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Ebreichsdorf 2013 earthquake series: Relative location

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Abstract

We study recent moderate-size earthquakes in the Southern Vienna Basin, focusing on the 2013 series of two earthquakes with local magnitudes of 4.2 and their aftershocks. Furthermore, we compare them to a similar series of earthquakes from 2000. Due to the superior dataset, we can jointly relocate all earthquakes from 2013 datasets. To reduce the influence of unmodeled velocity inhomogenities, we use the "double-difference-times" implemented in the HypoDD software. Additionally, we use velocity models with different degrees of complexity (1-D to 3-D). We also test the stability of the results with different sets of initial locations.

After relocation the main shocks are located only 40 m apart; the colocation is confirmed by the high inter-event coherence. Moreover, the aftershocks show a clear pattern with larger earthquakes having deeper hypocenters and location in the South West and shallower, smaller earthquakes in the northeast. We also locate the two main shocks from 2000 relative to the main shocks from 2013 using S-P-times. The main shocks from 2000 are located 4 km to the northeast of the 2013 main shocks.

This suggests that the earlier notion of "event clustering" in the Southern Vienna Basin needs to be reconsidered, since at least some of the earthquakes, here the aftershocks, seem to occur between the clusters that have been proposed previously. Still the question why earthquake collocation within short time intervals occurs, remains open.

In dieser Studie untersuchen wir die Erdbebenserie von 2013 bei Ebreichsdorf im südlichen Wiener Becken. Hier wurden zwei Beben mit einer lokalen Magnitude von 4.2, sowie ca. 30 Nachbeben aufgezeichnet. Im ersten Schritt relokalisieren wir die Serie relativ zueinander, denn im Unterschied zu früheren Erdbebenserien ist der 2013er Datensatz wesentlich umfangreicher. Im Anschluss vergleichen wir die relokalisierten Erdbeben mit einem (ähnlichen) Bebenpaar des Jahres 2000. Um den Einfluss von unmodellierten Geschwindigkeitsänderungen zu reduzieren, verwenden wir den den HypoDD Algorithmus, welcher auf der Verwendung von Doppel-Differenz-Zeiten basiert. Zusätzlich verwenden wir unterschiedlich komplexe Geschwindigkeitsmodelle (1-D, 2-D und 3-D). Weiters testen wir die Stabilität der Ergebnisse mit unterschiedlichen Startlokalisierungen der Erdbeben.

Nach der Relokalisierung befinden sich die beiden Hauptbeben von 2013 nur 40 m voneinander entfernt. Diese Kollokation wird von der hohen Kohärenz zwischen den Wellenformen der beiden Hauptbeben bestätigt. Die Nachbeben zeigen ein klares Muster, wobei die stärkeren Ereignisse in größeren Tiefen auftreten, und weiter im Südwesten, als die kleineren Erdbeben. Zusätzlich lokalisieren wir die beiden Hauptbeben von 2000 - relativ zu den Hauptbeben von 2013 unter der Verwendung von S-P-Zeiten. Hier zeigt sich, das die beiden Bebenserien ca. 4 km voneinander stattfanden. Sie zeigen jedoch auch eine hohe Ähnlichkeit untereinander, wenn auch geringer als die Beben von 2013.

Dies lässt darauf schließen, dass die frühere Vorstellung des "event clustering" im südlichen Wiener Becken überdacht werden sollte. Offenbar treten auch Beben zwischen den Clustern auf. Weiterhin bleibt es eine offene Frage, warum Erdbeben innerhalb kurzer Zeiträume kollokiert auftreten können.

1. Introduction

Due to ongoing convergence between the European Plate from the north and the Adriatic plate from the south, crustal blocks extrude laterally to the east into the Pannonian Basin (e.g., Gutdeutsch and Aric, 1987). At larger scale, two sinistral strike-slip fault systems show this process: the Salzach-Enns-Mariazell-Puchberg fault (SEMP) and the seismically active Mur-Mürz-Fault (MMF). The Vienna Basin lies in the northeastern extension of the MMF, in the transition of the Eastern Alps to the Western Carpathians. This pull-apart basin started forming in the Middle Miocene (e.g., Decker et al., 2005; Royden, 1985) and is now filled with several kilometers of sediments. The MMF links up with the Vienna-Basin-Fault-System (VBFS), which consists of seismically active sinistral strike-slip faults and non-active normal faults. Beneath up to 5 km of slow velocity Miocene fill and medium-velocity sedimentary rocks of Northern Calcareous Alps and Greywacke Units (Wessely, 1983) the Bohemian Massif forms the basement of the Vienna Basin. An overview of the main tectonic units, faults and seismicity is given in Figure 1.

The Vienna Basin is not only one of the most densely populated areas in Austria; it is also one of its seismically active regions. Particularly the southern part of the basin is susceptible to earthquakes with a maximum instrumentally recorded local magnitude (Ml) of 5.2 listed in the Austrian Earthquake Catalog (see Fig. 1; ZAMG, 2014). We will subsequently abbreviate it as AEC. Earthquakes in the Vienna Basin appear to cluster approximately every 15 to 20 km along the main fault of the VBFS. Most of the destructive earthquakes o,ccur on that fault. Moment tensor and fault plane solutions usually show strike-slip earthquakes (Decker et al., 2005), with southwest-northeast oriented nodal planes that are subparallel to the direction of the faulting.

Our study focuses on the area around Ebreichsdorf, 30 km south of Vienna shown in Figure 2: The first earthquake listed in the AEC for the vicinity of Ebreichsdorf occurred in 1899, with a magnitude above 3 and intensity above 5. In the 20th century, with the start of instrumental seismic records only 12 earthquakes were observed within a radius of 7.5 km. Therefrom, the earthquake from 1938 is the most notable with an estimated magnitude of 5.0 and intensity of 7.0.

