Multi-scale, structural analysis of geomechanical and petrophysical properties of Permocarboniferous red beds.

Vielskalige Strukturanalyse der geomechanischen und petrophysikalischen Eigenschaften von Permokarbonischen red-beds.

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Vorwort

Die vorliegende Habilitationsschrift ist das Ergebnis meiner, während der letzten sechs Jahre am Institut für Geologische Wissenschaften der Martin-Luther Universität, Halle-Wittenberg durchgeführten Forschungsarbeiten über das Permokarbon. Im Rahmen dieses Forschungsprojektes sind mehrere Diplomkartierungen und eine Diplomarbeit abgeschlossen, sowie eine Dissertation initiiert worden. Die wichtigsten Ergebnisse der bisher geleisteten wissenschaftlichen Arbeit liegen als Publikationen oder Manuskripte vor. Die Form der einzelnen Aufsätze entspricht ihrem status quo zur Zeit der Zusammenstellung dieser Arbeit.

Der übergeordnete Forschungsansatz des Projektes ist eine skalenübergreifende geomechanisch-geodynamische Betrachtung der besonderen Gesteins- und Gebirgs-eigenschaften des Permokarbons. In einer einfachen Verkettung der vorhandenen Publikationen und Manuskripte würde dieser Forschungsansatzes nicht genügend zum Ausdruck kommen, da die einzelnen Arbeiten thematisch fokussiert sind. Ich habe mich daher entschlossen, die relevanten Publikationen und Manuskripte im Originalformat der jeweiligen Zeitschriften zu verwenden und ausführlich einzuleiten und zu kommentieren. Eine durchgängige Nummerierung der Seiten war dabei nicht möglich, wofür ich um Nachsicht bitten möchte. Ich hoffe mit dieser Darstellungsform einen Weg gefunden zu haben, den Ansprüchen der klassischen Habilitationsschrift und der moderneren kumulativen Habilitation gleichermaßen Rechnung zu tragen. Die hier verwendeten Originalarbeiten sind oder werden in internationalen Fachzeitschriften veröffentlicht und in der Englischen Sprache verfasst. Aus Gründen der sprachlichen Einheitlichkeit und einer möglichen Begutachtung durch nicht Deutsch sprechende Personen wurde für die gesamte Habilitationsschrift die Englischen Sprache bevorzugt.

Preface

The presented "Habilitation" thesis is the result of my research work on the Permocarboniferous that I carried out during the last six years at the Department of Geosciences at the Martin-Luther University, Halle-Wittenberg. Within this research project several diploma mapping projects and one diploma thesis were finished and one PHD-thesis was initiated. The essential results of the conducted work are accessible in publications or manuscripts. The papers layouts reflect their "status quo" at the time when this work was compiled.

The general scope of this research project is a geomechanical-geodynamical study of the special rock characteristics of the Permocarboniferous across different scales. The scope of this project would not clearly come out by a simple line up of the papers and manuscripts, because the particular papers concentrate on certain themes. Therefore, I have decided to use the relevant papers and manuscript in the original format of the individual journals but to introduce and commend them in detail. It was not possible to number the pages continuously, for which I want to apologize. I hope that this type of presentation satisfies the requirements of the classical Habilitation thesis as well as the more modern cumulative Habilitation thesis. The original papers are published or to be published in international journals and hence written in English. For reasons of lingual uniformity and of a possible review through not German speaking persons the English language was preferred for the entire Habilitation thesis.

GEOMECHANICAL MODELS AND PETROPHYSICAL PROPERTIES OF COARSE GRAINED ROCKS.

Paper 1
Hecht, C.A. 2000. Appolonian Packing and Fractal Shape of Grains Improving Geome-chanical Properties in Engineering Geology. Pure appl. geophys. 157, 487-504

Paper 2
Hecht, C. A. 2004. Gomechanical Models for Clastic Grain Packing. Pure appl. geophys. 161, 331-349.

Paper 3
Hecht, C. A. and Bönsch, C., Bauch, E. (resubmitted after review) Relations of Rock Structure and Composition to Petrophysical and Geomechanical Rock Properties: Examples from Permocarboniferous red- beds. Rock Mechanics and Rock Engineering.

FRACTURE SYSTEMS AND GEOMECHANICAL BEHAVIOUR OF PERMO-CARBONIFEROUS ROCK MASSES.

Paper 1
Hecht, C. A. 2001. Geomechanical and Petrophysical Properties of Fracture Systems in Permocarboniferous „red-beds" . Proceedings of the 38Th U.S. Rock Mechanics Symposium, DC Rocks, Washington, 1237-1245. Balkema Rotterdam.

Paper 2
Hecht, C. A. 2003. Relations of self-similarity phenomena of multi-scale fracture systems to geomechanical and hydraulic properties of Permocarboniferous red beds. In: Benassi, A., Cohen, S., Istas, J. and Roux, D. (eds) Self Similarity and Applications. Annales de l` Universite de Clermont Ferrand.

Paper 1
Hecht, C. A., Lempp, C. and Scheck, M. (2003) Geomechanical Model for the Post-Variscan Evolution of the Permocarboniferous-Mesozoic Basins in Northeast Germany. Tectonophysics, 373, 125-139.

