Heterogeneity patterns of Quaternary glaciofluvial gravel bodies (SW-Germany): application to hydrogeology

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Abstract

The architecture of sedimentary bodies determines the heterogeneity of many aquifers. Thus, for environmental risk-assessment and quantification of clean-up efficiencies, determination of the spatial distribution of hydraulic properties is required. In this study, outcrop analogues of glaciofluvial gravel-bed deposits are used for a process-based analysis of sedimentary heterogeneities, which in turn are transformed into hydraulic parameters. Three scales of heterogeneities are distinguished: (a) the lithofacies-scale is formed by unique transport and depositional processes that form the fundamental building blocks (hydrofacies types), (b) the depositional element-scale shows distinct geometrical characteristics (internal structure and bounding surfaces) and determines the local distribution of lithofacies and, hence, the correlation structure of permeabilities, (c) the architectural-scale of gravel bodies is formed by the stacking of depositional elements, which is controlled by the dynamics of aggrading paleofluvial systems. Comparison of numerous gravel pits in SW-Germany revealed three major architectural patterns of glaciofluvial gravel bodies that can be distinguished statistically by the preservation of depositional elements as well as the frequency of lithofacies types. The facies analysis results in three conceptual facies models of proglacial river systems, which are regionally classified as ‘main-‘, ‘intermediate-‘ and ‘minor‘ discharge types. Based on calculated and laboratory measured hydraulic properties of the various lithofacies types detailed outcrop wall maps were digitized into polygons of defined hydrofacies types by using the GIS system Arc Info. The two-dimensional fields of hydraulic properties were then transferred into a numerical model of groundwater flow. Modeling results clearly illustrate that the three heterogeneity patterns of gravel bodies also have distinguishable hydraulic response characteristics.

Keywords: Coarse-grained braided river deposits; Lithofacies; Hydrofacies; Hydraulic parameterization

1. Introduction

Contamination of groundwater in shallow fluvial aquifers (e.g. valley-fills) is frequently encountered. Risk assessment and remediation strategies require basic knowledge in sedimentary facies distribution as well as hydraulic property distribution coupled to a hydrogeological model of the sedimentary aquifers. Sedimentary processes in gravel-bed rivers are well understood by research in modern coarse-grained river systems (e.g. Goedhart and Smith, 1998; Dinehart, 1992), by outcrop studies (e.g. Smith, 1990; Siegenthaler and Huggenberger, 1993), by flume experiments (e.g. Ashmore, 1993; Major, 1998) or
by qualitative and quantitative physical simulations (Bridge, 1993; Leddy et al., 1993; Whittaker and Teutsch, 1999; McEwan et al., 1999). Some of these aspects are discussed in this paper where we particularly focus on the formation of lithofacies (Section 3), depositional elements (Section 4) and their preservation in different paleo-discharge regions (Section 5).

The hydrogeological modeling of sedimentary aquifers just recently received increasing scientific attention. In the past 10 years—following the early papers of Fogg (1986) and Anderson (1989)—numerous publications focus on the hydraulic modeling of heterogeneous aquifer systems (e.g. Fogg, 1990; Poeter and Gaylord, 1990; McFarlane et al., 1994; Ritzi et al., 1994, 1995; Webb and Anderson, 1996a, b). A book recently published by Fraser and Davis (1998) summarizes the state of the art concerning this issue. The authors agree that the understanding of heterogeneities (sedimentary and hydraulic) and their representation in the model is the critical issue for characterizing fluid flow and transport in aquifers (e.g. Webb and Davis, 1998; Galloway and Sharp, 1998a, b). The representation (image creation) in the numerical models may vary depending on the data base and the required goal. The different methods (descriptive approach, structure imitating, process imitating) are reviewed in Koltermann and Gorelick (1996a, b). The geological information can be transferred into the flow grid by using different stochastic simulation techniques (Scheibe and Murray, 1998), by geostatistical analysis (Dominic et al., 1998) or by transition probability geostatistics (Markov chain analysis; Carle et al., 1998; Weissmann and Fogg, 1999). Another approach to characterise the sedimentary structures in fluvial systems involves geophysical methods, e.g. ground-penetrating radar (Asprion and Aigner, 1999, Beres et al., 1999). The transformation of the geophysical parameters (velocity) into hydraulic parameters is still questionable (Kowalsky et al., 2001).

The existing hydrogeologic models of sedimentary aquifers as described above focus on large-scale investigation and use geostatistical or geophysical methods for getting high resolution grid information. In contrast to that, this study follows the method of Huggenberger and Aigner (1999) and focuses on small-scale aquifer analog studies in the order of tens of meters (see also Willis and White, 2000). The investigations are based on “close to reality” data regarding the distribution of the lithofacies as well as the determination of hydraulic properties. This paper emphasizes that understanding of sedimentary processes (lithofacies, depositional elements, stacking pattern) helps to predict fluid flow and transport in gravelly valley aquifers. Based on investigations in many outcrops, the heterogeneity patterns in the glaciofluvial gravel bodies were studied and categorized in terms of lithofacies and hydrofacies distribution, which were then used in a numerical model to characterize the flow patterns in these deposits.

2. Area of investigation

The gravel pits investigated in this study are situated in SW-Germany beyond the maximal extension of the Würmian Rhine glacier (Fig. 1). They are located in former fluvial drainage zones of the Rhine glacier that are closely linked to older Pleistocene valley morphologies. The drainage system of the Würmian Rhine glacier can be subdivided into two main directions. Several drainage zones pass northward to the river Danube (Upper Swabia). The other (single) zone passes in the modern Rhine valley first to the west before bending in the Oberrhein valley to the north.

The sites at the northern part (Upper Swabia) are proximal to the terminal moraine. Presently, the ground slope ranges from 8% to 14%, and a clear transition to the terminal moraine complexes is visible. Therefore, it is possible to correlate these deposits with the maximal Würmian ice extension in Europe which is usually placed between 23,000 and 14,000 years BP (Schreiner, 1992). A coarsening-upward trend described by Heinz and Aigner (1999) also identified these proglacial fluvial gravels being deposited during a glacial advance. In the northern zone, there is a rapid decrease in thickness of the sediment package and a high groundwater level prevents outcrop studies in more distal zones. In contrast, it is possible to study gravel deposits in the Rhine valley which are exposed up to 100 km away from the terminal moraine.