In 2000 two earthquakes with a Ml of 4.8 and 4.5 (intensity 6.0 and 5.0) took place in the region of Ebreichsdorf within less than 10 hours. Most of the aftershocks could be recorded with temporary seismometer deployments by the Comprehensive Test Ban Treaty Organisation (CTBTO) (Anonymus, 2002). Locations of these aftershocks are shown in Figure 5 for comparison. With additional data from semi-permanent stations deployed by the Technical University of Vienna due to e.g. the ALPAACT project (Brückl et al., 2014), more than 20 earthquakes were recorded between 2001 and 2012 in the vicinity of Ebreichsdorf.

In autumn 2013 another earthquake series was recorded in the Southwest of Ebreichsdorf. In a period of less than a month the Zentralanstalt für Meteorologie and Geodynamik (ZAMG) recorded two earthquakes with a Ml of 4.2 and almost 30 aftershocks. In this paper we discuss the recordings from 2013, and the constraints on (precise) earthquake locations that they provide.

2. Ebreichsdorf 2013 series

The earthquake that occurred on September 20th 2013 at 02:06 UTC had a Ml of 4.25, and it was located close to Ebreichsdorf according to ZAMG. Over the following days 8 smaller aftershocks were detected. After a few events in the night of October 2nd, the second main shock with a Ml of 4.18 occurred at 17:17 UTC. 17 aftershocks followed in October. Until April, eight more earthquakes took place, all with a local magnitude smaller than 1.5. All of those events are listed in Table 4.

Numerous stations from various seismic networks recorded data from the events in autumn 2013: The ZAMG operates seismic broadband stations spread all over Austria, where continuous data is available online. Furthermore, strong-motion sensors are triggered for large magnitude events. Also, national institutes in the neighboring countries operate seismic stations. Most of their data are collected by ORFEUS (Observatories and Research Facilities for European Seismology) and are available online. GeoRisk Earthquake Engineering supplied this study with additional data from seismic stations in the Pannonian Basin. Seismic data from the project ALPAACT with its focus on eastern Austria is of particular importance for this study, as they recorded all earthquakes in the 2013 series.

Following the second main shock, seismologists from the University of Vienna deployed 3 temporary seismic stations (VB01-03) close to Ebreichsdorf on October 3rd. All three stations were equipped with 60-second 3-component broadband sensors and set to 100 Hz continuous recording. Table 1 lists the station locations. Station VB02 and VB03 were dismantled on December 5th, and station VB01 was equipped with GSM for real-time data transmission to the datacenter of the Department of Meteorology and Geophysics (DMG) at the University of Vienna and to the ZAMG.

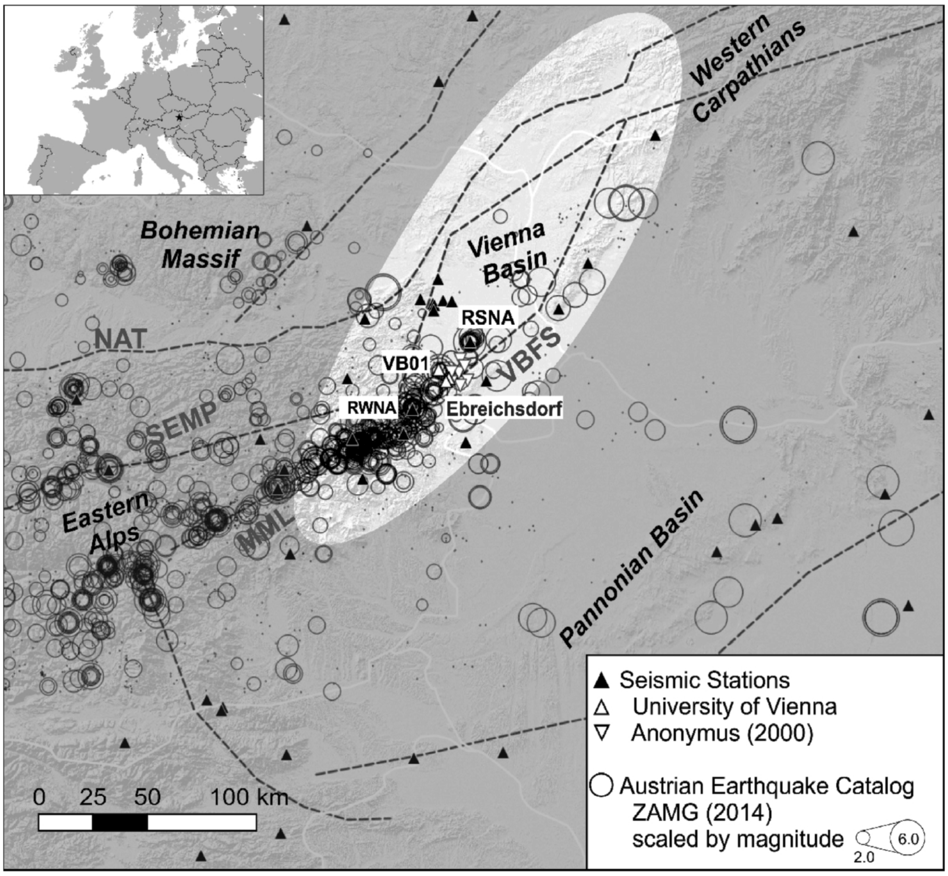

Figure 1: Seismotectonic overview of the Vienna Basin: main tectonic units and generalized faults from GBA (2010). Earthquakes from the Austrian Earthquake Catalog scaled by magnitude (ZAMG, 2014). Triangles indicate the positions of seismic stations used in this study.

Station	Longitude	Latitude	Altitude	Location
VB01	16.3971 ° E	47.9629° N	200 m	Ebreichsdorf Schloss
VB02	16.4583 ° E	47.9291° N	241 m	Leithaprodersdorf Friedhof
VB03	16.4409 ° E	47.9183° N	236 m	Wimpassing Stall Szdenk

Table 1: Locations of temporary seismic stations deployed on 03/10/2013 around Ebreichsdorf for recording of aftershocks.

