A new mining concept for extraction metals from deep ore deposits by using biotechnology

Deliverable D2.3
Stimulation design and cost report
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Date: 2018-08-02

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## Deliverable 2.3

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Executive summary

This report was submitted in the framework of the BIOMOre project which aims to investigate a new mining concept for extraction metals from deep ore deposits by using biotechnology. As it was described in the Tasks 2.3 and 2.5 of Technical University Freiberg (TUBAF) Chair of Geomechanics, rock mechanics and rock engineering, the ultimate goal was generating stress field and stimulation sub-models (Task 2.3) parallel with the cost estimations of drilling and stimulation designs (Task 2.5). The 3D geological and numerical models were generated by using softwares, RHINO and 3DEC (ITASCA), respectively. The North Sudetic Trough which encloses the Weisswasser city was selected as a modelling region. The calculated stress results were successfully calibrated with those from literature and measured ones from the Rudna Mine. Thereafter, a hypothetical drilling site was selected at the geological model in order to transfer the calculated stress profile into the sub-models and to provide further information for cost estimation of drilling and stimulation designs. All the important information was submitted to experts from the Department of Drilling Engineering (TUBAF) which is responsible for the cost estimation of the drilling and stimulation designs.

Several technologies used for stimulation at shales in North America were reviewed at respective literatures which were mainly published within a time span from 2010 to 2017. Furthermore, intensive discussions were held with the experts from the German industry. Only few important latest and widely used technologies were presented at this work. The final decision on selecting the most convenient stimulation design will be made after obtaining the costs for the stimulation technologies and whole drilling design. However, it is recommended to employ plug-and-perforate fracturing with perforation guns due to the literature survey, stimulation simulations, geological setting, the opinions of experts and requirements of the BIOMOre Project.

Since it was decided to consider the Rotliegend & Grauliegend Sandstone as a target horizon for a possible stimulation design, the sub-models included only this layer together with the overlying layer, (Zechstein) limestone. The sub-models were generated by using the software FLAC3D and their results were initially calibrated with analytical solutions. Following that feasibility of modelling the multi-stage hydraulic fracturing treatment is pointed successfully and obtained results are presented. An optimized fracturing treatment design is developed and supporting points for look-up table relations are generated.
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1. Introduction

Technical University of Freiberg Mining and Technology (TUBAF) is a member of the Workpackage 2 (WP 02) and so involved in Tasks 2.3 and 2.5. Task 2.3 includes two parts, numerical stress field simulation as well as hydraulic fracturing simulation and optimization. Task 2.5 considers the development of an optimized technical concept for drilling and stimulation. In addition to these objectives cost estimation is included in Task 2.5, too.

Since fracture initiation and propagation strongly depend on the in-situ stress condition and its spatial distribution, a three dimensional stress field simulation based on measurements, literature data and an adapted large scale geological model is necessary (Task 2.3). The obtained stress field calculation results are used to estimate a suitable site for permeability enhancement of the copper bearing target zone in the underground. This site selection assists to the generation of a sub-model necessary for hydraulic fracturing simulation in a smaller scale compared to the geological model.

Based on the sub-model, a representative elementary volume (REV) for the hydraulic fracturing calculation is built. Due to the strong dependency between in-situ stresses and fracture propagation, a simulation regarding the fracturing processes is used to design the multiple fracture system in an optimal way. Optimization parameters are a fracture surface and permeability enhancement which should be reached at minimum costs under high long-term protection standards for the biosphere. The numerical fracture simulation is performed with fully hydro-mechanical coupled code FLAC3D. Therefore, a prediction of breakdown and shut-in pressure as well as fracture opening, size and permeability is realised.

This report at hand provides a comprehensive information of calculations to the results of fracturing sub-models; 3D geological and numerical modelling of the selected region (Task 2.3), stimulation technologies (Task 2.5), stress field data transfer from a hypothetical selected drilling site for a possible stimulation design and generating sub-models based on that transferred stress field (Task 2.3). This approach is followed both chronologically and scientifically.
2. Stress field simulation (Task 2.3)

2.1 3D CAD Geological Model

During the meetings and negotiations between project partners since 2015, it is decided to model the in-situ stress state of whole North-Sudetic Trough before planning any fracturing operation. This basin encloses the licensed field of Weisswasser area (see Figure 1). At the end of October 2015 the project partner CNRS (The National Centre for Scientific Research, France) delivered 22 geological layers with the topographic surface, 69 faults and 5 model boundaries as a mesh file format. These meshes form the geological model with the coordinate system WGS84/UTM33N. It has dimensions of 140 km length in the NW/SE direction, 40 km width in the NE/SW direction and it extends between 790 m (a.s.l.) to -2200 m (b.s.l.). This model was generated within the framework of the ProMine Project (2009 – 2013). Some of these layers contain inaccurate topological and geometrical features (holes, self-intersections and very low thickness) regarding the stress-field modelling purposes. The location of the geological model on the map with layers, faults and boundaries are depicted in the Figure 1. The layers are aligned with respect to their depth as the shallowest one (Quaternary) is located on the topmost left and the deepest one (Rotliegendes) is located on the lowermost right.

Some layers were selected by considering most present lithostratigraphic units, geometrical conditions (CAD modelling stage), numerical limitations (numerical modelling stage) and requirements of the BIOMOre project. These are Buntsandstein (or Bunter sandstone), Tertiary, Lower Werra Anhydrite, Zechstein Marl and Rotliegendes. During this study, a comprehensive literature research together with borehole data (CuWW01, CuWW02, CuWW03 and CuWW04) and geological data supplied from KGHM Corporate (Poland) was conducted to evaluate material properties and stratigraphy. Those used literature is; Brocher, 2005; Dec et al. 2011; Kutschke et al. 2015; Lamarche & Scheck-Wenderoth, 2005; Mejía-Herrera et al. 2015; Oszczepalski 1999; Pearce et al. 2004; Scheck-Wenderoth & Lamarche 2005; Vaughan et al. 1989 and Zientek et al. 2015.
Figure 1: The delivered geological model with layers, faults and model boundaries together with its location on the map (with the courtesy of CNRS).

The so-called “reverse engineering” process was applied to generate a CAD solid model as a predecessor to the numerical model. Reverse engineering in the means of CAD modelling indicates the converting of meshes into surfaces. The commercial software RHINO (Version 4) was used for this purpose. Following that, several surfaces were transformed into closed solids which were planned to use as a numerical model. First of all, the curvature of the selected layers and faults were modified to generate realistic surfaces. However, after several solid models it is decided to flatten the layers and faults for the sake of simplicity. Some dispersed faults with similar strike and dip were then joined to obtain a single fault. As a conclusion the final CAD model has these below given geometrical properties, assumptions and limitations:
- Generated faults and layers are planar surfaces with different strike and dip, and they are assumed to cut through all the lithological units in the vertical direction.

- Two types of faults were generated: Main faults which cut through the modeled region transversely and longitudinally. Small scale faults cut the modeled region partly. To prevent possible meshing errors, it is ensured that small scale faults except three of them were located in-between other faults or in-between model boundaries and other faults.

- The WGS84/UTM33N coordinate system was transformed into the three dimensional Cartesian coordinate system (x, y, z). The depth values have a negative sign beneath the topographic surface. In Figure 2.2 the triad of the CAD model origin was depicted.

- The topographic surface was flattened and thereby the surface topography was neglected.

It is found that these selected layers intersect with each other which can cause some erroneous results such as stress singularities and strong stress de-couplings due to the inaccurate aspect ratios of mesh elements in the numerical model. Therefore, the thicknesses of them were manually adjusted with using the optimum values in order to avoid layer intersections. During this process the maximum thickness values of corresponding layers were adapted from Oszczechalski (1999), Pytel (2010) and the data delivered by KGHM Corporate (Poland). Due to the lack of information the thickness of metamorphic rock had to be optimized to keep the model dimensions proportional for the subsequent numerical calculations. Therefore, the depth of the model is considered to be 6 kilometers. Finally, using these edited layers, a solid box model was generated (Figure 2). Six main lithological units between selected layers are depicted in the same figure. These are Cenozoic sediments, Bunter sandstone, evaporite, limestone, Rotliegend - Grauliegend sandstone and metamorphic rock. The triad of the model origin, the stratigraphy of selected layers, faults and the dimensions of the model are depicted in the same figure, as well.
2.2 Literature research and available data for the modelling

In-situ or virgin stress state of a rock mass indicates the stress distribution caused by natural processes such as tectonism. In this work, in-situ stress state of modelled rock masses is considered to be influenced only by gravity and tectonism. The information about the tectonic past and present activity is thus essential for the site selected for the stress field model. Other geological factors such as erosion and topography are neglected. The model region covers the area between north-eastern (NE) part of Germany and south-western (SW) part of Poland. Therefore, the literature research for the tectonic stress regime in the near vicinity of the model has been conducted considering both countries. By using fault-slip data, many authors mentioned that in the Central European and Polish Basin, which partly encloses the modelled region, NE–SW oriented maximum principal stress ($\sigma_1$) was assumed to play a role about the tectonic incidents (Hakenberg & Swidrowska, 1997; Jaroszewski, 1972; Lamarche et
Scheck-Wenderoth & Lamarche (2005) mentioned that NE–SW oriented paleo-maximum stress may be responsible for the orientation of blocks affected by inversion and transpressively reactivated faults (NW–SE). Additionally the 43 out of 69 delivered faults at the North-Sudetic Trough have a strike of approximately NW-SE (see Figure 1 and Figure 2) which is consistent with the above given statement. However, the governing strike pattern of faults are not necessarily representative because of the questionable reliability of the source. Stress field analyses based on the WSM database (World Stress Map, Reinecker et al. 2005) were conducted in the area within the coordinate intervals of 45°-54° latitude and 13°-26° longitude. The results show that maximum horizontal stress (σ\(_H\)) tends to exhibit in the NW-SE direction which is contrary to the above mentioned information. The nearest measured data to the model region is listed in the Table 1 with the corresponding explanations.