3. Analysis of lithofacies—translation into hydrofacies

Understanding transport and depositional processes in gravel-bed rivers helps to explain the ap-
appearance of different lithofacies types. They can be characterized by different grain-size, degree of roundness, sorting, stratification, fabric and texture. A lithofacies concept proposed by Miall (1978, 1985) classifies primary sedimentary features. This scheme was extended for glacial deposits by Eyles et al. (1983) and specific features for glaciofluvial deposits were added by Siegenthaler and Huggenberger (1993). While Keller (1996) tried to combine this sedimentological code with geotechnical information from core data, Anderson (1989) and Klingbeil et al. (1999) used this concept to classify hydraulic units of gravel deposits. Bierkens (1996) and Anderson (1989) showed that sedimentary properties (grain-size distribution, texture, fabric) can be connected directly to hydraulic properties such as hydraulic conductivity and porosity. The term ‘hydrofacies’ was thus introduced for units with relatively homogeneous hydraulic properties (Poeter and Gaylord, 1990; Anderson et al., 1999).
Applying the code-scheme of Keller (1996) to lithofacies- and hydrofacies description, we document in this paper a close link between genetic lithofacies description (representing sedimentary processes) and hydraulic parameters (Tables 1 and 2). The following five dominant lithofacies types have been recognized in glaciofluvial deposits of the Rhine glacier: (1) pure sand, (2) well-sorted gravel, (3) poorly sorted gravel, (4) alternating gravel, (5) cobble- and boulder-rich gravel (Fig. 2). However, transformation of lithofacies into hydrofacies required in some cases a further differentiation. Variations of grain size and matrix content are not critical for process-based lithofacies description but have a strong impact on the resulting hydraulic properties (Table 2 and Fig. 3).

The assessment of the hydraulic properties of lithofacies (hydrofacies) was done by measuring the hydraulic conductivities of disturbed samples (only sand facies undisturbed) in a permeameter column (disturbed samples: 40 cm in length by 10 cm in diameter; undisturbed samples: 10 cm*4 cm) at different hydraulic heads. The results were compared to values calculated by empirical equations based on the information of the grain-size distribution and porosity (Kozeny, 1927; Carman, 1937; Beyer, 1964; Panda and Lake, 1994; Koltermann and Gorelick, 1996a, b). Additionally, the values were compared to data from the literature (e.g. Jussel et al., 1994).

3.1. Pure sand lithofacies (S-x)

3.1.1. Description

This type of lithofacies is represented by very well-sorted sands. The grain-size ranges from fine to coarse sand with a dominance of medium sand. Finer material such as clay and silt is not present. Pure sand is often found in local depressions either as a carpet covering the basal morphology, internal cross-stratification units or as marginal wedges laterally from coarser sediments. Horizontal units with a lateral extension of meters to tens of meters also occur. With a thickness up to 0.7 m, these units are characterised by horizontal stratification. Occasionally, planar cross-stratification (indicating migration of ripples with straight crests) was noticed.

3.1.2. Discussion and hydraulic consequences

In contrast to gravel deposits, this lithofacies represents deposits of low energy. Internal stratification reflects the transport of single particles as bedload charge. Deposition occurs either at the decreasing limb of flow or at protected positions within the fluvial system, probably under 'lower flow regime' conditions (according to the association of sedimentary structures). Using undisturbed flow-through columns of 10 cm length and 4 cm diameter, 10 different samples (similar grain-size distribution) showed hydraulic conductivities ($k_f$) ranging from $3.6 \times 10^{-5}$ ms$^{-1}$ up to $1.1 \times 10^{-4}$ ms$^{-1}$. Predicted $k_f$ values based on the empirical equation of Beyer (1964), using an empirical constant (depending on the ratio of the grain size at 10% and at 60%) and the grain-size at 10% of the cumulative sieve curve were within a factor of two. Within this column size we found no significant influence of internal stratification on $k_f$ values (each sample was taken horizontal, vertical and in direction of layering). This is probably due to uniformity (good

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Lithofacies-code for description of gravel deposits in outcrops (modified and extended after Keller, 1996; Kleineidam, 1998)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indices/Features</td>
<td>Abbreviation</td>
</tr>
<tr>
<td>i₁</td>
<td>grain-size</td>
</tr>
<tr>
<td>b, boulder</td>
<td>c, cobbles</td>
</tr>
<tr>
<td>f, fines (silt/clay)</td>
<td></td>
</tr>
<tr>
<td>I₁</td>
<td>grain-size</td>
</tr>
<tr>
<td>G, gravel</td>
<td></td>
</tr>
<tr>
<td>S, sand</td>
<td></td>
</tr>
<tr>
<td>f, fines (silt/clay)</td>
<td></td>
</tr>
<tr>
<td>i₂</td>
<td>texture</td>
</tr>
<tr>
<td>c, clast-supported</td>
<td></td>
</tr>
<tr>
<td>m, matrix-supported</td>
<td></td>
</tr>
<tr>
<td>i₃</td>
<td>stratification</td>
</tr>
<tr>
<td>x, stratified</td>
<td></td>
</tr>
<tr>
<td>m, massive (no bedding)</td>
<td></td>
</tr>
<tr>
<td>g, graded (normal, inverse)</td>
<td></td>
</tr>
<tr>
<td>i₄</td>
<td>additional information</td>
</tr>
<tr>
<td>i, imbrication</td>
<td></td>
</tr>
<tr>
<td>a, alternation: e.g. o=open framework, b=bimodal</td>
<td></td>
</tr>
<tr>
<td>h, horizontally stratified</td>
<td></td>
</tr>
<tr>
<td>p, planar stratified</td>
<td></td>
</tr>
<tr>
<td>t, trough cross-stratified</td>
<td></td>
</tr>
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</table>

*This code can be described as follows ($i₁i₂i₃i₄$): the grain-size is given by $i₁$ and $I₁$ whereby $I₁$ represents the main component (e.g. G=gravel) and $i₁$ (optional) gives additional information on subordinate components or matrix. Index $i₂$ describes the texture of the sediment and is either clast-supported or matrix-supported. Index $i₃$ gives stratigraphic features. For simplification we distinguish between cross-bedded=x, graded=g and massive=m. Additional information can be put at position $i₄$ which is separated by a comma. ‘—’ is used in order to keep the sequence.*
Fig. 2. The five major lithofacies types occurring in gravel-bed deposits of the Rhine glacier area. The change in the cumulative sieving curve indicates the increase in flow energy (maximum grain size) and rate of sedimentation (poorer sorting) from lithofacies S-x to bGcm,i.
sorting) and the lack of mudrakes on foresets in the samples investigated.

3.2. Well-sorted gravel lithofacies (GS-x)

3.2.1. Description

This lithofacies consists of well-sorted, well-rounded gravel to sand/gravel mixtures. The grain size ranges between medium sand and medium gravel. While gravelly dominated units are clast-supported, sand/gravel mixtures may show a matrix-supported texture. Stratification of inclined units (3–25°) is due to orientation of particles or grain-size changes. Interfingering and interbedding with lithofacies S-x are common. Unit thickness of lithofacies GS-x commonly does not exceed 0.7 m.
3.2.2. Discussion and hydraulic consequences

Sorting indicates a continuous process of deposition. Therefore, transport of more or less single particles as tractional bedload is assumed. Changes in grain-size reflect both variable current energy and differences in grain-size supply. Hydraulic conductivity for three different samples ranged from 9.3 × 10⁻⁵ ms⁻¹ to 2.1 × 10⁻⁴ ms⁻¹. The narrow range in values can be attributed to the very similar grain-size distribution investigated in the field (Table 2).

