INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS SELECTED PAPERS

9

# Groundwater in Fractured Rocks

Editor: Jiří Krásný
John M. Sharp

Taylor & Francis
Taylor & Francis Group

# GROUNDWATER IN FRACTURED ROCKS

*Few tasks in hydrogeology are more difficult than locating drilling sites for water wells in igneous and metamorphic rocks.*

Davis SN and DeWiest RJM (1966)
Hydrogeology, p. 318.
Wiley and Sons, Inc., New York-London-Sydney.

*The hydrologist cannot blindly select a model, turn a crank, and accept the answers. He must devote considerable time and thought to judging how closely his real aquifer resembles the ideal.*

Ferris JG, Knowles B, Brown RH and Stallman RW (1962)
Theory of aquifer tests, p. 102.
*Geol. Surv. Water-Supply paper* 1536-E, Washington.

SELECTED PAPERS ON HYDROGEOLOGY

# 9

*Series Editor*: Dr. Nick S. Robins
*Editor-in-Chief IAH Book Series*
*British Geological Survey*
*Wallingford, UK*

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

# Groundwater in fractured rocks

## Selected papers from the Groundwater in Fractured Rocks International Conference, Prague, 2003

Edited by

Dr. Jiří Krásný
*Associate Professor, Charles University Prague, Czech Republic*
*Scientific Programme Member and Chair of the Commission on Hardrock Hydrogeology, International Association of Hydrogeologists*

Dr. John M. Sharp, Jr.
*Carlton Professor of Geology, The University of Texas, Austin, USA*
*Treasurer, International Association of Hydrogeologists*

Taylor & Francis
Taylor & Francis Group
LONDON / LEIDEN / NEW YORK / PHILADELPHIA / SINGAPORE

**Cover photograph: Outcrop of the weathered granite in the Melechov region, Central Bohemia, Czech Republic.** Fractured granite merges upwards into its regolith with granite blocks and a thin soil cover on the top (Photo: Jiří Krásný). Deep parts of the Melechov Granite were selected as one of the places for possible radioactive waste disposal.

*Taylor & Francis is an imprint of the Taylor & Francis Group, an informa business*

This edition published in the Taylor & Francis e-Library, 2007.

"To purchase your own copy of this or any of Taylor & Francis or Routledge's collection of thousands of eBooks please go to www.eBookstore.tandf.co.uk."



Published by: Taylor & Francis/Balkema
P.O. Box 447, 2300 AK Leiden, The Netherlands
e-mail: Pub.NL@tandf.co.uk
www.balkema.nl, www.taylorandfrancis.co.uk, www.crcpress.com

Library of Congress Cataloging-in-Publication Data

Groundwater in Fractured Rocks International Conference (2003 : Prague, Czech Republic)

Groundwater in fractured rocks : selected papers from the Groundwater in Fractured Rocks International Conference, Prague, 2003 / edited by Jirí Krásný, John M. Sharp, Jr.

p. cm. – (Selected papers on hydrogeology ; 9)

ISBN 978-0-415-41442-5 (hardcover : alk. paper) 1. Hydrogeology–Congresses. 2. Rocks–Fracture–Congresses. I. Krásný, Jirí. II. Sharp, John Malcolm, 1944–III. Title.

GB1001.2.G78 2007
551.49–dc22 2007009818

ISBN 0-203-94565-4 Master e-book ISBN

ISBN13: 978-0-415-41442-5 (Hbk)
ISBN13 e-Book: 978-0-203-94565-0

# Contents


Preface XI

About the editors XV

Introductory paper: Hydrogeology of fractured rocks from particular fractures to regional approaches: State-of-the-art and future challenges 1
*Jiří Krásný and John M. Sharp, Jr.*

HYDROGEOLOGICAL ENVIRONMENT OF FRACTURED ROCKS

Chapter 1. Hydrogeology of granite rocks in Sardinia 33
*Giovanni Barrocu*

Chapter 2. Groundwater exploitation of fractured rocks in South America 45
*Emilia Bocanegra and Gerson C. Silva Jr.*

Chapter 3. Groundwater and tectonics – semiarid Northeast of Brazil 57
*Benjamim B. de Brito Neves and José do Patrocínio T. Albuquerque*

Chapter 4. Regional study of hard rock aquifers in Alentejo, South Portugal: methodology and results 73
*António Chambel, Jorge Duque and João Nascimento*

Chapter 5. Groundwater in volcanic hard rocks 95
*Emilio Custodio*

Chapter 6. Regional transmissivity distribution and groundwater potential in hard rock of Ghana 109
*Philip K. Darko and Jiří Krásný*

Chapter 7. Hydrogeology of hard rocks in some eastern and western African countries 121
*Costantino Faillace*

Chapter 8. The fractured rocks in Hellas 133
*George Stournaras, George Migiros, George Stamatis, Niki-Nikoletta Evelpidou, Konstantinos Botsialas, Barbara Antoniou and Emmanuel Vassilakis*

Chapter 9. Determining a representative hydraulic conductivity of the Carnmenellis granite of Cornwall, UK, based on a range of sources of information 151
*David C. Watkins*

Chapter 10. Estimating the change of fracture volume with depth at the Koralm Massif, Austria 163
*Gerfried Winkler, Hans Kupfersberger and Elmar Strobl*

CONCEPTUAL MODELS, GROUNDWATER FLOW AND RESOURCES IN FRACTURED ROCKS

Chapter 11. Fractured Old Red Sandstone aquifers of the Cork Harbour region: Groundwater barriers between adjacent karstic systems 179
*Alistair Allen and Dejan Milenic*

Chapter 12. Non-Darcy two-phase flow in fractured rocks 189
*Giovanni Brighenti and Paolo Macini*

Chapter 13. GIS based assessment of groundwater recharge in the fractured rocks of Namaqualand, South Africa 203
*Julian Conrad and Shafick Adams*

Chapter 14. The use of environmental isotopes to establish a hydrogeological conceptual model in a region with scarce data: the Table Mountain Group of South Africa as a case study 219
*Arie S. Issar and Johanita C. Kotze*

Chapter 15. Hard rock aquifers characterization prior to modelling at catchment scale: an application to India 227
*Jean-Christophe Maréchal, Benoît Dewandel, Shakeel Ahmed and Patrick Lachassagne*

Chapter 16. Estimating groundwater recharge in fractured bedrock aquifers in Ireland 243
*Bruce D.R. Misstear and Vincent P. Fitzsimons*

GROUNDWATER QUALITY IN FRACTURED ROCKS

Chapter 17. Interpreting the evolution and stability of groundwaters in fractured rocks 261
*Adrian Bath*

Chapter 18. Universal controls on the evolution of groundwater chemistry in shallow crystalline rock aquifers: the evidence from empirical and theoretical studies 275
*Bjørn Frengstad and David Banks*

Chapter 19. Factors influencing the microbiological quality of groundwater in Norwegian bedrock wells 291
*Sylvi Gaut, Atle Dagestad, Bjørge Brattli and Gaute Storrø*

Chapter 20. Evaluating mineral water quality trends of Pedras Salgadas (Portugal) 305
*Carla Lourenço and Luís Ribeiro*

Chapter 21. Questions and answers about the evolution of $CO_2$-rich thermomineral waters from Hercynian granitic rocks (N-Portugal): a review 313
*José M. Marques, Mário Andrade, Paula M. Carreira, Rui C. Graça, Luís Aires-Barros*

Chapter 22. Origin of salinity in a fractured bedrock aquifer in the Central West Region of NSW, Australia 329
*Karina Morgan and Jerzy Jankowski*

Chapter 23. Isotope studies of a groundwater-flow system in granite, Middle Hungary 343
*László Palcsu, Éva Svingor, Mihály Molnár, Zsuzsanna Szántó, István Futó, László Rinyu, István Horváth, György Tóth and István Fórizs*

Chapter 24. Structure conditional thermal springs in Central Brazil 355
*Uwe Tröger*

INVESTIGATION AND INTERPRETATION METHODS IN FRACTURED ENVIRONMENT

Chapter 25. Characterization of fractured porous media: Aquifer Analogue Approach 375
*Ralf Brauchler, Martin Sauter, Christopher I. McDermott, Carsten Leven, Matthias Weede, Peter Dietrich, Rudolf Liedl, Heinz Hötzl and Georg Teutsch*

Chapter 26. Application of the oriented core drilling/sampling method to an environmental site investigation 393
*James P.G. Bunker*

Chapter 27. Probabilistic delineation of groundwater protection zones in fractured-rock aquifers 405
*Júlio F. Carneiro*

Chapter 28. Interconnected flow measurement between boreholes using a borehole flowmeter 423
*Lasse Koskinen and Pekka Rouhiainen*

Chapter 29. Characterizing flow in natural fracture networks: comparison of the discrete and continuous descriptions 437
*Tanguy Le Borgne, Olivier Bour, Jean Raynald De Dreuzy and Philippe Davy*

Chapter 30. New analysis of pump tests in fractured aquifers 451
*Gerard Lods and Philippe Gouze*

Chapter 31. Estimating groundwater flow rates in fractured metasediments: Clare Valley, South Australia 463
*Andrew Love, Craig T. Simmons, Peter Cook, Glenn A. Harrington, Andrew Herczeg and Todd Halihan*

Chapter 32. Fracture networks in Jurassic carbonate rock of the Algarve Basin (South Portugal): implications for aquifer behaviour related to the recent stress field 479
*Inga Moeck, Michael Dussel, Uwe Tröger and Heinz Schandelmeier*

ANTHROPOGENIC IMPACTS ON FRACTURED ENVIRONMENT

Chapter 33. Using specific capacity to assign vulnerability to diffuse pollution in fractured aquifers in Scotland 495
*Mark Betson and Nick Robins*

Chapter 34. Environmental impacts of tunnels in fractured crystalline rocks of the Central Alps 507
*Simon Loew, Volker Luetzenkirchen, Ulrich Ofterdinger, Christian Zangerl, Erik Eberhardt and Keith Evans*

Chapter 35. Groundwater modelling approaches as planning tools for WISMUT's remediation activities at the Ronneburg uranium mining site 527
*Michael Paul, Manfred Gengnagel and Michael Eckart*

Chapter 36. Active groundwater monitoring and remediation during tunneling through fractured bedrock under urban areas 541
*Kim Rudolph-Lund, Frank Myrvoll, Elin Skurtveit and Bjarne Engene*

NUMERICAL MODELLING OF FRACTURED ENVIRONMENT

Chapter 37. A double continuum approach for determining contaminant transport in fractured porous media 553
*Matthias Beyer and Ulf Mohrlok*

Chapter 38. Coupled hydro-mechanical modelling of flow in fractured rock 567
*Philipp Blum, Rae Mackay and Michael S. Riley*

Chapter 39. Hydrogeologic modelling with regard to site selection for an underground repository in a granite formation in Krasnojarsk, Russia 575
*Christine Fahrenholz, Wernt Brewitz, Eckhard Fein and Matthias Schöniger*

Chapter 40. Development and qualification of a smeared fracture modelling approach for transfers in fractured media 587
*André Fourno, Christophe Grenier, Frederick Delay and Hakim Benabderrahmane*

Chapter 41. Sensitivity of fracture skin properties on solute transport and back diffusion in fractured media 605
*Terence T. Garner, Thandar Phyu, Neville I. Robinson and John M. Sharp, Jr.*

Chapter 42. Averaging hydraulic conductivity in heterogeneous fractures and layered aquifers 617
*Sassan Mouri and Todd Halihan*

Chapter 43. Time-resolved 3D characterisation of flow and dissolution patterns in a single rough-walled fracture 629
*Catherine Noiriel, Philippe Gouze and Benoît Madé*

Subject index 643

Author index 647

Series IAH-Selected papers 649

# Preface

Crystalline (igneous and metamorphic) and consolidated sedimentary rocks – so called hard or fractured rocks – are found in many regions of the world. They occur mainly in large areas – shields, massifs, and in cores of major mountain ranges. Their outcrops cover more than 20 per cent (i.e., approximately 30 million square kilometres) of the present land surface. In addition, these mostly old rocks form the basement of younger sedimentary rocks that are often concentrated into large basins. Thus, hard rocks represent at depths a continuous environment enabling extended, deep regional or even global groundwater flow.

During past decades adequate attention had not been paid to groundwater in this specific hydrogeologic environment. The exception is in some arid and semi-arid regions where, under typical non-availability of surface water resources, groundwater represents the major water resource. In temperate climatic zones, groundwater users had paid attention mostly to sedimentary basins that can host aquifers of high yield. These are economically and technically more profitable than scattered, often small-yield wells common in hard rocks.

In the last decade of the 20th century, however, there has been increasing interest in hardrock hydrogeology because of many theoretical and applied issues in both tropical and temperate climatic zones. These include:

- Natural groundwater resources of hardrock terrains, mainly those in mountainous regions, have been shown to be very important in maintaining flow of surface water courses in adjacent piedmont zones during dry periods. They may also provide significant recharge to adjoining sedimentary systems. Therefore, understanding these resources is indispensable for sustainable integrated water management.
- As water demands increase in many regions, adequately sited water wells or other water intake systems in hardrock areas typically can meet requirements on water supply for small communities, industry, and irrigation and for domestic water consumption. In some areas, groundwater abstraction possibilities are sufficiently high to supply even small cities. Siting of wells in open fracture systems or thick permeable overburden and the evaluation of permeability with depth to assess well yields are some of the important issues of applied hardrock hydrogeology. Social and economic considerations of groundwater development help to decide and justify whether development of groundwater in hardrock areas is preferable to other water-supply options.
- Knowledge of groundwater flow and transport in fractured rocks is vital in addressing groundwater pollution and environmental protection. Impacts of industrialisation and urbanisation, landfills, deep hazardous waste repositories, and agricultural chemicals must be studied and monitored in hardrock environments. Knowledge of the complex groundwater flow and contaminant transport in weathered and fractured zones of hard rocks is decisive for siting both surface and deep waste repositories and the assessment of future environmental impacts of potential contamination sources.
- Clear hydrogeologic understanding and quantitative hydrogeologic assessments are important for many geotechnical and engineering-geological activities, such as construction of tunnels, building foundations, and utility systems as well as in mining. Recent studies of deep repository sites for radioactive, toxic and other hazardous

wastes, many involving crystalline rocks, have extended our hydrogeologic knowledge of these environments to depths of hundreds or even thousands of metres. These data present an important and useful concepts to compare with results provided by other hydrogeologic methodologies and techniques.

- Results of recently deep boreholes in crystalline rocks, mostly connected with geothermal studies, have re-opened the issue of deep-seated groundwater flow and brine occurrences and discussions on the origins of mineral and thermal waters often associated with hard rocks.
- Increasing available data has stimulated efforts to regionalise and generalise results from different hydrogeologic environments. Knowledge of hierarchy of inhomogeneity elements and of a scale effect influencing spatial distribution of hydraulic properties might enable us to simplify real natural conditions when defining conceptual and numerical models of groundwater flow and solute transport.
- Data on hydraulic properties, groundwater availability, and water quality, obtained by different methodological approaches in different regions of the Earth, offer possibilities for correlative hydrogeologic studies so that conclusions can be drawn to understand hydrogeologic properties of fractured rocks both in local and regional scales.

Many international meetings have reflected the increasing attention paid to groundwater in hard rocks. The 24th Congress of the International Association of Hydrogeologists (IAH) held in 1993 in Oslo, focused directly on hardrock hydrogeology. This has been followed by several other professional meetings covering similar topics. Recent IAH Congresses in Cape Town, South Africa (2000), in Munich, Germany (2001), in Mar del Plata, Argentina (2002), in Zacatecas, México (2004) and many other international conferences have contributed significantly to hardrock hydrogeology.

Acknowledging the importance of groundwater in the hardrock environment, IAH established the Commission on Hardrock Hydrogeology to stimulate international co-operation and facilitate exchange of information between hydrogeologists and other specialists on groundwater issues in hard rocks (Commission web site: www.natur.cuni.cz/iah or www.iah.org/). The Commission assembles specialists from about 50 countries all over the world. In Europe, four regional working groups regularly convene workshops on different topics of hardrock hydrogeology starting from 1994. Thus, so far eleven workshops have been organised and all have published proceedings. Recently, a new South Asian regional working group was established.

In 2003 the IAH International Conference on “GROUNDWATER IN FRACTURED ROCKS” was held in Prague. The Conference provided an effective professional forum for presentations and discussions of many issues of fractured rock hydrogeology. The conference proceedings (Krásný et al., 2003) published 206 extended abstracts selected from over 286 submissions from 52 countries. Primarily out of these materials, the editors of this volume requested 43 papers, taking into account their goals, originality, relevance, and technical quality. The selected papers cover a wide field of important issues of modern hydrogeology of fractured environments. These include sustainable groundwater development, protection and management, evolving methodological approaches, new concepts of hydrogeologic properties both on local and regional scales and both quantitative and qualitative aspects of groundwater flow. We also desired to consider different hardrock regions on all the continents. There could be discussion on whether or not all the published papers fulfil these criteria, but our intention was to select representative contributions on the issues presented at the 2003 Prague conference. Three years have passed since the conference, and the authors were asked to update and/or extend their original findings. Some of these revisions were very extensive. As in the conference, the selected papers are subdivided into 6 sections as follows:

1. Hydrogeologic environment of fractured rocks
2. Conceptual models, groundwater flow and resources in fractured rocks
3. Groundwater quality in fractured rocks
4. Investigation and interpretation methods in fractured environment
5. Anthropogenic impacts on fractured environment
6. Numerical modelling of fractured environment.

We would like to thank to the reviewers that supported us in enhancing the submitted manuscripts. These include G. Barrocu, A. Bath, A. Chambel, J. Chilton, J. Conrad, E. Custodio, A.S. Engel, T.T. Garner, A. Grmela, K. Howard, Z. Hrkal, P. Kralj, R. Marrett, H. Marszalek, A. Mayo, A. Moench, H.S. Nance, P. Neill, L. Ribeiro, W.R. Robertson, P. Rouhiainen, T.K. Rubbert, K. Rudolph-Lund, K.-P. Seiler, R. Senger, C. Simmons, J. Slezák, D.T. Slottke, E. Steinhauer, G. Stournaras, U. Tröger, F. Villarroya, A. Voronov, J. Vrba, D. Watkins, and H. Wu, as well as many reviewers who chose to remain anonymous.

We think that the volume is the representative monograph discussing key issues, methodologies, and techniques in the field of hydrogeology of fractured (hard) rocks as well as summarising the results achieved in recent years. It is our hope that this will stimulate new ideas and considerations and lead to advances in the hydrogeology of fractured hard rocks. It should be a valuable reference for studies in fractured rock hydrogeology worldwide.

Prague-Austin, August 2006

Jiří Krásný and Jack Sharp
Editors of the volume

# About the editors

**Jiří Krásný** has worked most of his professional career with the Czech Geological Survey and from 1991 with the Charles University Prague. He was at long-term hydrogeological missions in Iraq and Nicaragua. His main interests are regionalisation of hydrogeological data, hydrogeological mapping, mineral water investigations, and studies in different hydrogeological environments. He is the chairman of the IAH Commission on Hardrock Hydrogeology and the Scientific Programme Member of the IAH Council.

**John M. (Jack) Sharp, Jr.** is the Carlton Professor of Geology at The University of Texas. He and his students research a variety of hydrogeological issues, including flow in fractured rocks, free convection, karstic hydrogeology, decision support systems, urban hydrogeology, and application of hydrogeology to geological problems. He is the Treasurer of the IAH and the President of the Geological Society of America.

# Hydrogeology of fractured rocks from particular fractures to regional approaches: State-of-the-art and future challenges

Jiří Krásný[1] and John M. Sharp, Jr.[2]

[1] *Faculty of Science, Charles University Prague, Czech Republic*

[2] *Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, U.S.A*

ABSTRACT: Groundwater flow and transport in fractured rocks are important for development of groundwater, petroleum, and geothermal fluids and also for understanding the movement of anthropogenic and natural solutes in geological settings. Relative permeabilities and storage properties differentiate fractured media into purely fractured media, fractured formations, double-porosity media, and heterogeneous media. *A priori* understanding of flow in these systems requires knowledge of geological controls on fracture orientations, connectivities, apertures, roughnesses, spacings/densities and skin effects. More geological input, geophysical techniques and the use of proxy data are needed to address challenges in fractured rock hydrogeology. We require greater insights into geological controls of flow and transport in fractured porous media; better predictions of solute transport and the influence of fracture flow on other fundamental geological problems; and how or if we can scale these properties. This compendium addresses these issues, presents new techniques, and evaluates groundwater in fractured rocks in a variety of hydrogeological settings.

## 1 INTRODUCTION

Fractured rocks present complex, heterogeneous, and anisotropic hydrogeological environments with irregular distribution of groundwater flow pathways. Fractured rocks and hard rocks are often used synonymously even though there is no general agreement among hydrogeologists on the precise definition of hard rock. It is commonly understood by geologists that hard rocks are crystalline (i.e., igneous and metamorphic rocks), and some hydrogeologists (e.g., Larsson et al., 1987) define "hard rocks" as igneous and metamorphic, non-volcanic, and non-carbonate rocks. However, these definitions are restrictive and, in many hydrogeological studies, "hard rock" is used in a wider, but not precisely defined sense. This is because other rock types, such as well-cemented sedimentary rocks often occurring with crystalline rocks in shields and massifs have hydrogeological properties similar to crystalline rocks. In these terrains, it is often impossible to define exact boundaries between metamorphic ("crystalline") and sedimentary rocks where metamorphic rocks grade into slightly metamorphosed sedimentary rocks. Similar situations occur where nonindurated deposits lose their primary (intergranular) porosity and transition into intensively cemented sedimentary rocks. Consequently, because of lithification and complex geologic processes, such as faulting and folding, intergranular primary porosity of clastic deposits can be altered to an intergranular-fracture (double) or to fracture-dominated porosity: Well-cemented claystones, shales, carbonates, and sandstones, occurring both in basins and in folded mountainous zones, can display hydrogeological properties comparable to crystalline rocks.

