# A geomechanical reservoir modeling tool

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*Abstract: A link between the geological software Irap RMS and ABAQUS is established using ABAQUS scripting interface in order to have; (1) automated generation of geomechanical reservoir simulation models, (2) to better account for geomechanical effects in the reservoir simulation and 4D feasibility studies.*

*The link consists of a set of Python scripts that rebuild the reservoir geometry in ABAQUS/CAE: (1) the tool may connect corresponding hanging wall and foot wall grid blocks in order to generate an unfaulted global model, (2) the tool may open up the grid along the fault surfaces and introduce the geometry of the fault fill material, (3) It adds the geometry of the over-, side- and under-burden. In other words all developments are geometry based which is believed to be a unique feature of the tool. The tool has been tested out on a faulted North Sea oil and gas field.*

*Keywords: Petroleum Engineering, Reservoir, Geomechanics, Irap RMS, ECLIPSE.*

## 1. Introduction

Computer programs from three vendors are involved in the geomechanical reservoir modelling workflow illustrated in Figure 1: (1) Irap RMS™ (trademark of Roxar software Solutions) for geological modelling, (2) ECLIPSE™ (trademark of Geoquest Schlumberger) for reservoir modelling and (3) ABAQUS™ (trademark of ABAQUS Inc.) for geomechanical reservoir modeling/stress analysis. In Statoil ASA, the faulted reservoir geometry is preferably built using the geological tool Irap RMS. After gridding and upscaling a simulation ready model is exported to the industry standard reservoir simulator ECLIPSE. A similar coupling between the industry-standard stress-simulator ABAQUS and Irap RMS did not exist starting this project.

Parts and assemblies can be imported into ABAQUS/CAE from a third-party CAD system. However Irap RMS does not support the CAD industry standards implying that the reservoir geometry must be generated from scratch within ABAQUS/CAE using the geometry creation tools: Solid features, cut features, shell features, wire features, datum geometry and partition tools.

It is also necessary to modify the Irap RMS geometry in order to address the important question of fault reactivation during depletion. This question will be answered introducing the geometry of the fault fill material with its mechanical properties into the ABAQUS/CAE simulation model.

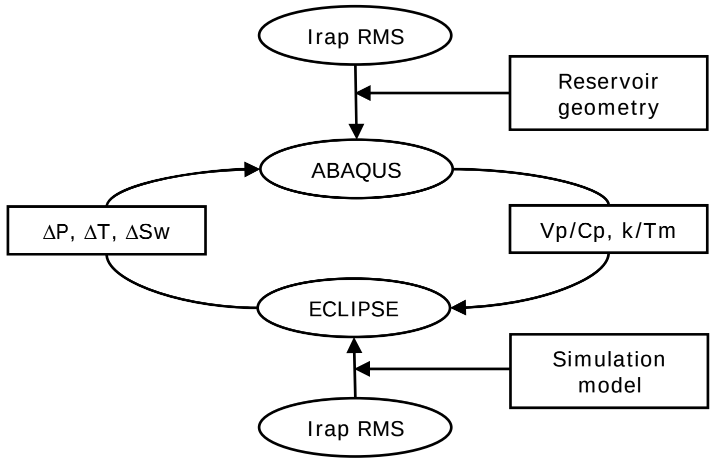



**Figure 1. Geomechanical reservoir modelling workflow.**

Figure 1 also indicates the data exchange between ECLIPSE and ABAQUS, however this is not a topic in this paper. The specification, programming and verification of the link between Irap RMS and ABAQUS are the main issues of this paper. Verification and demonstration of capabilities of the tool is done using a faulted North Sea oil and gas field.

## 2. Solution strategies

Some modelling strategies that have a direct influence on the tool development will be outlined here.

### 2.1 Submodelling technique

In order to keep the geomechanical model at a convenient size the submodelling technique available in ABAQUS will be used to obtain an accurate, detailed solution in a local region from an initial, relative coarse, global mesh. Three levels with submodels may typical be used: (1) Unfaulted global model, (2) Faulted submodel (regional model) and (3) Sub submodel addressing casing integrity, wellbore stability in shales and sand production potential .

### 2.2 ABAQUS model

Two obvious choices exist regarding establishing a geomechanical reservoir simulation model for ABAQUS: (1) Rebuild the geometry within ABAQUS/CAE or (2) Use the grid of the geological model or the reservoir model directly in ABAQUS.

Earlier developments within this field typically generate the simulation model or input file to the stress simulator. This is normally done by extending the reservoir simulation grid up in the surrounding shale as shown in Figure 2. This last approach lack the flexibility needed to handle displacement localization in the overburden that may occur when reservoir is produced by huge depletion.

