EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Zentrum für Angewandte Geowissenschaften (ZAG)

TÜBINGER GEOWISSENSCHAFTLICHE ARBEITEN (TGA)

Reihe C: Hydro-, Ingenieur- und Umweltgeologie

Schriftleitung: P. Grathwohl, G. Teutsch

Jürgen Heinz

Sedimentary Geology of Glacial and Periglacial Gravel Bodies (SW-Germany)

TGA, C59, 2001

Herausgeber: Institut für Geowissenschaften der Universität Tübingen
Sigwartstraße 10, D-72076 Tübingen

Schriftleitung der Reihe C: Lehrstuhl für Angewandte Geologie
Prof. Dr. Peter Grathwohl & Prof. Dr. Georg Teutsch

Redaktion: Dipl.-Geol. Björn Sack-Kühner

ISSN 0935-4948
ISSN 1610-4706 (Internet)

Sedimentary Geology of Glacial and Periglacial Gravel Bodies (SW-Germany): Dynamic Stratigraphy and Aquifer-Sedimentology

Jürgen Heinz

Institut für Geologie und Paläontologie
Universität Tübingen
Sigwartstr. 10
72076 Tübingen
Germany

Abstract:

Würmian, coarse-grained meltwater deposits were studied in more than 70 gravel pits of SW-Germany. The enormous heterogeneity and complexity of sedimentary architecture of gravel bodies and its distribution within the Rhine glacier area and its discharge zones required the use of various sedimentological, stratigraphic, geophysical and hydrological methods.

In order to understand the processes of formation of these glacial deposits the principles of 'Dynamic Stratigraphy' were applied. Stratigraphic units were classified into a hierarchy of temporal and spatial scales (1. particles; 2. strata; 3. depositional elements; 4. facies bodies; 5. sequences; 6. basin fills). Their genesis and geophysical record but also their relevance for hydrogeology is discussed.

A particular focus is placed on the qualitative and quantitative characterization of fluvial gravel-bed deposits which represent important groundwater storages in many valley fills in Europe. The translation of sedimentary units into hydrogeological properties (lithofacies - hydrofacies; depositional elements - correlation structures; gravel body architectures - heterogeneity patterns) provided important fluid-flow parameters. Detailed outcrop-wall maps were digitalized and transformed into 2-dimensional permeability fields. The numerical simulations show how sedimentary architectures determine the flow-paths and flow-velocity of groundwater.

Additionally, 3-D georadar surveys were carried out in order to calibrate and characterize fluvial gravel deposits. The method resolves a detailed structural image of the spatial subsurface architecture and allows the recognition of the different gravel bodies. Quantified geometrical data from both braided river deposits and meandering river deposits are documented.

Various meltwater-controlled facies bodies were formed during an overall ice-retreat of the Würmian Rhine glacier. Due to a combination of outcrop analysis, georadar measurements and modern topography investigations (digital elevation models) several depositional environments could have been reconstructed. A summary of lithofacies types, stratal organizations and deformation structures is documented.

Kurzfassung:

Würmzeitliche, grobklastische Schmelzwasserablagerungen wurden in mehr als 70 Kiesgruben in SW-Deutschland untersucht. Um die Bildungsprozesse zu verstehen, wurde die Methodik der ‚Dynamischen Stratigraphie' angewandt. Sedimentäre Einheiten werden dabei in eine Hierarchie zeitlicher und räumlicher Größenmaßstäbe eingeordnet (1. Partikel, 2. Schichtung, 3. Ablagerungs-Elemente, 4. Fazies-Körper, 5. Sequenzen, 6. Beckenfüllungen). Neben ihrer Genese und ihrer geophysikalischen Erfassung wird auch die jeweilige Bedeutung für die Hydrogeologie diskutiert.

Ein Schwerpunkt dieser Arbeit liegt auf der Charakterisierung von fluviatilen Kiesablagerungen. Proglaziale ‚braided river'-Ablagerungen unterscheiden sich anhand der Ausbildung und Häufigkeit von Lithofaziestypen und Ablagerungs-Elementen sowie ihres sedimentären Stapelungsmusters. Die Übersetzung der Grundtypen von Kieskörpern in hydrogeologische Heterogenitäten (Lithofazies - Hydrofazies, Ablagerungs-Elemente – Korrelationsstrukturen, Kieskörperarchitektur – Heterogenitätsmuster) lieferte wichtige Parameter zur Ermittlung des Fließverhaltens von Grundwasser. Resultate numerischer Aufschlussmodellierungen zeigen deutlich, wie die sedimentäre Genese sowohl die Fließpfade als auch die Fließgeschwindigkeit bestimmen.

Zusätzlich wurden 3-D Georadar Messungen durchgeführt. Die Methode liefert ein genaues strukturelles Bild der Architektur des Untergrundes. Die Reflektionen können besonders hinsichtlich der Ablagerungs-Elemente interpretiert und dadurch die Kieskörpertypen unterschieden werden. Es werden quantifizierte geometrische Daten sowohl von ‚braided river'- Ablagerungen als auch von ‚meandering river'- Ablagerungen dokumentiert.

Vielfältige schmelzwasser-kontrollierte Fazieskörper sind während des Zerfalls und Rückzugs des würmzeitlichen Rheingletschers entstanden. Mittels Aufschlussanalysen, Georadarmessungen und der Landschaftsmorphologie (digitale Höhenmodelle) konnten verschiedene Ablagerungsmilieus rekonstruiert werden. Dokumentiert werden Lithofaziestypen, Schichtungsmuster und Deformationsstrukturen.

Acknowledgements

I would like to thank my advisor Prof. Thomas Aigner for the excellent collaboration and helpfull discussions and ideas that fundamentally influenced my understanding of sedimentary geology. I greatly appreciate his interest for this study and the pleasant and positive atmosphere in his working group. My co-advisor Prof. Georg Teutsch is thanked for discussions and support over the last three years.

Special thanks go to my colleagues Sybille Kleineidam and Jens Tronicke for all their help and collaboration during field- and laboratory work and also for editorial advice.

This work profited very much from inspiring discussions with Dr. André Pugin (Illinois State Geological Survey) - special thanks for the introduction into seismic data aquisition and processing! I am also grateful to Mike Kowalski (University of California, Berkeley) for the forward modeling of georadar data.

Furthermore I would like to acknowledge the collaboration with the Geological Survey of Baden-Württemberg (Dr. D. Ellwanger, Dr. W. Werner) and the gravel pit companies in SW-Germany. Particular thanks to RST Rheinfelden and their skilled conductors of the shovel dredgers.

For their help in data acquisition and processing I would like to thank Patrick Russel, Friedrun Marc, Ulrich Müller, Marc Gropius, Monika Schrem, Matthias Schuh, Igor Borel, Avi, Uli, Peter Bayer and Michael Hoch. Without their help this work could not have been finished in the way it finally was.

Sincere thanks to Gerhard Lörcher for the neverending support with GIS, the creation of digital elevation models and all his other advice. Peter Süss introduced me into the ‘Gocad world’ and I thank him for his comprehensive help. Once again, thanks to Ulrich Asprion for the exchange of georadar experiences.

I thank all my friends from the Leibnizhaus for many nice hours and for providing me with vital food particularly during the last weeks of work on this thesis.

Finally, I would like to thank my parents for all their support during the last 30 years.

This work was part of the Collaborative Research Center SFB 275, project C3 ‘Quaternary gravel bodies: sedimentology, hydrogeology and climatic history’ funded by the German Research Foundation.

Contents

1. General introduction

During the Würmian glaciation gravel deposits were formed in different sedimentary environments within the Rhine glacier area and its discharge zones in the Alpine Foreland.

Today these gravel bodies represent important resources for both groundwater storage and raw materials. The lasting high demand of gravel and sand material in the building industry but particularly the need of clean, uncontaminated water requires a comprehensive understanding of the genesis, construction and distribution of these sediments.

Thus the new field of aquifer-sedimentology arised in the last few years (Aigner, 1995; Huggenberger & Aigner, 1999). Prediction of aquifer heterogeneity in different scales is needed for various hydrogeological problems (‘dynamic stratigraphy’). A multidisciplinary approach is demanded in order to interpret the dynamic character of groundwater systems.

This thesis is embeded into a project (SFB 275, TP C3) which focusses on the quantified characterization of gravel bodies. Outcrop analogue- and subsurface- studies are used to assess sedimentological, hydrogeological and geophysical information. The data provide input parameters for the simulation of fluid flow and contaminated transport in ‘real’ aquifers.

Together with geomorphological data (digital elevation models) the present work aims to achieve a qualitative and quantitative characterization of gravel deposits in SW-Germany.

Because of the relatively large area of investigation, the variety of methods as well as the different tasks and applications this thesis is organized into 5 major chapters. Each chapter can be read on its own and in each a detailed introduction and abstract to the specific study is given.

Chapter 2 (Dynamic stratigraphy in glacial deposits: concept, examples and application to aquifer sedimentology) introduces the approach of ‘dynamic stratigraphy’ which represent the red thread trough the whole study. Key points and results from all the following chapters are compiled here. In order to understand the genetic processes of formation, glacial deposits are systematically classified into a hierarchy of spatial and temporal scales (particle-, strata-, depositional element-, facies body-, sequence- and basin fill- scale). In this chapter, the influence of each scale to the hydrogeological properties of aquifers is shown. For a sufficient characterization the need of different investigation tools is emphasized.

Chapter 3 (Characterization of proglacial fluvial gravel bodies: Heterogeneity pattern and application to hydrogeology) focuses on the sedimentary architecture of braided river deposits. 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. Comparison of numerous gravel pits in SW-Germany revealed three major architectural patterns of glaciofluvial gravel bodies which can statistically be distinguished by the preservation of depositional elements as well as the frequency of lithofacies. Outcrop wall maps and laboratory hydraulic property measurements of refined hydrofacies were combined and transformed in a numerical model for groundwater flow and transport. The modeling illustrates that the styles of heterogeneity of gravel bodies have distinguishable hydraulic response characteristics.

In **chapter 4** (Using 3-D georadar surveys to characterize glaciofluvial gravel bodies: Subsurface- and calibration- studies of braided river deposits) closely spaced georadar profiles are used for a 3-D characterization and comparison of the different sedimentary architectures of proglacial gravel bodies. 3-D georadar datasets have been acquired in active gravel pits in order to calibrate the radar profiles with outcrop walls and to analyse, in 3 dimensions, the depositional elements and their stacking pattern in the subsurface. Radar facies and radar sequence boundaries are used to define and map depositional elements. Particularly due to their size and proportion it was possible to distinguish the three regional architecture styles of gravel bodies, as established in chapter 3.

In **chapter 5** (Using 3-D georadar surveys to characterize glaciofluvial gravel bodies: subsurface- and aquifer- studies of meandering river deposits) two examples of coarse-grained meandering river deposits from valley-fills in SW-Germany (Neckar valley, Danube valley) are discussed using 3-D georadar surveys. They differ both in their structural inventory as well as in the preservation of depositional elements. The 3-D georadar information enables the reconstruction of the the paleo-fluvial style and the depositional history without outcrop data. Additionally, the georadar images illuminate the heterogeneity of the subsurface resulting in an appraisal of aquifer behaviour and prediction of local groundwater flow.

In **chapter 6** (Characterization of glacial gravel bodies: outcrop analysis, morphology and georadar surveys) meltwater-controlled facies bodies are documented which have been investigated inside the area of the last maximal ice-extension of the Rhine glacier in SW-Germany. Lithofacies types and their stratal organization and stacking pattern were analysed in active gravel pits indicating both depositional processes and postdepositional deformation structures. The internal sedimentary architecture is combined with external geomorphological features derived from digital elevation models of the area. Four major glacial environments of meltwater deposits are deducted (delta and kames delta-, supraglacial-, englacial- and subglacial- environments). Again georadar surveys have been carried out within outcrops and nearby areas. The results clearly reflect the complex structural architecture of glacial gravel bodies.

2. Dynamic stratigraphy in glacial deposits: concept, examples and application to aquifer sedimentology

2.1 Chapter abstract

The approach of 'dynamic stratigraphy' aims to understand the genetic processes that form stratigraphic units in a hierarchy of spatial and temporal scales. A systematic process-based investigation in glacial deposits was carried out in order to characterize the construction and distribution of stratigraphic units in terms of their sedimentology, but also in terms of their geophysical and hydrological characteristics. On the following scales a newly established database of sedimentary heterogeneities is documented:

1) **particles and pores:** (micro scale) reflecting depositional and diagenetic fluid dynamics as well as source material behaviour (e.g. grainsize, roundness, lithological composition); this may be important for the hydrogeochemistry of groundwater in glacial aquifers (e.g. higher sorption capacity of organic pollutants at C-rich limestone particles).

2) **strata:** (meso scale) contains the recognition of sorting, fabric, texture and stratinomic features which indicate transport and depositional dynamics; the resultant lithofacies types determine basic hydraulic units, called hydrofacies.

3) **depositional elements:** (macro scale) enable reconstruction of sedimentary/geomorphic elements and their dynamics within a depositional system (e.g. gravel-bed braided river system are dominated by gravel sheet-, gravel dunes- and scour pool- depositional elements); the architecture of depositional elements influences the hydraulic connectivity and local permeability structure/distribution within an aquifer body.

4) **facies-bodies:** (mega scale) composed of a stack of depositional elements and strata recording distinct environmental systems and their dynamics (e.g. a coarse-grained prograding delta system); facies bodies represent major compartments of an aquifer.

5) **genetic sequences:** (mega scale) reflect the shifts of depositional environments caused by allocyclic changes (e.g. glacial advance recorded by a coarsening upward sequence); these sequences form separate aquifer storeys.

6) **basin fill:** (giga scale) comprising the lateral and vertical stacking of facies-bodies and genetic sequences controlled by (long-term) glacier dynamics; this level builds the larger-scale hydrostratigraphy.

Outcrop and core data remain crucial for sedimentological investigations, but particularly applications to groundwater- and raw material resources require the use of geophysical tools (e.g. georadar, seismic).

2.2 Introduction

Glacial deposits are commonly characterized by an extreme degree of vertical and lateral heterogeneity. These heterogeneities occur on various spatial and temporal scales and are formed due to a variability of material-composition (with distinct material - properties) and its geometrical and 3-dimensional distribution. Both material-composition and distribution are controlled by sedimentary processes. The resultant heterogeneities have implication for applied sedimentology: notably for the exploration of gravel- and sand deposits and for the properties of groundwater aquifers, which are commonly formed by Quaternary sediments. Their sedimentary patterns determine the hydraulic conductivity which controls the migration and storage of fluids and are thus important parameter for the prediction, protection and clean-up of groundwater resources.

In order to improve the prediction of these heterogeneities a better understanding of sedimentary processes and their controlling factors is needed. Therefore, a simple, but systematically process-based analysis of glacial deposits is proposed addressing the various scales of heterogeneities in a rigorously hierarchical manner (Fig. 2.1).

Glacial deposits have a long history of study and an enormous literature describes depositional systems in different settings according to glacier-position (e.g. sub-, en-, supraglacial, ice-marginal). Major reviews are given by Menzies (1995, 1996) and Brodzikowski & Van Loon (1991).

The purpose of this chapter is three-fold:

1. a systematic analysis of glacial deposits in a hierarchical way covering the different spatial and temporal scales in order to deduce the sedimentary processes of their formation on each level. This approach attempts to integrate the commonly used lithofacies concept (Miall, 1978; Eyles *et al.*, 1983; Keller, 1996), consideration of facies preservation (Siegenthaler & Huggenberger, 1993), the concept of architectural elements (Miall, 1985)

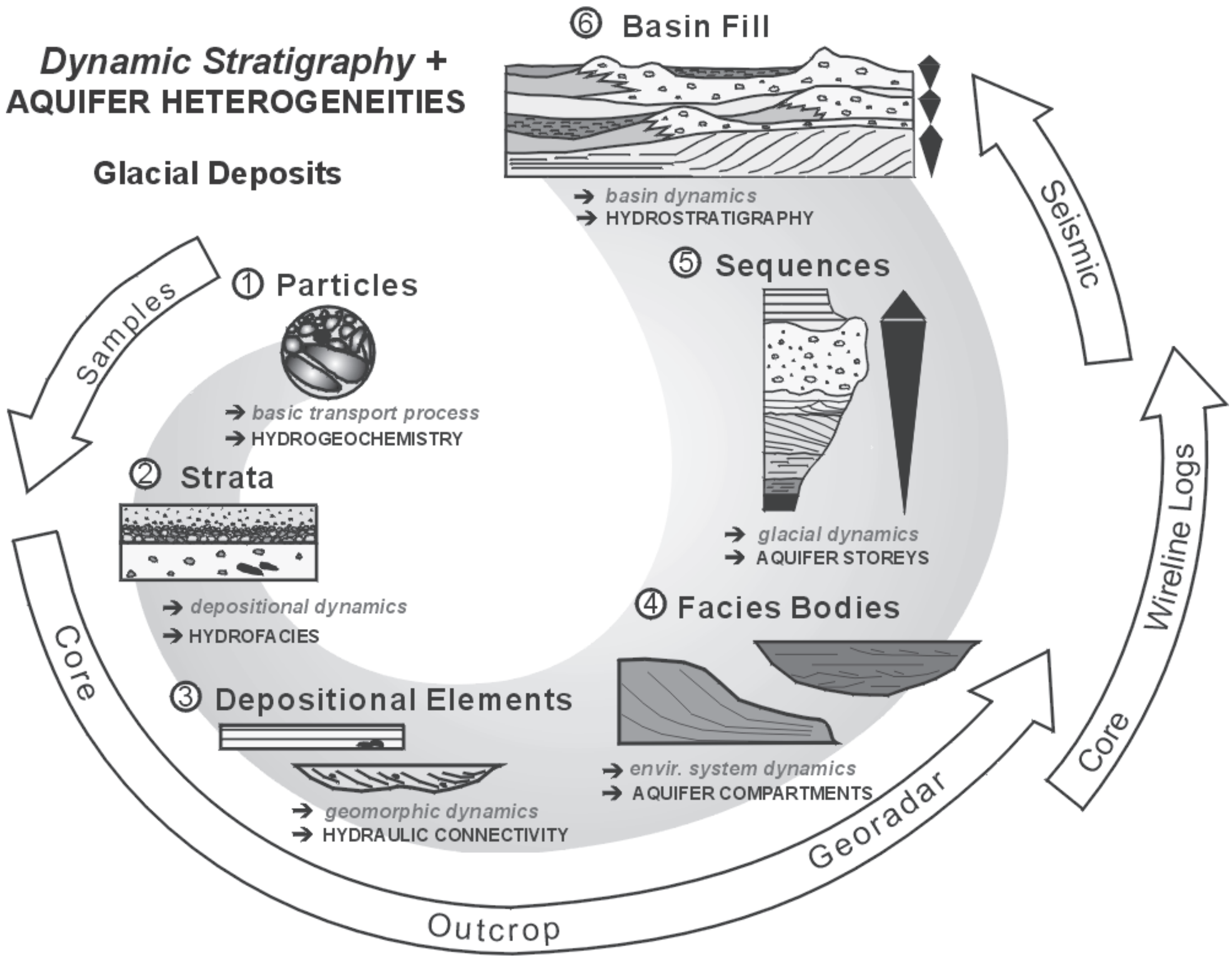


Fig. 2.1: Concept of 'dynamic stratigraphy' as applied to the characterization of glacial deposits. The hierarchy of spatial and temporal scales is systematically studied in a process-based analysis; each scale has implications for the heterogeneity in hydrogeological properties. Note that different investigation tools are necessary for each scale (modified after Aigner et al. 1999).

and large-scale sequence-stratigraphic considerations (e.g. Johnson & Hansel, 1989; Oviatt *et al.*, 1994; Martini & Brookfield, 1995; Brookfield & Martini, 1999) as well as seismostratigraphic investigations (Eyles *et al.*, 1991; Boyce *et al.*, 1995; Pugin *et al.*, 1996, 1999; Lanz *et al.*, 1996; Lysa & Vorren, 1997; van Rensbergen *et al.*, 1999).

2. to illustrate this approach of 'dynamic stratigraphy' by examples from the Rhine glacier area in SW-Germany (Fig. 2.2) with a focus on the facies-analysis of meltwater deposits: 62 glacial and periglacial gravel pits represent the major database for this study. In addition geophysical results are presented emphasizing the need of geophysical techniques for 3-D characterization of these deposits.
3. as the various scales of heterogeneity affect and control the subsurface permeability distribution, their impact for aquifer characterization (see also Koltermann & Gorelick, 1996a) is emphasized and qualitative data on geometries and hydraulic properties of rock units are presented.

2.3 Results

2.3.1 Analysis of particles: basic transport processes and hydrogeochemistry

The analysis of individual sedimentary particles refers to the petrography of the components, their size, roundness and sphericity as well as the recognition of their surface features. These analyses are carried out in a standard way in order to derive the source area (provenance study) of the sediments which often change with time, and to roughly estimate mode and duration/length of transport (e.g. striated components indicate ice-transport).

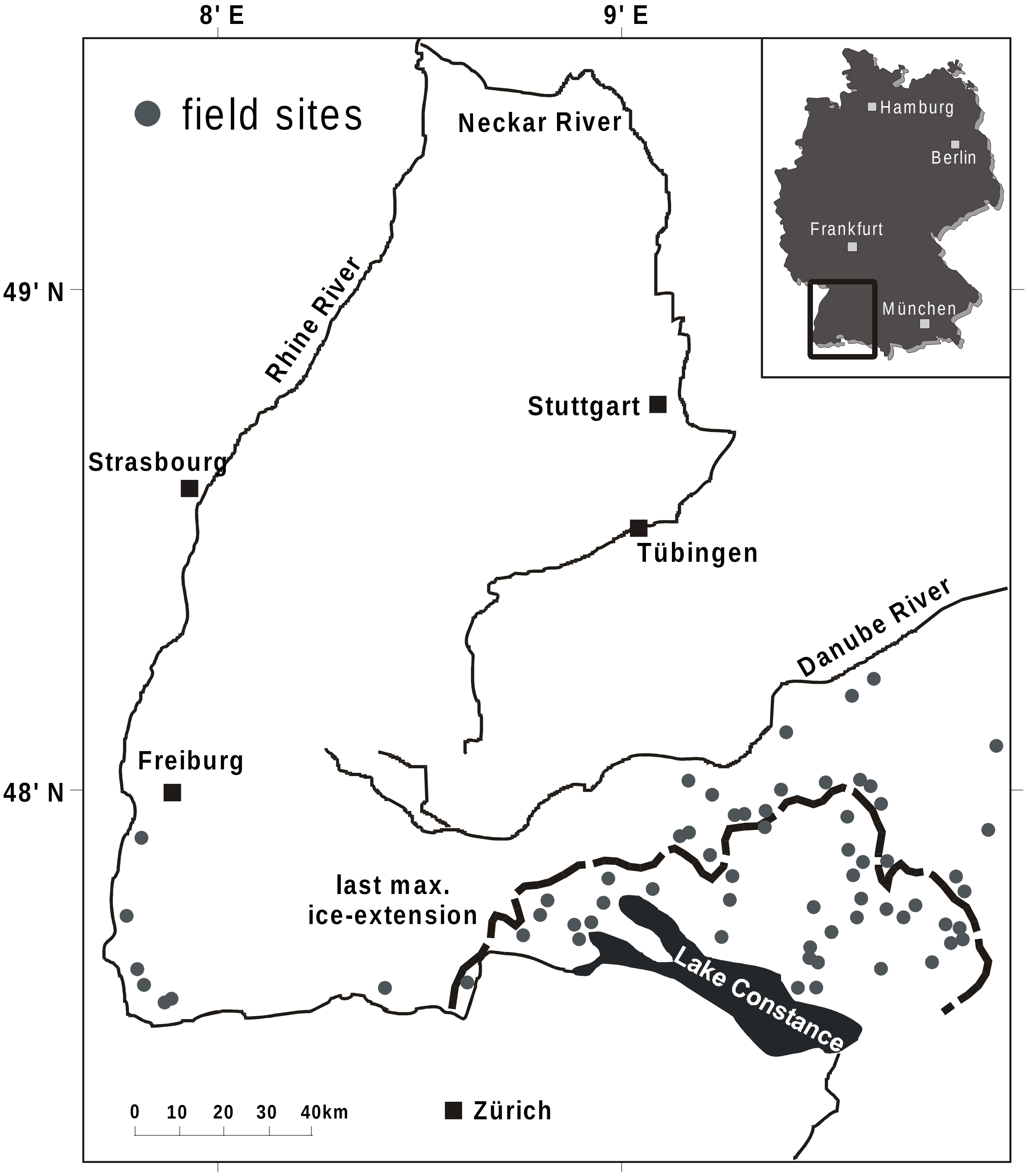


Fig. 2.2: Location map showing the position of the studied sites (mainly gravel pits) according to the last maximum ice-extension of the SW-German Rhine glacier. The investigated deposits mainly have been formed during the Würmian glaciation.

In addition, however, the source material shows very different physical and chemical characteristics. While for instance the sorption of heavy metals is conditioned by the specific surface area (SA) of the lithocomponents, Kleineidam (1999a,b) demonstrated that sorption and desorption behaviour of organic pollutants is mainly determined by the intra-particle distribution of organic material (Table 2.1). Hence dark limestone particles with an c_{org} amount of 0.8 mg/g show a 1000 - time higher sorption capacity then quartz material (c_{org} = 0.04 mg/g). To assess the retardation of organic pollutants - critical for clean up efficiency of contaminated groundwater - within e.g. gravely aquifers it is important to quantify the portion of occuring petrography caused by the source of origin.

Lithology	$CaCO_3$ [%]	C_{org}-content [mg g^{-1}]	log K_d [L kg^{-1}] [C_w = 1µg L^{-1}]	specific surface-area SA [m² g^{-1}]
Dark-coloured limestone	68 ± 7.7	0.80 ± 0.06	3.96 ± 0.02	0.79
Dark-coloured sandstones	33 ± 4.0	0.81 ± 0.14	3.27 ± 0.03	2.19
Light-coloured limestone	75 ± 1.8	0.24 ± 0.04	2.08 ± 0.03	1.84
Light-coloured sandstone	39 ± 7.7	0.29 ± 0.08	1.86 ± 0.07	3.28
Quartz / feldspar minerals	1.4 ± 0.7	0.04 ± 0.01	1.05 ± 0.27	0.092
Igneous/metamorphic rocks	4.0 ± 1.5	0.07 ± 0.01	-0.07 ± 0.46	0.78
Coals	< 0.5	400 ± 0.20	4.30 ± 0.04	7.59

Tab. 2.1: Summary of selected physical and chemical parameters of lithocomponents from the site Singen (after Kleineidam 1999a,b). Content of organic matter (C_{org}) significantly control the sorption capacity [log k_d] of hydrophobic contaminants. The (grain size - conditioned) specific surface area [SA] is an important property for sorption of e.g. heavy minerals.

A)

	indices/ features	abbreviation
i_1	**grain-size**	**b** boulder **c** cobbles **s** sand **f** fines (silt/clay)
I_1	**grain-size**	**G** **G**ravel **S** **S**and **F** **F**ines (silt/clay)
i_2	**texture**	**c** clast-supported **m** matrix-supported
i_3	**stratification**	**x** stratified **m** massive (no bedding) **g** graded (normal, inverse)
i_4	**additional information**	**i** imbrication **a** alternation: e.g. **o** = open framework, **b** = bimodal **h** horizontally stratified **p** planar stratified **t** trough cross-stratified …

B)

lithofacies	hydrofacies	K_f [m/s] experiment	K_f [m/s] calculated	porosity [-] experiment
(c,b) Gcm,i	bGcm		$4.7\cdot10^{-5}$ (1	0.08
	cGcm		$2.3\cdot10^{-4}$ (1	0.15
Gcm	Gcm	$2.5\cdot10^{-4}\pm2.1\cdot10^{-4}$	$3.3\cdot10^{-4}\pm3.3\cdot10^{-4}$ (2	0.17±0.07
	sGcm	$6.1\cdot10^{-5}\pm5.9\cdot10^{-5}$	$7.1\cdot10^{-5}\pm2.2\cdot10^{-5}$ (2	0.13±0.04
	fGcm	$1.6\cdot10^{-6}\pm1.1\ 10^{-6}$	$1.3\cdot10^{-4}\pm3.2\cdot10^{-5}$ (2	0.15±0.02
Gcx	Gcx	$2.3\cdot10^{-4}\pm7.5\ 10^{-5}$	$3.5\cdot10^{-4}\pm1.7\cdot10^{-4}$ (2	0.18±0.03
	cGcg,o		$3\cdot10^{-0}$ (3	0.26±0.02
Gcg,a	Gcg,o	$4.8\cdot10^{-1}\pm2.6\cdot10^{-2}$	$2.0\cdot10^{-1}\pm1.8\cdot10^{-1}$ (3	0.26±0.02
	sGcg,o		$9.5\cdot10^{-2}\pm6.5\cdot10^{-3}$ (3	0.23
	Gcm,b	$6.1\cdot10^{-5}\pm1.8\cdot10^{-4}$	$2.8\cdot10^{-5}\pm2.8\cdot10^{-5}$ (1	0.20±0.08
GS-x	GS-x	$2.3\cdot10^{-3}\pm4.5\cdot10^{-3}$	$5.2\cdot10^{-4}\pm2.4\cdot10^{-4}$ (4	0.27±0.07
S-x	S-x	$1.4\cdot10^{-4}\pm5.0\cdot10^{-3}$	$1.3\cdot10^{-4}\pm1.5\cdot10^{-4}$ (4	0.36±0.04

Tab. 2.2: A) Facies-code (after Keller 1996, modified and extended) used for the description of lithofacies and hydrofacies in fluvial gravel-bed deposits, B) summary of measured and calculated hydraulic properties (conductivity, porosity) for the refined hydrofacies types appearing in fluvial gravel-bed deposits (after Kleineidam, 1998, modified and extended). [1] calculated based on ($K_f = K_f$ (Gcm; Sand) $(1-V_{(C/B)})$), [2] based on empirical equation according to Panda and Lake, [3] based on Kozeny-Carman equation, [4] based on empirical equation according to Beyer.

2.3.2 Analysis of strata: depositional dynamics and hydrofacies

Stratinomic analysis records the orientation of components (fabric), their grading and sorting, texture and stratification. Commonly, the lithofacies-concept (Miall, 1978; Keller, 1996) is applied which proved a useful tool to describe and classify these stratinomic features with a standardized code. However, this coding system has to be extended in order to include hydraulic aspects (Table 2.2 A) (see also chapter 3.4).

For glaciofluvial gravel-bed deposits Fig. 2.3 shows a schematic classification of the 5 major lithofacies types relating to (relative) current energy and rate of sedimentation as well as to transport and depositional processes. The composition of the source material fundamentally determines the resulting lithofacies. In the case of the Rhine glacier, a typical alpine and proximal grain size spectrum is present. The major lithofacies types are all clast-supported and show a dominance of the gravel-fraction (70-85%) whereas the sandy matrix portion is often less then 30%.

Beside recording genetic processes, lithofacies types also affect hydraulic properties. Bierkens (1996) and Anderson (1989) showed that sedimentary properties (grainsize distribution, texture, fabric) can directly be connected to hydraulic properties such as hydraulic conductivity and porosity. The term ‘hydrofacies’ was thus introduced for relatively homogeneous but anisotropic units that are hydrogeologically meaningful (Poeter and Gaylord 1990). These properties have been measured either in the field (pneumatic tests, e.g. Klingbeil, 1999) or in the laboratory (column tests, e.g. Jussel *et al*, 1994; Kleineidam, 1998) or can theoretically be calculated based on grainsize distribution (Kozeny, 1927; Carman, 1938; Beyer, 1964).

The 5 lithofacies types of the fluvial gravel-bed deposits have been subdivided into 14 different hydrofacies (Table 2.2 B). The hydrofacies types have an enormous range of conductivity over several orders of magnitudes (kf = 1m/s for open-work gravels, kf = 10e-7 for massive and matrix-rich (silty) gravels). This means that distribution of lithofacies types significantly determines the value of conductivity and its distribution in porous aquifers (Fig. 2.4). It is essential to know these properties because groundwater flow can be focused to highly permeable and connected zones (e.g. open framework gravels) and hydrogeologists often have to deal with preferential flow paths within aquifers (Fogg, 1990; Poeter & Townsend, 1994; Anderson *et al*., 1999). A more detailed account on the hydraulic properties of various lithofacies types is found in chapter 3.4 and Kleineidam (1998).

2.3.3 Analysis of depositional elements: geomorphic dynamics and hydraulic connectivity

Outcrop studies showed that the various lithofacies types are organized in 2- and 3- dimensional macroscale sedimentary bodies. Miall (1985) introduced the concept of architectural elements showing that former geomorphic units of a fluvial system (e.g. channel, levee, crevasse, floodplain) are preserved in the geological record as bodies with distinct shape, bounding surfaces and internal structure and also with characteristic petrophysical behaviour. Architectural element analysis in 3 dimensions enable the correct reconstruction of paleo-fluvial systems (e.g. Brierley, 1996).

The gravel-bed deposits of the Rhine glacier area have been interpreted as ‘in channel’ sediments and no floodplain strata could be observed (Fig. 2.5). According to Siegenthaler & Huggenberger (1993) the term ‘depositional elements’ is used here in order to describe these characteristical macroform bodies (Jackson, 1975). Two groups of elements were recognized within the glaciofluvial deposits (Heinz & Aigner, 1999):

a) ‘cut-and fill’ elements show a distinct erosional lower bounding surface and are filled mainly with concave upward dipping beds. These forms are either interpreted as channel-based scour pool fills (Siegenthaler & Huggenberger, 1993) or as small trough elements on unit bars (Bluck, 1979).

b) ‘accretionary’ elements are characterized by an aggradational and progradational macroform growing on a flat lower bounding surface. Examples of this group are massive beds of traction carpets, stacking of diffuse gravel-sheets and cross-stratified gravel dunes which are interpreted as in-channel accumulations (see also chapter 3.5).

Due to the distinct position within the fluvial system (channel basis, scour pool) as well as the distinct flow energy and sediment load during their formation, depositional elements are not only characterized by their shape and size but also by their characteristic make-up by distinct lithofacies types.

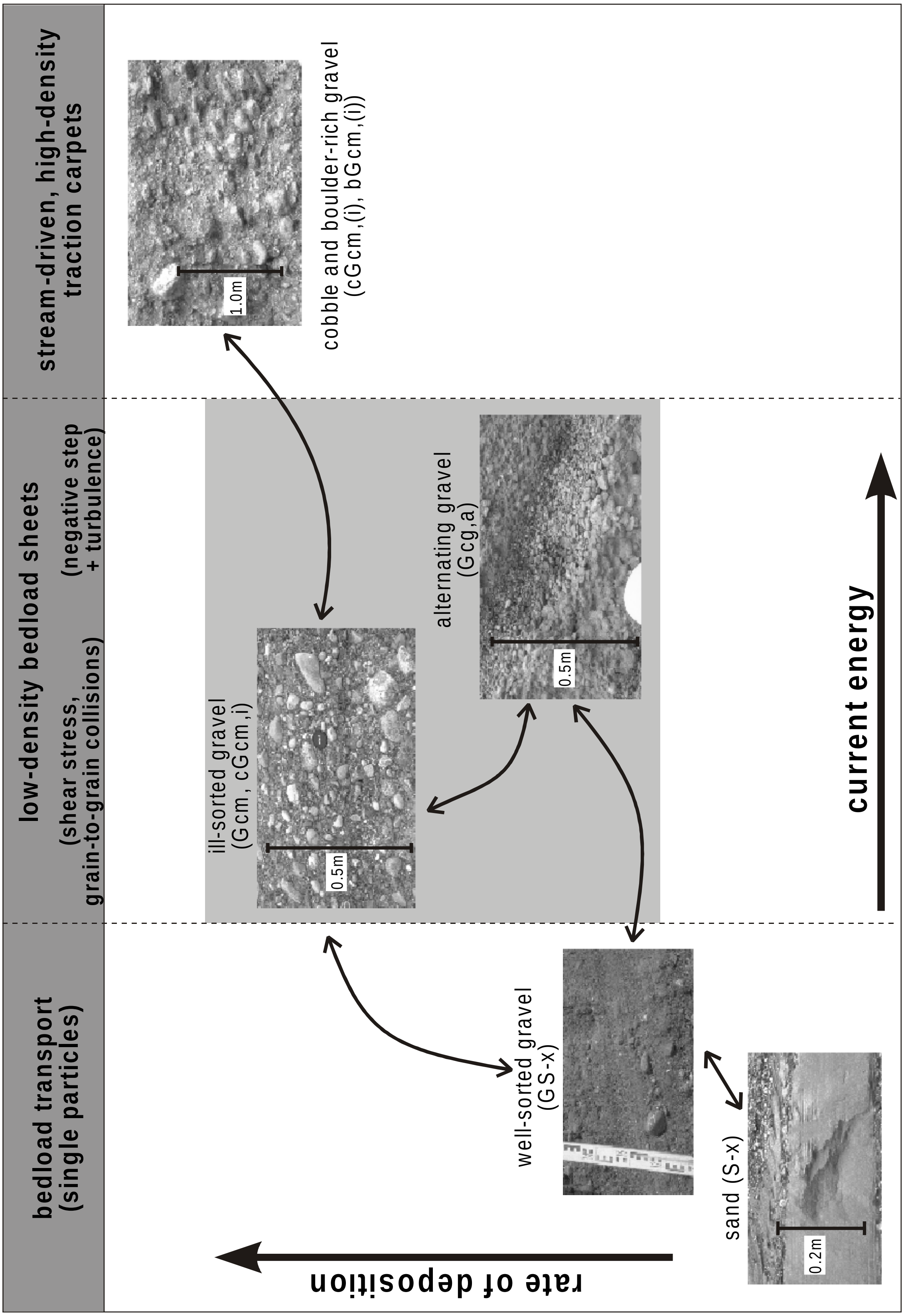


Fig. 2.3: Classification of the five lithofacies types appearing in glaciofluvial gravel-bed deposits in SW-Germany. These are here interpreted as the result of transport- and depositional processes controlled by current energy and sediment charge. At relatively low rate of discharge, sand and gravels are transported as single bedload-particles resulting in the lithofacies types 'pure sands' (S-x) and 'well sorted gravels' (GS-x). At higher flow magnitudes gravel- to sand- mixtures with large clasts are transported as low-density bedload sheets (Gcm) or high-density traction carpets (cGcm). Sorting processes develop due to negative steps and turbulence mechanism and lead to the formation of lithofacies type 'Gcg,a'. Arrows indicate possible transitional lithofacies types.

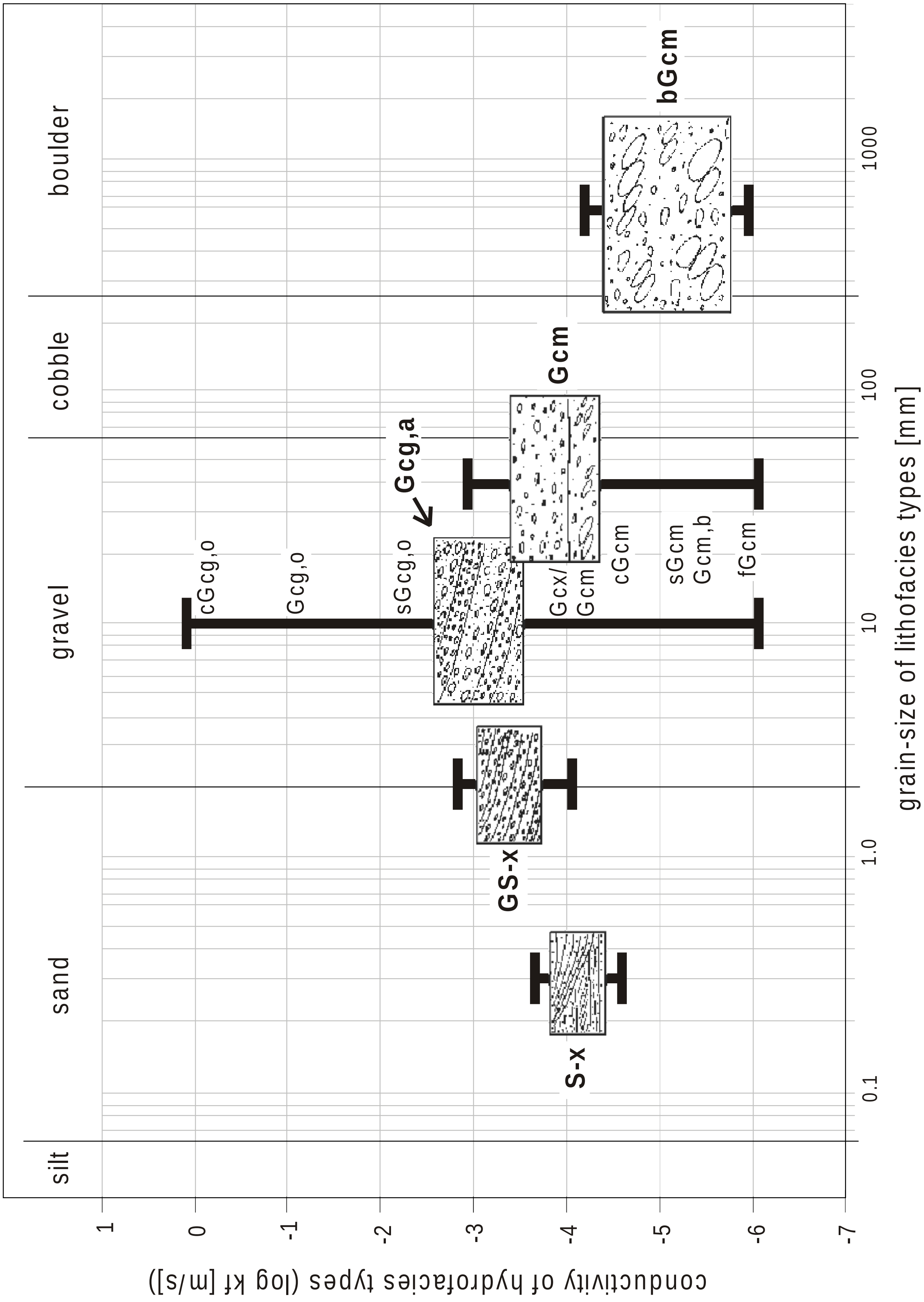


Fig. 2.4: Due to their characteristic textural make up, lithofacies control hydraulic conductivity. For transformation into hydrofacies types, the broad lithofacies types need to be further subdivided (see Tab. 2.2 B). Note, for instance, that lithofacies type ‘Gcg,a’ (alternating gravel) embodies hydraulic conductivities within a range of 7 orders of magnitude.

Comparing deposits of paleo-discharge zones of the Würmian Rhine glacier (see chapter 3) systematic regional paleogeographic differences among the sizes and abundance of cut and fill elements could have been revealed. Gravel bodies developed in the direction North of the Rhine glacier are characterized by small and solitary scour pool fills, while a dominance of large and migrating scour pool fills is found in the region West of the glacier following the modern Rhine valley (Fig. 2.5). The amount of draining meltwater as well as the valley cross section are concluded to be the critical controlling factors for the formation of depositional elements.

For hydrogeologists the comprehension of formation, preservation and construction of depositional elements is of great importance (e.g. Webb & Davis, 1998). They determine the local distribution of permeabilities, the hydraulic correlation lengths and thus the connectivity of permeable units. Hence they are important for local clean-up of contaminated groundwater. Whittaker & Teutsch (1999), for instance, showed a clear directional control of contaminant movement due to large inclined foresets within a scour pool fill.

Within the studied coarse-grained braided river deposits (chapter 3) scour pool fills for instance reflect 3-dimensional bodies with a heterogeneous alternation of cross-stratified low- and high permeable zones. In contrast, massive beds of traction carpets and stacking of diffuse gravel sheets (accretionary elements) are characterized by homogeneous and low-conductive units with a sheet-like extension. Gravel dunes also have a sheet-like geometry but show an cross-stratified internal architecture with alternating high and low permeability zones.

In recent years ground penetrating radar (GPR) is used for the detection of sedimentary structures in the subsurface (e.g. Jol & Smith, 1991; Stephens, 1994; Bristow, 1995; Olsen & Andreasen, 1995; Asprion & Aigner, 1997,1999; Smith & Jol, 1997; Bridge & Alexander, 1998; Huggenberger, 1998; Rea & Knight, 1998; Van Overmeeren, 1998; Beres *et al*., 1999; Vandenberghe & Van Overmeeren, 1999; Van Dam & Schlager, 2000). The transmitted electromagnetic waves are reflected when there is a contrast in dielectric properties of the beds, which is closely coupled with the material properties and water content in the saturated zone or with the material properties and portion of air- and water- filled (capillary water) pores in the unsaturated zone (Huggenberger, 1993). Gravel deposits show high contrasts in the electromagnetic behaviour (clear reflections). Moreover, the lack of fine sediments (silt and clay) enable an adequate penetration depth. GPR profiles therefore support an undisturbed structural image of the subsurface which can be interpreted sedimentologically (see chapter 4,5 and 6). Three-dimensional surveys increase the reliability of the data and enable the spatial mapping of depositional elements. Figure 2.6 shows an example of a three-dimensional data set of braided river deposits with a dominant preservation of large scour-pool fills.

2.3.4 Analysis of facies bodies: environmental system dynamics and aquifer compartments

Facies bodies are constructed by the stacking of several depositional elements and strata within distinct environmental systems (Fig. 2.7). They are characterized by a combination of sedimentary processes (e.g. currents, avalanching, background settling). Facies bodies are 3-dimensional and can reach a lateral extension ranging from hundreds of metres to several tens of kilometres and a thickness of some decameters.

Within the German Rhine glacier area the following major types of facies bodies have been examined in outcrops (see chapter 6):

- proglacial fluvial bodies that build up whole valley-fills are characterized by a lateral and vertical stacking of depositional elements of the ‘cut-and fill’ and ‘accretionary’ type. A regional differentiation in the scale and geometry of scour pool fills has been recognized which is controlled mainly by the discharge regime draining the valley-region.
- terminal moraine complexes of the last maximal ice-extension are build up by less sorted, coarse-grained gravel deposits and diamict deposits, the later being often interpreted as flow tills. The interfingering of gravel and till deposits as well as the deformation of stratification due to ice-compression reflects the oscillation of the ice front.
- prograding delta bodies are characterized by large and inclined foresets of gravel- and sand- beds formed due to avalanching- and current- processes. They can prograde over sandy bottomsets and are often truncated by fluvial topsets. Asprion & Aigner (1999) showed typical examples of ‘Gilbert - type’ deltas in the Singen Basin.

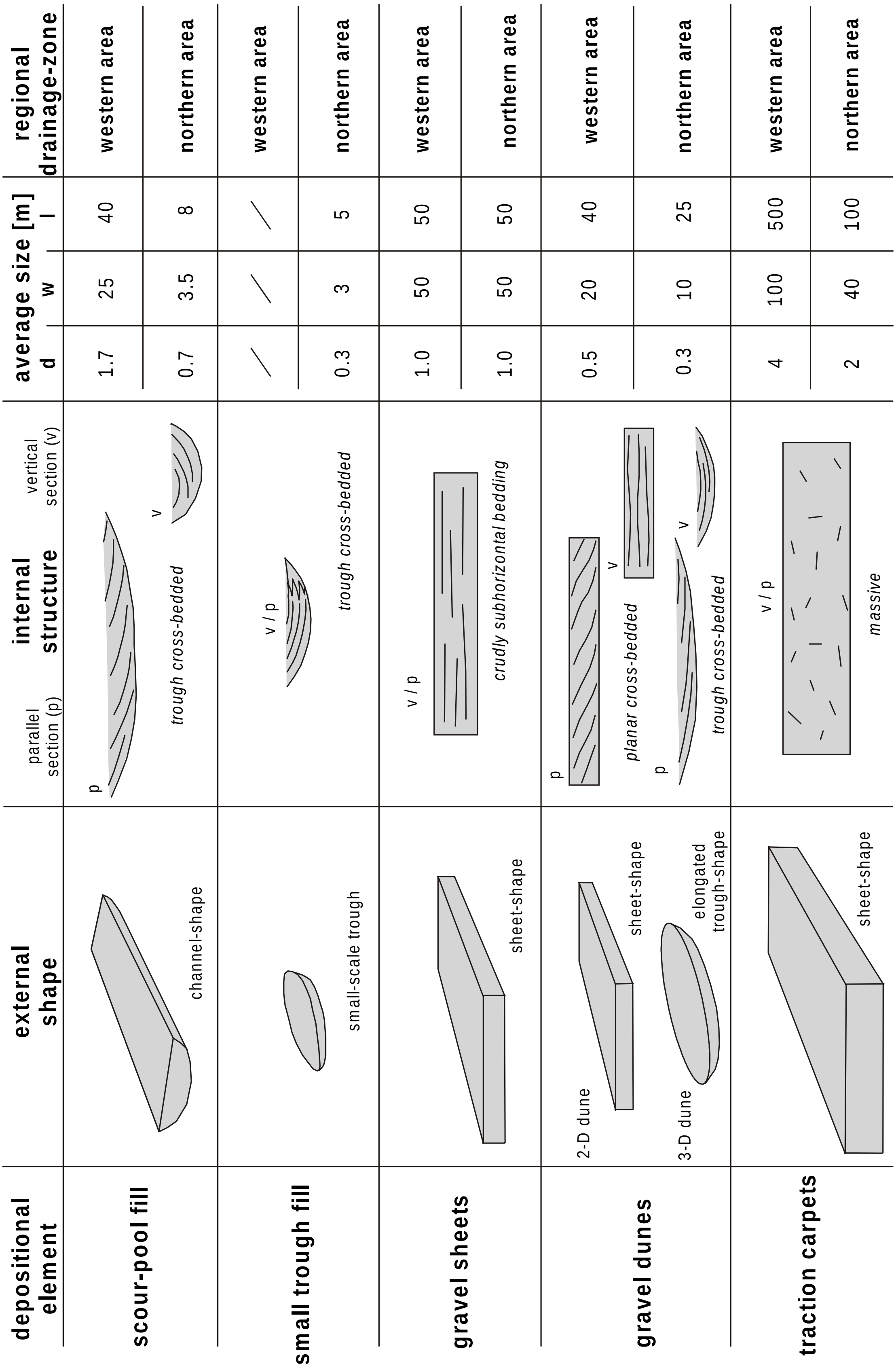


Fig. 2.5: Summary diagram to show quantified data on the geometry and internal structure of depositional elements within paleo-discharge zones of the Rhine glacier. Particularly the size of scour pool fills significantly differs between small drainage areas in the northern parts and the focused area of the Rhine valley in the western part. Depositional elements are characterized by a distinct distribution of lithofacies and hence they control the local correlation structure of permeabilities. Based on wall data of 29 gravel pits plus 7 sites of ground-penetrating radar surveys.

