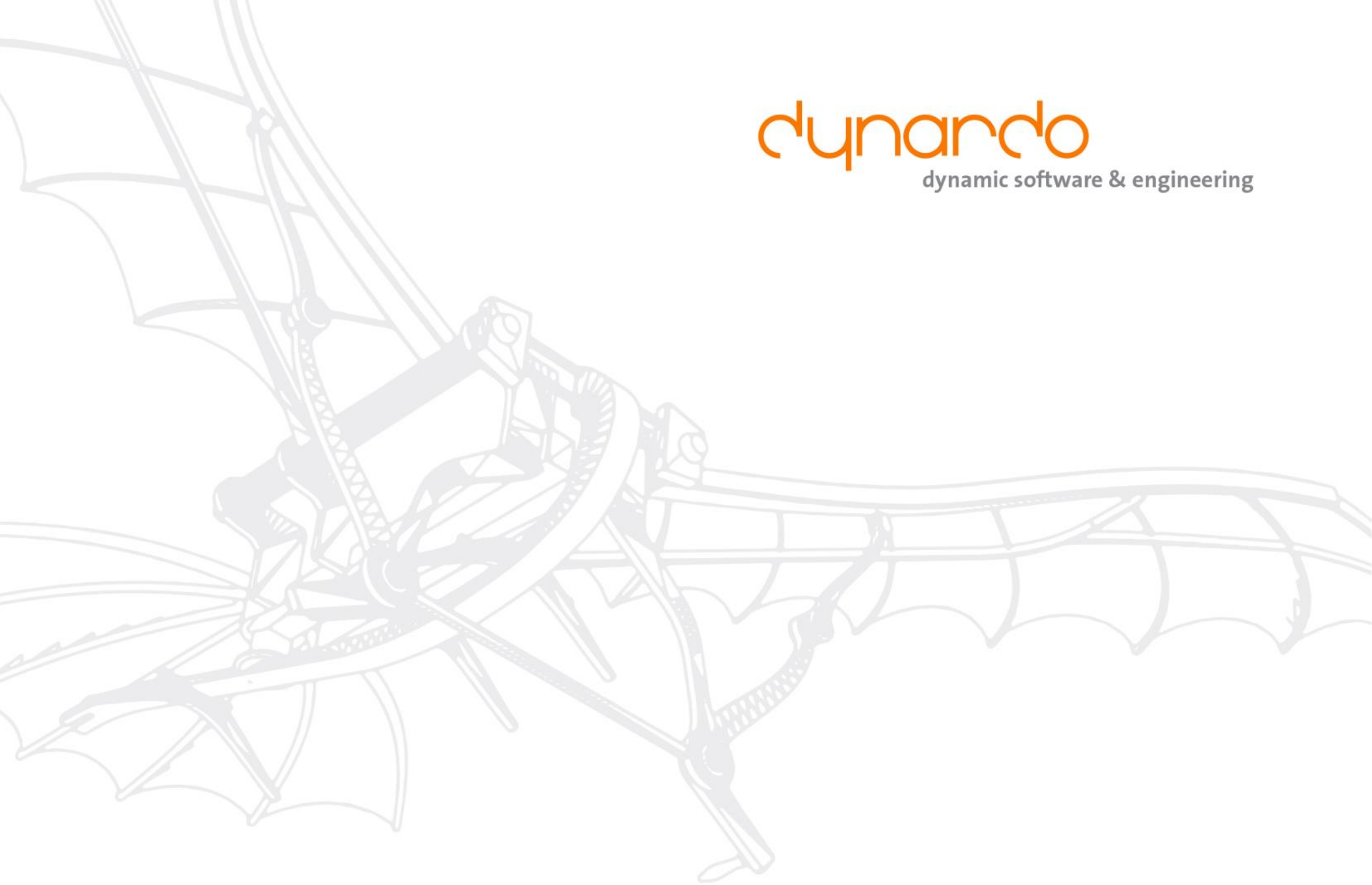

Lectures

Ranking of Importance of Reservoir Uncertainties and Operational Condition Variation Windows to Stimulated Rock Volume (SRV)

Johannes Will

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Ranking of Importance of Reservoir Uncertainties and Operational Condition Variation Windows to Stimulated Rock Volume (SRV)

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Introduction

A large amount of unconventional hydro carbon is produced from shale reservoirs. Due to low permeability, reservoir rocks need to be stimulated by hydraulic fracturing to increase the permeability and to improve hydro carbon production.

This project is aimed at modelling the sensitivity and relative importance from reservoir uncertainties as well as variation of operational parameter to the hydraulic fracturing performance of naturally fractured reservoirs using the Dynardo software toolkit [Dynardo 2013]. The toolkit combines three commercial software's ANSYS, multiPlas and optiSLang, for parametric FEM modeling, material modeling of naturally fractured sedimentary rocks and fast sensitivity study of large amount of reservoir parameters as well as engineering and operation conditions and their rankings in regard of influencing result variation respectively.

One of the most important outputs of the hydraulic fracturing simulator is the three dimensional (3D) distribution of Stimulated Rock Volume (SRV). Simulating the 3D body of stimulated rock volume using the Dynardo toolkit was first deployed in a study for a Barnett Shale asset in 2008/2009 [Will 2010]. Here, one stage was simulated and a shape factor of the stimulated volume was derived. Using the shape factor together with the maximal fracture extension of additional stages from micro seismic results, the total fractured rock volume of a horizontal well was calculated. Using field correlation data between stimulated rock volume and hydro carbon production, the six months hydro carbon production was estimated. With that approach the model predictions show good correlation with production data of multiple wells with multi-staged hydraulic fracturing in the neighborhood of the calibration well.

Because of many, more or less unknown, material parameters of naturally fractured rocks, any sophisticated numerical model of hydraulic fracturing needs to be calibrated to best available data from the reservoir [Weijers 2007]. Therefore, the paper begins with the calibration of the reservoir model based on available pressure and micro seismic data. To calibrate the large amounts of uncertain parameters to best available experimental data optiSLang [optiSLang 2013], the DYNARDO commercial toolbox for sensitivity analysis and optimization is used.

With optiSLang, large amount of parameters from a parametric FEM model can be effectively updated [Most 2012] and the simulation of a design realization is initialized and performed automatically. Thus, a large number of sensitivity runs and ranking of parameters can be achieved.

After calibrating the reservoir model and checking the forecast quality of the calibrated model, a second sensitivity analysis is performed for a predefined window of variation of operational parameter. In this sensitivity study, the importance of operational parameter for variation of SRV is identified and sensitivities to optimize the SRV within the window of variation are used

Finally, the results of sensitivity analysis due to reservoir uncertainties and variation of operational parameter are used to rank the influence of all parameter regarding variation of SRV.

3D Hydraulic fracturing simulator

The hydraulic fracturing simulator combines three commercial software's ANSYS, multiPlas and optiSLang. ANSYS is used for parametric FEM modeling and for coupled hydraulic and mechanical FE analysis. ANSYS mechanical analysis functionality for material modeling of naturally fractured rocks is extended by the library of non-linear material models in multiPlas. OptiSLang is used to perform efficient calibration and sensitivity analysis having a large amount of uncertain reservoir parameters as well as operation conditions.

The most important phenomena to reach sufficient forecast quality in the simulation of hydraulic fracturing in shale hydro carbon reservoirs is the ability to model the three dimensional anisotropic stress, strength and conductivity condition of naturally fractured sedimentary rocks. In case of shales the rock is usually classified as jointed rock having relatively strong "intact" rock strength, represented with UCS strength values and multiple sets of strength anisotropies which we call "joints sets". Obviously, the sedimentary rock has a bedding plane, but from authors' experience it also has at least two other sets of joint sets.

