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Thin Section Based Cutting Analysis as a New Approach in Rock Type Determination While Drilling Deep Geothermal Wells

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ABSTRACT

Microfacies analyses using thin sections made up from cutting material and side-wall cores are an essential tool in order to scientifically accompany geothermal deep drilling projects. Components and microfabrics which are included in washed cutting material give information about geological origin, mineral composition, diagenetic processes as well as porosity and permeability of the drilled rock formations. Components can be qualitatively observed and quantitatively estimated by particle analyses with the purpose to reconstruct depositional environments. Mineral shape and composition demonstrate diagenetic history and the development of microfabric characteristics. Finally, the occurrences of open porosity and precipitated cements can be identified in thin section based cutting material from deep wells helping to evaluate the porosity of the rock. 3D reconstruction of fracture systems is possible from oriented side-wall cores and indirectly by cutting form analysis from cutting material. In combination with stress field analysis and structural geological analysis from 3D seismic the cutting form analysis helps to identify the dominated fracture pattern in situ which might be below the seismic resolution.

These important informations about cap rock and reservoir rock quality needs to be gathered as quick as possible to steer the drilling process and refine targeting. Thin section analysis of cuttings after the drilling operation may help to evaluate reservoir rock properties but cannot steer the drilling process anymore. In a newly established mobile lab, fast thin section production while drilling enables well-site geologists to obtain early information about rock properties within a few hours. This method facilitates rock type determination immediately after sample recovery at the drill-site.

This approach of thin-section based cutting analysis-while drilling is newly developed for geothermal wells and represents an essential part in reliable determination of casing shoes, reservoir rock identification and – if the suggested reservoir rock formation is not proven through thin section cutting analysis – drilling targeting. Thin section based cutting analysis requires a detailed understanding of facies and paleontology, opening obviously a new research field in geothermal exploration and well site geology.

1. INTRODUCTION

Microfacies analysis of reservoir rocks is an essential tool to investigate depositional properties and reservoir potential resulting from diagenetic alterations and tectonic influence. Drilling operations normally comprise the production of cutting material, side-wall cores or normal cores of the target formations. In scientific drilling projects complete coring of the drilled formations are preferred in order to get undisturbed rock material. The Deep Sea Drilling Project (deep sea drilling.org), the IODP and various scientific continental drilling programs as well as the drilling of ice cores are based on the investigation of complete rock cores. These continuously contain informations about rock properties, facies development and paleontological and stratigraphic evolution. Depending on the budget, industrial wells are mostly not completely cored because of time constraints and expensive operations. Especially in geothermal projects risk management is very important to avoid project failure. In order to minimize costs sampling procedures are reduced to rock analyses performed by mudlogging services and drilling of side-wall cores. Rock analyses and thin sections of these cores normally were made for scientific purposes long after drilling activities. In this way, important informations are not present during the drilling process. Finally, samples of cutting material are observed for lithological aspects from the surfaces of the cuttings and chemical and mechanical indications of the observed rock types. The scientific monitoring methods have to be performed in a mobile lab that contains special grinding and sawing devices. The work flow consists of a sequence of mechanical steps which guarantee the fast production of cutting slabs and thin sections.

Stratigraphic work with the aims of dating the drilled sequence, to quantify facies types and porosities and finally correlating the well with other wells needs more focus on lithologic monitoring.

2. METHODOLOGICAL APPROACH

Thin sections of cuttings and side-wall cores require UV-curing mounting media with appropriate refraction index. These need to be finished contemporaneously with the drilling progress. As soon as a samples comes up to the sieves it has to be washed, dried and separated into fractions. Due to the fact that fine cutting fractions "are closer to the drilled formations", coarse fractions more than 2 mm cutting diameter contain more break-out components. This effect is increasingly present in clayey environments. Nevertheless coarser cutting fractions should be preferred for microfacies analyses. Especially for stratigraphic and environmental purposes larger components are necessary to analyse microfabrics and porosity distributions. Cutting material for thin section production should be embedded in blue resin to make open porosities visible under transmittent light. Thin sections should be stained with Alizarin red S for Calcite. Other staining substances can be used for special minerals such as aragonite, gypsum and iron-dolomite.