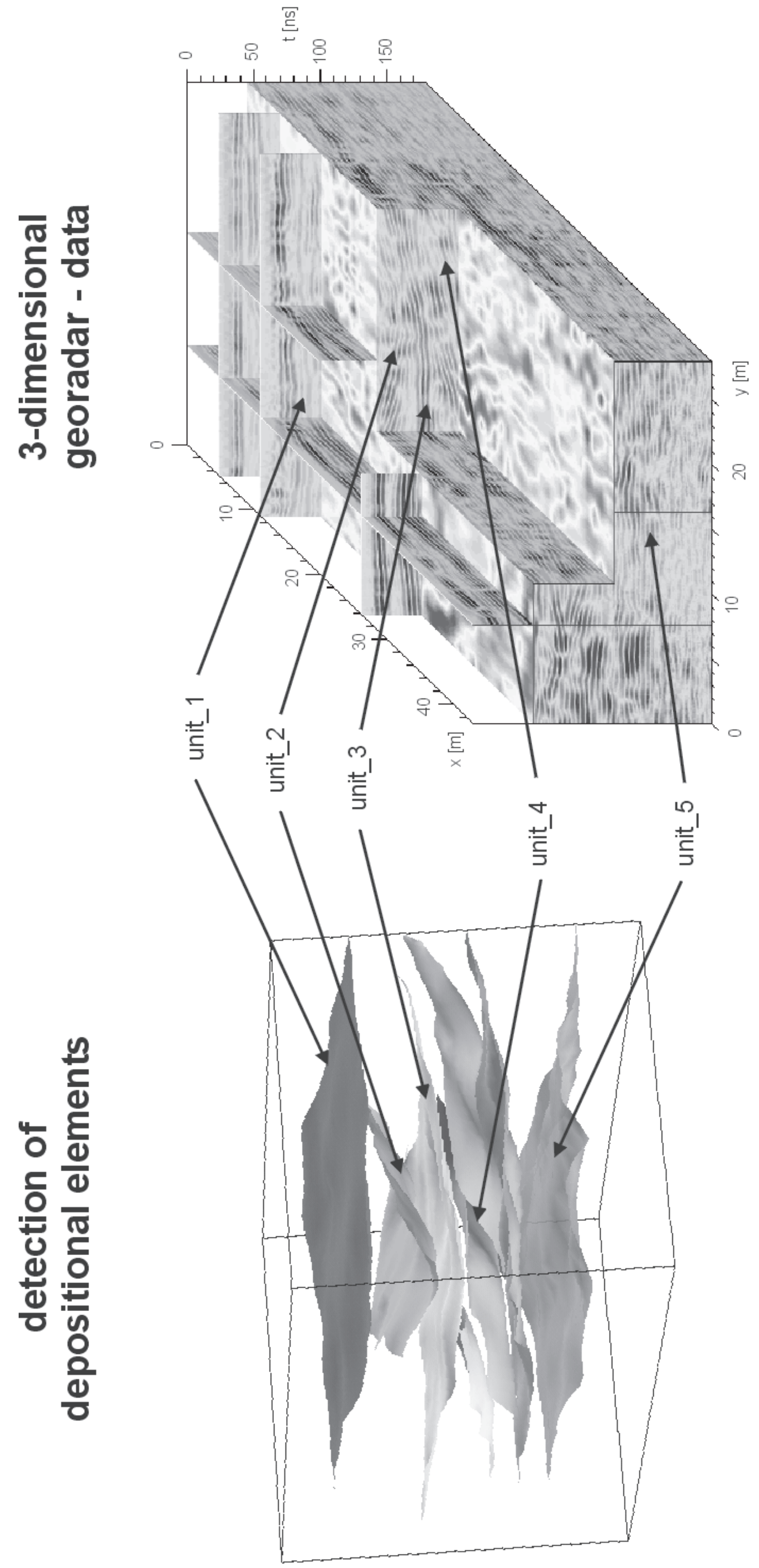


Fig. 2.6: GPR can be used in gravel deposits to map the 3-dimensional geometry of depositional elements in the near subsurface. In this example the horizontal reflector pattern on the top (unit 1) and at the base (unit 5) reflect the record of accretionary elements (gravel sheets + traction carpets) while the trough-shape reflectors in between reveal a zone of dominant scour pool preservation (unit 2,3,4).

- kames bodies can be formed due to different sedimentary processes. In the Rhine glacier area large kames deltas have been studied showing similar deposits as described above. The contact to the ice is reflected by postdepositional normal faults (ice-retreat) and by contemporous deposition of tills sheets and gravel foresets (non-erosive contact).
- facies bodies formed during a phase of rapid ice decay are dominated by supra-glacial, gravelly sediments which are characteristically poorly sorted, coarse grained (boulder-rich) and massive containing many angular to subangular components.
- subglacial esker bodies are regionally characterized by an alternation of inclined gravel- and sandbeds. Particle orientation and stratification often indicate a high rate of shearing during transport and deposition (inverse graded gravels) reflecting the high pressure of subglacial drainage. Also the morphological shapes (drumlin-, hill - shapes) of these facies bodies reflect the deposition in ice cavities (Brennand, 1994).

Facies bodies and their internal architecture form major compartments within glacial aquifers and thus influence groundwater flow. This has been documented by Bersezio *et al*. (1999) for a pro-glacial delta environment, by Boyce & Eyles (2000) for subglacial deposits and for fluvial aquifers by Galloway & Sharpe (1998) and Anderson *et al*. (1999). Figure 2.8 schematically illustrates the predicted (local to regional) flow path patterns of groundwater within facies bodies of different glacial environmental systems.

In addition, the comprehension of formation and construction of facies bodies is important for the exploration of raw materials like sand and gravel deposits. Firstly it is critical to understand the dynamic processes of the different facies bodies in order to predict the quality of material. Secondly the genetic comprehension of their spatial distribution is the base for exploring new production sites.

Figure 2.9 gives a conceptual illustration of the stratigraphic control for the preservation of proglacial gravel-bed deposits. Both accommodation and frequency/quantity of discharge are regarded as the major controlling factors whereas sediment supply is recognized to be high in all cases. While the frequency and quantity of discharge determine the morphology of a fluvial system, the rate of accommodation is responsible for the preservation potential of depositional elements that originally occured in different geomorphic levels. Figure 2.10 (upper part D) is a real example of type A1 in Fig. 2.9. This type of gravel body is characterized by interfingering of gravel sheet and gravel dune deposits. Cut and fill elements are rare and very small (0.2-0.6m in thickness, 1-7m in lateral extension). The sedimentary record of example A1 (high accommodation) indicate a shallow braided stream environment of unconfined flow, where sediment was transported and deposited in short pulses. In the case of low accommodation (A2) the pattern of the fluvial system is the same but only exceptionally high magnitude events (traction carpets, gravel sheets) have the potential of being preserved in the sedimentary record. Lower energy, day-to-day deposits are continuously reworked resulting in a low diversity and a stacking of thicker units. A real example of gravel body type B1 is shown in Fig. 2.7 C. Here the deposits are characterized by a dominance of accretionary elements (gravel sheets and dunes) and a solitarily appearance of comparatively larger cut and fill elements (0.5-1.2m in thickness, 5-20m in lateral extension). According to this sedimentary record a braided river environment (intermediate frequency and quantity of discharge) with less stable channels and local scour pools can be deducted. When accommodation is high, channel accumulations and scour pool fills can be preserved. When accommodation is low, scour pool fills which are developed in the deepest part of a braided river system are preferentially preserved (Siegenthaler & Huggenberger 1993) and only high magnitude events can be preserved occasionally. Gravel bodies developed under a regime of high frequency and quantity of discharge (examples C1 and C2) are characterized by a record of large and migrating scour pool deposits (1,5-4m in thickness and 10-100m in lateral extension). A real example of this style of gravel body is given in Fig. 2.10 (middle part C). The dimension of scour pools is approximately proportional to the size of the channels indicating in this example a braided river system with deep and stable channels. When accommodation is high, scour pools are fully preserved and relicts of channel accumulations occur (C1). In contrast, when accommodation is low (C2), a stacking of basal scour pool fills with abundant lag-deposits results, i.e. a diminishing in the diversity of preserved depositional elements.

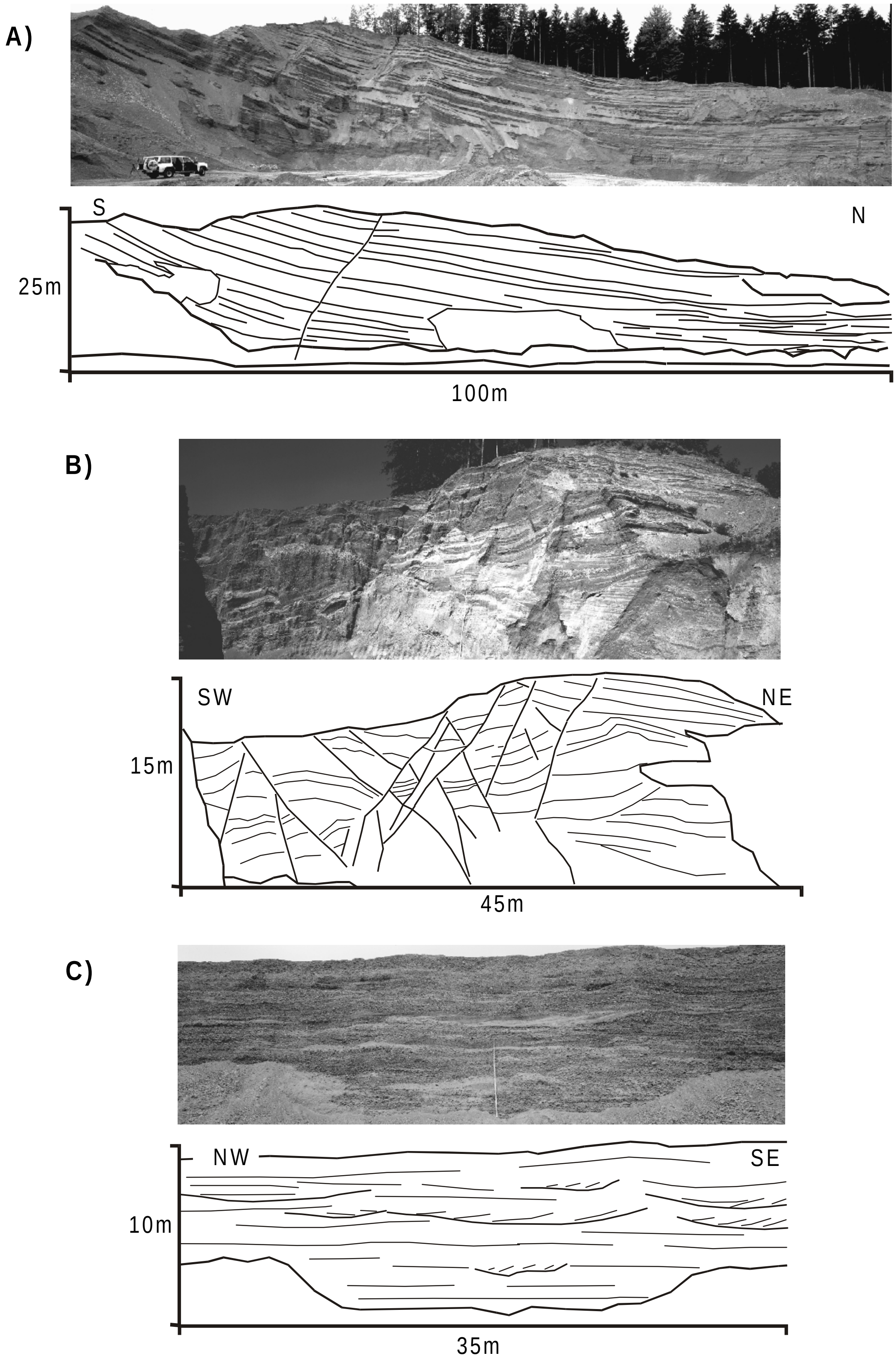


Fig. 2.7: Examples of glacial facies bodies:

A) a delta body is characterized by a progradation of gravel and gravel/sand strata. Lateral fining indicate deposition into a lake (gravel pit Baindt), B) esker body showing an alternation of inclined gravel- and sand dominated strata. The frequent faults and block rotations are the result of post-depositional ice melting (gravel pit Edenhaus), C) braided river gravel body (gravel pit Ostrach) characterized by accretionary elements (gravel sheets and dunes) and solitarily cut and fill elements (scour pool fills). Outcrop wall is parallel to paleoflow (from right to the left).

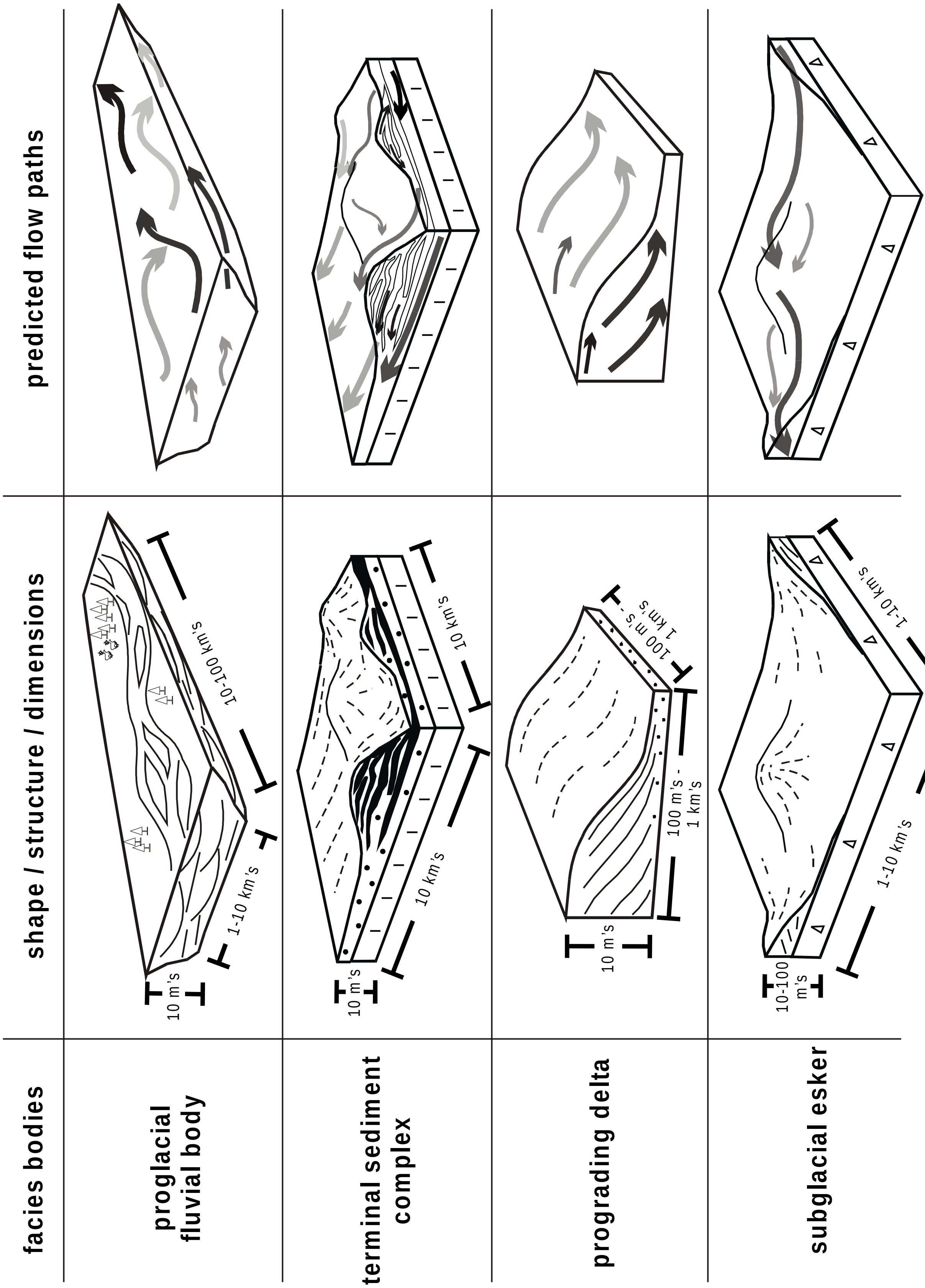


Fig. 2.8: Synthetic illustration of size, geometry and internal construction of selected glacial facies bodies and their impact on local to regional groundwater pathways. Based on data of 62 gravel pits, 5 sites of ground-penetrating radar surveys and topographical landform investigations.

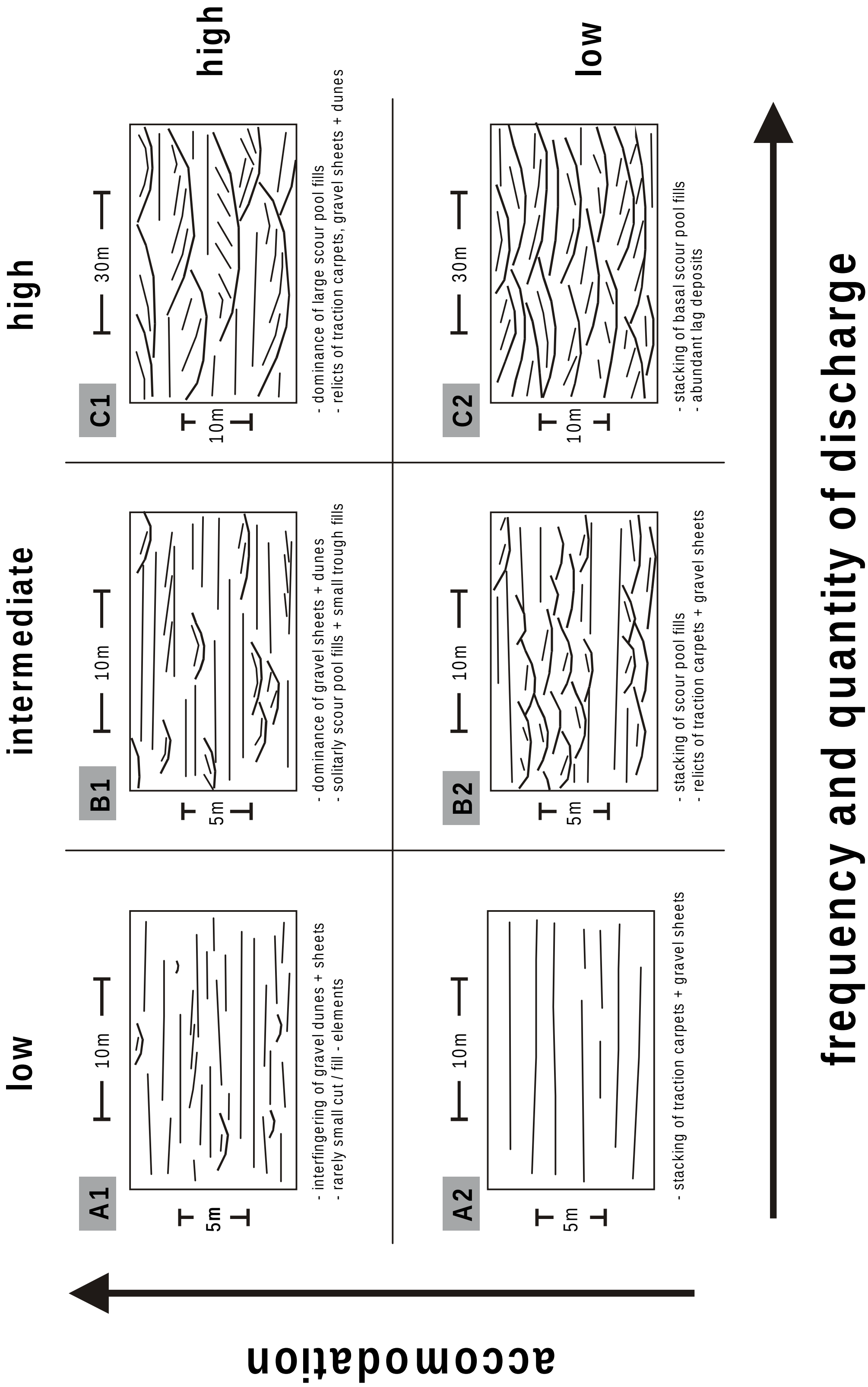


Fig. 2.9: Conceptual diagram showing the stratigraphic control of proximal, coarse-grained gravel deposits. Frequency and quantity of discharge are thought as being mainly responsible for the morphology and dynamic of the braided river system (e.g. size and stability of channels) and thus for the formation of depositional elements. Particularly the size and proportion of cut and fill elements increases with higher discharge. Accommodation space controls the preservation of depositional elements. Generally, the diversity of elements decreases with lower accommodation space. For instance, scour pools which develop in the deepest geomorphic level of a braided river system have the highest potential of being preserved. Real examples for types A1 and C2 are shown in Fig. 2.10 (upper + middle part) and for type B1 in Fig. 2.7 C.

It is obvious, that the stratigraphically controlled preservation of depositional elements within different braided river environments leads to characteristic distributions of lithofacies and hydrofacies, respectively. The resulting patterns of heterogeneity (permeability distributions) will control local groundwater flow as well as spreading behaviours of contaminants. Yet, the architectural styles depicted in Fig. 2.9 form just a selection of possible architectures of heterogeneities in coarse-grained deposits. For instance, the switch of braided river systems into straight- or meandering river systems (particularly at low accommodation rate and relatively small and continuous discharge behaviour) is not included.

2.3.5 Analysis of sequences: glacier dynamics and aquifer storeys

Even within the scale of outcrops vertical changes in the dynamics of environmental systems are sometimes visible. Vertical trends in grainsize or in a switch in architectural style of facies bodies are caused by changing sedimentary processes. While small-scale cycles (cm-m scale) often represent autogenetic processes, larger-scale cycles (several metres to tens or hundreds of metres) are allogenetically controlled and reflect the dynamics of the glacier (e.g. ice-advance, ice-decay). Heinz & Aigner (1999) described a glacial advance within proglacial gravel deposits as reflected in a coarsening upward trend, in a change in the proportions of depositional elements and in the transition of current-dominated deposits at the base to mass-movement deposition (flowtills) at the top of the cycle.

As an example, in the gravel pit Friedingen (Singen basin) several architecture styles of glaciofluvial gravel deposits are vertically stacked (Fig. 2.10).

A) The lowest part is characterized by horizontal gravel sheets and rarely gravel dunes with a thickness of 0.4 - 0.7m and a lateral extension of hundred of meters. Erosional elements are absent indicating the lack of channel features on this scale. The components are well rounded and larger clasts are often imbricated.

B) This lower gravel body is overlain by a relatively thin layer of matrix-supported and compacted diamict which can be traced in the Singen basin over several kilometres. Components are mostly well rounded, few of them show striations on their surface.

C) In contrast, the following gravel deposits are characterized by erosional elements (thickness of 1-3m and a lateral extension of 10-70m) with concave upward and cross-bedded lithofacies. These elements are often elongated in paleoflow direction and according to Siegenthaler & Huggenberger (1993) they are interpreted as migrating scour pool fills. At the base of these cut and fill elements sometimes subangular to angular boulders occur (lag deposits). Additionally post-depositional ice-collapse structures have been recognized in this middle part.

D) The uppermost part is dominated by the preservation of thin and discontinuous gravel sheets (5-20 cm in thickness, 10-30m in extension), where only rarely small cut and fill elements appear.

The three basic architecture styles of gravel deposits have a minimum thickness of 5-10m and reflect different discharge behaviour of changing fluvial environments. It is assumed that the vertical changes in the sedimentary record are not of autocyclic nature but are controlled here by glacier dynamics. According to the described deposits four sequences are deducted caused by short-term glacial dynamics:

A) The lowermost part is interpreted as a sequence of glacier stagnation or slow glacier advance. Deposits of relatively high magnitude events were preserved within one broad river-environment. Imbrication measurements show a direction of paleoflow from NE to SW, which is parallel to the glacier lobe situated in the SE (Schreiner, 1992).

B) The diamict-intercalation between the first and the second gravel body is interpreted as a ‘direct’ glacier deposit (lodgement till) formed during a glacial advance or even a glacial surge.

C) The gravel body of the middle part is interpreted as a record formed during ice decay. Both the occurrence of angular boulders and ice-collapse structures indicate proximity to the source (i.e. the ice). Typical elements of a dynamic braided river system are revealed in this part. For the preservation of migrating scour pool fills, large and relatively stable channels and an overall high amount of discharge is required (compare with chapter 4.5.1). This can be explained by the high amount of released water during ice decay and the narrowing of discharge areas (and thus focusing of the draining water) due to large and blocking ice relics.

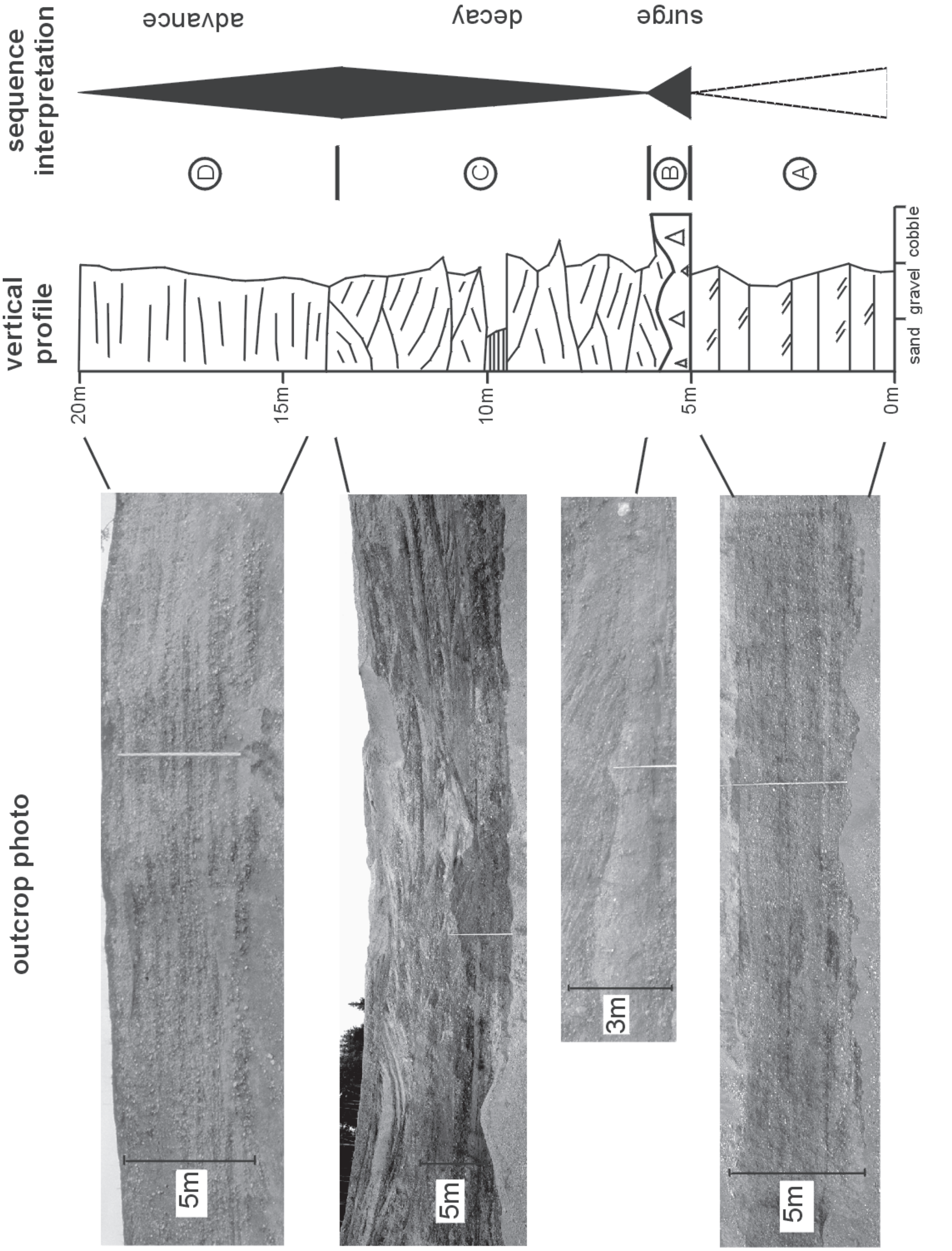


Fig. 2.10: Vertical stacking of different architectures of gravel bodies in the area of Singen (site Friedingen). The lowest part (A) is characterized by a stacking of horizontal gravel sheets formed within a single and broad river environment. The middle part, clearly truncating an intercalated till (B) at the base, is characterized by a complex stacking of scour pool fills (C) typically for braided river deposits. The upper part (D) show a preservation of thin, discontinuous gravel sheets which are interpreted as deposits of an unconfined, shallow braided stream. Such sequences are interpreted according to sediment sorting, grain size and structural make up of the deposits which are controlled by short-term glacier dynamics.

D) The gravel deposits of the upper part show an environment of shallow and unconfined flow which is typical for shallow braided streams or shallow alluvial fans (Goedhart & Smith, 1998). The change to an overall smaller amount of available discharge (compared to the deposits of the middle part) is interpreted as a stabilisation and repeated advance of the glacier.

Genetic sequences are the critical units for regional correlation. Contrary to purely lithostratigraphic or morphologic correlation, a correlation based on sedimentary sequences is independent of local depositional environments and focuses on the dynamics of the glacier. Thus it is possible to correlate e.g. areas of glaciofluvial deposits with areas of lacustrine deposits or even with zones of non-deposition and erosion. Although several sequence stratigraphic studies within glacial deposits (Oviatt *et al*., 1994; Scholz & Finney, 1994; Martini & Brookfield, 1995) have been successful, correlation is still very often difficult because of the lack of time markers (e.g. obtained by pollen-analysis), the extreme potential of local erosion (e.g. subglacially) and the simultaneous deposition in different topographic levels.

Regional glacial cycles often translate into major aquifer storeys. The change of glacier position and dynamics result in a vertical and lateral stacking of facies bodies. While glacial meltwater deposits (e.g. eskers, deltas, proglacial sediments) often represent well permeable aquifers, deposits of diamict and fine-grained sediments (aquitards and aquicludes) separate these aquifers. In Fig. 2.11 fluvial sediments deposited during one cycle of glacial advance are envisaged to form continuous aquifers, while meltwater deposits during ice decay are characterized by a patchy distribution forming isolated aquifer storeys. As an example, Szenkler (1996) build up a 3-dimensional hydraulic model embodying several aquifer storeys in the Singen Basin on the basis of core data and deducted genetic sequences.

2.3.6 Analysis of basin fills: basin dynamics and hydrostratigraphy

Glacial basin analysis records the 3-dimensional distribution and stacking of facies bodies and sequences, controlled by long-term glacial dynamics and thus by a combination of climate changes and basin history.

Quaternary geologists have traditionally studied the modern relief of glacial landforms. A milestone in this research has been the recognition of the 'glacial series'(juxtaposition and interconnectedness of glacial deposits within one single ice-period; Schreiner, 1992) by Penck & Brückner (1909) leading to the commonly applied morphostratigraphic approach. Although it is now clear that morphological properties on their own are not sufficient and a combination with the internal architecture is necessary, the shape of the landscape provides important indications for major glacial and glaciofluvial environmental reconstruction (Shaw, 1987; Rains *et al*., 1993; Shaw *et al*., 1996; Munro & Shaw, 1997).

Within the German Rhine glacier area several overdeepend glacial basins are known (Ellwanger *et al*., 1995) which are frequently elongated in ice-flow direction and show variable extensions and thickness (1-100 km in length, few decametres to hundreds of metres in thickness). Depending on their age of formation and geographical position, one to several glacial advances and retreats are recorded resulting in a complex basin architecture.

The analysis of sequences in drill cores and their hierarchical stacking pattern lead to a basin wide correlation and thus to a rough appraisal of lateral and vertical distribution of facies bodies. For a more accurate analysis, shallow seismic reflection technics are used for exact location and geometrical detection of facies bodies in the subsurface as well as their internal architecture (Eyles *et al*., 1991; Pullan *et al*., 1994; Boyce *et al*., 1995; Pugin *et al*., 1996, 1999; Van Rensbergen *et al*., 1999).

Regional groundwater models need information about distribution and connection of individual hydrostratigraphic units. It is, for instance, important to know if vertically stacked groundwater storeys are continuously separated by impermeable till sheets or if local erosional cannibalism lead to hydraulic windows and thus to an interconnection of aquifer storeys. Pugin *et al*. (1999) recorded with seismic profils (seismic facies analysis) the regional architecture of the Oak Ridge Moraine area (southern Ontario) and clarified the effect of large buried subglacial tunnel channels on regional groundwater storage and interconnectedness of hydrostratigraphic units.

In Fig. 2.12 part of a complex Pleistocene glacial basin fill (Hoßkirch basin) is shown. The seismic profile which strikes nearly parallel to the elongate basin (Ellwanger *et al.*, 1995) from NW to SE has been calibrated with two closely spaced cores.

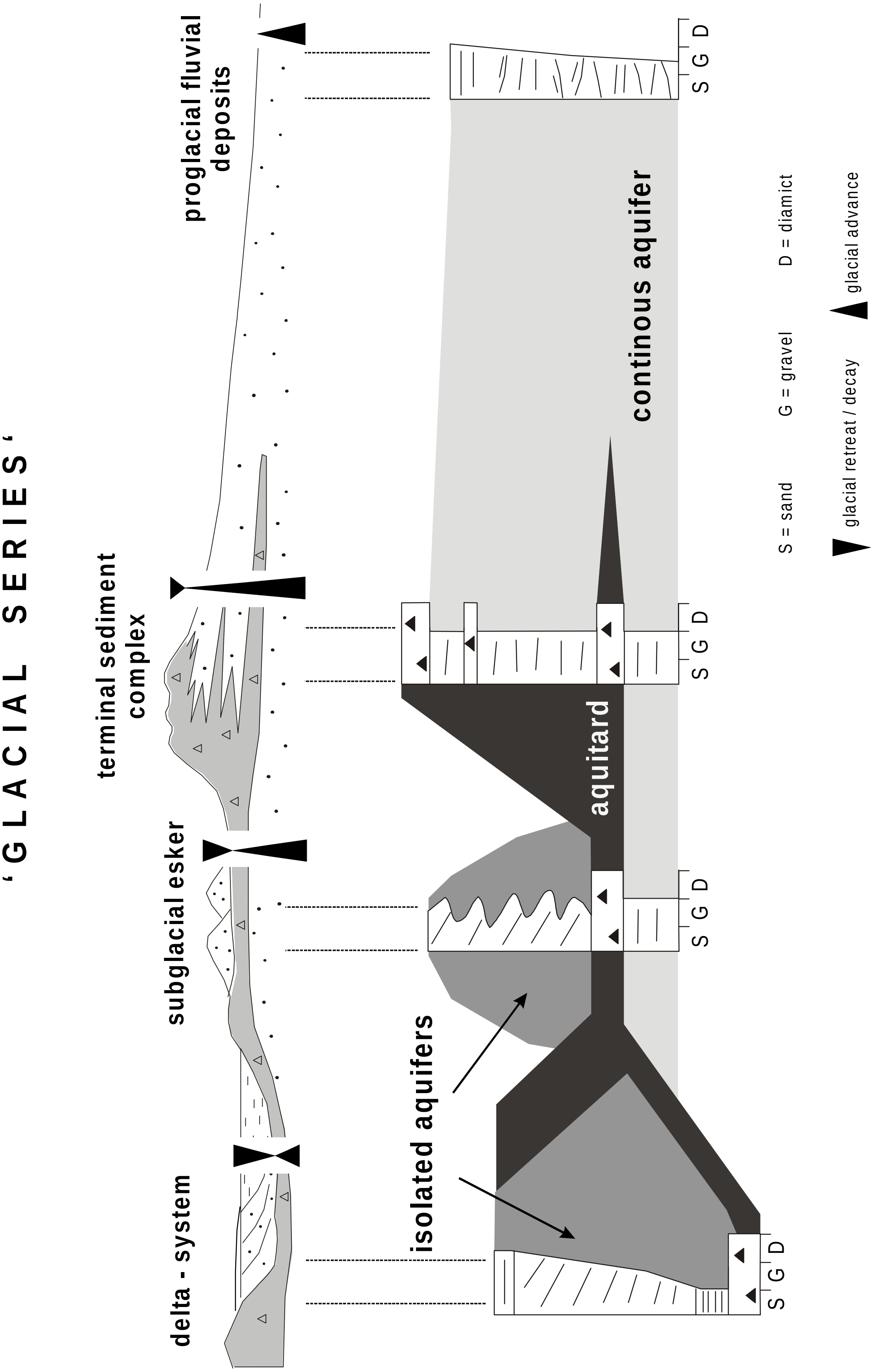


Fig. 2.11: Schematic illustration of isolated and continuous regional aquifer storeys formed during a glacial cycles at different times and positions within a classical 'Glacial Series'.

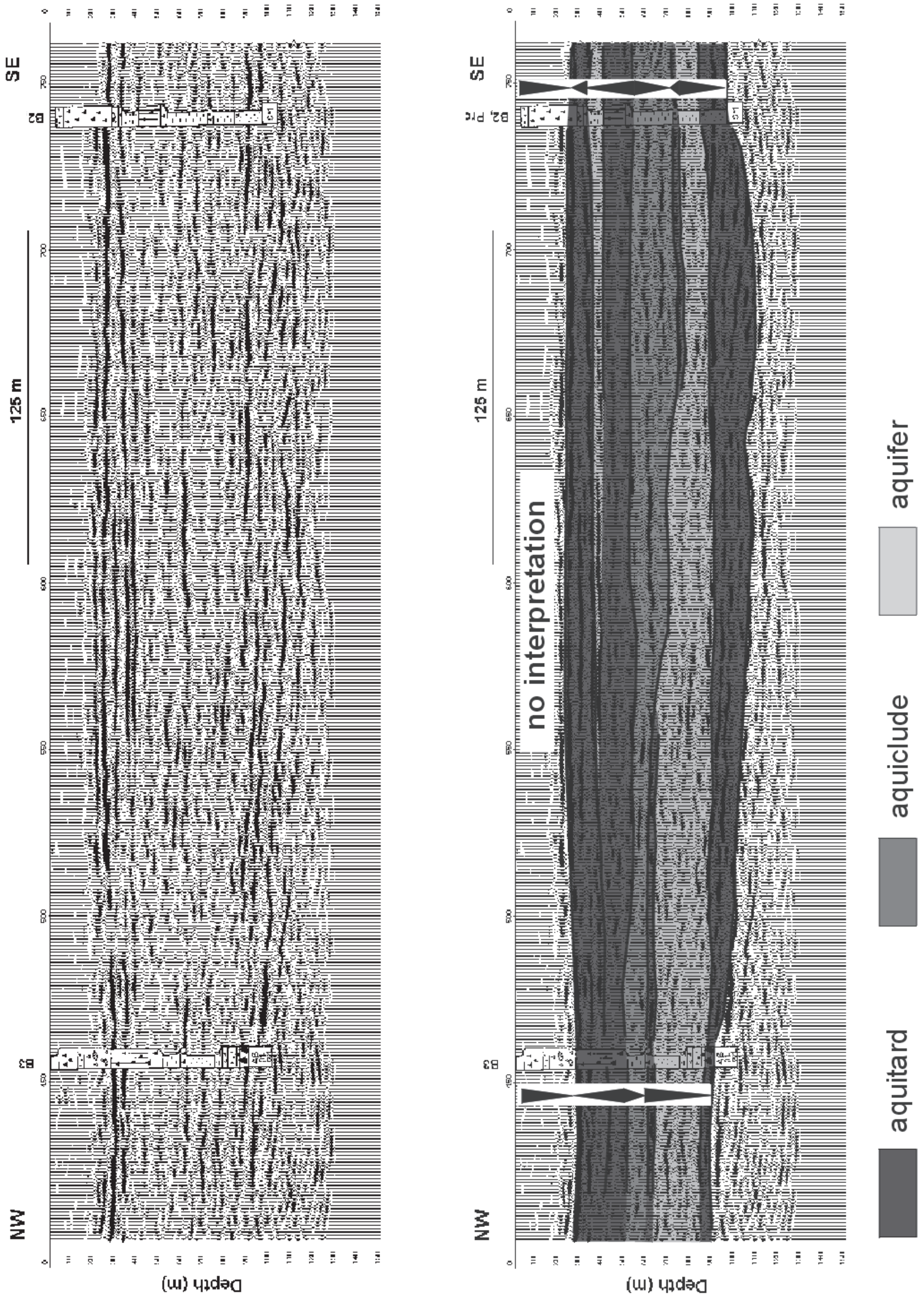


Fig. 2.12: Shallow seismic profile within the glacial basin of Hosskirch (Upper Swabia) used for the resolution of the large-scale subsurface architectures. Core data are classified according to overall hydraulic properties (aquitard: diamicts and compacted clay and silt deposits; aquiclude: mixture of sand, silt and clay; aquifer: well sorted gravel and sand deposits) and can be traced in the profile. For the quantification of hydrostratigraphic units regional groundwater models need information about location and distribution of facies bodies. Compare, for instance, the continuous basal aquifer and the isolated aquifer-zone in the upper part.

The core data has been interpreted according to glacial sequences and classified with regard to hydrostratigraphic units. Hence, deposits of diamict and compacted clay/silt are regarded as non-permeable aquitards whereas mixtures of sand and silts with small amount of clay behave as an aquiclude. Units with a domination of sorted gravel and sand deposits are zones of high permeability and classified as aquifers. The seismic profile enables a 2-dimensional tracing of these units. It becomes clear that the lower aquifer is continuous and major groundwater flow is focused in this lower part. In contrast the thin intercalated upper aquifer is fully enclosed by aquitards forming an isolated aquifer.

2.4 Conclusions

In this chapter a simple, process-based approach is proposed in order to analyse highly variable glacial deposits by means of a systematic breakdown of sedimentary deposits into a 6-fold hierarchy of objectively defined units of different scales: (1) particles, (2) strata, (3) depositional elements, (4) facies bodies, (5) sequences and (6) basin fills.

For the Rhine glacier area, a database is presented, showing quantitative data on types, geometries and dimensions of lithofacies, depositional elements and facies bodies.

Moreover, recognizing the hydraulic effects of these different scales from local hydrofacies (meso scale) to regional groundwater modeling (giga scale) helps to improve predictions on aquifer properties and provide quantitative input parameters for numerical simulations.

A combination and integration of different methods (e.g. sedimentological, geophysical, geochemical, morphostratigraphical) is necessary for a comprehensive qualitative and quantitative characterization of glacial aquifers.

3. Characterization of proglacial fluvial gravel bodies: Heterogeneity pattern and application to hydrogeology

3.1 Chapter abstract

The architecture of sedimentary bodies determines the heterogeneity of porous groundwater 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 different transport and depositional processes and represent the fundamental building blocks (hydrofacies), b) the depositional element - scale shows distinct geometry-characteristics (internal structure and bounding surfaces) and determine 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 formation and dynamics of aggrading paleofluvial systems. Comparison of numerous gravel pits in SW-Germany revealed three major architectural patterns of glaciofluvial gravel bodies which statistically can be distinguished by the preservation of depositional elements as well as the frequency of lithofacies. The facies analysis results in three conceptual facies models of proglacial river systems which are regionally classified as 'main-, intermediate- and minor- discharge' types. Using the GIS system Arc-Info lithofacial outcrop wall maps and laboratory hydraulic property measurements of refined hydrofacies were combined and transformed in a numerical model for groundwater flow and transport. This modeling illustrates that the three styles of heterogeneity of gravel bodies also have distinguishable hydraulic response characteristics.

3.2 Introduction

Contamination of groundwater in shallow fluvial aquifers (valley-fills) are nowadays frequently encountered. Risk assessment and remediation strategies require basic knowledge in sedimentary facies distribution as well as hydraulic property distribution coupled in 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 & Smith, 1998; Dinehart, 1992a), in outcrop studies (e.g. Smith, 1990; Siegenthaler & Huggenberger, 1993), by flume experiments (e.g. Ashmore, 1993; Major, 1998) or by qualitative and quantitative physical simulations (Bridge, 1993; Leddy et al., 1993; McEwan et al., 1999). Their aspects are discussed and compared in the individual chapters particularly with a focus on the formation of lithofacies types (chapter 3.4), depositional elements (chapter 3.5) and their preservation in different regions (chapter 3.6).

The hydrogeological modeling of sedimentary aquifers just recently received increasing scientific attention. In the past ten years - following the early papers of Fogg (1986) & Anderson (1989) - numerous publications focus on the hydraulic modeling of heterogeneous aquifer systems (e.g. Fogg, 1990; Poeter & Gaylord, 1990; Ritzi et al., 1995; Webb & Anderson, 1996a,b). A book recently published by Fraser & Davis (1998) summarizes the state of the art concerning this issue. The authors agree that the comprehension 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 & Davis, 1998; Galloway & Sharp, 1998a,b). The representation (image creation) in the numerical models may vary regarding the data base and the required goal, the different methods (descriptive approach, structure imitating, process imitating) are extensively reviewed in Koltermann & Gorelick (1996a). The geological information can be transferred into the flow grid by using different stochastic simulation techniques (Scheibe & Murray, 1998), by geostatistical analysis (Domenico et al., 1998) or in the context of Markow chain analysis (Carle et al., 1998). An other approach to characterize the sedimentary structures in fluvial systems are geophysical methods, e.g. georadar (Asprion & Aigner, 1999, Beres et al. 1999). The transformation of the geophysical parameters (velocity) into hydraulic parameters is still questionable (Kowalsky et al., submitted).

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, the following study follows the method of Huggenberger & Aigner (1999) and focuses on *small scale aquifer analog studies* (tens of meters). The investigations are based on a “close to reality" information regarding the distribution of the lithofacies as well as the determination of hydraulic properties. In this study, it shall be emphasized that understanding of sedimentary processes (lithofacies, depositional elements, stacking pattern) help to predict fluid flow and transport in gravelly valley aquifers.

3.3 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. 3.1). They are located in former fluvial drainage zones of the Rhine glacier which 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 8-14‰ , 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 & 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 distal outcrop studies. 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.

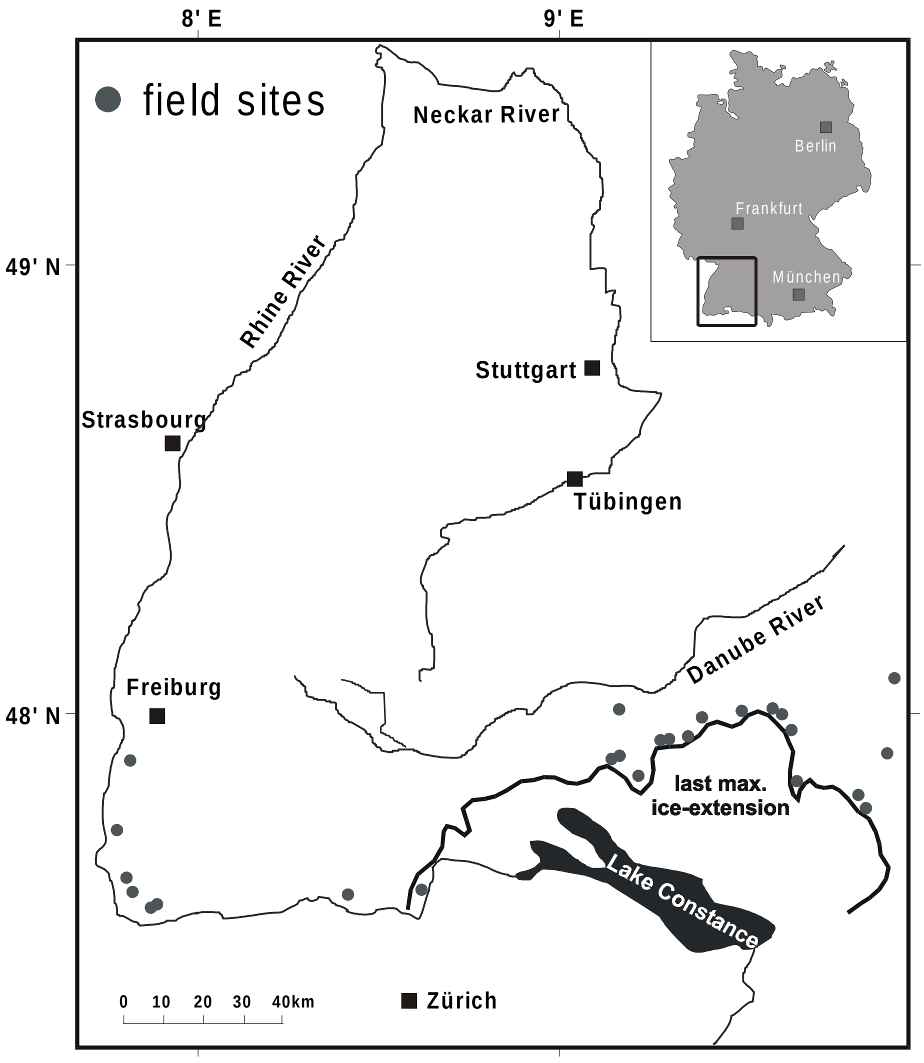


Fig. 3.1: Location of the study area showing the distribution of field sites. The gravel pits are located within paleodischarge zones of the Rhine glacier (last glaciation). One portion of field sites are situated at the northern marging of the ice lobe (Upper Swabia), while the other portion occur along the Rhine river (to the West/North).

