

REVIEW 1: Anonymous Referee (minor revision)

REVIEW 2: Janina Kammann; University of Copenhagen (minor revision)

			agreed	not agreed	comment
1	Abstract	Anonymous: page 1 line 9-10 - word 'strongly' twice in same sentence	X		We replaced the second 'strongly' with 'heavily'.
2	1 Introduction	Anonymous: page 2 line 15-18 - 'can also do' = expression	X		We have removed the colloquial language.
3		Anonymous: page 2 line 21 - 'Ulrikse, 1982' = spelling	X		Spelling mistake corrected.
4	2 Geological setting	Anonymous: page 4 line 1 - '...1962)(F)...' = missing blank space	X		We added the missing space.
5		Kammann: page 3 line 12- Kelbra is not shown in the map	X		We removed the unimportant information.
6		Anonymous: page 4 line 2 - '...south of Kyffhäuser ...'	X		We changed '...south of the Kyffhäuser is ...' to 'south of the Kyffhäuser hills is ...'.
7		Anonymous: page 4 line 14 - (Fig. 2)	X		Sorry, the images of figure 3 did not match the numbering within the text. We have changed the order of the images.
8	2 Geological setting	Anonymous: page 4 line 18 - (Fig. 3a)	X		Sorry, the images of figure 3 did not match the numbering within the text. We have changed the order of the images.
9		Kammann: page 4 line 20 - '...which exceeds the inclination of the leaning tower of Pisa at 3.97°'	X		We changed the text in accordance with the suggestion of the reviewer.
10	3 Seismic survey	Kammann: The authors mention that the profiles were acquired with two different generations of the ELVIS source and two pictures are provided in figure 6. I am missing a comparison of these sources, what are the differences and which profiles were acquired with which source? If there are no differences in data quality, mentioning the two source types and the figure seem unnecessary.	X		Profile S1 was acquired with ELVIS 6 and S2, S3 and S4 were acquired with ELVIS 7. We now inserted this information into the text. Both sources are basically comparable, as described in the text. Comparison of single records acquired with ELVIS 6 and ELVIS 7 reveal minor differences. The older ELVIS 6 has a stronger weighting of the lower frequencies and the new ELVIS 7 has a stronger weighting of the higher frequencies, resulting in better resolution. After data processing, these minor differences are not visible anymore because of the energy loss of higher frequencies, since the useful signal of our data contains mostly frequencies below 80 Hz. However, as this article is a case study and not a technical paper, we decided not to go into too much detail regarding the electrodynamic micro-vibrators, because information about this source have already been published by, e.g. Krawczyk et al., 2012/2013 or Polom 2003/2013. Thereby, we keep the main focus of this article on the imaging of near-surface subsurface structures.
11		Anonymous: On page 4 "3 Seismic survey" the chapter starts by giving a general introduction of the position and elevation of the profiles. Adding the length of the profiles would give an idea about the special dimension of the study.	X		We added the length of each seismic profile.
12		Anonymous: page 5 line 2 - the authors write about profile 4: "To meet the requirements of this challenging investigation area the equipment and the configuration used for the shear wave reflection seismics had to be adapted by splitting the streamer." - It is not clear what is meant by that as the receiver number seems to be constant for all profiles (Figure 7). Please clarify what is meant.	X		We added 'see below for detailed description' at the end of this paragraph. The explanation is given later, when the survey setup is described in detail. Here the explanation from our text: 'Prior to survey, the landstreamer was adapted for the limited space in Bad Frankenhausen and separated into three parts for manual handling, each containing 24 geophones.'
13		Anonymous: page 5 line 7 - '...(e.g. Dasios et al., 1999; Inazaki, 2004)'	X		We added 'e.g.' to the reference.
14		Anonymous: page 5 line 6 - The authors write: "This source-receiver combination reduces the converted waves", this however is slightly incorrect. The reduction of converted waves is achieved by vertical stacking of opposite polarization of the SH data after crosscorrelation.	X		We have explained this now more detailed for a better understanding.
15	Anonymous: page 5 line 32 - "Therefore the mean CMP-fold of the profiles results in 18 traces..."	X		We changed the text in accordance with the suggestion of the reviewer.	
16	4 Data processing	Anonymous: page 6 line 29-60 - I missed an explanation how the velocity analysis was done. That doesn't need to be a big paragraph but maybe just stating the type of analysis that was used to gain the velocity field.	X		In a short sentence we now state the type of velocity analysis
17		Kammann: page 7 line 2 - 'although' = ?	X		The word 'although' was misplaced. We removed it.
18		Anonymous: The sections "Seismic survey" and "Data processing" appear partly too detailed, especially the description of pre-processing steps. Shorter and more concise description emphasizing the essential information on the measuring setup and processing would benefit the reader. However, as the FK-filter is crucial, this part could be supported with a plot of the FK-spectrum and the applied filter in figure 8. Alternatively, make a reference to the FK-plot in table 2.	X		We added a reference to the FK plot in Table 2 and shortened the text of the 'Seismic survey' section.
19	Anonymous: page 6 line 14 - '...improve the signal-noise ratio, by...'	X		We changed the text in accordance with the suggestion of the reviewer.	
20	Anonymous: page 6 line 23 - 'Besides the vertical stack the S/N ratio was improved...'	X		We changed the text in accordance with the suggestion of the reviewer.	
21	5 Structural imaging and Interpretation	Anonymous: page 7 line 16 - change '100-150 ms' to '100 to 150 ms'	X		We changed 'to' to 'to' in the entire section.
22		Anonymous: page 7 line 18 - 'between 30 m and 80 m distance and 100 to 200 ms TWT' = hard to see in small figure	X		Now the images in Figure 10 are bigger. We shortened the sections down to 1000 ms instead of imaging 1200 ms, and we have omitted two of the repeated time axes.
23		Anonymous: page 7 line 25 - insert 'but more reflectivity'	X		We changed the text in accordance with the suggestion of the reviewer.
24		Anonymous: page 7 line 26 - 'similar for all profiles' = not true	X		Sorry for the mistake. In this part we describe the similarities of profiles S1, S2 and S3. We have changed this to make it clear.
25		Anonymous: page 7 line 32 - change '...VINT of the seismic sections S1, S2 and S3 do not constantly increasing with depth, rather...' to '...VINT in the seismic sections S1, S2 and S3 do not constantly increase with depth, in fact...'	X		We changed the text in accordance with the suggestion of the reviewer.
26	5 Structural imaging and Interpretation	Anonymous: page 8 line 12 - describe differences, similarities as you did in structural interpretation	X		We added a short comparison of S4 to S1, S2 and S3.
27		Kammann: page 7 line 28 - '...that have vertical offsets of ca. 1 m...'	X		We changed the text in accordance with the suggestion of the reviewer.
28	5.1 Interpretation	Anonymous: page 8 line 32 - 'Fig. 10a' = is Fig. 11b meant here?	X		Yes, we meant Figure 11 b.
29		Anonymous: page 9 line 3 - 'Fig. 10b' = is Fig. 11c meant here?	X		The numbering is correct. The figure reference is referring to the low-velocity zones mentioned at the beginning of the sentence. For a better understanding we have shifted the reference from the end to the beginning.
30		Kammann: page 8 line 29 - 'reflections observed in the seismic image' instead of 'reflectors'	X		We changed 'reflectors' to 'reflections'.
31		Anonymous: page 9 line 13 - 'Section 3 reveals another 30m wide and 20 deep depression structure (Fig. 11b, c, S3), located 15 m south of the church.'	X		We changed the text in accordance with the suggestion of the reviewer.
32		Anonymous: page 9 line 16 - '...in the near-surface, low velocity zones or significant diffractions.'	X		We changed the text in accordance with the suggestion of the reviewer.
33	5.1 Interpretation	Anonymous: page 9 line 21 - '...only 8 m...' = '...only 80 m...'	X		Sorry for the mistake. Of course the average profile length is 80 m.
34		Anonymous: page 10 line 8 - 'voids' = rephrase	X		We changed the first 'voids' to 'cavities'.
35	6 Discussion	Anonymous: page 11 line 15 - 'P-wave profile' = show data and fault	X		The P-wave section is not shown, because the data is still in the processing stage. In the future, this P-wave seismic section, together with other P- and SH-wave profiles, will be shown in a separate publication regarding the regional geology of Bad Frankenhausen. We left out this information here, and changed Fig. 4 accordingly.
36		Anonymous: page 11 line 34 - insert comma	X		We changed the text in accordance with the suggestion of the reviewer.
37		Anonymous: page 12 line 3 - insert 'upper 15 m'	X		We changed the text in accordance with the suggestion of the reviewer.
38		Kammann: page 9 line 21 - '80 m'	X		Sorry for the mistake. Of course the average profile length is 80 m.
39	Anonymous: page 9 line 24 - '...to asphalt, concrete or cobblestone streets.'	X		We changed the text in accordance with the suggestion of the reviewer.	