The first approach is chosen here as we aim at: (1) High quality mesh with a limited total number of elements in the model, (2) Adaptive re-meshing requires tetrahedral meshing (localization), (3) Extend fault fill material geometry out in the surrounding shale and (4) Finer discretization level for the fault fill material utilizing cohesive elements.

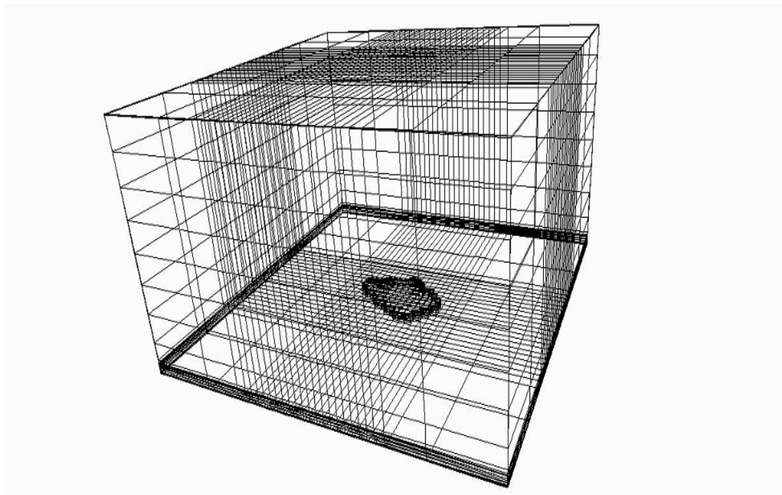


**Figure 2. ECLIPSE 300 grid for a North Sea oil and gas field (structured gridding).**

## 3. Tool specifications

Specifications of the tool RMS2ABA will be given below.

### 3.1 Reservoir geometry from Irap RMS

The starting point for generating a faulted reservoir model in Irap RMS is the irregular fault surfaces that penetrate the reservoir. Interpreted horizons from the seismic are added in a consistent way. Thereafter the reservoir volumes are discretized using a corner point grid as shown in Figure 3. This is a structured grid where the horizontal distance between the grid block corners may vary.

A consequence of representing heavily faulted reservoirs with a structured grid is concave blocks along the fault surfaces. These blocks are easily identified in Figure 3 as all concave blocks are split into two wedge elements before visualization in ABAQUS/viewer. In addition the pinchout of layers will generate problems in the finite element representation of the faulted reservoir grid.

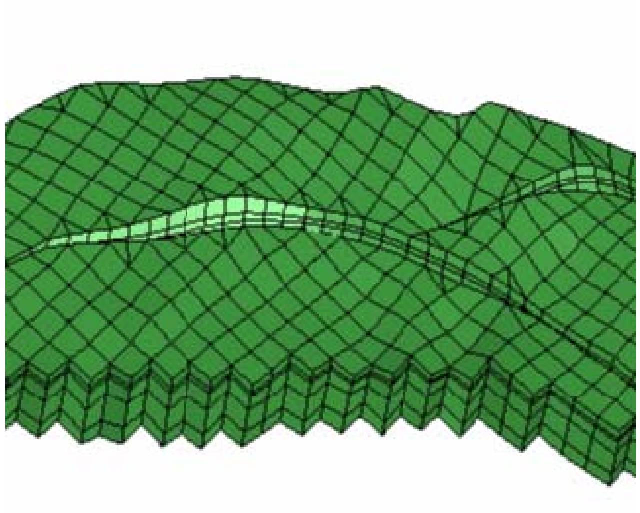


**Figure 3. Irap RMS corner point grid visualized in ABAQUS/Viewer. Note that concave blocks along the faults are split into two wedge elements.**

### 3.2 Merge grid blocks

RMS2ABA must be able to merge grid blocks. There are two reasons for that: (1) pinch-out of layers in the geological model and (2) necessary reduction of the number of reservoir grid blocks for the stress simulator.

Layers that pinch-out create problems representing the grid blocks with hexahedral elements. Neighboring blocks within the same layer to undefined blocks with zero thickness due to the pinch-out of the layer can not be represented by a hexahedral element.

The total number of reservoir grid blocks is reduced effectively by merging layers, which may be necessary keeping in mind that the volume of the surrounding shale is much larger than the reservoir volume.

Some restrictions must be set to the merging process: (1) Layers that are merged should have the same pressure depletion history and material properties and (2) Merging is restricted to vertical blocks only.

