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HAVANA - A Fault Modeling Tool

Knut Hollund[a] Petter Mostad[a] Bjørn Fredrik Nielsen[a]
Lars Holden[a] Jon Gjerde[a] Maria Grazia Contursi[b]
Andrew J. McCann[b] Chris Townsend[b] Einar Sverdrup[c]

[a] *Norwegian Computing Center, P.O. Box 114 Blindern, N-0314 Oslo, Norway*
[b] *Statoil's Research Center, N-7005 Trondheim, Norway*
[c] *Roxar Software Solutions AS, P.O. Box 165, N-0212 Skøyen, Norway*

Abstract

Improved knowledge on faults and hydrocarbon seal put pressure on Geologists and reservoir engineers doing reservoir modeling. All geo-knowledge must be built into the reservoir models to assure that it is taken into account in the decision processes. The need for advanced modeling tools is increasing. This paper describes the development of a fault modeling tool, the methodology behind it and examples of fault modeling studies. The general focus of is on the uncertainty related to faults. The tool can be used for sensitivity analysis of fault effects, including:

- Studies of the flow effects of all faults scales
- Adding faults to simulation grids
- Studies of the geometric uncertainty of the faults

The work started out as a development of a tool for stochastic modeling of subseismic scale faults. The faults can be added to a flow simulation grid as both displacement and seal. The current tool has been designed to operate together with the Eclipse flow simulator and the Irap rms program package. Irap rms is the main tool for visualizing output and Eclipse is used to examine effect of the faults on hydrocarbon recovery. The techniques for modeling of fault seal, outputting results in a format that Eclipse can directly utilize, and the possibility for displacing simulation grids has proved useful also to seismic scale faults. This has lead to further development, more detailed fault models and improvements of the general fault modeling capabilities.

Examples of fault modeling, including three field examples, Statfjord, Heidrun and Sleipner, are presented to illustrate ways of including fault modeling as part of the reservoir modeling workflow.

Key words: faults, stochastic model

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1 Introduction

Faults of widely varying sizes are present in most geological rock formations. In petroleum reservoirs, faults are likely to influence fluid flow patterns and they contribute significantly to defining the size and the shape of the reservoir. Whether the focus is on exploration, field development or well planning for a producing field it is important that all available knowledge is taken into account in the decision processes. Possible effect of faults on hydrocarbon recovery and in-place volumes must be estimated.

Fault properties are usually highly uncertain. In order to examine the possible outcomes it might be necessary to run a significant number of sensitivities. A fault sensitivity study typically involve the whole reservoir modeling workflow. The faults are modeled by geologists, but to study their effect on hydrocarbon recovery, they usually are built into a flow simulation model and examined by reservoir engineers. To make this feasible the modeling procedures must be efficient. Fault modeling tools are called for.

The fault modeling tool, Havana has been developed at the Norwegian Computing Centre (NCC) in cooperation with Statoil, Norsk Hydro and formerly Saga Petroleum. The first version was released in 1993 as the result of a fault modeling research project. At that time NCC been involved in fault modeling research since 1989. Since the first release, several fault modeling features have been developed and implemented within the Havana code. The first model with a detailed parametric representation of each fault (PFM) was introduced in 1998 and a combined uncertainty model for faults and horizons was released in 2001. Development is still ongoing.

Havana was originally designed as a tool for stochastic modeling of sub-seismic faults. As such it generates elliptical fault objects, which can be added to a flow simulation grid as both displacement and seal. The inputs to the seal calculations are fault thickness and permeability parameters and its output is transmissibility multipliers. These multipliers can be used directly in flow simulations.

The techniques in Havana for modeling of fault seal, outputting results in a format that ECLIPSE can directly utilize, and the possibility for displacing simulation grids has proved useful also to seismic scale faults. This has lead to further development of Havana to improve its capabilities as a general fault-modeling tool. A parametric fault model (PFM) has been implemented. This is a more complex fault format than the elliptical one.

The current version of Havana has been designed to operate together with the ECLIPSE flow simulator (Eclipse, 1999) and the IRAP RMS program package (Irap RMS, 2000). Havana has a focus on integration and interaction with an Eclipse reservoir model. Properties are modeled in terms of geological concepts, but the results will typically be explored by running flow simulation using Eclipse. Irap rms is the main tool for visualizing output from Havana. Havana has a close integration with Irap rms formats for faults and surfaces, making it possible to transport objects in both directions for visualization or as part of building a model in Irap rms.

2 Features

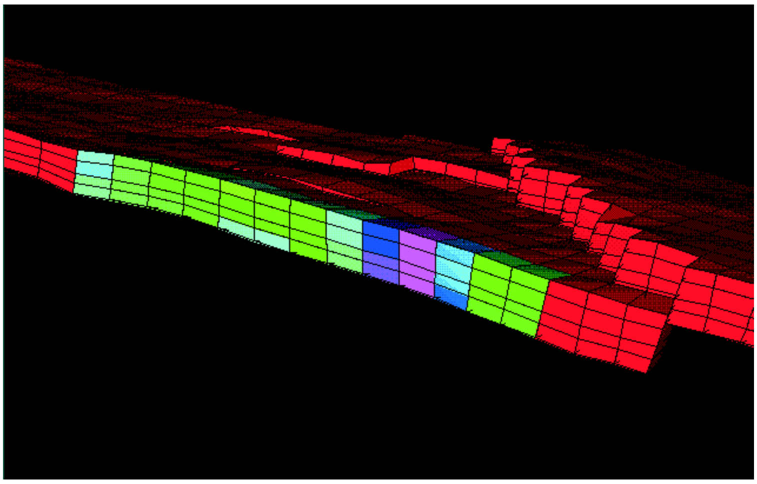

Fig. 1. Fault displacement and properties modeled using Havana

Havana features include: 3D modeling. Modeling of both fault planes and reservoir. Advanced stochastic models including fault truncation and fault interaction or use of fault displacement density for generation of realistic fault patterns. Conditioning on well observations of the presence (or absence) of faults and their properties. Conditioning on well observations of geological horizons. Flexible stochastic models for both fault geometries and fault permeability properties.