It is important to note that the joints in the homogenization approach [Wittke 1984] which is used by Dynardo are not geometrically modeled explicitly. But the influence of the activated joints is taken into account by the anisotropic strength behavior of the jointed rock and the related anisotropic conductivity of the jointed rock when the joints are opening up as a result of tension or shear failure. Tension and shear failure modes are checked at every discretization point in space for intact rock and every joint set and if stress states violate plastic strains combined with strength degradation occur. Taking into account the frequency of joints, the joint openings and related joint conductivity values are calculated for every joint set at every discretization point. As a result, homogenized joint set openings and related conductivities for every joint set are calculated.

For details in the hydraulic fracturing simulator refer to [Dynardo 2013], [Will 2015].

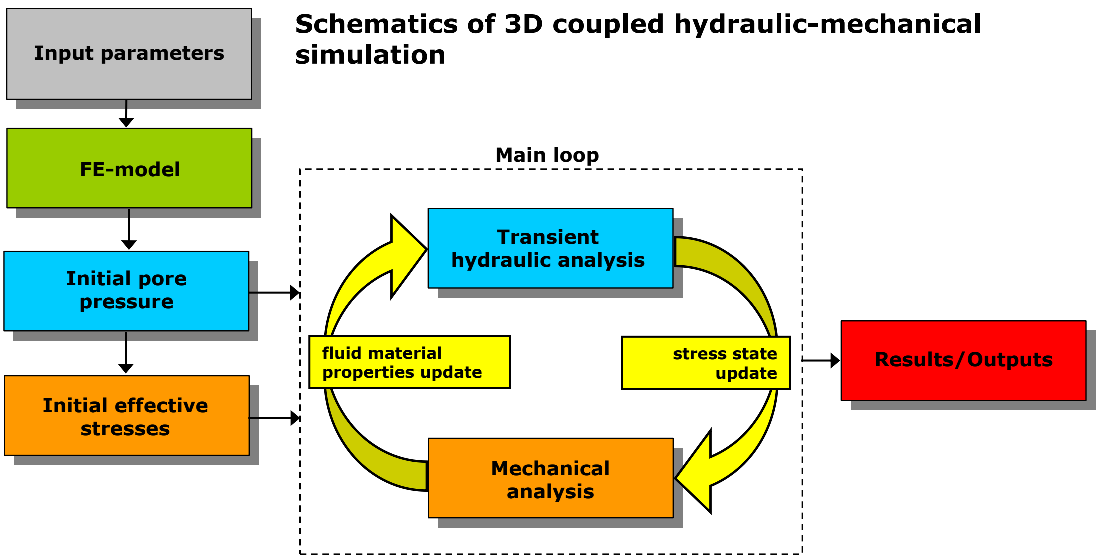

Fig. 1: Schematics of 3D coupled hydraulic-mechanical simulation

Calibration of the hydraulic fracturing model

In this paper, the model is calibrated with measurement data of pressure and micro seismic data from one stage (calibration stage). Then stimulated rock volume from a second stage (forecast stage) is predicted. Thus, the quality of model prediction can be checked with real data.

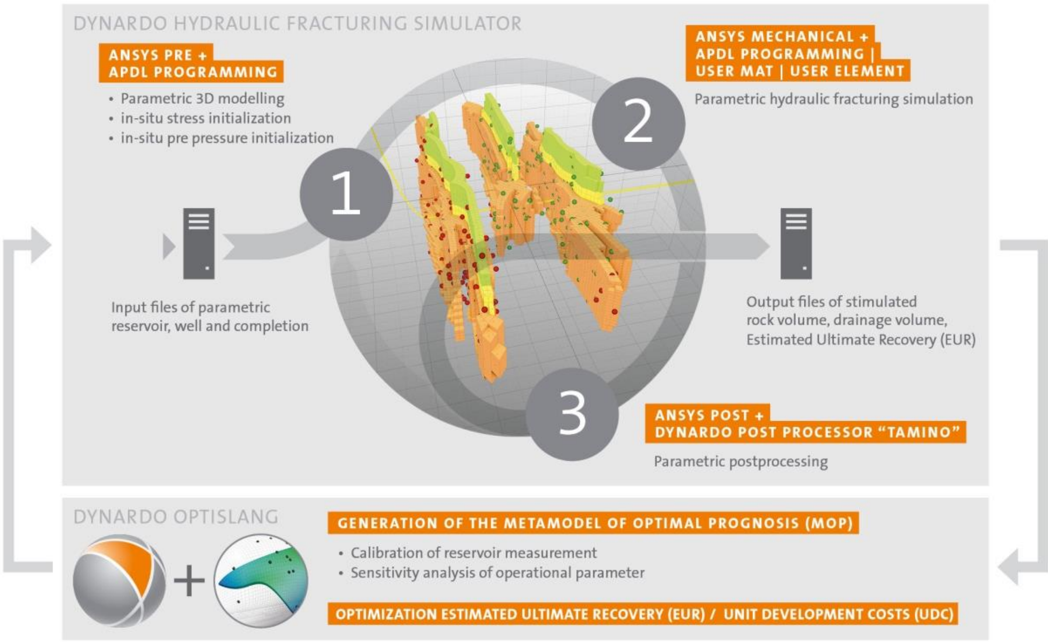

Fig. 2: Schematics of tool flow of the calibration process

Building the parametric FE-model

To be able to perform automated variation analysis of reservoir conditions or operational parameter variation, the simulation needs to be parametric. The reservoir FE-model covers a block of jointed rock surrounding multiple stages of a horizontal well. Original horizontal well position is close to North-South in the direction of minimal horizontal stress. Parametric geometry model definition includes the position of stages, the number of stages, the number of perforation clusters per stage, the distance between perforations and stages, the definition of FE model boundary and fine-coarse mesh boundary, the well landing depth, the horizontal well orientation, the depth and thickness of all rock units, etc.

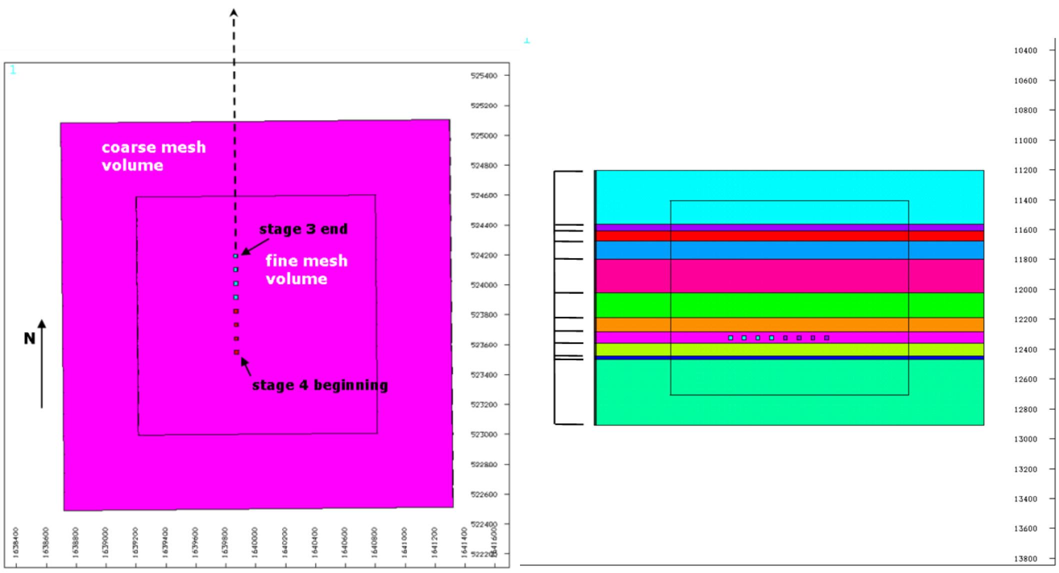

Fig.3: Model geometry in map view and model geometry in transverse view (layers)

For meshing, only brick elements are used. High aspect ratios are avoided to reduce mesh influence on fracture growth. Sizes of fine-mesh and coarse-mesh volumes are input parameters of the model.

