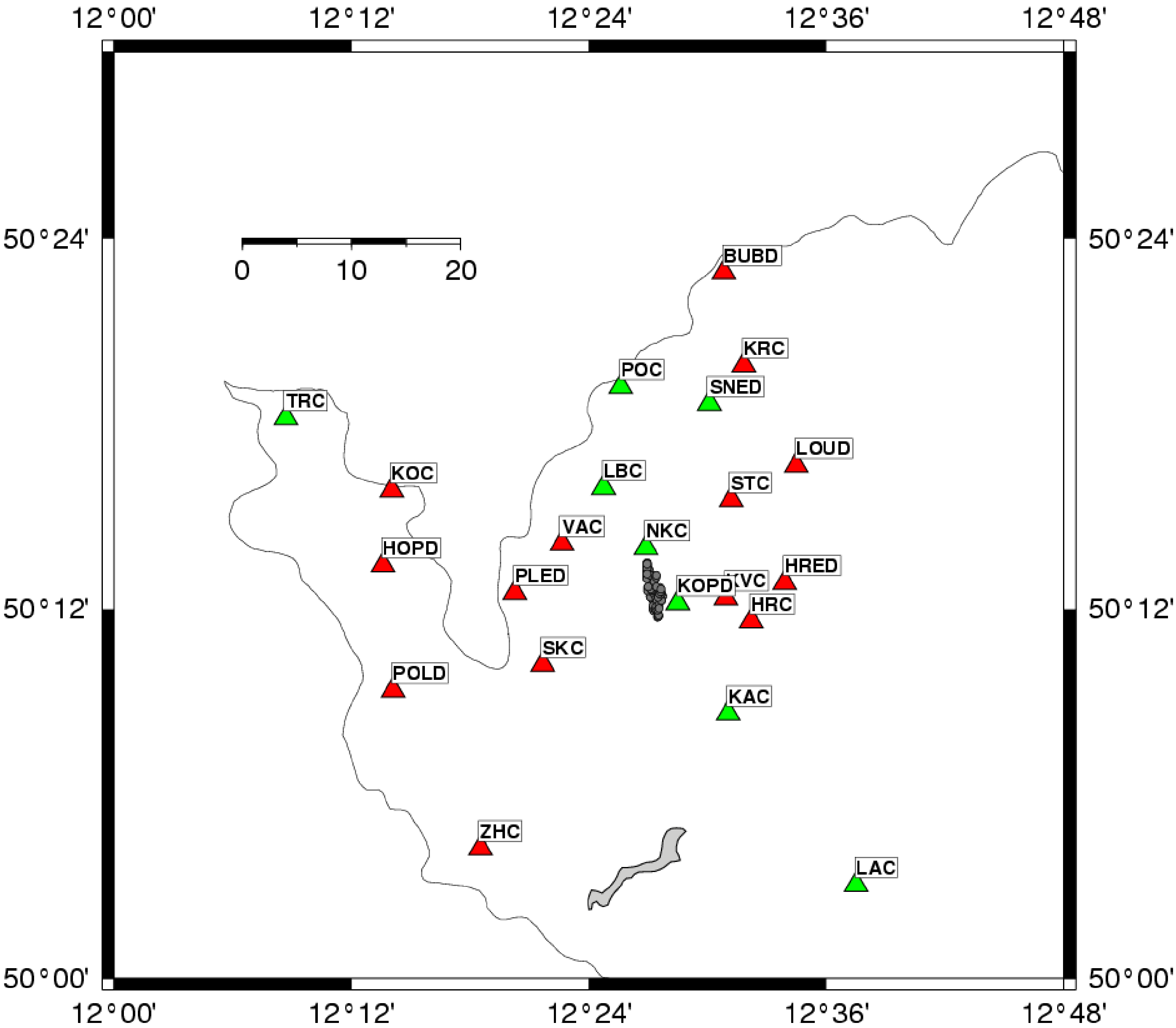

Fig.1: West-Bohemia swarms region. Triangles show the WEBNET stations network. The green and red triangles mark stations with positive and negative (or zero) model travel-time corrections, respectively. These model travel-time corrections are used to derive local modification of the WEBN crustal model. Dots are the epicenters of the 156 event selection of the 2008 swarm, located by the HYPO71PC algorithm.