Table 1: Stress magnitude values in the nearest vicinity of the model region obtained from WSM database (Reinecker et al. 2005)

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<td>Overcoring or other strain relief measurement</td>
<td>D - Low</td>
<td>TF - thrust faulting (^1)</td>
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<td>The Czech Republic</td>
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<tr>
<td>2</td>
<td>167 NW/SE</td>
<td>Overcoring or other strain relief</td>
<td>D - Low</td>
<td>SS - strike-slip (^2)</td>
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<td>Germany</td>
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<td>3</td>
<td>22 NE/SW</td>
<td>Single focal mechanism</td>
<td>D - Low</td>
<td>NF - normal faulting (^3)</td>
<td>1300</td>
<td>Poland</td>
</tr>
<tr>
<td>4</td>
<td>162 NW/SE</td>
<td>Single focal mechanism</td>
<td>D - Low</td>
<td>SS - strike-slip (^2)</td>
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<td>Poland</td>
</tr>
<tr>
<td>5</td>
<td>112 NW/SE</td>
<td>From analysis of individual breakouts</td>
<td>D - Low</td>
<td>U - Unknown</td>
<td>1110</td>
<td>Poland</td>
</tr>
</tbody>
</table>

Footnotes: \(^1\) σ\(_H\) > σ\(_h\) > σ\(_v\), \(^2\) σ\(_H\) > σ\(_v\) > σ\(_h\), \(^3\) σ\(_v\) > σ\(_H\) > σ\(_h\)
Beside WSM data, the stress magnitude-depth and lateral stress coefficient $(k = (\sigma_h + \sigma_H) / 2*\sigma_v) – depth profiles based on the worldwide measurements are very useful during the calibration stage of stress field simulations. Amongst others, comprehensive data compilation can be found at Aydan and Kawamoto (1997), Brady and Brown (1978), Brown and Hoek (1978) and Jarosiński (2006). They showed the linear increase of individual stress magnitudes and nonlinear decrease of lateral stress coefficient with increasing depths. Based on the measured data, Jarosiński (2006) stated that the prevailing mean azimuth angle of the maximum horizontal principal stress $(\sigma_H)$ is 173° in Poland which is approximately NNW/SSE direction.

On 07.04.2016 measured stress data at the area of Legnica and Głogów cities in Poland were delivered by KGHM Corporate (Poland). The spatial distribution of measured data together with an explanatory inset table containing dip direction [°] and magnitude values of them [MPa] are depicted in Figure 3. The stresses here are compressive and they have a negative sign. The dip directions of measured maximum horizontal principal stresses and their depth values at the measuring points are shown on the same figure with the orange coloured arrows and numbers, respectively. The inset map at the top right on that figure shows the model region (red rectangle), some selected cities in Poland (blue icons) and location of measurements (yellow icons). The $\sigma_H$ is roughly in NW/SE direction at five out of seven measurement locations within the depth range from -892 to -1054 metres (b.s.l.). Considering the general trend of measured stress magnitudes, it can be summarized that $\sigma_H > \sigma_v > \sigma_h$ then $\sigma_H = \sigma_1$, $\sigma_v = \sigma_2$ and $\sigma_h = \sigma_3$ which is consistent with the information given in the Table 2.1. It means that dominating tectonic regime is probably the strike-slip ($\sigma_H > \sigma_v > \sigma_h$) in the near vicinity of the model region.
Figure 3: Measured stress data at the area of Legnica and Głogów cities in Poland together with inset table and inset map (with the courtesy of KGHM Corporate, Poland).

The reliability of the delivered data by KGHM was cross-checked by employing an analytical equation before using them for the numerical model. The percentage residual approach was then used by neglecting the surface topography:

\[
 r_d = \frac{\left| \sigma_{\text{measured},d} - \sigma_{\text{anticipated},d} \right|}{\left| \sigma_{\text{measured},d} \right|} \times 100
\]

\( r_d \) Percentage residual [%] between the measured and anticipated vertical principal stresses at the measurement depth, \( d \)

\( d \) The measurement depth [m] (b.s.l.)
The measured vertical stress magnitude value at the respective depth, \( \sigma_{\text{measured},d} \) [MPa]

The anticipated vertical stress magnitude (or lithostatic pressure) value at the respective depth, \( \sigma_{\text{anticipated},d} \) [MPa] calculated by using the analytical equation:

\[
\sigma_{\text{anticipated},d} = \rho_{\text{mean}} \cdot g \cdot d
\]

\( \rho_{\text{mean}} \) Mean value of the minimum dry volumetric densities of the geological units used in the CAD and numerical model, 2342 kg/m\(^3\). These values are obtained from the data provided by KGHM Corporate (date: 07.04.2016)

\( g \) The gravitational acceleration, -9.81 m/s\(^2\)

<table>
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<th>Measurement Cycles</th>
<th>( d ) [m]</th>
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<td>8.6</td>
<td>1.10</td>
</tr>
<tr>
<td>SM52</td>
<td>-892</td>
<td>-27.7</td>
<td>-20.5</td>
<td>26.0</td>
<td>1.08</td>
</tr>
<tr>
<td>SM53</td>
<td>-892</td>
<td>-27.9</td>
<td>-20.5</td>
<td>26.6</td>
<td>1.07</td>
</tr>
<tr>
<td>SM54</td>
<td>-892</td>
<td>-22.7</td>
<td>-20.5</td>
<td>9.7</td>
<td>0.91</td>
</tr>
</tbody>
</table>
In Table 2 calculated percentage residual values are given with measured stress ratio values. The measured values at SM12 and SM43 were selected as the most reliable ones according to their lower residual values. Therefore, the stress ratio values from them (red marked on the table) are adapted during the calibration phase of the numerical model. These values are: \( K_H = 1.12 \) (SM12) - 1.52 (SM43), \( K_h = 0.81 \) (SM12) - 1.21 (SM43) and \( k = 0.97 \) (SM12) - 1.37 (SM43). For determining the tectonic stress direction, these most reliable data’s dip directions are taken into account together with the Stereonet analyses performed with all measurements (see Annex 1). The Stereonet results showed that the azimuth angle of \( \sigma_H \) ranges between 125° to 169°. Besides, the azimuth angle of \( \sigma_H \) is 110° and 124° at the measurement locations SM12 and SM43, respectively. These values are in a good agreement with the results from WSM and the statements from Jarosiński (2006). Finally, the primary component (\( \sigma_H \)) of the tectonic stress at the model region is assumed to be roughly in NW/SE direction with the Azimuth angle of 122° and it is compressive. The delivered model was originally rotated by 32° along the z-axis in the clockwise direction (see Figure 2). The tectonic stress will be hence applied perpendicular to the outer surface normals of the model with an azimuth angle of 122° due to the numerical issues explained in the Chapter 2.3.

### 2.3.3D Numerical Model

The dimensions and geological units of the aforementioned geological model were transferred one-to-one into the numerical model. Simulations were performed by the commercial software 3DEC (Version 5.2) which employs discrete elements on the contrary to the classical continuum approach. By using the features of this software the hydro-mechanical response of a geological medium bearing discontinuities can be simulated. The simulation of in-situ stress state is divided into two parts: calculation of gravitational and tectonic stresses. In order to implement tectonic activity around and inside of the model domain, different type of stress boundary conditions were applied along the outer surfaces. Therefore auxiliary blocks around the model domain were generated to prevent invoking differential stresses due to possible interactions of applied stress with element edges. The transferred CAD model into the numerical model is called “inner model domain” and the subsequently generated auxiliary blocks are called “outer model domain” (Figure 4). The distance between inner and outer model domain’s outer surfaces is 20 km in x- and y-directions. Several model runs were performed considering: Mesh resolution; material and joint parameters; model depth; dimensions and parameters of auxiliary blocks; initial and boundary conditions. In this report two decisive factors are presented and these are; Boundary conditions

<table>
<thead>
<tr>
<th></th>
<th>SM62</th>
<th></th>
<th>SM72</th>
<th></th>
<th>SM73</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-898</td>
<td>-27.7</td>
<td>-20.6</td>
<td>25.5</td>
<td>1.16</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>-935</td>
<td>-27.6</td>
<td>-21.5</td>
<td>22.2</td>
<td>1.00</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>-935</td>
<td>-18.2</td>
<td>-21.5</td>
<td>18.0</td>
<td>1.05</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Footnotes: \( K_H = \sigma_H / \sigma_v, K_h = \sigma_h / \sigma_v, k = (\sigma_H + \sigma_h) / (2*\sigma_v) \)
applied along the outer surfaces as mimicking the tectonic activities (or shortly tectonic stresses) and joint friction angle. The tectonic stresses were selected due to their higher uncertainty in comparison to other factors. The joint friction angle was chosen due to the statements of Hyett (1990), Homberg et al. (1997) and Zoback & Healy (1984) that they considered this property as the most influencing one on magnitude and orientation change of stresses around faults.

![Diagram of numerical model with domains, faults, blocks cut by faults and mesh refinement.](image)

**Figure 4:** Numerical model with domains, faults, blocks cut by faults and mesh refinement.

The material parameters before applying different tectonic stress types along the outer surfaces of outer model domain are given in Table 3. The inner and outer model domains were assumed to exhibit material behaviours of Mohr-Coulomb plasticity and linear elasticity, respectively. Both domains were considered to be isotropic. Roller boundary condition was applied along all surfaces except the uppermost one. The inner model domain was gradually meshed by considering the target drilling depth at the Rotliegend & Grauliegend sandstone (see the Chapter 3.4). Ten times higher the value of the target drilling depth (30 metres x 10) is set to be the level of mesh graduation transition. The mesh resolution is “350 metres” from the surface to the level 300 metres beneath the bottom of limestone and the mesh resolution is “750 metres”
from that level up to the model ground. The refined mesh thus enables more stress values from greater numbers of zones. The outer model domain has a mesh resolution of “750 metres”. Pore water pressure has not been considered, so the dry mean volumetric densities (ρ) were assigned and so the total stress magnitudes were obtained as output. Finally, the model domain is refined by cutting it with axillary joints (with spacing 5 km) along the x and y directions. The aim was to avoid bigger block volumes for numerical issues.

Table 3: Mechanical parameters of intact rocks in the whole model.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material-1</td>
<td>2740^1</td>
<td>10.26^1</td>
<td>8.5^1</td>
<td>59^1</td>
<td>12.5^1</td>
<td>29^4</td>
<td>3.5^1</td>
</tr>
<tr>
<td>Material-2</td>
<td>2740^1</td>
<td>10.26^1</td>
<td>8.5^1</td>
<td>59^1</td>
<td>12.5^1</td>
<td>29^4</td>
<td>3.5^1</td>
</tr>
<tr>
<td>Material-3</td>
<td>2895^1</td>
<td>38.5^1</td>
<td>22^1</td>
<td>58^1</td>
<td>5^1</td>
<td>28^4</td>
<td>6.25^1</td>
</tr>
<tr>
<td>Material-4</td>
<td>2770^1</td>
<td>45.6^1</td>
<td>26.7^1</td>
<td>63^1</td>
<td>16.5^1</td>
<td>33^4</td>
<td>7.5^1</td>
</tr>
<tr>
<td>Material-5</td>
<td>2320^1</td>
<td>14.6^1</td>
<td>12.1^1</td>
<td>59^1</td>
<td>12.5^1</td>
<td>29^4</td>
<td>3.5^1</td>
</tr>
<tr>
<td>Material-6</td>
<td>2700^2</td>
<td>45.8^2</td>
<td>21.2^2</td>
<td>35^2</td>
<td>31^2</td>
<td>17^2</td>
<td>9^2</td>
</tr>
<tr>
<td>Material-7</td>
<td>2740^3</td>
<td>10.26^3</td>
<td>8.5^3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Footnotes:

ρ dry volumetric density [kg/m³], K bulk modulus [GPa], G shear modulus [GPa], Φ friction angle [°], C cohesion [MPa], Ψ dilation angle [°], σt tensile strength [MPa]

1 These values are obtained from the data provided by KGHM Corporate on 07.04.2016

2 These values are based on the data given by Zeeb et al. 2014 and Landesamt für Umwelt 2011

3 These are the same parameters with the Cenozoic sediments. The minimum values of bulk and shear modulus have been assigned so that stress propagation was eased.

