

Tracing past extreme floods on an alluvial fan using geophysical surveying

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Summary

Sedimentary units in alluvial fans may record gradual transport and deposition during multiple floods or sediment-laden flows or, conversely, during few catastrophic events. While outcrops are a valuable source of direct information to constrain past geomorphic and hydrologic processes, such exposures are scarce, especially along aggrading rivers or those that have been subject to recent catastrophic sedimentation. In this context, near-surface geophysical techniques can constrain the dimensions, internal architecture, composition, and petrophysical properties of different sedimentary units. We consider the Grimmbach alluvial fan in the cuesta landscape of southwestern Germany, which was heavily impacted by sediment and wood loads during a flash flood in 2016; published radiocarbon dates indicate that at least three floods similar to the one in 2016 may have occurred since the 17th century. To test whether and to which detail near-surface geophysics might reveal the sedimentary legacy of these floods, we survey the Grimmbach alluvial fan using detailed topographic data and geophysical imaging based on electromagnetic induction, electrical resistivity tomography (ERT), and ground-penetrating radar. Our geophysical results indicate former channel courses and two coarse bar deposits up to 3 m below the surface, which are comparable with the more extensive bar deposits of the 2016 flood. From the ERT models, we interpret coarse, up to 5 m thick, gravel lag overlying bedrock at a maximum depth of 10 m. Our geophysical results also highlight patches of finer materials derived from gradual sedimentation and soil development. Overall, our results show that the Grimmbach alluvial fan may have formed and reshaped during catastrophic flows, which likely caused channel avulsions. Our findings point to the need to reconsider flash flood and debris-flow hazards in similar headwaters and fans of this seemingly quiescent cuesta landscape in southern Germany.

KEYWORDS

alluvial fan, cuesta landscape, flash flood, near-surface geophysics, sedimentary architecture, avulsion

1 | INTRODUCTION

Alluvial fans are key sedimentary environments for understanding and constraining past geomorphic and hydrologic processes in the catchment upstream. The sedimentary architecture of alluvial fan systems results from different cycles of erosion and sedimentation (e.g., de

Haas et al., 2019; Harvey, 2012; Mather et al., 2017). Although the sediments stored in an alluvial fan are a fraction of those transported from its feeder catchment, they can document the legacy of floods, sediment-laden flows, and debris flows (Bruni et al., 2021; Davies & Korup, 2007; Korup, 2004). Careful investigations and analyses of such sediments may help to understand how and under which

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conditions sediments were transported, deposited, and preserved (e.g., Bardou & Jaboyedoff, 2008; Crosta & Frattini, 2004). Inferring the frequency of such events may help to inform and improve hazard models of extreme sediment transport (Crosta & Frattini, 2004; Santangelo et al., 2012; Schürch et al. 2016).

Studying recently aggrading alluvial fan systems can be challenging because of few (if any) natural exposures. Even if outcrops are available, interpretations might be compromised by unrevealing orientations that provide limited stratigraphic information of lateral variations (Hickin et al. 2009). Boreholes obtain detailed vertical information but only provide local information (e.g., Bazin & Pfaffhuber, 2013; Nickschick et al., 2019). Near-surface geophysical techniques are a noninvasive alternative that can constrain the dimensions, internal architecture, composition, and petrophysical properties of different sedimentary units of alluvial fans. For example, Hornung et al. (2010) and Franke et al. (2015) used ground-penetrating radar (GPR) data to reveal the sedimentary architecture of two alluvial fans in the Swiss Alps up to depths of 10 m. Dietrich and Krautblatter (2017) showed that electrical resistivity tomography (ERT) can help to identify contacts between debris-flow deposits and morainic till of an alluvial fan in the Austrian Alps. Savi et al. (2014) and Brardinoni et al. (2018) used seismic methods together with borehole data and radiocarbon dating to unravel the postglacial sedimentary development of two alluvial fans in the Italian Alps for more than 100 m below the surface. Schoch-Baumann et al. (2021) combined GPR with 40-MHz and 200-MHz antennas and ERT to characterise massive postglacial debris-flow deposits (up to 40 m deep) that generated large fans in the upper Rhone valley, Swiss Alps.

Most geophysical studies of alluvial fans have thus focused on mountainous terrain, where erosion and sediment deposition rates are high. Little is known, however, about the sedimentary architecture of alluvial fans in more moderate terrain with commensurately lower rates of geomorphic process activity. In this study, we focus on the Grimbach alluvial fan in the cuesta landscape of southwestern Germany. This fan was heavily impacted by sediment and wood load during a flash flood in 2016 (see Figure 1a–f). The hazard of extreme geomorphic and hydrologic processes (e.g., flash floods and debris flows) may have been underestimated in this southwestern German region, as demonstrated by the widespread damage to settlements of villages and towns in the alluvial fan and flood plain areas after the 2016 flood. Our goal is to characterise the general sedimentary architecture of the Grimbach alluvial fan by using several geophysical imaging techniques, including electromagnetic induction (EMI), ERT, and GPR. Using this information, we hypothesise about the general evolution of the Grimbach fan in terms of whether its formative events have been gradual or catastrophic in nature.

2 | STUDY AREA

Our study focuses on the catchment outlet of the Grimbach, with features a ~ 0.1 km² large alluvial fan at the confluence with the Kocher river near the village of Braunsbach, northeastern Baden-Württemberg, Germany (Figure 1a). The annual average temperature in this region is 8.6 °C, and the mean annual precipitation is 860 mm, representing a temperate oceanic climate (Bronstert et al.

2018). The Grimbach catchment is part of a regional cuesta landscape, where numerous creeks dissect the Kocher-Jagst plateau forming short, steep, and gully-like valleys with rectangular drainage patterns (Figure 1a). The headwaters of the Grimbach are located on a plateau between 420 and 460 m above sea level (a.s.l.). The plateau surface is gently inclined (slopes up to ~ 0.05) and mainly used for agriculture, small settlements, and rural roads except for highway A6, which crosses the plateau along the southern catchment boundary. The headwater streams are narrow, steep (local slopes of up to 1.1), and mostly covered by forest. The Grimbach drains an area of about 30 km² with an average slope of ~ 0.11 . The stream flows across the plateau for ~ 4 km before cutting into bedrock at the plateau margin, running another 6.6 km before joining the Kocher river at ~ 245 m a.s.l. The average slope of the stream along 4 km upstream of this confluence is 0.024, characterised by a single-thread to braided river pattern (Schönleber et al., 2022).

The geological map (scale of 1:300 000) by the Landesamt für Geologie, Rohstoffe und Bergbau, Baden-Württemberg (LGRB, [maps.lgrb-bw.de/](https://lgrb-bw.de/)) depicts the underlying geology as mainly horizontal Triassic calcareous rocks (Figure 1b). The plateau is mostly formed by the Lower Keuper formation (Upper Triassic), featuring claystone, marlstone, sandstone, and dolomite beds. When weathered, these rocks produce loamy-clayey Cambisols and Luvisols, while some soils on the plateau derive from Quaternary loess. These plateau soils have low permeability and saturate quickly following rain (Schönleber et al., 2022). According to the LGRB, the plateau soils are prone to moderate to high annual erosion rates ranging from 100 to 600 t/km². Incised creeks expose different sections of the Middle Triassic Muschelkalk formation including the Upper, Middle, and Lower Muschelkalk units, featuring limestone, marlstone, dolomite rocks, claystone, and sandstone. Lenses of gypsum, anhydrite, and salt are common, especially in the Middle Muschelkalk formations. The uppermost reaches of the Grimbach run along the Upper Muschelkalk, whereas the middle reaches are dominated by the Middle Muschelkalk, which can be traced topographically by more gentle slopes. The lower Muschelkalk is present in the lowermost reaches of the Grimbach and exposed in a cliff on the left (west) flank of the Kocher opposite the Grimbach outlet. The main soil types are Calcaric Leptosols and Calcaric Regosols, which are less than 0.5 m thick.

The active channel of the Grimbach runs along the true right (north) of its fan and is incised into the floodplain by up to 2 m. In Figure 2a,b, Schönleber et al. (2022) describe two stratigraphic sections (G1 and G2) in the fanhead area. For sections G1 and G2, these authors identify 10 (G1-1 to G1-10) and eight (G2-11 to G2-18) different units of alternating unconsolidated fine and coarse beds, respectively. Note that section G1 shows coarser beds compared with section G2. This highlights the lateral stratigraphic variability of the fan head area, where deposits towards the edges of the valley floor are highly influenced by fine-grained hillslope deposits. Schönleber et al. (2022) also report radiocarbon dates of 330 ± 30 and 350 ± 30 years for the silty/clayey units G1-9 and G2-15, respectively. Considering that unit G1-1 corresponds to gravelly materials from the most recent flash flood in 2016, the authors conclude that at least another three flash floods may have occurred in the Grimbach catchment since the 17th century, likely with similar magnitudes to the flood in 2016.