2.1 Additional Data

Meurers et al. (2004) published isoseismals for the first main shock of 2000. The ZAMG offers an earthquake testimony map for the event from September 20th 2013 online. Those maps show the same asymmetric intensity anomaly (e.g., Hammerl and Lenhardt, 2013) often observed in the area: the earthquakes were felt twice as far to the northwest than the southeast.

Due to the more numerous instrumental recordings for higher magnitude earthquakes it was possible to calculate focal mechanisms for events with a Ml above 4. Focal mechanisms for the two main shocks in 2000 by the Schweizer Erdbebendienst (SED) as well as for 2013 by the ZAMG are shown in Figure 3.

Supplementary we estimate the fault area for the main shocks of 2013 using their local magnitude (4.2), corner frequencies (1-6 Hz), and scaling relationships (Geller, 1976; Madariaga, 1976; Stein and Wyssession, 2003). The main shocks have a fault length of 500 m and a width of 250 m.

3. Event location and relocation

Primary locations for the earthquakes were taken from the AEC provided by ZAMG (2014). Standard processing uses only absolute arrival times and a 1-D velocity model, which is a considerable disadvantage in a subsurface with complex 3-D structure, such as the Eastern Alps. Advanced methods like NonLinLoc by Lomax et al. (2000) can handle 3-D velocity models, but are strongly dependend on model accuracy. Apoloner et al. (2014) used NonLinLoc together with a 3-D P and S velocity model for obtaining accurate locations using all available seismic stations in a 240 km radius of Ebreichsdorf, which corresponds to the extent of the used 3-D models. Small scale imhomogenities not modelled where included in the processing by using station corrections obtained in the location process.

3.1 HypoDD

For this study we use the software HypoDD, which is described in detail in Waldhauser and Ellsworth (2000). Double-difference relocation with HypoDD is based on the assumption that arrival times from events located close to each other will be perturbed similarly by the unknown subsurface structure. Events close to each other, with similar source mechanism and stress drop, produce similar signals at a seismic station. The distance to which this similarity persists is given by the λ/4-criterion (Geller and Mueller, 1980), thus depending on the dominant frequency of the signal.

HypoDD uses "differential travel-times", which are calculated with Equation 1, to relocate pairs of events relative to each other. To do so arrival time differences can be determined either by the difference of "picked" arrival times or by waveform correlation.

If the velocity model diverges from the real underground structure, residuals between calculated and observed travel-times increase. Calculating the diffe-

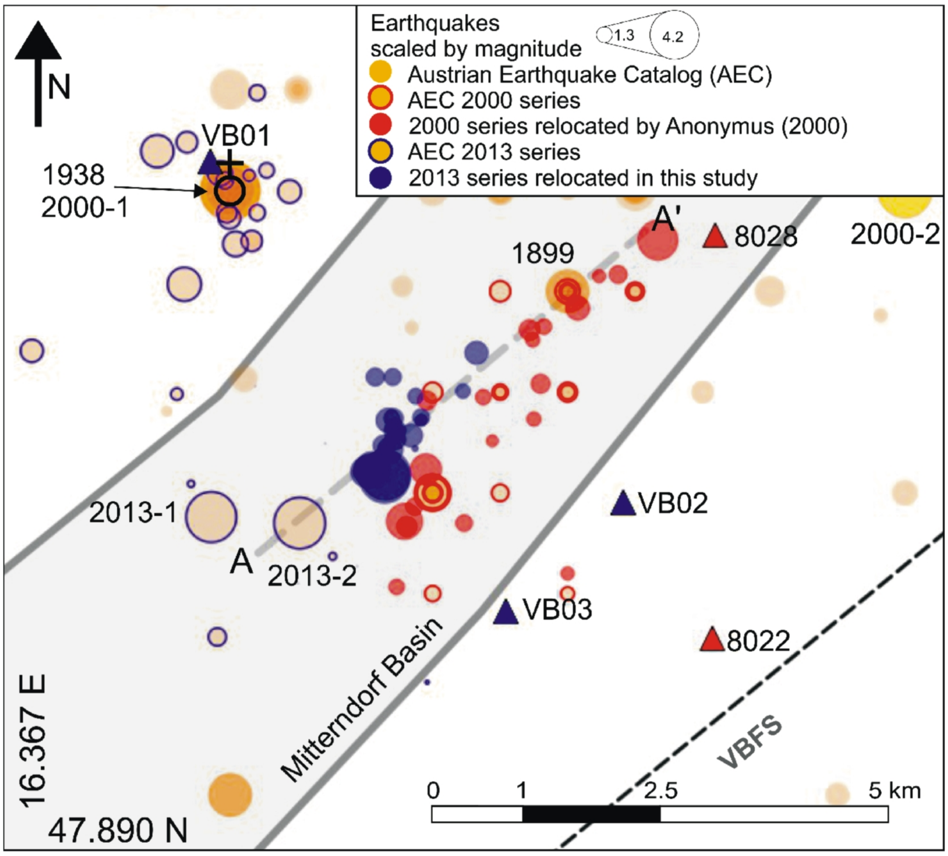

Figure 2: Seismotectonic overview of the area around the VBFS close the Ebreichsdorf. Micone faults from Hinsch and Decker (2011) as solid grey lines. Earthquakes from the Austrian Earthquake Catalog scaled by magnitude (ZAMG, 2014), events mentioned in the text are labeleld with year of occurence. Triangles indicate the positions of seismic stations used in this study. Profile A – A' parallel to VBFS is used in Figure 4.

rence between two wave arrivals of the same phase at one station removes this effect mostly, as is shown in Figure 4 (a). By minimizing the residuals between observed and calculated travel times (double-difference) for pairs of events, HypoDD adjusts the difference vector (Δx, Δy, Δz, Δt) between those events. The algorithm iteratively does this for all event pairs at each station. For datasets containing less than 100 events singular value decomposition solves the equation system and calculates error estimates. The system only solves, if events are well linked through observations of multiple events at the same station. For this reason data has to preselected.