For a really useful fault modeling tool, more than an advanced fault model is needed. It is important that the fault modeling is part of the reservoir modeling workflow. To be of any value the modeled faults must show up in a geological model or a flow simulation model. Large variation in reservoirs and fault data call for flexibility. Faults generated or read into a Havana model may be manipulated or applied in several ways: Fault sets can be "split" according to the sizes for different treatment. Reading several sets into Havana can also join fault sets. A flow simulation grid can be deformed according to the fault models and the transmissibility multipliers may be generated according to the simulated fault surface properties. Alternatively, geometry and seal effect of faults can be transformed into a change in permeability field values. Modeled faults may also be used to deform surfaces as part of building a geological model. Havana can also compute intersections of well paths with fault sets.

The need for a fault modeling tool for larger faults (near and above seismic resolution) lead to the Havana PFM and more features: The displacement is allowed to vary by any amount along the fault surface in the PFM model, and strike changes and variable heights along the fault can be modeled. Fault permeability can now be modeled using shale gauge ratio (Yielding et al., 1997), shale smear or clay smear potential (Lindsay et al., 1993) in addition to the absolute and displacement dependent fault permeability models which was previously implemented. Several ways of modeling fault thickness are available. These range from simple Gaussian og Lognormal distributions, to models of spatial variations along the fault surface, via methods were the uncertainty is linked to displacement or facies information.

3 Fault Models

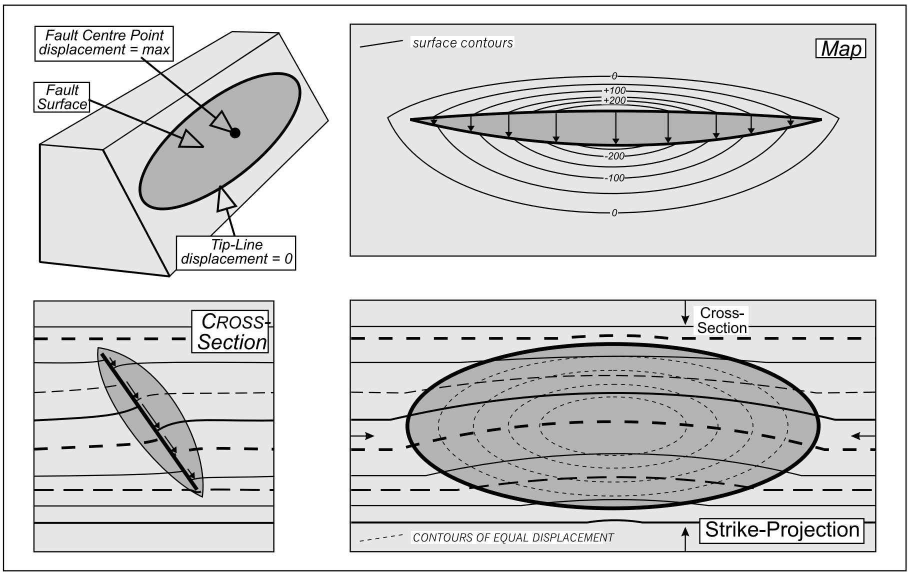

Fig. 2. Elliptic fault model

Faults vary hugely in size and the level of detail needed in order to examine their impact on fluid flow is variable. Consequently, Havana uses different fault models, differing in complexity from very simple quite flexible. The two types currently implemented are:

- The elliptic fault model. The fault plane in this model is an ellipse (Fig. 2). Elliptic faults are typically used for modeling small (below seismic resolution) faults.
- The parametric fault model (PFM). The fault surface is here a sequence of

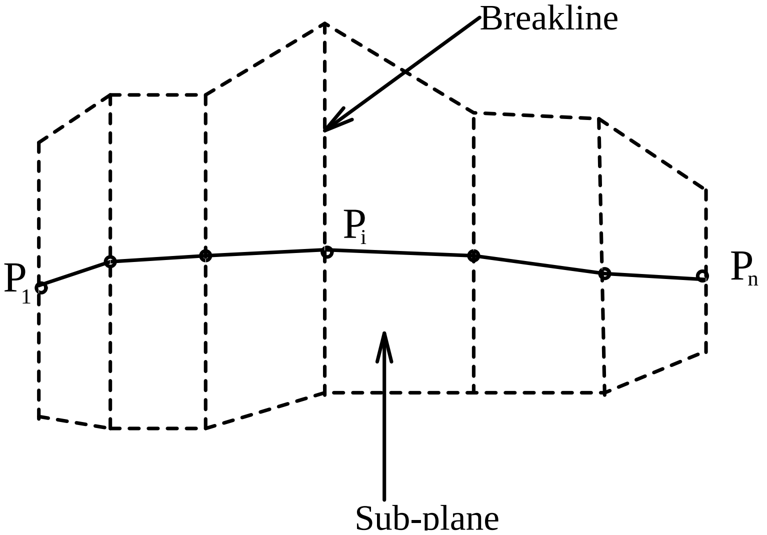

Fig. 3. Parametric fault model

bilinear planes. The planes meet at pillars (Fig. 3). PFM faults are typically used to model larger faults known or partially known from seismic data.

In addition Havana use Irap rms and Eclipse fault data. As mentioned, Havana faults can be exported to Irap rms for visualization or further modeling. The other way round is also possible and relevant. For Irap rms faults the fault plane is a triangulated surface i.e., it is very flexible. Havana reads, writes and uses Irap rms fault data including the fault surfaces. The fault surface can be used directly in the simulation of sub-seismic faults, extensions of Irap rms faults can be modeled in Havana and the Irap rms faults can be approximated by elliptic or PFM faults and used in the Havana modeling. For details of the Irap rms fault data consult Irap RMS (2000).

The Eclipse grid used by Havana is a corner-point grid with straight pillars. A such grid is specified by the coordinates of the top and bottom of the pillars (called “coord lines”) and the vertical position of the grid cell corners for each coord line (called “zcorn values”). For Eclipse a fault can be modeled by adjusting the zcorn values, causing non-neighboring cells to be connected and/or adding fault seal as transmissibility modifiers at cell boundaries. The main purpose of Havana can be said to be generation of Eclipse fault data, i.e., deform a grid and calculate transmissibility modifiers. Havana reads, writes and uses Eclipse data in order to accomplish this. In addition Havana can read faults previously specified in an Eclipse grid using the Eclipse codeword faults for further modeling of sealing properties. The data specified by the Eclipse codeword faults is simply a specification of a collection of grid cell connections.