3.3. Poorly sorted gravel lithofacies: (Gcx, Gcm, Gcm,i)

3.3.1. Description

This is the most frequently observed lithofacies type in all localities. It is characterized by a moderate to poorly sorted sediment mixture with a grain-size distribution from fine sand to cobbles. Gravel particles representing the main grain-size are well rounded and clast-supported. Bed boundaries are vague and single beds are one to several decimeters in thickness. Preferred clast orientation can occur parallel (a(p)) to bedding in cross-stratified units while in horizontal beds, larger clasts (e.g. cobbles) often show imbrication (a(t), b-axis upward dipping). Individual beds can be separated by thin sandy layers, variable proportion of matrix and by differences in maximum grain-size.

3.3.2. Discussion and hydraulic consequences

This facies is very common in gravel-bed deposits and has often been described from outcrop studies (e.g. Siegenthaler and Huggenberger, 1993; Steel and Thompson, 1983; Smith, 1990). As noted by Whiting et al. (1988) and Reid and Frostick (1987), the movement of sediment in gravel-bed rivers commonly occurs in pulses. A close relationship between movement of sand and initiation of entrainment of gravel is described resulting in a wavelike transport process (Kuhnle, 1996). The ill-sorted lithofacies of the SW-German Rhine glacier deposits includes 10–30% of the sand fraction and 70–90% of the gravel fraction. Although there is no accurate determination of sediment motion (Reid and Frostick 1987) describe bedload motion at the rising limb of a flood hydrograph as well as at the recession limb, this transport process always takes place at high flow stage. Deposition of low-density tractional bedload sheets occurs very rapidly, as shown by the lack of a sorting mechanism. Although the sand/water matrix is important for movement of gravel sheets, a later infill of sandy matrix should also be considered (Goedhart and Smith, 1998). While parallel clast orientation (a(p)) indicates a high rate of shearing, the occurrence of imbricated clasts (b(i)) highlights inert grain-to-grain collisions.

In terms of hydraulic properties, a differentiation of the genetic code was required (Table 2). Particularly, the make-up of the matrix has to be considered. Lithofacies Gcm (cGcm,i) and Gcx will have similar \( k_f \) values (2.3 × 10⁻⁴ ms⁻¹) if the matrix is similar. To further characterize the matrix, we introduced the code sGcm indicating an increased amount of medium sand in the matrix which results in a decrease of hydraulic conductivity (6.1 × 10⁻⁵ ms⁻¹) compared to the original Gcm. In some localities, the matrix contains small amounts of fines (mainly silt). Just 1–2% of finer material causes a decrease in hydraulic conductivity by one order of magnitude (1.6 × 10⁻⁶ ms⁻¹), in this case, the lithofacies is designated by the code fGcm. Predictions based on the grain-size distribution (Panda and Lake, 1994) were within a factor of 2–5 without any physical explanation. The influence of imbrication on \( k_f \) values could not be investigated using disturbed samples, results were reported by Siegenthaler and Huggenberger (1993) to be in the order of 50% lower \( k_f \) values in horizontal compared to vertical flow through direction.

3.4. Alternating gravel lithofacies (Gcg,a)

3.4.1. Description

This facies is very common in gravel-bed deposits and has often been described from outcrop studies (e.g. Siegenthaler and Huggenberger, 1993; Steel and Thompson, 1983; Smith, 1990). As noted by Whiting et al. (1988) and Reid and Frostick (1987), the movement of sediment in gravel-bed rivers commonly occurs in pulses. A close relationship between movement of sand and initiation of entrainment of gravel is described resulting in a wavelike transport process (Kuhnle, 1996). The ill-sorted lithofacies of the SW-German Rhine glacier deposits includes 10–30% of the sand fraction and 70–90% of the gravel fraction. Although there is no accurate determination of sediment motion (Reid and Frostick 1987) describe bedload motion at the rising limb of a flood hydrograph as well as at the recession limb, this transport process always takes place at high flow stage. Deposition of low-density tractional bedload sheets occurs very rapidly, as shown by the lack of a sorting mechanism. Although the sand/water matrix is important for movement of gravel sheets, a later infill of sandy matrix should also be considered (Goedhart and Smith, 1998). While parallel clast orientation (a(p)) indicates a high rate of shearing, the occurrence of imbricated clasts (b(i)) highlights inert grain-to-grain collisions.

In terms of hydraulic properties, a differentiation of the genetic code was required (Table 2). Particularly, the make-up of the matrix has to be considered. Lithofacies Gcm (cGcm,i) and Gcx will have similar \( k_f \) values (2.3 × 10⁻⁴ ms⁻¹) if the matrix is similar. To further characterize the matrix, we introduced the code sGcm indicating an increased amount of medium sand in the matrix which results in a decrease of hydraulic conductivity (6.1 × 10⁻⁵ ms⁻¹) compared to the original Gcm. In some localities, the matrix contains small amounts of fines (mainly silt). Just 1–2% of finer material causes a decrease in hydraulic conductivity by one order of magnitude (1.6 × 10⁻⁶ ms⁻¹), in this case, the lithofacies is designated by the code fGcm. Predictions based on the grain-size distribution (Panda and Lake, 1994) were within a factor of 2–5 without any physical explanation. The influence of imbrication on \( k_f \) values could not be investigated using disturbed samples, results were reported by Siegenthaler and Huggenberger (1993) to be in the order of 50% lower \( k_f \) values in horizontal compared to vertical flow through direction.
Thompson, 1983). The two subunits can be very asymmetric with the end-members consisting of only one subunit (upper or lower one). The matrix of the lower subunits can range from well-sorted medium sand to a polymodal grain-size distribution (containing even fines). Alternating units with a bimodal lower zone often show well-developed grading (compared with gravel couplets) with an openwork zone from coarse pebbles (cobbles) to granules or coarse sand. In contrast to units with polymodal lower zones, grading is often vague even within the openwork upper zone.

