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# Imaging and characterization of facies heterogeneity in an alluvial aquifer using GPR full-waveform inversion and cone penetration tests

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SUMMARY

Spatially highly resolved mapping of aquifer heterogeneities is critical for the accurate prediction of groundwater flow and contaminant transport. Here, we demonstrate the value of using full-waveform inversion of crosshole ground penetrating radar (GPR) data for aquifer characterization. We analyze field data from the Krauthausen test site, where crosshole GPR data were acquired along a transect of 20 m length and 10 m depth. Densely spaced cone penetration tests (CPT), located close to the GPR transect, were used to validate and interpret the tomographic images obtained from GPR. A strong correlation was observed between CPT porosity logs and porosity estimates derived from GPR using the Complex Refractive Index Model (CRIM). A less pronounced correlation was observed between electrical conductivity data derived from GPR and CPT. Cluster analysis of the GPR data defined three different subsurface facies, which were found to correspond to sediments with different grain size and porosity. In conclusion, our study suggests that full-waveform inversion of crosshole GPR data followed by cluster analysis is an applicable approach to identify hydrogeological facies in alluvial aquifers and to map their architecture and connectivity. Such facies maps provide valuable information about the subsurface heterogeneity and can be used to construct geologically realistic subsurface models for numerical flow and transport prediction.



## 1. Introduction

Reliable prediction of groundwater flow and solute transport is needed for environmental engineering tasks such as the definition of protection zones for drinking water wells or the development of efficient remediation strategies at contaminated sites. However, predicting subsurface flow and transport is challenging due to the complex heterogeneity found in most geologic media. Physical and chemical properties in the subsurface vary over orders of magnitude and their spatial variability exerts a primary control on groundwater flow and solute migration (e.g. Dagan, 1989). Sedimentary deposits, which commonly represent soils and aquifers, are often composed of several distinct units or facies, separated by recognizable boundaries at which subsurface properties such as grain size or hydraulic conductivity may abruptly change (Miall, 1985; Fogg, 1986; Koltermann and Gorelick, 1996). This has motivated the conceptualization of heterogeneous sedimentary aquifers as assemblages of distinct (hydro-)lithological facies with less variability within than between facies (Anderson, 1989; Webb and Anderson, 1996; Barrash and Clemo, 2002; Riva et al., 2006; Bayer et al., 2011).

Field and modeling studies have highlighted the influence of facies architecture and geometry on flow and transport processes (Zheng and Gorelick, 2003; Feyen and Caers, 2006; Ronayne et al., 2008; Zheng et al., 2011; Haendel and Dietrich, 2012). In particular, the spatial connectivity of facies appears to be of substantial importance, because connected structures of high permeability act as preferential flow paths and lead to increased water fluxes and increased transport velocities, while connected structures of low permeability act as flow barriers and lead to decreased water fluxes and decreased transport velocities (Zinn and Harvey, 2003; Knudby and Carrera, 2006; Huysmans and Dassargues, 2009; Bianchi et al., 2011; Renard and Allard, 2013). Hence, reliable prediction of flow and transport in the subsurface critically depends on a detailed characterization of the spatial distribution of subsurface facies.

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Unfortunately, a detailed characterization of the subsurface is difficult to obtain in practice because the subsurface is not easily accessible through measurements. Conventional subsurface characterization techniques tend to rely on pumping tests or borehole based geophysical or lithological logs. Pumping tests yield appropriate upscaled properties with regard to flow but suffer from a limited spatial resolution of local properties, which are needed for proper transport prediction. Borehole logs provide detailed information about the vertical distribution of local properties but are inherently one-dimensional in nature. Any inference based on one-dimensional vertical profiles, will be blind to the lateral distribution of subsurface properties, and thus, the interconnectivity of facies. Outcrop analyses can be applied to map the distribution of facies on outcrop walls, which provides valuable information about the lateral connection of facies (Huysmans et al., 2008; Huysmans and Dassargues, 2009; Bayer et al., 2011; Comunian et al., 2011). However, the characteristics derived from an outcrop are not necessarily valid for the specific conditions at locations some distance away from the outcrop.

In contrast, minimally invasive tomographic geophysical imaging methods such as crosshole ground penetrating radar (GPR) can be used to map the spatial distribution of subsurface properties on full cross-sections directly at the location of interest. The two-dimensionality of the tomographic images provides the opportunity to characterize the lateral distribution of structures and to evaluate their architecture and connectivity. Traditional tomographic inversion of GPR data is carried out using ray-based techniques (Holliger et al., 2001; Maurer and Musil, 2004). Because ray-based methods consider only the first arrival times and the first-cycle amplitudes they exploit only a limited amount of the information contained in the full recorded waveform. As a consequence, the spatial resolution of such methods is limited, and only relatively smooth images of the subsurface can be obtained (Belina et al., 2009; Klotzsche et al., 2010). In contrast, full-waveform inversion techniques make use of the full recorded waveform, which includes information beyond the first arrival times and first-cycle amplitudes. As a consequence, full-waveform inversion techniques are capable to resolve subsurface properties with higher spatial resolution and yield tomographic images with a significantly improved level of detail (Ernst et al., 2007b; Meles et al., 2010; Yang et al., 2013; Klotzsche et al., 2013, 2014).