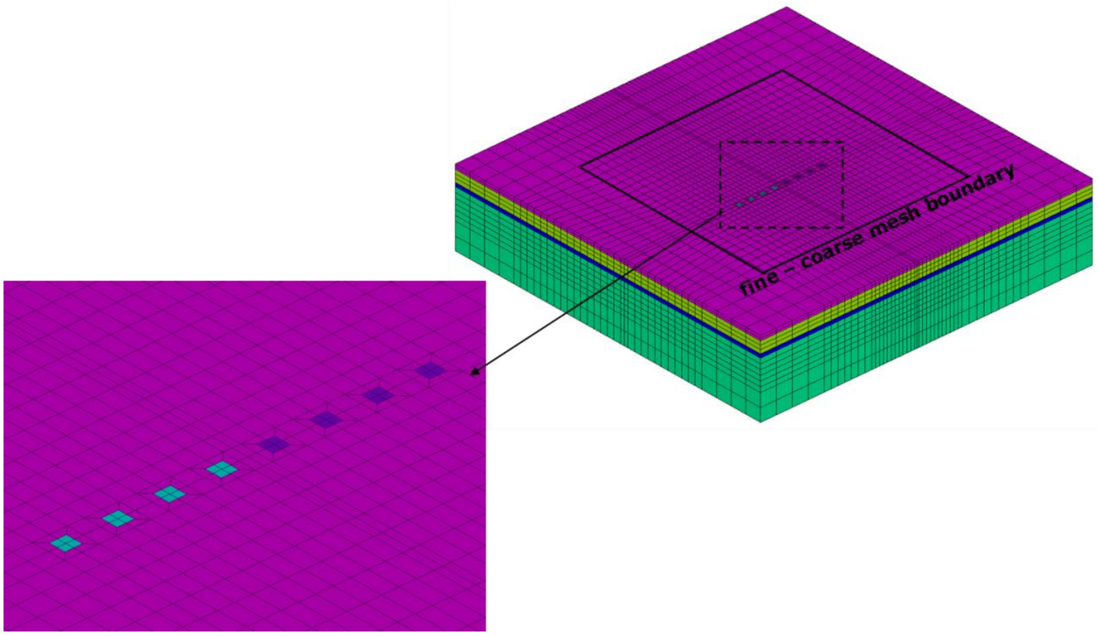

Fig. 1: Mesh in map view

Size of volume for fine mesh is estimated from micro seismic events (see Fig. 5) and is chosen such that all micro seismic events are covered inside fine mesh area.

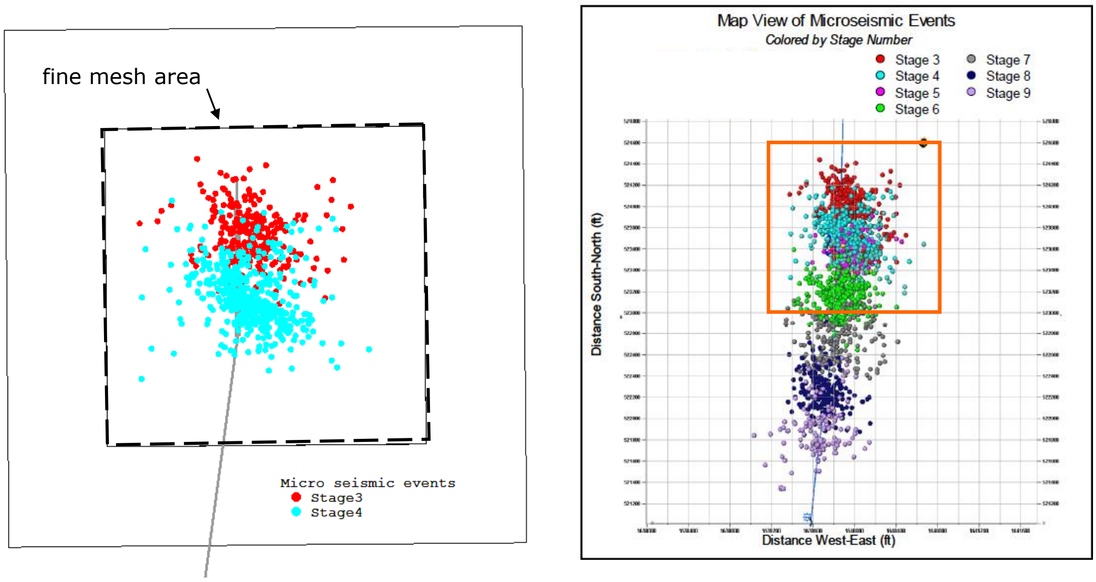

Fig. 5: Fine mesh area in map view

Initial in situ pore pressure and effective stress conditions

Initial pore pressure is defined for all layers. Initial in-situ effective stress field is independently defined for every layer of the reservoir as follows:

- effective vertical stress: $S_Z = IniStrGradZ \times z$,
- effective min. horizontal stress: $S_{H,min} = S_Z \times k0$,
- effective max. horizontal stress: $S_{Hmax} = (S_Z - S_{H,min}) \times ShMaxRatio + S_{H,min}$,

where: *IniStrGradZ* is the initial effective vertical stress gradient , *k*0 is ratio between minimal horizontal and vertical stress, *ShMaxRatio* defines maximum horizontal stress in relation to vertical and minimum horizontal.

Direction of minimum effective horizontal stress is North-South.

Verify that the model starts and stops to fracture at DFIT/ISIP pressure conditions

DFIT and ISIP conditions define the pressure level where fracture starts (DFIT) or stops (ISIP). From the available data Dynardo extracted a window of fracture gradients representing fracture closure pressure, mean ISIP condition and fracture propagation pressure. By initializing bottom hole pressure of all three conditions (closure, propagation and ISIP conditions) for 20 minutes, it is checked whether the fracture start, stop or growth around the perforation.

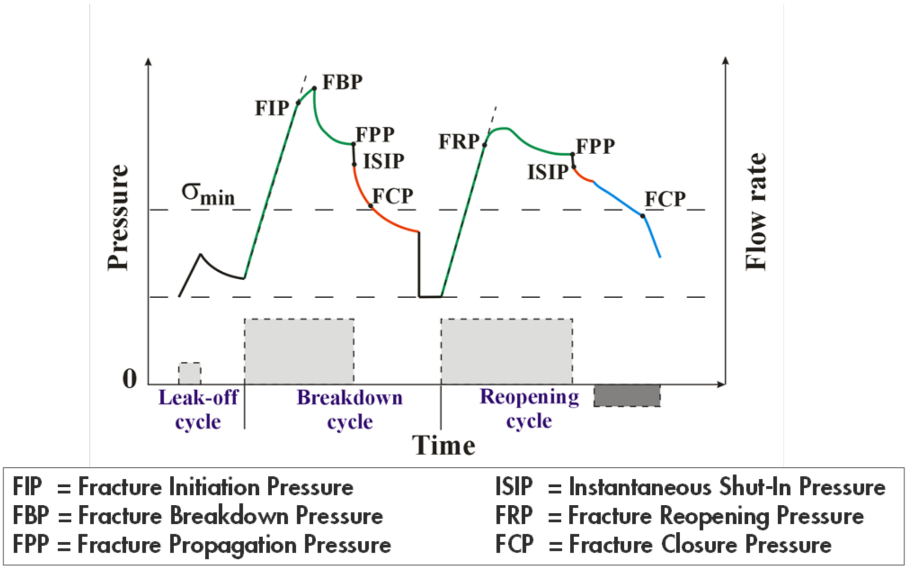

Fig. 6: Visualization of different pressure conditions during fracture opening and closing

In the ISIP calibration step it needs to be ensured that the mean ISIP stress condition results in plasticity around perforation, but the growth of plasticity should come to an end during the 20 minutes of pressuring. By applying the fracture closure pressure almost no plastic activity is expected. Applying fracture propagation pressure condition should result in propagation of fracture.