3.4.2. Discussion and hydraulic consequences

Gravel couplets are a widespread fluvial gravel type often described in the literature (e.g. Bluck, 1979; Steel and Thompson, 1983; Smith, 1990; Siegenthaler and Huggenberger, 1993). Because of its vast range in appearance we prefer the descriptive term ‘alternating gravel’ (Smith, 1990; Heinz and Aigner, 1999). Steel and Thompson (1983) interpreted this alternation as a result of waning flow and clast segregation over the surface of a bar. In contrast, Carling and Glaister (1987) and Carling (1990) showed that this alternation can be produced without flow fluctuation by migration of gravel dunes. At the brinkpoint of a dune, flow separation occurs initiating a grain-size segregation (grading). Counter flow at the lee-side enables the infiltration and mixing of suspended sand with the basal zones. While these mechanisms produce horizontal alternating beds, Siegenthaler and Huggenberger (1993) suggested that inclined gravel couplets result from gravel dunes migrating across an oblique plane. We also observed large foresets of alternating gravel in glacial Gilbert-type deltas (basin of Singen, Asprion, 1998) more resembling a turbidite mechanism. Acknowledging all these varieties of alternating gravel, we assume that different mechanisms can lead to similar alternating gravel lithofacies. Although all mechanisms are not known, the following conditions are thought to be critical for their formation: a negative step (e.g. slope of a dune or scour pool) initiating grading and turbulence for winnowing or infiltration of the matrix.

In contrast to poorly sorted gravel, the described sorting mechanism results in different hydraulic conductivities (Table 2). The lithofacies code Gcg,a therefore needs to be extended and specified. If a polymodal construction of the basal subunit occurs, the same codes as for ill-sorted gravel are used (Gcm, sGcm, fGcm). The basal subunit could also be made up by a bimodal grain-size distribution (clasts and sand matrix) with code (c)Gcm,b. For this lithofacies an empirical relationship to the overall porosity in bimodal grain-size distributions (Koltermann and Gorelick, 1996a,b) was adopted to predict the hydraulic conductivity. According to the findings from Koltermann and Gorelick (1996a,b) porosity and $k_f$ values depend on the volume fraction of the clasts and the matrix. Down to a volume fraction of the matrix to the porosity of the clasts permeability can be calculated based on the permeability of the matrix times the matrix volume fraction (the clasts do not contribute to the flux). In the field, we never observed lower volume fraction of the matrix, in which case the clasts and their pore space contribute significantly to the overall permeability. The measured to predicted values are given in Fig. 4A and summarized in Table 2.

Hydraulic conductivity of the upper openwork subunits is determined by particle size or by the size of their pores. We classified three subunits: grain-size from cobbles and coarse pebbles (code cGcg,o; $k_f=10^{10}/C^2$ ms$^{-1}$), grain-size from coarse to fine pebbles (code Gcg,o; $k_f=10^{10}/C^2$ ms$^{-1}$) and grain-size from granules grading to sand (code sGcg,o; $k_f=10^{10}/C^2$ ms$^{-1}$). The hydraulic conductivities were calculated using the Kozeny (1927) and Carman (1937) equation, based on grain-size, porosity and tortuosity (1/porosity). Measured and calculated values are given in Fig. 4B and show an overall good agreement, up to grain-sizes of 16 mm, which is the upper size limit for the experimental column size we used.

3.5. Cobble- and boulder-rich gravel lithofacies (c,b)Gcm,i

3.5.1. Description

This lithofacies type contains large clasts such as cobbles and boulders. Regarding the pebbles (which dominate) the lithofacies shows a clast-supported texture. As the matrix ranges from fine sand to granules sorting is poor to very poor. Most clasts are well-rounded with occurrence of subrounded and infrequently subangular components. Beds commonly can reach a thickness of up to 1.5 m and are characterized by a horizontal and massive appearance.
Coarse clasts typically show imbrication within these sheet-like units. In one case, a stacking of several 0.5-m- to 0.7-m-thick beds was observed building up a 5-m-thick composite unit. The beds dip with a very low angle in the paleoflow direction.

3.5.2. Discussion and hydraulic consequences

Apart from the incorporation of an increased amount of silt and clay, this lithofacies can be compared to the ‘brown gravel’ described by Siegenthaler and Huggenberger (1993). This gravel type is interpreted as a product of a stream-driven, high-density traction carpet (Todd, 1989). Lack of sorting and stratification accounts for an ‘en-masse’ transport of sediment where a mixture from sand, gravel and boulders is transported simultaneously. Theoretical considerations describing the effect of dispersive pressure, quasi-static grain to grain collisions and
buoyancy forces imply that transport mechanisms transitional between debris flow and fluvial bedload transport are responsible for these products (Nemec and Steel, 1984). Due to the appearance of imbrication and lack of grading, a low rate of shearing and high celerity of deposition is proposed. Development of such massive sheet-like deposits requires high-magnitude floods including a suspension-rich discharge.

Hydraulic conductivities could not be determined using a permeameter due to the large grain sizes. Compared to the results for the bimodal lithofacies the coarser clasts diminish the effective flow plane, resulting in lower permeabilities compared to the matrix (lithofacies Gcm). We therefore removed the large clasts from the sample and measured the matrix hydraulic properties. Afterwards, the value was corrected by the volume fraction of the matrix. The results are summarized in Table 2.

4. Analysis of depositional elements

This section describes how geometries, bounding surfaces and associated sedimentological characteristics are used to classify depositional (or architectural) elements. Within a fluvial system, depositional elements develop at different geomorphic positions, under different energetic conditions and also with changing availability of sediment. This means that depositional elements are closely related to transport and depositional processes, while position and geometry (e.g. channel-form) determine the distribution of lithofacies. In addition, distinct processes are only possible at distinct geomorphic positions. Therefore, the comprehension of the external geometry of depositional elements and its internal lithofacies construction not only enables the reconstruction of fluvial systems but is also critical to the understanding of the three-dimensional distribution of permeabilities. All investigated localities exclusively show elements that are developed in the active channel belt (in-channel elements). In none of the outcrops sedimentary units have been preserved showing floodplain or channel marginal (e.g. levee, crevasse) features. Additionally, the dimension of the ‘in-channel elements’ as well as their internal construction can be highly variable. For this special case, we decided not to use the expression ‘architectural element’ (Miall, 1978; Keller, 1992) but neutrally ‘depositional element’.

The stock of depositional elements can be grouped into two categories: (1) ‘cut-and-fill’ elements, (2) ‘accretionary’ elements. The first group is characterized by an erosive concave lower bounding surface filled in a second step with sediment (compare with Steel and Thompson, 1983; Morison and Hein, 1987; Smith, 1990). In comparison, accretionary elements show an aggradational and/or progradational stratification style built up on a more or less flat lower bounding surface.

4.1. Examples of cut-and-fill elements

4.1.1. Scour pool elements

These depositional elements are characterized by a distinct concave erosional surface. The internal structure consists of trough-shaped cross-bedded sets comprising lithofacies S-x, GS-x, Gcm and Gg.,a. The thickness of scour pool elements ranges from 1 to 4 m. Laterally, they can extend from a few metres to several tens of metres (see also Section 4.2.1).