ABSTRACT

This work comprises analyses of the petrophysical rock properties and the geomechanical behaviour of coarse grained sedimentary rocks on different scales. It covers the scales of rock samples, of rock sequences and of sedimentary basins. The papers and manuscripts are mainly concerned with red-beds of Permocarboniferous age. In essence, the studies relate observations of rock structures and rock compositions to the geomechanical behaviour of rocks and derive principle geomechanical models of complex geological systems. The applied methods include rock description techniques on and across different scales and a wide variety of laboratory testing methods. The results show that similar principles of order and disorder apply on different scales of observation. This study presents a new, scale invariant principle called "geomechanical order", which is defined as a function of the structural order and the compositional order of a geological system. Within this work, the principle was applied to systems governed by brittle deformation. The different papers comprise details of the determination of the geomechanical order on different scales and of its relevance for petrophysical properties and for the geomechanical behaviour of rocks. Because rock formation is not a static process the papers also include some considerations on dynamic systems. Because of the limited scale of observation techniques and laboratory testing, the results are limited to the particular scales of the data sets. However, the single contributions also reveal information of geomechanical relations across scale boundaries, for example the relation of sample stiffness to fracture systems. In the context of up-scaling procedures, methods of fractal geometry were applied and their limits and potentials are discussed in some detail. The combination of different approaches with the related methods gives a comprehensive picture of the geomechanical properties of Permocarboniferous red beds. This work contains a number of general theoretical considerations and models, which in particular may also be applicable to other projects of material sciences, engineering geology and structural geology.

key words: Permocarboniferous, red beds, rock mechanics, geomechanical behaviour, fracture systems, grain fabrics, scale relations, fractal geometries.

1. INTRODUCTION

The general scope of this study is to analyse the relations of structural and geometrical characteristics to the mechanical behaviour of Permocarboniferous rocks and rock units on different scales. The concept of this study follows the geomechanical-geodynamical principle that the petrophysical condition and the geomechanical behaviour of a rock unit is the summary of its compositional features and its strain history. Consequently, the study is concerned with various processes of rock formation, deformation and alteration through time and across scale boundaries.

The classical scale of observation in geosciences has been the outcrop scale. As analytical techniques advanced, more and more observations on the lower and higher scales of resolution became possible. Presently the scales of observation in geology reach from the smallest scale of samples for high-resolution methods, across the scale of outcrops to the scale of orogens and basins. Each scale range has its own analytical inventory performed by geoscientists and neighbouring scientific disciplines (Table 1).

Scale of observation	Methods	Scientific disciplines
Sample scale	Microscopy	Geoscience
	Phase analysis	Material science
	Petrophysical experiments	
Outcrop scale	Sedimentological analysis	Geoscience
	Structural analysis	
	Large-scale experiments	
Crustal Scale	Drilling	Geoscience
	Seismic experiments	Geophysics
	Remote sensing	

Table 1. Summary of geoscientific methods and disciplines in relation to scales of observation

As is largely believed the degree of resolution decreases with increasing scales of observation. In fact, this depends on the point where one starts to look at a system and how far one goes towards lower and higher scales. What is true is that resolution is increasing at any scale as a result of technical progress and that the images that we obtain from modern observation tools contain more and more details. From a fractalists point of view the perfect image of an object

would be infinite towards both ends of the scale so that he or she can zoom through scales and compare structures and objects for phenomena like self-similarity, self affinity or scale invariance. Opposed to human imaginations and computer animations real images are always restricted within certain limits of resolution. Some of them are looking very similar and we are not able to tell the size of the objects on a picture without scale information. This leads us to the presumption that the processes that create similar structures may also be similar.

Rocks are static systems and hence the primary observations are static as well. It is not surprising that geological sciences started with the description of rocks and the identification and correlation of similar rock suites across regions and oceans. The classical approach to geology was litho-stratigraphy and bio-stratigraphy. Considering static questions there is less a problem with the reliability of results even if their spatial distribution covers different scales, because the actual observations are not so sensitive to scale transitions. For example, a stratigraphic boundary appears clear in a single borehole, in a perfect 3-D outcrop, as well as in an interpolation between a series of 1 D boreholes that cover a large area. Even though there is a difference in the observation scale and spatial resolution, the quality and reliability of the individual observations are quite similar.

Presently geoscientists are rather interested in dynamic processes of rock formation at all available scales. Some dynamic processes can be derived from active geo-environments, from small-scale experiments and from analogous and numerical models. As is well known, the transfer of laboratory results to larger scales causes severe calculation problems. Natural environments and analogous models are scale dependant and hence transformations of results into other scales are problematic. Numerical models are dimensionless on the first view, but the calculation parameters of a certain object that is simulated are scale related empirical results so that the problem of scale dependence remains. Dynamic analyses cause much more problems because the effective system parameters vary through time and space and systems may behave deterministic, random or chaotic. Another big problem is the lack of long-term experiments and large-scale experiments. In fact, we know a little about dynamic processes from comparably fast experiments on the laboratory scale and from a few large-scale experiments but almost nothing about long-term processes on large scales.