From ISIP simulations following conclusions are obtained:

1/ **Difference of minimum and maximum horizontal stress needs to be smaller compared to the initial assumption**. Initially the maximum horizontal stress was initialized to be half the way (50%) between vertical and minimum horizontal stress. Calibration using ISIP shows that maximum horizontal stress is much closer to minimum horizontal stresses otherwise fracture growth during ISIP conditions show unphysical behavior.

Simulation of calibration stage - base of sensitivity analysis

After calibration of ISIP conditions, we use the calibration stage to calibrate other important uncertain reservoir conditions.

For pressure initialization at the perforation clusters, the Bottom Hole Pressure (BHP) regime which was measured during hydraulic fracturing is used. To represent reasonable fracture grow speed and extension compared to micro seismic events, two important hydraulic parameters, maximum hydraulic conductivity K_{max} and specific storativity S_s are calibrated in a second calibration step.

The total stimulated rock volume at the end of the calibration stage is calculated to be 46 million ft^3. Shape of stimulated volume is shown in Fig.7. Comparison of the cracking speed, representing the distances from stage center in time with distances of micro seismic events (MSE) shows reasonable agreement (see. Fi**g 8** right). Main difference between MSE and simulation is that the stimulated volume does not cover all micro seismic events in the West-East direction. Plastic activities plot (see. **Fehler! Verweisquelle konnte nicht gefunden werden.** left) shows that simulated fracturing events are dominated by shear failure of vertical joint sets.

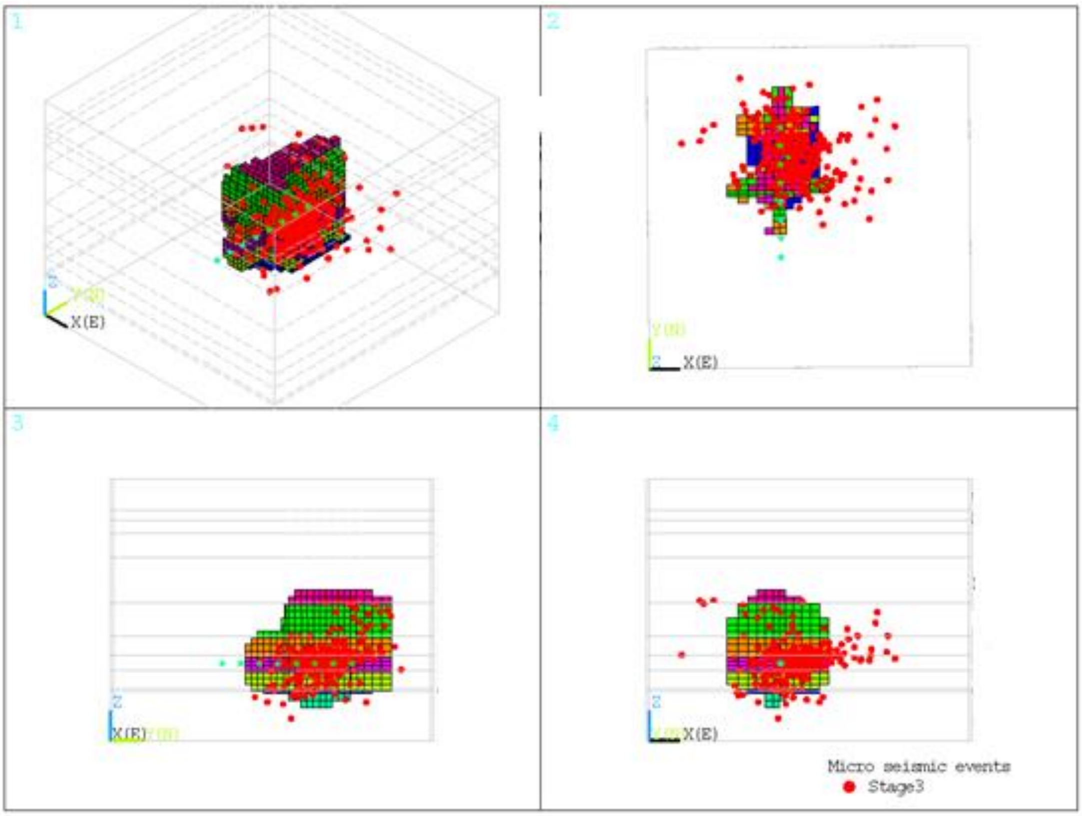

Fig. 7: Base of 1st sensitivity - stimulated volume at end of the stage 3 compared with micro seismic events

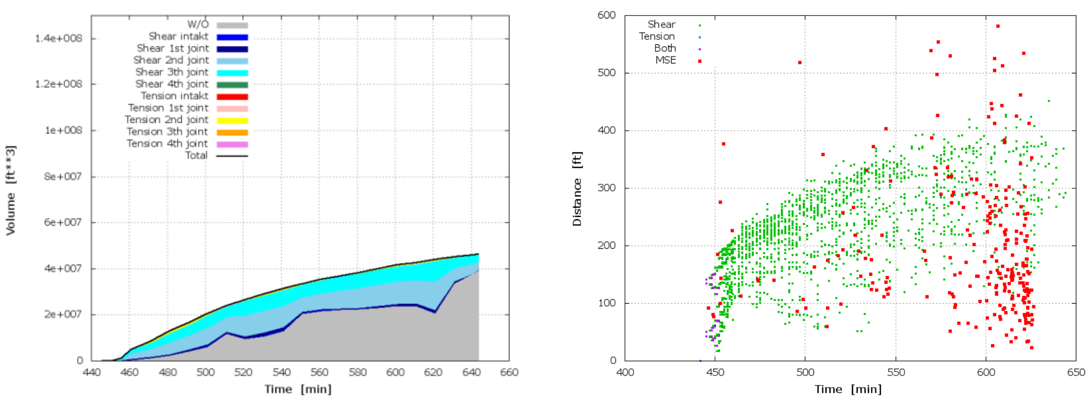

Fig. 8: Base of 1st sensitivity - plastic activities plot (left) and distance plot with micro seismic events (right)

Calibration of reservoir parameters using sensitivity analysis

The model of calibration stage, which shows overall reasonable physical behavior will be used to calibrate important rock mechanical reservoir parameter in a third calibration step by using optiSLang sensitivity analysis approach.

To calibrate the most important rock mechanical reservoir parameters, uncertainty windows for all possibly important reservoir parameters out of best available customer measurements as well as DYNARDO experience are defined.

For setting up the uncertainty windows 2 Sigma value bounds from customer's rock material data for following parameters are used:

- horizontal and vertical Young modulus and Poisson ratio per layer,
- k0-effective minimum stress values per layer,
- pore pressure ±200 psi,
- compression (UCS) and tensile strength of intact rock per layer,
- initial permeability -50%...+100% per layer,
- layer thicknesses ±10 ft,

additional windows of uncertain parameters are chosen from DYNARDO experience:

- dilatancy angle of intact rock 10...20°,
- uncertainty of max. hydraulic conductivity and specific storativity values ±20%,
- uncertainty of joint direction: dip direction ±30°, dip magnitude ±20° (bedding plane ±5°),
- joint tension strength 20...60 psi, joint initial friction angle joints 30...40°, joint initial cohesion 20...60 psi, joint dilatancy 10...20°,
- direction of minimum horizontal stress ±30°,
- ratio of maximum horizontal stress in relation to distance between minimum horizontal and vertical stress 10%...30%.

It is important to note that some of the uncertain parameters are uncorrelated in reality. Therefore, expected correlations of uncertain parameters are introduced

The following correlated uncertainty are considered

- dilatancy angle for intact rock of all layers
- dilatancy/friction angle & cohesion/tension strength of horizontal joints for all layers
- dilatancy/friction angle & cohesion/tension strength of vertical joints for all layers

After introduction of correlations the number of uncorrelated uncertainties is reduced to 128 uncertain variables.