The feature that distinguishes Havana from many other fault modeling packages is that it models not only the fault surface, but also the deformation that created the fault (or at least an idealized version of this deformation). Inside the volume of deformation a deformation operator is defined, moving the reservoir in different directions on each side of the fault plane. The definition of the deformation operator is based on results presented in Barnett et al. (1987) and Walsh and Watterson (1989). The displacement is defined as a dip-slip displacement.

For elliptical faults, the volume of deformation extends in an ellipsoid around the fault plane (see Fig. 4). PFM faults have a triangulated region around the fault surface in which the deformation occurs.

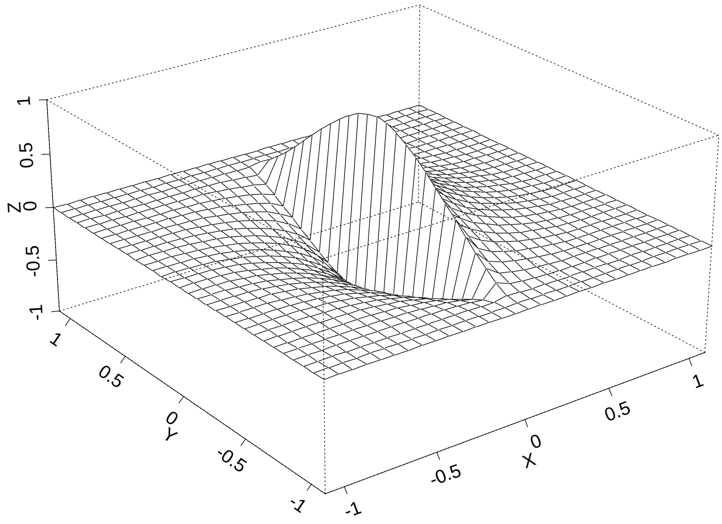

Fig. 4. Elliptic fault deformation operator

The fault deformation operator makes it possible to model for example subseismic faults, and then study their "geometric" effects on the reservoir, in addition to the flow effects of the fault surfaces. In heterogeneous reservoirs, the geometric effect may be quite important. The modeling of the faulting deformation for larger faults also makes it possible to easily and accurately generate correspondingly faulted Eclipse grids, where the faults appear as non-neighbor grid cell connections.

The deformation is determined by a mathematical formula that can be inverted. This makes it possible to both "apply" and "remove" faults. This is very useful from a modeling point of view as can be seen in the section 4.3.

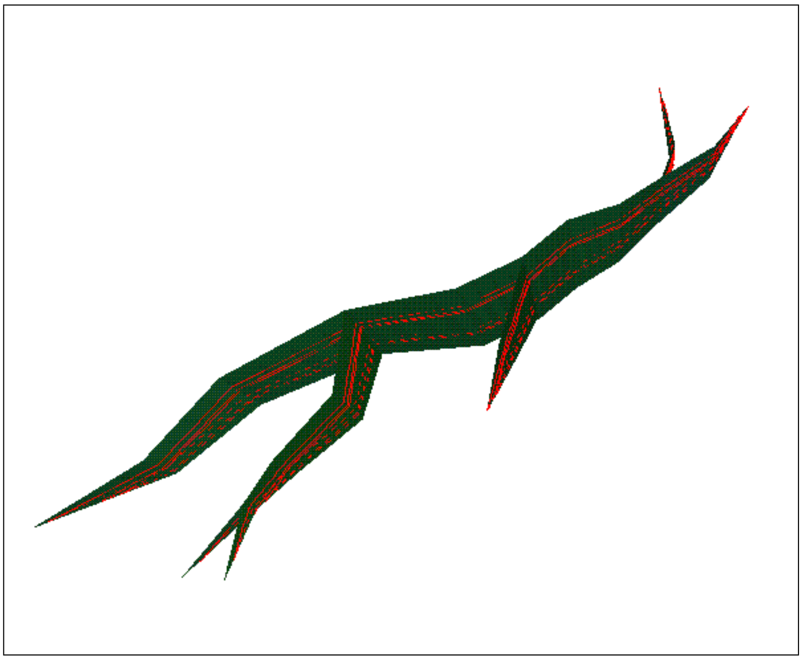

Fig. 5. Branching fault modeled using truncations

3.2 Fault Truncation

Truncation is another part of the fault modeling that greatly improves the geological realism of modeled fault patterns (see Fig. 5). Both elliptic and PFM faults may be truncated against other fault planes. The truncation also applies to the model of the deformation. Thus one may model patterns of branching fault planes.

3.3 Impact on the Flow Properties

Both the thickness and permeability in the fault plane are modeled (see Fig. 6). These properties are important in determining the impact the faults have on the flow. The models for thickness and permeability are quite flexible, and there are also ways to visualize these properties along the fault planes before they are transformed into transmissibility multipliers. There are options for smear-gauge-ratio and shale-smear factor. These may also be applied to faults on ECLIPSE format.

There are two ways in Havana to study the impact of faults on production and flow properties. The first is to add the faults to the ECLIPSE grid (Fig.1). Faults are added to the ECLIPSE grid by first adding their displacement effect, and thereafter adding the transmissibility multipliers to represent the fault seal effect. Only the component of the displacement parallel to the COORD lines is used for displacement, so if the grid is dipping in a different direction

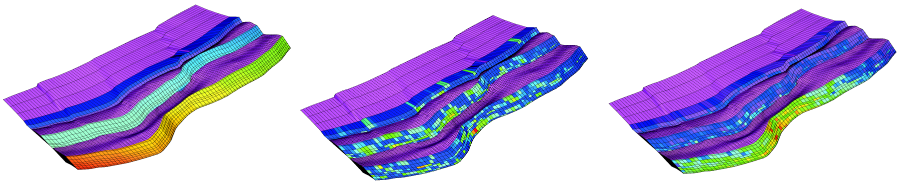

Fig. 6. Fault properties: (left) displacement property and two realizations of thickness property.

than the faults, then their total displacement appears to be reduced. The transmissibilities are computed so that this effect appears in the same cells as the discontinuity of the displacement.