Natural systems are often irregular and non-isotropic and we can see or measure this even on one scale of observation. Because any observation is more or less scale dependent, the degree of order of an object or system is very difficult to characterize and to quantify across several scales. This is particularly true, if we analyse a rock sequence on many scales, and need to change observation strategies and rock-testing methods at existing scale boundaries. If a system contains distinct scale boundaries across which the petrophysical or structural elements that define the degree of order are not compatible, the attempts of upscaling or

downscaling of results get arbitrary. On the opposite, we observe scale invariance and hierarchical phenomena in geological systems. Scale invariance commonly relates to fractal patterns or systems, which are recognizable by linear correlations of their geometries and parameters on double logarithmic plots. If scale invariance across several orders of magnitude is recognized, the renormalization group method (RNG) can be applied, which means to transform the system equations from one scale to another by changing of their variables. In other words, the same principal model applies on different scales. Summaries of definitions and applications are published in Korvin (1992) and Turcotte 1997). The story becomes interesting at the point when the different steps of data collection and interpretation are connected and we start to analyse the dynamics of the multi-scale system itself. Considering the dynamic evolution of a sedimentary basin a variety of physical processes are involved (Table 2).

Stage of basin formation	Physical Processes	Diagnostic Data
Early basin stage	Crustal extension	Seismic profiles Major structures
Basin fill	Thermal subsidence Tectonic subsidence	Rock composition Sedimentation rates
Diagenesis	Mineral growth	Type of cements Fluid inclusions
Deformation	Fault kinematics	Geometry and kinematics of thrusts, faults, folds,
Exhumation	Thermal uplift Tectonic uplift	Fault reactivation Joint patterns
Erosion	Disaggregation of minerals Fragmentation of rocks	Mineral composition Fracture patterns

Table 2. Summary of processes and data related to basin formation.

From the processes listed in Table 2, it becomes obvious that during the development of a sedimentary basin rather dynamic processes alternate with rather static ones. The intensities of the processes may vary but in essence, these are the steps of a dynamic basin evolution. The different processes also cover different scale ranges and leave diagnostic traces at

different scales. The dimension of a diagnostic observation to the assumed process can span several orders of magnitude, for example when fluid inclusion measurements are used for the interpretation of regional diagenetic processes. Other observations, for example strength measurements of a certain rock sample are only valid for the deformation process within the size of the sample.

Another interesting scale effect is that time conserved in a geological system increases with increasing scale of observation in a certain direction. In horizontally bedded sedimentary rocks, for example, time increases with the prolongation of the vertical observation axes by adding older strata and processes of millions of years to the system but not on the horizontal observation axes, which represents the uppermost and youngest stratigraphic layers and the processes therein. From a stratigraphy point of view, this is not a very exiting statement but from the point of view of structural analysis of basin dynamics it certainly is, because the vertical axes does contain much more information of the basin evolution than the horizontal axes does. The larger the scale of a geological system in a 3D analysis is, the more important this scale effect gets.

The following study characterizes the mechanical behaviour of Permocarboniferous red beds in terms of principal structural characteristics and petrophysical properties from which principal geomechanical laws are derived. One general observation for the rock units investigated in this study is that at any scale the dominant behaviour is brittle which means that the type of deformation is scale-invariant. A principle attempt of this study is to define the characteristic degree of order of the system in two ways. The first, which is called here "structural order", is determined at a certain scale by distribution statistics of the systems elements and by the determination of the masses, shapes and sizes of the single elements. Beyond the pure structures and geometries, the degree of order of a system further depends on differences of the petrophysical properties of its elements. This second type of order is the "compositional order" of the system. Finally, the total degree of order, the "geomechanical order" of a structure is a function of the geomechanically relevant geometries (structural order) and material properties (compositional order). To give a simple illustrative example we consider two sandstones that have identical grain size distribution curves in other words that have the same structural degree of order. We assume that sandstone number one comprises 95 % of quartz grains and 5% of feldspars and sandstone number two 70 % of quartz grains and 30 % of feldspars. Because quartz grains and feldspars have differing single grain properties for example shape and strength, sandstone number two has a lower degree of geomechanical order because it comprises a higher percentage of weaker elements than sandstone number one. This principle applies to many structures at different scales. The following table contains a summary of examples that are relevant to this study (Table 3).

Type of order	Sample scale	Outcrop scale	Crustal scale
Structural order	Grain size distribution Packing density Grain contacts Coordination numbers	Fracture patterns Multi-layer geometries	Fault patterns Basin geometries
Compositional order	Grain composition Grain properties	Fracture properties Multi-layer properties	Fault properties Basin fill properties
Geomechanical Order	Fabric behaviour	Fracture propagation Fracture connectivity	Fault kinematics Basin development

Table 3. Theoretical types of order listed for different geological scales of observation.

Facing the problem of upscaling one may ask the question: "Does the composition of a rock influence or determine the geomechanical behaviour of a single bed, does the single bed behaviour influence the behaviour of a multi-layered rock sequence, does the behaviour of a rock sequence influence the development of a large geological system and so forth?" The first attempt to answer this question would be to look at a system with a high degree of order for example a sequence of sandstone layers of similar composition that was subjected to one phase of deformation for example extension. The expected result would be that in a given stress field the statistic spacing distribution and dimensions of the extensional joint set are related to the stiffness of the sandstones and the picture would not be very complicated.