Accordingly, we suggest the acceptance of the definition of "hard rocks" proposed by Gustafsson (1993): *"Hard rocks include all rocks without sufficient primary porosity and conductivity for feasible groundwater extraction."* This implicitly highlights the most important hydrogeological property of hard rocks – fractures that are common to all hard rocks irrespective of their great variety of mineralogy, petrology, and stratigraphy. Hard rocks include magmatic rocks from granites to basic rocks, metamorphic rocks, and many sedimentary rocks, including fractured shales, graywackes, sandstones, conglomerates, and some carbonate rocks. Carbonate rocks, especially if karstified, and neovolcanic rocks (e.g., unwelded tuffs) may differ hydrogeologically from hard rocks, but there occur many common features and the methodologies used in carbonate and volcanic rocks can often be applied in hardrock environments.

Hard rocks occur in all the continents. They often extend in geologically continuous areas – shields, massifs, and in cores of many mountain ranges. The largest areas belong to Canadian, Guyana, and Brazilian shields in the Americas and to extended areas in Africa, Asia and Australia. Some of these areas belong, at least partly, to arid or semi-arid zones with acute scarcity of water resources. In Europe, hard rocks occur in the Baltic Shield and in numerous smaller areas. Hardrock outcrops cover more than 20 per cent (i.e., approximately 30 million square kilometres) of the land surface. The total extension and volume of all fractured rocks (partly of double porosity), however, is much larger as old crystalline rocks commonly form the basement beneath sedimentary rocks including those in large sedimentary basins.

Historically, hydrogeologists underestimated the occurrence and importance of preferential pathways for groundwater flow, represented by fractures and other heterogeneities. Simplified solutions were based on assumptions of homogeneity and isotropy. However, the importance of fractures and fracture networks on flow and solute transport is now recognised and has led in the last decades of the 20th century to a greater focus on the hydrogeology of fractured systems.

This increasing interest in the hydrogeology of fractured rocks, especially in hard rocks, has led to a number of review papers and monographs. These are too many to mention all of them but the first may have been Davis and DeWiest (1966, Ch. 9) and IAHS/UNESCO (1967). These were followed by two UNESCO monographs (Larsson 1987; Lloyd 1999). Marinov (1974, 1978), Geothermal Resources Council (1982), LaPointe and Hudson (1985), Black et al. (1986), Evans and Nicholson (1987), Barton and Hsieh (1989), Ehlen (1990), Chernyshev and Dearman (1991), Wright and Burgess (1992), National Research Council (1996), Pointet (1997), Krásný (1999), Singhal and Gupta (1999), Faybishenko et al. (2000), Robins and Misstear (2000), Stober and Bucher (2000), Olofsson et al. (2001), Cook (2003), and Neuman (2005) are some of the more recent compilations.

The 24th IAH Congress focused on the "Hydrogeology of Hard Rocks" (Banks and Banks, 1993); it initiated a world-wide scientific co-operation and led to eleven workshops convened by four European Regional Working Groups of the IAH Commission on Hardrock Hydrogeology (Krásný and Mls 1996; Bochenska and Stasko, 1997; Yélamos and Villarroya, 1997; Annau et al., 1998; Knutsson, 1998; Rohr-Torp and Roberts, 2002; Stournaras, 2003; Rönkä et al., 2005; Stournaras et al., 2005). Ten years after the 24th IAH Congress, the IAH Conference on "Groundwater in Fractured Rocks" in Prague (Krásný et al., 2003) demonstrated the variety of excellent research on fractured rock hydrogeology and led to this compilation of research papers that document the state of the art and recognition of future challenges in this field and that expand upon the concepts of hardrock hydrogeology to fractured rocks in general.

## 2 TOPICS

This compendium is grouped of papers that reflect the current status of the hydrogeological knowledge of hard or fractured rocks:

- Hydrogeological environment of fractured rocks
- Conceptual models, groundwater flow and resources
- Groundwater quality
- Investigative and interpretative methods
- Anthropogenic impacts, and
- Numerical modelling

In the first section, the *hydrogeological environment of fractured rocks,* the hydrogeology of different hard rock regions is summarized. Barrocu and Watkins discuss granitic rocks in Sardinia, Italy, and Cornwall, UK, respectively. Faillace presents a historical view and generalization of his many years developing groundwater supplies in Africa; Darko and Krásný evaluate hydrogeological properties and groundwater potential in Ghana; Bocanegra and Da Silva consider fractured rocks aquifers of South America and Brito Neves and Albuquerque discuss the relationships of tectonics and groundwater in northeast Brazil. European systems discussed include the Alentejo region of Portugal (Chambel et al.), the Aegean or Hellenic Arc encompassing Greece and the Aegean islands (Stournaras et al.), and the Koralm massif of Austria (Winkler et al.) where fracture network modelling is used in conjunction with discrete fracture models. Finally, Emilio Custodio characterizes groundwater in volcanic rocks in which flow is also fracture dominated.

In the section on *conceptual models of groundwater flow and water resources,* Issar and Kotze use environmental isotopes to establish a conceptual model for flow in fractured metamorphosed sedimentary rocks. Allen and Milenic evaluate the role of fractures in low-permeability sandstone confining units. Conrad and Adams use GIS to assess groundwater recharge in fractured rocks in South Africa in areas with a paucity of data, while Misstear and Fitzsimons estimate recharge in Irish fractured aquifers using soil moisture budgets and stream gauging. Marechal et al. characterize hard rock aquifers in India at the catchment scale. Finally, Brighenti and Macini conceptualize non-Darcy two-phase flow in fractures.

*Water quality* is a key water-resources issue in fractured media because of the speed and directions of solute transport. Bath interprets the evolution and stability of groundwaters in fractured rocks in England and Sweden as do Frengstad and Banks in Norway. Gaut et al. discuss factors controlling the microbial quality of such groundwaters. Two Portuguese studies discuss quality issues of mineral waters. Lourenço and Ribeiro evaluate trends in mineral water quality and Marques et al. review the evolution of $CO_2$-rich waters in granitic rocks. Morgan and Jankowski investigate the origin of salinity in fractured rocks that is affecting agricultural activities. Palcsu et al. use isotopic analyses to infer flow systems in a granite massif to evaluate its potential as a waste repository. Finally, Troeger reports on structural controls on several Brazilian thermal springs and their water chemistry.

*Methods of investigating* in fractured rock systems are also evolving. Bunker discusses the use of oriented core drilling of environmental site investigations. Moeck et al. relate fracture networks and aquifer characteristics as related to the current stress field. Carneiro uses Monte Carlo methods of modelling to delineate groundwater protection zones for fractured-rock aquifers. Brauchler et al. use an aquifer analogue approach to characterize fractured porous media with a travel-time based tomographic inversion. Le Borgne et al. compare discrete and continuous descriptions for characterizing flow in fracture networks. Love et al. present a new method of borehole dilution with tracer tests to estimate flow horizontal and vertical rates in fractured metasediments in Australia. Of course, pumping tests are still the prime technique for gathering hydrogeological data. Lods and Gouze present a new method for pump test analyses in fractured rocks. Koskinen and Rouhiainen characterize groundwater flow in fractured crystalline rocks with borehole flow meters.

*Human effects* on fractured rock systems are becoming increasingly important. Water quality issues are discussed in a previous section, but physical effects are also important. Betson and Robins use unit specific capacity to assess vulnerability of fractured aquifers to pollution. Loew et al. review unique case histories of the effects of tunnels on groundwater flow in crystalline rocks of the Swiss Alps. Rudolph-Lund et al. examine monitoring and remediation activities along tunnels through urban areas of Norway and Paul et al. discuss model prediction of the flooding of an underground uranium mine in Germany.

The last section of this volume has 7 papers on various aspects of *modelling*. Beyer and Mohrlok use a double continuum approach for contaminant transport in fractured porous media. Because waste repositories are often planned in rocks of low primary permeability, fractures are a vital assessment item. 3 papers deal with these sites. Blum et al. use fracture data from the Sellafield (UK) site to define 3 important hydrogeological issues for modelling flow in fractured rock. Fourno et al. use a smeared fracture approach to predict post closure conditions, and Fahrenholz et al. discuss modelling and performance assessment at a site in Siberia with few hydrogeological data. Mouri and Halihan compare averaging of hydraulic conductivities for heterogeneous layered and fractured aquifers. Garner et al. model the transport of solutes in fractures in granites with fracture skins using an analytical model. Finally, last but not least, Noriel et al. use X-ray microtomography to measure fracture properties in a rough fracture undergoing dissolution.

Even the wide range of topics and geographic areas included in this compendium do not exhaust the range of hydrogeological studies in fractured rock. For instance, we do not cover geophysical methods (surficial or borehole) or rock mechanics to any great extent. There is also no discussion of the role of flow in fractures in permafrost regions and its role in glacial processes. However, we think that this collection of articles is generally indicative of the wide and growing field of the hydrogeology of fractured and "hard" rocks. Many of the papers suggest future applied and theoretical research needs in this field of science.

## 3 GENERAL HYDROGEOLOGICAL FEATURES AND VERTICAL ZONING OF HARD ROCKS

Hardrock environment typically consists of three vertical zones, upper weathered, middle fractured and deep massive (e.g., Biscaldi 1968, Larsson et al. 1987, Chilton and Foster 1993, Rebouças 1993, Krásný 1996b, Faillace, this volume, and Maréchal et al., this volume). Hydrogeological knowledge and understanding of this intricate environment, based on sound interdisciplinary geological, hydrogeological, hydrochemical, and geophysical studies are indispensable to provide adequate basis for theoretical considerations, development of methodological and technical tools, implementation of conceptual and numerical models, and many practical applications.

*Vertical sequence of the three zones* is defined from the land surface downwards as follows:

– *Upper or weathered zone* formed by regolith, colluvium, talus, etc. often juxtaposed with alluvial, fluvial, glacial, and lacustrine (mostly Quaternary) deposits. Intergranular (interstitial) porosity prevails. The usual thickness is several metres but under special conditions, mainly along deeply weathered fractures or in residual tropical soils this zone may be much deeper.
– *Middle or fractured zone* usually represented by fractured bedrock to depths of some tens to hundreds of metres. Fracture aperture depends mostly on exogeneous geologic processes so permeability in this zone generally decreases with depth.
– *Deep or massive zone* in massive bedrock where fractures, faults, or fracture-fault zones are relatively scarce and fracture apertures are commonly less than in the middle zone. Deep fractures may act as isolated, more or less individual hydraulic bodies. In a regional scale, however, these inhomogeneities may form interconnected networks enabling extended and deep, regional to continental groundwater flow reaching depths of hundreds or even thousands of metres. Under suitable structural conditions, mineral and thermal waters ascend along deep faults.

This vertical sequence is common but, under specific conditions, the upper-weathered zone can be missing (e.g., in recently glaciated regions, the weathered zone and, in some cases, portions of the middle/fractured zone have been eroded).

Intergranular porosity is important in the upper zone; fracture porosity dominates in the deeper zones. However, varying petrographic and mechanical properties of hard rocks can create in different hydrogeological characteristics. Permeability variations may reflect lithologically distinct intercalations and form stratiform aquifers that are more characteristic of sedimentary basins. Folded, fractured, and sometimes karstified layers of crystalline limestones (and marbles) and intercalations of other rocks (e.g., quartzites) may be more transmissive than the surrounding hard rocks but form part of the same aquifer systems.

The upper and middle zones can form a regionally extended *"near-surface aquifer"* that is generally conformable to the land surface with a thickness of tens to more than 100 metres with permeability generally decreasing with depth. This aquifer usually offers the best groundwater abstraction possibilities. However, the thickness and character of this complex and heterogeneous aquifer changes spatially in relation to tectonic deformation (faulting and fracturing), lithologic facies, and weathering.

## 4 GEOMETRY AND PROPERTIES OF PARTICULAR FRACTURES

Fractures are the most important hydrogeological element in almost any setting and especially in hardrock environments. They control the hydraulic characteristics and solute transport. Without fractures, except for the upper-weathered zone, there is no significant groundwater flow in hard rocks. Therefore, understanding of the fluid-transmission properties in fractures is important for production of critical natural resources and environmental protection as well as understanding of natural processes, such as formation of mineral and petroleum deposits, sediment diagenesis, the cooling of plutons, mass wasting, and the movement of nutrients and chemicals in the soil zone. Finally, fluid flow and solute transport in fractures is important in many geotechnical and mining issues.

## 4.1 *Fractured media*

Fractured media can be classified into four gradational categories (Figure 1) depending upon the relative hydraulic properties of the fractures and the blocks or matrix between the fractures. In purely fractured media, the hydraulic conductivity and fluid storage are completely in the fractures. The rock matrix has virtually no porosity or permeability. Examples include unweathered plutonic and metamorphic rocks, such as granites, gabbros, schists, gneisses, and slates. Some volcanic rocks are also purely fractured. With respect to their transport properties, even purely fractured formations may have "diffusional" porosity (Norton and Knapp 1977; Neretnieks, 1980) created by microfractures and defects along

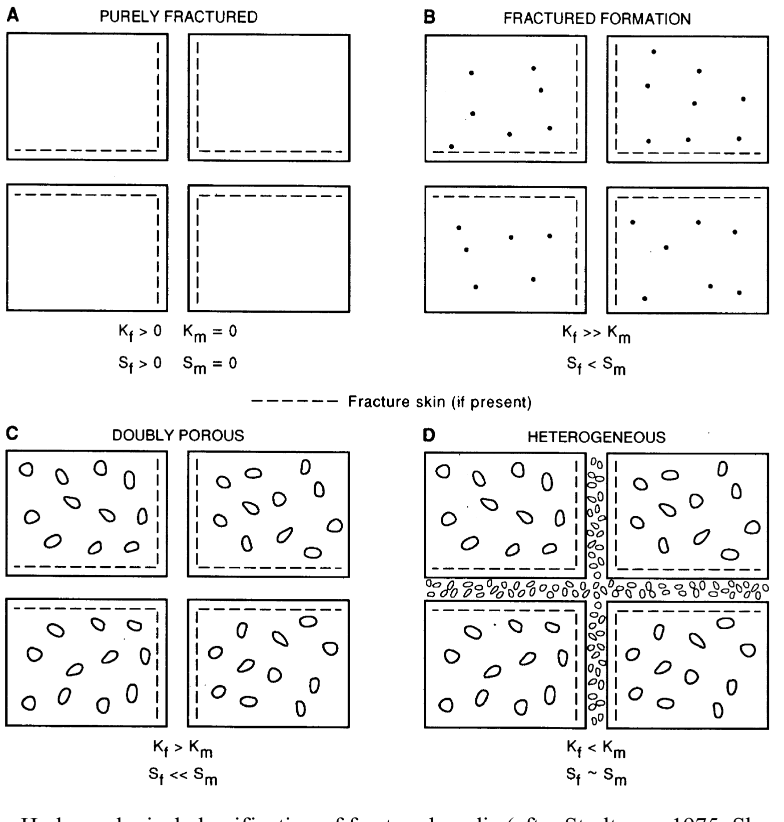


Figure 1. Hydrogeological classification of fractured media (after Streltsova, 1975; Sharp, 1993). $K_f$ and $K_m$ and $S_f$ and $S_m$ are the hydraulic conductivities and storativities of the fractures and matrix, respectively. A: purely fractured media. B: fractured formation. C: double porosity medium. D: heterogeneous formation. Especially, in cases A, B, and C, the fracture coating or "skin" may be in solute transport significant.

crystal boundaries that contribute significantly to transport on long time scales. In fractured formations, the flow is controlled by the fractures, but the fluid is stored primarily within the matrix. A fractured formation represents a common situation of great interest to the petroleum industry. Examples of fractured formations include "tight" gas sands, shales, and extrusive volcanic rocks, such as tuffs. In double porosity media, the relative permeability of the matrix can approach that of the fracture. Many aquifers, including sandstones, some basalts, and some carbonates can be considered double-porosity media. As in the fractured formation, most of the fluid is stored in the matrix. Double-porosity media constitute a particularly difficult challenge in modelling because flow in both the matrix and the fractures and interaction between the matrix and the fractures must be quantified. Finally, in some fractured rocks, the fractures are filled with material that is different in permeability than the matrix. This is termed a heterogeneous formation which may be modelled with standard equivalent porous medium techniques.

Also shown in Figure 1 is the fracture "skin" – a fracture surface or thin zone immediately beneath the surface which is altered by mineral deposition or coating with detrital or "infiltered" clays (Moench 1984, Fu et al. 1994). Fracture skins may possess significantly different hydraulic properties from the unaltered matrix (Fuller and Sharp 1992; Robinson et al., 1998; Phyu, 2002; Garner and Sharp, 2004; Garner et al., this volume). Skin permeabilities, porosities, sorptivities, and diffusion coefficients can be considerably different from the unaltered fracture surface or matrix and can be important in solute transport.

## 4.2 *Fracture characterization*

We conclude that hydrogeological characterization of fracture systems is vital to the understanding of flow and associated processes. Some characterization procedures are well documented, but for many fracture parameters, characterization remains uncertain because requires data on the orientation of the fractures, their frequency (fracture density), size, flow characteristics (aperture, fracture roughness, and channeling characteristics), and interconnectivity. We also need to evaluate how these properties vary with geological heterogeneity, scale, changing *in situ* stresses, and, in the case of hazardous waste disposal, how these properties evolve over centuries or millennia. This is so difficult that some (e.g., Voss, 2003) have suggested that hydrogeological characterization of fracture systems *a priori* might be impossible.

### 4.2.1 *Orientation*

In most cases, the assumption is made that a fracture is planar or curviplanar so that fracture orientation can be defined by strike and dip. Orientations can be illustrated by rose diagrams, stereonets, or directly on geological maps. A wealth of fracture data can be inferred from geological maps and aerial photographs (e.g., Mayer and Sharp, 1998). Uliana (2001) and Sharp et al. (2000) used length weighted rose diagrams to predict the directions and relative magnitude of permeability as a function of azimuth.

### 4.2.2 *Fracture density*

Fracture density quantifies the number fractures per unit length (along a scan line), in a unit area, or in a unit volume of rock. The number of fractures which cross a scan line or traverse is called the fracture spacing. The correlation of fracture spacing with fracture density has been discussed by LaPointe and Hudson (1985), among others. Recent studies by Marrett (1996), Marrett et al. (1999), and Ortega et al. (2006) extrapolate from thin sections or outcrop measurements to field scale.

#### 4.2.3 *Aperture*

Aperture is the distance between the fracture walls. The discharge and hydraulic conductivity of a fracture with smooth parallel walls are proportional, respectively, to the cube and square of aperture. Apertures may follow a power law scaling, but aperture variability within a fracture (Mouri, 2005) may overwhelm the scaling attempts. Natural fractures do not have smooth, parallel walls; the irregularities on the fracture surface are termed asperities. Asperities create roughness to reduce fluid velocity and create channels of preferential flow. This process is well known, but it is not yet commonly considered in studies of flow and transport.

#### 4.2.4 *Channeling*

Channeling in a fracture is where fluid flow takes a preferred path or channel so that flow velocities are highly irregular and the flow paths are difficult to predict. Channels may be anastomose or meandering, and channeled flow can occur without the saturation of the entire fracture. Channels are controlled by fracture geometry, roughness, the source and distribution of recharge to the fractures, and the hydraulic gradient. Tsang and Tsang (1987) suggest that, at depths of greater than 500–1000 metres, *in situ* effective stress causes all fracture flow to be channeled. The transport of solutes is also affected by channeling because effective porosity is reduced so that average linear velocity estimates for a given hydraulic gradient is greater (Mouri, 2005). Where diffusion into a porous matrix is an important attenuation mechanism for contaminants, channeling reduces the attenuation because the area for diffusive flux is reduced.

#### 4.2.5 *Fracture connectivity*

How fractures are interconnected is critical importance in fractured media. Longer fractures have a better of chance of intersecting another fracture. Barton et al. (1987) defined a ternary diagram to plot abutting, crossing, and blind fracture terminations. Another ternary classification was proposed by Laubach (1992) who noted that fracture terminations may splay and may interfinger with similar "diffuse" fracture ends; he grouped terminations into blind, diffuse, and crossing (which includes abutting). Abutting and crossing fractures provide connectivity; diffuse terminations provide limited connectivity; and blind fractures provide neither. Sets of blind fractures may, however, greatly influence the permeability tensor. Examples of sets of subparallel blind fractures commonly include neotectonic fractures (Hancock and Engelder 1989) and fracture sets in lenticular sand bodies (Lorenz and Finley 1989) that were subparallel to regional structure.

#### 4.2.6 *Fracture skins*

The movement of groundwater along fractures commonly alters the fracture surface. Fracture and vein fillings and altered fracture surfaces are observed in many rocks (Robinson et al., 1998); fracture skins are ubiquitous; they show that that fracture permeability and transport characteristics can change over time (Garner et al., this volume).

### 4.3 *Hydrogeological properties of fractures*

Key fractures parameters (including the hydraulic conductivity and the porosity both of the fractures and the fracture skins) are critical for estimating aquifer yields and transport of mass and energy. Methods for the estimation of fracture or effective porosity in the field are improving, but may not yet be adequate for the task of characterization because of variation in fractures properties. Halihan et al. (2005) discuss the effects on fracture connectivity on these types of analyses.