4 The value of dilation angle is estimated as ψ = φ - 30° based on other modelling concepts and empirical results from Vermeer and Borst (1984)

The mechanical behaviour of joints can be determined by means of experiments. Unfortunately, due to the lack of information, the assumptions have to be made based on values from the literature and former distinct element modelling approaches. Two types of joints were used for the numerical model; artificial - lithological discontinuities which represent auxiliary cuts and lithological boundaries; and natural joints which represent faults. The initial values of joint parameters are given in Table 4 with respective explanations. It should be noticed that the motion (sliding) is only allowed along the joints representing faults. Furthermore, all joints were assumed to exhibit material behaviour of Coulomb slip failure.
Table 4: Mechanical properties of all created joints in the model – base case.

<table>
<thead>
<tr>
<th>Discontinuity Type:</th>
<th>(K_n) [GPa]</th>
<th>(K_s) [GPa]</th>
<th>(\Phi_j) [^\circ]</th>
<th>(C_j) [GPa]</th>
<th>(\Psi_j) [^\circ]</th>
<th>(\sigma_{t,j}) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary cuts and lithological</td>
<td>0.01 (^1)</td>
<td>0.01 (^1)</td>
<td>35 (^2)</td>
<td>10 (^1)</td>
<td>0 (^4)</td>
<td>10 (^5)</td>
</tr>
<tr>
<td>boundaries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faults</td>
<td>0.01 (^1)</td>
<td>0.01 (^1)</td>
<td>0 (^3)</td>
<td>0 (^3)</td>
<td>0 (^4)</td>
<td>0 (^3)</td>
</tr>
</tbody>
</table>

Footnotes:

1. Although higher stiffness prevents the higher displacements along the joints, here the stiffness was set to be equal to the minimum value found at the literature (KULHAWY 1975) in order to ease the sliding along the faults in the gravitational and tectonic phases. For the sake of consistency, the same value is then assigned to all other kind of joint types. These values will be calibrated in further model studies.

2. Higher friction angle prevents the sliding along the joints so the maximum value of friction angle has to be set for artificial and lithological joints. Furthermore, the friction angle value of joints should be less than those from intact part of a rock. The minimum value from the metamorphic rock (35\(^\circ\)) was hence assigned.

3. In order to mimic the often observed displacement-weakening response of natural joint behaviour, the joint friction, cohesion and tensile strength values have been set to reduced (usually zero) values when the tensile or shear strength is exceeded. As the cohesion means "the shear strength when the compressive stresses are equal to zero" so setting the cohesion to zero would enable free movement of the faults then model can reach easily to the initial force-equilibrium state.

4. Dilation is prevented on all joints for the sake of simplicity (non-associative flow rule).

5. The value of tensile strength from artificial and lithological joints were maximized in order to prevent possible tensile failure thereby avoiding splitting.

It is important to notice that before applying the tectonic stresses, simulation was brought into the mechanical equilibrium by employing prescribed stress ratios \((K_H\) and \(K_n\)) at the gravitational phase. The vertical stresses were first calculated by means of gravity, density of rocks and depth. Ratios were then assigned so that horizontal stress components could have been calculated at the respective depths, as well. Subsequent to fulfilling the initial equilibrium in the gravitational phase where the consolidation of rocks is ensured, different types of tectonic stresses were applied as a boundary condition. Among numerous modelling approaches only six of them will be introduced.
here (see Table 5). The pictograms in Figure 5 summarize applied boundary conditions used in these modeling approaches.

![Pictograms summarizing the applied boundary conditions to mimic the tectonic stress ($\sigma_{\text{tectonic}}$)](image)

Figure 5: Pictograms summarizing the applied boundary conditions to mimic the tectonic stress ($\sigma_{\text{tectonic}}$)

Tectonic stress component was invoked through applying total stress with the initial value and its gradient in the $z$-direction (depth). They are applied throughout the respective outer surfaces which’s normal is parallel to the applied direction of stresses (Figure 5). Differential stresses have been thus prevented. It is stated in the 3DEC Manual (First Revision Version 5.2) that all loads and stresses are assumed to be constant and permanent by default, and are added to the existing permanent loads. The formulation of these applied stresses are given below:

$$\sigma_{\text{tectonic},z} = \sigma_{d,z} = \sigma_{d0} + (\sigma_{d,z} \cdot z)$$

- $d$  Direction where the stress has been applied, for instance x- or y- directions [-]
- $z$  Changing depth [m] – internal calculated
- $\sigma_{d,z}$  Calculated total stresses [Pa] applied along the prescribed direction (d) and at the respective depth (z) – internal calculated
- $\sigma_{d0}$  Initial stress value [Pa] at the topographic surface where the depth is equal to zero ($z = 0$) – assigned
- $\sigma_{dz}$  $z$ - component (depth) of the stress gradient applied [Pa/m] along the prescribed direction (d) – assigned

Model settings with different tectonic regime considerations are summarized in Table 5. Except applying different types and values of tectonic stress boundary conditions, all other settings are kept same for all these models (see Table 3 and Table 4). In order
to obtain realistic solutions, model settings were created based on the approaches given by Jarosiński (2006) and Zang & Stephansson (2009).

Table 5: Model settings using different types of tectonic stress boundary conditions

<table>
<thead>
<tr>
<th>Model settings:</th>
<th>Applied boundary conditions throughout the outer surfaces (see Figure 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surfaces - a</td>
</tr>
<tr>
<td>Basic-1_1</td>
<td>Type-3:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -0.42$ MPa and $\sigma_{xz} = 41000$ Pa/m</td>
</tr>
<tr>
<td>Basic-1_2</td>
<td>Type-3:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -8$ MPa and $\sigma_{xz} = 30000$ Pa/m</td>
</tr>
<tr>
<td>Basic-1_3</td>
<td>Type-3:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -8$ MPa and $\sigma_{xz} = 25000$ Pa/m</td>
</tr>
<tr>
<td>Basic-2</td>
<td>Type-4:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -22$ MPa</td>
</tr>
<tr>
<td>Basic-3</td>
<td>Type-3:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -8$ MPa and $\sigma_{xz} = 30000$ Pa/m</td>
</tr>
<tr>
<td>Basic-4</td>
<td>Type-3:</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{x0} = -8$ MPa and $\sigma_{xz} = 30000$ Pa/m</td>
</tr>
</tbody>
</table>

In all the tectonic calculation phases, simulation results for above-mentioned model settings were observed at 347 points. The results were quantitatively and qualitatively evaluated under these constraints:

- Calculated stresses should follow the measured stress trend, however the number of measurement points are very few. Their areal and vertical extent is limited, too (Figure 3).
Displacements and velocities of the selected points of a model should converge to the non-zero value which may indicate that the model has been in the equilibrium.

Displacement of selected points on the inner model domain should be within an acceptable range after the end of simulation to prevent massive motions of intact rocks along the faults especially in the vertical direction.

Although it is postulated in the literature that some tensile stresses were already measured in Poland, tensile stresses (with a plus "+" sign) at the model should not be obtained considering further stimulation model.

Calculated stress values of selected points should converge to a non-zero value and should preferably have a "-" sign (compressive).

Along the selected scanlines at the model (Figure 6), calculated stress ratio values should be in the intervals provided by measurements as: $K_H = 1.12 - 1.52$, $K_h = 0.81 - 1.21$, $k = 0.97 - 1.37$ and the azimuth angle of the $\sigma_H$ should lie between N110 - N124 (see Chapter 2.2).

The tendencies of stress magnitude-depth and lateral stress coefficient-depth described in the Chapter 2.2 are preferred to be fulfilled by the model results but one-to-one fitting is not an obligation due to the modelling limitations and simplifications performed.

As it is postulated in the 3DEC Manual (Version 5.2) the region of active yielding which indicates non-elastic behavior should be decreasing which may indicate the equilibrium.

The joint normal displacement should not be greater than roughly 10 % of an adjacent zone size which may indicate the underestimated value of joint stiffness (3DEC Manual Version 5.2).

Numerous simulation results were obtained. However, the selected best-fit model setting the “Basic_1-3” which fulfills most of the constraints will be presented at this work. Figure 6 depicts the selected scanlines in the inner model domain to display the calculated stress magnitudes and orientations.
In Figure 7 the change of calculated absolute stress magnitudes (Basic-1.3) with the depth along the scanline-z is depicted. Different block colors on these figures indicate different lithological units (see Figure 2) and the dashed black line shows the border of mesh graduation transition (see Figure 4). Model results along the scanline-z show that the maximum ($\sigma_H$) and minimum horizontal principal stresses $\sigma_h$ align roughly in directions of NW/SE and NE/SW, respectively. The $\sigma_H$ has mostly the maximum magnitude ($\sigma_1$) except under the depth -5.5 km. This can be explained by the domination of vertical stress with increasing depth. The three principal stress magnitudes $\sigma_H$, $\sigma_h$ and $\sigma_v$ vary in ranges of 12 to 147, 4 to 127 and 2 to 148 MPa. The measured variations of stress magnitudes as well as their orientations with depth is called stress decoupling (Haimson 1980; Stephansson 1993; Martin and Chandler 1993; Roth and Fleckenstein 2001; Ask and Stephansson 2003). This phenomenon was also encountered at the simulations along the evaporite interval (white, material-2). Along the scanline-z; the magnitude of $\sigma_H$ was increased from 42 (depth = -1.2 km at the material-2) to 67 MPa (depth = -1.5 km at the material-3). This sudden change corresponds to approximately 60% magnitude increase. The stress decoupling through the lithology change with the depth is caused by the stiffness contrast. This statement was proved by the analyses. Simulations were performed without faults then this phenomena was encountered again. The gradual meshing does not have an influence, because no stress decoupling is encountered along the gradual mesh transition. However, additional analyses are recommended to be performed. As a final statement, it can be said that under the presence of external loading as stresses along boundaries ($\sigma_{tectonic}$), stiffness contrast between layered lithological units leads to stress decoupling.
Figure 7: Calculated stress magnitude values [MPa] in comparison with the trends from the literature (Aydan et al. 1997 and Jarosiński 2006) along the scanline-z obtained by the best fit model, Basic-1_3
Calculated lateral stress coefficient, \( k \) (Figure 8) is in a good agreement with the measured one (red line, see Table 2). The value of lateral stress coefficient varies within the range between 3.5 (\( z = 0 \)) to 0.9 (\( z = -6 \text{ km} \)). On that figure peaks can be seen especially along the evaporite (white block) due to the stress decoupling. Up to the depth of 3 km the calculated stress coefficient falls within the estimated lower and upper limits determined by Brown and Hoek (1978). Under this depth, it exceeds the upper limit which can be explained by the insufficient tectonic stress magnitudes against the increasing vertical stress magnitudes with depth.