36		page 11 line 15 - Figure 4 shows the location of a P-wave profile which is further discussed in chapter 6 for comparison with profile S4. For me as a reader, it would be interesting to compare these two profiles, however, the profile was not accessible as referenced (Wadas et. al., 2016). Please ensure that the work is referenced properly or include the P-wave data.	X	The P-wave section is not shown, because the data is still in the processing stage. In the future, this P-wave seismic section, together with other P- and SH-wave profiles, will be shown in a separate publication regarding the regional geology of Bad Frankenhausen. We left out this information here, and changed Fig. 4 accordingly.
37		page 11 line 22 - '. are shown to be associated with salt dissolution (...).'	X	We changed the text in accordance with the suggestion of the reviewer.
38	7 Summary and Outlook	Kammann: page 12 - In section "Summary and Outlook" the planned LIDAR scans could be mentioned as well (or instead).	X	Now the planned LIDAR scans are mentioned in section 'Summary and Outlook'.
39		Anonymous: The manuscript seems a bit over-referenced, especially the introduction and geological setting chapters are highly fragmented by numerous references, some of them repeated several times.	X	We removed some repeated or unnecessary references.
40	References	Further to that more than 20% of the references are in German which for an international audience is of no use.	X	We are aware of the large amount of German references. Since most of the data about the geological setting of our research area were acquired by German scientists a few decades ago, at a time Bad Frankenhausen was located in the German Democratic Republic, the common scientific language was German. Research in this area started to be published in English only during the 90s. However, we removed some of the repeated or unnecessary German references.
41		page 16 line 6 & page 17 line 24 - "Knoth & Schwab, 1972" in bibliography but not in text, same for "Palom, 2013"	X	We removed the references from the bibliography.
42		page 18 line 20 - Ulriksen in text - Ulriksen in bibliography	X	We corrected the spelling mistake.
43		Anonymous: A few figures suffer from small annotation. While it is fine to have them on screen, for the printed journal they seem to be too small.	X	We checked the images and used a larger font size. For all figures we had to take into consideration that the maximum width of a two-column figure is 12cm and a one-column figure is 8.3 cm, which is predefined by the LaTeX template of SE. This limits the overall size of the figures.
44		Figure 1: text in figure too small	X	We used a larger font size.
45	Figure 2: in caption change 'yellow lines' to 'light green lines'	X	We changed 'yellow lines' to 'light green lines'.	
46	Figure 4: annotation for printed version too small, especially street names which are referred to in text	X	We replaced the entire image and used a larger font size.	
47	Figure 7: upper part too small; the fold is very similar for each line and might not be as interesting as the elevation	X	We removed the fold and used a larger font size for the elevation.	
48	Figure 8: this figure is certainly worth being shown as big as figure 9, maybe in the same manner	X	We changed the figure in accordance with the suggestion of the reviewer.	
49	Figure 10: missing description of red circles	X	We added a description of the red circles in the caption.	
50	Figure 10 and 11: A seismic interested person would certainly like to see the seismic data in a larger display. Both figures could gain from: - not showing all data down to 1200ms or 150m - omitting some of the repeated time and depth axis and annotations - less gaps between the panels.	X	Now the images of Figures 10 and 11 are bigger. We shortened the sections down to 1000 ms instead of imaging 1200 ms, and we omitted two of the repeating time-/depth-axes.	
51	Figure 11: I personally think that the interpreted results should be overlaid on the seismic. I find it very hard to transfer the faults and especially the depressions from 11c to 11b and therefore hard to follow the interpretation at all.	X	In the first version of the manuscript, Figure 11 was shown in the same manner you suggested, but after showing it to some neutral colleagues, all of them agreed that the interpretation is not clearly visible due to the seismic in the background. After some discussions we decided that the best style to show the interpreted results is as it is now.	
52	Kammann: Figure 1: could be more clear and maybe simplified, especially the legend. The reference LBEG (2015) is not in the reference list. The caption is unclear. Also the borehole information used for interpretation of the shear-wave data differ a lot from the average stratification.	X	The reference for 'LBEG 2015' is in the reference list, but it was written out. Now we added the abbreviation in the bibliography. The legend is already simplified. It shows only the abbreviations of the geological units seen on the geological map. The average stratification on the right covers the entire area of the geological map and was included in order to give a general overview of the stratification in the area. The borehole stratification gives detailed information about the geological units at the borehole location, which is located in profile S1. Variations are normal and depend on the complexity of the local geology.	
53	Figure 7: compares 4 shots of the different profiles in means of noise and surface conditions. Which processing steps were applied to these shots?	X	The only processing steps applied to the data are vibroseis correlation, an AGC, a bandpass filter around the sweep frequency range and amplitude normalization. We added this information to the caption.	
54	Anonymous: While it is interesting and might for some readers be appealing, some parts of the manuscript are written in great detail and a bit repetitive. The manuscript could gain much from more conciseness.	X	We shortened some parts of the manuscript a little bit.	
55	Please be careful with the use of 'seismics' as opposed to seismic. 'Seismics' it is not a noun and often only used in the informal language or colloquial speech (probably check with the desk editor in which way it is used in the journal).	X	We changed 'seismics' to 'seismic'.	
56	Kammann: The numbering of the figures, parenthesis and use of capital letters should be checked in the text.	X	We checked the numbering, the parenthesis and use of capital letters.	
57	There are some inconsistencies writing S/N ratio or signal-to-noise ratio in the text, please check.	X	We checked for consistent spelling.	
58	Please also check that the terms "reflector" and "reflection" are used correctly.	X	We checked the text for the correct use of the words 'reflector' and 'reflections'.	
59	The term Tertiary is not used anymore and should be substituted by Paleogene or Neogene (e.g. Page 3 Line 29 and following, Figure 1).	X	We replaced Tertiary with Paleogene and Neogene.	

High-resolution shear wave reflection ~~seismies~~ seismic as tool to image near-surface subsrosion structures — a case study in Bad Frankenhausen, Germany

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Abstract. Subrosion is the subsurface leaching of soluble rocks that results in the formation of depression and collapse structures. This global phenomenon is a geohazard in urban areas. To study near-surface subsrosion structures four shear-wave reflection seismic profiles, with a total length of ca. 332 m, were carried out around the famous leaning church tower of Bad Frankenhausen in northern Thuringia, Germany, which shows an inclination of 4.93° from the vertical. Most of the geological underground of Thuringia is characterized by soluble Permian deposits, and the Kyffhäuser-Southern-Margin Fault is assumed to be a main pathway for water to leach the evaporite. The seismic profiles were acquired with the horizontal micro-vibrator ELVIS developed at LIAG and a 72 m long landstreamer equipped with 72 horizontal geophones. The high-resolution seismic sections show subsrosion-induced structures to a depth of ca. 100 m and reveal five features associated with the leaching of Permian deposits: (1) lateral and vertical varying reflection patterns caused by strongly heterogeneous strata, (2) discontinuous reflectors, small offsets, and faults, which show the underground is ~~strongly~~ heavily fractured, (3) formation of depression structures in the near-surface, (4) diffractions in the unmigrated seismic sections that indicate ~~an~~-increased scattering of the seismic waves, (5) varying seismic velocities and low-velocity zones that ~~were~~ are presumably caused by fractures and upward-migrating cavities. A previously undiscovered, southward-dipping, listric normal fault was also found, ~~located northward~~ northwards of the church. It probably serves as a pathway for water to leach the ~~Zechstein formations~~ Permian Formations below the church and causes the tilting of the church tower. This case study shows the potential of horizontal shear-wave reflection ~~seismies in imaging~~ seismic to image near-surface subsrosion structures in an urban environment with a horizontal resolution of less than 1 m in the uppermost 10–15 m.

1 Introduction

Subrosion, the underground leaching of soluble rocks, is a global phenomenon and the entire process is not yet well understood. It requires the presence of soluble rocks (e.g. evaporites), unsaturated water (e.g. groundwater and meteoric water), and fractures or faults that enable the unsaturated water to circulate ~~in order~~ to create subsurface cavities (Smyth, 1913; Martinez et al., 1998; G. Depending on the leached material and the parameters of the subrosion process, especially the dissolution rate (Cooper, 1986),

different kinds of structures may evolve in the subsurface. The two main types are (1) collapse and (2) depression structures (for a detailed classification see Waltham et al. (2005); Gutiérrez et al. (2008)). Strong dissolution creates sinkholes with diameters up to several tens of meters due to the development of large underground cavities and the subsequent collapse of overlying deposits (Davies, 1951; White & White, 1969). A low dissolution rate results in sag depression structures (Beck, 5 1988).

Subrosion by itself is a natural process, but it can be influenced by anthropogenic factors, such as mining (Brady & Brown, 2006), manipulation of the aquifer system and/or the groundwater flow (Bell, 1988), and the extraction of saline water (Getchell & Muller, 1995). ~~Especially the~~ The formation of sinkholes is a dangerous geohazard if ~~they occur~~ it occurs in urban areas, where ~~they~~ it can then lead to building and infrastructure damage and life-threatening situations (~~O'Connor & Murphy, 1997; Waltham, 2000~~ 10 Because of the constant increase in the world's population and rapid growth of urban areas towards zones affected by subrosion, detailed knowledge of these structures and their generation process is increasingly in demand.

A few studies have dealt with the understanding of the processes and the imaging of subrosion structures e.g. cavities, collapse sinkholes and depressions (Waltham et al., 2005). To monitor sinkhole development, ortho-rectified aerial photos and differential field GPS are used (Yechieli et al., 2002; Abelson et al., 2006), while the vertical displacement is detectable by 15 radar interferometry (~~?Baer et al., 2002; Abelson et al., 2003~~) (Baer et al., 2002; Abelson et al., 2003) and plane-table leveling (Scholte, 2011). Gravimetric methods are suitable for the detection of cavities and mass movement (~~Arzi, 1975; Neumann, 1977; Butler,~~ but they also deliver information about possible cavity fills, as ~~geoelectric~~ (~~?Militzer et al., 1979; Bataynek & Al-Zoubi, 2000; Miensopust~~ geoelectric (Militzer et al., 1979; Bataynek & Al-Zoubi, 2000; Miensopust et al., 2015) and geomagnetic (Bosch & Müller, 2001) methods ~~can also do~~. Analogue and digital mechanical modeling of the development and the propagation of collapse sink- 20 holes is also a valuable tool (~~?Abdulla & Goodings, 1996; Tharp, 1999; Augarde et al., 2003~~). ~~Seismic (Steeple et al., 1986; Evans et al.~~ Seismic (Steeple et al., 1986; Bolger et al., 1995; Shtivelman et al., 2002; Krawczyk et al., 2012) and ground-penetrating radar (GPR) (~~Kaspar & Pecen, 1975; Ulriksen, 1982; Bolger et al., 1995; Forkmann, 1997; ?; Miensopust et al., 2015~~) (Kaspar & Pecen, 1975 deliver an image of the underground and provide physical attributes. Most of the previous case studies were carried out in rural areas, since especially geophysical methods based on electric and electromagnetic principles are often affected ~~in urban areas~~ 25 by strong electromagnetic noise and the presence of ferrous materials in urban areas (Bosch & Müller, 2001). Investigations using boreholes (Yechieli et al., 2002; Miller et al., 2009) are also not applicable at the most urbanized locations due to the densely built-up areas, strict approval procedures and high costs (Schmidt, 2005). Reflection ~~seismies~~ seismic is widely used for mining exploration purposes (Ziolkowski & Lerwill, 1979), but also in the context of geohazards such as subrosion (~~Miller & Millahn, 2006; Miller & Steeples, 2008~~) (Miller & Steeples, 2008). Several studies of reflection ~~seismies~~ seismic in 30 karst regions exist, but again mostly in rural areas (~~e.g. Evans et al., 1994; Odum et al., 1999; Miller & Millahn, 2006; Miller & Steeples,~~ whereas investigations in urban areas are sparse, especially using shear-wave reflection ~~seismies~~ seismic (Krawczyk et al., 2012). This method delivers high-resolution images of the near-surface, even in urbanized regions (Polom et al., 2010; Krawczyk et al., 2013). Compared to ~~for exmaple~~, for example GPR, it is not affected by saline water, which is the case in regions with e.g., Permian deposits (Annan, 2008). This is also the case in the study area in Bad Frankenhausen, located in 35 Thuringia in Germany.

Thuringia has a widespread sinkhole problem because of Permian deposits close to the surface that are exposed to natural and man-made subsidence processes. One of the most famous examples for the destructive consequences of subsidence is the leaning church tower in the medieval city center of Bad Frankenhausen. To date, geophysical methods that image the near-surface down to ca. 100 m depth with high-resolution, are still missing. Here, the application of shear wave reflection ~~seismies~~ seismic using equipment and surveying configurations adapted for urban areas ~~may is designed to~~ fill this gap. This is tested for the specific location in Bad Frankenhausen, with four shear wave reflection seismic profiles that were carried out around the leaning church tower. This paper shows the capabilities of high-resolution shear-wave reflection ~~seismies~~ seismic to detect and characterize subsidence-controlled unstable zones and structures.

2 Geological setting

10 The city of Bad Frankenhausen is located in northern Thuringia in Germany, at the southern border of the Kyffhäuser hills (Fig. 1), which are a small range of hills in Germany, bounded by the Harz ~~mountain~~ Mountain range to the north and the Thuringian Basin to the south (for an entire regional overview see Seidel (2003)). The N–S extension of the Kyffhäuser hills is ca. 6 km and the W–E extension ca. 13 km, with the highest peak being at 473 m a.s.l. The surrounding areas have a mean altitude of 150 m a.s.l.