The second way to study the impact of faults on production and flow propertiesis to add them directly to some gridded permeability field representing the reservoir (Fig.9).

The choice between the two options may have a significant impact on the result. Generally, faults that are larger than the Eclipse grid cells should be entered into the Eclipse grid. Both their displacement and their fault seal effect are then reasonably well represented. However, if the faults are equal or smaller in size than the Eclipse grid blocks, they may very well disappear completely. Such faults should be added to the permeability.

4 Simulation

4.1 Simulation of Sub-seismic Faults

The first stochastic fault model implemented in Havana (reported in Munthe et al. (1993)) did not easily generate realistic fault patterns compared to real fault systems. A study of a South Yorkshire fault map provided by the Fault Analysis Group, University of Liverpool, lead to the current fault pattern model (reported in Munthe et al. (1994)). The model is built on the following premises for sub-seismic faults:

- The larger of these faults tend to “repulse” each other, i.e., they are more separated in space than they would have been if they were located randomly and independently.
- The smaller faults tend to be located around the larger faults.

To accommodate these effects, the elliptic fault model differensiate between the larger faults - which are called mother faults - and the smaller faults - which are called children faults. There is one stochastic model for mother

Fig. 7. A Havana fault pattern realization.

faults, and one stochastic model for the children faults, given the mothers. The basic simulation algorithm is:

(1) Read in interpreted faults (or previously simulated faults).
(2) Simulate new mother faults, using a point process with interaction.
(3) Simulate children faults based on the realization of the mother faults.
(4) Truncate faults.

The mother faults are distributed throughout the reservoir according to a marked point process (Stoyan et al., 1987), i.e., the state-of-the-art geostatistical technique for modeling geological "objects" like sand bodies, calsite deposits, faults and so on. The location of the faults as well as the properties of the faults are stochastic. The locations of mother and children faults are specified by intensity maps which should indicate regions more likely to have sub-seismic faults than other regions. Intensity maps could be derived from seismic attribute maps.

To accommodate that the larger faults are separated in space, interaction functions must be specified. It is important to include the interpreted faults when new faults are added, so that they may interact with each other.

Children faults are located in a neighborhood around the mother faults. Their location is therefore based on the point process which governs the mother faults as well as the deviation from the mother location. Both interpreted and new faults will be given children faults.

The user can specify how the children faults should be distributed in the length direction, the height direction, and the reverse drag direction of their mother. Several parameters are available to control the distribution. E.g., it is possible to have increased intensity at fault tips, within fault relay ramps and/or different fault intensity at footwall and hangwall side of the mother fault (see Fig. 8).

The properties concerning the orientation of the faults like strike and dip, can be specified in several ways. Both variables are on a continuous scale and nothing indicate need for asymmetric distributions, thus they are modeled using a simple Gaussian distribution with a given mean (expectation) and standard deviation. These parameters can be given as constants or trend maps. There is also a third option for the strike direction, where the user may specify a number of main directions. Each main direction is given by an expected value and standard deviation as well as the fraction of faults to be simulated for each main direction.

The strike and dip for the children faults are also assumed to follow Gaussian distributions. The expected value in these distributions is controlled by the strike or dip direction for the mother fault, while the standard deviation is given by the user. Parameters are available to control how the expected strike of the children faults relate to the strike of the mother fault. E.g., a fraction of the children faults can be specified to have expected strike perpendicular to the strike of mother fault.

In Heffer and Bevan (1990) and Childs et al. (1989) the maximal displacement in fault populations are reported to follow a fractal distribution. Relationship between the displacement and the size parameters are reported in Walsh and Watterson (1988), Barnett et al. (1987) and Gillespie et al. (1992). For Havana the fault displacements are drawn from a fractal distribution with fractal dimension, minimum displacement and maximum displacement as specified by the user. Mother faults will however always have displacements that are larger than those of the children faults. The length of the principal axes for both mother and children faults are derived from the displacement. The length (l), height (h) and reverse drag (r) of the fault is assumed to approximately be related to the displacement (d)in the following way:

$$l = (d/c_1)^{1/p_1}, \quad c_1 l^{p_2} = d, \quad h = l/c_2, \quad c_3\sqrt{l \cdot h}$$

The parameters have to be given by the user, together with a variability around the values from these deterministic functions.

4.2 Conditioning

A fault realization may be conditioned to assure that individual faults observed in wells are reproduced by the simulations. A fault realization may also be conditioned so that none of the fault operators move the positions where seismic surfaces have been observed in the wells. Further, a fault realization may be conditioned so that seismic horizons are not moved outside the specified seismic resolution band.

The fact that a seismic horizon has been observed in some well does not imply that sub-seismic faulting never moved the observed point. Rather, it means that the point has been moved to its present location by all the faulting events that have taken place.

Havana models “pre-faulted” or “non-faulted” horizons corresponding to how the observed seismic horizons were before any sub-seismic faulting took place. These “pre-faulted” horizons must be constructed so that when simulated faults are added to them, the seismic horizons will pass through the wells where they have been observed, and they will stay within the seismic uncertainty band. In Havana, the “pre-faulted” horizons are constructed by adding an “adjustment operator”, a 3D Kriging operator, to the seismic horizons. The operator moves points vertically, and is zero except for places where seismic horizons have been observed in the wells, or where the fault realization sends the seismic surfaces out of the seismic uncertainty band. At these points, special “conditioning points” are computed. Around these points, the value of the adjustment operator is Kriged with an exponential variogram, with ranges determined from the size of the largest simulated faults.

Now, conceptually, to make a stochastic reservoir description, one should first simulate a sub-seismic fault system, then apply the resulting adjustment operator to the seismic horizons to get “pre-faulted” horizons, then simulate facies and petrophysics between these horizons, and finally applying the sub-seismic fault system to the result. This is clearly impractical, but fortunately, it is possible to make a shortcut. Almost the same result as the above is obtained by first simulating facies and petrophysics realizations between the seismic horizons, and then apply the adjustment operator. In fact, the adjustment operator of Havana is viewed as a part of the fault system realization, and is stored together with it.