![Figure 8: Calculated and measured lateral stress coefficient values [-] in comparison with the lower and upper limits given by Brown and Hoek (1978) along the scanline-z obtained by the best fit model, Basic-1_3.](image)

In order to analyze the most influencing parameters of faults on calculated stresses, the friction angle of joints (\( \Phi_j \)) were changed at the best-fit model setting Basic-1_3 as mentioned before. It should be noted that only the joint friction angle value of faults was changed while keeping all other parameter values unchanged. Due to the lack of data, general values were used from the literature. So the minimum value was set to 20° considering the values given by KULHAWY (1975). The maximum value was accepted to be equal to the value of an intact rock which has the minimum value among others. This is the metamorphic rock with the friction angle value of 35°. Subsequent to determining the range of joint friction angle values, the values per each model variation are assigned as Variation-1 (\( \Phi_j = 25° \)), Variation-2 (\( \Phi_j = 30° \)) and Variation-3 (\( \Phi_j = 35° \)). In Figure 9 calculated biaxial stress tensors at the Rotliegend & Grauliegend sandstone were depicted from the model settings; Basic-1_3, Variation-
2 and gravitational-only stress results. The last mentioned one indicates the model which was run only considering gravitational acceleration. This model has the same settings with the Basic-1_3. In the same figure minimum and maximum values of calculated $\sigma_1$ and $\sigma_3$ per each model setting together with the applied tectonic stress (arrow doublets) and faults (black lines) are also depicted. The direction of $\sigma_1$ changed from vertical to NW/SE direction in the model settings Basic-1_3 and Variation-2 after applying tectonic stresses along outer surfaces. The stress tensor directions exhibit very scattered behavior due to the zero joint friction angle (Basic-1_3) wherein the sliding of faults were eased. Subsequent to applied tectonic stresses, stress tensor directions significantly changed at the model due to the deformation change along and near to faults via eased sliding property of faults. On the contrary to the results of Basic-1_3, the stress tensor directions followed the direction of tectonic stresses because of the increased joint friction angle value which had comparatively hindered the sliding along faults. At the NW part of the model, the stress tensor directions exhibit exceptionally a different pattern. The $\sigma_1$ direction changed from NW to upwards (vertical) against the faults which can be explained by propagation of tectonic stress directly perpendicular to the fault surface. The depth of the Rotliegend & Grauliegend sandstone upper surface ranges between -1484 to -2637 meters (b.s.l.). The measured stress magnitudes given by Jarosiński (2006) under these depths (see Figure 2.7) vary between; -43 to -76 MPa and -29 to -51 MPa for $\sigma_1$ and $\sigma_3$, respectively. These values are in a good agreement with those from Variation-2. However, stress amplifications were encountered at the Basic-1_3 with values of $\sigma_1 = -170$ MPa. This can be explained by stress singularities occurred at sharp edges of faults due to the reduced joint friction angle of faults ($\Phi_j = 0^\circ$).

![Figure 9: The calculated stress distribution ($\sigma_1 - \sigma_3$) and their magnitudes per each model setting at the Rotliegend & Grauliegend sandstone including the faults together with applied tectonic stress.](image)
3 Technical report (Task 2.5)

3.1 Introduction to the stimulation

Fracturing or stimulation can be described as creating fractures by using several technologies (fluids, explosives and etc.) at a rock which bears oil, gas or raw materials, to ease the flow between a reservoir and a wellbore by enhancing permeability. Relying on employed technology and reservoir characteristics, some more equipment such as perforation tools, proppants and acids may be considered as well. Beaman & McNeil (2012) indicated that the ultimate goal is to make production economically and maximize well performance; however environmental safety is also an essential subject. Fracturing technologies have been applied for more than 60 years. Several technologies used for fracturing at shales in North America were reviewed at respective literatures which were mainly published within a time span from 2010 to 2017. Furthermore, intensive discussions were held with the experts from the German industry. Only few important latest and widely used technologies will be explained at this work. Wellbore completion design for fracturing determines fracture pattern with reservoir parameters. Some basic steps and factors are required to design a wellbore wherein fracturing will be performed. Those controlling factors during a fracturing treatment planning at a reservoir are summarized below and depicted as a flow schema in Figure 10.

![Figure 10: Simplified flow schema defines the interdependency between the factors of rock stimulation which influences fracture placement designs together with reservoir parameters.](image)

3.2 The technical instruments and materials used

Important technical instruments used during and after the rock stimulation are: Annular isolators (e.g. straddle packers), mechanical isolators (e.g. shift or sliding sleeves, ball sealers and ball seat systems), plugs, pipes, coiled tubing and perforation tools. It was
noticed during the literature research that, fracturing applications by using “coiled tubing” is the mostly preferred one. Coiled tubing is a ductile steel tubing or conduit with small diameters (usually 1” to 1-3/4”) which is coiled onto a reel and used for pumping fluids (also cement) into the wellbore (API 1993). Keshavarzi (2011) defined a perforation as a process of creating tunnels through the cemented steel casing and thereby rock formation lets the formation fluid flow into the well. This definition is valid for applications in petroleum industry and perforation can be conducted along uncemented parts of a wellbore, too.

Diverse fracturing materials are found in the literature and those are summarized in Table 6. It should be noticed that when a gas is used as a fracturing material then this treatment is not usually defined as „hydraulic fracturing”. The term “hydraulic fracturing” is mostly given to a stimulation treatment at which a liquid is used, for instance water, acid or oil. As an alternative stimulation technology to hydraulic fracturing, “radial jetting” has been developed for more than a decade. Although this technology was reported to be more controlled, more economical and less risky than hydraulic fracturing, its site-specific applications are limited and these applications are still under development. Peters et al. (2015) gave comprehensive information about this technology.

Table 6: Fracturing materials used during stimulation at shales.

<table>
<thead>
<tr>
<th>Fluid type</th>
<th>Acid, foam, gel, high brine tolerant polymer,(liquid) resin, nitrogen, polysaccharide fracturing fluids, propane (LPG), propellant, (supercritical) CO₂, viscous oil and etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Others</td>
<td>Chemical additives, explosives, proppants, surfactants</td>
</tr>
<tr>
<td>Hybrid fluid</td>
<td>Slickwater (composed primarily of water and sand) together with proppant and etc.</td>
</tr>
</tbody>
</table>

In case of considering only hydraulic fracturing, the fluid used can be then divided into three main components (Xiong et al. 1996 and Gandossi 2013):

Fracturing Fluid = Base Fluid + Additive + Proppant

The common base fluids are water-based, foam-based, oil-based, acid-based, alcohol-based, emulsion-based and other fluids (liquid gases). Chemical additives (e.g. Methanol and Liquid CO₂) are used to retard the growth bacteria around the wellbore, and it also serves for lowering viscosity of base fluid. In order to prevent the closure of created fractures after the fracturing treatment at a rock, it is necessary to introduce some type of particles called propping agents or proppants to hold the faces of fracture apart and afford a highly permeable conductive channel from the formation
to the well (Donaldson et al. 2013). These can be any natural or synthetic material such as well-sorted sand, glass beads, walnut hulls and other types of synthetic particles.

According to Gomaa et al. (2014), created fracture complexity has a strong relation with the fracture fluid type since viscosity and acidity plays an important role. Reducing the viscosity and (or) increasing the acidity of the fluid may increase fracture complexity. Moreover, the author concluded that Nitrogen gases will maximize the fracture complexity. The lowest and highest fracture complexity might be obtained by using crosslinked gel (very high viscosity) and gases, respectively. The comparative illustration of a fracturing material influence on a fracture pattern is given by Safari et al. (2013) in Figure 11. By using hydraulic fracturing (a) one single fracture can be generated which is expected to align with the direction normal to the minimum principal stress. However by using explosive (b) and pulsed gas (c) the fracture pattern can be more complex which is consistent with the statement from Gomaa et al. (2014). By using these methods radial fractures may be observed which seems to be preferential. Nevertheless, this may trigger uncontrolled fracture growth and seismic events due to the complex behaviour of gas and destructions by explosives, respectively. A very recent and encouraging method as a special application of fracturing using pulsed gas is investigated by Al-Nakhli et al. (2014). The results were obtained from laboratory experiments performed at shale, limestone and sandstone block samples. Basically, the chemicals are injected into the wellbore together with the catalyst and this causes an exothermic chemical reaction which releases gas and heat. Through temperature and gas pressure rise, shear fractures are formed at the rock around the wellbore. However, the applicability of this technique at field is still under development and beside this, unforeseen incidents due to the interaction between pulse gas and following bioleaching reactions may arise.

Figure 11: Fracture patterns from various techniques; Hydraulic (a), explosive (b) and pulsed gas (c) fracturing (Safari et al. 2013).
Advantages and disadvantages together with the applicability of most recent fracturing fluids and techniques applied for shale gas production are summarized under chosen key factors in the Annex 2. Fracturing techniques are classified under three categories as; Dynamic, hydraulic, pneumatic and other. This concept is adapted from Gandossi (2013). At this table the symbols plus (+) and minus (-) indicates an advantage and a disadvantage for a fracturing fluid or technique under regarding key factor, respectively. Using a thermal fracturing technique for instance which is classified under the other will exhibit one advantageous and two disadvantageous features during an on-site operation (a key factor). According to this table, the fracturing fluid LPG seems to be a convenient since it exhibits nine advantageous and only two disadvantageous features. Although the applicability of this method is considered to be not available by the author, some studies considering LPG based fracturing performed at shales have been found (see Soni 2014 and Leblanc et al. 2011). Unlike the LPG, electric fracturing technique exhibits two advantageous and three disadvantageous features and its applicability at shales is given as under development, so this technique should be considered to be inconvenient.

3.3 The wellbore completion design

One of a criteria to classify the wellbore completion types is the fracturing entry number and instruments used during the treatment. Under the Chapter 3.2, most frequently used instruments for a fracturing treatment are briefly explained. The fracturing stage indicates a location at a wellbore where a fracturing treatment is performed within an intended time interval. Per fracturing stage it is possible to perform fracturing along single or multiple points of entry and these treatments are then called single stage or multistage fracturing, respectively. There are several multistage fracturing treatments, however only three most effective and efficient methods used in American shale plays for gas/oil production will be examined at this work. These are coiled-tubing-activated, plug-and-perforate and ball-activated systems (Algadi et al. 2015, Beaman & McNeil 2012, Kennedy et al. 2012 and Yuan et al. 2013).