According to Best (1988) and Siegenthaler and Huggenberger (1993), these elements are interpreted as scour pool fills. In braided river systems scour pools occur at channel bends and channel confluences (Ashmore, 1982). Their forms depend on channel shape, confluence angle, discharge and bedload (Siegenthaler and Huggenberger, 1993). The position can remain stationary, but Ashmore (1993) also showed in small-scale hydraulic models different possibilities of changes in the position of channel confluences (e.g. translation, expansion, rotation, obliteration). Based on the migration of scour pools, Siegenthaler and Huggenberger (1993) convincingly explained geometrical forms resulting from different positions of the sections according to paleoflow direction. Two processes contribute to the filling of pools: (1) foreset deposition at the upstream end and (2) lateral accretion along the flanks.

These processes enable the formation of different small-scale lithofacies types alternating and interfingering with each other. For permeability distribution, scour pool elements therefore represent very heterogeneous three-dimensional bodies (vast range in size) that are internally cross-stratified with an extreme variability of hydraulic lithofacies.
4.1.2. Small dissection elements  
These minor depositional elements show similar types of lower bounding surfaces as those described for trough elements. However, they are much smaller in size reaching a thickness often smaller than 0.7 m and a lateral extension of one to several meters. Cross-stratification dominates consisting of lithofacies S-x, GS-x (interfingering), ill-sorted gravel and alternating gravel.

Due to the small size and lithofacies types typical for ‘lower flow’ conditions, these elements are interpreted as dissection elements of unit bars. At waning flow, newly formed channel accumulations are often dissected. Bluck (1979) described several sedimentary structures on bar supra-platforms as being comparable to these depositional elements. In order to preserve such high topographic positions in gravel-bed rivers, a high rate of accommodation of the depositional system is required. If preserved, these elements represent small-scaled, three-dimensional bodies with an increased probability of pure sand deposits. However, small dissection elements appeared only rarely in the investigated outcrops and because of the size, their proportion was always less than 5%. Thus, for the overall hydraulic network of a whole gravel package, these elements are not important.

4.2. Examples of ‘accretionary’ elements  

4.2.1. Horizontally bedded gravel sheets  
This depositional element mainly consists of ill-sorted gravel. Individual beds are typically 1–2 dm thick with a range in lateral extension from a few metres up to several tens of metres. A vague horizontal to subhorizontal stacking of several beds results in a crudely horizontal stratification.

These deposits are interpreted as a vertical accretion of gravel carpets (e.g. Hein and Walker, 1977; Ashmore, 1993) within the active channel. Pulsatory, low-density bedload sheets, only one to two grains in thickness, are the most important mechanisms for gravel transport in gravel-bed rivers (e.g. Reid and Frostick, 1987; Whiting et al., 1988; Kuhnle, 1996).

Apart from slight deviations in matrix construction and maximum grain-sizes, these elements represent hydraulically homogeneous units with a sheet-like (two-dimensional) geometry ranging laterally from tens up to hundreds of meters.

4.2.2. Massive gravel sheets  
This depositional element is composed of cobble- and boulder-rich gravels with the large clasts often showing imbrication (b(i), a(t)). Massive single beds or sets of beds up to 1 m in thickness build up laterally extensive units (100–500 m). The lower bounding surface often indicates an initial erosional degradation that is also supported by the occurrence of reworked material (underlain frozen gravel beds).

For the development of these elements, high-magnitude floods are required (glacial outburst, jökulhlaup). They are interpreted as high-density bedload-movements (traction carpets) driven by suspension-rich stream flow (Todd, 1989). The very poor sorting and the appearance of massive units are considered to be the result of a rapid deposition. Such events can lead to destruction and reorganization of the whole fluvial system.

Again, this process forms a sheet-like homogeneous hydraulic unit. In comparison to horizontal-bedded elements, this element is laterally more extensive (hundreds of metres) and can reach up to 5 m in thickness. In comparison to the horizontally bedded gravel sheets the hydraulic conductivity is reduced due to the occurrence of abundant large clasts (see Section 4.2.1).

4.2.3. Cross-bedded gravel dunes  
Within the studied gravel bodies, 0.3- to 1-m-scale cross-bedded sets formed on a flat or weekly concave lower bounding surface have also been recognized. Since no clear erosional phase is visible, this depositional element is included in the ‘accretionary’ group. Alternating gravel (Gcg,a) mainly composes the stratification, the angle of which can range from very low inclined (3°) to steep (30°). Ill-sorted gravel occurs, and well-sorted gravel (GS-x) and pure sands (S-x) occur infrequently as well. Laterally, these elements show extensions from few metres up to several tens of metres.

We propose for this cross-bedded element the term ‘gravel dune’. Carling (1996) showed that the development of dunes is not controlled by grain-size and presented many examples of coarse-grained gravel dunes. However, the description and classification is mainly based on morphological features like dune-height/length, wavelength, symmetry, crest-form (Ashley, 1990; Carling, 1999). The non-preservation
of any topological features (positive formsets) within gravelly formations forces one to distinguish these preserved bedforms only by size/extension, internal structure and lithofacies (Todd, 1996). Crucial for our interpretation is the development of an avalanching face at the downstream end of a bedform. In contrast to low-relief bedload sheets, gravel dunes form higher elevated bedforms, and coupled with the negative step at the downstream end, the formation of alternating gravel seems possible. Sediment is supplied mainly as bedload sheets or as smaller ‘piggyback’ gravel dunes migrating over the stoss side of larger bedforms (Dinehart, 1992). The infrequent appearance of lithofacies GS-x and S-x indicates decreasing or low-energy flow conditions.

The determination of gravel dunes at two-dimensional sections in the field is often ambiguous. Two-dimensional gravel dunes look similar to flow-parallel scour-pool fills, and three-dimensional gravel-dunes can also fill trough-like structures. Khadkikar (1999) worked out characteristics for discriminating trough cross-bedded conglomerates but gave no distinctive features for a possible genetic separation of gravel dunes and scour pool fills. Often, three-dimensional information, gained, for example, by different oriented outcrop sections or radar profiles (Beres et al., 1999), is needed for a correct interpretation. For hydraulic characterization gravel dunes represent highly heterogeneous units characterized by an inclined interbedding of high and low permeable zones. While migrating two-dimensional dunes generate sheet-like geometries, 3-D dunes are probably preserved as trough-shaped bodies.

5. Analysis of gravel body architecture—patterns of heterogeneity

The size of depositional elements determines the required size of outcrop walls for their analysis (if possible, perpendicular sections in different directions). In some cases an outcrop wall of 20 m × 7 m is sufficient, in other cases outcrop walls of more than 100 m × 10 m are needed to understand the architecture of gravel bodies (compare also the different lengths of the examples from Fig. 5). According to the required outcrop conditions we refer in this section to a database of 11 selected gravel pits.