An example is shown in Figure 4. The three layers seen in the geological model to the top is reduced to two layers is the ABAQUS simulation model shown in the bottom figure. This merging process is handled in RMS2ABA by picking the top/bottom reservoir horizons and user defined layer interfaces. Horizons and layer interfaces are numbered from 1 to NZ+1, starting at top reservoir. NZ is the number of layers in the geological model.

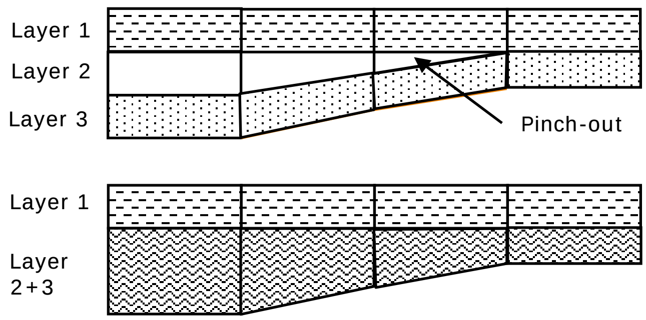



**Figure 4. Block merging shown in a cross sectional view. (a) Pinch-out of layer 2 in the geological model (top figure) and (b) Merging of grid blocks in layers 2 and 3 (bottom figure).**

### 3.3 Connect grid blocks

RMS2ABA must be able to smooth faults, i.e. connect FW/HW grid blocks. Three alternatives are sketched in Figure 5. These are: (1) Move HW nodes, (2) Move FW nodes, and (3) Move both FW/HW nodes. RMS2ABA use the last option.

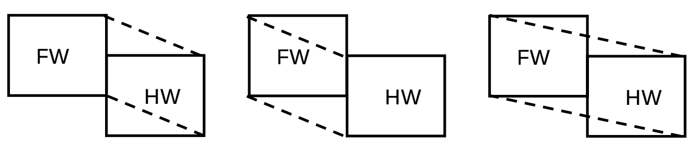



**Figure 5. Connection of two grid blocks shown in a cross sectional view. (a) Move HW nodes, (b) Move FW nodes, and (c) Move both FW/HW nodes.**

### 3.4 Open grid

RMS2ABA must be able to open up the grid along the fault surfaces and introduce the geometry of the fault fill material when a detailed fault model is wanted in ABAQUS/CAE. A parametric representation of the cell sides along the fault is used deciding the blocks shrinkage normal to the fault surface as indicated in Figure 6. In addition blocks with only an edge along the faults surface must be handled according to the shrinkage of its neighboring blocks.

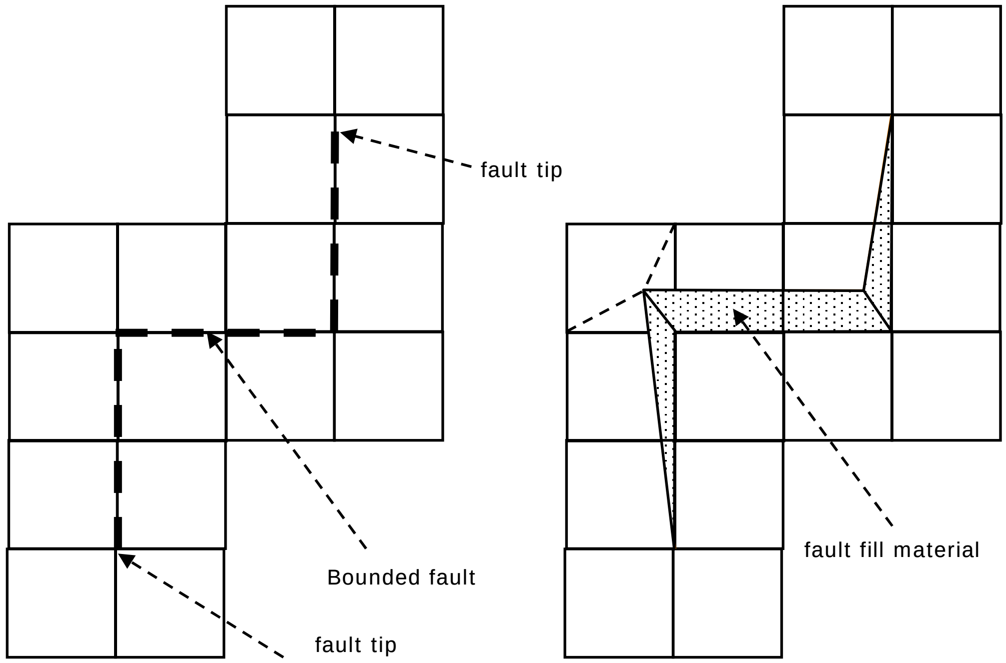



**Figure 6. Grid opening and placement of the fault fill material (map view). (a) Irap RMS grid that includes a bounded fault and (b) ABAQUS/CAE representation of the faulted reservoir geometry.**

Unique material properties will be given for the fault fill material.