Coiled tubing fracturing method relies mainly on the “Bottom Hole Assembly” or shortly the BHA concept. This is a combination of packers and perforation tools integrated on coiled tubing (see Figure 12). The packer has a function of zonal isolation between perforated intervals. The perforation tool is used to ease the flow by perforation along the intended zone before the stimulation will be conducted by pumping the selected fracturing material. The clean-up of any residual after a fracturing procedure can be also performed within a coiled tubing work string at a wellbore annulus. Instead of packers, other instruments such as casing sleeves and hydrajets (on coiled tubing) can be used as well. One of a very promising and widely used coiled tubing fracturing method using hydrajets is called “pinpoint fracturing” (for more information see Lopez-Bonetti et al. 2014). In the Figure 3.2 the basic fracturing procedure (from step 1 to 3) by coiled tubing is depicted. It should be noted that all zones were perforated (shown by blue triangles) before the stimulation has been initiated. The BHA is driven into the bottom of a wellbore against an intended zone to create fractures. Straddle packers are blown up to ensure the isolation during the fracturing treatments. If required the
clean-up will be performed upon completion of a fracture treatment while BHA pulling up to a next zone by loosening packers. The procedure (isolation, fracturing, clean-up) will be started from the beginning for other zones.

Figure 12: Sequential illustration of coiled tubing fracturing procedure (adapted from Gulrajani et al. 1999).

The second mostly used plug-and-perforate fracturing is performed by moving coiled tubing through different stages at a well lateral. It is performed by using a perforation tool integrated on a coiled tubing and then injection of a selected fracturing material. At the end of an intended fracturing operation, plugs are removed by a milling head. A brief illustration of this method is sequentially depicted (from step 1 to 5) at the Figure 13. At the beginning, a plug is emplaced by using coiled tubing at the toe of a horizontal wellbore (step 1) and perforation is conducted along an intended stage (step 2). In order to perform fracturing operation, selected fracturing material (here a fluid) is then injected through cased borehole (step 3). After accomplishing the first fracturing procedure as plug emplacement, perforation and stimulation (Steps 1-3), same procedure will be started from the beginning for other stages along an intended interval from toe to heel of a horizontal wellbore (step 4). At the end of a planned fracture treatment, plugs are removed by using a milling head or coiled tubing. Plugs have an important function of isolating the different stages where fractures were created by perforation and stimulation.
The third most used ball-activated systems can be defined as a completion performed by dropping of gradually sized balls into sliding sleeves. It consists of three mechanical parts integrated on a liner hanger or on a long-string. These are: Frac ports at where a fracturing material is pumped, *sliding sleeves* which contains frac ports on it and shifts via pressure rise through the sealing of a dropped ball and then opens frac ports, and *gradually sized* balls dropped from surface into sliding sleeves. Sliding sleeves shift and open frac ports along an intended stage of fracturing. Frac ports can be then activated and fracturing can be conducted at an intended operational depth by pumping the selected fracturing material. Balls have a vital importance of offering both activation and sealing functions and thus fracturing can be conducted at different stages. Figure 14 gives a brief sequential illustration (steps 1 to 5) of frac ports activation through seating of gradually sized balls in a wellbore.
Figure 14: Sequential illustration of ball-activated fracturing procedure (adapted from Daneshy, 2011).

The SWOT (Strength-Weakness-Opportunity-Threat) analyses of those aforementioned wellbore completion systems are given in Table 7. In order to provide a brief comparison between those three systems, several technical and scientific papers were reviewed.
Table 7: **SWOT** analyses of three common wellbore completion systems: Coiled-Tubing, Plug & Perforate and Ball-Activated systems (Daneshy 2011, Gulrajani & Olmstead 1999, Kennedy *et al.* 2012, Lindsay *et al.* 2012, Moslavac *et al.* 2010 and Thomson 2014)

<table>
<thead>
<tr>
<th>Coiled-Tubing system:</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td>Strength:</td>
<td>Weakness:</td>
</tr>
<tr>
<td></td>
<td>- Most accurate fluid placement into each stage during shut-downs</td>
<td>- Lower injection rates</td>
</tr>
<tr>
<td></td>
<td>- Coiled tubing readily available for premature screen outs*</td>
<td>- Available <em>weight on bit</em> at depth for setting tools – causes depth limitations</td>
</tr>
<tr>
<td></td>
<td>- Efficient fracture treatment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Accelerated production</td>
<td></td>
</tr>
<tr>
<td><strong>External</strong></td>
<td>Opportunities:</td>
<td>Threads:</td>
</tr>
<tr>
<td></td>
<td>- Reduced maintenance and logistical issues</td>
<td>- Higher surface pressures required due to increased frictional pressure losses</td>
</tr>
<tr>
<td></td>
<td>- Less fluids required</td>
<td>- Slower than sliding sleeves</td>
</tr>
<tr>
<td></td>
<td>- Perforating, fracturing and diversion in a single trip</td>
<td>- Increased pump time versus plug &amp; perf method</td>
</tr>
<tr>
<td></td>
<td>- Less chance of over-flushing near wellbore</td>
<td></td>
</tr>
<tr>
<td>Plug-and-perforate system:</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
<td>----------</td>
</tr>
</tbody>
</table>
| **Internal** | Strength:  
- Considered reliable and efficient  
- Best overall recoveries  
- With micro-seismic fracture mapping can avoid geo-hazards or need of offset wells  
- Full bore after plug mill out | Weakness:  
- Multiple trips into well  
- Depending on number of stages, this technique can take several days or more |
| **External** | Opportunities:  
- Best placement of fractures  
- Flexibility: Treating individual stages and changing design at the same time  
- Advanced fracturing techniques | Threads:  
- Has higher intervention costs when compared to other techniques such as sleeves  
- High amount of over-flushing – reduced fracture conductivity |
3.4 The preliminary results of drilling and stimulation cost estimations

In the framework of the BIOMOre project, optimum borehole profile and drilling design subsequent to in-situ stress simulations were planned as an ultimate goal of the Task 2.5. Some technical perquisites had been already specified as it was described in the “Grand Agreement” of this project: *The final process will consist of an array of so-called well doublets, which consists of deviated and pair-wise parallel injector and extractor wells.* The target zone wherein stimulation would be conducted is chosen to be the Rot- & Grauliegelend sandstone (see the Report BIOMOre Deliverable 3.1). The

<table>
<thead>
<tr>
<th>Ball-activated systems:</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td>Strength:</td>
<td>Weakness:</td>
</tr>
<tr>
<td></td>
<td>- More efficient – reduced field operating time (allows for wells to come on production faster than does the plug-and-perforate method)</td>
<td>- Less control on fracture location and number</td>
</tr>
<tr>
<td></td>
<td>- Less frequent screen out</td>
<td>- Difficulty to re-fracture</td>
</tr>
<tr>
<td></td>
<td>- Several stages can be stimulated in a single day</td>
<td>- Harder to clean out in case of premature screen out-drill out baffles (plates)</td>
</tr>
<tr>
<td><strong>External</strong></td>
<td>Opportunities:</td>
<td>Threads:</td>
</tr>
<tr>
<td></td>
<td>- Reduced cost due to field operation time</td>
<td>- Possible tool malfunctions and unless milled loss of full bore</td>
</tr>
<tr>
<td></td>
<td>- Reduced amount of over-flushing required compared to the plug &amp; perf method</td>
<td>- Risk of poor isolation due to enlarged boreholes or washouts</td>
</tr>
<tr>
<td></td>
<td>- Simpler from a logistical point of view (e.g. no need of composite plugs and perforation-tools)</td>
<td>- In-flexible: Changes cannot be made in stage depths</td>
</tr>
</tbody>
</table>

Footnote: * screen out: Interference occurred at flow area due to transported solids in a fluid (e.g. Proppant) used for stimulation.
candidate site for a possible drilling operations were determined at the 3D CAD model by considering factors given below:

- **Layer thickness along the wellbore trajectory:** Geological data, information from boreholes and the literature survey showed that higher copper concentrations have been observed along the bottom of (Zechstein) Limestone. The maximum layer thickness of the Rotliegend & Grauliegend Sandstone under a well trajectory is hence preferred to be lowest in order to have reliable results, because all the rock thicknesses in the numerical model were maximized to avoid numerical problems (see the Chapter 2.1).

- **Lower impact of tectonic activity and realistic in-situ stress state:** In order to prevent unwanted seismic activity during and after a possible stimulation, it is important to select a drilling location which is not close to the faults. The critical distance between a candidate site and faults should be at least 1 km. Furthermore, the calculated in-situ stress values should be in reasonable ranges which were discussed in the Chapters 2.2 and 2.3. Another important point is the gradual meshing transition between inner and outer model domains at the numerical model which’s effect should be minimized to prevent the numerical influence on calculated stresses.

- **Drilling depth:** This is the depth of the target horizon (b.s.l.) where the wellbore trajectory starts to be horizontal. Its value should be kept a minimum to prevent higher drilling costs. The distance between the lateral (horizontal part of the wellbore) and bottom of the Limestone (possible copper mineralization) should be optimized to avoid the higher drilling costs, too.

Subsequent to the selection of the most suitable site for drilling, a target drilling depth was set. This is done by considering the BIOMOre Consortium criteria based on environmental safety-biochemical processes (see Report BIOMOre Deliverable 3.1) and by using chemical analyses data from the final reactor at the Rudna Mine supplied by GEOS Corporation (date: 14.10.2016). These BIOMOre Consortium criteria are briefly: Shale layer thickness, carbonates in the sandstone layer, ventilation, logistics – safety and salinity. The target drilling depth is then set to 30 meters beneath the limestone bottom, so the True Vertical Depth (TVD) of the target drilling depth is 1564 meters. This value is adapted from the recoverable resources zone depth determined at the Rudna Mine. The recovery zone is found between 5.7 to 8.2 meters from the shale bottom (see Report BIOMOre Deliverable 3.1). In Figure 15 the selected drilling site at the 3D CAD model, the representative design of multibranch wellbore and the selected target drilling depth on the stratigraphy column are depicted. All this information was submitted to experts from the Department of Drilling Engineering (Technical University of Freiberg) which is responsible for the cost estimation of the drilling and stimulation designs.
Figure 15: The selected drilling site at the 3D CAD model with the target drilling depth on the stratigraphic profile as well as the representative design of multibranch wellbore.

The final decision on selecting the most convenient stimulation design will be made after obtaining the costs for the whole drilling and stimulation technologies. However, it is recommended to employ plug-and-perforate fracturing with perforation guns due to the literature survey, stimulation simulations, geological setting, the opinions of experts and requirements of the BIOMOre Project.
4 Hydraulic fracturing simulation (Task 2.3)

4.1 Introduction

4.1.1 Simulation Software and numerical modelling algorithm

As mentioned in Chapter 1 hydraulic fracturing simulation and optimization has to be performed in order to achieve reasonable productivity of the target formation in the North Sudetic Trough. The target formation is shown by the first 30 m of Rotliegend-sandstone below the Zechstein horizon (Chapter 3.4) since the limestone (Zechstein) should not be penetrated by the hydraulic fractures. If the fractures are penetrating limestone the whole bioleaching process will be disturbed and copper production becomes ineffective. This situation shows the necessity of numerical simulations.