The comparison of the outcrops revealed regionally different patterns of sedimentary architecture. Three basic recurrent patterns appear within the paleo-discharge zones of the Rhine glacier. They differ both in size and frequency of ‘cut-and-fill’ elements and in the frequency of the different lithofacies (Fig. 6). Especially the size of ‘cut-and-fill’ elements is an important indicator. We imagine that apart from sediment supply, gradient, and valley cross-section, the quantity of discharge is the most critical controlling factor for the formation of ‘cut-and-fill’ elements in these coarse-grained deposits. Hence, we refer to three basic architectural patterns or facies assemblages as ‘main’-, ‘intermediate’- and ‘minor’ discharge areas (see Section 6).

5.1. Main discharge area (Rhine Valley)

Gravel bodies in the main discharge area are characterized by a dominance of thick and extensive ‘cut-and-fill’ elements which are interpreted as (migrating) scour pool fills. The internal structure is built up by cross-bedded sets consisting chiefly of the lithofacies alternating gravel (Gcg,a) and poorly sorted gravel (Gcm). ‘Accretionary’ elements occur only as relics. They are represented by horizontal to massively bedded gravel sheets built up by poorly sorted gravel with variable amount of large clasts (Gcm, cGcm).

The style of heterogeneity is therefore determined by stacking of scour pool fills. The result is a highly complex interfingering and interbedding of permeable (cGcg,o/Gcg,o/sGcg,o) and less permeable (Gcm/sGcm/Gcm,b) zones. Hence, hydraulically similar units can be connected to each other which, for example, enables the formation of highly permeable networks. Relics of ‘accretionary’ elements are horizontal and homogeneous zones of lower permeability.

5.2. Intermediate discharge area (Upper Swabia)

The sedimentary construction of gravel bodies of the intermediate discharge areas displays smaller scale depositional elements. ‘Accretionary’ elements dominate, represented in this example by horizontal to subhorizontal units of gravel sheets (Gcm) and traction carpets (c,bGcm). ‘Cut-and-fill’ elements appear solitary and are built up by cross-bedded sets of
Fig. 5. Comparison of different styles of sedimentary architecture in gravel bodies. The three major regional and recurrent patterns differ according to the stacking of depositional elements and associated lithofacies. Example ‘main discharge area’ is oriented parallel to the overall paleoflow direction (from the left to the right), example ‘intermediate discharge area’ is oriented perpendicular to paleoflow (direction to the outcrop wall) and in example ‘minor discharge area’ paleoflow was from the right to the left.
poorly sorted gravel (Gcx). Well-sorted gravel (GS-x) and sand (S-x) occur frequently, whereas the frequency of alternating gravel (Gcg,a) is reduced. These ‘cut-and-fill’ elements are interpreted as local (non-migrating) scour pools and small dissection elements.

Fig. 6. Statistical survey within the studied gravel pits: the frequency of depositional elements, their size and occurrence of lithofacies types enable the regional classification of gravel bodies into ‘main’-, ‘intermediate’- and ‘minor’ discharge area. (A) Ratio of the element groups (‘cut-and-fill’/‘accretionary’), (B) size of ‘cut-and-fill’ elements, (C) lithofacies portions, (D) comparison of the frequency of highly permeable openwork gravels occurring within lithofacies ‘alternating gravel’ (Gcg,a).
The heterogeneity of these gravel bodies is therefore characterized by a ‘matrix’ of homogeneous ‘accretionary’ elements in which small and heterogeneous ‘cut-and-fill’ elements are interbedded and often not connected to each other.

5.3. Minor discharge area (Upper Swabia)

Gravel bodies of the minor discharge area are characterized by a mosaic of very small-scaled interfingering of many sedimentary units. The clear-cut identification of depositional elements is often difficult and indistinct. While poorly sorted gravel (Gcm/Gcx/sGcm/fGcm) dominates the lithofacies record, alternating gravel (Gcg,a) appears irregularly distributed particularly within cross-bedded units. Sand (S-x) and well-sorted gravel (GS-x) occur rarely. The deposits are interpreted as sedimentary records of gravel sheets (horizontal to subhorizontal units) and gravel dunes (inclined units).

The small-scaled interfingering of sedimentary units leads to a complex pattern of heterogeneity. In this case, however, the thin and finely distributed units of alternating gravel are not connected with each other and often separated by low permeability zones (e.g. fGcm).

5.4. Statistics

Classification into the three groups—‘main-’, ‘intermediate-’ and ‘minor’ discharge area—resulted from comparison and statistical survey of many outcrops. At each site the fractional portion of depositional elements, their size and their lithofacies buildup was recorded (Fig. 6). To document changes in the ongoing gravel excavation and reduce local deviations, this standardized survey was carried out four to five times, respectively, at each repeated visit of the gravel pit over a time period of 1.5 years. To increase objectivity, this was done by several persons. While sizes of depositional elements could be measured accurately at different oriented sections, the internal fill of lithofacies had to be estimated within a certain error margin. However, statistical differences could be recognized underlining the grouping into three patterns of heterogeneities. Fig. 6A/B highlights the dominance of large ‘cut-and-fill’ elements in deposits of the ‘main discharge area’. While gravel bodies of the ‘intermediate discharge area’ are built up mainly of larger portions of ‘accretionary’ elements, the size of ‘cut-and-fill’ elements as well as their frequency is clearly reduced within the ‘minor discharge area’.

Fig. 6D shows the occurrence of alternating gravel. Large (migrating) scour pools of the ‘main discharge area’ represent favourable positions for the development of alternating gravel (Gcg,a). Within the small ‘cut-and-fill’ elements of the intermediate discharge area, this lithofacies is rare. The gravel dunes of the ‘minor discharge area’ contain again portions of alternating gravel.

In addition to the sedimentological classification into groups, these analog data may in the future also represent important input parameters for geostatistical modeling of such highly heterogeneous deposits.

6. Facies models

Based on these three major facies assemblages, three conceptual facies models are deduced (Fig. 7) for proglacial river systems appearing in regional paleodrainage systems of the Rhine glacier.

The ‘main discharge area’ is characterized by large and stable channels with a permanent transport of water and sediment. Discharge behavior could be described as high frequency/high amplitude. Deep and large scour pools, with changing position in time (migration), form particularly at channel confluences. Due to their topographic deepest position within this fluvial system, these depositional elements are preserved preferentially (Siegenthaler and Huggenberger, 1993). Channel accumulations (gravel sheets, gravel dunes) deposited at elevated topographic levels remain only as relics in these highly dynamic systems.

Within the ‘intermediate discharge zone,’ channels are more smooth and less stable. Small ‘cut-and-fill’ elements form locally and remain at their position (little migration). High magnitude floods easily can destroy and reorganize the active fluvial system (moderate frequency/high amplitude) resulting in a preservation of small ‘cut-and-fill’ elements and channel deposits.