15 The Kyffhäuser hills are bounded by several faults. To the north, ~~south-of-the-city-of-Kelbra,~~ is the NW–SE trending Kyffhäuser-Northern-Margin Fault, which belongs both to the Kyffhäuser-Crimmitschau Fault Zone and the Kelbra Fault Zone. The ~~fault has an offset of ca. 600m in the central part and ca. 250m near the tips of the fault (Schriel & Bülow, 1926a, b; ?)~~. The northward-dipping W–E trending Kyffhäuser-Southern-Margin Fault (KSM Fault) is located south of the Kyffhäuser hills in the northern part of Bad Frankenhausen (Schriel & Bülow, 1926a, b). Other large fault zones of this region are the Kelbra Fault 20 Zone, the Finne-Gera-Jachymov Fault Zone and the Hornburger Fault (~~Katzung & Ehmke, 1993; Puff, 1994; ?~~) (Puff, 1994).

The sediments in the south of the low hill range and north of Bad Frankenhausen are deposits from the Zechstein Sea, which was an epicontinental ocean during the Permian. Due to sea-level changes, conglomerates, carbonates, sulfates, and salt were cyclically deposited (Richter & Bernburg, 1955). The main marine formations, in order from stratigraphically lower to higher, are Werra, Staßfurt and Leine, with the first two being the most common in the research area. The Werra Formation consists 25 of anhydrite, limestone, copper shales, and conglomerates (~~Schriel & Bülow, 1926a, b~~). Anhydrite and gypsum layers are also part of the Staßfurt Formation (~~Schriel & Bülow, 1926a, b; Kugler, 1958; Reuter, 1962~~) (Kugler, 1958; Reuter, 1962).

The marine sedimentation phase was followed by the terrestrial sedimentation phase of the Triassic Buntsandstein with claystones, sandstones and shales, which are only found outside the low hill range at isolated spots, whereas ~~Muschelkalk and Triassic Muschelkalk and Triassic~~ Keuper are found a few kilometers south of Bad Frankenhausen. Cretaceous and Jurassic 30 deposits are not found in the entire area (~~Schriel & Bülow, 1926a, b; ?; Knoth et al., 1998; Beutler & Szule, 1999~~) (Schriel & Bülow, 1926a,

During the Early ~~Tertiary~~ Paleogene, the northern part of the Kyffhäuser hills was uplifted again (Freyberg, 1923) and tilted, resulting in a 300 m fault throw on the northern margin and a southward-dipping terrain. Therefore, the low hill range is described as a half-horsta ~~is the Harz Mountain (Katzung & Ehmke, 1993; Puff, 1994; ?)~~. Tertiary, as are the Harz Mountains

(Katzung & Ehmke, 1993; Puff, 1994). Paleogene deposits are exposed only at isolated locations at the southern and western margins (Schriel & Bülow, 1926a, b). In contrast the Quaternary sediments, with e.g., glacial till, detritus and loess cover a large area (Schriel & Bülow, 1926a, b; Kahlke, 1975–1990).

The entire region south of the Kyffhäuser hills is affected by subsidence (Schriel & Bülow, 1926a, b; Reuter, 1962) (Fig. 2).
5 The accumulation of subsidence structures south of the Kyffhäuser hills is the result of the combination of soluble rocks (Zechstein Formations) in the subsurface and their contact with fresh-ground water from the southward-draining hill range that ascends alongside the KSM Fault (Reuter, 1962). The presence of salt springs due to salt water ascension and the occurrence of numerous sinkholes and depressions at the surface are indicators of soluble rocks near the surface like the Zechstein Formations (Kugler, 1958; Reuter, 1962). Especially these formations (Kugler, 1958). These formations especially contain many
10 fractures and faults, which disturb the mechanical integrity of the subsurface. Additionally the fractures and faults serve as pathways for meteoric and groundwater. The dissolution probably occurs along these features, as shown by a study of Kaufmann (2014), who investigated three research areas in the vicinity of the Harz Mountains in Germany with geophysical surveys using gravimetric, electric, and magnetic methods, and numerical modelling.

The Barbarossa Cave, located ca. 5 km westward of Bad Frankenhausen, is situated in anhydrite of the Werra Formation
15 and is proof of the leaching processes that occurred in the geological past (Steinmüller & Siegel, 1963). One of the oldest sinkholes of the region is called Quellgrund 'Quellgrund', first mentioned in records in 998, and located in the medieval center of Bad Frankenhausen (Fig. 3a). The largest sinkhole of the Kyffhäuser region is the so called 'Äbtissinnen Grube' between Rottleben and Bad Frankenhausen. It probably developed in the 16th Century and has a diameter of 160 × 120 m and a depth of ca. 40 m. Many other subsidence features document the continuing subsidence until today. The most recent sinkholes are found
20 in the north-east of Rottleben directly next to the 'Äbtissinnen Grube and Bilzingsleben' and Bilzingsleben, a few km south of Bad Frankenhausen (Fig. 3b). The most famous subsidence phenomenon is the leaning church tower (Fig. 3c) in the medieval center of Bad Frankenhausen, north-east of the Quellgrund sinkhole (Reuter, 1962) 'Quellgrund' sinkhole. It is estimated that the tower started tilting in 1640 and its current inclination is 4.93° from the vertical (Scheffler & Martienßen, 2013), which exceeds that of the leaning the inclination of the tower of Pisa at 3.97°. Additionally, almost all buildings in the area around
25 the leaning tower have cracks. Repeated leveling surveys indicate a constant subsidence of the whole area (Scholte, 2011).

Surveying around the leaning church tower is challenging regarding geophysical investigations. Since the church is located in the medieval center of the town the area is densely built-up. In addition the topography is strongly alternating and different soil conditions are present at the surface.

3 Seismic survey

30 Four shear wave reflection seismic profiles were carried out around the leaning church tower of the Oberkirche 'Oberkirche' in Bad Frankenhausen (Fig. 4, 5 & 65). Profile S1 has a length of 86.5 m and was carried out on unpaved ground beside the church and crossed over remains of walls of the medieval city. Along the profile the topographic elevation decreases from 155.2 m to 146.6 m from NE to SW (Fig. 5a,b). Profile S2 with a length of 82.5 m runs to the east of the leaning tower on

unpaved ground and on a cobbled street known as Schwedengasse. As an additional challenge stairs were crossed with this profile (Fig. 5c,d). The topographic elevation alongside profile S2 increases from 148.3 m to 157.4 m from south to north. Profile S3 has length of 79.0 m and was carried out on unpaved ground and is located on a ca. 0.5 m narrow path behind the church. The topographic elevation decreases from 151.2 m to 148.3 m from SE to NW (Fig. 5e,f). Profile S4 with a length of 84.5 m investigated the subsurface below the street ~~Am Schlachtberg~~ 'Am Schlachtberg', which is surfaced by asphalt and concrete. The topographic elevation decreases from 158.3 m to 147.8 m from north to south (Fig. 5g,h). To meet the requirements of this challenging investigation area the equipment and the configuration used for the shear wave reflection ~~seismies~~ seismic surveys had to be adapted by splitting the landstreamer (see below for detailed description).

For the seismic surveying a horizontal micro-vibrator as source (Fig. 6) and horizontal geophones as receivers were used in SH configuration. This source-receiver combination reduces ~~converted waves and the registration of converted waves. These waves were additionally suppressed by vertical stacking of records with opposite polarization during data processing. As a result this survey configuration~~ enables straight forward data processing. The slower seismic velocities of SH waves enable images of higher resolution than using P waves (~~Dasios et al., 1999; Inazaki, 2004~~) (e.g. Dasios et al., 1999; Inazaki, 2004). A further advantage is the autonomous suppression of surface Love waves, which occurs if the first subsurface layer is of higher seismic velocity than the second layer, which is often the case on paved or compacted roads.

The electro-dynamic micro-vibrators ELVIS 6 and ELVIS 7 (Fig. 6) are basically comparable and are used to generate horizontally-polarized shear waves (Polom, 2003; Druivenga et al., 2011; Krawczyk et al., 2012). ELVIS 6 was used on profile S1, and ELVIS 7 was used on profiles S2, S3 and S4 due to technical problems with ELVIS 6. The most important advantage of these small sources is the usability in urban areas (~~?Krawczyk et al., 2013~~) (Krawczyk et al., 2013), such as the medieval center of Bad Frankenhausen, which is extremely built-up. ~~Secondly, an enhanced signal-to-noise ratio (S/N ratio) due to the correlation of the sweep and the recorded data, which compresses the time-stretched signal to a short wavelet comparable to an impulse signal and the noise outside of the sweep frequency range is also reduced (Yilmaz, 2001).~~

The micro-vibrator enables good ground coupling even in areas difficult to access due to the small base plate and a total weight of ca. 95 kg, which can be increased by a person sitting on top of the micro-vibrator (Krawczyk et al., 2012). ~~Coupling to the ground is important, because the maximum investigation depth depends partly on the emitted energy; other important factors are e.g., the thickness of the weathering layer, the scattering of the seismic wave and the number and size of fractures (Brückl et al., 2005).~~

To record the reflected seismic shear waves, 72 horizontal geophones of type SM-6 (Input/Output Inc., 1999) attached to a landstreamer were used (Krawczyk et al., 2012). The landstreamer was mainly adapted for near-surface reflection seismic profiling on paved or compacted ground and uses a fixed geophone spacing of 1 m. Typically, the streamer is towed by a car that contains the recording system (~~Krawczyk et al., 2012~~). The trigger signal was emitted simultaneously with the start of the sweep signal to begin the digital recording. Both ~~,~~ trigger and sweep were sent via cable from a generator developed at LIAG (~~Krawczyk et al., 2012, 2013~~) (Krawczyk et al., 2013).

The four shear-wave reflection seismic profiles (total length of ca. 332 m) were gathered-acquired in July 2014. Since the target depth was ca. 80 m and due to the limited space at the surface, a fixed receiver-configuration with only the source moving

forward was used. Prior to the survey the landstreamer was adapted for the limited space in Bad Frankenhausen and separated into three parts for manual handling, each containing 24 geophones. The vibration point distance was 2 m, 4 vibrations were excited at each vibrator location using alternating polarities. Therefore the mean CMP-fold of the profiles results in ~~an average of~~ 18 seismic traces per CMP. The sweep frequency was 20 to 160 Hz and the sweep had a length of 10 s (~~Table 1~~) and the record length was 12 s (Table 1). Each profile was geodetically surveyed using an electronic tachymeter referenced by DGPS-based fix points.

4 Data processing

The data processing contained two main steps: first, the preprocessing and second, the post-geometry processing ((Table 2); for detailed explanations regarding the processing algorithms see Hatton et al. (1986); Lavergne (1989); Baker (1999); Klingen (2001); Yilmaz (2001); Brückl et al. (2005); Stark (2008); Zhang et al. (2008); Fatima et al. (2010).

The first step of data preprocessing was to check the geodetic coordinates for induced DGPS errors caused by limited satellite access. ~~If the derivation was $\geq 1\text{cm}$ the coordinates were manually corrected. The mean errors were 5cm for S1, 8cm for S2, 2cm for S3, and 5cm for S4.~~ After loading the data into the processing software a visual examination of each single record was done for quality assessment and to remove noisy traces(~~Fig. 7~~). ~~The following~~. The vibroseis correlation correlated the pilot sweep with the recorded traces in order to compress the time-stretched signal to a short wavelet such as an impulsive signal. Afterwards the survey geometry was installed and a crooked-line binning using a 0.5 m bin interval was applied.