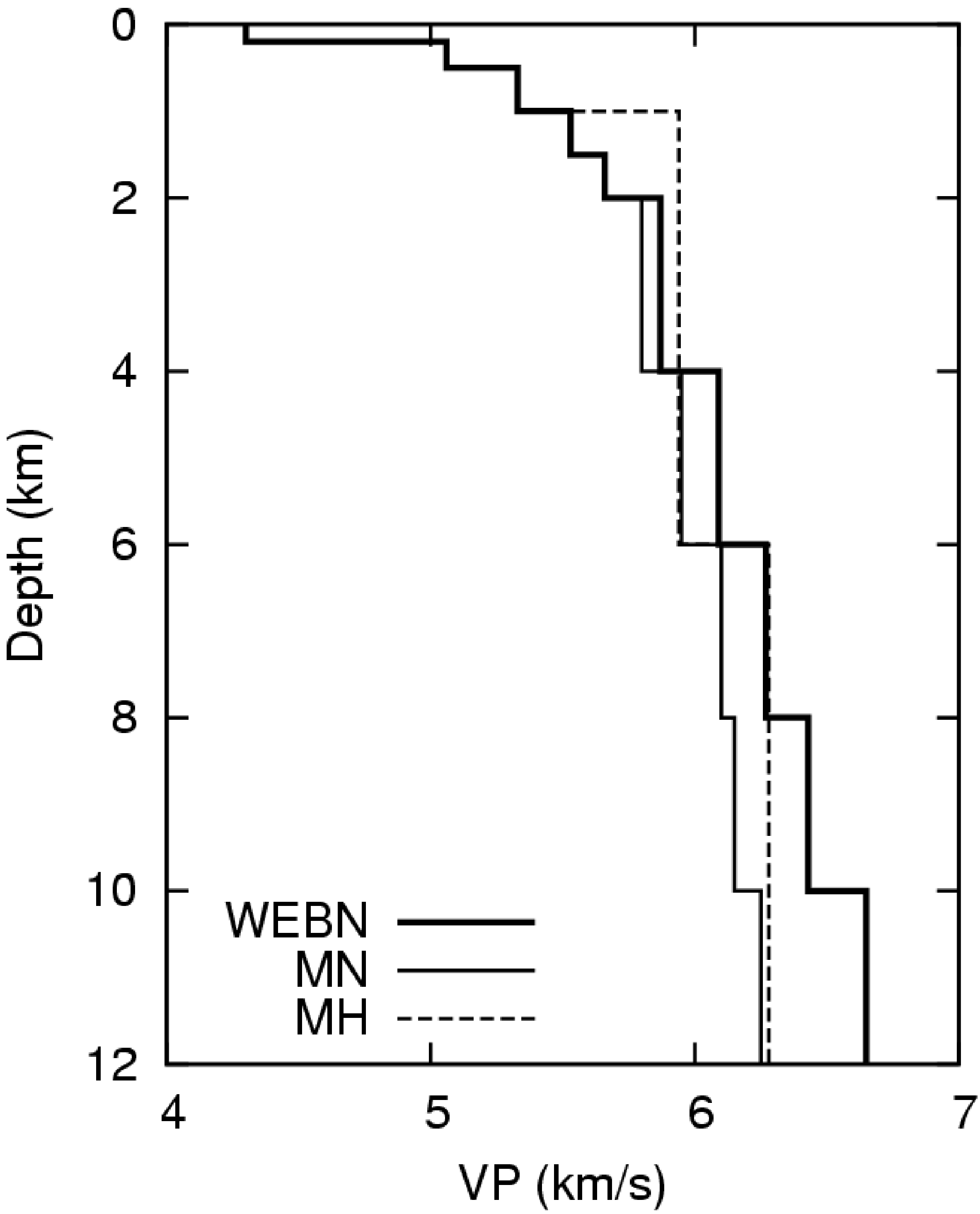

Fig. 2: Upper crustal P-wave velocity models of the area: Heavy solid line – model WEBN, solid line –model MN, dashed line – model MH.