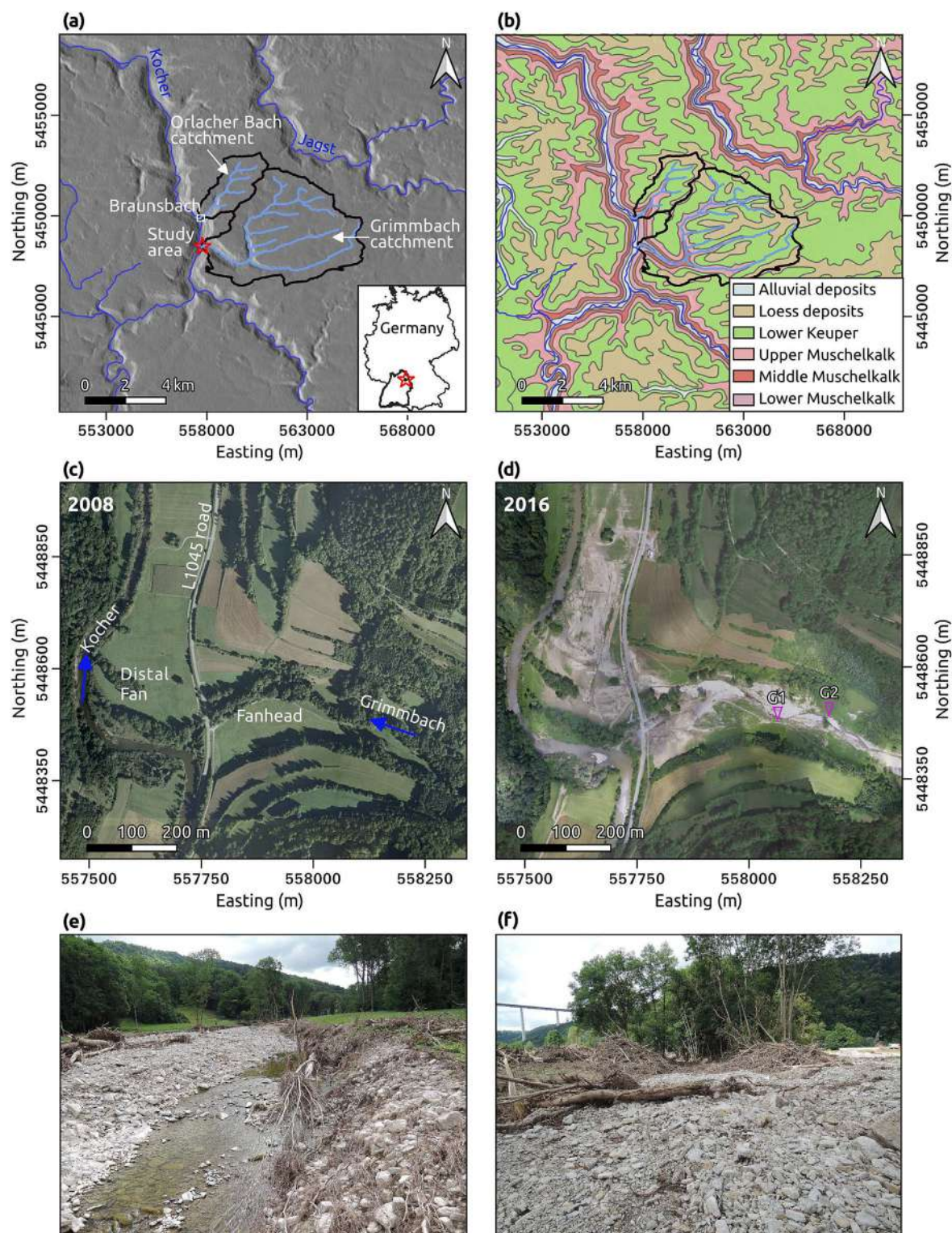


FIGURE 1 General setting of our study area and context of the 2016 flash flood. (a) Hillshaded digital elevation model of the cuesta landscape in northeastern Baden-Württemberg, Germany, derived from the Shuttle Radar Topography Mission data (lpdaac.usgs.gov/products/srtmgl1v003/). (b) Geological map in scale 1:300 000 adapted from the Landesamt für Geologie, Rohstoffe und Bergbau, Baden-Württemberg. (c) Google Earth image of the Grimm bach alluvial fan taken in December 2008. (d) Orthophoto taken one month after the May 2016 sediment-laden flood with the location of cut-bank profiles G1 and G2, from Schönleber *et al.* (2022). Photos of coarse debris deposits (e) upstream and (f) downstream moved during the 2016 flash flood. Coordinates in (a)–(d) refer to UTM zone 32 N (EPSG:25832). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

On 29 May 2016, heavy rainstorms delivered about 150-mm precipitation in a single day, and with a peak of 130 mm in only 2 h (Bronstert *et al.*, 2018), to many headwaters of the Kocher and Jagst valleys in the region (Figure 1). The rainstorm triggered flash floods and sediment-laden flows fed by large amounts of soil from the

plateau and coarse debris from the steeper creeks and hillslopes (Lucía *et al.*, 2018; Ozturk *et al.*, 2018). Judging from the extreme rainfall intensities, discharge, and sediment loads, the May 2016 flash flood has been considered a rare event for this region of moderate relief (Bronstert *et al.*, 2018). One lesson from the 2016 flash flood is

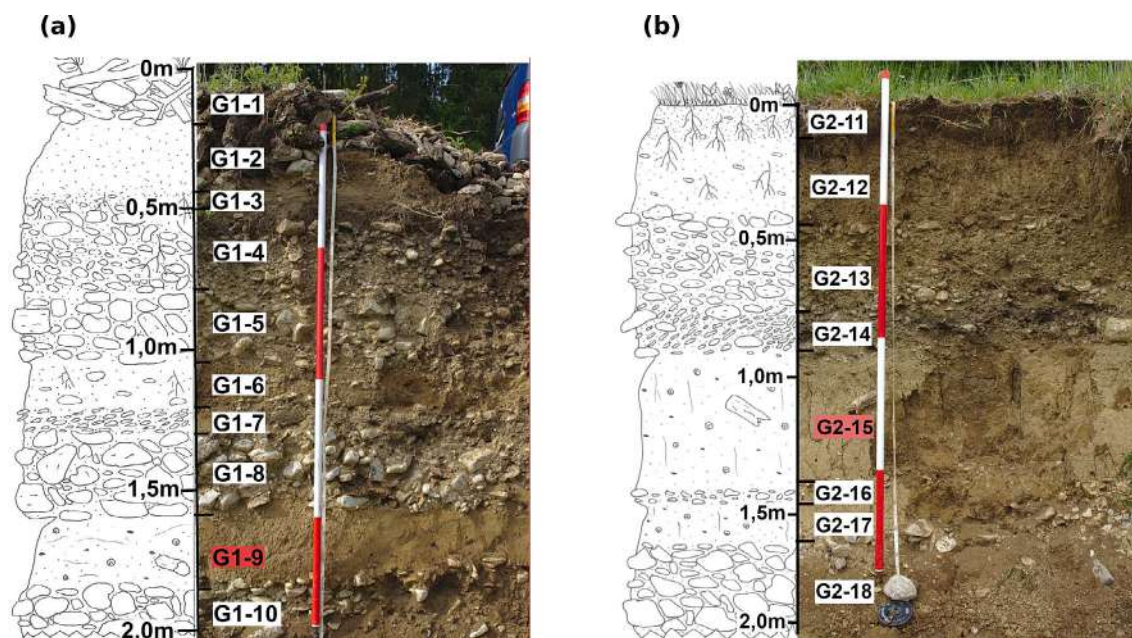


FIGURE 2 Stratigraphic sections of the Grimbach alluvial fan from Schönleber *et al.* (2022). (a) Profile G1 and (b) G2 with the locations indicated in Figure 1d. The units G1-9 and G2-15 (highlighted in red) were sampled for radiocarbon dating. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

the importance of low-permeable soils of the plateau tops that are mainly used for agriculture, promoting fast run-off and high amounts of soil erosion during major rainstorms (Bronstert *et al.* 2018).