There is a considerable uncertainty in the large seismic faults modeled by the parametric format. The uncertainty is in both the exact position and the displacement. This uncertainty is important for both volume calculations and positioning of wells, as well as in a full reservoir characterization framework.

A common stochastic model for the horizons and faults has been established. The model for the horizons may include depth conversion. Each horizon is described by a time horizon or an expected horizon in depth. A linear velocity model is assumed. All horizons are modeled as correlated Gaussian fields, and erosion is handled by truncation of the Gaussian fields. Parameters in the velocities and trend surfaces are conditioned using Bayesian conditioning, see Abrahamsen (1992). The model handles a large number of horizons and well observations simultaneously. Observations of deviating wells influence position and uncertainty in position above and below the observations. The inversion of the fault operator is necessary in order to condition on the well observations.

Realizations of the structural model are generated by the following work flow:

(1) Generate the horizons based on time horizons, trend maps, the velocity model, prior model for all parameters and all well observations of horizons.
(2) Apply the inverse fault operator
(3) Smooth the horizons in the neighborhood of the fault planes.
(4) Add Gaussian field (noise) for maintaining well observations and variability in the support area of the smoother.
(5) Apply the fault operator.
(6) Calculate foot-walls, hanging-walls and branch lines for all faults.

5 Fault Modeling Examples

Only a few papers describing applications of Havana have been published (Damsleth et al., 1998; England and Townsend, 1998), but Havana is used as part of the reservoir modeling workflow for both Norsk Hydro and Statoil and have been used for several fault studies. The program is also in use at Conoco and British Gas.

Statoil has used Havana for fault studies on several fields, including: Åsgard and Norne (small seismic faults (elliptical) and fault seal calculations), Statfjord, Sleipner, Heidrun, Gullfaks (sub-seismic fault modeling) and Huldra. A

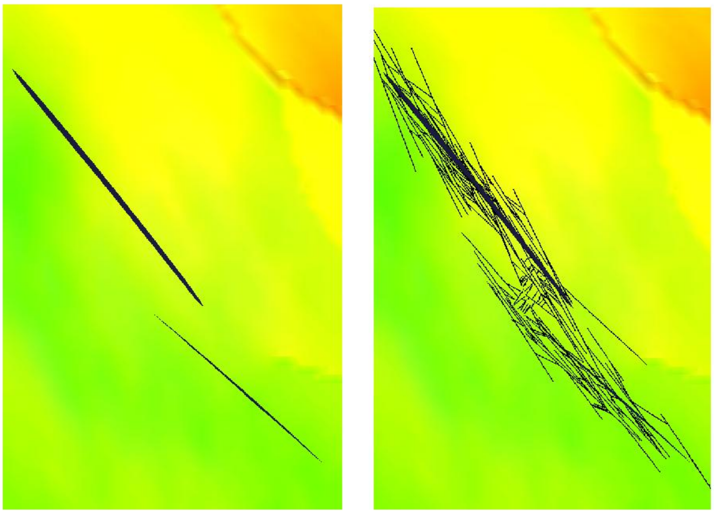

Fig. 8. (left) A relay ramp structure and (right) its damage zone

few examples are presented below.

5.1 Modeling a Relay Ramp Structure

Figure 8 shows two examples that demonstrate sub-seismic realizations as created by Havana. The first example shows two single, sub-parallel Havana faults (mothers) that exhibit a relay zone in between (left display). The typical character of a relay zone is that of a complexly deformed (faulted) area. The children faults in this example are those structures that are located in the damage zones of the mother faults and within the relay ramp structure (right display). The realization of 300 children faults as shown here, was modeled in one single step by specifying the intensity field of the relay structure, the damage zone geometry, strike and dip variations, number of (children) faults, as well as fault population rules. As will be demonstrated below, the introduction of such structures will have impact on the permeability field of the reservoir.

Small faults are commonly included in the flow simulation grid without displacement, but by modifying the grid permeability. Figure 9 displays a part of an Eclipse grid where the effect on the permeability field by the relay ramp structures in Figure 8 has been implemented. The introduction of fault plane effects depends on parameters such as fault rock permeability and thickness, as specified by the user. Because the faults in this example have been given lower permeability values than the surrounding reservoir rocks, the permeability is reduced in the area close to the relay ramp structure.

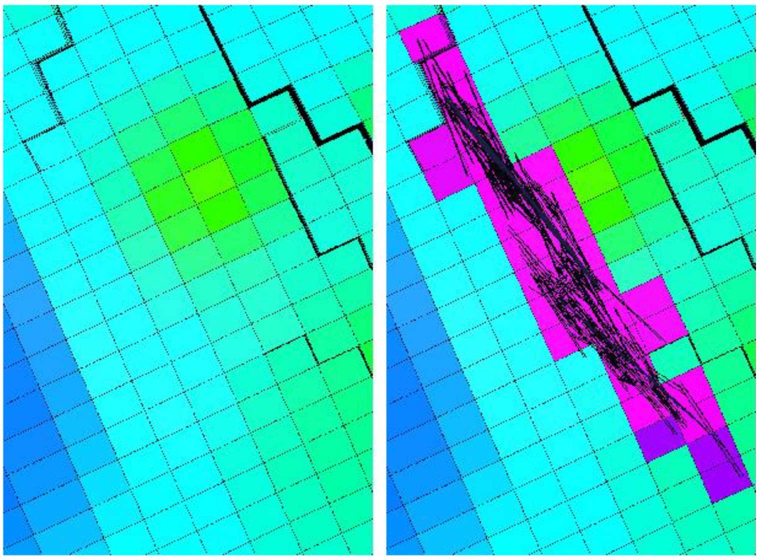

Fig. 9. A part of an Eclipse grid colour coded by the permeability values. The original permeability field is shown to the left, while the modified permeability field is shown to the right.