The differential travel-times mentioned above can be calculated from catalog data. Time differences are calculated for one station and multiple events. In this case seismograms can be very similar. However, arrival time picks in catalogs are made for each event separately, irrespective of their similarity. If seismic waveforms are available it is possible to dramatically improve time difference accuracies (e. g., Schaff et al., 2004) with cross-correlation. Here, the relative arrival times between multiple events can be determined with sub-sample precision as shown in Figure 4 (b) and discussed in detail in Deichmann and Garcia-Fernandez (1992) and Schaff et al. (2004). Furthermore, Waldhauser and Ellsworth (2000) mention that location accuracy can be improved 5 times using cross-correlation compared to using only catalog data.

$$dr_k^{ij}=(t_k^i-t_k^j)^{obs}-(t_k^i-t_k^i)^{cal}$$

Equation 1: Calculation of double-difference dr for station k and events i and j.

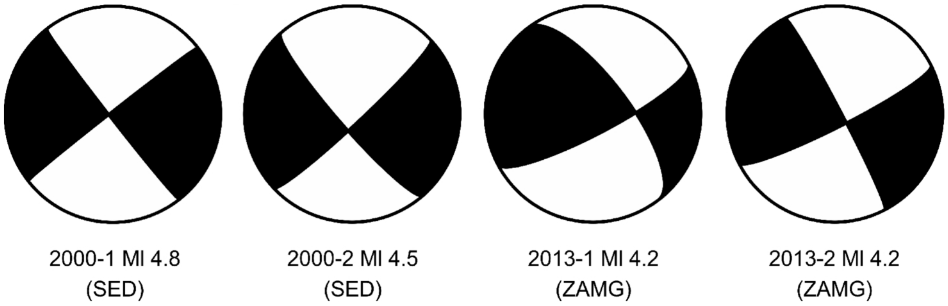

Figure 3: Focal mechanisms from left to right: main shocks in 2000 around Ebreichsdorf from SED (2000) and for the two main shocks in 2013 from Hausmann et al. (2014)

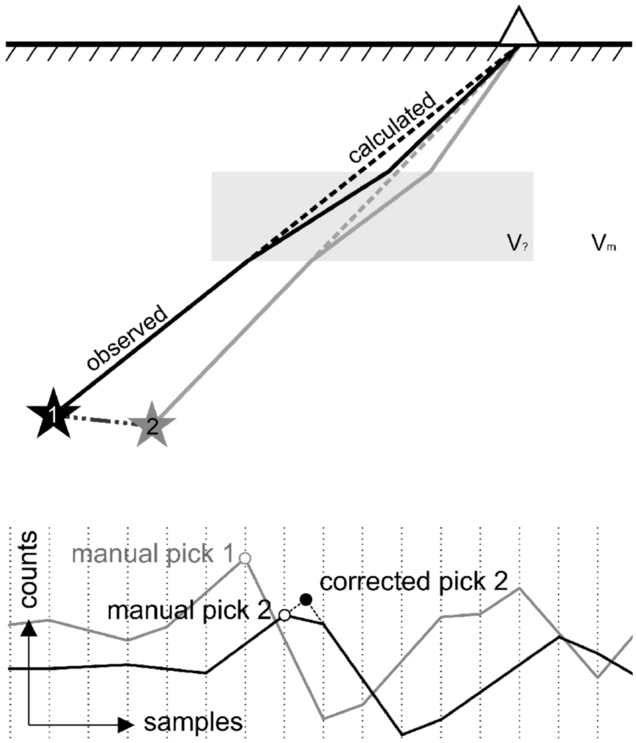

Figure 4: (a) The principle of double-difference calculation: Two earthquakes (star 1 and 2) with close-by location produce similar arrivals at a station (triangle), as they are affected nearly equally by small-scale velocity inhomogenities. Using double-differences between the observed and calculated arrival times for the events reduces the effect of unmodelled velocity changes. (b) Seismograms (P-phases) of two events at station VRAC, showing a sub-sample shift that can be resolved using cross-correlation.

3.2 Parameters and Settings

Depending on observation type (cross-correlation or catalog), accuracy and distance, the effect of different types of observations on the results needs to be adjusted. For this reason an elaborate weighting scheme is part of HypoDD algorithm. We adapted the values as follows, to fit our dataset:

The first set of 5 iterations removes double-differences from the catalog data with high residual times, e. g. if Pn is picked instead of the Pg arrival. Travel time differences based on S waves enter the relocation with a smaller weight than P-waves. The second set of 5 iterations weights the cross-correlation and remaining catalog double-differences similarly and simultaneously. Only double-differences from inter-event distances of less than 2 km are used and are re-weighted depending on distance. We derive the weights directly from picking accuracy for each pick individually.

To use HypoDD, we first calculate double-differences from the available picks. Furthermore, the data needs to be pre-selected to assure solvability with HypoDD. We calculate double-difference times for earthquakes with a maximum separation distance of 2 km and a minimum of 4 links in between them. From 738 picks we approximately compute 3400 phase-pairs. We cross-correlate the phase picks in a 2.0 – 7.0 Hz range, which corresponds to the dominant frequency in the observed earthquakes. P-phases were picked on the vertical components, for S-phase picking we use all 3 components. We obtain more than 500 difference times with a cross-correlation higher than 0.7.

In this study we use 3 different velocity models to evaluate their influence on location. The first is a 1-D model, taking only the top layer of IASP91, a widely-used velocity model for

Velocity Model	1-D	2-D	3-D
Events located	17	21	20
Mean depth	5.9 km	9.3 km	9.3 km
Horizontal error	180 m	170 m	150 m
Vertical error	960 m	360 m	250 m
RMS cross-correlation	0.15 sec	0.17 sec	0.18 sec
RMS catalog	0.14 sec	0.14 sec	0.15 sec
Mean number of difference-times per event used	191	250	305

Table 2: Location with different velocity models (initial locations are from Apoloner et al. (2014); see text.

the earth. The second model is a layered 2-D model by Hausmann et al. (2010) composed of four layers above the crust-mantle boundary "Moho", the top layer beeing a 5 km thick slow velocity layer. With the last version of HypoDD 2.1b it is possible to use a 3-D velocity model. We based our 3-D model on the P-velocity model of Behm et al. (2007a) and the S-velocity model of Behm et al. (2007b).