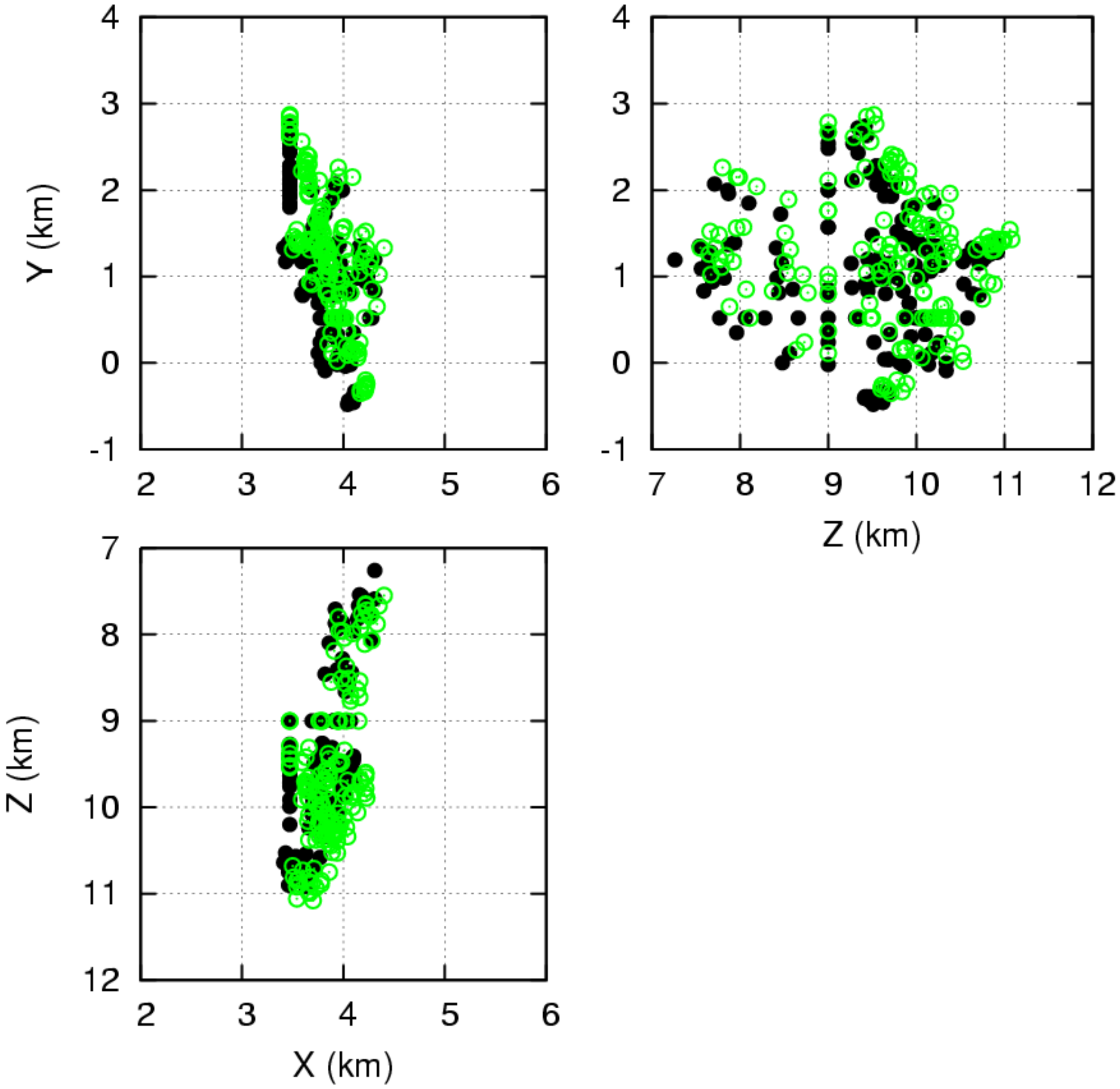

Fig. 3: Map view and two vertical cross-sections of the hypocentres of the swarm in Cartesian coordinate system. The coordinate [0, 0, 0] of X, Y and depth (Z) axes is at the point 12.4°E and 50.2°N of geographical coordinates. The axe X is positive to the East, the axe Y positive to the North. The origin of the axe Z equals to 0 at the elevation of 0.5 km above the sea level, and is positive to down. The Cartesian coordinate system is also given in Table 1. Green circles mark the hypocentres obtained by the "basic" location (location No: 1 in Table 2), black dots represent the hypocentres located without the elevation corrections (location No: 10 in Table 2), see text.