Carbonate cuttings easily can be described and classified by the established carbonate classification methods on site (Folk, 1959, Dunham 1962, Emby & Glovan 1972, Logan & Semeniuk, 1976). For reservoir evaluations porosity types and pore distributions are calculated and classified after Choquette & Pray (1970). The methods of microfacies analytics are presented by Flügel (2004). Reservoir characteristics and general models of depositional environments are based on the identification of Standard-Micro-Facies types (Wilson 1975). In connection with geophysical data such as logging curves the drilled rock formations can be investigated by sequence stratigraphic methods (Vail et al., 1984, Catuneanu, 2006).

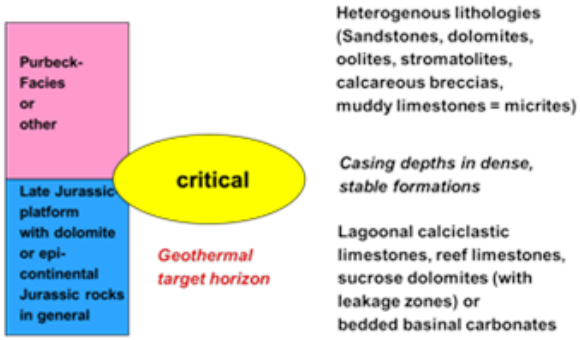

Figure 1: Target horizon. Casing depths on top of reservoir formations are sensitive parts of the drilled rock sequence. Stable lithologies for final casings have to be predicted and carefully monitored by short sample intervals and permanent production and observation of thin sections on site.

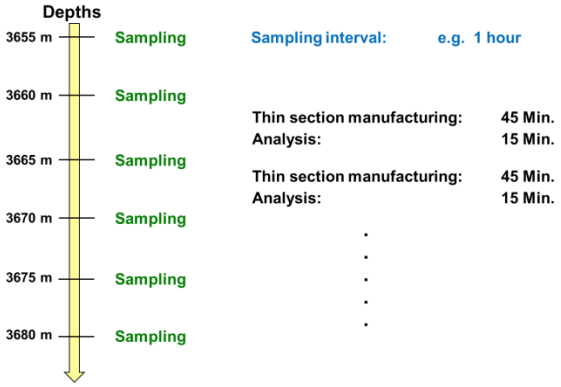

Figure 2: Procedure of taking samples and thin section analysis during the drilling process. The sample intervals can be shortened when necessary. This however requires slow drilling rates or short interruptions of the drilling activity.



Figure 3: Thin section of cutting material prepared in the on-site thin-section lab within one and three hour time intervals. The size of the slides are 60 x 40 mm and depth informations are engraved on the back side.

Thin section analyses are most efficient, when they are prepared and investigated parallel to the drilling operations. In the case of important decisions such as calculating the position of casing shoes or drilling lithological changes sample intervals must be shortened and drilling speed must be reduced or operations stopped.

