Descriptive and quantitative analysis of fracture systems in a carbonate rock mass complex

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Abstract. The study area is located in the Franconian Alb in Southern Germany and is an Upper Jurassic, karstified and fractured, regularly bedded carbonate rock mass with thin marl interlayers. Structurally, these deposits are heterogeneous and a classification into structural types is striven for in this study. The structural classification is based on discontinuity and fault characteristics gained from field work. The study area is considered an analogue for Germany’s most productive deep geothermal reservoir horizon in the South German Molasse Basin. The aim of the field study is to describe and quantitatively analyse the different structural types, and to optimize the scanline method for a specific geological setting to gain comprehensive information with regard to fracture permeability and rock mass behaviour. The structural types are described in terms of discontinuity orientation and density, rock strength, and fault characteristics. To optimize the scanline method for the field study additional discontinuity attributes were added. One of these accessory attributes, the existence of discontinuity lags, will be discussed. It occurs when vertical and sub-vertical fractures cross sedimentary layers and continue with a small horizontal displacement in the next sedimentary layer. The results of this study are used to improve derived fracture networks with respect to thermo-hydro-mechanical models in the geothermal sector. Following article discusses the first results of the above-mentioned field study.

1. Introduction

The discontinuity network governs not only the deformation but also hydraulics of rock mass. While the former is of importance for analysis of subsidence and presumably fault reactivation in deep reservoirs, the latter is of particular importance in regard to flow rates [1, 2, 3]. So-called petrothermal reservoirs are prospective geothermal plays that rely on the conductivity of the discontinuity network as the matrix permeability is very low [4]. An example of this is the Malm reservoir in the Southern German Bavarian Molasse Basin, which represents the major horizon for deep geothermal energy production in Germany [5]. Due to the nature of deep reservoirs, lying out of reach for outcrop studies, numerous fault and fracture models are based solely on reservoir data (e.g. borehole data, seismic imaging). These methods give a vast amount of enriching data, but are accompanied by an indefinable uncertainty due to the methods limitations [6]. Heterogeneous discontinuity systems as well as crucial fault characteristics are two important factors that cannot be dealt with satisfactory by these indirect measurements.

To tackle the issue, we propose a mapping objective with focus on structural heterogeneity in an analogue formation situated in the Southern Franconian Alb. The analogue was chosen, due to its
similarities to the geothermal site of Geretsried south of Munich, where hydraulic enhancement is planned in relation to the ZoKrateS project.

To account for the structural heterogeneity of the analogue formation, it is classified into three structural types throughout the study area. In the course of the study the structural typing has proven reasonable and two of these types will be discussed in the following article.

Central aspects of the study are the variation of the discontinuity system in the different structural types with regard to discontinuity density, orientation and differences in surface strength. To deliver this comprehensive description of the discontinuity system an adapted scanline approach including newly established additional discontinuity attributes is used. A further essential aspect of the study is the analysis of fault characteristics (e.g. fault core width, core filling, mechanical stability, discontinuity density) with regard to the structural type they appear in. The fault and discontinuity system is of particular interest due to the general connection to microseismic activity and the occurrence of microseismic events associated to deep geothermal production in the area of interest [7, 8]. To bring together the results of the analogue study and the existing reservoir data, an evaluation of the link between structural heterogeneity and the fault system is striven for in the long-run to establish a comprehensive reservoir model.

2. Study area and methods

The study area lies in Southern Germany close to the city of Weißenburg on the upland of the Weißenburg Alb. It is part of the Southern Franconian Alb, an upland of moderate height consisting mostly of Jurassic sediments, which lies circa 30 km south of the city of Nuremberg. The chosen outcrops belong to the Upper Jurassic (‘Malm’) and consist of stratified carbonates with marl interlayers and local dolomitization which belong to the Treuchtlingen Formation [9, 10].

The discontinuity data was gained with the scanline method which documents all discontinuities and their primary attributes along a line of an outcrop [11]. Among others, the standard attributes length and orientation were measured, which are addressed when describing the discontinuity system (figure 1). Additional attributes are established and added to the standard documentation of discontinuities. These attributes are custom-built for the geological and structural set-up of the study area and are thought to forward the use of basic geological techniques for scientific field data collection. The intersection count is a discontinuity attribute introduced to collect information on the discontinuity density and connectivity by counting the number of discontinuities, which intersect the by the scanline measured discontinuity itself. The attribute analysis of the measured discontinuities was carried out separately for the two main sets (set 1, set 2), which provides information on the overall attribute presentation in one set as well as trends or differences between the sets. Vector graphs including Terzaghi weighting, vector density and cluster analysis were generated using Rocscience Dips [12]. The information gained by the scanline method is used to describe the discontinuity system as well the variation of precisely that system with regard to the structural types. Additional to the scanline data, outcrops sketches were prepared containing outcrop wall rock strength and the number of fractures per m² (fractures/m²) to help differentiate the structural types. Rock strength was estimated in the field with the Schmidt Hammer [13]. Large scale discontinuities were mapped in different areas of the mentioned structural types of the study site to gain information on the fault system. The large-scale mapping includes discontinuities > 3 m and their characteristics (e.g. orientation, fault type, fault throw etc.), which were mapped for several areas. The data was collected on walls and floors of an active quarry.
3. Structural typing