#### 4.3.1 *Hydraulic conductivity*

Conceptual models for hydraulic conductivity of fractured media follow well understood generalizations, but the quantitative estimation of the hydraulic conductivity tensor in such systems is not simple (Neuman, 2005). In hard crystalline rocks, valleys typically occur in areas of more intensive fracturing and, hence, higher permeability and fracture sets can impart a strong anisotropy. Greater numbers of fractures and more interconnected fractures will tend to reduce permeability anisotropy. Longer fractures, greater fracture densities, and greater apertures increase hydraulic conductivity, which also varies spatially (and temporally) because of geological constraints. The prediction of fracture domains, wherein fracture systems maintain some uniformity of hydrogeological properties and their hydraulic characteristics needs to be considered in simulation models, especially with regards to issues of upscaling.

#### 4.3.2 *Porosity*

Porosity can be subdivided in several ways. Fracture versus matrix porosity is one distinction, but this is simplistic even for double-porosity systems. In a classic study of cooling plutons, Norton and Knapp (1977) differentiated "flow (i.e., effective) porosity" (the porosity which controls fluid flow, mostly in fractures) from: 1) diffusion porosity that contributes to fluid and mass flux but fluid flow) and 2) residual porosity (isolated pores). This classification recognizes the nature of the fractured formation and extends it under geological scales to purely fractured formations. In a fractured medium, the effective porosity may assume tensor characteristics (Khaleel, 1992; Neuman, 2005). Finally, analyses may need to consider fracture porosities corresponding to different size fractures and fracture sets, as well as matrix and fracture porosities.

### 4.4 *Modelling of fracture systems*

Approaches for modelling of flow and transport in fractured media include: analytical solutions for flow between parallel plates (slot flow); equivalent porous medium models; discrete fracture models; theoretical or synthetic fracture models; double-porosity models; and an equivalent parallel plate method. Models hybridizing these various approaches also exist (Neuman, 2005).

#### 4.4.1 *Parallel plate models*

The discharge in fracture of a planar, uniform aperture per unit width (or height for vertical fractures) with no asperities is given by the cubic law (Lamb, 1932), expressed as:

$$Q = -\frac{b^3 \rho_w g}{12\mu} \nabla h \tag{1}$$

Where Q is discharge, b is aperture, $\rho_w$ is fluid density, g is gravitational acceleration, $\mu$ is dynamic viscosity, and $\nabla h$ is the hydraulic gradient in the plane of the fracture. The parallel plate can be applied to fractured media by integrating fracture densities and apertures with parallel fracture sets into the hydraulic conductivity tensor. This simple approximation can be useful, but it is strictly valid only for laminar flow. However, it is used in most of the approaches discussed below. Equation 1 must be modified for fractures with channeling and asperities by adding the appropriate empirical coefficients. For instance, Lomize's (1951) equation for hydraulic conductivity (K) is:

$$K = \frac{1}{f}\frac{b^2}{12\rho_w g} \tag{2}$$

where f is a friction or roughness factor, which is either determined by field tests or an empirical formula based upon roughness data. When dealing with upscaling issues, how does one upscale Equation 2?

#### 4.4.2 *Equivalent porous media*

The equivalent porous medium approach is commonly used in estimating flow and transport. It assumes a continuum and not ignores discrete fractures. Equivalent porous media models utilize estimates of hydraulic conductivity, storativity, and porosity that assume that a representative elemental volume (REV) can be defined at the appropriate scale. These models can yield adequate results when estimating discharge rates for a limited range of conditions, but they fail in calculating mass transport and, generally, in cases where the fractures are not efficiently interconnected. In this case, an REV may not exist (Shapiro and Bear, 1985). Scaling equivalent porous medium models is uncertain, but is attractive because it avoids data needed to characterize the actual hydraulic properties of the fractured media.

#### 4.4.3 *Discrete fracture models*

These models input as much detail as possible, based upon field data, about the geometry and properties of individual fractures, sets, and zones into 3D networks (Sahimi, 1995; Zhang et al. 2002; Neuman, 2005). Each transmissive fracture is usually assigned a uniform aperture and hydraulic conductivity. Connectivities must be assumed among other characteristics. Mapping of fractures for hydrogeological studies is rarely sufficient because mappable exposures and techniques are limited. Although quantitative field data on fracture spacings and hydraulic properties are generally lacking, semi-quantitative or qualitative estimates can be made of expected hydraulic properties, including upscaling based upon fractal or power-law relationships (e.g., Marrett et al., 1999). The only means to date for the characterizing of discrete fractures systems are by cross hole testing or tracer tests (e.g., Illman, 2003). These are expensive and time consuming, and extrapolation to adjacent areas or different scales is also difficult.

#### 4.4.4 *Theoretical statistical models*

Because of the limitations and disadvantages of the above approaches, theoretical models (e.g., Long et al. 1985; Blum et al., 1997; Hofrichter and Winkler, 2006) for flow in purely fractured and fractured formations have been developed to evaluate flow in fractures or fracture sets with synthetic distributions of apertures, orientations, spacings, and dimensions, centered on distributions of fracture nucleation points. However, application of these models to natural systems is limited because sufficient real data for input are generally lacking.

On the other hand, theoretical models increase our basic understanding of processes in fractured systems and we can use these models in an inverse-fashion to predict sets of more realistic conceptualizations.

### 4.4.5 *Double-porosity models*

Double-porosity systems include many aquifers and petroleum reservoirs, and require calculation of the flow and transport in both fractures and matrix, as well as the interaction between them (e.g., Moench, 1984; Beyer and Mohrlok, this volume; Garner et al., this volume). This interaction is commonly treated as empirical transfer used to make model outputs reasonable, but the actual conceptualization of how this flow takes place is difficult, and experimental verification of this process uncertain (Moench, 1984). Both "pseudo-steady" flow between the matrix and the fractures and fully transient conditions, as well as fracture-skin effects, should be considered.

### 4.4.6 *Equivalent parallel plate models*

Equivalent parallel plate or integrated fracture density of apertures, IFDA (Singhal and Gupta, 1999), applies geological data or inferences on fracture systems to models of flow and transport, particularly on a regional basis or over time spans where tracer tests or cross-hole testing are impractical. The precision of these models will depend on data availability, the hydrogeological conceptual model, and modeller insights. Aerial photography, remote sensing data, published and field geological maps, borehole and tunnel fracture studies, and data from tracer, cross hole, and geophysical tests, as well as other, standard hydrogeological analyses can provide inferences on fracture set properties which can then be input using the classical techniques of Snow (1968, 1969) into a variety of models. IFDA gives insight into the geological controls of fracture systems (e.g., Mayer and Sharp, 1998), although there are not always sharp distinctions between the above models. Again, scaling uncertainty and model evaluation are issues that need to be addressed.

## 5 UPSCALING, REV, HIERARCHY OF INHOMOGENEITY

Hydrogeological studies must often *scale data up* from laboratory tests and local site-studies to a regional scale. Rats (1967) first determined the relation between the magnitude of inhomogeneity elements of rocks and the extent of the study area. This was hydrogeologically interpreted by Rats and Chernyshev (1967) and, later, by Kiraly (1975) and Halihan et al. (2000) who focus on karstic terrains. Consequently, hydraulic parameters might differ considerably depending on methods of their determination. Conspicuous changes in permeability typically occur at a local scale. These variations are evidenced by different yields of near-by wells drilled in the same rocks that might reach several (usually up to three but sometimes even four) orders of magnitude (Figure 2a) because of variously permeable fractures. Distinct character and frequency of faults, fractures, joints and bedding planes of different orientation are observed at rock outcrops or inferred with borehole logging techniques. Identification of these inhomogeneities is important for local hydrogeological studies, particularly in analyzing preferential flow pathways and spreading of groundwater contamination or in designing remediation procedures.

By extending a tested area average permeability, based on either laboratory or aquifer tests, typically (Rovey, 1998; Schulze-Makuch and Cherkauer, 1998; Halihan et al., 2000)

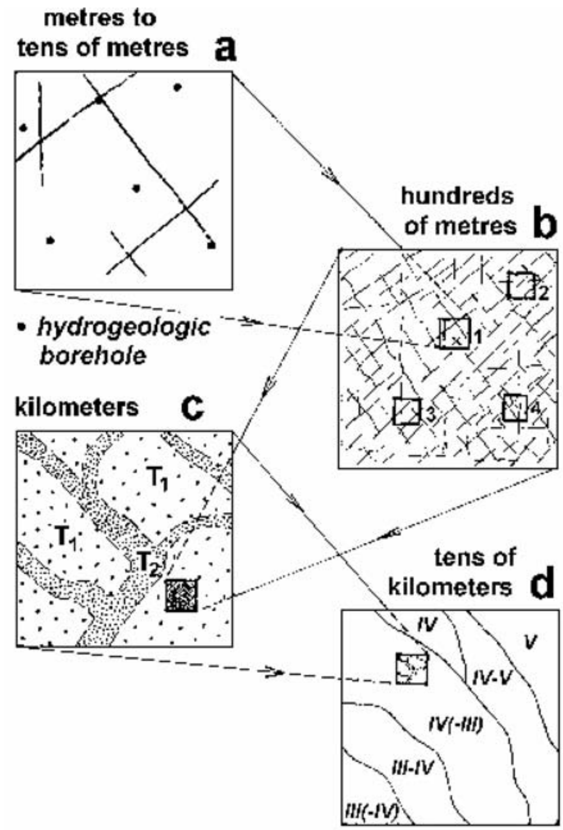


Figure 2. Relation of size of inhomogeneity elements to the extension of a study area (after Krásný 2000).
**a** – fractures and fracture zones in a local scale;
**b** – (sub-) regional more or less regular fissuring representing hydrogeological background; squares 1–4 represent different statistical samples characteristic of usually similar mean transmissivity magnitude and variation;
**c** – sub-regional inhomogeneities often following valleys with water courses: $T_1$ – lower prevailing transmissivity, $T_2$ – higher prevailing transmissivity;
**d** – regional changes in transmissivity caused by different neo-tectonic activity; roman numbers express the class of transmissivity magnitude after Krásný (1993a).

but not always (e.g., Robins, 1993) increases in spite of significant local variability. It has been suggested (Clauser 1991) that at some sufficiently large scale in crystalline rocks, the average permeability remains roughly constant, irrespective the position of the tested area within the whole environment (Figure 2b). If so, this represents a regional permeability/transmissivity background that corresponds to a *representative elemental volume* (REV), the smallest scale above which practically no change in mean values occurs. Then the average properties can be defined over scales larger than the REV. This is an important concept with consequences for groundwater protection and development as it suggests to what extent real, natural, or artificially influenced hydrogeological conditions can be schematized when implementing conceptual and numerical models. Whether or not this concept can be extended either to solute transport or to noncrystalline fractured rocks is unclear.

Occurrence of *larger inhomogeneities*, superposed upon a regional permeability background, however, may increase in permeability at greater than the REV scale. These are usually structural zones and/or belts of regional higher permeability along the river valleys. Important structural or tectonic features can form zones of higher permeability with transmissivities reaching 90–100 $m^2/d$ or more, an order of magnitude higher than regional transmissivity background. These are of importance for groundwater abstraction in hardrock environment. Various authors have noted differences in the permeability of rocks depending on distinct topographical or morphological position (LeGrand, 1954; Krásný, 1974; Henriksen, 1995). Belts along river valleys may display 2 to 4.5 times higher permeabilities than surrounding areas represented by slopes and summits (Figure 2c). The position of valleys or depressions in tectonically-affected areas may be cause of this finding, and the position of recharge or discharge zones is another important factor (Krásný, 1998).

Consequently, hardrock terrains cannot be considered regionally homogeneous but rather a complex system where belts of regionally high permeability occur, usually following the valleys and depressions, in comparison with "intra-valley" blocks of lower regionally prevailing permeability. This is analogous to double-porosity medium, but at a large scale. Similar differences in regional permeabilities between valleys and slopes have been documented in other environments (Krásný 1998). Regional trends in transmissivity in some crystalline areas are reported in Norway (Rohr-Torp, 1994) and the Czech Republic (Krásný, 1996c) that reflect distinct intensity of neotectonic activities caused in Norway by isostatic uplift after Quaternary glacial retreat and in the Bohemian Massif by tectonic stress due to Alpine-Carpathian folding (Figure 2d).

Fractured environments are *intricate hierarchic systems* consisting of inhomogeneities on local, sub-regional, and regional scales and hydraulic parameters differing with different scale. Such a hierarchic system of permeability is expected in most, if not all, fractured media. Practical conclusions should be drawn for conceptual model implementation, groundwater flow and solute transport modelling, safe yield assessment, well siting, and studies on groundwater vulnerability and protection.

*Fracture properties also change with time*. Permeability of fractures and of fault zones may decrease because of processes as hydrothermal alteration, mineral precipitation and mechanical clogging (e.g., Mazurek 2000). Soluble rocks as carbonates, gypsum and salt deposits are the exceptions to this general rule; their permeability typically increases with time and in karst can be very high. In fractured rocks, geologically young fractures are typically the most permeable. Differences in hydrogeological position (clogging in recharge zones and outwash of fine particles in discharge zones) can also change fracture permeability over time (Krásný 1998).

## 6 EXACT AND COMPARATIVE HYDRAULIC PARAMETERS AND CLASSIFICATION OF TRANSMISSIVITY DATA

Most modern hydrogeological projects are of *local or site-specific character*. These include studies of water supply, contaminant and remediation, and groundwater problems in environmental planning, civil engineering, and mining. However, *regional studies* are indispensable for administrators, decision-makers, and hydrogeologists because regional studies influence land-use planning and determine conditions for integrated groundwater/surface water management, sustainable groundwater use, and groundwater protection. Based on results of regional hydrogeological studies, reasonable strategic decisions in regional, state, or even continental scales can be made. Regional studies enable us to compare hydrogeological conditions in different areas and to draw generalized conclusions. Small-scale maps offer excellent possibilities to exchange findings at regional, national and international levels. Data regionalisation is important in hard/fracture rock terrains, but such studies are not plentiful.

Hydraulic parameters, such as hydraulic conductivity, transmissivity, storage, different types of porosity, etc., can be designated as exact parameters and are determined by laboratory and field tests, but few data, usually on hydraulic conductivity and transmissivity, are commonly available in quantities useful for analyzing regional distribution (Chambel et al., this volume). Sometimes only well yields are available. These data may not be precise enough for use in regional studies or statistical treatment (Fahrenholz et al., this volume).

Although the data may not be sufficient to estimate the exact hydraulic parameters, they might be sufficient to provide general models of regional permeability. Therefore, *comparative or regional parameters*, expressing permeability and transmissivity, were introduced by Jetel (1964) and Jetel and Krásný (1968). Assuming that permeabilities and transmissivities are log-normal distributions indexes of permeability Z and of transmissivity Y were defined. Using these parameters simplifies data analysis. The two logarithmic parameters completed the system of comparative or regional parameters expressing permeability and transmissivity (Table 1). The specific capacity index or unit specific capacity is discussed by Betson and Robins (this volume).

Although *permeability*, especially in hardrock terrains, is variable at even close distances, different averaged, estimated, or prevailing values of hydraulic parameters are used in hydrogeological studies. Hydraulic conductivity, originally derived to characterise granular porous media, is used to interpret results of aquifer tests in any setting. In fractured rock, this approach can be used, but should consider scale differences in pathways of groundwater flow and objectives of hydrogeological studies (Krásný 2002). In a typical well with a depth of several tens of metres in fractured rock, only few fractures might have significant permeability so the hydraulic conductivity represents an ideal non-existing mean value between highly permeable fractures and a lower, sometimes negligible, permeability matrix.

Table 1. The system of hydraulic parameters expressing permeability/hydraulic conductivity and transmissivity (modified from Jetel and Krásný 1968).

| Property of aquifer or hydrogeological environment | Exact hydraulic parameters | Comparative/regional parameters | |
|---|---|---|---|
| | | Non-logarithmic | Logarithmic |
| Transmissivity | Coefficient of transmissivity $T = kM$ | Specific capacity $q = Q/s$ | Index of transmissivity Y $Y = \log(10^6 q)$ |
| Permeability | Coefficient of hydraulic conductivity k | Specific capacity index* $q' = Q/sM$ | Index of permeability Z $Z = \log(10^6 q')$ |

*The term used by Walton and Neill (1963); Q = well yield; s = drawdown; and M = thickness of aquifer/length of open section of a well.

In contrast, *transmissivity* expresses the property of the entire thickness of an aquifer. Because the main objective of many hydrogeological studies is the characterization of water yields or prevention of inflows during underground construction, transmissivity is a useful parameter. Where sufficient data exist for statistical analysis, sample populations delimited by different rock types, hydrogeological units, areas, structural, geomorphologic and hydrogeological position of water wells etc. can be treated to determine the mean and standard deviation. Transmissivity data can be graphically represented in a probability paper by cumulative relative frequencies of transmissivity values (Figure 3). Thus, the comparative parameter expression of transmissivity, the index of transmissivity Y, can be used with advantage.

To classify rock transmissivity, Krásný (1993a) presents a *classification system of magnitude and variation*. The range of transmissivity values is separated into six classes representing the orders of magnitude from very high (*I* class – transmissivity more than 1,000 $m^2$/day) to imperceptible transmissivity (VI class – less than 0.1 $m^2$/day) that indicate potential groundwater yields in different environments.

Another important property of these data is their variation. This reflects permeability heterogeneity and, consequently, indicates the character of the hydrogeological setting.

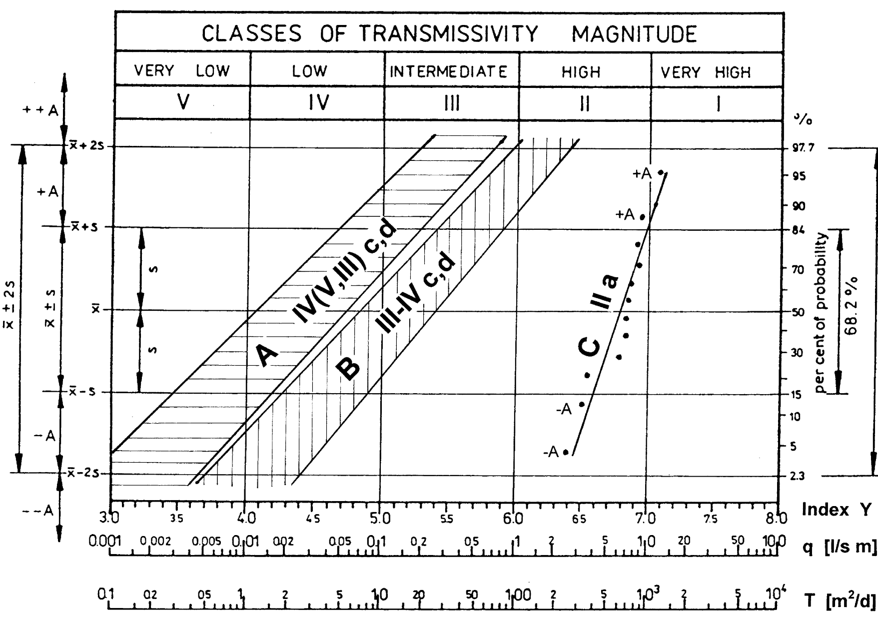


Figure 3. Prevailing transmissivity of hard rocks as fields of cumulative relative frequencies (after Krásný, 1993a, 1999). q = specific capacity in L/s m, T = coefficient of transmissivity in $m^2$/d, Index Y = index of transmissivity ($Y = \log 10^6 q$), $\bar{x}$ = arithmetic mean, s = standard deviation, $\bar{x} \pm s$ = interval of prevailing transmissivity (transmissivity background) including approximately 68% of transmissivity values of a statistical sample, ++ A, +A, −A, −−A = fields of positive and negative anomalies (+A, −A) and extreme anomalies (++ A, −−A), resp. outside the interval $\bar{x} \pm s$ of prevailing transmissivity. A – field comprising transmissivity values of the majority of hardrocks, B – field of transmissivity values in crystalline limestones and/or in other hard rocks of higher prevailing transmissivity, C – cumulative relative frequency of transmissivity of fluvial deposits along the Labe River in the Czech Republic (for comparison).

Transmissivity variation is also classified by six classes, which are designated a to f, based on a standard deviation. This classification assesses aquifer capability to produce groundwater in different areas and the factors causing regional differences in transmissivity. A range of prevailing transmissivity values $\bar{x} \pm s$ ($\bar{x}$ = arithmetic mean, s = standard deviation of a statistical sample) represents the *transmissivity background* of a statistically-analyzed hydrogeological setting. Transmissivities outside the background are considered *anomalies* or extreme anomalies, both positive and negative.

## 7 PREVAILING TRANSMISSIVITY IN A REGIONAL SCALE, EXCEPTIONS AND DEPTH-RELATED CHANGES

Transmissivity distributions are similar in the *near-surface aquifer* of hard rocks in areas ranging from several to hundreds $km^2$, including Korea (Callahan and Choi, 1973), Sweden (Carlsson and Carlstedt, 1977), Poland (Staśko and Tarka, 1996), the Czech Republic (Krásný 1999), and Ghana (Darko and Krásný 1998, Darko 2001). Represented as cumulative relative frequencies, most transmissivity data form more or less parallel lines having fallen into a relatively narrow field A (Fig. 3). These samples belong to *classes IV(V,III) c,d* (i.e., very low to intermediate transmissivity with moderate to large transmissivity variation). Therefore, despite irregular local permeability/transmissivity changes usually scattered in a wide interval of several orders of magnitude, regionally prevailing values – transmissivity background encompasses the most frequent transmissivity values in *units* $m^2/d$ *up to slightly more than* $10\,m^2/d$. Comparison of regional prevailing transmissivity indicates only small differences in distinct hardrock areas. Therefore, except for certain rock types, influence of petrography on permeability and transmissivity spatial distribution is not significant because fracture distributions control the hydrogeology.

