Structural uncertainty modelling and the representation of faults as staircases

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Abstract

Quite often, structural uncertainty is the dominating uncertainty of the oil production of a field. The structural geology of an oil field is a large-scale property with non-linear effects on flow. Hence, its effect on production can't be quantified simply by varying a few parametres and as a consequence, uncertainty quantification of the future production from a reservoir should often include the generation of several possible realisations of the structural model, where all models are consistent with the available data.

Producing a large number of structural models may be a very tedious and costly exercise if carried out manually. In particular, this is the case when seismic data is of poor quality or when one expects a high density of subseismic faults with strong effects on the flow. Consequently, we need automatic tools for simulating structural features. These tools should produce results that can be carried on to the flow simulation model for further evaluation of the effect of structural uncertainty on oil rates and total production.

This paper focuses on the representation of many faults that truncate each other making y-shaped faults in the xy and xz planes. The faults are stochastically modelled using a parametric format. The parametric faults are represented as reversible operators on the reservoir, making both faulting and defaulting possible. This option is used in order to validate the fault pattern using structural reconstruction, to improve the facies model, to interpolate and extrapolate data on both sides of the fault plane, to calculate the sealing properties of the fault plane, and to represent the deformation effect in the matrix on both sides of the fault plane. In the flow simulation grid, such complex fault patterns must be represented as staircases in the z-direction if faults are not vertical. The staircases are generated automatically from the parametric representation. It is ensured that sealing faults also are sealed in the staircase grid. The staircase representation is as simple as possible in order to model the flow parallel with the fault plane satisfactory. In particular, isolated blocks due to dense faulting are avoided if this is not done on purpose representing an isolated compartment.

The approach described is included in a large software package for modelling faults that has been developed over the last 15 years. It is tested together with an oil company on a heavily faulted reservoir with extended compartmentalization.

1. The importance of structural uncertainty

Optimal reservoir management depends on reliable handling of available knowledge about the reservoir and its uncertainty. The main sources of uncertainty come from the reservoir's geological structure, the variability of petrophysical properties and the locations of oil-water and gas-oil contacts. The spatial uncertainty in the interpretation of seismic data comprises random measurement uncertainty (noise), data resolution (frequency), systematic error caused by geological and seismic anisotropies, migration uncertainty, non-uniqueness, error introduced by human interpreters, as well as positional errors in well ties.

Given the large effect of inhomogeneities on flow, it should not come as a surprise that structural uncertainty has a large and sometimes dominating effect on the uncertainty of a reservoir's production [1]. Nevertheless, structural uncertainty is seldom carried through to flow simulation and history matching. The reasons may be multiple, including lack of appreciation of the importance of the structural uncertainty, lack of suitable software tools, and last but not least, the immense computational cost of maintaining several structural models, each with several realizations, through facies modelling, petrophysics modelling and history matching. As a consequence, history matching does not always explore the most probable realizations. In the end, one gets erronous predictions and wrong decisions.

2. The field

The field applied as a test case in this study is an offshore gas and oil deposit. Oil is produced from an heterogeneous shallow marine succession with thickness 100–150 meters, covering an area of around 40 kilometers.