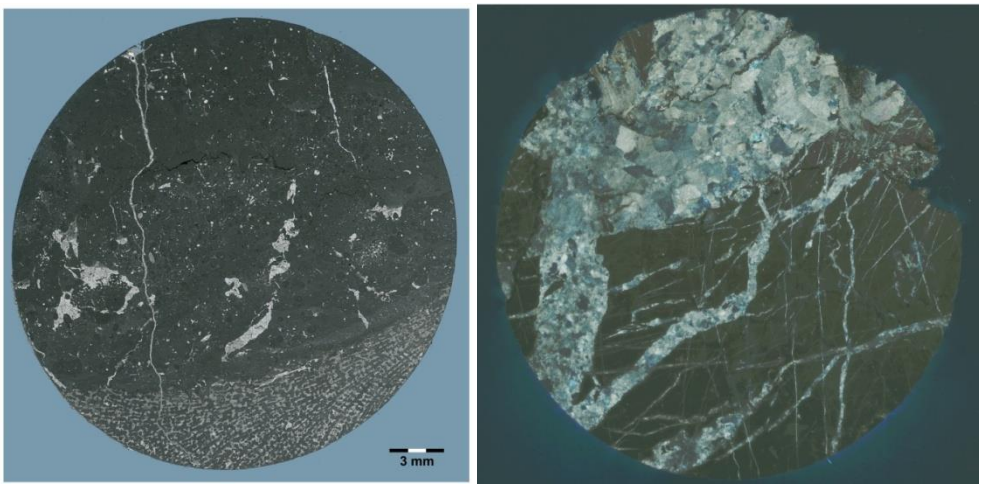

Figure 4: High resolution scans of on-site thin sections of two side-wall cores. The images show Late Jurassic siliceous sponge-bearing limestones in various stages of tectonic influence. The left photograph presents a stylobedded micritic limestone with interlayered sponge skeletons and tuberoidal wackestone rock types. These are bioturbated, partly dissolved, recemented and tectonically.

Cuttings are occasionally affected by mechanical stress which is derived from the drilling process. These are called artificial oder pseudocuttings and represent newly formed particles which are composed of original formation lithologies and various mud components. Tricone roller bits generate twisted cuttings with alteration effects due to heat and pressure. Cuttings of clayey and marly material produced by PDC bits show typical thinly bedded microstructure with a harnish-like surface perpendicular to the microbedding. These effects depend on drilling parameters such as "weight on bit", speed and torque.

3. ANALYSIS OF CUTTING SPECTRA

Cutting spectra are composed of drilled material transported to the surface by mud which is pumped up. The original depth is calculated using specific formula including mud weight, pumping rates and specific weight of the drilled formation. Many attempts have been made to investigate the potential of cutting spectra analyses in order to get informations about lithostratigraphy and biostratigraphy, diagenesis and porosity of the recovered material. Problems of correctly interpreting cutting spectra are to separate break out cuttings from those derived from the formations just drilled, the presence of lost circulation material and the reconnaissance of artificial cuttings. Cuttings are very useful when sample intervals are short and constant. Stratigraphic boundaries can be recognized by quantitative analysis with the help of counting programs and special equipment such as point-counter devices. Quantitative analyses also provide informations about stratigraphic repetitions and gaps. Finally, unexpected components indicate complicated tectonic situations or casing damage.

4. RECONSTRUCTION OF DEPOSITIONAL ENVIRONMENTS

Cutting spectra contain original formation, break outs and artificial cuttings. The content of break outs depends on the distance of the last casing shoe upwards. The amount of such components is also related to the original lithologies. Soft lithologies can be detected as a permanent break out part through the entire open hole sequence. The alteration of original formations by the development of artificial cuttings is sometimes so severe, that microfabrics cannot be analysed.

Qualitative and quantitative lithological analyses of the cutting spectra from thin sections have to be interpreted in terms of stratigraphic boundaries and units. New lithologies start with minor quantities. Percentages of the different rock-types are estimated in 5% intervals. The values can be documented in data spreadsheets or in logging programs. Most recently, rock typing of continuous sample sequences is used for the identification of depositional environment with standard microfacies types, intervals of open porosity and diagenetic patterns.

5. BIOSTRATIGRAPHIC DATING

Biostratigraphic monitoring during drilling activity includes thin section observation und determination of fossil sections as well as extraction of microfossils from washed samples. Experienced facies geologists are familiar with determining microfossils of biostratigraphic value from the thin section aspect. Important microfossil groups are Late Mesozoic and Cenozoic planktonic foraminifera (Toumarkine & Luterbacher, 1985, Bolli & Sounders, 1985, Caron, 1985), Late Jurassic to Lower Cretaceous calpionellids (Remane, 1985), and any cenozone fossils from specific ecologic environments such as dasycladacean algae (Sartoni & Crescenti, 1961) and other algae. Computerized stratigraphic data processing can be performed by specific programs such as Analyseries , Rasc (Agterberg & Gradstein, 1999) and Biograph (Unitary Association Method, Guex, 1991).

6. POROSITY AND PERMEABILITY ESTIMATIONS

Using blue dye in mounting raisins for thin section preparation, open spaces within cutting components are marked. In combination with other staining procedures, the diagenetic history and porosity characterizations can be identified. Porosity types are determined using established porosity classifications (Choquette & Pray, 1970). Increasingly important will be the use of image analysis programs (Image J, Rasband, W. in Burger & Burge, 2006)) to perform fast porosity quantification. Porosity form analysis extrapolated from various sections of the same rock type give informations about permeability using the Kozeny-Carman equation (Haro, 2013).