3.4 Analysis of lithofacies - translation into hydrofacies

Understanding transport and depositional processes in gravel-bed rivers helps to explain the appearance of different lithofacies types (mesoscale). They can be characterized by different grain size, degree of roundness, sorting, stratification, fabric and texture. A lithofacies concept proposed by Miall (1978) classifies primary sedimentary features. This was extended for glacial deposits by Eyles et al. (1983) and specific features for glaciofluvial deposits were added by Siegenthaler & Huggenberger (1993). While Keller (1996) tried to combine this sedimentological code with geotechnical information from core data, Anderson (1989) & Klingbeil (1998) 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 directly be connected to hydraulic properties such as hydraulic conductivity and porosity. The term ‘hydrofacies’ was thus introduced for units with relatively homogeneous hydraulic properties (Poeter & Gaylord, 1990; Anderson et al., 1999).

Applying the code-scheme of Keller (1996) to lithofacies- and hydrofacies description, a close link between genetic lithofacies description (representing sedimentary processes) and hydraulic parameters is documented in this study (Tab. 3.1). The appearance of 5 dominant lithofacies 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. 3.2). However, transformation of lithofacies into hydrofacies required in some cases a further differentiation. Variations of grain-size and matrix content not critical for process-based litho-facies description but with a strong impact on the resulting hydraulic properties, had to be taken into account (Tab. 3.2 and Fig. 3.3).

The transformation of lithofacies into hydraulic properties (hydrofacies) was done by measuring hydraulic conductivities of disturbed (and only sand facies undisturbed) samples in a permeameter column (disturbed samples: 40 cm * 10 cm; 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 & Lake, 1994; Koltermann & Gorelick, 1995). Additionally, the values were compared to data from the literature (e.g. Jussel et al., 1994).

indizes/ features		abbreviation
i_1	**grain-size**	**b** boulder **c** cobbles **s** sand **f** fines (silt/clay)
I_1	**grain-size**	**G G**ravel **S S**and **F F**ines (silt/clay)
i_2	**texture**	**c** clast-supported **m** matrix-supported
i_3	**stratification**	**x** stratified **m** massive (no bedding) **g** graded (normal, inverse)
i_4	**additional information**	**i** imbrication **a** alternation: e.g. **o** = open framework, **b** = bimodal **h** horizontally stratified **p** planar stratified **t** trough cross-stratified ...

Table 3.1: Lithofacies-code for description of gravel deposits in outcrops (modified and extended after Keller, 1996 and Kleineidam 1998). This code can be described as followed ($i_1 I_1$ i_2 i_3 ,i_4): the grainsize is given by i_1 and I_1 whereby I_1 represents the main component (e.g. G = gravel) and i_1 (optional) gives additional information to the components or matrix. Index i_2 describes the texture of the sediment and is either clast-supported or matrix-supported. Index i_3 gives stratinomic features. For simplification we distinguish between cross-bedded = x, graded = g and massiv = m. Additional information (depending on the task of description) can be put on position i_4 which is separated by a comma. - is used in order to keep the sequence.

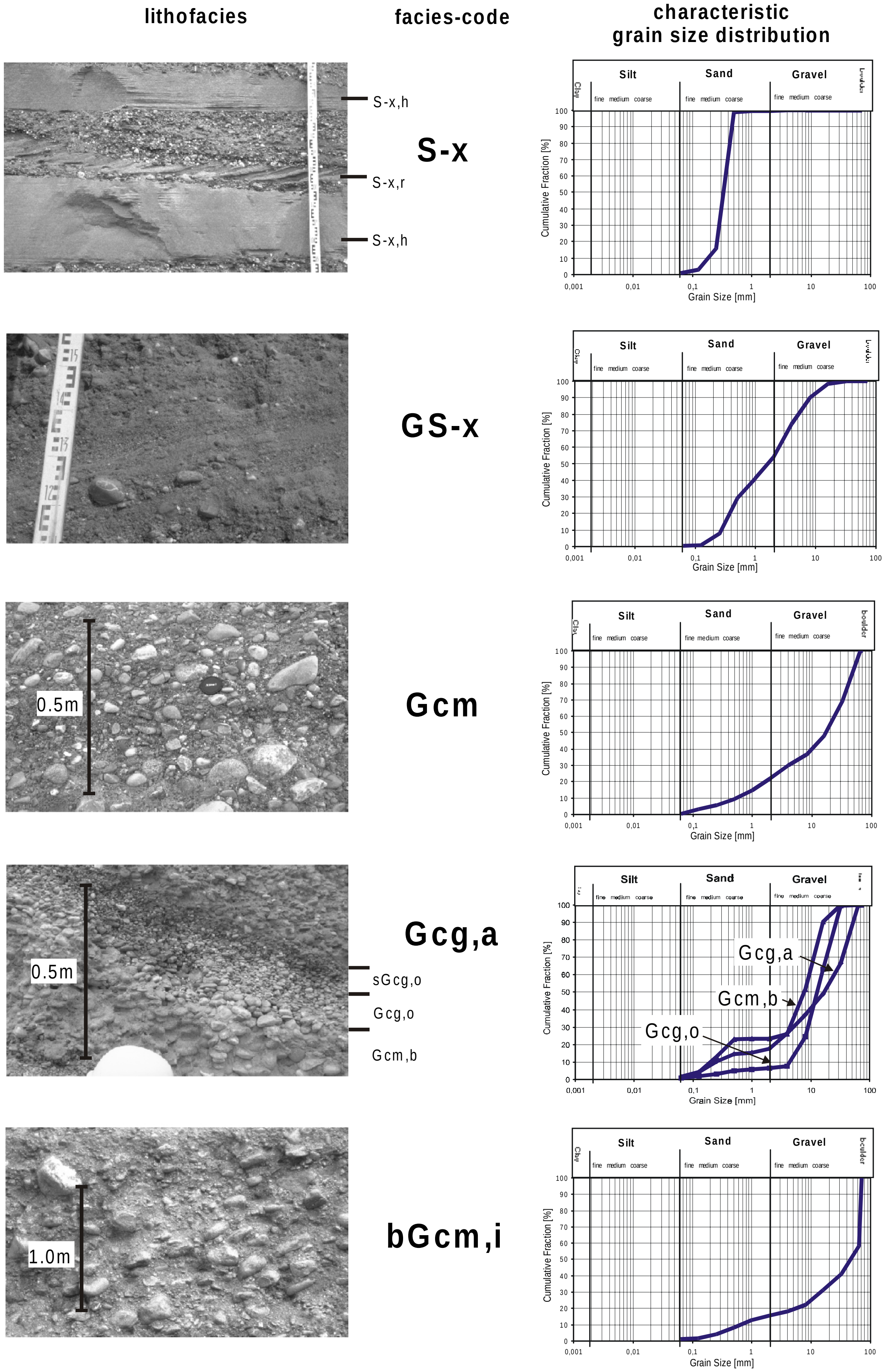


Fig. 3.2: The 5 major lithofacies types occuring in gravel-bed deposits of the Rhine glacier area. The change in the cumulative sieving curve indicate the increase of flow energy (max. grainsize) and rate of sedimentation (sorting) from lithofacies S-x to bGcm,i.

lithofacies	hydrofacies	K_f [m/s] experiment	K_f [m/s] calculated	porosity [-] experiment
	bGcm		$4.7\cdot10^{-5}$ (1	0.08
(c,b) Gcm,i	cGcm		$2.3\cdot10^{-4}$ (1	0.15
Gcm	Gcm	$2.5\cdot10^{-4}\pm2.1\cdot10^{-4}$	$3.3\cdot10^{-4}\pm3.3\cdot10^{-4}$ (2	0.17±0.07
	sGcm	$6.1\cdot10^{-5}\pm5.9\cdot10^{-5}$	$7.1\cdot10^{-5}\pm2.2\cdot10^{-5}$ (2	0.13±0.04
	fGcm	$1.6\cdot10^{-6}\pm1.1\ 10^{-6}$	$1.3\cdot10^{-4}\pm3.2\cdot10^{-5}$ (2	0.15±0.02
Gcx	Gcx	$2.3\cdot10^{-4}\pm7.5\ 10^{-5}$	$3.5\cdot10^{-4}\pm1.7\cdot10^{-4}$ (2	0.18±0.03
	cGcg,o		$3\cdot10^{-0}$ (3	0.26±0.02
Gcg,a	Gcg,o	$4.8\cdot10^{-1}\pm2.6\cdot10^{-2}$	$2.0\cdot10^{-1}\pm1.8\cdot10^{-1}$ (3	0.26±0.02
	sGcg,o		$9.5\cdot10^{-2}\pm6.5\cdot10^{-3}$ (3	0.23
	Gcm,b	$6.1\cdot10^{-5}\pm1.8\cdot10^{-4}$	$2.8\cdot10^{-5}\pm2.8\cdot10^{-5}$ (1	0.20±0.08
GS-x	GS-x	$2.3\cdot10^{-3}\pm4.5\cdot10^{-3}$	$5.2\cdot10^{-4}\pm2.4\cdot10^{-4}$ (4	0.27±0.07
S-x	S-x	$1.4\cdot10^{-4}\pm5.0\cdot10^{-3}$	$1.3\cdot10^{-4}\pm1.5\cdot10^{-4}$ (4	0.36±0.04

Table 3.2: Summary of the measured and calculated hydraulic properties for the various hydrofacies types; [1] calculated based on ($K_f = K_f$ (Gcm; Sand) $(1-V_{(C/B)})$), [2] based on empirical equation according to Panda and Lake, [3] based on Kozeny-Carman equation, [4] based on empirical equation according to Beyer.

3.4.1 Pure sand lithofacies (S-x)

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 0.7m, these units are characterized by horizontal stratification. Occasionally, planar cross-stratification (indicating migration of ripples with straight crests) was noticed.

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 (derived from the association of sedimentary structures). Using undisturbed flow through columns of 10cm * 4 cm, 10 different samples (similar grain size distribution) showed hydraulic conductivities (k_f) ranging from 3.6 10^{-5} ms^{-1} up to 1.1 10^{-4} ms^{-1}. Predicted k_f values based on the empirical equation of Beyer (1964), using the unconformity of the grain size distribution sieve curve and the grain size at 10 % of the cummulative sieve curve were within a factor of 2. Within the used column size no significant influence of internal stratification on kf values was found (each sample was taken horizontal, vertical and in direction of layering). This is probably due to uniformity (well sorting) and the lack of muddrapes on foresets in the samples investigated.

3.4.2 Well sorted gravel lithofacies (GS-x)

description:

This lithofacies is built up by 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 can show a matrix-supported texture. Stratification of these inclined units (3-25°) are obviously due to orientation of particles or grain size changes. Interfingering and interbedding with lithofacies S-x is common. Unit thickness of lithofacies GS-x often does not exceed 0.7m.

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 3 different samples ranged from 9.3 10^{-5} ms^{-1} – 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 (Tab. 3.2). Calculations based on empirical correlations (Beyer, 1964) are within a factor of 4-6.

3.4.3 Ill sorted gravel lithofacies (Gcx, Gcm, Gcm,i)

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.

This facies is very common in gravel-bed deposits and has often been described from outcrop studies (Siegenthaler & Huggenberger, 1993; Steel & Thomson, 1983; Smith, 1990). As noted by Whiting et al. (1988) and Reid & Frostick (1987), the movement of sediment in gravel-bed rivers happens 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 & Frostick (1987) describe bedload motion at rising limb of a flood hydrograph as well as at the recession limb), this transport process always take 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 & 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.

discussion and hydraulic consequences:

In terms of hydraulic properties, a differentiation of the genetic code was required (Tab. 3.2). Particularly, the make-up of the matrix has to be considered. Lithofacies Gcm (cGcm,i) and Gcx will have similar kf values (2.3 10^{-4}ms^{-1}) if the matrix is similar. To further characterize the matrix the code sGcm is introduced indicating an increased amount of medium sand in the matrix which results in a diminishing of hydraulic conductivity (6.1 10^{-5} ms^{-1}) compared to the original Gcm. In some localities, the matrix con-

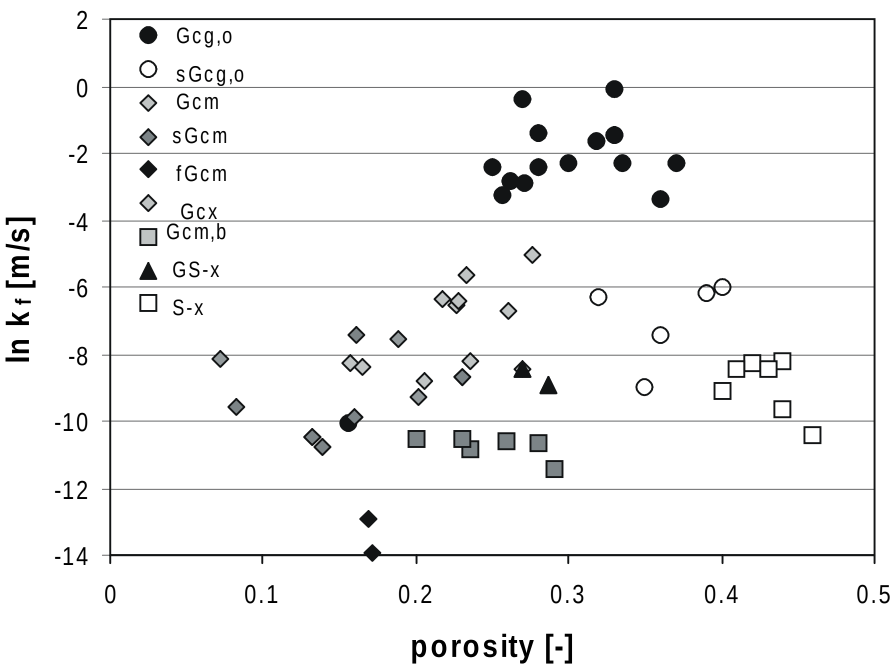


Fig. 3.3: Summary of measured hydraulic conductivities and porosities for different hydrofacies types. Highest values were found for the open framework gravels (dots) and lowest conductivities were measured in the Gcm (grey triangles) were higher fraction of clays were found (fGcm; black triangles). The porosity varies from almost 10 % to 42 % while the hydraulic conductivities change by orders of magnitude (from Heinz et al.).

tains small amounts of fines (mainly silt). Only 1-2% of finer material leads to 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 & Lake, 1992) 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 & Huggenberger (1993) to be in the order of 50 % lower k_f values in horizontal compared to vertical flow through direction.

3.4.4 Alternating gravel lithofacies (Gcg,a)

description:

This lithofacies consists of a bipartite unit with a lower zone consisting of matrix-filled, clast-supported gravel and an upper zone of very well-sorted open framework gravel (matrix-free). Both zones together often show a normal grading; this is the reason for interpreting this alternation as one genetic unit. Sieve analysis shows that a mixture of both zones together displays a similar grain size distribution as the ill-sorted gravel 'Gcm' (see Fig. 3.2). Again, all particles are well rounded. Beds occur in horizontal and in inclined manner with a thickness ranging from several centimetres to a maximum of 0.7m.

Many varieties of alternating gravel have been recognized. There is a positive correlation between maximum particle size and bed thickness (Steel & Thompson, 1983). The two zones can be very asymmetric with the end-members consisting of only one zone (upper or lower zone). The matrix of the lower zone 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 a mature development of 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.

discussion and hydraulic consequences:

Gravel couplets are a widespread fluvial gravel type often described in the literature (e.g. Bluck, 1979 ; Steel & Thompson, 1983; Smith, 1990; Siegenthaler & Huggenberger, 1993). Because of its vast range in appearance the descriptive term 'alternating gravel' is introduced (Smith, 1990; Heinz & Aigner, 1999). Steel & Thompson (1983) explained this alternation as a result of waning flow and clast segregation over the surface of a bar. In contrast, Carling & 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 mechanism produce horizontal alternating beds, Siegenthaler & Huggenberger (1993) pointed out that inclined gravel couplets result from gravel dunes migrating across an oblique plane. The described polymodal basal zone is certainly a result of an avalanching mechanism (Steel & Thompson 1983) and large foresets of alternating gravel have also been seen in glacial Gilbert-type deltas (basin of Singen, Asprion, 1998) more resembling a turbidite mechanism. Acknowledging all these varieties of alternating gravel, it is assumed that different mechanisms can lead to similar alternating gravel lithofacies. Although all mechanisms are not known, two 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 matrix.

In contrast to ill-sorted gravel, the same sediment mixture experiences a sorting mechanism that is important for resulting hydraulic conductivities (Tab. 3.2). The lithofacies code Gcg,a therefore need to be extended and specified. If a polymodal construction of the basal zone occurs, the same codes as for ill-sorted gravel are used (Gcm, sGcm, fGcm). The basal zone 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 correlation for the prediction of the overall porosity in bimodal grain size distributions (Koltermann & Gorelick, 1996b) was adopted to predict also the hydraulic conductivity. According to the findings from Koltermann & Gorelick (1996b) porosity and kf 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 don´t attribute to the flux). In the field a lower volume fraction of the matrix was never observed in which case the clasts and their pore space contribute significanty to the overall permeability. The measured to predicted values are given in Fig. 3.4 A and summerized in Tab. 3.2. Hydraulic conductivity of the upper openwork zone is determined by particle size or better by the size of their pores. Three subunits are classified: grain size from cobbles and coarse pebbles are given the code cGcg,o (kf = 10 10^0 ms^{-1}), grain size from coarse to fine pebbles correspond to Gcg,o (kf = 10 10^{-1} ms^{-1}) and grain size from granules grading to sand are termed sGcg,o (kf = 10 10^{-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). The validation of the method (measured to calculated values) are given in Fig. 3.4 B showing an overall good agreement, up to grain sizes of 16 mm, which is the upper size limit for the used column size.

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

description:

This lithofacies type contains large clasts such as cobbles and boulders. Relating to pebbly grain size (which is dominating) the lithofacies shows a clast-supported texture. Together with a matrix ranging 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 1.5m 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 0.5m to 0.7m thick beds was observed building up a 5m thick composite unit. The beds dip with a very low angle in the paleoflow direction.

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 & 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, gravels 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 & 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 require high-magnitude floods including a suspension-rich discharge.

Hydraulic conductivities could not be determined with the used column due to the large grain-sizes. Compared to the results for the bimodal lithofacies the coarser clasts diminishes the effective flow plane, resulting in lower permeabilities compared to the matrix (lithofacies Gcm). Therefore, the large clasts were removed from the sample and the hydraulic properties of the matrix were measured. Afterwards the values were corrected by the volume fraction of the matrix.

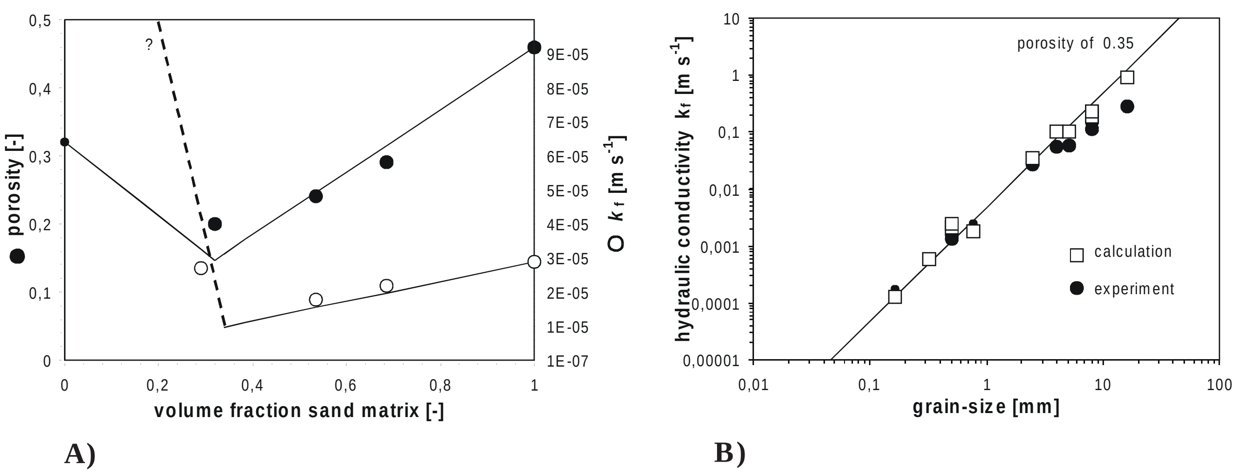


Fig. 3.4: A) development of porosity and conductivity in the bimodal lithofacies ‘Gcm,b’. Analogue to porosity the conductivity decreases to the minimum of porosity. Below this sand portion both increase again. B) validation of the Kozeny Carman equation for the uniform open framework facies showed a very good agreement between measured and calculated hydraulic conductivities, justifying the calculation of hydraulic conductivities for the cGcg,o, Gcg,o and sGcg,o (from Heinz et al.).

3.5 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, they 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 construction and geometry of depositional elements not only enables the reconstruction of fluvial systems but is also critical for the understanding of the 3-dimensional distribution of permeabilities.

All investigated localities exclusively show elements which 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 it was decided not to use the expression ‘architectural element’ (Miall, 1985; 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 & Thompson, 1983; Morison & 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.

examples of cut and fill - elements:

3.5.1 Erosive scour pool elements

These elements are characterized by concave erosional surface with a distinct boundary. The internal structure consists of trough-shaped cross-bedded sets comprising lithofacies S-x, GS-x, Gcm and Gcg,a. The thickness of trough elements ranges from 1m to 4m. Laterally, they can extend from a few metres to several tens of metres (see also chapter 3.6.4).

According to Best (1988) and Siegenthaler & 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 & Huggenberger, 1993). The position can remain stationary, but Ashmore (1993) also showed in small-scale hydraulic models different possibilities of changes in position of channel confluences (e.g. translation, expansion, rotation, obliteration). Based on the migration of scour pools, Siegenthaler & 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-scaled lithofacies types alternating and interfingering with each other. For permeability distribution, trough elements therefore represent heterogeneous 3-dimensional bodies (vast range in size) which are internally cross-stratified with an extreme variability of hydraulic lithofacies.

3.5.2 Small dissection elements

These minor 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 0.7m and a lateral extension of one to several metres. 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 aggradation of the depositional system is required. If preserved, these elements represent small-scaled, 3-dimensional bodies where an increased probability of pure sand deposits is expected. For the overall hydraulic network of a whole gravel package, these elements are not important.

examples of 'accretionary' elements:

3.5.3 Horizontally-bedded gravel sheets

This element mainly consists of ill-sorted gravel. Individual beds are typically 1-2dm 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 (Hein & 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 (Reid & Frostick, 1987; Whiting, 1988; Kuhnle, 1996).

Apart from slight deviations in matrix construction and maximum grain sizes, these elements represent hydraulicly homogeneous units with a sheet-like (2-dimensional) geometry ranging laterally from tens up to hundreds of meters.

3.5.4 Massive gravel sheets

This 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 1m in thickness build up laterally extensive units (100-500m). 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 5m in thickness. In comparison to the horizontally-bedded gravel sheets the hydraulic conductivity is reduced due to the occurrence of many large clasts (see chapter 3.4.5).

3.5.5 Cross-bedded gravel dunes

Within the studied gravel-formations, 0.3 to 1m - 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 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) occurs infrequently as well. Laterally, these elements show extensions from few metres up to several tens of metres.

For this cross-bedded element the term 'gravel dune' is proposed. 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 formation of lithofacies (Todd, 1996). Crucial for our interpretion 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 'piggy-back' gravel dunes migrating over the stoss side of larger bedforms (Dinehart, 1992a). The infrequent appearence of lithofacies GS-x and S-x indicates decreasing or low-energy flow conditions.

The determination of gravel dunes at 2-d sections in the field is often ambiguous. 2D gravel dunes look similar to flow-parallel scour-pool fills, and 3D 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 3-dimensional information, gained for example by different oriented outcrop sections or radar profiles (Beres et al., 1999), are 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 2-D dunes greate sheet-like geometries, 3-D dunes are probably preserved as trough-shaped bodies.

3.6 Analysis of gravel body architecture - patterns of heterogeneity

For stacking pattern analysis an adequate size of the outcrop is needed. Particularly the size of depositional elements determine the required size of outcrop walls (if possible perpendicular recently excavated and section in different directions): In some cases an outcrop wall of 20m x 7m is sufficient, in other cases outcrop walls of e.g. more than 100m x 10m are needed to understand the architecture of gravel bodies (compare also the different lengths of the examples from Fig. 3.5). According to the required outcrop conditions it is refered in this chapter 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. 3.5). Especially the size of 'cut and fill'- elements is an important indicator for the resulting groups. It is imagined that apart from factors like 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, I refer to these patterns as 'main-', 'intermediate-' and 'minor' discharge areas (chapter 3.7).

3.6.1 Main discharge area (Rhine valley)

Gravel bodies in the main discharge area are characterized by a domination 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 changing 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 assemblage of 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 inclusions of horizontal and homogeneous zones of lower permeability.

3.6.2 Intermediate discharge area (Upper Swabia)

The sedimentary construction of gravel bodies of the intermediate discharge areas clearly display smaller scaled elements. 'Accretionary'- elements dominate, represented in this example by horizontal to sub-horizontal 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 poorly sorted gravel (Gcx). Well-sorted gravel (GS-x) and sand (S-x) occur frequently, whereas the frequency of alternating gravel (Gcg,a) is clearly reduced. These 'cut and fill'- elements are interpreted as local (non-migrating) scour pools and small dissection elements.

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.

3.6.3 Minor discharge area (Upper Swabia)

Gravel bodies of the minor discharge area are characterized by a mosiac 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).

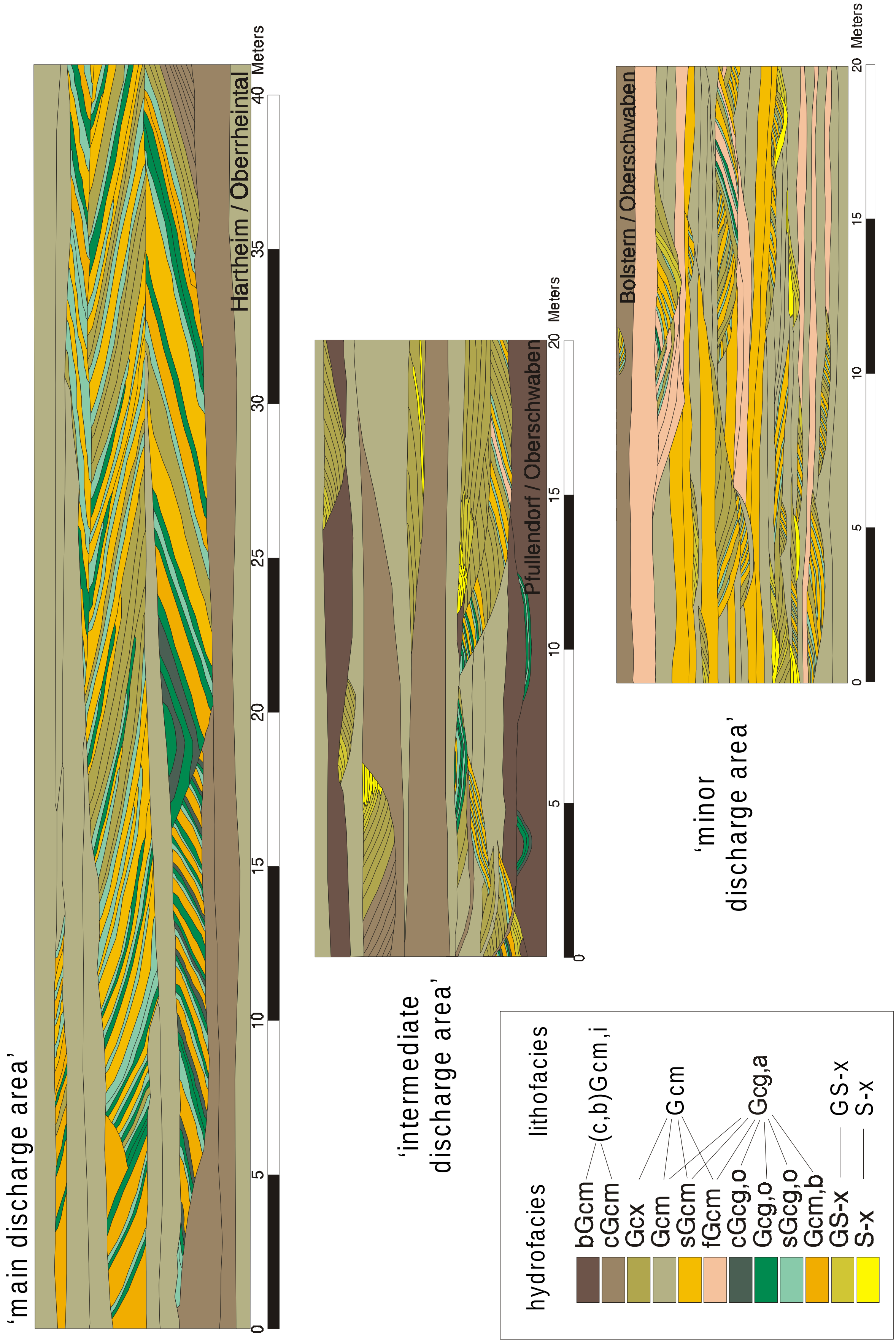


Fig. 3.5: Comparison of different styles of sedimentary architecture in gravel bodies. Three major regional and recurrent pattern are distinguished due to stacking pattern of depositional elements and their lithofacies build up.

3.6.4 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 build-up was recorded (Fig. 3.6). To document changes in the ongoing gravel excavation and reduce local deviations, this standardized survey was carried out 4 to 5 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 differencess could be recognized underlining the grouping into three patterns of heterogeneities. Figure 3.6 A/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. 3.6 D shows the occurrence of alternating gravel. Large (migrating) scour pools of the ‘main discharge area’ represent favourable positions (negative step) 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, this analog data may in the future also represent important input parameters for geostatistical modeling of such highly heterogeneous deposits.

architecture of gravel body	‘main discharge area’					‘intermediate discharge area’			‘minor discharge area’		
site nr.	1	2	3	4	5	6	7	8	9	10	11
accretionary -/ cut and fill- elements	20 / 80	5 / 95	15 / 85	25 / 75	50 / 50	70 / 30	70 / 30	65 / 35	95 / 5	95 / 5	85/ 15
size of c/f - elements [m]											
median thickness	1.7	2.2	1.9	1.8	1.0	0.8	0.7	0.8	0.3	0.5	0.6
max. thickness	4..0	5	3.5	3.0	1.5	1.5	1.4	1.5	0.5	0.8	1
median width	21	28	30	26	19.3	8	7.3	9	2.1	3.7	4.3
max. width	40	45	38	50	25	13	11	15	4.0	8.0	12
median length	45	32	38	39	24	12	11.8	13	2.1	3.7	4.3
max. length	70	100	>60	60	>30	20	30	20	4.0	8.0	12
hydrofacies portion [%]											
bGcm	0	0	0	0	40	14	1	0	0	0	0
cGcm	2	2	3	5	13	22	11	20	10	15	8
Gcm	13	3	16	4	0	30	25	34	20	10	21
Gcx	16	21	20	20	10	6	20	18	9	10	23
sGcm	12	24	2	23	17	4	14	7	38	30	18
fGcm	0	0	0	0	0	0	0	0	2	3	0
cGcg,a	4	0	0	0	0	1	0	0	0	0	0
Gcg,a	23	10	13	5	5	6	2	5	1	0	2
sGcg,a	12	20	25	21	8	2	6	2	15	16	15
fGcg,a	2	0	0	0	0	0	0	0	0	5	0
Gcg,o	0	0	4	4	3	0	2	0	1	0	0
Gcm,b	8	5	9	2	2	2	0	2	0	0	1
GS-x	4	10	4	4	1	8	12	9	2	6	9
S-x	4	5	4	12	1	5	7	3	2	5	3

Table 3.3: Summary of the statistics (lithofacies, depositional elements) carried out in the studied gravel pits; (1) Hartheim, (2) Haltingen, (3) Herten, (4) Rheinheim, (5) Wyhlen, (6) Pfullendorf, (7) Ingoldingen, (8) Ostrach, (9) Reichenbach, (10) Bolstern, (11) Saulgau

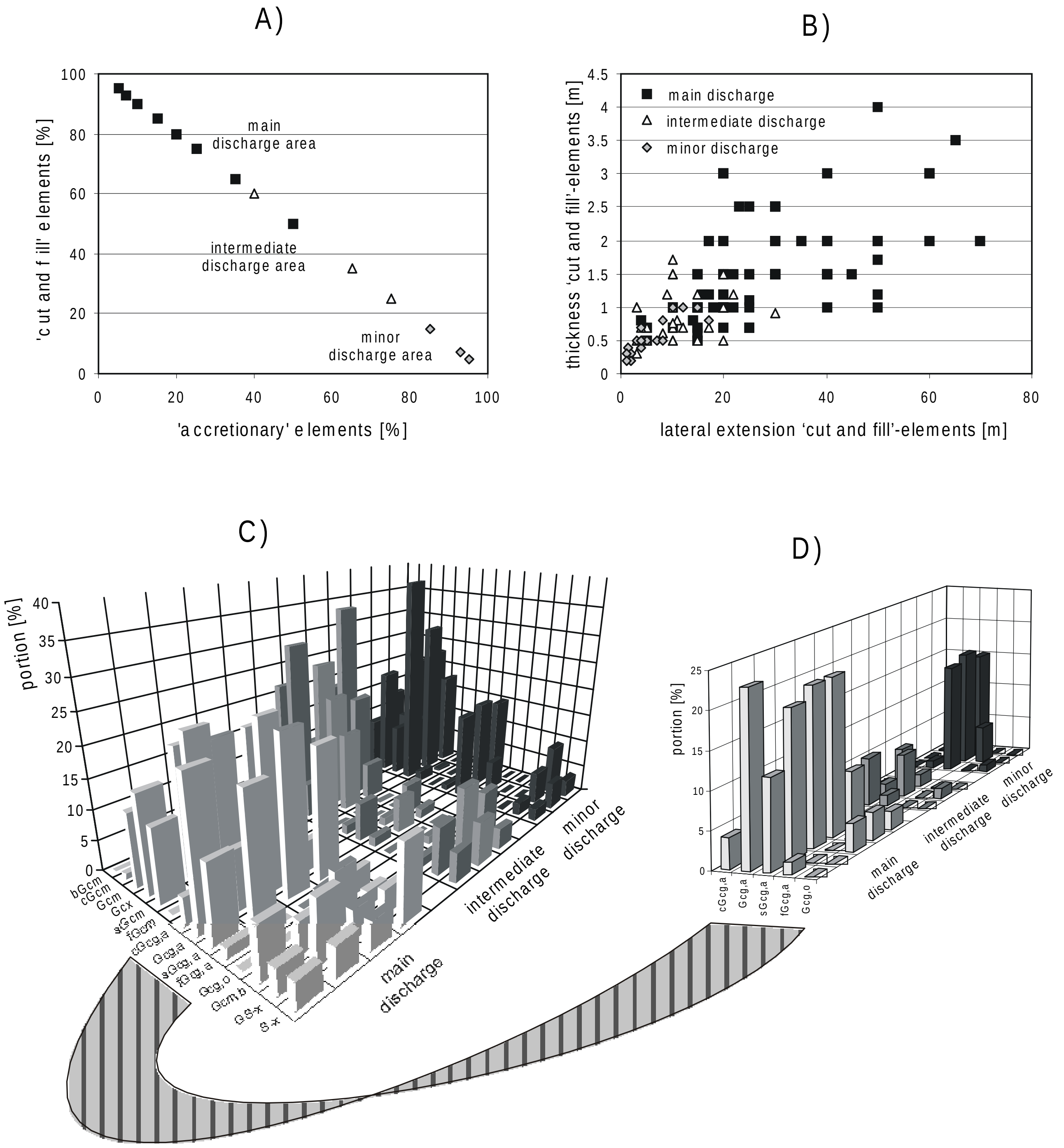


Fig. 3 6: Statistical survey within the studied gravel pits: the frequency of depositional elements, their size and occurrence of lithofacies-types enable the regional classification of gravel bodies into ‘main-, intermediate- and minor discharge area’. A) ratio of the element groups (‘cut and fill’/ ‘accretionary’), B) size of ‘cut and fill’- elements, C) lithofacies portions, D) comparison of the frequency of high permeable openwork gravels occurring within lithofacies ‘alternating gravel’ (Gcg,a).

3.7 Facies models

Based on these three major facies assemblages, three conceptual facies models could be deduced (Fig. 3.7) for proglacial river systems appearing in regional paleodrainage systems of the Rhine glacier.

The 'main discharge area' is characterized by large and stabile channels with a permanent transport of water and sediment. Discharge behaviour 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 & 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 stabile. Small 'cut and fill'-elements form locally and remain at their position (no 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-scaled interfingering of sedimentary units within the 'minor discharge zone' indicates a pulsatory (flashy) transport and deposition of sediment (low frequency/high amplitude). At low magnitudes, water is flowing only in small and less dynamic channels (rills) and no 'sedimentary work' is done. Flashy high-magnitude events, however, lead to a short-term transport and deposition of gravel dunes and gravel sheets within the active zone.

3.8 Flow modeling

Following the procedure of Klingbeil et al. (1999) the outcrop maps were digitized onscreen as arcs of different lithofacies at the bounding surfaces using the GIS- software ArcInfo. The arcs were changed to polygons, which were labeled by lithofacies ID´s and connected to a polygon attribute table containing the hydrogeological parameters for the lithofacies as characterized above and listed in Tab. 3.2 (hydraulic conductivity and porosity). This procedure results in a high resolution permeability field based on the outcrop (lithofacies) information (see Fig. 3.5). The polygon based coverages can be transferred into a grid with specified cell sizes. The grid cell size was in the order of 5cm * 5cm a resolution that ensures that thin non-horizontal elements (mostly the high conductivity units (cGcg,o, Gcg,o and sGcg,o) are adequately represented and local scale dispersion could be neglected. The grid itself can than be exported as ASCII file data to a flow and transport model (in our case finite-difference numerical code MODFLOW (McDonald & 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 advective transport model starts with the distribution of particles along the left (inflow) boundary. The distribution of particles was based on the total inflow per cell along the inflow boundary. Fig 3.8 shows selected particle pathlines trough the example data sets and illustrates how the high conductivity units clearly focus the particles (e.g. main discharge area, Hartheim). It is seen that the heterogeneous structure of the subsurface leads to the development of a considerable flow channelling, with most of the flow to occur in the scour pool dominated area, where medium to high conductivity hydrofacies prevail. The intermediate and minor discharge areas (Pfullendorf and Bolstern) display a more homogenous flow field due considerable 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 were accomplished. For a direct comparison of the three parameter fields the Hartheim data set was reduced to 20.5 m (area from 20.5 m – 41 m). Arrival times for 1000 flux distributed particles are displayed on a cumulative base in Fig. 3.9. 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 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). 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 for the sedimentary environment based on field tracer experiments. Part of the ongoing research is to prove this observations statistically.

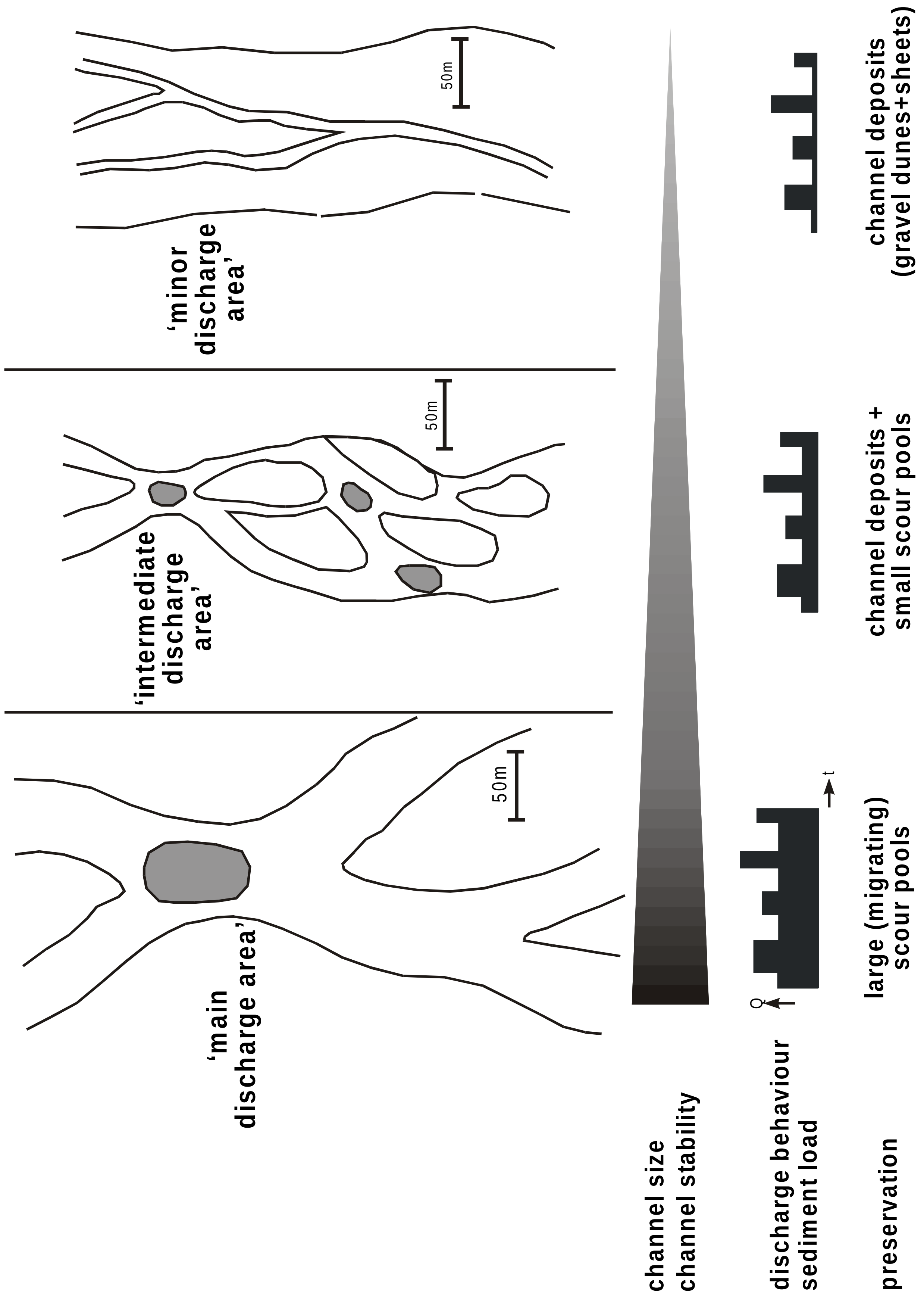


Fig. 3.7: Three major facies models derived from sedimentary architecture of regional styles of gravel bodies (see text for explanation).

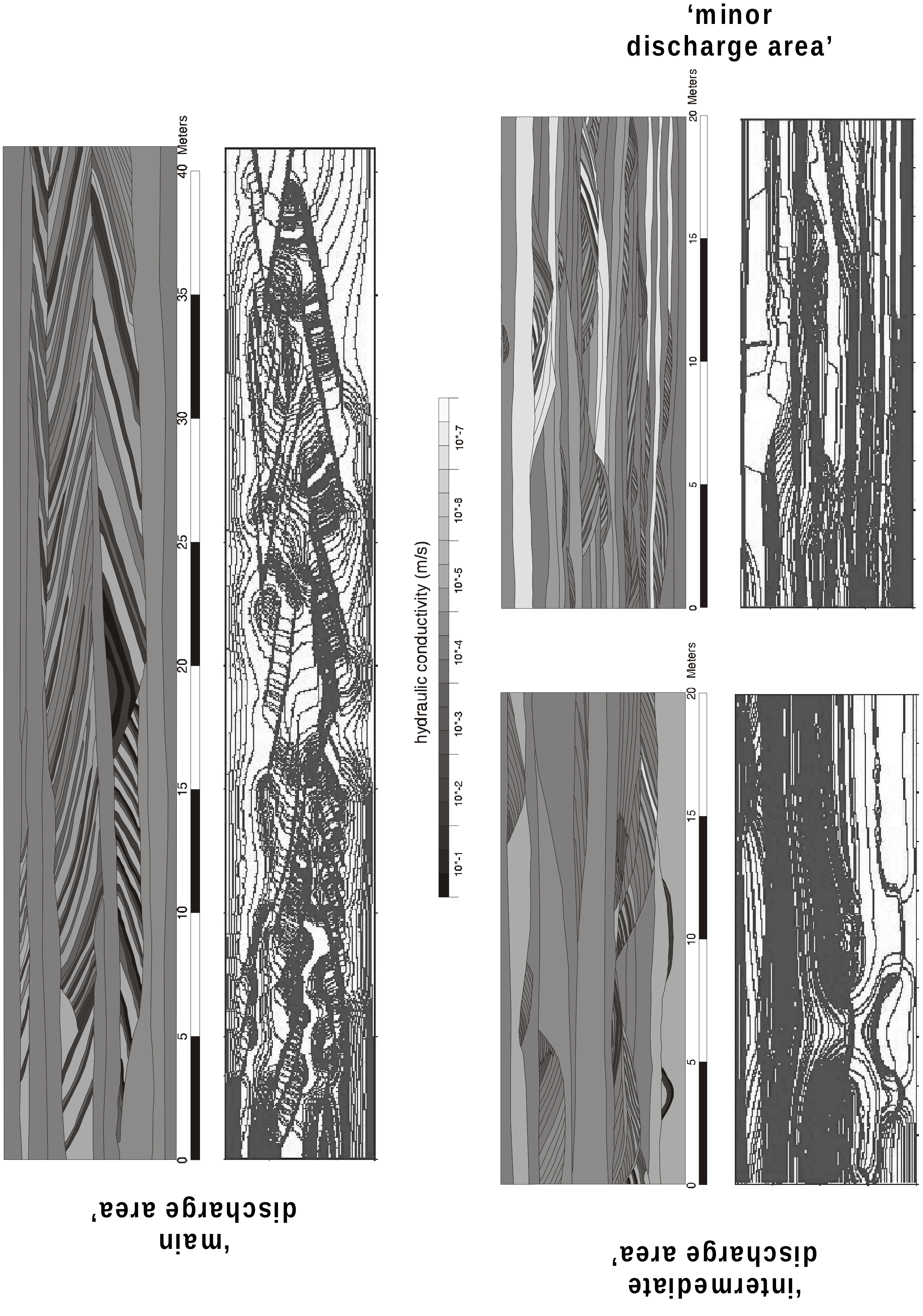


Fig. 3.8: Comparison of permeability distribution and modeled flow lines for the three gravel body architectures. Pathlines of 120 particles tracked through the different heterogeneity pattern. In all cases the initial distribution of particles is flux dependent on left hand side. In general the high hydraulic conductivity units (cGcg,o; Gcg,o, sGcg,o) clearly focus the flow lines (from Heinz et al.).