There are exceptions of this general rule; *crystalline limestones* (marbles) are one conspicuous exception. Because of their mechanical and chemical properties – suitability to fracturing and karstification – the prevailing transmissivity of limestones is usually half to one order of magnitude higher than in other crystalline rocks (field B in Figure 3). Higher permeability of limestone intercalations is often indicated by larger springs than in other hardrock terrains.

There are indications that relatively higher prevailing permeability/transmissivity may be expected in areas of *basic igneous rocks* (Havlík and Krásný 1998) that are subject to more fracturing. The gabbros complex of Beja in the south Portugal has been proved of water management importance (Chambel et al., this volume). On the other hand, *phyllites* may display lower regionally prevailing transmissivity (Krásný 1993b).

*Quartzite* hydrogeological properties differ depending on their extension. If reduced in thickness and forming part of a hardrock sequence, their prevailing transmissivity is usually comparable with their surroundings. On the other hand, where extended and exposed to intensive fracturing, quartzite bodies, due to their rigid geomechanical properties, can form highly transmissive aquifer systems with intensive and deep (as indicated by elevated water temperatures) groundwater flow (Issar and Kotze, this volume; Tröger, this volume).

Hydrogeological properties of *acidic igneous rocks* depend upon their position, geomechanical properties, weathering character. Depth-related decreasing permeability in granitic rock, orthogneisses, and migmatites is more significant than in metasedimentary rocks (Biscaldi and Derec, 1967: Krásný, 1975; and Havlík and Krásný, 1998). The regolith and weathered zone of these rocks, often sandy and coarse-grained, is permeable; metasediment regolith is typically more clayey and not as permeable. Fracturing in granites is usually not intense and reaches shallower depths than in other hard rocks. However, granite exfoliation fractures form a unique hydrogeological setting.

Depth-related changes in permeability can be used to predict productive depths of wells in hardrock near-surface aquifers (Davis and Turk, 1964; Read, 1982; and Darko and Krásný, 2000). Presence of generally more permeable products of weathering, regolith, debris and other juxtaposed young alluvial, fluvial, and eolian sediments commonly create higher transmissivity of wells where they overlay hard rocks.

Differences in geomechanical properties between granites and other hard rocks also exist in the *deep/massive zone* as indicated by thermal and mineral waters that typically occur in granitic or more generally, in acid igneous rocks, although uncertainty exists about the deep permeability distribution. The deep zone represents by far the largest volume of existing hard rocks, comprising the brittle part of the Earth's crust, i.e., extended hardrock regions below the near-surface aquifer, the basement of hydrogeological basins, and rocks underlying sedimentary nappes in intensively folded, mountainous areas. Traditionally, this zone has received little attention, but, in recent decades, applied projects as construction of deep waste repositories, construction of deep tunnels and underground cavities, deep mines, geothermal investigation of non-traditional energy sources, and few ultra-deep boreholes have been carried out (e.g., Boden and Eriksson, 1987; Stober and Bucher, 2000).

All these activities have extended our knowledge of hardrock environment up to the depths of many hundreds or even thousands meters. It has been found that hard rocks are permeable to some degree even in these depths. We do not know, however, whether any general regional scheme in permeability spatial distribution can be anticipated as depth-related changes or dependence of hydrogeological properties with respect to petrographic composition and structural position of rocks. If we admit that general decrease in permeability within the fractured zone of a near-surface hardrock aquifer is mostly connected with exogenous processes that enlarge aperture of originally existing tight fracture network, we can suggest that permeability in deep hardrock zone should not decrease considerably downwards if such a decrease occurs at all (Krásný 2003).

## 8 GROUNDWATER RESOURCES

In most hardrock terrains, the regionally extended near-surface aquifer is generally conformably with the land surface. This is where the most intensive groundwater flow and groundwater resources occur in hard rocks. However, local hydrogeological setting determines the geometry and anatomy of the hydrogeological units and their parameters. The availability of groundwater resources depends upon: 1) the hydraulic properties and their distribution, and 2) climatic conditions. For instance, because of limited precipitation and high evaporation in arid and semi-arid regions, groundwater resources are commonly limited. Intensive withdrawals, especially for irrigation, can cause regional water-table declines, deterioration of water quality, and serious environmental impacts even in hardrock terrains of low transmissivity (Marechal et al., this volume). On the other hand, in temperate climatic zones, there is abundant potential recharge, but limited transmissivity represents the controlling factor groundwater extraction. Global natural groundwater resources and recharge by Struckmeier et al. (2004) and by Zektser and Everett (2004) offer general information on ranges of natural groundwater resources in different parts of the world and in distinct climatic zones.

Depending on climatic and general hydrogeological conditions, a regional assessment of natural groundwater resources in hardrock terrains can be based upon:

- Analyses of available climatic and hydrological data resulting in water balance estimations.
- Analysis of records from river gauging stations – e.g., methods by Castany et al. (1970), Kille (1970) – partly modified by Köpf and Rothascher (1980) and field measurements of changes in total runoff along river courses in dry periods.
- Application of regionally prevailing transmissivity and morphometric characteristics of the area (Krásný and Kněžek 1977, Buchtele et al. 2003) can be used to check up results based on hydrological measurements.
- Implementation of deterministic precipitation-runoff models to simulate total runoff and its components (e.g., Sacramento SAC-SMA – Burnash 1995).
- Point/local measurement of direct or indirect groundwater recharge (e.g., Lerner et al. 1990).
- Interpretation of results of (long-term) monitoring of spring yield and groundwater level fluctuations.
- Use of environmental and radioactive tracers.

In the *temperate climates*, most streams are effluent or gaining and, under natural conditions, the separation of the baseflow component of streamflow is an acceptable method to assess groundwater resources. Investigations in Europe have revealed the importance of a hardrock environment in groundwater resources (e.g., Karrenberg and Weyer 1970, Krásný et al. 1982, Apel et al. 1996, Bocheńska et al. 1997, Kryza and Kryza 1997; and Watkins, this volume). Regional distribution of a long-term average groundwater runoff/baseflow within Central and East Europe was presented by Konopljancev et al. (1982).

In hardrock terrains, groundwater resources depend on present recharge which, under comparable hydrogeological conditions, is controlled mainly by climatic conditions. The highest natural groundwater resources in hard rocks occur in mountainous areas due to favourable climatic and geomorphologic conditions. High precipitation and low evapotranspiration enable high and relatively equable recharge. Large hydraulic gradients of groundwater level often result in intensive groundwater flow in spite of prevailing low transmissivity of rocks (Figure 4). In summits of Centro-European mountain ranges, specific long-term average groundwater runoff can exceeds 10–15 L/s km$^2$ that corresponds to 300–450 mm/a of recharge; maximum recharge may reach 20–30% of average annual precipitation. The highest values, however, should be viewed with caution, especially if snowmelt is important. On the other hand, snowmelt can positively influence the time distribution of groundwater runoff.

The *residence time* based on isotope studies was estimated to be between half to one year for shallow flow systems and several up to ten years for deeper groundwater flow systems in crystalline rocks in the Krkonoše Mts. in Czech Republic and in the Bavarian Forest in Germany (Martinec 1975, Seiler and Müller 1996). Thus, these aquifers have limited groundwater storage, but can maintain relatively intensive and continuous groundwater flow under favourable climatic conditions that helps maintain stream flows in the adjacent piedmont zones. Because of decreasing precipitation, higher evaporation rates, and generally lower hydraulic gradient with decreasing elevation, groundwater runoff diminishes (Figure 4). Relationships between climatic and hypsometric conditions and groundwater runoff in hardrock areas under temperate Central European climatic conditions are given in Table 2, which can be compared with other hardrock regions with similar climatic conditions.

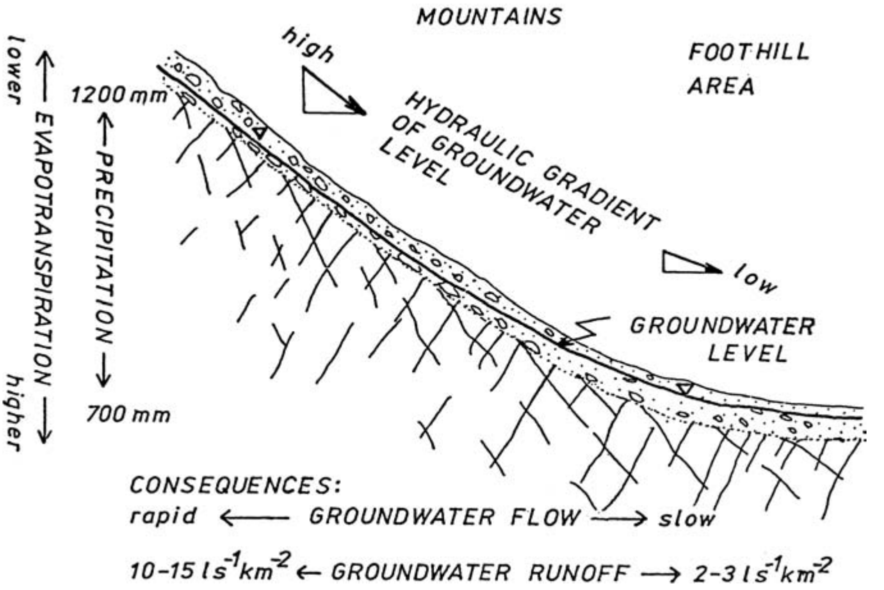


Figure 4. Groundwater flow and natural resources formation in the near-surface aquifer of mountainous hardrock terrains under temperate climatic conditions (after Krásný 1996a).

Table 2. Climatic and hypsometric conditions and groundwater runoff (baseflow) in hardrock areas of the Bohemian Massif (after Krásný 1996a).

| Morphological (hypsometric) unit | Approximate elevation (m a.s.l.) | Mean annual precipitation (mm) | Mean annual potential evaporation (estimation in mm) | Groundwater runoff (natural groundwater resources) (L/s km$^2$) |
|---|---|---|---|---|
| Mountains | 1200–1600 | 1000–1200 | 450 | 10–15 |
| Lower mountains | 800–1200 | 800–1000 | ↑ | 7–10 |
| Piedmont areas | 300–800 | 600–800 | ↓ | 3–7 |
| Flat areas, lowlands | less than 300 | 500–600 | 650 | 1–3 |

Importance of hardrock terrains for groundwater resources in temperate climatic zones is demonstrates by studies from the Bohemian Massif (Krásný 1996a) where hard rocks cover only 68% of the area, but more than 71% of total groundwater resources are recharged there.

In *semi-arid and arid regions* where few perennial streams exist, groundwater resources assessment is mostly based on water balance methods or on point/local measurements of direct or indirect groundwater recharge. Lerner et al. (1990), Struckmeier et al. (2004) and Zektser and Everett (2004) assess very low groundwater recharge that may be less than 20 mm/a in extended dry regions. It is even less than 5 mm/a in about 34% of the continent of Africa (Döll and Flörke 2005). In these arid climates, climatic zonality depending on surface elevation might be important as is shown in Table 2 for temperate conditions.

## 9 GROUNDWATER QUALITY IN HARD ROCKS

Groundwater quality in hardrock near-surface aquifers, under comparable hydraulic properties, depends mainly on climatic and geomorphologic conditions.

In the *temperate climates*, the dominant ions in groundwater are usually bicarbonate and/or sulphate and calcium. Total dissolved solids (TDS) are typically low, reaching up to 100–300 mg/L, somewhere even less. General decreases in TDS and pH (usually between 6.0 and 5.0) occur with increasing altitude, sometimes accompanied by higher relative content of sulphate that may be the result of acid rain contamination (Knutsson et al. 1995, Hrkal et al. 2006). Variations on this generalization can occur. Basic igneous rocks (gabbro, amphibolite, serpentine) are usually distinguished by higher magnesium and marbles (crystalline limestones) by pure bicarbonate-calcium types, higher hardness (and TDS), and pH about 7. This may be of practical importance for indication of limestone intercalations often representing zones of higher transmissivity. Higher sulphate and TDS are typical for some sedimentary rocks (especially shales) that may contain scattered sulphide minerals (e.g., pyrite). Hydrochemical or temperature anomalies appearing in some areas may indicate vertical upward flux of deep-seated mineral and thermal waters.

Elevated concentrations of some minority and trace constituents are typical of some hardrock areas (e.g., Frengstad and Banks, this volume). High contents of trace elements can indicate occurrences of mineral deposits and, in mining regions, water pumped from mines or outflows from mining galleries or tailings may represent a threat to the environment (Bocanegra and Cardoso, this volume). Near-surface hardrock aquifers are often exposed to bacteriological pollution from the surface as reported by Gaut et al. (this volume).

In *semi-arid and arid climatic zones*, groundwaters with low TDS contents occur only in areas with adequate recharge and relatively continuous natural groundwater discharge. Many hardrock regions in these climatic zones, however, have lost these processes because of human activities. Here (ground)water and soil are generally prone to salinisation.

In arid regions all over the world (Africa, the Americas, Asia and Australia) there are naturally closed basins without any (ground)water outflow. This is often the case of hardrock terrains where outcrops of these rocks along topographic divides represent low permeable zones. Then, negative water balance results in accumulation of salts. Similar "closed basins" can form where large amounts of groundwater are abstracted for irrigation or water-supply purposes so that lowering of groundwater levels impede groundwater outflow. Thus, under these conditions groundwater salinity can increase on long-term scales. This situation concentrates groundwater constituents and may change groundwater chemical composition from originally prevailing calcium-bicarbonate-(sulphate) type to different highly concentrated Na-Cl-rich saline waters or brines. Anthropogenic factors can also increase in contents of various contaminants from municipal, industrial, and agricultural wastes. The process can be accelerated in areas with intensive irrigation return flows, urbanization, or artificial recharge.

## 10 COUPLING GROUNDWATER FLOW AND QUALITY

Groundwater flow and water quality (its chemical composition, TDS content, temperature, etc.) in different hydrogeological environments are closely coupled. In accordance with general hydrogeological concepts, extension, depth, and rate of groundwater flow, *three vertical zones* reflecting main general features *of groundwater flow*, had been schematized in hydrogeological basins by many authors, starting from Ignatovitsh (1945) to Chebotarev (1955), Marinov et al. (1978), Tóth (1988, 1999) and many others. The zones were designated, from land surface downwards, as *local* (intensive, shallow), *intermediate* (retarded) and *regional* (slow or negligible, deep, stagnant) as shown on Table 3. Similar to the vertical zonation of groundwater flow (vertical hydrodynamic zonality*)*, vertical changes in groundwater quality, expressed by its chemical composition, were defined as *vertical hydro(geo)chemical zonality* in sedimentary basins. In the shallow zone, which is characterized by the more intensive groundwater flow, calcium/magnesium and bicarbonate/sulphate groundwater composition typically prevails, except in arid zones where soil and shallow groundwater salinisation can occur. Groundwater composition commonly changes with depth from calcium-bicarbonate or sulphate types to sodium-bicarbonate and finally to sodium(-calcium)-chloride types in the deepest zones of basins. Depth limits between particular zones might differ considerably depending on hydrogeological conditions. With depth chemical changes are typically accompanied by increases in temperature and TDS and with possible occurrence of $CO_2$ and some hydrocarbon gases (Table 3).

Similar vertical zonations are documented in hardrock terrains – hydrogeological massifs, which were found permeable even to depths of more thousand metres and where also brines occur – mostly of sodium(-calcium)-chloride types (e.g., Gavrilenko and Derpgol'c, 1971 who designated this globally extended zone as a "hydrochlorosphere"; Collins 1975; Ingebritsen and Sanford, 1998; Stober and Bucher, 2000; and Krásný, 2003).

Regardless of near surface groundwater systems, varying petrography, and different climatic zones, we find common hydrogeological conditions globally that are manifested by vertical hydrodynamical and hydrochemical zonality at depths. Deep permeable zones enable flow groundwater over *geologic time-scales*. The origin of these deep-seated brines is a challenge for hydrogeologists. In general, there are two opinions regarding *brine origin: endogenous* and *exogenous*. Brines of an endogenous origin are considered to have ascended as different hydrothermal fluids limited to unstable zones of the Earth's crust. Water-rock interaction, often under specific pressure-temperature conditions and during

Table 3. Vertical scheme of combined hydrodynamic and hydrochemical zonality.

| Depth can reach up to | | Groundwater flow | Main groundwater constituents | TDS | General increase with the depth in |
|---|---|---|---|---|---|
| Basins | Massifs | | | | |
| hundreds of m | several tens of m | local (intensive, shallow) | $Ca(-Mg)-HCO_3(-SO_4)$ | 0.0x–0.x g/L | temperature and gas content |
| few thousands of m | hundreds of m | intermediate (retarded) | $Na-HCO_3(-SO_4)$ | several g/L | ↓ |
| thousands of m | ↑<br>many thousands of m<br>↓ | regional (slow, deep, negligible – stagnant)<br>global (planetary) | $Na-Cl$<br>↓<br>$Na(-Ca)-Cl$<br>↓ | several hundreds g/L | ↓ |

long geologic periods, could result in brine origin in hardrock environments. In stable regions, often within the interior of tectonic plates, the exogenous concept can also explain origin of deep-seated brines.

During geologic history, because of past plate-tectonic movement, different regions have been exposed to variable climatic conditions (Schwarzbach 1974). Under arid climates, salts had been accumulated in soils and water during long past geologic periods, typically in extended closed continental basins as presently occur in arid regions. Gradual long-term downward percolation from saline soils and different surface water bodies containing brines had occurred. During very long intervals and under all the time changing natural conditions, when geologic time-scales are to be considered (i.e., up to hundreds of million years), a complex and dynamic groundwater system developed, mostly as a result of a gravity-driven and density-driven flow. After the original idea of Filatov (1956) the concept was supported and substantiated by Marinov et al. (1974, 1978) and Tóth (1999). Such a complex hydrogeological – hydrodynamic and hydrochemical system forms part of a *global (planetary) groundwater flow system* where deep-seated crystalline rocks play important, perhaps decisive role (Krásný 2003).

## 11 FUTURE CHALLENGES

Understanding flow and transport in fractured rock has proven challenging (Sharp, 1993; Voss, 2003; Neuman, 2005). This is largely because high transmissivity fractures control flow and transport and we are limited in our ability to predict where they occur and how they connect with other features, particularly other fractures. We are also limited in our understanding of the flow within a fracture and generally assign some "equivalent" permeability for an idealized uniform aperture fracture. Therefore our models are only predictive for a limited set of hydraulic conditions; different conditions can lead to vastly different results as is commonly observed in karstic aquifers. In addition, we need evaluate fracture effects in a variety of geologic scenarios, including free convection, petroleum migration, and multiphase flow. Sharp (1993) addressed future challenges. For some, progress has been made in the past decade, as is summarized in many of the papers in this volume. We have new compendia (e.g., Krásný et al., 2003; Faybishenko et al., 2000) and textbooks on fractured rock hydrogeology; new analytical and numerical models have been developed; there have been some field studies useful in testing numerical predictions; and new geophysical, GIS, and tracer methods have been developed that may yet prove fruitful. These recent studies have extended our knowledge up to the depths of hundreds or even thousands meters and it has been found that hard rocks are permeable to some degree even at great depths. However, many of the challenges posed over a decade ago remain largely unresolved.

Significant challenges include:

- Scaling – Can we scale up or down from measured or inferred properties at a given site?
- Field characterization of fracture domains – can we predict fracture properties *a priori* and the domain over which these properties are appropriate?
- Can we predict hydrogeological properties of fractures as a function of present and paleostress fields?
- Which are the depth-related changes in permeability of the deep/massive zone and what controls these changes?

- Can we predict geomechanical properties of rocks that determine their hydrogeological feature (e.g., fracture frequencies and apertures) as functions of depth?
- What techniques can determine hydraulically conductive fractures (distinguishing impermeable and permeable inhomogeneities)?
- Can we utilize geological, petrological, geophysical, well logging, or other proxy data, including data on paleoflow systems to provide insight on the extent and rates of flow and transport in fractures?
- Can we assess how fracture surfaces and skins control key processes?
- Can we assess the effects on fracture networks on density-driven flow and transport?
- How have paleohydrogeological conditions influenced the origin and evolution of deep-seated brines?
- What is role of endogenous processes in omnipresent and almost uniform vertical distribution of deep saline waters, occurring under extremely variable geological and geochemical conditions?
- Can we develop numerical codes that can simulate local-dominant effects in regional or aquifer studies?
- How can we apply fracture rock hydrogeology to:
  - Ore body mineralization
  - Petroleum migration
  - Diagenesis
- With respect specific lithologies:
  - Plutons and massifs:
    - Do fracture skins vary with fracture orientation?
    - How does fracture roughness control flow and channeling?
    - Do there exist important petrographic/rock-mechanical controls in forming fractured systems?
  - Tuffs:
    - Does pre-existing topography control fracture patterns?
    - Can we use petrographic and geological data, such as degree of welding, to make *a priori* estimates of hydrogeological parameters?
  - Carbonate systems – How and what rates do these systems change from a fractured to a karstic system?
  - Consolidated sandstones and other rocks of sedimentary origin:
    - Can microfractures observed in thin section be upscaled to aquifer or reservoir properties?
    - Can we predict attenuation properties in these double-porosity systems and estimate the effects of fracture skins?
    - What is the hydrogeological role of quartzites in hydrostratigraphic sequences?