Recent studies showed the potential of GPR full-waveform tomography for hydrogeological application by comparing GPR results with independent measurements of porosity (Yang et al., 2013; Klotzsche et al., 2013) and hydraulic conductivity (Klotzsche et al., 2013). Within the scope of hydrogeological site characterization the strength of full-waveform GPR tomography lies in its potential to bridge the gap in terms of resolution and coverage that exists among traditional hydrogeological methods such as small-scale core analyses and large-scale pumping tests. However, this advantage comes along with difficulties regarding the hydrogeological interpretation because GPR returns the electrical properties which are only indirectly related to hydrogeological parameters such as porosity or hydraulic conductivity. Without information about the site-specific relationship between electrical and hydrogeological properties, the use of GPR for hydrogeological site characterization can therefore be limited. Another difficulty, in field applications, is to evaluate the reliability of the obtained tomographic images, because in the absence of secondary information it is difficult to validate if the structures seen in the tomographic images represent real subsurface structures and not inversion artifacts.

In the present study we show the value of applying full-waveform GPR tomography in combination with complementary investigation tools to hydrogeologically characterize a site. We analyze field data from the Krauthausen test site, where GPR data were recently acquired along several cross-borehole planes. Because the Krauthausen test site has been intensively investigated in previous studies (e.g. Vereecken et al., 2000; Tillmann et al., 2008), we are able to confront the GPR results with densely spaced secondary data from cone penetration tests (CPT), grain size analyses and flowmeter measurements which allow detailed validation and interpretation of the tomographic images obtained from GPR. In detail, our approach consists of the following steps: Firstly, a GPR full-waveform inversion is applied to infer the subsurface permittivity and electrical conductivity distribution along a vertical aquifer cross-section of approximately 20 m length and 10 m depth. Results are validated by comparison with co-located CPT porosity and electrical conductivity logs. Secondly, a cluster analysis is conducted to partition the obtained GPR tomographic images into clusters. In this way, different lithological facies such as sand and gravel that differ in their permittivity and electrical conductivity signatures can be distinguished. The outcome of the cluster analysis is a cross-sectional map showing the spatial distribution of different facies in the aquifer. We discuss the reliability of the facies classification by comparing the distribution of facies obtained from GPR with the distribution of facies obtained independently from CPT. Finally, we use the combined information from GPR, CPT, grain size analyses and flowmeter measurements to develop a hydrogeological interpretation of the obtained facies and to characterize them in terms of grain size, porosity and hydraulic conductivity.

## 2. Material and methods

### 2.1. Study site

The Krauthausen test site, set up by the research center Jülich in 1993, is located approximately 10 km northwest of the city of Düren, Germany, in the southern part of the Lower Rhine Embayment. A detailed description of the test site is given by Vereecken et al. (2000). In the last decades, several laboratory and field techniques have been applied at Krauthausen with the goal to study the spatial distribution of aquifer parameters and its effect on solute migration. These techniques include laboratory characterization of sediment samples (Döring, 1997), field pumping and flowmeter tests (Li et al., 2007, 2008) tracer experiments (Vereecken et al., 2000; Vanderborght and Vereecken, 2001), geophysical imaging methods (Kemna et al., 2002; Müller et al., 2010; Oberröhrmann et al., 2013), and cone penetration tests (Tillmann et al., 2008). Due to the extensive set of subsurface information retrieved in previous studies, Krauthausen provides excellent opportunities to test and validate novel aquifer exploration techniques.

The present study focuses on the uppermost aquifer in the central part of the test site where a series of closely spaced boreholes and cone penetration tests were available (Fig. 1). The unconfined aquifer is approximately 10 m thick and composed of alluvial terrace sediments, which were deposited by a local braided river system of the river Rur on top of older Rhine and Maas sediments (Englert, 2003). According to Döring (1997) and Tillmann et al. (2008) the uppermost aquifer can be broadly divided into three layers (Fig. 2a): A bottom layer composed of sandy to gravely grain size, which extends from 6 to 11.5 m depth and is characterized by varying sand to gravel ratio; a well sorted sand layer extending from 4 to 6 m depth; and a poorly sorted gravel layer extending from 1 to 4 m depth. The base of the aquifer is formed by thin layers of clay and sand, at approximately 12 m depth. On top of the aquifer, a loamy soil layer has developed. The groundwater level shows seasonal variations from 1 to 3 m depth. The aquifer sediments are characterized by an average clay content of 2%