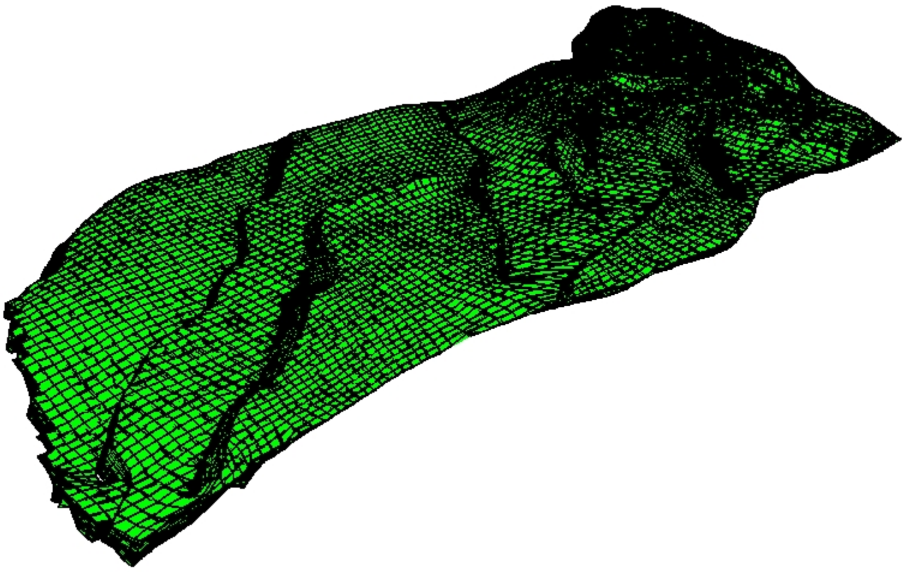


Figure 1: Overview of field

The field has several major segments. The model described in this paper is covering the A-segment, which has the lowest quality rock of the field. In this area, one expects a recovery factor of only 6% despite use of advanced horizontal drilling techniques. The main reason for the low recovery is numerous sealed or partially sealed faults, which give rapid depletion of the small fault compartments. Many of the faults are of low angle, making 3D grid modelling quite challenging.

The field in general, and the A-segment in particular, is heavily faulted with resulting sealed off compartments. In order to get as much oil as possible, it became necessary to drill advanced horizontal wells taking into account details of the structural model.

The effect of subseismic faults was subject of case study on another heavily faulted reservoir [2]. The main conclusions were that the sealing properties were instrumental to the overall effect on recovery. Unless subseismic faults were almost completely sealing, it was found that their effect on recovery were negligible. However, with a large number of sealing subseismic faults production was typically reduced by 20–25%. For individual wells the consquences were even larger.

3. Fault modelling

Faults are fractures with offset by shear displacement parallel to the fracture surface. Faults can be single discrete breaks or a fault zone with countless closely spaced fracture surfaces. Along faults one finds deformed rocks with different petrophysical properties than the material on either sides. Typically, however, the fault minerals are confined in a layer with a thickness much smaller than the grid resolution of the flow simulation grids. Most fault models therefore focus on the fault surface and model it as modified permeability and porosity fields or as transmissibility multipliers in the simulation grid [3]. The former approach requires knowledge about the thickness of the fault zone.

In this paper we use a fault modelling tool developed at the Norwegian Computing Center in cooperation with oil companies [4]. It was originally designed as a tool for stochastic modelling of subseismic faults using a marked point process [5]. Later it has been extended to a general fault modelling tool.

3.1. Modelling of faults on different scales

A number of studies in many different geologic environments have shown that when fault size is plotted against fault density (surface area/unit volume) on a log-log plot, the result is a straight line [6, 7, 8]. The slope and intercepts of the line vary, but the line is always straight. Due to this fractal behaviour one can interpolate between the largest faults seen on the seismic and the smallest ones from the well cores.

The ultimate goal of reservoir modelling is of course to get reliable predictions for future production under different production strategies. This means that any modelled fault must end up with a representation in the flow simulation grid. The largest faults are modelled deterministically. Their displacements are incorporated directly into the gridding of the simulation grid. The effect on flow is usually incorporated using transmissibility multipliers across the fault surface. One the other end of the scale, the small subseismic faults which are smaller than the grid cells of the simulation grid must be modelled stochastically as modifications to the permeability of the grid cells. Faults on intermediate scales which are subseismic or near seismic resolution are modelled stochastically as permeability or transmissibility multipliers depending on their size.

Since details of small faults cannot be resolved in the simulation grid, they are simulated using a simpler representation than the larger ones. The software [4] employed in this study supports both an elliptic fault representation and a more advanced parametric fault model. These two representations are explained in the sequel.