Continuing on this example the degree of order can theoretically decrease in two ways. The first way is to add single beds with strongly differing lithologies to the rock sequence, which results in single bed behaviour within the multi-layers through interlayer stress transfer that creates more complex statistic spacing distributions and dimensions of the fracture sets. The second way is to increase the number and styles of applied stress fields, which reactivates existing fractures or produces new ones. The first example represents an increase of the internal structural complexity while the second example gives an increase of the external forces that affect the system. The question in many natural examples is what drives or dominates the "self-organisation" during the development of a system, the internal or the external parameters. In non-linear geodynamic systems, both parameters discussed above are alternating and balancing each other over time. Local effects such as special lithological features or stress concentration are also important to consider. Going back to the initial question one can answer yes, rock composition does determine the geomechanical behaviour

at any scale because whatever the external forces are the self-organisation ever depends on the internal parameters, even on those at the smallest scales.

The key to the understanding of a particular rock system the status quo of which we see and measure presently is to decipher the relations of the relevant driving forces. Firstly, data collections of the details of the internal and external parameters relevant to the scale of the particular system are necessary. Secondly, the data sets must be checked for relations of symmetry, order and disorder and other phenomena such as self-similarity, scale invariance across as many scales as possible. Thirdly, the potential geomechanical behaviour types like deterministic, stochastic or chaotic need to be evaluated. Finally, one may be able to elaborate the linearity of the dynamic evolution of the system for a given time period.

Following multi-scale geomechanical/geodynamical aspects this study covers observation scales that reach from the scale of clay minerals to the scale of sedimentary basins for example the Northeast German Basin. We are looking at a time span from the first appearance of red-beds in Upper Carboniferous times to their present status quo. The selected Permocarboniferous basins developed in different tectonic positions in Northeast Germany, Southwest Germany and the Southern Alps. The effects of older basement properties and pre-Permian structures on the basin evolution were also taken into account. In terms of rock condition, the study is mainly concerned with hard rocks, but also with primary grain packing properties of sedimentary rocks, which play an important role in a geodynamical context.

One of the repeating concepts in this study is that of fractals. Since the publication of the book "The Fractal Nature" by Mandelbrot (1976) fractal methods have been widely applied to geological structures. The applicability and wealth of fractal methods, however, has largely been neglected perhaps because in the years when fractals were "en vogue" many examples of misunderstanding and misapplication were published. Today fractal methods are well confined and their applicability for example in material sciences is unquestioned. Although we know, that many if not most geological structures are not fractal "sensu stricto" the concepts of fractal geometry have conducted our minds to new principles like hierarchy, self-similarity and scale invariance of geological structures and processes. Fractal principles also deeply support our thoughts about the self-organizing phenomena of dynamic geological processes. One of the perhaps most famous examples of fractal behaviour in geology is fragmentation (for summary see Turcotte 1999).

During Permocarboniferous times the mega-continent Pangea, which was finally created by the closure of the Rheic ocean during the Variscan orogeny, started to fall into pieces. This was certainly the beginning of the largest continental fragmentation that has ever taken place on earth. It was associated with extraordinary thermal processes that produced very large

amounts of acidic volcanic rocks in places, the calculation of which is yet not possible with the existing differentiation models. At a closer view, the break-up of Pangea was a complex fragmentation process controlled by the diversity of regional geodynamic processes and structural conditions. Thermal re-equilibration and erosion resulted in the formation and filling of the Permocarboniferous basins which can be correlated across the world. The Permocarboniferous clastic rocks in the intra-continental basins are mostly red and coarse grained, which is an indication for a dry climate, fast sedimentation and short transport distances. The basin formation was regionally further triggered by pre-existing basement domains and long-lived tectonic structures. Basins of Permocarboniferous age contain valuable hydrocarbon reservoirs, many of which have already been exploited, particularly those in the North European Basin. However, there are still economically very interesting tight-gas reservoirs in existence and Permocarboniferous strata are supposed to be used for the generation of geothermal energy and for the storage of CO_2. Furthermore, many geotechnical underground operations like excavations and tunnels are involved with Permocarboniferous strata. From many respects, the geomechanical behaviour of these rocks is of high economic and scientific interest.

The geomechanical and hydraulic behaviour of a rock sequence depends on the petrophysical properties of the individual rock types, which is why the story always starts with the small scales of observations. The present work includes studies of Permocarboniferous rocks and rock sequences on different scales from different regions in Europe. The chapters line up follows an upscaling manner starting from sample scales crossing the outcrop scales and ending at the scales of sedimentary basins. The chapters contain published papers or manuscripts related to the general theme: Multi-scale geomechanical and petrophysical properties of Permocarboniferous red beds.

2. CHAPTER 1

GEOMECHANICAL MODELS AND PETROPHYSICAL PROPERTIES OF COARSE GRAINED ROCKS

2.1 Introduction to Chapter 1

Paper 1
Submitted: October 1999   Published: 2000

Hecht, C.A. 2000. Appolonian Packing and Fractal Shape of Grains Improving Geomechanical Properties in Engineering Geology. Pure appl. geophys. 157, 487-504

Paper 2
Submitted: August 2002   Published: 2004

Hecht, C. A. (2004). Gomechanical Models for Clastic Grain Packing. Pure appl. geophys. 161, 331-349.