The first steps of the post-geometry processing sequence were amplitude scaling and frequency filtering to enhance the reflection response and to attenuate noise to improve the resolution and the data quality. To accomplish that an automatic gain control (AGC, 220 ms), a bandpass filter (15/17 Hz–163/165 Hz) and amplitude normalization were applied to our data. Subsequently, the four records of every vibrator location were vertically stacked to improve the ~~Signal-to-Noise~~ signal-noise ratio (S/N ratio), by reducing the statistically-distributed noise and amplification of the seismic response. In this processing stage the records of the four seismic datasets needed different handling because of varying data quality, caused by the different surface conditions ~~(Fig. 7)~~. In the proximity of the source high-frequency noise and harmonic distortions caused by impaired source coupling were observed in the records in all profiles. S1 and S2, which have a noticeable change in the topographic elevation of almost 10 m, were carried out mostly on unpaved soil and on cobblestone. As a consequence the coupling of the base plate to the surface was often hampered, resulting in partly strong harmonic distortions (Fig. 7). S3 was also carried out on unpaved soil, but the source could be balanced better leading to better ground coupling of the base plate. S4 was surveyed on a sloping terrain, but in contrast to S1 and S2 the surface was paved by asphalt and concrete, leading to less harmonic distortions due to better ground coupling of the source. Besides the vertical stack the S/N ratio was additionally improved by individually muting the data parts of each profile that were irrelevant for the following processing steps using a top mute.

The following processing steps were performed iteratively. Since most of the reflection signals were covered by noise and harmonic distortions the top mute was followed by a frequency-wavenumber filter (FK ~~Filter~~ filter), which eliminated the disturbing effects of the noisy frequencies and the harmonic distortions (Fig. 8, Table 2). For each of the four datasets an

individual FK filter was applied followed by a bandpass filter of 15/17 Hz–85/87 Hz, because iterative frequency analyses revealed that the reflection signals contain mostly frequencies below 85 Hz. To prepare the data for the next processing steps (e.g. the velocity analysis), the datasets were sorted from shot domain sort to CMP domain sort. The ~~analysis intervals~~ velocities were picked manually using the semblance, the offset gathers and the constant velocity stacks. The intervals for the velocity analysis were 5 m or 10 m in order to capture the lateral velocity variations. Using the ~~Normal Move-Out~~ NMO correction the reflection hyperbolas were corrected to get zero-offset travel times. Residual statics correction reduced the inaccuracies at the near-surface. Afterwards the CMPs were stacked and the first seismic sections were created. After generating the seismic time sections of the four SH-wave profiles, they were examined in detail in order to iteratively improve the velocity analysis and the data processing (Fig. 9a). Due to some remaining noise a frequency analysis was conducted on the stacked data and as a result a ~~Bandpass Filter~~ bandpass filter was applied (Fig. 9b). The final frequency bandwidths were 17/19 Hz–68/70 Hz for S2 and 17/19 Hz–73/75 Hz for S1, S3 and S4, ~~although the~~ The main parts of the reflection signals were between ca. 20 and 60 Hz. In combination with the application of individual ~~Spectral Balancing~~ spectral balancing applied on each of the four profiles the resolution was improved (Fig. 9c). Afterwards a FD-migration processing was applied to shift the reflectors towards their correct position and to remove diffraction signatures. Finally the seismic sections were converted into depth sections to enable a lithological correlation with five wells located near the leaning church tower.

5 Structural imaging and Interpretation

In the following, reflection patterns, seismic velocities and interpretations of the seismic sections are described (Figs. 10, 11). The seismic attributes, amplitude, and continuity, were used for the analysis of the reflection pattern in the unmigrated time sections (Fig. 10a). Profile S1 shows reflectors of high amplitudes from the surface down to 100 ms TWT, especially between 20 m and 60 m horizontal distance (Fig. 10a, S1). The underlying patterns down to ~~1200~~ 1000 ms TWT are characterized by discontinuous reflectors with small offsets and vertical differences of up to ca. 60 ms TWT (ca. ~~1–10~~ to 10 m) (e.g. between 60 m and 80 m distance and ~~200–600~~ 200 to 600 ms TWT), and by a partly weaker reflection pattern that is recognizable by lower amplitudes. Dipping reflectors are also present, particularly in the near-surface (e.g. between 50 m and 80 m distance and ~~50–300~~ 50 to 300 ms TWT). Besides these features, diffractions are present, especially in the area below 600 ms TWT. In section S2 the highest amplitudes are found in the uppermost ~~100–150~~ 100 to 150 ms (Fig. 10a, S2). Down to ~~1200~~ 1000 ms TWT the seismic section S2 shows the same characteristics as S1 with offsets that result in discontinuous reflectors (e.g., between 40 m and 80 m distance and ~~200–600~~ 200 to 600 ms TWT). Shallow-dipping reflectors at the near-surface (e.g. between 30 m and 80 m distance and ~~10–200~~ 10 to 200 ms TWT) and diffractions, especially below 400 ms TWT are also present. Section S3 is comparable with S1 and S2 because the reflectors are strongly discontinuous (e.g. between 40 m and 70 m distance and ~~150–600~~ 150 to 600 ms TWT). The highest amplitudes are found in the uppermost 200 ms TWT (Fig. 10a, S3). Diffractions, which are not as pronounced as in sections S1 and S2, are visible below 500 ms TWT. Some dipping reflectors are present in the first 200 ms TWT between 40 m and 60 m distance. The reflection pattern of S4 is not comparable with the other profiles, because in contrast, the reflectors are more continuous, of higher amplitude, and most of them dip southward (e.g., between

15 m and 60 m distance and ~~200–600~~200 to 600 ms TWT). No diffractions occur in the lower half of the profile, but more reflectivity is observed (Fig. 10a, S4).

Six features are similar for ~~all profiles~~profiles S1, S2 and S3. Firstly, the reflection patterns show lateral variations. Secondly, the highest amplitudes are found in the uppermost ~~150–200~~150 to 200 ms TWT, ~~at least in the sections S1, S2 and S3, and and~~
5 thirdly, there is a partly weak reflection pattern below 200 ms TWT. Fourthly, discontinuous reflectors exist with small offsets that have vertical ~~differences~~offsets of ca. 1 m to 10 m. Fifthly, the downward-dipping reflectors located at the subsurface form depression-like structures. Sixthly, diffractions are visible in the sections S1, S2 and S3.

One of the key factors in obtaining a good image of the underground is the generation of a proper velocity field (Fig. 10b). The shear-wave interval velocities ~~V_{INT} of (V_{INT})~~(V_{INT}) in the seismic sections S1, S2 and S3 do not constantly ~~increasing~~increase
10 with depth, ~~rather in fact anomalous~~ low-velocity zones are present ~~in the near-surface~~between ca. 100 to 400 ms TWT. This results in lateral and vertical velocity variations, especially in the uppermost 1000 ms TWT. In general, the shear wave velocities range between ca. 160 m s⁻¹ and 580 m s⁻¹. The velocity field of S1 shows an increase of the velocity from 0 to 100 ms TWT with V_{INT} values of 150 m s⁻¹ to 270 m s⁻¹ (Fig. 10b, S1). From 50 m to 80 m distance and 100 to 300 ms TWT a low-velocity zone is visible with values of 100 to 270 m s⁻¹. West of this, and in the same time interval, velocity values of
15 270 m s⁻¹ to 300 m s⁻¹ were determined. Below this zone the velocities almost constantly increase with depth to the highest observed velocity of ca. 480 m s⁻¹. In general, the velocity field of S2 contains velocity values that range between 180 m s⁻¹ and 550 m s⁻¹ (Fig. 10b, S2). In the first 100 ms TWT the interval velocity increases from 180 m s⁻¹ to 300 m s⁻¹. A low-velocity zone is visible from 20 m to 80 m distance and between 100 to 400 ms TWT in the southern part of the profile with the lowest velocity value of ca. 180 m s⁻¹. The velocity field of S3 shows increasing shear wave velocities from ca. 160 m s⁻¹
20 to 280 m s⁻¹ between 0 and 100 ms TWT (Fig. 10b, S3). Similar to the sections S1 and S2, S3 shows a low-velocity zone between ca. 200 and 350 ms TWT and 40 m to 78 m distance with the lowest value of ca. 185 m s⁻¹. Below this zone, the velocities almost constantly increase with depth up to ca. 555 m s⁻¹. The interval velocities of S4 range from ca. 180 m s⁻¹ to 580 m s⁻¹ ~~and show no~~. In contrast to the velocity fields of S1, S2 and S3, which show remarkable low-velocity zone-zones the velocities constantly increase with depth and the values are generally higher (Fig. 10b, S4).

25 5.1 Interpretation

For geological interpretation the ~~reflection patterns~~reflectors and the shear wave velocities were correlated with lithologies derived from nearby boreholes (Fig. 11). Since the three boreholes located around the leaning church tower all show almost identical lithologies, only the lithologies of the research borehole Ky 1/2014 are described in detail (Fig. 11a). The first 3 m consist of anthropogenic deposits e.g. back fill, sand, gravel and debris. Clay and solifluction soils of the Quaternary are found
30 between ca. 3 m and 7 m depth, followed by deposits of the Zeehstein Permian, in this case the Staßfurt-furt- and the Leine Formations, which are discontinuous due to several cavities and cavity fillings that indicate karst. The Staßfurt anhydrite is found between ca. 7 m and 74 m depth, and the ~~Stinkschiefer~~‘Stinkschiefer’ that belongs to the Staßfurt carbonate, reaches down to a depth of ca. 80 m. The Werra Formation at depths of 80 m to 163.8 m consists of anhydrite, carbonate and clay. The oldest Zeehstein Permian deposits are conglomerates, which are found between 163.8 and 165.2 m depth. From ca. 165.2 m to

347.7 m deposits of the Kyffhäuser Formation, with sandstones, silts, argillites and conglomerates, are found. At the base of this formation, the KSM Fault is detected with a 40° dip. Below, a second package of the Staßfurt- and the Werra Formations was drilled, which indicates that the KSM Fault is a thrust fault that was probably active during the TertiaryPaleogene and the Neogene. The KSM Fault is assumed to act as the main pathway for water to leach the Permian deposits in the near-surface.

5 Combining all structural and lithologic information leads to the following geological interpretation (Fig. 11b, c). The uppermost 10 to 15 m depth of the four profiles, with increasing V_{INT} values of 160 m s^{-1} to 300 m s^{-1} , are typical of unconsolidated Quaternary deposits, if compared to studies in other research areas (Gomberg et al., 2003; Brückl et al., 2005). The reflectors reflections below, down to 150 m depth, represent various Zechstein-Permian deposits. The discontinuous reflection patterns and the small offsets are indicators of faults and a-strongly fractured strata. This is visible in sections S1 and S2 at ca. 40 m
10 and 80 m depth (Fig. ~~10a~~11b, S1 & S2). The faults in the near-surface partly form conjugate normal faults, and the layers are displaced along these structures. The sediments are falling into these secondary openings due to the constant subsrosion. As a result, depressions are forming at in the near-surface, also visible as dipping reflectors. The depressions consist of anthropogenic and Quaternary deposits and of the Staßfurt anhydrite.