### 3.5 Fault network

RMS2ABA must handle different type of faults as each of these requires different treatment at the crack tip. Three different types of faults is identified in the fault network as shown in Figure 7: (1) Bounded fault, (2) Semi-bounded fault and (3) Open-fault. In addition we may have crossing fault/truncated faults. Segment boundaries are indicated by the dashed lines. Tip identification and treatment are automated in the tool.

This case is later on used to verify the tool RMS2ABA.

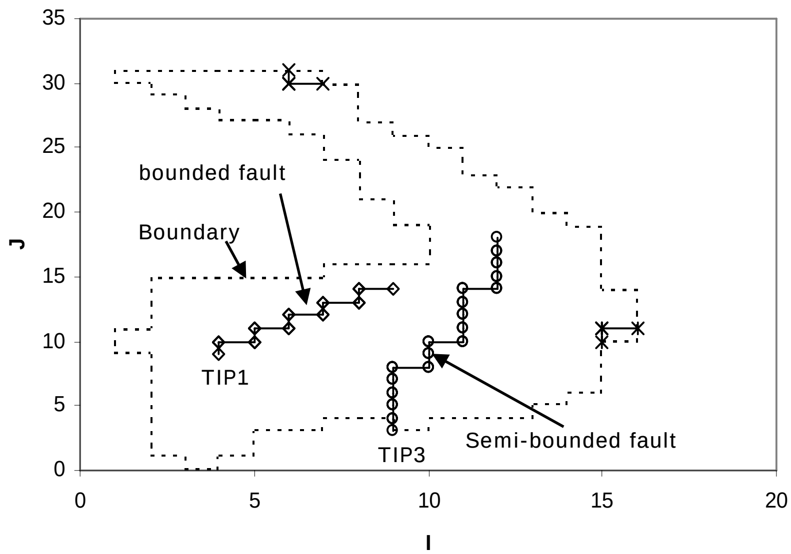



**Figure 7. Map view of fault network with the different tip types: TIP1 - fracture tip, and TIP3 – intersection of boundary. Note that blocks with a unit size are used for visualization purposes.**

### 3.6 Geometry for surrounding shale

RMS2ABA must add over-, under- and side-burden geometries to the reservoir geometry. This is obtained by a simple CUT operation between the global box (solid) and the surface representation of the reservoir geometry (Boolean operation). The global box includes the reservoir and the surrounding formations up to seabed, possibly down to base rock and some reservoir width to each side in order to limit the effects of the imposed displacement boundary conditions on the global box. This implies that modelled volumes outside the reservoir are far larger than the volume of reservoir represented in Irap RMS/ECLIPSE.

Overburden horizons may be included if interpreted, either from Irap RMS or other seismic software. These can be imported into ABAQUS/CAE as a surface (shell representation using ABAQUS terminology).

## 4. Tool programming

RMS2ABA is programmed in Python™ (trademark for the Python Software Foundation).

### 4.1 ABAQUS scripting language

An automated generation of a surface representation of the Irap RMS reservoir geometry is obtained utilizing the scripting interface in ABAQUS. The flowchart for the script RMS2ABA is given in Figure 8.