This report should point out the feasibility of numerical simulation for hydraulic fracturing with the numerical code FLAC3D. FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) from Itasca company employs a Finite Difference Method (FDM) in the framework of continuum mechanics. For simulation of hydraulic fracturing treatments with FLAC3D, an algorithm for fracture generation and propagation was developed. This algorithm allows the prediction of fracture opening and hydraulic parameters. The model is built up of several elements (zones) acting as a continuous rock mass. Induced cracks are indicated by individual zone failure due to fluid injection. A failed element contains a virtual crack plane through the zone at its centre.

The algorithm is based on the concept of Zhou & Hou (2013) dividing the model into fractured (failed), unfractured (intact) and fracture-front (partially fractured) elements (Figure 16). Figure 17 shows a flowchart illustrating the key features of the developed FLAC3D algorithm for hydraulic fracture simulations.

Figure 16: Classification of fractured elements in FLAC3D (Zhou & Hou, 2013).
All geomechanical parameters are assigned and the proper boundary conditions are selected. The fluid injection into a zone causes a pressure build up which leads to failure of the rock during calculations. A pointer on the flowchart checks the Mohr-Coulomb (M-C) failure of each zone. If an element fails due to fluid injection it changes from un-fractured (or fracture front) to fractured element. The direct neighbours of fractured elements become partially fractured elements building the new fracture front. The volumetric strain of fractured zones forms the fracture width. Since the crack opens, fracture permeability increases according to cubic law (Snow, 1965; Louis, 1967). Afterwards, a particular mean value between fracture and rock permeability is calculated for each zone. Permeability of the fracture front elements is updated by a
specific weighting between its neighbouring elements’ permeability. Due to fluid injection, failure of zones and permeability enhancement a fracture propagates further.

This algorithm was implemented into FLAC3D via FISH, a particular programming language. A verification model was then used to evaluate the functionality of the algorithm by comparing numerical output with analytical results.

4.1.2 Look-up table relations

Task 2.3 contains the calculation of supporting points for look-up table relations. The complete concept of this topic was presented in Yildizdag & Weber (2016). Two kinds of look-up table relations are elaborated:

- Single-fracture relations and
- Multi-fracture relations.

The first one provides an insight to fracture propagation within a homogenous single layer and the second one describes interactions between several fractures in more detail. Supporting points are created for specific combinations of parameters wherein two types of parameters exist. Independent design parameters (IDP) can be artificially controlled during or before a hydraulic fracturing treatment. Fracture geometry parameters (FGP) are the hydraulic spatial parameters describing the shape and size of a fracture. Latter one is directly related to productivity. A look-up table relation describes the dependency between one FGP and one IDP.

The single-fracture relations contain the interaction between fracture geometry (height, length and opening) and injected volume (injection rate) of liquid. However multi-fracture relations represent the following interactions:

- Fracture length - injected volume (injection rate)
- Fracture height - injected volume (injection rate)
- Fracture opening - injected volume (injection rate),
- Fracture length - fracture density (spacing)
- Fracture height - fracture density (spacing)
- Fracture opening - fracture density (fracture spacing) and
- Fracture height - wellbore distance.

Effective fracture opening indicates the average available fluid path generated by the fracture. For each relation a particular numerical single- or multi-fracture simulation is needed which results in one supporting point for the relation. Simulations are
performed in the REV which is represented by the sub-model. The calculated dependencies will be delivered to GEOS for further simulations.

4.2 Verification model

The set-up of a verification model is necessary to ensure physical and numerical significance. The later used analytical solution for verifying the numerical results is the so called Perkins-Kern-Nordgren (PKN) model (Nordgren, 1972), (Perkins & Kern, 1961), (Yew & Weng, 2015). The numerical model is built in such a way that PKN analytical assumptions have been fulfilled. Figure 18 shows the developed verification model.

Figure 18: Verification model with model dimensions, fracture surface, area of fluid injection and alignment of principal stresses.

Cubic zones with edge length of 2 m are used to simulate the rock mass. The model extends 334 m in x-, 100 m in y- and 30 m in z-direction, by assuming symmetry within the bottom x-y-plane and x-z-plane on the right side. The model therefore shows only the upper half of one fracture wing (quarter model). Roller boundary conditions are applied at the outer model faces. The half-height of the fracture is restricted to 10 m to fulfil PKN assumptions and fluid is injected over the whole fracture height. Since a quarter model is used complete fracture height is 20 m. With these assumptions the vertical fracture is forced to propagate in horizontal direction as shown by the fracture surface. When injection starts, the fluid pressure in the injection zones increases and the rock fails according to M-C which initiates the fracture growth. In order to fulfil PKN...
assumptions a pure tensile crack is generated in this verification model. It is important to mention that the fracture surface is not predefined. Principal stresses are aligned with directions of the coordinate axes.

Table 8: Geomechanical parameters used at the verification model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>2300.0</td>
</tr>
<tr>
<td>Young’s modulus [GPa]</td>
<td>28.4</td>
</tr>
<tr>
<td>Poisson’s ratio [-]</td>
<td>0.184</td>
</tr>
<tr>
<td>Cohesion [MPa]</td>
<td>12.5</td>
</tr>
<tr>
<td>Friction angle [°]</td>
<td>60</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>3.5</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>12.0</td>
</tr>
<tr>
<td>Injection rate [m³/s]</td>
<td>0.1</td>
</tr>
<tr>
<td>Fluid density [kg/m³]</td>
<td>1000.0</td>
</tr>
<tr>
<td>Maximum principal stress [MPa]</td>
<td>50.0</td>
</tr>
<tr>
<td>Intermediate principal stress [MPa]</td>
<td>40.0</td>
</tr>
<tr>
<td>Minimum principal stress [MPa]</td>
<td>20.0</td>
</tr>
</tbody>
</table>

The rock is assumed to be homogenous, isotropic and impermeable described by M-C constitutive model. The geomechanical parameters for Rotliegend-sandstone are given in Table 8. Water is used as injection fluid with a fluid viscosity of 1E-3 Pas, injection rate is 0.1 m³/s.
4.3 Sub-model

Based on the numerical stress field simulations, a sub-model adapted from the large scale geological model is created in FLAC3D to perform single- and multi-hydraulic fracture simulations. The inner part of this model marks the REV for particular fracture stages and the look-up table relations. It is a simplified part from the geological model (Chapter 2.1) at the selected site (Chapter 3.4). The sub-model is shown in Figure 19.

![Figure 19: FLAC3D sub-model created from site selection.](image)

Dimensions of the sub-model are 1024 m in x-, 1024 m in y- and 384 m in z-direction. Zone volumes become larger towards the boundaries in order to reduce calculation time. The fractures are simulated within the centre area which consists zone sizes of 2 x 2 x 2 m. Depth of the model is between -1372 m at top and -1756 m at the bottom. The lower part of the Zechstein and the upper part of the Rotliegend sandstone are included. Roller boundary conditions are applied to outer model faces.

![Figure 20: Adapted principal stress distribution at the selected site.](image)
except the upper boundary. A stress boundary condition is applied on top of the model. In contrast to the verification model hydraulic fractures are modelled completely and no symmetry planes are considered. Water is used as the injection fluid. Geomechanical und fluid parameters for the numerical simulations are given in Table 9 and Table 10. The rock is again assumed to be homogenous, impermeable and isotropic. The assumption of impermeable rock is selected since permeability tests at sandstones samples performed by AGH show only: poor flow properties of Sandstone (AGH, 2015). Adapted vertical stress distribution for the selected site is given in Figure 20. Only the stresses in necessary depth range are used for simulation.

Table 9: Geomechanical parameters for the sub-model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Zechstein</th>
<th>Rotliegend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>2770.0</td>
<td>2300</td>
</tr>
<tr>
<td>Young's modulus [GPa]</td>
<td>67.0</td>
<td>28.4</td>
</tr>
<tr>
<td>Poisson's ratio [-]</td>
<td>0.255</td>
<td>0.184</td>
</tr>
<tr>
<td>Cohesion [MPa]</td>
<td>16.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Friction angle [°]</td>
<td>63.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>7.55</td>
<td>3.5</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Dilation angle [°]</td>
<td>33.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Table 10: Fluid parameters in the sub-model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid viscosity [Pas]</td>
<td>0.001</td>
</tr>
<tr>
<td>Fluid density [kg/m³]</td>
<td>1000.0</td>
</tr>
</tbody>
</table>

The porosity value is set to 20 % in order to achieve numerical stability in reasonable times since the verification simulation with sandstone parameters (Table 9) and
porosity of 12% from CNRS (2016) show very high calculation times (one order of magnitude). Former simulations show that higher porosity values have no significant influence on hydraulic fracture propagation and characteristics. However, calculation time is lower and numerical stability increases. Therefore, a higher value is preferred in order to reach fast convergence of the solution, without much influences on numerical results.

Again water is injected into the injection points. Initial pore pressure in the area is assumed to follow the hydrostatic pressure condition:

\[ p_{hydr} = \rho_{water} \cdot g \cdot h \]

- \( p_{hydr} \) hydrostatic pore pressure
- \( \rho_{water} \) water density
- \( g \) gravitational constant
- \( h \) model depth

For the inner part of the model where fractures are produced the M-C constitutive model is used. The larger outer zones where no fracturing takes place are modelled as elastic material.

### 4.3.1 Single-fracture simulation (sub-model)

First of all the significance of the hydraulic fracturing simulation has to be proved. So it is necessary to perform a simulation for one fracture in order to check if all algorithms work properly and no errors occur during calculation.

Since look-up table relations for single fractures are part of Task 2.3, several simulations are conducted within a modified sub-model. For the single-fracture relations the fracture propagates from a specified injection point for 68 s. Injection stops immediately and the fracture geometry (length, height, opening) is stored. For this case, one layer model is used which is based on the sub-model but assuming that only Rotliegend sandstone is present. This provides answers about fracture propagation in homogenous layers for the specific geology at the depth of interest. The injection point is located at the coordinates (1.0 m, 1.0 m, -1564 m) in the modified sub-model (Cartesian coordinates). Five simulations are performed with an injection time of 68 s. The IDP changes are given in Table 11.

The final fracture geometries of single fracture simulations can be compared to an analytical radial (penny-shaped) fracture model (see e.g. Economides et al., 2002). Even if the assumptions are not entirely fulfilled comparison is possible since the fractures propagate nearly radial even if they have a slight upwards trend due to acting gravitation. Fracture opening is approximately elliptical and injection is near to the centre of the final fracture. Comparison to the analytical model is necessary to get an insight if the numerical algorithm is working correctly since no practical hydraulic
fracturing treatment was performed during the project. Therefore no calibration data was available.

