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Three-dimensional high resolution fluvio-glacial aquifer analog – Part 2: Geostatistical modeling

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SUMMARY

The heterogeneity of sedimentary structures at the decimeter scale is crucial to the understanding of groundwater flow and transport. In a series of two papers, we provide a detailed analysis of a fluvio-glacial aquifer analog: the Herten site. The geological data along a series of 2D sections in a quarry, the corresponding GPR measurements, and their sedimentological interpretation are described in the companion paper. In this paper, we focus on the three-dimensional reconstruction of the heterogeneity. The resulting numerical model is provided as an electronic supplementary material for further studies. Furthermore, the geostatistical parameters derived from this analysis and the methodology described in the paper could be used in the future for the simulation of similar deposits where less data would be available. To build the 3D model, we propose a hierarchical simulation method which integrates various geostatistical techniques. First, we model the subdivision of the domain into regions corresponding to main sedimentological structures (e.g. a sedimentation event). Within these volumes, we use multiple-point statistics to describe the internal heterogeneity. What is unusual here is that we do not try to use a complex training image for the multiple-point algorithm accounting for all the non-stationarity and complexity, but instead use a simple conceptual model of heterogeneity (ellipsoidal shapes as a training image) and constrain the multiple point simulations within the regions by a detailed interpolation of orientation data derived from the 2D sections. This method produces realistic geological structures. The analysis of the flow and transport properties (hydraulic conductivity and tracer breakthrough curves) of the resulting model shows that it is closer to the properties estimated directly from the 2D geological observations rather than those estimated from a model of heterogeneity based on probability of transitions and not including the modeling of the large-scale structures.

1. Introduction

This paper is the second of a two-part series investigating the heterogeneity of a fluvio-glacial aquifer analog. The overall motivation of the work is that a realistic modeling of aquifer heterogeneity requires on the one hand accurate data on the expected sedimentological structures and on the other hand appropriate modeling techniques.

While the first paper Bayer et al. (2011) in this series describes the field work and proposes a sedimentological interpretation of the data, this second part focuses on the modeling aspects and follows two aims. The first is to build a high resolution three-dimensional model of the heterogeneity of the Herten fluvio-glacial aquifer analog. This model constitutes an important preliminary step for future studies investigating the impact of heterogeneity on hydrogeological processes or on the significance of field experiments.

The second aim of the paper is to propose a hierarchical approach for the modeling of such environment types. Among the various existing methods to model heterogeneity reviewed by Koltermann and Gorelick (1996) and de Marsily et al. (2005), multiple-point (MP) statistics (Guardiano and Srivastava, 1993; Strebelle, 2000; Hu and Chugunova, 2008) is appealing because it provides a simple mean to integrate a conceptual geological model in a stochastic simulation framework. The conceptual model is provided as a training image (TI) representing the heterogeneity patterns that the user expects at a given site. For example, the TI can represent meanders if the user knows that the geological environment that he wants to model is made of meanders. Then, when using MP statistics, one of the most important questions to answer is how to get the TI? A possibility often cited in the literature is to directly use the geological maps or sections obtained from analog studies as TI.

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In practice, only a few attempts to use real geological analogs as training images have been made so far (Maharaja, 2005; Huysmans et al., 2008). These works have shown that analogs often display significant non stationarity (because of the physical nature of the geological processes that lead to the heterogeneity). Using them directly as training images produces often unacceptable simulations (e.g. Boucher, 2009); indeed MP statistics assume that there is a repetition of the spatial heterogeneity patterns in the TI to build the MP probability distributions (ergodicity). If the TI is not stationary, the different patterns are mixed in the probability distributions. Different techniques have been developed to overcome this limitation. The main idea is to provide not only the TI but also some additional information (i.e. orientation maps, results of geophysical surveys, probability maps) to avoid mixing the patterns when computing the probability distributions (Boucher, 2009; Chugunova and Hu, 2008; de Vries et al., 2009; Mariethoz et al., 2010; Straubhaar et al., 2011). Even if the problem of non stationarity is important, one has to remember that it is not specific to MP statistics. It affects, in a similar manner, all the standard geostatistical methods based on lower order statistics. However, when only two-point statistical moments are used, the simulated structures are not expected to resemble the original ones (because the two-point moments do not contain enough information to constrain the shape of the structures, see e.g. Strebelle (2000)) and the non stationarity is less apparent.