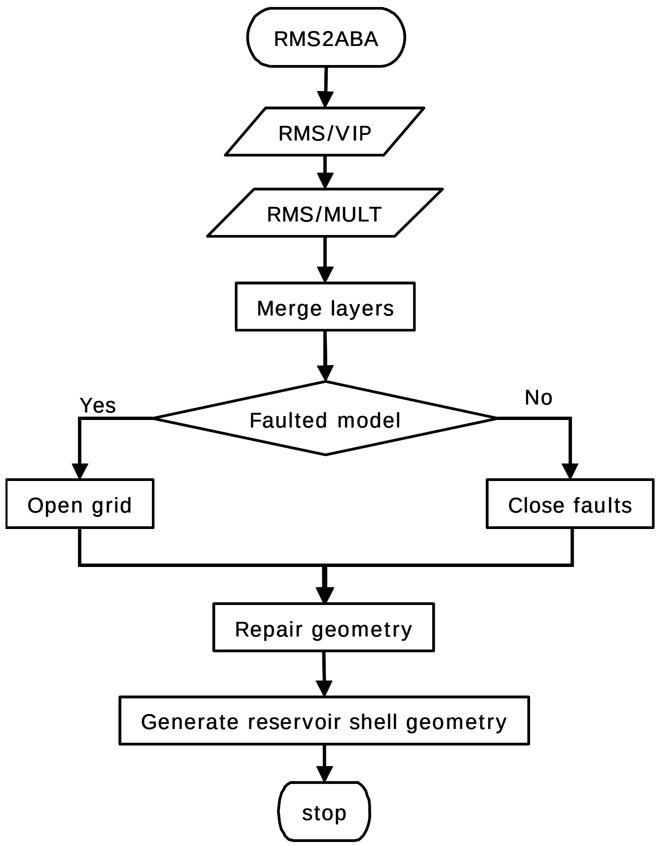



**Figure 8. RMS2ABA flowchart.**

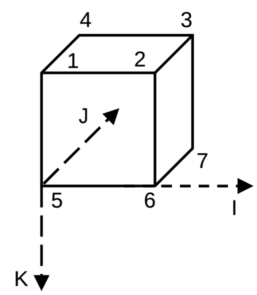
RMS2ABA is started in ABAQUS/CAE. After initialization, block geometry and fault definition are read from the Irap RMS ASCII files VIP and MULT respectively. The merging of grid blocks, fault opening and closing are discussed above. Grid repair is restricted to repairing gaps in the Irap RMS grid. Finally a reservoir surface (shell using ABAQUS terminology) representation of the reservoir geometry in within ABAQUS/CAE is generated utilizing the geometry creation tools: Datum geometry, wire feature and shell feature. Interpreted horizons in the overburden may be constructed in ABAQUS/CAE using the same geometry creation tools.

### 4.2 Interface against Irap RMS

Irap RMS can export 3D grids to several commercial available reservoir simulators. Amongst these are the reservoir simulator VIP™ (trademark of Landmark). The file format for this simulator, named VIP CORP format, uses the corner point description. Corner point coordinates (X,Y,Z) for each grid block (number given by its indices I, J and K) are grouped together as shown in Table 1. Grid blocks are ordered with I index cycling fastest, followed by the J and K indices. Undefined blocks are inactive grid blocks in the simulation model.

**Table 1. Irap RMS grid block coordinates.**

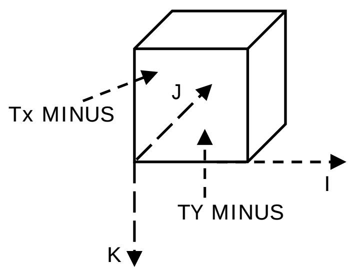
```
C
C GRID BLOCK:  I =   2 , J =   7 , K =   1
C UNDEFINED BLOCK
C
   4842.64   -6240.09   4274.01   4929.84   -6327.09   4224.11
   5004.11   -6253.06   4231.87   4918.62   -6168.40   4274.01
   4842.64   -6240.09   4274.01   4929.84   -6327.09   4224.11
   5004.11   -6253.06   4231.87   4918.62   -6168.40   4274.01
C
C GRID BLOCK:  I =   3 , J =   7 , K =   1
C
   4929.84   -6327.09   4224.11   4994.99   -6397.25   4219.05
   5069.00   -6324.16   4226.38   5004.11   -6253.06   4231.87
   4926.37   -6323.62   4237.74   4991.42   -6393.40   4233.48
   5066.17   -6320.62   4240.66   5001.16   -6249.80   4245.45
```




The fault model generated in Irap RMS is based on a fault network, and consists of a set of gridded fault surfaces, with corresponding fault lines along the intersections between the selected horizons and the fault surfaces. Table 2 gives the syntax used in the MULT file that defines the fault location within the simulation grid. I1 and I2 are lower and upper I-coordinate of cells along the fault. J1, J2, K1 and K2 are defined in a similar manner. The face of the block that is part of the fault surface is either TX MINUS or TY MINUS (see sketch in Table 2). This implies that the fault surfaces description given in the MULT file typically are made up of both block faces from the HW and FW side. An algorithm has been made that transform this definition to either a FW or HW description of the fault surface before a shrinkage of the blocks can be performed according to Section 3.4.