Paper 3
Resubmitted after revision: April 2004

Hecht, C. A., Bönsch, C. and Bauch, E. in review. Relations of Rock Structure and Composition to Petrophysical and Geomechanical Rock Properties: Examples from Permocarboniferous red- beds. Rock Mechanics and Rock engineering.

2.1 Introduction to Chapter 1

Most of the empirical knowledge about petrophysical properties of rocks was achieved on the sample scale. Many of the laboratory techniques applied by rock engineers and petro-physicists are standardized with respect to sample sizes and treatment so that results became repeatable and comparable. Over the last decades this lead to compilation of standard tables of petrophysical properties of certain rock types which are addressed to practitioners in the first place. The large number of empirical results is a good basis for correlations of petrophysical properties some of which are successful and well known. Concerning the accurate description of rocks and even more the modelling of rocks, there are still some fundamental problems to be solved. The standard images of rocks are 2 D and have different magnifications for example the conventional microscope magnifications where single grains and grain assemblages of the silt to sand size are well imaged and the electron microscope magnifications where grain surfaces and minerals of clay size become visible. Quartz grains appear angular to round while clay minerals have various shapes. Consequently, images from the same rock samples may look different and are hence scale dependant. On the opposite images can look similar at different magnifications. Without any scale information, an image of a conglomerate can be indistinguishable from that of a sandstone. In other words images of coarse-grained sedimentary rocks are scale-invariant. It is obvious that for scale reasons the compilation of a complete picture of a rock sample from sequential images of different size is impossible. In order to make rock descriptions comparable to the numbers obtained from laboratory measurements the question arises how to determine the structure of a rock more precisely. The use of fractal methods for the description of complex grain surfaces and grain envelopes in material sciences has brought some progress in this direction. Less advanced methods are available for grain packing modelling where disks or spheres are still used. Models of rocks that use disks or spheres as representatives for mineral grains do not really satisfy images of rocks created by our minds eyes but they help to calculate and model granular materials. The algorithms for clastic grain packing models do not yet include all aspects of settling and compaction of loose grain assemblies, cementation and deformation. The models however illustrate different packing types and allow the calculation of parameters like density, porosity and coordination numbers. Simulations of loading and deformation of packing models are presently under development preferably by the use of finite element methods (FEM) and differential element methods (DEM).

The following papers are concerned with packing models and petrophysical property analysis of Permocarboniferous sedimentary rocks. Of special interest are the potentials and limits of packing models and the parameter variability of certain types of rocks with respect to the derivation and prediction of geomechanical properties. A brief introduction to the individual papers is given in the following.

Paper 1

The first paper is concerned with the theories of dense packing and the relevance of dense packing for rock composition studies and for the geomechanical behaviour of clastic rocks and industrial mineral mixtures. The so called "Appolonian Packing" is a prominent fractal composed of circles in a plain. Compared to the other models of this study it is the most universe two-dimensional disk model. The first theoretical part of the paper shows the derivation of the fractal dimension D from the cumulative grain-size distribution. The second part presents a variety of examples for sedimentary rocks and industrial mineral mixtures with fractal grain-size distribution. The paper also contains some considerations about the processes of sedimentation and mixing that lead to fractal packing. From the theory of dense packing, it is suggested that such materials have extraordinary petrophysical properties like very low porosities, very high densities and high strengths. The observations contain an example of the increase of values for the friction angle of a granular laboratory mixture from a non-fractal to a fractal grain-size distribution. The discussion is concerned with the origin and the behaviour of materials with a fractal composition and their applicability in engineering geology and rock industry. The paper contributes to the general theme of this chapter, because some basic theories are introduced that are also important for the following papers.

Paper 2

In the second paper, the special cases of dense packing are extended to general cases of packing of granular materials. The paper includes symmetric and random sphere models with respect to the arrangement of spheres, and homogeneous and inhomogeneous models with respect to the single sphere properties. For completion, the classification also includes cemented sphere models. For each model the structural characteristics like, density, coordination numbers and the potential geomechanical behaviour e.g. the settlement potential is theoretically derived. The observations contain results from a series of petrophysical experiments that were conducted on loose mineral mixtures as well as on hard rocks. The selected mixtures and samples respond to the principle sphere models of this study. The loose material stems from weathered granite and contains mainly angular quartz grains and a low amount of strongly weathered feldspar grains. The hard rock samples are from outcrops of Permocarboniferous sequences in East- and South Germany. The results clearly show the relation of primary grain packing to petrophysical properties and the effects of different types of cements namely calcite and quartz on the range of values. The study shows that the main petrophysical properties of a certain rock type are predictable from structural and

compositional parameters directly obtained from thin section images or derived from sphere models.