3.1. Overall
The structural architecture of the study area is heterogeneous. Fracture density, rock strength and fracture orientations vary significantly. These variations appear systematic and are restricted to individual areas. The study area covers the full range from chaotic zones with many small-scaled fractures and partially reduced rock strength to more competent rock mass with clean-cut surfaces and lower fracture density. Until now, three structural types were classified, whilst (1) a relatively uniform, less disturbed structural type and (2) a more chaotic cube-shaped structural type, account for most of the study area. Additionally, strongly disturbed areas with smaller-scale fractures and prominent conjugates appear as well as areas with increased karst structures at all scales. Lithologically, the study area is comparatively homogenous with horizontal compact layers that can be traced along the whole study area and beyond. The used data for the following structural types was taken in the same lithologic layer at different locations within the quarry.

3.2. Type 1 (background-type)
Most of the study area is characterised by smooth outcrop surfaces with few irregularities (figure 2). The clean-cut outcrop walls often display orange to brown colourings or incrustations. Discontinuities are mostly vertical to sub-vertical and display as narrow, slightly irregular lines without exposed fracture surfaces. The occurrence of discrete normal faults is characteristic for this structural type. The normal faults exhibit a regular and narrow (< 30 cm) running fault core with a sharp contact into the surrounding rock and fault throws from 0.3 m to 2.0 m. The discontinuity system of Type 1 displays a low fracture density with a mean value of 2.5 fracture/m² (figure 3 a). Field rock strength estimates of Type 1 outcrops show a mean value of $\sigma_c = 45.5$ MPa uniaxial compressive strength with a comparatively uniform strength distribution ($\Delta \sigma_c = 6.7$ MPa) (figure 3 b). The fracture system of Type 1 displays a low discontinuity density with a mean value of 2.5 fractures/m². The spatial variation of discontinuities can be considered being low due to the dense discontinuity clusters. The apparent missing of E-W trending discontinuities is a result of missing N-S striking scanline data (figure 3 c).

3.3. Type 2 (cube-type)
Other parts of the study area show an orderly block-like architecture accompanied by a chaotic smaller-scale fracture system (figure 4). Distinct vertical discontinuities as well as overhanging sedimentary boundaries set limits to the separate medium-scale blocks. The larger vertical discontinuities show local deformation in the form of splintering parallel or semi-parallel to their plane. Colouring as seen in
Type 1 appears less frequent and incrustations are rare. The fracture density is comparatively high with a mean value of 9.3 fractures/m² (figure 3 a). The rock strength of the outcrop wall shows $\sigma_c$ values...
ranging from below measurability (purple values) to 142 MPa (figure 3 b). This large scattering of rock strength values is caused by the inhomogeneous structure typical of Type 2 outcrops. The spatial set-up of the fracture system shows a deviation in fracture orientation from the typical clearly clustered N-S and E-W orientation of Type 1. The clusters are less dense as documented by the larger number of outliers plotting outside the set-windows (figure 3 d).

![Figure 4](image_url)

**Figure 4.** Sketch of Type 2 outcrop with bedding and discontinuities. Vertical to semi-vertical fractures are dominant. Some vertical fractures are accompanied by local deformation structures (splintered vertical smaller-scaled features). Fracture surfaces are visible and fractures occur in high numbers creating a more chaotic impression.

4. Discontinuity System
The discontinuities of the study area exhibit three main spatial discontinuity orientations (figure 5 a). All outcrops of the study area show two discontinuity groups which are close to vertical and orientated orthogonal to each other. The regular sub-horizontal (5° dip) lying bedding is orientated orthogonal to these vertical discontinuity groups. The vertical discontinuities are grouped into sets by cluster analysis of the Terzaghi weighted data. The hemispheric pole vector density plot shows a dense cluster of the N-S trending set 1 with a maximum density of ~ 15 %, whereas the E-W trending set 2 is clustered with a maximum density of around ~5 %. With this cluster analysis 73 % of the data is grouped into sets and all planes lying outside the cluster windows are classified as secondary spatial orientations (‘others’). This structural organization of two discontinuity sets oriented orthogonal to each other and to the bedding is common for regularly bedded horizontal lying sedimentary deposits and may be referred to as the fundamental joint system [14, 15]. Measurements show a mean discontinuity length of 1.5 m with no significant length differences between the main sets (set 1, set 2). In comparison to the main sets, secondary discontinuities (‘others’) appear to be of shorter length. This is indicated by only 10 % of the secondary discontinuities displaying a length > 2.5 m in comparison to set 1 and set 2 exhibiting each ~30 % of discontinuities in this length class (figure 5 b). Recording the end type of discontinuities showed that 80 % of the discontinuities terminate at other discontinuities and only 20 % in massive rock. To gain a better understanding of the interconnectivity of discontinuities, an additional attribute was measured, the intersection count (intersections). This value gives the number of other discontinuities cutting the recorded discontinuity and shows a mean of two intersections per discontinuity for the study area (figure 5 c). The orientation of sets, the intersections, the end type and the length of the discontinuities illustrate the existence of a connected discontinuity network, and therefore the significance of discontinuities in regard to the reservoir study.
5. Discontinuity lag