**Table 2. Irap RMS fault description.**

```
MULT TX ALL MINUS MULT
  FNAME  Acw_SE1
-- I1   I2    J1   J2    K1  K2
   51   51    50   51     1   28    1.000
   50   50    52   54     1   28    1.000
   49   49    55   56     1   28    1.000
   48   48    57   57     1   28    1.000
   47   47    58   64     1   28    1.000
   48   48    65   71     1   28    1.000
   49   49    72   73     1   28    1.000
MULT TY ALL MINUS MULT
  FNAME  Acw_SE1
   50   50    52   52     1   28    1.000
   49   49    55   55     1   28    1.000
   48   48    57   57     1   28    1.000
   47   47    58   58     1   28    1.000
   47   47    65   65     1   28    1.000
   48   48    72   72     1   28    1.000
   49   49    74   74     1   28    1.000
C
C next fault
C
MULT TX ALL MINUS MULT
  FNAME  Pw1_NE3
   30   30     8    9     1   28    1.000
   29   29    10   24     1   28    1.000
MULT TY ALL MINUS MULT
  FNAME  Pw1_NE3
   29   29    10   10     1   28    1.000
```




## 5. Tool verification

Verification and demonstration of capabilities of the tool is done using a faulted North Sea oil and gas field. The results from one out of 13 reservoir segments are given here. A map view of the fault network is given in Figure 7.

### 5.1 Global model

Recall that the full-field (or global model using ABAQUS terminology) geomechanical reservoir model will be un-faulted. Geological layers will be merged in order to reduce the number of grid blocks and to handle pinch-out of layers. As a user of the tool RMS2ABA one has to specify the interfaces that will be included in the model. These are numbered from 1 to NZ+1, starting at top reservoir. NZ is the number of geological layers in the Irap RMS model. Here it is 28.

Interface 14 and 20 are included in the un-faulted version of the segment as shown in Figure 9. A cut through the model reveals interfaces 14 and 20.

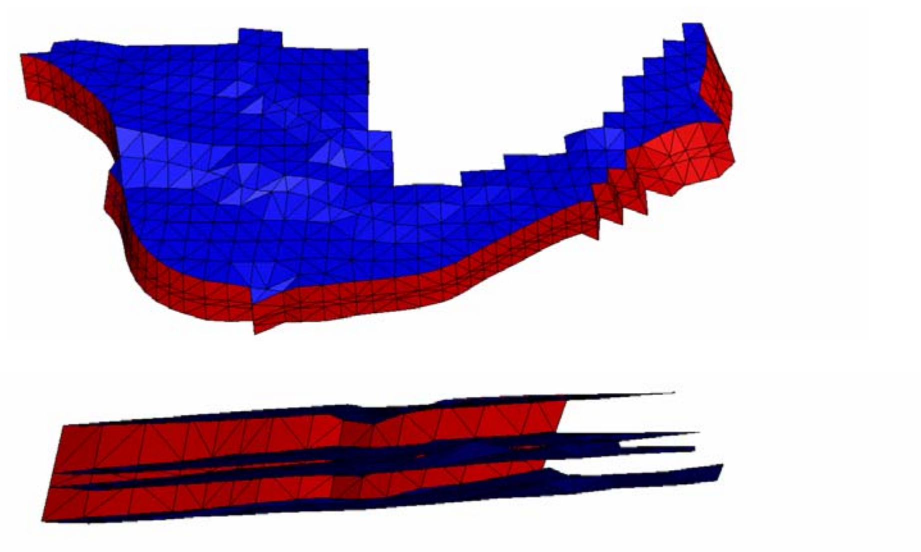


**Figure 9. An un-faulted model that includes top/bottom reservoir horizon and two interfaces. (a) Surface representation of the reservoir geometry, (b) A cut through the model that reveals the interface surfaces.**

### 5.2 Faulted model

An ABAQUS/CAE faulted versions of the reservoir segment in section 5.1 will be generated in order to validate both the merging of layers, fault opening process and the generation of the geometry for the fault fill material. This model will only include interface 20 in addition to the top/bottom reservoir horizons.

The resulting surface representation of the reservoir geometry in ABAQUS/CAE is visualised in Figure 10.a-b; Triangulated top/bottom horizons surfaces are blue, boundary edge surfaces are yellow and fault surfaces are red. As may be seen, the model includes one bounded fault, one semi-bounded fault and a part of two open faults (cut by the segment boundaries). Figure 10.b focuses on the geometry of the bounded fault. Wedge shape geometry is used at the fault tips, while brick shape geometry is used elsewhere.