Among the most affected areas were different catchments of the Braunsbach municipality, especially the Orlacher Bach catchment, which drains an area of $\sim 6 \text{ km}^2$ with an average slope of 0.12, just north of our study area. This creek flows through the village centre of Braunsbach, and had a specific peak discharge of $12\text{--}30 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ estimated from a rainfall-run-off model (Bronstert *et al.*, 2018); the lower limit of this estimate already exceeds the 100-year return period flood discharge. Ozturk *et al.* (2018) inferred the volume of sediments moved at $\sim 7000 \text{ m}^3 \text{ km}^{-2}$ with yields that rival those of flash flood prone catchments in semiarid to Mediterranean climates. The Grimbach catchment was also severely affected. Lucía *et al.* (2018) estimated a specific peak discharge for the Grimbach creek of $23\text{--}25 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ using the Manning–Strickler formula. They also reported large wood recruitment of $\sim 167 \text{ m}^3 \text{ km}^{-2}$, similar to that in Orlacher Bach ($\sim 172 \text{ m}^3 \text{ km}^{-2}$). These rates are characteristic of much steeper catchments draining mountainous terrain (Lucía *et al.* 2018). Based on aerial photographs before and after the 2016 event, Lucía *et al.* (2018) also reported that the Grimbach widened sevenfold on average, while the Orlacher Bach widened three-fold on average.

The 2016 flood highlighted how the Grimbach alluvial fan had changed during a single flash flood, when most of the sediments that reached the alluvial fan were deposited in the widened channel and also on the $\sim 2 \text{ m}$ high floodplain. Aerial photos taken after the 2016 flood show that coarser sediments remained on the fanhead, while finer sediments spread out over the distal fan after overcoming the state road L1045 (Figure 1d). A few days after the flash flood, the channel in the fanhead area was artificially trenched to avoid the avulsion of the Grimbach. Ozturk *et al.* (2018) suggested that the Orlacher Bach is prone to major sediment pulses even during rainstorms of lower intensities than the one observed in 2016. The situation may differ for the Grimbach, given its wider floodplain, larger

channel, and lower slope. These characteristics only favour sediment transport over short distances. Only major flash floods such as the one in 2016, which transported blocks of up to 0.5 m, may be capable of leaving distinct sedimentary evidence in the alluvial fan beds (Lucía *et al.* 2018).

3 | METHODS

To gain insights into the sedimentary architecture of the Grimbach alluvial fan, we surveyed the fanhead using detailed topography data and different geophysical imaging techniques (Figure 3a–c). We chose the fanhead area to focus more on past geomorphic processes associated with the Grimbach rather than those resulting from the interactions of the Grimbach with the Kocher (Figure 1c). This area was advantageous for our geophysical surveys because it is mainly used for grazing and remains free of infrastructure, except for a minor unpaved road parallel to the Grimbach stream. This road was our main impediment to extending most of our survey area to the north because it was often used by local farmers and hikers (Figure 3c). Another natural boundary to our survey area is the forested hillslope toe to the south of the fanhead.

We acquired our geophysical data in two field campaigns in November 2019 and September 2020. In the first campaign, we collected ERT and ground penetrating radar (GPR) data, while in the second, we collected EMI and additional ERT data (Figure 3a). We also obtained topography elevation as a by-product of our EMI surveying strategy (Figure 3b).

Fan sediments commonly feature high electrical conductivity contrasts (e.g., Gonzales Amaya *et al.*, 2019; Schoch-Baumann *et al.*, 2021), which are ideal for electromagnetic and ERT techniques. Low conductivity values (resulting from EMI and ERT measurements) and high GPR amplitudes are often related to coarse materials, while high conductivity values and low GPR amplitudes indicate sandy to loamy

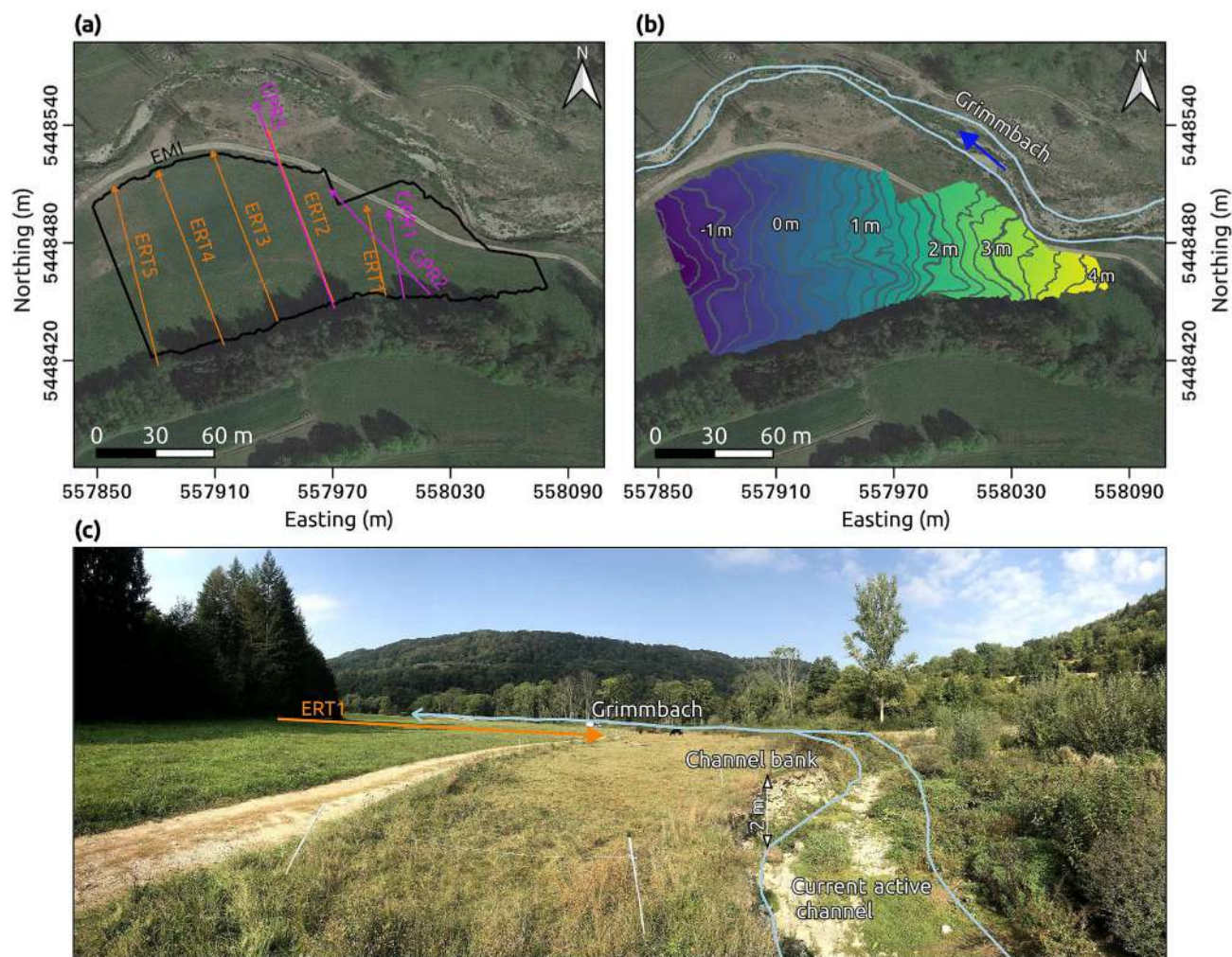


FIGURE 3 Details of our study area on the Grimm bach alluvial fan. (a) Location of geophysical soundings. The tail and head of the thin arrows indicate the origin and end of each profile, respectively. The black polygon is the convex hull of the EMI survey area. (b) Elevation map (altitude above a reference point) obtained alongside EMI measurements. (c) Photo of the study area with a view from upstream to downstream. Panels (a) and (b) use a background Google Earth image (2020) in UTM zone 32 N (EPSG:25832) coordinates. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

materials. In this study, we use the term “electrical conductivity” instead of its reciprocal, “electrical resistivity,” to avoid switching units when referring to EMI and ERT data and models. We refrain from considering other kinds of conductivities (e.g., hydraulic or thermal); therefore, in this study, conductivity refers to electrical conductivity. In the following, we briefly outline each geophysical technique, along with the processing and inversion procedures applied to the field data.

3.1 | EMI

An EMI device (loop-loop system) consists of one transmitter loop emitting a time-harmonic electromagnetic field that induces eddy currents below the ground surface. These eddy currents generate a secondary magnetic field, which is sensed by a receiver loop. The recorded secondary magnetic field is proportional to the subsurface electrical conductivity (McNeill, 1980). Using coils with different orientations (e.g., vertical and horizontal) and spacing allows the estimation of the subsurface electrical conductivity at different depths and within different subsurface volumes. By moving an array of coils with different orientations and spacings along multiple profile lines, we can

recover (after inversion) a 3D subsurface distribution of electrical conductivity (e.g., Guillemoteau & Tronicke, 2016; Guillemoteau et al., 2017; von Hebel et al., 2014).