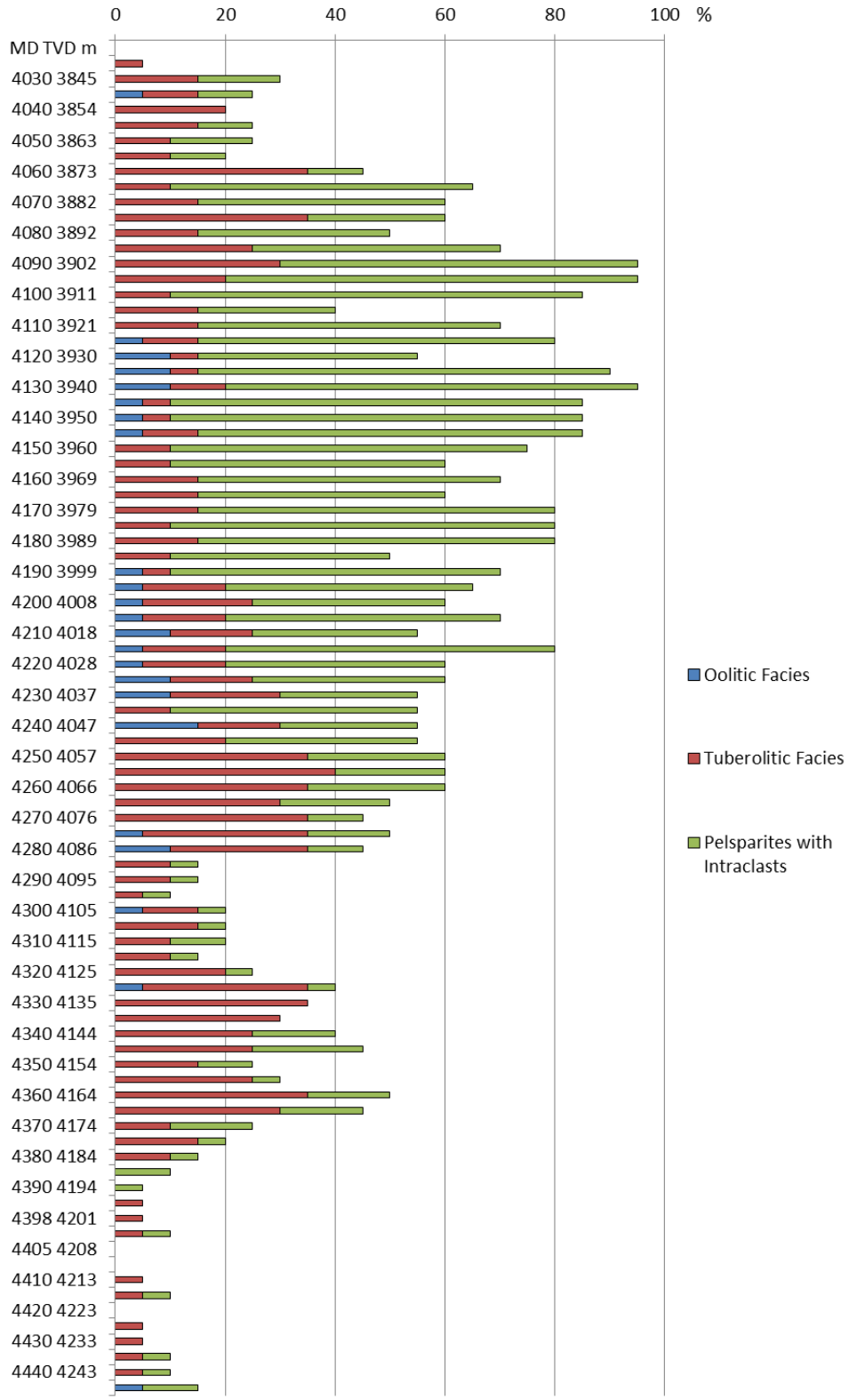

Figure 5:Quantitative analyses of cutting spectra from drilled material in geothermal well St. Gallen GT1 in Switzerland. The column comprises the Jurassic section which represents the geothermal aquifer.