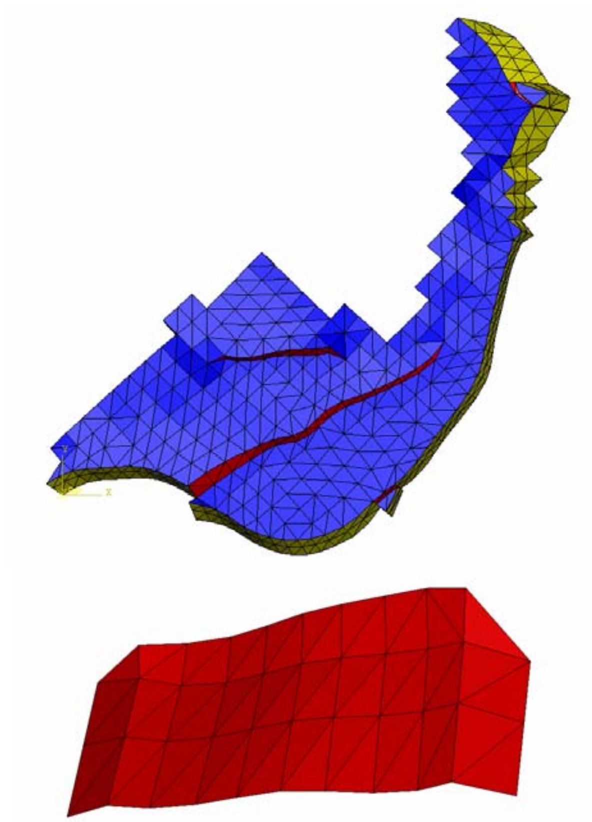


**Figure 10. A faulted reservoir model that includes top/bottom reservoir horizon and one interface. (a) Surface representation of the reservoir geometry, (b) Surface representation for the fault fill material of the bounded fault.**

## 6. Geomechanical reservoir modeling workflow

All steps in a reservoir geomechanical analysis are considered in this simplified reservoir depletion case presented below. Irap RMS reservoir geometry (small part of the reservoir) is first regenerated in ABAQUS/CAE as shown in Figure 11. Surfaces of the fault fill material are colored red, while the top and bottom horizon of the reservoir are colored yellow.

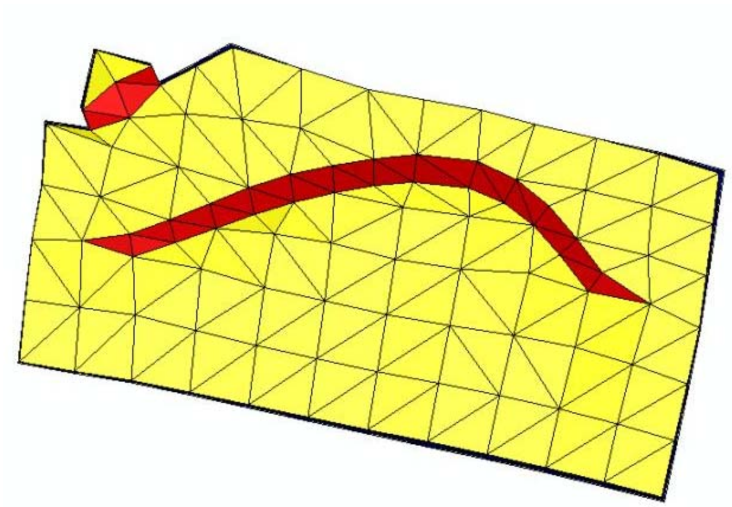


**Figure 11. ABAQUS/CAE surface representation of the reservoir geometry.**

The next step is to generate the global box (solid) that includes the reservoir and the surrounding formations as shown in Figure 12. Recall that the final geometry is established through a CUT operation between the global box and the surface representation of the reservoir geometry. Problem geometry is now established in ABAQUS/CAE.

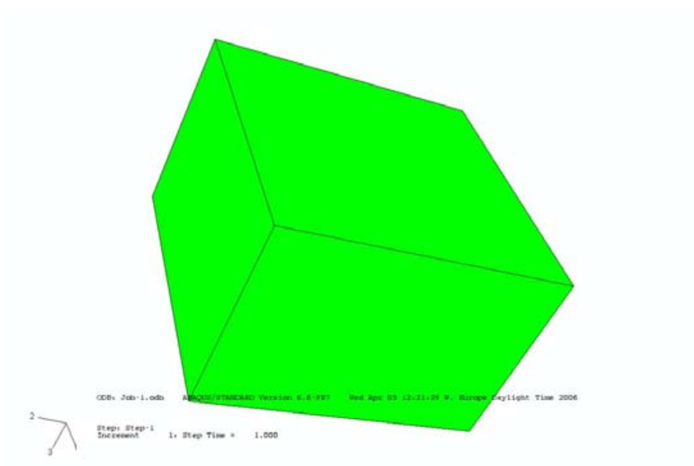



**Figure 12. Global “box” that includes the reservoir and the surrounding formations.**

Supply model parameters: (1) Material data for the reservoir and the surrounding formations, (2) Boundary conditions for the global box and (3) Loading in form of a depletion history.