Perhaps, we need to assess again whether or not some general regional schemes in permeability distribution can be anticipated as depth-related changes or dependence of hydrogeological properties with respect to petrographic composition and structural position.

## 12 CONCLUSIONS

Fractured aquifers often contain important water resources and the groundwater flow and solute transport in porous media are key processes in groundwater contamination, petroleum and geothermal energy production, as well as fundamental geological problems. Three major vertical zones are common: an upper or weathered zone, a middle or fractured zone, and a deep or massive zone. The upper zone and part of the middle zone may form a near-surface aquifer that is regionally extensive with important ramifications for stream flows and water resources. Despite high spatial variability in fractured rock properties, reasonable generalizations can be made about regional hydraulic and chemical properties. These aquifers are critical in many arid zones of the world and recent consideration of hard rocks for waste depositories has demonstrated how much more we need to know. Fractured geological materials are subdivided into four basic types depending principally upon the relative permeabilities of the fractures and the matrix (intrafracture materials). These are purely fractured rocks, fractured formations, double-porosity systems, and heterogeneous systems. Characterization of this flow and concomitant transport of solutes requires a knowledge of fracture orientations, apertures, asperities, flow channeling, fracture connectivity, and the nature of fracture skins, if present. The primary hydrogeological parameters, hydraulic conductivity and effective porosity, are tensor properties and the concept of a representative elemental volume for the characterization of the parameters is difficult. A variety of modeling approaches estimate flow and transport in fractured aquifers, reservoirs, and fractured geological materials of low permeability. Each has advantages and limitations. However, a major deterent to understanding of fracture systems has been reluctance or inability to obtain and apply realistic geological, geochemical, and hydrological data to these models.

Fractured rocks are vital water and environmental resources and they are being considered for new uses in waste disposal and in construction. There are many unanswered questions that require attention and, undoubtedly, new scientific questions will be posed in the next few decades. Administrative and legislative approaches must be based on general understanding and knowledge of hardrock hydrogeology and adequate professional terminology.

## ACKNOWLEDGMENTS

Acknowledgement is made to the National Science Foundation (Grant No. 0439806), the Petroleum Research Fund of the American Chemical Society (Grant No. 38949-AC9), the Geology Foundation of The University of Texas, the Grant Agency of the Czech Republic (GACR – Grant No. 205/05/177) and Grant Agency of the Charles University Prague (GAUK – Grant No. 364/2004/B-GEO/PPrF) for partial support of this research. Reviews by members of the Physical Hydrogeology graduate seminar at The University of Texas are appreciated.

## REFERENCES

Annau R, Bender S, Wohnlich S (eds) (1998) Hardrock hydrogeology of the Bohemian Massif. Proc. 3rd Internat. Workshop 1998, Windischeschenbach. Münchner Geol. Hefte B8: 79–86.

Apel R, Klemm A, Rüdiger F (1996) Grundlagen zum Wasserwirtschaftlichen Rahmenplan, Naabregion, Hydrogeologie. Bayerisches Geologisches Landesamt.

Banks D, Banks S (eds) (1993) Hydrogeology of hard rocks. Memoires, 24th Congress, Int Association Hydrogeologists, v. 24, 2 parts.

Barton CC, Hsieh PA (1989) Physical and hydrologic properties of fractures. Field Trip Guidebook T385, International Geological Congress, Washington, DC.

Barton CC, Larsen E, Page WR, Howard TM (1987) Characterizing fractured rock for fluid-flow, geomechanical, and paleostress modeling: Methods and preliminary results from Yucca Mountain, Nevada. US Geological Survey Open-File Report 87.

Biscaldi R, Derec G (1967) Un example d'application des méthodes statistiques en hydrogéologie. B.R.G.M. DS. 67 A.150.

Biscaldi R (1968) Problèmes hydrogéologiques des régions d′affleurement de roches éruptiv et métamorphiques sous climat tropical, Bulletin du BRGM III, 2: 7–22.

Black JJ, Alexander J, Jackson PD, Kinbell GS, Lake RD (1986) The role of faults in the hydrogeological environment. British Geological Survey, Natural Environmental Research Council FLPU 86–9.

Blum P, Mackay R, Riley MS, Knight JL (1997) Performance assessment of a nuclear waste repository, upscaling coupled hydro-mechanical properties for far-field analysis. Int. Jour. Rock Mechanics and Mining Sciences, 42: 781–792.

Bocheńska T, Marszalek H, Staśko S (1997) Hard rocks of the Sudety Mts. as a groundwater collector and its vulnerability. In: Bocheńska T, Staśko S (eds) (1997) Hydrogeology, 2nd Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Univ. Wratislaviensis, 2052:11–19.

Bocheńska T, Staśko S (eds) (1997) Hydrogeology. 2nd Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Univ. Wratislaviensis, 2052.

Boden, A., and Eriksson, K.G. (eds.), 1987, Deep drilling in crystalline bedrock. Springer-Verlag, Berlin.

Buchtele J, Čurda S, Hrkal Z, Krásný J (2003) New approach to using GIS in groundwater runoff assessment: the Krušné Mts, Czech Republic. In: Krásný J, Hrkal Z, Bruthans J (eds) Proceedings, Int Association Hydrogeologists, International Conference on Groundwater in fractured rocks, UNESCO IHP-VI, Series on Groundwater 7, Prague.

Burnash JCR (1995) The NSW River forecast system – catchment modelling. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, 311–366.

Callahan JT, Choi SI (1973) Development of water from fractured crystalline rocks, Republic of Korea. Proceedings, 2nd International Symposium on Ground Water, Palermo 299–316.

Carlsson L, Carlstedt A (1977) Estimation of transmissivity and permeability in Swedish bedrock. Nordic Hydrology 8: 103–116.

Castany G, Margat J, Albinet M, Delarozière-Bouillin O (1970) Evaluation rapide de ressources en eaux d′une région. In: Atti Convegno Internaz. sulle acque sotterranee, Palermo.

Chebotarev II (1955) Metamorphism of natural waters in the crust of weathering. Geochimica et Cosmoschimica Acta 8: 198–212.

Chernyshev SN Dearman WR (1991) Rock fractures. Butterworth-Heinemann, London.

Chilton PJ, Foster SSD (1993) Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. In: Banks S, Banks D (eds) Hydrogeology of hard rocks. Memoires, 24th Congress, Int Association Hydrogeologists 1083–1100.

Clauser C (1991) Permeability of crystalline rocks. EOS, 73(21): 233–238.

Collins AG (1975) Geochemistry of oilfield waters. Elsevier.

Cook PG (2003) A guide to regional groundwater flow in fractured rock aquifers. CSIRO Land and Water. Australia.

Darko PK (2001) Quantitative aspects of hard rock aquifers: Regional evaluation of groundwater resources in Ghana,. PhD, Charles University Prague.

Darko PK, Krásný J (1998) Comparison of hardrock hydraulic parameters in distinct climatic zones: the Ghana and the Bohemian Massif areas. In: Annau R, Bender S, Wohnlich S (eds) . Proc. 3rd Internat. Workshop 1998, Windischeschenbach. Münchner Geol. Hefte B8: 3–10.

Darko PK, Krásný J (2000) Adequate depth of boreholes in hard rocks: A case study in Ghana. In: Sililo O et al (eds) Groundwater: Past achievements and future challenges, Proceedings, 30th Congress, Int Association Hydrogeologists 121–125.

Davis SN, Turk LJ (1964) Optimum depth of wells in crystalline rocks. Ground Water 22: 6–11.

Davis SN, DeWiest RJM (1966) Hydrogeology. John Wiley and Sons, New York.

Döll P, Flörke M (2005) Global scale estimation of diffuse groundwater recharge. Frankfurt Hydrol. Paper D3. Inst. of Phys. Geography.

Ehlen J (1990) Fractures in Rock: An Annotated Bibliography. US Army Corps of Engineers Report ETL-0555.

Evans DD, Nicholson TJ (1987) Flow and transport through unsaturated fractured rock. American Geophysical Union Monograph 42.

Faybishenko B, Withewrspoon PA and Benson SM (eds) (2000) Dynamics of fluids in fractured rock. American Geophysical Union Monograph 22.

Filatov KB (1956) Gravitational hypothesis of formation of groundwater chemical composition in platform depressions [in Russian]. Izdat. AN SSSR.

Fu L Milliken KL, Sharp JM Jr (1994) Porosity and permeability variations in the fractured and liesegang-banded Breathitt Sandstone (Middle Pennsylvanian), eastern Kentucky: Diagenetic controls and implications for modeling dual porosity systems. Journal of Hydrology 154: 351–381.

Fuller CM, Sharp JM Jr. (1992) Permeability and fracture patterns in welded tuff: Implications from the Santana Tuff, Trans-Pecos Texas. Geol. Soc. America Bulletin 104: 1485–1496.

Garner TT, Sharp JM Jr. (2004) Hydraulic properties of granitic fracture skins and their effects on solute transport. In: Proceedings, 2004 U.S. EPA/NGWA fractured rock conference: State of the science and measuring success in remediation, National Ground Water Association, Dublin, Ohio 664–678.

Gavrilenko ES, Derpgol'c VF (1971) Deep-seated Earth hydrosphere [in Russian]. Naukova Dumka. Kiev.

Geothermal Resources Council (1982) Fractures in geothermal reservoirs. Special Report 12.

Gustafsson P (1993) SPOT satellite data for exploration of fractured aquifers in southeastern Botswana. In: Banks S, Banks D (eds) Hydrogeology of hard rocks. Memoires, 24th Congress, Int Association Hydrogeologists 562–576.

Halihan T, Mace RE, Sharp JM Jr. (2000) Flow in the San Antonio segment of the Edwards aquifer: matrix, fractures, or conduits? In: Sasowsky ID and Wicks CM (eds) Groundwater flow and contaminant transport in carbonate aquifers 129–146.

Halihan T, Love A, Sharp JM Jr. (2005) Identifying connections in a fractured rock aquifer using ADFTs. Ground Water, 43(3): 327–335.

Hancock PL, Engelder T (1989) Neotectonic joints. Geol. Soc.America Bulletin 101: 1197–1208.

Havlík M, Krásný J (1998) Transmissivity distribution in southern part of the Bohemian Massif: Regional trends and local anomalies. In: Annau R., Bender S. and Wohnlich S. (eds.): Hardrock Hydrogeology of the Bohemian Massif. Proc. 3rd Internat. Workshop, Windischeschenbach. Münchner Geol. Hefte, B8: 11–18.

Henriksen H (1995) Relation between topography and well yield in boreholes in crystalline rocks, Sogn og Fjordane, Norway. Ground Water, 33(4): 635–643.

Hofrichter J, Winkler G (2006) Statistical analysis for the hydrogeological evaluation of fracture networks in hard rocks. Environmental Geology, 49: 821–827.

Hrkal Z, Prchalová H, Fottová D (2006) Trends in impact of acidification on groundwater bodies in the Czech Republic; an estimation of atmospheric deposition at the horizon 2015. J. Atmosph. Chemistry 53: 1–12.

IAHS/UNESCO (1967) Hydrologie de roches fisurées. Actes du colloque de Dubrovnik, October 1995

Ignatovitsh NK (1945) To the question of oil deposits origin and conservation [in Russian]. Dokl.Akad.Nauk SSSR 46(5: 215–218.

Illman WA, Neuman SP (2003) Steady-state analysis of cross-hole pneumatic injection tests in unsaturated fractured tuff. Journal of Hydrology, 281: 36–54.

Ingebritsen SE, Sanford WE (1998) Groundwater in geologic processes. Cambridge University Press.

Jetel J (1964) Application of specific capacity and new derived parameters in hydrogeology [in Czech]. Geol. Průzk 5: 144–145.

Jetel J, Krásný J (1968) Approximative aquifer characteristics in regional hydrogeological study, Věst. Ústř. Úst. geol. 43(5): 459–461, Praha.

Karrenberg H, Weyer KU (1970) Beziehungen zwischen geologischen Verhältnissen und Trockenwetterabfluss in kleinen Einzugsgebieten des Rheinischen Schiefergebirges. Z. Deutsch. Geol. Gessell. 27–41.

Khaleel R (1992) Equivalent porosity estimates for colonnade networks. Water Resources Research 28: 2783–2792.

Kille K (1970) Das Verfahren MoMNQ, ein Beitrag zur Berechnung der mittleren langjährigen Grundwasserneubildung mit Hilfe der monatlichen Niedrigwasserabflüsse. Z. Deutsch. Geol. Gessell, 89–95.

Király L (1975) Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques. In: Hydrogeology of karstic terrains. IAH Paris, 53–67.

Knutsson G, Bergström S, Danielsson L-G, Jacks G, Lundin L, Maxe L, Sandén P, Sverdrup H and Warfinge P (1995) Acidification of groundwater in forested till areas. Ecological Bulletin 44: 271–300.

Knutsson G (ed) (1998) Hardrock hydrogeology of the Fennoscandian shield. Proc Workshop on Hardrock Hydrogeol, Äspö, Sweden. May 1998, Nordic Hydrol. Programme Report 45:37–47.

Konopljancev AA et al. (1982) Podzemnyj stok territorii Centralnoj i Vostočnoj Evropy [in Russian]. VSEGINGEO Moskva.

Köpf E, Rothascher A (1980) Das natürliche Grundwasserdrgebot in Bayern im Vergleich zu den Hauptkomponenten des Wasserkreislaufes. Schriftenreihe Bayer Landesamt für Wasserwirtschaft, 13.

Krásný J (1974) Les différences de la transmissivité, statistiquement significatives, dans les zones de l'infiltration et du drainage. In: Memoires, 10th Congress, Int Association Hydrogeologists 204–211.

Krásný J (1975) Variation in transmissivity of crystalline rocks in southern Bohemia. Vest. Ústr. Úst. geol. 50(4): 207–216, Praha.

Krásný J (1993a) Classification of transmissivity magnitude and variation. Ground Water 31(2): 230–236.

Krásný J (1993b) Prevailing transmissivity of hard rocks in the Czech part of the Krkonoše and Jizerské hory Mts. In: Poprawski L, Bocheńska T (eds) Sb. Sympozia "Wspólczesne problemy hydrogeologii VI" Polanica Zdrój 79–86.

Krásný J (1996a) State-of-the-art of hydrogeological investigations in hard rocks: the Czech Republic. In: Krásný J, Mls J (eds) (1996) 1st Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Universitatis Carolinae Geologica, 40(2): 89–101.

Krásný J (1996b) Hydrogeological environment in hard rocks: an attempt at its schematizing and terminological considerations. In: Krásný J, Mls J (eds) 1st Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Universitatis Carolinae Geologica,40(2):115–122.

Krásný J (1996c) Scale effect in transmissivity data distribution. In: Krásný J, Mls J (eds) (1996) 1st Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Universitatis Carolinae Geologica 40(2):123–133.

Krásný J (1998) Groundwater discharge zones: sensitive areas of surface-water – groundwater interaction. In: Van Brahama J, Eckstein Y, Ongley LK, Schneider R, Moore J (eds) Gambling with groundwater – physical, chemical, and biological aspects of aquifer-stream relation. Proceedings joint meeting 28th Congress, Int Association Hydrogeologists and annual meeting American Institute of Hydrology, Las Vegas, Nevada, 28 September–2 October 1998, 111–116.

Krásný J (1999) Hard-rock hydrogeology in the Czech Republic. Hydrogéologie, 2:25–38.

Krásný J (2000) Geologic factors influencing spatial distribution of hardrock transmissivity. In: Sililo, O., et al. (eds) Groundwater: past achievements and future challenges, Proceedings 30th Congress, Int Association Hydrogeologists 187–191.

Krásný J (2002) Understanding hydrogeological environments as a prerequisite for predicting technogenic changes in groundwater systems. In: Howard KWF, Israfilov RG (eds) Current problems of hydrogeology in urban areas, urban agglomerates and industrial centres. Proc. Advanced Research NATO Workshop, May 2001, 381–398.

Krásný J (2003) Important role of deep-seated hard rocks in a global groundwater flow: possible consequences. In: Krásný J, Hrkal Z, Bruthans J (eds) (2003) Proceedings, Int Association Hydrogeologists, International Conference on Groundwater in fractured rocks, UNESCO IHP-VI, Series on Groundwater 7: 147–148, Prague.

Krásný J, Kněžek M (1977) Regional estimate of ground-water run-off from fissured rocks on using transmissivity coefficient and geomorphologic characteristics. Jour Hydrological Sciences Warszawa, 4(2): 149–159.

Krásný J, Kněžek M, Šubová A, Daňková H, Matuška M, Hanzel V (1982) Groundwater runoff in the territory of Czechoslovakia [in Czech]. Český hydrometeor úst Praha.

Krásný J, Mls J (eds) (1996) 1st Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Universitatis Carolinae Geologica 40(2).

Krásný J, Hrkal Z, Bruthans J (eds) (2003) Proceedings, Int Association Hydrogeologists, International Conference on Groundwater in fractured rocks, UNESCO IHP-VI, Series on Groundwater 7, Prague.

Kryza J, Kryza H (1997) Renewal rate of groundwater in the Sudety Mts. – its disposable and exploited resources. In: Bocheńska T, Staśko S (eds) (1997) Hydrogeology. 2nd Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Univ. Wratislaviensis, 2052: 223–227.

Lamb H (1932) Hydrodynamics (6th edition). Dover Publications, New York.

LaPointe PR and Hudson JA (1985) Characterization and interpretation of rock mass joint patterns. Geol. Soc. America Special Paper 199.

Larsson I. et al. (1987) Les eaux souterraines des roches dures du socle. UNESCO Études et rapports d`hydrologie 33.

Laubach S (1992) Fracture networks in selected Cretaceous sandstones of the Green River and San Juan Basins, Wyoming, New Mexico, and Colorado. In: Schmoker JW, Coalsen, EB, Brown, CA (eds) Geological studies relevant to horizontal drilling: Examples from Western North America, Rocky Mt. Assoc. Geologists 61–73.

LeGrand HE (1954) Geology and ground water in the Statesville area, North Carolina: North Carolina Dept. of Conservation and Development, Div. of Mineral Resources Bull, cited in Davis SN, DeWiest RJM (1966) Hydrogeology. John Wiley, New York.

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge. A guide to understanding and estimating natural recharge. Int Associaton Hydrogeologists. International Contribution to Hydrogeology 8.

Lloyd JM (ed) (1999) Water resources of hard rock aquifers in arid and semi-arid zones. UNESCO Studies and Reports in Hydrology 58.

Lomize GM (1951) Flow in fractured rocks [in Russian]: Gosenergoizdat, Moscow.

Long JCS, Endo KH, Karasaki K (1985) Hydrologic behavior of fracture networks. In: Hydrogeology of Rocks of Low Permeability, Memoires, 17th Congress, Int Association Hydrogeologists 449–462.

Lorenz JC, Finley SJ (1989) Differences in fracture achracteristics and related production: Mesaverde Formation, northwestern Colorado. SPE Formation Evaluation, March, 11–16.

Marinov NA et al (1974) Hydrogeology of Asia [in Russian]. Nedra, Moscow.

Marinov NA et al (1978) Hydrogeology of Africa [in Russian]. Nedra, Moscow.

Marrett RA (1996) Aggregate properties of fracture populations. Journal Structural Geology 18: 169–178.

Marrett RA, Ortega OJ, Kelsey CM (1999) Extent of power-law scaking for natural fractures in rock. Geology, 27: 799–802.

Martinec J (1975) Subsurface flow from snowmelt traced by tritium. Water Resources Research 3: 496–498.

Mayer JM, Sharp JM Jr. (1998), Fracture control of regional ground-water flow in a carbonate aquifer in a semi-arid region. Geol. Soc. America Bulletin 110: 269–283.

Mazurek M (2000) Geological and hydraulic properties of water-conducting features in crystalline rocks. In: Stober I, Bucher K (eds) Hydrogeology of crystalline rocks. Kluwer Academic Publishers 3–26.

Moench AF (1984) Double-porosity models for a fissured groundwater reservoir with fracture skin. Water Resources Research 20: 831–846.

Mouri S (2005) Comparison of varying aperture calculations. Geol Soc. America, Abstracts with Programs 37(3): 8.

National Research Council (1996) Rock fractures and fluid flow. National Academy Press, Washington, DC.

Neretnieks I (1980) Diffusion in the rock matrix: An important factor in radionuclide retardation? Journal Geophysical Research, 85(B8): 4379–4397.

Neuman SP (2005) Trends, prospects and challenges in quantifying flow and transport through fractured rocks: Hydrogeology Journal 13: 124–147.

Norton D, Knapp R (1977) Tranport phenomena in hydrothermal systems: Cooling plutions. Americn Journal Science, 277: 913–936.

Olofsson B, Jacks G, Knutsson G, Thunvik R (2001) Groundwater in hard rock – a literature review. Kassam Report. Stockholm, Sweden.