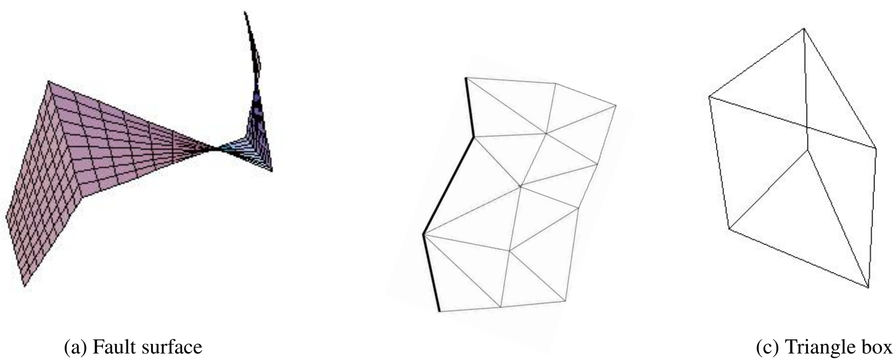
3.2. The elliptic fault model

The elliptic fault model [5] represents the fault surface as a plane acting as a baffle or barrier to flow. Real fault data [9, 10] inspired a model where displacement is controlled by a reversible operator acting in an ellipsoid around the fault plane. Displacement reduces from a maximum in the middle of the fault surface to zero at the edge of the ellipsoid. Since the elliptic fault has no effect outside its defining ellipsoid, it is an object of finite extension.

In reality fault surfaces are not always planar. Hence, for larger faults with non-neglible curvature one needs a more complex model.

3.3. The parametric fault model

In the parametric fault model (PFM) [4] the fault surface is represented by a set of bilinear surfaces each defined by a pair of lines called *pillars* (Figure 2 (a)). Another important feature of this fault model is that it models not only



(a) Fault surface

(b) Triangulation

(c) Triangle box

Figure 2: Elements of the parametric fault model. (a) On the left a twisted fault surface is modelled as a set of three bilinear surfaces. (b) The illustration in the middle depicts a horizontal cross section of the grid. The thick line segments on the left represent three bilinear segments of a fault surface. In each joint there is a pillar. Additional pillars have been inserted to the right of the fault surface, and this region has been triangulated. (c) In 3D the triangles become triangle boxes of the type on the right.

the location of the fault surface but also the relative displacement and the resulting deformation of the surrounding volumes. In the PFM model the displacement operator are piecewise linear invertible functions acting on points along the pillars. To support deformation off the fault surface, additional pillars are introduced by a triangulation of the horizons giving rise to triangle boxes in which displacement can be computed for any point by simple interpolation [11]. In Figure 2 we show a rather twisted fault surface, a cross section of a fault surface with triangle boxes drawn on one side, and a single triangle box.

For a fault system the deformations are carried out in a predefined order. Since the deformation operators are non-commutative, prescribing a different order produces a different result.

However, this representation has several weaknesses. Firstly, the pillars are assumed to have a large vertical component. This makes modelling of slide-slip, detachment or thrust faults impossible. Secondly, the use of bilinear surfaces requires use of iterative equation solvers to answer simple questions such as to determine if a given point is on the left or right side of a surface. This is computationally expensive. The advantage is that the representation is close to that of pillar-based simulator grids.

4. Structural modelling workflow

A traditional workflow for structural modelling comprises

1. Interpretation of seismics in the two-way travel time (TWT) domain gives horizon and fault planes, while interpretation of well logs and cores provides subseismic zonation. The seismic interpretation need to be depth converted for reservoir modelling.

2. The seismic horizons and fault sticks are combined into a *consistent* fault model; a seismic framework.

3. Within the seismic framework, zones below seismic resolution are mapped as thickness maps, and these are "snapped" into the seismic framework, making a more detailed geological framework.

4. Based on the geological framework, 3D pillar-based grids for both geological property modelling and for flow simulation are constructed.