<table>
<thead>
<tr>
<th>Case</th>
<th>Injection rate [m³/s]</th>
<th>Injected volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1</td>
<td>0.010</td>
<td>0.68</td>
</tr>
<tr>
<td>SF2</td>
<td>0.025</td>
<td>1.70</td>
</tr>
<tr>
<td>SF3</td>
<td>0.050</td>
<td>3.40</td>
</tr>
<tr>
<td>SF4</td>
<td>0.075</td>
<td>5.10</td>
</tr>
<tr>
<td>SF5</td>
<td>0.100</td>
<td>6.80</td>
</tr>
</tbody>
</table>

4.3.2 Multi-fracture simulation

The multi-fracture simulation is performed by using the sub-model from Chapter 4.3. Figure 21 shows a cut-out from the complete sub-model containing the injection points for hydraulic fracture initiation. As described in Chapter 3.4, the planned horizontal borehole drilled up to a TVD of -1564 m and the injection points are placed along the same model depth. Five points for fluid injection are placed. A spacing of 20 m is assumed since diffusion processes need small fracture spacing. The position of individual injection points is given in Figure 22. In y-direction the injection points are located at the coordinate 1.0 m.

The injection starts at the first injection point with a constant flow rate of 0.05 m³/s for safe and fast fracture propagation. When rock failure takes place the fracture is then initialized and propagates. Injection stops after 68 s injection time. This time is selected since fractures may touch the lower limestone boundary. Since the fracture should not penetrate these boundary injections stops early enough. Afterwards the fluid is enclosed within the fracture and the injection at the next point starts. This procedure is repeated until 5 hydraulically induced fractures are generated. Due to fluid enclosing in the generated cracks, a stress shadow is encountered which causes the fractures to influence each other. After the five fractures are generated fluid backflow is allowed. Therefore a hydrostatic pressure boundary conditions is applied at the injection points.
Figure 21: Cut-out of the sub-model in the given dimensions.

Figure 22: Location of injection points within the cut-out of the sub-model.
For look-up table relations several additional simulations with either different fracture spacing or different injection rates were performed. The number of fractures, the geomechanical and fluid parameters as well as other boundary conditions remain the same. The performed simulation cases are given in Table 12.

### Table 12: Performed additional simulations for look-up table relations for multi-fractures.

<table>
<thead>
<tr>
<th>Case</th>
<th>Injection rate [m$^3$/s]</th>
<th>Spacing [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF1</td>
<td>0.010</td>
<td>20</td>
</tr>
<tr>
<td>MF2</td>
<td>0.025</td>
<td>20</td>
</tr>
<tr>
<td>MF3</td>
<td>0.075</td>
<td>20</td>
</tr>
<tr>
<td>MF4</td>
<td>0.100</td>
<td>20</td>
</tr>
<tr>
<td>MF5</td>
<td>0.050</td>
<td>30</td>
</tr>
<tr>
<td>MF6</td>
<td>0.050</td>
<td>40</td>
</tr>
<tr>
<td>MF7</td>
<td>0.050</td>
<td>50</td>
</tr>
<tr>
<td>MF8</td>
<td>0.050</td>
<td>60</td>
</tr>
</tbody>
</table>

4.4 Hydraulic fracturing simulation results

#### 4.4.1 Verification model

The simulations within the verification model are performed until a 75 m long fracture develops considering that PKN analytical solution is valid if the fracture length $>>$ fracture height. Figure 23 shows displacement vectors at grid points on failed zones (left) and the fracture opening in plain view (right). The elliptical shape and opening of the fracture as postulated by PKN model is visible. Maximum fracture opening of approximately 2.3 mm is reached.
Figure 23: Displacement vectors visualizing fracture shape (left) and fracture opening in plain view (right).

Figure 24: Pressure distribution within the fracture.

Figure 24 shows the fluid pressure within the crack which is nearly equally distributed. Negative fluid pressure indicates a decrease in effective stress. Figure 25 (bottom) shows again the distribution of pressure within the fracture compared with PKN analytical solution. The error between numerical and analytical results is less than 10 % and thus a well agreement between both solutions is obtained.
Figure 25: Bottomhole pressure at injection point (top) and fluid pressure within the fracture (bottom).

Bottomhole pressure at the injection point (Figure 25, top) shows an accurate behaviour. Breakdown pressure reaches a value of about 24 MPa, which is close to analytical formulations (minimum principal stress + tensile strength of rock). Afterwards pressure drops to propagation pressure. The slight increase at later times
is referred to PKN assumptions, because the analytical solution assumes an increase of bottomhole pressure during fracture propagation.

The permeability distribution within the fracture (based on failed zones permeability) is shown in Figure 26. The maximum permeability is located at the injection point marking the middle of the fracture wing. An elliptical distribution is visible according to fracture opening distribution.

The development of fracture length and maximum fracture width over time is given in Figure 27. The stepwise increase in fracture length is referred to the spatial discretization of the model (mesh effect). Every time a zone fails and the fracture becomes longer the graph jumps to the next level. The maximum length is 75 m because the calculation stops at this point. The maximum difference between numerical and analytical solution is about 10 % which is satisfying.

Fracture width (Figure 27, bottom) is recorded at the bottom injection zone marking the middle of the complete fracture wing. The difference between numerical and analytical model is much less than 10 %.

Finally, the verification of the developed hydraulic fracturing algorithm in FLAC3D was successful achieved. It is possible to apply the developed algorithm for modelling hydraulic fracturing in the BIOMOre framework.
Figure 27: Fracture length (top) and maximum fracture width at the injection point (bottom) compared to PKN analytical solution.
4.4.2 Single-fracture simulations

Hydraulic fracturing simulation is verified successfully so the algorithm from Chapter 4.1.1 is adapted for the sub-model in order to conduct hydraulic fracturing simulation and optimization in the chosen site of North Sudetic Trough. The results of a single fracture propagation (case SF1) with an injection rate of 0.05 m$^3$/s are presented and discussed firstly. The fracture is initiated at the injection point and is allowed to propagate into all directions. Calculation stops immediately after 68 s of injection.

The generated fracture is shown in Figure 28. The injection point is located in -1564 m b.s.l. within the Rotliegend layer (see black square in Fig. 28). The fracture propagates more or less in a radial manner, but gravity forces the crack to propagate slightly more upwards. The crack opening reflects this trend of fracture propagation. The maximum value for fracture opening is about 1.65 mm. Since the fracture opening is approximately elliptical, it shows characteristics of a penny shaped crack in a simplified manner.

![Fracture pattern and opening of single-fracture simulation within modified one layer sub-model (injection rate = 0.05 m$^3$/s, plain view on fracture surface).](image)

Figure 29 contains the bottomhole pressure and the fracture width at the injection point. The pressure curve includes the reservoir pressure. The fracture is initiated at about 42 MPa of bottomhole pressure afterwards it drops to the level of propagation pressure. Fracture width at the injection point increases up to 1.6 mm.
Figure 29: Bottomhole pressure (red) and fracture width at the injection point (green) for single fracture simulation with an injection rate of 0.05 m³/s.

Figure 30: Total fracture height and length for single-fracture simulation with an injection rate of 0.05 m³/s.

Fracture length and height (Figure 30) seem to increase with the same trend, but fracture geometry (Figure 28) indicates an upwards propagation. A total fracture length of 62 m and height of 60 m is reached.

Due to fracture opening and change in deformation, the stress field around the generated crack changes as well. Distribution of total minimum principal stress ($\sigma_3$) in a depth of -1564 m is depicted in Figure 31. The fracture is marked by a thicker black
line. Compressive stress (minus sign) increases normal to the fracture and decreases at the fracture tip due to fracture opening. The increase is about 2.1 MPa (blue) and the decrease 1.8 MPa (red), it should be noted that the initial \( \sigma_3 \) was at about 35 MPa in this depth. This characteristically shape of stress redistribution was also observed by other researchers (Zeeb, et al., 2014, Wangen, 2011).

![Figure 31: Minimum principal stress in top view at a depth of -1564 m (thicker outline marks fracture).](image)

As mentioned in Chapter 4.1.2 a look-up table relation for the generation of single fractures is part of Task 2.3. Values for length, height and fracture width are affected by the injection rate. For elaborating look up tables the injection rate is changed within the different simulation cases (Table 11). The final results of fracture width and length can be compared to an analytical radial (penny-shaped) fracture model as mentioned in chapter 4.3.1. The numerical values of mean fracture radius (estimated from length and height) and maximum fracture width for each injection rate are given in Table 13 together with the corresponding analytical solutions. The simulation results and analytical solutions show good coincidence. Aperture and fracture radius increase for higher injection rates.

It is important to mention that zone failure is not related to tension only; shear failure takes place immediately after tensile zone failure. During fracture propagation slight asymmetry of the fractures occurs resulting in shear displacements at the fractures. This behaviour is consistent with other studies. For example (Zeeb, et al., 2014) investigated the same behaviour within a 3DEC hydraulic multi-fracture simulation generated for geothermal purposes. The calculated shear displacement gives the opportunity of calculating residual fracture openings considering the given dilation.
angle. Therefore fractures remain open after fluid backflow and a residual fracture width is obtained.

Table 13: Results for fracture geometry from single fracture simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Injection rate [m³/s]</th>
<th>Aperture num. [m]</th>
<th>Aperture ana. [m]</th>
<th>Radius num. [m]</th>
<th>Radius ana. [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1</td>
<td>0.010</td>
<td>9.83E-4</td>
<td>1.01E-3</td>
<td>15.0</td>
<td>20.0</td>
</tr>
<tr>
<td>SF2</td>
<td>0.025</td>
<td>1.33E-3</td>
<td>1.38E-3</td>
<td>22.5</td>
<td>27.2</td>
</tr>
<tr>
<td>SF3</td>
<td>0.050</td>
<td>1.65E-3</td>
<td>1.73E-3</td>
<td>30.5</td>
<td>34.2</td>
</tr>
<tr>
<td>SF4</td>
<td>0.075</td>
<td>1.87E-3</td>
<td>1.98E-3</td>
<td>35.0</td>
<td>39.2</td>
</tr>
<tr>
<td>SF5</td>
<td>0.100</td>
<td>2.03E-3</td>
<td>2.18E-3</td>
<td>40.5</td>
<td>43.1</td>
</tr>
</tbody>
</table>

Figure 32: Fracture pattern and opening for simulation case SF5 as well as locations of half-lengths, upper and lower height.
In order to illustrate the results, an example geometry is depicted. Fracture pattern and width distribution are shown in Figure 32 for case SF5 (0.1 m³/s) for an injection time of 68 s. As it can be noticed, fracture area increases clearly for higher injection rates as well as fracture aperture (compare Figure 28 and Figure 32). Furthermore, the upwards trend of fracture propagation is visible. Injection point is marked with a black coloured frame.

The supporting points for the relations: length-injection rate, height-injection rate, width - injection rate, residual width - injection rate and borehole distance - fracture height are given from Figure 33 to Figure 38. Total fracture length increases continuously for higher injection rates as well as both half lengths. The left and right half-length are equal which indicates that the fracture propagates similar in both sides independent from injection rate, since initial stress distribution in horizontal direction is constant. The upper height of the fracture is always bigger than the lower one proving the upwards propagation trend of the fracture due to gravitation. For increasing injection rate, the difference between upper and lower height increases accordingly. A picture of half-lengths as well as upper and lower height is given in Figure 32.