The lack of sorting processes (lithofacies fGcm, nearly complete absence of pure sand deposits) as well as the small-scale interfingering of sedimentary units within the ‘minor discharge zone’ indicates a pulsatory (flashy) transport and deposition (low fre-
quency/high amplitude). At low magnitudes, water is flowing only in small and less dynamic channels (rills). Flashy high-magnitude events, however, lead to a short-term transport and deposition of gravel dunes and gravel sheets within the active zone.

7. Flow modeling and particle tracking

Following the procedure of Klingbeil et al. (1999), the outcrop maps were digitized onscreen as arcs of different lithofacies at their bounding surfaces using the GIS-software Arc Info. The arcs were changed to polygons, which were labeled by lithofacies identifications and connected to a polygon attribute table containing the hydrogeological parameters for the hydrofacies as characterized above and listed in Table 2 (hydraulic conductivity and porosity). This procedure results in a high resolution permeability field based on the outcrop (lithofacies) information (see Fig. 5). The polygon-based coverages can be transferred into a grid with specified cell sizes. The grid cell size was of the order of 5 cm x 5 cm, a resolution that ensures that thin non-horizontal elements (mostly the high conductivity units: cGg,o, Gg,o and sGg,o) are adequately represented and local scale dispersion could be neglected. The grid itself can then be exported as an ASCII data file to a flow and transport model (in our case, the finite-difference numerical code MODFLOW (McDonald and Harbaugh, 1984) and semi-analytical code MODPATH (Pollock, 1989) and the particle tracking module (PMPATH)). The aquifer is assumed to be confined with a hydraulic head gradient of 0.01 between the left- and the right-hand fixed-head boundary. The particle tracking model starts with the distribution of particles along the left (inflow) boundaries. The distribution of particles was based on the total inflow per cell along the inflow boundary. Fig. 8 shows selected particle pathlines through the example data sets and illustrates how the
Fig. 8. Comparison of hydraulic conductivity distribution and modeled flow lines for the three gravel body architectures. Selected pathlines (one particle each cell) show that the high hydraulic conductivity units (cGcG, GcG, GcG) focus the flow lines.

`intermediate discharge area`

`main discharge area`

`minor discharge area`
high conductivity units focus the particles (e.g., main discharge area, Hartheim). It is seen that the heterogeneous structure of the subsurface leads to the development of considerable flow channeling, with most of the flow occurring in the scour pool dominated area, where medium to high conductivity hydrofacies prevail. The intermediate and minor discharge areas (examples Pfullendorf and Bolstern) display a more homogenous flow field due to thick and extended horizontal gravel sheets, although the water flow is forced through higher permeable units (e.g., lower part of Pfullendorf) even if they are separated and quite small. To compare the hydraulic signal for the different discharge types, particle breakthrough curves (arrival times) were created. The hydraulic heterogeneity divided down to a 5-cm grid accounts for the macroscopic dispersion. According to Charbeneau (1981), pore-scale dispersion and molecular diffusion can be neglected in advection-dominated situations. For a direct comparison of the three parameter fields the Hartheim data set was reduced to 20.5 m (area from 20.5 to 41 m). Arrival times for 1000 flux distributed particles are displayed on a cumulative base in Fig. 9. The fastest arrival, as expected, occurs in the main discharge area where higher fractions of interconnected high permeability units (hydrofacies cGcg,o, Gcg,o, sGcg,o,) are present compared to the other two sedimentary architectures, both of which show increasing arrival times. The mean arrival time varies between 5.6 days and almost 18 days. The observed long tailing of more than 10% of the particles (arrival times larger than 40 days) especially in the minor discharge area is due to extended low permeability units (fGcm). From the flow budget calculations (Darcy’s law), the geometry of the model, and the mean arrival time, an effective hydraulic conductivity \( k_{\text{eff}} \) and an effective porosity \( n_{\text{eff}} \) were calculated for each zone (see Klingbeil, 1998 for details). The results show, as expected, that the highest \( k_{\text{eff}} \) and \( n_{\text{eff}} \) occur in the main discharge area \( (k_{\text{eff}}=7.6 \times 10^{-4} \text{ ms}^{-1}, n_{\text{eff}}=17.6) \) followed by the intermediate \( (k_{\text{eff}}=2.2 \times 10^{-4} \text{ ms}^{-1}, n_{\text{eff}}=13.8) \) and minor discharge areas \( (k_{\text{eff}}=1.5 \times 10^{-4} \text{ ms}^{-1}, n_{\text{eff}}=11.2) \).

The observed hydraulic signal is significantly different for the three discharge areas indicating the importance of precise characterization of the litho- and hydrofacies distribution. Vice versa it might be possible to draw conclusions on the sedimentary architecture based on field tracer experiments.

8. Discussion

The results of the two-dimensional modeling are only an approach to illustrate groundwater flow pat-
tern within these different styles of gravel body architectures. Of course, the motion of water particles is not restricted to a two-dimensional plain and in nature three-dimensional pathways must be considered. Up to now, three-dimensional detection and modeling which detect in such detail (cm scale) the facies distribution have not been carried out.

In order to characterize the effects of the third dimension it is important to understand facies length characteristics relative to paleoflow. Because lithofacies distribution is closely connected to the formation of depositional elements within the braided river environments, the size as well as the elongation and direction of depositional elements generally determines the correlation length of litho-/hydrofacies. It is obvious that the effects of the third dimension vary between the three described regional gravel body architectures.

Gravel bodies formed within the minor discharge area show no relevant differences of facies lengths in different directions. The depositional elements are very small scale and interfinger within a distance of decimeter to meter. Simplified, the litho-/hydrofacies are more or less randomly distributed and no preferred elongation has been noticed in the outcrops. It is assumed that natural groundwater flow in a three-dimensional gravel body of this style is very similar in direction parallel and perpendicular to paleoflow and that the two-dimensional modeling reflects an almost homogeneous flow pattern.