To identify the most important parameter optiSLang sensitivity analysis approach is used which uses optimized Latin Hypercube Samplings (LHS) to scan the 128-dimensional design space with a minimum of designs. Using measurements of prognosis quality of the correlation model to forecast design points (Coefficient of Prognosis – COP) is verified. Calculation of new design points can be stopped after a certain amount of prognosis quality of the most important response parameters is reached. In the paper the CoP charts show the ranking of importance of reservoir uncertainties due to response values using the CoP-measure. Also 3D correlation plots between the two most important reservoir uncertainties and the response value are shown.

After 185 design evaluations the sensitivity study is stopped because there is high CoP for the variation of total volume (83% see Fig 9). That means the correlations between stimulated rock volume variation and reservoir uncertainty has been identified, which explain 83% of the total variation of stimulated jointed rock volume seen in the variation study.

Sensitivity analysis shows a large variation in the total stimulated volume (20-70 mil. ft^3). An expected large influence is shown from the two important hydraulic parameters maximum hydraulic conductivity (MaxHydrCond) and specific storativity (SpecStorage) (see *Fig.*). It pointed out how important it is to calibrate these two values, which represents fracture speed to the reservoir conditions.

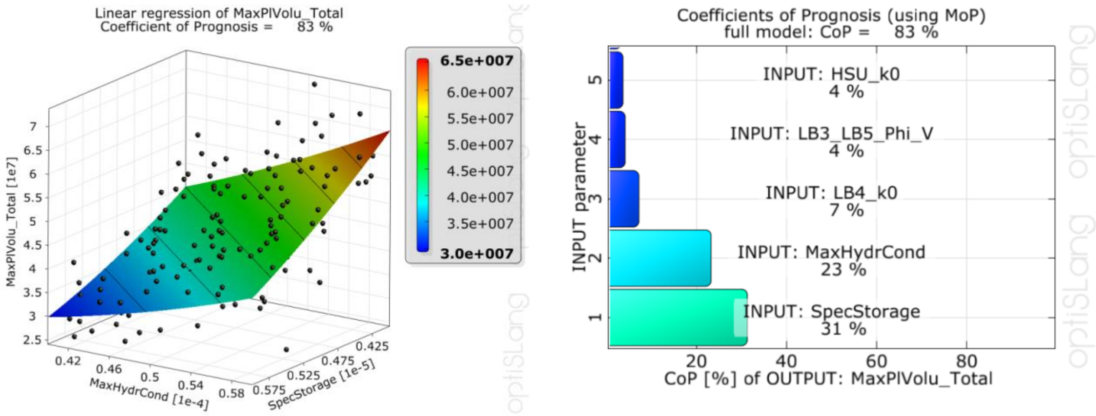

Fig. 9: 3D response surface plot (left) and coefficients of prognosis (right) for total stimulated volume

The reference simulation (base of the sensitivity) showed that the most visible difference between micro seismic events and simulation so fare is the missing East crack extension. Therefore there is a need to learn the most important reservoir parameter for cracking distance in East direction. Variation in East cracking distance shows that the vertical joint dip directions (Dip_Dir_V1/Dip_Dir_V2) are the most important variables and explain 30% of the variation. Other important parameters are maximal hydraulic conductivity (MaxHydrCond) and k0-value at HSLV_U (HSU_k0).

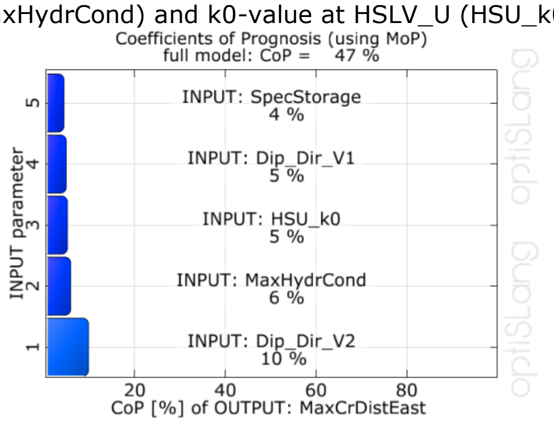

Fig. 10: Coefficients of prognosis for maximal cracking in East direction (right)

From sensitivity analysis four most important reservoir parameters are identified as well as their best values within the uncertainty windows for improving east cracking direction:

- Dip_Dir_V2 = 180° (dip direction of 2nd vertical joint, now East-West),
- Dip_Dir_V1 = 330° (dip direction of 1st, now max tilt to East),
- HSU_k0= 0.55 (smaller k0-value of layer HSU),
- MaxHydrCond = 6.00E-06 (increased max. hydraulic conductivity).

Of course, this lesson learned from correlation analysis needs to be checked. Therefore the lesson learning design is recalculated by modifying only the calibrated four most important parameters from the reference design. Indeed the "lesson learned" design represents the best design from sensitivity analysis regarding East-West crack extension.

With only updating the four most important reservoir parameters we show a better fit to the micro seismic than with any design from the sensitivity study were we have varied all 128 uncertain parameters. Also South-North crack growth now shows better agreement. That is the proof that the lesson learning from sensitivity study was successful.

Results of the design with calibrated parameters are shown in Fig. 11.

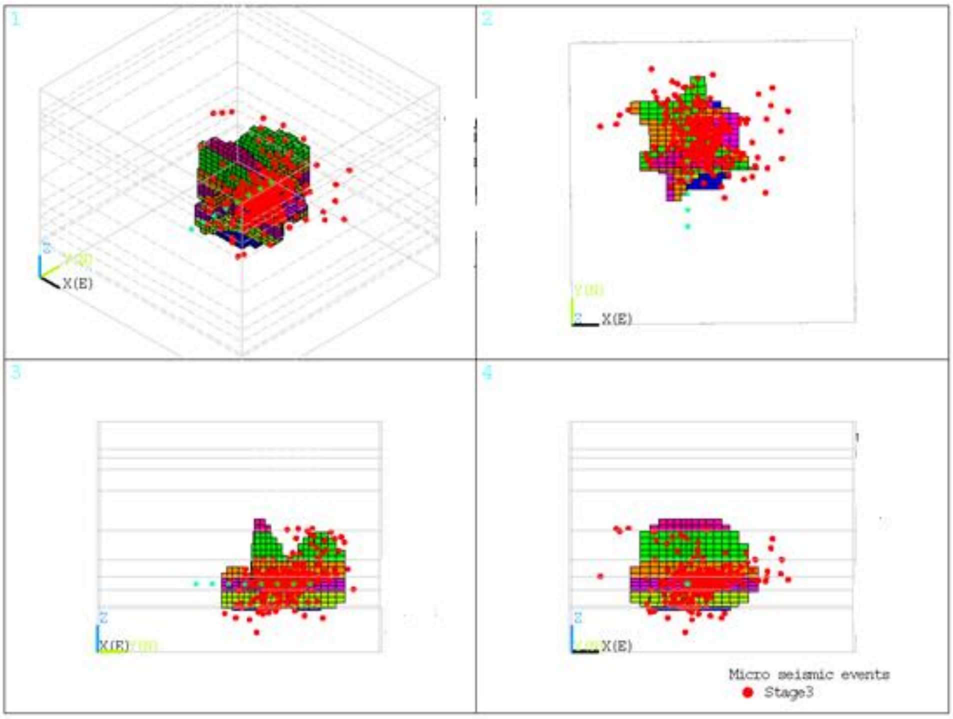

Fig. 11: Design with calibrated parameters from 1st sensitivity - stimulated volume at end of the stage 3 compared with micro seismic events

Check of forecast quality for second stage

Forecast of stage 4 is done using calibrated model from stage 3. Slurry rate input curves are extended to cover also pressure regime at stage 4. Total stimulated rock volume at the end of stage 4 is calculated as 140 million ft^3. Important results (stimulated volume, slurry rates and BHPs, plastic activities, cracking distances, joints openings and hydraulic conductivities of joints) are shown in Fig 12. The forecast stage shows good agreement with the micro seismic of stage 4 (see Fig 13).