The low-velocity zones (Fig. 10b) occur predominantly in the proximity of these depressions at ca. 20 to 40 m depth(Fig. 10b). The depression in the W-E trending profile S1 is located ca. 8 m north of the church (Fig. 11c, S1). It has an extent of ca. 30 m and reaches a depth of ca. 20 m. The immediate proximity of this depression to the leaning tower and the diffractions at depths of 40 m, which are probably induced by small subsurface structures due to the strongly fractured underground, indicate that these subsrosion structures are the main reason for the tilting of the tower. The same holds for the northern depression in the N-S trending profile S2, which is located 5 m east of the tower (Fig. 11c, S2). It shows an extent of ca. 40 m and a depth of
20 ca. 20 m. The southern depression of S2 is located below the Schwedengasse-'Schwedengasse' road, 25 m south of the church, with an extent of 20 m and a depth of ca. 15 m. The depression-like structure, as imaged by profile S2 at the tower, is probably the same as the one in section S1, but viewed from another direction. The diffractions in both sections imply small-scale structures in the subsurface at depths of 40 m and below e.g. a fractured underground/strata, faults or cavities; the latter was drilled by the research boreholes. In section Section S3 ,there is indication of another reveals another ca. 30 m wide and 20 m
25 deep depression structure (Fig. 11b, c, S3).It is, located 15 m south of the churchwith an extent of ca. 30m and a depth of ca. 20m.

Section S4 shows a different image of the subsurface compared to the other seismic sections (Fig. 11c, S4). The section does not show depression structures in the near-surface, and-low-velocity zones or large diffractionsare also missing. Insteadsignificant diffractions. Instead, the main features of S4 are southward-dipping reflectors that represent a listric normal
30 fault.

6 Discussion

Carrying out seismic surveys in an urban environment is always a challenge due to traffic-passingpassing traffic, noise from construction sites and any other typeother types of industrial noise. These factors lead to many interruptions of the surveys

in Bad Frankenhausen. Two ways to reduce these disturbances would be road closure or night ~~surveys~~surveying. Due to the average profile length of only ~~880~~ m and sufficient time schedule these options were not used.

Another problem are densely built-up areas with limited space, like the medieval center of Bad Frankenhausen. In addition, the ground conditions differ from unpaved soil to paved soil to ~~streets-consisting-of~~ asphalt, concrete or cobblestone streets.

5 The equipment used was accordingly adjusted to meet these special requirements.

Different seismic sources are generally available, e.g. explosive charges, hammer blows or weight drops, but these are not applicable in Bad Frankenhausen due to the lack of space and/or the resulting damage of the surface (Drijkoningen, 2003). For that reason the micro-vibrator ELVIS, which was developed at LIAG, was used for the seismic surveys (Fig. 6). Another advantage of the vibroseis technique is that, compared to impulse sources, the emitted high-precision frequency-modulated
10 signal generates a repeatable and consistent wavelet (Klauder et al., 1960; Goupillaud, 1976; Nijhof et al., 1998; Drijkoningen, 2003).

The data processing here was based on general processing procedures, as described by Krawczyk et al. (e.g. 2012) and Pugin et al. (2013a). Additionally, spectrum balancing was applied to improve the vertical resolution. Velocity analysis was a difficult task, because reflection hyperbolas were barely visible, due to the discontinuous reflectors and weak reflection
15 patterns (Fig. 10a). Additionally, an often observed decrease of the interval shear-wave velocities in the shallow subsurface in the uppermost 1000 ms TWT indicated low-velocity zones resulting in lateral and vertical velocity variations of an average value of 100 m s^{-1} (Fig. 10b). These velocity variations and the low-velocity zones also impaired the depth conversion process. To prevent imaging artifacts, simplified 1D velocity profiles derived from the 2D velocity fields were used.

The discontinuous reflection patterns, the partly low amplitudes and the low-velocity zones indicate the formation of frac-
20 tures, faults (Fig. 11b,c), and probably cavities leading to lower density and higher porosity values. The formation of these structures is mainly caused by leaching processes in the subsurface. The ~~voids~~cavities or the disturbances of the wavefield caused by ~~the~~these voids and other small structures are detectable by e.g., the presence of diffractions within the unmigrated sections (Fig. 10a), if the size of the ~~scatterer~~scattering object is smaller than the wavelength of the seismic signal. The voids also have an effect on the surrounding material, like the formation of fractures due to instabilities. This change of rock integrity
25 is detectable by the presence of discontinuous reflectors and shear wave velocity variations.

Seismic velocities strongly vary depending on the physical rock properties. Shear wave velocities of anhydrite range from 2000 m s^{-1} to 3600 m s^{-1} , and gypsum ranges from 700 m s^{-1} to 2700 m s^{-1} , as derived from laboratory experiments (Brückl et al., 2005; Mielsch & Priegnitz, 2012). Wave propagation within an intact rock is faster than in a rock with fractures, faults and cavities, due to their disturbing effect on the wavefield (Barton, 2007). The observed velocities of the four seismic sections
30 here, which contain a mixture of anhydrite and gypsum, are slower with a maximum value of ca. 580 m s^{-1} (Fig. 10b), because the strata is strongly fractured.

FracturesIn general, fractures can range in size from microcracks (up to a few micrometers) to faults (up to hundreds of km in length and tens of km in depth), and there are always smaller fractures present than those imaged in the seismic sections. The horizontal resolution is determined by the radius of the Fresnel zone, the smaller the zone the higher the resolution. The
35 radius of the Fresnel zone is determined by the wavelength, which depends on the central frequency and the velocity of the

seismic wave. As a result, a high frequency and a slow seismic velocity will lead to a smaller wavelength and therefore to an improved resolution (Brückl et al., 2005). The strongly fractured strata/underground below Bad Frankenhausen and the unconsolidated sediments ~~at~~in the near-surface result in slow seismic velocities between 160 and 580 m s⁻¹. For the sweep signal a frequency bandwidth from 20 to 160 Hz was chosen and data analyses revealed that the useful signal mainly contains
5 frequencies between 20 and 85 Hz. This results in high-resolution imaging of the shallow subsurface with a resolution of less than 1 m ~~in~~at depths down to ca. 15 m and a resolution of ca. ~~2–3~~2 to 3 m ~~in~~at 50 m depth.

Boadu & Long (1996) found that seismic amplitudes and phases change at fractures, depending on the fracture parameters, such as fracture length and fracture spacing. Only part of the energy is reflected at the fault itself and the rest is either scattered or guided by the fracture. This results in a loss of reflected energy and a reduced amplitude size; this effect is less pronounced
10 for lower frequencies (L’Heureux et al., 2009). This is the case here (Fig. 10a), where many small structural features induce scattering.

Depressions are visible in the seismic sections S1, S2 and S3 (Fig. 11). The tilting of the church tower and the subsidence of the surface are associated with the subsrosion structures seen in S1 and S2 (Fig. 10, 11). Seismic section S2 shows a depression structure below the ~~Schwedengasse~~‘Schwedengasse’ road. Additionally, in a small area between the church and the
15 ~~Schwedengasse~~‘Schwedengasse’ road, ca. 10 m north of the eastern end of profile S3, slight subsidence of the surface is visible. This is also the case in the eastern part of section S3. Probably a new depression structure is forming at this location and is proceeding to the surface. For further observation of the evolution of this structure repeated LiDAR scans of this area are planned. Such sagging of layers and upward migration of voids were also shown by Miller & Millahn (2006) and McDonnell et al. (2007) from research areas in Texas and Kansas in the USA.

To interpret the structures imaged by profile S4, the results of outcrop investigations, geological mapping (Schriel & Bülow, 1926a, b), and research and exploration boreholes were taken into consideration (Figs. 1, 11). These geological investigations indicate a west-to-east striking northward-dipping thrust fault at the southern margin of the Kyffhäuser ~~–~~also hills, known as the Kyffhäuser-Southern-Margin Fault (KSM Fault). The ~~Zechstein~~Permian deposits of the Werra-, Staßfurt- and Leine Formations have been thrust along this fault, which is probably an important pathway for water to leach the ~~Zechstein~~
25 Permian deposits. Similar observations of leaching processes were made by Abelson et al. (2003) and Frumkin et al. (2011) along the western Dead Sea shoreline, where a rift valley that features several normal faults was identified as a possible water pathway. The imaging of the KSM Fault at depth of ca. 347 m was not possible because of the limited investigation depth of the used equipment and the survey configuration. Instead another, so far unknown, fault is imaged on profile S4~~and also by a P-wave profile carried out along the same track~~. The visible structure is a southward-dipping listric normal fault ~~and it that~~ can
30 be observed down to a depth of ca. 120 m in the shear wave section (Figs. 10, 11)~~and down to ca. 350m depth in the P-wave section (Wadas et al., 2016)~~.

The observations in Bad Frankenhausen can be compared with the results of other studies, which have determined seismic velocities in the context of characterizing subsrosion-induced structures, but with a lower resolution. P-wave refraction ~~seismies~~
seismic has been used to detect the subsurface velocity structure, ~~and as~~ the inversion of surface waves have been used to
35 calculate shear wave velocities. In ~~the refraction seismies~~refraction seismic strong lateral variations of the velocities and zones

with decreased seismic velocities are shown ~~that are to be~~ associated with salt dissolution (e.g., Karaman & Karadayilar, 2004; Dobecki & Upchurch, 2006). With a resolution of 15 to 20 % of the investigated depth (Briaud, 2013), this technique has a lower resolution with respect to the shear wave reflection method. Especially shear wave velocities are of importance, because of their relationship to the shear modulus, which is an indication of the stiffness of subsurface rocks. Therefore low-velocity zones could be used to determine hazard-prone areas and this will be further investigated by future work.

The inversion of Rayleigh surface waves helps to deliver shear wave velocities (e.g. using the Multichannel Analysis of Surface Waves (MASW)). Some studies (Debeglia et al., 2006; Dobecki, 2010) revealed vertical and in particular lateral variations in the subsurface with low-velocity zones associated with loosening of shallow sediment layers during the formation of voids and the development of sinkholes. This correlates with the results of this study (Fig. 10b). The advantages of the MASW method are less acquisition and processing time compared to active shear wave reflection ~~seismies~~ seismic. The disadvantages of MASW are the lower penetration depth, the inferior vertical and lateral resolutions (Ismail et al., 2014), and that the method is based on a 1D inversion process leading to smearing effects in 2D (Park & Taylor, 2010). If only an overview of the velocities is required, Rayleigh surface wave inversion is a valuable tool to estimate the ground stability. For a detailed analysis the use of shear wave reflection ~~seismies~~ seismic is recommended. As shown, even in urban areas this method delivers a high-resolution image of both the structures and the shear wave velocities in the near-surface (Polom et al., 2010; Krawczyk et al., 2012; Pugin et al., 2013b). In this study, we provide images down to a depth of ca. 100 m with a resolution of less than 1 m in the shallow subsurface (upper 10 to 15 m).