This workflow is quite deterministic, and most commercial tools today offer no or just limited support for uncertainty modelling. Reference [11] describes different alternatives on how uncertainty modelling of faults and horizons may be handled. All the alternatives given there may be combined with staircasing faults.

5. Requirements for flow simulation grid

The most popular oil simulators are based on corner-point grids with hexahedral grid cells. In two dimensions non-degeneracy of quadrilateral cells is ensured by positivity of the Jacobian at all four corners (the corner point test). By linearity the Jacobian will be positive at any point in the whole area if it positive on the corners. In three dimensions, however, we no longer have linearity, and therefore the corner point test is not sufficient to establish non-degeneracy [12]. For some cells it is necessary to search for the global minimum of the Jacobian in order to establish if a cell is degenerated or not [13]. This is computationally expensive.

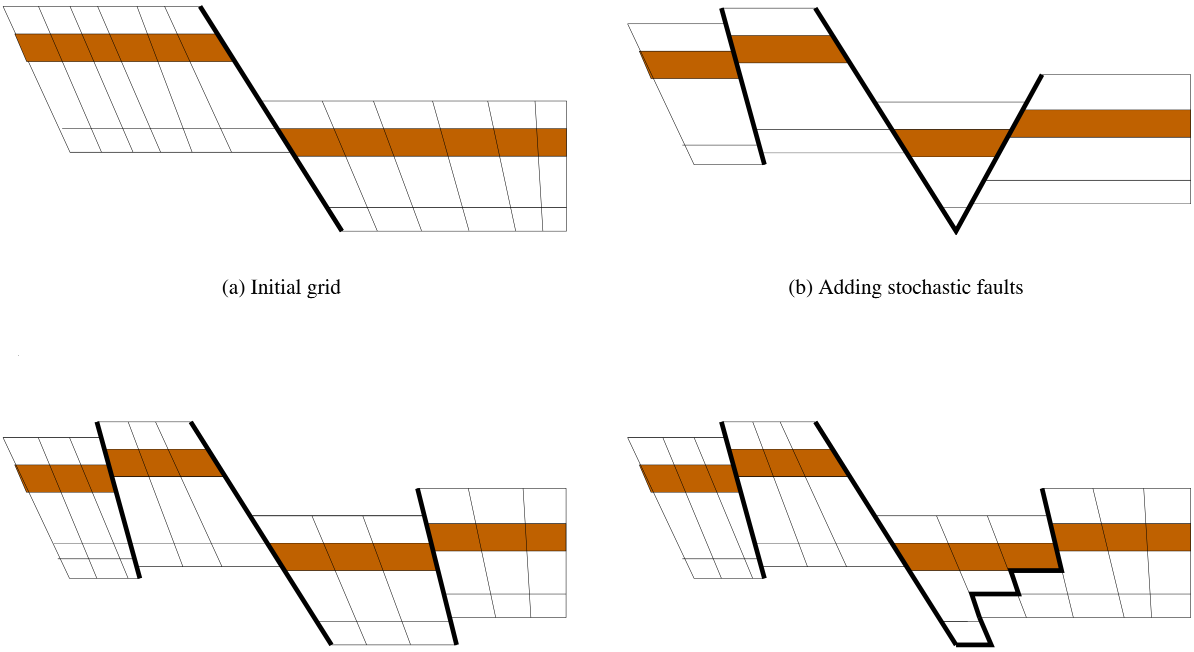
5.1. Staircasing

Stochastic faults almost never happen to be parallel to simulation grid pillars. Sometimes it is sufficient to make a small adjustment of pillars, but often the only way to get faults near their correct position and of the right type requires use of staircasing. This is illustrated in Figure 3 where two stochastic faults are added to a flow simulation grid using traditional pillar adjustments and a staircase. In the traditional approach depicted in Figure 3 (c) one of the faults is transformed from a normal fault to a reverse fault causing wrong volumes of the compartments on either side of the fault. The staircase of Figure 3 (d) fares much better.