Ortega OJ, Marrett RA, Laubach SE (2006) A scale independent approach to fracture intensity and average spacing measurement. American Assoc. Petroleum Geologists Bulletin 90: 193–208.
Phyu T (2002) Transient modeling of contaminant transport in dual porosity media with fracture skins. MS, University of Texas, Austin, Texas.
Pointet T (ed) (1997) Hard rock hydrosystems. Proceedings, Int. Symposium S2 1997. Rabat, Morocco. IAHS Publication 241.
Rats MV (1967) Inhomogeneity of rocks and of their physical properties [in Russian]. Nauka, Moskva.
Rats MV, Chernyshov SN (1967) Statistical aspect of the problem on the permeability of the jointed rocks. Proc. Dubrovnik symposium on hydrology of fractured rocks . IAHS Publication 73: 227–236.
Read RE (1982) Estimation of optimum drilling depth in fractured rock. In: Papers of the groundwater in fractured rocks AWRC conference, Series 5: 191–197.
Rebouças A da C (1993) Groundwater development in the Precambrian shield of South America and West Side Africa. In: Banks S, Banks D (eds) Hydrogeology of hard rocks. Memoires 24th Congress, Int Association Hydrogeologists 1100–1114.
Robins NS (1993) Reconnaissance survey to determine the optimum groundwater potential of the Island of Jersey. In: Banks D and Banks S (eds) Hydrogeology of hard rocks. Memoires 24th Congress, Int Association Hydrogeologists 327–337.
Robins NS and Misstear BDR (eds) (2000) Groundwater in the Celtic Regions: studies in hard rock and Quaternary hydrogeology. Geol. Soc. Special Public. 182.
Robinson NI, Sharp JM Jr, Kreisel I (1998) Contaminant transport in sets of parallel finite fractures with fracture skins. Jour. Contaminant Hydrology, 31: 83–109.
Rohr-Torp E (1994) Present uplift rates and groundwater potential in Norwegian hard rocks. Geological Survey of Norway, Bulletin 426: 47–52.
Rohr-Torp E, Roberts D (eds) (2002) Hardrock hydrogeology – proceedings of a Nordic Workshop. Geological Survey of Norway 439: 7–14.
Rönkä E, Niini H, Suokko T (eds.) (2005) Proceedings Fennoscandian 3rd regional workshop on hardrock hydrogeology. Finnish Environment Institute. Helsinki, 1–9 June 2004.
Rovey CW (1998) Digital simulation of the scale effect in hydraulic conductivity Hydrogeology Journal 6: 216–225.
Sahimi M (1995) Flow and transport in porous media and fractured rock. VCH, Weinheim, Germany
Schulze-Makuch D, Cherkauer DS (1998) Variations in hydraulic conductivity with scale of measurement during aquifer tests in heterogeneous, porous carbonate rocks. Hydrogeology Journal 6: 204–215.
Schwarzbach M (1974) Klima der Vorzeit. Ferdinand Enke Verlag, Stuttgart.
Seiler KP, Müller K (1996) Discharge and ground water recharge in crystalline rocks of the Bavarian Forest, Germany. In: Krásný J, Mls J (eds) (1996) 1st workshop on hardrock hydrogeology of the Bohemian Massif. Acta Univ. Carolinae Geologica 40(2): 205–219.
Shapiro AM, Bear J (1985) Evaluating the hydraulic conductivity of fractured rock from information on fracture geometry. In: Hydrogeology of rocks of low permeability, Memoires, 17th Congress, Int Association Hydrogeologists, 463–472.
Sharp JM Jr. (1993) Fractured aquifers/reservoirs: Approaches, problems, and opportunities. In: Banks D, Banks S (eds) Hydrogeology of hard rocks: Memoires 24th Congress, Int Association Hydrogeologists 23–38.
Sharp JM Jr., Halihan T, Uliana MM, Tsoflias GP, Landrum,, MT, Marrett R. (2000) Predicting fractured rock hydrogeological parameters from field and laboratory data. In: Sililo, O., et al. (eds) Groundwater: past achievements and future challenges, Proceedings 30th Congress, Int Association Hydrogeologists 319–324.
Singhal BBS, Gupta RP (1999) Applied hydrogeology of fractured rocks. Kluwer Academic Publishers, Dordrecht, The Netherlands.
Snow DT (1968) Fracture deformation and changes of permeability and storage upon changes of fluid pressure. Quarterly Jour Colorado School of Mines 63: 201–244.
Snow DT (1969) Anisotropic permeability of fractured media. Water Resources Research 5: 1273–1289.

Staśko S, Tarka R (1996) Hydraulic parameters of hard rocks based on long-term field experiment in Polish Sudetes. In: Krásný J, Mls J (eds) (1996) 1st Workshop on hardrock hydrogeology of the Bohemian Massif. Acta Universitatis Carolinae Geologica 40(2): 167–178.

Stober I, Bucher K (eds.) (2000) Hydrogeology of crystalline rocks. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Stournaras G (ed) (2003) Proceedings,1st workshop on fissured rocks hydrogeology. Athens 12–14 June 2002.

Stournaras G, Pavlopoulos K, Bellos Th (eds) (2005) 7th Hellenic Hydrogeological Conference and 2nd MEM workshop on fissured rocks hydrogeology, Athens.

Streltsova TD (1975) Hydrodynamics of groundwater flow in a fractured formation. Water Resources Research, 12: 405–413.

Struckmeier W et al (2004) WHYMAP and the groundwater resources map of the world at the scale 1:50 000 000. Special edition for the 32nd Internat. Geol. Congress, Florence, Italy, August 2004.

Tóth J (1988) Ground water and hydrocarbon migration. In: Back, W, Rosenshein JS, Seaber PR (eds) Hydrogeology, the geology of North America, Geol. Soc. America ,O-2: 485–502.

Tóth J (1999) Groundwater as a geologic agent: An overview of the causes, processes, and manifestations. Hydrogeology Journal 7: 1–14.

Tsang YW and Tsang CF (1987) Channel model of flow through fractured media. Water Resources Research 23: 467–479.

Uliana MM (2001) Delineation of regional groundwater flow paths and their relation to structural features in the Salt and Toyah Basins, Trans-Pecos Texas. PhD, The University of Texas, Austin, Texas.

Voss CI (2003) Announcing a Hydrogeology Journal theme issue on "The Future of Hydrogeology" Hydrogeology Journal 11: 415–417.

Walton WC, Neill JC (1963) Statistical analysis of specific capacity data for a dolomite aquifer. Cited in Davis S.N., DeWiest R.J.M. (1966) Hydrogeology. John Wiley and Sons, New York.

Wright EP, Burgess WG (eds) (1992) The hydrogeology of crystalline basement aquifers in Africa. Geol. Soc. Special Publ. 66.

Yélamos JG, Villarroya F (eds) (1997) Hydrogeology of hard rocks: Some experiences from Iberian Peninsula and Bohemian Massif. Proceedings, Workshop of Iberian Subgroup on Hard Rock Hydrogeol.

Zektser IS, Everett LG (2004) Groundwater resources of the world and their use. UNESCO IHP-VI, Series on Groundwater 6.

Zhang X, Sanderson DJ, Barker AJ (2002) Numerical study of fluid flow in deforming fractured rocks using a dual permeability model. Geophys Jour. International 151: 452–468.

# Hydrogeological environment of fractured rocks

CHAPTER 1

# Hydrogeology of granite rocks in Sardinia

Giovanni Barrocu
*Professor of Engineering Geology, University of Cagliari, Department of Land Engineering, Faculty of Engineering, Piazza d'Armi, Cagliari, Italy*

ABSTRACT: Hydrogeological investigations consisting of structural, petrographical and geomorphological studies, geophysical and drilling operations and pumping tests, have demonstrated that the groundwater in the granite rocks in Sardinia may occur in fracture zones, weathered parts of the rock, and microgranite dikes. It has been confirmed that structural analysis is a valid method for determining the local fracture pattern in the rock. Tensional, shear, and overthrust fractures were produced by lateral stresses related to the different tectonic phases that have affected Sardinia during the Caledonian, Hercynian and Alpine orogeneses. The state of openness is strictly dependent upon the type of fracture, and is maximum along the tensile cracks and overthrust zones, and is strongly influenced by weathering and hydrothermal alteration. The dimensions of the aquifers may be limited by the presence of lamprophyre dikes, which act as flow barriers between contiguous granite sectors. In cases where these dikes are frequent, the granite aquifers may have good hydraulic conductivity but their storage capacity is poor. The aquifers in the granite rocks of Sardinia may contribute decisively to solving local water supply problems.

## 1 INTRODUCTION

The problem of developing groundwater in hard rocks in Sardinia was systematically tackled in the late sixties by the Institute of Engineering Geology, at the University of Cagliari. The results of early investigations were discussed with scientists and technicians from different countries at the international symposium held in Cagliari in October 1971 (Montaldo et al., 1971). In 1973 the Regional Government of Sardinia financed a pilot investigation in different areas of Sardinia, which involved a group of researchers in Engineering Geology, Cagliari and the Department of Land Improvement and Drainage, Stockholm. The results were summed up in the report by Barrocu et al., (1974) and presented in two official meetings, in Stockholm, in April 1974, and in Cagliari, in October 1974. The cooperation between the Faculty of Engineering of the University of Cagliari and the Royal Institute of Technology, Stockholm, continued into a second project financed by the Regional Government of Sardinia and the Swedish Board for Technical Development. The results of these investigations were the subject of the applied part of the International Seminar on Groundwater in Hard Rocks (Stockholm Cagliari, September 22–October 7 1977). The seminar was convened by UNESCO and organized in cooperation with the Royal Institute of Technology, Stockholm and the University of Cagliari, with the financial support of the Swedish International Development Authority and the Technical Cooperation Department of the Italian Ministry for Foreign Affairs and in collaboration with FAO and the UNESCO-IHP Committees of Sweden and Italy, for the benefit of participants from developing countries.

The two essentially scientific research projects aimed to identify the best methodology for the development of groundwater in hard rocks under the climatic conditions of Sardinia. A research methodology was adopted which has since proven effective and has become routine in groundwater investigations carried out so far in granite rocks, mainly for the benefit of local communities.

The local interest for this type of investigation is evident if we consider that hard rocks, mainly consisting of granites, make up about one quarter of the total surface area of Sardinia (i.e., about 6,000 $km^2$ of its 23,833 $km^2$ or 24,089 $km^2$ including the small coastal islands). There is a pressing need for rationally developing all the island's water resources. Average annual rainfall for the region as a whole is not particularly low (about 660 mm/year in the period 1921–2002). Precipitation is concentrated in the cold periods and is highly variable from one year to another. In fact Sardinia has a typical Mediterranean climate. Because of the small rural centers and of the widely dispersed population in a rather rugged and scantily populated region (45 inhab/$km^2$, disregarding the provincial capitals), it is economically important to exploit all available groundwater resources, especially where the user points are scattered to meet the needs of shepherds, farmers and seasonal vacation communities.

## 2 GEOLOGICAL OUTLINE

The granite rocks in Sardinia are mainly muscovite-biotite- and biotite-granites, granodiorites, diorites, gabbrodiorites, aplites, and their frequent microgranular, porphyritic and pegmatitic varieties. The granite bodies are often intersected by swarms of lamprophyre and microgranite dikes. They generally belong to the crystalline basement of the island, which from the late pre-Cambrian up to the present time has been affected by all the geodynamic events that have taken place in the Mediterranean basin, namely the Caledonian, Hercynian, and Alpine orogenesis. As indicated in the geotectonic map of Figure 1, the granite rocks make up the northern and northern-central part as well as the south-eastern corner of Sardinia. Other major outcrops are present in the south-west and along the east coast. On the whole, they are associated with the Caledonian and especially the Hercynian orogenesis. Observations on the relationships between the different rock types within the granite bodies have suggested that the latter might have been reactivated in some way during the different orogenic phases.

The crystalline basement of Sardinia and Corsica, partially covered by Mesozoic and Cenozoic deposits, has also been strongly affected by the Alpine orogenesis. According to a number of authors (Zarudski et al., 1971; Montaldo et al., 1971; Van Bemmelen, 1972; Cocozza and Jacobacci, 1975; Pala et al., 1982 a, b; Ciminale et al., 1985; Egger et al., 1988), the Corsican-Sardinian block, which at the end of the Hercynian cycle formed part of Spain and France, in the late Cenozoic was separated along the present French-Spanish coast, and rotated 50° anticlockwise to its present position. This megatectonic process opened up two major tectonic trough structures, the western Mediterranean and the Campidano graben, in south-west-central Sardinia, interpreted as subparallel features of crustal extension. It has been suggested that the Campidano tectonic trough, as well as the Tyrrenian one, was produced by tensional actions (Barrocu and Larsson, 1977). Other secondary tectonic

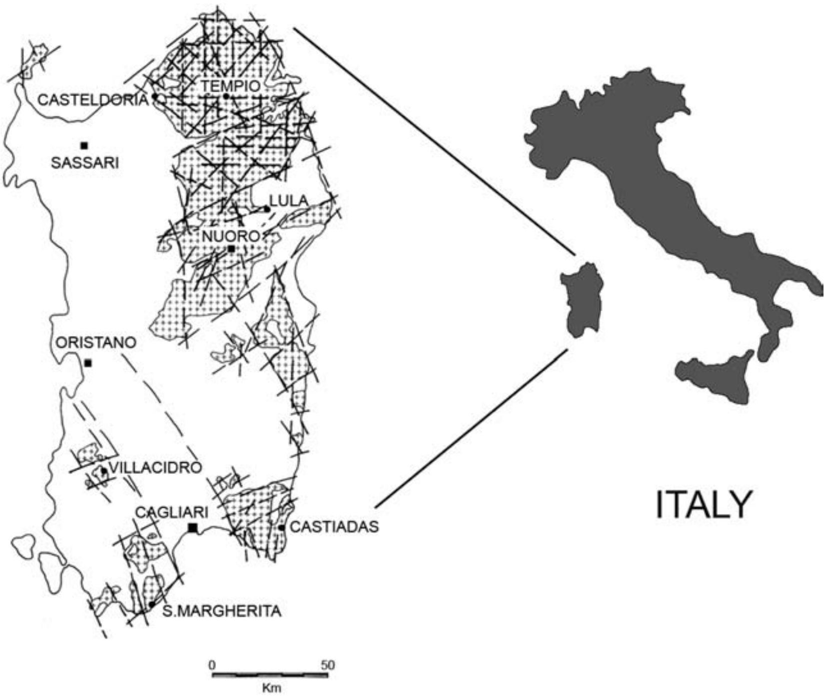


Figure 1. Granite rocks in Sardinia.

troughs formed on both sides of the Campidano, to the north-east (Chilivani – Ozieri), central east (Tirso, Marreri-Isalle, Cedrino) and to the south-west (Cixerri). These physiographic features are the most representative of the tectonic pattern of Sardinia.

Because of the up- and downfaulting of the different tectonic blocks during the Alpine orogenesis, the physiography of the crystalline basement has been rejuvenated and afterwards partly leveled by a strong denudation. At present, it is characterized by partly weathered, mostly rounded and almost flat-topped massifs, often separated by deep and intractable valleys. The scree covered slopes are bordered at the foot by piedmont deposits in the valleys and tectonic troughs.

## 3 METHODOLOGY OF GROUNDWATER INVESTIGATIONS

The hydrogeological investigations systematically carried out in different areas of Sardinia have consisted chiefly in determining the geological, petrographical, and geomorphological characteristics, structural analysis (field studies and photogeological interpretation), geophysical investigations, drilling operations, logging and test pumping, and hydrochemical analysis.

In order to determine the different parameters of the hydrological cycle (rainfall, surface run-off, infiltration and evapotranspiration) in relation to the structural pattern under different climate conditions, the elementary basins of Santa Margherita (0.45 $km^2$), Castiadas (3.37 $km^2$) and Nuoro-Monte Ortobene (0.43 $km^2$) were initially taken into consideration

(Fig. 1). The first two basins are situated by the sea, respectively on the south-west and south-east coast, and the third near the top of a mountain in central Sardinia, at about 700 m a.s.l. All basins were equipped with recording rain gauges and V-notch and sharp crested weirs installed in concrete barrages. Water level recorders were placed in all weirs and recently also in two wells at Santa Margherita.

Geophysical investigations (refraction seismic, earth resistivity, magnetic and VLF electromagnetic methods) were carried out only where strictly necessary, because of the high costs involved. The results indicated that the combined VLF electromagnetic and magnetic surveys, can provide a useful and economical support in interpreting the anomalies identified by seismic and earth resistivity measurements, namely in determining the nature of low velocity zones (Barrocu and Ranieri, 1977).

Wells were drilled with a compressed air powered drilling rig operating with down-the-hole hammer. As the rig was mounted on a wagon drill, it was possible to drill wells even in rather rugged areas, down to a maximum depth of 18 m in the weathered granite and 85 m in the fractures. Internal diameters ranged from 75 to 100 mm in the exploration wells and from 100 to 165 mm in the productive wells. The latter were generally steel or plastic cased in order to prevent them from collapsing.

Structural analysis combined with geophysical surveying was generally adopted in subsequent investigations to identify the most favourable drill sites. Wells are generally drilled down to 50–80 m, but fresh groundwater was found down to a few hundred metres. In south-western Sardinia, in a tunnel of an old molybdenite mine, a constant fresh groundwater yield of 4.0 L/s was measured at −700 m in a shear zone crossing several tension fractures (Barrocu and Vernier, 1971).

Using an iterative procedure, the conceptual model defining hydrogeological and hydrochemical processes should be defined and progressively updated in relation to the local structural pattern. Hydrostructure model definition generally requires expensive field investigations, and for this reason problems need to be carefully examined so as to minimize costs and maximize benefits.

## 4 GROUNDWATER OCCURRENCE

Preliminary hydrogeological surveys carried out in the early seventies indicated that the granites in Sardinia first underwent plastic deformation during their intrusion, prior to being completely crystallized, and subsequently post-crystalline ruptural deformation (Barrocu and Larsson, 1977; Barrocu et al., 1974).

The plastic deformation may be indicated by the orientation, sliding and rotational movements of certain crystals, especially biotite and quartz, and generally by tension cracks "en echelon" parallel to the main compression stress and perpendicular to the deformation axis (Sander, 1948; Larsson, 1968, 1972; Barrocu and Larsson, 1977).

Tensional, shear and overthrust fractures were recognized as having been produced by lateral stresses associated with the different tectonic phases that affected Sardinia during the Caledonian, Hercynian, and Alpine orogenesis (Barrocu and Larsson, 1977).

According to the deformation model proposed by Larsson, 1972 (Fig. 2), the post-crystalline deformations due to tangential stresses acting on a rock body consist of: (1) tensional joints, generally vertical and perpendicular to the axis of deformation,;

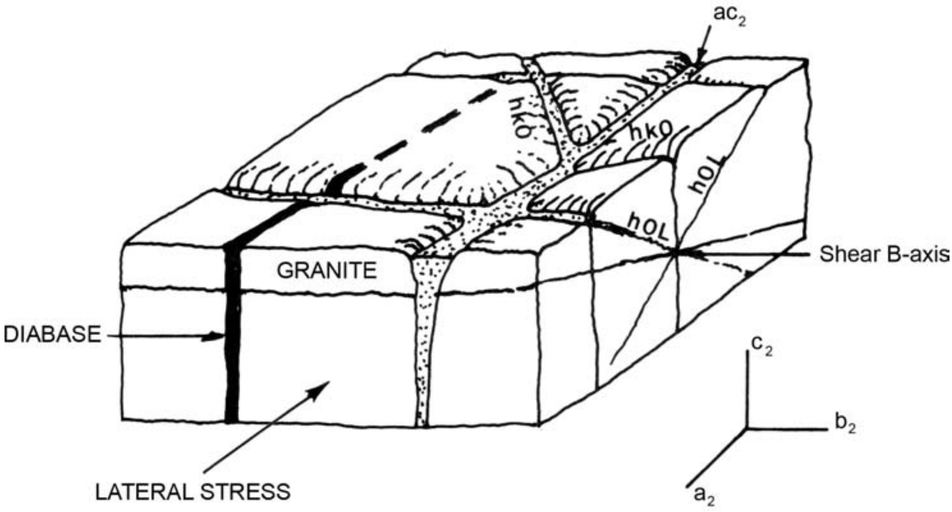


Figure 2. Granite deformation model representing tension fractures ($ac_2$), shears (hk0), and overthrusts (h0l) (Larsson 1972, slightly modified).

(2) shear fractures, usually vertical and oblique in relation to the tensional joints, often with slickensides, breccias, and mylonites; and (3) overthrust shear fractures from compression movements along sub-horizontal planes. Openness of fractures strongly depends on fracture type, and attains a maximum along the tensile cracks and overthrust zones.

Since tensional fractures are well developed both lengthwise and depthwise, they tend to create empty spaces enabling the intrusion of lamprophyre, aplite and microgranite dikes and thus generally indicate tensional forces in the earth crust.

Overthrust shear fractures, which indicate a shortening of the granite block in the direction of the main stress, may be distinguished by joints due to load release and cooling effects of the intrusive mass. They are often accompanied by slickensides and cataclastic phenomena, and their effective porosity consists of empty spaces clearly due to fracture gouge erosion produced by groundwater flow.

Aquifer dimensions may be limited by the presence of lamprophyre dikes, consisting of hornblende-plagioclase-spessartite with minor interstitial orthoclase and quartz. We have found in several areas under different conditions that they usually act as underground barriers between contiguous granite sectors. The damming effect seems to be caused by: the sealing of open fractures by the intrusion of lamprophyric magma, and especially, the intense weathering of the lamprophyres, which are generally much more argillified than the granites of the wall rock. In areas where these dikes occur, granite aquifers between them may have good hydraulic conductivity but their storage capacity is poor, depending on fractured granite zone dimensions. The closer together the dikes are the fewer the possibilities of finding a good aquifer (Barrocu and Vernier, 1975).

In conclusion, groundwater in the granite rocks of Sardinia may be found in fracture zones, weathered parts of the rock, and microgranite dikes. It may be difficult to determine the mutual relationship of the different type of aquifers because the groundwater reservoirs and the catchment areas do not often coincide (Barrocu, 2005).