We collected our EMI data in September 2020 using a DUALEM-21S system mounted on a cart at a fixed height of 0.25 m above the ground surface. This system consists of a horizontal transmitter coil (operating at 9 kHz), and two horizontal (HCP) and two vertical (PERP) receiver coils. The HCP coils are located at 1 and 2 m offset from the transmitter coil, while the PERP coils are at distances of 1.1 and 2.1 m. Following Böniger and Tronicke (2010), we recorded the relative positions (x -, y -, and z -coordinates) of our DUALEM-21S device during surveying using a self-tracking total station to localise our EMI readings and to generate a digital elevation model of the survey area (Figure 3b). We collected data points along profile lines approximately perpendicular to the axis of the Grimm bach valley to target linear or elongated deposits such as channel fills, bars, and levees that we assume to be oriented mainly in the along-valley direction. In total, we collected 387 lines with a spacing of ~ 0.5 m and an in-line average point spacing of ~ 0.07 m covering an area of $\sim 13\,800\text{ m}^2$, which resulted in 397 544 four-configuration soundings (after removing low-quality data points).

We inverted the EMI data set using the full non-linear 1D laterally constrained inversion based on the minimum gradient support regularisation, as proposed by Klose et al. (2022). For the inversion, we resampled our data to obtain an in-line and cross-line sounding spacing of ~ 0.5 m in the resulting pseudo-3D model. In the inversion procedure, the focusing parameter was set to 1, and the number of layers to 15 with increasing thickness towards deeper layers (for further details regarding these inversion parameters, see Klose et al. (2022)). The deepest layer is an infinite homogeneous half-space whose top boundary was set at a depth of 4 m.

3.2 | ERT

For recording ERT data, an electric current is injected into the ground using two electrodes (current electrodes), and the resulting voltage is measured using another pair of electrodes (voltage electrodes). Systematically moving such a four-electrode array configuration along a profile and increasing the electrode spacing allows for recording a 2D pseudo-section of apparent electrical conductivity, which needs to be inverted to obtain a 2D subsurface model of electrical conductivity.

We collected five semi-parallel profiles about 30 m apart from each other during two different field campaigns (Figure 3a). Two ERT profiles (ERT2 and ERT5) were collected in November 2019 under moist conditions with some light rain and wet soils, while the other three (ERT1, ERT3, and ERT4) were collected in September 2020 (like the EMI data) under dry conditions without rain before or during surveying. We used a Syscal Pro system and a Wenner-Schlumberger array configuration with an in-line electrode spacing of 1 m. Using 48 electrodes for profile ERT1 and 96 electrodes for profiles ERT2 to ERT5, we recorded 564, 2209, 2376, 2376, and 2209 apparent conductivity measurements for profiles ERT1 to ERT5, respectively.

We inverted our ERT data using the open-source finite-element library pyGIMLi (Rücker et al., 2017). To favour geologically plausible models consistent with our geological understanding of the Grimmach fan, we considered different geostatistical regularisation constraints as proposed by Jordi et al. (2018). For this inversion strategy, we need to set four parameters: the regularisation or trade-off parameter λ (which controls the relative weight of data and model misfits), the correlation lengths (i.e., distances at which model parameters are considered to be correlated) along the horizontal (C_x) and vertical (C_z) axes, and a rotation angle to describe inclined structures. In Appendix A, we show how we selected these parameters to invert our ERT data. For a more detailed description of the influence of these parameters and a comparison with other smoothness-constrained inversion approaches, the reader is referred to Caterina et al. (2014), Hermans and Irving (2017), and Jordi et al. (2018).

3.3 | GPR

A GPR system emits a high-frequency electromagnetic wavelet (for geological applications, commonly in the order of 40 to 500 MHz) from a transmitter antenna into the subsurface. The wavefield is reflected at interfaces where the dielectric properties change and is recorded by a receiver antenna. By moving the pair of antennas

along a profile, we obtain, after some data processing, a 2D image of subsurface structures such as layer interfaces in sedimentary environments.

In November 2019, we collected our GPR data using a PulseEKKO Pro GPR system equipped with a pair of 100-MHz antennas mounted on a sledge with a fixed offset of 1 m. Similar to our EMI survey, the positions of the recorded traces were measured using a self-tracking total station (Böniger & Troncke, 2010). We also collected common-midpoint (CMP) data to derive a subsurface propagation velocity of 0.077 m/ns using spectral velocity analysis. This velocity estimate was used for migrating our common-offset data and for performing a time-to-depth conversion. We also applied other standard data processing steps such as band-pass filtering, amplitude scaling, and removing the direct arrivals of the air and ground waves by applying a local background removal.

4 | RESULTS

In the following, we present in separate subsections the results after processing/inverting our acquired geophysical data (EMI, ERT, and GPR data). We focus more on the general description of the subsurface geophysical models and images, whereas the geological interpretation is part of the subsequent section.

4.1 | EMI results

Our EMI inversion results reveal major sedimentary variation in the fanhead (Figure 4a–e). To visualise this in our 3D model, we extracted two depth slices at 1 and 2 m with respect to the ground surface (see Figure 3b), and two profiles (vertical slices EMI1 and EMI2) at the locations of profiles ERT2 and ERT5, respectively (see Figure 3a). Figure 4a highlights three main structures labelled C1, R1, and R2. Structure C1 spans the entire length of the southern survey area and shows high conductivities (>0.02 Sm $^{-1}$). It appears to be several metres wide upstream (eastward) and narrows in the downstream (westward) direction. The low conductive structure R1 is a linear pattern of conductivities < 0.003 Sm $^{-1}$ that separates into two sub-parallel branches downstream. Another low conductivity structure (labelled R2) in the northeastern part of the survey area shows a semi-circular shape and slightly higher conductivities than R1. In the depth slices at 1 m and 2 m (Figure 4b,c), C1 and R1 are still traceable at these depths, while R2 is almost absent at a depth of 2 m. Our 2D profiles EMI1 and EMI2 (Figure 4d,e) show that C1 is well defined down to 1 m depth, though it can reach depths >3 m with slightly lower conductivities (Figure 4d). Profiles EMI1 and EMI2 indicate that R1 is ~ 3 m thick while profile EMI1 shows a maximum depth of ~ 2 m for R2. The effective investigation depths for our EMI models is ~ 3 m; hence, the maximum depth of R1 needs to be evaluated using our deeper penetrating ERT data.

4.2 | ERT results

In Figure 5a–e, we illustrate the resulting electrical conductivity models, which were obtained considering a regularisation parameter

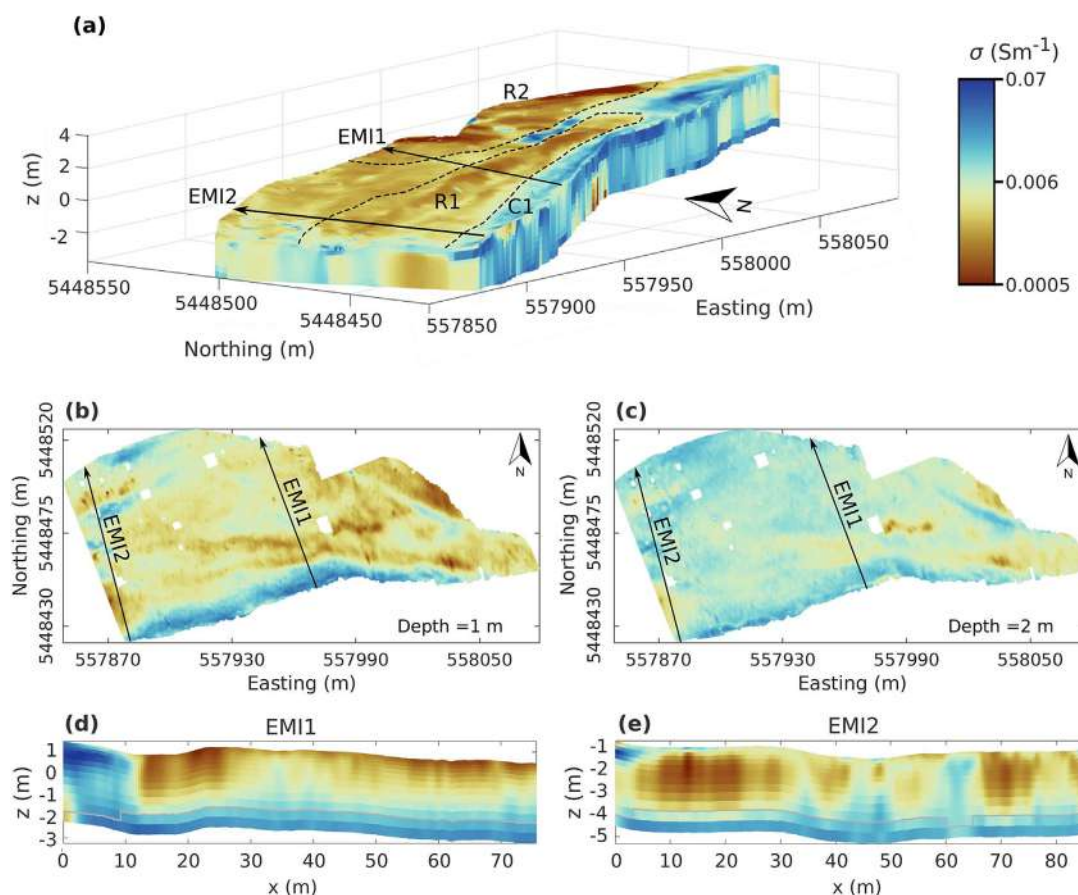


FIGURE 4 Inverted electrical conductivity model of the EMI data. (a) Three-dimensional view of the EMI conductivity model. Depth slices at constant depths of (b) 1 m and (c) 2 m with respect to the ground surface (see Figure 3b). (d) Vertical slices (2D profiles) EMI1 and (e) EMI2 with effective investigation depth are shown as grey lines. All subplots share the same colour map as in (a). In (b) and (c), the tails and heads of the arrows indicate the origin and end of each profile, respectively. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