Another issue when trying to use analog data to simulate 3D heterogeneity with MP statistics is that one needs a 3D training image to simulate the 3D domain. In general, analog observations only provide 2D training images. It is therefore necessary to develop specific methods that allow using MP statistics in that situation. If we look at standard geostatistical procedures, the practice in those cases would be to assume some invariance of the probability laws by rotation (Chilès and Delfiner, 1999). The covariances or variograms would be inferred along the available data in the directions included in the geological section, and the variability in the perpendicular directions would be assumed to follow the same laws or to be simply rescaled to account for some anisotropy. Here similar assumptions could be made, but the current implementations (both commercial and open source) of MP statistics do not yet offer these possibilities. When no other technique is available, the user has to build a 3D training image that is, as far as possible, compatible with the 2D observations. One can do it for example by using object based techniques, as proposed by Caers (2005) and Maharaja (2008), or by using 3D geometrical modeling techniques. If the geological structures are highly complex and intricate, this can be very tedious.

To overcome the problem of non stationarity and the problem of insufficient access to a 3D training image, the approach proposed in this paper consists of subdividing the domain in smaller regions corresponding to a series of successive sedimentological units corresponding to the large scale heterogeneity. In these units (also named regions), the heterogeneity is simpler and one can use basic but reasonable 3D training images constructed with object based techniques. In other words, the non stationarity related to the presence of major sedimentological units is treated by modeling a set of regions. The non stationarity of orientations of the

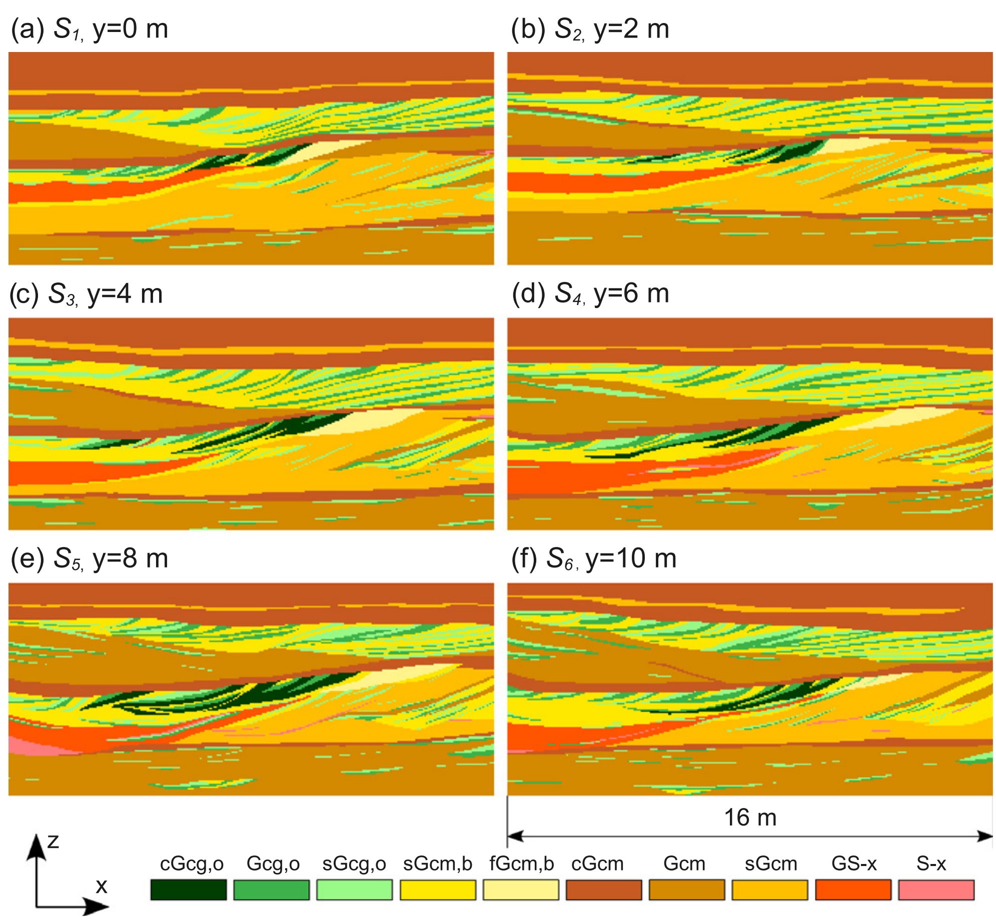

Fig. 1. Rasterized six sections S_j (16 by 7 m) of the Herten case study. Fig. 7a provides an *ensemble* view. The hydrofacies codes are explained in detail in the companion paper (Bayer et al., 2011).