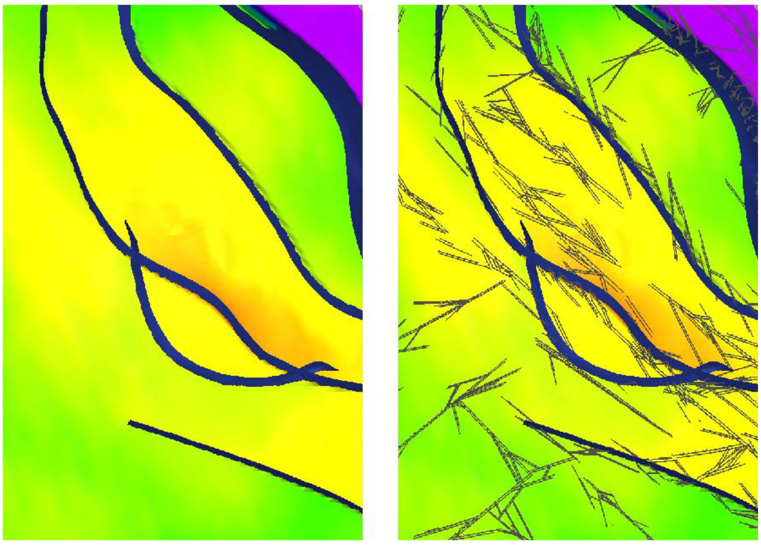

Fig. 10. A realization of sub-seismic faults (right display) generated into a model with interpreted faults (left display).

5.2 Streamlines for Investgation of Fault Effect on Fluid Flow

As an quick alternativ to a full Eclipse flow simulation. The effect of sub-seismic faults can be examined by streamline calculations. Figure 10 shows a realization of a fault model that is introduced to a reservoir that already contains large, interpreted faults. In the new fault model both new "mother" faults (50) and "children" faults (950) are introduced according to fault population and distribution relationships defined by the geologist.

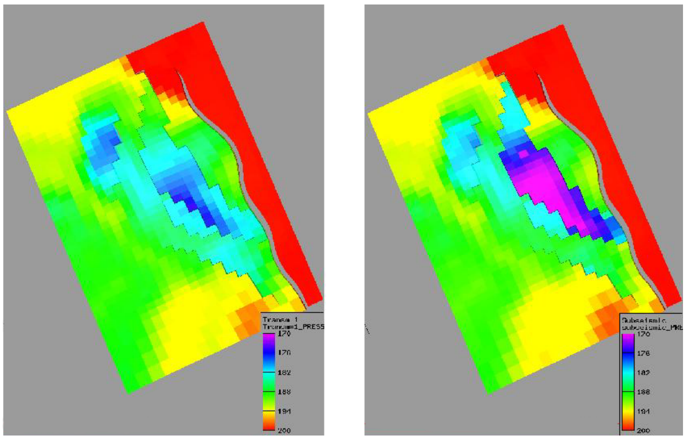

Fig. 11. Reservoir pressure after 100 days of production/injection. The original model to the left and the model with sub-seismic faults to the right.

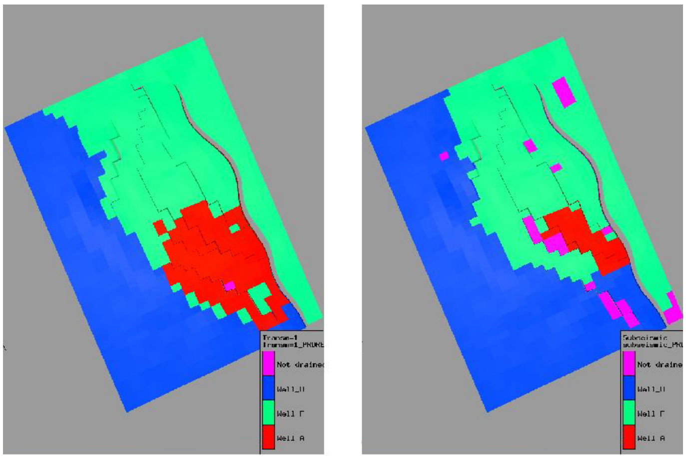

Fig. 12. Production regimes. The original model to the left and the model with sub-seismic faults to the right.

By changing fault parameters such as the number of faults, size and throw variations, strike and dip, as well as repulsion and truncation rules, new fault realizations can be generated rapidly. The effect of introducing the sub-seismic fault structures on the hydrocarbon recovery of the reservoir will be shown below.

Fig. 11 to Fig. 14 demonstrates how the effect of sub-seismic faults on fluid flow can be investigated by the use of the streamline module within Irap rms. The method includes dynamic information from wells, and represents a quick and visually important step in validating fault models for continued modeling. In the example below modified permeability fields have been obtained from the sub-seismic fault pattern shown in Fig. 10, as well as transmissibility information for the large faults as derived from Havana.

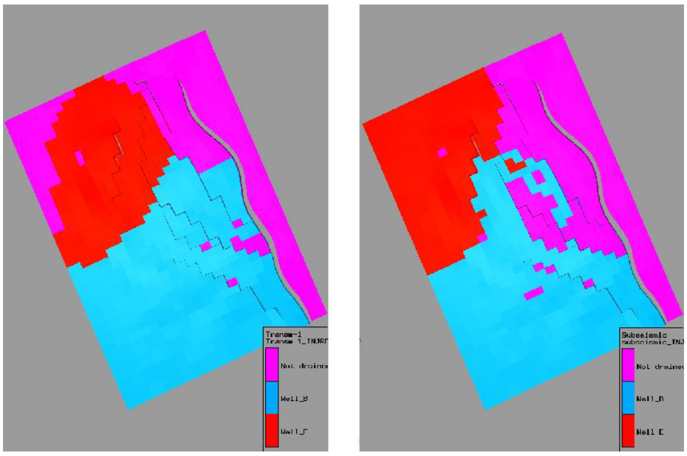

Fig. 13. Injection regimes. The original model to the left and the model with sub-seismic faults to the right.