To check the dependence on initial location/s, we test HypoDD with different sets. In the first run we use the locations calculated with NonLinLoc and station corrections. HypoDD also offers the possibility to use the center of the earthquake cluster as starting position. As it can be strongly influenced by outliers, we use the location of the Ml 4.2 main shock on the September 20th 2013 as initial location for all events. In addition, we also compare the locations with those in the ZAMG-Bulletin.

4. Results

Using the 1-D velocity model destabilizes the result, as the algorithm removes one third of the observations due to large misfit and moves the entire earthquake series 10 km to the southwest. The 2-D and 3-D velocity models influence neither the location nor the mean depth of the earthquakes significantly. Apart from this the main influence is in the change in location errors, which is shown in Table 2. E. g. mean location errors for depth reduce from 960 m (1-D) to 360 m (2-D) to 250 m (3-D). Although, the RMS residual is almost the same for all models, the mean number of phase-pairs used is much higher for the 3-D model, indicating a better fit of observations to the model.

Initial locations are another important aspect, as they control the difference-times used as input for the relocation process. Also, the difference-vectors between events are not recalculated at each iteration step, but only adjusted. Table 3 shows that the final locations are strongly constrained by the initial location used. For example, the initial mean depth controls the final location depth.

Final locations are given in Table 4 and plotted in Figure 5 (left) in top view and Figure 5 (right) in a cross section along the fault strike. Independently from initial locations, both Ml 4.2 earthquakes locate less than 100 m apart. Moreover, the depths of the earthquakes are between 7.5 and 10.5 km, which means that they are situated on the fault beneath the negative flower structure (Hinsch et al., 2005). In addition, the depth of events changes with magnitude, with smaller events being rather shallower than bigger events. However, even with relative locations, no distinct event pattern in time is apparent in Table 4.

In the next step we compare the 2013 series to the 2000 series. Each of the two earthquake series is composed of two main shocks with Ml > 4 and an aftershock sequence of around 30 events. Figure 5 shows that the aftershocks of 2000 are close to the 2013 sequence, but shallower. However, the main shocks from 2000 given in the AEC are more than 7 km away from the events in 2013 and located 7 km apart from each other. The focal mechanisms computed by SED and ZAMG are very similar though (Fig. 3). To distinguish wether the location difference for the main shocks is due to the network geometry or different location, we compare the waveforms from stations, which recorded both pairs of main shocks.

The two closest strong motion stations RSNA (Schwadorf) and RWNA (Wr. Neustadt) of the ZAMG network are triggered and therefore recorded only the main shocks. Figure 6 shows the waveforms aligned at the P phase for all four events in chronological order. As a reference we use the pick of the S phase of the first main shock in 2013, due to its higher location accuracy. Since variations in S-P-time differences from event to event are associated with variations in distance with respect to the station, this allows investigating whether events are in the same place or not. The S-P-time difference between the 2000 and the 2013 events differs by about 0.6 seconds, which corresponds to a difference in distance of approximately 4 km. The events from 2013 have almost the same distance to the stations. However, to fit the data, the events from 2000 need to be around 4 km further away from station RWNA and 4 km closer to station RSNA. This suggests that the events from 2000 are located 4 km to the northeast from the 2013 sequence. The type of constraint provided by the S-P times (distance), and the relative locations of the events are illustrated in Figure 7.

Collocation can be also determined by inspecting the inter-event coherence. The criterion of Geller and Mueller (1980)

Initial Locations	Mean Initial Depth	Mean Result Depth	Standard Deviation	Distance between Main Shocks
Apoloner et al. (2014)	9.1 km	9.3 km	0.7	40 m
Apoloner et al. (2014), all 20/09/2013 4.2	10.6 km	10.7 km	0.7	75 m
ZAMG Bulletin	11.7 km	11.7 km	1.9	70 m

Table 3: Initial locations used for relocation calculation with HypoDD.

Date	Time (UTC)	Ml	Lat. [°]	Lon. [°]	Depth [km]	CC DT	Cat DT	Ex [m]	Ey [m]	Ez [m]
04.09.13	11:00	1.9	47.9439	16.4365	9.4	15	176	158	178	456
20.09.13	02:06	4.2	47.9318	16.4230	10.5	55	293	97	100	202
20.09.13	02:42	1.7	47.9353	16.4245	9.6	41	283	82	87	223
20.09.13	03:17	1.3	47.9362	16.4246	9.7	42	255	78	101	218
20.09.13	23:24	1.2	47.9401	16.4345	9.0	23	228	98	120	313
24.09.13	13:53	2.7	47.9322	16.4207	9.8	68	339	72	77	166
25.09.13	10:08	1.7	47.9347	16.4227	9.1	39	209	82	99	210
01.10.13	23:54	1.4	47.9415	16.4241	7.5	5	33	237	290	868
02.10.13	04:09	2.0	47.9372	16.4234	9.2	47	376	70	82	177
02.10.13	05:12	1.3	47.9396	16.4275	8.0	10	89	164	235	565
02.10.13	05:26	2.1	47.9343	16.4237	8.9	51	299	74	85	193
02.10.13	05:33	1.8	47.9362	16.4244	8.4	23	156	102	121	278
02.10.13	17:17	4.2	47.9315	16.4229	10.5	46	275	99	105	211
02.10.13	19:38	1.6	47.9374	16.4242	8.9	50	273	75	85	196
02.10.13	19:42	2.8	47.9324	16.4210	10.0	47	344	76	81	179
05.10.13	01:27	1.0	47.9372	16.4283	9.8	23	181	113	113	167
07.10.13	18:22	1.5	47.9415	16.4215	9.8	25	238	111	111	163
13.10.13	23:26	0.5	47.9344	16.4274	9.2	15	243	80	90	155
14.10.13	02:34	1.9	47.9357	16.4268	9.9	64	367	80	76	134
16.10.13	02:19	1.4	47.9375	16.4283	9.3	35	319	79	89	139
23.10.13	19:34	2.6	47.9321	16.4202	9.6	58	344	81	75	130