7. CALCULATION OF TECTONIC FRACTURE PATTERNS BY CUTTING FORM ANALYSIS

Cuttings drilled by tricone roller bits have polygonal outline with straight linear sides. This phenomenon is used by ovality measurements but also gives information about fracture systems. On the basis of methodological agreements and normalized positions of the polygons by turning the polygon until its longest side forming a baseline with 90 degrees azimuth) it is possible to find the maximum number of longest sides and the interdependence of all other angles of the polygon. The strike directions of the remaining sides of the polygons are generated by the angles. Azimuths of the polygons are measured starting at the sharpest angle

on the left side and counted. These azimuths and all other azimuths of the polygon are entered into a rose diagram. The baseline is finally reoriented parallel to the fracture maximum and displaying conjugating fracture directions which are mostly oriented diagonally with minor maxima.

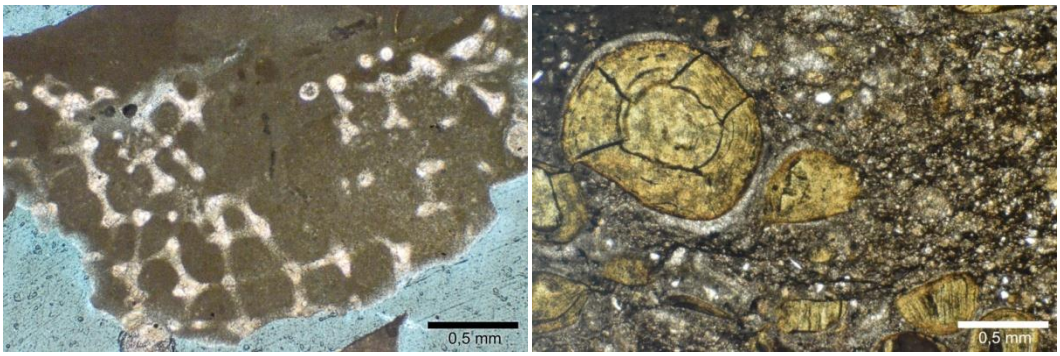

Figure 6: Reconstruction of depositional environments after thin section analysis. Samples are from cutting material and side wall cores from the Sankt Gallen geothermal well (Steiger & Uhlig, 2014). The interpreted facies distributions display the general bathymetric and sedimentary trends on the European epeiric platform bordered by the Alpine front southward. (Left) Late Jurassic mud mound environment, dominated by low energy depositonal conditions, cyanobacterial incrustation and neomorphic calcitisation of silica spicules and dolomitization. (Right) Latest Dogger and Earliest Jurassic iron oolites deposited in marginal platform depressions probably formed by cyanobacterial activity. The oolite horizon is an important marker bed.

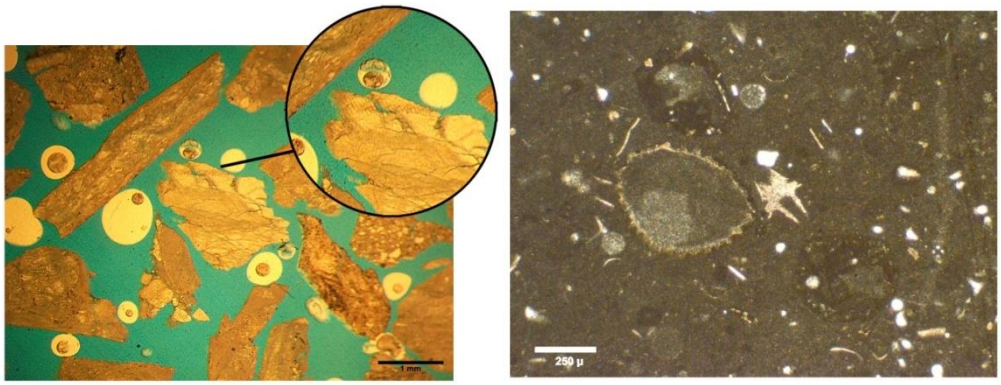

Figure 7: Photomicrographs of Cenozoic and Mesozoic cutting material from south German geothermal wells. The cuttings contain sections of Eocene foraminiferal genus Discocyclina with rectangular median chambers (Steiger & Uhlig, 2012) and remains of Late Jurassic echinoderm remains (*Saccocoma*, secundibracchials of a small nectic feather star). These fossils date the drilled sections and can be identified immediately.