of $\lambda = 10$, correlation lengths of $C_x = 20$ m and $C_z = 2$ m, and a rotation angle of zero degrees (Appendix A). We use the same inversion parameters for all our ERT profiles because we expect similar subsurface structures in our study area. Because of different weather and soil moisture conditions, the conductivity values of the ERT profiles collected in summer 2020 show overall lower conductivity values than those collected in autumn 2019, especially in the shallowest parts. Thus, we display our results considering different colour scales to highlight conductivity contrasts and structures, respectively. Yet, some of the most prominent structures, although showing different absolute values of conductivity, can be tracked between neighbouring profiles.

All inverted ERT models (Figure 5a–e) are characterised by alternating (sub)horizontal layers of high and low conductivity with some horizontal variations. The models ERT2–ERT5 show high conductivities at depths below 10 m. Overlying this layer, on the right side of all ERT models, there is a ~ 5 -m-thick low-conductivity layer. Above this layer, we see a 2- to 4-m-thick conductive layer, which is in contact at the top with a ~ 3 -m-thick more heterogeneous layer with patches of low and high-conductivity materials. We note that the horizontal structures of profile ERT3 are less continuous than in the other ERT profiles. This might be caused by higher noise levels in the measured apparent resistivities observed for ERT3 compared with the other ERT data sets.

4.3 | GPR results

In Figures 6 and 7a, we present the migrated profiles GPR1, GPR2, and GPR3 using a conventional grey-scale colour map ranging from white (minimum negative amplitudes) to black (maximum positive amplitudes) colours. These GPR lines are characterised by continuous events that vary laterally in amplitude. We also identify locally some concave-up reflectors as highlighted by the white arrows in Figures 6 and 7a, and a concave-down reflector highlighted by the dashed line in Figure 7a. In general, areas with higher amplitudes are partly associated with larger penetration depths (up to 3 m). The overall penetration depth is limited to ~ 2 m.

For a qualitative comparison between the profile GPR3 and the subsurface electrical conductivity models from our EMI and ERT data, we superimpose the EMI1 (Figure 4d) and ERT2 (Figure 5b) models onto the migrated GPR3 data in Figure 7b,c, respectively. A one-to-one comparison of the conductivities from EMI1 and ERT2 is difficult because the data were collected under different soil moisture conditions. However, we still expect some correlation associated with the main structures. For example, we notice in profile GPR3 that the high amplitudes in the concave-down structure ($15 \text{ m} < x < 35 \text{ m}$) and at the end of the profile ($80 \text{ m} < x < 95 \text{ m}$) correspond to low electrical conductivities. In contrast, low amplitudes like the ones observed at the beginning of our profile ($x < 10 \text{ m}$) and at $35 \text{ m} < x < 55 \text{ m}$ are associated with high

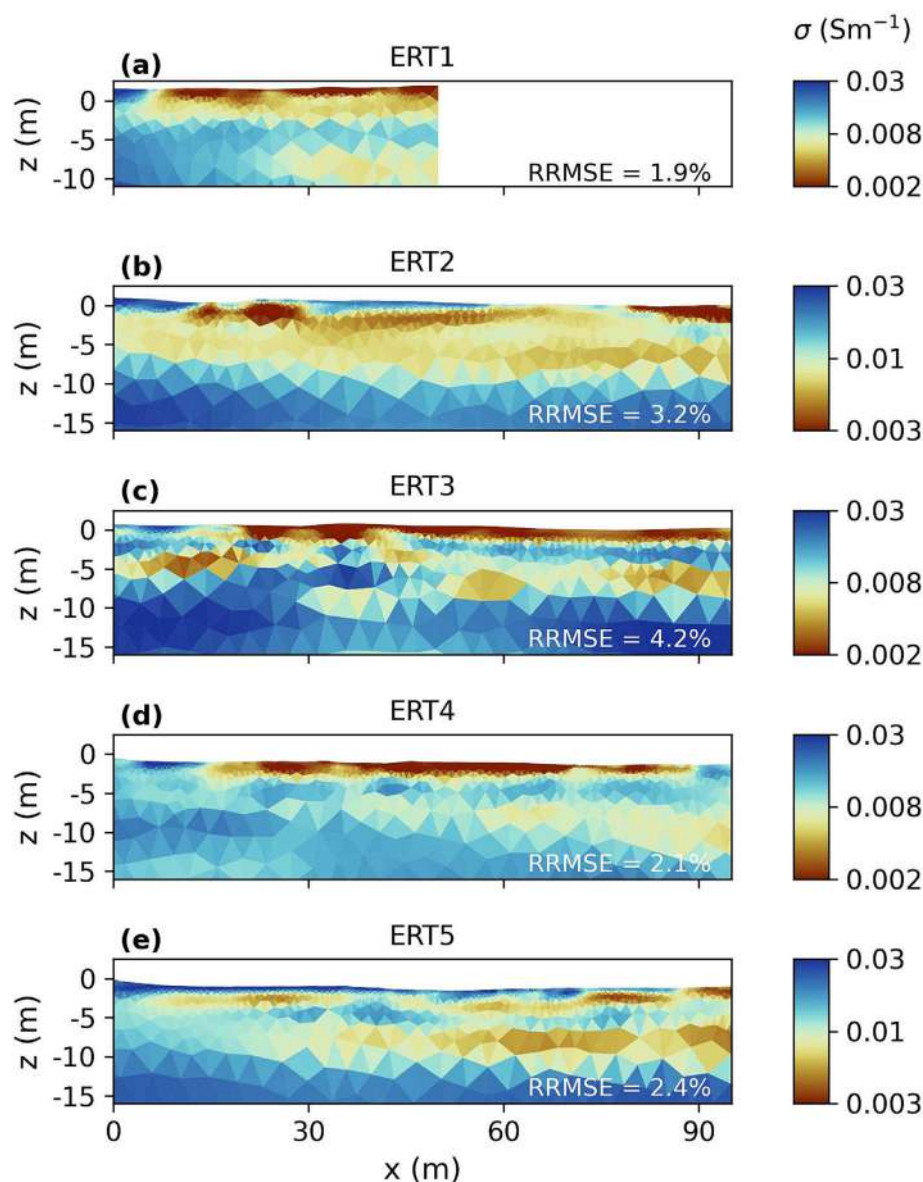


FIGURE 5 Inverted electrical conductivity models of the five profiles ERT1 to ERT5 (for locations see Figure 3a) considering correlation lengths of $C_x = 20$ m and $C_z = 2$ m. Note that the colour bar varies for the data sets collected in late autumn 2019 (ERT2, ERT5) and late summer 2020 (ERT1, ERT3, ERT4). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

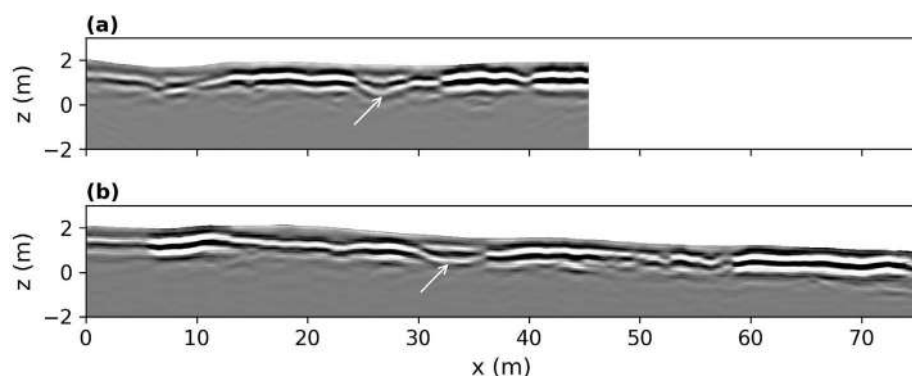


FIGURE 6 GPR cross-sections. (a) Profile GPR1 and (b) profile GPR2 (see locations in Figure 3). The white arrows point to concave-up structures.

conductivities. Note that the last conductive structure is less prominent in model EMI1 compared with model ERT2, because the ERT data were acquired in moister conditions than the EMI data.