Discontinuity lag is an often seen phenomenon in the study area and its existence is documented for all scanline measurements as additional attribute. It occurs when vertical to sub-vertical discontinuities (1) cross sedimentary layers (2) show horizontal displacement called lag (3) and continue in the next layer (4) (figure 6 a, b). Measurements taken in the whole study area show that approx. 25% to 45% of the discontinuities display a discontinuity lag (figure 6 c). This phenomenon is of interest, due to its unknown effect on mechanical stability and in particular rock mass permeability. Quantifying the amount of discontinuity lags in the study area is a first step to evaluate the need to integrate this phenomenon into fracture models. To gain a better understanding of the phenomenon following question will be addressed in the progress of the study: Which layers act as mechanical interfaces? What is the mean lag length? Does lag appear more often with a specific set of discontinuities? Does the documented discontinuity exhibit the same discontinuity attributes (orientation, roughness, aperture etc.) as the adjoining discontinuity?

Figure 5. a) Discontinuity pole vector density graph with Terzaghi weighting of all scanline measurements with notations of the two main sets gained from cluster analysis. b) Chart displaying the distribution of discontinuity length into classes separated into sets. c) Chart displaying the number of intersections measured on discontinuities as an additional attribute for the scanline method and divided into sets.

Figure 6. a) Close-up of a discontinuity displaying a lag on its upper terminus. b) Graphic display of the same image illustrating the discontinuity lag at a sedimentary layer acting as a mechanical interface. c) Chart displaying the percentage of discontinuities exhibiting a discontinuity lag.
6. Fault System

In one area of type 1 consisting of 500 m of N-S and E-W striking outcrop walls, all discontinuities larger than 3 m were documented with regard to their type, orientation and movement indicators (figure 7). Four of these structures showed fault throw and were identified as normal faults, the remaining could not be specified with regard to their type. Despite one, all normal faults strike E-W. This strike direction matches with the strike of the normal faulting dominated regional fault zone running close to the study area (Schwarzwald-Bayerwald-line) [16]. E-W striking faults are also typical for the region of interest, the Geretsried geothermal study site. An Upper Jurassic fault network consisting of E-W and WSW-ENE striking normal faults was recently described at reservoir depth for the Geretsried GEN-1 drill site [17]. These first structural results from the analogue presenting a similar fault strike and fault type like the deep reservoir at the Geretsried study site indicate the transferability of structural data between those two formations.

7. Conclusion

A separation of the study area into structural types has proven a reasonable approach. Type 2 for example is distinguishable from Type 1 by its higher fracture counts, a wider and more chaotic dispersion of surface strength, and a less dense clustering of the main spatial orientations of the sets. Additionally, the faults encountered in Type 2 areas are more chaotic and display blurred boundaries in comparison to the discrete and narrow faults of Type 1. The description of at least one further structural type which occurs in the study area will follow as well as additional data collection in general. One fracture system occurs throughout the whole study area and comprises of two orthogonal to each other situated semi-vertical discontinuities, both of which are orthogonal to the semi-horizontal bedding. The fundamental joint system shows a good connectivity, which is apparent from the intersection number, the orthogonal set-up, and the percentage of discontinuities that terminate in or at other discontinuities. A clear variation of the fracture system of the structural types is visible, but only in regard to the density of the discontinuity clusters. First results of the analogues fault system in regard to fault type and orientation
show that normal faults with an E-W strike occur frequently, which coincides with the findings of the fault system of the Geretsried reservoir. This similar fault pattern indicates a transferability of the Franconian analogue results onto the Upper Jurassic at the Geretsried deep reservoir study.

The use of additional attributes for the scanline method proved sensible. Recording discontinuity lag in the study area proved to be of significance, due to the high number of discontinuities showing this phenomenon. Our results demonstrate the feasibility of our concept since the adapted methods helped gain information and the structural set-up is similar to the deep reservoir of interest.

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