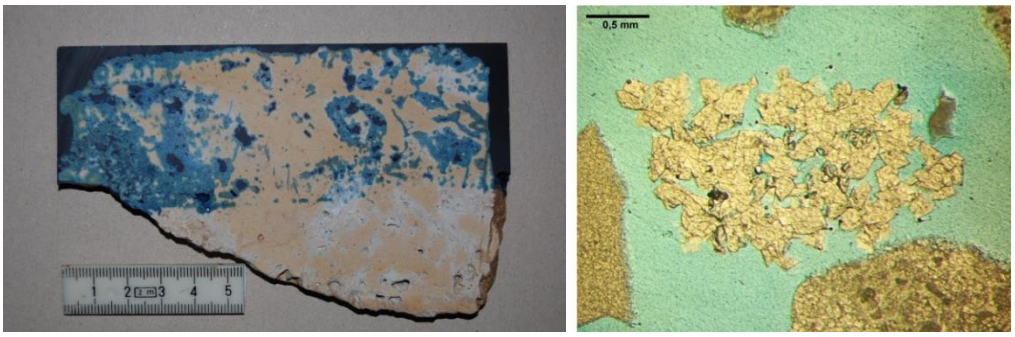

Figure 8: Porosity estimations. Left side: A rock slab of sucrosic dolomite is impregnated with blue raisin and displays porous areas. Franconian Dolomite. Right side: Cutting particle of porous dolomite showing an aggregate of euhedral dolomit crystals. Submolasse Late Jurassic in Bavaria.

8. 3D RECONSTRUCTION FROM SIDE-WALL CORES

Oriented side-wall cores give the opportunity establish 3D reconstructions microfracture systems and spatial composition of sedimentary material as well as porosity distribution.

The thin sections have to be oriented longitudinal and perpendicular to the drilling direction. At least in one direction (for example horizontal) two thin sections must be prepared in order to interpolate visible structures and connect them.

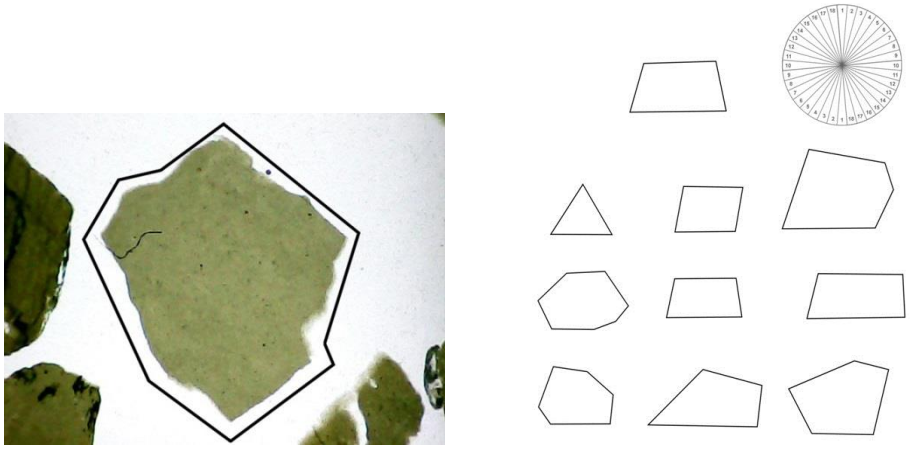

Figure 9: Principle of cutting form analysis. Left side: microscopic image of a micrite cutting marked as a polygon along its straight sides . Left side: Azimuth rosette with segments and polygons which are oriented with shortest angle on the left side and longest sides of the polygons down. At each point of the polygon angles can be measured with the rosette which give numbers of azimuth values corresponding to the polygon edges.