5 | DISCUSSION

Our geophysical data provide insights into the geomorphic and sedimentary history of the lower Grimbach. Our EMI results offer a 3D

image of the electrical conductivity distribution in the floodplain on the left (south) flank of the current Grimbach stream. The GPR profiles provide structural information that is not easily visualised by our EMI models. The lateral changes in the amplitude of our GPR images might also be used to interpret grain size variations. Thus, GPR and conductivity data provide complementary pieces of information (e.g., Hickin et al., 2009; Schoch-Baumann et al., 2021). At our field site, both EMI and GPR were sensitive up to investigation depths of ~ 3 m. Therefore, using ERT was indispensable for getting

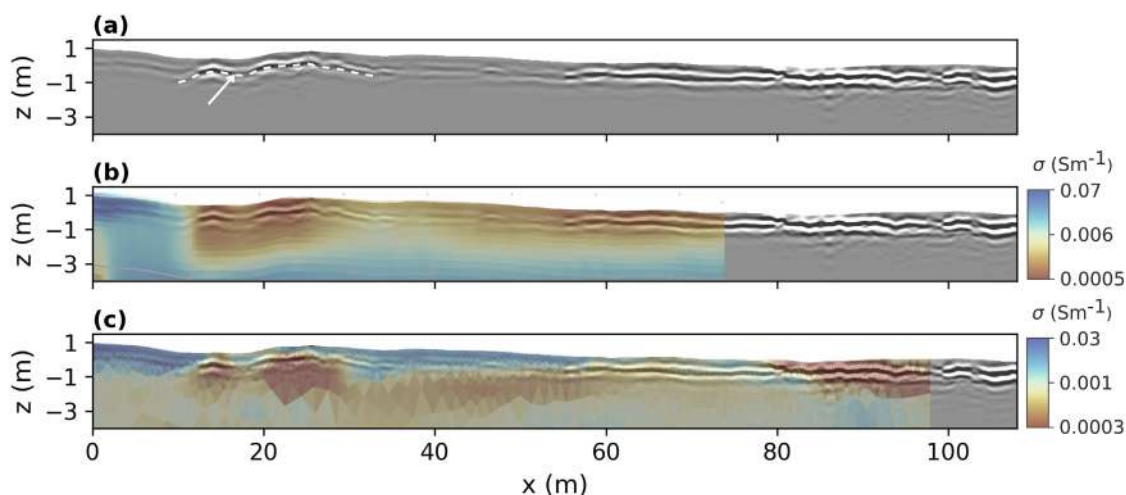


FIGURE 7 Comparison of GPR with electrical conductivity models resulting from EMI and ERT data. (a) GPR3 profile, (b) GPR3 overlying EMI1 (data collected under relatively dry conditions), and (c) ERT2 models (data collected under relatively moist conditions). In panel (a), the white dashed line indicates a general concave-down structure with a small concave-up structure marked by the white arrow. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

penetration depths of up to 16 m, which is useful for learning more about the different sedimentation cycles of the Grimbach.

We highlight that the observation scale of our geophysical results is different from the outcrops. For example, from outcrops (Figure 2a,b), we can identify layers with thicknesses of up to half a metre. However, the subsurface layers that we are able to resolve with GPR, EMI, and ERT correspond to thicknesses of 1–2, 2–3, and 3–5 m, respectively. This is mainly due to the resolution capabilities of these geophysical methods that, instead of imaging individual units, obtain some sort of averaged information across different subsurface units (e.g., Schrott & Sass, 2008). Although it might be challenging to learn of individual episodes from our geophysical results, we can still infer some larger structures (former channels and bar deposits) and distinguish sedimentation cycles characterised by more quiescent periods favouring fanhead trenching as opposed to periods of aggradation with likely more frequent floods.

Reconciling all geophysical and geological information, we identify both (semi)elliptical structures and linear patterns below the fan surface (black and blue dashed lines, respectively, Figure 8a). We interpret the elliptical structures as former bars, while the linear structures likely correspond to former channels.

The southernmost interpreted bar structure (to the far left of the current channel) has an area of $\sim 4000 \text{ m}^2$ (Figure 8a) and is about 3 m thick as interpreted from Figure 4d,e; for example, note at $x = 20 \text{ m}$ (Figure 4d,e) a $\sim 3\text{-m}$ -thick low conductive layer is found above a more conductive layer. Judging by the semi-elliptical shape of this structure, we are likely only seeing a fraction of its total extent, which might extend in the downstream direction. Our profile GPR3 (Figure 7a) crosses this structure upstream and shows a concave-down structure at $10 \text{ m} < x < 35 \text{ m}$, with a minor concave-up structure at $x = 17 \text{ m}$. Although our profiles GPR1 and GPR2 do not cross this inferred bar, they also show concave-up structures (Figure 6) that can be followed downstream in our EMI model as low-conductive bodies (Figure 8a). These linear structures are likely former channels that are associated with the bar; a modern analogy of this sedimentary association is exposed along the active cut banks as in Figure 1e.

The interpreted bar closer to the current channel has an area of $\sim 5000 \text{ m}^2$ (Figure 8a) and is $\sim 2 \text{ m}$ thick (note that in Figure 4c, the low conductive material corresponding to this interpreted bar is almost absent; we therefore conservatively assume that this structure could be up to 2 m thick). This structure is characterised in our EMI model (Figure 8a) by low conductivities upstream that gradually increase downstream, consistent with a downstream fining of sediment. We extended the interpretation of this structure in the direction of the current channel considering the ERT2 and GPR3 profiles (Figure 7c), in which we noticed at $35 \text{ m} < x < 60 \text{ m}$ and $z = -2 \text{ m}$ low conductivities, and at $60 \text{ m} < x < 80 \text{ m}$ and $z = 0 \text{ m}$ intermediate conductivities and a flat-lying, high-amplitude GPR reflector. We interpret the low conductive and high-amplitude GPR reflectors at $80 \text{ m} < x < 100 \text{ m}$ in Figure 7c as amalgamated bar deposits containing in the shallowest part coarse deposits from the 2016 flood (see Figure 8a). Profiles GPR1 and GPR2 also cross this structure upstream with similar responses to GPR3; however, these profiles are too short for delineating the outer boundary of the bar. Therefore, we outline the upstream limit of this bar structure by considering a 2 m height outcrop (Figure 8b) characterised by a sudden transition of layered sediments (leftmost part of Figure 8b) to a poorly stratified layer (rightmost part of Figure 8b) of up to 50-cm large cobbles, which are consistent with a high energy (coarse-grained) bar deposit.

To investigate deeper structures in the Grimbach valley fill including the depth to bedrock, we rely on our ERT conductivity models, which effectively probe depths of up to $\sim 16 \text{ m}$. We interpret bedrock in our ERT models as the lowermost conductive layer at maximum depths of $\sim 10 \text{ m}$. This interpretation agrees with two boreholes in the nearby Orlacher Bach alluvial fan, in which depth to bedrock was found at 12 to 13 m below ground surface (Ozturk et al., 2018). However, to confirm and validate this interpretation, complementary geophysical surveys such as seismic refraction (e.g., Juhojuntti & Kamm, 2015) or borehole-based explorations are needed. Furthermore, using layer-based parameterisation approaches to invert the geophysical data (e.g., Arboleda-Zapata, Angelopoulos et al., 2022; Arboleda-Zapata, Guillemoteau et al., 2022) might be helpful to resolve the bedrock structure. Overlying this inferred