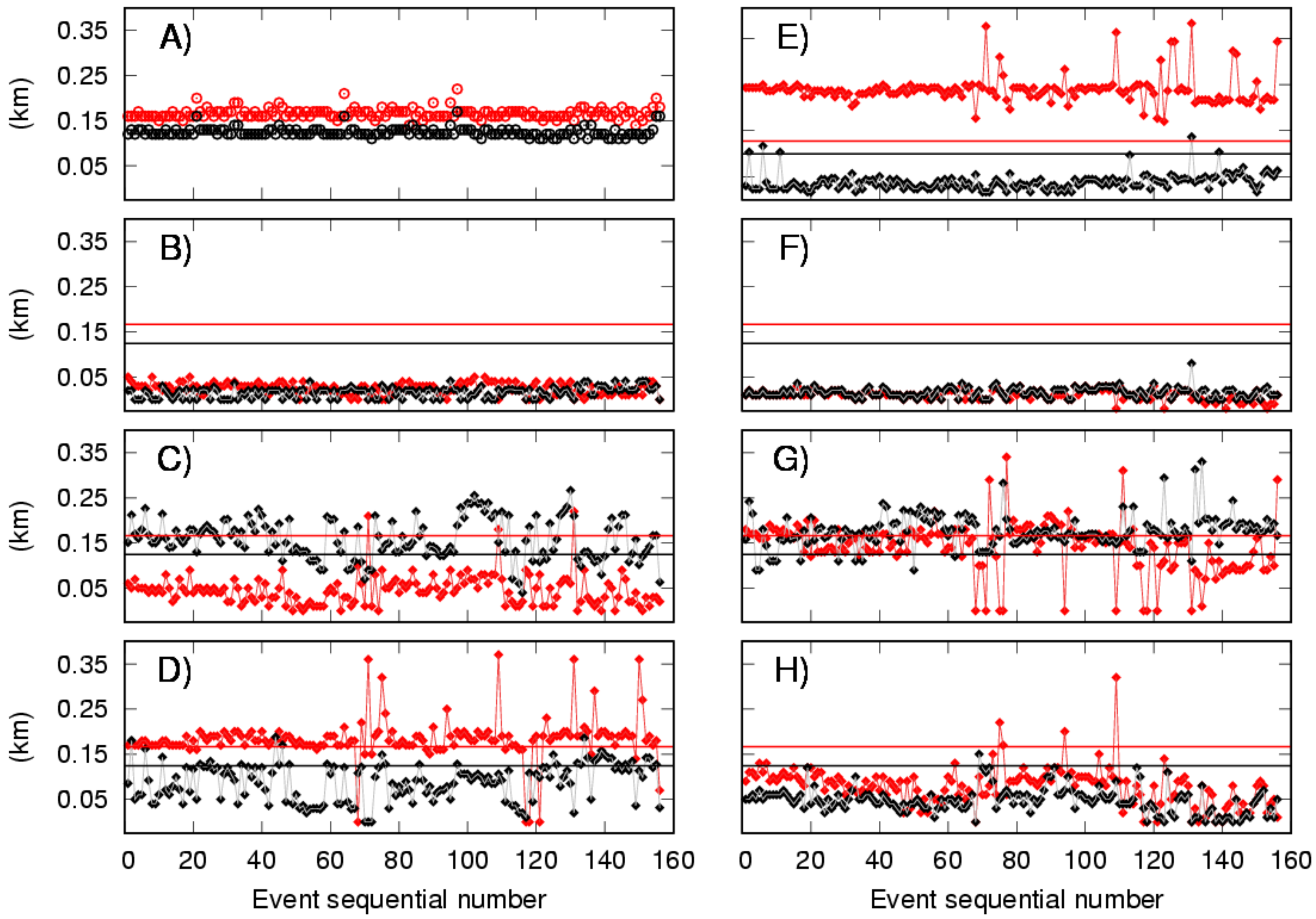

Fig. 4: Differences in the swarm locations, caused by the use of different input parameters.

Panel A shows the location standard error value (km) in the depth (ERZ – red circles) and epicenter (ERH – black circles) for individual swarm events as a function of event sequence number. "Basic" location input parametres: crustal model WEBN, starting depth of 9 km, Vp/Vs=1.70, P phase weight=100%, S phase weight 50%, elevation station corrections applied.

Panel B: Differences in location (in km) between the basic location and location that uses the S-wave weight 0.25. Other parameters are the basic ones. Red diamonds – differences in the depth, black diamonds – differences in the epicenters, both as a function of event sequence number. For comparison we give two lines that represent the average value of ERZ (redline) and ERH (black line) from Panel A

Panel C: Differences in locations as in Panel B but between the basic location and the location where the starting depth equals to 7 km.

Panel D: Differences in location as in Panel B but between the basic location and location that uses Vp/Vs of 1.68

Panel E: Differences in location as in Panel B but between the basic location and locations in the model MN.

Panel F: Differences in location as in Panel B but between the basic location and locations in the model MH.

Panel G: Differences in location as in Panel B but between the basic location and locations where the station elevation corrections are not applied.

Panel H: Differences in location as in Panel B but between the basic location and locations where both the station elevation and station model corrections are applied.