Table 4: Relocated earthquakes from 2013 around Ebreichsdorf. Ml taken from ZAMG bulletin. CC and Cat DT give the number of cross-correlation and catalog double-difference times used for location.

states that waveforms can be similar up to an inter-event distance of λ/4, with wavelength λ. Figure 8 shows the inter-events coherence around the S wave arrival for the two main shocks in 2013 and 2000. We note for the 2013 events that coherence is very high at low frequencies, and it drops gradually with increasing coherence, as expected for nearby events. At a frequency of 8 Hz the mean coherence has dropped to a value near 0.7. This frequency of 8 Hz corresponds to a quarter-wavelength of around 100 m, assuming a shear-wave velocity of 3 km/sec. The Geller and Mueller criterion suggests that this is the maximum distance between the events, which can be successfully correlated. The behaviour of the two events in the year 2000 is quite different, with a low-value of mean coherence at low frequencies. With increasing frequency the coherence rises to a very high value, and it drops subsequently. This curve shape is not consistent with waveform similarity depending on distance alone. Indeed, the character of the coherence is very different for the two stations. For one RWNA, the frequency dependence follows the expected decay with frequency, although with a surprisingly sharp decay, around 5 Hz. The other station, RSNA shows the unexpected behaviour of an increase with frequency. Why the characteristics are so different on the two stations, is not clear. However, the criterion should be used with caution in this circumstance. Applied as such, it implies that the maximum between the event, using

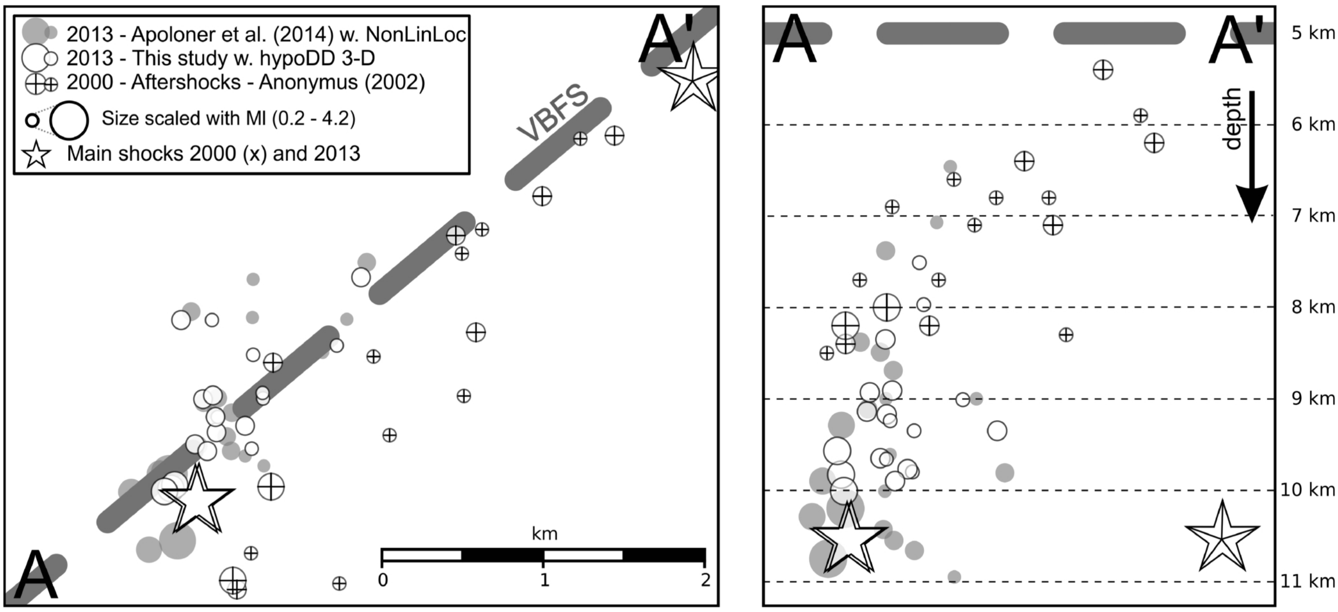

Figure 5: (left) Map of earthquakes near Ebreichsdorf area from 2000 and 2013. Initial locations for 2013 (grey) by Apoloner et al. (2014) with NonLinLoc, relocations with HypoDD (blue). Red dots show aftershocks of the earthquakes in 2000 (Anonymus, 2002). The red star indicates the location of main shocks in 2000 relative to the two 2013 main shocks, determined with S-P-differences (right) .Vertical profile along the VBFS with events projected on a vertical fault plane.