![Figure 33: Supporting points for look-up table relation: fracture length - injection rate.](image)

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Figure 34: Supporting points for look-up table relation: fracture height - injection rate.

Figure 35: Supporting points for look-up table relation: fracture width - injection rate.

The maximum fracture width (aperture) increases for higher injection rates, as well (Figure 35). It ranges from about 1 mm up to 2 mm. The fracture width at the injection points behave in a similar manner. The aperture there is slightly smaller due to acting
gravitation. Average fracture width increases too. However, the relative increase between the supporting points is smaller compared to the supporting points of maximum fracture width. The residual apertures (Figure 36) increase in a similar way.

Figure 36: Supporting points for look-up table relation: residual fracture width - injection rate.

Figure 37: Supporting points for look-up table relation: VWD - injection rate.

The vertical wellbore distance (VWD) in respect to fracture height and injection rate assumes a second borehole directly above the injection well. For production phase the
injection well for hydraulic fracturing will change to the production well. The additional upper wellbore becomes the injection well for production phase. The VWD increases for larger upper fracture height (Figure 38) as well as for higher injection rates (Figure 37).

![Graph showing VWD vs upper fracture height](image)

Figure 38: Supporting points for look-up table relation: VWD - upper fracture height.

The single-fracture simulation is conducted in a successful way. Numerical results are reliable since fracture mechanics are verified with PKN and radial analytical solutions. A comparison with other simulations (Zeeb, et al. (2014), Wangen (2011), Zhou et al. (2014)) show same characteristics for fracture propagation. The supporting points for look-up table relations of single fractures are successfully calculated and delivered to GEOS.

### 4.4.3 Multi-fracture simulation

The hydraulic multi-fracture simulation is conducted within the sub-model as described in Chapter 4.3.2. Figure 39 show the fracture pattern for the conducted multi-fracture simulation within the centre cut-off. The injection points are aligned perpendicular to the smallest principal stress. Injection stops after 68 s injection time for each frac. Afterwards fluid backflow is enabled corresponding to a hydrostatic pressure condition at the injection points.
Figure 39: Fracture pattern of hydraulic multi-fracture simulation with four generated cracks.

The first fracture propagates similar to the single-fracture simulation slightly upwards. Due to stress shadow effects the second crack develops different. It propagates much more into negative z-direction since the minimum principal stress is increased in upwards direction. The propagation of the third crack shows a reduced height since the stress shadow of the second crack influences its development. The fourth crack propagates more similar to the second one. The shape of fifth fracture develops similar to the first fracture.

Figure 40: Bottomhole pressure at the injection points during multi fracture design.
Bottomhole pressure is shown in Figure 40 (including formation pressure). The breakdown pressure for the first fracture is about 42 MPa. Due to stress shadow effects the breakdown pressure for the following fractures increases. The pressure than decays to a value slightly above the minimum principal stress. After fracture generation a constant hydrostatic pressure is applied to the injection points in order to make fluid backflow possible. The obtained results show the same characteristics as in other fracture optimization investigations (Zeeb, et al., 2014).

Figure 41 shows the fracture length and height during the hydraulic fracturing treatment. Fracture propagation at the beginning is nearly radial but occurring interactions between the cracks are visible. Since the fractures are interacting with each other and the present gravitational effects propagation process of one fracture can be effected by other fractures. Especially fracture three is growing more in length even after injection stops. This occurs due to the generation of the next two fractures. A mean length of 65 m and a mean heigh of 58 m is reached.

![Fracture height and length](image)

**Figure 41:** Fracture height and length for the fractures of the multi-fracture design.

Fracture opening (width) values at the injection points are depicted in Figure 42. Each fracture aperture increases over time until its injection stops. The interaction between the particular injection points is visible. Maximum widths of 1.6 mm (Frac 1), 1.4 mm (Frac 2) and 1.3 mm (Frac 3, 4, 5) are reached. The first fracture opens according to the single fracture simulation. Width of the first fracture decreases when the second injection starts. The fractures close more and more with further injections. Frac 3 which grows significantly in length even after its injection stops closes the most during production of the following fractures. After application of hydrostatic pressure the fracture width decreases instantaneously to the residual values, since the pressure boundary condition is applied suddenly.
Figure 42: Fracture width at the injection point for the fractures of the multi-fracture design.

Figure 43: Optimized multi-fracture design with residual fracture width, illustrated injection well (IW) and production well (PW) as planned for production phase.

The residual aperture distribution for the individual fractures is given in Figure 43 together with the planned production (PW) and injection well (IW) used for production phase. The size of the wells is stilted because of zone size. Maximum residual fracture width is between 0.6 and 0.5 mm. Compared to the work of Jung (1986) this values are in a good range for residual fracture widths. During fracture propagation slight asymmetry of the fractures occur resulting in shear displacements at the fractures.
Considering the given dilation angle these shear displacements lead to residual fracture widths. Other authors also noticed such effects (Zeeb, et al., 2014). In reality anisotropy and inhomogeneity in the material (which are not represented in the presented continuum mechanical approach) will amplify such effects.

The locations of the borehole are selected based on two aspects. The first is the assumption that copper mineralization occurs 30 m below the limestone horizon and the second one are technical feasibilities discussed together with the borehole department from TUBAF.

For further use of the simulation results in Task 2.6 (DMT) the residual apertures as well as hydraulic parameters from the simulation are delivered to DMT for further simulations. For Task 2.4 the supporting points for look-up table relations are calculated based on the simulations cases from Table 12.

For look-up table relations several simulations with either different fracture spacing or different injection rates were performed. The supporting points for the multi-fracture relations: length - injection rate, height - injection rate, width - injection rate, residual width - injection rate and borehole distance - fracture height are given from Figure 44 to Figure 49. All supporting point values for length, height and width are average values over the five generated fractures.

Mean total fracture length (Figure 44) increases continuously for higher injection rates as well as both mean half lengths. Total mean fracture length is between 28 and 97 m. The length values for injection rates of 0.075 and 0.1 m$^3$/s are higher compared to single fracture relation since the fractures are restricted in height due to the present limestone horizon.

The mean total height (Figure 45) is increasing from 27 to 73 m for higher injection rates. For injection rates larger than 0.05 m$^3$/s the upper height is constant since the fractures are in touch with the lower limestone boundary. The fractures then propagate into greater depths or become longer.

Mean values for maximum aperture (Figure 46) are also increasing for higher injection rates. The values are in a range from 0.8 mm to 1.5 mm. Residual apertures (Figure 47) are increasing as well when injection rate is raised.
Figure 44: Supporting points for multi-fracture look-up table relation: fracture length - injection rate.

Figure 45: Supporting points for multi-fracture look-up table relation: fracture height - injection rate.
Figure 46: Supporting points for multi-fracture look-up table relation: fracture width - injection rate.

Figure 47: Supporting points for multi-fracture look-up table relation: residual fracture width - injection rate.
Figure 48: Supporting points for multi-fracture look-up table relation: VWD - injection rate.

Figure 49: Supporting points for multi-fracture look-up table relation: VWD - upper fracture height (depending on injection rate).

The VWD increases for injection rates between 0.01 and 0.05 m³/s and becomes constant for higher injection rates (Figure 48). The reason for this behavior is again
the restriction of upper fracture height. If upper fracture height increases VWD becomes longer until the maximum value is reached (Figure 49).

The supporting points for the multi-fracture relations: length - spacing, height - spacing, width - spacing, residual width - spacing and borehole distance - fracture height are given from Figure 50 to Figure 55. All supporting point values for length, height and width are again average values over the five generated fractures.

Figure 50: Supporting points for multi-fracture look-up table relation: fracture length - spacing.

If the spacing between the fractures is increased mean fracture lengths (Figure 50) and mean fracture heights (Figure 51) are decreasing. The interaction between the fractures becomes less. For large spacing the values are nearly constant.

In contrast to fracture length or height the fracture aperture is increasing for larger distances between the cracks (Figure 52). The effect of stress shadow is reduced and therefore fractures can open more easily. Residual apertures (Figure 53) are also increasing for larger fracture distances but they show only a slight increase compared to apertures before fluid backflow.
Figure 51: Supporting points for multi-fracture look-up table relation: fracture height - spacing.

Figure 52: Supporting points for multi-fracture look-up table relation: fracture width - spacing.
Figure 53: Supporting points for multi-fracture look-up table relation: residual fracture width - spacing.

Figure 54: Supporting points for multi-fracture look-up table relation: VWD - spacing.

The VWD (Figure 54) decreases slightly for larger spacing according to the changes of upper fracture height. For spacing larger than 30 m VWD is nearly constant. Figure 53 points out these effect since only two supporting points are visible.
Finally, the presented results show that modelling of multi-stage hydraulic fracturing treatment with FLAC3D is feasible using the own developed routines (constitutive relations). The necessary parameters for Task 2.6 could be extracted from the optimized multi-fracture design. They are delivered to DMT. Several simulation cases based on changing either injection rate or spacing of the fractures show the dependencies between the IDP and FDP. These results lead to supporting points for look-up tables. The supporting points are delivered to GEOS for further simulations in Task 2.4.

Figure 55: Supporting points for multi-fracture look-up table relation: VWD - upper fracture height (depending on spacing).
5 References

AGH (2015) Email correspondence regarding actual permeability tests on sandstone samples (23.08.2015)


CNRS (2016) Deliverable 2.2 Geological model, deposit block model and reservoir model report, BIOMOre Deliverable 2.2, CNRS.


Itasca Consulting Group, Inc. (2016) First Revision, 3DEC Version 5.2, November 2016, Minnesota USA


Szubert, A.(2016) BIOMOre Report, Site selection and drilling, Deliverable Number D.3.1 ,Version 1.2


Annex 1 Stereonet results by using the measured stress data provided by KGHM Corporate (Poland). Maximum and minimum horizontal principal stress directions ($\sigma_H$, $\sigma_h$) were shown on the left and right stereonets, respectively. These stereonets were generated by using the software Stereonet 9.5 (Allmendinger et al. 2012 and Cardozo et al. 2013)
### Annex 2 Qualitative comparison of fracturing fluids and fracturing techniques applied for shale gas production (adapted from Gandossi 2013).

<table>
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<tr>
<th>Frac-Fluids Or Key Factors</th>
<th>Fluid Usage</th>
<th>Environmental Impact</th>
<th>On-site Operation (Before &amp; After)</th>
<th>Reservoir Productivity</th>
<th>Reservoir Integrity</th>
<th>Costs</th>
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Annex 2 Qualitative comparison of fracturing fluids and fracturing techniques applied for shale gas production (adapted from Gandossi 2013).

**Footnote:** "NA" stands for “information not available”, "UD" stands for “under development"