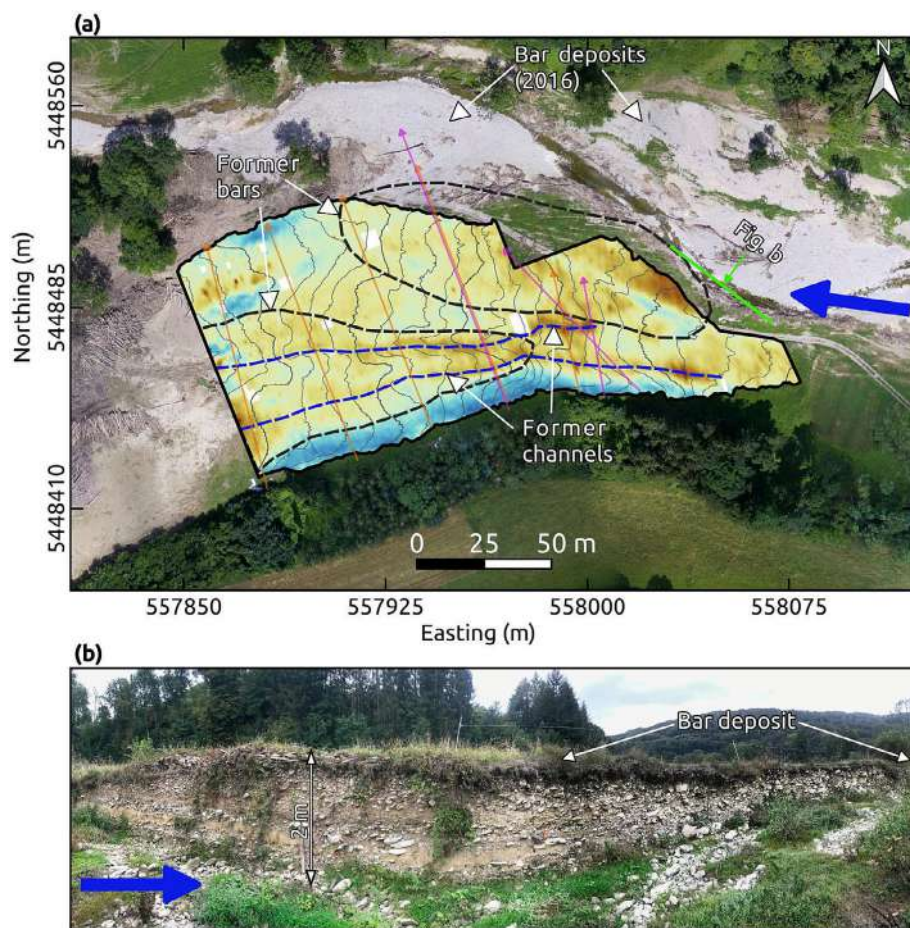


FIGURE 8 Sedimentary evidence of abrupt channel shift (avulsion) and inferred past flash floods deposits. (a) EMI slice at 1 m depth including contours of surface elevation (Figure 3b) and profile locations with the same symbols and colours as in Figure 3a. (b) Panoramic view of an outcrop upstream of our study area; approximate location shown in (a). In panels (a) and (b), the blue arrow indicates flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

bedrock, all ERT profiles show a relatively low conductive layer with a thickness of up to 5 m, which may represent coarse gravel lag deposits. The layer may also indicate massive sedimentation following bedrock incision in the early history recorded by this alluvial fan. This coarse layer is topped by a more conductive layer, indicating finer sediments deposited by either less competent flows or distal portions of high-energy flows linked to sediment depletion upstream. Like in our EMI inversions, the shallowest sediments (<3 m) are characterised by low conductivities associated with channels and bars, and may indicate a new, younger cycle of fine to coarse sedimentation.

Repeated deposition and entrenchment have formed intercalated fine and coarse beds, such as those exposed along the cut channel banks in the Grimm bach fanhead (Figures 3e and 8b). While the gravel beds can be interpreted as evidence of past floods, the fine layers were likely formed during periods of relative geomorphic quiescence, favouring the gradual accumulation of fine particles and soil development. Some loamy to sandy layers could also represent overbank deposits dumped by the Kocher river (e.g., Schönleber et al., 2022). From our geophysical results, we can infer the location of some fine-grain lenses in the floodplain. For example, we interpret the linear, high conductive structure at the extreme left (south) of the active channel (C1 in Figure 4a) as a silty to clayey bed. This bed corresponds well to a colluvial deposit associated with the steep and vegetated slope that abuts the Grimm bach channel to the south (Figure 8a). These colluvial deposits correspond to the slightly inclined low amplitude reflector located in the first section of our GPR profiles (Figures 6 and 7a). In the profile GPR3 (Figure 7a), a similar structure is observed adjacent to the interpreted former channel at

35 m < x < 55 m. Assuming a common origin for these units, we can infer that such colluvial deposits were incised by the inferred former channel in Figure 8a. Future sampling in the floodplain (e.g., using trenches) may focus on patches of intermediate conductivities and low GPR amplitudes because these areas may be characterised by intercalated fine and coarse materials (e.g., overbank deposits like the one between the units G1-1 and G1-2 in Figure 2a) with sharp contacts indicative of different floods.

The 2016 flood formed bar deposits with sizes of up to 5000 m² and thicknesses of up to 1 m. The two inferred bars (Figure 8a) have similar areas though they are likely thicker than the ones observed after the 2016 flood. For the bar deposit adjacent to the current channel, some faint bedding supports the idea of several deposition episodes instead of a single one (see Figure 8b), calling for a more detailed and rigorous sedimentological study of more outcrops as they emerge. However, we lack available outcrops in the southern part of our survey area to check if this gravelly deposit arose from single or multiple floods.

In Figure 9d, we summarise our general understanding of the sedimentary architecture of the Grimm bach fanhead. We consider the section along the profile ERT2 and extend it to both flanks of the current channel. The bedrock is interpreted as a bowl-shaped valley with a maximum depth of 10 m. The bedrock at this location would be the Lower Muschelkalk formation, which crops out on the left (west) bank of the Kocher opposite the Grimm bach junction (Figure 9f). The valley fill has a basal gravel lag, especially in the central part, and is likely mixed with lateral contributions from hillslopes similar to modern deposits some 3–4 km upstream of our survey area (Figure 9g). In