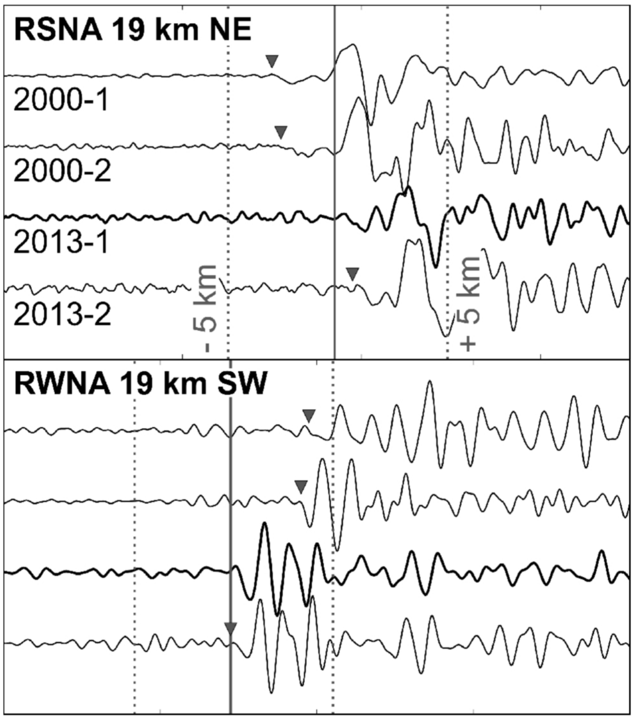

Figure 6: S-arrivals of main shocks of 2000 (1st: 2000-1, 2nd: 2000-2) and 2013 (1st: 2013-1, 2nd: 2013-2) earthquake series aligned at the P-arrival. S-arrival on 2013-1 is marked by a continous grey line (picked using all three components). Dashed lines show 5 km distance difference to the station, based on S-P-time difference with respect to 2013-1 suggested S-arrival. Main shocks from the 2000 series are ~4 km closer to station RSNA (top) and 4 km further from RWNA (bottom).

the 5Hz frequency is slightly larger, about 150 m. However, doubt remains whether the criterion may be applied for the 2000 series.

5. Discussion

Although, the 3-D velocity model used only approximates the rather heterogeneous underground structure in the area, it considerably enhances the number of phase observations usable for relocation, which in turn improves location accuracy. If no 3-D model is available, at least a locally adapted model like a 2-D crust model should be used for the Vienna Basin. If only one cluster of events is relocated, locations obtained with HypoDD are strongly dependent on the initial hypocenter location. Therefore, it is important to use high-qualitiy initial locations like the ones calculated in the previous study. However, relative locations in the cluster are much less affected. Similar events, like the two main shocks, are always located close to each other, neither depending on velocity model used nor absolute position of the initial locations. The relative locations are at close range to those obtained using NonLinLoc. This results from the high quality of the NonLinLoc locations and also from the small number of events in the cluster. Due to the small number of links and to large inter-event distances, several events could not be relocated. After relocation, the earthquake series clusters on a smaller area and depth range, as can be seen in Figure 5. In particular the two main shocks are now less than 40 m apart. This study focuses only on one cluster of earthquakes which are located within a few kilometers. To extend this kind of study to the whole Vienna Basin, and therefore more clusters of earthquakes, either more accurate absolute locations or an improved velocity model of the Vienna Basin and its surroundings are needed.

A comparison with the 2000 series shows that the pairs of main shocks are 4 km apart and that both aftershock sequences have apparently occurred in between. Indeed, the (slightly) different S-P times indicate that the main shocks of 2000 are not collocated as closely as the main shocks in 2013. The bigger difference in source size is probably important. There may be further differences, e.g. in the source mechanism. The notion of clustering of earthquakes along the Southern Vienna Basin fault segment appears to be less clear than thought before. The 2000 events, that were supposed to part of the "cluster" at Ebreichsdorf, are in reality about 4 km further to

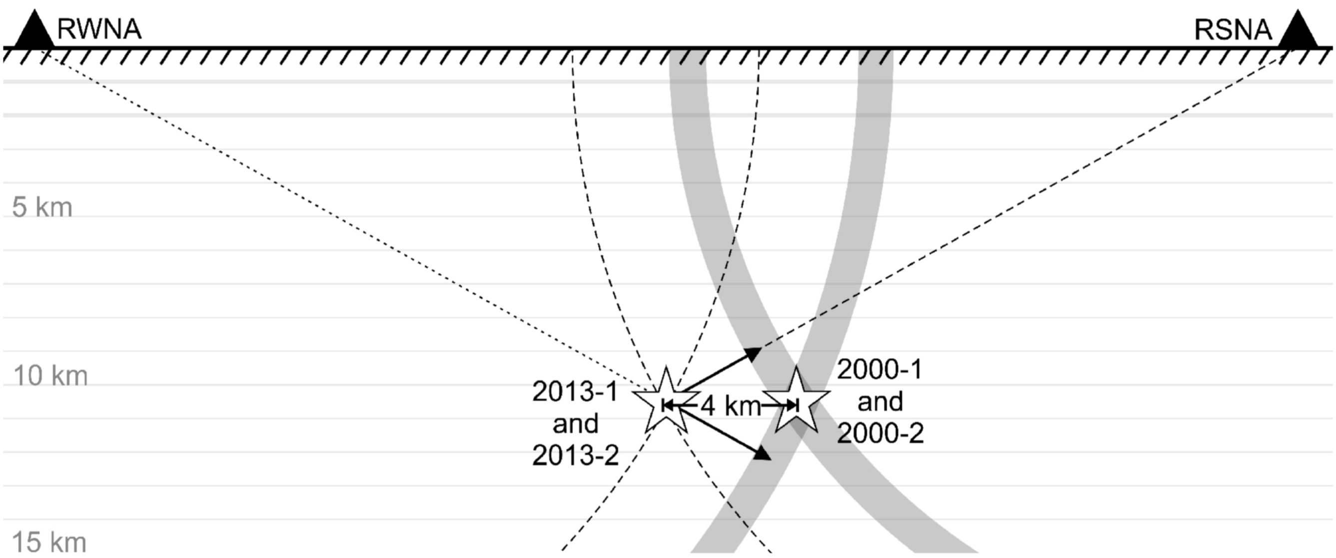

Figure 7: Cross-section along the fault indicating the constraint on relative location, suggested in Figure 6.

