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Solid Earth
Discussions

Interactive comment on "Indications for different types of brittle failure due to active coal mining using waveform similarities of induced seismic events" *by* S. Wehling-Benatelli et al.

S. Wehling-Benatelli et al.

sebastian.wehling@rub.de

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We appreciate the opportunity to resubmit our article "Indications for different types of brittle failure due to active coal mining using waveform similarities of induced seismis events". The whole paper has been revised and all comments by the Referees have been addressed, with corresponding changes made directly to the manuscript where appropriate. Accompanying this letter, please find a revised version of our manuscript. Detailed responses to the Referees' comments are included below.

Referee 1 - Henryk Marcak:

Question: Description of similarity matrices P663 line 4 The similarity of two rows is

presented along with the question What next? The further procedures isn't following The main element of the paper should be described preciously. This remark is also relevant in description of station matrix.

Answer: This part of the paper has been improved. The authors hope that the sorting procedure is now presented more clearly. The new section reads:

"The idea of sorting the SMs in order to obtain clusters of similar events is that if the pattern of similarity of two events to all the others is similar these two events have to be similar to each other as well. Thus, sorting the matrix by similarity of the rows gathers all events belonging to a cluster. Since the SMs are symmetric it is sufficient to sort for either rows or columns. In order to stabilize the sorting procedure the SM can be smoothed or sharpened before sorting. Therefore, the individual values of the SM are exponentiated by the smoothing parameter ξ. Values higher than one increase the contrast in the SM and thus results in more clusters with less members than without smoothing the SM. The opposite case holds for smoothing parameter values $0 < \xi < 1$.

The algorithm starts by finding the particular event which exhibits the highest similarity with respect to all the other events, i.e. the row of the SM having the largest cumulative sum. This can be written as

$$i_{sort,1} = m_0, where \max_{m=m_0}(\sum_{n=1}^{L} b^{\xi}_{m,n}). \tag{1}$$

This events row index m_0 is the first entry of an index vector, the so-called sorting vector i_{sort}, which is subsequently utilized to establish the sorted SM. m and n are the row and the column indices of B, respectively. Consecutively, the event exhibiting the highest similarity with respect to its sequence of cross-correlation coefficients (similarity pattern of the rows) to the previously found is searched for. Therefore, the similarity of two rows of the SM is calculated by cross-correlating them without admitting any shift of the respective rows m. In case the cross-correlation coefficient is not normalized, this is mathematically identical to the scalar product of the row vectors (see also Maurer and Deichmann, 1995). All other entries of the sorting vector are iteratively found in this manner."

Question: Spectra The similarity of waveform should be visible also in the similarity of waveform spectra. The interpretation of spectra similarity is simpler and could strengthen the final conclusions of the paper.

Answer: As the full waveform contains more information than the amplitude spectra and the method yields good results, in the opinion of the authors it is of no benefit to go back to the simplification of using amplitude spectra to obtain information on the similarity of the underlying source properties.

Question: Geology The important missing information is geological structure in the region of investigations. The geological and mining situation in the vicinity of the long-wall is the main factor determining the level of seismicity. Strata, mechanical properties of the rocks, tectonics, and edges in seams over the exploited long-wall are all important elements in determining the differences in the seismic emission. Without this information the conclusions in the paper are not convincing.

Answer: A new figure has been compiled which summarizes the results and put them into the geological setting. A lithological column beside a mapview, containing an overview about the tectonic features and the three main types of brittle failure investigated by the authors, summarize the conclusions made by the authors in the discussion. The figure is meant to give a brief overview, so it is held schematic. In the mapview both types I and II match the area of active mining (orange rectangular). Seismicity of type II is more concentrated to the north whereas type I is found over the whole area of mining. For sure, there are not only the faults present which are skteched, but the figure reflects very well where the most disturbed areas can be found, which correspond to the areas where failure type III has been identified. The lithological column on

the left sketches the occurence of the different failure types, identified by the authors, by depth and abundance of typical rocktypes. Alber et al. (2009) showed that it is most likely that the silt-/sandstone layers form the seismogenic zone for this mining environment which also nicely matches the results found in this study within the errors. The figure is appended as supplement to this answer. The corresponding caption reads:

"Mapview of the relocated seismicity of the eight largest clusters (gray circles) and the three main types of brittle failure. On the left hand side there is a lithological column (modified after Alber et al. (2009)) illustrating the abundance of the observed failure types in the context of the geological setting underground. Events of type I (yellow) are directly accompanying the longwall face at mining level reflecting direct stress release by many small magnitude events. Type II (blue) are also events occurring horizontally within panel S 109 but at shallower and greater depth reflecting potentially larger magnitude events in prominent rock layers which do not follow GR. Type III (dark red) are events which occur at all depths but concentrated at the northern edge of the longwall panel. This event type shows FMD following GR, thus this failure type has been associated to tectonic faults (information from personal conversation with the mine operator) which are concentrated in this area. Depth values are given relative to the mining level of panel S 109. Although only a limited lithological profile is available the alternating sequences of more and less competent layers are also characteristic for the sedimentary bedding between the other indicated coal seams."

Question: Network The method used for installing the sensors, accuracy of the hypocenter locations and the energy estimations, would be helpful in assessing the differentiation of the similarity catalogues.

Answer: The network consists of 15 temporary stations. Besides one station installed in the field, all stations were installed on the basements of private houses and public institutions. The basements assured a good coupling to the ground. In order to obtain good coupling to the ground, the station in the field was buried. In addition, broadband stations were thermally isolated. The magnitude was calculated from the maximum amplitude of the displacement seismograms, averaged over the whole network and calibrated by comparison with the magnitudes of the regional network and catalogue. Sections 1, 3.1 and 5.2 have been modified to address the remarks concerning network configuration, location accuracy (especially in vertical direction) and the energy estimation.

Question: Velocity The differences between the catalogues can also be due to local velocity changes as a result of an increase in stresses. The velocity and attenuation of seismic waves can change markedly as a result of changes in stress levels

Answer: Differences in the locations may in some cases be artefacts of the location procedure. If the velocities of the subsurface are varying on a small scale, the applied velocity model does not sufficiently represent the true subsurface. Reasons for small-scale variations are, for example, local heterogeneities of the rock material or – which plays an important role in mines – stress changes which are induced by the mining and may result in huge deviations from the assumed velocities. However, in our case we disregard the influence of stress changes on our velocity model and locations, respectively. Firstly, since the clusters of different depth levels cover the same epicenter region and are above, at or below the mining level, we conclude that one averaged velocity model is sufficient to locate all events. In fact, we use a homogenous velocity model here which was calibrated by a ground truth event, namely a rock burst event within the mine. In addition, the homogenous velocity model is justified by the network geometry: stations directly above the hypocenter control the depth determination. The good station quality and high signal-to-noise ratio ensure that onset times of stations above the hypocenter are used for the vast majority of the events. The ray paths to these stations are nearly vertical and therefore only the average velocity is relevant here.

The location accuracy has been estimated by a grid search procedure for representative events and amounts to about 50 m. The centroids of the clusters are clearly seperated by depths, although – as discussed above – the epicenters and thus the ray

paths are similar.

The discussion section has been improved to account for the possibilty of veloctiy changes due to stress changes in the vicinity of the longwall.

Referee 2 - Grzegorz Mutke:

Question: Because the clusters with large magnitude events up to ML 1.8, which tend to locate slightly above or below the two largest clusters, do not follow G-R low, it would be important to describe in more details how the authors calculated “b” value and what was the errors of specified values of “b” ?

Answer: In the second paragraph of section 4.2 we added a section describing the calculation of b-values:

"B-values in this study are calculated using the maximum likelihood approach of Aki (1965) incorporating a correction for the binning width of the catalogue (Bender, 1983) which is 0.1 magnitude units in our case. Magnitudes of completeness are determined using the Goodness-of-fit test (GFT) (Wiemer and Wyss, 2000) demanding an R value at least below 10 but preferentially below 5. The R value describes the absolute difference in the number of events in each magnitude bin between the observed magnitude distribution and a synthetic power law distribution with parameters from the maximum likelihood estimation (see Wiemer and Wyss, 2000, for details). An R value of 0 indicates a perfect fit to the assumed GR power law. FMDs with an R value above 10 for all possible completeness magnitudes are regarded as non-GR distributions and accordingly no b-value is calculated for them. Presented b-values (Fig. 10) are mean b-values of 1000 bootstrap runs of the respective cluster and error bounds indicate the standard deviation of these bootstrap results."