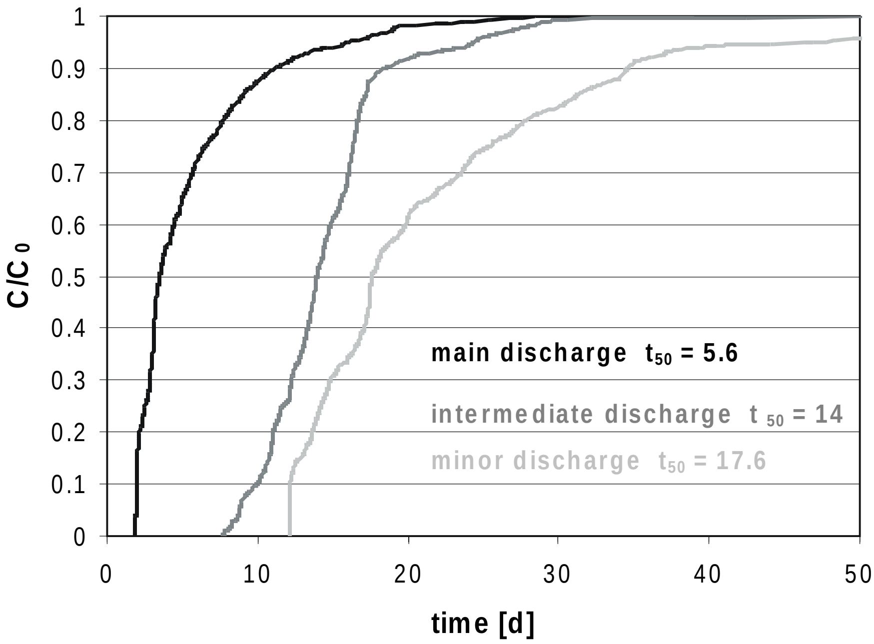


Fig. 3.9: The travel time of 1000 particles illustrated as breakthrough curves show a fast arrival in the main discharge area where higher fractions of open framework hydrofacies were identified compared to the other two sedimentary architectures. Especially for the minor discharge area long tailing is expected due to a large fraction of low permeability layers with great extension (from Heinz et al.).

3.9 Conclusions

Glaciofluvial gravel-bed deposits form highly heterogeneous bodies. Facies analysis, and comparison of numerous gravel pits (statistical surveys) revealed three reoccurrent pattern of sedimentary architecture. According to the regional appearance of these architectures distinct facies models have been deducted. The river environments are thought to be controlled by sediment supply, hydraulic gradient, valley cross-section and particularly by the quantity of draining water.

Three architectural pattern are classified: 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 (trough 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 lithofacies.

The lithofacies types, which are crucial for the hydraulic properties, have been transformed into hydrofacies types. According to their genesis and hydraulic properties 5 major lithofacies have to be subdivided into 12 hydrofacies types. A range of 7 orders of magnitudes ($10^0\,ms^{-1} < kf < 10^{-7}\,ms^{-1}$) have been both measured in column tests and theoretically calculated respectively.

Sedimentological outcrop wall mappings which show an accurate distribution of lithofacies could be transferred into 2-dimensional hydraulic parameter fields. For each type of gravel body architecture a numerical modeling of fluid flow and transport has been carried out which showed, that the sedimentologically classified gravel bodies (heterogeneity pattern) are also characterized by a distinguishable hydraulic response signal.

Thus it is possible to combine the sedimentological analysis of extremly heterogeneous gravel deposits with a hydrogeological characterization. In this study it has been shown that sedimentary processes are responsible for the genesis of heterogeneity pattern which determine local groundwater flow in aquifers.

4. Using 3-D georadar surveys to characterize glaciofluvial gravel bodies: subsurface- and calibration- studies of braided river deposits

4.1 Chapter abstract

Closely spaced georadar profiles are used for a 3-D characterization and comparison of glaciofluvial gravel-bed deposits in paleo-discharge zones of the Würmian Rhine glacier (SW-Germany). For this study use was made of previous sedimentological outcrop investigations which revealed three regionally reoccurring architecture styles of gravel bodies. For each of these styles a 3-D georadar dataset has been acquired in active gravel pits in order to calibrate the radar profiles with outcrop walls and to analyse, in 3 dimensions, the depositional elements and their stacking pattern in the subsurface.

The radar data are interpreted using principles of seismic stratigraphy by mapping reflector terminations to delineate genetically related units. In particular, radar facies and radar sequence boundaries are used to define and map depositional elements. Both ‘accretionary-’ and ‘cut and fill-’ depositional elements could be identified. ‘Accretionary’ elements are characterized by horizontal- to low inclined and continuous reflector patterns terminating on flat ‘sequence boundaries’ and represent deposits of gravel sheets and gravel dunes. In contrast ‘cut and fill’ elements are characterized by low- to steeply inclined, often discontinuous reflector patterns, terminating on concave- to though- shape lower truncation boundaries which are interpreted as scour pool fills and small dissection elements.

The three regional architecture styles of gravel bodies can be distinguished based on the size and proportion of ‘cut and fill’ elements. One style of gravel body (type A) reveals an amalgamation of large ‘cut and fill elements’ whereas the other two styles are dominated by ‘accretionary’ elements and differ by the proportion of smaller ‘cut and fill’ elements. The results clearly show that 3-D georadar surveys are useful to reflect the sedimentary architecture of gravel bodies. They provide detailed 3-D information about depositional elements and their stacking pattern which are difficult to reconstruct in outcrop studies alone.

4.2 Introduction

Glaciofluvial gravel-bed deposits of dynamic braided river systems form highly heterogeneous bodies with regard to depositional elements, their internal lithofacies make-up as well as their preservation (Siegenthaler & Huggenberger, 1993). Sedimentologists often have to reconstruct the fluvial environments on the base of 1-D drill core information and/or 2-D outcrop wall sections. However, for a detailed and correct comprehension of a paleo-fluvial environment as well as an adequate quantification of the corresponding deposits, three dimensional information is required (Brierley 1996).

Starting with the work of Ulriksen (1982) the georadar- (or ground-penetrating radar-) technique has been applied in sedimentology for a (continuous) resolution of sedimentary structures and architectures in the shallow subsurface (about 2m - 40m). This technique works well in low conductive sediments like sand- and gravel deposits and many studies documented that the geophysical (dielectric) properties are closely related to primary sedimentary structures. Hence, 2-D radar profiles are often used for the interpretation of the subsurface architecture. This has been shown, for instance, for delta deposits (e.g. Jol & Smith, 1991; Smith & Jol, 1992, 1997), for fluvial deposits (e.g. van Overmeeren, 1998; Bridge et al., 1998; Vandenberghe & Overmeeren, 1999) and for proximal glaciofluvial deposits (e.g. Huggenberger, 1993; Olsen & Andreasen, 1995; Beres et al. 1995). A large-scaled (>5m) arrangement of parallel profiles or profiles arranged in a large-scaled grid additionally enabled the geometrical demarcation of prominent fluvial sedimentary units (e.g. Stephens, 1994; Bridge et al., 1995; Bristow, 1995; Asprion & Aigner 1997). However, these measurements are still often inadequate to resolve the 3-D character of fluvial architectural elements. Recently, closely (<1m) spaced radar profiles have been measured (e.g. Beres et al., 1995; McMechan et al., 1997; Asprion & Aigner, 1999) leading to a highly detailed cube of continuous radar information. Beres et al. (1999), for instance, illuminated the 3-D architecture of highly heterogeneous braided river deposits in the Swiss part of the Rhine valley by using 3-D georadar data. The results showed the possibility of an accurate mapping of architectural elements and their stacking pattern in the subsurface.

In this study 3-D georadar data are used to compare different architecture styles of coarse-grained braided river deposits. These different architectural styles have already been documented in sedimentological investigations of many gravel pits in former discharge zones of the Rhine glacier (see chapter 3). Thus the major objectives in this chapter are:

1) to calibrate the radar profiles with corresponding outcrop walls in order to show the possibilities for the resolution of highly heterogeneous gravel deposits

2) to use 3-D georadar surveys in order to characterize the different architecture styles, geometries, depositional elements and their preservation potential in different regional environments

The overall aim is to complete an existing sedimentological data base of lithofacies and preserved depositional elements with 3D-georadar characterization and thus make it usable for applied subsurface studies (e.g. prediction of aquifer heterogeneity) in the future.

4.3 Sedimentological background and investigated sites

The facies analysis of fluvial gravel-bed deposits is covered in the previous chapter (chapter 3) and here only a brief summary is given.

The morphology of a fluvial system is mainly controlled by the amount of discharge, sediment supply and the cross-section of the drainage area. In proximal positions, braided river systems are preferentially developed. Coarse-grained glaciofluvial braided river systems are highly dynamic in terms of their discharge behaviour (frequency and amplitude) and their geomorphic changes (e.g. migration or avulsion of channels), resulting in highly variable deposits. The fluvial environment can be reconstructed according to the record and preservation of depositional (or architectural) elements (Miall, 1985; Siegenthaler & Huggenberger, 1993), which are characterized by specific external shapes and internal structures. Two groups of depositional elements can be classified (Heinz & Aigner, 1999):

1) ‘cut and fill’ elements and 2) ‘accretionary‘ elements.

The first group is characterized by an erosive concave lower bounding surface filled in a second step with sediment. Examples are scour pool fills which are formed at channel bends and channel confluences (Ashmore, 1993) of a braided river system and small dissection elements occurring, for instance, on bar-complexes. In comparison, ‘accretionary’ elements show an aggradational and/or progradational stratification style build up on a flat lower bounding surface. These deposits are interpreted as in-channel accumulations and the dominant forms are ‘horizontally stratified gravel sheets’, ‘cross-stratified gravel dunes’ and ‘massive traction carpets’.

Internally, depositional elements are characteristically made up of different lithofacies types. In glaciofluvial gravel deposits of the Rhineglacier area the major lithofacies types are: 1) poorly sorted gravel, 2) alternating gravel, 3) well sorted sand and gravel and 4) cobble- and boulder- rich gravel. They are the result of transport- and depositional processes controlled by flow energy and sediment charge (see chapter 2.3.2 and chapter 3.4). The most frequent lithofacies is ‘poorly sorted gravel’ and occurs in cut and fill elements as well as in accretionary elements. Lithofacies ‘alternating gravel’ (composed of a lower zone of bimodal to polymodal gravel and an upper zone of graded, well sorted openwork gravel) appear dominantly in cross-stratified elements (scour pools, gravel dunes). ‘Well sorted sand and gravel’ are mostly found as small lenses in areas of diminished flow (e.g. in marginal parts of scour pools or in flow-shadows of channel accumulations). In contrast lithofacies ‘cobble- and boulder- rich gravel’ indicate high magnitude events and exclusively appear in accretionary elements.

Comparison of 25 gravel pits in paleo-drainage zones of the Würmian Rhineglacier revealed three regionally reoccurring sedimentary architectures of gravel bodies classified here in type A, B and C.

A) Gravel deposits formed in a braided river environment with high discharge (high frequency, high amplitude discharge behaviour) and relatively deep and stable channels are characterized by abudant large scour pool fills. Regionally this type of gravel body mainly occurs in the Rhine valley, which drainaged the glacier to the West. In two gravel pits of the studied discharge zone adequate conditions for the acquisition of 3-D georadar data have been found. One site near the city of Basel (gravel pit Herten) is situated more proximal to the Würmian Rhineglacier and the other site near the city of Freiburg (gravel pit Hartheim) is situated more distally (see Fig. 4.1).

B) Gravel deposits formed in a braided river environment with moderate discharge (moderate frequency, high amplitude) and relatively smooth and less stable channels are characterized by a domination of accretionary elements and locally small cut and fill elements. This type of gravel body (B) occurs in paleo-drainage zones North of the glacier, towards the river Danube. A 3-D georadar example has been acquired in the gravel pit of Ostrach (Upper Swabia) which is closely situated to the last maximum ice-extension of the Würmian Rhine glacier (Fig. 4.1).

C) Gravel deposits formed in a fluvial environment with minor discharge (low frequency, high amplitude) and unconfined and pulsatory transport of sediment are characterized by elements of gravel sheets and gravel dunes (accretionary elements). Cut and fill elements (small dissection elements) appear only rarely in the sedimentary record. Again this type of gravel body (C) appears more in the northern paleo-discharge zones of the Würmian ice-sheet. 3-D georadar data has been acquired in the gravel pit Saulgau (Upper Swabia) which is situated closely to the terminal moraine complex of the last maximum ice-extension (Fig. 4.1).

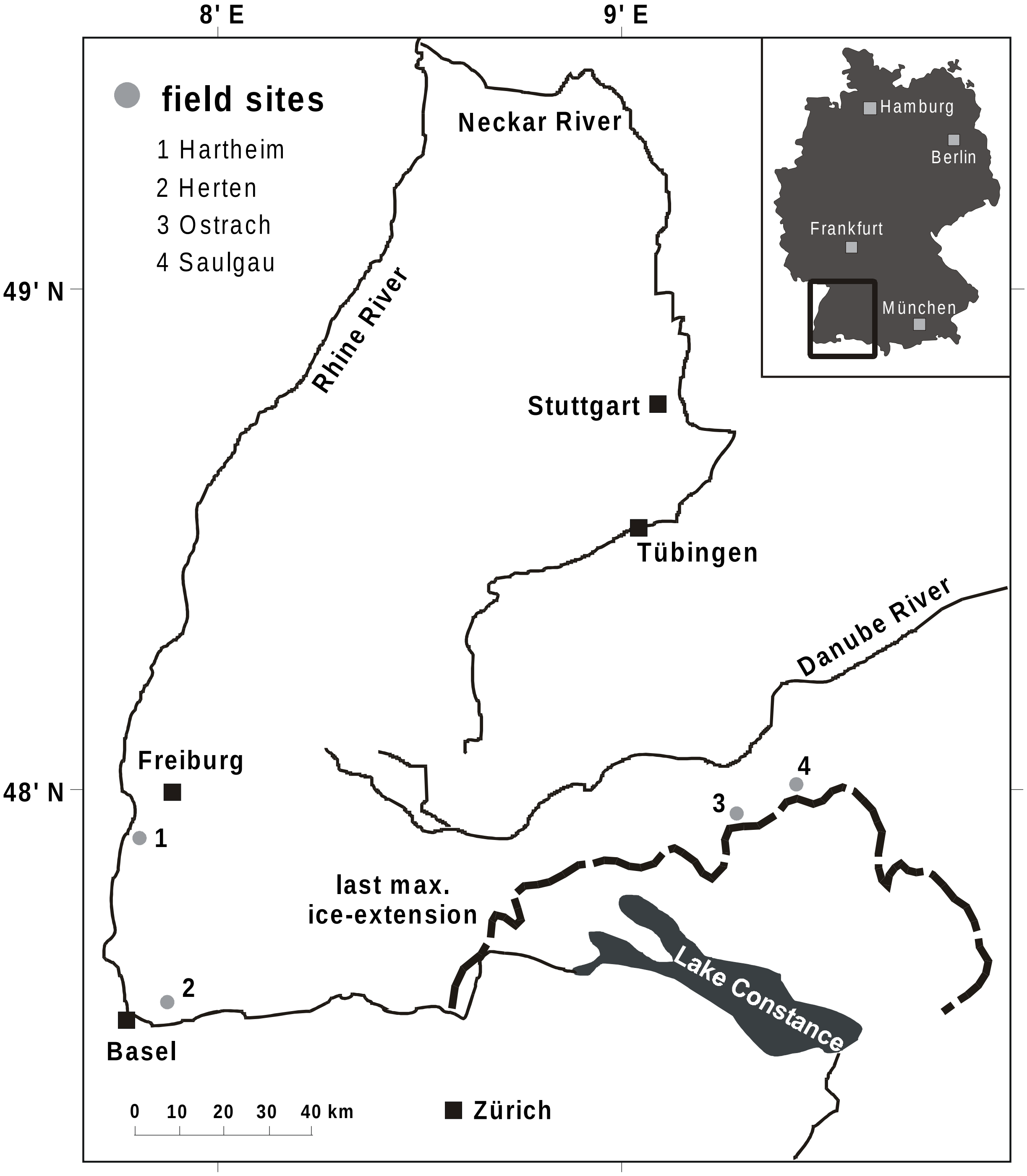


Fig. 4.1: Location of the studied sites in SW-Germany according to the last maximum ice-extension of the Würmian Rhineglacier lobe.

4.4 Georadar method

Georadar profiling is a high-resolution, shallow subsurface geophysical technique. Short pulses of high-frequency electromagnetic (EM) energy (10-1000 MHz) are transmitted into the ground and due to bulk electrical properties of lithologies in the subsurface some of the energy is reflected back to the surface whereby the strength of reflected energy is approximately proportional to the differences in relative permittivity of the sediment interfaces. Attenuation of energy increases as electrical conductivity increases. In fluvial sediments, for instance, penetration depth is strongly controlled by the amount of clay and silt particles. Resolution is controlled vertically by the frequency of the used antennas (high frequency = high resolution), whereas the lateral resolution is conditioned by the 'Fresnel-zone' (mean volume of the reflected wave-front) which is controlled by the wavelength and the depth of the object (lateral resolution diminishes with depth). The theory of georadar and principles of measurements are well described by several authors (e.g. Ulriksen, 1982; Davis & Annan, 1989; Huggenberger, 1993).

The georadar data presented here were measured with a GSSI SIR-system 10A and a pair of 300 MHz antenna (separation of transmitter and receiver was fixed to 1.4m). For this study the used frequency represented the best compromise between high resolution and adequate penetration depth. Thus useful information was obtained to a depth of 6-10m below surface. Common midpoint- and radar-tomography measurements (e.g. Beres et al., 1999; Tronicke et al., 1999) give an average near-surface wave velocity of 0.1m/ns, resulting in an effective vertical resolution in the order of few decimetres. This has also been shown by the close comparison of georadar records with outcrop wall sections.

Georadar reflectors appear to be associated with changes in the residual water content of different lithofacies types (Huggenberger, 1993) which is primarily controlled by their grain-size and sorting. In the studied gravel deposits clear reflections are expected between poorly sorted lithofacies types (poorly sorted gravels, cobble- and boulder-rich gravels), matrix-free, openwork gravel (upper zone of lithofacies 'alternating gravel') and sand dominated lithofacies types (e.g. well sorted sand, bimodal gravel, sand-rich gravel).

Data acquisition was carried out in parts of the selected gravel pits where soil and weathered material has already been removed and uniform surface conditions predominated. The 3-D grids were arranged by parallel radar profiles with a spacing of 1m in one direction and 1-5m in the orthogonal direction, covering right-angled areas of 600-1750m^2.

Data were processed with band-pass filter, automatic gain control and Kirchhof - migration using the PC - based system 'Reflex' (K.J. Sandmeier, Karlsruhe, Germany). Further steps of interpretation and visualization of the 3-D data were carried out with the software programs 'slicer dicer' and 'Gocad'.

4.5 Results

4.5.1 Calibration of radar profiles

Calibrating radar data is important to appraise the reliability of the radar method in different depositional environments. In former studies comparison has been carried out, for instance, with core data (e.g. Bridge et al. 1995, 1998) or nearby outcrop faces (e.g. Huggenberger, 1993; Asprion, 1997; Rea & Knight, 1998). In this study two methods were applied:

a) direct comparison of radar profiles with the excavated outcrop wall and b) forward modeling of radar images on the base of detailed outcrop wall maps.

4.5.1.1 Direct comparison of radar profiles with excavated outcrop wall

In the gravel pit Herten, several radar profiles were measured and marked at the surface. During the progress of excavation (parallel to the radar lines) the vertical outcrop sections could be positioned exactly at the sites of the previously measured radar profiles resulting in a direct comparison of outcrop walls and corresponding radar image (see also Bayer, 2000).

One example of photographed outcrop wall, radar image and interpretation according to depositional units (A-F) is shown in Fig. 4.2 and will be described in the following.

Unit A is characterized in the radar image by continuous and high amplitude, horizontal reflectors. This simple pattern corresponds well with the horizontally stratified gravel sheets in the uppermost 1.8m of the outcrop.

Within unit B inclined, low to moderate amplitude reflectors downlap and onlap on relatively continuous high amplitude reflectors which show a truncation of lower units. Both depth-position and geometry of unit B correspond well with the sedimentary ‘reality’. The lower base of this depositional unit consist of a matrix-rich (silty) gravel-layer which is responsible for the strong (double wavelet) reflection zone. Internally, unit B comprises trough cross-stratified ‘alternating gravel’ with a large proportion of openwork gravel. Reflectors in the radar image indicate the inclined stratification but reflector dipping not fully correspond to the angle of beds, particularly in the left part of unit B. Additionally, the number of bundles of lithofacies ‘alternating gravel’ is higher than the number of reflectors indicating that not each single contrast or layer, respectively, can be resolved.

The wedge-shape of unit C is well represented in the radar image. The low to moderate amplitude, discontinuous internal reflector pattern show that this unit is comparatively homogeneous (mainly sand-rich, poorly sorted gravel).

Unit D is constructed by the cross-stratified lithofacies ‘alternating gravel’ (left and middle part) and (sand-rich) ‘poorly sorted gravel’ (right part of unit D). In the radar image this unit is not clearly to identify. High amplitude reflectors appear in the left and middle part of unit D where ‘alternating gravel’ is situated below ‘poorly sorted gravel’ of unit C. In contrast, in the right part of unit D low- to moderate amplitudes are shown indicating slight contrasts of lithofacies. The internal cross-stratification could not be recognized without outcrop information.

Unit E is dominated in the outcrop section by cross-bedded, ‘poorly sorted gravel’ where thin (5-10cm) and discontinuous layers of openwork gravel are intercalated. While position and geometry of unit E can be identified in the radar profile, the internal cross-stratification and their contrasts in permittivity is not shown. On the contrary, the reflectors are subhorizontal with low to moderate amplitudes.

The lowermost unit F consists of sand-rich, poorly sorted gravel intercalated with patches and discontinuous beds of openwork gravels (10-20cm in thickness) which indicate subhorizontal stratification. Unit F and E show no clear boundary and are difficult to separate in the radar image. The reflector pattern of unit F can be described as subhorizontal, moderate to highly continuous, with moderate to high amplitudes. However, the length of reflectors do not correspond with the discontinuous openwork beds as seen in the outcrop section.

The detailed comparison of radar image and outcrop wall showed that the depth position (velocity = 0.1m/ns) and external shape of the depositional units are well reproduced in the radar profile. They can be defined due to reflector terminations, distinct reflector patterns and in some cases by the appearance of high amplitude radar boundaries. The amplitudes of reflectors are controlled by the permittivity contrasts between the single lithofacies types constructing the depositional units. Thus the contrasts in these gravel-bed deposits are often more dominant within a depositional unit than between them. This means, that for the demarcation of the units a sedimentological interpretation is required. In the upper and middle part (Unit A,B,C) the internal structure of depositional units have well been depicted in the radar image. Contrary this was not possible in the deeper parts (unit D, E). Within unit D, signals of the internal contrasts are surely overlapped by the high contrast between the interface of element C and D (especially in the left part). Within unit E it is assumed that the transmitted wavelength (of the EM wave) was to long to detect the small-scaled beds (5cm thick openwork gravels), particularly because this unit is relatively deep (3,2 - 4,8m) resulting in a (3-D) larger mean volume of the transmitted wave (Fresnel zone), the reflected signal, respectively. In unit F this larger reflection volume is probably responsible for the relatively continuous reflections, although the openwork gravel-layers are more discontinuous. Additionally, when comparing outcrop and radar sections, it must be considered that the image of radar profile results of a three-dimensional reflection signal from the subsurface contrary to the ‘pure’ 2-D outcrop section.

Small-scaled lithofacies changes can not be recognized in the radar images. This is explained due to 3-D effects, interference of signals, diffractions, differences in velocity and the theoretical resolution (controlled by the wavelength and the depth). High amplitude reflectors indicate high contrasts in relative permittivity but from this data alone it is often ambiguous to assign the correct change of lithofacies.

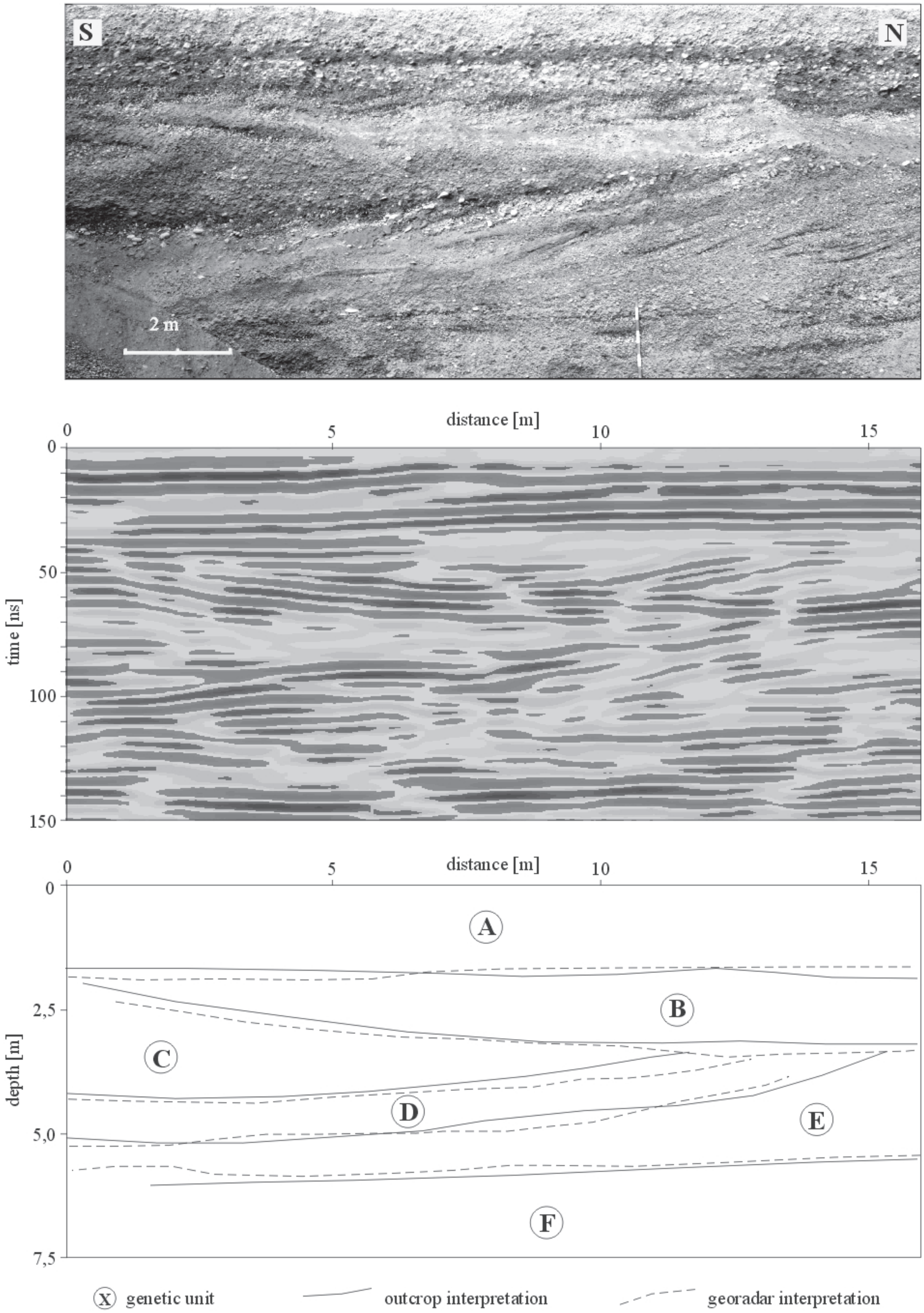


Fig. 4.2: Comparison of outcrop wall and radar image within the gravel pit Herten. Position and external shape of the depositional units (A-F) correspond well with the radar profile. Internal structures are indicated in the upper units (A,B,C) whereas within the lower units (D,E,F) stratification is not resolved adequately. Amplitudes refer to changes in lithofacies types but statements of single strata are ambiguous without outcrop information.

4.5.1.2 Forward modeling

A major problem for the calibration of outcrop sections with corresponding radar profiles is the high organisatory and technical expenditure (planning of excavation progress, exact positioning of the vertical outcrop sections by the excavator) in the gravel pits.

In order to gain more calibration data GPR simulations based on outcrop wall information were carried out (Kowalsky et al.). Therefore, detailed outcrop wall panels of lithofacies distribution were digitized on screen using the GIS-software Arc Info (see also data of chapter 3.6 /3.8 and Klingbeil et al., 1999). The lithofacies are classified according to their material composition (e.g. grain-size, sorting, texture) which significantly determine porosity and water saturation respectively. In Table 4.1 the values of porosity, water saturation and the calculated velocity of each of the defined lithologies is given. According to their petrophysical parameters reflection coefficients between the interfaces of lithologies can be calculated for EM waves. The numerical simulation was carried out using a petrophysical model (described in Wharton et al., 1980) and a centre frequency of 100 MHz for the transmitted wave. The presented simulations have been carried out by Mike Kowalsky (University of California, Berkeley) and a detailed discussion of petrophysical theory, models and simulation conditions are given in Kowalsky et al..

Three examples (A,B,C) of GPR-simulations are shown in Fig. 4.3. The upper parts of the examples show the distribution of porosity which represent the lithofacies mapped in the outcrop. The lower parts are the result of the simulations for each case. The selected examples differ in dimension of depositional units and length and thickness of the lithologies. In general, the complexity of sedimentary structures (heterogeneity) increases from example A to C.

Example A shows relatively thick (0,8-2,0m) cross-stratified units consisting of an alternation of beds indicating high contrasts in porosity (lithofacies alternating gravel: white colours represent openwork gravel and grey colours poorly sorted gravel). The lowermost and uppermost part is characterized by homogeneous units with slight differences in porosity (matrix-rich poorly sorted gravel). The GPR simulation represent very well the size, shape and position of the depositional units and their internal stratification. In some cases single beds of mapped lithology are shown in the radar image and amplitudes correspond with the contrasts of the interfaces.

Example B generally shows smaller units which are often homogeneous (dark grey and black colours: poorly sorted gravel and cobble- and boulder rich gravel). In parts, local intercalation of higher porosity occurs in patches or small-scaled interstratifications (white colour: well sorted sands, light grey colour: openwork and well sorted gravels). In the simulated radar profile the main sedimentary units can be detected but the small-scaled patches and cross-bedded layers are geometrically not resolved. In some parts the inclined stratification is indicated but it is not possible to detect the thin single beds with the used frequency.

lithofacies	indicators	porosity [n]	water saturation values	velocity (m/ns)
	bGcm	0.08	0.13	1,16E+08
(c,b) Gcm,i	**cGcm**	0.17	0.13	1,19E+08
Gcm	**Gcm**	0.13	0.13	1,18E+08
	sGcm	0.17	0.13	1,19E+08
	fGcm	0.18	0.13	1,19E+08
Gcx	**Gcx**	0.15	0.17	1,16E+08
	cGcg,o	0.26	0.08	1,27E+08
Gcg,a	**Gcg,o**	0.26	0.08	1,27E+08
	sGcg,o	0.23	0.08	1,25E+08
	Gcm,b	0.22	0.17	1,17E+08
	sGcm,b			
	fGcm,b			
GS-x	**GS-x**	0.27	0.13	1,22E+08
S-x	**S-x**	0.36	0.17	1,19E+08

Table 4.1: Summary of petrophysical properties of the classified lithofacies types used as input parameters for the petrophysical model. Grainsize and sorting of lithofacies types influence both the porosity and the residual content. The resulting velocity contrasts are responsible for the reflection of radar waves.

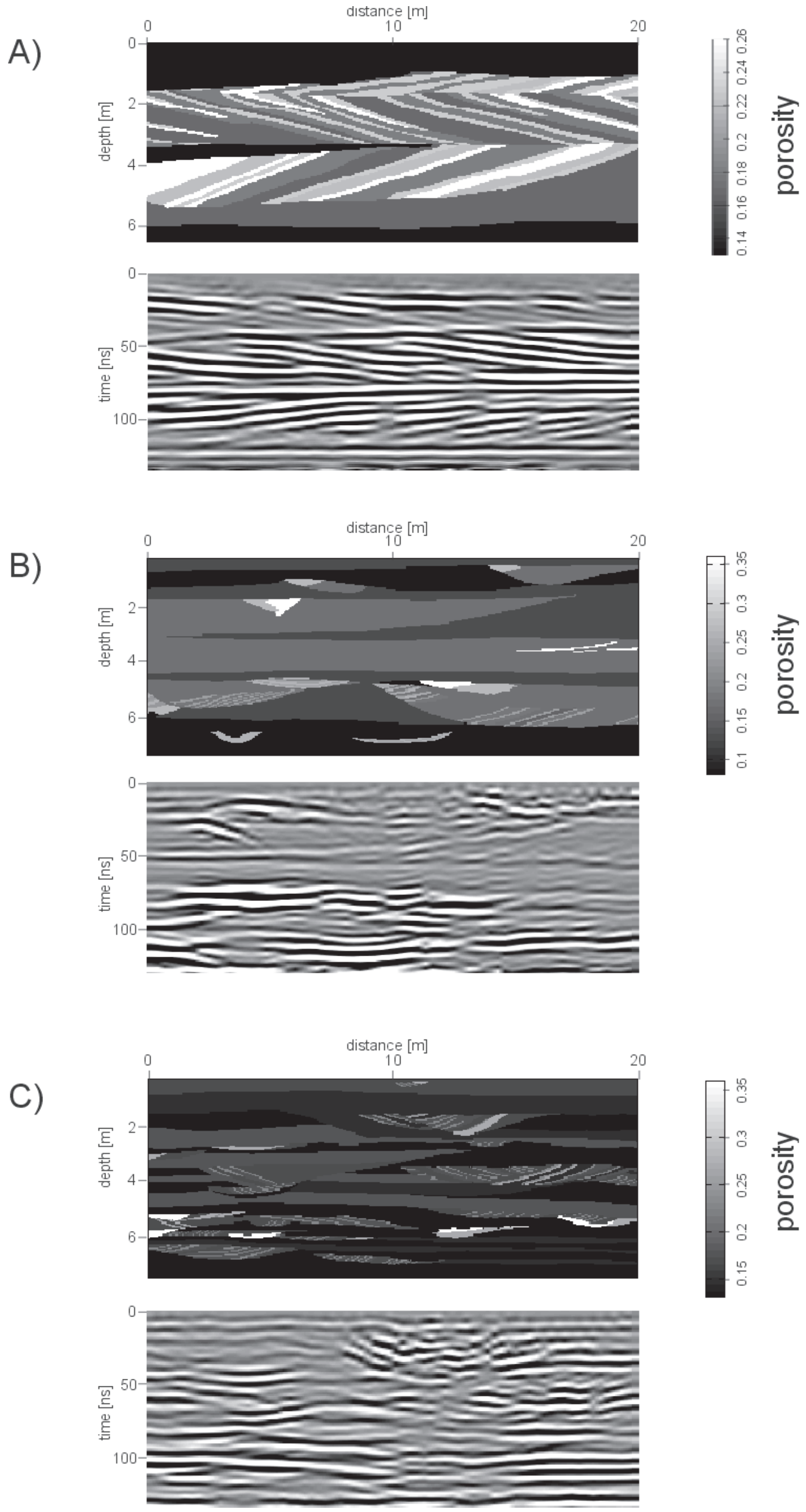


Fig. 4.3: Forward modeling of radar images on the base of detailed outcrop wall maps. Lithofacies types were classified according to their porosity (controlled mainly by grainsize and sorting). The resulting radar images of the petrophysical models were simulated using a frequency of 100 MHz and the data were migrated (Kirchhoff-migration) afterwards. Complexity of the glaciofluvial gravel-bed deposits increases from example A-C illustrating the possibilities of resolution of the radar technique. A) relatively large-scaled depositional units with simple internal structure (site Hartheim) are very well reproduced in the corresponding radar image; B) geometry and location of prominent units are resolved in the simulation but only some of the stratification structures are indicated (site Pfullendorf); C) interfingering of small-scaled units with highly variable internal structures (site Bolstern) are hardly to recognize in the radar image and only few units can be detected.

Example C is characterized by interfingering of many small-scaled units. Internally some are cross-stratified and very thin discontinuous beds of higher porosity (openwork gravel, well sorted sand and gravel) are finely dispersed resulting in a highly complex porosity pattern. In the simulated radar profile only few prominent structures are visible. Many parts are characterized by a subhorizontal reflector pattern with low continuity. It comes clear, that this highly heterogeneous distribution pattern can not adequately be resolved. In the radar image only some (few) of the depositional units can sedimentologically be interpreted.

Comparison of the different examples sheds some light on the strenghts and limitations of the radar method for the subsurface resolution of these gravel deposits. Simply structured, large units (example A) can be resolved in detail and sometimes even inferences about single beds and their contrast are possible. In contrast, highly complex, small-scaled constructions can not be detected in the simulated radar profiles.

In general, the results of forward modeling are very useful for the appraisal of possibilities of the georadar method in different depositional environments. The advantage of the simulations is that several scenarios can be carried out easily for one given model. For example different wave-frequencies (resolution and penetration depth) but also different water saturation (important for the comparison of unsaturated sediments versus saturated sediments representing aquifer materials) can be tested (Kowalsky et al.). Thus this method enables both to calibrate and to predict reflector patterns of sedimentary environments.

4.5.2 Case studies

4.5.2.1 Gravel pit Hartheim / Herten

The two studied sites are situated in the Rhine valley (see Fig. 4.1). Sedimentologically, both case studies show a very similar architectural style which corresponds to gravel body type A (see chapter 4.3). Data acquisition in the gravel pit Hartheim was carried out on the top floor of the outcrop. Soil and weathered material have already been removed and radar lines could be measured on a dry and flat area of 1750m^2. The grid had a length of 50m in NE-SW direction and a width of 35m in NW-SE direction. Parallel, continuously measured radar lines were spaced at 1m distance (35m lines) and at 5m distance perpendicular (50m lines). An electrical power line about 20m away from the grid produced noise signals (hyperbolas) in the deeper part of some radar images.

Fig. 4.4A shows a typical radar profile of this site which is characterized by large units of inclined reflector patterns terminating (downlap and onlap) on top of lower truncation surfaces. Reflectors are generally discontinuous showing high to low amplitudes. These units are interpreted as cut and fill elements. In some parts of the radar image horizontal to subhorizontal, more continuous reflectors occur, which are interpreted as accretionary elements. A nearby outcrop face revealed a record of complex scour pool fills and relics of gravel sheets confirming the radar data.

One single radar profile is often insufficient for a correct interpretation of depositional elements and several parallel and /or orthogonal lines significantly improve the reliability. Due to the closely spaced radar lines acquired at this site it was possible to map depositional elements in three dimensions. From line to line the depositional units were outlined and traced, also controlled by the orthogonal lines.

The interpretation is given in Fig. 4.5 and shows a three-dimensional stacking of cut and fill elements with relicts of accretionary elements. The uppermost units (unit 07 and 08) are interpreted as gravel dune deposits, while unit 02, 03, 04 and 05 represent scour pool fills. The depositional elements are sometimes far larger than the extension of the radar grid. Cut and fill elements are often amalgamated and some are clearly elongated in paleoflow direction (from S to N). Extension and thickness of the detected cut and fill elements are given in Fig. 4.8. It has to be noted that these values represent minimum dimensions, as incomplete detected cut and fill elements must be assumed.

In order to obtain more data about dimensions of cut and fill elements in this architectural style of gravel body (type A) a second site (Herten) with an area of 28 x 44m was investigated with 3-D georadar surveys. A similar architectural pattern is revealed in the radar profiles with a dominant preservation of large cut and fill elements and few proportion of accretionary elements (see also caption 2.6 and Fig. 4.2). The thickness, length and width data of cut and fill elements have been added to the ones of the site Hartheim in Fig. 4.8.

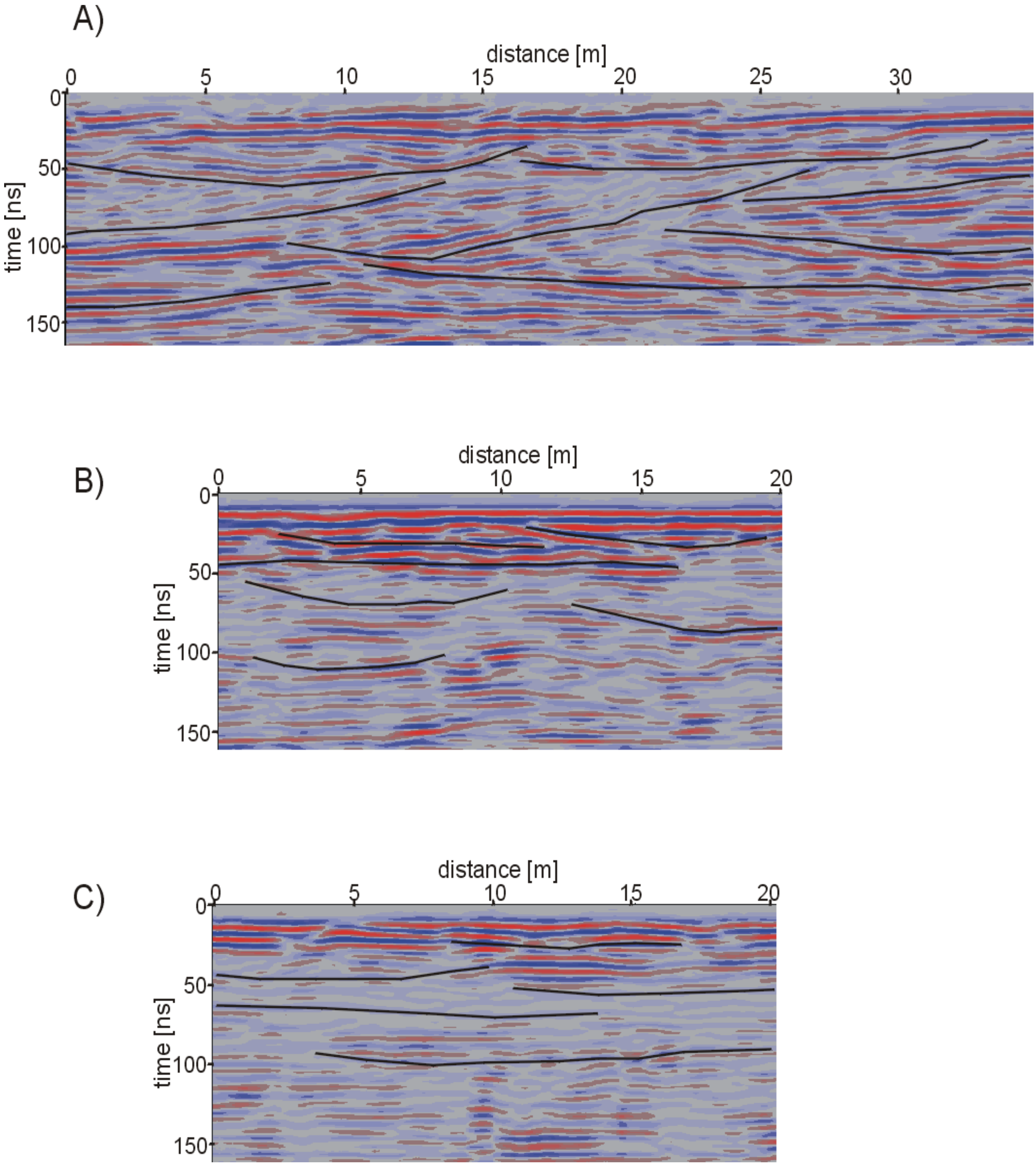


Fig. 4.4: Comparison of 2-D radar profiles reflecting different types of gravel body architecture. Data are processed (bandpass filter, Kirchhof migration) and depositional elements are outlined within the images. A) amalgamation of mainly large-scaled cut and fill elements indicated by units of inclined reflectors terminating on lower truncation zones; B) dominance of accretionary elements (subhorizontal to horizontal reflector pattern) with local cut and fill elements (small truncation zones); C) stacking of accretionary elements indicated by subhorizontal reflector pattern.

In both sites radar images could be interpreted to a depth of 8-10m. This is probably due to the large dimensions of the depositional elements and thicker lithofacies units with distinct petrophysical contrasts (compare with Fig. 4.3A).

The obtained 3-D georadar data of the two investigated sites clearly reproduce the architectural style of gravel body (type A). Depositional elements can be interpreted and classified according to their geometry and their internal structure. Some of the major depositional elements are shown in Fig. 4.10.

4.5.2.2 Gravel pit Ostrach

This outcrop revealed a sedimentary architecture of gravel body termed here type B (see chapter 4.3). Radar lines were measured on a middle terrace of the gravel pit Ostrach, positioned about 6m below the original surface. Acquisition was carried out in winter and a thin (5cm) layer of snow covered the flat gravel surface. The size of the grid was 20 x 30m. Parallel radar lines of the longer profiles were directed NW-SE and spaced 1m while the orthogonal profiles (NE-SW direction) had a distance of 2m.

In Fig. 4.4B a characteristic radar image of this site is shown. Large parts of the image are characterized by a stacking of horizontal to subhorizontal reflectors with moderate to high continuity. These zones are interpreted as accretionary elements and a nearby outcrop wall revealed a dominance of gravel sheet deposits (compare also to Fig. 4.3B). This reflector pattern is disrupted by smaller and local truncations. Internally low inclined, discontinuous, low to moderate amplitude reflectors occur. These depositional units are referred to local cut and fill elements (scour pool fills) as also seen in the nearby outcrop face.

The interpretation of the 3-D radar survey is shown in Fig. 4.6. The lower truncation-zone of cut and fill elements is relatively easy to delineate whereas it is difficult to map the (sub-) horizontal reflector pattern of stacked accretionary elements (i.e. gravel sheets). Therefore, beside the cut and fill elements (e.g. unit 04, 07, 10, 14), only few dominant individual packages of horizontal reflectors of accretionary elements have been mapped in the subsurface (e.g. unit 12). In the uppermost 4m of the volume it was possible to detect small-scaled cut and fill elements while below only larger and more prominent units could be recognized. Downwards from a depth of 7m no sedimentological interpretation according to depositional elements could be carried out. It is clear that not every depositional unit which would be noticed at the outcrop wall is represented in the radar image. This can be explained by low contrasts, thin beds and relatively large mean reflection volume in comparison to the size of the units (see Fig. 4.3B). The investigated radar volume revealed 11 local, partly amalgamated cut and fill elements which are slightly elongated in the direction of paleoflow (from SE to NW). Their dimension are shown in Fig. 4.8.

Generally, the architectural style of the gravel body (type B) can be sufficiently resolved by the radar data and most of the prominent depositional elements could be mapped and interpreted (see also Fig. 4.10).

4.5.2.3 Gravel pit Saulgau

The architectural style of gravel body revealed at this site is termed here type C (see chapter 4.3). Radar lines were measured on the top floor of the gravel pit where soil and weathered material has already been removed. A grid of 30 x 20m was acquired on a flat and slightly humid gravel surface. The longer lines were directed E-W and the orthogonal lines N-S, both spaced at 1m distance.

A typical radar profile of the site is shown in Fig. 4.4C. The whole radar image is characterized by a subhorizontal, moderately continuous, moderate to low amplitude reflector pattern. In this case the sedimentological interpretation with regard to depositional elements was very difficult. The nearby outcrop walls showed an interfingering of diffuse gravel sheet- and sometimes gravel dune- deposits and only rarely very small-scaled cut and fill elements occur (type C, compare also with Fig. 4.3, example C). Hence, the interpreted surfaces shown in Fig. 4.7 do not represent mainly boundaries of depositional elements but show relatively prominent and traceable reflectors, which reproduce the diffuse architectural style of the gravel body. Within the uppermost 3m it was possible to detect 4 small cut and fill elements. Their sizes (see Fig. 4.8) are similar to those of the site Ostrach but no directional elongation could be recognized. Interpretation of the reflectors was carried out to a depth of 5m. Below 5m, the signal could not be interpreted anymore in terms of sedimentology. This may be due to the low and thin contrasts as well as the larger mean reflection volume of the radar wave.

In conclusion the 3-D radar patterns reflect the sedimentary architecture of this gravel body, particularly in the uppermost 5m. Depositional elements are difficult to recognize in both the outcrop walls and in the radar profiles.

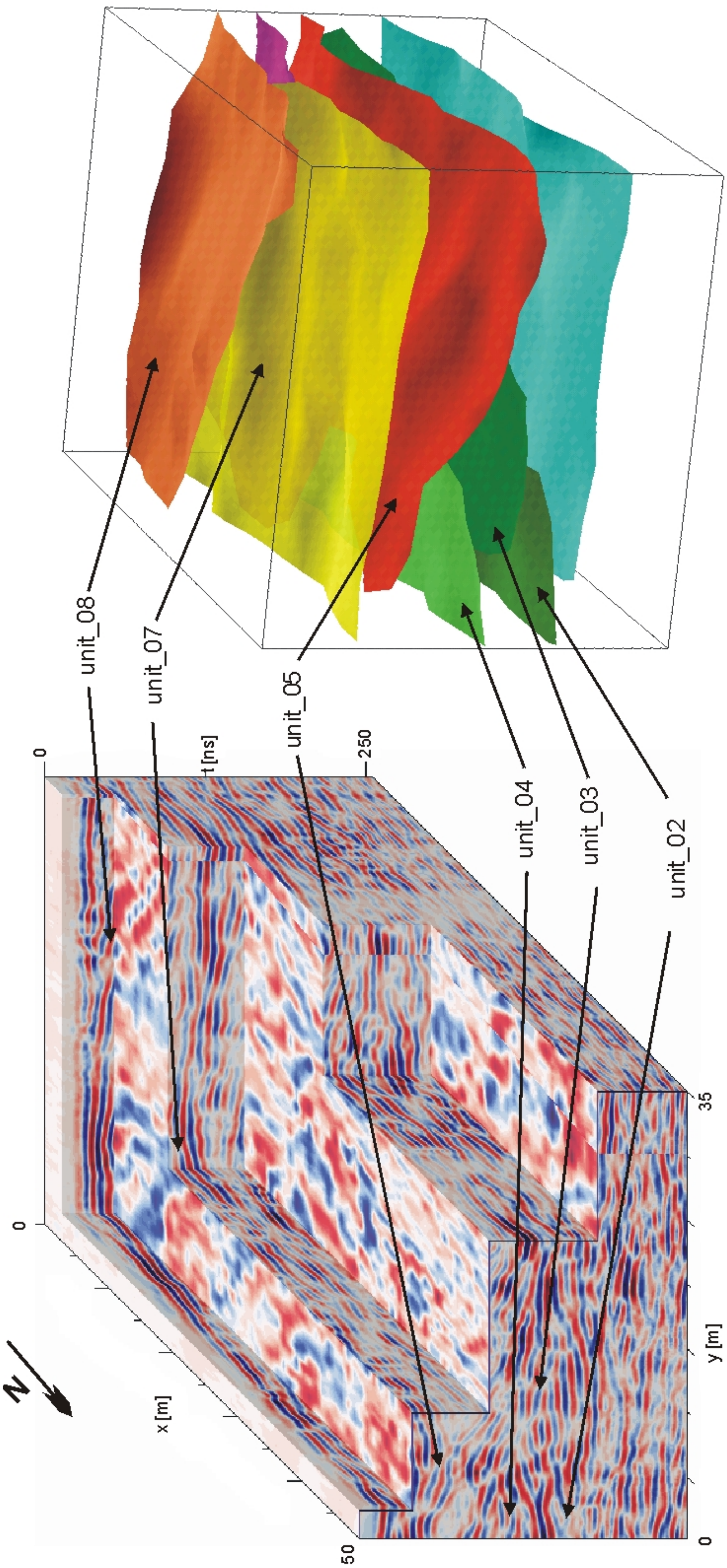


Fig. 4.5: 3-D georadar data and spatial position of depositional elements as interpreted at the site Hartheim (gravel body type A). Surfaces represent the lower boundaries of depositional elements. Deposits of unit 07 and 08 are interpreted as gravel dunes (accretionary elements) while unit 02, 03, 04 and 05 build up complex scour pool fills (cut and fill elements).