7 Summary and Outlook

In this study we show the potential of shear-wave reflection ~~seismies~~ seismic to identify subrosion-induced structures in the near-surface in an urban environment. The survey carried out in the medieval city center of Bad Frankenhausen confirms the benefits of this technique, e.g. to detect and characterize unstable zones. The seismic sections reveal five main features associated with subrosion:

1. laterally and vertically variable reflection patterns caused by strongly heterogeneous strata,
2. discontinuous reflectors, small-scale offsets and small normal faults, which were caused by a strongly fractured strata due to leaching of the Zechstein ~~formations~~ Formations,
3. dipping reflectors and depression structures at the near-surface caused by deposits slowly sagging into secondary openings and cavities,
4. diffractions in the unmigrated seismic sections are possible indicators of cavities in the subsurface, which developed due to the subrosion processes, and,
5. laterally and vertically varying seismic velocities and low-velocity zones in the near-surface caused presumably by fractures and upward migrating cavities.

A previously undiscovered southward-dipping listric normal fault was found northward of the church. This fault probably serves as a main pathway for water to leach the Zechstein Formations below the church leading to the tilting of the tower.

Future work will comprise advanced data processing such as pre-stack migration, ~~and~~ additional shear wave reflection seismic surveys in Bad Frankenhausen ~~and, e.g. repeated LiDAR scans to observe the development of a new depression structure south of the church.~~ In order to compare the results from Bad Frankenhausen, seismic surveys in Schmalkalden in southern Thuringia, another area affected by subsrosion, are planned.

8 Data availability

The seismic data, which was used in this paper, is the property of LIAG. The data is available from the authors upon request. Please contact the first author (Sonja Wadas) for details.

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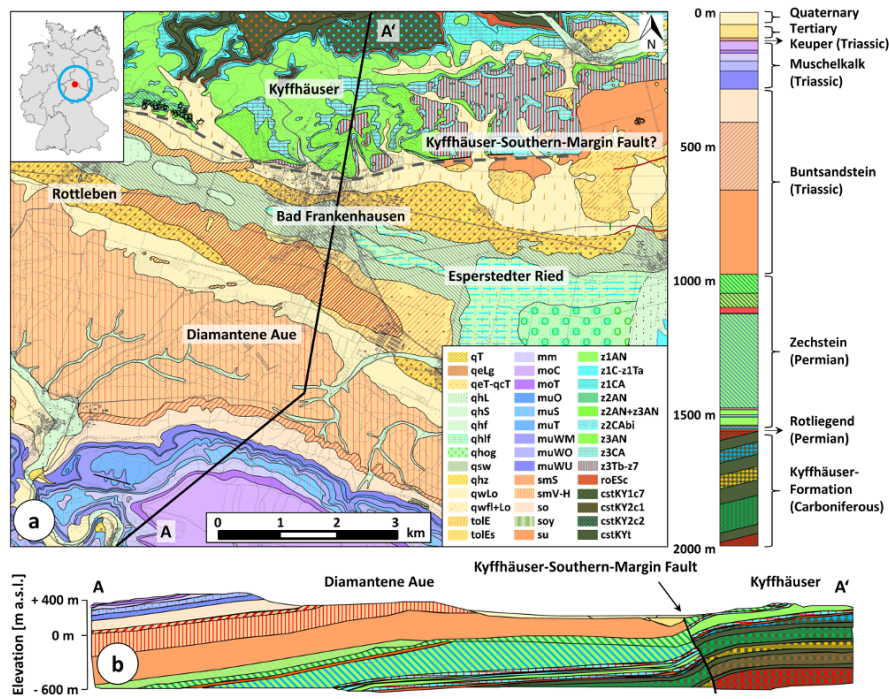


Figure 1. ~~Geological setting~~ Geology of the research area. Bad Frankenhausen (red dot) in Thuringia (blue circle) is located centrally in Germany (see inset). (a) ~~Geological map showing~~ Map shows the Permian deposits of the southern part of the Kyffhäuser hills and the 'Diamantene Aue', which consists of mainly Quaternary deposits (for an explanation of the stratigraphic abbreviations, see LBEG (2015)). The average thickness of the geological units in the area of Bad Frankenhausen is shown right of on the geological map right. (b) The cross section A–A' (black line in geological map) passes through the research area and shows the northward-dipping Kyffhäuser-Southern-Margin Fault (dashed line) (after Schriell & Bülow (1926a, b)).

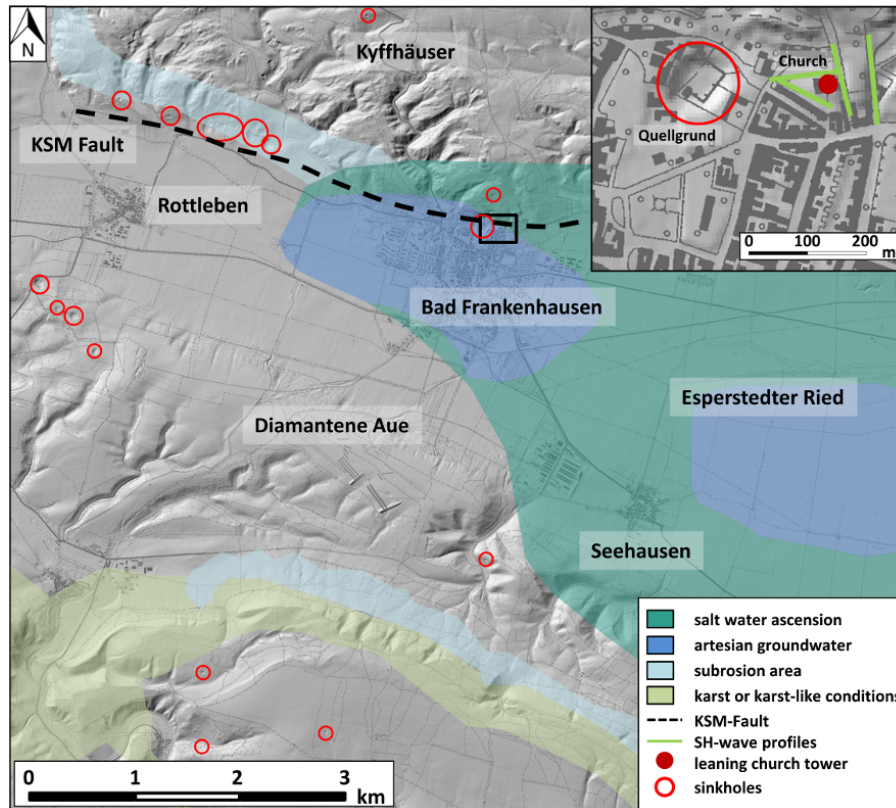


Figure 2. Digital elevation model showing the hydrogeological assessment of Bad Frankenhausen and the surrounding areas (provided by Thuringian State Institute of Environment and Geology, 2016). The city of Bad Frankenhausen is located in a region of salt water ascension and artesian groundwater conditions along the Kyffhäuser-Southern-Margin Fault (dashed line). The research area with the leaning church tower of the ‘Oberkirche’ (red dot) and the shear wave reflection seismic profiles (yellow-light green lines) are shown detailed in the inset. A zone influenced by subrosion is defined based on the occurrence of a line of sinkholes (red circles).



Figure 3. Subrosion signatures at surface in Bad Frankenhausen and the surrounding area. (a) The ~~most famous subrosion phenomenon is the leaning church tower of Bad Frankenhausen (height of 56m); note drilling in foreground.~~ (b) The oldest sinkhole of the region, called 'Quellgrund', is located in the medieval city center of Bad Frankenhausen and used today as recreation area. (eb) One of the most recent sinkholes is found directly beside the 'Äbtissinnen Grube' (red circle marks a person standing at the sinkhole margin). (c) The most famous subrosion phenomenon is the leaning church tower of Bad Frankenhausen (height of 56 m); note borehole in foreground.

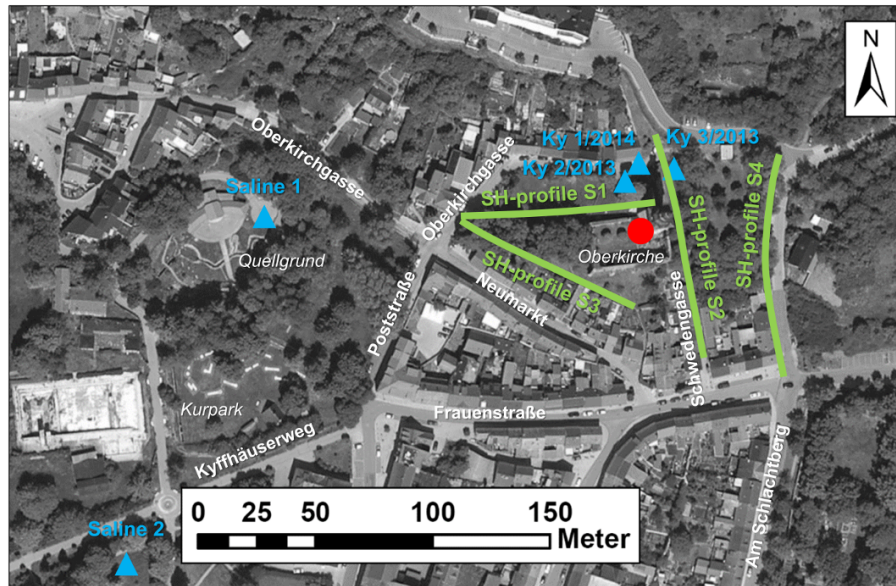


Figure 4. Reflection seismic profile locations in the survey area. The four SH-wave reflection seismic profiles (light green lines) were carried out around the leaning church tower of the ‘Oberkirche’ (red dot) to investigate subsurface structures responsible for the constant sagging of the surface. Profile S4 runs partly along the same location as a previously carried out P-wave reflection seismic profile (dark green line), enabling the comparison of both seismic sections. Close to the ‘Oberkirche’ 5 boreholes exist for calibration (blue triangles; for a detailed description see Fig. 11). Saline 1 and Saline 2 are historical boreholes from 1857 and 1866, drilled to extract brine. Their stratigraphy is rather approximate. Ky 2/2013 and Ky 3/2013 are pre-investigation boreholes for the deep research borehole Ky 1/2014. These wells are well documented, including e.g. stratigraphy, density, susceptibility, gamma ray logging, temperature and conductivity.