In Fig. 9 we now added the standard deviation of the b-value as resulting from 1000 bootstrap runs for the respective cluster events. Because now the presented b-value in Fig. 9 is also the average from the bootstrap calculation and not the b-value from the unperturbed cluster events also these values changed slightly when compared with the first version of the manuscript. However, all former values are within the error bounds of the bootstrap results. Taking errors from bootstrapping is a more conservative approach than using the standard deviation from the maximum likelihood calculation of the original catalogue and thus we hope that the presented results are convincing enough to show a b-value difference between the two largest clusters as well as between these clusters and the orange one in the North containing events possibly linked to pre-existing structures.

Question: The next important question is: what was the accuracy of the seismic events location (especially vertical component – you used surface stations network, so as to proof location quality is enough for the purpose of the study presented)?

Answer: See answer to similar questions by Referee 1 above.

Question: And the last one question: What methodology was used to calculate the seismic moment tensors. Did the Authors use full moment tensor inversion or allowed only for shearing type of focal mechanism ?

Answer: Full moment tensor inversion has been performed to calculate the seismic moment but not by the authors themselves. Detailed information on the methodology can be found in the work of Sen et al. recently published, thus the following citation has been added:

Sen, A. T., Cesca, S., Bischoff, M., Meier, T., and Dahm, T.: Automated Full Moment Tensor Inversion of Coal Mining Induced Seismicity, Geophys. J. Int., in press, 2013.

Question: In my opinion lack of cross-section and lithological profile and the location of major faults, left edges and remnants makes difficult to read the source mechanisms analysis and individual clusters characteristics in relation to real mining and geology conditions.

Answer: For lithological profiles see new figure (supplement) and corresponding an-

swer to question of Referee 1 above.

Interactive comment on Solid Earth Discuss., 5, 655, 2013.

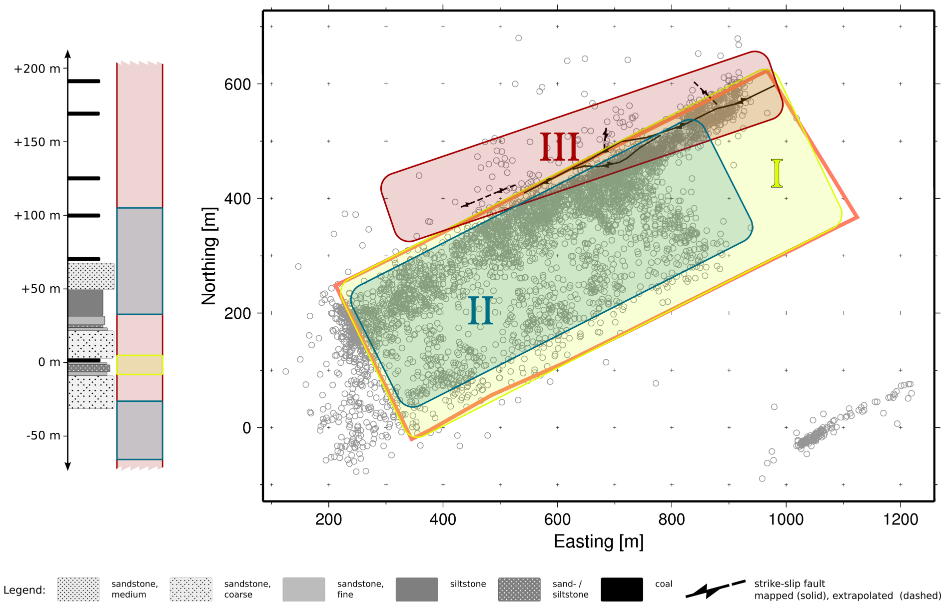

Fig. 1. Mapview of the relocated seismicity of the eight largest clusters (gray circles) and the three main types of brittle failure.