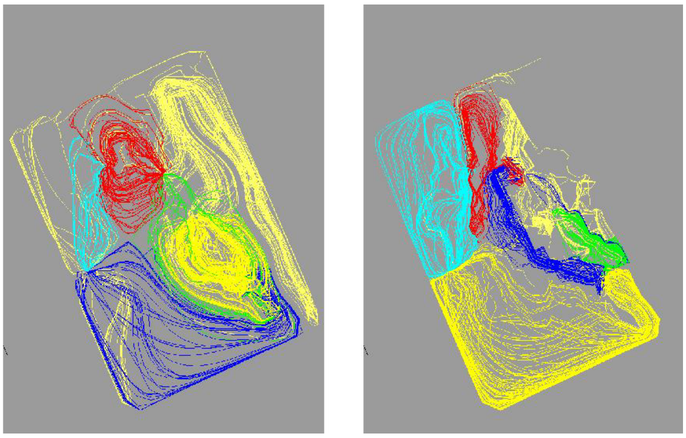

Fig. 14. Streamlines after 100 days of production/injection. The original model to the left and the model with sub-seismic faults to the right.

5.3 Statfjord

Havana formed a crucial role in building the first geometrically realistic model of the Statfjord East Flank. This structure comprises 3 main slumped fault blocks sitting at the top of a major rotated fault block. This rotated block forms the main part of the Statfjord Field. The seismic data quality over the East Flank is generally very poor with only the Base Cretaceous unconformity and the basal slope failure to the slump blocks visible. The three main slump faults can usually be mapped on seismic along with several smaller slump faults and it has been observed that these slump faults detach deeper in the stratigraphy the further east they lie.

Previous models have relied heavily on well data, because there is little structural control from the seismic data this often lead to a model where geological horizons became deeper eastwards. The slump faulting downthrows the stratigraphy to the east, but the actual layering dips westwards towards the east dipping slump faults. Consequently these previous models were not able to realistically capture the known structural geometries.

The modeling process used relied upon the geological concepts outlined above in order to try and generate a realistic 3D framework model. The well data were not used until the final stage of modeling and even then not all the data could be utilized. The following modeling steps were followed:

(1) A set of unfaulted and extrapolated geological horizons was created. These were generated using an intra Ness horizon from the main field where it is well constrained and projecting it eastwards. The other horizons were then isochored using a combination of main field thickness data and well data from the East Flank.
(2) The three main slump faults were converted into Havana's PFM fault format. Two versions of these faults were generated, the first had zero displacements and the second had true displacement values that were extracted from the seismic data at 4 or 5 specific points along the length of each fault.
(3) The zero-displacement PFM faults were converted to the IRAP RMS fault format, using the extrapolated surfaces to generate fault lines for each horizon. These faults were then imported into IRAP RMS.
(4) A 3D grid was built in IRAP RMS using the extended surfaces and the zero-displacement faults. The faults were used to control the positioning of the i-coordinate lines of the grid so that later the displaced faults can be added without forming a zig-zag structure. The number of grid blocks included in the model was varied in its different regions. This was to improve the efficiency of the simulation where details were not required (ie few blocks were used on the main field and on the most easterly slump block) and in the 2 main slump blocks, where more detail was required, a finer grid size was used.
(5) This 3D grid was exported as an ECLIPSE format and Havana was used to displace it using the true displacement faults. The faults had the same location as their zero-displacement counterparts and therefore allowed the displacement to be located exactly along a single i-coordinate line. Havana has a function for displacing a selected number of layers within a 3D grid. This option was used to help include the effect of the detachment surfaces.
(6) The smaller faults were modeled as Havana elliptical faults and these were added to the grid as zigzag structures.
(7) The final grid was then adjusted to the wells wherever possible. In some cases this gave unsatisfactory results, in which case the wells had to be either relocated to give a more acceptable result or omitted altogether.
(8) The 3D grid was then truncated by the erosional Base Cretaceous unconformity and the main bounding fault to the east (not illustrated in the

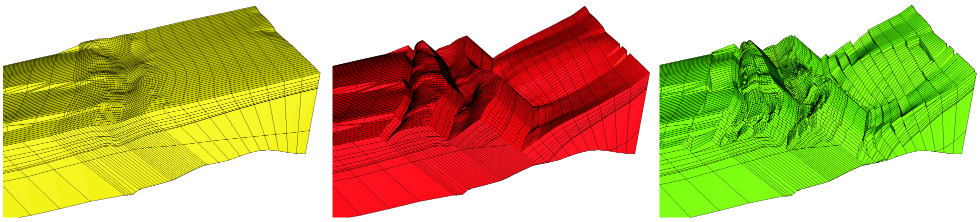

Fig. 15. Statfjord East Flank fault modeling. (left) 3D grid built around the fault framework (zero displacement), (middle) 3D grid displaced by major faults, (right) 3D grid displaced by smaller seismic faults.

figures).

(9) The final step of the modeling was to use Havana to estimate the effects of fault seal and convert this to Eclipse transmissibility multipliers.

5.4 Heidrun

A detail 3D reservoir model was built covering a 3 fault blocks from within the Heidrun Field (H, I & J blocks). The main aim of the study was to examine the effects on production and well placement of the smaller intra-block faults. These smaller faults are only just visible on the seismic data and because of this there is considerable uncertainty to their precise geometry. When the dataset was given to two different seismic interpreters, two distinctly differing fault patterns emerged.

A 3D structural model was built using the main horizons and the block-bounding faults by 'conventional' modeling techniques in IRAP RMS. The intra-block faults were included in this model with zero displacement so that the locations of the displaced structures were pre-defined. They were initially described using Havana PFM format and then converted to the IRAP RMS format as surfaces and fault lines. The intra-block faults were then added later as displacements using Havana. The advantage to taking this approach was that the uncertainty in displacement could be assessed because the displacement values lie within the PFM fault format files, which could be easily edited. Moreover, the different fault geometries could also be assessed by generating different sets of PFM format faults which reflect the different interpreted fault patterns.

Havana was used to generate the fault related transmissibility multipliers. These were modeled using stochastic techniques for the estimation of fault permeability and thickness. This allowed the uncertainties related to fault sealing to be assessed and compared to those related to fault geometry and displacement.