Hence, when mapped into the flow simulation grid, the transmissibility multiplier surfaces of faults often have to be staircased both horizontally and vertically.

Algorithm 1 has been implemented for converting PFM faults into transmissibility staircases in the simulation grid. While the algorithm is very simple, there are several practical challenges in this approach. On Line 21 in Algorithm 1 we deform the grid. Here we have to make sure that adjecent grid cells remain adjacent but non-overlapping and that all active grid cells remain non-degenerated. As mentioned earlier for hexahedral grid cell even the test for non-degeneracy is non-trivial.

A simple way to implement staircasing would be to represent sealing fault surfaces as staircases of grid cells with vanishing permeability. Doing this would, however, imply loss of a volume corresponding to one sliver of grid cells. We don't want this, and therefor we represent them as transmissibility multiplier staircases instead. The price paid is difficulties with holes and protruding shelves and baffles along the staircases. The problem of volume loss due to sealed-off cells only happens occationally in individual cells and not in full slices along the staircase as it would if we used a permeability representation. To sum up, the results are promising, and in the field study the algorithm has produced sensible staircases as illustrated in Figure 4.



(a) Initial grid

(b) Adding stochastic faults

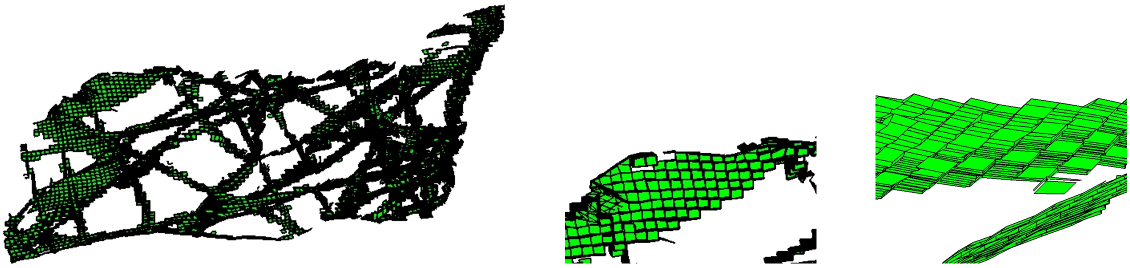
(c) Traditional representation

(d) Staircase

Figure 3: Adding faults to grid. We start with an initial grid (a) with a deterministically interpreted fault. Then two additional faults are added (b). First we represent the new faults by adjusting pillars and mapping them into the nearest ones (c). Then, we represent one of the faults as a staircase (d).

Algorithm 1 Staircasing

```
for all cells in flow simulation grid do
    set cell status unfaulted                                ▷ initialize data structures
end for
for all faults do
    for all cells in flow simulation grid do
        for all corners of cell do
            find location relative to the fault surface
        end for
        determine affected cells
    end for
    for all affected cells do
        for all faces of cell do
            determine facing neighbours
            for all neighbouring cells do
                determine affected faces
            end for
        end for
        add segments to simulation grid faults
    end for
    for all cells in displacement operator support volume do
        deform
    end for
end for
for all faults do
    compute sealing    ▷ using smear gouge ratios and/or shale smear factors and/or clay smear potentials
end for
```



(a) Overview (b) Details (c) Other details

Figure 4: Staircased faults in flow simulation grid

6. Conclusion

In order to get correct volumes in reservoir compartments and as correct positioning of faults as possible in pillar-based flow simulation grid, it is often necessary to use a staircase representation for faults. We have developed and implemented a staircasing algorithm for hexahedral pillar-based flow simulation grids and applied it to a field test case. Deterministic staircasing of certain types of faults is also available in other software [14].

We have pointed out problems related to detection of degenerated grid cells in general hexahedral grids as well as the risk of generating grid cell degeneracy when applying grid deformation operators as a representation of displacement in staircased faults. Despite these problems the results are so promising that the algorithm now is made available in the software described in Refs. [4, 15].

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