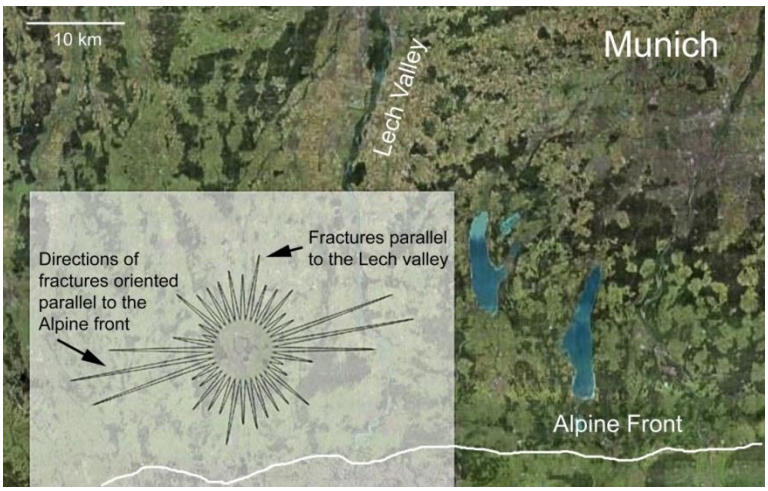

Figure 10: Results from cutting form analysis. The rosette shows fracture directions of the recent stress system. The main stress field generates fracture and fault directions which are parallel to the northern margin of the Alps (Alpine Front). Corresponding diagonal fracture directions are oriented parallel to the present-day river valleys (for example the Lech valley)

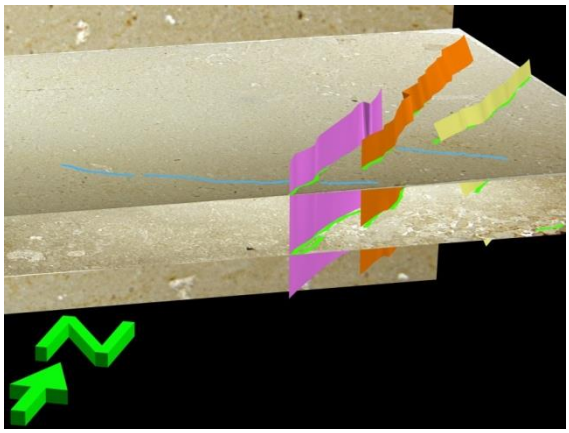

Figure 11: 3D reconstruction of fault systems in Late Jurassic limestones. Oriented thin sections (3 or 4 from the same sample) provide strike and dip values of a core. In the image the distance between the reconstructed faults is about 2 cm.

9. STRUCTURAL SETTING AND STRESS FIELD OF THE MAUERSTETTEN PROSPECT

The well Mauerstetten truncates an ENE-WSW oriented normal fault which has an offset of 250 m (Fig. 12). Normal faults with an E-W trend are the dominating structures in the Molasse basin and reflect the local extension during flexural bending and foreland basin formation from Early Oligocene onwards (Bachmann et al., 1987, Moeck et al., submitted). These faults may have formed in the Early to Late Cretaceous related to rifting in the Helvetian-European shelf (Moeck et al., this volume). The faulting style does not reflect the present-day stress field with a SHmax direction about N-S. The normal faults are therefore considered as fossil normal faults in the present-day stress field (Moeck et al., this volume).

Drilling and reservoir engineering is affected by the present-day stress field and behavior of fossil faults in the present-day stress field and changing stress conditions during reservoir operation. It might be important to consider possible fault and fracture directions that are likely to form under the present-day stress conditions. After the Andersonian fault-stress relation (Anderson, 1951) a N-S oriented maximum horizontal stress direction (either S1 or S2, the maximum or the intermediate principal stress component of the stress tensor), would cause NW and NE trending strike-slip faults, N-S oriented tensile fractures and normal faults, and E-W oriented reverse faults (Fig. 12b).