Model discretization is shown for the reservoir in Figure 13, and for a cross section view through the whole model in Figure 14.

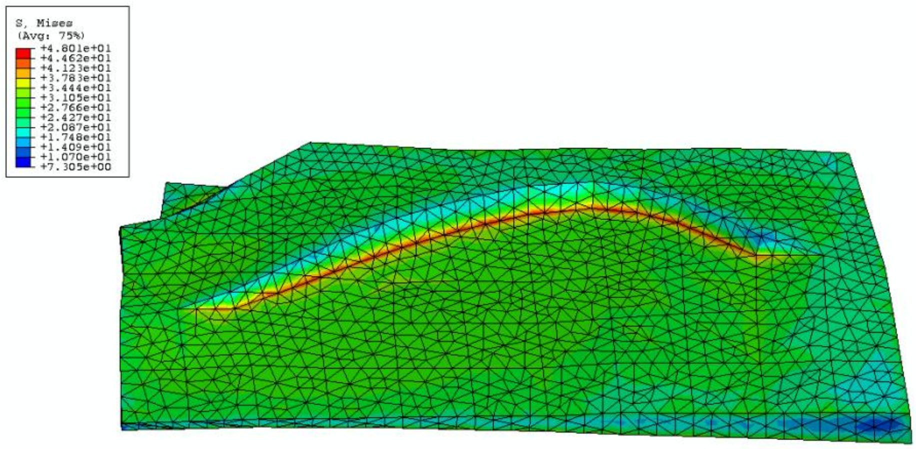



**Figure 13. Tetrahedral mesh and Mises stress in the reservoir after 50 MPa depletion.**

After simulation ABAQUS/Viewer is used to display the result of interest as indicated in Figures 13 and 14.

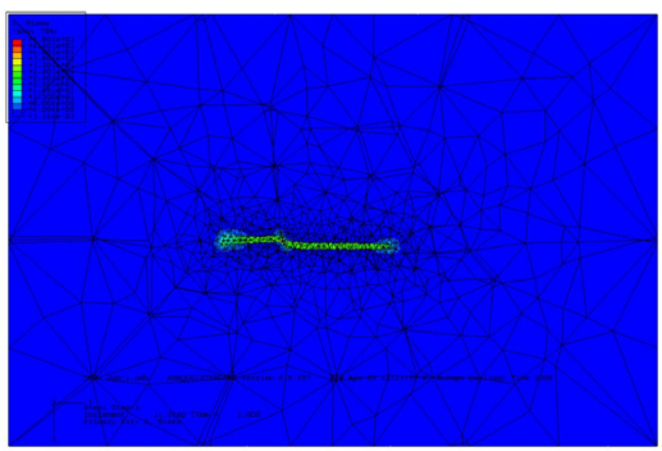


**Figure 14. Cross sectional view through the model showing Mises stresses.**

## 7. Conclusions

A geomechanical reservoir modeling tool is established utilizing the ABAQUS scripting interface.The link consists of a set of Python scripts that rebuild the Irap RMS reservoir geometry in ABAQUS/CAE:

1. The tool may connect corresponding hanging wall and foot wall grid blocks
2. The tool may open up the grid along the fault surfaces and introduce the geometry of the fault fill material
3. It adds the geometry of the over-, side- and under-burden

In other words all developments are geometry based which is believed to be a unique feature of the tool. This is in contradiction to earlier developments within this field that typically generates the simulation model or input file to the stress simulator.

A key ingredient in establishing a full-field geomechanical reservoir model is the submodelling technique available in ABAQUS. Current strategy is to generate an unfaulted full-field geomechanical reservoir model, i.e. where blocks along the fault surface are connected. Fault details will be added to submodels or regional models that typically include a part of the reservoir and surrounding formations. Finally a subsubmodel may be established addressing casing integrity, wellbore stability is shales or sand production potential.

## 8. References


1. Irap RMS™ (trademark of Roxar software Solutions). Official web site www.roxar.com
2. ECLIPSE™ (trademark of Geoquest Schlumberger). Official web site www.slb.com.
3. Python™ (trademark for the Python Software Foundation). Official web site www.python.org.
4. VIP™ (trademark of Landmark, a division of Halliburton). Official web site www.halliburton.com.