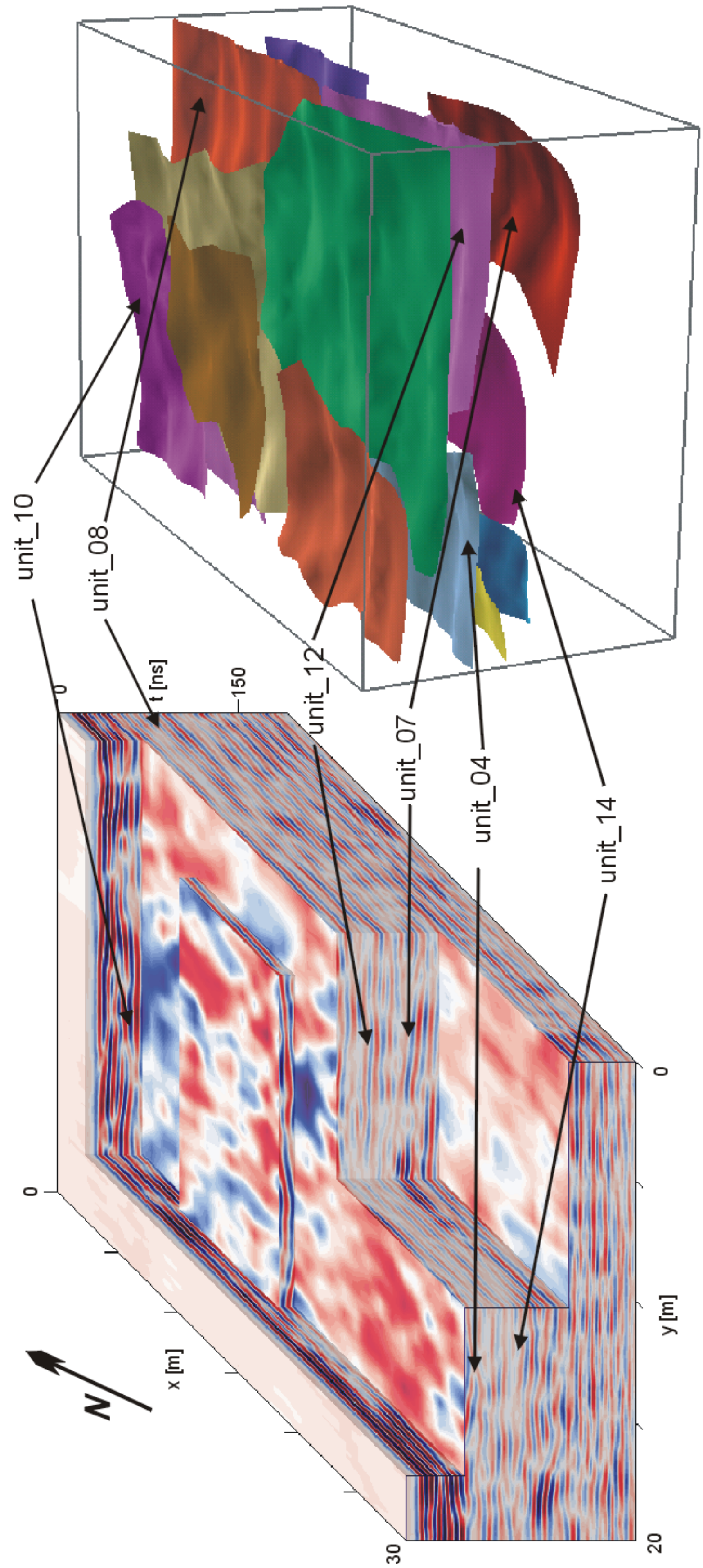


Fig. 4.6: 3-D georadar data and interpretation of depositional elements obtained at the site Ostrach (gravel body type B). Flat and relatively extensive surfaces (e.g. unit 12 and 08) represent accretionary elements (gravel sheet deposits) while small and slightly concave surfaces show the position of local cut and fill elements (e.g. unit 07, 10 and 14).

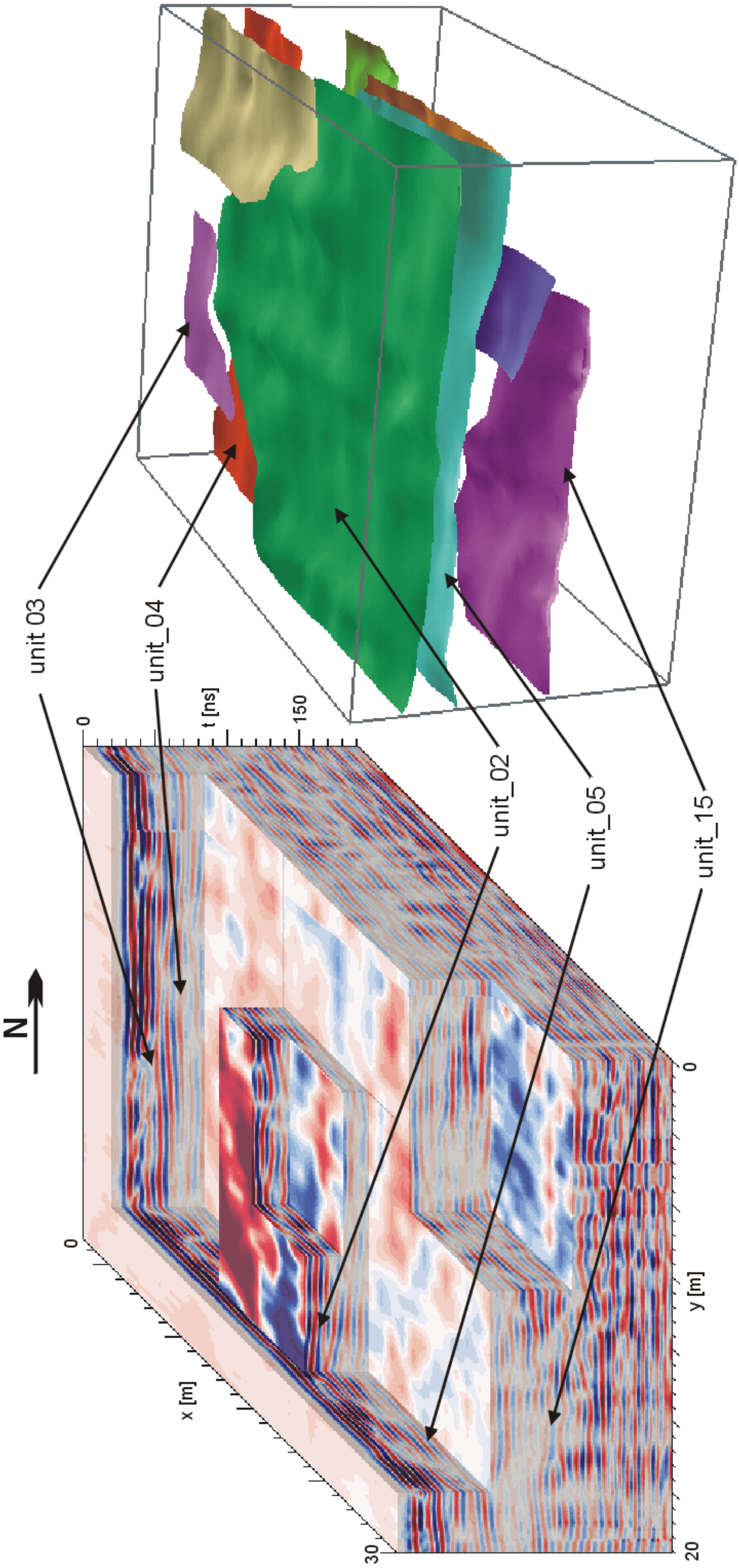


Fig. 4.7: 3-D georadar data of the site Saulgau (gravel body type C). The deposits are characterized by a subhorizontal reflector pattern indicating the record of stacked accretionary elements (e.g. unit 02,04, 05 and 15). Rarely small-scaled cut and fill elements could be detected (e.g. unit 03).

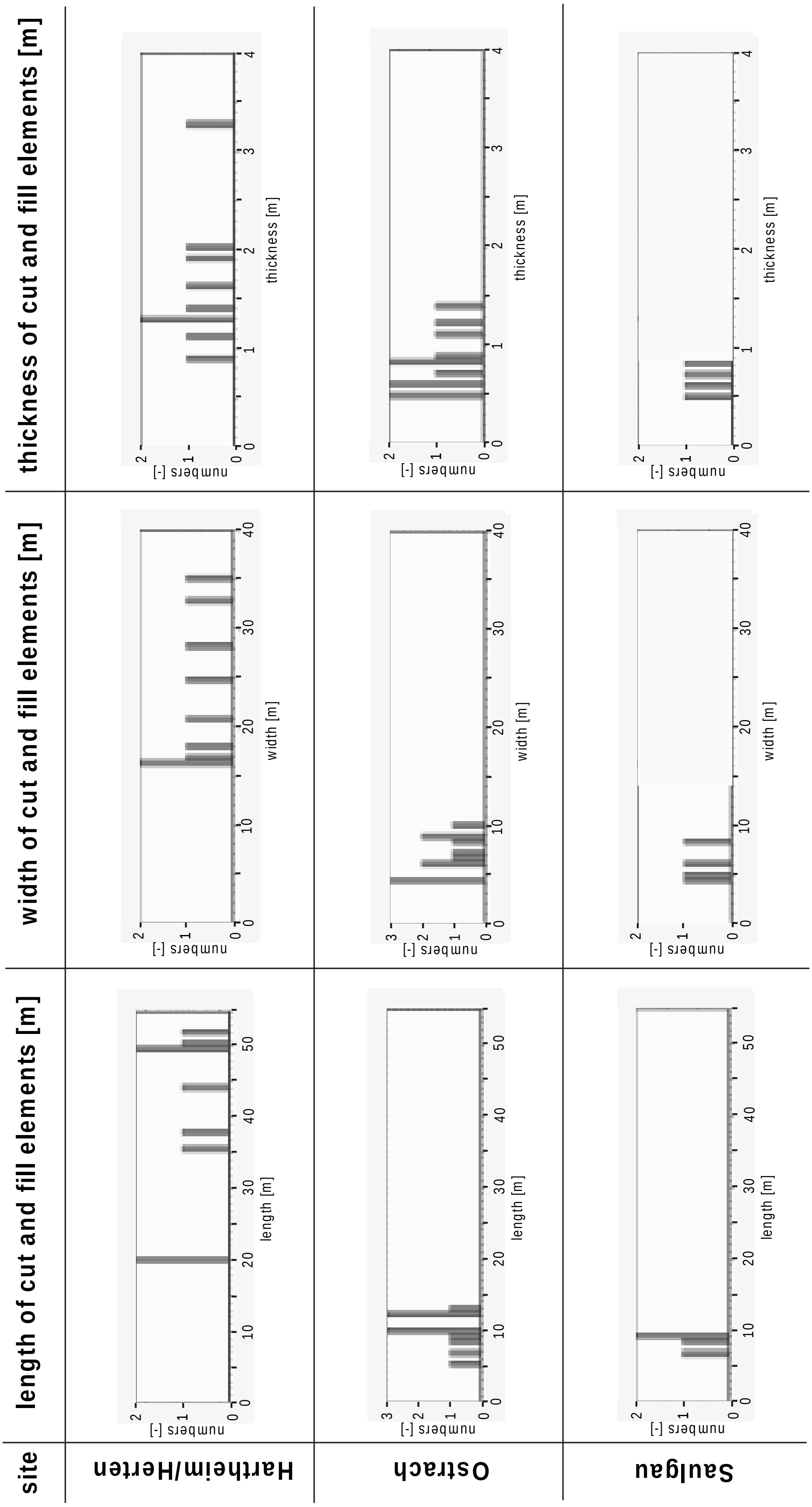


Fig. 4.8: Dimensions of cut and fill elements as mapped with 3-D georadar surveys of the different investigated sites. Within the sites Herten and Hartheim cut and fill elements are characterized by large dimensions within a broad range. Site Ostrach can be distinguished from site Saulgau due to the total number of detected cut and fill elements and slightly larger sizes.

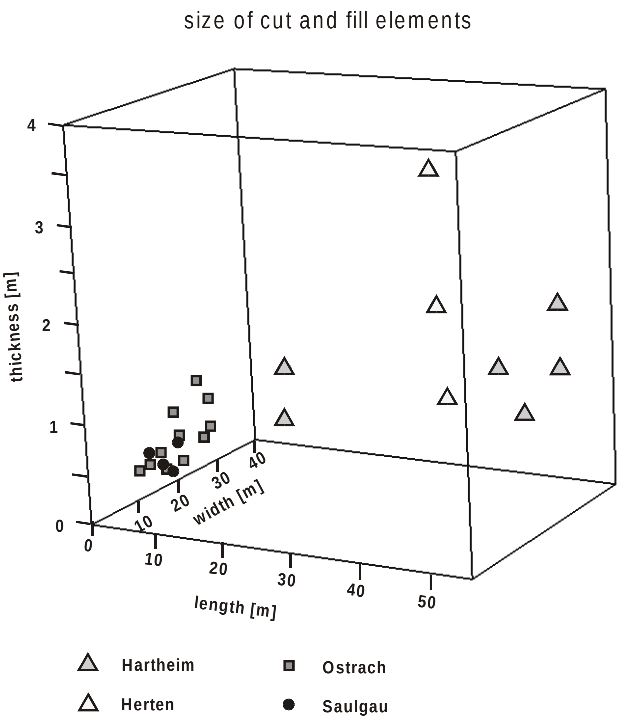


Fig. 4.9: Dimensions of cut and fill elements from the 4 investigated georadar sites. The three architectural styles of gravel body can clearly be distinguished due to the total number and sizes of the detected cut and fill elements. Note that the larger elements are often elongated in paleoflow direction.

4.6 Conclusions

In this 3-D georadar study, highly heterogeneous glaciofluvial gravel-bed deposits have been investigated in paleo-discharge areas of the Würmian Rhine-glacier lobe. Calibration of radar profiles has been carried out using a) exact comparison of radar images with the corresponding outcrop sections and b) forward modeling of radar images based on detailed outcrop wall maps. Both showed that:

- depositional elements can well be detected in the subsurface and interpreted according to their reflector pattern and external shape
- the internal structure is often indicated by the dipping and termination of reflectors
- the amplitudes can be referred to contrasts between different lithofacies types constructing depositional elements but no unambiguous evidence of single strata properties can be given

In general, the resolution is a function of wavelength and depth as well as size of lithofacies units and contrasts between the interfaces.

Different architecture styles of gravel bodies were characterized and compared using 3-D georadar surveys. They were interpreted and classified according to the preservation of depositional elements (Fig. 4.10) and could be distinguished due to the proportion and size of cut and fill elements (Fig. 4.9).

Gravel body type A (examples Hartheim / Herten) consists mainly of large units of inclined reflectors terminating at a lower truncation zone. They refer to a stacking of cut and fill elements (complex scour pool fills) which can be mapped clearly in the radar images.

Gravel body type B (example Ostrach) are characterized by a dominance of horizontal to subhorizontal reflectors (indicating gravel sheet deposits) and local erosional reflector truncations (interpreted as small cut and fill elements).

Reflectors of gravel body type C (example Saulgau) are dominantly subhorizontal and the diffuse stacking pattern often disabled the mapping of depositional elements. However, the stacking of small-scaled gravel sheet- and gravel dune deposits as seen in the outcrop walls is revealed in the 3-D radar pattern.

It has been shown that 3-D georadar surveys are very useful to illuminate the architecture of glaciofluvial gravel bodies and provide a means for qualitative and quantitative three-dimensional characterization of these deposits.

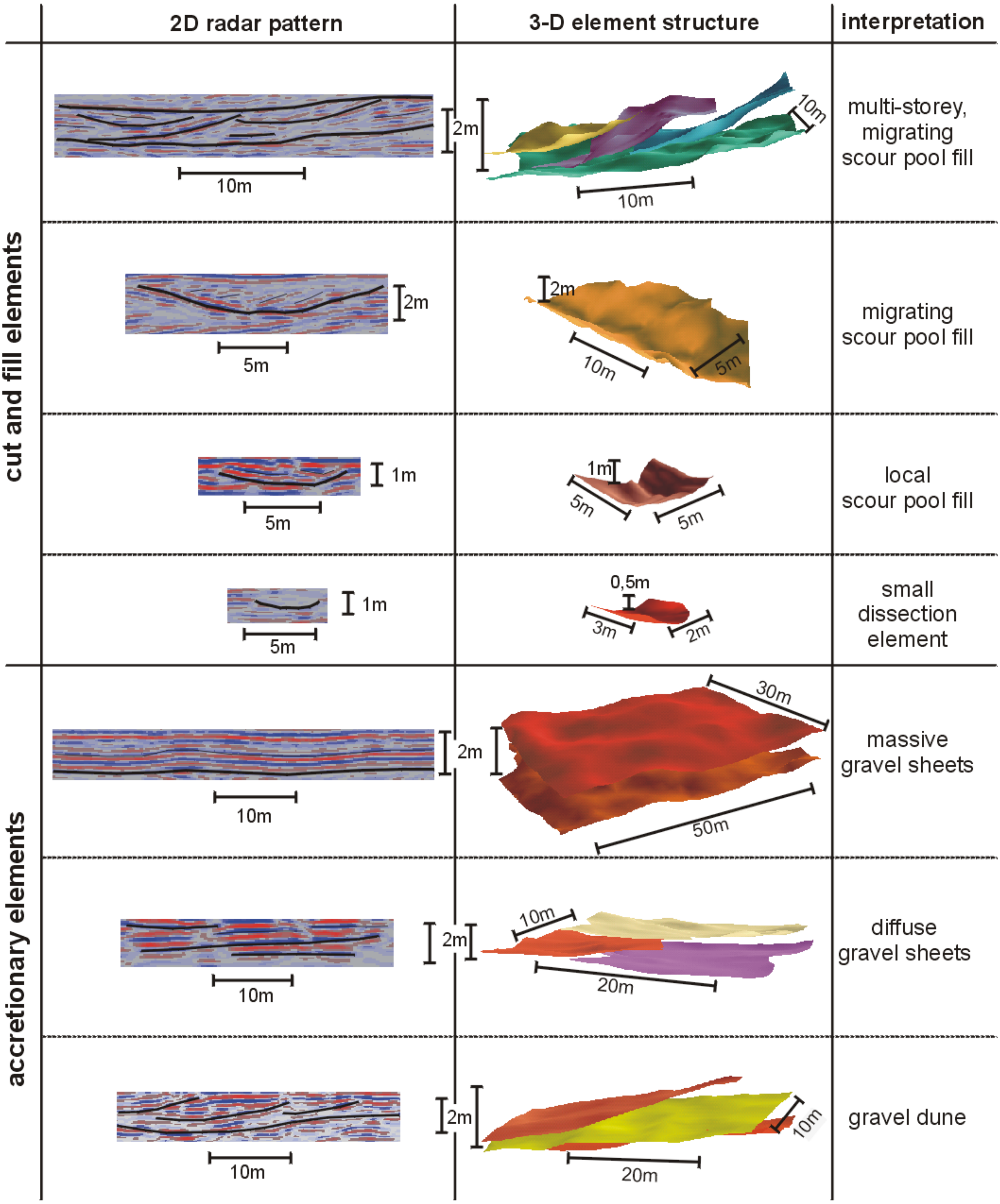


Fig. 4.10: Summary diagram on the geometry and internal structure of the major depositional elements occurring in glaciofluvial gravel-bed deposits as detected in the 3-D georadar surveys.

5. Using 3-D georadar surveys to characterize glaciofluvial gravel bodies: subsurface- and aquifer- studies of meandering river deposits

5.1 Chapter abstract

Georadar surveys allow a destruction-free imaging of subsurface structures such as variable sedimentary units responsible for aquifer heterogeneity.

In this chapter two examples of coarse-grained meandering river deposits from valley-fills in SW-Germany (Neckar valley, Danube valley) are discussed using 3-D georadar surveys. The site in the Neckar valley is characterized by extensive lateral accretion structures (continuous, low inclined reflector pattern) and local channel fill structures (onlaps of discontinuous reflectors on lower truncation zones), both covered by overbank deposits (horizontal to subhorizontal, partly smeared and indistinct reflectors). In contrast, deposits of the Danube valley site are dominated by complex trough cross-stratified units (discontinuous reflectors terminating on lower truncation zones) interpreted as a stacking of gravel dunes. Continuous, horizontal to slightly inclined reflector pattern of the uppermost part indicate upper pointbar (accretionary) deposits.

According to the sedimentological interpretation of the 3-D georadar information the paleo-fluvial style and the depositional history can be reconstructed.

Additionally, the georadar images illuminate the heterogeneity of the subsurface and allows the appraisal of aquifer behaviour and prediction of local groundwater flow, respectively. For instance, continuous lateral accretion represent units of homogeneous, low conductive but directed groundwater flow whereas heterogeneous gravel dune deposits induce undirected, probably highly permeable flow.

5.2 Introduction

Several sedimentological and geophysical studies have already been initiated in glacial outwash deposits leading to a detailed characterization of coarse-grained braided river deposits with respect to lithofacies types, depositional elements and their preservation potential (see chapter 3 and chapter 4). In contrast, there are only few data in the literature about the sedimentary architecture of (periglacial) gravelly meandering river deposits (Gustavson, 1978; Nijman & Puidefabregas, 1978; Bluck, 1979; Ramos & Sopena, 1986; Schirmer, 1995; Miall, 1996). In SW-Germany, for instance, these deposits are rarely exposed in outcrops and a detailed sedimentological facies analysis is often prevented by a high groundwater table.

However, periglacial fluvial gravel-bed deposits form widespread aquifers in many valley-fills of central Europe and elsewhere. In order to understand groundwater flow and contaminant transport in these often populated and industrialized regions a detailed description of hydraulic parameter distribution is required. In unconsolidated sediments these heterogeneities are mainly controlled by sedimentary processes operating in distinct paleo-depositional systems. This causes a characteristic distribution of lithofacies types which determine the hydrogeological properties of the aquifer. Fluvial gravel-bed deposits are characterized by lithofacies variability at the metre- to decimetre scale incorporating several orders of magnitudes of hydraulic conductivity.

Borehole data are mostly inadequate to reflect the complex sedimentary architecture of the subsurface gravel deposits. Standard coring techniques destroy the fabric and association of the lithofacies types and only deliver a mean grain-size distribution. Hence, even closely spaced core data are not appropriate to provide an adequate picture of the natural distribution of heterogeneity (e.g. Ptak & Teutsch, 1994; Jussel, 1994).

As a consequence, application of high resolution non-destructive techniques are demanded. Particularly ground penetrating radar (GPR or georadar) is used for several years for the detection of sedimentary structure in the shallow subsurface (e.g. Huggenberger, 1993; Bridge et al., 1995; Asprion & Aigner, 1997; Vandenberghe & Van Overmeeren, 1999; Van Dam & Schlager, 2000). In general, transmitted electromagnetic waves are reflected due to contrast in dielectric properties of the lithofacies beds. This is controlled by the material properties of the components and in particular by the water content (Huggenberger, 1993). Residual water content in the unsaturated zone depends on the size of pores (capillary water) whereas in the saturated zone the overall pore volume is significant. More details about the technique and theory are given in e.g. Davis & Annan (1989), Jol (1991), Huggenberger (1993). It has been demonstrated in the past that 3-D georadar surveys are a powerful tool for accurate images of the spatial distribution of sedimentary units and a few studies have already been initiated to characterize aquifer heterogeneity (e.g. Young & Sun, 1996; Rea &

Knight, 1998; Beres et al., 1999; Asprion & Aigner, 1999; see also chapter 4).

In this study the results of 3-D georadar surveys are reported which were carried out within two different sites of periglacial valley-fills. The objectives are (1) to show that the georadar technique is suitable for an accurate subsurface characterization in the unsaturated and the saturated (aquifer) zone, (2) to document different pattern of lateral accretion elements in coarse-grained deposits and (3) to translate the sedimentological radar interpretations into hydrogeological heterogeneity patterns in order to appraise local groundwater flow within depositional elements of meandering river deposits.

5.3 Case study Neckar valley

5.3.1 Field site Lauswiesen

The field site Lauswiesen is situated in the Neckar valley near Tübingen, SW-Germany (see Fig. 5.1). It is used as a natural environmental research field site in order to carry out hydrogeological and geophysical field investigation methods (Sack-Kühner, 1996). Hence, several cores were drilled within a relatively small area. A representative grain-size distribution is shown in Fig. 5.2. The investigated gravel deposits consist mainly of Jurassic and Triassic limestone components delivered from a nearby source area during the last glaciation. Water has been supplied from the

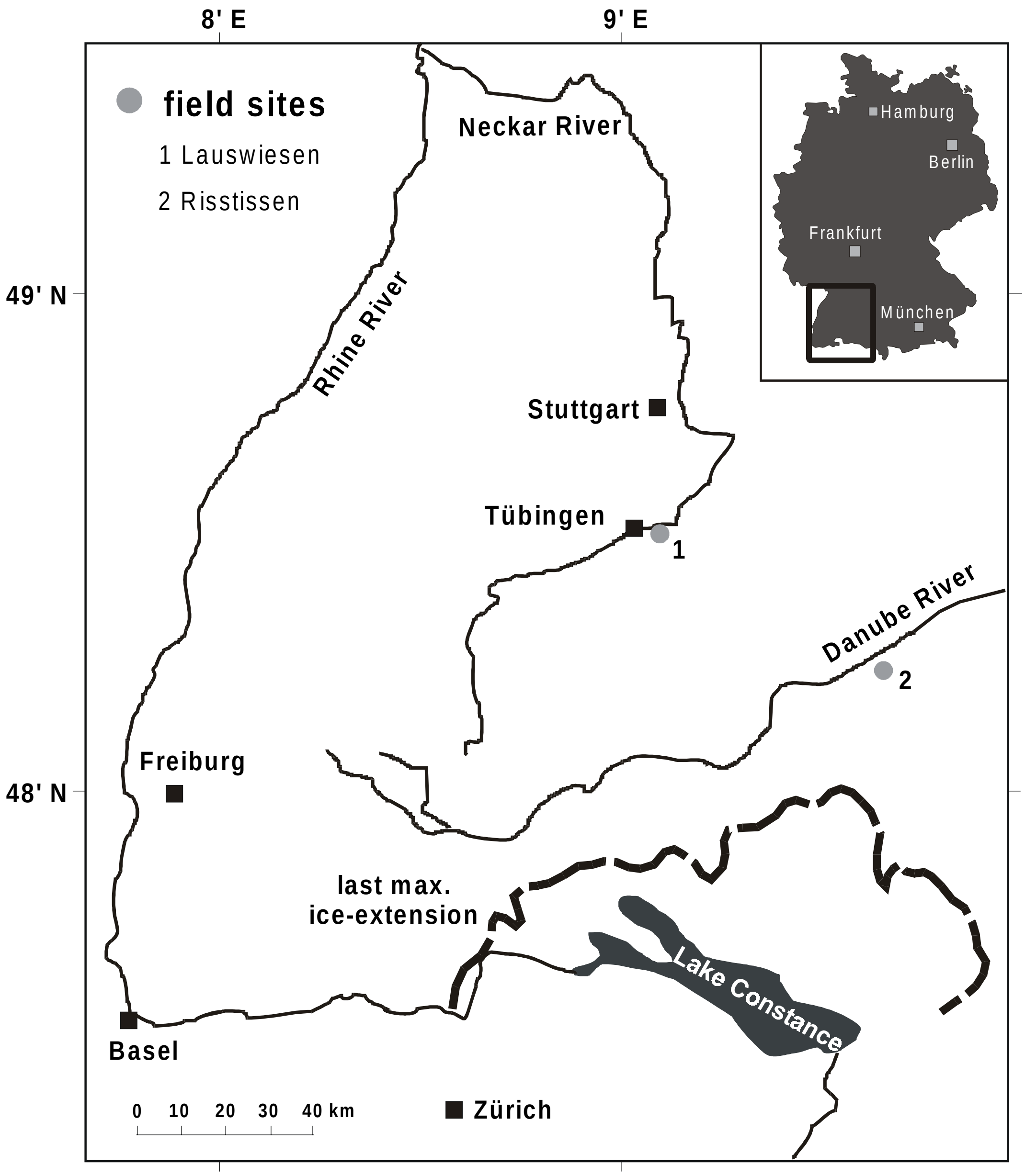


Fig. 5.1: Map showing the location of the two sites investigated with 3-D georadar surveys. Both are situated in periglacial valley-fills (Neckar valley, Danube valley).

black forest area which was partly glaciated in the Quarternary cold phases. Kleinert (1976) noted, that the gravelly sediments were deposited during the cold phases and probably might be reworked during the Holocene (through a meandering river system). Particularly overbank fines have been deposited until the 18th century. The generally 9m thick gravel body is covered at the Lauswiesen site by 0.5-2.0 m thick overbank fines. The present groundwater table is about 4m below surface (Sack-Kühner, 1996).

The georadar data were acquired on a relatively flat, grassy ground using a GSSI SIR 10A system and 300 MHz antennas with a constant offset of 1.4m. The 3-D survey covered an area of 28 x 46m with an inline and crossline spacing of 0.5m. Data processing included trace time zero correction, bandpass filtering, AGC gain and Kirchhoff migration with a constant velocity of 0.1m/ns (see also Tronicke et al., 1999). Penetration depth was limited due to the overlying fine grained overbank deposits and a sedimentological interpretation was only possible within the unsaturated zone to a depth of 4m.

5.3.2 GPR results Lauswiesen

Figure 5.3 shows a characteristic radar image of this site. It is dominated by inclined, moderately to highly continuous reflectors downlapping on a lower zone (60-75ns). Due to internal reflector terminations three depositional units (unit 3,6,7) are determined. At the left side of the profile this reflection pattern is disrupted by a distinct erosional truncation. In this part subhorizontal reflectors with moderate to low continuity onlap on the lower truncation zones and two trough-shaped units are outlined. The uppermost part (unit 1) is characterized by continuous, horizontal to subhorizontal reflectors which are in places smeared and indistinct. A depression structure can be outlined downcutting to a depth of 2m. The lower reflection pattern show comparatively smaller amplitudes in this part of the profile.

The described major units can be identified and traced through the 3-D georadar data with the help of different vertical cuts, horizontal timeslices and chair diagrams (Fig. 5.4A) allowing a sedimentological interpretation and mapping of depositional elements. Figure 5.4B shows three extensive, inclined surfaces (unit 3,6,7) which are interpreted as subunits of a prominent lateral accretion element. The trough-shaped units 4 and 10 were mapped as elongated channel elements showing an aggrading internal structure. Unit 1 represent the base of the covering overbank deposits. The 3-D shape of this unit reveals again a channelized depression. The voluminous enrichment of fine grained sediments causes an increased attenuation of the wave energy indicated by the lower amplitudes of the buried units.

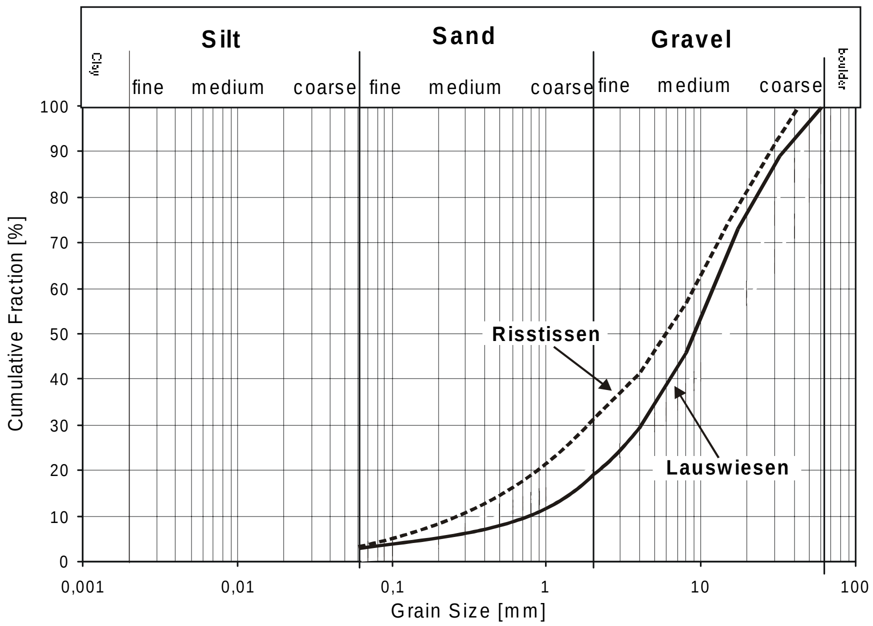


Fig. 5.2: Representative grain-size distribution of the studied locations. The Risstissen site show a comparatively higher proportion of the sand- to medium gravel fraction. In the Lauswiesen site an overall higher portion of coarse gravels occur indicating a more proximal source area.

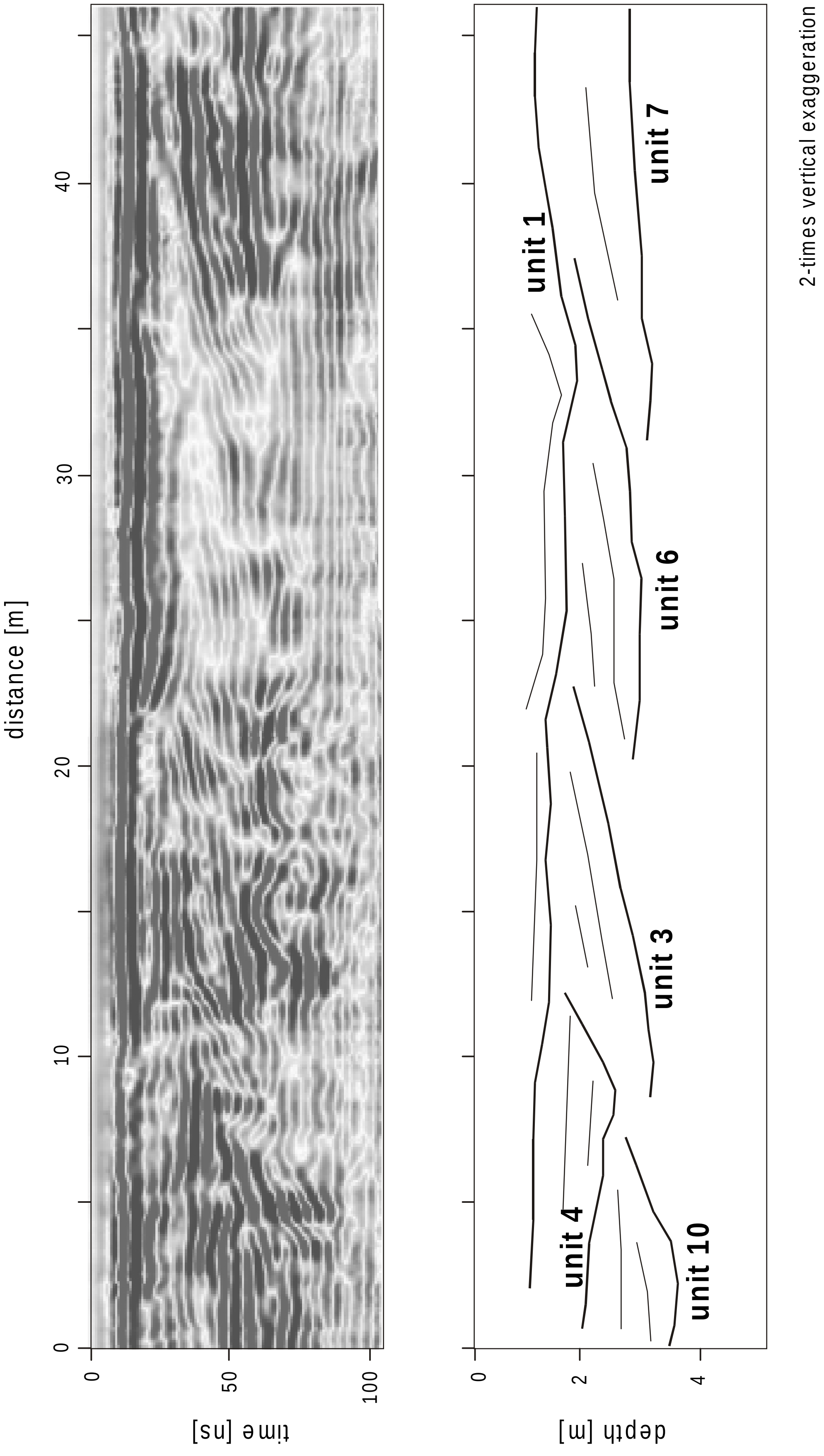


Fig. 5.3: Characteristic radar image gathered at the Lauswiesen site and the corresponding interpretation according to sedimentary units. Unit 3, 6 and 7 build up a prominent lateral accretion structure truncated by trough-shape channel structures (unit 4 and 10). Unit 1 represents the covering overbank deposits.

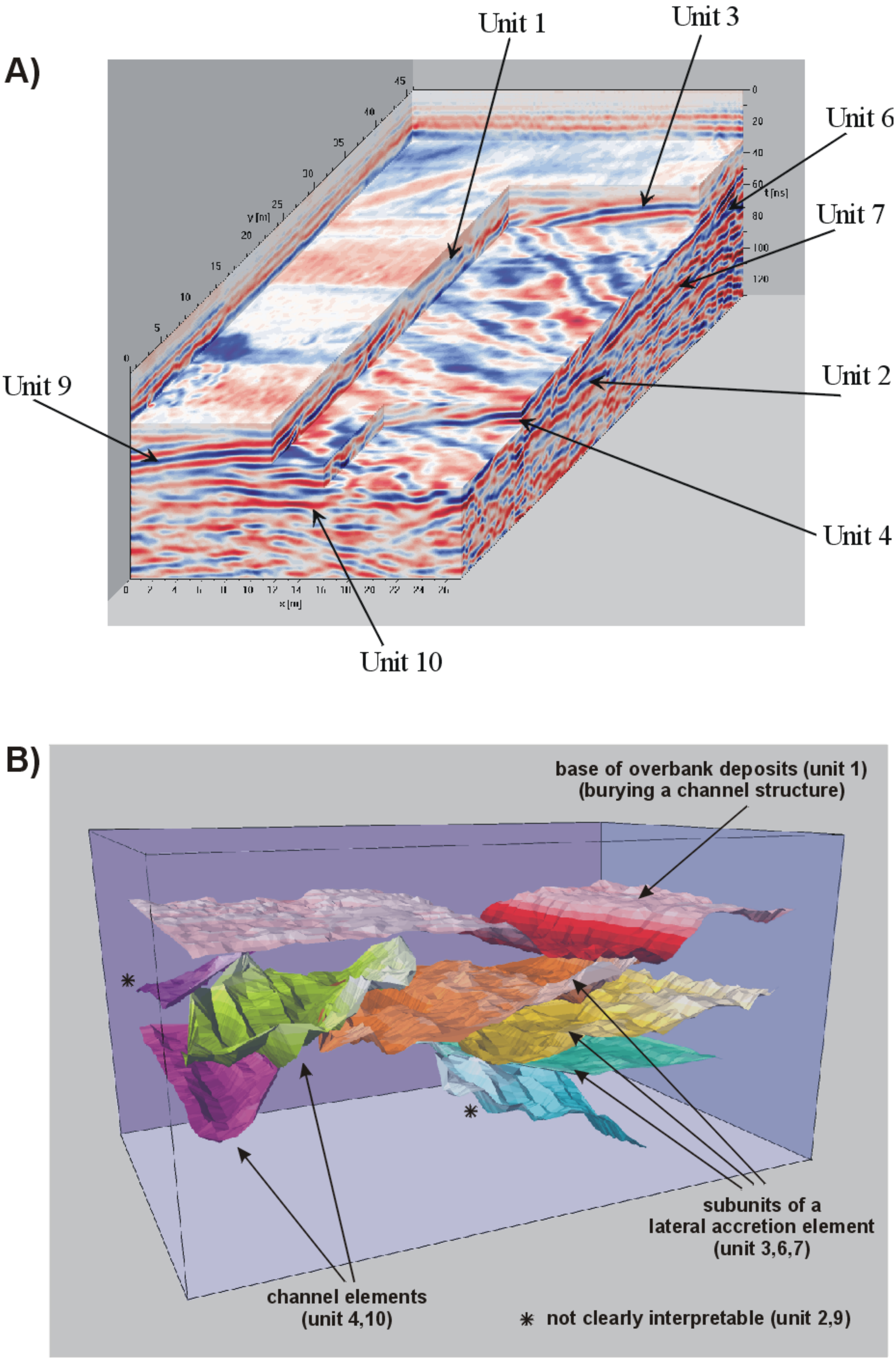


Fig. 5.4: 3-D visualization of the periglacial gravel deposits within the Lauswiesen site. A) continuous, high resolution volume of georadar data acquired with an inline and crossline spacing of 0.5m; B) Spatial extension of detected depositional elements interpreted from the 3-D reflection pattern.

5.4 Case study Danube valley

5.4.1 Field site Risstissen

The site Risstissen is an active gravel pit located at a river terrace within the Danube valley sout-west of the city Ulm (see Fig. 5.1 and Fig. 5.5). The uppermost 3m of the gravel deposit are situated above the groundwater table and another 5-6m are digged in the saturated zone (see grain-size distribution in Fig. 5.2). A layer of 0.5-1.0m thick clay represents the base of the aquifer. The investigated gravel deposits consists mainly of alpine components delivered by glacial meltwater from the Rhineglacier but also regional (Jurassic limestones) material can be intercalated. The age of this terrace is uncertain but can roughly be placed into the 'Würm-Riss-Complex' (Ellwanger et al., 1995).

The georadar data were acquired on a lower floor of the pit a few centimetres above the groundwater table. A grid of 100 x 30m has been investigated (equipment as described before) with an inline spacing of 2.5m (100m profiles in NNW direction) and a crossline spacing of 5m (30m profiles in WSW direction). The data were processed using bandpass filter, AGC gain and Kirchhoff migration (constant velocity of 0.07m/ns). Penetration depth of the radar wave down to the base of the aquifer allowed a characterization of the whole saturated gravel body.

5.4.2 GPR results Risstissen

Figure 5.6 shows a characteristic radar profile gathered at the site Risstissen. The basal clay layer which represents the base of the aquifer can clearly be recognized as a continuous, high amplitude double wavelet reflector indicating a high contrast. The following gravel deposits are dominated by complex and small-scaled reflector patterns. The outlined units show (often high amplitude) lower truncation surfaces with internally discontinuous, low to moderate amplitude and inclined reflector patterns (downlaps and onlaps). Contrary, in the uppermost 50ns (1.75m) a stacking of subhorizontal to low inclined, highly continuous reflectors occur which show downlaps, onlaps and partly toplaps.

The 3-D structural analysis of the radar profiles revealed several phases of aggradation of depositional elements (see Fig. 5.7). Within the deeper section of the gravel body (phase I and II) 17 depositional elements with concave lower boundaries were mapped. According to their shape and internal structure they are interpreted as gravel dune deposits. Their external sizes are quantified in Fig. 5.8. The lower bounding surfaces frequently show a preferential inclination to the south and thus indicate a lateral accretion pattern of these elements. In the uppermost section (phase III) the lower base of the continuous, subhorizontal to slightly inclined reflector pattern can be traced and only few depression- fill structures appear. The reflectors thus indicate an extensive and composite lateral- and vertical- accretion element.

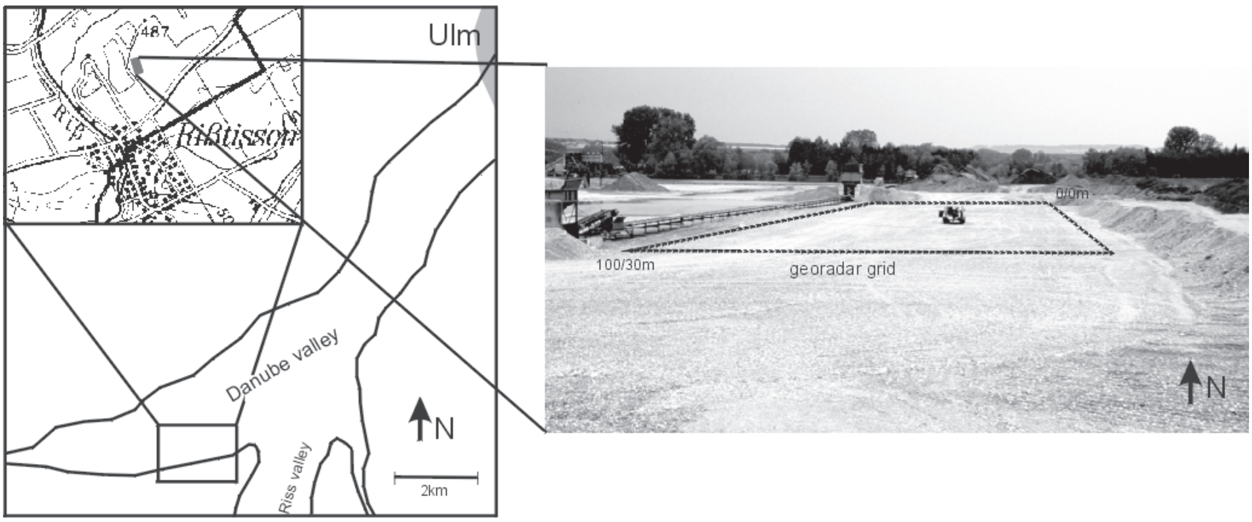


Fig. 5.5: Regional situation and field site documentation of the Risstissen site.

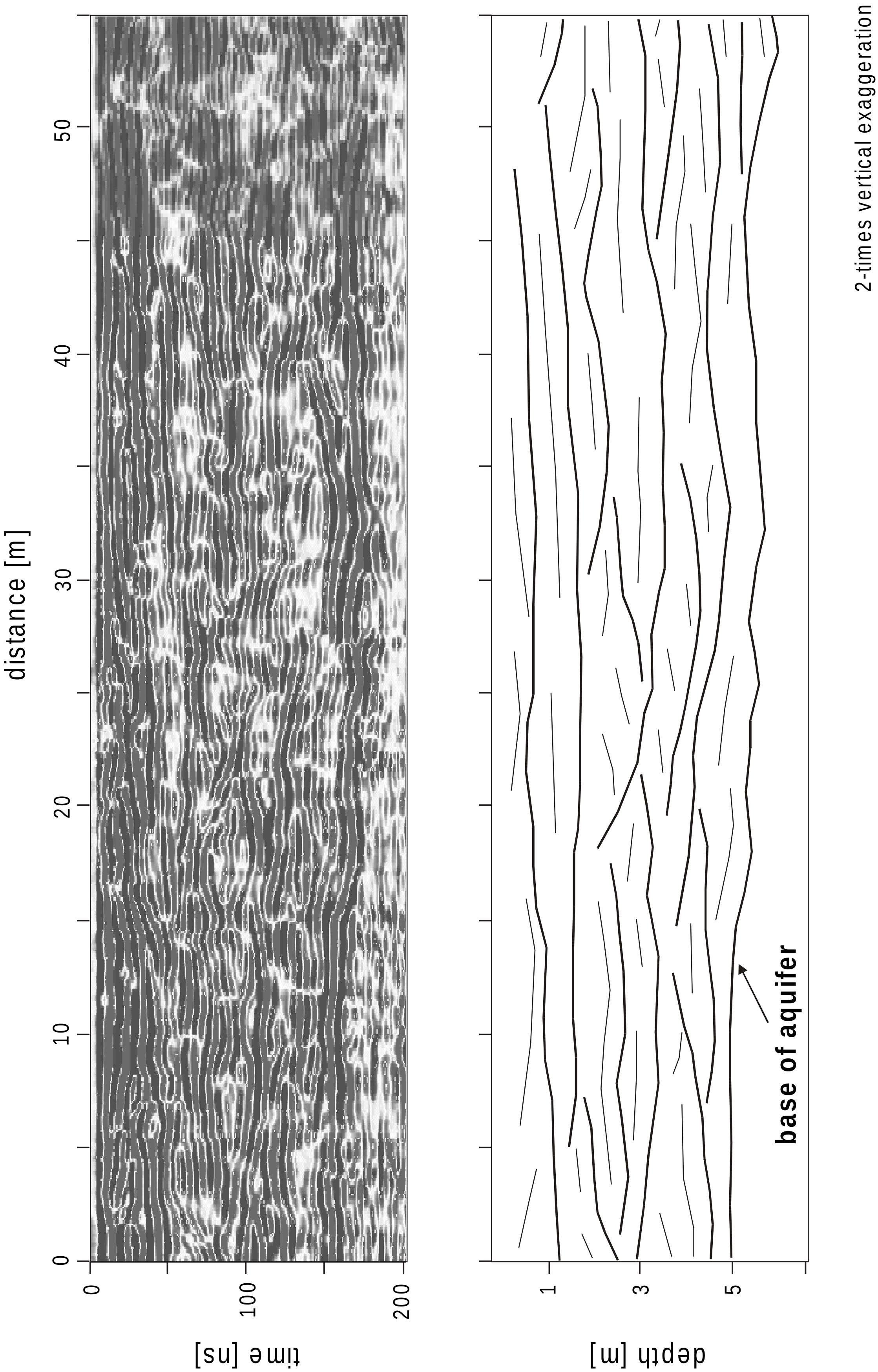


Fig. 5.6: Characteristic radar image gathered at the Risstissen site under saturated conditions. The gravel body is dominated by a complex stacking of trough cross-stratified units interpreted as gravel dune deposits. Only in the uppermost part of the profile an extensive lateral and vertical accretion element is recorded.