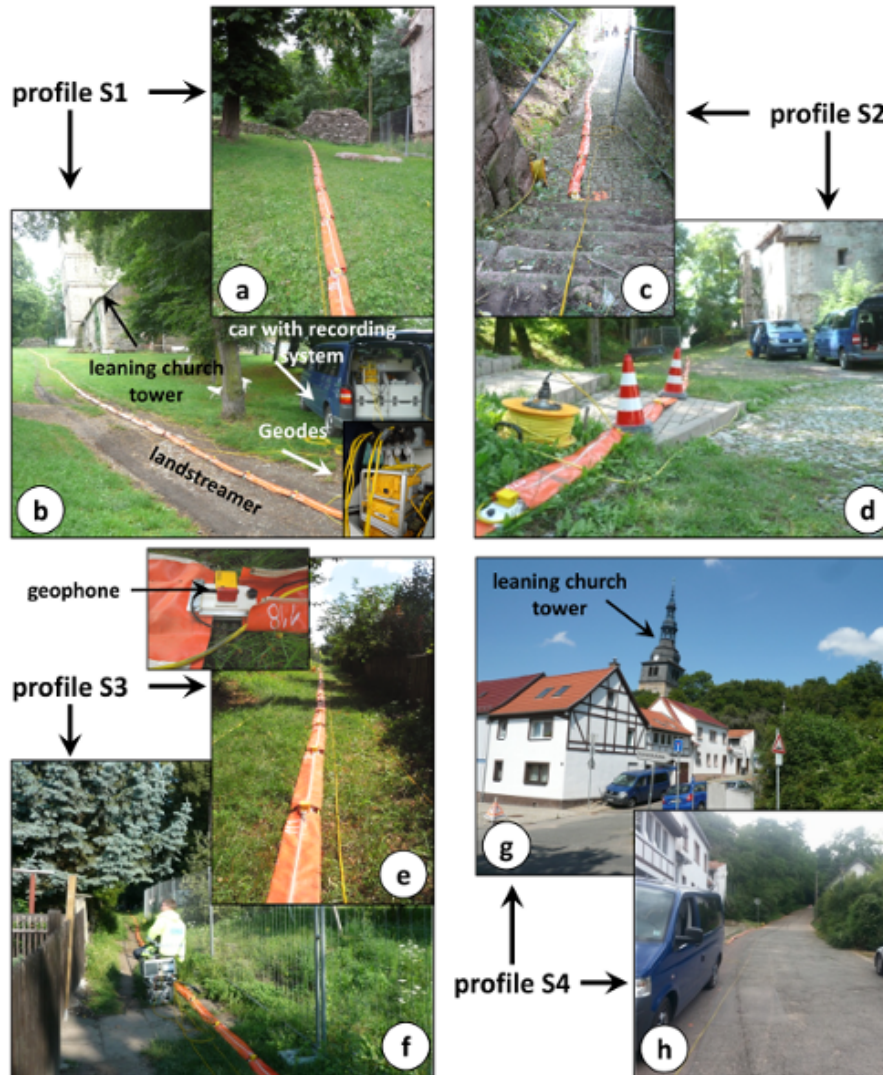


Figure 5. Field campaign in July 2014 under variable survey conditions. The shear-wave reflection seismic profile S1 (a) and (b) was carried out next to the church with the landstreamer (orange covering) crossing over remains of walls of the medieval city. Profile S2 (c) and (d) runs east of the leaning church tower. An additional challenge are stairs along the profile track. Profile S3 (e) and (f) was carried out behind the church, adjacent to private gardens on a ca. 0.5 m narrow path. Profile S4 (g) and (h) was carried out along the street ‘Am Schlachtberg’.

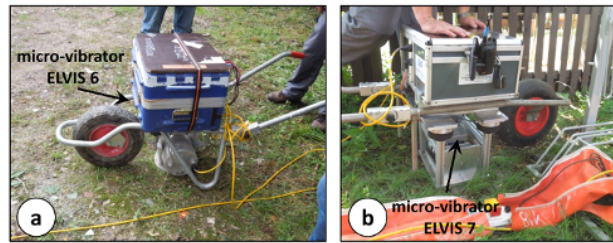


Figure 6. Field campaign in July 2014 using different two basically comparable seismic sources. (a) Micro-vibrator ELVIS 6 on paved ground, (b) micro-vibrator ELVIS 7 on unpaved ground and landstreamer beside it. Both-The vibrators are ideally suited for application in densely built-up areas such as the medieval city center of Bad Frankenhausen.

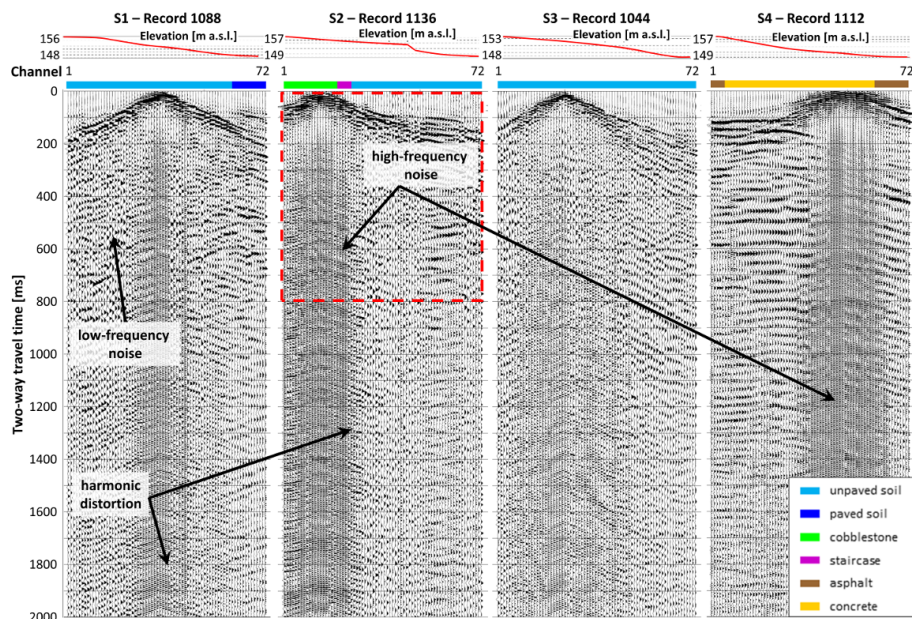


Figure 7. Comparison of records of the four SH-wave seismic profiles showing the differing data quality although the four profiles are not far from each other (c.f. Fig. 4). The [processing steps applied to the data are vibroseis correlation, an AGC, a bandpass filter around the sweep frequency range and amplitude normalization.](#) The main controlling factor are near source inhomogeneities in the subsurface leading to harmonic distortions, which cover the reflection signals by high-frequency noise. Also the coupling quality on unpaved soil or cobblestone is impaired compared to a paved surface e.g. an asphalt- or concrete-paved road. Besides the harmonic distortions, low- and high-frequency noise caused by environmental noise also down the reflection signals, especially on profiles S1, S2, and S3.

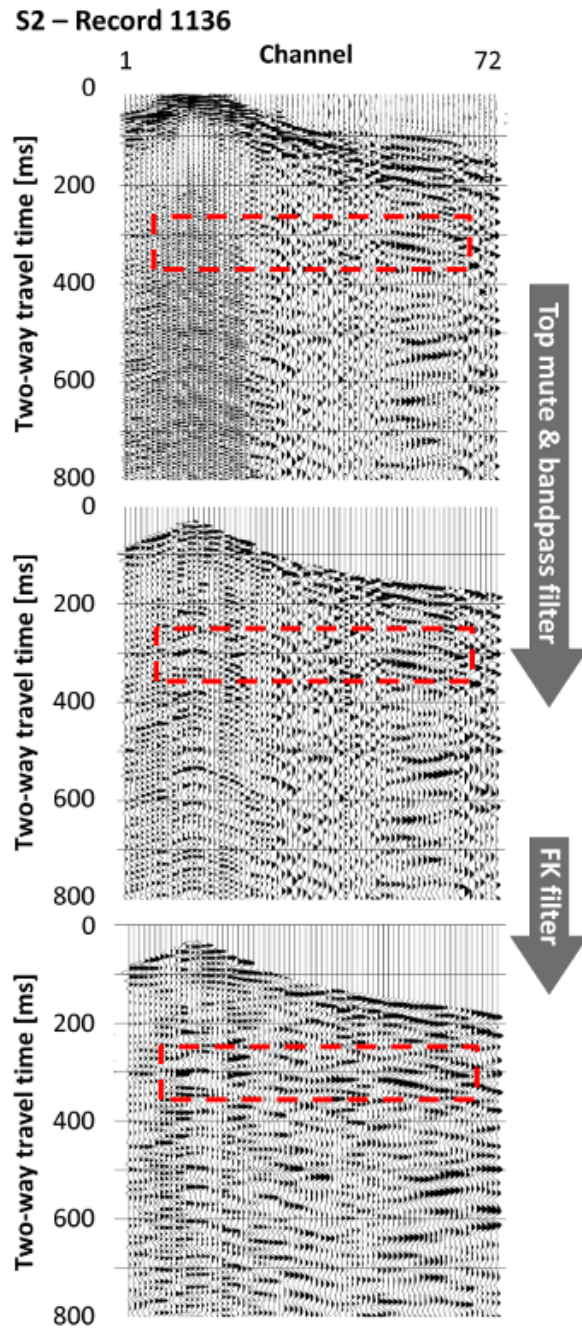


Figure 8. To eliminate noise and harmonic distortions, a bandpass filter and individual FK filters were applied to the records of each profile. The filtering in the frequency-wave number domain was one of the key processing steps to get interpretable seismic sections (note red box, showing the improved S/N -ratio N -ratio of near-surface reflectors).

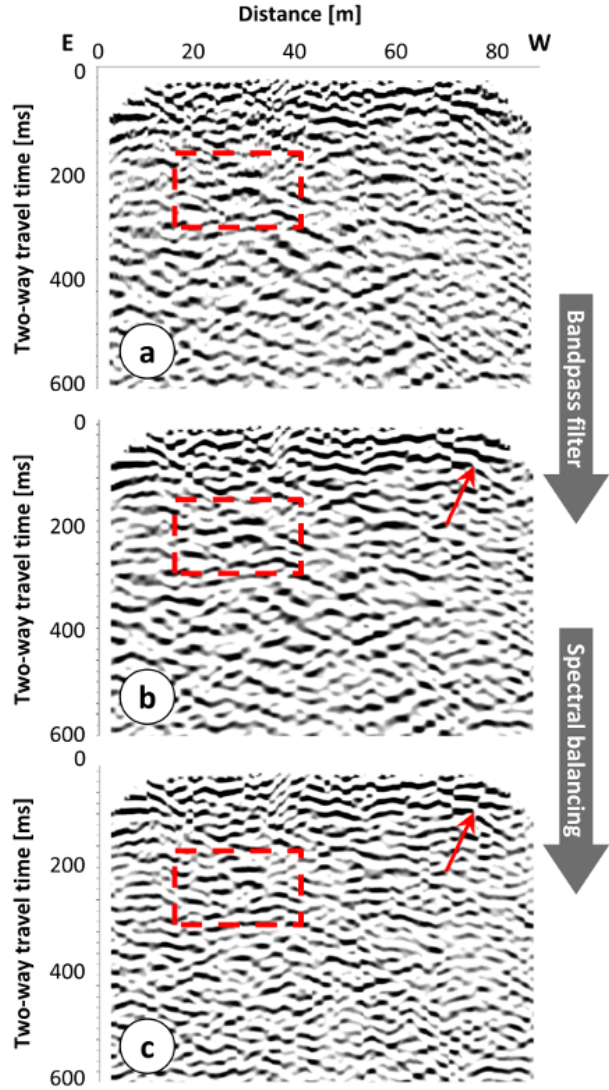


Figure 9. CMP-stacked sections of profile S1 after different processing steps. (a) The first CMP-stacked section shows residual noise. (b) After applying a bandpass filter to the stacked data the reflectors have an improved S/N ratio, especially from 0 to 400 ms TWT. (c) By using spectral balancing the lateral resolution is further improved (note red boxes and arrows showing the improved resolution of near-surface reflectors).