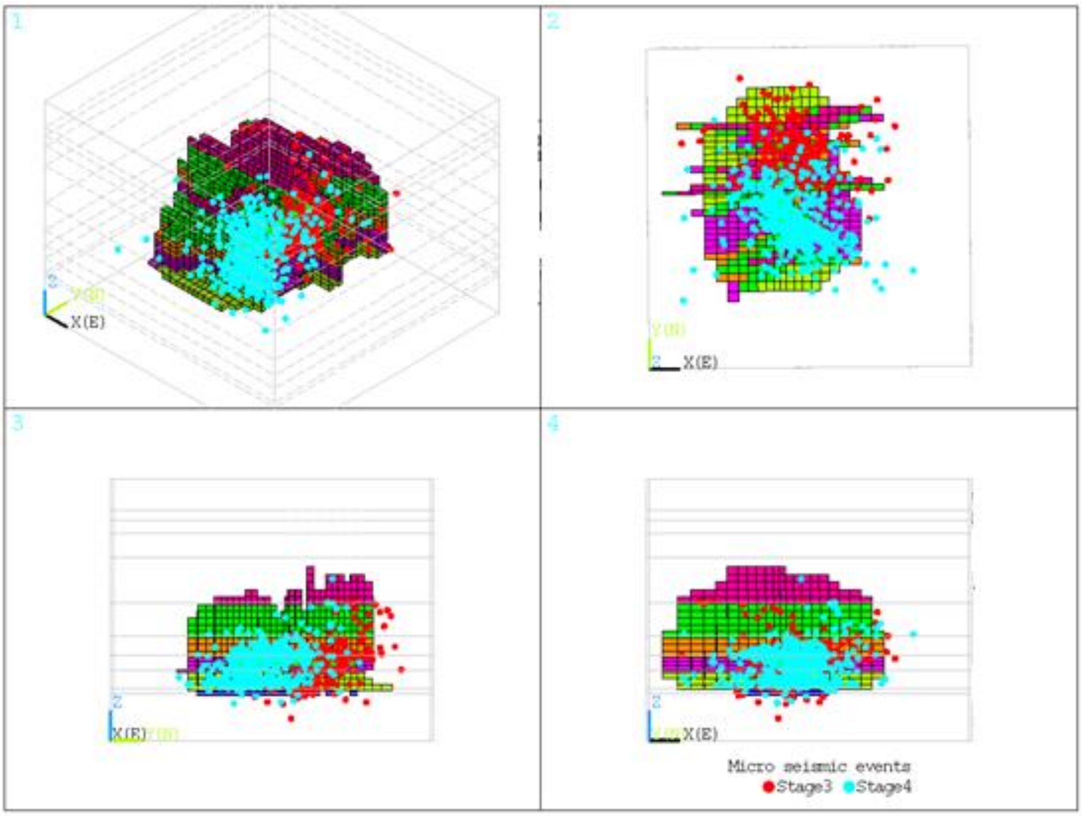

Fig. 12: Forecast of stage 4 - stimulated volume at end of the stage 3 compared with micro seismic events

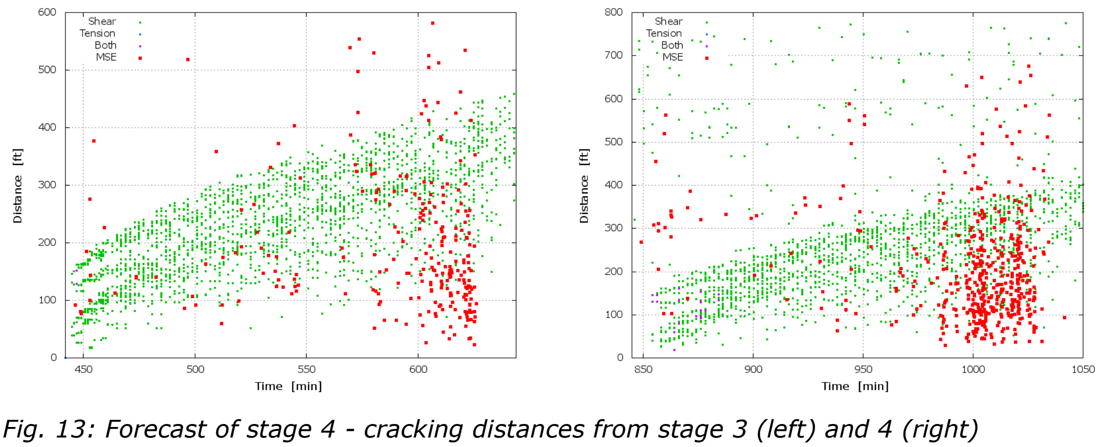

Fig. 13: Forecast of stage 4 - cracking distances from stage 3 (left) and 4 (right)

Sensitivity of well design and operation conditions

To optimize the well design and operational conditions, the two stage simulation is used as a base of the sensitivity study due to variation of operational parameter. The influence of well design and operation conditions for optimization of stimulated rock volume is investigated using the following set of parameters:

- Stage center distance (StageCentDist) - spacing between stages
- perforation spacing (PerfSpacing) - spacing between perforation cluster within a stage
- slurry rate (SlurryRate) - variation of max slurry rate
- well depth (WellDepth) - landing depth, 10 discrete landing depths within the pay zone are defined
- drill direction (DrillDir) - horizontal well orientation between 0°and +90° out of South-North

Operation conditions parameters are shown in *Fig.* . Scanning of the 5 dimensional space using optiSLang through sensitivity analysis, points out the most important well design and operation condition parameters for the hydraulic fracturing performance.

In the sensitivity analysis, at first the output parameter overlapping factor – the factor which expresses overlapping of stimulated volumes at stages 3 and 4 is investigated. Positive value implies overlapping, zero value - no overlapping and negative value means that stress field (shadowing) impact from stage 3 increases fracture in stage 4.

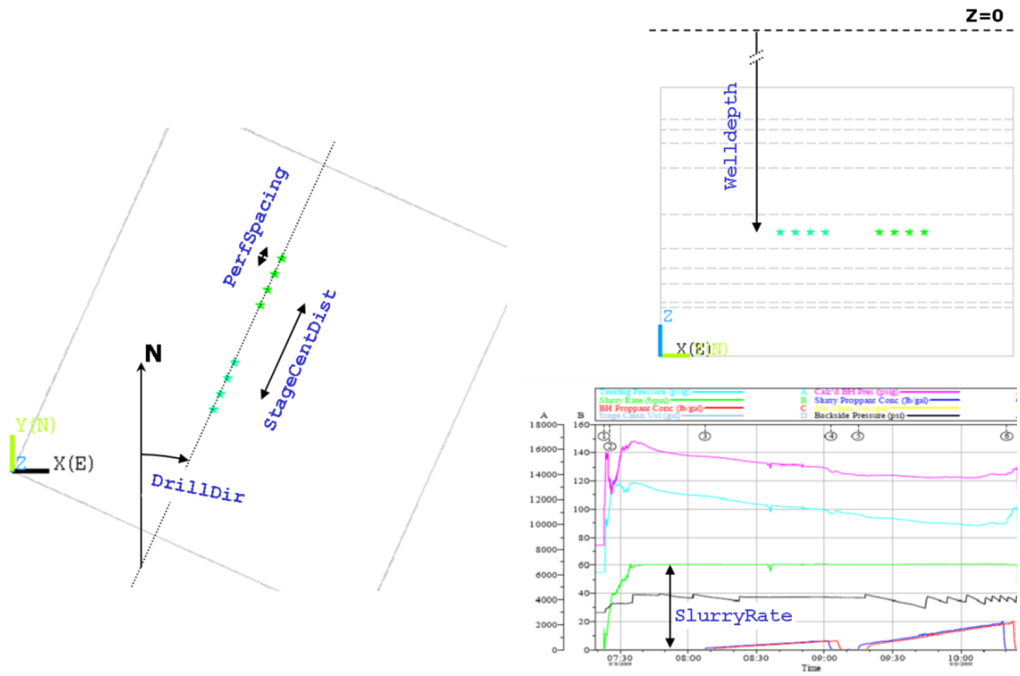

Fig. 14: Operation conditions used in sensitivity analysis

Investigating the correlation of the overlapping factor (*Fig.*) shows that besides drill direction, the distance of stages (StageCentDist) is most important. Fracture opening in *Fig.* clearly shows the separation of fractured volume between the stages for the best design. However the best design has negative overlapping factor, that means the fractured bodies do not overlay but stress field impact from stage 3 increases fracture in stage 4 (see. Fig. 14)

Large spacing between stages will result in gaps between the fractured rock bodies which are not optimal. To find a suitable measure of optimal design total fractured rock volume is derived which is normalized to the total lengths of the stages.