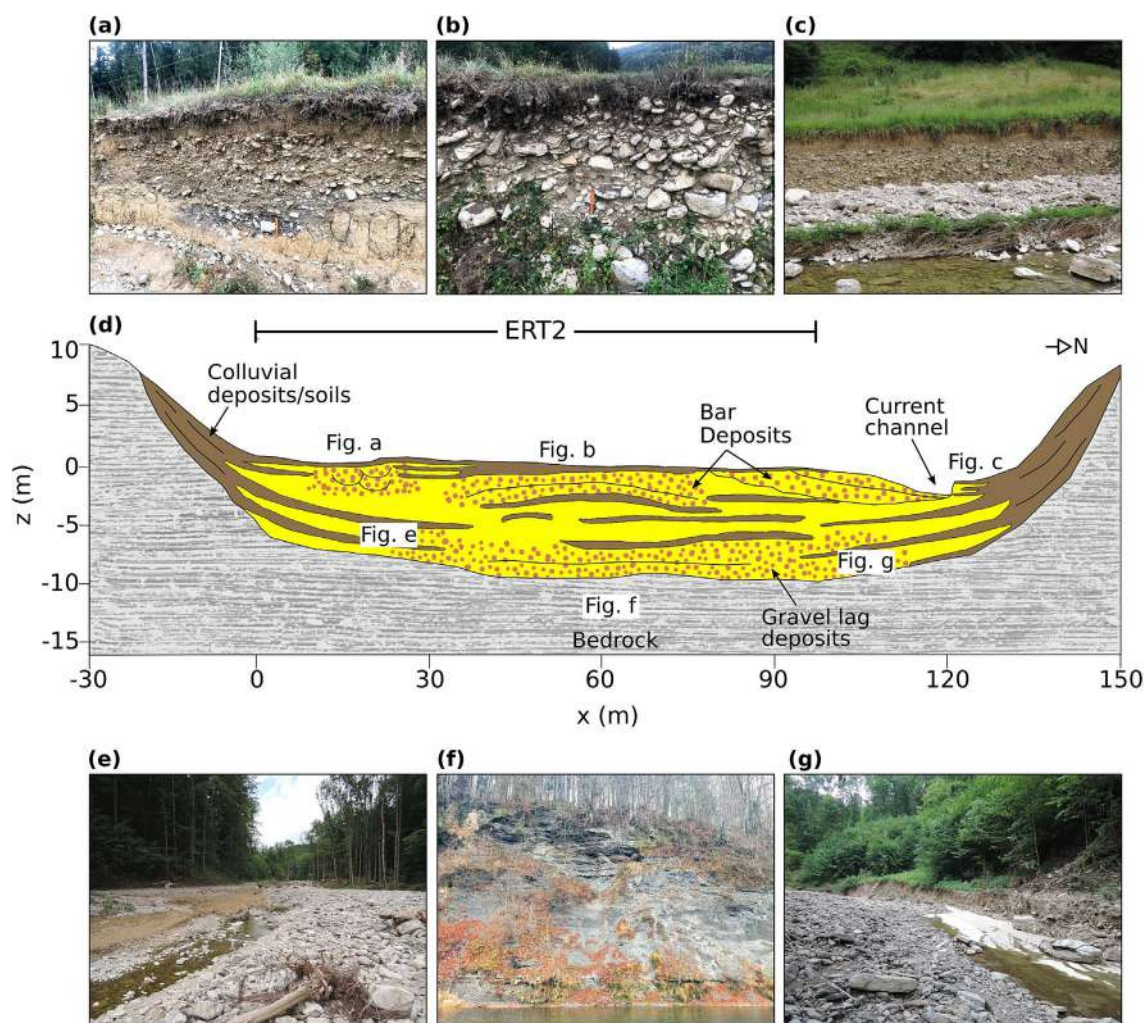


FIGURE 9 Sedimentary architecture of the Grimbach fan. (a) Exposed channel-fill structure ~ 500 m upstream of the Grimbach–Kocher confluence. (b) Detail of the interpreted bar deposit of Figure 8b. (c) Colluvial deposits overlying channel-bed deposits ~ 570 m upstream from the Grimbach–Kocher confluence. (d) Inferred fan stratigraphy considering profiles ERT2, EMI1, GPR3, and available outcrops, where $x = 0$ m corresponds to the origin of the ERT2 profile and $x = 95$ m to its end. Here, layers coloured brown, yellow, and yellow dotted with red correspond to materials varying from fine to coarse grain-sized materials, respectively. (e) Deposits of the last flood overlay a layer composed of fine materials in the middle reach of the Grimbach (1–2 km upstream from our field site). (f) Outcrop of the bedrock on the left (west) bank of the Kocher opposite the Grimbach outlet. (g) Coarse (to the left) and fine (to the right) materials overlying bedrock in the upper reach of the Grimbach (3–4 km upstream from our field site). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5695)]

general, we expect thicker colluvial deposits close to the hillslopes but also soil development in the middle of the valley (Figure 9c,e), as has been suggested in a study in a similar setting by Hirsch et al. (2008). The sediments overlying the gravel lag deposits have larger concentrations of fine materials related to a period that favoured soil accumulation and development. In the shallowest part, in contrast, we identified accumulations of several bar deposits such as the ones interpreted in Figure 8a and visualised in Figure 9b. The bar deposit at the far left (south) flank has been reworked, forming channel-like structures (as observed in Figure 9a) characterised by concave-up GPR reflectors and low conductivities.

To characterise the sedimentary architecture of the Grimbach alluvial fan further, we see different future expansions to our geophysical survey. For example, we could extend our 3D EMI data such that we cover a larger portion of the fanhead area, collecting data from the very few outcrops flanking the Grimbach. We could complement such a data set by also collecting 3D GPR data covering the

same area as the EMI data. Using both data sets might help to trace further the shallow former channel structures interpreted in our EMI models and GPR cross-sections. Collecting intermediate ERT profiles might also be interesting for a 3D interpretation of the deeper structures. To constrain the depth to bedrock and identify the hillslope deposits from both flanks of the Grimbach, we could consider an electrode spacing of 2 m. An ERT profile in the downstream direction could help identify the limit of lobe deposits but would also be more affected by 3D artefacts.

To learn more about the history of this alluvial fan, direct exploration via boreholes (e.g., Hirsch et al., 2008; Martin et al., 2020) that allow for centimetre-scale resolution of the stratigraphy and dating at different depth levels (e.g., Brardinoni et al., 2018; Savi et al., 2014) may be necessary, especially for distinguishing multiple lobes of single or multiple floods. In this context, the fanhead area may be more informative than the distal alluvial fan, which is likely more influenced by the trunk channel of the Kocher. However, it is important to note

that the displacement of the Kocher channel by the Grimbach fan indicates that this creek contributes substantial sediment loads and that the trunk channel is unable to evacuate swiftly.

In terms of hazard assessment, alluvial fan information may be complemented with other catchment processes like the supply of sediments and wood and their renewal development, as well as possible triggers such as rainfall thresholds (Bardou & Jaboyedoff, 2008; Savi et al., 2014; Schürch et al., 2016). Although we focused on the Grimbach alluvial fan in this study, other alluvial fans impacted by the 2016 event may also record information about past flash floods, thus filling in substantial knowledge gaps about the recurrence of such destructive events in this southern German region. The 2016 flash floods in southern Germany have demonstrated that this cuesta landscape with gentle relief is prone to rare but catastrophic episodes of erosion and sedimentation that rival those in mountain regions.

6 | CONCLUSIONS

In this study, we demonstrated how combining different types of non-invasive geophysical imaging techniques can be used to trace various architectural elements in an alluvial fan to constrain past geomorphic and hydrological events. Alluvial fan areas are often composed of complex sedimentary processes and landforms, while outcrops might be unavailable or provide limited information. Therefore, geophysical profiles perpendicular to the main axis of the valley might help to characterise better linear or elongated deposits such as channel fills, bars, and levees with suspected main axes aligned along that of the valley.

To illustrate this, we considered the Grimbach alluvial fan, which was severely impacted by unprecedented erosion and sedimentation (>100 years return period). While comparable events and their geomorphic and sedimentary legacy have been studied primarily on mountainous terrain, little evidence of such events in much gentler topography is known. Even such seemingly quiescent fans can be subject to catastrophic events such as those in the cuesta landscape of southwestern Germany in 2016. We expect similar deposits on many of the small tributary fans in the greater region.

Using EMI, ERT, and GPR in the Grimbach fan, we inferred traces of two bars and former channel fills at shallow depths below the surface, as well as buried soils. Such characteristics indicate that the current channel has been incising, favouring stable floodplains and soil development interrupted only by sudden channel avulsions. The methods and workflow presented in this study might be followed to guide similar geophysical exploration of valley fills in the cuesta landscape region of Germany to obtain additional sedimentary information. This may be useful in hazard models of extreme sediment transport, especially in areas with poor records of such events.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used in this manuscript is only available upon reasonable request.

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APPENDIX A: CHOOSING ERT INVERSION PARAMETERS

After some initial parameter testing, we found that $1 < \lambda < 20$ provided similar and stable results and fixed this regularisation parameter to $\lambda = 10$. For the correlation lengths, we follow Gelhar (1993) and Tronicke and Holliger (2005), who suggest a ratio C_x/C_z of about 10 for typical alluvial sediments. Therefore, we considered C_x - C_z pairs (in units of metres) of [10, 1], [20, 2], [30, 3], and [40, 4], which is also consistent with the size of the structures observed in the channel bank and the current channel deposits (Figures 1e,f and 4b), as well as with our EMI results (Figure 4).

In Figure A1, we present the inversion results for ERT2, which show consistent models of the overall electrical conductivity structure for the different pairs of correlation lengths considered. When considering larger values for the correlation lengths, we observed slightly smoother models with similar relative root mean square errors (RRMSE). However, in general, we found that using different reasonable correlation lengths yields similar results, which is comparable to the findings of Jordi et al. (2018). Finally, we fix the rotation angle at zero degrees because we expect horizontal to sub-horizontal structures.

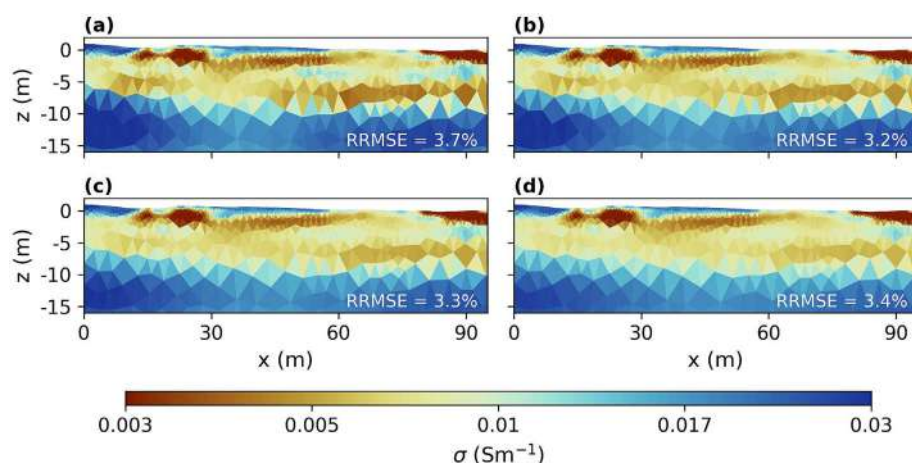


FIGURE A1 Inverted electrical conductivity models of profile ERT2 considering different horizontal (C_x) and vertical (C_z) correlation lengths for geostatistical regularisation during data inversion. (a) $C_x = 10$ m and $C_z = 1$ m, (b) $C_x = 20$ m and $C_z = 2$ m, (c) $C_x = 30$ m and $C_z = 3$ m, and (d) $C_x = 40$ m and $C_z = 4$ m. [Color figure can be viewed at wileyonlinelibrary.com]