Paper 3

In the third paper structural and compositional characteristics of clastic rocks are relate to the variation of results from petrophysical tests and rock mechanic experiments. The order or disorder of selected lithotypes was determined from thin section image analysing using the software DIANA and correlated with statistical results, the standard deviation in particular from petrophysical and rock-mechanical experiments. The observations show, that the primary sedimentary composition of a rock predetermines its geodynamic development including cementation, deformation and alteration. Additionally, they shown that the scattering of the geomechanical results is a measure of the internal order of a rock and vice versa. These findings are important for the validation of single rock parameters on sites, where the number of rock samples is limited. This is the regular case in reservoir analysis and in many underground operations like tunnels, excavations and deep foundations.

3. CHAPTER 2

FRACTURE SYSTEMS AND GEOMECHANICAL BEHAVIOUR OF PERMO-CARBONIFEROUS ROCK MASSES.

3.1 Introduction to Chapter 2

Paper 1
Submitted: November 2000   Published: June 2001

Hecht, C. A. 2001. Geomechanical and Petrophysical Properties of Fracture Systems in Permocarboniferous „red-beds" . Proceedings of the 38Th U.S. Rock Mechanics Symposium, DC Rocks, Washington, 1237-1245. Balkema Rotterdam. Colour version identical to the publication in black and white.

Paper 2
Submitted: March 2002   Accepted: November 2002

Hecht, C. A. (2003) Relations of self-similarity phenomena of multi-scale fracture systems to geomechanical and hydraulic properties of Permocarboniferous red beds. In: Benassi, A., Cohen, S., Istas, J. and Roux, D. (eds) Self Similarity and Applications. Annales de l` Universite de Clermont Ferrand.

3.1 Introduction to Chapter 2

The medium scale behaviour of rock sequences is of huge economic and ecologic interest because this is the scale of the most intensive geotechnical interaction with geological structures. Humans act on scales of tens to hundreds of meters when they are working natural deposits, exploiting reservoirs and building their infrastructure. On this scale, they seriously disturb naturally balanced systems like morphology, hydraulic systems, natural barriers and many others. Even though hazards occur frequent, surprisingly few direct measurements are available from larger, geotechnical scales compared to the engineering activity. In practice economic reasons often provide the conductance of large scale experiments not necessarily because the experiments as such are to expensive but because they are time consuming and interrupt the building progress which is often even more expensive than the experiments themselves. From a theoretical point of view, the increasing complexity of geological systems with scale is still an unsolved problem. The present trend in engineering geology clearly favours numerical modelling which progresses with the exponential growth of computer power. It appears however, that the geological knowledge falls behind in this progress. There are many examples where forward modelling fails for reasons of poor or wrong input parameters into numerical calculations. Backward modelling is far more successful but of debatable use in order to predict economic and ecologic risks and to provide hazards. In essence, two reasons are responsible why calculations go wrong. Either a calculation model does not contain all mechanically relevant geological structures, or the rock parameters introduced into the calculation are over- or underestimated. In the first case, mistakes are often made during the generation of a model by simplifying geological structures for example fracture sets by missing important structures for example a fault zone locally cutting through a jointed rock mass. This happens either due to poor knowledge of the modelled structures or simply due to the model generation tools provided by the calculation program. In the second case of rock parameter selection one is involved with in the problem of scale effects, which means that rock parameters for example strength or permeability numbers are dependant on the scale at which they are measured. There is no general way to overcome this problems, but with a good knowledge of the spatial distribution of rock types and geological structures and a reasonable set of rock measurements it is possible to compile a decent picture of a particular rock mass of a given size. The most comprehensive pictures develop in our minds but it is difficult to print them from there. Therefore, the best way is still to draw the basic pictures by hand, which is quick and prevents simplifications. Numerical models generally do not allow the introduction of too many details into one calculation. In that case, it is useful to perform sequential calculations of simple models that contain the relevant geometries and parameters at different scales and to compile a comprehensive model for example through best case/worst case scenario evaluations.

This chapter focuses on the influence of medium scale structures on the geodynamical geomechanical behaviour of Permocarboniferous red-beds. The following papers describe the geometrical and genetic characteristics of fractured multi-layered sequences from a statistical and geomechanical point of view. The papers account to the results from rock mechanic experiments on sample scales in that they contain a series of correlations of joint characteristics to petrophysical properties of single beds and multi-layers.

Paper 1

This paper is concerned with geomechanically relevant characteristics of red beds on the medium scale. It includes both theoretical considerations and geological observations. The geological objects on this scale are single-beds, multi-layers and fracture systems including joints and smaller faults. The observations show the relationships between petrophysical rock properties of the single beds, the dimensions and composition of multi-layer sequences, and the statistic distribution and spatial characteristics of rock fractures. The results reveal that fracture patterns are controlled by stiffness contrast and layer bounding through boundary friction between single-layers, and that opposed to many studies on foreland basin flysch rocks the spacing dimensions of red-beds are not simply related to mechanical bed thickness. The discussion focuses on the special mechanical behaviour of coarse grained sedimentary rock units especially those of Permocarboniferous age.

Paper 2

The paper illustrates self-similarity phenomena of fracture patterns of different size and different orientation with respect to the earth surface. The fracture sizes range from micro-cracks to large regional faults. The study distinguishes images of horizontal fracture patterns from images of vertical fracture patterns and outlines the distribution characteristics and scale relations of the two groups. The discussion is involved with the different genetic questions of fracture patterns and their implications on geomechanical and hydraulic models.