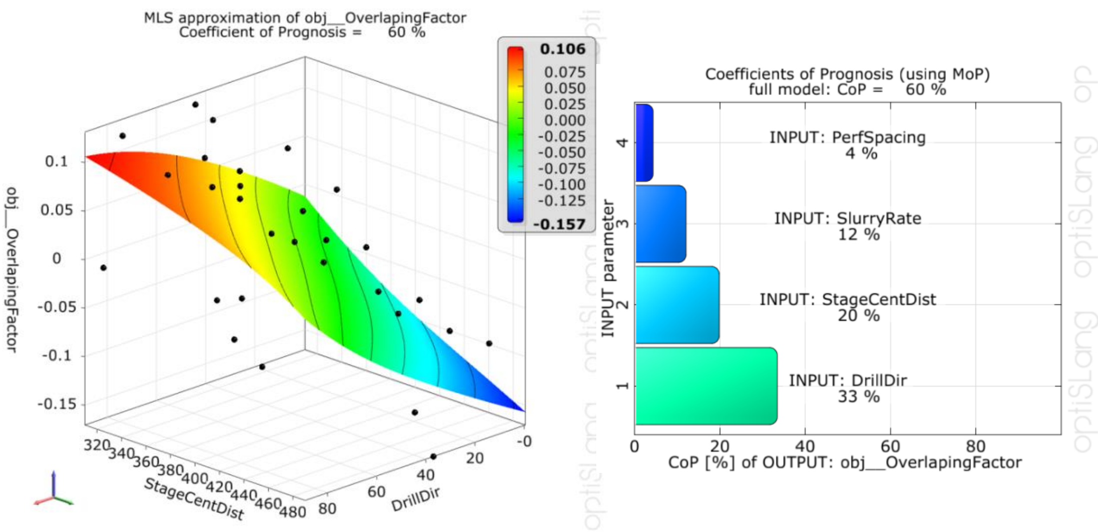

Fig. 15: 3D response surface plot (left) and coefficients of prognosis plot (right) for overlapping factor

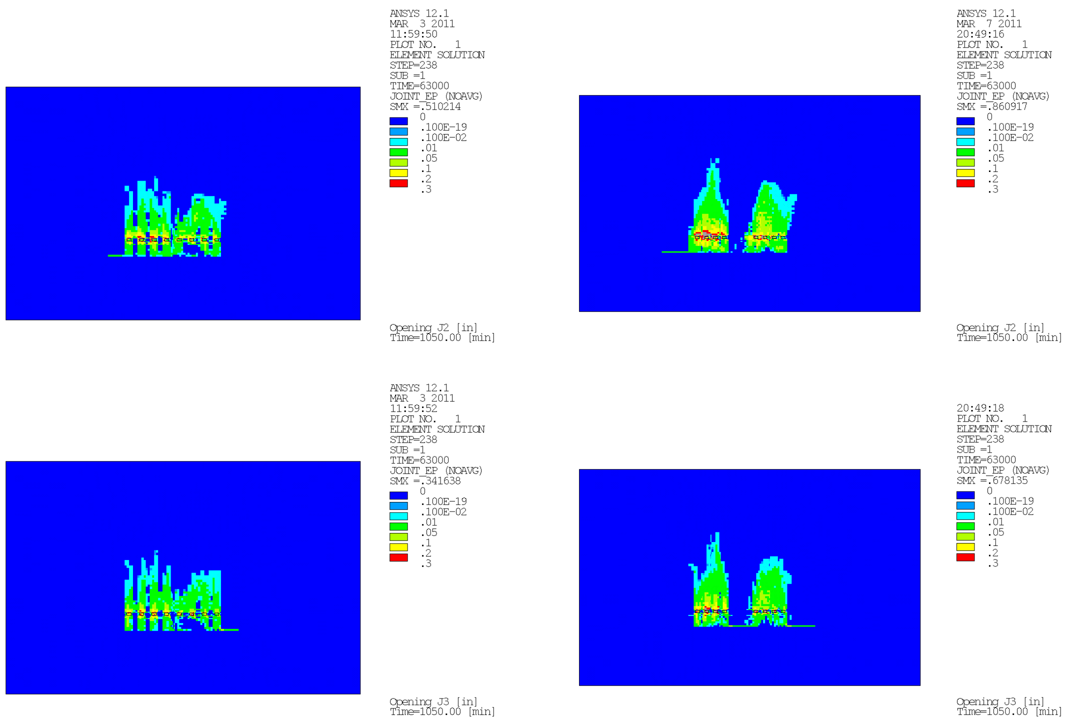

Fig. 16: joint set opening of vertical joints of reference (left) and best design of sensitivity (operation conditions) (right)

To investigate the maximum possible stimulated volume with a given length of the horizontal well the stimulated rock volume is normalized by dividing the total fractured volume by the sum of stage center distance and stage length.

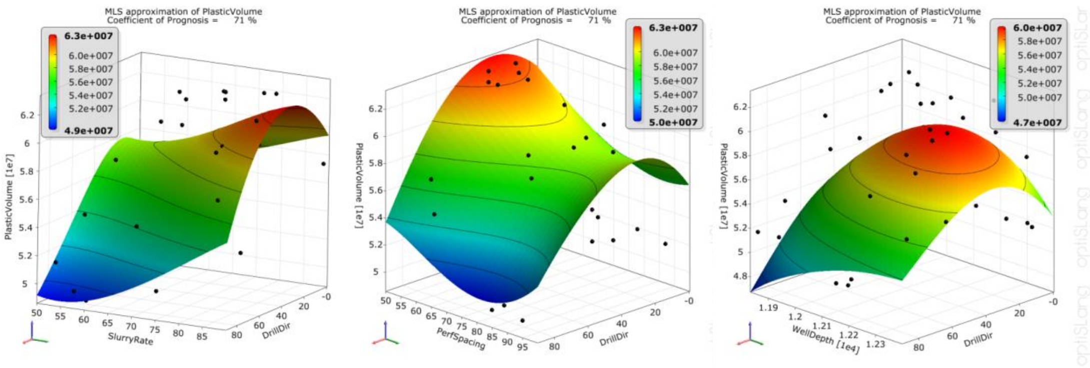

Fig. 17: 3D Response surface plots for plastic volume and most important input parameters (SlurryRate, DrillDir, PerfSpacing, WellDepth)