## 4.1 *Aquifers in fracture zones*

Larsson (1968) demonstrated that the tension cracks formed in the plastic stage, on account of their shortness and "en echelon" development, represent poor aquifers unless their original pattern has been disturbed by later deformations. On the other hand, the post-crystalline tension fractures, which are much longer, are potentially good groundwater reservoirs and collectors of the water stored in the smaller fractures communicating with them.

Overthrust zones have high storativity as well, both because of their intense fracturing and of the fact that they are good conductors of surface infiltration, owing to their orientation in relation to the topography. The storativity of the shear fractures may vary considerably, depending on the state of weathering of the fractured rock. Fractured zone porosity may be greatly increased by relative rotational movements of the different blocks separated by faults as observed in Santa Margherita in the fracture zones between blocks A and B (Fig. 3). These phenomena may be surveyed using detailed structural analysis to determine the differential movements of the parts of a rock body. Similar block rotation effects, creating voids of hydrogeological interest, have also been recognized in other areas in northern and central Sardinia.

When exploring for groundwater in granite rocks, one should understand that the structural model may be much more complicated than expected, especially if the granite bodies have been affected by several phases of post-crystalline deformation. For instance, at Castiadas and Santa Margherita, respectively on the south-east and south-west coast of

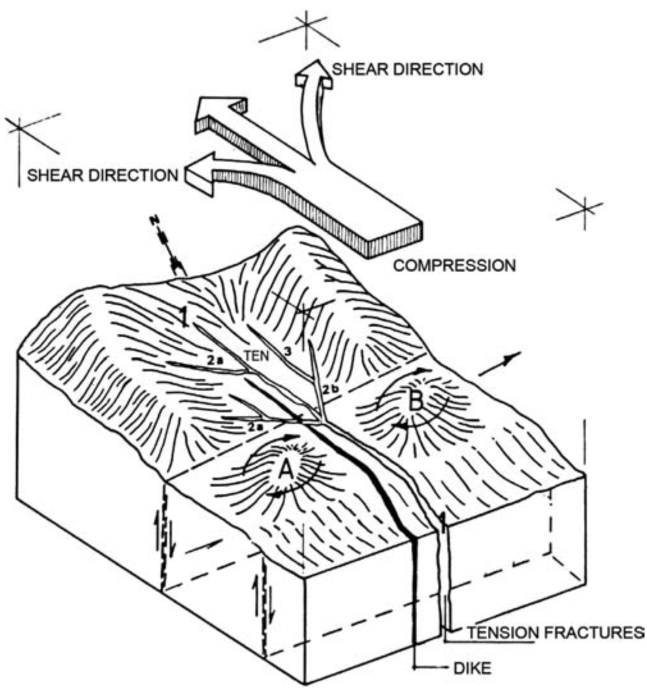


Figure 3. Postcrystalline deformations at Santa Margherita, southern Sardinia. Two ENE-WSW normal faults, perpendicular to a main tension fracture, displaced the southern part of the block in the two sub-blocks A and B, displaced en echelon, and sloping down into the coastal plain. Sub-blocks A and B, were rotated clockwise by nearly 10° (Barrocu and Larsson, 1977).

Sardinia, the granite bodies are crossed by swarms of N60°W–S60°E trending vertically dipping microgranite dikes, which, on account of their length (up to 1–2 km) and thickness (up to 40–50 m) seem to indicate an intense phase of post-crystalline deformation, which affected the whole crust at depth. It is possible that the intrusion of these dikes represents a reactivation phase of the granite batholiths. The lamprophyre dikes intersect them almost perpendicularly and may be associated with a successive deformation phase.

Yearly rainfall is in the order of 1000–1100 mm in the highlands of northern and central Sardinia, and ranges between 500 and 600 mm in southern Sardinia on the coast. Surface water is rapidly absorbed into fracture zones. A surface runoff coefficient of 0.02 was measured in 1976 at the catchment of Santa Margherita with a yearly runoff of nearly 18,000 $m^3$. In granite areas, potential evapotranspiration values ranging between 636 and 862 mm/year have been calculated. An average evaporation of 2,353 mm/year has been measured in the Lake Omodeo, in central Sardinia, and of 2,720 in the coastal pond of Santa Gilla, in southern Sardinia.

Several wells drilled in the Rio Pagghiolu valley demonstrated that the most productive aquifer is hosted in a large shear zone, which crosses several granite sectors and acts as their drain (Barrocu et al., 1974). An inclined well drilled through this fracture in the summer of 1973, gave a yield of about 2.1 L/s (7.6 $m^3$/h), and this value was confirmed in a pumping test in summer 1977. Further systematic *in situ* and laboratory investigations were carried out in the area, with a view to finding correlations between fracturing parameters, geomechanical characteristics, and permeability data measured down to $-50$ m below the land surface (Barrocu and Manca, 1979). A number of productive wells were drilled and groundwater has since been developed for a well known oligomineral water in Sardinia. The single granite sectors between the lamprophyre dikes, even if heavily fractured, form hydrological units quite independent of one another, with different water levels and a yield of only a few L/h. In an investigation carried out in the outskirts of Tempio to study the hydrogeology and hydrochemistry of the catchment area of the Rinaggiu oligomineral spring, the damming effect of the lamprophyre dikes was confirmed with several exploration and productive wells drilled spaced a few meters apart (Barrocu, Jacks and Vernier, 1976).

In the area of Nuoro, in central Sardinia, which has average annual rainfall of 800 mm, the tectonic pattern is dominated by rather tight shear fractures. A storativity of 0.05% was determined. This figure would correspond to a bed storativity of about 4,000–7,000 $m^3/km^2$. The yield of a number of drilled wells ranged from 0.10 to 0.86 $m^3$/h, the specific capacities being from $4.1\times10^{-2}$ to $2.9\times10^{-2}$ $m^2$/h (Rosén, 1974).

In the granite area of Santa Margherita di Pula, southern Sardinia, the main aquifer is represented by a tension fracture zone draining smaller cracks. Applying the Theis, Jacob and Cooper, and Chow methods, coarse fractures showed transmissivity T ranging from $8\times10^{-6}$ to $3\times10^{-5}$ $m^2$/s and storativity S from 0.3 to 2.2%. In the fine fractures transmissivity ranged between $1.5\times10^{-6}$ and $4.0\times10^{-6}$ $m^2$/s, and storativity between 0.15 and 0.8%. The fracture pattern had an average storativity S = 0.5%. Assuming a general coarse fracture depth of 10–15 m a storage capacity of 27,000–40,000 $m^3$ was obtained in the experimental catchment area of 0.45 $km^2$. Very rough calculations give storativity of about 50,000–80,000 $m^3/km^2$ for the fracture pattern of the granite. It was observed that the lag effect of precipitation on the drawdown during the recharge after the removal of water by pumping from the wells was very low, varying in relation to the soil moisture content according to previous rainfall and rain intensity. With a relatively dry soil the lag effect is longer. The discharge is strongly affected by rainfall, which is rapidly absorbed in the fractures. Three wells drilled in the most open fractures yielded 0.4, 0.14 and 1.50 $m^3$/h, the corresponding specific capacity being 0.02, 0.0067 and 0.063 $m^2$/h. Unfortunately, in the area of Santa Margherita the groundwater drains into the sea by the same fracture zone along which the rainfall and surface runoff are absorbed.

## 4.2 *Aquifers in weathered granites*

Most of the granite rocks in Sardinia are covered with a weathered mantle, especially in the flat or gently sloping plateaux and valley bottoms. The maximum thickness of this mantle does not generally exceed 15–20 m, but in heavily fractured zones weathering effects have been observed at a depth greater than 60 m, especially along overthrust fractures (Barrocu, 1971).

In the area of Milizzana, Tempio, northern Sardinia, several wells were drilled down to the bed-rock, at 15–17 m, in different semiconfined aquifers in weathered granite. Owing to the damming effect of the lamprophyre dikes, the mutual influence between the different wells, drilled very close to each other, is negligible. Yields ranging between 0.5 and 2.30 L/s (1.8–8.3 $m^3$/h) have been measured in different periods in 1975–1977. The water has been found in heavily weathered fractured zones 30–40 m thick, interpreted as overthrusts. Barbieri and Vernier (1977) calculated a transmissivity ranging between $1.37 \times 10^{-4}$ and $1.67 \times 10^{-4}$ $m^2$/s and a storativity S = 0.33–0.49%. A hydraulic conductivity value K ranging from $2.74 \times 10^{-4}$ to $3.34 \times 10^{-4}$ m/sec was calculated.

At Lula, central Sardinia, one productive and three observation wells were drilled in June 1973 in a mantle of weathered diorite, down to a maximum depth of about 12 m. The productive well yielded 1.4 L/s (5.04 $m^3$/h) at a drawdown of 3.2 m (Barrocu et al., 1974). A hydraulic conductivity of about $5 \times 10^{-4}$ m/s was calculated, and a storativity of 2–3% was estimated. The average rainfall at Lula amounts to around 500 mm/year.

## 4.3 *Aquifers in microgranite dikes*

Investigations carried out at Santa Margherita, south-west coast, and Fonni, central Sardinia, showed that microgranite dikes can be locally important hydrogeological reservoirs (Barrocu and Vernier, 1975). The capacity of such aquifers is determined by the dike dimensions, the fracture pattern, the wall rock lithological and structural characters, and the recharge conditions, which can be continuous or discontinuous, depending on rainfall. Because of their brittleness, microgranite dikes generally appear to be highly fractured. On the other hand, they are not affected to any great extent by weathering. It was observed in different areas that they may act as good drains for wall rock fractures, unless hydrothermal effects related to the intrusion of the dikes are present. In such cases abundant clay products naturally seal the fractures in the granite, which may become even tighter if weathering occurs as well. Because of the rugged morphology and their peculiar shape, the recharge areas are quite small and do not generally coincide with the catchment areas.

In a well drilled at Santa Margherita in a microgranite dike down to a depth of 36 m, groundwater issued from several 30–40 cm thick fracture zones, interpreted by the authors as overthrusts. After pumping for 72 hours, the yield remained stable for one week at 2 L/sec (7.2 $m^3$/h) with a drawdown at 16 m, after which it slowly decreased down to a stable value of 0.25 L/sec, after one month. Two observation wells drilled at the sides showed that slabs of argillified granite were included in the dike. Their yield was insignificant.

Wells drilled for water supply in a microgranite dike in the area of Fonni, central Sardinia, at altitudes of 900–1400 m, after 48 hours of pumping tests exhibited a stable yield in the order of nearly 1–2 L/sec (3.5–7.5 $m^3$/h) with a drawdown of 17–20 m, again fairly stable. In both cases the granite country rock is rather disintegrated because of intense fracturing and weathering.

Values of transmissivity T ranging from $1.26\times10^{-4}$ to $1.72\times10^{-4}$ $m^2$/s, storativity S = 0.15–0.45%, and hydraulic conductivity K ranging from $2.52\times10^{-4}$ to $3.34\times10^{-4}$ m/s were calculated.

## 4.4 *Thermal groundwater*

Very few deep boreholes have been drilled in Sardinia granite rocks, namely in the immediate vicinity of the major fracture zones where the thermal springs of Casteldoria issue groundwater at the temperature of 73.3 °C. Between 1956–63 systematic investigations for geothermal research were carried out in the area where two major N-S and E-W trending orthogonal faults cross in a graben which abruptly limits the north-western border of the Hercynian granite block of Gallura. The granite basement in the tectonic trough is overlaid by Tertiary and Quaternary sedimentary and volcanic formations of Anglona (Fig. 1). Groundwater with a head of 12 m a.s.l. issuing from exploration wells drilled down to −100 m, located at 5 m a.s.l., was an early confirmation that it flowed from a deep syphon circuit. Drilling operations and borehole logging ascertained that the granite bedrock is very fractured down to −1,000 m, with repeated higher permeability levels, which can be interpreted as overthrusts. In two boreholes thermal groundwater with a temperature of 98 °C was found at a depth of −735 and −260 m below sea level, with a head of 18 m a.s.l. (Trudu, 1971).

Subsequent geophysical investigations carried out in Sardinia identified deep thermal anomalies with temperatures of up to 150 °C at 2,000 m depth (Loddo et al., 1982). Major faults control thermal water circulation, with a downward movement schematically interpreted as a multi-cell system with relatively fast upward movement due to gas pressure (Panichi, 1982). Mixing of shallow groundwater with the deep saline water is marked by increasing TDS, in the range of 6,500–9,100 mg/L, decreasing Ca/Mg ratios, Na/Cl dominant character, and higher concentrations of B, and Sr. The Na/Cl ratios are close to values observed in seawater; and Cl, Na, K, B, and Sr show high correlation coefficients, indicating an origin from diluted, modified seawater (Caboi et al., 1986; 1993). The origin of thermal waters salinity can be chiefly attributed to sea level fluctuations during geologic history, especially during the Quaternary. Seawater saturated the deep fractures of the crystalline basement and is presently remobilised by circulating fluids. Isotope analysis results confirm that faults should be considered as always active circuits controlling mobility for water and gases in cratonic areas. Former active areas or quiescent areas are still producing hot water and deep gases (Angelone et al., 2005).

## 4.5 *Conceptual models*

Only the upper crust, where recent groundwater mostly circulates, is generally taken into consideration in groundwater investigations, but the conceptual model of fissured rocks may be rather complex and requires different methods of investigation, depending on the targets and scales of observation.

It is known that meteoric waters may partly circulate in fractures at shallow depths, and partly infiltrate at depth along major fractures, along which old groundwater stored therein flows up towards the surface. The groundwater flow in major hydraulically connected vertical and horizontal fracture zones having considerable dimensions (several kilometers) can create flow systems which would be very difficult to recognize in fractured media.

Fractured media may be so heterogeneous and complex with preferential pathways for groundwater and pollutants and with highly variable hydraulic conductivity and storage capacity so that modelling is a difficult task. Conceptual model uncertainty grade level is also high because of uncertainties in structure, boundary conditions, limits, and properties.

Precipitation and surface waters that infiltrate through the soil and formations overlaying the basement, flow partly along the discontinuities of the upper crust issuing from springs and wells as fresh groundwater, and down in depth, where they are heated, to rise again along major fractures of the crystalline bedrock, issuing as thermal waters in a number of springs located along the major faults which dissected Sardinia into uplift and downlift tectonic blocks.

The degree of interconnection between the flow systems of the fractured bedrock and the overlaying porous deposits defines, at the regional scale, the nature of the entire flow domain, and is a function of the hydraulic properties of the two components. These properties include fracture-network distribution, orientation, apertures, connectivity, sediment porosity and hydraulic conductivities of the entire bulk system.

## 5 CONCLUSIONS

The results of investigations carried out to date and those still in progress in different granite areas of Sardinia confirm the reliability and validity of a geomechanical approach on a local scale. Structural analysis has proven a useful method for determining the local rock fracture pattern. In the areas taken into consideration, the geological and structural studies, with the support of the photogeological interpretation and the use of geophysical methods (refraction seismic, magnetic, VLF electromagnetic and earth resistivity surveys) have made it possible to reconstruct the local tectonic pattern.

Aquifer characteristics are strongly conditioned by the presence of dikes and effects of weathering and hydrothermal alteration. Dikes can be strongly weathered in depth, so that they act as underground barriers between contiguous granite sectors.

The granite rocks of Sardinia may represent a valuable source of groundwater for farms and small rural villages as well as for tourist resorts along the coast. A well yield of 0.3–0.5 L/s (2.6–4.3 $m^3$/day) may be sufficient to satisfy human and animal drinking water demand and provide irrigation of some hectares on the basis of a yearly demand estimated at 5 $m^3$/ha. However, it is essential that the exploitation of these water resources be scientifically controlled in terms of safe yield considering local conditions.

Data are not sufficient yet to evaluate the amount of effective infiltration which recharges fractured granite aquifers in the upper and lower crust. Land use and morphology strongly affect water budget parameters, particularly in fracture zone aquifers. Thus, they should be calculated with reference to representative areas kept in observation, especially as concerns effective infiltration and runoff.

In certain cases the granite rocks can create fairly good reservoirs. In others, because rainfall is not very abundant and especially not evenly distributed throughout the year, yield tends to be fairly high after rainfall events, then decreasing as the groundwater finds its way to the sea. The investigations carried out so far have indicated that in certain cases the fracture zones and the microgranite dikes might be usefully and easily sealed off at their outlet, in order to create groundwater reservoirs.

## REFERENCES

Angelone M, Gasparini C, Guerra M, Lombardi S, Pizzino L, Quattrocchi F, Sacchi E, Zuppi GM (2005) Fluid geochemistry of the Sardinian Rift-Campidano Graben (Sardinia, Italy): fault segmentation, seismic quiescence of geochemically "active" faults, and new constraints for selection of $CO_2$ storage sites. Applied Geochemistry, 20: 317–340, Elsevier.

Barbieri G, Vernier A (1977) Subsurface hydrology – Tempio Pausania. "Geohydrological Investigations of Ground Water in Granite Rocks in Sardinia", II 3:21A, Dept Land Impr Drain, R Inst Technology, Stockholm.

Barrocu G (1971) Idrogeologia sotterranea dei graniti cataclastici della valle del Rio San Gerolamo fra Monte su Sinzurru e Monte Pauliara, Capoterra (Sardegna meridionale).

Barrocu G (2005) – Groundwater investigation planning and management in fissured rocks. Keynote, Proc 7th Hellenic Hydrogeol Conf on Fissured Rocks Hydrology. Athens 2005, Oct. 4–6, II, 55–68, ISBN 960-88816-2-5.

Barrocu G, Jacks G, Houtkamp H, Larsson I, Montaldo P, Vernier A, Wiberg L (1974) Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia. Dept Land Impr Drain, R Inst Techn, Stockholm, I 3:15: 1–74.

Barrocu G, Jacks G, Vernier A (1976) Hydrogeological and hydrochemical Investigations on the Spring of Rinaggiu, Tempio. Techn Report, Cagliari.

Barrocu G, Larsson I (1977) Granite tectonics at groundwater prospection in southernmost Sardinia. In: Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia. Dept Land Impr Drain, R. Inst Techn Stockholm, II 3:21A: 3–27.

Barrocu G, Manca PP (1979) Geomechanical characteristics of a granite body at a dam site. In: Proc Int Symp IAEG on Eng Geol Probl in Hydrotechn Constructions, Tbilisi, URSS – Bull IAEG, 20: 32–35.

Barrocu G, Vernier A (1971) Acque nella miniera di Perd'e Pibera (Sardegna sud-occidentale). In: Proc Int Sym on Groundwater in Crystalline Rocks. Cattedra di Geologia Applicata Fac Ing Univ Cagliari, 142–149.

Barrocu G, Ranieri G (1977) Preliminary considerations on the utilization of very low frequency electromagnetic methods in hydrogeological investigations in a granite area "Atti Fac Ing Univ Cagliari", 8.

Barrocu G, Vernier A (1975) Notizie preliminari sulla idrogeologia di alcuni filoni di porfido in rocce granitiche della Sardegna. III Conv Int Acque Sott Palermo Nov 1975. In: "Atti Cattedra di Geologia Applicata Fac Ing Univ Cagliari", 1–9.

Caboi R, Cidu R, Fanfani L, Zuddas P (1986) Geochemistry of thermal waters in Sardinia (Italy). In: Proc 5th Int Symp WRI Reykjavik, Iceland, August 8–1, 1986.

Caboi R, Cidu R, Fanfani L, Zuddas P, Zanzari AR (1993) – Geochemistry of the high-$pCO_2$ waters in Logudoro, Sardinia, Italy. Applied Geochemistry, 8: 153–160.

Ciminale M, Galdeano A, Gibert D, Loddo M, Pecorini G, Zito G (1985) – Magnetic Survey in the Campidano Graben (Sardinia): description and interpretation. Boll Geof Teor Appl, 27: 221–235.

Cocozza T, Jacobacci A (1975) Geological outline of Sardinia. In Geology of Italy. The Earth Science Soc of the Lybian Arab Rep, Tripoli, II: 49–81.

Egger A, Demartin M, Ansorge J, Banda E, Maistrello M (1988) The gross structure of the crust under Corsica and Sardinia. Tectonophysics, 150: 363–389.

Larsson I (1968) Groundwater in Precambrian rocks in Southern Sweden. Proceedings of the International Symposium on Groundwater Problems. October, 1966, Stockholm.

Larsson I (1972) Groundwater in granite rocks and tectonic models. Nordic Hydrology, 3.
Loddo M Mongelli F, Pecorini G, Tramacere A (1982) Prime misure di flusso di calore in Sardegna. In: Ricerche Geotermiche in Sardegna con particolare riferimento al Graben del Campidano. PFE-RF 10, CNR-Rome 181–209.
Montaldo P (ed), Proc Int Symp on Groundwater in Crystalline Rocks Cattedra di Geologia Applicata, Fac Ing Univ Cagliari, 115–126.
Pala A, Pecorini G, Porcu A, Serra S (1982 a) Schema geologico strutturale della Sardegna. In: Ricerche Geotermiche in Sardegna con particolare riferimento al Graben del Campidano. CNR-PFE-SPEG-RF10, CNR-Pisa 7–24.
Pala A, Pecorini G, Porcu A, Serra S (1982 b) Geologia e idrogeologia del Campidano. In: Ricerche Geotermiche in Sardegna. CNR-PFE-SPEG-RF10, CNR-Pisa 87–103.
Panichi C (1982) Carta delle temperature sotterranee. CNR-PFE-RF 10, CNR, Roma.
Rosén B (1974) Subsurface hydrology. In: Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia, Dept Land Impr Drain, R Inst Techn, Stockholm, II, 3:21A: 69–82.
Sander B (1948) Einführung in die Gefügekunde der geologischen Körper, I Springler Verlag, Wien Insbruch.
Trudu R (1971) Esami fisici in fori sonda per ricerche di aree termali in Regione Casteldoria (Sardegna). Proc Int Sym on Groundwater in Crystalline Rocks. Cattedra di Geologia Applicata, Fac Ing Univ Cagliari, 29–40.
Van Bemmelen RW (1972) Geodynamic models, an evaluation and synthesis. "Developments in Geotectonics", 2, Elsevier, Amsterdam.
Zarudski EFK, Wong HK, Morelli C, Finetti IR (1971) Regional NW-SE seismic reflection profile across Tyrrenian. "Trans Am Geophys Union", 52, 4.