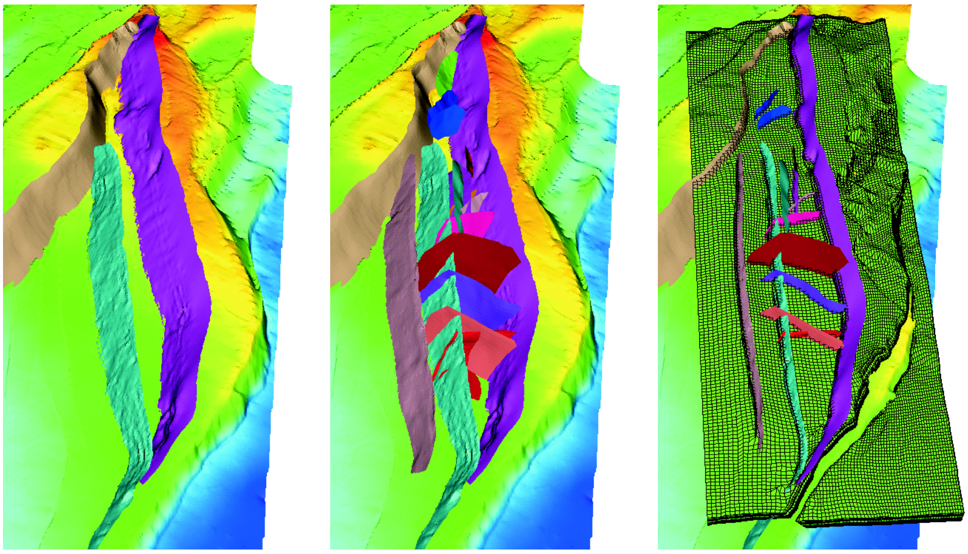

Fig. 16. A 3D fault model from the Heidrun field showing (left) the larger block bounding faults, (middle) the block bounding faults and the smaller block internal faults, and (right) 3D grid built on the structural model.

5.5 Sleipner

Havana fault modeling techniques have been applied to the Sleipner Field where a reservoir simulation model already existed. The Sleipner Field has possibly one of the most complex fault patterns of any of the fields in the North Sea. The segment of the field being studied had a number of small seismically mapped faults, which had not been included in the simulation grid. These faults were converted to Havana's elliptical fault format and added to the grid as a displacement operator. The smaller faults within the Sleipner field often intersect, so the truncation option in Havana was used in an attempt to recreate the correct fault geometry. There was some uncertainty to the extent of the smaller seismic faults, the concern was that some of the faults might have been longer than they had actually been mapped. Therefore a second set of faults was generated whereby the length of the faults were increased by 500 m. This was carried out by simply editing the length parameter in the elliptical fault file.

Havana was used to account for the effects of fault seal, using the SGR and shale smear algorithms. A comparison of the different techniques was used against known production data. The best history match was achieved when SGR and shale smear were both used in combination with the extended fault lengths. Part of the fault seal modeling in Havana includes calculating a number of fault properties (e.g. displacement is calculated from the 3D grid and thickness is modeled as a function of displacement). Some of these parameters are shown in Fig. 17.

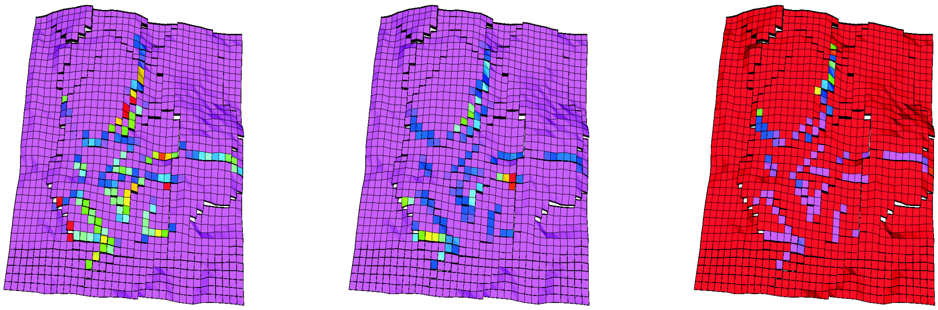

Fig. 17. Fault modeling of the Sleipner field. (left) displacement, (middle) thickness and (right) transmissibility multiplier

6 Conclusions

Advanced fault models and flexible fault modeling tools are essential if the uncertainty related to fault geometry and fault sealing should be efficiently and consistently examined. For proper examination of the effect on fluid flow the fault models must be incorporated into the reservoir modeling workflow that results in flow simulation models.

The development of improved fault modeling techniques is still ongoing. Havana still is a research product, nevertheless, Havana already is a flexible tool that can be introduced at a number of stages in any 3D modeling process. Some of these options have been outlined in the examples presented. A summary workflow diagram is presented in Fig. 18 which attempts to summarize how Havana fault modeling techniques can be used in combination with a number of other tools. The tools that have been specified are not necessarily unique in any sense whatsoever and Havana could also be used in combination with alternative commercial software products.

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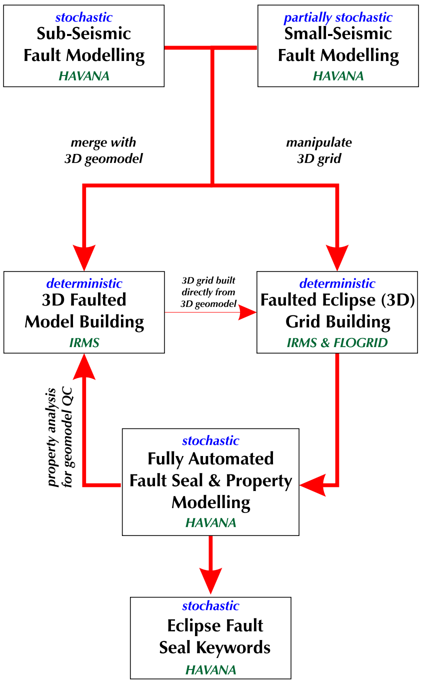

Fig. 18. Possible workflow for fault sensitivity studies. Sub-seismic faults (top, left) simulated using Havana can be incorporated in a geomodel (middle, left), the geomodel can be used for generation of a flow simulation model (middle, right), for quality control or well-planning purposes. Alternatively the sub-seismic faults can be added directly to the flow simulation model. Faults partially known from seismic data and modeled by Havana (top, right) can be included into the reservoir models similar to the sub-seismic faults. Some of the fault properties modeled in Havana can be read into the geomodel for quality control or further modeling, other parts of the seal modeling (typically larger faults) can be entered directly to the flow simulation grid (last box).

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