

# Flow and Transport in Fractured Porous Media

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# Flow and Transport in Fractured Porous Media

With 306 figures and 65 tables

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## Preface

Fractured porous aquifers are an important source of water for public, industrial and agricultural use, both in developed and developing countries. Recently, understanding, characterizing and modeling physical and chemical interactions within fractured porous aquifers has become increasingly important, particularly with regard to the question of water resources development and groundwater contamination. This book presents concepts and methods for characterizing flow and transport in fractured porous media from an experimental and modelling perspective on the basis of the aquifer-analogue concept.

A fundamental understanding of the response of a system to particular tests is a prerequisite, especially for the characterization of fractured porous aquifers, which are highly heterogeneous systems. This understanding is essential to identifying the governing flow and transport processes as well to calculating and predicting flow and transport in such systems.

In the classical concept of the aquifer analogue, which was established in the petroleum industry, the potential reservoir rocks are investigated in outcrops and characterized by detailed sedimentological studies. The properties of the system under investigation, i.e. the geometry and petrography of the sedimentological elements in the outcrop, are considered to be directly transferable to similar reservoir rocks. In the field of fractured porous rock hydrogeology, this approach has very rarely been applied. In the application of the aquifer-analogue approach presented in this book, accessible outcrops of the unsaturated fractured porous aquifer are examined. This concept allows sections of an aquifer to be investigated on several scales with field and laboratory techniques.

Employing appropriate investigation methods on each scale meant that a high resolution and precise data sets could be obtained, e.g. detailed information on the geometry of the fracture network and on the hydraulic characteristics of the porous matrix. The results of the investigations and the processes thus revealed are then assumed to be applicable to the inaccessible section of

the saturated aquifer. While this approach offers considerable advantages, basic assumptions have to be made.

The choice of outcrop for the analogue investigation is crucial, because the samples chosen determine how representative the results are for the fractured porous aquifer system. Effects of the experiments themselves, for example a widening of the fracture apertures as a result of a pressure decrease following the removal of a sample, also have to be taken into account. In the investigation, the main focus is on basic experimental techniques for determining the effects of the heterogeneous system on flow and transport processes. The investigations that are based on the analogue concept usually cover small volumes of the aquifer or the aquifer analogue (ranging from centimeters to tens of meters) so that possible scale-dependency effects of the hydraulic properties need to be taken into account. On this assumption, the aquifer-analogue approach can be utilized in experimental and modelling investigations to characterize inaccessible fractured porous aquifers.

The work on the aquifer-analogue approach is divided into two parts. Firstly, flow and transport experiments are developed and applied to obtain highly resolved data sets enabling a detailed investigation of the system under consideration. Secondly, these data sets are used to develop reliable models, allowing the verification and interpretation of the observed results. Additionally, these models are simplified and verified in order to study the principle behavior of the fractured porous system. The proposed models are realized by using a discrete and a multi-continua modeling approach.

The experiments and model approaches used here allow the effects arising from heterogeneity to be analyzed and the heterogeneous nature of the investigated system to be characterized. In addition, the processes that can be expected to occur during flow and transport within fractured porous media are understood more clearly.

The aquifer analogue approach was also used as the basic concept of the research initiative "Fractured-Rock Aquifer-Analogue Approach". This research initiative was launched in 1996 and funded by the German Research Foundation (DFG). It was headed by the University of Tübingen and supported by research groups from the universities of Aachen, Karlsruhe and Stuttgart. While the emphasis of the groups from Tübingen and Karlsruhe was mainly on the design of appropriate and adapted experimental techniques on the laboratory and field scale, the Stuttgart and Aachen groups concentrated on the development of suitable modelling tools using discrete and continuum approaches. The major results of the research initiative "Fractured-Rock Aquifer-Analogue Approach" are presented in this book.

The work on the aquifer-analogue approach in the frame of the research initiative is divided into two parts. Firstly, flow and transport experiments are developed and applied to obtain highly resolved data sets enabling a detailed investigation of the system under consideration. Secondly, these data sets are used to develop reliable models, allowing the verification and inter-

pretation of the observed results. Additionally, these models are simplified and verified in order to study the principle behavior of the fractured porous system. The proposed models are realized by using a discrete and a multi-continua modeling approach.

The experiments and model approaches used here allow the effects arising from heterogeneity to be analyzed and the heterogeneous nature of the investigated system to be characterized. In addition, the processes that can be expected to occur during flow and transport within fractured porous media are understood more clearly.

The book is divided into three main parts. In the first part *Assessment of Fractured Porous Media*, the aquifer-analogue approach and model concepts are introduced. The realization and results of flow and transport experiments in fractured porous media are described in the second part *Project Scale Studies*. The investigated objects range from small cores with a diameter of 10 cm to the field block with a dimension of approx.  $10\text{ m} \times 8\text{ m} \times 2\text{ m}$ . In the final part, scale-independent approaches and investigations are presented and illustrated by examples. The final part, *Scale-independent Approaches and Investigations* are presented and illustrated by examples.

The research initiative "Fractured-Rock Aquifer-Analogue Approach", funded by the German Research Foundation (DFG), was launched in 1996. It was headed by the University of Tübingen and supported by research groups from the universities of Aachen, Karlsruhe and Stuttgart. While the emphasis of the groups from Tübingen and Karlsruhe was mainly on the design of appropriate and adapted experimental techniques on the laboratory and field scale, the Stuttgart and Aachen groups concentrated on the development of suitable modelling tools using discrete and continuum approaches.

Our thanks are due to the German Research Foundation for funding the project. We are grateful to the firm Fauser, which supplied the block for the laboratory experiments, to Michel Lambert for his technical support and to the town of Pliezhausen where the quarry is situated. Thanks also to the publishing house Springer, particularly Dr. Thomas Ditzinger. Finally, we would like to thank all the numerous technicians, computer network administrators, student assistants and others for their indispensable contributions.

Tübingen and Stuttgart,  
August 2004

Peter Dietrich  
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