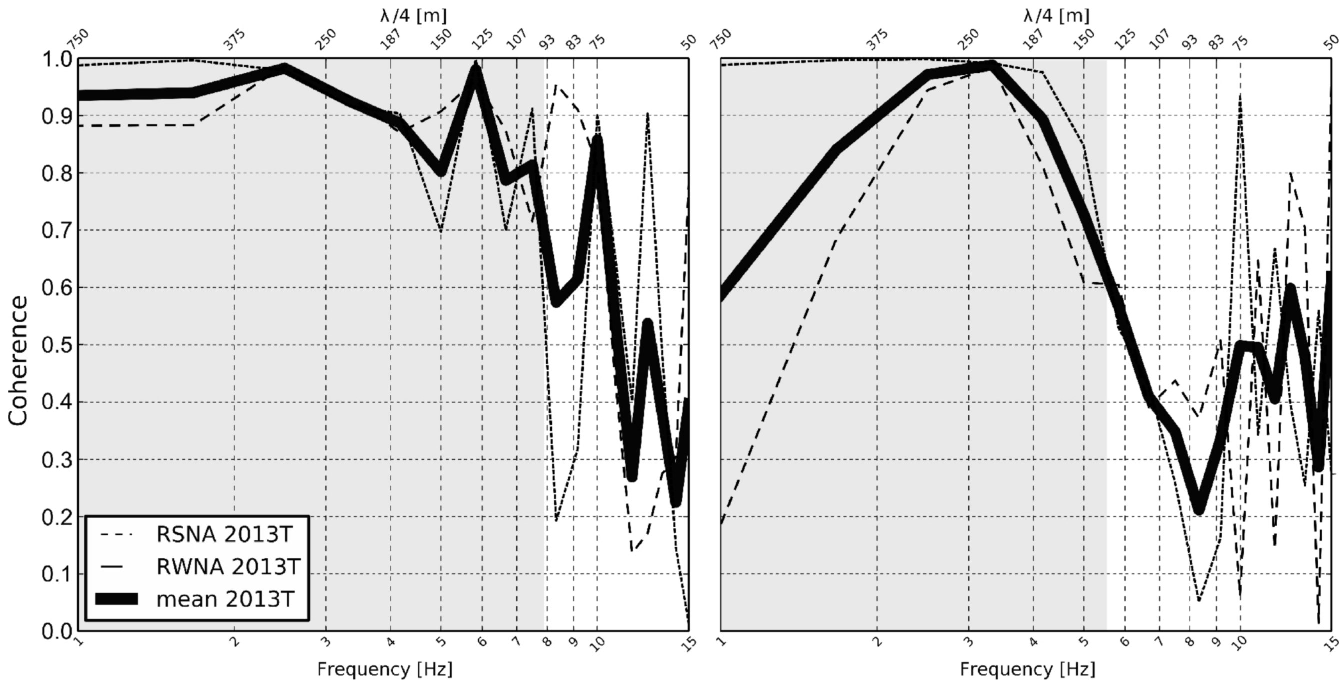

Figure 8: Inter-event coherence for both pairs of main shocks on the transverse component, (left) for the 2013 series, and (right) for the 2000 series (see text). Top x-axes shows λ/4, as a criterium for inter-event distance, marked grey for coherences above 0.7.

the northeast, and thus closer to a position between the villages of Unterwaltersdorf and Leithaprodersdorf. Furthermore, the new locations of the main shocks from 2000 also indicate that the aftershock locations from Anonymos (2002) also need to be relocated to compare them to the data from 2013.

Coherence measurements at the two closest stations confirm also that the two 2013 events are collocated well within the length of the rupture, since coherence is very similar for both stations.The coherence constraint on collocation is weaker for the 2000 events, firstly by a faster decay of coherence with frequency, but more importantly by the unexpected increase of coherence with frequency. It shows that the 2000 events are less similar than the 2013 events, although its behaviour is not fully understood. Explanations may lie in the larger difference in magnitude, or by a different characteristic of the rupture. Changes in the wave propagation behaviour by the earlier event may play a role, and the radiation characteristics of the earthquakes. Station RWNA records higher frequencies than station RSNA for all four main shocks. This effect could be either caused by site effects or directivity of the rupture towards the South East. However, given to the relative large magnitude difference of the ain shocks in 2000 and 2013 and similar subsurface conditions a directivity effects appears more likely.

For studies of seismicity in the area, it is important to have recordings, including the strong-motion stations available in real-time. If this had been the case in 2000, we could produce high-resolution relative locations now also for aftershocks in 2000, which were too weak to be recorded by the more distance regional network stations – and resolve the question of whether there is a significant migration between main shocks and aftershocks.

6. Conclusions

We have studied the spatial relation between the earthquakes that have occurred in the Ebreichsdorf area in 2013 and their aftershocks, and find that larger aftershocks have the tendency to occur at larger depth on the fault, and tend to migrate northeast. For the 2000 series, the spatial relation is less clear, since they have been recorded by different stations unfortunately – the national network for the main shocks, and the temporary CTBT network for the aftershocks. Continuous recordings at stations in the area would help to address such issues in the future.

There are interesting findings for rupture mechanisms resulting from this study: the two events in 2013 have occurred at the same place, apparently with overlapping rupture area, which is suggested by the relative location, but also by the high waveform correlation. We will address the question of stress transfer in a subsequent paper. This may help resolve the question of how rapidly repeated rupture is possible, even though the first event must have released (part of) the elastic strain already.

The relocated event from 2000 and 2013 show that the impression from the catalog, that seismicity occurs only in separated clusters is misleading at least for the Ebreichsdorf area and originates from the incomplete seismic cycle used in the AEC (see Hinsch and Decker, 2003 for details). The 2000 earthquake series took place between the villages Unterwaltersdorf and Leithaprodersdorf.

This raises a very important question about the other parts of the fault that have not ruptured in historical times: will they release the mechanical stress aseismically by creep, or seismically and if the latter – with which magnitude? We do not know the answer to this question, but resolving it requires gaining more observations about the seismic and aseismic deformation in the Southern Vienna basin. This is a major question for understanding the regional seismic hazard, in particular for the city of Vienna.

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