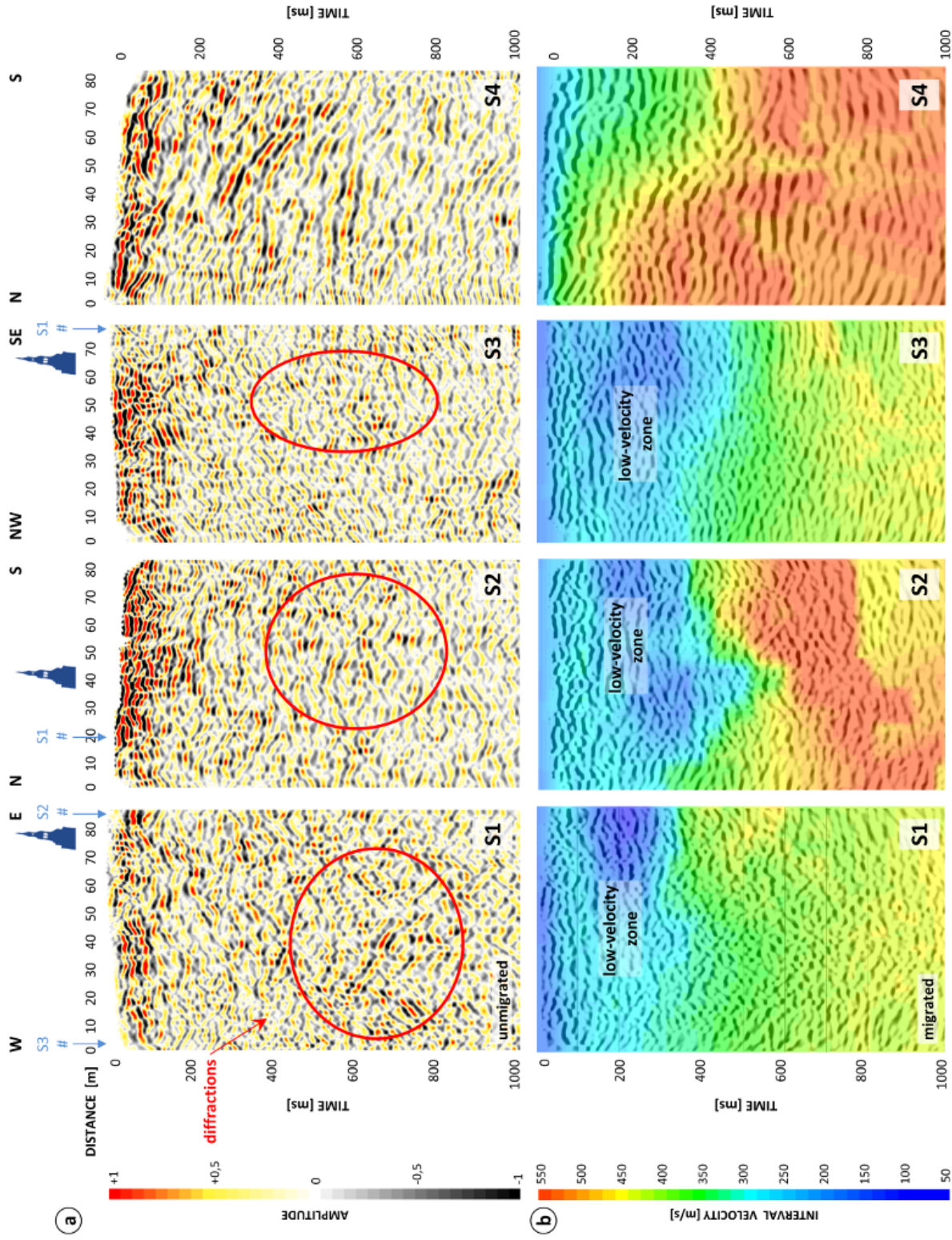


Figure 10. Shear-wave reflection seismic profiles S1–S4 with (a) stack in time domain showing diffractions and color-coded amplitudes and (b) FD migration in time domain with color-coded interval velocities. Position of the church tower is marked and, blue arrows represent intersection points of profiles and red circles reveal areas with diffractions.

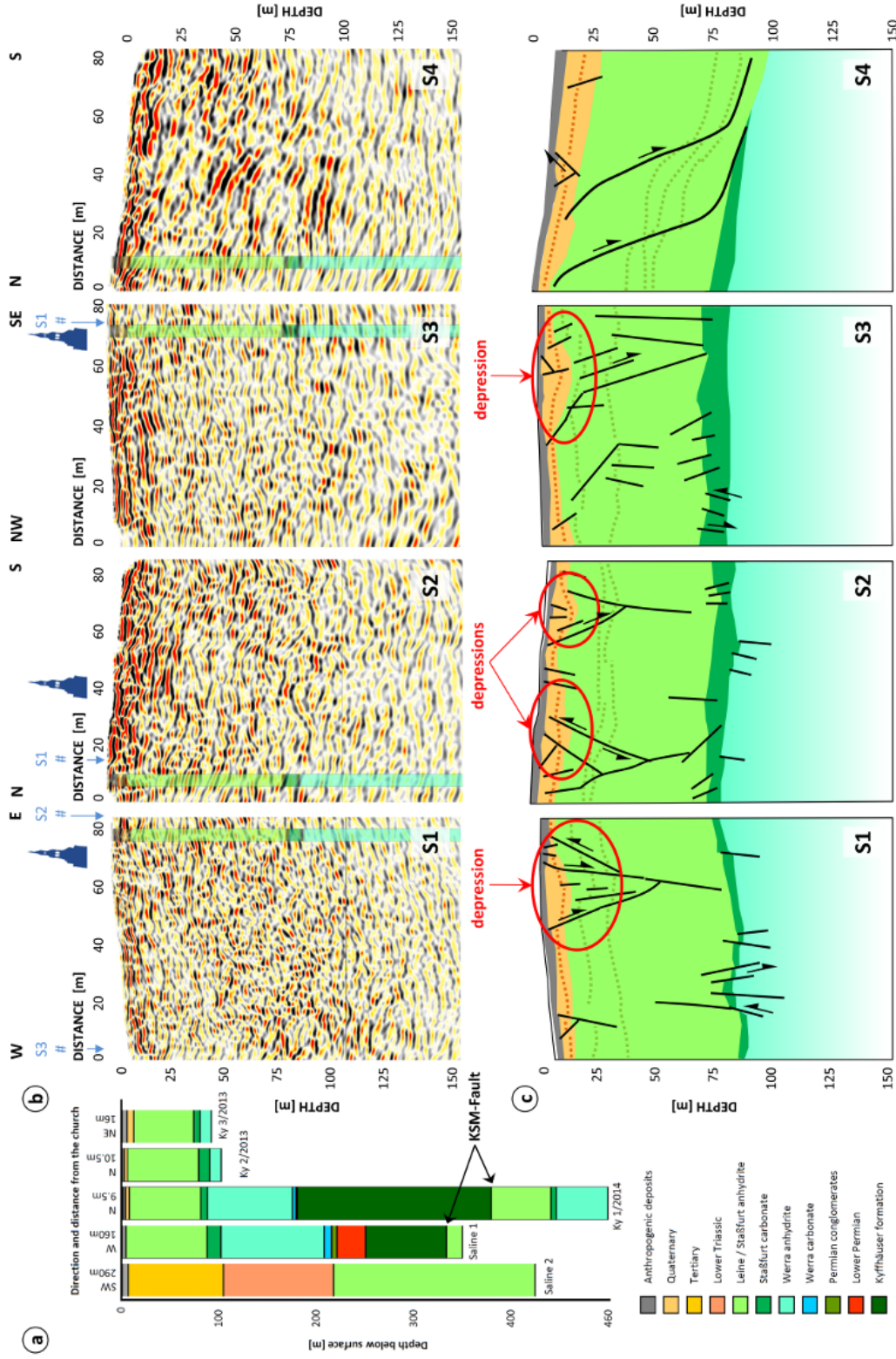


Figure 11. Five boreholes, located in the proximity of the church, give information about the lithologies (a). Since the three boreholes located around the leaning church tower all show almost identical lithologies, only the lithologies of the research borehole Ky 1/2014 were used for correlation of the reflectors in the migrated and depth converted seismic sections S1–S4 (b). The result are four interpreted sections (c). The dashed lines show the internal stratification of the Quaternary and the Staßfurt anhydrite. The church tower is marked and the blue arrows on top mark intersection points of profiles.

Table 1. Device and acquisition parameters of the seismic source, the receivers, and the recording system.

	Device specifications	Acquisition parameters
Source	micro-vibrators ELVIS 6 and 7 (weight 95 kg, peak force 1 kN, frequency range for shear waves 20–250 Hz)	sweep frequency 20–160 Hz, sweep duration 10 s source spacing 2 m, 4 excitations/point
Receiver	horizontal geophones (Sensor, type SM 6, resonance frequency 10 Hz, electric resistance 375 Ohm (coil) & 1000 Ohm (damping))	72 geophones mounted on a landstreamer, spacing 1 m, fixed configuration, mean CMP-fold 18
Recording system	Geode (Geometrics Inc.)	73 channels (72 data channels + 1 pilot sweep channel), record length 12 s (2 s correlated), sampling interval 1 ms

Table 2. Overview of the general processing sequence applied to the ~~shear-wave~~ shear wave reflection seismic data. Most of the processes were carried out iteratively. They are all individualized for differing data quality of the four profiles.

Processing step	Parameter
Geometry check	Manual correction of geodetic data to eliminate errors caused by DGPS reference points (mean errors are 5 cm for S1, 8 cm for S2, 2 cm for S3 and 5 cm for S4)
Quality control	Examination of seismic data
Vibroseis correlation	Cross-correlation of the sweep (frequency 20–160 Hz, length 10 s) and the recorded signal (length 12 s)
Geometry	Combination of GPS data and seismic data, crooked line binning using 0.5 m bin interval
Amplitude & spectral editing	Automatic Gain Control using a window of 200 ms length, a Bandpass Filter (15/17 Hz–163/165 Hz pass the filter) & an Amplitude normalization
Vertical stack	4-fold
Top mute	Individual zeroing of amplitudes at the top of the records
FK filter	Filtering out surface waves and other coherent noise using individual polygon filters in the frequency-wavenumber domain (e.g., FK filter of S1 on the right)
CMP sort	Sort from shot gathers to CMP gathers
Interactive velocity analysis	Analysis interval was 5 m to 10 m using 11 or 12 CMPs per analysis location
NMO correction	Shift hyperbolas to zero-offset traveltimes
Residual statics correction	Correction of near-surface velocity variations
CMP stack	Mean fold is 18 traces per CMP
Filter	Filtering out the remaining noise using an individual Bandpass Filter for each profile (e.g., 17/19 Hz–73/75 Hz)
Spectrum balancing	Individual correction of frequency attenuation to improve the resolution (e.g., bandwidth 15 Hz, slope 5 Hz, start 20 Hz, end 70 Hz)
FD migration	Movement of dipping reflectors, collapse of diffractions and increase in spatial resolution (filtered 45–65 degree)
Depth conversion	Conversion from time to depth