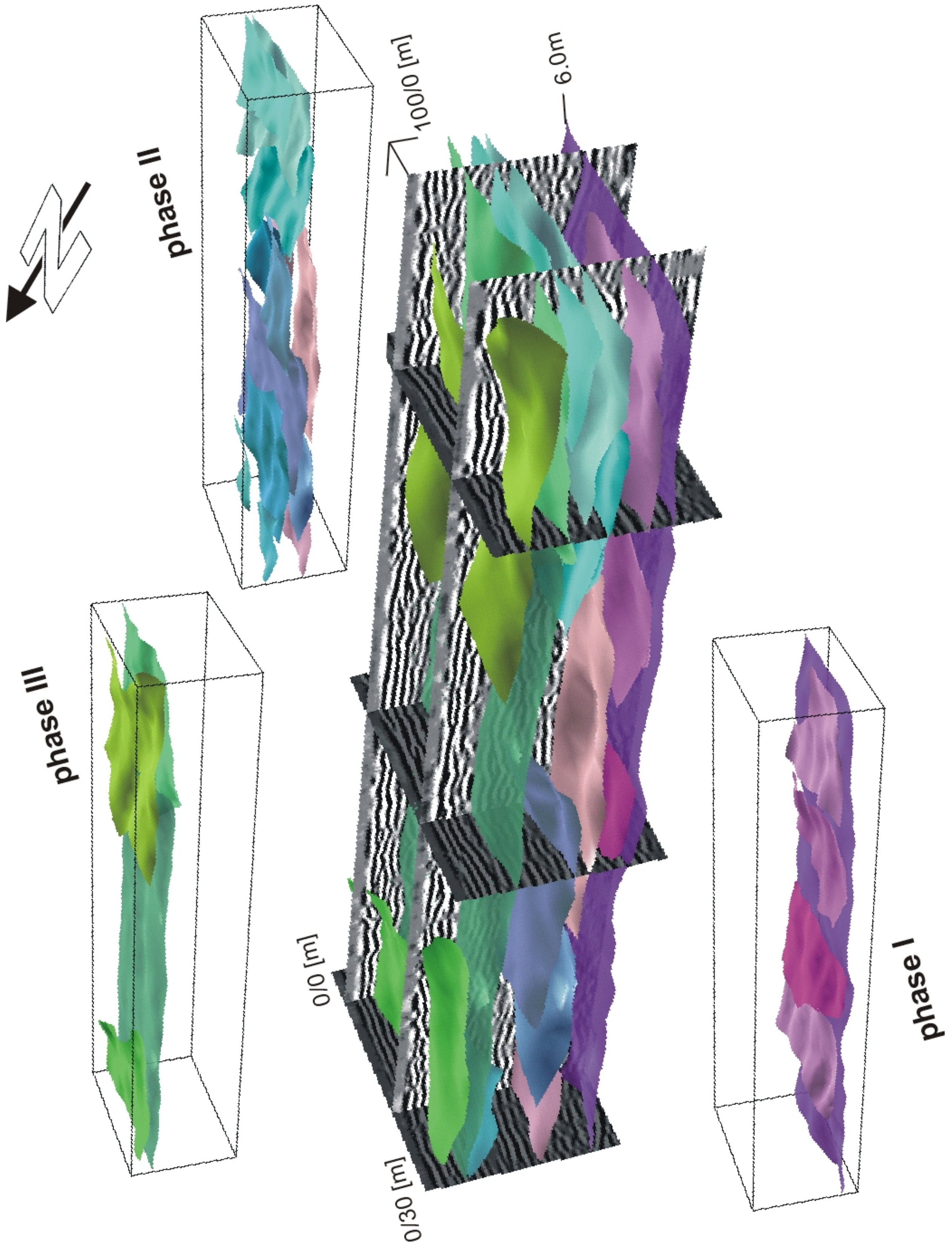


Fig. 5.7: Aggradational pattern of a gravel-bed meandering river system revealed with 3-D georadar surveys at the Risstissen site. In phase I and II (separated by a major erosional surface) exclusively gravel dune deposits are recorded. Phase III is characterized by the preservation of a composite lateral and vertical accretion element. Note that in phase II the trough-shape surfaces show preferential inclination to the south indicating a lateral accretion pattern of gravel dune elements.

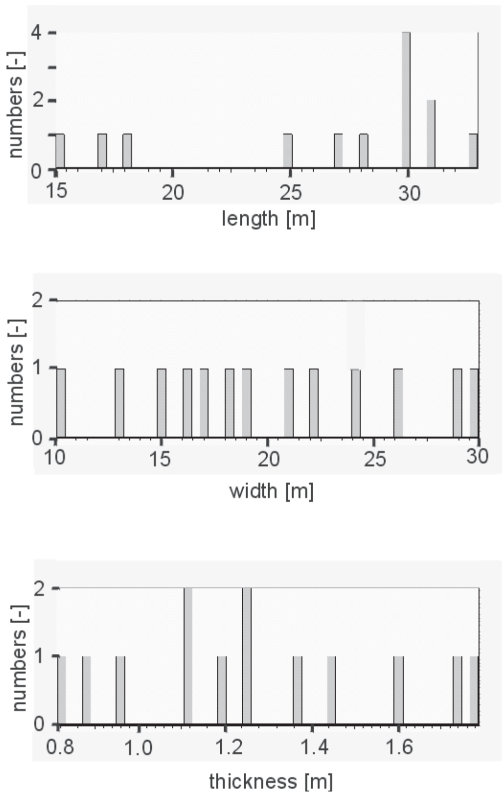


Fig. 5.8: Quantified scales of gravel dune elements as detected in the 3-D georadar survey of the Risstissen site. Note that the lateral scales (length and width) are partly limited by the size of the investigated radar grid.

5.5 Discussion

The presented 3-D georadar data showed that it is possible to map in detail sedimentary units of meandering river deposits in the subsurface. However, an appraisal of their small-scaled lithofacies make-up can not be derived from the georadar images (reflector pattern) alone and additional information (e.g. modern river- or outcrop- studies, petrophysical properties) are required.

In Fig. 5.9 a modern composite gravel meander lobe is illustrated (Gustavson, 1978) which shows a characteristic distribution of geomorphic elements and flow directions. Gravel dunes, called transverse bars by Gustavson (1978) occur along the cut bank in the deepest level of the river system. These bedforms are characterized by a slip face at the downstream end and a lithofacies composition of cross-bedded, partly openwork gravels (alternating gravel, gravel couplets, see chapter 3.4.4) occur. In the intermediate level of the point bar, a diffuse stacking of gravel sheet deposits dominate. This bedform type appears frequently in gravel-bed deposits and consists of thin beds of sand to gravel mixtures (Whiting et al., 1987; Siegenthaler & Huggenberger, 1993; see also chapter 3.5.3). The uppermost level is constructed of overbank deposits of sand and fines with occasionaly thin intercalations of gravel deposits (Gustavson, 1978).

The complex stacking of trough-shaped, cross-bedded units (termed here gravel dunes) dominating at the site Risstissen are thought to be analogous to the sedimentary record of the transverse bars described by Gustavson (1978). The internal cross-stratified (discontinuous, low to moderate amplitude) reflector pattern probably represent the small-scaled bedding of alternating (openwork) gravels. In contrast, the continuous, subhorizontal to low inclined reflector pattern as recognized in both the Lauswiesen and Risstissen sites indicate the record of gravel sheet deposits. Upper level overbank deposits were only preserved at the Lauswiesen site and show in particular a strong attenuation of the wave energy. The internal reflector structures may be induced by intercalation of thin gravel deposits. The detected channel fill structures (unit 4 and 10) of the Lauswiesen site are interpreted as chute channels dissecting composite point bars during high magnitude events.

Other geophysical parameters (velocity, attenuation) were measured at the research field site Lauswiesen using crosshole radar tomography (Tronicke et al. 1999). In the location of unit 4 and 10, exceptionally high values of the radar wave velocity have been measured. This indicates relatively low amount of residual pore water and a small proportion of matrix within the gravel deposits, respectively. As a conclusion, dominantly openwork, alternating gravel may be expected for the internal lithofacies construction of the investigated chute channels.

In general, the recorded depositional elements of both periglacial valley-fills show evidence for meandering paleo-fluvial river systems in these areas. The Risstissen site provides an example of a multi-phase aggrading meandering river system. Particularly the record of gravel dune deposits (or transverse bars) showed a preferential preservation of depositional elements formed in deeper levels of the fluvial system during phase I and II (see Fig. 5.7). A continuous erosion and reworking of the intermediate and upper level deposits was caused by the lateral shift of the meander belt over the whole valley indicating a low aggradation of the depositional system. Only in phase III (Fig. 5.7) the rate of aggradation was high enough to preserve slightly inclined gravel sheet deposits formed at an intermediate level of a pointbar.

At the Lauswiesen site (where only the upper 4m of the 9m thick sediments could be characterized with the georadar method) a depositional history of the valley-fill is ambiguous. The detected depositional elements (lateral accretion, chute channel, overbank fines) probably represent only the upper part of the paleo-meandering river system.

With regard to the hydrogeological characterization the investigated sites provide two types of heterogeneity pattern occuring in gravel-bed meandering river deposits. Figure 5.10 shows a summary of radar pattern, structure and dimension of depositional elements. In combination with sedimentological background information (e.g. outcrop- and modern river studies) a characterization in terms of hydraulic permeability and flow path behaviour is given. Gravel dune deposits which are formed in the deepest level of the active channel belt contain a high proportion of high conductive openwork gravels which are probably often interconnected. However, the complex stacking pattern, as seen at the Risstissen site, causes a multi-directional (confuse) groundwater flow in these places. In contrast, the slightly inclined gravel sheet deposits formed at an intermediate level of the point bar (or channel) construct a homogeneous depositional element (sand to gravel mixture) and overall moderate to low permeability is predicted. Yet, the flow paths are likely to be directed along the continuously inclined beds. The channel-fill structures (chute channels) detected at the Lauswiesen site contain an increasing proportion of openwork gravels. It is to be expected, that these structures may act as a focused zone of high permeability within the aquifer and can switch the local groundwater flow according to their direction. If preserved in the sedimentary record (within an aquifer) overbank deposits surely represent a flow barrier which can laterally range over extensive areas. Thus it is possible that these elements create compartments of vertically stacked aquifer storeys.

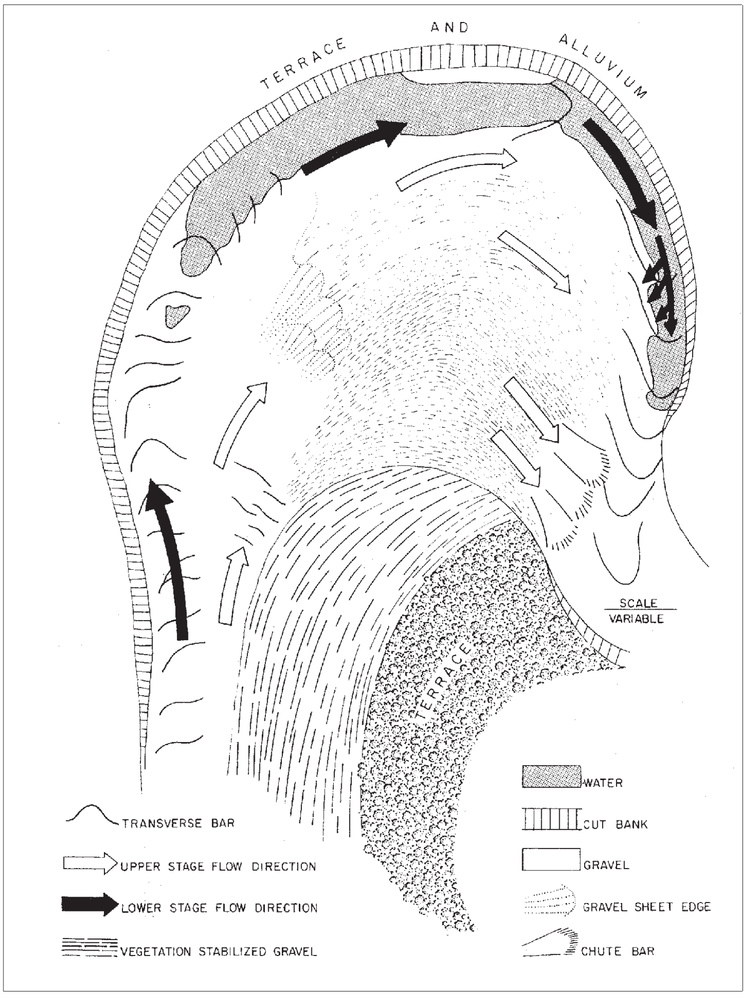


Fig. 5.9: Diagram of the distribution of depositional elements for a composite gravel meander lobe from Gustavson (1978). Note that transverse bar elements are termed gravel dune deposits in this study.

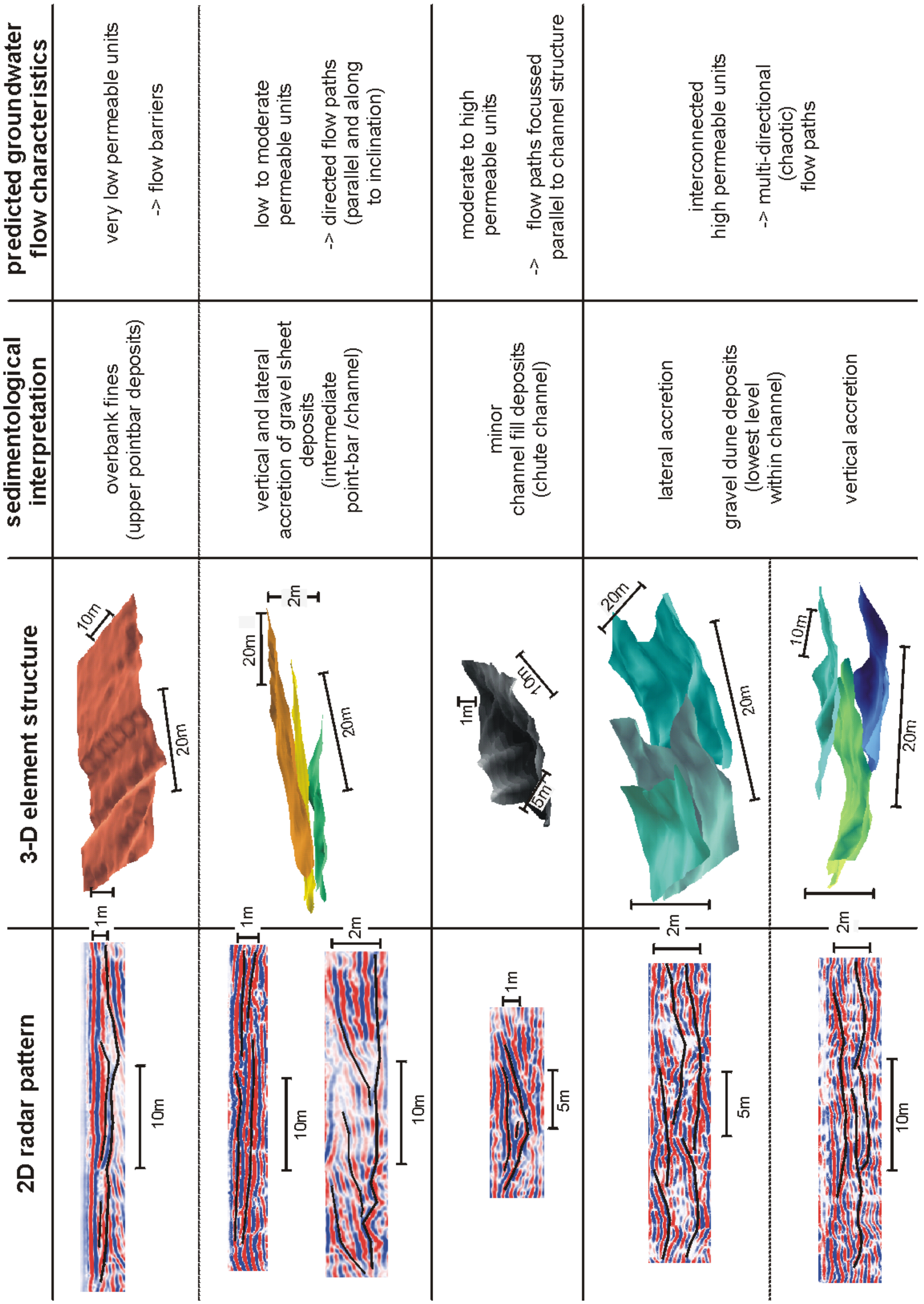


Fig. 5.10: Summary of the major depositional elements found in gravel-bed meandering river deposits of periglacial valley-fills in SW-Germany. For accurate lithofacies and hydraulic predictions, an integration with analogue studies (outcrops, modern river) or additional geophysical methods (providing petrophysical properties) is required.

5.6 Conclusions

This study records 3-D georadar surveys which have been carried out in periglacial valley-fills in order to characterize meandering-river gravel deposits:

(1) The georadar method provide a detailed structural image of the spatial subsurface and works both in the unsaturated and saturated (aquifer) zone.

(2) In both sites (Neckar valley, Danube valley) characteristic depositional elements of meandering river systems could be identified and detected in three dimension (gravel dunes, lateral and vertical accretion, chute channels, overbank deposits).

(3) The preservation and stacking of depositional elements which are formed in different positions within a meandering river system can be revealed in the radar profiles and provide information about the depositional history of the valley-fill.

(4) Detailed and closely spaced radar information allow the characterization of aquifer heterogeneities in the subsurface; permeability and flow pattern may be predicted by the shapes and orientation of depositional elements.

Although, georadar images provide a detailed structural resolution of the subsurface they do not allow accurate prediction of the lithofacies make-up of depositional elements. Additional information is required, such as analogue studies (e.g. outcrop, modern river) or a combination of different geophysical methods delivering petrophysical parameters which increase the predictive potential of georadar data.

6. Characterization of glacial gravel bodies: outcrop analysis, morphology and georadar surveys

6.1 Chapter abstract

Glacially influenced landscapes are characterized by a highly complex distribution pattern of sediments which have been formed within various glacial environments of dynamically behaving glacier systems.

This study focus on meltwater controlled facies bodies which have been investigated inside the area of the last maximal ice-extension of the Rhine glacier in SW-Germany. Lithofacies types and their stratal organization and stacking pattern were analysed in active gravel pits indicating both depositional processes and postdepositional deformation structures. The internal sedimentary architecture is combined with external geomorphological features derived from digital elevation models of the area. The studied gravelly meltwater deposits can be classified into four glacial environments:

(1) **delta and kames delta deposits** often occur in ice marginal environments. They are characterized by large foresets of well sorted gravel and sand strata. Externally they show either flat surface terrace landforms but also high-relief hill-shaped morphologies have been recognized;

(2) **supraglacial** sources are indicated by very coarse, poorly sorted and cruedly stratified deposits with frequently angular- to subangular components. Huge ice-collapse structures indicate postdepositional melting of buried ice which caused a high-relief hummocky terrain;

(3) **englacial environments** show both syn- and postdepositional deformation structure. The investigated example is internally made up of complex sedimentary units consisting of well rounded and well sorted gravel and sand deposits formed under changing flow conditions. The external hummocky morphology is determined by local sediment accumulation and post-depositional ice decay;

(4) **subglacial meltwater deposits** often show positive morphological shapes which can be described as drumlin-like or hummocky-like landforms. Sedimentologically, inclined avalanche beds of well sorted, well rounded gravel or sand- deposits predominate.

Additionally, georadar surveys have been carried out within outcrops and nearby areas. The results clearly reflect the complex structural architecture of glacial gravel bodies and can be used for the detection and interpretation of meltwater deposits in regions with lack of outcrop and core information.

6.2 Introduction

Glacial deposits are characterized by an enormous range of lithofacies associations, deformation structures and external morphologies which have been formed in different environments within a glacial system. A review of numberless studies and a systematic classification of sediments and forms as well as their genetic processes and dynamics is provided by Menzies (1995, 1996).

The Rhine glacier represents a typical alpine ice lobe which has been accumulated in the high-elevated areas of the Alps, advanced to the North in high-relief mountain valleys and spreaded out into the alpine foreland during several climate cycles of the Pleistocene. Alpine valley glaciers moved under wet-base or temperate ice conditions on their substratum. This means that the often coarse-grained alpine sediments have been transported to the foreland both through ice- and through (subglacial) water-forces. The (Würmian) alpine foreland can be described as a moderate-relief area controlled by structured Molasse rocks and older Pleistocene morphologies (Ellwanger et al., 1995). As pointed out by Menzies (1996) topography plays an important role with respect to glacial dynamics and sedimentation. Particularly during deglaciation stagnant ice became concentrated in valleys and basins and eventually separate into isolated ice blocks. As a result, sedimentation is concentrated between stagnant ice and valley side and around buried ice blocks as well as in subglacial conditions (Menzies, 1996).

In this study some of these deposits are characterized (in a local scale) which were formed within the Rhine glacier area after the last maximal ice extension during different stages of ice retreat and ice decay, respectively. The purpose of this chapter is to show and describe a first inventory of gravelly and sandy facies bodies. The present analysis combines (1) process-oriented facies analysis carried out in outcrops, (2) morphological features derived from digital elevation models and (3) geophysical subsurface studies using georadar surveys.

An enormous number of local and regional studies has already been carried out in the German Rhine glacier area, for instance by Weinhold (1973), German (1976), Rappol (1979), De Jong (1983) and Keller & Krayss (1980) to name only a few (see also Schreiner, 1992). For stratigraphic classifications the reader is referred to studies of Ellwanger et al. (1995) and Fiebig (1995).

6.3 Overview of the investigated outcrops

Glacial gravel bodies have been investigated in outcrops in all parts of the SW-German Rhine glacier area (see also chapter 2, Fig. 2.2). In this chapter 7 sites are selected in order to show in detail some of the characteristic facies bodies of meltwater deposits. These sites are predominantly situated in the eastern part of the Rhine glacier lobe (see Fig. 6.1). A photo documentation of the remaining outcrops studies of glacial gravel deposits is given in the appendix.

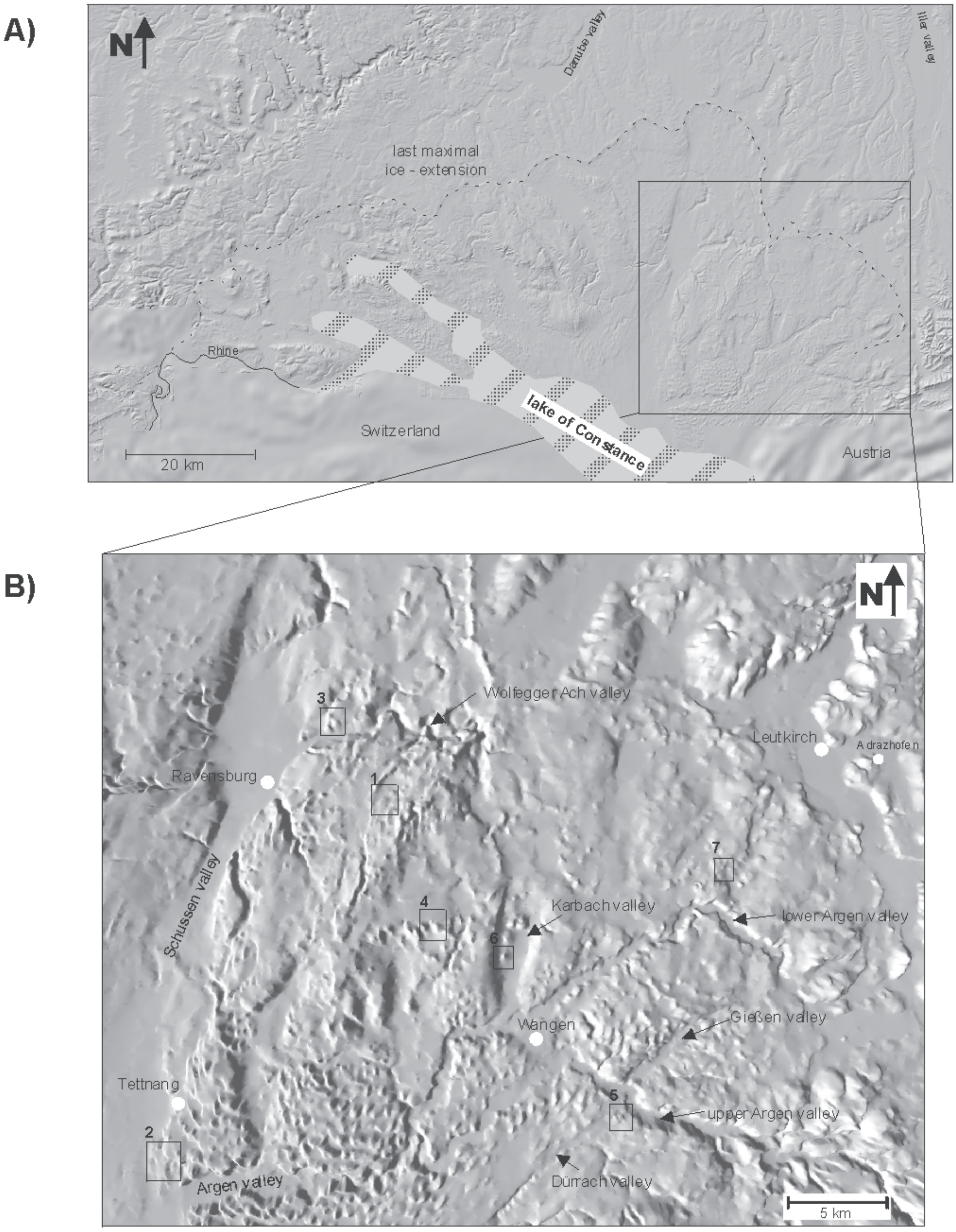


Fig. 6.1: Location of the investigated gravel pits within the SW-German Rhineglacier area; A) shaded relief data; B) digital elevation model (4 times vertical exaggeration) and position of the 7 selected sites: 1) Oberankenreute, 2) Tettnang, 3) Baindt, 4) Grenis, 5) Maria Tann, 6) Edenhaus, 7) Gebrazhofen.

6.4 Results

6.4.1 Ice-marginal delta bodies

In this section examples of delta bodies are documented which frequently occur in ice-marginal environments of retreating ice masses. According to Nemec (1990) an alluvial delta can be described as a prism of sediment which has been deposited by an alluvial system into a body of standing water. Thus, the principle mode of sediment transport changes from stream-driven bedload traction dominating in alluvial systems into gravity-driven mass-movements on subaquas slopes of a delta system (Nemec, 1990). All investigated delta deposits consists of coarse-grained (gravelly to sandy) material that has been deposited in shallow lake environments. An extensive and detailed compilation of coarse-grained deltas incorporating for instance the descriptions and classifications of modern and ancient systems as well as their sedimentary processes is found in Colella & Prior (1990).

6.4.1.1 Gravel pit Oberankenreute

The gravel pit Oberankenreute is situated at an inner edge of a terminal moraine complex which has been formed during a stagnant phase of an overall ice retreat (see Fig. 6.1, no.1). The internal construction of this high-relief ridge-like substratum is excavated within a nearby outcrop (Unterankenreute) revealing deformed (folding structures) fluvial and deltaic gravel deposits as well as cohesive debris flow deposits (interpreted as flowtills) both indicating close ice/source contact.

Contrary, in the gravel pit Oberankenreute typical Gilbert-type delta deposits (e.g. Nemec, 1990) can be recognized at an outcrop face, with relatively steep gravelly delta foresets prograding over horizontally stratified sandy bottomsets (Fig. 6.2). The topsets and upper parts of the foresets had already been removed in this part of the gravel pit. According to the dipping of foreset strata (directed to NNW) a distributary alluvial system delivering sediment from SSE is pre-

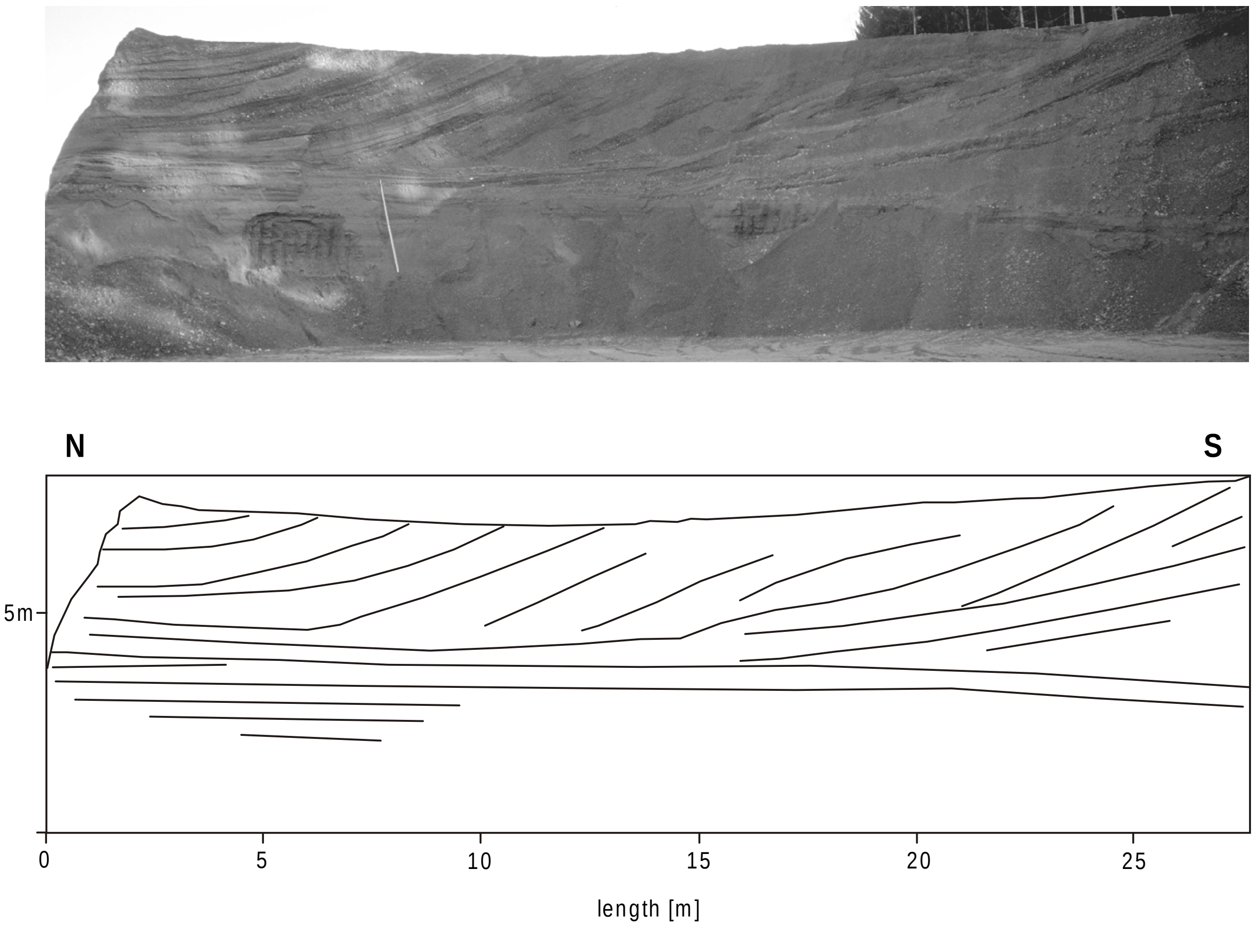


Fig. 6.2: Gilbert-type delta exposed at the gravel pit Oberankenreute. Gravelly delta forsets prograde over sandy bottomsets (topsets are already removed).

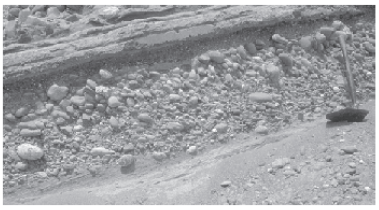
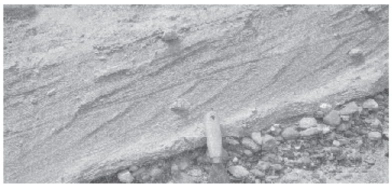
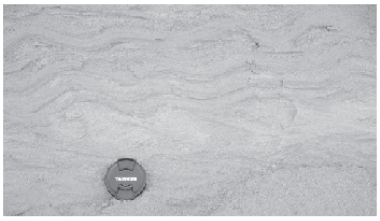
photo	litho-facies code	description	interpretation / processes
	Gmx / GS-x	strafied gravels and gravel to sand mixtures; - grain-size: coarse sand to gravel; - dominantly matrix-supported (sandy matrix); - rounded to subrounded clasts - prefered clast orientation: a(p), a(i)	cohensionless avalanche process (fluidal and gravity driven)
	Gcm,d	massive gravels (d = deformed) - grain-size: sand- to cobble - clast supported - rounded components - gradually steeper clast orientation from the bottom to the top	cohensionless avalanche process (combination of liquifed flow and slides with compression during final deposition)
	dropstone	- angular boulder intercalated within finer and rounded gravelly material	dropstone (resedimented?)
	Gcg,a	graded gravel (a = alternation) - upper zone: open framework - lower zone: bimodal - clast supported - rounded components - no prefered clast orientation	gravity-driven grainflow (basal reworking of previous sand deposits)
	S-x,cr	stratified sand (cr = climbing ripples) - medium sand (with pebbly intercalations) - climbing ripples migrate in upslope direction	backflow currents on a delta slope (during and lateral to turbidite avalanches)
	S-x,cr	stratified sand (cr = climbing ripples) - grain-size: medium sand - lower zone: ripple progradation and aggradation - upper zone: ripple aggradation	suspension-rich flow (sandy bottom sets)
	S-x,d	stratified sand (d = deformed) - grain-size: medium to fine sand - single beds are often graded - intercalation of pebbly layers - folding structures (deformation) within one zone	distal turbidites (syndepositional slumping)

Fig. 6.3: Summary of some major lithofacies types occurring in coarse-grained delta systems in the SW-German Rhineglacier area.

sumed. Maximal angle of the convex foreset inclination reaches 25^{O} and often a tangential transition into bottomsets is visible. At the same time the single foreset units pinch out downslope within a relatively short distance of 5-15m. The horizontally stratified sand-dominated bottomsets frequently show climbing ripple structures which indicates high sedimentation rates. Figure 6.3 gives a summary of lithofacies types occurring in coarse-grained delta environments (see table 3.1 for lithofacies-code).

In Fig. 6.4 a possible paleo-depositional scenario is illustrated which is based on the outcrop analysis and the recognized modern morphological features. During ice retreat a lake has been dammed between ridges and highs (terminal moraine complex in the East) and blocking ice masses (in the western part). For probably only a short time span an alluvial system delivered huge amounts of coarse sediment into the lake creating a rapidly prograding delta system. A relatively long-term establishment of the fluvial input into the dammed water body would have filled up this local and shallow lake environment. Thus, it is concluded, that the alluvial system 'quickly' changed position to the West during progressive ice melting.

A similar Gilbert-type delta has been studied at the gravel pit Böhringen using georadar surveys (Asprion, 1998; Asprion & Aigner, 1999). Figure 6.5 shows one of the georadar profiles reflecting the characteristic tripartite depositional geometry with distributary braided river deposits (delta topset segment) prograding onto relatively steep delta foresets (foreset segment). In the lowermost part low gradient delta-toe deposits (bottomset segment) are visible in the radar image (see also Fig. 6.6).

6.4.1.2 Gravel pit Tettnang

The gravel pit Tettnang is situated within a terrace-shape morphology at the eastern margin of the Schussen valley south of the city of Tettnang (see Fig. 6.1, no. 2). It represents a large excavation area of about 2km^2 in size.

The outcrop faces show thick (up to 20m high) deposits of an ancient Gilbert-type delta system (Fig. 6.7). The walls are dominated by a massive unit (> 15m) of large and steep foreset strata. In the uppermost part 2-4m thick horizontally stratified topset beds erosively cover the foreset segment. A transition of the foresets into lower bottomset deposits have not been revealed but in parts of the excavation area basal sand deposits have been recognized.

Dipping of the foreset units (15-35^{O}) as well as imbrication measurements of the fluvial topset deposits show a clear paleo-flow direction from East to West. A progradation of the Gilbert-type system over several hundreds of metres could be traced in this direction.

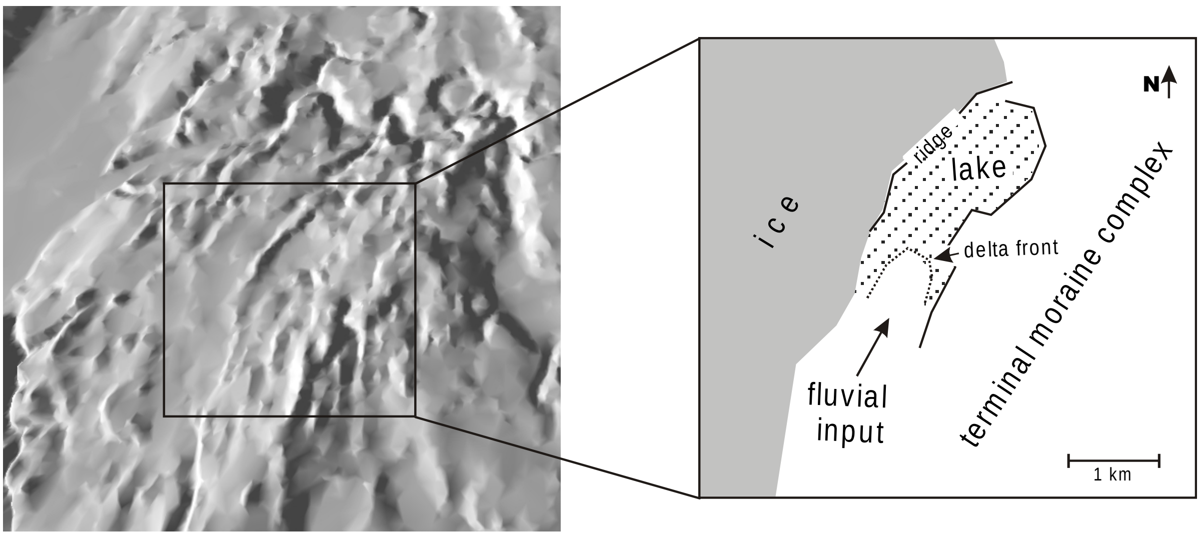


Fig. 6.4: Digital elevation model (4 times vertical exaggeration) and possible scenario of delta deposition at the site Oberankenreute. During ice-retreat a short-term lake environment was established with a fluvial input from SSW.

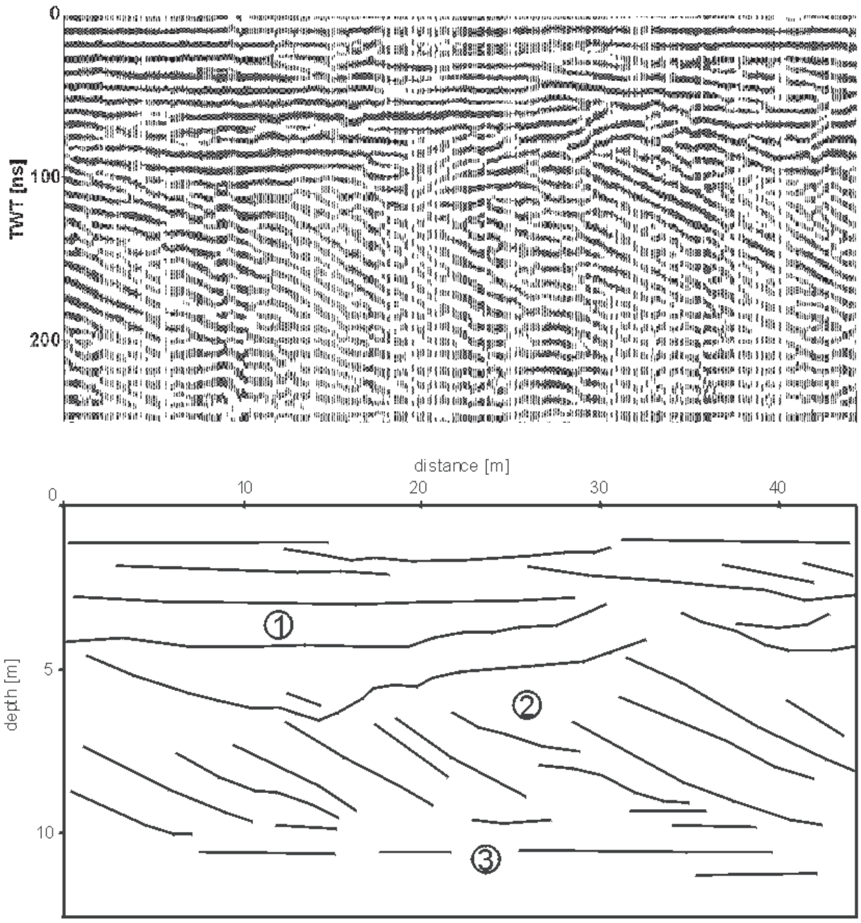


Fig. 6.5: Georadar image revealing a characteristic Gilbert-type delta: 1) complex topset deposits of a distributary plain, 2) prograding delta forsets, 3) horizontal bottomsets (georadar data from Asprion, 1998).

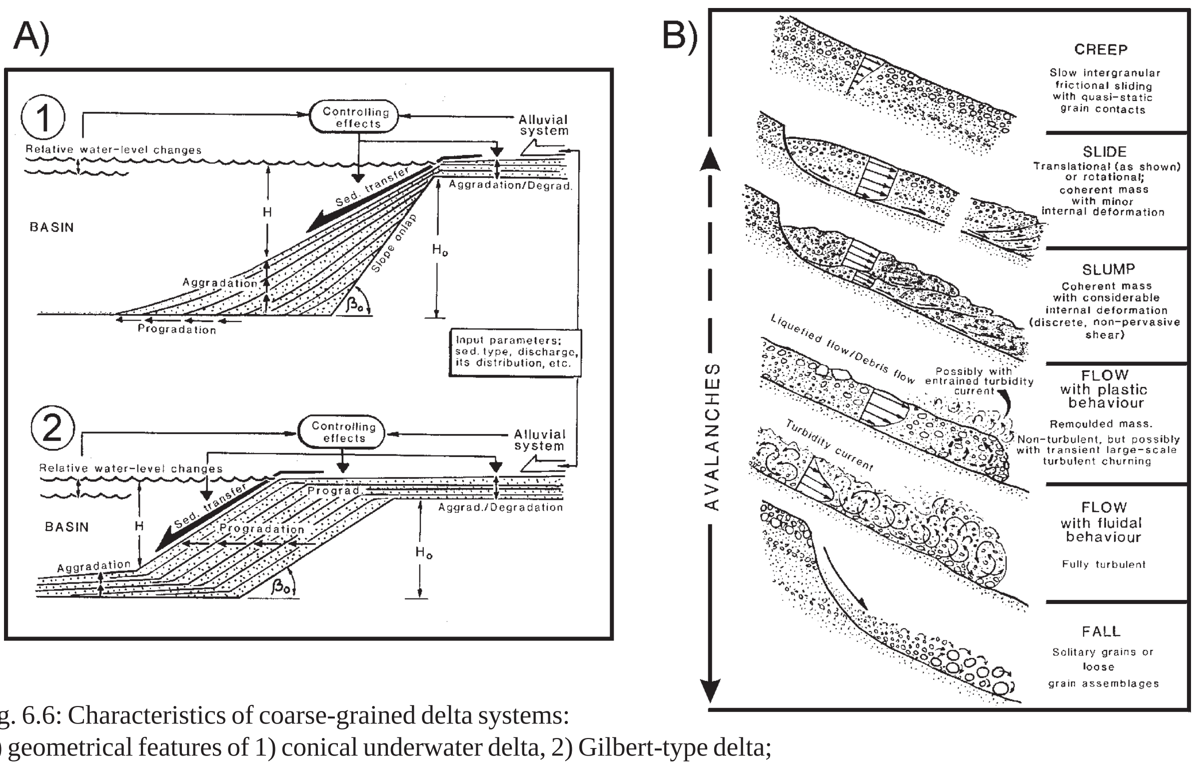


Fig. 6.6: Characteristics of coarse-grained delta systems:
A) geometrical features of 1) conical underwater delta, 2) Gilbert-type delta;
B) gravity-driven sediment-transport processes operative on steep slopes of coarse-grained deltas.

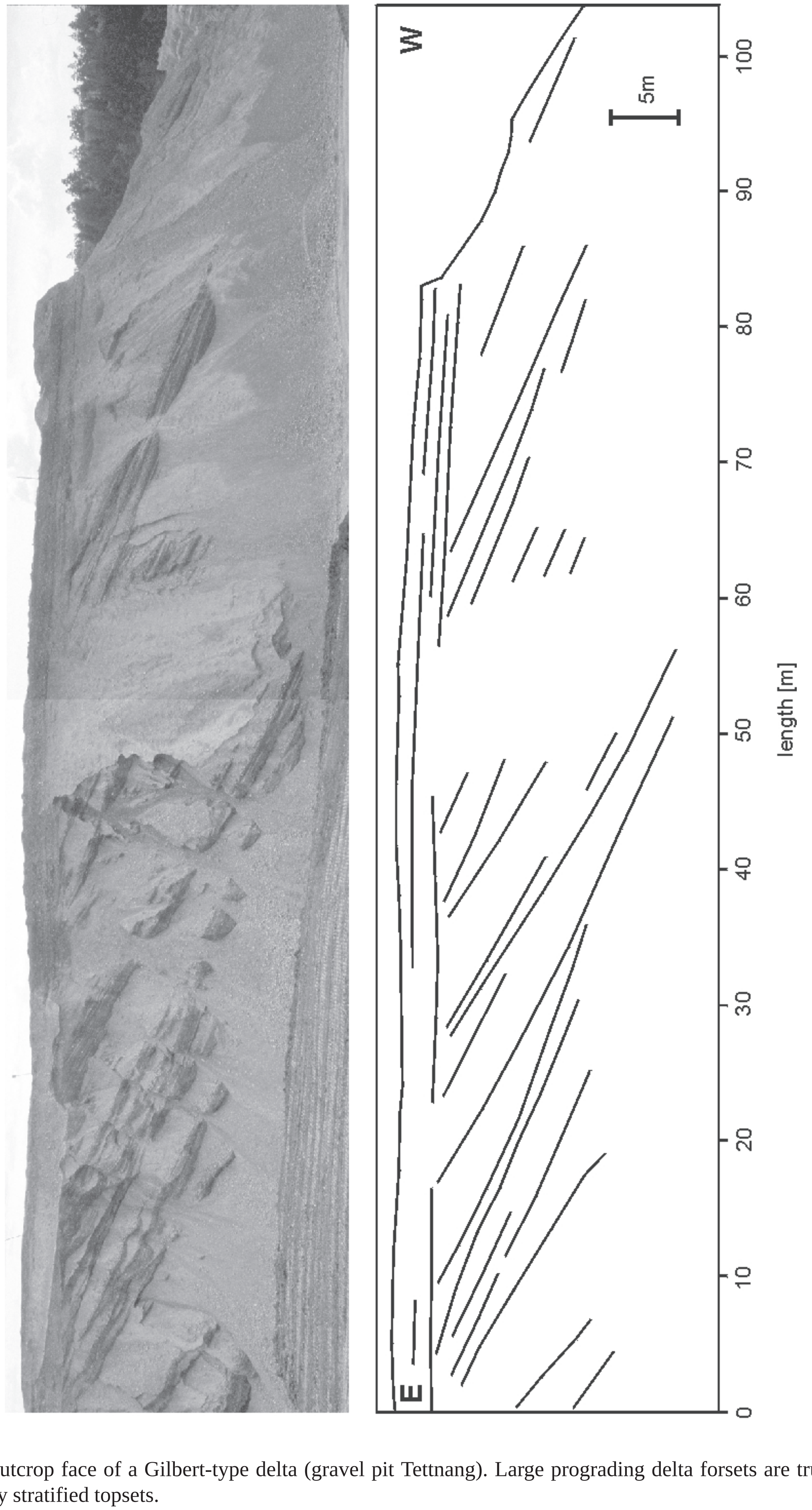


Fig. 6.7: Outcrop face of a Gilbert-type delta (gravel pit Tettnang). Large prograding delta forsets are truncated by horizontally stratified topsets.