4. CHAPTER 3
GEOMECHANICAL MODEL FOR THE EVOLUTION OF PERMIAN-MESOZOIC BASINS.

4.1 Introduction to Chapter 3

Paper 1
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Sedimentary basins are studied by sedimentologists, structural geologists, reservoir geologists and geophysicists rather than by engineering geologists. Apparently, there is a scale problem for engineering geologists, most likely because large geo-objects are difficult to calculate. Nevertheless, even though many geologists still neglect this fact, geomechanical approaches become more important for large-scale geological studies. An increase of advanced analogue and numerical modelling of large geo-objects indicates this. Since ever, geoscientists used illustrations to unravel the genesis of the rock puzzle on that we live. The early modelling was directed backwards starting from the present status quo of a geo-object. Classical examples are wonderful hand drawn pictures of mountain chains with rivers escaping from deeply incised canyons and meandering through foreland basin flood plains into the ocean. A lot of our present knowledge about the dynamic parameters of geological systems was collected through the studies of recent environments as analogues to geological environments. Sedimentologists made the greatest successes with this approach, because sedimentary processes are comparably fast. Slow processes like compaction, diagenesis and deformation of rocks are not directly observable and hence our knowledge about them is still fragmentary.

As a result, of intensive research by hydrocarbon reservoir analysts and academic groups, basin modelling has advanced most rapidly during the last decade. However, numerical models do not fully reflect all relevant parameters and phenomena, and modellers are increasingly interested in reliable input parameters. These are both detailed 3 D structural information and results from experiments under real conditions.

Paper 1

The paper presents geomechanical models based on litho-stratigraphical and structural observation from the different basin and the basement domains in Northeast Germany. Other than existing basin models, this study focuses on the geomechanical effects of different brittle basement domains and master faults in the tectonically most active area at the border to the present Northeast German Basin. The geomechanical influence of the Permocarboniferous rocks themselves on the basin development plays another key role in this study. On this basis, we distinguish three domains with different structural inventories and different basin dynamics.

5. DISCUSSION

The initial concept of this study is that the petrophysical condition and the geomechanical behaviour of a rock unit is the result of its structural and compositional features and its strain history. This concept requires the connection of different aspects of rock formation, deformation and alteration to the geomechanical behaviour of the Permocarboniferous clastic rocks at and across different scales. According to theoretical considerations made in the general introduction rock masses have a characteristic degree of order which is given by the summary of their structural and compositional elements. A system with strongly differing elements has a lower degree of order than a system that comprises similar elements. It was proposed that the self-organized dynamic evolution of a system, which is driven by internal structures and external forces will be the more complex the lower the degree of order of the system is at the starting point.

This concept was applied throughout this study to the description of geometries of system elements and their geomechanical properties on the main observation scales, namely the sample scale, the outcrop scale and the scale of sedimentary basins of Permocarboniferous age. The question how far to link the findings across scale boundaries and how to interpret the results is a matter of an individual point of view. A petrophysicist is rather interested in the rock types themselves especially in the variation of their grain size distributions and grain compositions and of their petrophysical properties. A reservoir analyst is rather interested in the reservoirs geometries, the porosity and permeability of a sequence or the frac behaviour of a prosperous sequence and a basin analyst in basin dynamics, which comprise tectonic and thermal processes that extend into great depth and over long time. The petrophysicist is certainly not so keen on basin dynamics than the basin analyst and the basin analyst not so on the petrophysical details of a certain rock type. However, both use observations from the same rocks and both need a certain range of scales for the interpretation of their results.

From, a fractalists point of view there are no scale limitations and no distinct working scales. He or she is interested in fractal phenomena of a system like hierarchy, self-similarity, scale invariance and so forth. Natural systems are not strictly fractal in a mathematical sense and the idea that fractals are everywhere is a sophism. There are good examples of fractals like, coastlines, river systems or fault zones, and less good examples like joint sets and others. The most striking example for scale invariance of this study is that of the brittle behaviour of Permocarboniferous on many scales. This does not necessarily mean that fractures are self-similar across many scales, which indeed is not ever the case as shown in chapter 2. There are some very intuitive images that display self-similarity for example the fragmentation of stiff single grains in a weak matrix and stiff single beds between weaker single beds. Both systems have a low compositional order because they contain objects of different strength. In this case,

the self-similarity indicates the same fragmentation process, caused by horizontal stress transfer along the margins of the strong objects. These observations can be expressed by the same principal model, which yields a good example for the applicability of the renormalization group (RNG).

It was also shown that the distribution of fractures is random in cases were the materials properties of objects are not so different. An example on the sample scale, are intra-granular fractures with a homogenous distribution but not necessarily with a preferred orientation, which results from multidirectional stress transfer through inter-granular contacts. On the outcrop scale, the picture depends on the orientation of a particular rock surface with respect to the bedding plane. In this case, preferentially orientated joint sets occur as well as random ones. Without regard to preferential orientation, the random distribution of the fractures on both scales is again an example of self-similarity. In this case, we are looking at objects with a high compositional order. The transition from sample scale to outcrop scale is quite easy for these particular cases.