Gravel bodies of the intermediate discharge areas are dominated by accretionary depositional elements (mainly deposits of gravel sheets and traction carpets). During their formation, single elements are elongated in paleoflow direction. However, downward, lateral and vertical stacking of countless of these elements during aggradation of a fluvial system leads to a more or less homogeneous sediment package (predominantly lithofacies Gcm; (c,b)Gcm). The cut-and-fill

<table>
<thead>
<tr>
<th>Architecture of gravel body</th>
<th>‘Main discharge area’</th>
<th>‘Intermediate discharge area’</th>
<th>‘Minor discharge area’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site number</td>
<td>1 2 3 4 5</td>
<td>6 7 8</td>
<td>9 10 11</td>
</tr>
<tr>
<td>Accretionary-/cut-and-fill elements [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>median thickness</td>
<td>1.7 2.2 1.9 1.8 1.0</td>
<td>0.8 0.7 0.8</td>
<td>0.3 0.5 0.6</td>
</tr>
<tr>
<td>max. thickness</td>
<td>4.0 5 3.5 3.0 1.5</td>
<td>1.5 1.4 1.5</td>
<td>0.5 0.8 1</td>
</tr>
<tr>
<td>median width</td>
<td>21 28 30 26 19.3</td>
<td>8 7.3 9</td>
<td>2.1 3.7 4.3</td>
</tr>
<tr>
<td>max. width</td>
<td>40 45 38 50 25</td>
<td>13 11 15</td>
<td>4.0 8.0 12</td>
</tr>
<tr>
<td>median length</td>
<td>45 32 38 39 24</td>
<td>12 11.8 13</td>
<td>2.1 3.7 4.3</td>
</tr>
<tr>
<td>max. length</td>
<td>70 100 &gt;60 60 &gt;30</td>
<td>20 30 20</td>
<td>4.0 8.0 12</td>
</tr>
</tbody>
</table>

Hydrofacies portion [%]

| bGcm          | 0 0 0 0 40 | 14 1 0 0 0 |
| cGcm          | 2 2 3 5 13 | 22 11 20 10 8 |
| Gcm           | 13 3 16 4 0 | 30 25 34 20 10 |
| Gcx           | 16 21 20 20 10 | 6 20 18 9 10 |
| sGcm          | 12 24 2 23 17 | 4 14 7 38 30 |
| fGcm          | 0 0 0 0 0 | 0 0 0 0 0 |
| cGeg,a        | 4 0 0 0 0 | 1 0 0 0 0 |
| Geg,a         | 23 10 13 5 5 | 6 2 5 1 0 |
| sGeg,a        | 12 20 25 21 8 | 2 6 2 15 16 |
| fGeg,a        | 2 0 0 0 0 | 0 0 0 0 0 |
| Geg,o         | 0 0 4 4 3 | 0 2 0 1 0 |
| Gcm,b         | 8 5 9 2 2 | 2 0 2 0 1 |
| GS-x          | 4 10 4 4 1 | 8 12 9 2 6 |
| S-x           | 4 5 4 12 1 | 5 7 3 2 5 |

Sizes of cut-and-fill elements were measured with respect to paleoflow (width=perpendicular to paleoflow, length=parallel to paleoflow).
elements developed in this environment are slightly elongated in direction of paleoflow (see Table 3). Because they often appear solitary, enclosed within a ‘matrix’ of accretionary elements, the influence of elongated facies lengths is limited to small-scale units and thus has only a minor effect on total three-dimensional flow. Within a three-dimensional gravel body of the intermediate style, we thus expect in all lateral directions a comparably homogeneous flow pattern as imaged in the two-dimensional example (see Fig. 8).

In contrast, within gravel body architectures of the main discharge style, the third dimension probably plays an important role on flow. Due to the lateral and vertical stacking of large cut-and-fill elements (scour pool fills), which are constructed of cross-bedded low and high permeable hydrofacies units, a much more complex pattern of facies distribution has to be assumed. The preserved migrating scour pool fills are strongly elongated in the overall direction of paleoflow (see Table 3). However, the length of these elements cannot directly be converted into lengths of litho-/hydrofacies. Due to downstream migration of scour pool fills and progressive sedimentation at upstream positions during their formation, the facies length is controlled by the original size of the geomorphologic scour pool element of the fluvial system. Additionally, cut-and-fill elements are often not exactly directed parallel to the overall paleoflow direction and in several cases a deviation of more than 90° was noticed (Siegenthaler and Huggenberger, 1993). In general, however, facies lengths are often distinctly longer parallel to flow direction than perpendicular to it. A quantitative evaluation of the facies-correlation lengths should be conducted in the future especially in this style of gravel body architecture.

The third dimension probably leads to major deviations of the flowpaths. As shown in the two-dimensional modeling of Fig. 8, the particles are focused within the highly conductive open framework units (Gcg,o). Water particle will always choose the paths with the longest way being in the high conductive layers and, simultaneously, the shortest distances within the low conductive units. Thus, the focusing-effects are likely to be more prominent in a three-dimensional gravel body of the main discharge style. For the first arrival time of particles this means that the time given in Fig. 9 represents the maximum time for this distance and there are probably faster paths in the third dimension. In contrast, the time given for the latest particles in Fig. 9 is a minimum time period. In the third dimension the possibility for particles to ‘see’ more low conductive hydrofacies is also likely. The mean arrival time is at least determined by the volumetric proportion of the various hydrofacies types where the mass of water particles has moved through during migration. Because the hydraulic values of low conductive facies differ from open framework units in the order of several magnitudes ($10^{-7}$ to $10^9$), particularly these hydrofacies will determine the mean arrival time. A quantitative estimation of both the changes of flowpaths and the variations in arrival times is very difficult. Thus, the influence on the third dimension can only be detected by modeling of several examples of three-dimensional gravel bodies.

9. Conclusion

Comparative facies analysis of numerous gravel pits and a statistical evaluation revealed three recurrent patterns of sedimentary architecture in glaciofluvial gravel-bed deposits in the Rhine glacier area. According to the regional appearance of these architecture styles the following facies assemblages were recognized:

1) gravel bodies of the ‘main discharge area’, which are dominated by a stacking of large cut-and-fill elements (scour pool fills),

2) gravel bodies of the ‘intermediate discharge area’, which are characterized by a dominance of accretionary elements (e.g. gravel sheets) and locally small cut-and-fill elements and

3) gravel bodies of the ‘minor discharge area’, which show an interfingering of many small-scaled accretionary elements with no distinct surface boundaries.

The major depositional elements (scour pool elements, small dissection elements, horizontally bedded gravel sheets, massive gravel sheets, cross-bedded gravel dunes) show differences in their size, geometry and internal structure and determine the distribution of their component lithofacies.

Within the glaciofluvial gravels at the Rhine glacier area five major lithofacies types were distin-
guished. They were subdivided into 12 hydrofacies types. A range of 7 orders of magnitude in hydraulic conductivity ($10^5$ m$^{-1}$ s$^{-1}$ < $k_r$ < $10^{-7}$ m$^{-1}$) was measured in column tests and calculated based on grain-size analysis.

Sedimentological outcrop wall mappings that show an accurate distribution of lithofacies were transferred into two-dimensional hydraulic parameter fields. For each type of gravel body architecture a numerical modeling of fluid flow and transport has been carried out. These models showed that the sedimentologically classified gravel bodies (heterogeneity pattern) are also characterized by a distinguishable hydraulic response signal.

Thus, it may be possible to combine the sedimentological analysis of extremely heterogeneous gravel deposits with a hydrogeological characterization. In this study, we showed that sedimentary processes are responsible for the heterogeneities that determine local groundwater flow in aquifers.

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