Within the foreset segment single foreset bed pinch out either upslope or downslope and distinct erosional surfaces can be recognized (see Fig. 6.7). According to the fabric, texture and stratification of single lithofacies types the major avalanching processes can be described as flow with fluvial and plastic behaviour (turbidites, liquified and debris flow) as well as fall mechanism (e.g. grainflows) (Fig. 6.6). The major occurring lithofacies types are summarized in Fig. 6.3.

However, in contrast to the Gilbert-type delta system of Oberankenreute, features of direct ice contact have been noticed:

1) normal faults: the association of foreset beds have in parts been destroyed by extensive stress causing normal faults. This can be explained by the retreat of melting ice masses after and during delta sedimentation;
2) dropstones: angular and partly very coarse components are irregularly intercalated in the continuous avalanche deposits (consisting of well rounded particles). These components are interpreted as ‘drop-deposits’ from melting ice blocks (see Fig. 6.3).
3) diamict deposits: an interfingering of diamict deposits and delta foresets have been found at one basal place of the excavated area. The diamict deposits are intercalated with coarse, stream-driven gravel deposits both deformed by ice-compression stress.

As a consequence the Gilbert-type delta system of Tettnang is classified as an ancient kames delta. In Fig. 6.8 a sketch of a possible local paleo-environment is illustrated based on outcrop and modern morphological information.

6.4.1.3 Gravel pit Baindt

The gravel pit Baindt is situated at the top of an relatively high-relief hill near the junction where the deeply incised river Wolfegger Ach joins the Schussen valley (see Fig. 6.1, no. 3)

In chapter 2 (see also Fig. 6.9) this gravel body has already been introduced as an example of a coarse-grained delta facies body. However, the classical tripartition of topset-, foreset- and bottomset-segments is missing. Instead, there is a transition of large convex delta forsets going into bottomsets with a gradual decrease in dip angle. A range of maximal 25^{O} at the upper part of the foresets to 2-5^{O} within the bottomsets has been recognized. Topset beds were totally absent in the outcrop. According to the dip of the foresets a paleo-flow direction to NNW is reconstructed.

The foreset strata show both downslope thinning and downslope fining resulting in an overall lateral fining trend. The foreset strata consist mainly of stratified sand to gravel mixtures as well as massive gravel lithofacies types (see Fig. 6.3). Clast orientation in the sand to gravel lithofacies is frequently parallel to flow (a(p)) indicating a relatively high shear rate within liquified or debris flow avalanche processes. At one place a downslope migrating gravel bedform was recognized which indicates even a stream-driven tractional bedload transport on the slope. The low gradient bottomsets are dominated by sand material with a distally increasing proportion of silt and clay. Gravelly intercalations appear as thin sheets or within small-scaled channels.

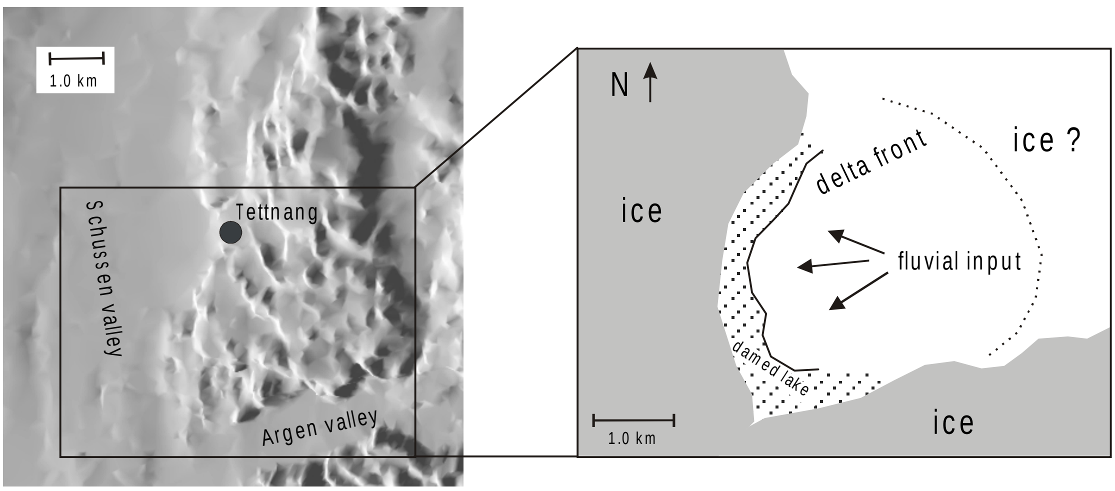


Fig. 6.8: Possible scenario of a paleo-kames delta at the site Tettnang; derived from outcrop information and morphological data (digital elevation model, 4 times vertical exaggeration).

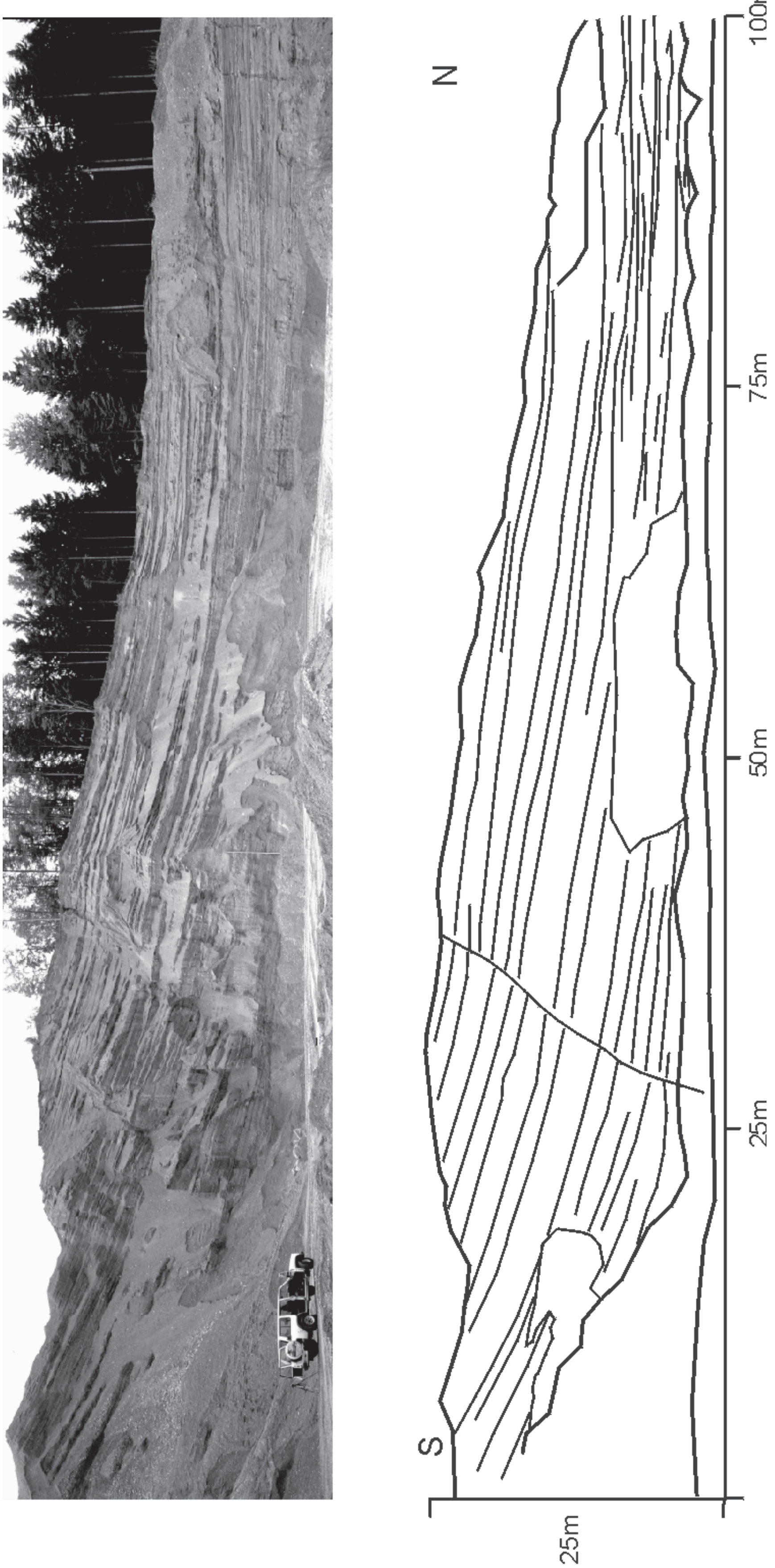


Fig. 6.9: Outcrop face at the site Baindt showing a conical delta-geometry. Gravelly dominated forsets gradually change into sandy bottomsets. Note the absence of topset deposits.

According to Nemec (1990) this coarse-grained delta is classified as a conical underwater delta (see Fig. 6.6). Although this type of delta has only been described in deep coastal settings (e.g. fjords in Norway) the foreset geometry and the lack of topset beds look comparable. In contrast to Gilbert-type deltas there is no subaerial distributary fluvial plain but a localized (narrow) sediment input into the standing water body.

Figure 6.10 gives one possible scenario which could have lead to the developement of this conical delta body on an elevated position. It is conceivable that during ice decay the ice-masses within the Schussen valley blocked the subglacial pathways from the East (the valley of the modern Wolfegger Ach is interpreted as an ancient subglacial tunnel valley). Thus, sediment charged subglacial meltwater was pressed up the northern valley border. When the water reached the top of the ice a local lake could have been created dammed by ice-masses and other morphologies. When entering the lake environment the delivered sediments then were deposited as a conical aggrading and prograding delta system.

A direct contact of the delta sediments to the ice is likely, because several normal faults have been recognized particularly at the SW part of the outcrop (see also Fig. 6.9).

6.4.2 Supraglacial sediment complex

There is no clear distinction between ice marginal and supraglacial environments and several depositional systems appear within this marginal complex (Brodzikowski & Van Loon, 1991). The classification used in this study mainly take into account the degree of roundness/angularity of the clasts. Thus, supraglacial gravel deposits are characterized here by a high proportion of angular and subangular very coarse components directly delivered from the ice surface.

6.4.2.1 Gravel pit Grenis

The Grenis pit is located in a north-sloping terrain forming part of an E-W elongated and curved belt of irregular hills (see Fig. 6.1, no. 4). The morphology is characterized by a high-relief hummocky terrain which ends abruptly with a steep slope to the south (basin situation). Previous studies have already been initiated in this outcrop by Weinhold (1973), De Jong & Rappol (1983) and Fiebig (1995).

The up to 35m high outcrop faces consist mainly of subhorizontally layered, dominantly coarse-grained beds (very poorly sorted cobble- and boulder- rich gravels). An obviously high portion of subangular and

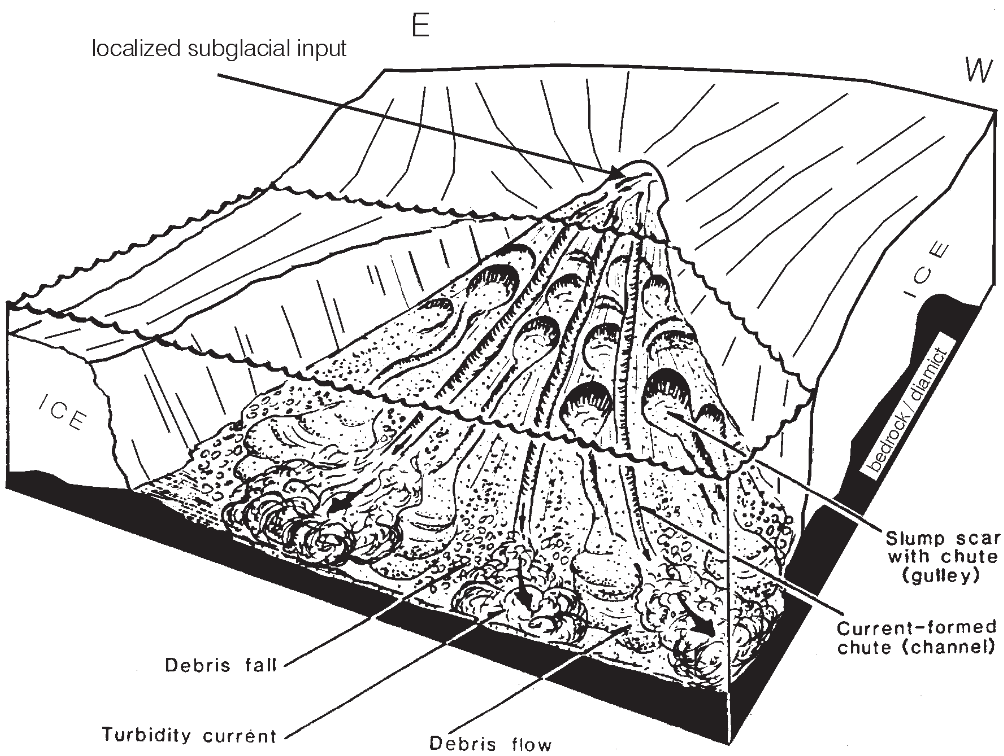


Fig. 6.10: Depositional model of a conical delta system with a subglacial input (modified after Nemec, 1990).

angular components appear in these units. Interstratified are diamict layers (particularly in the southern parts) and infrequently gravelly or silty sand-beds. For grain-size analysis and clast orientation see De Jong and Rappol (1983).

In general, the beds show a subhorizontal vertical aggradation (gradual build up). Slightly erosional lower bounding surfaces occur but only rarely convex erosional contacts have been recognized. The deposits exposed in the large outcrop area are characterized by extensive, postdepositional deformation structures (see Fig. 6.11). The collapse structures clearly correspond to morphological surface depressions in the way that the general stratification runs parallel to the surface.

The described deposits are the product of sedimentary processes which represent a continuum from cohesionsless stream flows to cohesive gravity mass flows (see Fig. 6.12). The major depositional process can be described as highly concentrated (poorly cohesive) flows with a small water to sediment ratio producing very poorly sorted, cobble- and boulder-rich, massive layers. Thus, it is interpreted as a hyperconcentrated flow typical for ablation processes (supraglacial ablation till).

A possible scenario of the sedimentary environment of this proximal deposits is shown in Fig. 6.13. An alluvial fan has been formed at the ice margin dominantly due to ablation processes from the surface of the glacier. Stream flow (subglacially induced ?) becomes more prominent towards the distal areas (to the North) (see also DeJong & Rappol, 1983).The modern hummocky landscape is explained by both postdepositional melting of buried ice and an unequal distribution of sediment at the ice-head.

In Fig. 6.14 a characteristic radargram of the described supraglacial deposits is shown indicating the dip of the subsurface strata subparallel to the surface, minor erosional surfaces and large boulders (generating diffractions).

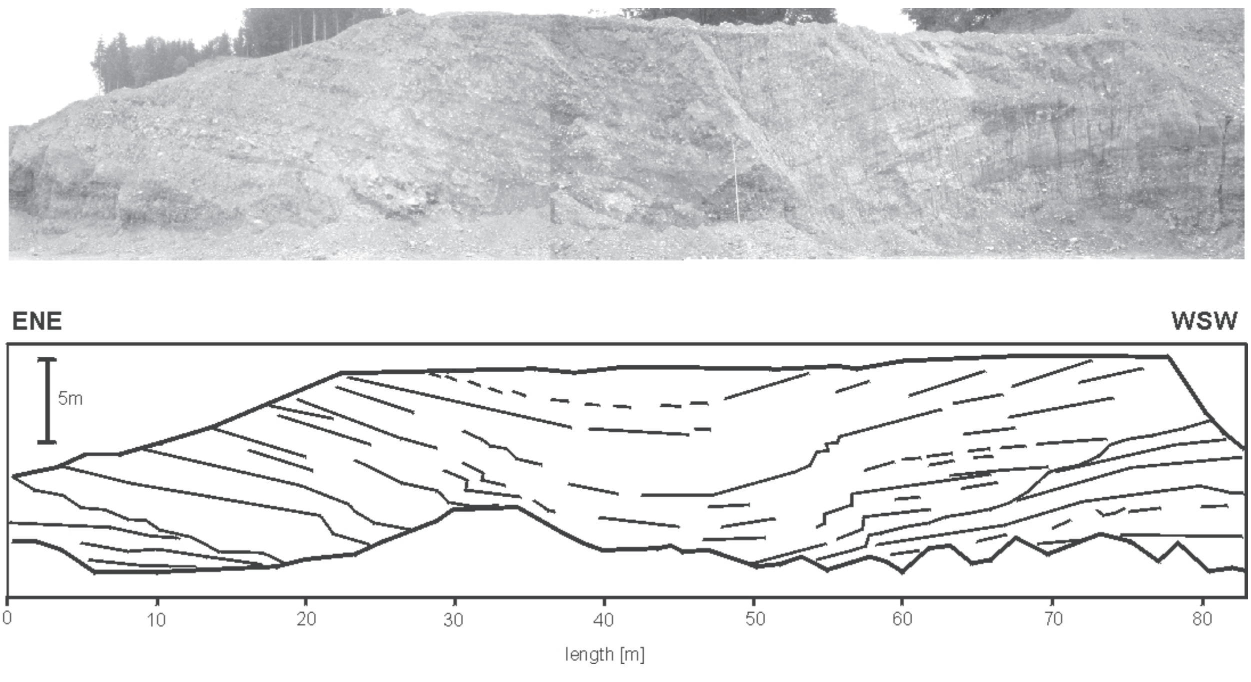


Fig. 6.11: Outcrop wall exposed at the gravel pit Grenis. Very poorly sorted, coarse-grained sedimentary units are vertically stacked and only minor erosional surfaces occur. The whole gravel body is deformed due to postdepositional melting of buried ice.

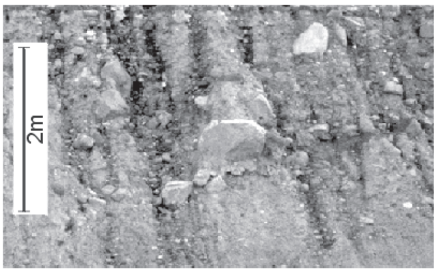
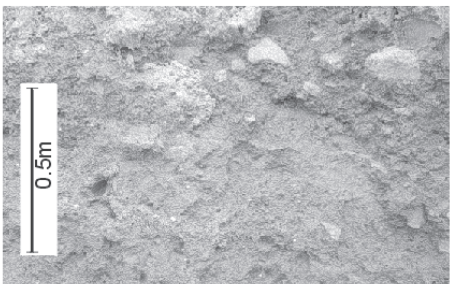
photo	litho-facies code	description	interpretation/ processes
	bGcm bGmm	cobble- and boulder-rich gravel; - very poorly sorted (grain-size from fines to boulders); - clast-supported and matrix-supported zones; - clasts: subrounded - angular - stratification: massive/cruedly stratified (rarely graded) - clast orientation unclear (postdepositional deformation)	high-density (poorly cohesive) gravity-driven flow
	sH-x	sand-dominated heterolithe - grain-size: fines to coarse sand; - alternation/interfingering of sand- and fines- dominated layers - erosional structures, load structures, convolute bedding; - rarely intercalation of gravelly particles	hyperconcentrated flow (gravity- and stream-driven) rapid flow pulses
	GS-g,inv / Gcg,inv	stratified gravel and gravel/sand mixtures (inv = inversly graded) - grain-size from fine sand to gravels; - clast and matrix supported - horizontal stratification; - prefered clast orientation: a(p) - subrounded to rounded clasts	cohesionsless stream flow (pulses of sorted sediment with an increase in flow energy)
	Dcx	stratified diamict - grain-size: fines (clay / silt) to cobbles; - clast supported - subangular to subrounded clasts - no prefered clast orientation	cohesive, dominantly gravity-driven flow (higher amount of pore water)
	Dmm	unstratified diamict - grain-size: fines (clay / silt) to boulders; - matrix supported - angular to rounded clasts (partly striated) - no prefered clast orientation	cohesive, gravity-driven flow (flowtill), (lower amount of pore water)

Fig. 6.12: Summary of some major lithofacies types occurring in the supraglacial sediment complex of the site Grenis.

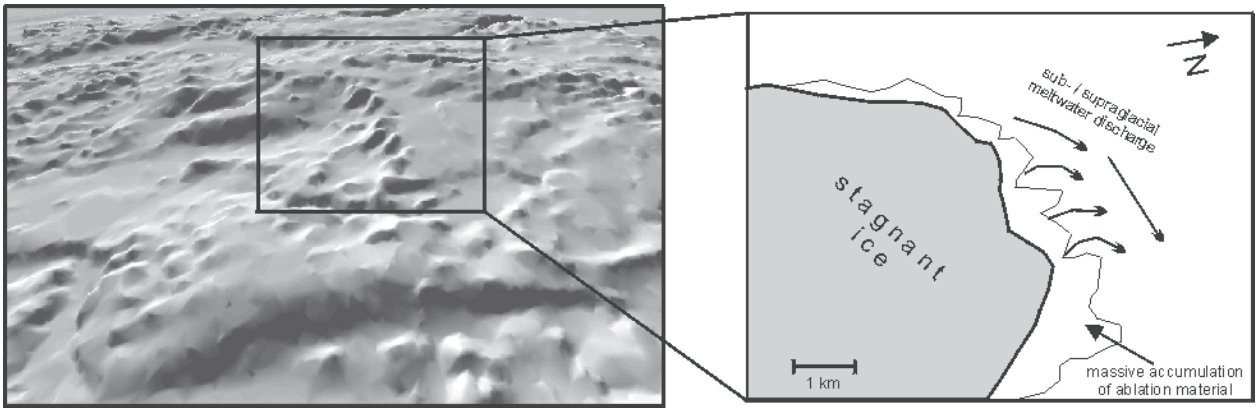


Fig. 6.13: Digital elevation model (4 times vertical exaggeration) and possible scenario for the formation of a supraglacial sediment complex. Huge amount of supraglacial debris is deposited at the ice margin due to ablation processes.

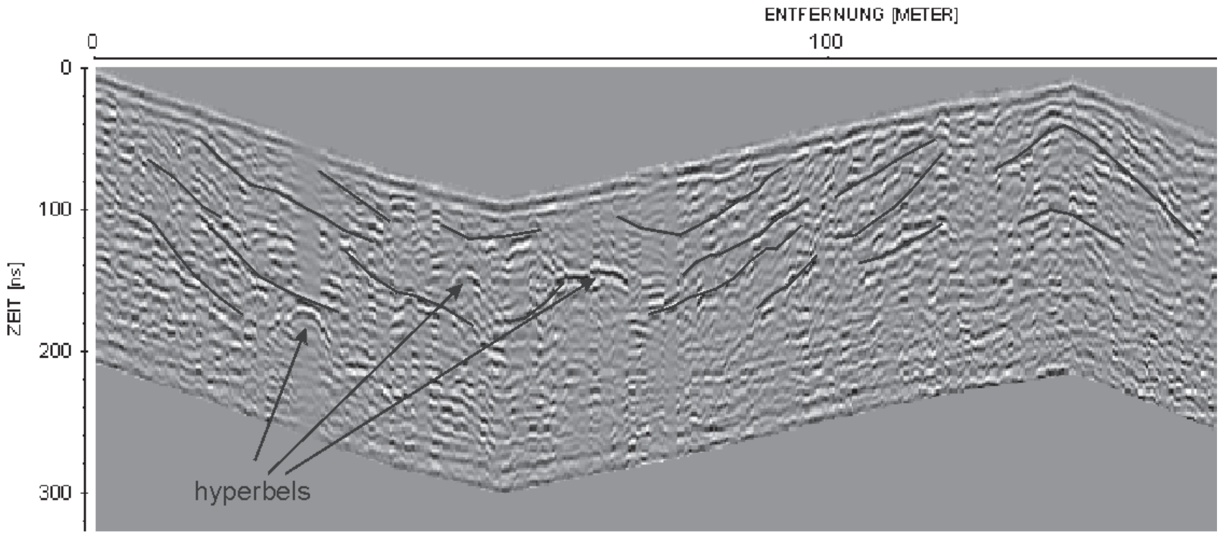


Fig. 6.14: 2-D georadar profile acquired at the site Grenis. Most of the reflectors dip subparallel to the surface morphology (artificially reworked and flattened). The hyperbels reflect large boulders in the subsurface.

6.4.3 Englacial sediment complex

Englacial deposits are formed in tunnels and cavities within the glacier ice. Water and sediment is supplied supraglacially (through moulins from the ice surface) and subglacially (from the base of the ice). Deposition may take place during the active and the passive stage of the ice. Depositional processes are discribed to be discontinuous and temporary (Brodzikowski & Van Loon, 1991). In general, hydraulic conditions and resulting processes are controlled by the dynamics of the ice sheet as well as by the hydrology of the englacial drainage.

6.4.3.1 Gravel pit Maria Tann

The pit Maria Tann is located SE of the city of Wangen. It is characterized by an elevated hummocky terrain morphology at the junction of the Upper Argen valley and the Gießen valley (see Fig. 6.1, no. 5).

The outcrop can be subdivided into a lower and upper segment. The lower segment is characterized by a highly complex architecture (see Fig. 6.15) where gravel, sand and diamict deposits show folding structures, press-up structures and collapse structure as well as erosional truncations. Both plastic and frictional deformation modes were recognized. With regard to the occurring lithofacies types (see Fig. 6.16) and sedimentary structures it is very difficult to deduct one distinct depositional system. Indicators for fluvial processes (e.g. trough-shaped lower bounding surfaces), avalanche processes (e.g. thick beds of bimodal gravel) as well as for cohesive mass-movement processes (diamict deposits) are found. However, it is obvious, that sedimentation and deformation happened contemporously.

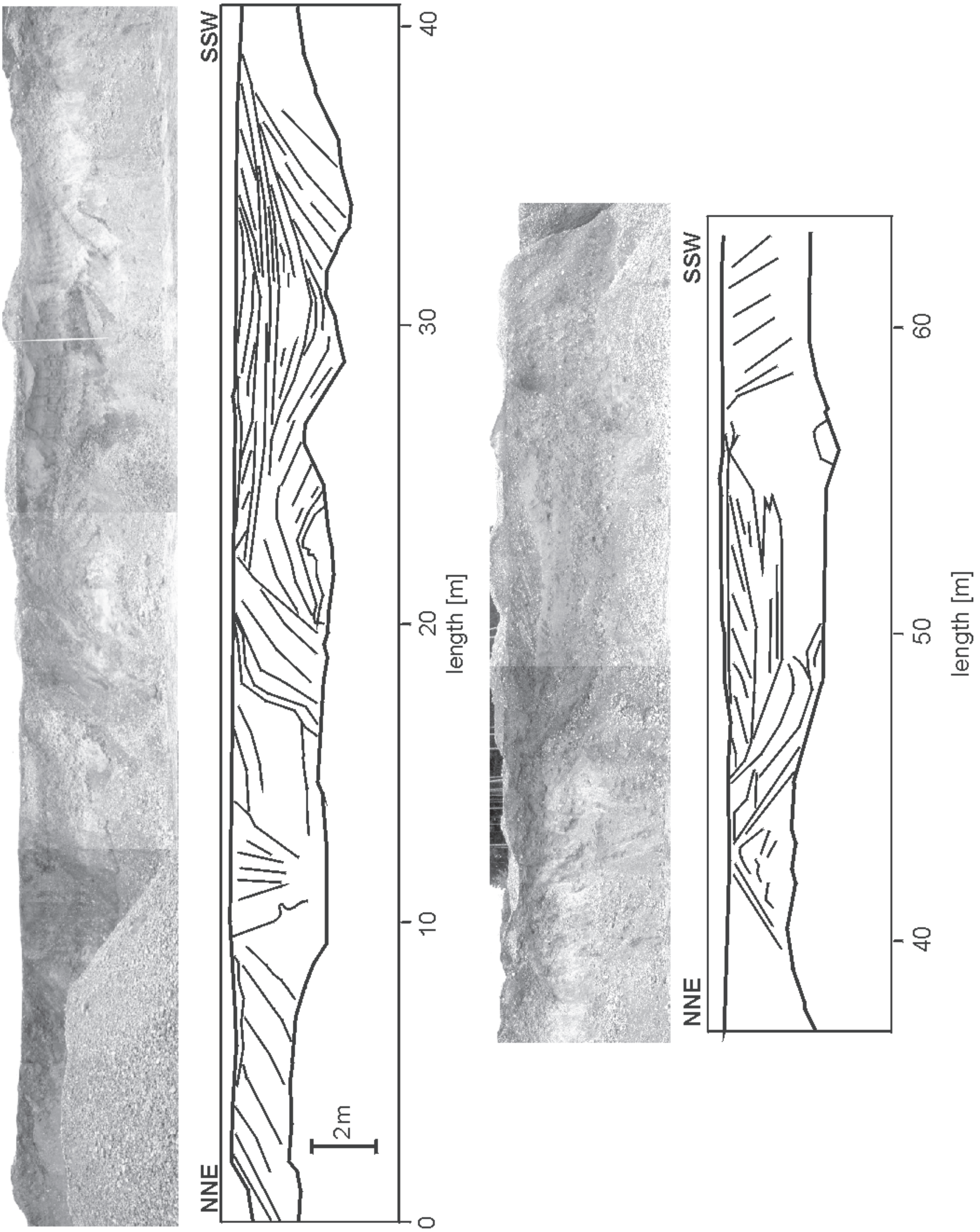


Fig. 6.15: Outcrop wall exposed in the lower part of the gravel pit Maria Tann. A complex architecture of erosional and deformational structures indicate the contact to active ice (see text for closer explanation).

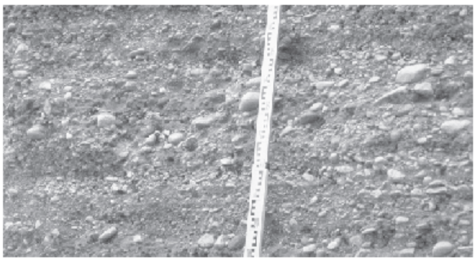
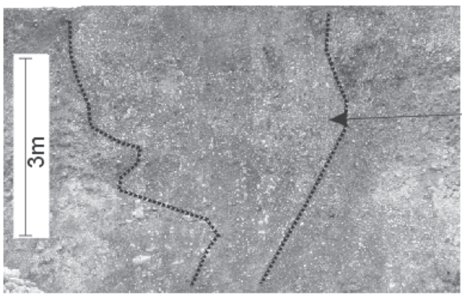
photo	litho-facies code	description	interpretation/ processes
	cGcm	massive to cruedly stratified gravel; - grain-size: sand to cobbles (c); - clast-supported - components subrounded - rounded - clast orientation: a(p), a(i), b(i)	cohesionsless, low-density bedload pulses (bedload sheets)
	GS-g / Gcg	cross-stratified gravel and gravel to sand mixtures (g = graded) - grain-size: fines to gravel; - normally graded layers - clast supported; - subrounded to rounded clasts - particle orientation: a(p)	pulses of bedload sheets passing over a negative step (gravel dune)
	Gcg,b	graded gravels (b = bimodal) - clast size: grading from cobbles to gravels; - matrix: coarse sand (lower zone) and fines (upper zone) - clast supported - rounded clasts - chaotic clast orientation	massive turbulent flow, sorted due to a negative step lower part: reworking of previous sands upper part: infiltration of suspension due to reverse flow
	S-x,t	trough cross-stratified sand - grain-size: fine to coarse sand; - single foresets partly graded, partly massiv	mega ripples with sinuous crests (3D-ripples)
	Gcm,d	massive gravel, deformed - grain-size: sand to cobbles; - clast supported - clasts orientation: (a-axis) oriented vertically	bedload sheets deformed due to compression (press-up structure)

Fig. 6.16: Summary of some major lithofacies types occurring in an englacial environment (site Maria Tann).

In Fig. 6.17 an outcrop face of the upper segment is documented. It is dominated by large foresets building an up to 2.5-3.5m thick unit which is interpreted as a gravel dune. This unit is erosively truncated at the top and covered by horizontal to slightly inclined gravel sheet deposits. Partly, hummocky-bedded geometries have been recognized. Components show a continuum of parallel orientation (a(p)), and imbrication of the long (a(i)) and the intermediate axis (b(i)).

In general, in most parts of the exposed outcrop area the deposits of both segments are postdepositionally deformed whereas the major collapse structures run parallel to the hummocky-shaped surface.

With regard to the described features the following interpretations are made:

(1) the lower section of the outcrop has been formed in direct contact to active ice within rapidly changing depositional conditions (fluvial, deltaic, massflows);

(2) deposits of the upper section indicate focused high energy flow conditions (large gravel dune, hummocky-shaped gravel sheets, clast orientation (a(p), a(i)) which frequently occur in sub- or englacial tunnels and cavities;

(3) major collapse structures concern the upper as well as the lower segment and are the product of postdepositional melting of buried ice.

As a consequence, the deposits excavated in the gravel pit Maria Tann are interpreted as englacial deposits (see Fig. 6.18). As most components are well rounded a dominantly subglacial source is assumed.

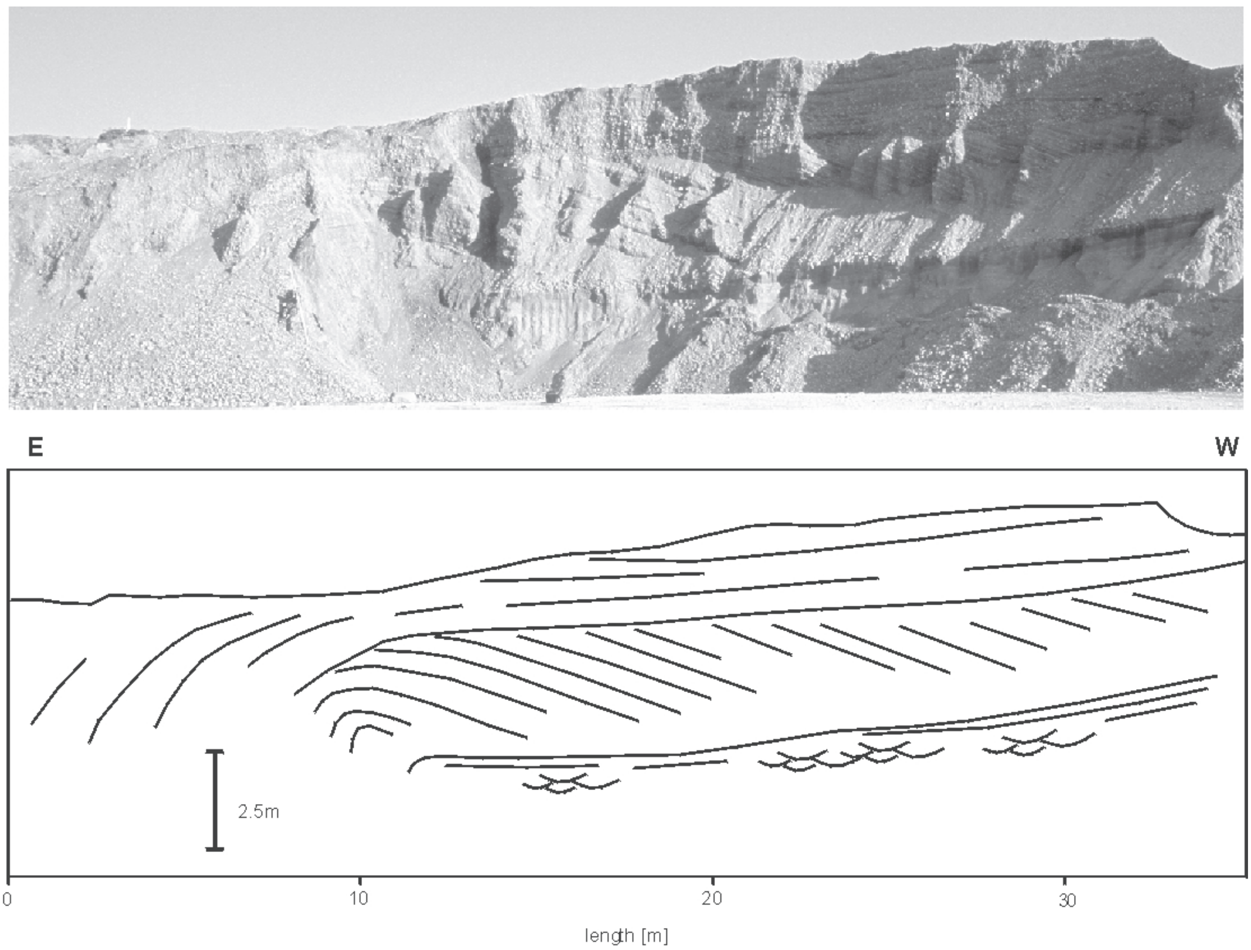


Fig. 6.17: Outcrop wall exposed in the upper part of the gravel pit Maria Tann. The large forsets are the record of a migrating gravel dune. This unit is truncated at the top by a unit of horizontally stratified gravel sheets. The whole gravel body is deformed due to postdepositional ice-collapse.

Several georadar profiles were measured near the outcrop area (Fig. 6.19). The images resolve particularly the deposits of the upper segment. In unit 1, for instance, the exposed gravel dune can be recognized by the parallel inclined reflectors. Note, that the detected units run parallel to the subsurface morphology indicating postdepositional ice melting.

It must be mentioned, that particularly in the upper segment paleoflow within this englacial system was directed from E to W (see foreset dipping of the gravel dune) - contrary to the direction of glacier advance. This means, that during late stage phases of ice decay also huge amount of sediment has been transported sub- and englacially back to the basin-centre (e.g. lake Constance).

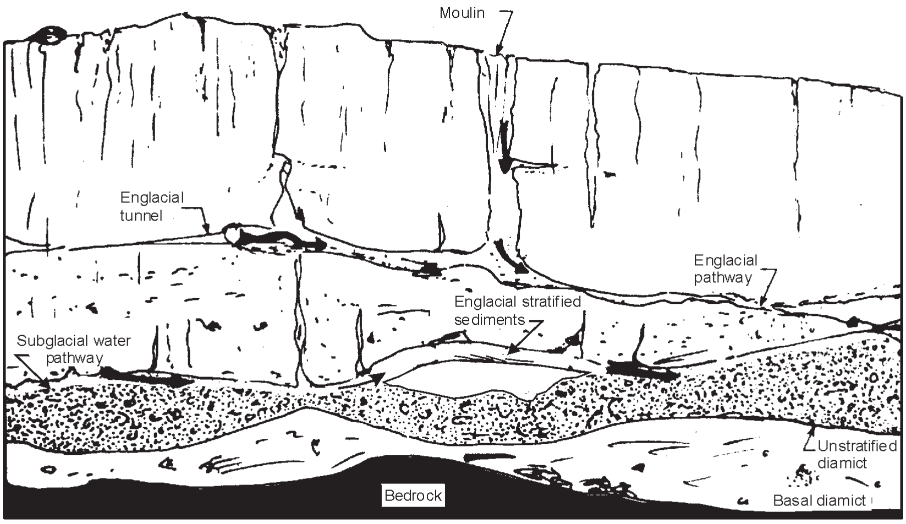


Fig. 6.18: Schematic model of englacial depositional environments (modified after Menzies, 1996).

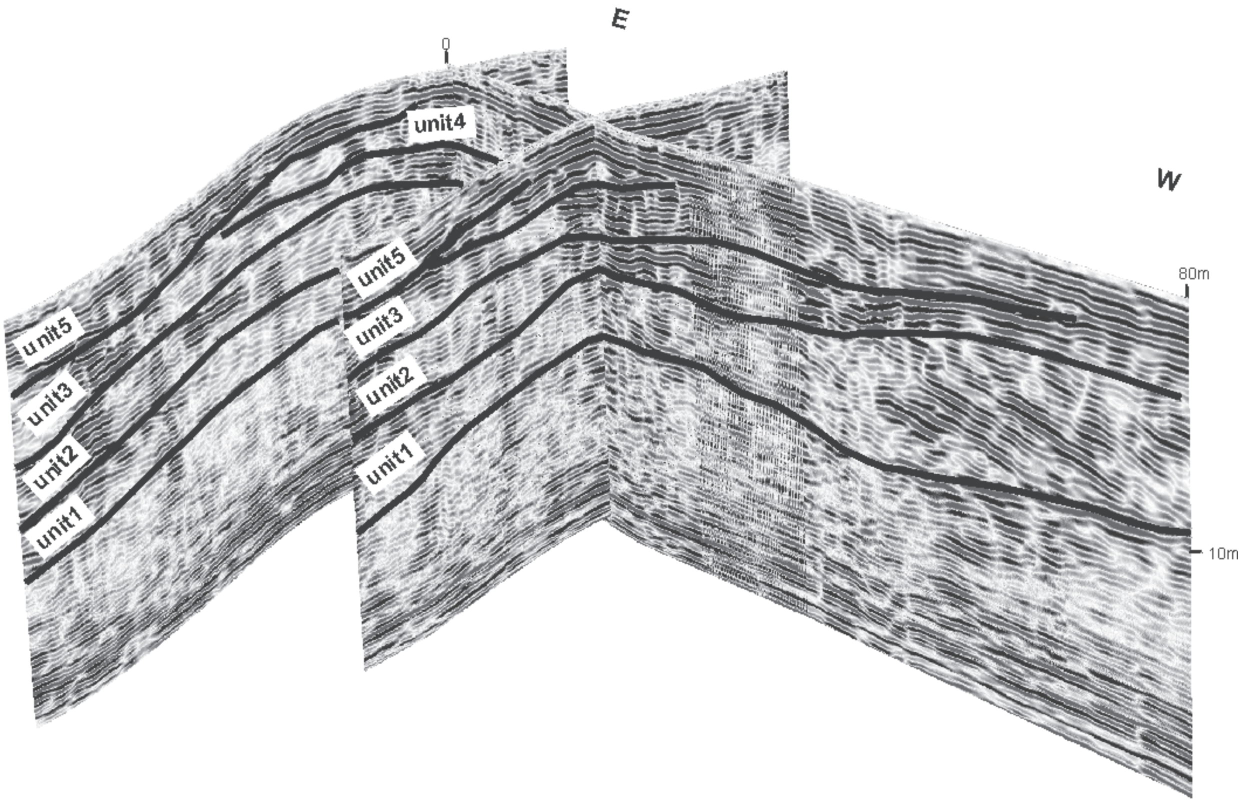


Fig. 6.19: Grid of radar profiles acquired at the gravel pit Maria Tann. The cross-stratified reflector pattern of unit 1 represent the described gravel dune deposits (see also Fig. 6.17). Note that the major sedimentary units run parallel to the surface morphology indicating postdepositional ice-collapse.

6.4.4 Subglacial gravel bodies

The contact zone between the ice body and its substratum is known as the subglacial environment. The thermal regime of the ice, the nature of the substratum and the amount of available debris are the major controlling factors in terms of the general (depositional, erosional, deformational) conditions (Brodzikowski & Van Loon, 1991). An enormous number of studies have been carried out so far with regard to subglacial processes, sediments and landforms. For a detailed discussion and a compilation of case studies the reader is refered to Dardis & McCabe (1994) and Piotrowski (1997). In the following section two examples of meltwater induced subglacial gravel bodies are discussed.

6.4.4.1 Gravel pit Edenhaus

The pit Edenhaus is situated in a hill on the bottom of the N-S striking Karbach valley (see Fig. 6.1, no. 6). Morphologically, a drumlin-like shape is visible, slightly elongated parallel to the valley. Previous studies were carried out by Weinhold (1973) and Fiebig (1995).

The excavated sequence (see Fig. 6.20) consists of an alternation of gravel- and sand-dominated beds as well as of sand- to gravel mixtures (see Fig. 6.21). Few intercalation of heterolitic beds (mixtures of sand and fines) were also recognized and at a basal marginal part of the exposed hill the gravel- to sand deposits are covered by a diamict layer. In general, the dominantly well sorted lithofacies types consist of subrounded components. However, also subangular to angular components were found, partly solitarly or in clusters, partly enriched in layers. The whole sequence is cross-stratified and shows an inclination to the North but many postdepositional normal faults and block-rotation distort the original angle of deposition (see Fig. 6.20). The beds show an overall gradual progradational and aggradational stacking pattern (containing also 'minor' erosional truncations). They partly pinch out downslope but no change in grain-size was recognized.

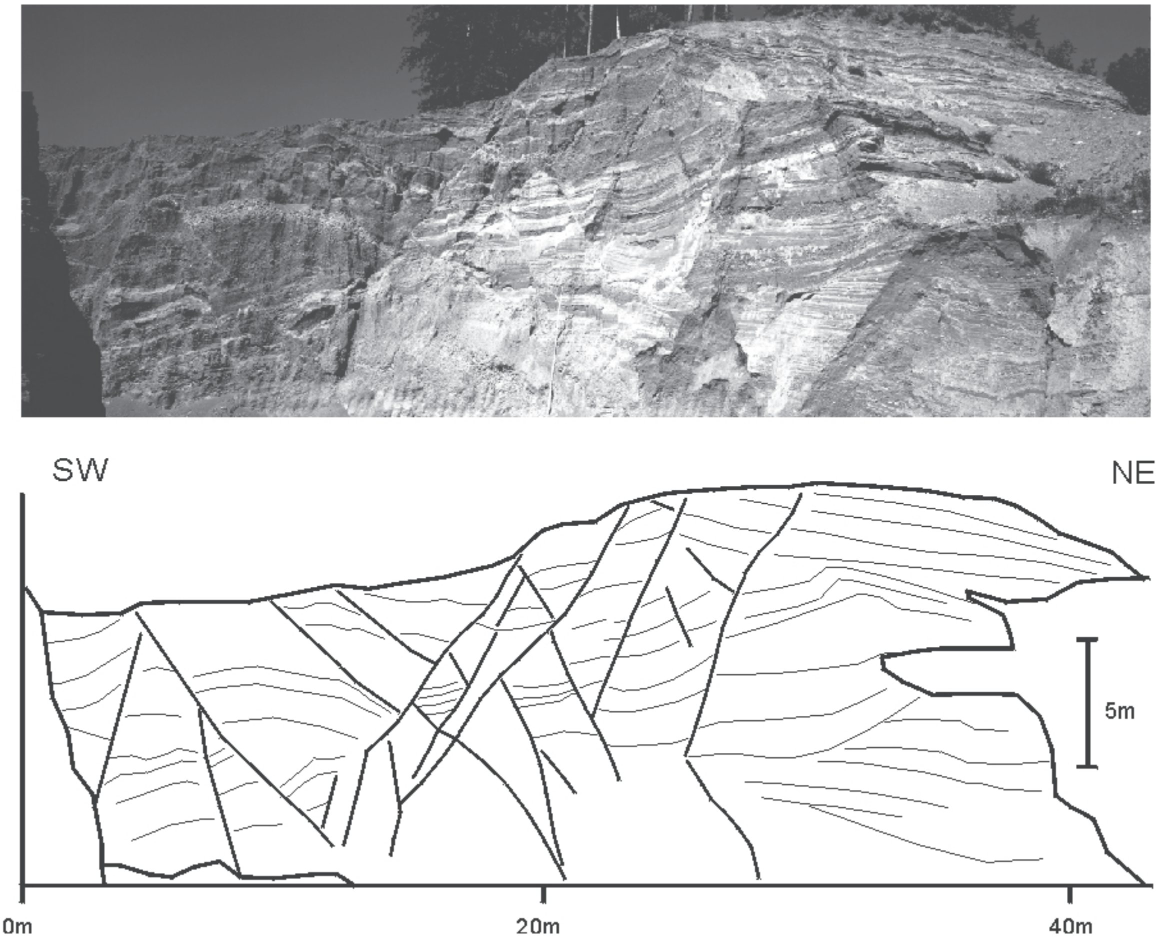


Fig. 6.20: Outcrop wall exposed at the gravel pit Edenhaus. The section consists of an alternation of sand- and gravel-dominated beds. The inclined and prograding units are displaced by normal faults and block rotation. This gravel body is interpreted as a subglacial esker.