Small scale shear fractures are often not resolved through reflection seismic data and the present-day fracture pattern is therefore rarely imaged in seismic data although these fractures may exist. Cutting shape may be influenced by modern fractures formed in the present-day stress field. It is therefore straightforward to systematically analyze the angular relations of cutting edges to get indications for a fracture pattern. Cuttings may be influenced by the fossil fracture pattern indicated by one dominant direction or by the modern stress field indicated by two trends reflecting shear fractures.

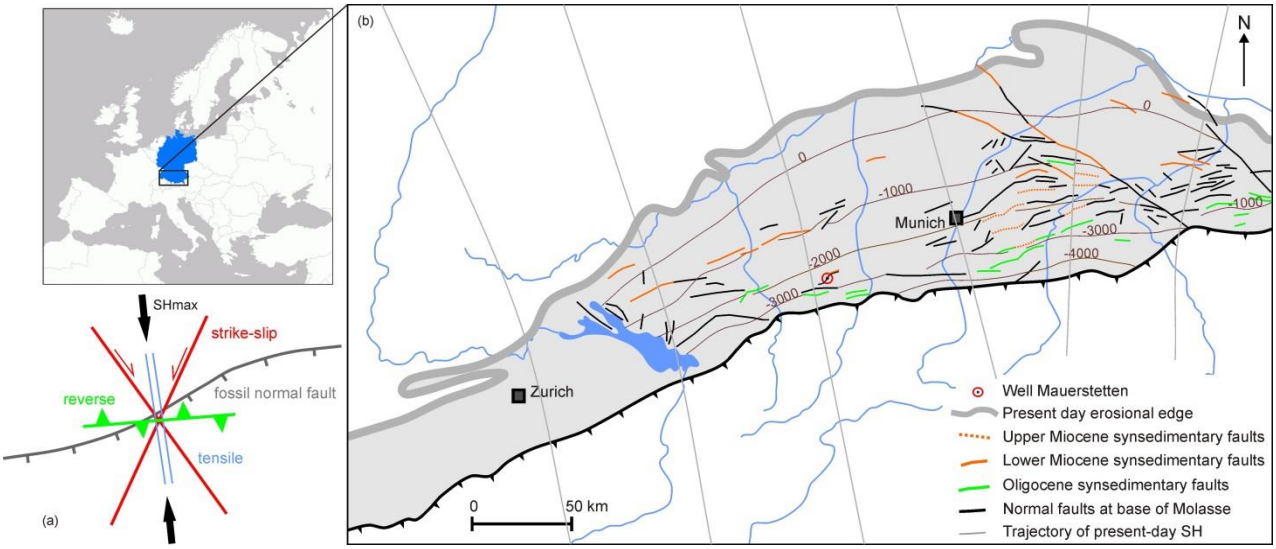

Figure 12: (a) Fossil fault and present-day stress direction SH with related fracture pattern for the Mauerstetten prospect. (b) Structural pattern and modern stress trajectories of the Molasse basin and structural position of the well Mauerstetten (modified from Bachmann et al., 1987 and Moeck et al., this volume).

CONCLUSIONS

Scientific geological monitoring by means of fast thin section analysis of cutting material and side wall cores is an effective method to support deep geothermal projects. In cooperation with mud-logging services a permanent control of the well during the drilling process is possible. This is most important, when limited budgets only allow a few down-hole logging measurements. In this case, the major question is: what can we do on the drill-site that helps while current drilling activity? The first holes in deep geothermal projects are explorative and basic informations about lithology, facies, depositional environment and diagenetic data are of particular interest. For permeability aspects, the configuration of fracture systems and porosity types is a fundamental purpose. On site, container based production and observations of thin sections also help to make adequate decisions such as the choice of bit types and weight on bit for example in interlayered sequences of silica-rich and marly limestones and also to avoid artificial cuttings. Finally, criteria for terminating drilling of a well also can be obtained from cutting analysis as soon as permeability and facies development is not sufficient enough. This is a basic factor for investors. Mid-European Late Jurassic geothermal reservoirs need intense investigation of facies development and distribution of microfabrics and fracture systems. In these carbonate enviroments, rocktypes and zones of good permeability are irregularly distributed and intergrade. Every well which is investigated intensely enough completes the overall facies map of the regions and can be compared with other neighbouring wells. This supports the predictibility of future geothermal projects.

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