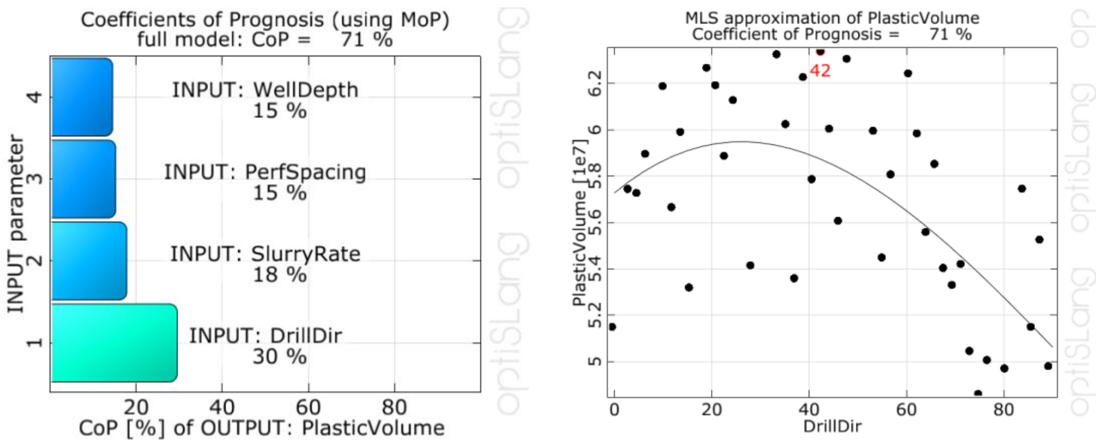

Fig. 18: Most important parameters for stimulated volume (left), Anthill Plot shows relation between plastic volume and most important parameter (DrillDir) (right)

From the sensitivity analysis due to well design and operation conditions, the four most important parameters for optimal well design can be identified as follows

- optimal well direction
- high slurry rate,
- low stage and perforation clustering,
- optimal landing depth

Note that the importance of measure of parameter being used is related to the investigated window of variation. Additional variation of other parameter or modification of variation windows will affect the importance.

Optimizing the stage design

Using the results of the sensitivity analysis the 3D stimulated rock volume within the window of variation of operational parameter can be optimized. The resulting stimulated plastic volume of optimal well design is 163 million ft^3. In comparison to the reference design there is an increase in stimulated volume about 16%. Stimulated volume for optimal well design is shown in Fig. 19.

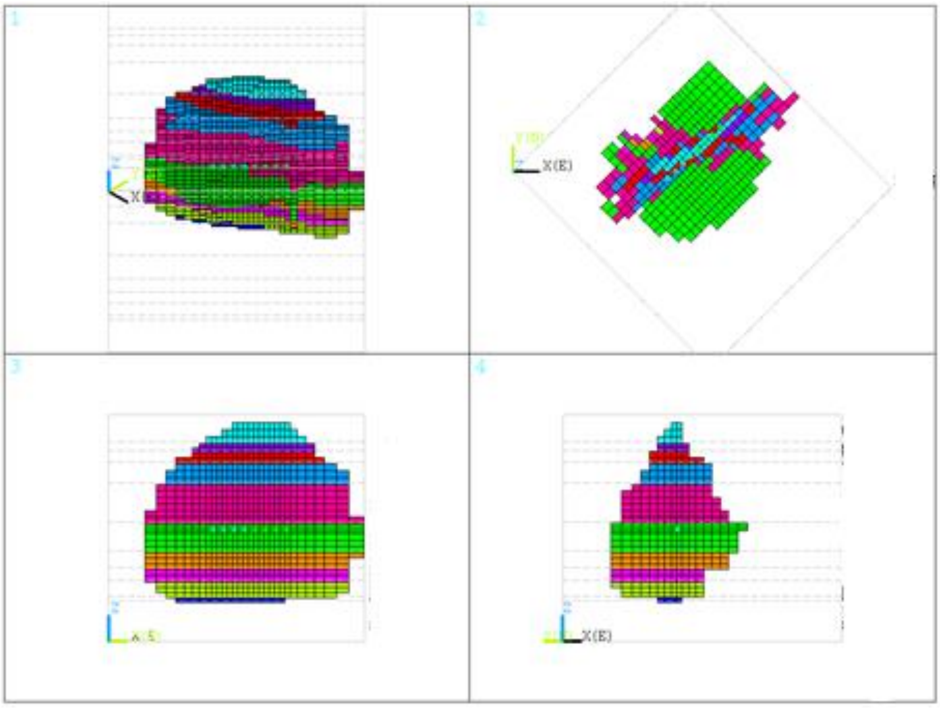

Fig. 19: Optimal well design - stimulated volume at end of the stage 4

Ranking of important parameter

Independent from investigating the uplift potentials due to optimization of operational parameters, the investigation of the relative importance of reservoir uncertainties and operation parameter can be continued. To rank and compare importance of reservoir uncertainties, well design and operation parameters, and the parameter importance to the related variation of fractured rock volume is normalized to the total amount of variation.

The variation of stimulated rock volume due to the uncertain reservoir conditions in the calibration stage is estimated to be 25 million ft^3. Varying the operation conditions in the calibration stage the variation of the total stimulated volume is 18 million ft^3. First important outcome of this comparison is that the variation range of total stimulated volume of reservoir uncertainties and the investigated variation window of operational parameter for well designs and stimulation conditions is approximately the same [25 million ft^3 to 18 million ft^3].

Using the ranges of variation and the Coefficients of Prognosis from both sensitivity studies the importance of the parameters by the related variation of stimulated volume can be ranked. Table 1 shows the most important parameters of reservoir uncertainty and operational conditions as well as their related variation of stimulated rock volume. Taking into account that the stimulated rock volume of one stage is 55 million $ft^{3,}$ the most important parameter - drill direction of the horizontal well results in a variation of 5.5 million ft^3 which makes a difference of 10% on hydro carbon production.

Uncertainty or operation condition	Effect of Variation (Mio ft^3)
Drill direction	5,4
k0 well landing layer	4,3
Slurry rate	3,2
Perforation/Stage spacing	2,7
Well landing depth	2,7
Friction angle vertical joints	2,5
K0 well surrounding layer	2..2,5
Initial pore pressure	2,0
Dip direction vertical joints	2,0

Tab. 1: Ranking the importance of parameters

The table shows the potential of optimization of hydro carbon production by optimizing well location and orientation, stage design and operation conditions. Also the importance of measuring and calibrating the in situ stress, pore pressure conditions, joint set orientation and strength in the reservoir is shown.

Summary

In the given project, the DYNARDO approach using 3D homogenized continuum modeling for hydraulic fracturing is able to represent major characteristics of fracture growth in unconventional layered hydro carbon reservoirs. With a stepwise calibration process from ISIP, single stage performance as well as sensitivity study due to a large amount of reservoir uncertainties most important reservoir conditions could be identified and calibrated. Following important information about the reservoir conditions are obtained:

- The difference between minimum and maximum horizontal stress is small
- Two vertical joints sets, which are rarely seen as cemented joints in some layers are extended as strength anisotropies into the whole reservoir layer. Otherwise large vertical growth of fractures seen in micro seismic cannot be reproduced
- The orientation of the initial joint system which is most important for the fracture growth was calibrated using micro seismic events
- Fracture of “intact” rock does not play an important role, because the joint system will fail before reaching intact rock strength limits. Therefore the reservoir stimulation is reopening and connecting to the naturally existing fracture system instead of a creating of a “new” fracture system.

With the calibrated model the forecast quality of stage 4 was in good agreement with the micro seismic events.

For a given project, its economics depend to a large extent on how wells are drilled and completed. Therefore a second sensitivity study has been performed with respect to operation conditions and well design, and their rankings in regard to influencing the final stimulated rock volume have been investigated. With an optimized set of well and operation parameters from the second sensitivity study the total fractured volume could be increased by 16%.

Furthermore by ranking uncertainties, well design and operation conditions, it could be shown that the potential of optimizing stimulated rock volume by varying operation conditions and well design is in the same order of magnitude as the variation due to reservoir uncertainties. Taking this into account, the reservoir uncertainties can be further identified (minimized) with calibration to measurements. Further, a predictable improvement (optimization) of project performance is possible by optimizing well design and operation conditions along with the important calibrated reservoir conditions like orientation of initial fracture system.

Results from this study will now be used to optimize well and completion designs for shale hydro carbon development. One of participants of the final meeting summarized the benefit of this study as: "All together the simulator shows the potential to teach things which we haven't known before and to verify assumptions which we have controversially been discussing since a long time. Results from the simulator, support a better understanding of the reservoir and the reservoir potentials and gives the key sensitivities for optimization of hydro carbon production."

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