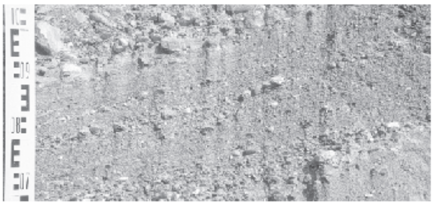
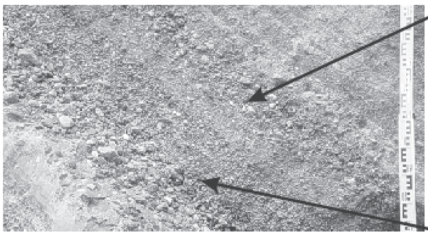
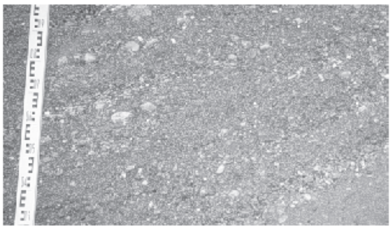
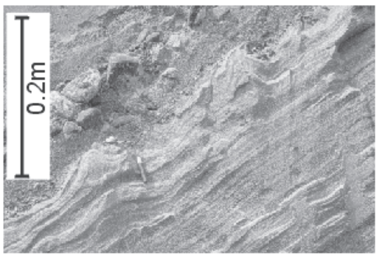
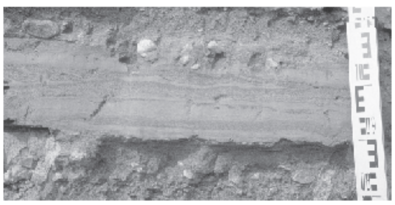
photo	litho-facies code	description	interpretation/ processes
	Gmx / GS-x	strafied gravel to sand mixtures - grain-size spectra: sand to gravel - matrix-supported; - components partly arranged in strings - subrounded- to subangular components - dominant clast orientation: a(p)	gravity-driven (cohensionless) fluidal avalanches
	Gcg,inv	inversly graded gravel - grain-size: sand to cobbles - lower zone: matrix supported; upper zone: clast supported - rounded to subangular components - clast orientation: a(p); a(i); b(i)	stream- and gravity-driven traction carpet (avalanche process) (high shear rate and sieving mechanisme during transport)
	Gcg	graded gravel - grain-size: sand to cobbles - lower zone: bimodal + clast supported; - upper zone: polymodal + clast supported - rounded to subangular components - no prefered clast orientation	high-density turbulent flow (turbidite) (lower zone: reworking of previous sand deposits)
	Gcm	massive gravel - grain-size spectra: sand to gravel - clast supported - subrounded to rounded components - no prefered clast orientation	cohesionless, fluidal mass-movement with turbulent churing
	Gcg,o / Gcx,o	cross-stratified gravels (o = openframe work) - grain-size: coarse sand to gravels - individual beds often graded - overall small amount of matrix (openframe work) - subrounded to rounded clasts - no prefered clast orientation	avalanches (turbidites or grain flows) of previously sorted gravels
	S-x,cb	stratified sand (cb = convolute bedding) - grain-size: coarse to fine sand - individual beds are graded - top zone: dewatering structures	sand turbidites (high rate of sedimentation)
	sH-x,lc	sand-dominated heterolithe (lc = load casts) - grain-size: coarse sand to silt - alternation of sands and fines, partly graded - load casts of coarse sand	hyperconcentrated flow (partly fluidal, partly cohesionsless)

Fig. 6.21: Summary of some major lithofacies types occurring in subglacial meltwater-dominated environments.

According to Brennand (1994) and Brennand & Shaw (1996) this gravel body is interpreted as an esker (composite large-scale macroform) formed in a subglacial conduit (see Fig. 6.22). The rhythmical alternation of sorted sand and gravel units is assumed to be the product of episodic flood flows. The occurring lithofacies types within these section are interpreted as the result of fluidal flow- or hyperconcentrated dispersion- processes (Brennand, 1994). Clast roundness indicates a dominantly subglacial sediment supply. Angular components are either delivered supraglacially through moulins or were melted out from the conduit wall experiencing only minor reworking (resedimented dropstones).

A deltaic sedimentary environment is excluded because no indicator (e.g. lateral fining) of deposition into a standing standing water body is found.

Resedimented dropstones, the appearence of marginal diamict units and the postdepositional extensional deformation clearly indicate a direct contact of the sediments to the ice body.

As a consequence, the external (drumlin-like) shape of this hill is interpreted as the original geometry as which the complex facies body has been deposited. There has been no signs for major erosional truncations at the top or compressional deformations. Postdepositional decay due to lateral ice melting only slightly deformed the body which has obviously been created at a late stage of ice decay.

6.4.4.2 Gravel pit Gebrazhofen

The sediments of the pit Gebrazhofen were exposed for a short time due to road building activities in the year 1999. The morphology can be described as a low relief hummocky terrain containing areas of flat topography (see Fig. 6.1, no. 7).

In Fig. 6.23 an outcrop face is illustrated which can be subdivided into a lower and an upper segment. The lower segment is characterized by cross-stratified units delineating a positive, more than 6m thick, mega-scale bedform. Deposition occurred contemporaneously at the core position and the flanks. The dip of the avalanche beds vary between 5^{O} and 30^{O} and several reactivation surfaces can be recognized. The beds consist dominantly of well sorted sand- to gravel deposits (see Fig. 6.21) and clast are mostly subrounded. This lower segment is clearly truncated at the top. The covering gravel deposits of the upper segment are distinctively coarser in grainsize and build up a sheet like geometry. Internally a simple subhorizontal stacking of poorly sorted gravel deposits is visible and only few small-scaled cut and fill elements are intercalated.

According to Brennand & Shaw (1996) and Shaw and Gorell (1991) the macro- to mega scale bedforms of the lower section are interpreted as gravel dunes. Striking of the core and the dipping geometry of the flanks indicate a paleoflow and migration directed towards the NE.

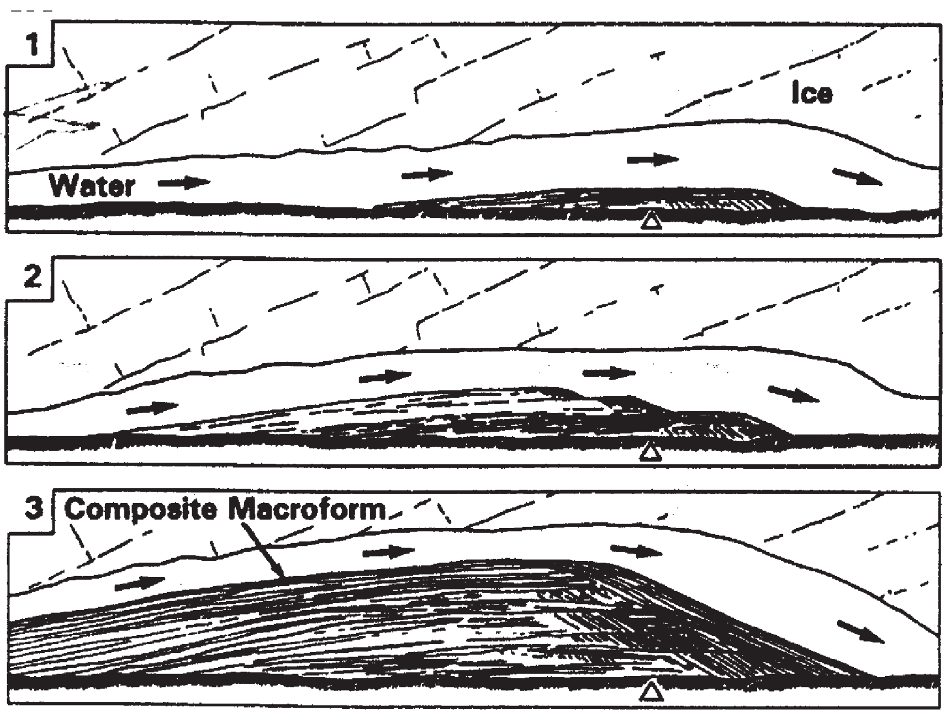


Fig. 6.22: Schematic model of the incremental formation (stages 1-3) of a composite macroform in a subglacial conduit enlargement. The ice roof melts up and back over time of sedimentation (from Brennand & Shaw, 1996).

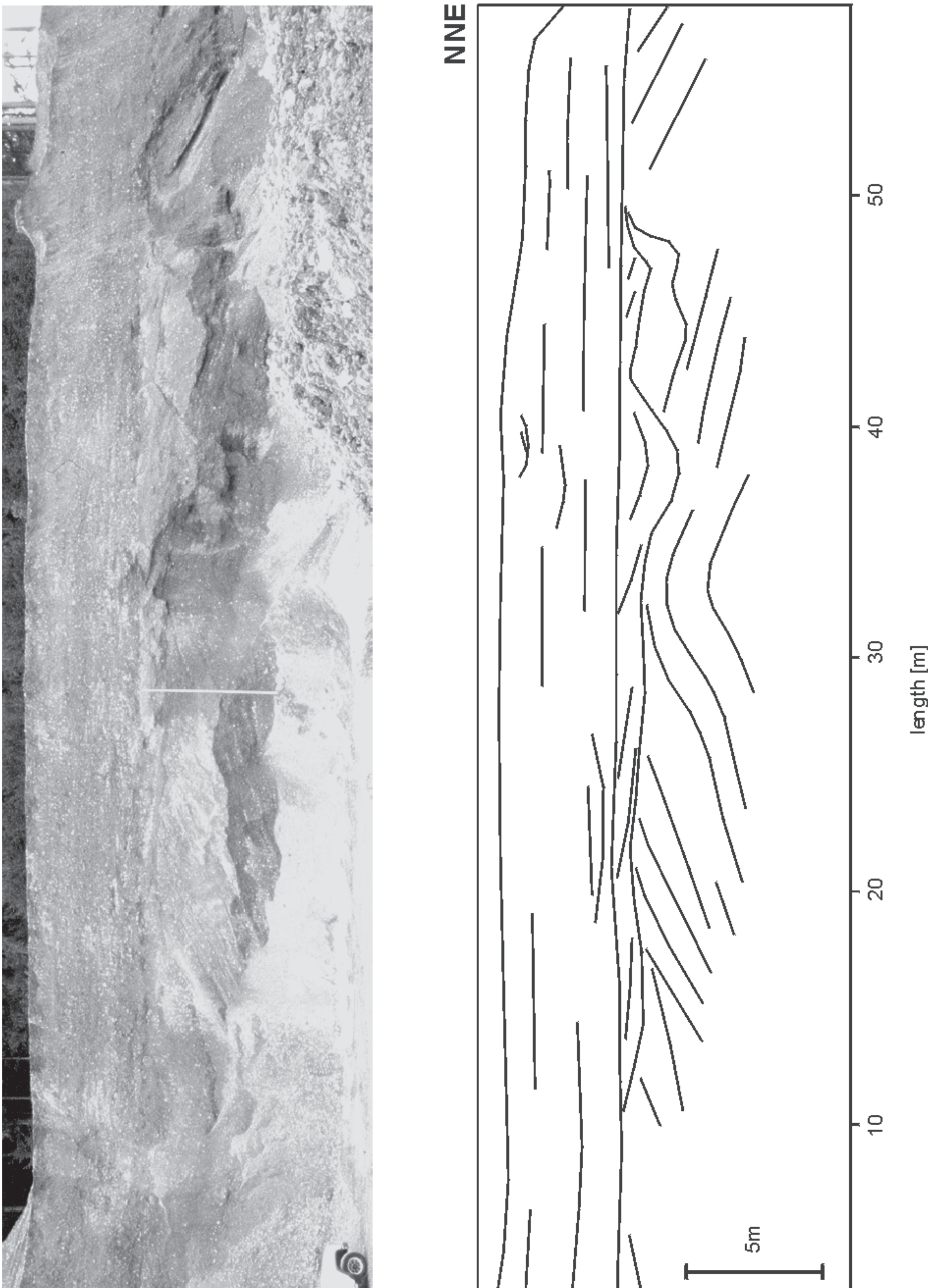


Fig. 6.23: Outcrop wall exposed in the pit Gebrazhofen. The lower segment represent a composite macroform (oblique avalanching beds) developed in a subglacial environment (paleo-flow towards the observer). The upper segment is made-up by a stacking of gravel sheets probably formed under subaerial, fluvial conditions.

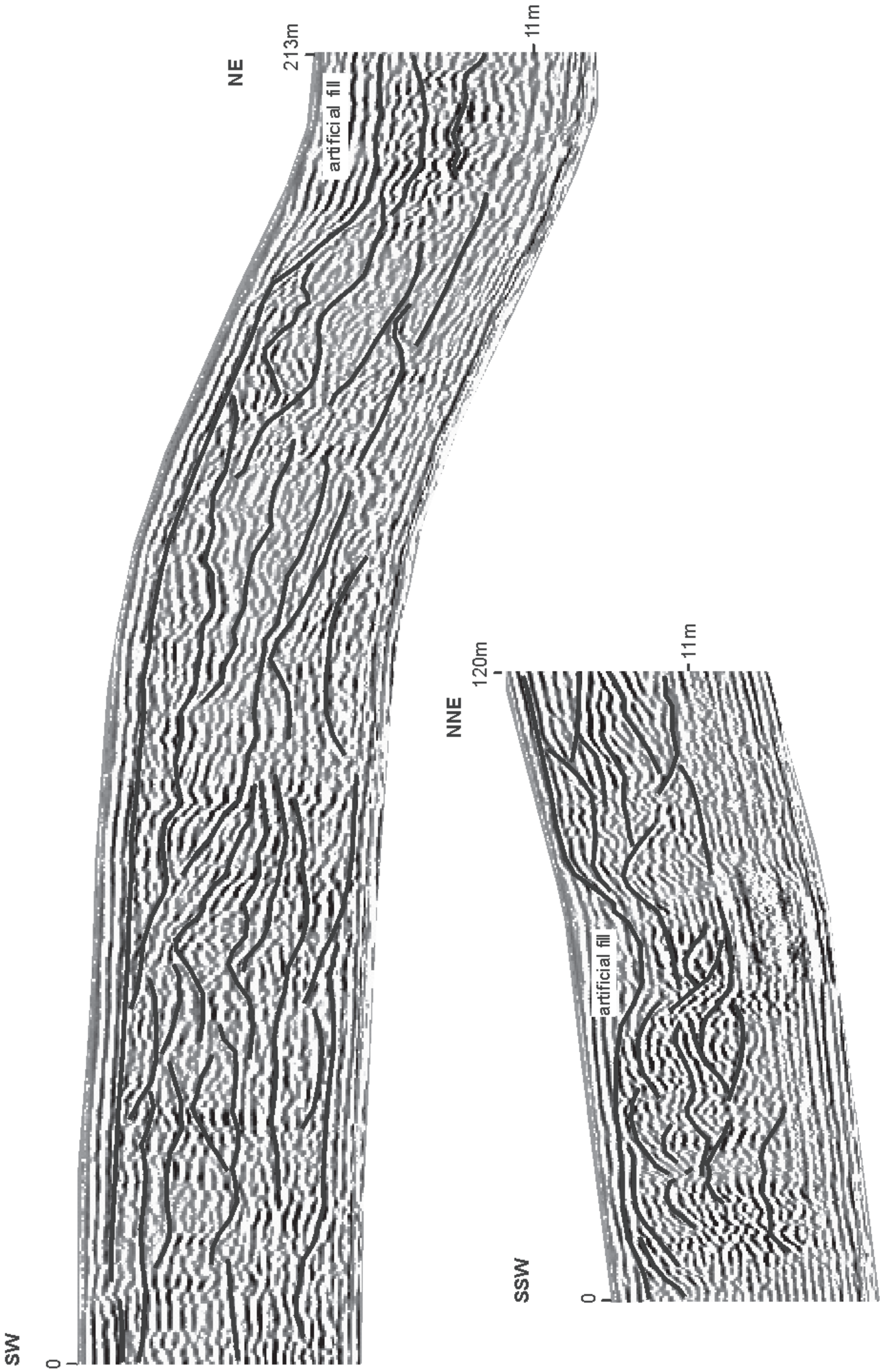


Fig. 6.24: Two examples of radar profiles acquired SW of the site Gebrazhofen. Note the complex stacking pattern of numberless subglacial (convex-shaped) macroforms.

Clast imbrication measurements (a(t), b(i)) within the upper segment indicate the same paleoflow direction. This segment is interpreted as a stacking of tractional gravel sheet deposits in an fluvially dominated environment. Intercalation of small cut-and fill elements in different levels indicate that this upper segment developed gradually and is not the product of one (short-time) high magnitude event.

Georadar measurements which were carried out within the hummocky terrain SSW of the pit revealed a structural pattern clearly corresponding to the lower segment of the outcrop. Interpretation of the reflector pattern show a highly complex architecture of a lateral and vertical stacking of positive shaped cross-stratified units (see Fig. 6.24). This reflects a multiphase (episodic) depositional history.

However, the sheet-like upper section of the outcrop could not be recognized in the radar images and only in parts a thin (0.5-1.0m thick) horizontal- to subhorizontal reflector pattern is revealed at the top. Additionaly, no major and extensive erosional surface is shown in the radar images.

With regard to both the outcrop and the georadar information the lower section which consists of positive-shaped, cross-stratified (mega- to macro scale) bedforms is interpreted as a complex of subglacial gravel-dune deposits. The origin of the local upper section is not clearly clarified but a fluvial, probably subaerial, system is assumed. This system might be established in a small zone and only for a short period during melting of the last ice remains.

6.5 Conclusions

In this chapter it has been shown, that various gravel bodies were formed in very different depositional environments during an overall ice-retreat of the Würmian Rhine glacier. Huge amounts of released meltwater created an accumulation of sand and gravel deposits within ice-marginal as well as in sub- and englacial environments. A combination of outcrop analysis and modern topography investigation has been carried out in order to characterize and understand the paleo-glacial conditions of sediment deposition:

- the facies bodies show an enormous variety of lithofacies types and stratal organization. Both are controlled by hydrodynamic conditions and sediment supply within the distinct glacial environments (e.g. supraglacial deposits are characterized by a vague vertical stacking of poorly sorted, gravity driven deposits);
- beside the textural and structural features clast roundness is important to appraise the source of the material (e.g. angular particels indicate supraglacial sediment source);
- syn- and post- depositional deformation structures (e.g. normal fault, ice-collapse structures) indicate position and dynamic of the glacier during and after sediment accumulation;
- digital elevation models revealed distinct imprints in the modern glacial landscape. The external geometry of facies bodies and the local to regional morphology give critical hints for the paleo-environmental reconstruction (e.g. drumlin-like forms of subglacial meltwater deposits).

Geoardar surveys proved to be a helpful tool in order to detect the complex sedimentary architecture of glacial gravel bodies. In future this method could be used in areas with limited outcrop information.

In general, the presented data are a further step in understanding the highly variable sediment distribution pattern within the Rhine glacier area. Particularly with regard to a regional and historical comprehension of the Würmian glacier dynamics a closely spaced net of sedimentological, morphological and geophysical data is required.

7. References

AIGNER, T., (1995), Arbeitskonzept zur Aquifer-Sedimentologie.- N. Jb. Geol. Paläont. Abh., 195, 147-157.

AIGNER, T., HEINZ, J., HORNUNG, J., ASPRION, U., (1999), A hierarchical process-approach to reservoir heterogeneity: examples from outcrop analogues.- Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine, 22, 1-11.

ANDERSON, M., (1989), Hydrogeological facies models to delineate large-scale spatial trends in glacial and glaciofluvial sediments.- Geol. Soc. of America Bulletin, 101, 501-511.

ANDERSON, M.P., AIKEN, J. S., WEBB, E. K., MICKELSON, D.M., (1999), Sedimentology and hydrogeology of two braided stream deposits.- Sedimentary Geology, 129/3-4, 187-199.

ASHLEY, G.M., (1990), Classification of large-scale subaqueous bedforms: a new look at an old problem.- Journal of Sedimentary Petrology, 60/1, 160-172.

ASHMORE, P.E., (1982), Laboratory modelling of gravel braided stream morphology.- Earth Surf. Processes, 7, 201-225.

ASHMORE, P.E., (1993), Anabranch confluence kinetics and sedimentation processes in gravel-braided streams.- Geological Society Special Publication, 75, (Braided Rivers, Edited by Best, J. and Bristow, C.), 130-146.

ASPRION, U., AIGNER, T., (1997), Aquifer Architecture Analysis Using Ground-Penetrating Radar: Triassic and Quarternary Examples (S. Germany).- Environmental Geology, 31, 66-75.

ASPRION, U., (1998), Ground-penetrating radar (GPR) analysis in aquifer-sedimentology: case studies, with an emphasis on glacial systems of SW Germany. Dissertation, Universität Tübingen, TGA, A43.

ASPRION, U., AIGNER, T., (1999), Towards Realistic Aquifer Models: a Three-Dimensional Georadar case Study of Quaternary Gravel Deltas (Singen Basin, SW Germany).-Sedimentary Geology, 129/3-4, 281-297.

BAYER, P., (2000), Aquifer-Analog-Studie in grobklastischen 'braided river' Ablagerungen: Sedimentäre/ hydrogeologische Wandkartierung und Kalibrierung von Georadarmessungen. Diplomkartierung, University Tübingen.

BERES, M., GREEN, A. G., HORSTMEYER, H., HUGGENBERGER, P., (1995), Mapping the architecture of glaciofluvial sediments with three-dimensional georadar.- Geology 23, 1087-1090.

BERES, M., HUGGENBERGER, P., GREEN, A. G., HORSTMEYER, H., (1999), Using two- and three-dimensional georadar methods to characterize glaciofluvial architecture.- Sedimentary Geology 129, 1-24.

BERSEZIO, R., BINI, A., GIUDICI, M., (1999), Effects of sedimentary heterogeneity on groundwater flow in a Quaternary pro-glacial delta environment: joining facies analysis and numerical modelling.- Sedimentary Geology, 129, 327-344.

BEST, J.L., (1988), Sediment transport and bed morphology at river channel confluences.- Sedimentology, 35, 747-755.

BEYER, W., (1964), Zur Bestimmung der Wasserdurchlässigkeit von Kiesen und Sanden aus der Kornverteilung.- Wasserwirtschaft-Wassertechnik, WWT: Berlin Ost, 165-169.

BIERKENS, M.F.P., (1996), Modeling hydraulic conductivity of a complex confining layer at various spatial scales.- Water Resources Research, 32/8, 2369-2382.

BLUCK, B.J., (1979), Structure of coarse grained braided stream alluvium.- Transaction of the Royal Society of Edinburgh, 70, 181-221.

BOYCE, J.I., EYLES, N., (2000), Architectural element analysis applied to glacial deposits: Internal geometry of a late Pleistocene till sheet, Ontario, Canada.- GSA Bulletin, 112, 98-118.

BOYCE, J.I., EYLES, N., PUGIN, A., (1995), Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario.- Can. J. Earth Sci., 32, 1331-1349.

BRENNAND, T.A., (1994), Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implication for esker genesis and meltwater regime.- Sedimentary Geology, 91, 9-55.

BRENNAND, T.A., SHAW, J., (1996), The Harricana glaciofluvial complex, Abitibi region, Quebec: its genesis and implication for meltwater regime and ice-sheet dynamics.- Sedimentary Geology, 102, 221-262.

BRIDGE, J., COLLIER, R., ALEXANDER, J., (1998), Large-scale structure of Calamus River deposits (Nebraska, USA) revealed using ground-penetrating radar.- Sedimentology, 45, 977-986.

BRIDGE, J.S., (1993), The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers.- Geological Society Special Publication, 75, (Braided Rivers, Edited by Best, J. and Bristow, C.), 13-71.

BRIDGE, S.J., ALEXANDER, J., COLLIER, R.E.LL., GAWTHORPES, R.L., JARVIS, J., (1995), Ground-penetrating radar and coring to study the large-scale structure of point-bar deposits in three dimensions.- Sedimentology, 42, 839-852.

BRIERLEY, G.J., (1996), Channel morphology and element assemblages: a constructivist approach to facies modelling.- Advances in Fluvial Dynamics and Stratigraphy, (Edited by Carling P.A., Dawson, M.R., John Wiley & Sons, West Sussex, England), 263-298.

BRISTOW, C., (1995), Facies analysis in the Lower Greensand using ground-penetrating radar.- Journal of the Geological Society, London, 152, 591-598.

BRODZIKOWSKI, K., VAN LOON, A.J., (1991), Glacigenic sediments.- Developments in Sedimentology, 49, Elsevier.

BROOKFIELD, M.E., MARTINI, I.P., (1999), Facies architecture and sequence stratigraphy in glacially influenced basins: basic problems and water-level / glacier input-point controls (with an example from the Quarternary of Ontario, Canada).- Sedimentary Geology, 123, 183-197.

CARLE. F. LABPLLE, E. M., WEISSMANN, G. S., VAN BROCKLIN, D., FOGG, G. E. ING, P.A., (1998), Geostatistical simulation of hydrofacies architecture: A transition probability Markov approach. In FRASER G.S., DAVIS, J.M.; (EDS.) (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1., 147-170.

CARLING, P.A., GLAISTER, M.S., (1987), Rapid deposition of sand and gravel mixtures downstream of a negative step: the role of matrix-infilling and particle-overpassing in the process of bar-front accretion.- Journal of the Geological Society, London, 144, 543-551.

CARLING, P.A., (1990), Particle over-passing on depth-limited gravel bars.- Sedimentology, 37, 345-355.

CARLING, P.A., (1996), Morphology, sedimentology and palaeohydraulic significance of large gravel dunes, Altai Mountains, Siberia.- Sedimentology, 43, 647-664.

CARLING, P.A., (1999), Subaqueous gravel dunes.- Journal of Sedimentary Research, 63/3, 534-545.

CARMAN, P.C., (1937), Fluid flow through granular beds.- Trans. Inst. chem. Eng., 15, pp. 150.

COLELLA, A., PRIOR, D.B., (Editors), (1990), Coarse-grained deltas.- IAS, Special Publication No. 10, 357 pp., Oxford.

DARDIS, G.F., MCCABE, A.M., (Editors), (1994), Subglacial processes, sediments and landforms (special volume).- Sedimentary Geology, Vol. 91, No. 1-4, 382 Seiten.

DAVIS, J.L., ANNAN, A.P., (1989), Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy.- Geophys. Prospecting, 37, 531-551.

De Jong, M.G.G., (1983), Quaternary deposits and landforms of Western Allgäu (Germany) and the deglaciation after the last major Pleistocene ice advance.- Publi. Flysisch geografisch en bodemkundig labora., 36, Amsterdam.

De Jong, M.G.G., Rappol, M., (1983), Ice-marginal debris-flow deposits in western Allgäu, southern West Germany.- Boreas, 12, 57-70.

Dinehart, R.L., (1992a), Gravel-bed deposition and erosion by bedform migration observed ultrasonically during storm flow, North Toutle River, Washington.- J. Hydrol., 136, 51-71.

Dominic, D. F., Ritzi, R. W. Jr., Reboulet, E. C., Zimmer, A. C., (1998), Geostatistical analysis of facies distributions: Elements of a quantitative hydrofacies model. In Fraser G.S., Davis, J.M.; (eds.) (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1., 137-146.

Ellwanger, D., Bibus, E., Bludau, W., Kösel, M., Merkt, J., (1995), Baden Württemberg: Das Quartär Deutschlands (edited by L. Benda), Schweizerbacher Verlag, Stuttgart.

Eyles, N., Eyles, H.C., Miall, A.D., (1983), Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences.- Sedimentology, 30, 393-410.

Eyles, N., Mullins, H. and Hine, A.C., (1991), The seismic stratigraphy of Okanagan Lake, British Columbia: a record of deglaciation in a deep 'fjord-lake' basin.- Sedimentary Geology, 73, 13-41.

Fiebig, M., (1995), Pleistozäne Ablagerungen im süddeutschen und im neuseeländischen Alpenvorland - ein Vergleich.- Dissertation, University Freiburg.

Fogg, G. E., (1986), Groundwater flow and sand body interconnectedness in a thick, multiple aquifer system. -Wat. Res. Res. 22, 679-694.

Fogg, G. E., (1990), Architecture and interconnectedness of geological media: role of low permeability facies in flow and transport.- Hydrogeology of low permeability environments (edited by Neuman and Neretniks), Heise Verlag.

Fraser G.S., Davis, J.M., (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1., Tulsa, OK, 188.

Galloway, W. E., Sharp, J.M. Jr., (1998), Characterizing Aquifer heterogeneity within terrigenous clastic depositional systems. In Fraser G.S., Davis, J.M.; (eds.) (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1., 85-90.

German, R., (1967), Landschaft und Natur. Geographie und Geologie: (Sonderdruck) Der Kreis Ravensburg, 53 pp. Konrad Theiss Verlag, Stuttgart und Aalen.

Goedhart, M.L., Smith, N.D., (1998), Braided stream aggradation on an alluvial fan margin: Emerald Lake Fan, British Columbia.- Can. J. Earth Sci., 35, 534-545.

Gustavson, T.C., (1978), Bed forms and stratification types of modern gravel meander lobes, Nueces River, Texas.- Sedimentology, 25, 401-426.

Hein, F.J., Walker, R.G., (1977), Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia.- Can. J. Earth. Sci., 14, 562-570.

Heinz, J., Aigner, T., (1999), Faziesanalyse und Dynamik würmzeitlicher Sander-ablagerungen (Raum Ostrach, Oberschwaben, SW-Deutschland).- Zbl. Geol. Paläont. Teil 1, Heft 5-6, 319-336.

Heinz, J., Kleineidam, S., Teutsch, G., Aigner, T., (in prep.), Architectures of Quarternary glaciofluvial gravel bodies (SW-Germany): Genesis of heterogeneity patterns and application to transport modeling.

HUGGENBERGER, P., (1993), Radar facies: recognition of patterns and heterogeneities within Pleistocene Rhine gravels, NE Switzerland.- Geological Society Special Publication, 75 (Braided Rivers, Edited by Best, J. and Bristow, C.), 163-176.

HUGGENBERGER, P., CARLING, P.A., PARNACHEV, S.V., (1998), GPR as a tool to elucidate the depositional processes of giant gravel dunes produced by late Pleistocene superflooding, Altai, Siberia.- Proc. of the 8th International Conference on Ground-Penetrating Radar (GPR' 98), Lawrence, Kansas, USA.

HUGGENBERGER, P., AIGNER, T., (1999), Introduction to the special issue on aquifer-sedimentology: problems, perspectives and modern approaches.- Sedimentary Geology, 129, 179-186.

JACKSON, R.G., (1975), Hierarchical attributes and a unifying model of bedforms composed of cohesionsless sediment and produced by shearing flow.- GSA Bulletin, 86, 1523-1533.

JOHNSON, H.W., HANSEL, A.K., (1990), Multiple Wisconsinan glacigenic sequences at Wedron, Illinois.- Journal of Sedimentary Petrology, 60, 26-41.

JOL, H.M., SMITH, D.G., (1991), Ground penetrating radar of northern lacustine deltas.- Can. J. Earth Sci., 28, 1939-1947.

JUSSEL, P., STAUFFER, F., DRACOS, T., (1994), Transport modeling in heterogeneous aquifers: 1. Statistical description and numerical generation of gravel deposits.- Wat. Res. Res., 30/6, 1803-1817.

KELLER, B., (1992), Hydrogeologie des schweizerischen Molasse-Beckens: Aktueller Wissensstand und weiterführende Betrachtungen.- Eclogae geol. Helv., 85/3, . 611-651.

KELLER, B., (1996), Lithofazies-Codes für die Klassifikation von Lockergesteinen.- Mitteilungen der Schweizerischen Gesellschaft für Boden- und Felsmechanik, Frühjahrstagung 1996.

KELLER, O., KRAYSS, E., (1980), Die letzte Vorlandvereisung in der Nordschweiz und im Bodensee-Raum (Stadialer Komplex Würm-Stein am Rhein).- Eclogae geol. Helv., 73/3, 823-833.

KHADKIKAR, A.S., (1999), Trough cross-bedded conglomerate facies.- Sedimentary Geology, 128, 39-49.

KLEINEIDAM, S., (1998), Der Einfluß von Sedimentologie und Sedimentpetrographie auf den Transport gelöster organischer Schadstoffe im Grundwasser.- PhD thesis, Tübinger Geowissenschaftliche Arbeiten, 41, Germany.

KLEINEIDAM S., RÜGNER, H., GRATHWOHL, P., (1999a), Influence of petrograhic composition/organic matter distribution of fluvial aquifer sediments on the sorption of hydrophobic contaminants.- Sedimentary Geology 129, 311-325.

KLEINEIDAM, S., RÜGNER, H., LIGOUIS, B., GRATHWOHL, P., (1999b), Organic matter facies and equilibrium sorption of Phenanthrene.- Environ. Sci. Technol, 33, 1637-1644.

KLEINERT, K., (1976), Das Grundwasser im Kiesaquifer des oberen Neckartals zwischen Tübingen und Rottenburg.- PhD thesis Geol. Institut University Tübingen, 209 pp.

KLINGBEIL, R., (1998), Outcrop analogue studies – Implications for groundwater flow and contaminant transport in heterogeneous glaciofluvial quaternary deposits.- PhD thesis, Tübinger Geowissenschaftliche Arbeiten, 43, Germany.

KLINGBEIL, R., KLEINEIDAM, S., ASPRION, U., AIGNER, T., TEUTSCH, G., (1999), Relating lithofacies to hydrofacies: outcrop-based hydrogeological characterisation of Quaternary gravel deposits.- Sedimentary Geology (129) 3-4, pp. 299-310.

KOLTERMANN, C.E., GORELICK, (1996a), Heterogeneity in Sedimentary Deposits: A Review of Structure Imitating, Process-Imitation, and Descriptive Approaches. - Wat. Res. Res. 32 (9); 2617-2658.

KOLTERMANN, C.E., GORELICK, (1996b), Fractional packing model for hydraulic conductivity derived from sediment mixtures. - Wat. Res. Res. 32 (12); 3283-3297.

KOWALSKY, M., DIETRICH, P., RUBIN, Y., TEUTSCH, G., (2000), Forward modeling of GPR data using digitized outcrop images and multiple scenarios of water saturation.- submitted to Wat. Res. Res., July 2000.

Kozeny, J., (1927), Über die kapillare Leitung des Wassers im Boden.- Akad. Wiss. Wien, 271 pp.

Kuhnle, R.A., (1996), Unsteady transport of sand and gravel mixtures.- Advances in Fluvial Dynamics and Stratigraphy, (Edited by Carling P.A., Dawson, M.R., John Wiley & Sons, West Sussex, England), 183-202.

Lanz, E., Pugin, A., Green, A., Horstmeyer, H., (1996), Results of 2- and 3-D high resolution seismic reflection surveying of surficial sediments.- Geophysical Research Letters, 23, 491-494.

Leddy, J., Ashworth, P., Best, J., (1993), Mechanisms of anabranch avulsion within gravel-bed braided rivers: observations from a scaled physical model.- Geological Society Special Publication, 75, (Braided Rivers, Edited by Best, J. and Bristow, C.), 119-127.

Lysa, A., Vorren, T.O., (1997), Seismic facies and architecture of ice-contact submarine fans in high-relief fjords, Troms, Northern Norway.- Boreas, 26, 309-328.

Major, J.J., (1998), Pebble orientation on large, experimental debris-flow deposits.- Sedimentary Geology, Vol. 117, 151-164.

Martini, I.P., Brookfield, M.E., (1995), Sequence analysis of upper Pleistocene (Wisconsinan) glaciolacustrine deposits of the North-Shore Bluffs of lake Ontario, Canada.- Journal of Sedimentary Research, B65, 388-400.

McDonald, M.G., Harbaugh, A.W., (1984), A Modular Three Dimensional Finite-Difference Ground-Water Flow Model - MODFLOW.- US Geological Survey Open-File Report 83-875.

McEwan, I.K., Jefcoate, B.J., Willetts, B.B., (1999), The grain-fluid interaction as a self-stabilizing mechanism in fluvial bedload transport.- Sedimentology, 46, 407-416.

McFarlane, P. A., Doveton, J.H., Feldman, H.R., Butler, J.J., Combes, J.M., Collins, D.R., (1994), Aquifer/aquitard units of the Dakota aquifer system in Kansas: Methods of delineation and sedimentary architecture effects on ground water flow and flow properties.- J. of Sed. Research, B 64, 464-480.

McMechan, G.A., Gaynor, G.C., Szerbiak, R.B., (1997), Use of ground-penetrating radar for 3-D sedimentological characterization of clastic reservoir analogs.- Geophysics, 62/3, 786-796.

Menzies, J., (1995), Modern glacial environments: processes, dynamics and sediments, 1, Butterworth & Heinemann, Oxford, 621 pp.

Menzies, J., (1996), Past glacial environments: sediments, forms and techniques, 2, Butterworth & Heinemann, Oxford, 598 pp.

Miall, A.D., (1978), Lithofacies types and vertical profile models in braided river deposits: a summary.- Fluvial sedimentology (Ed. by A.D. Miall), Can. Soc. Petrol. Geol. Mem., 5, 597-604.

Miall, A.D., (1985), Architectural-element analysis: A new method of facies analysis applied to fluvial deposits.- Earth-Sci. Rev., 22, 261-308.

Miall, A.D., (1996), The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology, Springer Verlag, 582 Seiten.

Morison, S.R., Hein, F.J., (1987), Sedimentology of the White Channel Gravels, Klondike Area, Yukon Territory: fluvial deposits of a confined valley.- Spec. Publ. Soc. econ. Palaeont. Miner.,Tulsa, (Recent Developments in Fluvial Sedimentology, Edited by Etheridge, F.G., Flores, R.M., Harvey, M.D.), 39, 205-216.

Munro, M., Shaw, J., (1997), Erosional origin of hummocky terrain in south-central Alberta, Canada.- Geology, 25, 1027-1030.

Nemec, W., Steel, R.J., (1984), Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits.- Sedimentology of Gravels and Conglomerates (Edited by Kostner,E.H. & Steel, R.J.), Mem. Can. Soc. Petrol. Geol., Calgary, 10, 295-320.

NEMEC, W., (1990), Aspects of sediment movement on steep delta slopes.- Coarse-grained deltas (edited by A. Colella & D.B. Prior), IAS Spec. Publ. 10, 29-73.

NIJMAN, W., PUIDEFABREGAS, C., (1978), Coarse-grained point-bar structure in a molasse-type fluvial system, Eocene Castisent Sandstone Formation, south Pyrenean Basin.- Fluvial Sedimentology (Edited by Miall, A.D.), Canadian Soc. of Petrol. Geologists, Memoir 5, 487-510.

OLSEN, H., ANDREASEN, F., (1995), Sedimentology and ground-penetrating radar characteristics of a Pleistocene sandur deposit.- Sedimentary Geology, Vol. 99, 1-15.

OVIATT, C.G., MCCOY, W.D., NASH, W.P., (1994), Sequence stratigraphy of lacustrine deposits: a Quarternary example from the Bonneville basin, Utah.- Geol. Soc. Am. Bull., 106, 133-144.

PANDA, M.N., LAKE, L.W., (1994), Estimation of single-phase permeability from parameters of particle -size distribution.- AAPG Bull**.** 78 (7), 1028-1039.

PENCK, A., BRÜCKNER, E., (1909), Die Alpen im Eiszeitalter, 3 Bde., Tauchnitz, Leipzig, Germany.

PIOTROWSKI, J.A., (Editor), (1997), Subglacial environments.- Sedimentary Geology (Special Issue), 111, 1-4, 330 pp.

POETER, E., GAYLORD, D.R., (1990), Influence of aquifer heterogeneity on contaminant transport at Hanford Site.- Ground Water, 28, 329-340.

POETER, E., TOWNSEND, P., (1994), Assessment of critical flow path for improved remediation management.- Ground Water, 32, 439-447.

POLLOCK, D.W., (1989), Documentation of Computer Programs to Compute and Display Pathlines Using Results from the US Geological Survey Modular Three-Dimensional Finite Difference Ground-Water Flow Model - MODPATH.- US Geological Survey Open-File Report 83-381.

PTAK, T., TEUTSCH, G., (1994), Forced and natural gradient tracer tests in a highly heterogeneous porous aquifer: instrumentation and measurements results.- Journal of Hydrology, 159, 79-104.

PUGIN, A., PULLAN, S.E., SHARPE, D.R., (1996), Observations of tunnel channels in glacial sediments with shallow land-based seismic reflection.- Annals of Glaciology (International Glaciological Society), 22, 176-180.

PUGIN, A., PULLAN, S.E., SHARPE, D.R., (1999), Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario.- Can J. Earth Sci., 36, 409-432.

PULLAN, S.E., PUGIN, A., DYKE, L.D., HUNTER, J.A., PILON, J.A., TODD, B.J., ALLEN, V.S., BARNETT, P.J., (1994), Shallow geophysics in a hydrogeological investigation of the Oak Ridges Moraine, Ontario. In: Symposium on the Application of Geophysics to Engineering and Environmental Problems, SAGEPP'94, Environmental and Engineering Geophysical Society, 1, 143-161.

RAINS, B., SHAW, J., SKOYE, R., SJOGREN, D., KVILL, D., (1993), Late Wisconsin subglacial megaflood paths in Alberta.- Geology, 21, 323-326.

RAMOS, A., SOPNA, A., PEREZ-ARLUCEA, M., (1986), Evolution of Buntsandstein fluvial sedimentation in the Northwest Iberian Range (Central Spain).- Journal of Sedimentary Petrology, Vol. 56, No.6, 862-875.

RAPPOL, M., (1979), On the glacial geology and morphology of the Subalpine Molasse region in western Allgäu, Southern Germany, 154 pp., M.Sci. Thesis. University Amsterdam.

REA, J., KNIGHT, R., (1998), Geostatistical analysis of ground-penetrating radar data: A means of describing spatial variation in the subsurface.- Water Resources Research, 34/3, 329-339.

REID, I., FROSTICK, L.E., (1987), Towards a better understanding of bedload transport.- Spec. Publ. Soc. econ. Palaeont. Miner.,Tulsa, (Recent Developments in Fluvial Sedimentology, Edited by Etheridge, F.G., Flores, R.M., Harvey, M.D.), 39, 13-20.

RITZI, R.W., JAYNE, D.F., ZAHRADNIK, A.J., FIELD, A.A., FOGG, G.E., (1994), Geostatistical modeling of heterogeneity in glaciofluvial buried-valley aquifers.- Ground Water, 32, 666-674.

RITZI, R.W., DOMINIC, D.F., BROWN, N.R., KAUSCH, K.W., MCALENNEY, P.J., BASIAL, M.J., (1995), Hydrofacies distribution and correlation in the Miami valley aquifer system.- Wat. Res. Res. 31, 3271-3281.

SACK-KÜHNER, B., (1996), Einrichtung des Naturmessfeldes 'Lauswiesen Tübingen', Erkundung der hydraulischen Eigenschaften, Charakterisierung der Untergrundheterogenität und Vergleich der Ergebnisse unterschiedlicher Erkundungsverfahren.- Diplom thesis Geol. Institut University Tübingen, 77 pp.

SCHEIBE, T. D., MURRAY, C. J., (1998), Simulation of geologic patterns: A comparision of stochastic simulation techniques for groundwater transport modeling. In FRASER G.S., DAVIS, J.M.; (EDS.) (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1., 107-118.

SCHIRMER, W., (1995), Valley bottoms in the late Quartenary.- Z. Geomorph. N.F., 100, 27-51.

SCHREINER, A., (1992), Einführung in die Quartärgeologie, 257 Seiten, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

SHAW, J., SHARPE, D.R., (1987), Drumlin formation by subglacial meltwater erosion.- Can. J. Earth Sci., 24, 2316-2322.

SHAW, J., GORRELL, G., (1991), Subglacially formed dunes with bimodal and graded gravel in the Trenton Drumlin Field, Ontario.- Geographie physique et Quaterneire, 45/1, 21-34.

SHAW, J., RAINS, B., EYTON, R., WEISSLING, L., (1996), Laurentide subglacial outburst floods: landform evidence from digital elevation models.- Can. J. Earth Sci., 33, 1154-1168.

SIEGENTHALER, C., HUGGENBERGER, P., (1993), Pleistocene Rhine gravel: deposits of a braided river system with dominant pool preservation.- Geological Society Special Publication, 75, (Braided Rivers, Edited by Best, J. and Bristow, C.), 147-162.

SMITH, D.G., JOL, H.M., (1992), Ground-penetrating radar investigation of a Lake Bonneville delta, Provo level, Brigham City, Utah.- Geology, 20, 1083-1086.

SMITH, D.G., JOL, H.M., (1997), Radar structure of a Gilbert-type delta, Peyto Lake, Banff National Park, Canada.- Sedimentary Geology, 113, 195-209.

SMITH, S.A., (1990), The sedimentology and accretionary style of an ancient gravel-bed stream: the Budleigh Salterton Pebble Beds (Lower Triassic), southwest England.- Sedimentary Geology, 67, 199-219.

STEEL, R.J., THOMPSON, D.B., (1983), Structures and textures in Triassic braided stream conglomerates ('Bunter' Pebble Beds) in the Sherwood Sandstone Group, North Staffordshire, England.- Sedimentology, 30, 341-367.

STEPHENS, M., (1994), Architectural element analysis within the Kayenta Formation (Lower Jurassic) using ground-probing radar and sedimentological profiling, southwestern Colorado.- Sedimentary Geology, 90, 179-211.

SZENKLER, C., (1996), In: Grundwasserbewirtschaftungskonzept Singen, Stutz & Kätsch GmbH, Sandhausen, Germany.

TODD, S.P., (1989), Stream-driven gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin.- Sedimentology, 36, 513-530.

TODD, S.P., (1996), Process deduction from fluvial sedimentary structures. In: Advances in Fluvial Dynamics and Stratigraphy, (Edited by Carling P.A., Dawson, M.R., John Wiley & Sons, West Sussex, England), 299-350.

TRONICKE, J., HEINZ, J., APPEL, E., (1999), Geophysical radar techniques for the characterization of heterogeneous Quaternary gravel deposits.- Proceedings of the 5th EEGS-ES meeting, Budapest, Hungary, 1999.

ULRIKSEN, C.P.F., (1982), Application of impulse radar to civil engineering.- PhD thesis, Lund University of Technology, Lund.

VAN DAM, R.L., SCHLAGER, W., (2000), Identifying causes of ground-penetrating radar reflections using time-domain reflectometry and sedimentological analyses.- Sedimentology, 47, 435-449.

VAN OVERMEEREN, R.A., (1998), Radar facies of unconsolidated sediments in The Netherlands: a radar stratigraphy interpretation method for hydrogeology.- Journal of Applied Geophysics, 40, 1-18.

VAN RENSBERGEN, P., DE BATIST, M., BECK, CH., CHAPRON, E., (1999), High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacigenic lake: Lake Le Bourget, Northwestern Alps, France.- Sedimentary Geology, 128, 99-129.

VANDENBERGHE, J., VAN OVERMEEREN, R.A., (1999), Ground penetrating radar images of selected fluvial deposits in the Netherlands.- Sedimentary Geology, 128, 245-270.

WEBB, E.K., ANDERSON, M.P., (1996a), Simulating the three-dimensional distribution of sediment units in braided-stream deposits.- J. Sed. Res. B 64 (2); 219-231.

WEBB, E.K., ANDERSON, M.P., (1996b), Simulating of preferential flow in three-dimensional, heterogeneous conductivity fields with realistic internal architecture.- Wat. Res. Res. 32 (3); 533-545.

WEBB, E.K., DAVIS, J.M., (1998), Simulation of the spatial heterogeneity of geologic properties: An overview. In FRASER G.S., DAVIS, J.M.; (EDS.) (1998), Hydrogeologic models of sedimentary aquifers.- SEPM (Society for Sedimentary Geology) Concepts in Hydrolgeology and Environmental Geology No. 1, 1-24.

WEINHOLD, H., (1973), Beiträge zur Kenntnis des Quartärs im Württembergischen Allgäu zwischen östlichem Bodensee und Altdorfer Wald.- Dissertation, University Tübingen.

WHARTON, R.G., HAZEN, G.A., RAU, R.N., BEST, D.L., (1980), Electromagnetic propagation logging: Advances in technique and interpretation.- Soc. Pet. Pap., 9267.

WHITING, P.J., DIETRICH, W.E., LEOPOLD, L.B., DRAKE, T.G., SHEREVE, R.L., (1988), Bedload sheets in heterogeneous sediment.- Geology, Vol. 16, 105-108.

WHITTAKER, J., TEUTSCH, G., (1999), Numerical simulation of subsurface characterization methods: application to a natural aquifer analogue.- Advances in Water Resources, 22, 819-829.

YOUNG, R.A., SUN, J., (1996), 3-D ground penetrating radar imaging of a shallow aquifer at Hill Air Force Base, Utah.- JEEG, 1, 97-108.

Appendix

(all data on CD)

Contents:

A1: Coordination of the outcrops (word6)

A2: Outcrop panels (tif)

- glacial (*Baindt, Edenhaus, Gebrazhofen, Grenis, Maria Tann*)
- proglacial
    - main discharge (*Haltingen, Hartheim, Herten, Lottstetten, Rheinheim, Schlingen, Wyhlen*)
    - intermediate discharge (*Ostrach, Pfullendorf*)
    - minor discharge (*Bolstern, Saulgau*)
    - others (*Aitrach, Leutkirch, Mennisweiler, Neubrunn*)

A3: Outcrop photos (tif)

- glacial (*Böhringen, Biggenmoos, Birkenbühl, Bonndorf, Edenhaus, Engen, Gebrazhofen, Grenis, Liezenhofen, Michelwinnaden, Schwarzenbach, Schweineberg, Tettnang, Unterankenreute, Unterrehna, Waldburg, Waltershofen*)
- proglacial (*Aitrach, Bolstern, Haltingen, Hartheim, Herten, Ingoldingen, Lottstetten, Mennisweiler, Ostrach, Reichenbach, Rheinheim, Saulgau, Tautenbronn, Winterstettenstadt, Wyhlen*)

A4: Sieve curves / Statistics (excel6)

A5: Digital files of the PhD thesis