Another question is whether high or low order on the sample scale also means high or low order on the outcrop scale or even above that. Magnifying system from the scale of samples to the scale of outcrops one needs to consider the vertical dimensions for example bed thickness, bedding relations and material changes and the square dimensions for example of ripple or dune shapes, of channel architectures and so forth. These geometries depend on rock formation processes and on the architecture of sedimentary environments. From sedimentary petrology, we know that the maturity grade of clastic rocks is a matter of transport energy and source area. Mature sediments are those with well-sorted grain-size distributions and equal single grain properties, for example dune sands or coastal sands. We know from modern environments that dunes cover large areas of the earth's surface with thick and uniform sediments and hence create large rock volumes with a high degree of order. If rock parameters and environmental parameters are uniform as in this case, the system is not sensitive to scale transitions over a large order of magnitudes, in other words the system is scale invariant in a broad sense. Fluvial sediments are less well sorted and fluvial depositional systems comprise of a variety of complex environments like channel sediments, overbank deposits, flood plain deposits and so forth. Again, the compositional variability of single rocks is a measure for the complexity of the larger environments. Fan deposits are an example where fluvial deposits may occur together with sheet flood deposits, which results in a lower degree of order compared to the individual depositional systems. Again, there is a similarity of the degree of order on both scales, in that the variability of environments produces a variety of different rock types. In these cases, scale transformations are more sensitive, because the number of different objects on both scales is higher. In summary, the degree of order of sedimentary environments seems to be self-similar across geological scale boundaries.

Another example is the dependence of distribution statistics of joints from single layer properties of different multi-layers (see paper 1 of chapter 2). The observations therein show that although the principle deformation style is similar variations of rock strength or grain sizes between single beds of one sequence lead to different joint spacing and single bed jointing. So, the more irregular the composition of a rock sequence is, the more irregular the joint pattern will be. These relations allow the prediction of joint patterns from single rock measurements for example from rock cores, which yields another example for a successful scale transition.

On the scale of sedimentary basins the picture gets more complicated because one encounters a variety of sedimentary environments on the horizontal level, and sequences of different age that reflect different stages of basin formation and different basement domains on the vertical axis. These relations were discussed in some detail in chapters 2 and 3. From observations made therein, it becomes clear that self-similarity is more likely to occur on the horizontal levels of observation than on the vertical axes of observation.

So far, the discussion was concerned with aspects of order and disorder, scale invariance and self-similarity of different observations of rock formation or deformation. In the following, the discussion will stronger focus on the dynamic relations of the observed phenomena of rock formation, deformation and rock alteration.

An important question is whether a dynamic system behaves deterministic, which means it follows specified initial conditions, stochastic, which means it behaves by pure chance, or chaotic, which means it reacts exponentially to very small changes of the deterministic conditions. A good example is the correlation of the degree of order of a rock derived from petrological observations with the standard deviation of results obtained from rock mechanic experiments (Paper 3, Chapter 1). The observation as such might not appear very surprising but it allows some very interesting conclusions in a geodynamic context. The most important conclusion is that the initial composition of a rock pre-determinates its development through diagenesis, deformation and alteration (see also Papers 1 and 2, Chapter 1). Details of the relevance of this conclusion to particular rock properties are discussed in the cited papers.

Considering self-organisation during rock genesis, the observations comprise a variety of examples of how initial compositional and structural properties influence particular processes. The key word in a geodynamic context is "geomechanical order", which is defined here as a function of structural order and compositional order of a system. It becomes obvious that the more complex a system is at the beginning the more complex its development will be, regardless of the particular scale of observation.

Fractal patterns or fractal statistics are closely related with chaotic behaviour of a system. As the observations of this study show, fractals only occur eventually under special circumstances, which is strongly indicative that processes involved with the development of Permocarboniferous red beds are rather deterministic. For example, rocks with a fractal grain-size distribution indicate chaotic processes of deposition through turbulent flow. Another example from this study is the fractal fragmentation pattern of small-scale faults, which in this case most likely represents a reactivation and overprinting of single joints through horizontal shearing. Apart from these particular examples, the majority of structures in Permocarboniferous red beds do not indicate chaotic behaviour. Structures are commonly distributed normal, log normal or exponential. This leads to the assumption that many initial conditions had a continuous influence at different steps of rock development, for example the initial properties of grain packing or bedding relations, which shows that rock formation processes of Permocarbonifeorus red-beds are fairly linear and deterministic.

6. CONCLUSIONS

The geomechanical order, which characterizes the geomechanically relevant parameters of a geological system is a function of the structural order and the compositional order of the system. This principle applies to geological systems on different scales.

Permocarboniferous coarse-grained red beds are dominated by intergranular friction, boundary friction and brittle deformation, and behave geomechanically different to other multilayerd sequences. This scale invariant behaviour is evident on the sample scale, the outcrop scale and the scale of sedimentary basins.

The geodynamical order of Permocarboniferous red beds indicates a rather linear dynamic evolution, which is a result of the high degree of internal structural and compositional order and of comparably moderate influences of external forces.