CHAPTER 2

# Groundwater exploitation of fractured rocks in South America

Emilia Bocanegra[1] and Gerson C. Silva JR.[2]

[1]*CIC. Centro de Geología de Costas y del Cuaternario Casilla de Correo Mar del Plata – Argentina*

[2]*Departamento de Geologia, Instituto de Geociências – Universidade Federal do Rio de Janeiro. Ed. CCMN Sala Rio de Janeiro – RJ BRASIL*

ABSTRACT: South America has a generous natural supply of water although it also has a notorious heterogeneous spatial distribution. Groundwater is an important resource that occurs mostly in sedimentary basins occupying 70% of the territory and in areas of igneous and metamorphic rocks that include mechanically fissured water bearing units of low permeability. Some study cases of intensive exploitation in fractured aquifers are presented in this paper, with examples of the semi-arid northeast of Brazil, in the large metropolis of São Paulo (Brazil), in the basin of the Bogotá river (Colombia), and in the city of Cuzco (Peru), among others. The knowledge of the hydrodynamic and hydrochemical aspects of the fractured aquifers in South America is insufficient, so it is necessary to improve the study of their potentiality inasmuch as, in all cases, groundwater extracted from these aquifers constitutes an essential support for the development of economic activities.

## 1 INTRODUCTION

South America has a population of over 345 million living in an area of 17.8 million km$^2$. The continent has significant water resources, with some of the more important and voluminous river basins of the world and a mean precipitation of 1600 mm/year, by far the best-ranked continent in terms of absolute water availability. Rainfall shows, however, a notorious heterogeneity regarding its distribution, ranging from a few mm/year in southern Peru and northern Chile (the driest area on the planet), to more than 8000 mm/year in southern Chile and northeast Colombia.

Large river basins with elevated rain modules such as the Amazonas and the Paraná River basins, as well as large wetlands, characterize South America. Sedimentary basins occupy approximately 70% of the territory, but some regions with acute water scarcity are located in crystalline terrains, where groundwater resources take place only in thin weathering mantles and rock fracture systems. Part of the hydrogeological properties and resources of the sedimentary aquifers is given by fracture systems, and sometimes close hydraulic interaction occurs between igneous rocks and sedimentary aquifers, as for example in the vast basalt lava flows of the Paraná and Amazon sedimentary basins. For this reason, sedimentary units where fracture systems play a significant role will be also considered in the present work, although most cases correspond to igneous and metamorphic fractured aquifers – crystalline rock aquifers. Crystalline basement rocks are commonly used as a source of groundwater because of their wide extent but yields are typically small and the low storage makes boreholes prone to drying up during drought (Morris et al. 2003).

Figure 1 shows the distribution of igneous and metamorphic rocks across South America. Those types of rocks generally coincide with the distribution of the so called "hard rock

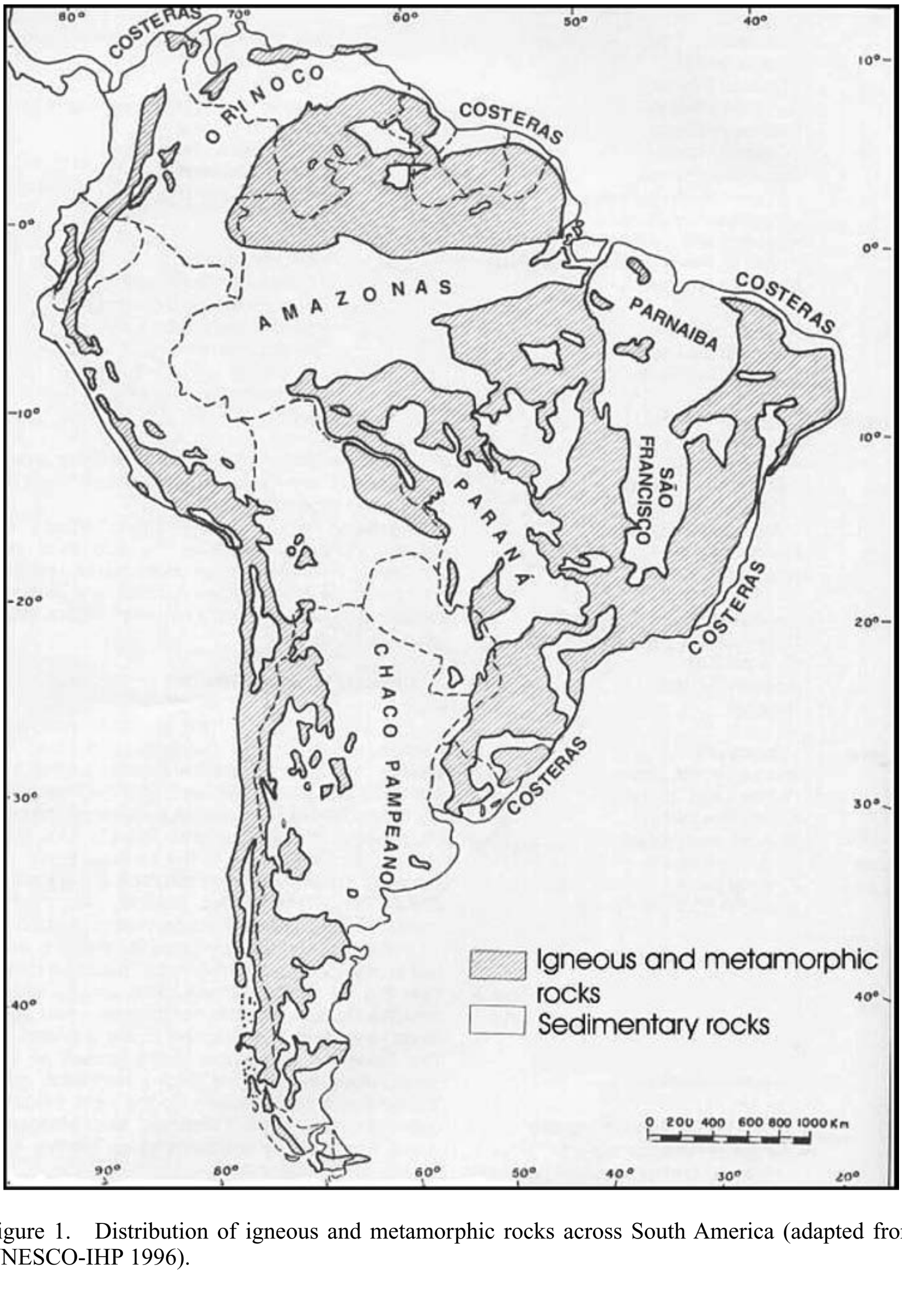


Figure 1. Distribution of igneous and metamorphic rocks across South America (adapted from UNESCO-IHP 1996).

aquifers" or "fractured aquifers" although there are important exceptions, like for example Andean volcanic ashes and tuffs, which are igneous rocks that may have an important primary porosity; and also some low grade metamorphic rocks which behave hydraulically more like sedimentary bodies than crystalline rocks. Important examples of this type of rock are the metasediments of Itabira, Andrelândia and Araxá Groups, covering large portions of the Brazilian Shield. Fractured rock aquifers are present in extensive areas of South America, and comprise a variety of igneous and metamorphic rocks generally with a relatively low permeability and small storage capacity, but of enormous social and economic importance for some regions, like Northeastern region of Brazil and Northern Chile. However, as pointed out by Anton (1993), when groundwater is considered as a potential source of water for large populations concentrated in comparatively small areas, the spectrum of possibilities to use this resource is considerably reduced, as frequently happens in crystalline areas in Latin America.

The proposal of this paper is to describe the location and main characteristics (extension, water quality and hydrodynamic aspects) of fractured aquifers in South America, with the presentation of some study cases of intensive exploitation of those resources.

## 2 FRACTURED AQUIFER OCCURRENCE AND USE IN SOUTH AMERICA

The hydrogeological map of South America prepared by UNESCO-IHP (1996) shows the identification of areas where fractured (also called "fissured") aquifers dominate (see Figures 2 and 3). A large portion of the continent corresponds to outcrops of crystalline rocks, consisting mainly of granites and gneissic or migmatitic suites, sometimes covered by relatively thin and narrow Cenozoic sediments (alluvial deposits, coastal sediments and residual or transported soils).

Those crystalline aquifers are present in the north portion of South America (Northern Shield), comprising eastern Colombia, southern Venezuela, northern Brazil, French Guyana, Suriname and Guyana; in the centre (Central Shield), encompassing the central portion of Brazil and eastern Bolivia, with small interesting reservoirs available only at a local scale; and also throughout the Andes Range, and along the Atlantic coast of Brazil (Oriental and Southern Shields).

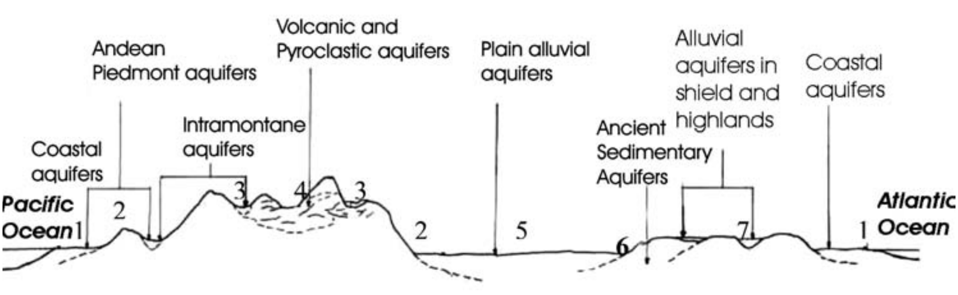


Figure 2. Generic cross-section of South America showing the location of various important cities and the main types of aquifers associated: 1. Lima, Iquique, Mar del Plata, Natal, Salvador, Maceió, Fortaleza and several other cities on the Brazilian coast; 2. Lima, Villavicencio, San Juan, Mendoza, Maracaibo, Santa Cruz; 3. Cochabamba, Valencia, Maracay, Querétaro, San Luis Potosí, Santiago; 4. Mexico City, Guatemala City, Managua, Quito; 5. Buenos Aires, San Nicolás; 6. Ribeirão Preto; 7. São Paulo, Santa Lucia (Montevideo) (adapted from Anton, 1993).

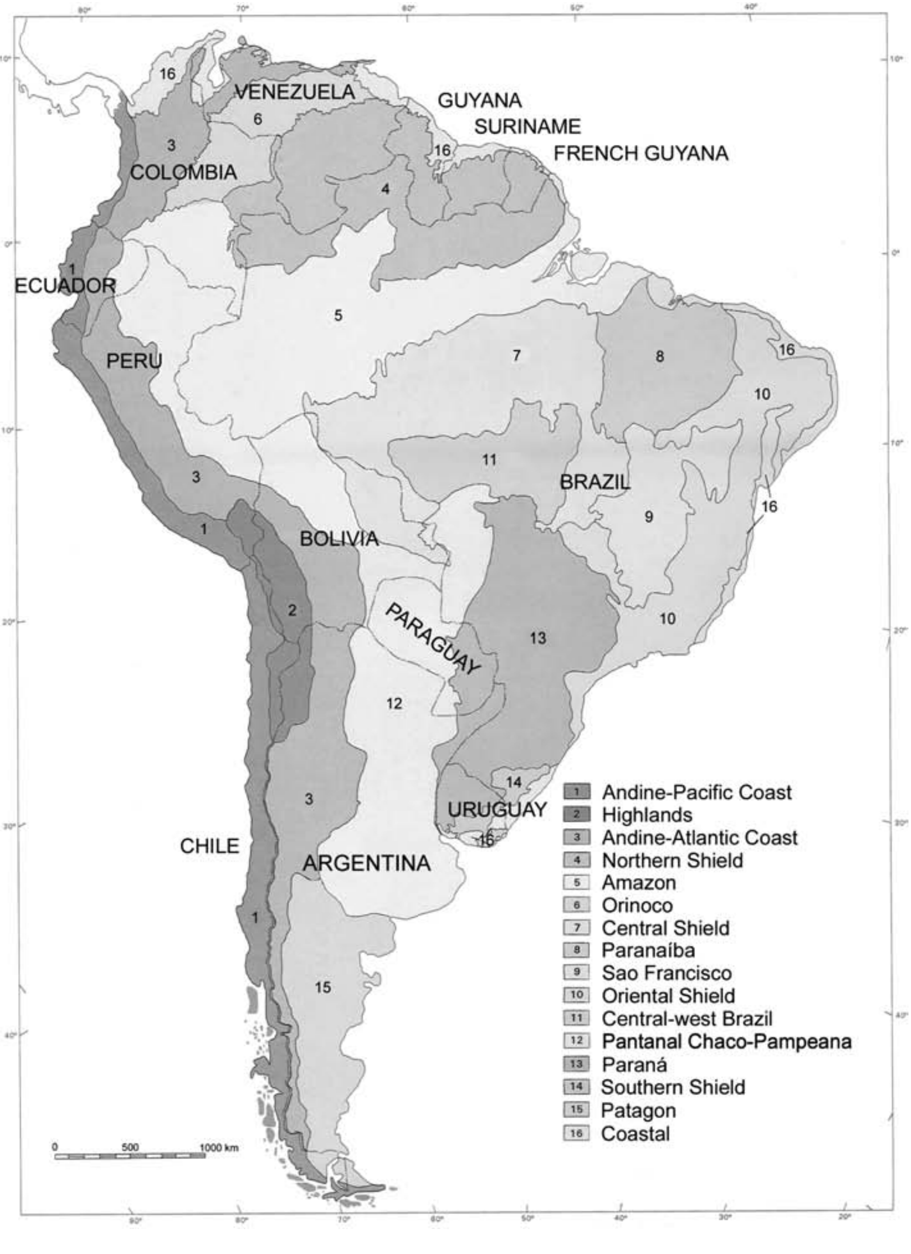


Figure 3. Hydrogeological units of South America (adapted from UNESCO-IHP 1996).

In the semi-arid northeast and humid southeast regions of Brazil (Oriental Shield), crystalline bedrock extends across approximately 3,000,000 $km^2$. Aquifer zones are associated to fractures and lineaments, exploitation levels ranging from 50 to 150 m depth, and specific capacity ranging from 0.001 to 7 $m^3h^{-1}m^{-1}$ (Celligoi and Duarte 1996).

The Guarani Aquifer System, in Paraná sedimentary basin, is overlain by basaltic lava flows (Serra Geral Formation) that stretches throughout approximately 1,000,000 $km^2$ in central southern South America. When it outcrops, forms a semi-confined aquifer with a low permeability and low salinity water, though sometimes with a high iron, fluoride and silica content. Exploitation levels range between 100 to 150 m and specific capacity varies between 0.01 to $10\,m^3h^{-1}m^{-1}$.

In the Argentine Patagonia, in the south of the country, aquifers of low permeability are exploited in some sectors.

Quaternary alluvial formations are found throughout the shield regions of South America, both in the valleys within the shields and at their periphery at the outlets of alluvial streams, with varying thickness (Figure 2). They are particularly well developed in the semi-arid Brazilian northeast following structural features like faults and important lineaments, and along the Brazilian coastal areas, as well as in the fluvial valleys of the Uruguayan-Río Grandense crystalline shield – the Southern Shield (Anton, 1993). Alluvial formation associated with fault zones are in fact the most important source of water in vast areas of the Brazilian shield, particularly in the dry Northeast, and the concept of the "fault-creek" has been useful for generations of groundwater prospectors: the association of fissured zones with the overlying alluvial deposits, formed by dissection of the shield and deposition of sediments in the more erodible fractured zones, enhances the possibility to obtain groundwater in both volume and quality acceptable in a region where none of those are easily achievable. It is important to consider that many important sedimentary units have their hydraulic behavior controlled by the fracture systems, since matrix permeability is low due to grain size or cementation of pores. In this regard, there are significant examples of those features in South America, even in some portions of the Guarani system, although unsatisfactorily mapped.

Some study cases of intensive exploitation in fractured aquifers are hereby presented, from drilling data in the semi-arid northeast of Brazil, in the large metropolis of Sao Paulo (Brazil), in the basin of the Bogota River (Colombia), and in the city of Cuzco (Peru), where the exploitation takes place by filtrating galleries.

### 2.1 *Brazil*

Brazilian territory contains about 12% of surface fresh water resources of the world (United Nations, 1997). Although groundwater data is much more uncertain, it is estimated that about the same percentage of global renewable groundwater resources is available in the Brazilian territory (permanent reserves are probably even bigger than this figure).

Nevertheless, huge contrasts in distribution prevail, with abundant and at times unexploited resources within the three big sedimentary basins of the country – units 5, 8 and 13 of Figure 3 – as compared to the densely populated areas of the oriental shield – unit 10 of Figure 3 – where groundwater resources are quite limited and insufficient to fulfil demand especially in the Northeast Region. For instance, the Northeast Region, with ca. 29% of the population, holds 3% of the country's water resources (Campanili, 2003).

Brazil is a nation of continental dimensions – more than 8.5 million $km^2$ – under humid equatorial/tropical conditions in its largest portion. Climate settings in tropical or equatorial areas include an annual rainfall between 1000 and 3000 mm/year and mild to hot temperatures. Bedrock of crystalline rocks covered by weathered mantle or detritic sediments, with a 30–50 m average thickness, occurs in approximately 4 million $km^2$.

Sedimentary deposits take place in 3.9 million $km^2$ of territory, with an average thickness close to 1000 meters. It results in perennial rivers in about 90% of the tropical territory. Nevertheless, in the central zone of Northeast Region, average rainfall varies between 500 and 800 mm/year and has a very irregular regime. Besides, combination of that climatic scenario with the domain of crystalline rocks reduces dramatically the permeability of the soil, resulting in a semi-arid climate, with periodic droughts.

Along the southern coast, there are few large rivers because the divides are not far enough from the ocean to allow development of extensive fluvial systems. Coastal rivers in Brazil tend to be short, with small basins, and average flows are rather limited in spite of high local levels of precipitation. This has promoted the use of groundwater in these areas, sometimes resulting in the intrusion or upwelling of saline water in aquifers.

### 2.1.1 *Northeastern Brazil*

Northeastern Brazil has an area of 1.6 million $km^2$, corresponding to 18.3% of the national territory and a population of 44.8 million (28.5% of the country population). In this region, the climate is semi-arid in 70% of the area. Regarding its groundwater resources, most of the area is dominated by a fractured aquifer in crystalline rocks with a very low permeability. Well yields are low, with a mean depth of 50 m, and discharges of about 1.5 $m^3$/h. Another serious problem in this aquifer is salinization, TDS values reaching 5000 mg/L due to the intense evaporation and low rainfall rates. Groundwater in fractured crystalline rocks has an important function in terms of water supply systems of the Northeastern Brazilian structural provinces (Borborema to the north, São Francisco to the south), the greater part of which under semi-arid climatic conditions (Neves and Albuquerque, 2004). The total number of deep wells drilled in this aquifer is believed to reach 150,000 during the last 150 years, although data is scarce and unreliable. Notwithstanding, 30% of them are deactivated due to low production and poor water quality.

Water consumptive use meets irrigation demands (59%), human consumption (22%), industrial and agricultural-industrial consumption (13%) and animal consumption (6%). Groundwater participation in this demand is complementary in some areas, although in others, mainly in small cities, is an almost exclusive source. In many areas of the Brazilian northeast region, intensive use of groundwater enhances risk of resources depletion, salinization and soil subsidence (Costa 2001).

The effects of scarcity of water are strongly felt in the Brazilian northeast semiarid areas. Nowadays, the surface water per capita is insufficient for the 15 million people that inhabit the rural area. In the central zone of the Northeast Region the combination of poor rainfall rates with the geological bedrock, formed by sub-outcropping crystalline rocks with a very low permeability, results in temporary rivers and conditions of semi-aridity over about 10% of the national territory (Rebouças, 2000). On the other hand, high temperatures and winds in the region provoke an intense evaporation, impairing long-term water reserves. Those annual average rainfall values can be concentrated in only one month in drought years or in the 3–5 months of the rainy season in the normal years. In practice, the drought in this context leads to the virtual impossibility of subsistence, unleashing migration to the southern and richer parts of the country, deteriorating social conditions of the country as a whole.

Northeast Region comprehends two different hydrogeological contexts: ca. 980,000 $km^2$ outcropping or sub-outcropping crystalline rocks, with extremely low permeability except in zones with fractured rocks; and 648,130 $km^2$ of sedimentary rocks, with large groundwater reserves (Rebouças, 1999). Sedimentary rocks are situated westwards from the "drought polygon" or in coastal zones of the region (units 8 and 16 in Figure 3). The crystalline area prevails in the inner portions in most the northeastern states, exactly where aridity is more pronounced (unit 10 of Figure 3).